# AXIAL INJECTION TO A COMPACT CYCLOTRON WITH HIGH MAGNETIC FIELD

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*Abstract*

One of advantages of a compact cyclotron over other type accelerators is a small size mainly defined by the facility's bending magnetic field. In such cyclotrons an application of an external injection is required in some cases. But for high magnetic field of the cyclotrons (over 4-5 T) there appears a severe problem to make the 1st turns in the machine with external injection of accelerated particles. This paper describes a proposal of a new central region structure of a compact cyclotron that permits one to successfully solve the problem of the axial injection into such a facility using a spiral inflector.

## INTRODUCTION

To reach the smallest accelerator size, application of an as high as possible magnetic field of the machine is required. In the compact cyclotron with high magnetic field its magnitude is mainly limited by the minimal focusing available. Thus, in sector structures with large spiral angles of 60-70 degrees and maximal possible deep valleys the practically reachable limit for the central field would be 4-5 T. In a cyclotron with external ion source the particle injection in the accelerator central region is one of the main problems. A design of the cyclotron central region is a key moment for such accelerators. An application of a conventional spiral inflector [1] leads to substantial particle losses on the first turns in the magnetic field.

A possible way to increase the particle transmission through the central region is the application of a higher dee voltage and increasing the number of the dees [2]. Such approach contradicts the main requirement to the modern compact accelerators – the minimum power consumption at their use. Application of higher particle injection energy also can help in solving the problem [3]. But the modern ion sources have restrictions on the maximal possible particle energy at the level of 25-30 keV for the singly charged ions. Besides, at high energies the inflector voltage also should be higher that essentially complicates development of the machine. Miniaturization of the central region structure [4] can also be a solution. This approach in the spiral inflector with minimum size implies very complicated structure of the cyclotron center.

In this report the authors propose a very different approach to the cyclotron central region configuration. In the suggested structure the trajectories of the injected particles on the first turns in the magnetic field and RF are axially separated from the inflector external surfaces [5].

## CENTRAL REGION STRUCTURE

The particle trajectory curvature in the high magnetic field is smaller than the spiral inflector external dimensions. Therefore, the injected particles get lost on the inflector case during their initial turn. To prevent those particle losses it is proposed to inject them under some angle with the accelerator median plane at the inflector exit. Such particles make the first turns with some offset to the median plane excluding in this way their collision with the inflector outside surface. The further consideration deals with some hypothetic compact cyclotron having the central magnetic field of 4.5 T. Simulations were performed by the SNOP program of particle tracing [6] in three-dimensional fields of the main magnet, the spiral inflector and the accelerating dees calculated in the Tosca\Opera3D program. As a test particle $H^-$ ion injected from axial line with energy 25 keV was used.

As mentioned above in the proposed method the particle trajectory radius on the first turn should not be larger than the effective inflector half-size. To provide required inclination of the particle trajectory to the median plane at the inflector exit, inflector electrodes should be cut off at its exit by some small angle defined by calculations. In our case 20 degrees was chosen to cut (Fig. 1).

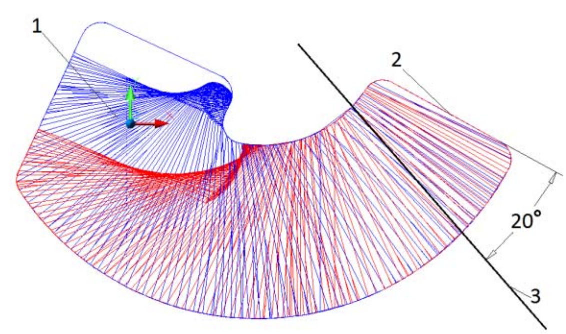


Figure 1: Spiral inflector cut: 1 – inflector entrance, 2 – inflector exit, 3 – cutting plane.

In this case the particle trajectory makes ~ 6 degree angle with the median plane, and the radius of curvature of the particle trajectory is 5.5 mm. Due to axial separation of the particle trajectory with the inflector they do not intersect despite larger effective radius of the inflector of 9 mm. To minimize the axial size of the inflector case the lower electrode is set at ground potential and connected electrically to the inflector case. The upper electrode is under the potential of +10 kV (Fig. 2).

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Calculations show that 3.7 mm axial shift of the inflector from the median plane is necessary to provide sufficiently small amplitude of the axial oscillations of particles on the first turns.

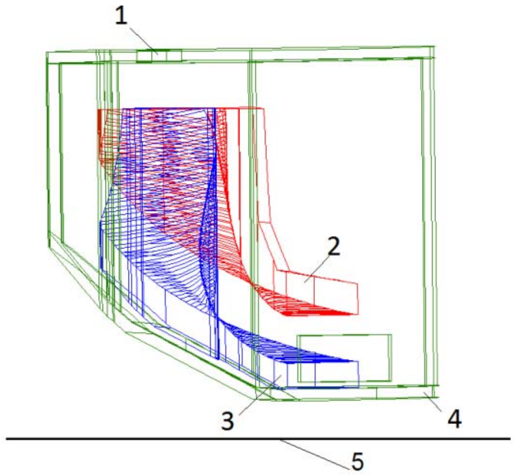


Figure 2: Inflector structure: 1 – inflector entrance, 2 – upper electrode, 3 – lower electrode, 4 – inflector RF shield, 5 – median plane.

Particle motion simulation using three-dimensional distribution of the electric field of one 180 degree dee confirmed stability of the axial oscillations of particles. The proposed method of the cyclotron central region construction allows application of rather small dee voltage. In our case 30 kV voltage with dee to dummy dee gap of 2.5 mm was chosen.

The structure of dee tip was chosen, such as to provide maximal electric focusing of particles on initial turns. The positive RF phase was provided when crossing with particles of the accelerating gaps, creating thereby conditions for quickly damped oscillations about the median plane. The calculations above showed that despite increasing an axial aperture of the dee structure required in the method, it is possible to create a central region with stable axial oscillations of the particles with their further capture in the acceleration process (Fig. 3, 4).

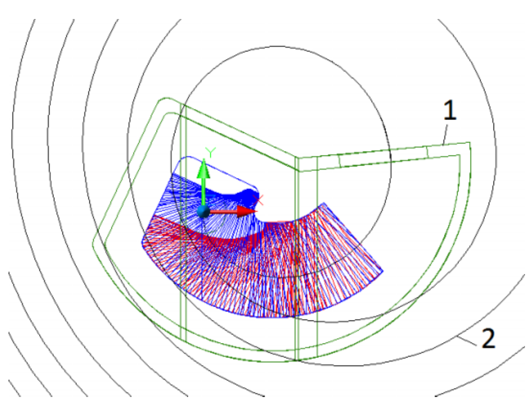


Figure 3: Particle trajectory in the central region: 1 – inflector RF shield, 2 – particle trajectory, 3 – dee, 4 – dummy dee.

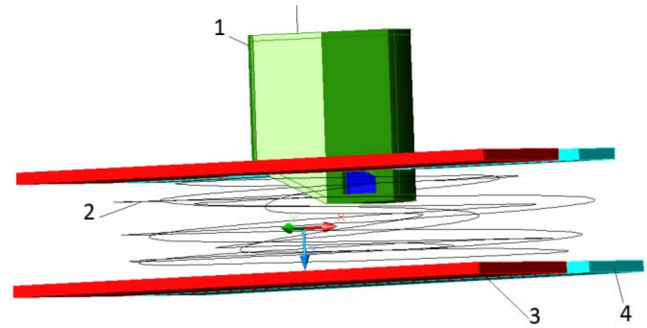


Figure 4: Central region structure: 1 – inflector RF shield, 2 – particle trajectory, 3 – dee, 4 – dummy dee.

## CONCLUSION

In this study a new structure of the central region of the compact cyclotron that allows us to solve a basic problem of cyclotron physics – axial injection from the external ion source in the cyclotron with a high magnetic field – was proposed. The new method of particle injection is based on innovative idea of axial separation of a trajectory of the injected particles with the inflector geometry. The described structure is rather simple in realization and doesn't demand a high dee and inflector voltages. The proposed injection can be applied in the design of accelerators with external injection and the highest magnetic field, like those described in reference [2].

## REFERENCES

[1] J. L. Belmont and J. L. Pabot, IEEE Trans. Nucl. Sci. NS-13, 191 (1966).

[2] D. Campo, L. Calabretta, M. Maggiore, L.A.C. Piazza, “Beam injection and extraction of SCENT300, a superconducting cyclotron for hadrontherapy”, Proc. of EPAC08, Genoa, Italy.

[3] V. S. PANDIT, “Study on using high injection voltage and spiral inflector in the central region of VEC”, PRAMANA journal of physics, Indian Academy of Sciences, Vol. 59, No. 6, pp. 1019-1024, 2002.

[4] A. Garonna, “Cyclotron designs for ion beam therapy with cyclinacs”, PhD Thesis, Ecole Polytechnique Federale de Lausanne, 2011.

[5] V.L. Smirnov and S.B. Vorozhtsov, “Axial injection to a compact cyclotron with an ultrahigh magnetic field”. Patent application RU 2014103854, 04.02.2014.

[6] V.L. Smirnov and S.B. Vorozhtsov, “SNOP – Beam Dynamics Analysis Code for Compact Cyclotrons”. Proc. of RuPAC’12, September 24 - 28, 2012, St. Petersburg, Russia.



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