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CYCLOTRON C235-V3 FOR DIMITROVGRAD HOSPITAL CENTER OF THE PROTON THERAPY

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Abstract

JINR-IBA C235-V3 isochronous cyclotron for 1st Russian hospital center of the proton therapy has been assembled and tested. Shimming of the magnetic field, optimization of the acceleration modes and testing with the extracted proton beam were done in frame of this work.

The paper presents experimental results of the beam dynamics in the accelerator. Proton transmission from radius 30cm to 103cm is 72% without beam cutting diaphragms. The extraction efficiency is 62%.

This cyclotron is a substantially modified version C235-V3 of the IBA C235 serial cyclotron. C235-V3 has the improved extraction system which was constructed and tested. This system allows raise the extraction efficiency up to 77% from 50% in comparison with serial C235.

Special mapping system (for B_r-component) of the magnetic field was developed and constructed by JINR for the shimming of the B_r-field in the middle plane of the cyclotron.

Total efficiency of the machine is 45%. Further improvement of the parameters expected after final tuning of the cyclotron in Dimitrovgrad.

PROTON THERAPY AT JINR

Dubna is one of the leading proton therapy research centers in Russia [1-2]. The JINR Phasotron with the proton energy of 660 MeV has been used for medical applications since 1967. The modern technique of 3D conformal proton radiotherapy was first effectuated in Russia at this center, and now it is effectively used in regular treatment sessions [1-2]. The irradiated dose distribution in 3D conformal proton therapy coincides with the tumor target shape with an accuracy of 1 mm. About 100 patients undergo a course of fractionated treatment here every year. About 880 patients were treated by proton beams during the last 12 years. Using of the accelerators intended for the fundamental researches is not lucrative. Thus a number of special machines were developed by industrial companies over the world.

C235-V3 PROTON CYCLOTRON

Federal Medico-Biological Agency in collaboration with JINR developed the Dimitrovgrad project of the first hospital proton center in Russia. The JINR-IBA collaboration has developed and constructed the C235-V3 proton cyclotron for this center.

C235-V3 has modified extraction system [3-4]. Basing on results of complete study of the beam dynamics in C235 geometry of the electrostatic deflector was optimized. The new extraction system was constructed and tested at the IBA C235 cyclotron for Orsay (France). The experimentally measured extraction efficiency was improved from 50% for the old system to 77% for the new one (Fig. 1). Up to the moment such an extraction system used in more than ten C235 machines.

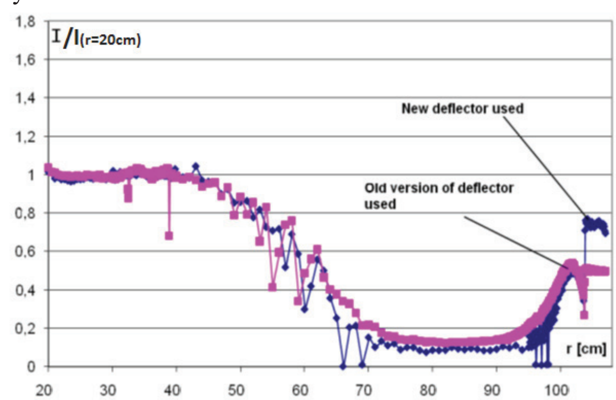

Figure 1: Circulating and extracted beam current in C235 cyclotron with old and new version of deflector.

CYCLOTRON ASSEMBY AND MAGNETIC FIELD MEASUREMENTS

The assembling of the machine started in June 2011 at JINR. A special engineering center (Fig. 2) was created at JINR for testing of the medical accelerators.

Figure 2: JINR engineering centre for the assembling and testing of the medical accelerators and equipment.

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The magnetic measurements and shimming of the cyclotron magnetic field was done. The axial magnetic field mapping is based on the Hall probe technique. The special platform was designed for fabrication of all sector edges simultaneously. The accuracy of the mechanical fabrication of the sector edge surface modification is about ±20 µm. Precision geometrical measurements of the sector edges at the shimming of the magnetic field are produced by the Eclipse 3D Carl Zeiss machine. The new JINR calibration magnet applied for magnetic field up to 2.9T was implemented in the scheme of the magnetic measurements. Estimated RF-phase motion in the final magnetic field map (see Fig. 3) in the limits ±15°RF [5].

The new equipment [6] with the search coils for measurements of the average radial component $<B_r>$ of the magnetic field and for correction of the magnetic field median plane in the C235-V3 cyclotron was developed and tested at JINR.

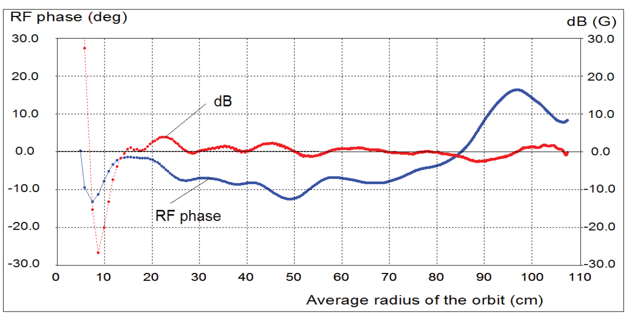

Figure 3: Difference between formed and isochronous field and integrated RF-phase shift.

The $<B_r>$ in the middle plane $z=0$ of the machine leads to vertical beam offset. This is critical for C235 cyclotrons due to small vertical gap (9mm) of the magnetic system at the extraction radii.

The $<B_r>$ measurements are based on integration of the signal from the coil during its movement in vertical direction near median plane. The measurement coil of the specified radius is moving in vertical direction from–Δz to +Δz (from median plane of cyclotron). During this motion the coil covers the cylindrical surface. The radial component magnetic flux change at this surface induces the voltage in the measurement coil and can be integrated by electronic equipment.

C235-V3 BEAM TESTS

Magnetic measurements and shimming of the magnetic field finished at mid-2012. After full assembly of the all cyclotron systems tests with the circulating and extracted proton beam were performed.

The machine was finally isochronized (Fig. 4), operating RF-frequency is 106.270 MHz, I_{mc}=760.7 A.

Calculated beam RF-phase motion (Fig. 5) based on Smith & Garren data (Fig. 4) confirms that there would not be remarkable phase beam losses during the acceleration in final configuration of the magnetic system.

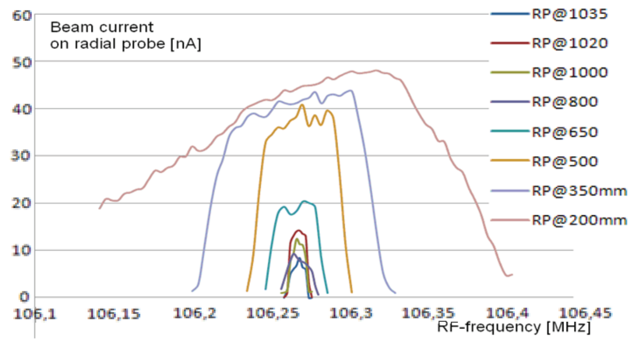

Figure 4: Smith & Garren curves at final configuration of the central geometry of the magnetic system.

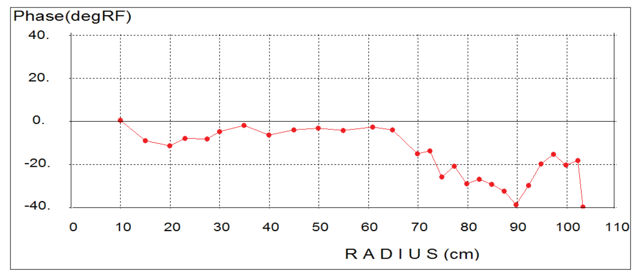

Figure 5: RF phase of the beam obtained after S&G calculations for I_{mc}=760.7 A, f=106.270 MHz.

Smith & Garren procedure gives the phase slip relatively first point examined. If we shift first point to 30-40ºRF which corresponds to maximal axial focusing due to RF field, then the beam RF phase at final radii will be close to 0ºRF.

Cyclotron tested in Dubna had Q_z–drop down to 0.04 at radii of 10cm – the lowest value of IBA previous C235 machines (Fig. 6).

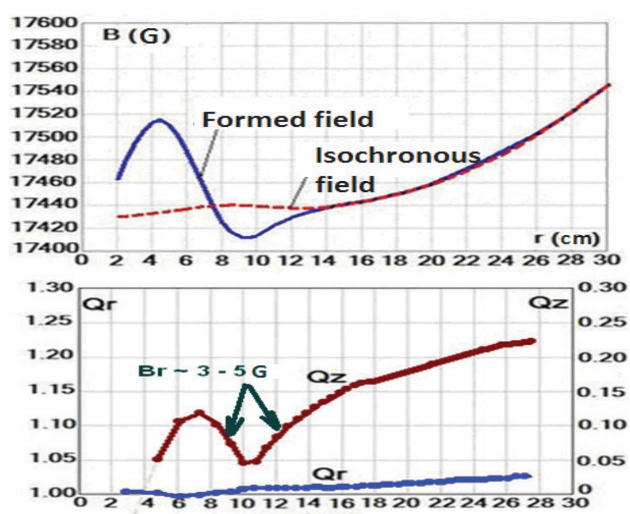

Figure 6: Formed and isochronous magnetic field in the cyclotron center (upper), frequencies of betatron oscillations (lower).

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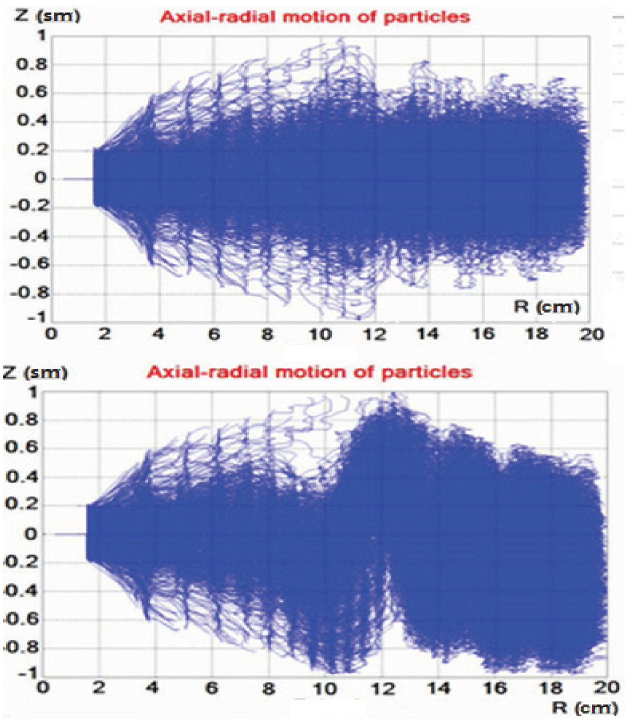

Figure 7: Vertical beam motion profile in the cyclotron centre: no B_r in the median plane (upper), B_r ~ 5G with gradient ~5G/cm at the r~10cm (lower).

This was cause to weak beam vertical focusing at this region. In case of presence of magnetic field imperfections in terms $\langle B_r \rangle$ in the median plane weak focusing leads to increased amplitude of the beam vertical motion. This is a consequence of transformation of coherent beam vertical motion into increased incoherent particles amplitudes (Fig. 7).

Finally, after accelerating through the region with low Q_z beam can essentially increase its vertical size (Fig. 7).

Correction of the vertical tune was done by shimming of the magnetic field at radii of ~10cm. Eight shims were installed symmetrically near upper and lower central plugs.

After correction of the Q_z–drop at r~10cm by increasing average magnetic field at these radii beam essentially decreased its vertical size (Fig. 8) due to more strong vertical focusing and reduced system sensitivity to a presence of the $\langle B_r \rangle$ component at this place.

Transmission from r=30cm to r=103cm is 72%. Then circulating beam was extracted by the electrostatic deflector (60kV voltage, 3mm deflector gap). Extraction efficiency is 62%. Thus, the total efficiency of C235-V3 is 45%.

Further optimization [3-4] of C235-V3 proposed by JINR is the modification of the sector spiral angle at R>80 cm which will provide larger vertical betatron tune Q_z and reduce the coherent beam losses at acceleration. The coherent beam displacement Δz from the median plane is defined by the vertical betatron tune: $\Delta z \sim Q_z^{-2}$.

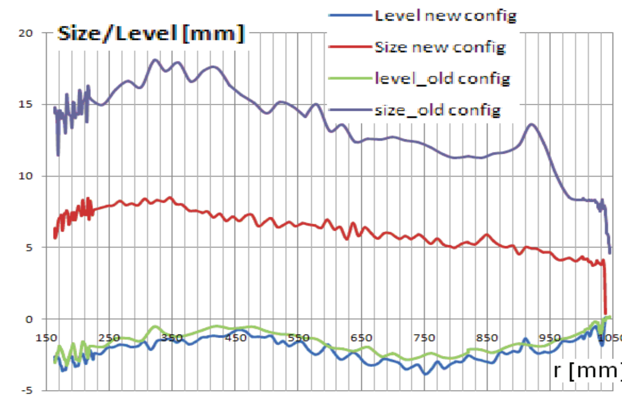

Figure 8: Parameters of the beam before and after correction of Q_z-drop at 100mm.

At Q_z~0.2 the vertical coherent beam displacement is 2.5 mm in presence of the magnetic field radial component B_r~2G, and having free axial oscillation amplitude of 2-3 mm in the proton beam it can cause significant beam losses due to a small sector gap (9mm) in the C235. An increase of Q_z from ~0.2 to ~0.4 permits to decrease the coherent beam displacement by a factor of 4 and to reduce the proton losses at acceleration.

CONCLUSIONS

C235-V3 version of serial C235 IBA cyclotron was developed by JINR-IBA collaboration. C235-V3 has the improved extraction system. It allows raise the extraction efficiency up to 80% from 50% in comparison with serial C235.

C235-V3 (for Dimitrovgrad) tests with accelerated and extracted beam were performed in JINR. Transmission from r=30cm to r=103cm is 72% without beam cutting diaphragms. Extraction efficiency is 62%. Total efficiency of the machine is 45%.

Proposal for further optimization of C235-V3 magnetic system was formulated. It concerned to increase the Qz from 0.2 to 0.4 at the extraction radii which can lead to decreasing of possible losses during the acceleration.

With increased intensity of the extracted beam C235-V3 has advantages in treating of large-volume tumors using pencil scanning.

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