# DESIGN OF THE CENTRAL REGION FOR AXIAL INJECTION IN THE MILAN SUPERCONDUCTING CYCLOTRON

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## Summary

This paper describes the design of the central region for the h=1 and h=2 modes of acceleration in the Milan superconducting cylotron, equipped with an axial injection system. The calculation of the mutual capacitance coefficients between the dees is also presented.

## Introduction

The Milan superconducting cyclotron[1] is a three sectors, three-dees machine with average magnetic field ranging from 22 to 48 kG; bending and focusing limits are respectively K=800 and KFOC=200.

An axial injection system is planned[2] ; the beam delivered by a compact ECR source will be injected on axis into the cyclotron and bent into the median plane by an electrostatic inflector.

The possible harmonic modes of acceleration are h=1,2,3; the second harmonic mode has been selected as the primary one, due to the possibility to accelerate ions in the energy range 8-100 MeV/n. Therefore the design of the central region has been optimized for the h=2 mode, preserving however the possibility to operate in h=1.

The selected inflector is an electrostatic mirror, with an outer shell diameter of 25 mm. Sparking problem on the mirror limits the maximum injection voltage at 20 kV. The vertical aperture of the dees is 30 mm; the peak dee voltage is 100 kV and the minimum distance between electrodes and ground has been set at 10 mm.

The central region will operate in constant orbit mode via an appropriate scaling of the injection voltage and dee voltage. The ion with charge to mass ratio Z/A=.5 and center field value $B_o$=31.3 kG has been selected to study the central region, since it requires the maximum injection voltage (20 kV) and peak dee voltage (100 kV).

Specific problems relevant to the design of a central region for superconducting cyclotrons are:

- the injected particles bend very strongly because of the high magnetic field, leaving very little space for the inflector and making difficult to reach a good clearance between the beam and the electrodes
- the full trasmission of the beam through the inflector requires very good transversal emittances and small beam sizes
- strong axial focusing has to be provided at the inflector exit to match the small beam size

The degrees of freedom left, for a given geometry of the central region, are the rotation of the mirror around its axis and the variation of the central-cone field level. The starting time of the ions can be changed only by a few RF degrees due to the small phase acceptance and to the requirement of a good isochronism at the exit of the central region.

The need of many electrodes in a reduced space, typical of the central region for a superconducting cyclotron, implies a rather complicate electric field distribution, with practically no electric field free region in the first few turns. The performances of the central region are therefore strongly dependent on the geometry of the defining field electrodes and a sequence of tentative designs must be developed in order to meet the requirements on centering, axial focusing and clearances.

## Field and orbit computations

The code RELAX3D[3] has been used to compute the three different potential maps corresponding to the independent excitation of each dee with the other ones grounded. This code is able to solve the Laplace equation for a tridimensional geometry via the finite-difference methode of discretization over a regular mesh. A cubic mesh, 1 mm size, covering a region of 140x140 mm in X and Y directions (X-Y plane coincident with the median plane) and 19 mm in Z direction has been used.

Each geometry has been tested with orbit computations carried out by means of the computer code CYCLONE[4]. This program allows to track particles from the mirror outer-shell up to the middle of the machine. Inside the region covered by the RELAX3D mesh the electric field is computed by the superposition of the potential maps of the three dees set at the proper phase (240° RF apart for the h=2 case). Outside, i.e. for radii greater than R=70 mm, the electric field is represented by a delta function for each of the six gap crossing per turn, with radial and azimuthal components specified by the spiral profile of the gaps. The code is also able to compute linear axial motion, calculating the axial component of the electric field via a linear expansion from the median plane.

The cone field[5] used in the orbit computations extends from the center up to R=20 cm and has been shaped to provide axial magnetic focusing $\nu_z$=.1 as far inside the machine as possible.

## Second harmonic acceleration

The selected geometry of the central region is shown in Fig.1, where all the electrodes of the dees and the

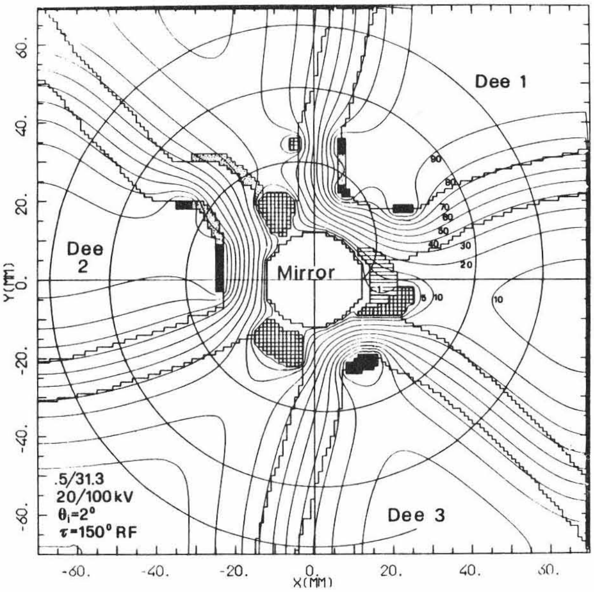

Fig.1 Central region geometry. The trajectory of the ion with Z/A=.5 and $B_o$=31.3 kG is plotted together with the equipotential lines corresponding to all the dees set at 100 kV.

dummy-dees are indicated. They are, in order:

- black areas, corresponding to the electrodes on the dees crossing the median plane, i.e. the dee-posts
- cross-hatched areas, corresponding to the electrodes on the dummy-dees, crossing the median plane, i.e. the grounded posts
- dotted areas, which mark a local reduction of the vertical aperture to 20 mm ( instead of the general 30 mm) in the following called simply vertical reductions
- a horizontal hatched area, which is a vertical reduction to 16 mm, on the first dummy-dee
- the section of the mirror outer-shell and the gap profiles

The equipotential lines on the median plane have been traced, with all the three dees set at the maximum voltage: each level is marked, from 1 to 90 kV. The plotted trajectory corresponds to the central ray selected via the optimization of the starting azimuth ($\theta$=2°), the starting time ($\tau$=150° rf) and of the central cone field level (450 gauss).

It can be clearly seen in Fig.1 the strong radial component of the electric field in the first gap; this is needed to clear succesfully the innermost post of the dee 1 since the radius of curvature of the ions at the inflector exit is only 9.2 mm. As a result, the particle trajectory suffers a strong off-centering effect: the curvature center at the entrance of the second gap is 15 mm far away from the cyclotron center in the positive Y direction. The posts located in the second gap, shrinking the field inside the gap, increase the energy gain (45 keV/n versus the 30 keV/n of the first gap), and the longitudinal momentum gain causing a shift of the curvature center in the negative Y direction, i.e. toward the cyclotron center. The third gap is shifted toward lower angles, in order to compensate for the particle delay, due to its abnormal path length during the first two gaps. The additional post on dee 2 is used to confine the field and to control the ratio of the longitudinal vs. radial momentum gain. The fifth gap is also sligth shifted towards lowest angles, in the first turn only, in order to decrease the longitudinal momentum gain, reducing the consequent shift of the curvature center toward the positive Y direction. The fourth and sixth gaps follow the normal spiral behaviour.

In Fig.2 is presented the acceleration of a beam defined by the central ray of Fig.1, four particles lying on an upright ellipse with an emittance of 400 mm·mrad (x=±1 mm, $p_x$=±130 mrad, T/A=10 keV/n), and the two particles with $\Delta\tau$=±10° RF. The minimum clearance of the whole beam is .8 mm versus the innermost post of the dee 1. The off-centering error at R=30 cm is 1.5 mm with a residual R.F. phase slip $\phi$=-2°. The centering requirement for the beam emerging from the central region are quite demanding to avoid resonances excitation[6]. The trim coils 1-2 will be operated as harmonic coils, in addition to the standard trimming mode, to center the beam. The indipendent excitation of two adjacent trim coils has been chosen to provide a large variety of form factors for the first harmonic field. The centering of the beam, corresponding to the central ray of Fig.1, using harmonic coil 1, requires less than 50% of the current available for harmonic coil operation. Therefore no attempts have been made to improve the intrinsic centering of the central region.

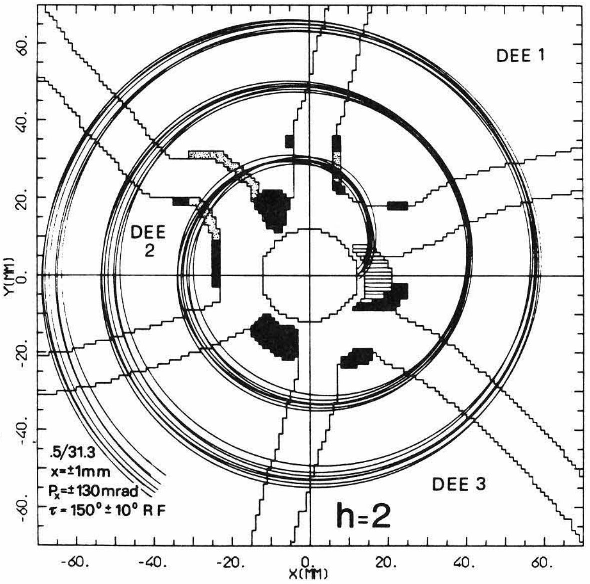

Fig.2 Second harmonic acceleration of a beam with a radial emittance of 400 mm·mrad and $\Delta\tau$ = ±10° RF.

The axial motion was always critical in the earlier tentative designs. The posts on dee 1,2, while useful to confine the electric field and to increase the energy gain, reduce drastically the axial focusing in the first turn since their reciprocal distance (10-15 mm) is quite lower than the vertical aperture of the gaps (30 mm nominal value). This can be simply understood considering that most of the electric field lines close themselves onto the post surfaces and not on the inner surfaces of the dees or dummy-dees: this fact inhibits the curvature of the field lines in the vertical plane, i.e. the axial field component.

In order to restore the axial field is necessary to reduce the vertical aperture in between the posts of the first gaps. The reduction strongly increases the axial component of the electric field, as can be seen in Fig.3 The dotted-line gives the axial field at z=3 mm out of the median plane along the trajectory shown in Fig.1, with all the dees fixed at 100 kV. The cross-line gives the axial field in the same points for an electrode geometry without the vertical reductions.

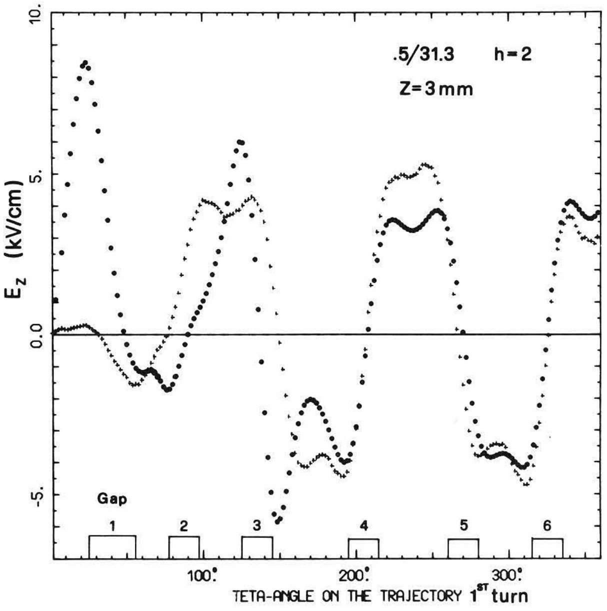

Fig.3 Axial electric field seen along the orbit plotted in Fig.1, versus the azimuth, at z=3 mm. Dotted line: with the vertical reductions. Cross-line: without. The position and width of the gaps are also indicated.

It is clearly shown in the figure the strong increase of the axial field obtained in the first three gaps, which corresponds to a reduction of a factor two in the axial beam size at injection. The axial beam envelope of a matched beam with an emittance of 500 mm·mrad at injection is plotted in Fig.4. The corresponding axial phase spaces at the mirror outer-shell for the three different starting times is presented in Fig.5. Traced back to the exit of the mirror grid this corresponds to a full beam size of about 3 mm.

Stable operation of the central region for variations of the main parameters respect to the nominal values has

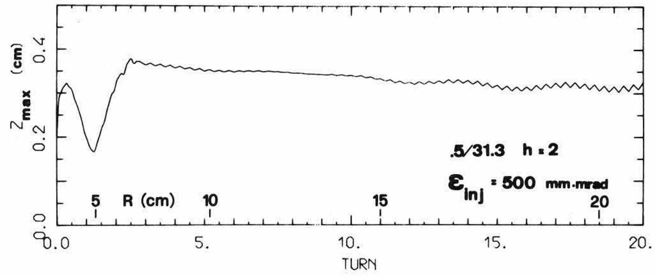

Fig.4 Axial beam envelope for the h=2 mode, matched at the eigenellipse at R=20 cm.

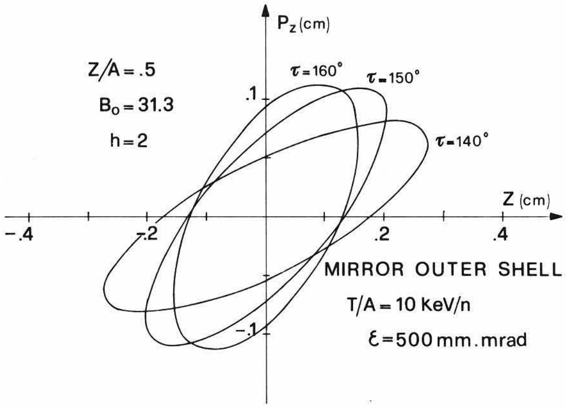

Fig.5 Axial phase spaces traced back from the eigenellipse at R = 20 cm , for the three indicated starting times.

been checked. A decrease of the dee voltage up to 90 kV progressively reduces the minimum clearance so that the beam, under this condition, grazes the innermost post of the dee 1. The other relevant quantities are practically not-affected. Rotation of the mirror in the range ±5° produces off-centering errors less than 2.2 mm and clearances greater than .5 mm (the increase of the starting azimuth produces larger clearances and off centering). To halve the level of the central cone field a shift of the starting azimuth is required; with initial conditions $\theta=6°$ and $\tau=148°$ RF (nominal values $\theta=2°$ and $\tau=150°$ RF) the minimum clearance is unchanged, the off-centering at the exit from the central region is nearly 2 mm, and the axial beam size at the mirror outer-shell is 4.8 mm versus a nominal 4 mm.

## First harmonic acceleration

Even though the central region has been designed for the operation in second harmonic mode, the possibility of a first harmonic acceleration, with the same geometry, has been considered.

The h=1 mode should be preferred, with respect to the h=2, for the most relativistic ions, in order to limit the phase excursion, above and below isochronism, in the extraction region. A disadvantage of the h=1 mode, beside the reduced range for the final energies (35-100 MeV/n ), is the difficulty to reach a good clearance in the central region due to the low energy gain (the effective voltage is 50% of the dee voltage versus 86.6% for the h=2 mode).

A working solution is presented in Fig.6, where a beam accelerated in h=1 is shown, with an injected emittance of 400 mm·mrad, represented by 7 particles corresponding to $x=\pm1$ mm, $p_x=\pm130$ mrad, $\tau=240°\pm5°$ RF. This solution has been obtained with a rotation of the mirror (starting azimuth $\theta=-8°$) and with a central cone field halved (peak level at 230 gauss). The beam clears all the electrodes in the first turn with a minimum distance of .8 mm from the innermost post of the dee 2 and dee 3.

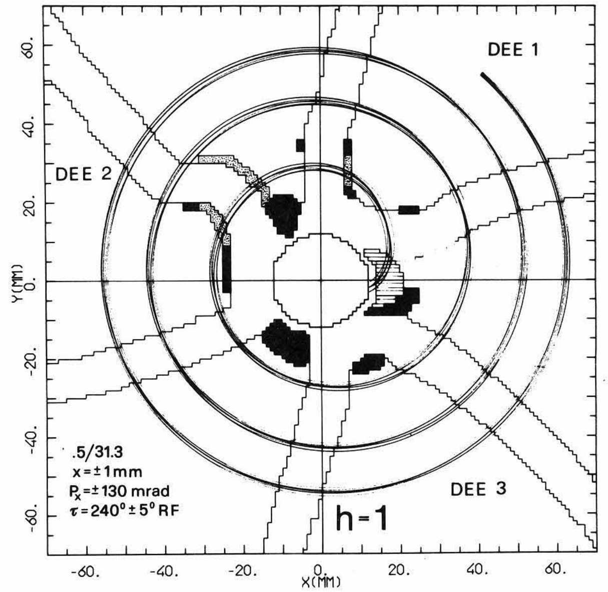

Fig.6 Beam acceleration in first harmonic mode with an emittance of 400 mm·mrad.

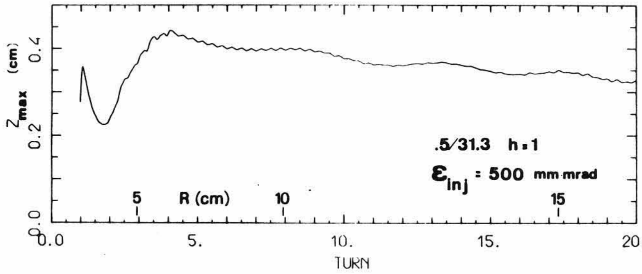

Fig.7 Axial beam envelope for the h=1 mode, matched at the eigenellipse at R=20 cm.

Axial focusing is good as can be seen in Fig.7 where the axial beam envelope of a matched beam, with an emittance of 500 mm·mrad at injection, is plotted. The increase of the maximum axial beam size to 9 mm is due to the reduction of the cone field level as can be seen by comparison with Fig.4, referring to the equivalent beam in the h=1 mode.

The phase space, for three different starting times, at the mirror outer shell is presented in Fig.8. The full size of the beam at the exit from the mirror grid is 3.5 mm; this value should be still compatible with a full transmission through the mirror.

The off-centering error of the beam emerging from the central region is about 5 mm. This large value is due mainly to an insufficient longitudinal momentum gain in

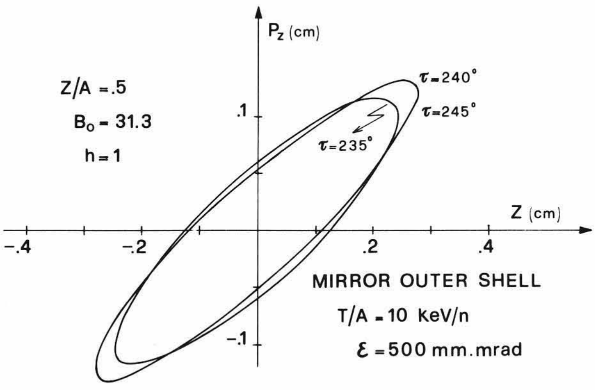

Fig.8 Axial phase spaces traced back from the eigenellipse at R=20 cm, for the three indicated starting times.

the second and third gap, causing a too low displacement of the curvature center in the negative Y direction. A first harmonic bump, with the excitation of the harmonic coils 1-2, can reduce the off-centering error to about 1 mm. An improvement of the beam centering, and perhaps of the clearance, seems feasible with small modifications of the geometry and without significant perturbations of the h=2 acceleration mode.

## Dee-dee capacitive coupling

For a three dees cyclotron, operating in the h=1 or h=2 harmonic mode, the capacitive coupling between the dees introduces an instability in the operation of the R.F. cavities, as extensively reported elsewhere[6]. Here it is sufficient to recall that this instability can be controlled, without modification of the cavities, if the mutual capacitances are lower than $10^{-2}$ pF.

Efforts have been made in the design of the central region to limit the coupling capacitances within this estimated value.

As will be shown later, the coupling between the dees is restricted to the central region where the dee-tips of the different cavities are close to each other. Therefore it is possible, with a good approximation, to treat the problem from an electrostatic point of view. The typical sizes of the coupling region are in fact small compared to the wavelength of the RF field, allowing to consider the dees as equipotential electrodes. The mutual capacitances can be calculated from the relation $C_{ij} = Q_i / \phi_j$ $i,j = 1,3$ , $i \neq j$, where $Q_i$ is the charge located on the i-th dee when the j-th dee is at potential $\phi_j$ and the two others are grounded. The charge $Q_i$ is known, once computed the flux of the electric field through any closed surface enclosing the i-th dee.

A special code has been written to compute electric field fluxes from the RELAX3D potential maps. A check of this procedure has been performed on a typical analitycal case, i.e. two not coaxial cylinders. The numerical $C_{ij}$-s were in agreement with the analitycal values within a few parts per thousand.

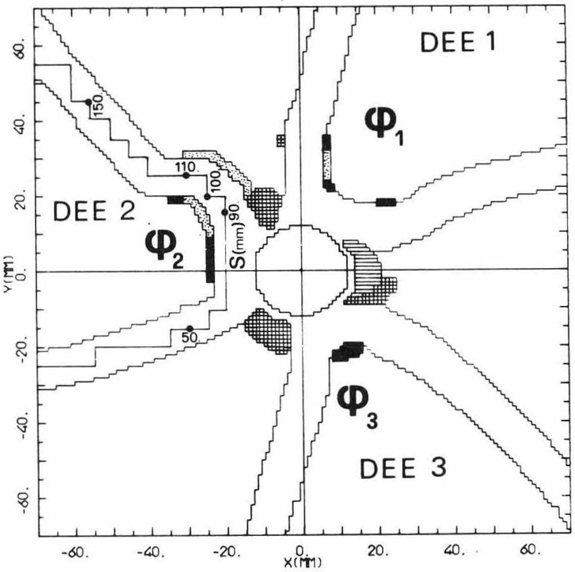

Fig.9 Flux surface used in the calculation of the mutual capacitance coefficients $C_{21}$ and $C_{23}$ ( see text )

The intersection between a surface enclosing dee 2, used to calculate the coefficients $C_{21}$, $C_{23}$, and the median plane is shown in Fig.9. The surface-section is constant from the median plane up to the maximum level (Z=19 mm) of the mesh. The surface part coincident with the boundary of the region covered by the mesh gives obviously no contributions to the flux, due to the specified boundary condition of a parallel field. The flux calculation is affected by truncation errors, since the region described in RELAX3D does not include the full radial extension of the dees. However this effect is rather small, as can be seen from Fig.10, where the flux through a strip of the surface, 1 mm height above the median plane, is plotted versus the reference coordinate S (flux is maximum on this strip, i.e. on the median plane). It must be pointed out that the strong oscillations of the flux are due to the particular shape of the surface, i.e. to the sharp corners typical of the RELAX3D code region descriptor. From the figure it is apparent that the dee-coupling is produced mainly in the region close to the posts and the mirror and that the posts on the dummy-dees are quite effective in shielding each dee from the others.

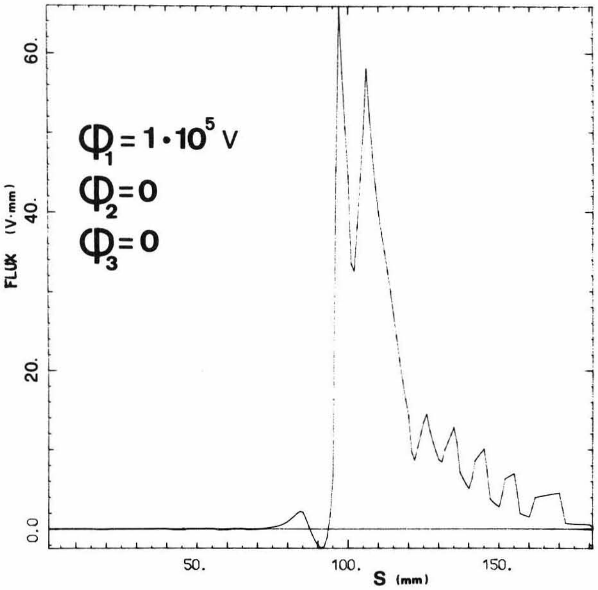

Fig.10 Electric field flux, versus the reference coordinate S along the surface of Fig. 9 (see text).

The prescribed symmetry of the mutual capacitance coefficients, $C_{ij} = C_{ji}$, has been checked to be valid within a few parts per thousand. Since the two symmetric coefficients are computed from different potential maps and flux surfaces, this is a satisfactory check for the whole procedure. The estimated error on the mutual capacitance coefficients is of the order of 10%, due mainly to the truncation of the problem region.

The computed values for the mutual capacitances are: $C_{12} = 2.0 \cdot 10^{-3}$ pF, $C_{23} = 2.7 \cdot 10^{-3}$ pF, $C_{13} = 3.0 \cdot 10^{-3}$ pF, lower than the estimated limit of $10^{-2}$ pF so that no modifications of the cavities should be required.

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