PS/AA/Note 85-12

ANTIPROTONS IN CERN

INDUSTRIAL TRAINING REPORT

R.James
(University of Bath)

29th August 1985
Geneva

1. INTRODUCTION

1.1 CERN

The European Laboratory for Particle Physics, CERN, came into being in the early 1950's as a result of moves financial, scientific and political, to pool European resources in order to continue research in the field of nuclear (or "high-energy") physics. This discipline, then barely 20 years old, was (and still is) of fundamental scientific importance, as it had already begun to uncover some of the mysteries of the strong and the weak nuclear forces, and thereby to forge the still far from finished path towards an understanding of the evolution of the Universe into its present "low-energy" state; a state in which one force, the electromagnetic, dominates, and in which the major rôles are played by only one of the quark pairs (u,d) and one lepton pair (e,ν_e).

In the thirty or so years since CERN's inception, particle physics has continued to raise new questions as others have been illuminated, reformulated or laid aside, but with the advent of the electroweak connection, a modern equivalent of Maxwell's unification of electricity and magnetism, its subsequent verification with the discovery at CERN of the W and Z bosons, and the improving success of quantum chromodynamics (the strong force analogue of man's most successful physical theory, quantum electrodynamics), there is hope that a more unified understanding of the apparent diversity of Nature (and her history) may be closer to hand. Since physical theories are of no value without experimental verification, the existance of top-class facilities, such as those provided at CERN, is absolutely essential if man is to continue his quest for a deeper understanding of the world in which he lives.

The research tools presently offered to European particle physicists are sited on some 560 ha of land straddling the Franco-Swiss border; they comprise a complex of 3 large particle accelerators, 2 particle storage rings and various experimental halls and interconnecting tunnels. This complex is managed, improved, maintained and added to by a staff of about 3500 drawn from the CERN member states. These 14 West European countries are the sole source of the CERN budget (which for 1985 is SF724.5 million) and provide most of the 2500 visiting experimental physicists who use CERN as a research facility.

1.2 The Accelerator Complex

Figure 1 is a schematic of the present accelerator layout. The first accelerator built at CERN, the 600 MeV synchro-cyclotron (SC) is still used as a source of protons in many useful ("low-energy") nuclear physics experiments. In 1959 the 28 GeV proton synchrotron (PS) came into operation; for a time it was the world's highest energy accelerator, and was one of the first to make use of the so-called alternating gradient focusing system, now universally used in circular accelerators, in which quadrupole magnets form a lens lattice which retains the particle beam within a required aperture. The PS still plays a central rôle in almost all hadron physics at CERN; it is used as an accelerator-injector into the large (7 km circumference) 450 GeV super proton synchrotron (SPS), and to provide beams for both the antiproton accumulator (AA) and the low-energy antiproton ring (LEAR).

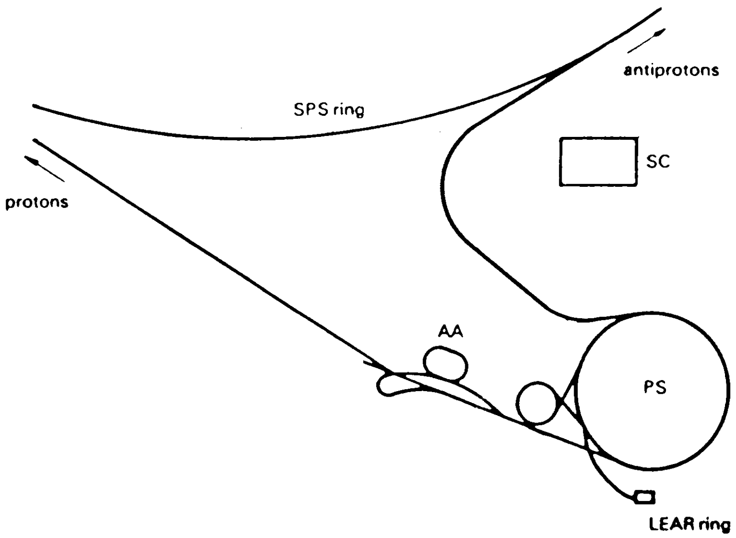


Figure 1. Schematic diagram showing the location of the present high energy machines at CERN and the beam lines that connect them.

The SPS was originally designed and used to take 26 GeV protons from the PS, accelerate them to some 400 GeV and distribute them to one of two experimental halls on its North and West sides, for use in "fixed target" experiments. However, with the invention and subsequent realisation of stochastic cooling, a method of producing intense beams of "rare" particles, in this case antiprotons, a bold project was launched to inject both protons and their oppositely charged counterparts into the same magnet lattice in the SPS, accelerate them with the same RF system, and observe their collisions. Since much of the energy in a fixed target goes into target nucleus acceleration by one relativistic particle, collisions between p and $\bar{p}$'s each at 315 GeV (the present maximum beam energy attainable with the SPS magnets run d.c.), giving a centre-of-mass collision energy of 630 GeV, is equivalent to hitting a fixed proton with a moving proton of energy 212 TeV! This enormous increase in collision energy provided sufficient "free energy" for the occasional production of one of the massive (80-90 GeV) W and Z bosons, the force particles of the weak interaction. The discovery of these bosons, at the energies postulated by the electroweak theory, earned the 1984 Nobel prize in physics for Carlo Rubbia, an inspiration behind the Sp$\bar{p}$S collider project and leader of one of its two large detectors, and Simon van der Meer, the inventor of stochastic cooling.

The next step in size and useful collision energy at CERN will come with the completion in 1989 of LEP, the Large Electron-Positron (Collider), which will take its beams from a linear accelerator and e^+/e^- storage rings, the PS and the SPS before accelerating them to a centre-of-mass collision energy of 100 GeV. Although this is much lower than the Sp$\bar{p}$S collision energy, electrons contain no inner structure that is mediated by the strong colour-force. This force has a potential which increases linearly with separation, which means that any quark "removed" from a proton (or any other hadron) must immediately be paired up with another from, say, vacuum fluctuation, so starting an extremely energy-consuming process; this is why W's and Z's of rest mass 80 and 90 GeV are so rarely observed in 600 GeV protonic collisions. However, electronic collisions at 100 GeV should provide a factory of vector bosons, in much "cleaner" events; that is without a great proliferation of unwanted quark-antiquark (meson) particles obscuring the view of the more interesting ones.

With this increase in collision "free energy" (and hopefully more if the member states will fund LEP's second phase of construction) it is also hoped to extract information about the so-called Higgs field, a convenience of the electroweak theory which is used to set energy thresholds at which the spontaneous symmetry breaking of the electroweak into the electromagnetic and weak interactions is supposed to occur. Also on the energy horizon is the search for more generations of quark and lepton pairs; Abdus Salam, one of the pioneers of the electroweak theory, recently stated that, based entirely on cosmological theories, the Sp$\bar{p}$S collider has produced evidence that there are no more than the three neutrinos so-far discovered, an assertion that would have profound scientific consequences if found to be true. There is thus much to look for in LEP, and the Large Hadron Collider (LHC), a proton-antiproton collider proposed for the same 27 km tunnel as LEP, if it were ever to be realised.

1.3 The Antiproton Accumulator

Antiprotons may be produced as part of the secondary debris from a proton - metal nucleus collision, but since they are produced with large angular and momentum spreads they cannot readily be constrained within the vacuum chamber of a particle accelerator, never mind within an intense narrow beam. However, with the invention of stochastic cooling in 1968, a feasible method to overcome this problem had been found, and after encouraging preliminary results the CERN Research Board authorized the construction of a 50 m diameter storage ring to produce the antiproton beams needed for a p$\bar{p}$ collider. Remarkably, within only two years this intricate machine, the AA, had been built and it has enjoyed continued successful operation in the five years since.

The required incident protons of energy 26 GeV, provided by the PS (about 10^{12} every 2½ seconds), bombard a metal target several metres upstream of the AA. The emergent antiprotons, of selected mean momentum 3.5 GeV/c, are focussed by means of either a magnetic horn, another van der Meer invention, in which the particles of greatest angular divergence see a focusing magnetic field for the longest time, or a lithium lens, a high current device which produces a strongly focusing solenoidal field through which the particles pass, before being introduced to the AA machine.

Once in the machine, the momentum (ie radial position) spread is still large and must be reduced sufficiently to prevent high loss of particles, and to obtain a manageable bunch of antiprotons before the next incident pulse from the PS. After this initial period of "pre-cooling", the $\bar{p}$'s are nudged across the machine aperture to the "top" (higher momentum side) of the high-intensity "stack" where further stochastic cooling systems gradually reduce the particle momentum spread and tranverse deviations from the ideal orbit, eventually producing the required intense "stack core".

Beacause of the low $\bar{p}$ per proton target yield, the limited acceptance of particles into the AA, the problems of achieving fast pre-cooling without disturbing the precious stack and so on, it takes upto 24 hours to achieve a decent intense beam core of, say, 3.10" antiprotons ready for extraction and transfer back to the PS, and finally injection into the Sp$\bar{p}$S collider. For this reason, a new antiproton machine (the Antiproton COLlector, or ACOL) is being built around the old one in order to achieve the collection of a larger fraction of the target antiprotons, and to cool them sufficiently well to inject a small beam into the AA, consequently improving the system stacking rate by an order of magnitude; in this way useful stacks should be obtained within a matter of a few hours. Thus all the present work in the AA group is aimed either at the construction of ACOL itself or towards an upgrading of the existing machine to cope with the higher particle flux entering the stack from the precoolers.

2. THE CONCEPTS OF STOCHASTIC COOLING

2.1 Introduction

Stochastic cooling is a method of reducing (or "cooling") the spread of particle energies around a desired value by means of continually pushing a random or "stochastic" sample of those particles towards a desired orbital position. (Since the particles are relativistic and above transition, an increase in orbital radius corresponds to an increase in momentum and a decrease in revolution frequency. Therefore a given radius is associated with a mean particle energy.) This is done by using electromagnetic sensors to find the centre of charge of a sample of the beam (by means of detecting its dipole moment) and apply a "kick" of the correct magnitude and phase to that sample in order to place the centre of charge on the correct orbit. Whatever the size of the sample, it is clear from figure 2 that the squares of the extreme values of deviation are reduced faster than those of the small values; thus the spread of orbit radius about the desired orbit has been decreased, or the beam "cooled".

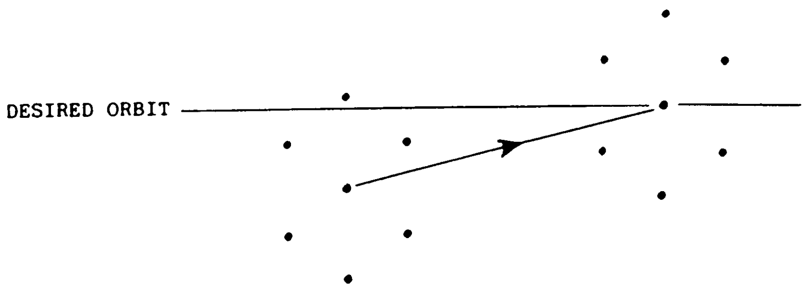


Figure 2. The effect of pushing the centre of charge of a sample onto the desired orbit.

This at first seems to violate Liouville's theorem, an analogue of the second law of thermodynamics, which states that the volume of a beam in phase space (conveniently chosen as a spatial displacement / angular divergence space) must remain constant under the influence of conservative forces. Thus, says the theorem, one may give an electromagnetic kick to the beam to one side, but this will not reduce the beam phase space volume. The loop-hole in applying Liouville's theorem here is that it applies only to a continuum, and since a particle beam is not continuous but grainy, one is allowed to replace the empty space in the middle of a beam by particles without violation of the theorem, and thereby produce intense dense particle beams. It may be noted that this process selectively lowers the beam entropy, which is why Viki Weisskopf, an eminent physicist and former CERN Director-General, refers to Simon van der Meer as "the Maxwell Demon of the twentieth century". Unfortunately, of course, this entropy decrease is achieved only at the cost of considerable energy input to the detector systems, causing an overall entropy increase rather than decrease; this is probably why it was not until 1984 that the idea was deemed to merit the Nobel prize.

2.2 Beam Orbit Deviations used in Stochastic Cooling

The most obvious cause of a particle being off the ideal orbit is that it simply has the wrong momentum. As figure 3 shows, any normal-ended sample of particles will become longitudinally "sheared" due to the higher velocity of the outer particles. For this reason the momentum cooling used to correct this shear (by accelerating the particles at the back and retarding those at the front) is also known as longitudinal cooling.

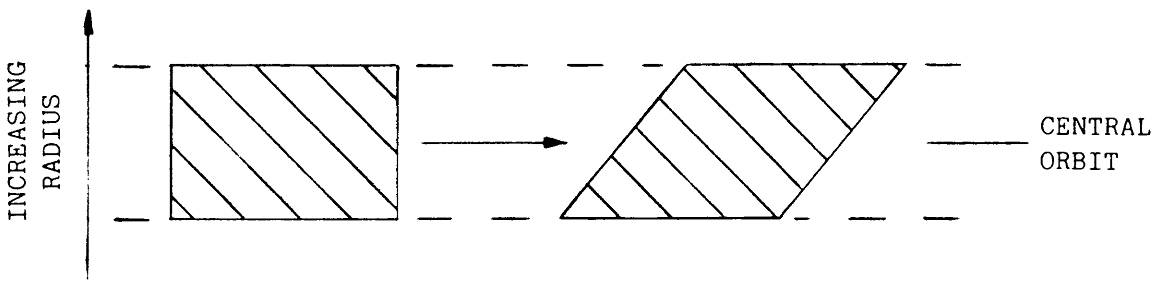


Figure 3. The shearing effect on a sample of particles due to the variation of momentum across the beam.

Momentum cooling is particularly useful in "precooling" the beam as it enters the AA from the target. By using a notch filter at harmonics of the nominal revolution frequency, particles from each side may be sucked towards the desired momentum, following the potential well of the notches, in a particularly short time.

The other form of stochastic cooling used in the AA, particularly for the high density stack region, is "betatron cooling". In an alternating gradient focusing machine, each quadrupole magnet is focusing in one transverse plane and defocusing in the other. Thus in the horizontal plane, say, each particle is repeatedly focussed and defocussed within the quadrupole lattice. The so-called betatron motion caused by this effect may be compared to that of a marble swinging to and fro as it runs down the inside of a gutter. In plan view the motion is sinusoidal in the two focusing planes (horizontal and vertical), and by reducing the amplitude of these oscillations the particles may be concentrated into a more monoenergetic, intense narrow beam.

In practice this is achieved by using detectors to sense the position of charge of a sample in terms of a signal proportional to its off-axis displacement, applying a similar signal in anti-phase on the betatron wave, so moving it to the correct orbit. Over a period of many turns both the horizontal and vertical beam emittances (the area of the beam in phase space) are found to be reduced.

2.3 System Practicalities

Figure 4 shows a schematic of a stochastic cooling system, consisting of a "pick-up" (PU) which senses the position of a sample's centre of charge, the amplifiers of the PU signal, and a "pick-up in reverse" structure, a "kicker" (K) which applies the appropriate electromagnetic deflection of the sample back onto orbit. Because of the delays in the cabling and amplifiers, the signal path must cut off a bend in the particle trajectory.

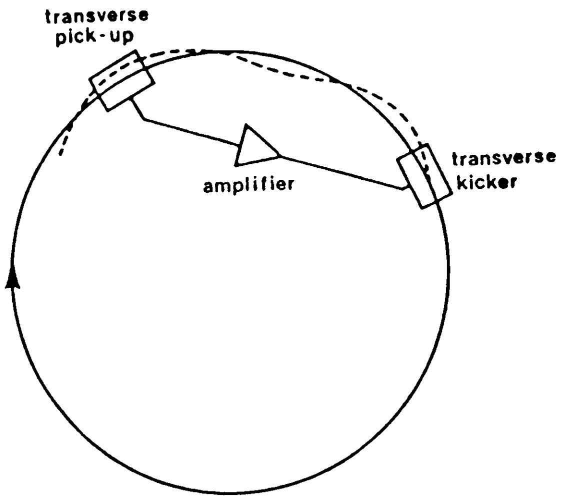


Figure 4. The basic components of a stochastic cooling feedback system, in this case for horizontal betatron cooling.

Stochastic cooling requires a random sample of particles; clearly if the corrected sample of figure 2 comes back to the PU unchanged, no cooling will occur, as the centre of charge is already on orbit. Thus we require that between K and PU the particles become randomly rearranged to form fresh samples; we require good sample "mixing", which in the AA is generally achieved within a revolution due to momentum spread and so on. On the other hand, we wish to correct the same sample we have detected; this need for "bad mixing" between PU and K means that we should cut as small a chord of the ring as possible to achieve efficient cooling.

If we consider betatron cooling, it is clear that if our sample length is of the order of a betatron wavelength (about 70 m in the AA) it will take a long time to reduce the amplitude appreciably. We therefore need to be able to resolve much shorter lengths (such as 10-20 cm) to achieve reasonably fast cooling. This requires a fast rise-time of the feedback electronics, equivalent to needing a big bandwidth. Thus the PU's are large-bandwidth microwave devices, whose signals are amplified by travelling wave tube amplifiers, working in the GHz band. This need for an appreciable bandwidth (which will contain many revolution harmonics and therefore a large amount of beam information) tends to push the systems towards higher frequencies; an octave band over 4-8 GHz spans some 2160 revolution harmonics, for example. The desire for this much information puts considerable constraints on the design of PU's, which must couple into the weak evanescent space-charge field of the beam and be able to operate over a large band without inducing potentially beam-disturbing resonances.

There are also processes within the beam which limit the cooling efficiency by contributing an unwanted beam spreading; the effect of neighbouring particle signal on that of any given particle causes a Schottky-type noise, or "incoherent heating", as does beam-beam scattering. These effects are characteristic of diffusion, in that their time evolution varies with the square of amplitude; stochastic cooling is comparable to a "diffusion in reverse" process, except that it goes proportionally with amplitude; thus if the system gain is chosen correctly, the cooling processes are faster than those of heating, and the beam spread shrinks. The sum of all these phenomena tends to produce an approximately Gaussian beam distribution, as predicted by the central limit theorem for the sum effect of different statistical distributions. This may be caused either by the diffusive effects of heating on an otherwise "delta-function" cooled beam, or, since the incident proton beam itself approaches a Gaussian, it may be that stochastic cooling alone, without heating, would produce a normally-distributed beam.

Most of my work at CERN has been concerned with the existing "high frequency" (1-2 GHz) stack-core stochastic cooling system in the AA, and its pending improvements to produce cooling over frequencies from 1-8 GHz ready for the introduction of ACOL some time in 1987. The routine work has involved frequency-domain analysis of various RF structures and components in the feedback system; this type of work is already well documented[1], so I shall not treat it here; instead I shall concentrate on the more interesting, specific projects on which I have worked.

3. A ČERENKOV RADIATION PICK-UP

3.1 General Requirements of a PU Structure

A stochastic cooling pick-up detects the position (or actually the dipole moment) of the centre of charge of a sample of particles. This it does by coupling into the electric fields (since they are stronger than the magnetic) associated with the passing of charged particles through a closed conducting chamber. Roughly speaking, the stronger the coupling, the closer is the beam; thus by using detectors each side of the beam, and differencing / summing networks, one may deduce the beam position. At present, two types of coupler are used; the loop and the slot (figure 5), the latter being used in the HF systems, and of more interest here.

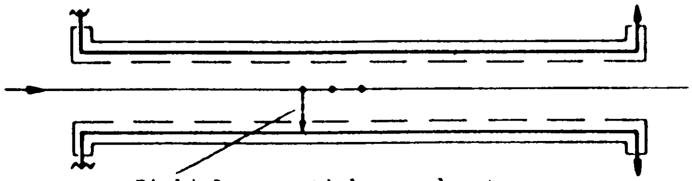


Figure 5. Schematic of a slot-type pick-up structure.

The signal from a given particle in a slot structure is carried along a coaxial waveguide behind the slots at (almost) beam velocity; hence there is an additive effect of the weak coupling at each slot which by the end of the PU provides a sufficiently strong signal to be useful. This coherence of a particle with its signal is an important consideration in the design of any such pick-up.

3.2 Čerenkov Radiation

The passage of a charged particle through a dielectric medium momentarily polarizes the local electric dipoles; if the particle is travelling at βc, faster than light velocity in the medium, this will result in the production of a coherent wavefront and a cone of so-called Cerenkov radiation at an angle θ to the particle trajectory given by

$$\cos\theta = \frac{1}{\beta n} \qquad (1)$$

where n is the refractive index of the dielectric. In most cases, the wavelength of this radiation is around that of blue light. Therefore, in normal applications, including particle physics Čerenkov detectors, the wave is travelling in what is effectively a semi-infinite medium, so that the angle θ is well defined.

There is also, however, a less well-known form of this radiation caused by the passage of a charge close to a dielectric wall. In this case equation 1 still results, but the radiation wavelengths now move into the microwave region, because the fields associated with the moving charge are transversely evanescent, and therefore only radiation with a wavelength comparable to or greater than the beam-wall separation (a few millimetres) can be coupled into with any appreciable strength. In this case a slab of dielectric a few millimetres thick does not represent a semi- infinite medium, and the Čerenkov-type radiation, of less definite angle, can be used to stimulate the propagation of e.m. waveguide modes in the dielectric. It is hoped to use this effect to produce a stochastic cooling PU with an inherent bandwidth of some 20% around 5 GHz; this idea was first considered over 20 years ago[2], but only now seems to be coming to fruition.

3.3 The Proposed Čerenkov Radiation Pick-up

Figure 6 is a diagram of the proposed quartz Čerenkov pick-up. In a simplistic way it may be compared to a slot structure with an infinite number of slots; this should make the coupling much stronger for a given length of pick-up. The broadening of the PU at the ends is designed to draw the power out of the longitudinal E-field, whose tails skim along the dielectric surface. There is then a transition from dielectric into vacuum in order to make a final transition from vacuum into coaxial cable. The structure is made the same at both ends in an attempt to prevent unwanted reflections or waveguide mode asymmetries.

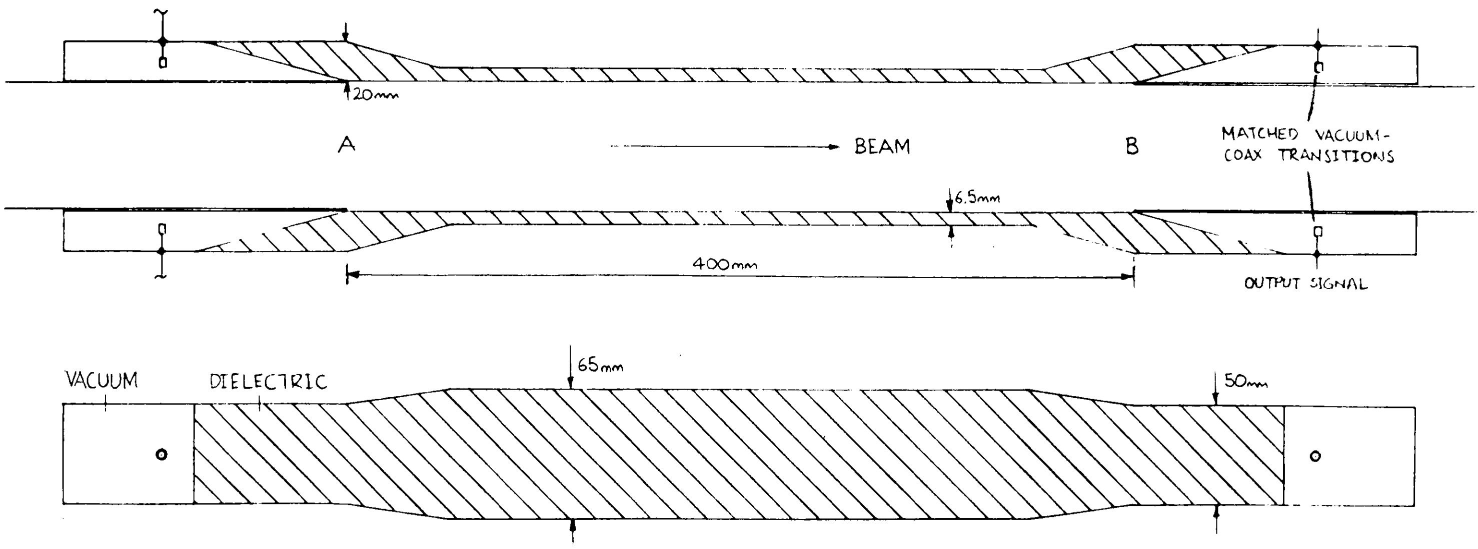


Figure 6. Side elevation of the proposed Čerenkov PU, and plan view of one slab. The beam "sees" the dielectric from A to B; the coupled signal travels via waveguide modes to B, is sent through a dielectric-vacuum interface and finally from vacuum into coaxial cable. The antennae at the upstream end are terminated in a characteristic impedance.

Happily, my work on the Čerenkov pick-up included both practical and (slightly) theoretical aspects. On the practical side, I found an antenna configuration for the vacuum-coax transition that provided a 750 MHz bandwidth (loosely defined as the frequency interval with 20 dB or better isolation) around the working point of 5.45 GHz. Also, using a bakelite mock-up of the PU, we were able to establish the transmission efficiency and optimum distance from the antenna of the dielectric-vacuum interface. It is now hoped that a low-loss model of the PU in polystyrene will shine light on the remaining practical problems; those of determining the optimum angle of the broadening region of the dielectric, and the extent of coupling between the two pick-up slabs. Neither of these parameters is determined by the extensive theory of the PU[3,4]. We can at least be confident, however, that when the prototype pick-up is inserted in the AA (probably in January 1986), the "standard" RF components will transmit a recognisable signal if any is there.

On the theoretical side, I concerned myself with the problem of achieving a coherence between a particle and its signal. Clearly radiation in a dielectric can travel no faster than c/n; hence since quartz has a refractive index, n, of about 1.94, and the AA beam circulates with a mean velocity of 0.96c, we cannot hope to achieve a single-particle coherence in the same way one associates with a slot-type structure.

The PU theory assumes a beam to have a longitudinal structure that can be represented in terms of Fourier components of charge density. "Coherence" is then achieved by matching the Fourier wavenumber of the beam with those of the possible guide modes in the slab. The Čerenkov condition is then imposed to determine the dominant mode that will propagate.

If we consider the case of a slab of length L able to propagate the Čerenkov signal at a velocity $\beta c/2$ parallel to the beam, a single pass of one particle will not generate an accumulated power at the downstream end of the structure. Instead, the power will be distributed throughout the second half of the slab, and will take a time $2L/\beta c$ (or more if the dielectric constant is higher) to pass the end point. Hence the spectrum of this particle will appear as a "weak signal for a long time", rather than a "strong signal for a short time" given by a slot structure. The only way we can achieve a strong enough signal to be observed is to add to the signal of one particle those of others behind, spaced by Fourier wavelengths (hence the matching of wavenumber rather than particle position). This means that a Čerenkov pick-up effectively works as a parallel processor of many samples spaced out over a number of Fourier wavelengths, compared with a slot pick-up which is a serial processor of localised samples. The net effect on the Schottky power scan of the beam should be the same, but for differences in the "effective sample size", coupling impedance of the structure, and so on.

The desire to mimic the production of single-particle power at one point leads to the suggestion of a conical pick-up around the beam chamber, of the same angle as the expected Čerenkov radiation, and of sufficient length to support Čerenkov waves. In this structure, any normal plane to the Čerenkov wave-vector will contain all the PU information about a given particle; if this can be focussed,the total power from the passage of one particle would be amplified at the same time. Another alternative is to use the fact that both the space charge fields around a coasting beam and Čerenkov radiation are axisymmetric phenomena. This leads to a "cylindrical shell" design centred on the beam which, at least intuitively, ought to produce stronger beam-dielectric coupling. The obvious difficulty in implementing either of these suggestions is in drawing the power out of the dielectric into a coaxial cable.

4. OTHER PROJECTS

The remaining work in which I have been involved has been written up in the form of internal technical notes, which are included as appendices to this report. The first (PS/AA/ACOL Note 35) deals with the prevention of unwanted RF loops between a kicker structure and its pick-up, and the second (PS/AA/Note 85-10) with a method for determining the electrostic potential associated with the presence of a charged beam in a conducting vacuum chamber.

5. ACKNOWLEDGEMENTS

I would like to thank Colin Taylor, my placement supervisor, for spending a great deal of time in the discussion of the contents of this report, and also of many other topics, not included here, throughout the year. Colin has also been generous in allowing me to spend a great deal of my time at CERN thinking about physics not entirely relevant to stochastic cooling systems; for this I am particularly grateful.

I should also like to thank the other members of the AA group for offering a good deal of friendship and knowledge, and particularly Steve Hancock, for having versed me in the fine art of FLT operating systems.

6. REFERENCES

(1) S. Hancock, The Cooling of Beams in CERN, PS/AA/Note 79-5,Sept.1979

(2) E. Jones, A proposal utilising Čerenkov radiation for the observation of longitudinal structure in relativistic particle beams, CERN/AR/Int.SR/62-5, April 1962

(3) E. Brambilla, A microwave Čerenkov pick-up for stochastic cooling, CERN/PS/85-45 (AA), June 1985

(4) L. Faltin, Image line pick-ups for stochastic cooling,I&II, May 1985

C.S. Taylor, Stochastic cooling hardware, CERN/PS/84-8 (AA), March 1984

S. van der Meer, Stochastic cooling and the accumulation of antiprotons, CERN/PS/84-32 (AA), December 1984

PS/AA/ACOL Note 35 12.7.1985
RJ

APPENDIX I

The prevention of unwanted RF loops in the ACOL cooling systems

R.James

Introduction

A brief summary of the needs for (and the present methods of) prevention of unwanted RF loops in the AA cooling systems is presented, followed by a résumé of the measurements made so far with materials which may be used in so-called "passive dampers" of kicker-to-pick-up communication via the ACOL vacuum chamber.

Present methods of preventing RF loops

The coupling between the K output and PU input levels, due to RF leakage out of and into the beam chamber, was found to cause problems in the original 1-2 GHz AA stack-core cooling system(1), many of which disappeared with the introduction of the concrete shielding blocks, acting as absorbers and scatterers of microwave radiation. Attempts to prevent actual machine leakage, such as the installation of "egg-boxes" in ion and sublimation pump manifolds, also reduced the amount of stray RF power.

The most obvious route for microwaves to form an undesirable positive feedback loop, (that is, via the beam chamber itself) did not cause a problem in the AA, probably due to the placement of a cut-off screen, of internal square 69mm (giving a low frequency cut-off f_c of 2.17 GHz), in the zero dispersion region in section 12. Since the highest cooling frequency was originally 2 GHz, this screen prevented the propagation of any waveguide mode via the shorter PU-to-K path. It is believed that in the longer path the absorbent ferrite tiles lining the pre- and stack-tail- cooling and the injection/ejection kicker tanks in the longer path may have provided sufficient damping of propagated RF. It remains to be seen whether they can continue to prevent the problem once the HF systems are operating above the screen cut-off (ie 2-8 GHz). One additional possibility is to use a screen which moves in with the kicker electrodes as the beam emittance is reduced. (At 5pi mm.mrad aperture, the 4-8 GHz kicker has an f_c = 8.33 GHz.)

Unfortunately, the use of cut-off screens is not so profitable in ACOL, since the minimum betatron amplitude of about 50mm(2) gives a maximum possible cut-off frequency of only 1.5 GHz, which does little to cover the 1-3 GHz cooling band. Hence to be perfectly safe, one has to achieve 148 dB of broad-band attenuation by absorbent structures which will upset neither the beam nor the magnetic field profiles.

In similar measurements made with a waveguide of section 330x130 mm (more closely representing that of ACOL), with ferrites again covering the inner walls, Mark found attenuations of 46 dB/m over 1-2 GHz and 41 dB/m over 2-3 GHz. Thus he concluded that the critical factor is the cross-sectional area of the chamber. His measurements have since been repeated and suggest, for a typical ACOL chamber, one can achieve 40-50 dB broad-band attenuation per metre of "ZN" ferrite covering. This means that to prevent K-to-PU feedback one needs up to 4 m of ZN-covered wall per possible route between them, or its equivalent. The obvious problem here is that since ferrites are magnetic, a passive damper using them cannot be placed in a magnet chamber, and must occupy some of the precious straight-section space. There will be, however, a considerable amount of ferrite, inherent to the design of various elements, inside the ACOL vacuum chamber. The twelve stochastic cooling tanks will all contain "NZ" ferrites, and the injection and ejection kicker tanks Philips "91C" ferrites; the probable damping effects caused by the presence of these materials are studied in the next section.

Inherent RF damping in the existing ACOL design

Figure 2 shows the position of the ACOL stochastic cooling systems; all three bands have a nominal gain of 148 dB, which is therefore the minimum damping required in each possible K-to-PU path around the machine. Also shown are the positions of the injection and ejection kickers. These are to be of similar design to the AA structures[5], and will thus contain ferrites seen by the beam, which can act as attenuators of RF radiation.

Each stochastic cooling element will contain ferrite tiles covering something like 15% of its surface. These tiles, of the NZ51 type, have properties comparable to those of the ZN's. Hence, taking 40 dB/m for a fully-covered chamber, one could hope to obtain roughly 10 dB per 2 metre tank. Since both routes between any given kicker and its pick-up contains 5 such tanks, we may assume (choosing 160 dB/path as a completely safe figure) that we need to find a further 110 dB for each possible path.

Now, the total effective length of the injection & ejection kickers in "quadrant" Q of figure 2 is 4.56 m[2], which would give the further required 110 dB if we could assume a modest 25 dB/m for the attenuation of "C" ferrites. (The attenuation measurements performed using these C ferrites have been limited, but they indicate that equal volumes of ZN and C give very nearly the same loss for the frequencies and chamber sections tested. Thus it seems reasonable to expect the quoted 25 dB/m to be a conservative estimate of the damping achievable in these kickers.)

Attenuation in a ferrite-loaded waveguide; implications for ACOL

By placing high-loss ferrite tiles of characteristic impedance close to that of free space on the walls of a waveguide, such as a beam vacuum chamber, one can prevent the propagation of non-TEM modes through the guide, a technique applied in the AA low frequency cooling tanks. With sufficient tiles placed on the vacuum chamber walls one could thus hope to attain the necessary RF attenuation.

Much of the work on the amount of attenuation achievable for a given length of ferrite-covered wall was performed by Mark Robinson[3] with 60x60x3 mm "ZN" tiles. Making transmission measurements using a network analyser, he found that with the tiles placed 8 mm off the chamber walls (an optimum established in earlier work)[4], a waveguide of section 100 mm square and length 1.5 m (figure 1) gave the following approximate attenuations:

Frequency / GHz	Attenuation / dB/m
2.00	67
2.60	78
3.25	97
3.95	101

These figures were obtained by comparing the transmission characteristics of different numbers of 4-tile layers, each providing 60 mm of ferrite covering.

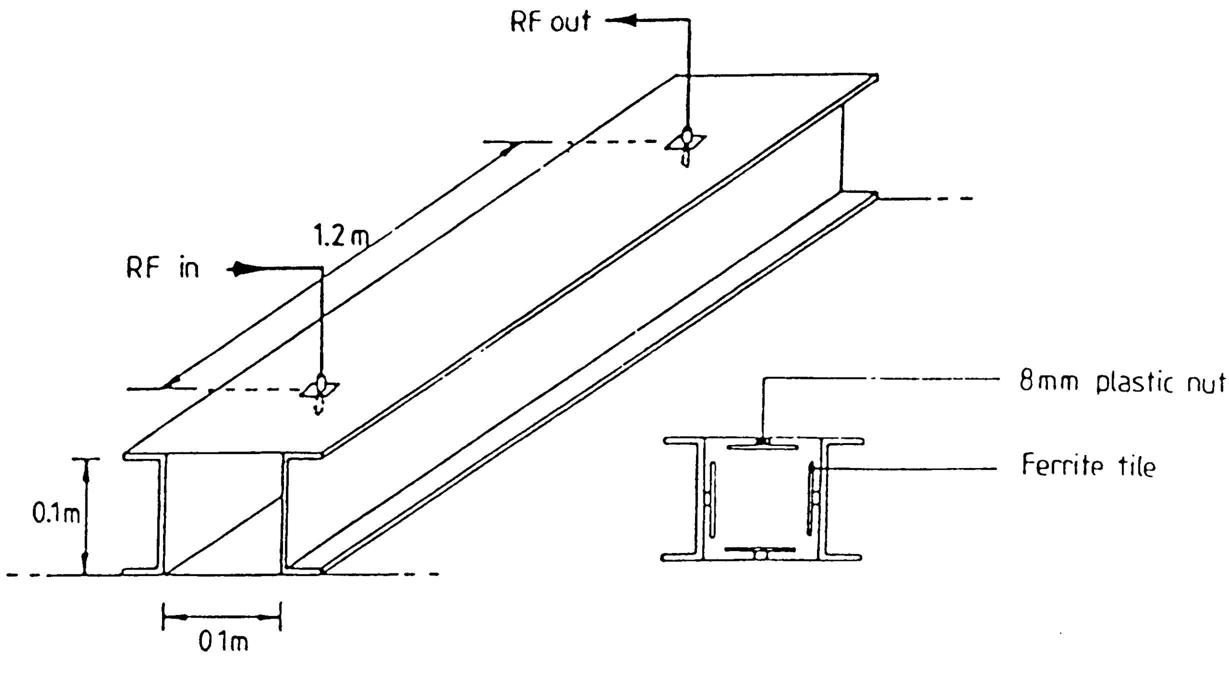


Figure 1. Experimental set-up used to measure the attenuation of ZN ferrite tiles.

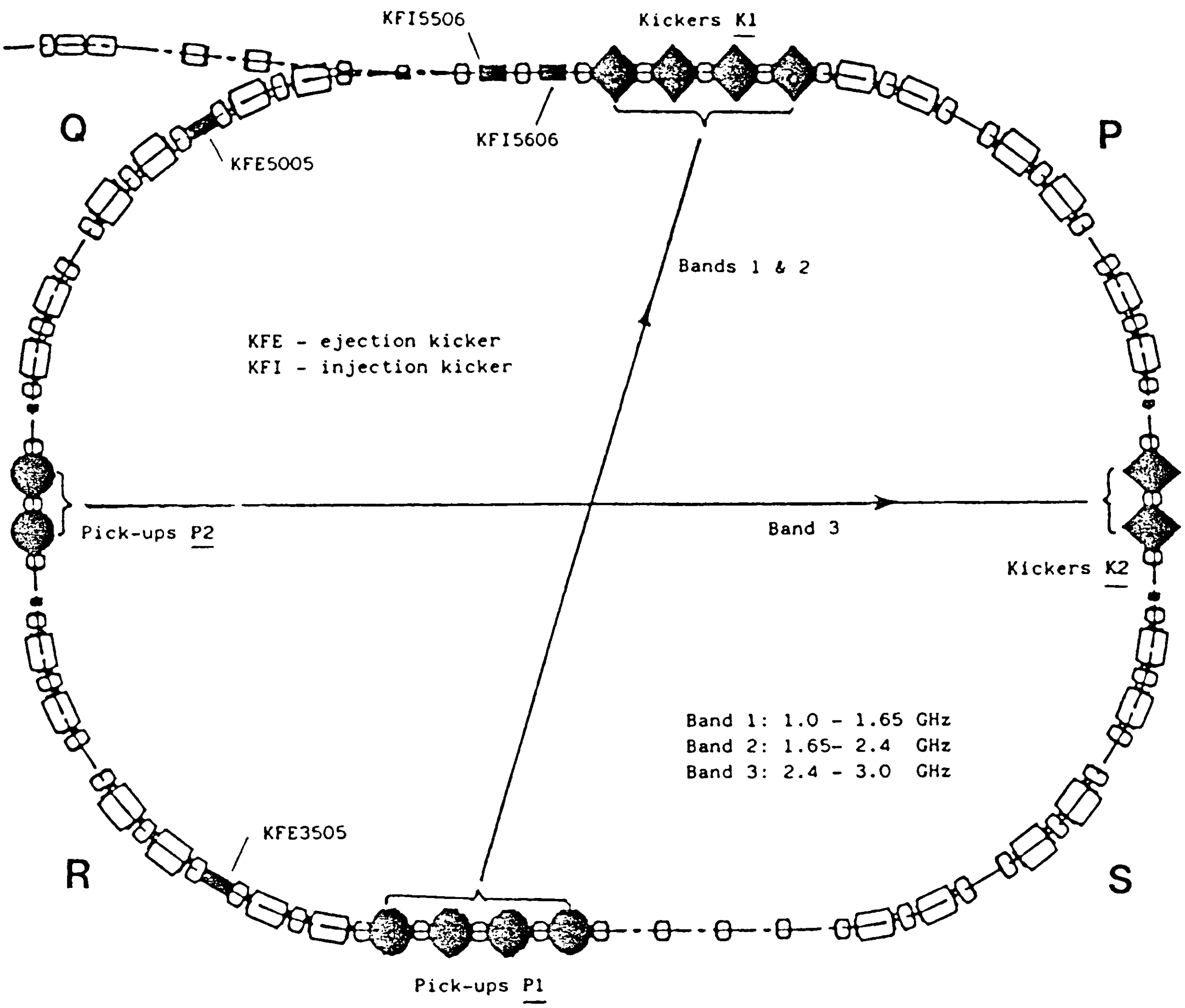


Figure 2. ACOL layout showing the positions of the stochastic cooling and the injection/ejection kicker tanks.

The presence of this 160 dB in quadrant Q means that the paths K1 to P1 via Q and R, and K2 to P2 via P and Q are completely blocked, leaving only the routes K1-P1 via P and S and K2-P2 via S and R as the ones which could cause feedback problems. The latter route does contain, however, the ejection kicker KFE3505, worth (at 25 dB/m) just under 30 dB. Thus to be sure of averting our problem, we need 110 dB attenuation in the P,S path and 80 dB in the S,R path. Placing a lumped attenuation of 110 dB in quadrant S would obviously prevent having to apply damping to all three vulnerable quadrants.

Possible sources of the required attenuation

Although it is unlikely that straight-section space will be found for a passive damping chamber, it would seem, after experiment with other materials, that ferrites still offer the easiest method of achieving the required blockage of K-to-PU paths, particularly if a high attenuation region can be incorporated into quadrant S. To that end, Peter Bramham has proposed a ferrite-lined elliptical tank (figure 3) which hugs the beam as much as possible between two quadrupoles. With 12 tiles per layer, and a wall-tile spacing of 8 mm, simulations of this structure suggest it would provide between 40 and 50 dB attenuation per metre, over all three cooling bands.

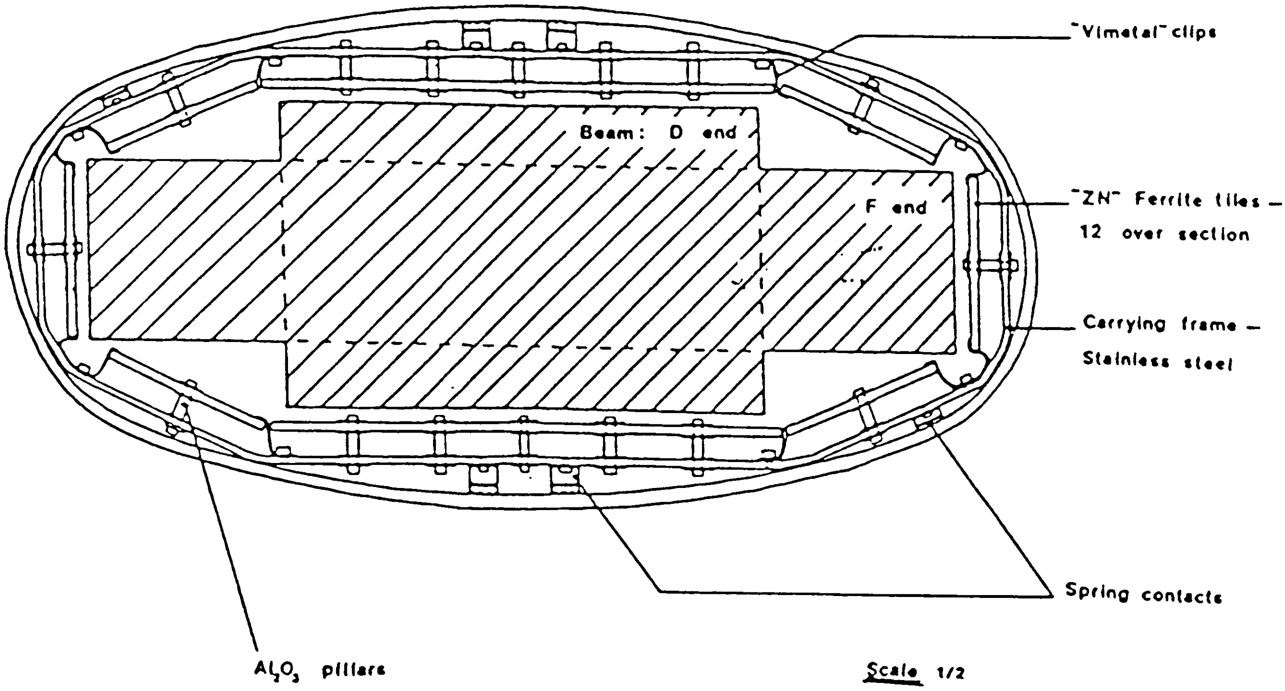


Figure 3. Elliptical design of a straight-section ZN ferrite passive damper

There are, of course, many other materials capable of reducing RF transmission around the vacuum chamber, but most of those offered for testing in the lab. were in such small quantity that their damping effects were completely swamped by those of reflections in the waveguide. For the record, however, materials such as silicon carbide may produce high attenuation per unit length.

One form of attenuator of which we have a reasonably plentiful supply, and which can be placed inside a magnetic field, is the nichrome-coated alumina resistor. We managed to aquire all the old ISR resistors, which are all nominally 100 ohm per square and 30 mm diameter. Transmission measurements have been made in a set-up similar to that of figure 1, with various resistor configurations, all of which must have the resistors close enough to the chamber walls so as not to interfere with the passage of the beam.

Unfortunately, though not surprisingly, the resistors seemed to couple almost entirely into the electric field, so that all feasible configurations, with them standing or lying on or close to the vertical walls, gave an approximate attenuation of only 0.1 to 0.2 dB per resistor, or between 6 and 12 dB/m for a chamber with both walls completely lined. Fritz Caspers suggested that resistors should be laid horizontally, three high, and shorted to the waveguide walls top and bottom, so providing a high impedance shunt. Although one metre of this structure took out roughly 40 dB at around the fundamental frequency, the broad-band attenuation was no better than before. Fritz suggested that a thicker coating of nichrome might improve this situation, but this obviously requires considerable work to achieve.

Although the attenuation per metre of the resistors is too low for them to be used in a straight-section damper, they can of course be placed in magnet chambers. Therefore use could be made of the many metres of dipole chamber in each undamped quadrant. Peter Bramham has calculated that up to 100 30 mm resistors can be placed in an ACOL dipole chamber without restricting the maximum expected beam dimensions. Thus with 0.1-0.2 dB/resistor one could hope to achieve between 60 and 120 dB per 6-dipole quadrant. The obvious drawback here is in having to attach so many resistors to the chamber walls in order to achieve reasonable attenuations. It is also doubtful whether we have sufficient resistors to furnish all the dipoles in the vulnerable regions.

Conclusions

Although the ferrite in the ACOL injection and ejection kickers and the stochastic cooling tanks should provide considerable RF damping, there is still a need of up to 110 dB attenuation, particularly in the quadrant furthest from the injection line, in order to prevent K-to-PU feedback via the vacuum chamber. A combination of a straight-section ferrite damper with nichrome coated alumina in the dipole magnet chambers would almost certainly perform this task; on its own, the nichrome solution requires rather too many resistors, the ferrite too much straight space. The use of cut-off screens, as in the AA, is not of much use in ACOL.

Acknowledgements

Thanks to Colin Taylor, Lars Thorndahl, Peter Bramham and Steve Hancock for reading and correcting various draft versions.

References

(1) C.S.Taylor, Stochastic Cooling Hardware, CERN/PS/84-8 (AA), 1984

(2) H.Koziol, Antiproton Collector (ACOL) parameter list, 3rd Ed.,PS/AA/Note 85-6, June 1985

(3) M.Robinson, The CERN Antiproton Accumulator, Industrial Training Report, September 1984

(4) K.Hollingworth, The Stochastic Cooling of Beams in the Antiproton Accumulator, Industrial report, period 1/8/82-30/7/83, July 1983

(5) E.J.N.Wilson, Design Study of an Antiproton Collector for the Antiproton Accumulator (ACOL), CERN 83-10, 1983

 APPENDIX II

8.8.85

Determination of Electrostatic Beam Potentials by a Finite-Element Numerical Method

R.James

Abstract

A method is presented for determining the electrostic beam potential due to the passage of a Gaussian beam through simple 2- and 3- dimensional structures. The method uses the powerful finite-element program DOT[1], which is described briefly, followed by a summary of how to implement various programs that have been developed to run DOT on CERN's CDC computers.

Introduction

The electrostatic potential, U, due to the presence of a beam of charged particles in a stainless-steel vacuum chamber, may be deduced by solution of the familiar equation

$$\nabla^2 U(r) = \frac{-\rho(r)}{\varepsilon_0} \qquad (1)$$

where $\rho(r)$ is the charge density as a function of position and ε_0 the permittivity of the vacuum.

This potential gives rise to electric fields which can play an influential rôle in determining the dynamical behaviour of the beam itself. In addition, the fine structure of these fields for a negative space charge potential (such as is the case with $\bar{p}$ and e beams) governs various exotic phenomena linked to the trapping of residual gas ions and charged dust particles in the beam potential well[2]. These phenomena, believed to include the excitation of non-linear resonances and multiple Coulomb scattering[3], give rise to sometimes violent emittance growths, particularly at high stack intensities, in the AA. With the introduction of ACOL, the AA will be expected to handle large stacks; thus it is desirable to determine the electrostatic potential accurately in order to understand (and hopefully prevent) the unwanted effects of trapped positive charges.

There are, of course, simple situations for which the electric fields can be calculated exactly. For simple chamber geometries, and a uniform charge density throughout the beam, equation (1) reduces to Poisson's equation, which may in this case be solved rigorously. However, attempts to solve (1) for a more realistic beam profile and/or a complex chamber geometry result in series solution and Bessel-function approximations for U[4], which are not sufficiently accurate to provide the required information on the fine-structure of the resulting electric field. The obvious alternative is to use a numerical method to solve equation (1), where (r) may take on any distribution, and boundary and initial conditions can be imposed as required. The program chosen, DOT, is a powerful finite-element program developed for use in the "Determination Of Temperatures". However, because of the complexity of finite-element programs, pre- and post-processing software had to be developed to convert DOT into the useful, easily handled tool for accelerator physicists it will hopefully prove to be.

The finite-element program DOT

DOT is designed to solve the non-linear heat transfer equation

$$\nabla^2 T + \frac{Q}{K} = \frac{1}{d}\frac{\partial T}{\partial t} \qquad (2)$$

where T is the temperature as a function of position and time, Q is the heat generation rate, K is the thermal conductivity and d the diffusivity, by means of the so-called "finite-element" formulation, wherein a solid continuum is idealised by an ensemble of discrete elements. These elements may be of variable shape and size, and are connected via node points which form the mesh. Any or all of the elements or nodes may carry boundary or initial condition parameters, which may be altered on a given node independently of all the others. DOT can handle planar 2-dimensional and axisymmetric geometries, both of which have been used here. (Each geometry can be generated in rectangular or curvilinear coordinates, though for this study only the former have been used. Hence we treat only rectangular cross-sectional and cylindrical chambers).

Clearly the use of DOT to solve equation (1) requires the RHS of (2) to be set to zero. We then substitute potential for temperature, charge density for heat generation rate, and electrical permittivity for thermal conductivity to recover the form of (1). It should be noted that there is thus considerable scope within DOT to improve the modelling of chambers and their beams (such as monitoring the effect of transverse movement of the beam with time) than has been exploited so far. It is hoped, however, that the facilities presented here will provide a framework around which future improvements can be made.

Formulation of the problem for the AA beam

Because of its complexity and flexibility, DOT requires a vast amount of input for each system studied. Even the moderately simple mesh shown in figure 1 generates some 2200 data entries if we set the outer rim to zero potential and all elements in the dense central (beam) portion are ascribed a number of charges. Since this is precisely the kind of thing we wish to do, we clearly require a pre-processing program which will generate all these data from a few input variables. The wish to run this pre-processor (and some of the other programs developed) interactively has resulted in all the computing facilities described being written and run on the CDC machines at CERN.

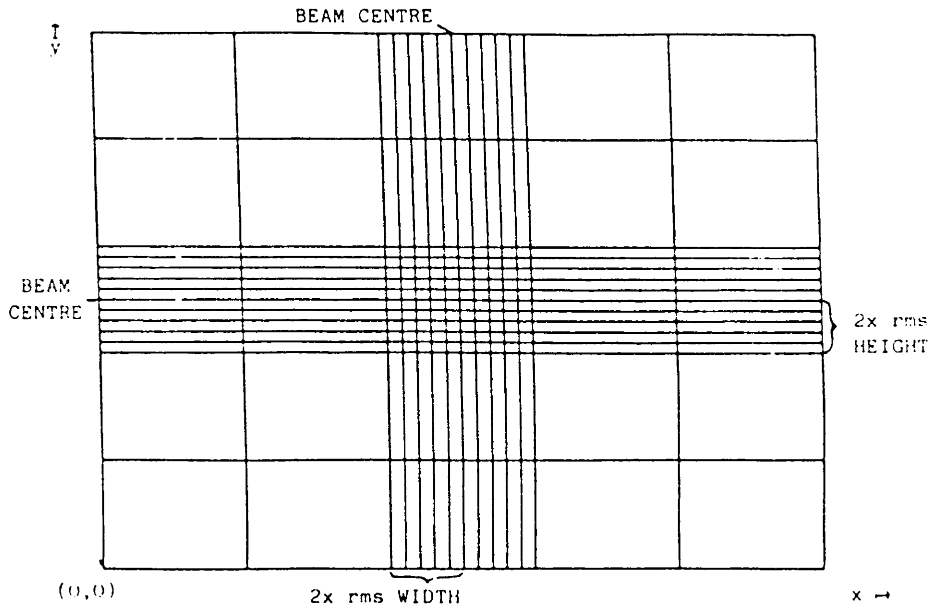


Figure1. Typical rectangular mesh used for generating DOT input.

The pre-processing program in its present form is a development of Alain Poncet's "MESHDOT" program called "NEAT". It is capable of dealing with the two geometries mentioned earlier. The first is a rectangular section transverse to the beam, such as in figure 1, with a dense portion of 10 x 10 elements* each ascribed a characteristic charge according to the uncorrelated bi-Gaussian beam distribution

$$\rho(x,y)\,dxdy = \frac{Ne}{2\pi C\sigma_H\sigma_V}\, e^{-\frac{x^2}{2\sigma_H^2} - \frac{y^2}{2\sigma_V^2}}\, dxdy \qquad (3)$$

This dense portion of the mesh extends over 2σ each side of the beam centre coordinates. (It is observed that the balance between natural or forced cooling effects, and coherent diffusive heating effects seems to produce beams in the AA and electron machines that are approximately Gaussian.) NEAT thus requires for input the chamber dimensions, the position and r.m.s. size of the beam, and the number of "non-beam" elements required. The user is also given the option of placing a clearing voltage on all node points along y=0, thereby allowing an analysis of the clearing necessary to prevent ion pockets around the machine.

The second geometry is that of axisymmetry. Again the generated mesh (such as in figure 2) is two-dimensional, but with the x=0 line taken as an axis of symmetry. Hence we may model a longitudinally uniform, radially Gaussian beam

$$\rho(r)\,drdz = \frac{Ner}{2\sqrt{2\pi}C\sigma_r^3}\, e^{-\frac{r^2}{2\sigma_r^2}}\, drdz \quad \text{for} \quad r \leq 2\sigma_r \qquad (4)$$

passing along the centre of a length l of cylindrical chamber. Again

* This may be changed to 13x13, 16x16, 19x19 etc,by changing the value of NBEL in NEAT.

the walls (that is r=a) are set to zero potential, and NBEL determines the number of beam elements. Input variables this time are chamber radius and length, the number of longitudinal and "non-beam" radial elements required and the r.m.s. beam dimension σ_r.

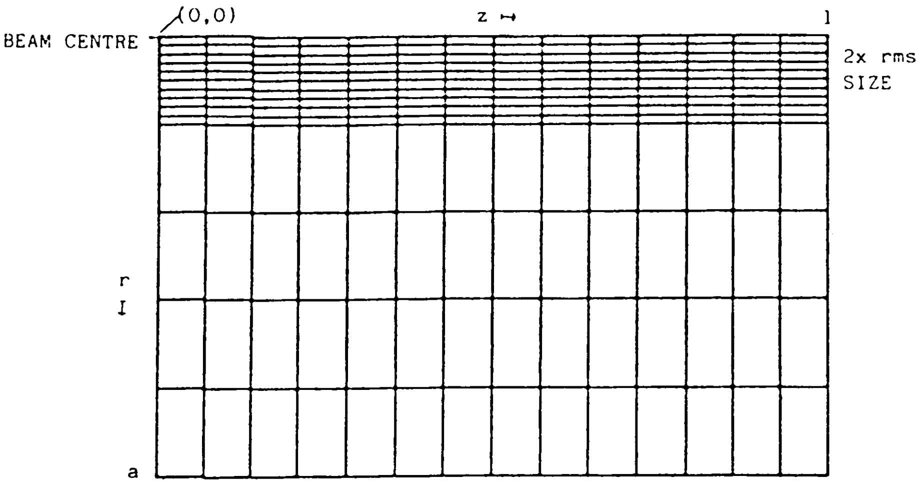


Figure 2. Typical mesh forming the DOT model of an axisymmetric structure

Clearly all this input information is easily attainable, but for the r.m.s. beam sizes. These can be deduced from beam emittances which in turn are found from scraper measurements of the horizontal and vertical beam sizes X and Y at QDN13 in the AA. The conversion of X and Y into the σ is outlined in annex 2 of reference 2 and gives

$$\sigma_H = \frac{X}{2.4477} \quad ; \quad \sigma_V = \frac{Y}{2.4477} \qquad (5)$$

It may be noted that the input variables to NEAT produce meshes which cover a fairly limited range of situations. However, once the DOT input has been generated, it may be edited "by hand", thus introducing a far greater flexibility. For example, the effect of a charged dust particle in the beam can be emulated by changing the beam charge at just one node point, giving the chance to study situations which are far from easy to treat analytically[3,5].

The use of DOT and its peripheral programs on the CDC

The running of DOT (and the various programs that have been written to aid its running) requires a good deal of laborious file handling. Therefore, with considerable help from Tony Shave of the TIS division, two interactive macros have been developed to make much of this manipulation transparent to the user.

Once logged on to the CDC machine, one should "ATTACH,MENU1,ID=PS026P0NC", and then type "MENU1" and return. This will run the interactive DOT pre-processor NEAT which produces the DOT input file, TAPE1. MENU1 automatically calls the main menu, MENU2, which offers 9 options, outlined briefly below:

1. RE-RUN PROGRAM TO GENERATE DOT INPUT. This simply re-calls MENU1.

2. PLOT THE GENERATED MESH. This facility uses a graphics program AMBIT written by Juli Hargreaves in 1982, which produces plots of the generated mesh similar to those in figures 1 and 2. AMBIT still contains a few bugs, but these are confined to the more refined options offered by the program.

3. EDIT DOT INPUT FILE (TAPE1). Instructions are sent to the terminal on how this should be done. The format required in TAPE1 can be found in appendix A1 of the DOT manual (reference 1).

4. RUN DOT. This will batch the most recent TAPE1 and bring the output file to the terminal. The DOT output file is extremely copious, but does include the sometimes useful job history on the last page. For this reason, TAPE11 is generated in NEAT and DOT, and forms a concise output file containing the NEAT input information, the mesh node coordinates and the resulting potential in volts at each of those points. The DOT output file and TAPE11 can be studied at the terminal by opting for numbers 5 and 6 respectively.

7. OBTAIN A LIST OF THE LOCAL FILES. All files which are brought into a user's space are given a "local file name", which must be known in order to perform option 8;

8. SEND A LOCAL FILE TO A PRINTER using the CDC LP facility.

9. EXIT. To re-enter the main menu, simply type "MENU2" and return.

Options 1, 2, 4, 7 and 8 automatically return the user to the main menu after (or sometimes, thanks to the idiosyncrasies of the CDC, before or during) execution. To finish the session, one should EXIT the menu (option 9) and LOGOUT. Since there can be a considerable amount of information on the screen at once, and AMBIT requires a terminal capable of handling graphics, it is recommended that a Tektronix T2 terminal be used when running this system. (As a further note, the macro requires that TAPEs 1 and 11 are stored as permanent files each time DOT is batched; since only 5 cycles of a permanent file are allowed, one should be careful not to crash the menu by having too many cycles at any one time.)

<u>Preliminary Results</u>

Unfortunately, time has not permitted a thorough comparison of the DOT output with previous work, though the preliminary results appear to be encouraging. Figure 3 shows a handplot of beam potential vertically through the centre of a beam in a square chamber. By changing the

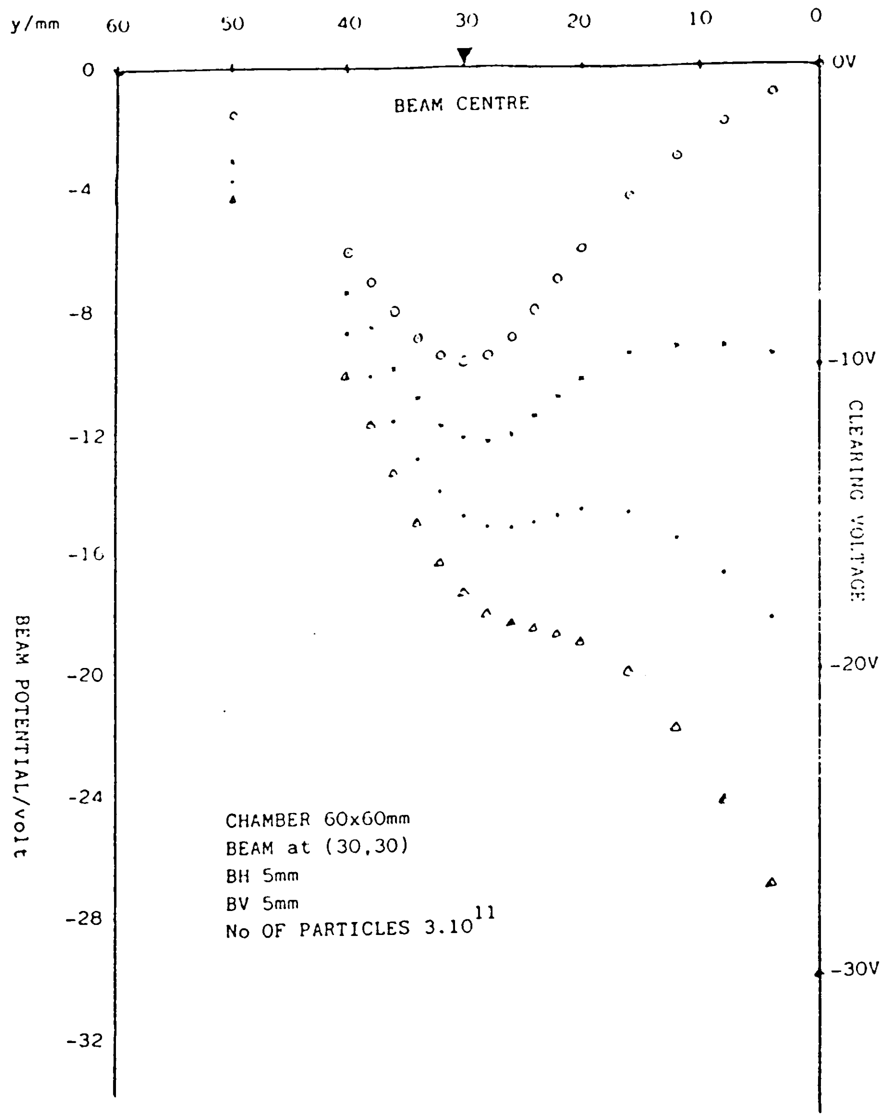


Figure 3. Handplots from DOT output showing the effect of a clearing voltage on the beam potential well

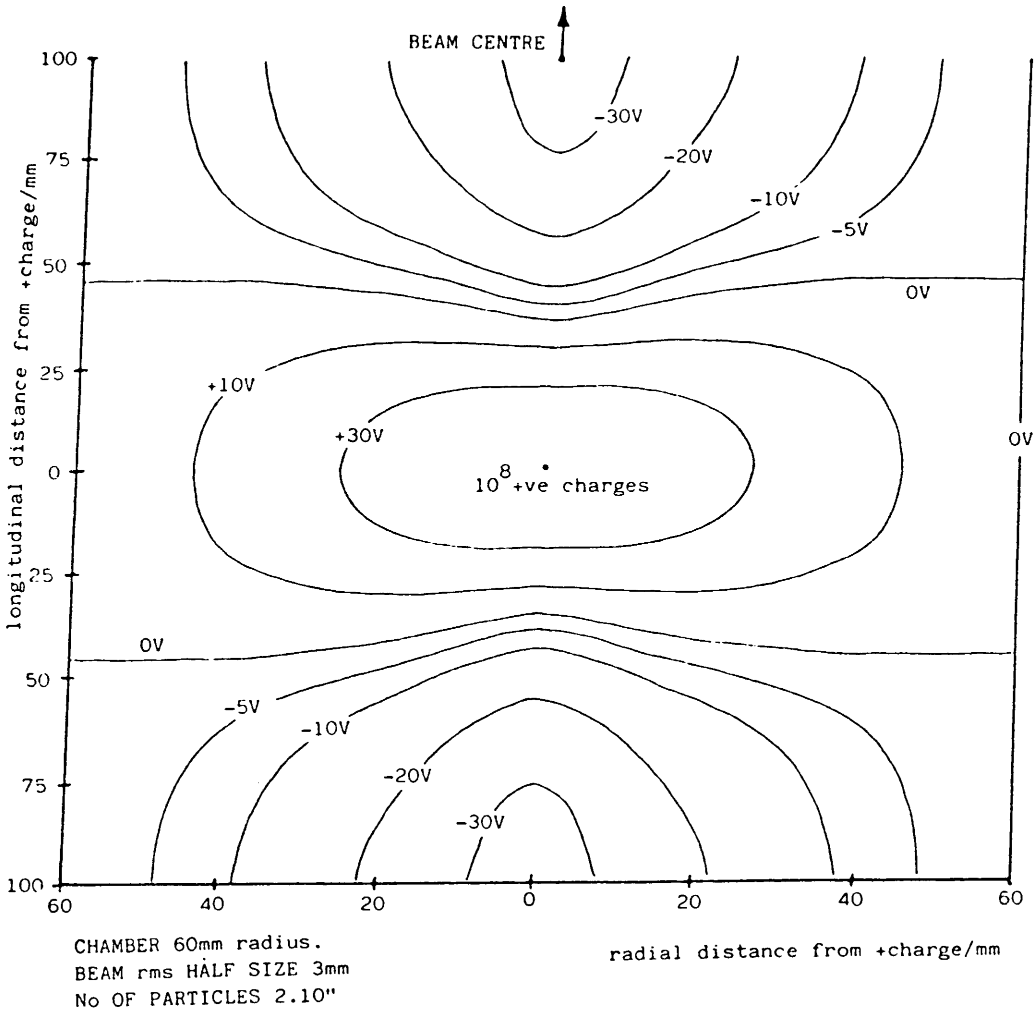
clearing voltage at y=0, one may deduce that for this configuration -30V will remove the possibility of an ion pocket.

Figure 4 shows an example of the use of axisymmetric geometry. The effect of a large number of oppositely charged particles in a beam can be treated analytically as long as the region of neutralisation does not extend to the chamber walls[5]; this imposes a restriction which is not necessary in numerical analysis, which can thus treat any number of charges placed anywhere in the beam chamber.

Suggested improvements and developments to the existing programs

The most glaring omission in the facilities provided is that of a post-processing graphics program to plot the beam potentials to the terminal. Unfortunately, SIGMA, one of the more usable graphics

(a)
right



(b)
below

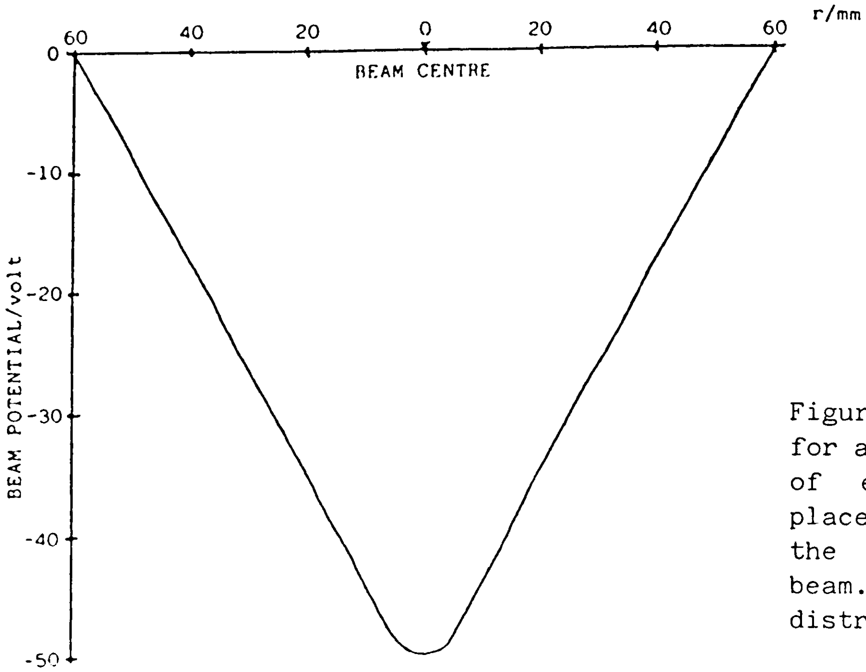


Figure 4. Handplots from DOT output for an axisymmetric case. (a) Lines of equi-potential caused by the placement of 10^8 positive charges in the centre of a negative Gaussian beam. (b) The radial potential distribution of the undisturbed beam.

packages available, which we hoped to use for this purpose is to be phased out in the near future. Probably the safest option is to try to develop a program using the PLOT10 library, as used in AMBIT. AMBIT takes TAPE12 from NEAT as its input file; clearly a version of TAPE11 (which already contains the node numbers, coordinates and potentials) in the correct format could be used as a similar input file to an interactive potential plotting program. It is then a relatively simple task to add this facility to the options in MENU2.

The other most obvious improvement to the system that could be made is the expansion of NEAT to offer a range of beam charge distributions and also to make use of DOT's ability to handle curvilinear coordinates. By this means some of the more awkward sections of beam chamber (and for example that of LEP) could be modelled. This could be particularly useful for analysing the electric fields in suspected ion-pocket regions.

Conclusions

DOT should provide a useful tool in the analysis and understanding of electrostatic beam potentials. In their present form the programs developed around DOT can model situations which should be of use in specifying clearing voltages and in coming to terms with the effects on the beam of single-site scatterers such as dust particles and residual gas ions.

Acknowledgements

I would like to thank Alain Poncet for all his help, advice and explanation concerning particle beams and finite element programs. Thanks are also due to Tony Shave for helping with the computing and to Tracy Marshall for typing the manuscript.

References

(1) Finite Element Analysis of non-linear heat transfer problems, R.Polivska, E.Wilson, University of California, Berkeley, June 1976.
(2) Proton-antiproton instability in the AA, A.Poncet, PS/AA/ME Note 81, March 1985.
(3) Transverse instabilities due to beam trapped ions and charged matter in the CERN Antiproton Accumulator, E.Jones, F.Pederson, A.Poncet, S.van der Meer, E.J.N.Wilson, CERN/PS/85-15 (AA), May 1985.
(4) Computation of the electrotsatic beam potential in vacuum chambers of rectangular cross-section, O.Grübner and K.Hübner, CERN/ISR-TH-VA/75-27, May 1975.
(5) Private communication, F.Pederson.