MULTI-CELL RF DEFLECTING SYSTEM FOR FORMATION OF HOLLOW HIGH ENERGY HEAVY ION BEAM*

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Abstract

Terra Watt Accumulator project (ITEP-TWAC) aims for accumulation of an intense ion beam, up to 10^{12} ppp and accelerated up to 0.7 GeV/u, in a storage ring for experiments on heavy ion beam-plasma interaction. For advanced experiments on high energy density physics the hollow cylindrical target is needed. A new method for RF rotation of the ion beam is applied for reliable formation of the hollow cylindrical beam. A principle of fast beam rotation by using a system of the multi-cell RF deflectors is considered in this paper. A four-cell H-mode deflecting cavity operating at the frequency of 297 MHz has been developed; similar 1.5 m long cavities being applied for both x- and y- directions. The shape of the deflecting electrodes has been optimized in order to provide the uniform deflection over the whole aperture taking into account both electric and magnetic components of the RF field. A deflecting system and a focusing quadrupole triplet applied to the beam with the energy of 450 MeV/u and normalized transverse emittance of 10*pi mrad*mm may form the quasi-hollow configuration with the inner radius up to 1.5 mm and thickness of 1 mm

INTRODUCTION

The 98% of visible matter exists predominantly either as hot dense plasma in the interior of stars or in stellar atmospheres, or as hot plasma of very low density in interstellar space [1]. The practical application of man made plasmas is very extensive and ranges from material modification to the future prospects of energy production in fusion plasmas. Nevertheless matter properties in high energy density state are not well investigated yet. Therefore, it is an interesting field with promising applications to astrophysics, plasma physics and material sciences. For high energy density states generation, traditional methods are based on dynamic shock compression. Chemical explosions, high current Z-pinches, high power lasers and in a few cases even nuclear explosions were used to expose matter to the Gbar regime. Consequently, the investigated sample undergoes a number of phase transitions during the experiment [2].

Intense heavy ion beams are an excellent tool to research the field of high energy density state in matter. Due to their unique way of interaction with matter, they open new pathways for high energy density state generation and it's diagnosing at the same time [3].

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ITEP-TWAC project aims for accumulation of an intense ion beam, up to 10^{12} ppp and accelerated up to 0.7 GeV/u in a storage ring for experiments on heavy ion beam-plasma interaction [1].

An intense ion beam can be efficiently used to achieve low-entropy compression of a piece of material like hydrogen or ice that is enclosed in a heavy cylindrical tamper shell. This experiment was called Laboratory Planetary Sciences (LAPLAS). A hollow beam with a ring shaped (annular) focal spot will drive such target. In this experiment, it will be possible to achieve physical conditions that exist in the interior of giant planets, Jupiter and Saturn. Another goal of the LAPLAS experiment is to study the problem of hydrogen metallization [4]. The main parameters of the heavy ion beam expected for LAPLAS experiments at future ITEP-TWAC facility are given by the Table 1.

Generation of a hollow high energy heavy ion beam is a standalone problem. One of the possible solution is to deflect a beam in horizontal and vertical directions by harmonic electromagnetic field as it is proposed in this paper. It was shown that if a deflection field frequency is about 300 MHz this beam could be treated as quasi-hollow [5, 6].

Table 1. The Main Parameters of the Heavy Ion Beam.

Reference ion species		$_{59}Co^{27+}$
Beam energy	AGeV	0.45
Particle number per pulse		$2*10^{12}$
Pulse length	ns	50
Effective x - emittance ($4*\beta\gamma*\varepsilon_{rms}$)	mm*mrad	8
Effective y - emittance ($4*\beta\gamma*\varepsilon_{rms}$)	mm*mrad	8
Phase space distribution		Gaussian

THE HOLLOW BEAM GENERAL PRINCIPLE FORMATION

The general layout of the deflecting system is shown on Fig. 1. A beam goes through two pairs of deflecting plates where the RF voltage applied. A beam gets a horizontal deflection at the first pair of plates and vertical at the second. As it is well known, the deflecting field should have a 90 degrees phase incursion between pairs of plates in order to make a circle beam.

The most effective interaction between RF deflecting field and beam can be achieved if a beam's time-of-flight thought one deflecting plates pair doesn't exceed a half of the RF period $D=\beta_z c/2f$, where β_z – is a normalized longitudinal speed, c – speed of light and f – field frequency. Otherwise, the transverse electric field changes the direction between plates.

Beam dynamics simulation has shown that such deflection system with electric deflecting field amplitude of 10 MV/m and field frequency of 297 MHz may deflect a $_{59}Co^{27+}$ beam with energy 450 MeV/u for maximum 1.4 mrad.

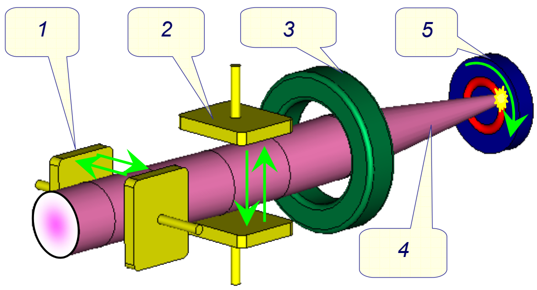

Figure 1: The general layout of the deflecting system.
1 – x-deflector, 2 – y-deflector, 3 – focusing system, 4 – ion beam, 5 – target.

It is not enough for required quasi-hollow beam formation because of space limitation at experimental beamline.

THE RESONANT DEFLECTION PRINCIPLE

In order to overcome the limitations for high energy beam deflection, a principle of resonant interaction of the beam with multi-cell RF structure may be applied.

Every cell must be as long as $D=\beta\lambda/2$, where β is the normalized particle velocity and λ is the RF wavelength as Fig. 2 shows.

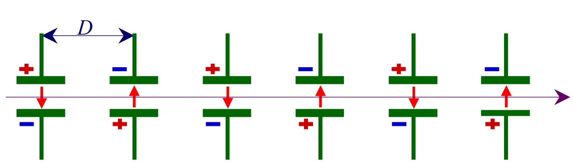

Figure 2: Multi-cell radio frequency structure.

If resonant condition is fulfilled, any particle crosses the cell centers at the constant phase of RF field, regularly increasing the transverse momentum dependently on the phase value.

Therefore, particle deflection $\Delta\alpha$ may grow with the length L as the next formula shows:

$$\Delta\alpha(rad) = \frac{eZ \cdot E_{ef}}{m_o c^2} \cdot \frac{\sqrt{1-\beta^2}}{\beta^2} \cdot L, \qquad (1)$$

where eZ, m_o are the charge and the rest mass of the ion, respectively; β is the normalized particle velocity; L is a deflecting cavity's length; E_{ef} is the effective deflecting field, which can be found by integration of the transverse field component E_y:

$$E_{ef} = \frac{1}{D} \cdot \int_0^D E_y(z) \cdot \sin\left(\frac{\pi}{D} \cdot z\right) \cdot dz \qquad (2)$$

This value may be interpreted as a main travelling wave harmonic of the transverse electric field, continuously interacting with the particles.

RADIO FREQUENCY DEFLECTING CAVITY

According to a scheme of the multi-cell RF deflection, a transverse electric component of the electromagnetic field should be dominant in the real deflecting cavity, being periodically varied along the longitudinal axis. In practice, the H_{11n} oscillating mode in the cylindrical cavity seems to be closest to the desired field distribution. Here n is the number of field variations along the full cavity length. The additional electrodes are needed for capacitive and inductive extra-load, reducing phase velocity to the speed of particles because of the spatial harmonic's phase velocity in the "flat" waveguide is always larger than the speed of light. Fig.3 shows a general view of the four-cell deflecting cavity designed for the operating frequency of 297 MHz. The deflecting plates are installed on the massive stems, whose thickness is chosen from the mechanical stability and RF losses optimization viewpoint.

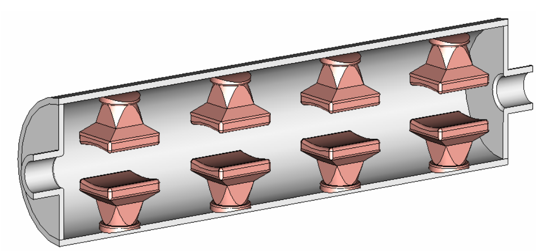

Figure 3: The general view of the four-cell deflecting cavity.

The plates themselves have to form a desired field configuration in the beam channel, avoiding capacitive overloading.

The electric field is concentrated between the plates while the magnetic lines surround the stems. Since the electric field direction at the adjacent cells is always opposite, π-mode may be identified as an operating for this cavity. The electromagnetic field structure enables to split a cavity into elementary deflecting cells with one deflecting plate's pair. Operating frequency does not depend on the number of the cells, allowing the flexible design of the deflecting cavity including arbitrary number of identical modules.

Besides the electric field, the magnetic component influences to the transverse particle motion as well. Since the magnetic and electric fields are shifted by 90 degrees in phase, magnetic field efficiently acts at the entrance and exit of every cell, where the electric amplitude is small. One can find that the magnetic influence is always opposite and reduces the main electric deflection, being typically about 10% of the total effect as the numerical simulations show. This value may be neglected at the preliminary stage of structure analysis, but should be taken into account during the final simulations.

The non-uniformity of particle deflection across the beam may result emittance growth and considerable distortions of beam portrait at the target. Since the amplitudes of both electric and magnetic components depend on the transverse position, this effect can not be completely avoided. In order to define the difference in deflection over the beam's cross-section, the dimensionless value δα is introduced:

$$\delta\alpha(x,y)=\frac{\alpha(x,y)-\alpha_0}{\alpha_0}, \tag{4}$$

where

$$\alpha(x,y)=\frac{eZ}{m_o c^2}\cdot\frac{\sqrt{1-\beta^2}}{\beta^2}\cdot\int_0^D E_y(x,y,z)\cdot\sin\left(\frac{\pi}{D}z\right)dz - \int_0^D \beta c\cdot B_x(x,y,z)\cdot\cos\left(\frac{\pi}{D}z\right)dz \tag{5}$$

is the deflecting angle, numerically calculated in the realistic electromagnetic field assuming the constant transverse position of the particle, $\alpha_0 = \alpha(0, 0)$. A non-uniformity of the certain RF deflecting cell is defined as a maximum value of $\delta\alpha(x, y)$ over the beam's cross-section.

A proposed shape of the deflecting plates shown at Fig.4 have been investigated and optimized. The saddle-shaped configuration gives the uniformity over the beam's cross-section not worse then 2.5%.

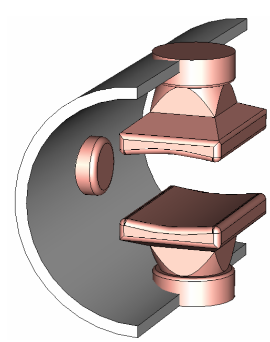

Figure 4: A proposed shape of the deflecting plates.

Main calculated parameters of the deflector cell are given in the Table 2. The prototype deflecting cell was constructed and manufactured (Fig. 5).

Table 2. The Main Parameters of the Deflector Cell.

Parameter	Unit	Value
Cell length	mm	368
Tank diameter	mm	342
Plate length	mm	170
Plate width	mm	140
Plate height	mm	121
Field frequency, MHz	MHz	297

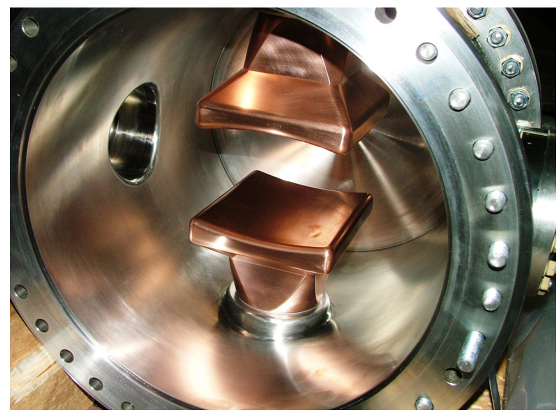

Figure 5: The prototype deflecting cell.

CONCLUSION

An original deflecting system for the hollow high energy beam formation was proposed. The deflecting RF cavity based on the H_{114} oscillating mode has been developed. The proposed deflecting plates shape has been investigated and optimized. The deflection uniformity is better then 2.5% over the beam's cross-section. The prototype of the deflecting cell was constructed and manufactured.

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