CUSTOMS CYCLOTRON AND BEAM DELIVERY SYSTEM

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Abstract

A source of 1.75 MeV protons was designed for detection of explosives using the gamma ray resonant absorption technique [1]. The facility consists of a compact cyclotron, a beam delivery system (BDS) and a storage ring. Given the marginal request for the beam intensity and quality, H^- ions were selected for acceleration in the cyclotron aiming at the high efficiency extraction by electrostatic deflector. The tracking calculations in the cyclotron were performed with the beam space charge effects taken into account [2]. The parameter selection of the BDS structure elements by the TRACE3D code [3] was performed. Dispersion control at the injection point to the ring was provided by insertion of dedicated structure elements in the injection channel. The set of the optical elements is wide enough to regulate the beam parameters at the target point (beta functions and dispersion) to cope with expected experimental uncertainties in the settings of the cyclotron and storage ring. The overall performance of the facility was optimized by adjusting the corresponding parameters of the cyclotron and the BDS in order to provide a necessary intensity and quality of the beam for injection to the storage ring.

INTRODUCTION

Figure 1 shows the facility structure layout, including the cyclotron, the transport line and the storage ring.

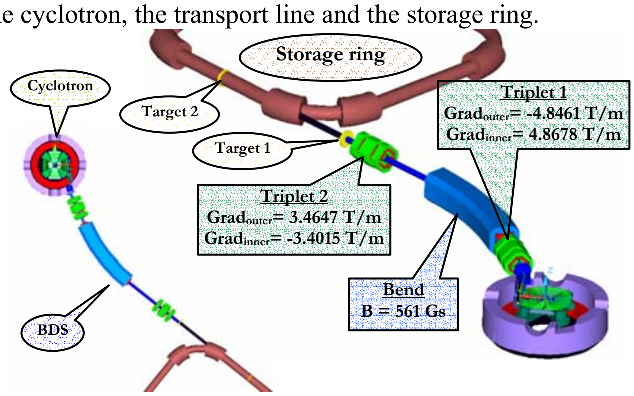

Figure 1: General view of the facility.

The complex was designed in collaboration with the Budker Institute of Nuclear Physics (BINP, Novosibirsk) [4]. The details of the Customs Cyclotron description are given in ref. [5]. H^- ions ejected from the cyclotron hit target 1 ($H^- \rightarrow H^0$) and, subsequently, target 2 ($H^0 \rightarrow H^+$). The dispersion function at target 2 should be controlled to provide the proper correlation between the particle momentum and horizontal position needed for the injection procedure. To this end the BDS should contain bending magnets or some optical elements with dispersion. As a result of the calculations, two triplets and a bending magnet configuration were selected as satisfying the majority of the requirements summarized in Table 2.

CYCLOTRON

Figure 2 shows the cyclotron structure, namely, the acceleration system (Dee), the magnet, the internal ion source (IS), the diaphragm set and the extracting system (two electrostatic deflectors - ESDs and the magnetic channel -MC).

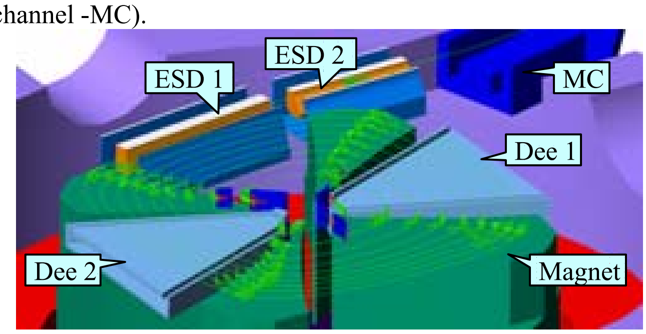

Figure 2: Cyclotron structure.

Calculation of the spatial (3D) distribution of the magnetic and electric fields for the cyclotron was made with the TOSCA and Mermaid codes. The maximum voltage on the Dee is 55 kV, ion the orbital frequency is 9.76 MHz, the acceleration RF harmonic number is 4. The maximum current from the IS for the dee voltage 55 kV is 2.35mA. The IS body has a rectangular spot measuring 0.6x4 mm^2. The intensity of the bunch injected from the ion source obeys the $I=A \cdot U^{3/2}$ law with A=const, U the dee voltage, and I the extracted current. The initial energy of the particles is 0.1 keV and angular size of the bunch is 0 mrad. The extracting system has the following parameters: ESD-1: E=28.6 kV/cm Grad=–3.7 kV/cm^2; ESD-2: E=28.6 kV/cm, Grad=–14.8 kV/cm^2; MC: B=0.45T, Grad=0 T/m. In Fig.3 accelerated particles are shown by green color, and lost particles on the structure elements by red color. Particle loss in the central region is about 85%, and in the extracting system less than 1%. The diaphragm position was selected such that only particles with RF phases from -8° to 8° are captured into the acceleration. The space charge effect was estimated by the particle-to-particle (PP, 3,000 macro-particles) method and the particle-in-cell (PIC, 20,000 macro-particles) method. The projections of the emittance of the extracted bunch at the entrance of the BDS are given in Fig.3.

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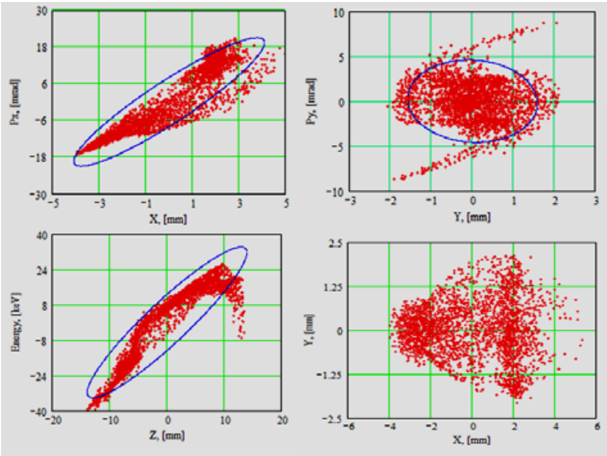

Figure 3: Effective emittance of the beam at the BDS entrance, 260 μA beam intensity.

BEAM DELIVERY SYSTEM

Estimation of the BDS parameters requires knowledge of the energy dispersion function D and its derivative along the beam central trajectory D' at the exit of the cyclotron since the cyclotron itself (due to the dipole component of the magnetic field) can be considered as a dispersive element, sitting upstream of the BDS. To define those parameters, the dependence of the particle energy in the output beam on its transverse horizontal displacement from the central trajectory X (Fig. 4) was calculated at two successive points along the trajectory.

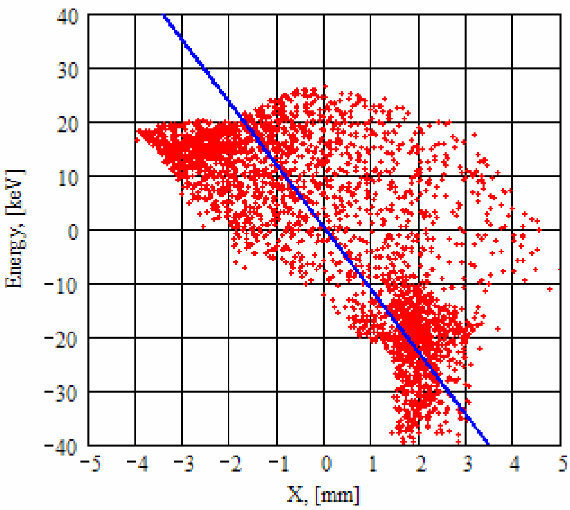

Figure 4: Dispersion estimation, 260 μA beam intensity.

The slope of the distributions permits one to define the corresponding values D = 15.3 cm and D' = 1.01. The parameters found can be used to assess the so called uncorrelated horizontal output emittance by subtracting from the effective emittance the effect of the dispersion function on the particle displacement and transverse momentum. The results obtained at the BDS entrance, showing the impact of the space charge on the beam quality, are summarized in Table 1. The results were used for particle tracing through the BDS to the injection point in the cooling ring.

Table 1: Beam characteristics at the BDS entrance

Intensity, μA	**100**	**260**
Effective horizontal emittance, π•mm•mrad	24.2	33
Uncorrelated horizontal emittance, π•mm•mrad	3.1	4.9
Energy dispersion function, cm	14.3	15.3
Energy spread, keV	31	34
Axial emittance, π•mm•mrad	3.2	7.2
Longitudinal emittance, π•mm•keV	155	177

The well-known code TRACE3D [3] with the particle space charge (SC) effects included was used for calculation of the beam delivery system (BDS, Fig. 5) part upstream target 1 (stripping $H^{-} \rightarrow H^{0}$).

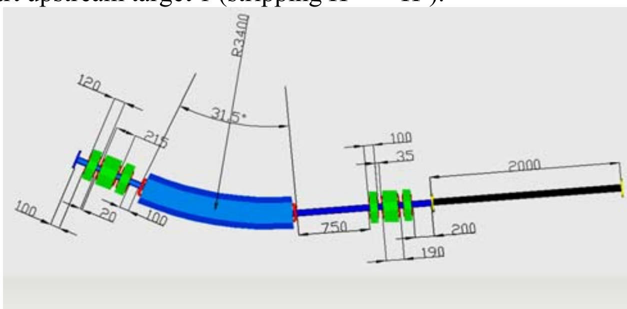

Figure 5: BDS layout.

Obviously, the SC effects were switched off in the simulation after the target 1: it is assumed that there is no charged particle in the beam downstream this target. The particle tracing in the structure selected by TRACE3D calculation was performed, using the information on the output beam from the cyclotron. A beam simulation taking into account the space charge effects was conducted by the home-made CBDA code [2]. Space charge effects were estimated using the PIC approach with 20,000 micro-particles, presenting the bunched beam. The spatial (3D) magnetic field for the simplified design of the structure elements with their effective length, defined by TRACE3D, was calculated and put into CBDA code for tracing. The BDS parameters were adjusted when appropriate to take into account the calculated quality and intensity of the beam from the cyclotron, space charge effects and ~50 % efficiency of the target 1 ($H^{-} \rightarrow H^{0}$). Thus, the cyclotron output beam intensities of 100 μA and 260 μA, mentioned above, correspond to 50 μA and 130 μA downstream the target_1. The simulation results (Fig. 6) were analysed similar to what was done at the exit of the cyclotron. The results are given in Table 2. It can be seen that the necessary dispersion of the beam on energy was produced in the injection channel as to eliminate a mismatch between the injection parameters and the beam, i.e. beam widening in the ring [4]. The improved qualities of the injected beam as compared to the previous case [2] permits a substantial (by a factor of 4, up to ~ 40%) increase in the intensity of the particles captured into the ring [4].

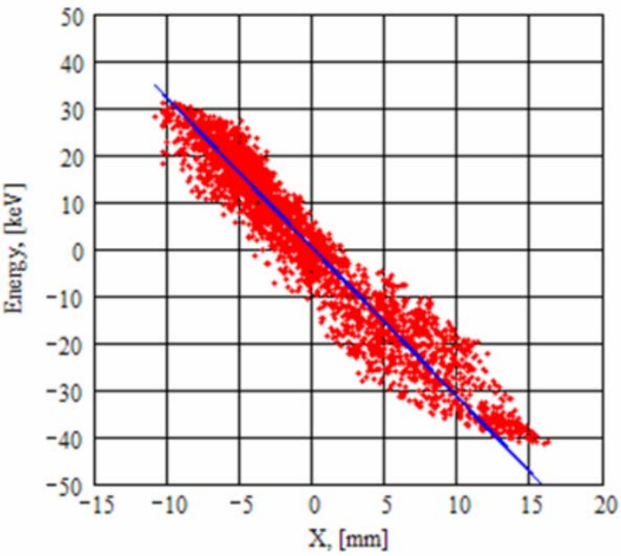

Figure 6: Dispersion estimation at injection point, 130 μA beam intensity.

Table 2: Cooling ring position, target-2 ($H^0 \to H^+$)

Motion	Parameter	Simulation	Required
	Intensity (μA)	~130	100÷300
Radial (uncorrelated emittance)	Displacement, 2σ (mm)	± 3.4	±2.5
	Momentum spread, 2σ (mrad)	± 3.5	± 3
	The tilt of the phase ellipse, α	0.4	≈ 0
	Emittance (π·mm·mrad)	11.1	7.5
Vertical	Displacement, 2σ (mm)	± 5	± 2.5
	Momentum spread, 2σ (mrad)	± 5.6	
	The tilt of the phase ellipse, α	2	≈ 0
	Emittance (π·mm·mrad)	12	7.5
Longitudinal	Particle Energy (keV)	1768 (*)	1747
	Energy spread, 2σ (keV)	± 38	± 30
Energy dispersion function	D (cm)	56	58
	D’	–0.005	0

(*) – Fine energy adjustment to the required 1747 keV could be obtained by a small variation of the dee voltage.

CONCLUSIONS

- The beam characteristics at the ring injection point are close to the required ones. The parameters of the injection allows ~ 0.1 A of the proton current to be stored according to the numerical simulation. This value is enough to conduct the experiments with the beam obtained [4].
- The beam space charge effects at the intensities considered are important for the beam dynamics in the cyclotron, but have less impact on the horizontal motion in the BDS. Nevertheless, the vertical emittance of the beam passing through the BDS noticeably increases at target – 2 due to these effects.
- The injection channel possesses a set of optical elements wide enough to regulate the beam parameters at the target point (beta functions and dispersion) to cope with expected experimental uncertainties in the settings of the cyclotron and storage ring.
- Ion tracing by the CBDA code fully confirmed the BDS parameter estimation by TRACE3D, including the space charge effects in the beam.
- To further increase the output beam intensity keeping beam quality intact or better than the already obtained in the simulations, the ***external particle injection*** into the cyclotron should be revisited again at the present rather moderate intensities. Some preliminary calculations have been conducted already.

ACKNOWLEDGEMENTS

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