EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN – PS DIVISION

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1. Introduction and Highlights

Although not a vintage year, solid progress was achieved in 2001 in the PS Complex. The year started with a short continuation of LIL operation, even though LEP had stopped some months earlier. This was because, after the prolongation of the LEP running time for the Higgs search, there was insufficient time left in 2000 to finish various vacuum tests essential for LHC. Thus, although it delayed the modification of LPI for CTF3, electrons were delivered from LIL for a last period of 8 weeks, culminating, as is usually the custom at CERN, in a reception and some speeches reviewing the successful operation of LPI for 16 years. Just before LPI stopped, the Division hosted MDK2001, a very successful Modulator Klystron Workshop (fifth in the series), which was attended by over 100 experts from all parts of the world and attracted sixteen international company sponsors. After the annual shutdown, the first and only PS run of the year was a long proton run interrupted by two short technical stops. There was no scheduled lead ion run this year. But there was more time to concentrate on protons, with intense machine development activity, especially on the PS. Further improvements were made to the future LHC beams, and a new intensity record for the PS beam was established. Another exciting result was progress on a new type of continuous transfer that should bring great benefits in the future, allowing the beam to be extracted from the PS with fewer losses. Meanwhile, ISOLDE and the AD facility both functioned well, and ISOLDE achieved its highest number of hours of physics since the move to the Booster. Overall, in spite of diminishing resources, we were able to keep the accelerators functioning well and the users happy. There was also good progress on R&D, with significant advances on CLIC, CTF and SPL, all of which have important implications for the future of CERN beyond LHC.

2. Operation of the Accelerators

The PS Complex shutdown finished earlier than usual when, after a week of hardware tests and a week of beam tests, regular operation of LPI started on 26th February. The clients were the photon beam lines, for LHC vacuum system testing, and the CMS irradiations in the LEA zone. This run continued until Easter, when LPI supplied its last electron beam on 12th April. Immediately afterwards work started to convert LPI to the CLIC Test Facility, CTF3.

By the third week of March, Linac2, the PSB and the PS were all running and getting ready to supply beam to the users. The SPS was not scheduled to start until late June, so beams were prepared for the East Hall, nTOF, AD and ISOLDE. At the end of March there was a serious vacuum leak at ISOLDE on the GPS front-end that looked at first as though it would prevent the GPS running for most the year, since the only spare front-end had been installed on the HRS during the shutdown. The leak was eventually repaired in situ and GPS operation started two weeks late in the middle of April. ISOLDE worked with both GPS and HRS taking beam at 1.0 and 1.4 GeV and the intensity on target regularly exceeded 3.2 x 10^{13} protons/pulse.

All the other PS Complex users started physics operation as planned. In the East Hall things were particularly busy with the new HARP experiment taking its place along side DIRAC and the Test Beam users. This was also the first period of data-taking for the nTOF collaboration. The first neutron studies at this facility began in April, with dedicated proton pulses up to 7 x 10^{12} at 20 GeV from the PS. By the end of the month the nTOF facility was also profiting from parasitic 20 GeV proton pulses on the EASTC cycles. The facility continued to run more or less continuously until June. However, the first measurements revealed an unexpectedly large neutron background in the experimental zone and data taking was stopped while the origin of the background was investigated.

Following four weeks of MD and setting-up, AD physics started in the second week of May. The run got off to a rather shaky start, with poor beam quality and availability, but by the end of May the antiproton beam quality had been improved for all the users. This was due to a number of improvements in the AD beam stability at 100 MeV/c and a steady increase in the production beam intensity from 10^{13} protons/pulse in April to 1.75 x 10^{13} in June. These improvements led to record circulating antiproton intensities of 4.5 x 10^{7} at 100 MeV/c.

After a very promising start in the East Hall, the HARP experiment had several detector problems and full data taking did not start until July. However this period was used to set up the HARP beam line at all the required beam energies from 2 to 15 GeV. DIRAC operation was relatively trouble-free until the beginning of June when a number of problems adversely affected the whole PS Complex. On 3rd June a transformer failure on the Prévessin site cut all electrical power. This was unfortunately a holiday weekend, and the restart took almost 24 hours. In addition, a number of problems were encountered in the following week as a result of the power failure.

During the first 12 weeks of operation, a large number of MD studies were possible at the PS, since the SPS was not scheduled to start until the end of June. An "improved" LHC beam was prepared. The double bunch splitting process at 26 GeV/c is completely new and gives better control over the bunch-to-bunch intensity variations, which must be less than 10% for the LHC. Although the new scheme worked well, it involved keeping the 72 short bunches in the PS longer than before, and this seemed to give some stability problems due to the build-up of electrons in the beam. Other studies included the PSB-to-PS transfer line matching, double batch PS injection at RF harmonic 8 (for the future SPS beam to CNGS), and dispersion measurements in TT2. A lot of work was also done on the proton beam to nTOF. This had the double objective of improving the number of neutrons for nTOF and investigating the bunch intensity limitations in the PS for all future high intensity beams.

The only schedule interruptions to PS Complex operation were two 12-hour technical stops in June and August. These are essential for maintenance work on the PS main power supply and the heat exchangers of the various cooling water systems. However, the recovery from the first stop in June was rather painful due to a high voltage breakdown on the cable of an electrostatic septum in the PS.

At the end of June a series of hardware problems dogged the East Hall beam lines. There was a serious water leak on a quadrupole in the South branch. At almost the same time another similar quadrupole in the North branch failed. Since no spare magnet was available (the spare had been installed during the shutdown to replace yet another broken quadrupole), a temporary repair was made in the South branch, and the North branch optics was adjusted to allow operation without the faulty magnet. These were the first in a series of breakdowns at the East Hall, but worse was to come. A dipole magnet (F61.BHZ01) failed in the South branch in early October. Again there was no replacement magnet available and, as a result, the failure of this dipole stopped both the DIRAC experiment and operation of the T7 irradiation line for the last 3 ½ weeks of the run.

It became clear by the end of June that the interruption to nTOF operation by the background problems would be quite long. In fact, apart from a few days of tests, nTOF operation did not restart in 2001. These background problems appear to be caused by the layout of the target and the nTOF experimental area.

However, there was some good news. At the AD things were running smoothly, and throughout the summer and autumn the antiproton beam availability steadily improved. In addition, improvements to the electron cooling performance led to a shorter AD cycle, which also increased the beam availability for all the AD users.

SPS operation started at the beginning of July after a very long shutdown for LHC civil engineering, and by mid-July it was back in regular physics operation, using the normal PS five-turn CT (continuous transfer) extraction at 14 GeV/c. As soon as the standard physics beam was in operation, a long programme of machine studies at the SPS started. The goal of this programme was to prepare the SPS for LHC. These studies required a number of different beams from the PS, ranging from single bunch beams to the full LHC beam, as well as an LHC beam with 50 ns bunch spacing instead of the usual 25 ns. For the full LHC beam, the PS RF manipulations with multiple bunch splitting were improved in June, leading to a much shorter delay between the final splitting and ejection. As a result, the instability problems due to the build-up of electrons in the PS beam are no longer a problem. In the autumn MD studies in the PS the main objective was to combine the work done to accelerate a very high-intensity single bunch for nTOF with the concept of double-batch injection, to produce the highest possible intensities in the PS. In this way over 4 x 10^{13} protons/pulse circulated in the PS, with more than 3.9 x 10^{13} extracted at high energy. This exceeds the previous maximum intensity by 15%. Meanwhile at the PSB, very promising studies were made towards speeding up the PSB cycle that could have very interesting consequences for ISOLDE.

At ISOLDE it was a year with two faces. On the positive side, a record number of 8.21 x 10^{19} protons were delivered by the PSB for a record number of 350 physics shifts. However, the serious vacuum leak on the GPS target station re-appeared in June. After several unsuccessful attempts to fix the leak in situ, it became obvious that GPS operation would have to stop, and some of the planned GPS runs were transferred to the HRS. As a new front-end was already in preparation as a spare, it was decided to accelerate the work and install it in September for the last two months of ISOLDE operation. Although the new equipment was installed as planned, an unfortunate oil contamination incident prevented it being used with proton beams. This meant that in spite of the heroic efforts to produce a new front-end rapidly, ISOLDE had to make do with just the HRS target station from June right through to November.

Operational statistics for the PS beams for the year are shown in Tables 1, 2 and 3.

Table 1. Beam availabilities for 2001. Note that after June there was very little nTOF beam requested

Protons for AD	94.9 %
AD physics	88.9 %
ISOLDE	95.3 %
EASTB	81.4 %
EASTC	94.4 %
SPS Physics	95.0 %
nTOF	93.1 %

Table 2. Operational statistics for proton operation in 2001

Total number of hours scheduled for PS Complex proton operation	6138 hours
Hours scheduled for PS Complex setting-up and machine development	434 hours
Hours schedule for proton production for SPS	3077 hours
Hours achieved for proton production for SPS	2923 hours
Protons produced for SPS (at PSB extraction)	1.67×10^{19}
Protons produced for SPS (at PS extraction)	1.51×10^{19}
Protons supplied for machine development studies (at PSB extraction)	2.49×10^{18}
Protons for supplied for AD (at PSB extraction)	2.25×10^{18}
Protons supplied for East Hall beams (at PSB extraction)	1.54×10^{18}
Hours scheduled for ISOLDE operation	3217 hours
Hours achieved for ISOLDE operation	3065 hours
Protons supplied by the PSB for ISOLDE operation	8.56×10^{19}

Table 3. Operational statistics for AD in 2001

Hours schedule for AD operation for antiproton physics	2253 hours
Hours achieved for AD operation for antiproton physics	2003 hours

3. Proton Operation

Linac2 is the proton source for the CERN accelerator Complex. Machine availability was somewhat worse than in previous years but downtime still remained below 2%. The main problems were associated with external services and the ion source. Three cathode failures occurred for an unknown reason, possibly related to small vacuum leaks into the plasma chamber. Then, following a severe high voltage flashover in early summer, the beam from the source developed a serious high frequency modulation. This was finally traced to back-streaming electrons from emissive points generated by the flashover which caused instabilities in the plasma expansion cup. Strangely, these emissive points did not cause any noticeable increase in HT flashovers.

At the PS Booster, however, performances were good. To decrease space-charge on the PS injection flat bottom, a new technique of bunch flattening was tested successfully in the Booster. By very carefully adjusting a second harmonic cavity, the particles from the edges of the bunch are transported to the centre, and vice versa. The central density of the bunch is thus dramatically decreased and hence the space-charge effects in the next machine, the PS, are reduced. Figure 1 shows a plot of the bunch intensity as a function of time, for the normal and the flattened bunch. It has been shown that by adiabatic crossing of a linear coupling resonance, the horizontal and vertical emittances are exchanged. This result was used to check the emittance measurements in the PSB measurement line, and particularly the effect of the residual dispersion in that line.

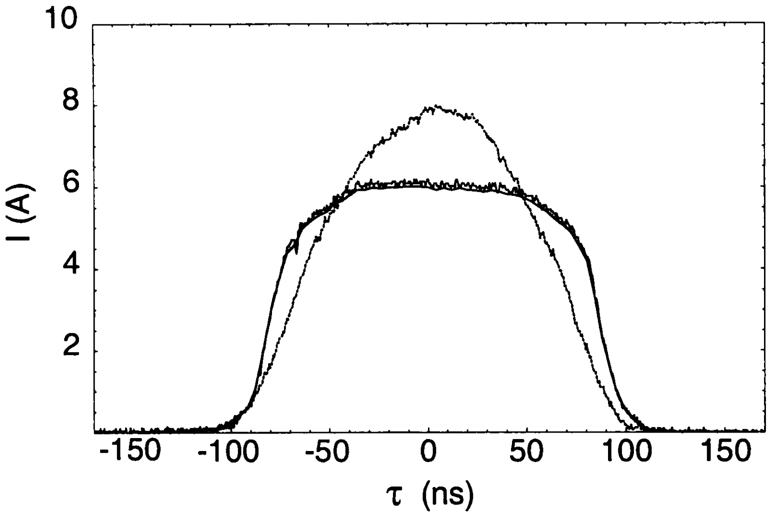


Figure 1: The bunch intensity distribution in the Booster before and after flattening.

A recent analysis has shown that the amount of protons the PS Complex is capable of producing is insufficient for the long list of clients now requesting beam (ISOLDE, AD, nTOF, East Hall, SPS, LHC); protons will soon be in short supply. One way out would be to cycle the PSB faster. The feasibility of cycling with a repetition rate of 0.6 sec (instead of 1.2 sec) has been investigated and the technical questions evaluated. There are some difficulties to be overcome, but it does indeed seem a possible route to make more protons available in the future. For the same reason, but also to try to decrease the losses at low energy when the space-charge tune spread is effective (tune spread ~0.6), a new working point has been tested for the Booster (around Q_h=4.2, Q_v=4.3) yielding the same performances as for the current working point (Q_h=4.2, Q_v=5.3). This is very encouraging and the tests will be continued so as to reduce the induced radioactivity.

There was even more intense machine development (MD) activity on the PS. About 600 hours of MD time were used in parallel with physics, while dedicated time amounted to about 114 hours. LHC-related studies absorbed most of the effort, particularly setting up the nominal LHC beam after the hardware modifications carried out during the shutdown. The reason for these modifications was the desire to reduce the bunch-to-bunch intensity fluctuations of the nominal LHC beam and to ensure strict synchronisation with the SPS at PS extraction. Studies on electron cloud phenomena were then resumed. At the end of the 2000 run, the presence of electron cloud build-up was revealed during the last turn in the PS, as well as in the TT2 transfer line. Unlike the SPS, the beam quality delivered by the PS is not influenced by such a phenomenon. On the other hand, beam diagnostics such as electrostatic pickups and SEM-wires, are strongly affected by the electrons.

Important MD work was also carried out to improve the intensity of the PS beam. A detailed analysis of the limiting factors of PS with regard to maximum intensity was made. This required a review of the different critical processes like injection, injection flat bottom, transition crossing, high-energy behaviour, etc. This resulted in the best beams being based on a double-batch injection (4+4 bunches) similar to that used for the LHC. As a result of the improvements, a new PS intensity record was established, with an internal intensity of over 4 x 10^{13} p/pulse and an extracted intensity of 3.9 × 10^{13} p/pulse. In Figure 2 a typical profile of intensity versus time is shown all along the cycle.

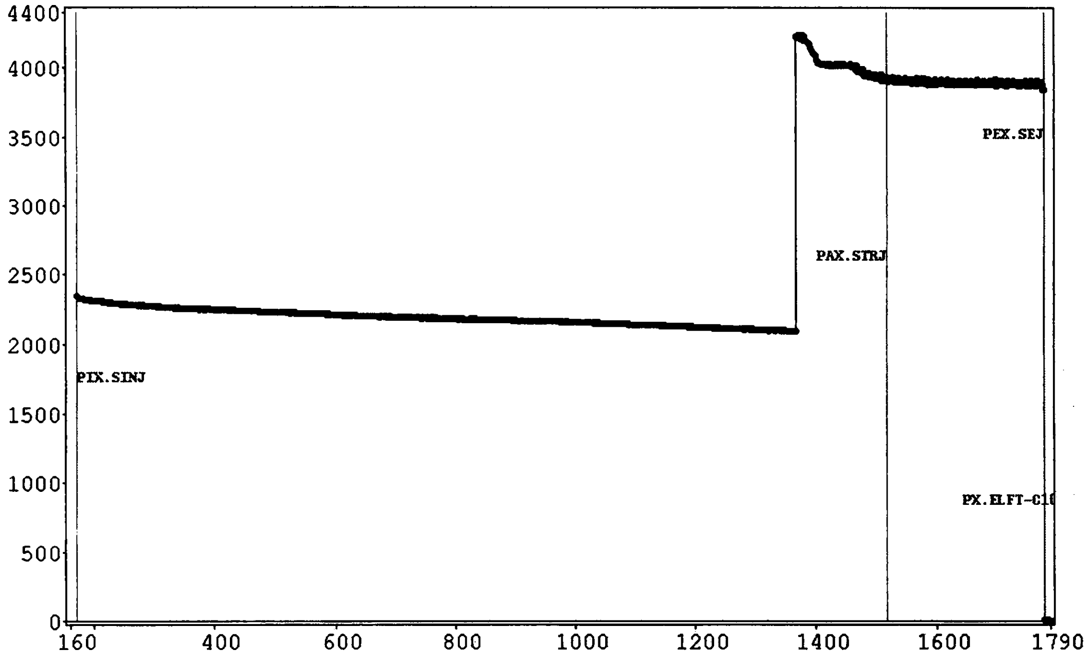


Figure 2: Intensity versus time for the new type of high-intensity proton beam showing the two injections. On the horizontal axis the time is in ms. The vertical axis represents the beam intensity in units of 10^{10} p/pulse. The peak intensity is well above 4×10^{13} p/pulse, while the extracted one is about 3.9×10^{13} p/pulse.

The other topic studied in MDs was the feasibility of a new type of Continuous Transfer (CT) based on adiabatic capture of particles inside islands of phase space. The principle worked on paper with simulations, confirming that it is possible to capture particles inside stable islands created by sextupoles and octupoles. Then, by varying the linear tune of the machine, it is possible to move the islands and the particles trapped inside them towards higher amplitudes for extraction. A comparison between the principle of the old CT extraction and the results of the simulations is presented in Figure 3. On the left is the principle of the existing CT, where the beam is sliced by means of an electrostatic septum. On the right, the five slices at the end of the capture inside the islands are shown.

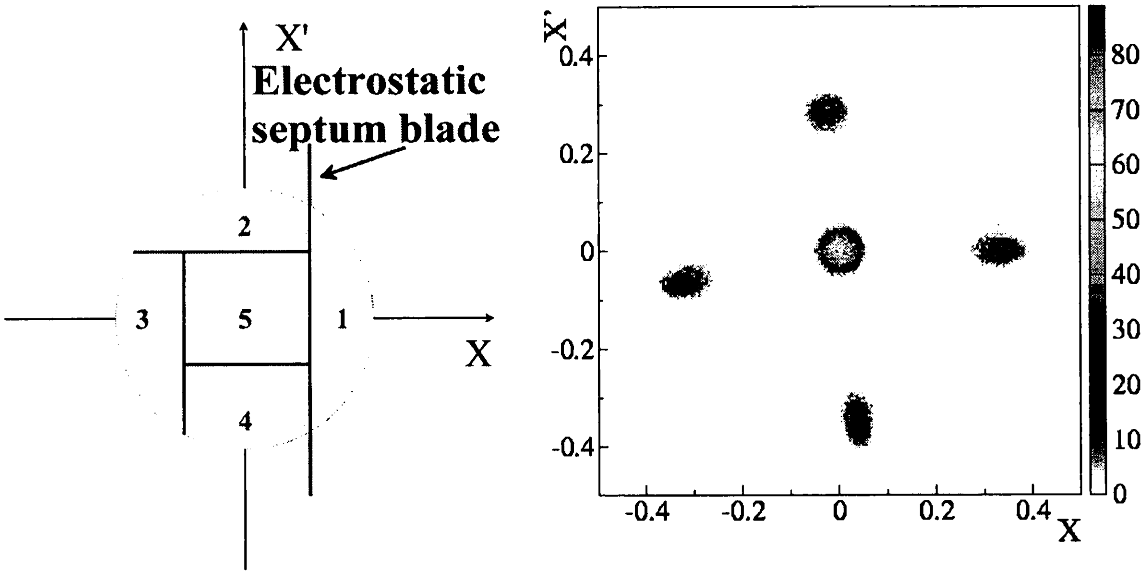


Figure 3: Comparison between the existing CT (left) and the new version based on adiabatic capture inside islands of phase space (right). The plot on the right represents the results of numerical simulations based on a simple model of the PS.

Efforts were devoted to developing the diagnostics tools needed to perform real tests of this novel concept. It is important to check whether the phase space has the proper topology to perform the capture inside the islands. For this, a multi-turn measurement of the beam trajectory allows the reconstruction of the phase space. By exciting the beam using a kicker magnet it is possible to visualize the phase space portrait provided by at least two pickups separated by 90^0 of betatron phase advance. In a second stage, when the actual trapping is tested, a flying wire is the key diagnostic tool to determine the shape of the different beam slices. Using the pickups of the CODD system together with a dedicated fast digitizer, it was possible to perform a number of measurements before the end of the 2001 run. These first tests were very encouraging and will clearly be an important topic for 2002.

4. Ion Operation

No physics run was scheduled for lead ions in 2001 but this did not mean that Linac3 remained idle. Tests of ion-induced desorption continued in order to find an optimum treatment for the vacuum chambers of the LEIR machine. Presently the main finding is that each ion lost on the chamber wall desorbs up to 20,000 molecules with a consequent deterioration of the vacuum.

A muon production experiment had requested an investigation of whether an α–particle beam could be produced. Injection into the PS Booster requires a He^{1+} beam from Linac3 (with similar characteristics to the Pb^{53+} beam), which would then be stripped between the PSB and the PS. The injection energy of 2.5 keV/u for the radio frequency quadrupole (RFQ) fixed the extraction voltage of the source to 10 kV. Experimentally, a slightly higher voltage (10.8 kV) gave more intensity at the end of the linac. For 500 eμA at the entrance of the RFQ, there was 270 eμA at the exit of the RFQ and 160 eμA at the end of the linac at 4.2 MeV/u. The high losses can be attributed to the limits of the accelerating structure and emittance problems. When the extraction gap was halved to give a similar extraction field to normal lead operation, the current was ~40% lower and unstable with a saw-tooth structure, thus reinforcing the loss theory.

In 2003 an SPS fixed target physics run with indium ions is scheduled. A test was carried out using metallic indium with our standard micro-oven evaporating the metal vapour into the ion source oxygen plasma. At the temperature required, the indium was very liquid and easily flowed out of the sample tube, wetting the ceramics and short-circuiting the heater filament. Closing the sample tube with a leaky plug of molybdenum alleviated the problem, and if the oven was run at constant power instead of voltage, the oven was able to maintain the temperature, even with a partial short-circuit. With up to 80 eμA of In^{21+} out of the RFQ and accelerated through Linac3 to 4.2 MeV/u, approximately 25 eμA of In^{37+} was obtained after the stripper foil, without optimizing the linac parameters (beyond a simple scaling). It is interesting that the theoretical optimum charge state for Linac3 operation (15+, which corresponds to 25+ for Pb ions) proved difficult to produce in any quantity, whereas 21+ could be produced much more easily. This could possibly be due to a too-high plasma temperature and a poor yield for this charge state in the afterglow mode. Modifications to heat the oven under power control proved successful in maintaining a stable beam for four days. The stability of the lead beam will also benefit from this modification.

Ions are normally accelerated in the PSB using the 2nd and 4th harmonic RF systems, with blending of the accelerating voltages at an intermediate energy. At top energy, the revolution frequency of indium ions would be too high for the 4th harmonic system, but by blending in the 16th harmonic RF system and only filling half the RF buckets, acceleration to full energy should be achievable. This technique was tested successfully using lead ions to simulate the indium ions. The four bunches were accelerated on harmonic 4 with the cavity C02 (2 MHz maximum), then transferred in flight to cavity C04 (4 MHz maximum) and finally, also in flight, to cavity C16 (16 MHz, but on harmonic 8 with only every second bucket filled). Indium should therefore be no problem in 2003, although a few more tests will be carried out in 2002.

5. East Hall Operation

Once more this year, the East Hall served numerous LHC and physics tests. Indeed, 22 different teams shared the four lines. The irradiation facilities (with primary protons in Irrad1, with secondary neutrons in Irrad2, and parasitic on the DIRAC beam) were heavily used, mainly to determine the radiation hardness of major subcomponents of the LHC experiments.

Two physics experiments took data and will continue to do so in 2002. One is HARP (PS214) which was scheduled to take data all year long on pion production cross-sections, but had technical problems. These were solved during the year and real data began to flow after experiment debugging, calibration, etc. Several PS teams worked closely with the physicists in order to get the best settings for this delicate and complex set-up. The other experiment is DIRAC (PS212) which continues to accumulate data in order to measure the lifetime of $\pi+\pi-$ atoms as a stringent test of medium range QCD. DIRAC and the irradiations suffered from three weeks of beam unavailability at the end of their run following the catastrophic failure of a magnet in the switchyard. Accessibility problems and unavailability of a spare magnet meant that the repair had to wait for the shutdown.

6. Electron Operation in LPI and its Experimental Areas

The LEP Pre-Injector (LPI), consisting of the LIL electron linac and the EPA storage ring, did not stop with LEP in 2000 but continued to provide beams to its experimental areas for 2 months in 2001. This was because the extension to the LEP schedule in late 2000 meant that some important studies for LHC were incomplete. As in past years, electron availability remained very high, greater than 98%. Intensive machine studies were also made during this time to prepare for the future CLIC Test Facility (CTF3). Given the importance of the LHC studies to be carried out on both the synchrotron light facilities, LIL and EPA were the first machines in the PS Complex to resume operation after the annual shutdown on 12th February 2001. They ran continuously until 12th April when the beam was turned off for the last time. The closure was celebrated in time-honoured fashion on 14th June with speeches and a celebratory drink. LPI had worked extremely well for 16 years as the first link in the LEP chain, and was now poised for re-birth under the guise of CTF3.

6.1 SLF (Synchrotron Light Facilities)

The two synchrotron light facilities in EPA received synchrotron light for 6 weeks. The SLF92 line was used by the COLDEX experiment to help define the LHC long straight section (LSS) cryogenic vacuum systems. A copper beam screen, operating in the range of 5^{O} K to 40^{O} K and equipped with cryosorber material, was inserted inside the COLDEX cold bore, operating at either 4.5^{O} K or 60^{O} K. Photon irradiation and gas injection confirmed that the chosen cryosorber could indeed be installed in the long straight sections of LHC. The other line (SLF42) was used by a new experiment called Desorption of Getter (DOG); sputter-deposited getters are used in the warm sections of the LHC for their pumping and anti-multipacting properties. Photon irradiation of a thin film of TiZrV getter material gave valuable input for the design and performance estimation of the LHC experimental regions, as well as for the LSS vacuum systems. Both beam lines were dismantled at the end of April. COLDEX was installed in building 113 for further LSS studies and will be moved to the SPS in 2002. Getter studies by DOG will also continue at the SPS.

6.2 PARRNe Experiment

The production of neutron-rich radioactive nuclei through fission is currently of prime research interest for future radioactive beam facilities. For example in the EURISOL project, photo-fission and fast neutron induced fission are both proposed as possible alternatives to the more traditional ISOLDE-style proton-induced reactions. The photo-fission cross-section for ^{238}U is about 0.16 barn (against 1.6 barn for fast neutrons of some MeV energy), but the conversion of an electron beam to gammas is much more efficient than that of deuterons to neutrons via a (d,n) reaction. Thus the yields of the radioactive nuclei of interest may be interestingly large using electrons. Following a request from the IPNO (Institut de Physique Nucléaire d'Orsay), a new, short experiment called PARRNe (Production d'Atomes Radioactifs Riches en Neutrons) was installed on the LIL electron linac. LIL experts made modifications to the linac in order to install the special equipment and safety precautions needed for the experiment, and the ISOLDE team provided a target. The experiment turned out to be extremely successful. The ^{238}U target received Bremsstrahlung gamma rays produced in a tungsten converter hit by a 50 MeV electron beam. The rare gases (krypton, xenon, radon) were collected and analysed. The results were so impressive that studies have now started for a new experimental area at IPNO, based on an electron linac. This development is crucial for any future machines based on photo-fission.

7. ISOLDE Facility

In 2001, the ISOLDE facility delivered 350 eight-hour shifts of physics with 8.3 x 10^{19} protons on 29 different targets. This makes it the best year since the move of ISOLDE to the PS Booster in the early 1990s. The evolution of the number of protons delivered, and the time devoted to physics is shown in Figure 4.

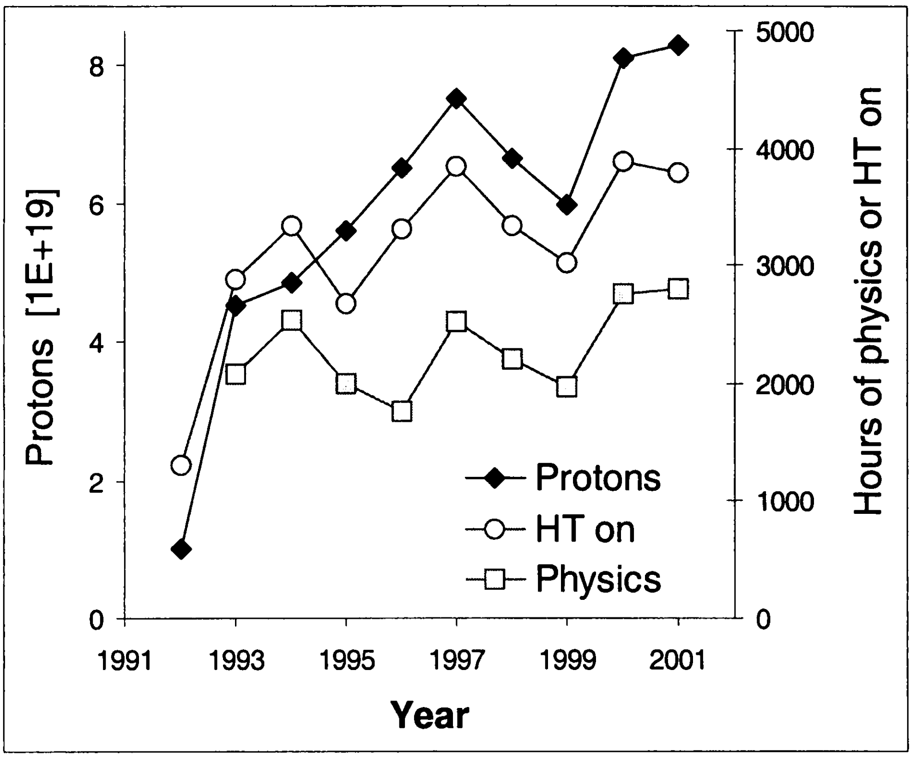


Figure 4: The evolution with time of the number of protons delivered to ISOLDE, the number of hours of physics achieved, and the time of HT on (which corresponds to stable beam time plus radioactive beam time).

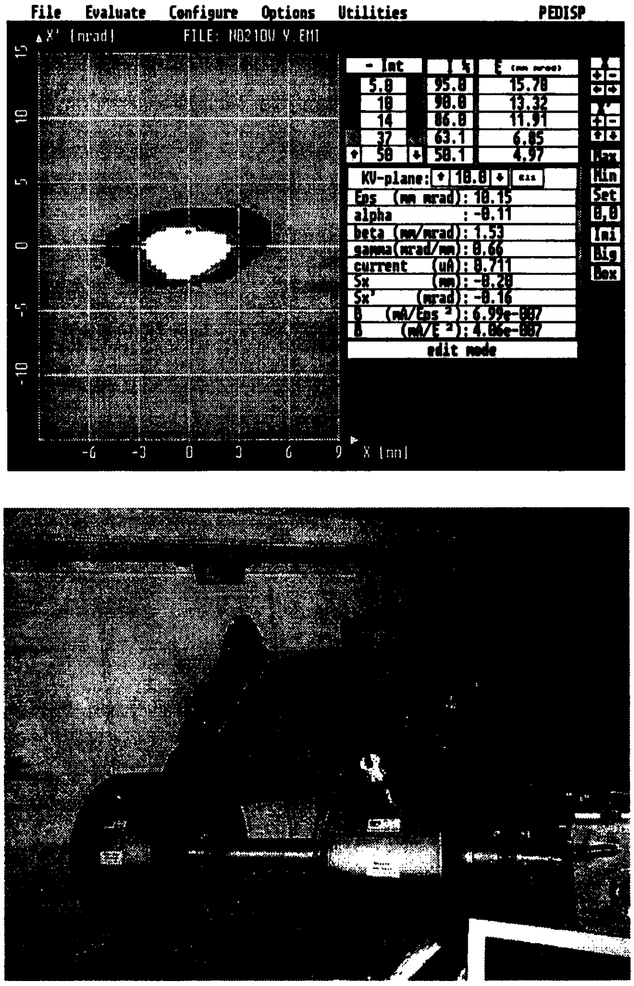
Both ISOLDE separators were initially used in the so-called "push-pull" mode, but unfortunately the GPS separator front-end sprang a serious vacuum leak in June and had to be abandoned; there was no way that the very old and radioactive front-end could be repaired. The newly commissioned HRS, which had been fitted with a new front-end during the shutdown, was thus called into service and received a baptism of fire, with the entire physics programme depending on its reliable operation. It proved to be both more reliable and easier to operate than many users had expected, and the results were excellent. The only part of the physics programme that suffered was solid-state physics, which lacks a well-equipped beam line for implantations from the HRS. A study is under way of a strategy to avoid a similar situation in the future.

Following this unfortunate breakdown of the GPS, the PS management decided on an accelerated programme for the construction of a new GPS front-end within the ISOLDE Consolidation Project. This was successfully completed very rapidly, and the commissioning of the front-end took place in September as planned. However, a current leak developed between the high voltage side of the front-end and ground during the commissioning, and the GPS could not be made operational. This was a serious blow to our plans.

The current leak was most probably due to severe oil contamination by the first target unit mounted on the new GPS front-end for the commissioning; in principle there is no oil in such a target unit, so it took some detective work to establish that oil in a valve was the likely cause of the breakdowns. Work is in progress to fully understand and resolve this problem and we are confident that the GPS will be fully operational for the 2002 run.

The ISOLDE Consolidation Project, which is jointly financed by the PS Division and the ISOLDE Collaboration, made major progress in 2001. The transformation of the experimental hall into a radioactive laboratory was started, new control units for the ISOLDE target robots were ordered, a new front-end was constructed, and the long-awaited renovation of the off-line facilities was started. A major undertaking by the Division was the renovation of the ISOLDE control system, including full refurbishment of the low-level interfaces between the power supplies and the control system. The design and preparation work was completed in 2001. The plan is that the facility should start in 2002 with the new control system using the existing Windows-based console applications software. If all goes well, this change will be transparent to the users, and it will provide us with a modern and maintainable low-level control, including industrial standard front-end computers (PLCs). Another important sub-project is the externally financed work on a low-energy beam-cooling device at ISOLDE. This work is led by a Project Associate from Jyväskylä University and is fully financed by the ISOLDE Collaboration, the European Union and the Ludwig Maximilian University in Munich.

The ISOLDE facility made use of 27 new target and ion source units in 2001. The target and ion source development programme, which aims at providing the ISOLDE user community with new isotopes, started an important new phase with the installation of an emittance meter in the off-line laboratory. This will permit all ISOLDE targets to be more fully characterized before they are brought into use, and hopefully the emittance of the ISOLDE ion sources can be gradually improved. This is of great importance, especially for the REX ISOLDE post-accelerator, which depends on good emittance for efficient beam handling. The new meter and its output are shown in Figure 5.



- Int	I %	E (mm mrad)
5.0	95.0	15.70
10	90.0	13.32
14	86.0	11.91
37	63.1	6.85
50	50.1	4.97

KV-plane: 10.0
Eps (mm mrad): 10.15
alpha : -0.11
beta (mm/mrad): 1.53
gamma (mrad/mm): 0.66
current (uA): 0.711
Sx (mm): -0.20
Sx' (mrad): -0.16
B (mA/Eps ²): 6.99e-007
B (mA/E ²): 4.06e-007
edit mode

Figure 5: A new emittance meter (bottom) was bought and commissioned in 2001. A systematic measurement campaign will permit a better understanding of the emittances of the ISOLDE ion sources and will point the way to improve them. The first measurements are encouraging (top).

In the autumn there was very good news from the REX ISOLDE experiment which announced that all the elements of the post-accelerator were in place and working. This is a world first for charge breeding and post-acceleration of radioactive ion species to over 2 MeV/u. It means that the programme of physics planned for this device can get under way in 2002.

8. The nTOF Facility

The setting-up of the first nTOF beam (6 x 10^{12} protons/bunch, 6 ns rms bunch length) caused no major problems. Rapidly, more than 7 x 10^{12} protons/bunch were routinely and reproducibly delivered, and a total of 10^{18} protons was furnished to nTOF in the first month of operation in dedicated mode. The parasitic mode was then set up in parallel with the East Hall users. Unfortunately, however, the presence of a strong, unexplained neutron background at the secondary target 200 m downstream of the primary neutron-production target (already observed in the 2000 run), prevented physics being done efficiently by the nTOF teams. Most of the time allocated to nTOF was therefore devoted to the study of the source of this neutron background and to methods of reducing it. Altogether the nTOF facility received 2.98 x 10^{18} protons on target during the year. The neutron background was finally attributed to muons generated in the primary target that caused neutron production downstream; it was concluded that this background would be eliminated by additional shielding. The installation of a first array of iron shielding along the neutron pipe gave very positive results, reducing the neutron background by a factor 10. Yet more shielding is to be installed during the next shutdown. The neutron background should then be sufficiently reduced that physics can start properly in 2002.

9. AD Operation

Before the start of the AD physics programme in May, the AD machine went through a long and hectic start-up and machine study period from 9th April. During the four weeks set aside for this, the operating crew worked round the clock in the ACR, including weekends. A considerable amount of time was spent on various machine topics in order to improve performance and come closer to the design figures. For a few days, the machine was run in the "protons via the loop" mode, where 3.5 GeV/c protons circulate in the counter-clockwise direction. The higher beam intensities in this mode make it possible to calibrate the longitudinal Schottky pickup in the AD ring. Important items on the agenda for the MDs were the improvement of beam cooling performance at lower energies, the reduction of beam losses during deceleration, shortening of the cycle length, studies of the ring optics, and the improvement of extracted beam parameters such as transverse emittances and bunch length.

By 7th May, physics started on schedule with the machine running from Monday 07:00 to Friday 23:00, and with the three experimental collaborations ASACUSA, ATRAP and ATHENA each taking the extracted beam for 8-hour periods. During the first few weeks, the beam quality and availability were disappointingly low due to the fact that only a few issues on the ambitious machine development programme had been completely solved. Continuous improvements were, however, made during the physics runs thanks to dedicated MD time every Monday morning, and also to four two-day dedicated periods during the year.

By the end of the run, many improvements had been made and the physics users were happy. The most noteworthy improvements were:

- The deceleration efficiency was increased to a peak value of 100%, (design specification, 25%). The previous transverse losses were eliminated thanks to the new electron cooling solenoid compensation scheme. The solenoid compensator magnets were re-aligned and equipped with independent power supplies, separating them from the main solenoid supply. This resulted in more available space in the tune diagram, especially important at low energies. Further improvements to the decelerating RF system signal transmission from the ACR low-level racks down to the cavity power supply made it possible to eliminate all longitudinal losses during the ramps.

- The cycle length was reduced from 112 to 96 seconds, thanks to further improvements to the electron cooler alignment and programming at 300 and 100 MeV/c. Since the AD cycle is synchronised to the PS supercycle, shortening of the AD cycle must be made in "PS supercycle units", presently around 14 seconds. The latest AD cycle is shown in Figure 6.

- The beam parameters at 100 MeV/c were improved. The length of the extracted bunch was reduced to the design value of 200 ns thanks to improvements in the low-level RF-hardware for the recapture and bunch rotation processes. The transverse emittances are now well below the design figure of 1 π.mm.mrad in both planes, which is another positive effect of the better alignment of the electron and antiproton beams in the electron cooler. The intensity of the circulating beam just before ejection reached a value well above the design specification of 1.2 x 10^7 with an operational value of some 3-4 x 10^7, and hitting a record of 4.7 x 10^7 on 19th July.

- The Beam Ionisation Profile Monitors (BIPMs) provided non-destructive beam profile measurements for the first time, which can be used to monitor beam cooling performance and orbit changes during the AD cycle.

- A second, low-frequency longitudinal Schottky pick-up with its associated summing amplifier was installed, which improved the quality of intensity measurements.

- Towards the end of the 2001 run, the first ever non-destructive on-the-fly tune measurements were made during the ramps of the AD cycle using digital signal processing techniques. These measurements will be very valuable in 2002 for further optimisation and shortening of the cycle.

On the downside, one has to admit that some severe problems still remain to be resolved. Throughout the run, orbit fluctuations at 100 MeV/c plagued the beam cooling performance and the transverse beam position as seen by the experiments. The cause of these fluctuations has not yet been fully identified. They are especially problematic for ASACUSA, as the aperture of their decelerating RFQD is so small.

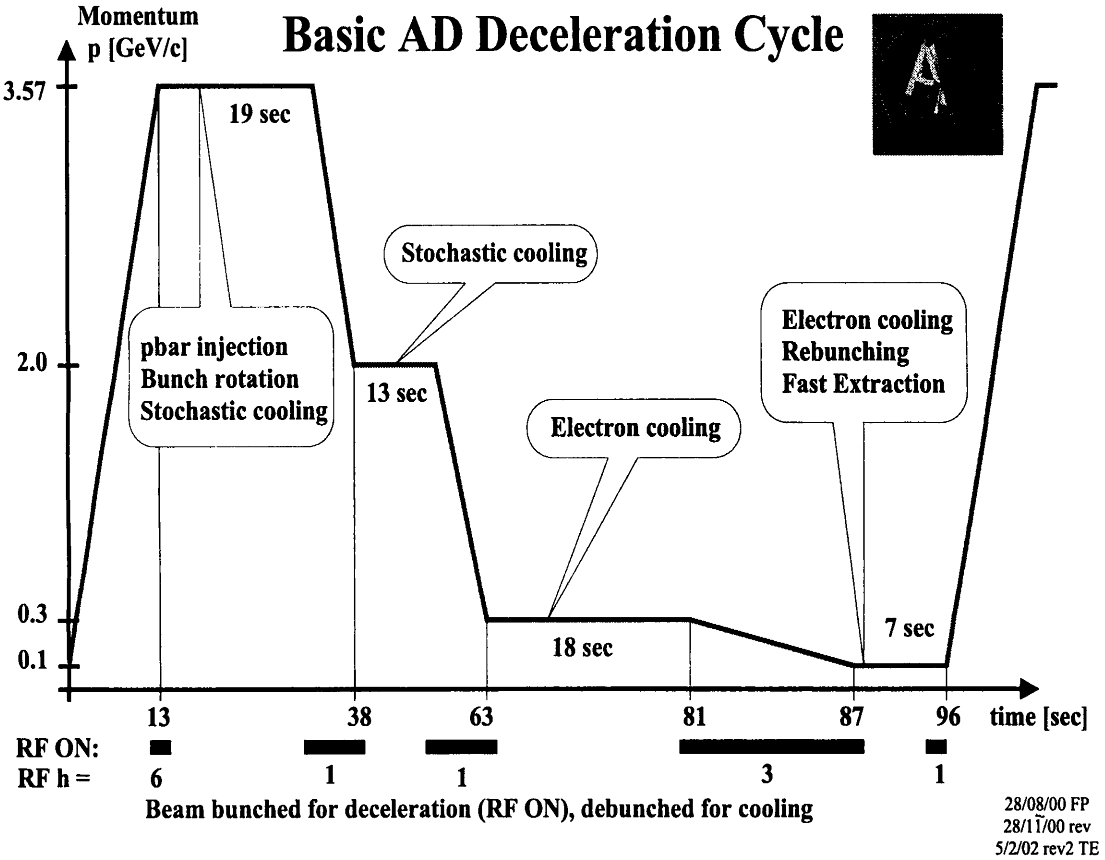


Figure 6: The latest AD cycle.

10. RFQD

The RFQD serves to post-decelerate the ejected antiproton beam in the ASACUSA zone. Several hardware improvements were made during the shutdown, in particular the enclosure of the RF power amplifier chain by a Faraday cage to reduce RF emissions that might have perturbed the adjacent physics experiments in the hall. The addition of a capacitor bank to the HV supply for the inner RFQ structure allowed us to break through a multipactor band and eliminate it by conditioning, thus permitting post-acceleration above a kinetic energy of 63 keV that had hitherto been precluded. This then allowed flexible operation over the whole range of energies, from ~10 keV to 120 keV, so as to fine-tune the parameters of the different downstream physics experiments. These included antiproton energy loss measurements in different materials, spectroscopy using laser excitation, and further deceleration down to eV energies in a superconducting solenoid together with a Penning trap.

Operation of the RFQD was very smooth and there was very little down time; however some areas for further improvement were identified. Before resuming operation in 2002 it is planned to improve the input diagnostics by the addition of transparent SEM-grids and to prepare a filter/spectrometer line to eliminate non-decelerated particles that create an unwanted background in some experiments.

11. Diagnostics

There are a large number of diagnostic devices of many different types around the PS Complex due to the different energies, intensity ranges, or particle types to be measured, but also due to the repeated adaptations that have been needed over the years to follow CERN's scientific programme. Keeping them all in working order requires the constant attention of the diagnostics group; a study is under way to try to reduce the diversity of the instruments, and a programme of standardization and modernisation has been put in place.

During the 2001 shutdown the 4 missing wire scanners built at TRIUMF (Vancouver, Canada) were installed in the PS Booster which opened the way to the long-awaited observation of beam profiles there. These devices are important for the transverse emittance control needed for LHC- type beams. In the TT2 transfer line from PS to SPS, a transition radiation monitor has been installed. Its image is digitized and the transverse beam emittance can be extracted. Such a device holds much promise for the future.

During the AD running period, a new measurement system for the electron trajectories in the electron cooler was put in place to ease the adjustment of co-linearity of the antiproton and electron beams. This played a prominent role in reducing the length of the AD cycle by speeding up the cooling process, as well as improving the emittance of the ejected 100 MeV/c beam. A non-destructive monitor based on ionization of the residual gas by the beam (the BIPM) produced excellent results and should soon allow the beam dimensions to be seen during the AD cycle, and in particular during the cooling process.

Various modifications and upgrades were made to the beam instrumentation in LPI in the framework of CTF3. New pickups enable the fine structure of the electron pulses to be observed with a resolution of several ps. A prototype wall current monitor with a large bandwidth (from 13 kHz to 10 GHz) has been installed and gives the desired results; once it has been engineered to have the correct vacuum properties it will be installed widely in CTF3. The same applies to a new magnetic pickup for transverse position measurements in the linac. For future linear colliders, the measurement of very high intensity lepton beams with very small transverse dimensions is a key problem. Classical interceptive techniques where the beam interacts with material in the beam are impossible due to the large energy deposition in the detector. One possibility is the interaction of a focused laser beam with the electron beam, and CTF2 has been used for preliminary studies.

12. Control System and Informatics

The exploitation of the PS Complex control system on a day-to-day basis is the central activity of the CO group, including support through an "on-call" team. Changes requested by the operators are continually being introduced as well as upgrades to the software and hardware components for better reliability or suitability to the needs. This activity proved once again to have been very successful, since the fault rate attributed to the controls system in 2001 stayed at the same low level of 0.2% as in 2000. The AD remained the most demanding machine of the PS Complex in terms of day-to-day care and follow-up of the evolving operating conditions. For ISOLDE, migration of the controls started at the front-end level towards standard solutions, but support remained the responsibility of a few specialists because of its specificity. A renovated control system for CTF3 was grown out of the existing LPI infrastructure, but its constant evolution obliged the implementation team to provide dedicated support to the system. Support was also provided to the physicists in the experimental areas to enable them to access machine parameters from their local programs. For the operating systems of our control system, both LynxOS and Linux were upgraded to the latest released versions.

On the development side, 2001 was rather prolific. All the consoles in the different PS control rooms were successfully converted to standard PC workstations running Linux, and all the AIX workstations were removed. In the offices of controls developers, the workstations were also replaced by PCs, often configured with double operating systems (Windows and Linux). New timing modules were developed using the VHDL design approach. In the framework of the "Middleware" project in collaboration with SL, servers were implemented in the controls crates of the AD machine, and a first software package was completely redesigned to give a faster response. All the existing XWindows/MOTIF application programs were ported to Linux, the Java programming environment was further developed using commercial tools, and a second version of the Accelerator Software Component (ASC) layer was delivered to the applications programmers. The software driving the analog observation system (nAos) was successfully ported to LynxOS to prepare for the migration of the dedicated VXI front-end controllers to standard VME modules.

As part of the ISOLDE Consolidation Project, the new front-end infrastructure for the power supplies was implemented together with the PS-PO group. Ethernet was introduced as the fieldbus to link the standard DSCs to the newly introduced PLCs. The necessary expertise had to be acquired, and the software was developed using a test stand installed in the laboratory. For the CTF3 project, new controls were implemented using the existing LPI control infrastructure. The system was put into operation in September and proved to work very satisfactorily. It was used until the end of the year with no problems. A completely new central timing system was designed to control the fast cycling electron linac and to fully decouple the running of CTF3 from the other machines of the PS Complex.

12.1 Office Computing

The massive migration to Windows 2000 of the desktop PCs in the Division started in September in collaboration with IT Division, after a pilot migration in June. Half the 380 PCs of the Division were migrated before Christmas and the remainder will be done before the end of April 2002. The older machines had to be upgraded to be able to run correctly under the new operating system. Upgraded Pentium 200 MHz machines are now the minimum configuration.

13. Preparations of the PS Complex for LHC

By the end of 2000, the implementation of novel bunch splitting techniques, notably splitting one bunch into three, had enabled the generation of a truly nominal LHC beam (i.e., with all parameters inside specification) at extraction from the PS. These nominal parameters are:

- 72 bunches with 25 ns spacing (leaving a gap of ~300 ns to extract the beam);
- 1.1×10^{11} protons/bunch;
- transverse normalized rms emittance ≤ 3.0 µm in both planes;
- bunch length ≤ 4 ns (to fit into the SPS 200 MHz buckets).

The SPS routinely used this beam for machine studies aimed at understanding electron cloud effects, which, if not cured, will jeopardize the beam in both the SPS and LHC machines. To this end, the analysis of bunch trains provided by the PS Complex with various lengths and bunch spacings is of the utmost importance. Indeed, the scheme based on bunch splitting enables the production of shorter bunch trains (or trains with voids), simply by varying the number and sequence of the PS Booster rings injected into the PS. Moreover, the removal of the 114 MHz lepton acceleration cavities from the PS ring, as well as a further reduction of the higher-order modes of the 80 MHz systems, have substantially reduced its coupling impedance, opening the way for a beam with 50 ns bunch spacing at nominal bunch intensity. Such a beam appears to be less prone to electron cloud effects in the SPS.

Naturally, once the LHC beam was readily available, it came under closer scrutiny. Early in 2001, the 72 bunches displayed a bunch-to-bunch intensity variation of some ±20%. This spread in bunch population would have led to irregular beam-beam effects in the LHC and to a significant reduction in luminosity. The key development to improve the bunch-to-bunch reproducibility was the introduction of a phase loop that remains active throughout the high-energy RF gymnastics at 26 GeV/c in the PS. This reduced the variation in bunch population to ±10% (Figure 7), a value more compatible with the needs of LHC.

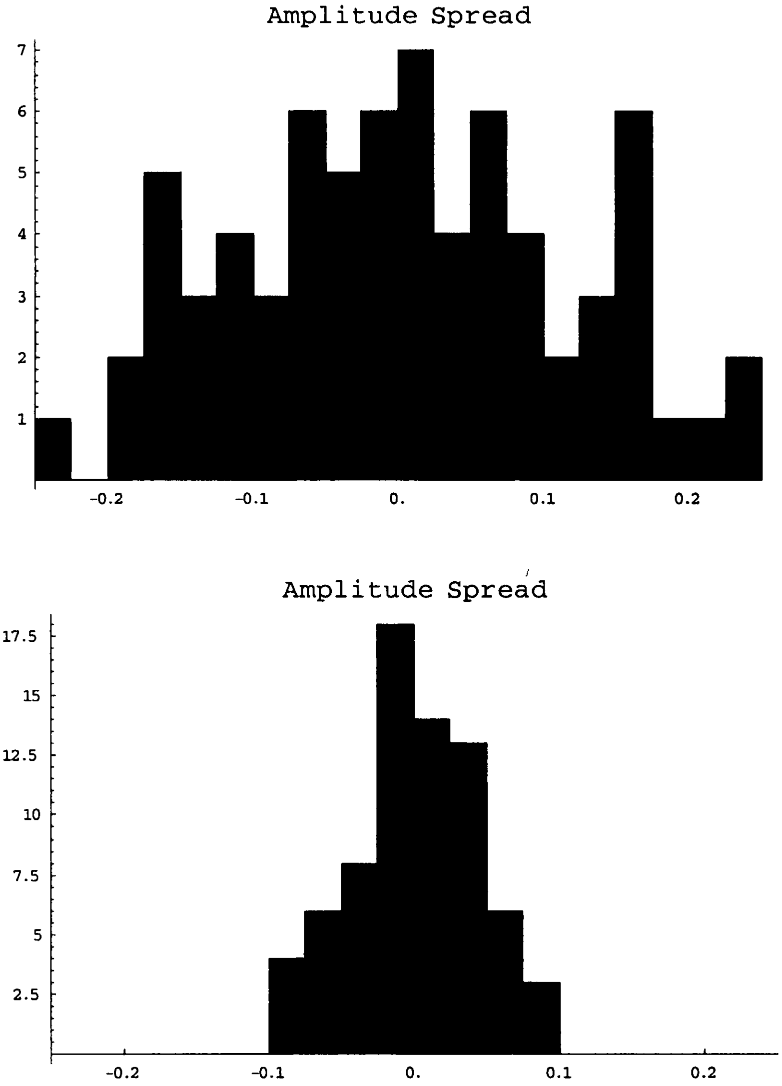


Figure 7: Histograms showing the spread of bunch population N_b in 72 LHC bunches at PS extraction before (top picture, about ± 20%) and after (bottom picture, about ± 10%) improvement of the low level RF system in the PS machine. Horizontal axis: $\Delta N_b / N_b$; vertical axis: number of bunches per bin.

To satisfy the stringent LHC beam specifications, a kick pulse shape improvement on both the PS injection kickers KFA45 and the PS ejection full aperture kicker KFA71-79 was required. Sophisticated modeling with powerful simulation tools permitted an iterative approach to identify critical circuit elements and achieve the best compromise in setting their values; certain components brought improvements to the pulse rise time but had a deleterious effect on the flat-top ripple. The hardware changes were fully implemented on the KFA45 system. Introduction of saturating ferrites and additional filter elements improved the rise-time (1%-99%) from 96 ns to 46 ns and the corresponding fall-time from 260 ns to 96 ns. Lack of time allowed only partial implementation on the twelve-module KFA71-79 system.

Some hardware items are still in the pipeline in order for the PS to be completely ready for LHC: (i) two RF cavities, each tunable at 20 and 13.3 MHz (the latter to enable 75 ns bunch spacing); (ii) two deflectors (horizontal and vertical) belonging to a new damping system for both injection oscillations and transverse instabilities, as well as their associated feedback electronics; (iii) final commissioning of the eight (4 rings × 2 planes) fast wire scanners in the PS Booster provided by the TRIUMF laboratory.

Further machine development work in 2002 will be devoted to producing the other beams required at various stages of the LHC. These include the "pilot" beam (one bunch of some 10^9 protons to explore the LHC at start-up), the "initial" beam (1.7×10^{10} protons/bunch for the first two years of LHC operation), and the "ultimate" beam (1.7×10^{11} protons/bunch for final high-luminosity operation). Although this latter high intensity beam is within reach, a number of studies to explore various limitations in the injector chain are still going on. In addition, other LHC-type beams will be required by the SPS to explore various beam dynamics limitations in the SPS and those anticipated in LHC.

14. Consolidation Work Around the Accelerators

Consolidation of the accelerators is not a glamorous task but it is essential if the performances are to be maintained and if down time is to be kept at reasonable levels. Unfortunately, the resources devoted to consolidation have been eroded over the last few years, but a limited amount is absolutely essential each year. In 2001, the replacement of ageing power supplies was the main thrust of the consolidation work. There are over 1500 supplies of many different types around the PS complex, and the electronics becomes rapidly out of date, with components needed for repairs becoming unavailable. Twenty new supplies for the PS skew quadrupoles and 24 new converters for the Booster pulsed dipoles were constructed in industry to our specification, and these will be installed in the next shutdown. A test power converter for the thyristor gate command of the PS main power supply was designed in collaboration with Argentinian experts and first results are expected in 2002. For the ISOLDE Consolidation Project, a novel 1000 A power supply with a new control system (employing Simatic S7) was successfully tested. New 1000 A and 500 A power supplies for target heating were ordered and the control interfaces for all the ISOLDE power converters (~300 units) were manufactured. They also will be installed during the next shutdown.

On the Booster, the KSW injection kickers needed urgent consolidation. New pulse generators were prepared, with improved control and status interfaces, plus a much lower main circuit operating voltage (500 V rather than 8 kV) that should result in improved reliability and ease of operation; a new feature is the possibility to programme a third type of current slope specifically for MD cycles. For septa, the main effort focused on the replacement of the electrostatic septum 31 (PESEH31). A new generation of septa has been designed, and the first one constructed. Due to the very late delivery of the vacuum vessels, construction of the septum did not start until October, but rapid progress was made at the end of the year and it should be installed in the PS in March 2002. This new generation uses standard vacuum seals and improved vacuum equipment to achieve a better vacuum and easier maintenance.

Because the resources available for consolidation are lower than is prudent, we run an ever-increasing risk that breakdowns will result in long repair times. A long-term Consolidation Project was therefore put together in 2001, aimed particularly at equipment affecting the performance of the machines for LHC. The decision to build LHC with the PS Complex as injector means that the PS must function at an extremely high level for many years to come. This implies the necessity for a longer-term consolidation. The project to prepare the PSB and PS for the LHC (PS-9514, from 1995 to 2000) should be considered as a first stage of this consolidation. A second stage is now needed for the longer term. This is essential for the future, not only to be able to guarantee the performance levels needed by LHC, but also because, due to the strong reduction in staff numbers, we must have a PS Complex that is more reliable since there will be less staff to run it.

The Consolidation programme consists of a set of topics needing attention prior to the LHC start-up in 2006, and a second list needing attention beyond that time frame. Details can be found in PS/DR/Note 2001-047. One major item that will one day require replacement is the ageing main PS motor-generator that has been in service now for 33 years.

15. Ions for LHC

15.1 The PIL Project (PS Ions for LHC)

In addition to proton-proton collisions, the LHC will provide collisions between lead ions, and possibly lighter ions at a later date. A feasibility study was made several years ago to consider the implications for the injectors of delivering lead ions to LHC. This has now been updated and will appear soon as a design report in which detailed reconsideration is given to the design and cost of the pre-injector chain under PS responsibility (from the source up to the entrance to the SPS); a similar report will treat the SPS. The scheme uses the present ECR-source (with a moderate upgrading), the existing ion RFQ and Linac3, the existing low energy beam transport, the old LEAR accelerator (modified as LEIR, an ion accumulation ring), and the PS. Note that the PS Booster is not used in this scheme. Although lead ions are the main objective, lighter ions are a distinct possibility at a future date, so the scheme needs to be compatible with other ions if at all possible. Detailed studies showed that space charge at injection in the PS and in the SPS will be a serious limitation. Consequently, it was necessary to make several changes to the original feasibility study to reduce this effect to an acceptable level:

- The LEIR-to-PS transfer energy was increased to 72 MeV/u for lead ions, corresponding to a Bρ of 4.8 Tm.
- After acceleration in the PS and a complicated set of rf gymnastics, the ion beam pattern consists of 4 pairs of bunchlets, the bunchlets being separated by 5 ns, and with 100 ns between consecutive pairs. This has the effect of reducing the instantaneous intensity seen by the SPS at injection by a factor 2, thus reducing the space charge effects. The SPS later recombines the pairs of bunchlets after acceleration.
- The transfer energy from the PS to SPS was increased to 6 GeV/u for lead ions.

An alternative scheme using the PS Booster (as in the present scheme of lead ion acceleration for fixed target experiments at the SPS) instead of LEIR has also been analyzed. This would save the cost of building LEIR, but would incur its own costs for the ion source. To reach the foreseen LHC luminosity, this alternative route requires a new, very bright ion source (e.g. an innovative ECR or a powerful laser ion source) delivering several mA of lead ions within the small emittances required by LHC. Research to develop such sources is under way (see below), but at the present time it is not at all clear if the challenge of the LHC ion programme could be met by taking this route, so the only realistic possibility at this time is to build LEIR.

15.2 The LEIR Machine

After acceleration in Linac3 to 4.2 MeV/u followed by stripping, the lead ion beam is transferred to LEIR as Pb^{54+}. A combined longitudinal-transverse multi-turn injection (~75 turns) is used. Electron cooling will then be applied for a maximum of 400 ms to merge the newly injected beam with the stack and to reduce the emittance to the desired value. Successive multi-turn injection and cooling sequences are applied to accumulate the number of ions required for LHC (~10^9 ions in LEIR, assuming that only 30% survive from LEIR through the PS and SPS to the LHC). After acceleration to 72 MeV/u, the beam is re-bunched on harmonic 2 and the two bunches are transferred to the PS. To satisfy the Twiss functions required at the injection section and at the cooling section, a lattice has been found which maintains the twofold symmetry. All the LEIR systems and the modifications needed in the PS were defined in 2001, and the required resources were evaluated. A project planning has been proposed which leads to commissioning in 2005, so that further tests in the PS and SPS can take place before the ions are needed in LHC. Figure 8 shows the layout of the LEIR machine.

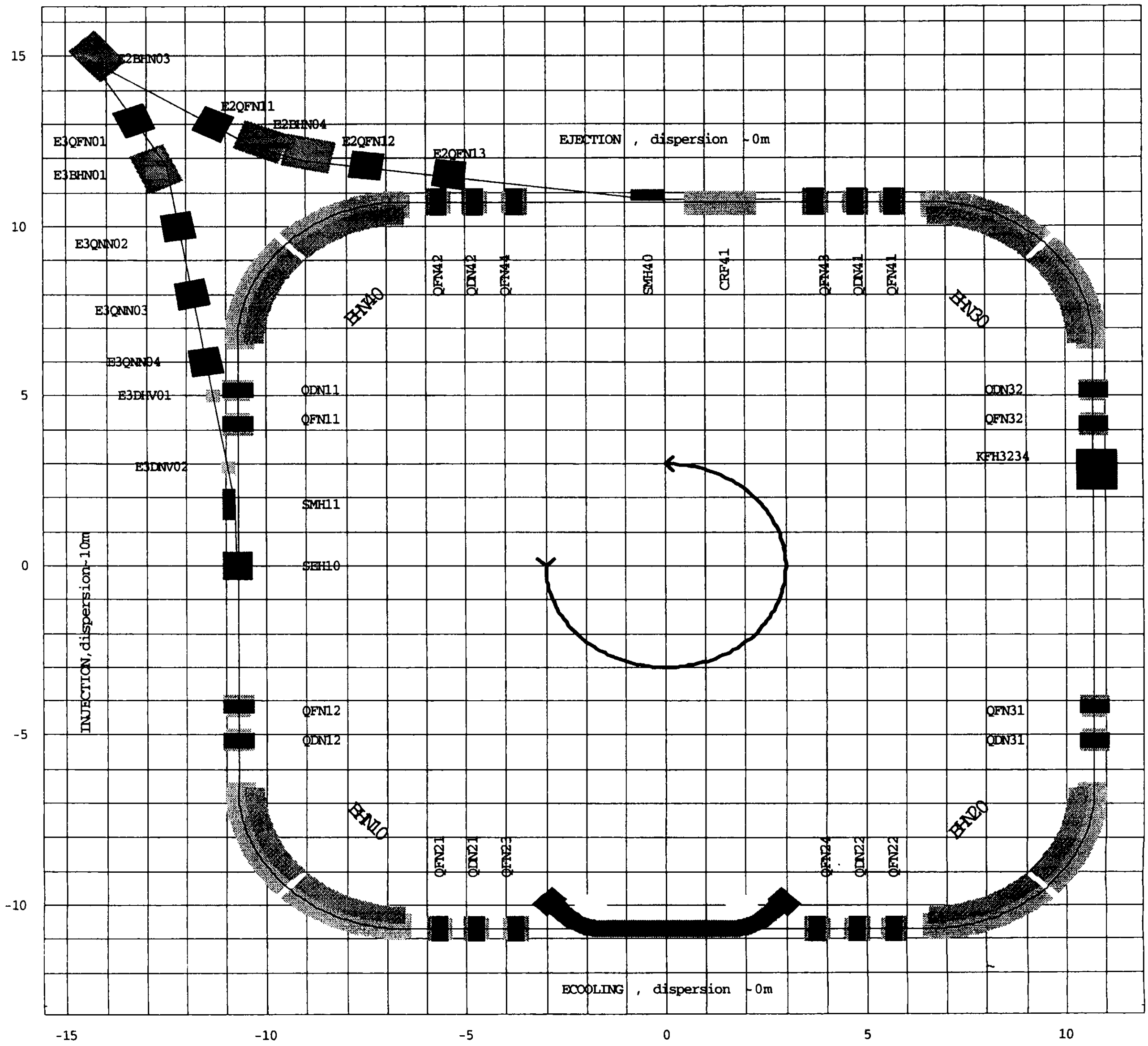


Figure 8: Layout of the LEIR machine.

15.3 ECR Collaboration

The innovative ECRIS collaboration with major funding from the Fifth Framework Programme of the European Commission and involving CERN, GSI (Darmstadt), INFN LNS (Catania), CEA (Grenoble) and UJF-ISN (Grenoble) moved into its second year in 2001, following the proof of principle tests at INFN in 2000. Unfortunately the gyrotron power supply did not survive the journey very well from Catania back to Grenoble ISN, and the subsequent repairs somewhat delayed the application of 28 GHz power to the PHOENIX source. Additionally, instabilities due to the interaction of the plasma on the gyrotron output, which were not experienced in Catania, had to be overcome. In spite of these problems, work on the PHOENIX concept source at 28 GHz started in the autumn, and preliminary beams were extracted. In parallel, the design of an upgraded SERSE superconducting source for 28 GHz continues in INFN and CEA using the experience gained in the initial 28 GHz tests.

15.4 The LIS Experiment

The aim of the LIS (Laser Ion Source) experiment is to demonstrate that a high-power laser ion source can provide a reproducible ion pulse at high pulse rate (1 Hz) in order to become an economic and reliable candidate as the source of heavy ions for LHC. The experiment is run by an international collaboration between CERN and Russian Institutes (ITEP and TRINITI). It is partly financed through the International Science and Technology Centre (ISTC). During the year, further progress was made towards a full-scale source, and it is now expected that the laser will be ready to show its capabilities in mid-2002.

At CERN, most of the effort went into the preparatory work to integrate the high-energy laser into the existing set-up and to convert the source to 1 Hz operation. The off-axis target illumination structure needed for the laser pulse with Gaussian intensity profile was commissioned, with much emphasis on the optical stability of the photon path. The source area was transformed to allow ion extraction from a HV platform at 120 kV. The infrastructure of Hall 363 had to be prepared to allow installation of the laser amplifier when it is delivered from Russia. The master oscillator to drive this amplifier, already at CERN, was re-commissioned after several years in moth-balls waiting for the arrival of the amplifier from Russia. In addition, three compact 60 kV pulse modulators were constructed and will soon be tested on the gridded electrostatic lens (GEL) assembly. These modulators employ high voltage semiconductor switches which have rise and fall times of 5 μs.

Meanwhile, in Russia, pre-commissioning of the 100 J laser was accomplished. The CO_2 laser, which will deliver 100 J in a 10-20 ns pulse once per second, worked extremely well as a free-running oscillator, yielding 220 J within 90 ns at 1 Hz for more than 20 hours, approaching 10^5 stable pulses with no intervention. The device is now ready for transportation from ITEP to CERN, where its conversion from oscillator to amplifier mode will take place in 2002. Once the laser system has demonstrated a satisfactory performance, the long-awaited tests of the high-power laser ion source can then begin.

16. CLIC Studies

An International Technical Review on linear collider project studies has recently been launched by ICFA, and as part of it, the CLIC design optimised for 3 TeV c.m. has been revisited for the lower c.m. energy of 500 GeV, in order to be able to make a comparison with other projects. This necessitated reviewing several of the sub-systems, whilst maintaining compatibility with the nominal 3 TeV energy. As a result, a first description of a 500 GeV CLIC has been written.

Meanwhile, preliminary investigations of the engineering feasibility of a CLIC facility of 3 TeV on a site near CERN have been carried out. The guidelines for the civil engineering were to have the main tunnel entirely positioned in the rock layer called "molasses", to locate the interaction point and the injector complex in the same central area on the CERN site, and to minimize the environmental impact and cost. These requirements can be met for a 40 km long tunnel at an average depth of ~140 m, containing both the main linacs and the beam delivery systems. Engineering shafts are planned every 3.2 km, and return loops are foreseen at each tunnel extremity. The total power dissipated in the main tunnel amounts to 167 MW, of which the main beam injector plus the drive beam generation system dissipates 152 MW. The cooling system consists of closed primary water circuits serving as sources for primary/secondary heat exchangers. The cooling water towers of the primary circuits are built around a small number of tunnel access pits and in the central area, in order to minimize their impact on the site. The air quality is maintained by a central chilled-water cooled unit whose aim is to reduce the temperature variations in the RF structures. A first study of a possible powering strategy has been carried out. Given the required power, the connection to the grid must be at 400 kV. The power needed for the drive beam requires a separate primary system at 36 kV and a secondary system at 7.2 kV.

In what follows, the main points where significant progress has been achieved in the various CLIC sub-systems are described. Firstly, the electron source has been redesigned in order to produce polarized electrons with a DC gun and a photo-cathode, instead of with an RF gun. Positron production and polarization have also been improved. Simulations with the present parameters of the damping rings showed potentially severe limitations here, and so more detailed studies were launched in order to address the electron-cloud and intra-beam scattering issues.

Simulation work on the main linac dealt principally with the feedbacks controlling the beam position, the evaluation of the effects of various accelerating structures on the beam stability, and the dependence of the efficiency of emittance-tuning bumps on their location. In these simulations, a more realistic model of independent feedbacks was introduced, and the optimum gain that is implemented by the feedbacks was evaluated. At this gain, the multi-feedback system takes a certain time to converge towards a status where it counterbalances the imperfections with a constant efficiency, but fortunately the emittance growth during this time was shown to be small. Concerning the accelerating structures themselves, the effects on the main-beam stability were calculated for different designs with different ratios of surface field to accelerating field, and this helped us select the most promising structure design for further study.

The simulation code PLACET used for the main linacs was improved in order to better evaluate the effects on the performance of distorted and blown-up bunches. This required the integration of linac simulations and beam-beam interactions. Similar work at TESLA indicated that the loss of luminosity associated with actual beam distortions could be large in the presence of static and dynamic imperfections. For CLIC, however, the simulations were performed by replacing the beam delivery system with a transfer matrix, and this showed that the effects in CLIC are more moderate. Such studies can only be done with integrated simulation tools. Interfaces were therefore created between PLACET and the codes SIXTRACK, MAD and TRANSPORT. Work has also been done with the code GEANT4 to simulate the CLIC beam delivery system. Scattering and secondary generation in spoilers and collimators is included in this approach, together with the generation and tracking of synchrotron radiation in the beamline elements. First estimates of collimation efficiency for halo distributions were obtained. For the experiments, a new PYTHIA-based generator for the hadronic background from $\gamma\gamma$ collisions was developed, which, in contrast to the old generator, can be used to predict the background for a full detector simulation. A new GEANT3-based simulation code has also been written to study the effect of pairs and hadrons.

The old power Extraction and Transfer Structures (PETS) of the drive beam decelerator were found to have some low frequency transverse modes, as well as insufficient damping. New designs were therefore necessary. The beam stability in the decelerators with structures of different apertures but the same output power was simulated, and higher apertures turned out to be better. The high group velocity in the PETS makes the single bunch effects important, and this reduces the power transfer efficiency. This can be resolved by having a PETS frequency shifted slightly with respect to the RF frequency, as confirmed by a simple model calculation. Drive beam stability simulations at this new frequency resulted in a new PETS design.

Development efforts on the linac accelerating structure focused on two main performance-limiting effects: electrical breakdown and pulsed surface heating. A picture of high-frequency breakdowns has emerged from the accumulated body of experimental data, with maximum surface electric fields of 300 to 400 MV/m for copper, the damage being caused by electron currents generated and accelerated during the breakdown. Using this understanding, new RF designs with reduced surface electric fields have been developed, and the use of arc-resistant materials inside the accelerating structures has been investigated. The potential of one such material, tungsten, has been demonstrated in CTF2 this year. Progress towards structures with reduced pulsed surface heating continued with the development of a new, very fast technique to calculate long-range transverse wake-fields. This calculation is essential for accelerating structure designs because the features that produce the desired transverse mode damping are the main source of the undesired pulsed surface heating. Basic material data for pulsed surface heating will be produced in collaboration with JINR, Dubna. A new system for assembling the accelerating structure elements by clamping and mounting them inside a vacuum manifold was also developed for experiments at CTF2 this year. Although this may appear to be an esoteric detail, it dramatically improved the turn-around time and costs, making tests of new materials feasible. The technique also opens new possibilities for transverse mode damping and for low cost mass production.

16.1 CTF2

This year the CLIC Test Facility CTF2 served mainly for RF structure R&D with the aim of improving our understanding of field limitations and finding remedies. Equipment tests started on 2nd April, with first beam a week later. Runs were roughly 2 weeks out of three until 14th December. The alternate weeks were used for installation of the various 30 GHz experiments and/or for laser repairs. During running weeks we ran five days a week for 8 hours. A series of single-cell cavities at 21, 30 and 39 GHz was built (two for each frequency) and powered by the drive beam to their breakdown limit, to obtain data on the frequency scaling of attainable fields. It came as a surprise that the maximum surface field for the 21 and 30 GHz cavities was 380 MV/m and 390 MV/m respectively, while the 39 GHz reached only 300 MV/m. For the 39 GHz cavities some uncertainty remains about the details of the geometry, which will be clarified once the cavity is cut open. However, this experiment does not support the assumption that higher frequencies allow higher fields.

Two new power extraction and transfer structures (PETS) were built and tested. The first is a 1 m long, four wave-guide design optimized for power production in CTF2. It obtained a new 30 GHz power record of 280 MW (with 16 ns pulse length). It is now routinely used as the power source for structure testing. The second PETS is of particular interest for later use as a 30 GHz source in CTF3. It is novel in many respects. It has a new power coupler design fabricated by electroforming, and features power re-circulation. Apart from a tuning error of about 200 MHz, this structure performed very well and in perfect agreement with theoretical predictions.

Another series of experiments tested the capability of different materials to support high RF fields and to withstand RF breakdowns. For this purpose an older 30 GHz copper prototype structure was opened and the part exposed to the strongest field was exchanged for a variety of machined samples of different materials. The materials tested were tungsten, electro-polished tungsten, Cu/W-matrix and a copper reference piece. The measurements showed that both tungsten samples supported RF breakdowns without major damage, while the Cu/W matrix and the copper sample where significantly damaged. With the tungsten samples it was also possible to reach fields about 20% higher than with copper. At these levels one is probably limited by the part of the structure consisting of copper.

Apart from the RF test programme, an experiment was performed to demonstrate the suppression of coherent synchrotron radiation emission by the vacuum chamber. Although the construction and installation of a dedicated 4-pole wiggler with exchangeable vacuum chambers was completed in time, the results of this experiment were unsatisfactory. The reason was the presence of a satellite electron bunch 36 ps behind the main bunch, which made the analysis of the measurement ambiguous. The problem of this satellite bunch was eventually traced to a faulty coating of the laser pockel-cells. This fault was the same for all pockel-cells of a recently delivered batch. Due to lack of time, it was unfortunately impossible to repeat the experiment after the satellite problem had been solved.

16.2 CTF3 Preliminary Phase

This year the new CLIC test facility CTF3 has become a reality. Its main goal is to demonstrate the feasibility of CLIC technology, in particular the generation of 30 GHz RF power. While the "nominal phase" is still under development, the existing installation of LPI is being modified such that "proof of principle" experiments will be possible. As soon as the last experiments with the LPI beam were finished in April, the modifications of LPI started. A great deal of old equipment had to be removed from the tunnels and new equipment for the high RF power in CTF3 had to be installed or reconfigured. Commissioning with beam began on 17th September and beam circulated for the first time in the ring on 7th December.

The first stage is the preliminary phase. Its purpose is to demonstrate the funnelling technique for multiplication of the electron bunch repetition rate by a factor of up to five at low bunch charge, compatible with the existing LIL accelerating structures. The first eight of the 16 LIL accelerating sections were removed from the linac and the front-end was moved forward. This created a separate area, shielded from the rest of the machine, for installation of the new injector for the later phases of CTF3. This area will also be used for testing cavities and other equipment with high power RF at 3 GHz. The front-end was fitted with a new thermionic electron gun manufactured by LAL (Laboratoire de l'Accelérateur Linéaire d'Orsay), which is very similar to the one installed on CLIO (Centre Laser Infrarouge Orsay). This gun was successfully commissioned in the summer and was conditioned up to 100 kV. The major modifications to the linac were the addition of new beam diagnostics equipment and a new matching section at the downstream end. A spectrometer line was installed after the linac, and new optics lines were added for beam diagnostics with optical transition radiation and Cherenkov light. The optics of the beam transfer line between the linac and the ring was modified to make the line achromatic and isochronous. The former EPA ring was modified to provide an isochronous optics configuration with a dispersion-free injection region, necessary to demonstrate the bunch interleaving technique. This required displacing some magnetic elements, a change in the number of quadrupole and sextupole families, a rearrangement of existing families, and the manufacture of some new power supplies. The circumference of the ring was reduced by 17 mm. An additional, different optics configuration with non-zero momentum compaction will allow accumulation of beam to study the optical properties of the ring. Although the RF deflectors are not yet installed, the klystron/modulator and the waveguides are being prepared; the modulator MDK33 will use for the first time switch mode capacitor charging power supplies and PLCs (Simatic S7) for the controls. Some development work was started on a solid state switching modulator to power a future 1.5 GHz klystron, using new technology IGCT solid-state switches.

Commissioning was done in an efficient manner by alternating beam operation with shutdown periods, leaving time to complete the hardware installations/modifications and to analyse the data. A total of six weeks of beam operation and seven shutdown/installation periods was scheduled. Typically, the machine ran for about 12 hours per day and five days per week during beam operation weeks. The commissioning work therefore progressed as the new equipment was installed in the front-end, the linac, the transfer line and the ring.

The new gun rapidly delivered an electron beam with the required parameters, both in single pulse and multi-pulse mode. About 60% of the current delivered by the gun was captured by the bunching system and later accelerated in the linac. The beam characteristics (Twiss parameters, bunch length) at the exit of the bunching system were close to the ones measured previously on LIL, as expected. The new linac optics also worked well, with a transport efficiency of 100% and a large momentum acceptance. In general, good agreement with the optics model was found. Bunch length at the end of the linac was measured both with a Cherenkov radiator plus streak camera and by measuring the energy spread as a function of the accelerating phase, confirming that the bunches are short enough to perform the combination process. Dispersion measurements in the injection line showed good agreement with the MAD optics model. The beam was injected and circulated in the ring, in both the isochronous and the finite momentum compaction configuration. Using the latter configuration it was possible to accumulate and store beam, with a lifetime of the order of tens of minutes. Streak camera measurements of the synchrotron radiation in the isochronous configuration confirmed a small value for the momentum compaction.

16.3 Preparations for the next CTF3 phase, the Nominal Phase

An important milestone for CTF3 was the design review that took place from 2nd to 4th October in the presence of three referees from USA, France and Germany. The project was presented in detail in 24 talks and was very well received by the referees.

A new thermionic electron gun and its high voltage pulser, as well as pre-buncher cavities, will be developed and built by LAL, for which design work has already started. The triode for this gun is provided by SLAC. The layout of the injector with sub-harmonic bunchers, pre-bunchers, travelling-wave buncher, accelerating sections and cleaning chicane was also developed in close collaboration with SLAC. The layout work is now finished, and the mechanical design is either well under way or finished, allowing the manufacture of most components to go ahead. As an alternative solution to the thermionic injector, a laser-driven photo-injector is being considered. Studies and prototype testing of the laser system are being done by Strathclyde University and RAL, and very promising work on photo-cathodes is under way at CERN.

A detailed design of the Drive Beam Linac has started and the accelerating cavities, requiring very strong damping of beam-induced Higher Order Modes (HOM), were the focus of much attention. A prototype of the Tapered Damped Structure (TDS) was built and successfully tested with high power RF. An alternative design (the Slotted Iris Constant Aperture (SICA) structure) was also developed, a short prototype having been manufactured and successfully tested with high power RF. Of the two, the SICA structure was chosen for series production. A contract for the fabrication of 18 cavities will soon be placed with industry. Optics studies of the linac were concluded and it was decided to adopt triplet focusing with two accelerating sections between the quadrupoles. This is expected to give adequate stability for the high beam currents, in particular in the presence of imperfections and jitter.

Encouraging power tests of the RF pulse compression system were made in order to demonstrate the production of a rectangular RF pulse with flat phase using the existing LIPS system with a carefully designed RF phase-switching and ramping programme. A power compression factor of about two was achieved, albeit not yet at full power. As an alternative to the two-cavity LIPS system, a single-cavity system, the Barrel Open Cavity (BOC) has been proposed. A prototype of such a cavity is being manufactured by the SL-CT group and will soon be available for high power tests. A new 45 MW klystron has been ordered, but its modulator is being manufactured in CERN. Two RF power sources at 1.5 GHz will be required in addition to the existing 3 GHz RF system: one is for the sub-harmonic buncher, with a large bandwidth of about 150 MHz and 500 kW power; the second one will have a narrow bandwidth and 20 MW output power. The narrow band klystron was ordered in industry, and production will start soon. The wide band klystron is a special, non-standard development and a feasibility/design study was requested from industry. The study is complete, and the klystron can be ordered as soon as the necessary funds are available. Work on the modulator for the wide band klystron has started in CERN.

The design of the transfer lines, Delay Loop and Combiner Ring is being done by INFN Frascati, in collaboration with CERN. The optical layout is close to completion and there is on-going work on the 1.5 and 3 GHz deflectors, the fast high-voltage kicker, and vacuum and beam diagnostic components for the Combiner Ring. Work on a mm-wave detector for beam diagnostics has started in Uppsala University.

17. Neutrino Factory Working Group (NuFACT)

The year 2001 saw good progress by the Neutrino Factory Working Group, in close collaboration with European (in particular CEA, INFN, RAL), American and Japanese laboratories. A neutrino factory consists of: a proton driver (which may be a linac followed by accumulator/compressor rings); a target to produce pions by bombardment with protons; a decay channel in which muons are produced by the decaying pions; a phase rotation and cooling channel (which depends on the acceptance of the subsequent machines); the muon accelerators; and a muon decay ring where the neutrino beams are produced. The "base-line scenario" has been refined this year, and would fit on the existing CERN site.

In the CERN scenario we have opted for a superconducting 2.2 GeV linac (the SPL) that injects H^- ions into an accumulator and subsequent compressor ring. Considerable effort was invested to calculate the transfer line after the linac in order to obtain a good injection into the accumulator (by reducing the energy spread and jitter from the linac and by scraping off the beam halo) and in demonstrating the absence of dangerous instabilities. The very short bunches are ejected and focused onto a Hg-jet target which is located inside a magnetic horn to collect the pions into the decay channel. Extensive theoretical and experimental work has started to solve the problems of the liquid metal target. A solid, fixed target is unlikely to survive for any reasonable time with the envisaged beam power of 4 MW, so a liquid metal target is preferred, although a target of solid micro-spheres is also under consideration. The target must be small in diameter to allow the pions to escape without too high a fraction being absorbed. As the target is completely destroyed by one proton pulse it has to be replaced within 20 ms, the repetition period of the linac. The splash of the Hg can cause considerable erosion of the magnetic horn due to the high velocity of the Hg droplets. Extensive measurements were performed both at the Brookhaven AGS and at ISOLDE. The velocity of the droplets has been measured and the time structure of the splash analysed using high speed cameras. Preliminary results are quite encouraging and seem to indicate that the velocities with which the Hg is dispersed will not cause erosion problems. Additional measurements were performed at the Institute for High Magnetic Fields at Grenoble by injecting the Hg-jet into a 13 T solenoid field. These results would be important if it were decided that a high field solenoid would be a better option than the magnetic horn for pion capture. The pion collecting lenses are excited by half-sinusoidal 300 kA pulses of 100 μs duration and 50 Hz repetition rate. The basic circuit layout and mode of operation of the power supply have been defined. A prototype horn is under construction in EP Division and will be ready for tests in spring 2002. To this end we have built a test power supply for 30 kA, 100 μs pulses at 1 Hz is being built. The next steps are to develop a fast 50 Hz charger section for the final power supply, and to upgrade the horn test supply to 300 kA, 1 Hz.

The muon cooling channel is one of the biggest problem areas for the neutrino factory. Although the concept was proposed thirty years ago and is generally considered very sound, ionization cooling of muons at the minimum of the ionisation curve has never been realized in practice. The channel consists of liquid hydrogen absorbers providing energy loss, combined with high gradient RF cavities to re-accelerate the particles, the whole ensemble being tightly contained in a magnetic channel. Cooling is a delicate balance between the "real" cooling effect (reducing the transverse and longitudinal momentum of the muons, and reconstituting the longitudinal one with the help of RF cavities) and the heating effect due to multiple scattering in the stopping medium. Many new practical and perhaps fundamental problems are bound to present themselves in such a combined system, which would not necessarily show up in a component-by-component approach. However, they could have a substantial impact on the cooling channel performance, design and cost; the cooling channel would be over 100 m in length and would clearly be a major cost item in the whole facility. It is therefore considered essential to make an experimental test of a section of such a cooling channel, and for this purpose an international collaboration has sent a Letter of Intent to RAL and PSI. For the cooling channel, detailed simulations were originally performed using rough approximations to the solenoidal and RF fields. However, after criticism that these did not reflect reality, it has been shown that if exact field maps are used, there is no substantial difference in the results. Using the simplified, rough (i.e. non-Maxwellian) approximations to the fields, the calculation times are orders of magnitude shorter than using the exact fields.

18. Superconducting H^- Linac (SPL)

The SPL design has undergone many improvements over the year. The block diagram is shown in Figure 9. Beam power and energy remain at 4 MW and 2.2 GeV respectively, and the construction cost is unchanged. However, the repetition rate has been reduced to 50 Hz (previously 75 Hz), and the accelerator's length has been reduced by 100 m, thanks to the decision to use only 5-cell β=0.8 cavities up to the highest energy. Beam dynamics has also been studied in more detail and refined in both the normal and the superconducting parts of the accelerator.

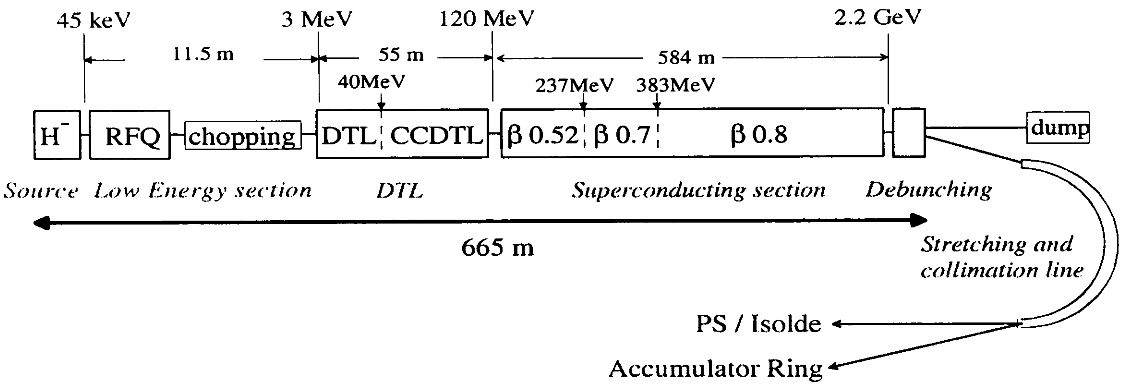


Figure 9. Layout of the 2.2 GeV SPL.

Major advances have also taken place concerning the hardware:

- it has been shown that only very limited modifications are necessary to operate the existing LEP klystrons and power supplies in pulsed mode;

- a new type of reduced width chopper structure on a ceramic substrate has been developed and tested (Figure 10). It eases the voltage requirements on the chopper driver by allowing a longer chopper length, extending inside the quadrupoles. A prototype of the chopper driver has been designed and is being constructed;

- accelerating structures have been designed for the Coupled Cavity Drift Tube Linac (CCDTL) part of the accelerator, and a scale model is under test (Figure 11);

- studies of the field stability in pulsed superconducting RF cavities driven in parallel by a single klystron have revealed the need for a separate control of phase and amplitude of the RF driving each cavity. This triggered the study of a high power phase/amplitude modulator whose prototype development is an important issue for the future of the SPL study.

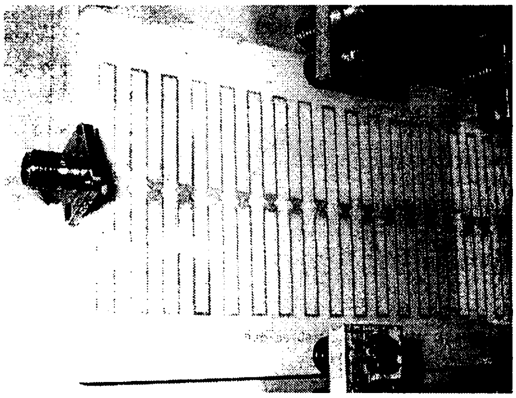


Figure 10. Double meander line chopper on a ceramic substrate

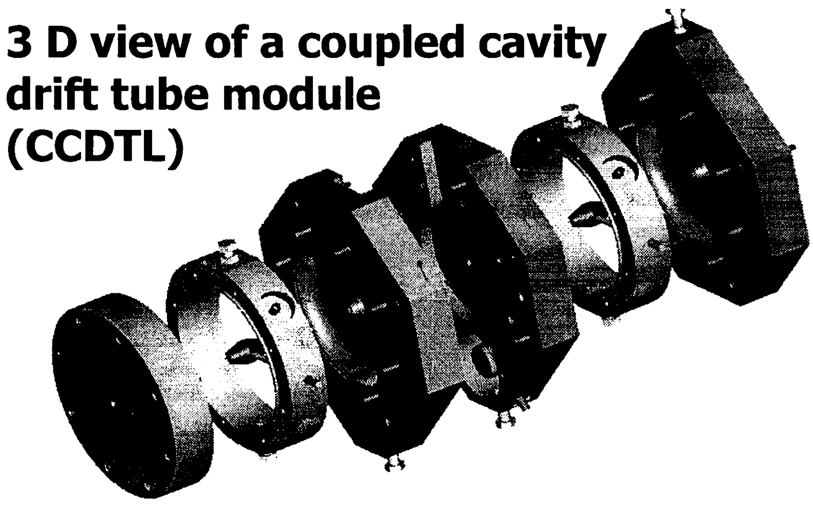


Figure 11. ACCDTL model

Although the SPL is tailored to the needs of a neutrino factory at CERN, there is interest in such a machine for the generation of radioactive ions (by EURISOL) and for a neutrino "super-beam" (neutrinos to an underground experiment in the Fréjus tunnel). Moreover, studies have revealed that the first 120 MeV part of the SPL could advantageously be used as a new injector for the PS Booster, to significantly upgrade the characteristics of the proton beams available at CERN, and to prepare the way for improving the LHC performance beyond the "ultimate" beam. A proposal is in preparation for a reduced cost 120 MeV machine, which could be housed in the existing PS South Hall extension building.

19. Other Collaborations

19.1 H^- source Collaboration

During 2001 a collaboration proposal involving eight European institutions (CEA, Saclay; IAP, Frankfurt; RAL; DESY; FZ, Juelich; EP, Palaiseau; DCU, Dublin; and CERN) was put forward to the Fifth Framework Programme to look into the development of high-performance, high-reliability negative hydrogen ion sources for future high power accelerators such as the proposed SPL. This proposal was accepted and will be launched in early 2002.

19.2 Controls Collaboration with IHEP, Protvino

The Controls Collaboration is involved with the upgrade of the U-70 accelerator complex. The activity during 2001 concentrated on the control of the new power supplies and their associated timing. These supplies were mass-produced using embedded low cost micro-controllers. In addition, the MIL1553 field bus was installed, and the timing system and VME crates were connected to the control LAN. On the software side, generic control programs were used for the newly available hardware. The real-time database, which is the kernel of the control software and which contains the "operating régimes" of the accelerators, has demonstrated its power and flexibility.

Success was achieved in the autumn run when the full functionality and reliability of the control system was evident, and the operating team took charge of their new facility. The run was a great success, both for the operators and the physicists using the beams. A management meeting regularly reviewed the progress of the project and its completion has been confirmed for 2002, following the updated planning of 1999. A preliminary proposal for a consolidation phase has also been discussed. The aim of this would be to enlarge the new control to domains that were not foreseen initially, to provide a more flexible timing system, and to suppress the major bottleneck in the network due to the volume of traffic generated during physics runs.