DYNAMICAL PROPERTIES OF THE ELECTROMAGNETIC FIELD OF THE CUSTOMS CYCLOTRON

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Abstract

The compact isochronous cyclotron is considered as a source of 1.75 MeV protons for detection of explosives using the gamma–ray resonant absorption technique.

Dynamical properties of the so-called Customs Cyclotron magnetic and acceleration fields were estimated analytically and digitally for the set of ion closed equilibrium orbits and by computer simulation of the beam acceleration process.

The acceleration of the injected bunched beam was attempted first. Axial beam profile shows that no axial losses are visible with axial aperture in the low intensity limit. But the final beam quality does not completely meet the requirements.

The results of the space-charge dominated beam acceleration revealed the axial losses. The transmission at ~5 mA injected beam intensity is less than ~30% making ~1.5 mA in the output beam only. Calculation of the 30 mA CW beam motion through the cyclotron gave a ~6 mA beam accepted in the acceleration regime. Several methods to improve the quality of the output beam were proposed.

INTRODUCTION

Requirements to the output beam [1] are summarized in Table 1.

Table 1: Required output beam parameters

Parameter	Value	Comments
Type of emerging particles	Proton	
Peak beam current	40mA	
Macro pulse width	Variable	
Pulse repetition rate	Variable	
Duty factor	25%	
Average beam current	> 10 mA	> $6.2 \cdot 10^{16}$ pps
Mean beam energy	1.747 MeV	
Energy spread	< 2 keV	
Beam spot at the target	10 mm^2	
Divergence at target	3 mrad	

The compact cyclotron, shown in Fig. 1, was selected to fulfill the requirements.

Dynamical properties of the cyclotron magnetic [2] and acceleration fields were estimated analytically and digitally for the set of ion closed equilibrium orbits (EO) and by computer simulation of the beam acceleration process. At the initial stage of the study, an analytical approximation of the spatial electrical field in the Dee-anti-Dee structure was assumed. The 3D electrical field simulation was provided for the further calculation (see Fig. 2).

Given the above mentioned marginal requirement for the beam intensity and quality, H^- ions were selected for acceleration in the cyclotron aiming at the high efficiency extraction either by stripping at the 1st stage or by ESD (Electrostatic Deflector) attempting to meet the output beam specifications.

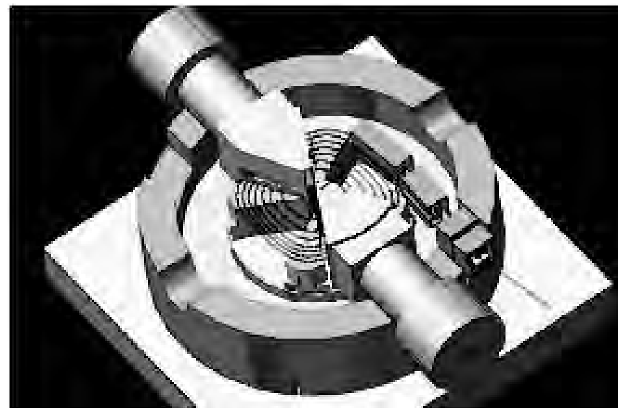

Figure 1: Cyclotron with the Upper Part of the Magnet Removed.

Figure 2: Central Region Acceleration Field Distribution.

EQUILIBRIUM ORBIT PROPERTIES

Main Acceleration Radial Region

Assuming 60 kV dee voltage amplitude with two ~45° dee structure and h_{rf}=4 acceleration mode harmonic, one can estimate the maximal energy gain per turn ~ 240 keV. Injecting H^- ions with energy ~ 30 keV, the energy of the beam after passing the 1st acceleration gap would be ~ 90 keV. Fig. 3 shows several EOs starting from the EO with the energy = 67 keV (somewhere inside the 1st acceleration gap) with the step 240 keV and the final orbit with energy = 1.747 MeV.

So, Fig. 3 depicts an accelerator turn structure in the case of maximal energy gain per turn.

Fig. 4 and Fig. 5 show particle betatron frequencies for the so-called "smooth" simulated magnetic field in the whole radial range 6 ÷ 29 cm.

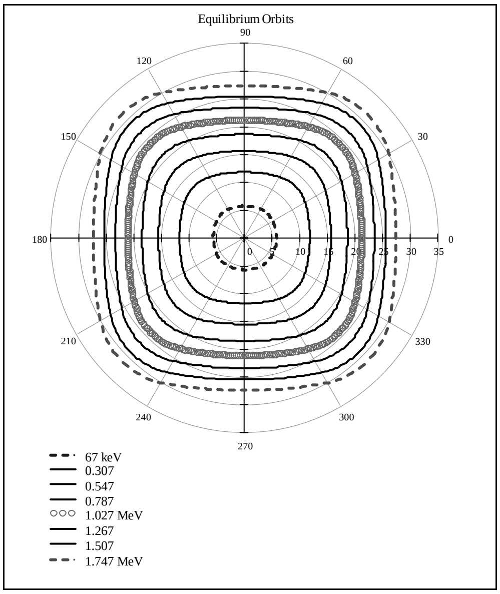

Figure 3: Closed Equilibrium orbits.

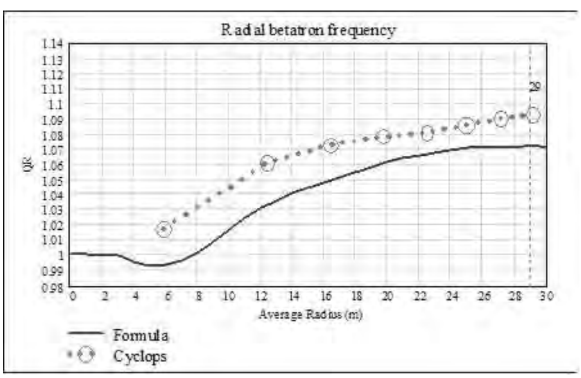

Figure 4: Radial betatron frequency.

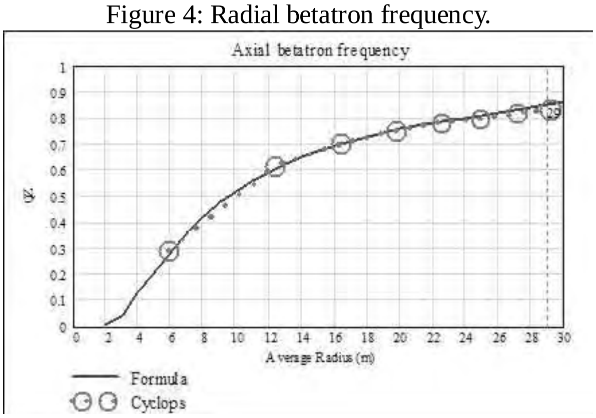

Figure 5: Axial betatron frequency.

The axial betatron frequency Q_z is equal to 0.3 at 1st EO and is greater than 0.5 at the rest of the acceleration range, which is close to the focusing condition of the separated sector magnet machine. No crossing of the dangerous resonances occurs during the acceleration. Orbital frequency differs from the reference value 9.7462 MHz no more than by ~ 15 kHz, which is quite sufficient for isochronous acceleration of the beam. The obtained result means that the average magnetic field is an isochronous one within the tolerance of ~ 1 mT.

BUNCHED BEAM ACCELERATION

Checking dynamical properties of the magnetic field at EOs is not sufficient for the full investigation. So, acceleration simulation was attempted. In Table 2 characteristic beam dimensions (2σ, i.e. 2 standard deviations of the particle distributions) are given.

The injected beam has rather arbitrary parameters defined by the emittance matching, since at that moment no information of the beam coming from inflector exit was available. No axial losses are visible with axial aperture of the cyclotron = 30mm (air gap between sectors).

The final beam parameters are also shown in Table 1. It is evident that the output beam quality does not completely meet the requirements formulated in Table 1, and some additional "gymnastics" with the beam should be performed either inside or after extraction outside cyclotron.

Table 1 Beam parameters.

Motion	Parameter	Initial	Final
Radial	Displacement (mm)	8	5
	Momentum spread (mrad)	50	16
	Emittance (π·mm·mrad)	100	
Axial	Displacement (mm)	4	4
	Momentum spread (mrad)	29	5
	Emittance (π·mm·mrad)	100	
Longitudinal	RF phase range (° RF)	14	4
	Energy spread (keV)	2	11

CONTINUOUS INJECTED BEAM

with the space-charge effects included was performed by new CBDA code, recently announced in [3].

The high-intensity beam self field leads to fattening of the beam, and under certain conditions (high particle volume density) would cause axial losses of ions, in particular at the low energy region. The particle-to-particle method with the field experienced by each macro-particle is the sum of the field of all other macro-particles at the position of the given macro-particle was used for the self-field calculations.

The initial beam emittance coming out of the inflector [4] was presented by the coordinates and velocity components and energy of the particles.

Calculation of the beam motion through the cyclotron is shown in Fig.6. The axial losses, which are ~66% of the total intensity, are marked by black color, radial losses of ~14% – by violet making in total ~80% of lost particles with only ~20% being accepted in the acceleration regime, which corresponds to ~6 mA under hypothetical CW injected beam of 30 mA.

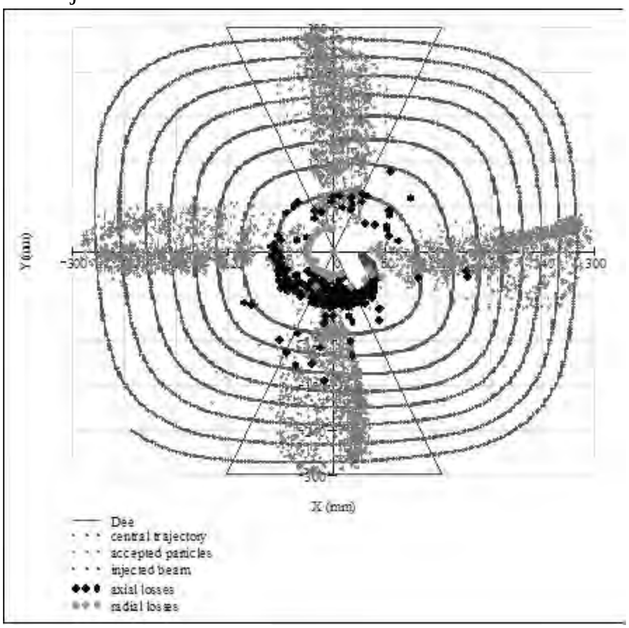

Figure 6: Continuous beam injection and acceleration.

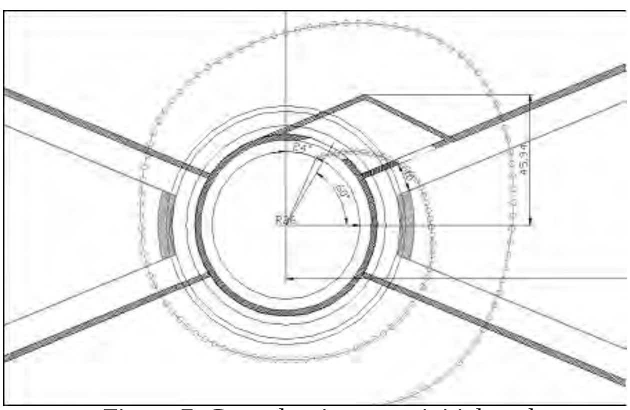

Figure 7: Central trajectory – initial study.

ELECTRICAL FIELD ANALYSIS

Acceleration field map in the central region of the cyclotron, shown in Fig. 2, was used in the orbit centering process when injecting the beam from the spiral inflector to the acceptance area of the 1st cyclotron orbits (Fig. 7).

Electrostatic field distributions in the ESD deflectors was simulated by the MERMAID 3D code and applied for the beam extraction process (see Fig. 8).

OUTPUT BEAM QUALITY

Rather large energy spread in the final beam is of primary concern. The remedy would be:

- Flat topping with longitudinal space charge compensation. But it looks complicated and not efficient in this energy range.
- Energy degrader at the exit. Factor of ~ 10 can be obtained in the energy spread improvement

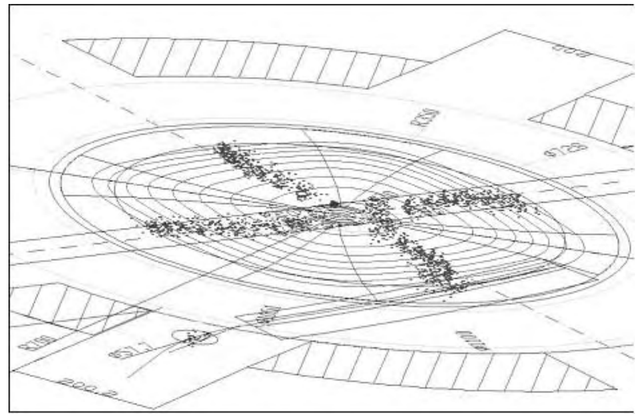

Figure 8: Extraction by ESD. 60 kV, aperture=21 mm.

- Debuncher at the extracted beam
- Cooling ring to inject the cyclotron beam in. it looks promising and presently is under investigation.

CONCLUSIONS

- Main parameters of the cyclotron related to the beam acceleration were selected.
- Dynamical properties of the magnetic and acceleration field, assessed at the equilibrium orbits and by simulation of the ion acceleration process, were found satisfactory.
- Preliminary estimation of the beam intensity at the final radius taking into account the space charge effects gave ~ 1.5 mA in the best quality case and ~ 5 mA otherwise.
- Initial analysis of the beam transport through the spiral inflector, central region and electrostatic deflector was performed.
- More scrutinized investigation of the beam dynamics with the space charge is presented elsewhere [5].

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