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EuCARD-2

Enhanced European Coordination for Accelerator Research & Development

Note

Report on Workshop: Accelerators for ADS

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Enhanced European Coordination for Accelerator Research and Development

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REPORT ON WORKSHOP: ACCELERATORS FOR ADS

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Abstract:

A workshop on accelerators for Accelerator Driven Systems jointly organised by the EuCARD2 AccApplic work package and the MAX project took place at CERN, Geneva over 2 days (20-21 March 2014). It focused on design and technical issues of high-power high-intensity linear accelerator specifically related to ADS applications with the aim of defining the necessary R&D and finding synergies amongst different European institutions.

The European Coordination for Accelerator Research and Development (EuCARD-2) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement no 312453. EuCARD-2 began in May 2013 and will run for 4 years.

Delivery Slip

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1. WORKSHOP SUMMARY

The workshop counted 42 registered participants and 30 contributions. The main European projects were represented with representative from Myrrha, Linac4/SPL, ESS, Saraf, and SPIRAL2/IPHI.

An accelerator for ADS should provide a beam of protons with energies above 800 MeV and a beam power between a few and 10-15 MW. Beam losses should be controlled to minimize the irradiation of the accelerator and of the environment, but the most important quality of an ADS accelerator is its reliability. The number of beam trips should be minimised and the limitation comes mainly from thermal stress in the fuel structure. As a guideline, MYRRHA requirement are not more than 100 trips per day lasting between 0.1 sec and 3 seconds and no more than 10 trips per trimester lasting more than 3 seconds. The energy efficiency, the size of the accelerator and its cost are as well important parameter. In the end, the solution chosen among LINAC, Cyclotron or FFAG will be the one best fulfilling all these requirements.

During the workshop several synergies have been identified between Max and Eucard2 AccApplic, amongst which are reliability issues, the dynamics in the low energy beam transport and neutralisation effects and the concept of a virtual Accelerator. In particular it is of interest the possibility of using the reliability run of linac4, presently scheduled for 2016, as a test bed for trying reliability models as well as possible mitigation measures and automated reaction.

2. BASIC DETAILS ABOUT THE WORKSHOP (LANDSCAPE FORMAT)

Type of activity	Workshop
Title	Accelerators for ADS
Date	20-21/03/2014
Place	CERN
Type of audience	Scientific Community
Size of audience	42
Scope of the workshop	International
Link	http://indico.cern.ch/event/300409/timetable/#20140320
Partners involved	Myrrha, Linac4/SPL, ESS, Saraf, SPIRAL2/IPHI

3. MAJOR OUTCOMES / RELATION TO OTHER EUCARD-2 WORK

A summary of each contribution is given in the following.

3.1. DAY 1: THURSDAY 20TH MARCH

General introduction – Roger Garbil

MYRRHA is strongly embedded in the Euratom Framework Programme, securing EU contribution in FP5, FP6 and FP7, in the general frame of promotion of European research infrastructures and in the wider societal context of the need to ensure future sources of clean, secure and efficient energy. A design review team gathered together in November 2012 to assess the progress status. The main conclusions were an appreciation of progress on the MAX project (accelerator design), and the assessment of a need to create a core accelerator competency within the MYRRHA team, fostering collaboration with other European accelerator projects. As follow-up of this comes the organization of the present workshop, which should concentrate on accelerators for ADS, identifying R&D needs and synergies and as a platform to launch future collaborations. The timing is also critical, coming just before the deadline for a MAX2 proposal due by the end of the year: several millions of euros funding could be made available for studies of transmutation leading to industrial applications (bridging between nuclear fission and radiation protection research). A collaboration between CERN and SCK-CEN was announced at the end of 2013, and an official visit was paid to SCK-CEN by a European delegation with attendance of Belgian state secretaries, focusing entirely on the MYRRHA project. A key decision on funding is attended this year.

Overview of ADS – J P Revol

At current development rates, world power consumption will have to increase by a factor of 3 by the end of the century and viable innovative alternatives to fossil fuel need to be researched. Renewable energy sources are dispersed and intermittent, interest is now turning towards fast critical reactors or thorium energy. Thorium is 3-4 times more abundant than Uranium, is fertile rather than fissile (potential x140 gain factor compared to ^{235}U in a reactor) and minimizes nuclear waste production. Thorium blankets have been used in India to breed ^{233}U, but it's a complex system. Pebble bed and molten salt reactors are alternative options for Thorium usage, but ADS systems are more promising wrt safety, waste management and military proliferation issues. ADS studies started in the '50s and were boosted in the '80s-'90s when C Rubbia at CERN promoted specific experiments to test basic concepts (FEAT, TARC) and the n_TOF facility to acquire neutron cross-section data. The main issue today is the absence of a demonstrator: Myrrha is currently the most important project in Europe, but is only partially funded and does not include Thorium application. Basic elements of an ADS system are a particle accelerator to provide neutrons and a sub-critical core. The accelerator should produce a 10-15MW proton beam at 800-900 MeV energy with minimal losses. Reliability is a crucial requirement for operation as well as beam power stability and control and a large operational range of beam intensities. 20 years could be a reasonable timescale for the development of a thorium-based economy if there is a clear high-level commitment from European states.

Accelerators for ADS – Mike Seidel (PSI)

Requirements for ADS proton accelerators (linear or cyclic) are a 1-2GeV beam energy, 2-10 MW beam power, low cost and losses, and high efficiency and reliability. CW beams are preferential, since pulsed heating is problematic for targets, pulsed RF power is less reliable and space charge effects are higher. Desired reliability goal is to have 0.01-0.1 trips per day (compared to current 10-100 /day). Efforts to achieve this focus on adopting conservative approaches and design redundancy. Superconducting linacs are very good candidates for high intensity accelerators thanks to all the technological progress and energy efficiency. They benefit from large apertures and consequent low losses and efficient power transfer. The intensity limit due to space charge and instabilities is relatively high. Among circular accelerators, isochronous cyclotrons are the best choice for high power beams; however beam dynamics is more complicated, failures are not easily compensated and injection/extraction schemes are challenging. Many new concepts are under investigation, including FFAGs.

Status of the Myrrha project – Dirk Vandeplassche

Myrrha is a Belgian project for a flexible and fast spectrum irradiation facility based on an accelerator driven reactor and spallation target. A 4mA CW proton beam is accelerated to 600MeV by a superconducting linac with required MTBF > 250 h (failure being a beam trip longer than 3s). The reactor is 6mx12m in dimensions with a core of less than 1m, and a robust decay heat removal system. Burnt fuel transmutation with Myrrha could reduce by a factor 1000 the natural decay duration and by a factor of 100 the volume of waste. Myrrha has already secured Belgian government commitment; an international consortium is under construction. Currently in the design phase, the horizon for installation and commissioning, if approved, would be around 2020, with full exploitation foreseen in 2024. In the present European strategy context, the Myrrha project would address the nuclear waste legacy of the present nuclear technology, provide a multi-purpose research infrastructure and irradiation facility for the fusion material community and address social needs for radioactive isotopes for medical applications.

Status of the construction of ESS – M Eshraqi

ESS is an international project for a European Spallation Source currently under construction in Lund, Sweden. It consists of a 2GeV 62.5mA proton linear accelerator, a solid rotating target station and a suite of 22 experimental areas. Average beam power is 5MW and availability should be >95%. Once built it will be the world's leading facility for research using neutrons (by 2025). Prototypes of individual accelerator parts have been developed by several European partners. The Linac is NC up to 90MeV and made of superconducting spoke, medium and high beta cavities at higher energies. A He-cooled 17-tonnes rotating tungsten target is suspended on a 6m long shaft and is made of 33 sectors. Rotational speed is 0.42Hz and estimated lifetime is 5 yrs. A reference suite of 22 instruments fans out of the target area. Total construction cost is estimated at 1.84 billion euros, with 50% cash and 50% in-kind contributions from a Scandinavian consortium and from all other European partners respectively. The installation and commissioning schedule by 2024 is very aggressive. Operations will start by delivering a measurable number of moderated neutrons to one instrument, followed by a quick ramp-up in power to find limitations and ascertain reliability before the start of proper user operation. In addition to the neutron measurements, ESS also opens possibilities for many other experiments such as neutrino oscillation measurements.

ESS is also a sustainable facility, with 75% of power being converted to heat for hot water production.

Status and plans of the SPL R&D – R Garoby

SPL studies were started at CERN in the framework of general renovation plans of the LHC injector complex, and at the same time opening options for neutrino physics (either in the form of a low energy superbeam, a neutrino factory or a high energy superbeam for a long distance underground experiment) and a next generation Radioactive Ion Beam Facility (EURISOL). After some of these projects were archived, the motivation to continue technological R&D on the SPL rests on the recognised need to update CERN competencies on SC RF and to upgrade the relative infrastructure, as well as to work in synergy with other applications at and outside CERN. The SPL was designed to be a 5GeV, 2-5MW H- beam SC linac with a 160MeV NC frontend (Linac4), presently under construction. The SPL is composed of medium beta and high beta cavities, developed in collaboration with ESS and with contributions from IN2P3 and CEA, and to be tested this year. Niobium cavities were fabricated at CERN, electro-polished and repaired with a new e-beam welding machine. A cavity reception area was built at CERN to house tests systems for measurements of cavity detuning, RF beampull etc. As part of specific infrastructure upgrades, a new cryogenic transfer line was commissioned by the end of 2013, the main clean room was extended and upgraded and an ultra-pure water station was delivered and commissioned. A high power RF upgrade at 704MHz (1.5MW klystron, modulator and new LLRF) are planned to be delivered by the end of 2014, and high power IOT development will take place in 2015-6 in collaboration with ESS.

Overview of the EuCARD2/AccApplic activities – R Edgecock

Eucard2 is the third in a series of Framework Programmes on accelerators R&D funded by the European Commission. It consists of 13 work packages, grouped under networking activities and joint research activities. The present workshop is organised within the activities of WP4 (AccApplic), a package on accelerator applications, whose objective is to make an inventory of existing accelerator applications and further study new or improved ones. Expected deliverables of the WP are a policy document, collaborations between institutes and proposals for Horizon2020. It is subdivided into 5 tasks, covering low and intermediate energy and high power accelerators and targets. The present workshop is the second being organised, and several others are in the pipeline. A Eucard2 annual meeting will take place in May at DESY. The final policy document, inspired by a similar one produced in 2009 in the USA, is meant to be presented to European policy-makers and funding agencies to demonstrate the potential of particle accelerators and the importance of continuing their development.

Overview of the MAX activities & possible H2020 prospects – J-L Biarrotte

In the frame of the Euratom FP7 (2011-2014), the MAX project united 11 international partners with the goal of providing a consolidated reference layout for the Myrrha linac, ready for a successive engineering design and construction phase. The project was organised into 4 distinct work packages, focusing respectively on:

- Global accelerator design, for the production of a global design of the Myrrha accelerator and consolidation of this via code benchmarking, error studies and sensitivity analyses

- Injector developments, for R&D work on the 4m long 176MHz 4-rod RFQ (with fabrication and high power RF tests of a 1m long prototype) and R&D work on the CH cavities (with fabrication of a NC 5-gaps and SC 7-gaps prototypes)
- Main linac developments, for R&D on the 352MHz spoke cryo-module and 704 MHz elliptical cavities (with fabrication and conditioning of 2 power couplers and first assessment on multipacting).
- System optimisation, focusing on reliability analysis (benchmarked on SNS logbook data), R&D on 700MHz solid state amplifiers and conceptual design of a cryogenic plant.

The MAX scientific programme is to be completed by the end of July 2014; a possible follow-up is being prepared within Euratom H2020.

Zero-current longitudinal beam dynamics – J-M Lagniel

Three different ways of studying zero-current longitudinal beam dynamics are presented and compared:

- Integration of the equations of motion with field maps (more precise)
- Mapping, integrating the effect of each cavity to give an energy kick (faster)
- Smooth approximation to obtain a second order differential equation

Integrating the equations of motion over one accelerating cell, the radial and velocity evolution along the cell can be isolated in the TTF. Due to its complicated expression one needs to simplify and assume constant particle speed and radius over the cell in order to have an analytical expression with which to calculate a mapping. This mapping is however not symplectic, and a 1st order phase correction must be added by neglecting the effect of the particle velocity spread (assuming the synchronous TTF for all particles). Considering the mapping without phase correction, one can combine the equations of motion into a second order differential equation with 3 terms, describing respectively small and large amplitude (non-linear) oscillations and long term behaviour (damping, more important at low energy).The phase advance error introduced with this smooth approximation is around 10deg. Without damping the phase advance changes as a function of the oscillations amplitude (non-linearity induced by the accelerating force). Increasing the synchronous phase has an effect of reduction of the available longitudinal acceptance. Comparing smooth approximation and mapping without damping at -90deg synch phase one finds no significant differences at low phase advance. Above 50 degrees phase advance however, resonances start to develop in the mapping case and chaotic areas which reduce the acceptance. The effect was cross-checked by direct integration of the equations of motion in a first-harmonic toy case, varying the length of the cell over the period. One finds two separate regimes: 1) for small drift space (Lc~L) the behaviour is similar to the smooth approximation case and no resonances are excited; 2) for large drift spaces (Lc<L) the behaviour is close to the mapping case, with resonances excited at large phase advances. In the case of smooth approximation with damping, one finds that the higher the damping coefficient, the higher is the energy spread and the larger the acceptance. The effect of damping is more difficult to study in the mapping case, since the particles are attracted by resonance islands at low damping rates. Only higher damping coefficients can annihilate the effect of the resonances. The damping coefficient k should therefore be considered as an important parameter in the design of new linacs. In the

ESS case k is very strong at low energy and decreases rapidly with almost no effect above 200 MeV. Adding space charge effects would complicate the scenario by adding possible coupling between transverse and longitudinal planes. It would be interesting to extend the study and find correlations between the damping factor and the control of losses in a linac, possibly using multi-particle tracking codes.

On the choice of linac parameters for minimal beam losses – M Eshraqi

Linac beam dynamics designs traditionally follow an equi-partition rule between the transverse and longitudinal planes, as the best choice to ensure minimal beam losses ($\square_t\square_t=\square_l\square_l$). An alternative approach consists however in focusing on the space charge induced tune depression, through a parameter □□□□□, where □□is the tune depression. □□is a growing function of the beam current, and almost counter-intuitively a decreasing function of the phase advance in both planes. The harder the beam is focused, the lower is the space charge effect. One can establish a new design rule, called equi-RTS: $\square_t\square\square_l$. Comparing the two rules, one can demonstrate that the equi-RTS approach allows 25% more current (lower space charge) than the equi-partitioned one, and hence provides a better working point with lower beam losses.

Fault tolerance in the Myrrha SC linac – F Bouly

MYRRHA's specifications for linac reliability are for an overall 80% beam availability and maximum 10 trips longer than 3s over a 3-month operational period. The main guidelines followed in the linac design to ensure this are: a robust design, redundancy (parallel or serial) and reparability. Parallel redundancy is the fault compensation strategy at low energy, with two separate injector lines and a switching magnet to swap from one to the other. Serial redundancy and independently powered cavities allow a local fault recovery scheme in the linac, whereby once a failure is localised, new set-points are found for the cavities adjacent to the failed one, to be detuned, in order to re-establish operation. At the level of linac architecture, the scheme requires a capability of significant cavity voltage increase, a fast tuning system and a large acceptance and margins for retuning. The overall beam dynamics design has followed these guidelines. Several scenarios were studied with even multiple failures and it was found that the developed fault recovery scheme is a priory capable to compensate for the loss of a single cavity or if a full cryo-module. Consequent system requirements are that SC cavities should accept fast gradient changes in CW operation, that RF power amplifiers should have a margin for errors and be flexible (10-20% more power from generator and 70% margin on RF power) and that the control system must be able to frequency detune faulty cavities and retune the compensating ones in less than 3 s. Simulation studies have predicted the feasibility of such a fault recovery scheme, the next step would be to test the results on a real scale dedicated experimental facility where to carry out reliability-oriented experiments with a fully equipped 700MHz prototype cryo-module controls by RF and Fast Cold Tuning systems.

The virtual accelerator concept – D Uriot

A virtual accelerator is a simulation code connected to the control system of the real machine. There are two different approaches to implement this concept, either integrating the simulation code into the control system, or vice-versa integrating part of the control system in the simulation code as a high-level application. Three different operating modes have been identified:

- The "control tower" mode: the machine is under the constant supervision of the virtual machine which has read-only access to the accelerator database. Provides direct visualisation of variables and direct comparison between real machine and simulations.
- The "flight simulator" mode: the control system action is applied to both the real and simulated machine, with possibility to switch from one database to the other and read-only access to the virtual database. New settings and procedures can be evaluated before testing on the real machine.
- The "Autopilot" mode: diagnostics measurements from the real machine are taken as input for algorithms to control real machine equipment. Needs read-write access to machine database. Allows automating tuning of the machine.

A light solution of the autopilot mode is being developed at CEA using the Tracewin simulation code and the EPICS control system. A first test was done on SILHI, by optimising beam injection through the cone. 90% matching was found in 10 minutes optimization with the virtual accelerator compared to 80% matching found manually in one day. Further tests were carried out at SPIRAL2 during injector commissioning. Development of the Autopilot code is 90% completed and the successful results obtained in low-energy machine clearly show the interest of such a tool. An application for high power beam operation with very strict reliability requirements remains however a huge challenge.

CEA proposition for SARAF-phase 2 linac – Design et beam dynamics - N Pichoff

The SARAF phase2 front-end and linac should accelerate a cw deuteron or proton beam from 20keV/u to 40 MeV, with beam currents ranging from 0.04 to 5mA, and losses below a 1W/m limit. The RFQ is a 176MHz, 4m long, 4-vanes structure taking the beam to 1.3MeV/u with >99% transmission on paper. The injected beam is close to the RFQ acceptance of about 5mm mrad (5□ of the input emittance 0.2mm mrad). A MEBT line matches the beam to the SCL and contains collimators, a fast chopper system and a beam stopper. The chopper is based on the SPIRAL2 and Linac4 designs: the plates are placed in a doublet and a ± 800V voltage is switched on in less than 4.5ns. Three sets of slits suppress beam tails at the exit of the RFQ. The SCL is composed of 13 low-beta and 12 high-beta cavities, with 4 cryo-modules. In the nominal beam dynamics design emittance growth is below 25% and halo formation is under control. Error studies were conducted on a sample of 1000 linacs (5×10^8 particles), showing an average emittance growth of 5.5% in the transverse plane (2% in the longitudinal) and an average halo parameter of 1.26. A more robust version of this first linac design is in progress, with a higher number of cavities, regularly distributed.

LEBT lines: simulations and experimental results - N Chauvin

Space charge compensation in low energy beams is longitudinally, radially and time dependent. LEBT simulations were performed at Saclay using 3 different codes: 1) Axcel INP to model ion source extraction, 2) SolMaxP (or Warp), a self-consistent PIC code to model beam interactions with the gas, and 3) TraceWin to transport the beam with space charge compensation. One case study was the LIPAc (IFMIF) frontend, commissioned in Saclay in 2012 and composed of a 2.45GHz ECR ion source producing a 140mA cw D+ beam at 100keV and a 2 solenoids LEBT. Experimentally it was found that the percentage of deuterons increases when increasing the source RF power, but also that it varies with the duty cycle, and that at higher duty cycle one needs to increase the extracted current (higher extraction voltage) to reach the same D+ current at the end of the line, at the risk of sparking. A map of the beam transmission vs solenoid settings was extracted from measurements, and 3 tuning points were selected for comparison with simulations (giving same beam current transmission but different beam emittances). The space charge compensation profile was calculated with the SolMaxP code and adjusted to fit the data. The maximum transmission area was found to be smaller in the experiment than in simulations. More work is needed to perform self-consistent simulations: a reasonable agreement is only found with a numerical model at beam intensities above 130mA. LIPAc beam commissioning will restart in July 2014 in Japan, with the possibility of emittance measurements right after the source. Another case study was that of the SILHI source and LEBT, with a 100mA CW H+ beam at 100keV energy. Here the LEBT transmission was first maximised experimentally by tuning the solenoids and an emittance measurement taken for these values. Then the input beam parameters and space charge compensation were tuned in simulations to match the measured emittance value. The LEBT transmission was then optimised for these beam settings and the solenoid values found applied to the machine and cross-checked with an emittance measurement. The agreement was reasonable at 40mA, but the maximal LEBT transmission settings were found to be not the same as the ones for RFQ optimal injection, validation at higher currents is pending. In conclusion, self-consistent codes for the calculation of space charge compensation profiles give qualitative results but are not predictive enough; it is a crucial exercise in machine commissioning to use simulation results as input to measurements (and vice-versa).

The Myrrha LEBT test stand – R Salemme

An experimental test stand was built at UCL/Louvaine-la-Neuve in Belgium to study beam operation of a MYRRHA injector prototype (source + LEBT). The 2.45GHz ECR ion source was built by Pantechnik and is based on a multi-electrode extraction design with einzel lens. Using a test diagnostics suite of Farady cup, Allison Scanner and dump, the maximum p current achieved was of 16mA with excellent stability. The total measured efficiency was 84%, with production of 3 species (H+, H2+ and H3+). Beam was characterised as a function of different einzel lens settings. The LEBT line was designed by IPNO-SCKCEN and is based on two magnetic solenoids (under procurement from Sigma-Phi), collimators, diagnostics (F cup and Allison scanner) and an electro-static beam chopper. This will allow the parallel delivery of beam to an ISOL@MYRRHA facility, exploiting the 200□s/250Hz beam interruptions needed for critical monitoring of the reactor. Goal of the test stand will also be tests on the control system under development by Cosylab, which is based on a 3-tier EPICS architecture.

Linac4 commissioning results – J-B Lallement

The first two Linac4 commissioning stages up to 3 MeV beam energy have just been completed, first in a dedicated test stand and then in the final tunnel installation. The source used in the commissioning was not the final design that will be used in Linac4 operation and provided an initial beam for testing of 15mA with a higher than nominal emittance of 0.7-0.8 mm mrad. This was measured after the first solenoid for a variety of settings and reconstructed at the source output via back-tracking with an effective space charge estimate. Best transmission from the RFQ was measured around 70%, in very close agreement to what expected from simulations when using an input beam distribution from LEBT measurements. The lower than nominal value is explained by the fact that the beam emittance at the test stand was bigger than the acceptance of the RFQ. Very good agreement between simulated and experimental values was found both in transverse and longitudinal beam emittance reconstruction. Another crucial goal of the commissioning was the validation of beam chopping. This is achieved via two sets of parallel plates to which a voltage is applied with rise and fall time lower than a few ns, with the aim of removing sequences of micro-bunches from the pulse train for cleaner injection into the PSB and different beam production schemes. The chopper dynamics was fully validated by different diagnostics instruments. It was also checked that the transmitted beam is not affected by the chopper and that its emittance stays constant with the chopper ON/Off. The last commissioning result was the calibration of the buncher cavities set points in the MEBT and matching of its output beam to DTL input conditions, in anticipation of the next phase of testing at 12 MeV.

3.2. DAY 2: FRIDAY 21TH MARCH

The MAX injector R&D - Dominik Mäder
Dominik reviewed the R&D activities at IAP for the development of the MAX Injector. First, the status of the design studies for an alternative injector solution was exposed. It is based on a more conventional beam dynamics using negative synchronous phases with a smooth phase advance variation to minimise emittance growth. Then, the properties of the MYRRHA 4-rod RFQ one meter test module were recalled. The module is under vacuum and almost ready for high-power RF tests. Work is now focused of the water cooling method to adjust and homogenise the temperature in the RFQ. The status on prototypes developments and conceptual design of the Quarter wave buncher cavities, room temperature CH-cavities and superconducting CH-cavities was also exposed. M.Vretenar also asked if the alignment of the RFQ electrodes have been measured. It has not been measured but simulation showed that 0.05 mm misalignment can be reasonably expected.

The Myrrha spoke cryomodule - Hervé Saugnac
Hervé presented the entire design of the spoke cryomodule for the first family of cavities in the superconducting linac of MYRRHA. The single spoke optimised RF design as well as its characteristics were first exposed. The mechanical calculations to optimise the cavity and its helium tank stiffness were then showed. The cryogenic vessel design, with thermal optimisation, is now finalised and the technical drawings produced for a possible construction. The magnetic shielding is based on the one developed for Spiral 2 cavities. One or two spoke prototypes are planned to be manufactured according to funding possibilities. The cold tuning system will be the same that the one developed at IPN Orsay for the ESS spoke cavity. It has already been successfully tested at room temperature. The power coupler design is frozen and some prototypes were already produced and operated within the EUROTRANS program.

Development of 700 MHz solid state amplifier - Serge Sierra
Serge presented the status on the ongoing developments for 700 MHz solid state amplifier at TED. RF transistor were chosen to develop individual 400 W cw module, which has been built and tested. Two modules have been successfully combined into an 800W water-cooled amplifier block using 3 dB micro-strip prototype couplers. The measured gain at the 0.3 dB compression point is ~20 dB with ~50% efficiency. Further development in order to try to

combine 800 W blocks into a 3.2 kW amplifier are envisaged. After the presentation, the price of such amplifier were discussed. Serge answered that it will be probably more expensive than an IOT but it will also depends on the final technological choices (ex: cooling systems). A question on how much time it is required to change an RF module was also asked: again this will mainly depends on the cooling strategy, water cooling leaves less flexibility.

DLLRF for reliability oriented linacs - Christophe Joly
Christophe started by an overview of DLLRF reliability for existing machines such as ESRF or SNS; typically their DLLRF systems have a 99% availability but with a MTBF of around ~20 h, while for MYRRHA a MTBF of 250 h is required, with an availability of 85% (due to the ADS shutdown). Therefore, it was exposed that reliable DLLRF implies careful choices of the architecture to make it easy to repair, simple (as much as possible) but with scalable boards ('commercial of the shelf'). Traceability is also a key point to ensure the maintenance and the reliability of the system; this implies a strong collaborative work with components suppliers. According to these rules the achieved development of DLLRF systems were described (collaborative work IPNO/LPNHE). In conclusion, it was proposed to have a dedicated topic on DLLRF system for reliability oriented studies and developments for the next PCRD "Horizon 2020".

Commissioning of the 700 MHz MAX - Marouan El Yakoubi
Marouan gave an overview of the developments and the commissioning of the MAX 700 MHz prototypical cryomodule dedicated to reliability oriented experiments. This cryomodule holds a 5-cells elliptical cavity (β_g=0.47, medium energy section of the MYRRHA linac) fully equipped with its coaxial blade tuning system actuated in parallel by a motor and piezoelectric elements. Recent encouraging experimental results were presented. Indeed for its first tests in high power configuration, with its coaxial power coupler, the cavity reached a maximum accelerating gradient of ~14 mV/m before quench (expected result). Preliminary measurements of the Lorentz factor were also presented ($9 < k_L < 16$ Hz/(MV/m)^2). The capability of the cold tuning system (CTS) had also been tested (20 kHz detuning range with piezos). Regulation of the cavity resonance frequency had been achieved: compensation of 'slow' oscillations (cryogenic and mechanical effect at 2Hz) with the piezoelectric actuators. The next step is to carry out reliability oriented experiments with a DLLRF control system coupled with the CTS and its associated adaptive control system.

C&C activities on cold tuning system - Isaías Martín Hoyo
Isaías started the presentation by quoting the last slide of Didier Uriot's presentation to insist on the importance of control system for a MW ADS: "Virtual accelerator is a nice concept but we are also aware that reality is not a dream world and like an air plane, an ADS accelerator doesn't support any approximation". The adopted strategy for the control of the cold tuning system (CTS) of the 700 MHz MAX cavity was described. This smart control system is based on the ADEX adaptive and predictive method. The hardware is now fully ready, and some instructive first tests have been performed last September IPN Orsay using an experimental setup at room temperature. The next and last step will then be to evaluate the performances of the system during the cold test of the 700 MHz cryomodule.

State of art and R&D plans for multipacting - Yolanda Gomez Martinez

Yolanda started her presentation by giving an overview of different theoretical approach which enable to model the multipacting phenomena in RF structure. All these models partially fits with experimental results or are only valid under certain conditions (travelling wave, or standing wave, flat surfaces, only for 2 points multipacting, etc). Further R&D is still needed to understand the occurrence of such a phenomena. A non-exhaustive list of the different existing codes which model multipacting in RF structures was also showed. For the 700 MHz accelerating structure (β_g=0.47 cavity + power coupler) a beginning of comparison between models/codes and experimental results was discussed: some measured multipacting barriers on the cavity were partially recovered with the multipac 2D code, while for the coupler some multipacting is to be expected around 40 kW and 70 kW in travelling wave mode according to Sommersalo laws (to be checked). Open questions were pointed out: influence of hypothesis on models/calculations results, TiN quality vs. efficiency. Finally A possible future program to carry dedicated experimental studies on multipacting at LPSC Grenoble was presented. As an answer for open question it was notified by Serge Sierra that one can take contact with the TTF community for exchanging data /experience with TiN coating for coupler ceramic windows.

Approach for a reliable cryogenic system - Tomas Junquera

Tomas first presented the main results obtained through the study of the cryogenic system optimisation for MYRRHA. The solution is to cool down every cavity at 2K, which represent a heat load budget of 2875 w, i.e. an equivalent electric power of 2.3MW without over consumption. Preliminary considerations over the design of such a cryogenic plant were given. Then, the second part of the presentation was focused on reliability aspects on existing machines like LHC or SNS. Recent encouraging results showed that one refrigerator operated 9 week without interruption at LHC (equivalent MTBF of 1500 h). But, reliability studies also showed that helium circuitry inside RF cryomodules are responsible for almost 20 % of the failure of SC modules. For MYRRHA, to maintain the high MTBF it will be necessary to take great care in the maintenance of the power plant and in the design. Still it was notified that the dynamic of a cryogenic failure is slow compare to the beam dynamics, so it is possible to anticipate on a clean beam stop or to slowly establish a compensation scenario (to be studied). Redundancy is very difficult to establish on such refrigerator. An important remark of the conclusion is that even if redundancy seems to be very difficult to establish on such refrigerator it should be studied in details for all the elements containing moving/vibrating parts.

Beam diagnostics for ADS - Dirk Vandeplassche

Dirk reviewed the requirement in terms of beam diagnostics and control systems for an ADS. It was underline that in the ADS concept beam diagnostics are facing contradictory requirements: diagnostics are here to ensure a full protection of the machine and must not be responsible for any interlock during operation, as well as any request or action on the control system. Therefore the border between measurement devices and control becomes very narrow. The diagnostics systems should be included in the reliability model. The main message from Dirk is that: it is time to consider the diagnostics within the ADS accelerator R&D program. The subject may be of broader interest and should profit from possible synergies with other programs/project/machines. In the future developments for MYRRHA, beam diagnostics studies are planned to be included in the injector R&D program.

Control system considerations for ADS - Mark Pleško

Mark presented some considerations from Cosylab and possible implementation of global control system for an ADS. The principle of global control systems and EPiCS were first reviewed. Then a possible guideline to design an ADS control systems was presented. Recommendation for hardware is to use mature and performant technologies already used in other facilities and to be careful with premature obsolescence of some devices. It was also pointed out that a virtual accelerator coupled with trustable, reliable and redundant element should be the best solution to reach the MTBF goal. The key recommendation from Mark would be to initiate collaborations on CC with similar projects, to quickly introduce naming convention, to standardize and define control system interface and to investigate reliability and the availability of the chosen hardware.

Reliability Modelling for ADS accelerator - Adrian Pitigoï

Adrian talk about the achieve work during the MAX project on the modelling of the MYRRHA linac reliability scheme. First of all the goal was to benchmark the methodology on an existing machine: the SNS linac. The input data for the model are coming from the public and available design documents. The quantifying model for reparability data were communicated by the SNS operation team (MTTF and MTTR). SNS operating data ('log-book') enable to complement/compare the model on component failure modes (cause, types of components, time to repair) and the failures causing beam trips (cause, system concerned, trip duration). The structure of the SNS fault tree model and the made assumptions was then detailed. The simulation results are in agreement with the SNS operation log-book records. This gives a good confidence in the validity of the method. This reliability analysis in the SNS showed (or confirmed) that the most affected linac systems are the RF components (klystrons and associated modulators). But it was also shown that malfunctions of the vacuum and cooling systems also decrease the availability. For the linac front end the most affected area are in the LEBT and the MEBT (electrostatic and vacuum system) as well as the ion source. In view of the reliability analysis of the MYRRHA accelerator it was recalled that redundancy for failure sensitive elements is to be favoured. There is also a need for intelligent fail over redundancy implementation in controllers for compensation purpose. The overall approach for the MYRRHA linac fault-tree was then presented. It is mainly based on the SNS model with adaptation corresponding to the MAX design. To achieve the full model some challenging key points are still needed such as:

_ the solid state amplifier reliability,

_ the fault compensation scheme for fast retuning,

_ reliability data on the ions source, LEBT elements, the RFQ (model is now based on the SNS one which is a 4 vane RFQ not a 4 rod),

_ the injector switching magnets is also an element which will have a strong impact on the overall reliability estimations.

The MYRRHA accelerator R&D roadmap - Luis Medeiros Romão

Luis gave an overview of a possible future road map for the MYRRHA developments and of the actual situation at SCK-CEN. He started by recalling the official 'aggressive' schedule for the MYRRHA project, with a full exploitation foreseen for 2024. The project is partially funded and strongly supported by the Belgian government who plan to invest around one third of the total cost of the machine for the 9 following years. The present situation in terms of working force and accelerator resources is nowadays limited in Belgium and particularly at SCK-CEN. It is clear that to be able to build and operate such an accelerator it is necessary to have a strong accelerator team at SCK-CEN. Presently the R&D is essentially carried out thanks to collaborations with MAX partners. Possible key collaborations are ongoing or envisaged for the future with institutes and industrial partners (a list is given in the slides). Still, the project of inj@UCL for the Developments of the MYRRHA injector is going on (ion source operational and LEBT under construction) and the developments of a spoke cryomodule prototype is envisaged. As a conclusion it was explain that presently one has to face budget restrictions which slow down the prototyping developments. The funding scheme and the planning of MYRRHA are pending. There is a need to build a strong internal core team at SCK-CEN. Until now, no realistic plan for the full linac production exist. “Nevertheless, we have many ingredients but lack the most important one to fully deploy the recipe”.

Discussion on possible synergies - Alessandra Lombardi, Jean-Luc Biarrotte, every body

The Goal of this session was to discuss about possible themes and R&D synergies between the different participants involved in the workshop.

First as reminder the main requirement for an ADS accelerator were recalled as well as the plan for the continuation of the R&D of the MYRRHA accelerator. The goal is to prepare a possible follow-up by answering to the H2020 Euratom FISSION call (deadline date: 17 Sept. 2014). It is plan to answer the call with only 1 integrated project with 3 main work packages inside; one of them will dedicated to the accelerators R&D. The accelerator WP will focus the efforts to build up a full scale injector demonstrator while trying to pursue the necessary R&D undertaken during the previous programs (Eurotrans, MAX). Jean-luc presented a possible list of topics to be included in the accelerator WP quoted below as shown on the slides:

- WP.1: construction of a full RFQ demonstrator (IAP, Univ Darmsdat…?)
- WP.2: 176 MHz RF power amplifier development (SCK?, …?)
- WP.3: Digital LLRF development (IPNO?, …?)
- WP.4: Beam diagnostics (CEA?, IPNO?, SCK? …?)
- WP.5: Controls (SCK?, CosyLab?, ADEX?…?)
- WP.6: Beam simulation code development (CEA?, LPSC?, IPNO? …?)
- WP.7: LEBT space-charge experiments (LPSC?, CEA?, SCK?, CERN?, …?)
- WP.8: Injector commissioning (SCK?, IAP?, IPNO?, LPSC?, CERN? …?)
- *WP.9: Detailed injector reliability analysis (EA?, SCK?, CERN? …?)*
- *WP.10: SRF spoke R&D – prototyping, multipacting (IPNO?, LPSC?, …?)*
- *WP.11: SRF CH demonstration with beam (IAP?, …?)*

➔ Additional/new ideas and partners are obviously very welcome

Among this list and all the talks of the workshop some possible topics for collaborative works were identified by Alessandra and Jean-Luc and proposed for discussion.

DEDICATED WORKSHOPS

First, the Possibility to use framework of EUCARD2/H2020 as a catalyst for organising mini-workshop on a very specific topic was suggested. Everybody agreed that this kind of "informal" meetings would be a great opportunity to freely exchange on the topics listed below.

RELIABILITY

- One goal of collaborative work could be to improve the reliability knowledge on accelerator components to create a kind of catalogue of faults.
- Alessandra notified that there will be a year dedicated to operation and reliability studies with linac 4 (2015/2016) before its connection to the LHC injectors. This could be the opportunity to learn from an existing machine with a possibility to benchmark /improve reliability models (EA).
- The UCL injectors (with RFQ) will also be used for reliability analysis.
- CERN also proposed to answer to the next EC infrastructure call (Sept. 2014) with an "accelerator reliability" project. This must be explored in the following weeks. CERN, SCK-CEN, CNRS, CEA, ESS showed a possible interest for such a program.
- ESS notified they have just hired an engineer to work on reliability aspects, there is a possible interest to be involved in such a collaboration.
- Cosylab also showed an interest to be involve in the collaboration as well as ADEX for optimisation
- Mainly all the MAX partners showed interest to continue to collaborate to this topic
- It was also mentioned by ACS (Tomas) that dedicated studies to cryogenic system reliability, especially focused on the cryomodule component are needed.
- One agreement for everybody is that it is time to dispose of real scale experiment to have more statistics on every components of a linear accelerator. Linac 4 reliability analysis will be one great opportunity for this purpose.

Possible partners: CERN, SCK-CEN, CNRS, EA, ESS, CEA, IAP, COSYLAB, ADEX, ACS, TED, GSI, PSI?

LEBT BEAM DYNAMICS & SPACE CHARGE COMPENSATION

- The Main goal would be to improve the understanding and the models for space charge compensation in magnetic transfer lines.
- CEA (Nicolas C.) mentioned that they will have a dedicated experiment (BETSI) on the subject. They are also looking for a PhD student to work on SCC.
- SCK-CEN and CNRS are building the MYRRHA LEBT, and are open for collaboration.
- CERN is also interested for collaboration on experimental results and analysis.
- In a first time, one can collaborate through data/experiences exchange via mini workshops.

Possible partners: SCK-CEN, CNRS, CERN, IAP?, GSI?, ESS?

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Possible partners: SCK-CEN, CNRS, CERN, IAP?, GSI?, ESS?

BEAM SIMULATION DEVELOPMENTS

- The goal is to go on with the virtual accelerator development. CEA will continue to complete its tools.

- This virtual accelerator could be tested on the MYRRHA injector. It should be implemented in close collaboration with the control system developments.
- A possibility to test the virtual accelerator on linac 4 was mentioned. To be discussed when the tool will be more advanced and if it fits with the linac 4 roadmap.
- Within the scope of fast retuning procedure developments for MYRRHA, it is also plan to develop dedicated algorithm for automatic set points reconfiguration by including more close to reality model (CNRS)

Possible partners: CEA, CERN, SCK-CEN, CNRS

CONTROL SYSTEMS & DLLRF

- DLLRF developments was also evocated as a possible topic for synergies. For the continuation of the MYRRHA accelerator R&D a dedicate topic is planned and partners are welcomed.
- Regarding global control systems Cosylab notified that it is important for the reliability scope that "everything start together": the control system must be thought at the same time than the developments of the accelerator. For MYRRHA, Cosylab is collaborating in the development of the injector control system.
- ADEX is interested to continue the collaboration on MYRRHA for performance increase of control systems. In addition to the work on cavity tuning systems, a new approach of beam control could be carried out on the MYRRHA LEBT.

Possible partners: CNRS, SCK-CEN, Cosylab, ADEX

MULTIPACTING STUDIES

- CNRS (Jean-Luc, Jean-Marie) mentioned that they are developing dedicated test stands to study the multipacting phenomena.
- TED is interested for collaborating on the subject, especially to test new coating type/method. Serge also mentioned that there are already PhD thesis going on on the subject (collaboration IPNO& TED)
- ESS is particularly interested to collaborate on multipacting issues in power couplers. Which is identified as a "week point" for SC cavities.
- CERN is also interested to collaborate on the subject

Possible partners: CNRS, ESS, CERN, TED

ANNEX: GLOSSARY

AccApplic is a networking activity with the funded EUCARD2 European project (http://eucard2.web.cern.ch/activities/wp4-accelerator-applications-accapplic) on particle accelerators, addressing the applied areas of industry, healthcare, energy production and security. Amongst its objectives is to" Determine the requirements for high power accelerator applications, in particular for Accelerator Driven Systems (ADS)".

MAX is a FP7 EURATOM project which participates in addressing the issue of high-level long-lived radioactive waste transmutation by pursuing the development of the high- power proton accelerator as specified by the MYRRHA Accelerator- Driven System (ADS) demonstrator project in Belgium. Its main goal is to increase the level of confidence in the fact that the MYRRHA linac requirements can be fulfilled; this is mainly performed through studies and simulations on general design and reliability issues, together with developments and experiments on dedicated accelerator test sections.

Acronym	**Definition**
MYRRHA	Multi-purpose hybrid research reactor for high-tech applications
SPL	Superconducting Proton Linac
SARAF	Soreq Applied Research Accelerator Facility
SPIRAL	Système de Production d'Ions Radioactifs en Ligne
IPHI	High Intensity Proton Injector