235 MeV CYCLOTRON FOR MGH's NORTHEAST PROTON THERAPY CENTER (NPTC): PRESENT STATUS

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Abstract

IBA-SHI's design of a compact isochronous cyclotron for proton therapy has been selected by Massachusetts General Hospital to equip its new NPTC. At the time of the EPAC'96 Conference the isochronous magnetic field is achieved, and initial beam tests are imminent. The present status of the different cyclotron subsystems is described.

1 INTRODUCTION

The global MGH equipment is well described in [1] and the references therein. In this paper we concentrate on the present status of the accelerator and its subsystems.

Construction of the C235 machine started May 1994, and it is planned to have the machine shipped to MGH after extensive factory beam tests by December 31, 1996.

The present status (as at the time of the EPAC'96 Conference) of C235 may be summarized as:

- the isochronous magnetic field for protons up to 235 MeV is achieved, simultaneously optimizing the performance of the extraction scheme.
- ultimate calculations are performed with the measured field data to optimize injection (central region) and extraction.
- the central region and the RF system are installed and trimmed for nominal performance (resonance frequency, radial voltage distribution).
- first beam tests will start soon.

The further sectioning of this paper corresponds to the main subsystems of the machine.

2 THE MAGNETIC FIELD

2.1 Mapping requirements for isochronisation

The intention is to give a coarse estimate of the field measurement accuracy needed to obtain correct isochronism.

Considering

- a maximum tolerable integrated phase shift of the beam w.r.t. the RF of $\pm 30°$
- an acceleration to 235 MeV in 800 turns
- an average magnetic field ≈ 2 T
- a mean value of $\gamma^2 \approx 1.2$ (γ is the relativistic factor)

we have

$$\Delta\Phi \approx n\Delta\phi_t = n \cdot 2\pi \frac{\Delta f}{f} = n \cdot 2\pi \frac{1}{\gamma^2} \frac{\Delta B}{\langle B \rangle} = \frac{\pi}{3}$$

with ϕ_t the phase error per turn, f the revolution frequency, yielding

$$\Delta B \approx 0.5 \text{ mT} \;\; \text{or} \;\; \frac{\Delta B}{B} \sim 10^{-4}$$

2.2 Field mapping system

The measurements were done with a calibrated Hall probe and a temperature probe for compensation. At regular time intervals, the Hall probe calibration was checked against NMR field values in the cyclotron center.

The usual angular grid has a $2°$ step. Test mappings with $0.5°$ step have shown that interpolation on a $2°$ grid is fully reliable. The usual radial grid has a 10 mm step up to 900 mm and a 5 mm step for larger radii. Even smaller radial steps are used for special purposes, e.g. mapping in the gradient corrector, radial edge shimming, central region,. . .

2.3 Field adjustments

The goal of the mapping and shimming process is to obtain an isochronous magnetic field with adequate focusing characteristics and an optimized extraction scheme. In this process the so-called "lateral edges" are milled to decrease the angle spanned by high field regions (hills) at all radii. After some iterations, the isochronous law of $\langle B \rangle$ vs. r is achieved.

C235 also features "radial edges": these removable parts are used to shape the field close to the extraction radius.

Finally, trimming of the main coil current allows for small overall isochronism corrections.

2.4 Mapping history

The isochronisation process can roughly be subdivided in 4 nearly independent units:

1. verification of the 4-fold symmetry
2. radial edge correction
3. central bump correction
4. lateral edge correction

Besides that, C235 being a prototype machine, special measurements and checks had to be performed at regular intervals, mainly concerning the comparison of the real machine with existing model calculations, and hence the refinement of our model descriptions.

2.5 Modelling

The initial design of C235 was based on 2d models, using stacking factors to account for the angle spanned by the hill at every radius. The average field values obtained with this method are in very good agreement (2% max. difference) with the final measured isochronous average fields.

3d models are then used to design local geometrical features like the pole spiralling yielding the adequate focussing properties. Median plane field values can be compared with measured data and show very good agreement (better than 1%) everywhere, even in regions of very strong field gradients (> 100 T/m) and in potentially problematic areas like the extreme tip of the hill. The comparison of derived properties like betatron oscillation frequencies is a more demanding check. The maximum differences between closed orbit analysis results from model fields and from the measured field are 0.1% for Q_H and 4% for Q_V (which is more sensitive).

Both 2d and 3d codes have been used during the isochronisation process, so as to make the convergence faster:

- the shape of the radial pole edge was obtained in 2 iterations only with 2d models.
- the gradient corrector and its facing radial edge was fully designed with a series of 2d models at different azimuths ($2°$ steps).
- a "response function", describing the field response at all radii due to a "unit steel cut" at a given radius, was set up for the lateral pole edge correction with a series of 3d models.

3 THE CENTRAL REGION

The central region of the cyclotron is a real multitask device:

- it houses the internal proton ion source.
- it belongs to the RF system: the puller voltage oscillates with the RF and thus provides the injection timing from the ion source.
- the correct shaping of the electrical field in the gap between source and puller and in the first acceleration gaps provides adequate vertical focussing in a region where the magnetic field does not provide it.
- it features one or several slits which aim at matching the injected beam to the acceptance of the cyclotron.

The central region was precalculated on the basis of the model calculations of the magnetic field. It has been restudied with the measured field data, including the effect of the harmonic correction coils and using as-built dimensional data of the RF components. The RF frequency has been fixed to the value obtained from the final mapping.

Finally a check of the agreement between the "far" central region calculations (for radii in the region $0.08 < r < 0.4$ m) and the closed orbit results has been included.

3.1 Results of the central region calculations

Horizontal centering of the beam (or eventually controlled off-centering) is a very important issue in this cyclotron. A study has shown that only the harmonic 1 of the magnetic field has a significant off-centering effect, not the higher order harmonics. Especially, the large second harmonic which is present due to the mechanical construction of the cyclotron center has a negligible effect on the centering of the beam. A set of harmonic coils allows to add a first harmonic field correction with an arbitrary phase angle by combining 2 orthogonal dipole circuits. The result of such a correction scheme is shown in fig. 1.

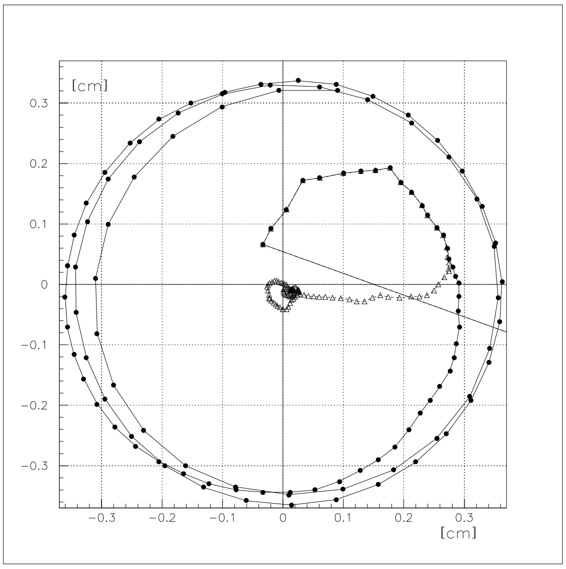

Figure 1: Center of curvature motion in C235. Bullets: raw magnetic field as measured. Triangles: the same magnetic field + 0.8 mT first harmonic correction from the harmonic coils. There is one symbol every turn. During the first 18 turns the harmonic coils have no effect, so bullets and triangles are superimposed in this region.

The vertical motion has been studied by calculating trajectories of particles starting at 1 mm from the median plane, i.e. the half-height of the ion source exit slit. The electrical vertical focussing is provided by the first four accelerating gaps. Beyond this first turn the magnetic field gradient corresponding to the decrease of the central field bump provides weak vertical focussing. From $r = 0.1$ m onwards the magnetic field has a hill/valley structure, and the focussing becomes of the alternating gradient type.

The vertical betatron frequencies estimated from central region calculations (in the region $80 < r < 400$ mm) are in full agreement with the results of equilibrium orbit calculations.

The results give confidence that the central region is now well designed, and that sufficient trimming possibilities exist for obtaining correct injected beam characteristics.

These trimming parameters will be fixed by the initial beam tests:

- exact position of the ion source
- exact position and opening of the first slit
- necessity of a second slit
- amplitude and phase of the first harmonic correction

4 RF SYSTEM

The acceleration of the beam occurs at the fourth harmonic of the revolution frequency, i.e. at 106.5 MHz. The acceleration is obtained through 2 RF cavities giving 4 acceleration gaps in total. Each cavity fills a valley of the magnetic structure, and the 2 cavities are connected to each other in the center of the cyclotron via the central region. Each dee is supported from the base plate by 2 pillars. Trimming of the resonance frequency and of the radial gap voltage law has been obtained by varying the diameters of these pillars.

The RF power is fed to the system of 2 cavities via a coaxial line and a capacitive coupler. It is generated by a 100 kW tetrode tube.

At the present time the fundamental setup and trimming of the cavities are finished, and power tests are imminent.

5 ACCELERATED BEAM CHARACTERISTICS

The closed orbit studies in the measured field provide us with the working point diagram along the acceleration in C235. This is shown in fig. 2. The systematic resonance $3Q_{\mathrm{H}} = 4$ is rapidly crossed just prior to extraction, and does not cause any significant detrimental effect to the beam. This result is obtained both through numerical resonance analysis (using the HARMON module in MAD), and through multiturn multiparticle tracking. The measured field map has also been used to check the good behaviour of the beam throughout the acceleration by a tracking calculation from 50 MeV up to 220 MeV.

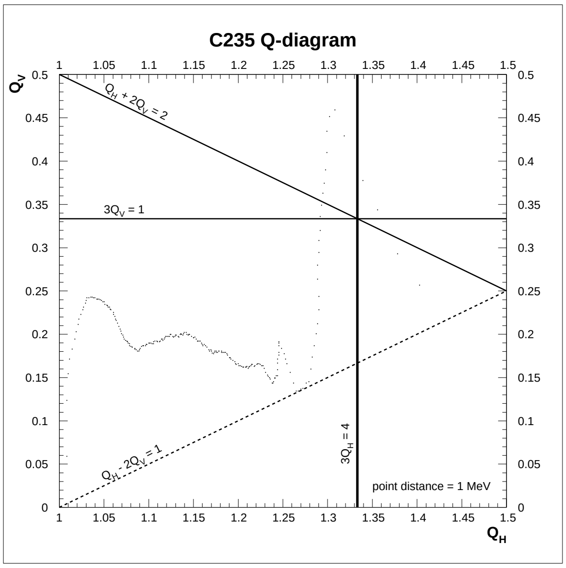

Figure 2: Working point diagram along the acceleration in C235. The point to point distance is 1 MeV.

6 EXTRACTION

The extraction system includes:

1. an electrostatic deflector located in a magnetic valley. Its shape is obtained from particle tracking in the measured field map, closely following the extracted beam path. Nominal values are: electric field 14 MV/m, gap width 4 mm, septum thickness 0.1 mm.
2. a gradient corrector. This device is used to correct the very steep field gradient experienced by the beam when leaving the pole. It is entirely passive, and its effects are fully contained in the field mapping data.
3. a permanent magnet quadrupole doublet. In spite of the presence of the gradient corrector, the extracted beam is strongly divergent in both planes. Therefore, in between the main coils a quadrupole doublet is installed. It is made from permanent magnet material (Sm_2Co_{17}), with 16 rectangular magnets around the circle, and screened from the coil field by suitable iron collars. The model calculations show a field gradient of 19.2 T/m.
4. an external coil quadrupole doublet.

The lengths of the individual permanent magnet quadrupoles are adjustable in steps of 10 mm. The nominal values are obtained from a MAD beamline description.

It is not expected to have a separated turn structure at the entrance of the deflector, and part of the beam will inevitably strike the septum. Note, however, that beam power is extremely low [1]. Tracking simulations indicate that an efficiency of more than 85% may be obtained in the case of a well centered beam. If off-centering occurs, it is compulsory to carefully position the septum in a dip of the radial current density, but equivalent efficiencies are then obtained. These dips are well pronounced due to Q_{H} being close to the third integer.

7 CONCLUSION

25 months after the start of this prototype project, the C235 machine is practically ready for the first beam tests, and extracted beam should be available shortly after.

8 REFERENCES

[1] Y.Jongen, S.Laycock, M.Abs, J.-C.Amélia, W.Beeckman, W. Kleeven, M.Ladeuze, G.Lannoye, D.Leyman, V.Poreye, D.Vandeplassche, S.Zaremba, T.Hurn, L.Nissley, E. Hubbard, M.Heiberger, M.Tabor, C.Silke, T.Tachikawa, M.Sano, T.Takayama, K.Ohtomo and T.Satoh, Proc. 14th Int. Conf. on Cyclotrons and their Applications, Cape Town, 1995, to be published