

# IBA Superconducting Synchrocyclotron for Proton Therapy: Central Region Design

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## Introduction

The first IBA superconducting synchrocyclotron (S2C2) is being developed in response to the market need for a more compact and lower cost proton therapy product. The S2C2 is a 230 MeV machine, of diameter 2.5 m and an extracted beam current of 20 nA. The magnet has a rotationally symmetric pole and a maximum magnetic field of 5.7 T supplied by superconducting coils. The central region is of crucial importance to the optical quality of the beam and so accurate design is mandatory. The IBA design has been developed in collaboration with the subcontractor AIMA Developpement. This poster describes the results of particle tracking calculations made with IBA tools on the central region design.

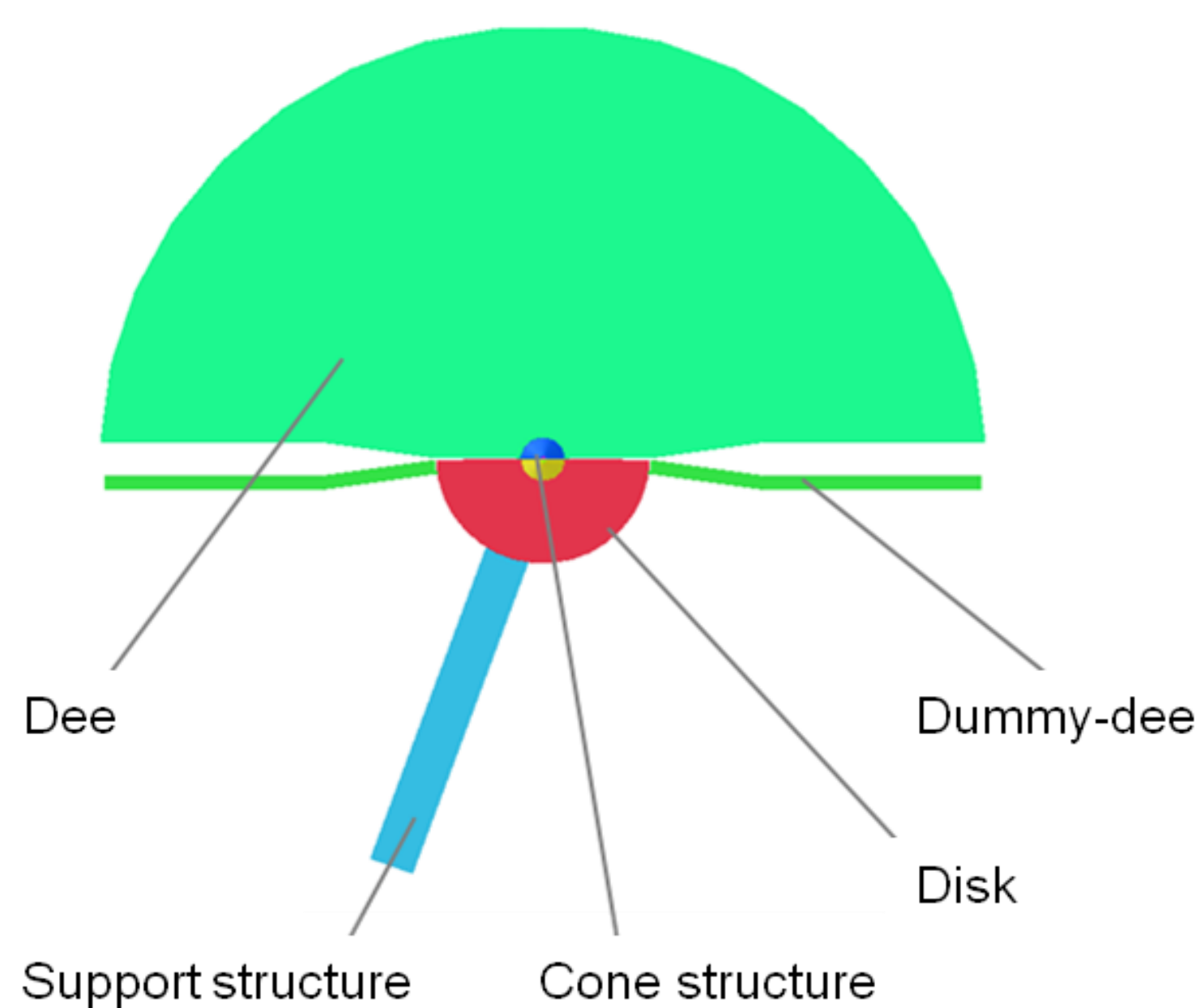
## Central Region Design

The S2C2 central region has been designed with a single dee of maximum AC voltage approximately 10 kV and a dummy dee at ground potential.

The machine operates with an internal ion source and the chimney is located at the centre of the dummy dee facing the puller. The chimney has cross-sectional dimensions of a few mm. The puller, also of scale a few mm in the cross-sectional dimension, guides the protons into orbit in the central region. It is located at the centre of the dee.

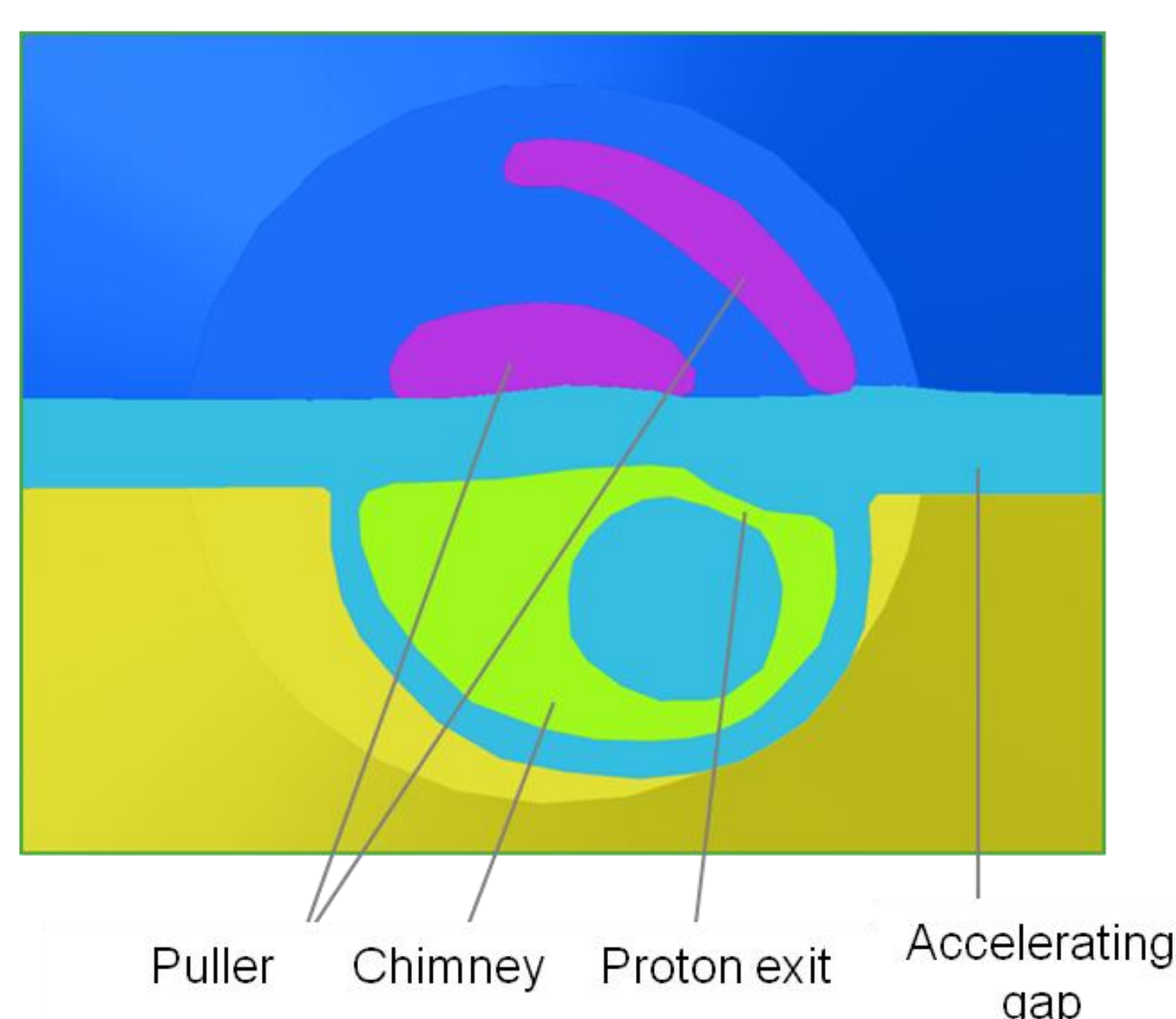
To avoid multipactoring effects, a DC bias voltage of 1.5 kV is applied to both the dee and a disk at the dummy dee.

A cone shaped structure surrounding the chimney and puller is used to reduce the transit time in the first few orbit turns and thereafter to accommodate the space charge expansion of the beam.



Median plane projection of the central region design for the S2C2 modelled in OPERA 3D (magnet not shown). The model has reflection symmetry in the median plane.

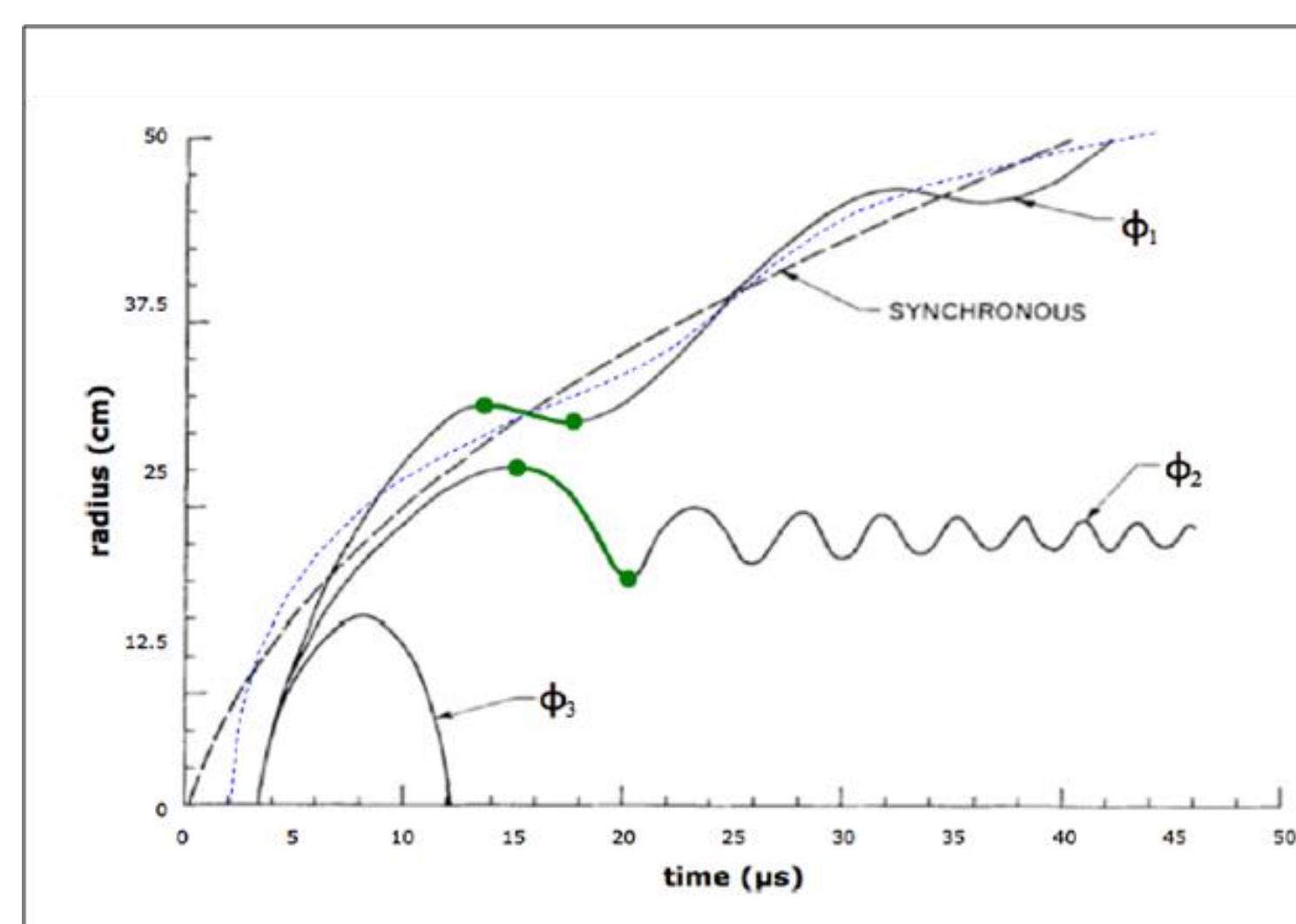
As the magnetic field index is very small in the first orbit turns, the vertical focusing of the proton beam is dominated by the electric focusing. The acceleration gap between the dee and the dummy dee provides the electric vertical focusing force in the central region.



Close up view of the S2C2 central region geometry, showing the ion source chimney and puller.

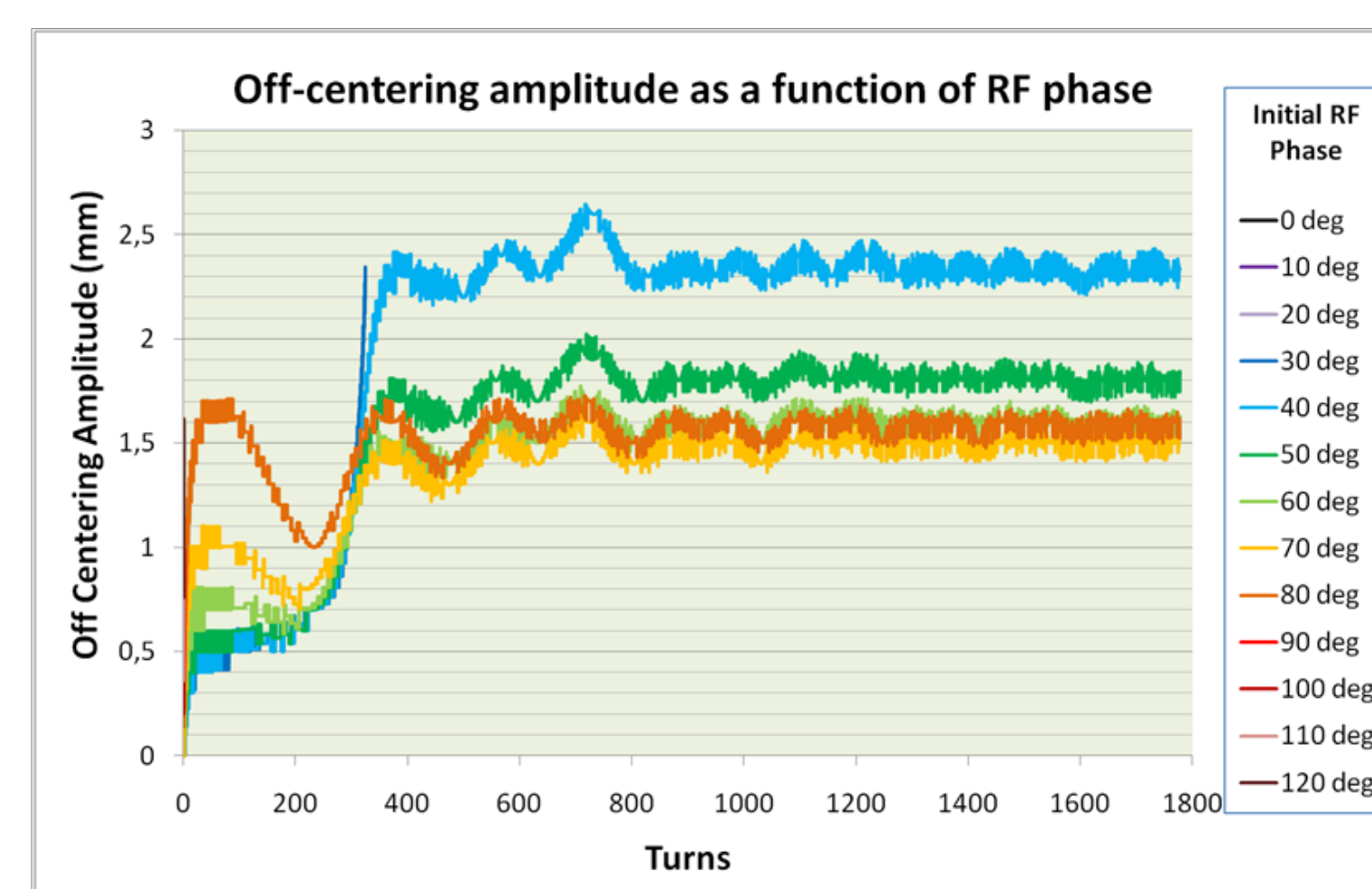
## Orbit analysis

Particle behaviour in a synchrocyclotron is shown below. The curve "synchronous" is a synchronous particle of phase  $\Phi_s$ . " $\Phi_1$ " represents particles executing stable oscillations around the synchronous particle. These are continuously accelerated (dashed line), or intermittently accelerated but stable (curve " $\Phi_1$ "). " $\Phi_2$ " represents particles which are started too late or too early to reach synchronicity; they do not undergo continuous acceleration and are lost. " $\Phi_3$ " represents particles for which the outward radial swing is too small to compensate the inward swing; these particles return to the machine centre and are lost.



Types of particle behaviour in a synchrocyclotron

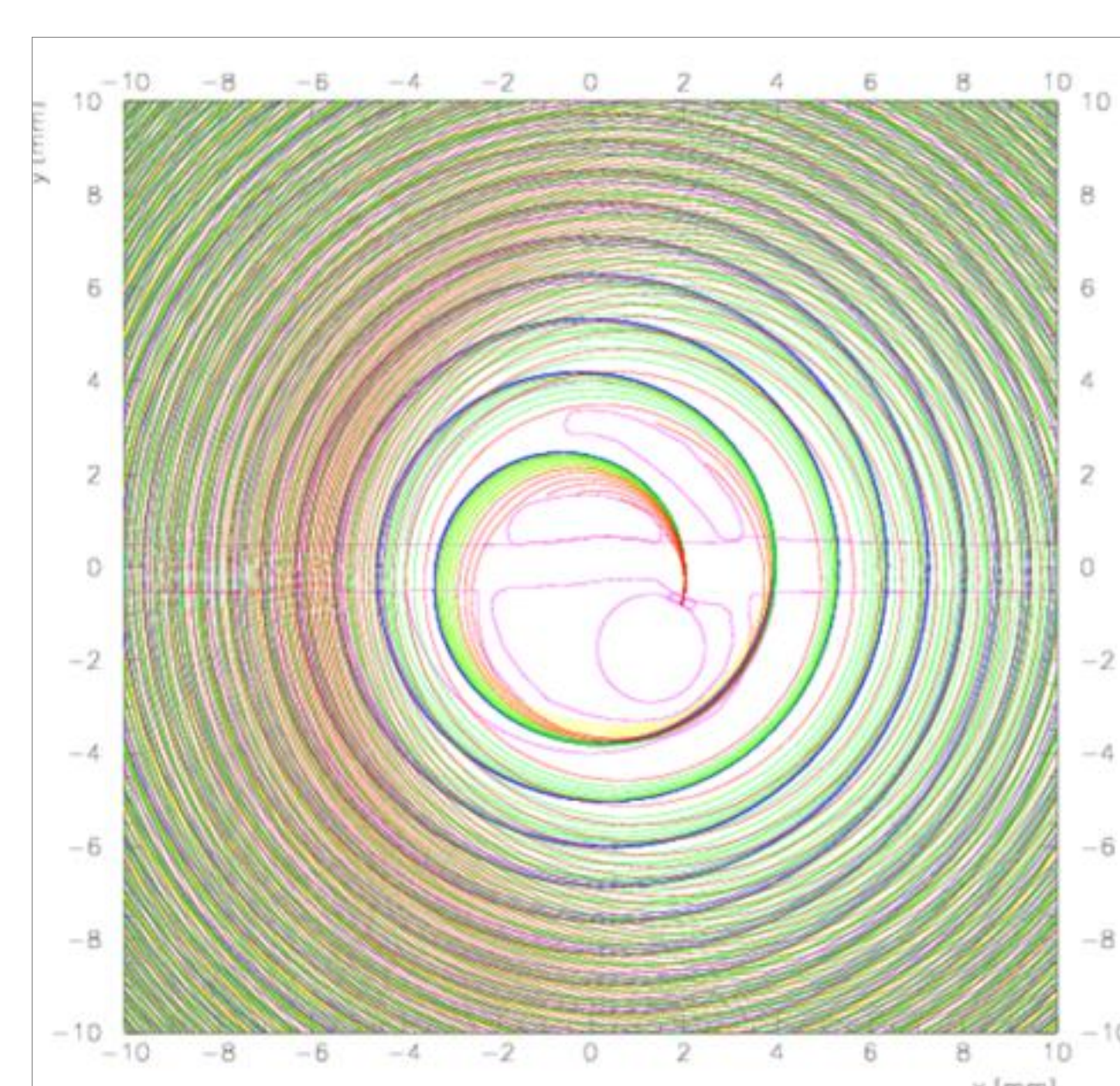
OPERA 3D models have been used to calculate magnetic and electric field maps for input into the IBA particle tracking code. Tracking calculations show that particles have fluctuating off-centering at the machine centre which stabilises to a low value of 1.5 mm to 2.4 mm after 1000 turns. Phase acceptance analysis shows that particles with initial RF phases between  $40^\circ$  and  $85^\circ$  are successfully accepted in the central region.



Evolution of particle off-centering amplitude as a function of turn number (time) for different initial RF phases. The particle starting time is approximately equal to the synchronous particle starting time.

Particles not accepted are lost vertically or by hitting the electrodes in the first orbit turns. The  $30^\circ$  phase particle (dark blue line) is lost by returning to the source after the first synchrotron phase oscillation.

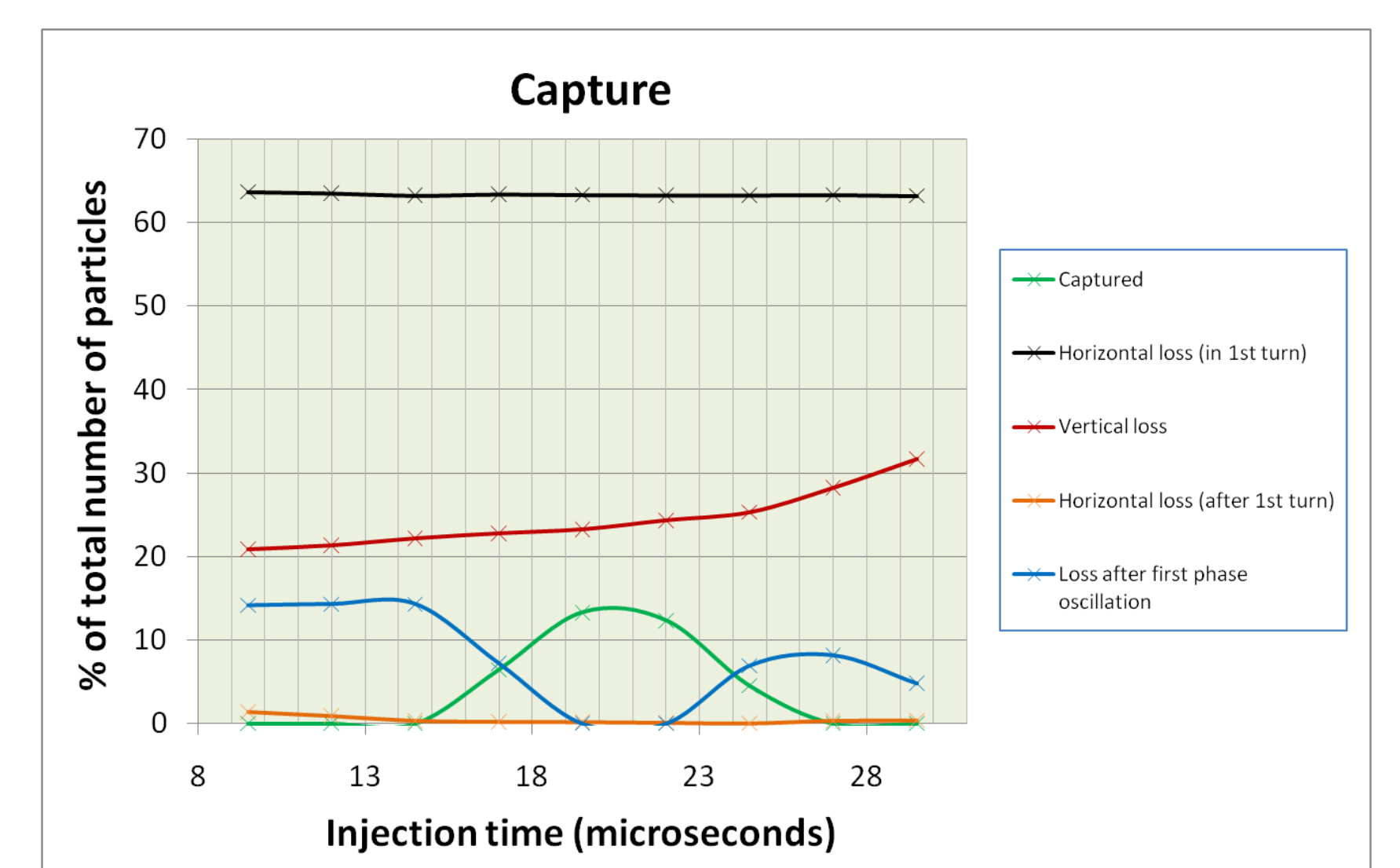
The turn pattern for the first 20 turns is shown below for 25 protons injected into the median plane.



Turn pattern for protons with initial phases between  $0^\circ$  and  $120^\circ$ , in  $5^\circ$  increments. Initial phases between  $0^\circ$  and  $30^\circ$  are yellow, between  $35^\circ$  and  $50^\circ$  are blue, between  $55^\circ$  and  $70^\circ$  are green and between  $75^\circ$  and  $120^\circ$  are red.

## Particle capture

Synchrocyclotrons can be more compact than classical cyclotrons, however, there is also a reduction in beam intensity. The reason is that particles in synchrocyclotrons are captured during only a small fraction of the frequency modulation cycle. Particle conditions at injection time therefore have a strong effect on acceptance and capture.



Capture as a function of injection time. The plot illustrates the strong interplay between captured particles and those returning to the source after the first synchrotron phase oscillation. The proportion of captured particles is highest at the synchronous particle injection time of  $\sim 19.5 \mu s$ .

## Present status

A test stand for the S2C2 ion source has been assembled and beam tests have begun. The source current is measured after half a turn, i.e. before the capture, extraction and other losses take place. Initial tests demonstrate a good level of measured total current and indicate that the final extracted current of 20 nA required for clinical use should be within reach.



Lower half of the S2C2 magnet in the IBA assembly hall.

The iron yoke and pole of the S2C2 magnet have been machined. The magnet iron has been assembled and waits in the IBA assembly hall for magnetic field measurements. The RF system is also currently under construction.

## Conclusions

This design work is unique at IBA as this is the first IBA superconducting synchrocyclotron for cancer therapy. When compared to the 4.34 m diameter IBA C230 cyclotron, the 230 MeV S2C2 of 2.5 m diameter clearly achieves IBA's goal of reduced size and cost. In addition, IBA are currently developing a new compact gantry to further reduce cost and size of the facility. Beam tests are currently in progress and have demonstrated a good level of total source current. The conclusion of the first S2C2 prototype development is expected in 2012.