DAΦNE TECHNICAL NOTE

INFN - LNF, Accelerator Division

Frascati, January 15, 2000

Note: **G-54**

Report by DAΦNE Machine Advisory Panel On meeting held on 13-15 January 2000

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1 General remarks, Introduction

The DAΦNE collider is a low energy (510 MeV/beam) machine with a very long synchrotron damping time of around 10^5 turns and a total horizontal crossing angle of 25 mrad. For comparison, the LEP collider has zero crossing angle with a damping time of between 360 (45 GeV) and 40 turns (100 GeV). Experience with previous colliders puts DAΦNE in a category where it could be very difficult to achieve very high values of the beam-beam strength parameter (ξ_y). In addition, the physics requirements have imposed a detector solenoid of very high integrated field that covers the interaction region. The combination of the low beam energy and the high solenoidal field would result in very strong betatron coupling and a change in transverse tilt of 41^0 across the interaction region if this field were uncompensated. The design parameters of the machine are indeed very challenging: a peak luminosity of $5\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a total beam current of more than 5 A in two beams of 120 bunches, a beam-beam strength parameter, $\xi_y = 0.04$, an emittance ratio, $\kappa = \varepsilon_y/\varepsilon_x = 1\,\%$ and a very small residual transverse tilt between the two beams at the interaction point.

The Advisory Panel was impressed to find that many of these challenging design parameters had already been approached in individual runs. In particular, a beam-beam tune-shift of $\xi_y = 0.03$ has already been achieved, with no signs of saturation, towards the end of 1998. This demonstrates that the design value of 0.04 is attainable. In addition, an emittance ratio significantly below the design value was achieved before the installation of the detector solenoid and values very close to the design value in the presence of the solenoid. Moreover, the machine conditions seem to be intrinsically reproducible. The main push now must be to approach all the design parameters simultaneously in a given physics run.

2 Comments on Topics presented

2.1 Conditions for the KLOE experiment

Findings: The mean peak luminosity delivered so far has been $3.5\times10^{30}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with significant differences between the electron and positron intensities. The peak luminosity has been constrained by the necessity of maintaining a beam lifetime of at least one hour for background considerations. No attempts have been made so far to reduce the background by the use of the installed collimation system.

The overall machine efficiency is around 40% (time in physics divided by total time scheduled) and the delivery efficiency is around ¼ (integrated luminosity divided by the integrated luminosity which would result from operating continuously at the peak maximum luminosity).

The detector is capable of furnishing many of the beam parameters e.g., luminosity, background rates, beam sizes, beam sizes at the IP and the beam energy. At present these parameters are delivered with a time delay of 4 hours and are used for post-run analysis.

The KLOE experiment needs an integrated luminosity of 500 pb^{-1} in order to reach the same accuracy on the ratio (ε'/ε) as experiments at FNAL and CERN. It was considered imperative that at least this integrated luminosity be delivered in the year 2000.

Comments: In the opinion of the Panel, an integrated luminosity of around 500 pb^{-1} is a reasonable and achievable goal for the year 2000-2001. With the present efficiencies this will necessitate a maximum peak luminosity (which, by definition, will be reached later in the year) of around $5\times10^{31}cm^{-2}\,s^{-1}$.

Recommendations: The detector should provide the measured beam parameters to the machine control system at as high a rate as possible. The detector people considered an update rate of 2 minutes to be feasible.

In order to allow progress in increasing the luminosity, every effort should be made to make the detector less susceptible to particle background. This will involve the use of the collimation system, aperture-limiting collimators and possibly changes in the operating conditions of the detector itself.

2.2 Optics

2.2.1 Machine model

Findings: A considerable effort has been made to improve the linear model of the machine. Measurements of the optical functions (β, D_x) agree quite well with the predictions of the empirically adjusted model. As a consequence, orbit corrections based on the model work well and closed orbit bumps, an important tool for optimising and understanding the machine are well closed, even across the IR with its strong but well compensated solenoid fields. Furthermore, if, based on the re-calibration, small optics changes are calculated and implemented on the machine, one still finds reasonable agreements.

Comments: However, the Panel learned that all the individual quadrupoles have been re-calibrated by as much as 5 % in order to fit the optical model to the measurements. This is to be expected in view of the overlap of fields between adjacent elements and the many sources of stray fields in a compact ring like DAΦNE. However the Panel has not learned anything about the predictive power of the fitted machine model for larger changes to the optics.

Recommendations: The Panel proposes to investigate the empirical model, compare it with magnet measurements, try to systematically introduce the mutual ring-to ring distortions in order to arrive at a good machine more systematically. In this way, it is expected that the machine model will work for a larger range of optical solutions as well. Sufficient time should be scheduled in machine studies to test and verify the improved machine model.

2.2.2 High and low emittance optics

Findings: In the 1999 running, a low emittance optics ($\varepsilon_x = 0.5\,\mu m$) was prepared and optimised in order to partly recover the loss of luminosity by beam current limitations.

Comments: It is expected that these limitations will be overcome in the year 2000 run.

Recommendations: The Panel recommends returning to the optics with the nominal emittance of $1\,\mu m$ in order to avoid limitations of luminosity by the beam-beam effect.

2.2.3 Coupling

Findings: The strong coupling that is introduced by the 2.4 Tm solenoid field of KLOE is corrected locally by an elegant scheme. The integrated solenoid field is corrected for by two compensating solenoids that are place symmetrically around the IP. In order to avoid coupling by the quadrupoles inside the compensator pair, within the main solenoid, the quadrupoles of the low-β triplet are tilted around the longitudinal axis so that their orientation follows the tilted beam co-ordinate system. In order to obtain a flat beam, this scheme needs some empirical optimisation of the solenoid and compensating-magnet strengths. In addition it turned out to be necessary to empirically adjust the skew quadrupoles around the machine in order to obtain an emittance ratio of 1%, the DAΦNE design value.

Comments: However, despite this good result, the residual coupling effects turned out to be significantly stronger after the installation of the KLOE solenoid and additional effort will be necessary.

The Panel would like to emphasise the importance of providing independent knobs for coupling control: minimisation of global coupling by minimising the closest distance between the tunes using orthogonal skew quadrupoles, the compensation of local IR coupling by optimising the strength of solenoid, compensators and, if necessary, additional skew quadrupoles. As well as the local compensation, it will be necessary to rotate the axis of the beam cross section ellipse by a closed tilt bump around the IR.

Recommendations: The Panel recommends the preparation of improved coupling compensation algorithms that should be tested on-paper before start-up of the next run. These algorithms should be implemented for each of the two beams.

2.2.4 Dynamic aperture

Findings: Although tracking studies were made at an earlier stage of the project, there has been little recent study of the dynamic aperture. In particular, the panel notes that the dynamic aperture of the low-emittance optics used after the installation of the KLOE solenoid has not yet been evaluated.

So far it has not been possible to make measurements of dynamic aperture as the necessary diagnostics (scrapers) have not been fully operational.

The generally satisfactory behaviour of the single beams suggests that the dynamic aperture is adequate for them to have good lifetime. However some of the observations in colliding beam mode suggest that there may not be sufficient margin to allow for the additional growth of the beam tails that may be induced by the beam-

beam force. The lifetime fluctuations observed could be related to such effects although there is insufficient information at present for this to be judged.

Values of the derivatives of betatron tunes with amplitudes, based on second-order perturbation theory were provided at the request of the Panel. It is notable that these quantities change in both magnitude and sign between the pre- and post-KLOE optics and also between the two rings of the machine. The DAΦNE design included some sextupoles in non-dispersive parts of the ring that can be used to modify the detunings with amplitudes. These have not been exploited so far.

Comments: The variations of the tune-derivatives with amplitude suggest that they depend strongly on details of the optics and their real values may well vary significantly in operational conditions. Thus the betatron tune-spread in one or other beam may be sufficient for some strong resonances to influence the tails of the beams. Indeed some aspects of the behaviour of DAΦNE are reminiscent of those of LEP at low energies when such phenomena were important.

The panel recognises that the long damping time and low synchrotron tune of DAΦNE mean that tracking studies of dynamic aperture will be afflicted with technical difficulties similar to those for hadron colliders. Nevertheless, present desktop computers should allow particles to be tracked for thousands and preferably some tens of thousands of turns of DAΦNE, approaching the equivalent of a damping time or a few hundred synchrotron oscillations.

Recommendations: Dynamic aperture studies, both computational and experimental, should be given very high priority.

A study of the difference in dynamic aperture between the high-emittance, pre-KLOE and the low-emittance, post-KLOE optics may well elucidate (or at least eliminate one explanation for) the differences in behaviour of the machine in 1998 and 1999. This should be done immediately.

Detuning with amplitude should be computed and used as one initial rough figure of merit for the optics. However systematic tracking studies are also essential and should always be done before using an optics in the machine. They should not be limited to simply finding the maximum stable amplitude: studies of the phase-space structure at large amplitudes, analysis of the Fourier spectra of orbits and other tools must be exploited to identify the physical mechanisms responsible for single-particle instabilities at large amplitudes. Machine conditions should be modelled as well as possible with the usual Monte-Carlo approach to the machine errors and simulation of the main operational corrections.

The particle tracking should be done with synchrotron oscillations included.

As soon as the machine has been re-started and the optics is in good shape, the dynamic aperture should be measured by available means. The beam lifetime can be measured as a function of scraper position (blowing up the emittances first if necessary). In the horizontal plane, a single bunch can be kicked once with an injection kicker and losses measured as a function of amplitude. As is the case at many other machines, there is no kicker available in the vertical plane. Measurements of the beam oscillations over many turns following a kick should also be pursued. If used in conjunction with the beam-loss monitors that are being installed in the ring, these measurements should provide insight into the structure of single-particle phase space. In the vertical plane, it may be possible to measure dynamic aperture by first driving the beam to large amplitudes by resonant excitation in the absence of a vertical pulsed kicker.

Improved understanding of single-particle dynamics may suggest that the sextupoles in the ring could be used either to adjust detuning with amplitude or provide compensation of resonances. If so, the appropriate "knobs" should be prepared for use.

2.2.5 Chromaticity correction scheme

Findings: The chromaticity correction scheme involves four families of sextupoles. Besides compensating the linear part of the tune-shift with momentum, it includes the minimisation of the tune-shift with amplitude in order to improve dynamic aperture.

Comments: The Panel notices that there is a rather strong residual non-linear chromaticity that leads to a considerable tune-shift for particles near the boundary of the momentum aperture. These particles may also suffer from considerable β-beats which, in turn, may lead to enhanced beam-beam tune-shifts and poor stability.

Recommendations: Since the stability of such particles may however be relevant for the beam lifetime in presence of the strong Touschek effect, the chromatic properties of the optics should be checked carefully. If necessary, the additional sextupole magnets in the dispersion-free region may be used to optimise on- and off-momentum dynamic aperture and stability simultaneously.

2.2.6 Exploration of minimum β-functions

Findings: The vertical β-function at the IP, $\beta_y^* = 4.5\,\mathrm{cm}$, is limited by the bunch length of up to 3 cm.

Comments: However, it appears to the Panel that there might be additional margin to decrease the horizontal beta function.

Recommendations: We therefore recommend that optical solutions with $\beta_x^* < 4.5\,\mathrm{m}$ should be investigated, prepared, and optimised during machine studies to make them available for empirical optimisation of beam-beam operation.

2.2.7 Dispersion effects

Findings: The horizontal dispersion is found to have a value of <5cm at the IPs. Furthermore, the vertical dispersion, which may be generated by sources of closed orbit distortion and the orbit correctors, has not yet been studied.

Comments: The horizontal dispersion at the IP makes a rather small contribution to the beam size compared to the effect of the crossing angle. However, it is expected that the effort required to provide perfect compensation is small. Vertical orbit distortion and its correction generate vertical dispersion that might make an important contribution to the vertical emittance and, thereby, the aspect ratio of the beams at the IP.

Recommendations: An effort should be made to correct the horizontal dispersion at the interaction point. Furthermore, the orbit correction algorithms should be upgraded to take into account the need for a minimum vertical dispersion. Such algorithms are available at other laboratories, in particular at CERN (LEP). The work and experience gained at these laboratories should be exploited for the DAΦNE orbit control.

The contribution of the vertical dispersion to the vertical beam size should be assessed.

2.3 Collective effects

Findings: The collective effects in DAΦNE are (in the opinion of the Advisory Panel) under remarkably good control for a machine at this stage of its development. The measured longitudinal coupling impedance (Z/n) of only 0.6 Ω is indeed an excellent result. Likewise the agreement between the expected and measured values of bunch lengthening is impressive.

The high frequency impedance that has been limiting the bunch current through transverse coupled bunch instabilities has been rapidly identified as originating from the injection kickers. The design of these elements has now been modified so to eliminate the harmful higher order mode fields at 1300 MHz. The Panel is convinced that the previous current-limiting transverse instability will be eliminated with the installation of the new kickers that are foreseen for the forthcoming start-up.

A harmful longitudinal quadrupole instability has been the source of a current limitation at the level of 10-15 mA. The threshold for this instability may be increased by the use of a lattice with an increased momentum dispersion function. Possible sources of the impedance driving this instability are the bellows in the IR region.

Recommendations: Although there is no clear over-riding need for a transverse feedback system, such a system is at present being studied. The panel fully supports the development and installation of this system, as it will allow much greater flexibility in the operation of the machine.

The panel also suggests the installation of at least one, and preferably two wide-band pick-ups that would allow the measurement of phase plane trajectories. This is a very useful facility in general and is particularly important for the experimental studies of the dynamic or physical aperture.

It was also considered worthwhile to provide sufficient temperature and vacuum logging in the region of the bellows suspected as the source of impedance for the quadrupole instability. This monitoring may allow identification of the offending object.

2.4 Beam-beam effects

2.4.1 Beam-beam theory and simulations

Findings: Simulation work with the pre-KLOE optics successfully reproduced the effects of small tune changes on lifetime and luminosity.

The simulations show that the beam-beam effect can increase the population of the beam tails, suggesting the possibility of interplay between beam-beam forces in the beam core and single-particle non-linear dynamics or other effects in the tails.

Comments: The beam-beam force itself should not affect the coupling compensation when the beams collide head-on with the same tilt. In the simulation there are indications that differences in beam tilt can have a strong effect on vertical beam sizes although the effect in the real machine seems to be less dramatic.

Recommendations: The extent to which the coupling compensation can be affected by the beam-beam force itself needs further investigation.

2.4.2 Beam-beam experience: single bunch without KLOE

Findings: Initial beam-beam operation was performed without the KLOE solenoid field but with a quadrupole triplet at the IP. The β-functions at the IP corresponded to the nominal values of 4.5/.045m. Since the single bunch intensity was limited by a longitudinally unstable quadrupole-mode, the emittance was reduced to half the design value. Furthermore, in order to overcome a transverse instability in multi-bunch operation, it was decided to optimise the machine with fractional betatron tunes of (0.15,0.21) which, according to beam-beam simulations, are less favourable from the beam-beam stability point of view than the originally foreseen tunes (0.07,0.09).

The laborious IR tuning includes relative and absolute beam positions in the IR, longitudinal position, relative and absolute beam orbit slopes at the IP in both planes, optimisation of beam tilts at the IP and optimisation of the beam waist position at the IP. Nevertheless this was accomplished rather successfully.

As a result, a specific luminosity of 0.85 times the expected value as calculated from the measured/expected beam parameters was achieved. The maximum single bunch luminosity was $L = 1.5\times10^{30}\text{cm}^{-2}\text{s}^{-1}$, about 1/3 the design value. If the luminosity is plotted against the square of the bunch currents, the points lie on a straight line with no sign of saturation up to the maximum beam-beam tune-shift of $\xi_y = 0.03$.

Comments: The achievement of single bunch luminosity within 30% of the design with about half the design single bunch current in each beam and corresponding to a beam-beam parameter of $\xi_y = 0.03$ has to be considered as very good result.

This is especially so in view of the non-optimum beam parameters chosen to overcome other difficulties and given the early stage of beam-beam commissioning in which this result was achieved. This result validates the overall machine design and it should be considered as a good base for achieving the design parameters of DAΦNE.

2.4.3 Beam-beam experience: single bunch with KLOE

Findings: The beam conditions after the installation and turn-on of the KLOE solenoid were not so good as before. In particular, it turned out not to be possible to achieve the same quality of coupling control. Moreover, it turned out that the behaviour of the beam-beam operation was quite different. The vertical beam size of the electron beam starts to blow up at rather low positron bunch intensities. The blow-up is deduced from the measurement of luminosity but can also be independently measured by the synchrotron light monitor. This blow-up becomes so strong that the luminosity starts to decrease beyond single beam currents of about 15 mA. The beam-beam tune-shift saturates at much lower values and does not exceed a value of $\xi_y = 0.018$. This limits the luminosity to $L = 2 - 3\times10^{29}\text{cm}^{-2}\text{s}^{-1}$, less than one-tenth of the design value. This blow-up seems to be rather stable and reproducible. No coherent signals have been observed when the blow-up occurs. It has been verified that the beams still collide well centred with all the relevant parameters like tilt, crossing angles and beam waist position under control. The blow-up seems to be happening preferentially in the electron beam.

Comments: The Panel considers the occurrence of a blow-up as presented as quite unusual and atypical.

Recommendations: The Panel would like to stress the importance of carefully controlled beam-beam experiments with comprehensive logging of all relevant parameters such as tunes, beam sizes, difference orbits, and coherent signals. A number of experiments should be considered with a view to shedding some light on the blow-up effect and eventually overcome the limitation.

These experiments should examine the following issues:

- The variation of tunes over a wider range that should include the tune-shift of the beam-core particles by the beam-beam interaction.
- It also appears to be useful to perform beam-beam collision studies with different β values at the collision point.
- Another important input will be to deliberately increase the vertical beam emittance before the onset of the blow-up by the beam-beam interaction.
- The influence of clearing electrodes should be checked, since at low beam current, one might be able to trap heavy gas molecules/atoms in the beam.
- The influence of the positron vertical beam size on the electron vertical blow-up is an important factor in the understanding of beam-beam behaviour.

2.4.4 Beam-beam experience: multi-bunch with the KLOE Solenoid

Findings: The multi-bunch operation was driven by the need to provide luminosity for the KLOE experiment. Multi-bunch operation was hampered by a transverse instability, which limited the minimum bunch spacing and also limited the maximum current. Furthermore, there is some evidence of ion effects, which require a considerable gap in the bunch train. These additional constraints added to the single bunch luminosity limitations. The vertical blow up appears to be the same in multi-bunch operation. These effects limited the multi-bunch luminosity to values of $L = 1\times10^{31}\text{cm}^{-2}\text{s}^{-1}$ during machine studies.

Comments: Given the single bunch luminosity limitations by the vertical blow up, the limitation of multi-bunch luminosity appears to be an unavoidable consequence. The Panel believes that it should be possible to increase the luminosity by a factor of at least two, if the intensity limitation due to collective effects is removed. However, the ion effects appear to be quite dangerous and it may not be impossible, that a combination of ion and beam-beam effects leads to a further reduction of specific luminosity.

Recommendations:

- Complete the ion clearing electrodes.
- Study luminosity and lifetime versus bunch train length,
- Take any available steps to improve the vacuum with in situ bake-out possible.
- Although the long-range beam-beam effects from parasitic encounters have not been important so far, their effects should be checked as the intensity is increased.

3 Summary of practical proposals

In this section we summarise the proposals for action that emerge from the above.

3.1 Preparations before the beginning of the run

- Implement a conveniently accessible **machine database** to contain all relevant machine parameters, settings and measurements, with time stamps and regular updating. The data on the beam available from KLOE should be integrated into

- Measure detuning with amplitude for optimised sextupole scheme and compare with modelling.
- Measure chromatic behaviour of the machine for final sextupole correction scheme and compare with modelling.
- Test orbit correction scheme with dispersion correction algorithms.
- Test improved local decoupling scheme.
- Test IR beam-ellipse tilt bumps.

3.3.2 Collective effects

- Verify that the replacement of the injection kicker has indeed removed the intensity limit.

3.3.3 Beam-beam operation

- Explore a wider range of working points.
- Explore the effect of tune-differences between the two rings. The range should exceed the tune-shift of the beam-core particles by the beam-beam interaction.
- It also appears to be useful to perform beam-beam collision studies at a lower level of beam intensity but covering the same range of beam-beam tune shift by increasing the β-functions.
- *Systematically study the effects of the coupling and tilt bumps on the beam-beam blow-up.* These studies should first be done at lower intensity in order to separate the purely "geometric" or optical effects from beam-beam effects at high intensity. The results should be compared with the predictions of the simulation.
- Another important input will be to deliberately increase the vertical beam emittance before the onset of the blow-up by the beam-beam interaction.
- The influence of clearing electrodes should be checked, since at low beam current, one might be able to trap heavy gas molecules/atoms in the beam.
- Study the beam-beam behaviour at IP2 with separation in IP1. Although this experiment might yield useful information, it should be given lower priority as it is likely to be time-consuming.

3.4 General recommendations

At this stage of development of the machine, the panel considers that operating a second interaction point would hinder progress in luminosity production. The commissioning of the second IP should be undertaken only when the understanding with a single IP is more complete.

There was a general impression in the panel that the interaction between the staff could be improved in terms of dissemination of experimental results and machine data. Technically a machine database which would contain all relevant machine parameters with time stamps and regular updating would greatly facilitate post-mortem analysis of machine experiments. In addition, the machine development studies and experiments should be organised in a more formal way and the management should ensure that any time allocated to such experiments results in a written report of the results. The reports themselves should not be too formal but rather describe the experiment and give the results in the form of the raw data.

this database. This would greatly facilitate post-mortem analysis and correlation studies of machine experiments and operational conditions. The ability to "roll-back" to reproduce previous operational conditions is an essential facility in the process of improving operational performance.

- Perform **tracking studies**, as detailed above, to clarify the differences in dynamic aperture between the high- and low-emittance optics. Take account of the results in preparing the optics for the next run. Review the chromaticity correction in this context.
- Prepare the high-emittance **optics** including the possibility to vary $\beta_{x,y}$*.
- Prepare improved **coupling compensation algorithms, tilt and coupling knobs** for the high-emittance optics.
- Prepare **orbit and dispersion corrections**. A "dispersion-free steering" algorithm such as used currently in LEP should be prepared.
- **Beam-beam simulations** should continue with a view to finding realistic optimum operational conditions and studying the interplay of beam-beam and other effects.
- Prepare the **scraper system and beam-loss monitors** for studies of beam tails and dynamic aperture.
- Prepare controls and data-acquisition for **multi-turn beam measurements** with at least one pickup.
- Complete the ion-clearing electrodes and take any available steps to improve the vacuum.

3.2 Studies and optimisations during start-up

The panel fully supports the proposed new coupling/tilt compensation scheme that localises perturbations to the IR region and recommends that it be implemented during the machine recommissioning after the present shutdown.

The panel recommends starting up the machine with the nominal emittance (1 μm) lattice since it is likely that the intensity will no longer be limited to 10 mA.

It is also recommended that the improved coupling compensation algorithms (see Section 2.2.3) be tested as part of the start-up procedure. These algorithms should be implemented for each of the two beams.

The dynamic aperture should be measured as soon as the machine has reached a stable state (orbits, chromaticity, tunes etc.) in order to evaluate the available number of transverse "sigmas" available in collision. Attempts should also be made to measure the particle distribution in the tails.

The "dispersion-free steering" algorithm will allow simultaneous correction of the closed orbit and the residual dispersion and may improve the vertical emittance.

3.3 Key experiments to be performed

3.3.1 Optics

- Prepare and study beam optics with different $\beta_{x,y}$* for studying beam-beam effect and optimise luminosity operation.
- Test improved model of the accelerator. Different optics should be implemented without making empirical corrections to the model.
- Perform dynamic aperture measurements and compare with modelling.

It was also suggested amongst the panel members that a performance workshop should be organised at least once per year to review the results of the previous year and plan the work for the coming year. The advice of external experts could be made available during these workshops. Similar workshops are organised on a yearly basis for LEP and HERA.

On the purely technical side several suggestions were made for improving the operational ease and efficiency

- A checklist of criteria, which must be met, should be drawn up for any future optics configurations. Before any new optics is installed on the machine it should be examined with respect to this checklist. The criteria will of course evolve with time and experience.
- For accumulation, a "Bunch Current Equalisation" scheme should be provided so as to inject automatically into bunches which contained the least current. The tolerances on the equality of the bunch and beam currents will need to be specified and may become tighter as the performance is increased. Such a scheme has proved invaluable in LEP.
- Finally it was considered worthwhile from the point of overall operational efficiency to make any hardware or software improvements that would allow faster switching between electron and positron injection. This would also help to equalise the currents of the colliding beams.
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Next Meeting The next Machine Advisory Panel will take place on May 4-5 2000.