600 MeV, 100 to 200 μA Proton Accelerator Designs at IBA

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Abstract

Following a request from the Lawrence Berkeley Laboratory in the framework of the Isospin project, IBA has undertaken a comparative study of industrially producible proton accelerators delivering a time averaged current of more than 100 μA at 600 MeV.[1] Among the many solutions which may be applied in principle, two have been considered as fulfilling the technological and economical feasibility requirements for an industrial approach. Consequently we studied (i) a 30 Hz cycling synchrotron with a 68 m circumference FODO lattice in racetrack based on 16 rectangular dipole magnets, and (ii) a room temperature ring cyclotron with 6 separated sectors and zero spiral angle. Both studies feature two- and three-dimensional magnet design calculations, beam dynamics investigations and preliminary engineering issues.

1 INTRODUCTION

This study has been undertaken at IBA following a request from the Lawrence Berkeley Laboratory in the framework of the Isospin project. They specified a proton energy of 600 MeV (corresponding to a momentum of 1.219 GeV/c) and a time averaged beam current $\geq$ 100 μA. This accelerator should be the primary driver for the generation of radioactive beams far from stability, produced by a spallation reaction on a heavy target. Thus no condition was set on the time structure of the beam.

In a first part of the study we treated the choice of the type(s) of accelerator to be considered. It was felt that the industrial approach could only be compatible with well-proven technological solutions. Hence our choice was largely based on the existence of other accelerators with similar characteristics. The a priori attractive alternative of an FFAG ring synchrocyclotron has not been retained: the technological unknowns are too important. Also the 600 MeV linac solution has been discarded, partly because of similar arguments, partly also because such a linac would clearly fall outside the normal scope of IBA's activities.

Two satisfactory solutions remained and were studied in more detail: (i) a fast cycling synchrotron, with the ISIS machine [1] as reference example; (ii) a separated sector isochronous ring cyclotron.

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2 THE FAST CYCLING SYNCHROTRON

2.1 General Design Considerations

The design of this machine is based on rather conservative choices. The lower intensity limit of 100 μA is adopted, but a relatively low repetition rate of 30 Hz has been used. This combination yields $2.1\,10^{13}$ protons/pulse, which is at the limit of the proven possibilities. The injection energy is taken as 70 MeV.

Separated function magnets have been used, and the field in the dipoles has been limited to 1.25 T. The dipoles are rectangular. The logical shape of the machine is a racetrack since only 2 long straight sections are needed. The lattice must provide dispersion free straight sections for the RF cavities, and the machine must operate below transition.

H^- charge exchange injection is used so as to allow phase space accumulation. Fast extraction occurs via a standard kicker-septum scheme.

2.2 The Lattice

The lattice has been calculated with the program *MAD* [2].

The rectangular dipole magnets have a bending angle of 22.5°, so 16 of them are used. A FODO lattice with a phase advance of 90° per cell is built around them. The cell has a length of 4.75 m. Missing magnet straight sections create a naturally close to zero dispersion, trimmable by the 2 mid-arc quadrupoles. The long straight sections for injection and extraction (ℓ = 5 m) are obtained with quadrupole doublet insertions, which automatically create the short straights (ℓ = 3 m) for the RF cavities. The total arc length is 68 m — a schematic layout is shown in fig. 1. The ring has 26 quadrupoles in 5 families.

The working point is chosen as $(3.20, 3.31)$. In the horizontal plane $\beta_{\max}$ is 15 m, but only 8 m at $D = D_{\max} =$ 4.2 m. In the vertical plane $\beta_{\max}$ is 7 m.

At present no chromaticity correction scheme is provided, because the natural chromaticity is correctly < 0 for transverse stability (below transition); but adequate places for correction sextupoles can easily be found in the lattice.

2.3 Space Charge Limitations

At low beam velocity ($\beta << 1$) the longitudinal coupling impedance is fully dominated by the space charge. At the

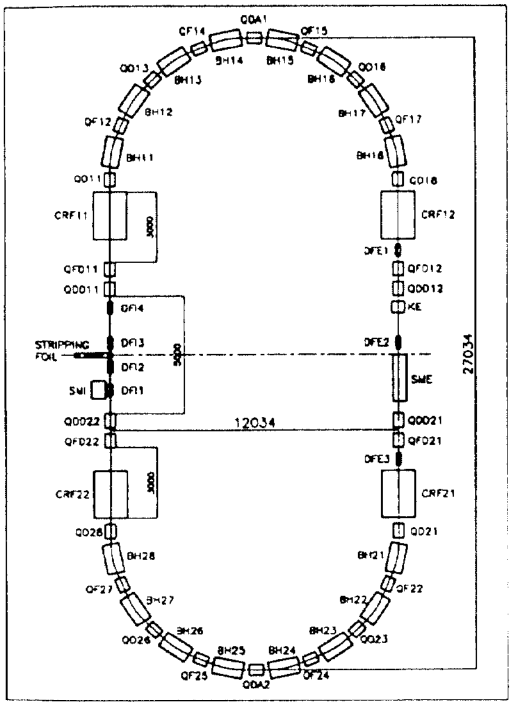

Figure 1: Schematic layout of the fast cycling synchrotron.

injection energy of 70 MeV one has

$$(Z_{\parallel}(p)/p)_{\text{s.c.}} \approx -1000\, j\, \Omega$$

Applying the Keil-Schnell criterion [3] results in

$$\left(\frac{\Delta p}{p}\right)_{1\sigma} \geq 3.3\, 10^{-3}$$

In the transverse planes the stability is expressed by Laslett's relation [4]. Limiting the vertical incoherent tune shift to 0.2, and taking $\epsilon_H = 2\epsilon_V$, we obtain (again at injection)

$$(\epsilon_V)_{1\sigma} > 50\ \pi \text{ mm mrad and } (\epsilon_H)_{1\sigma} > 100\ \pi \text{ mm mrad}$$

For the translation of these numbers to vacuum chamber dimensions the full beam emittance is taken as 3 times the 1σ value, and a safety factor of 2 for alignment and/or closed orbit errors is used. One also has to add the sagitta in the straight dipoles. It results in the following vacuum chamber diameters: $d_H \times d_V = 230 \times 90$ mm^2.

The coherent tune shift due to the space charge should be ~ -0.13.

2.4 RF

The RF frequency (harmonic 1) must sweep from 1.614 to 3.492 MHz. An RF cycle has been calculated for a constant bucket area of 2.23 eV·s and a 30 Hz sinusoidal field variation. The stationary bucket at injection requires a total ring RF voltage of 65 kV, and during the cycle the required voltage rises to 100 kV, with a stable phase between 0 and 16°. This voltage must be delivered by 4 ferrite loaded RF cavities.

The total RF power requirement has not been studied — the peak beam loading corresponds to 185 kW.

2.5 Injection and Extraction

The hardware for the multiturn charge exchange injection consists of a stripping foil at the center of the injection straight section, and 4 programmable fast dipole bumpers to sweep the closed orbit. The injected beam is bent onto its ring trajectory via a thin magnetic septum ($B = 0.5$ T) of 0.75 m long.

Extraction occurs in the horizontal plane in a single turn via a kicker and a 2 m long septum. A 3-bumper scheme reduces the kicker requirements.

2.6 Main Magnets

The dipole magnet gap is taken as 100 mm. For a field of 1.25 T it needs 100,000 ampere-turns. The pole shape has been optimized with the 2-dimensional electromagnetic code *Opera-2d* [5] so as to obtain a 10^{-4} homogeneous field region of 240 mm wide (in a DC solution). The resulting pole has a width of 350 mm, and the total dipole magnet ($\ell = 1.269$ m) a mass of ~ 4 t.

The quadrupole magnets have a bore of 80 mm and a field gradient of 5.5 T/m, needing 14,000 ampere-turns per pole. They are 0.6 m long. No model has been made of these magnets.

The main power supplies are resonating at 30 Hz. For the 16 dipoles powered in series the maximum induced voltage is close to 7 kV.

3 THE RING CYCLOTRON

3.1 General Considerations

There is a strong argument in favour of an H$^-$ cyclotron: it has a 100% extraction efficiency without a separated turn structure. However, the magnetic field limitation due to the electromagnetic stripping ($B_{\max} = 0.52$ T at 600 MeV) causes enormous magnet sizes, and therefore this option is discarded.

The main concern in the conceptual design of an isochronous cyclotron is the vertical focussing. The field index k is necessarily positive due to the relativistic mass increase, and thus causes a vertical defocussing. This has to be compensated by

- the flutter, defined as

$$F = \frac{\langle B^2\rangle - \langle B\rangle^2}{\langle B\rangle^2}$$

- the spiralling angle of the sectors ξ

The vertical tune is then *approximately* given by

$$Q_z^2 \approx -k + \frac{N^2}{N^2-1} F \left(1 + 2\tan^2\xi\right)$$

The number of sectors (i.e. the fundamental symmetry of the machine) is chosen so as to avoid the crossing of a systematic half integer resonance for the horizontal motion. For a machine of the size considered here, there is definite economical benefit in minimizing the spiralling angle. Hence a high flutter, or a maximized difference between hill and valley fields, is needed. This is a clear argument in favour of a separated sector design.

Is it advantageous to apply superconductivity ? Superconducting compact cyclotrons inherently have a low flutter, and they require very high spiralling angles. In fact, they cannot realize enough vertical focussing for 600 MeV protons. On the other hand, a superconducting separated sector machine requires $2N$ non-circular superconducting coils. Their cost is probably too high to be considered in a 600 MeV project.

For a magnetic structure with a radius of several metres it is certainly desirable to have a mechanical support both at the outer *and the inner* radii. This is a second strong argument in favour of the separated sector design.

Finally, in order to achieve a separated turn structure at extraction, one needs a high accelerating voltage and thus a powerful RF system. Here again the separated sector design is advantageous.

The principal drawback of a separated sector machine is due to the fact that its field does not extend to the center, whence its need for an injector — typically a small cyclotron. Yet, for the present case study this solution is considered to be cost effective.

3.2 The Magnet

The magnet design is based on:

(i) a 70 MeV injection energy

(ii) a maximum hill field of 2 T

(iii) 6 sectors (a trial design with 4 sectors failed due to resonances)

(iv) a hill/valley ratio ranging from $\approx 1/3$ at injection energy to $\approx 1/2$ at top energy, providing a large flutter and ample space for the RF cavities

(v) a zero spiralling angle

This magnet has a total length of 6.6 m, a maximum height of 5 m. It is positioned so as to have the outer hill radius at 5.7 m. A 3D model has been built with the *Opera-3d* software [5] — it requires 117,000 ampere-turns for a 5 cm gap.

The betatron tunes of the cyclotron are obtained from an evaluation of the one turn transformation matrices: From injection to extraction Q_H goes from 1.2 up to 1.8, Q_H from 2.0 down to 0.2.

3.3 The RF System

The RF uses the 6^{th} harmonic of the revolution frequency, giving 40.9 MHz. 4 RF cavities are installed, and each cavity has 2 accelerating gaps, 30° apart. This combination gives an optimal energy gain: 300 kV peak RF voltage gives 2.4 MeV per turn. Each of the 4 final stage RF amplifiers should deliver 250 kW.

A high extraction efficiency requires a small energy spread in spite of the wide phase acceptance. In order to realize this a so-called flat-topping cavity, functioning at the 3^{rd} harmonic of the main RF, is installed.

3.4 Injection and Extraction

The injector cyclotron delivers a 200 μA beam at 70 MeV, which is brought onto the first orbit via a C-framed bend and an electrostatic inflector. At injection the turn separation is 36 mm.

Extraction will be achieved by an electrostatic septum followed by an electromagnetic channel. If properly tuned a turn separation of $\sim$ 10 mm may be realized, whereas the radial extent of the beam should be around 5 mm. Therefore extraction efficiencies of more than 99% could be achieved.

4 CONCLUSION

In the comparison between the 2 types of accelerator the following point is striking: obtaining 100 μA DC-average beam current from a synchrotron is a hard job, since one has to operate at the limits of feasibility concerning space charge handling. For a cyclotron this level of beam current is hardly a challenge — it is proven that significantly higher levels can be realized.

On the other hand, whereas a 600 MeV synchrotron is a small and light machine, the corresponding cyclotron is rather heavy and bulky.

Preliminary cost estimates tend to indicate a fair equivalence between the 2 solutions.

Probably the most decisive argument is the specific application and the question whether it needs a definite pulsed time structure, or whether it can cope with a continuous beam. In the former case the synchrotron is the only possibility, in the latter case the cyclotron may well be the right choice.

5 REFERENCES

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