A LINAC-BASED APPROACH TO MODELLING AN ORBIT SEPARATED CYCLOTRON

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Abstract

An orbit separated cyclotron (OSC) is a new type of accelerator intended as a proton driver for Accelerator Driven Subcritical Reactors (ADSRs) [1]. A ring has been designed based on the new concept that accelerates a proton beam from 500 MeV to 1 GeV in four turns using multi-cell superconducting cavities in each period. From a beam dynamics point of view, the ring can be considered as a "wrapped-up" linac at four times the ring circumference. In this paper we present beam dynamics modelling details when using 3D linac codes and cavity field maps. We conclude that the versatility of codes such as TraceWin [2], allows detailed machine modelling and improved design procedures that take into account various aspects including orbit distortion caused by transverse deflecting fields in the cavities.

THE ORBIT SEPARATED CYCLOTRON

Accelerator Driven Sub-critical Reactors require proton drivers with a high degree of reliability capable of delivering MW level beam powers. As machine availability is paramount to limit thermal stress damage in the neutron target, new accelerator designs have been proposed as alternatives to conventional accelerators. One recent proposal is the Orbit Separated Cyclotron (OSC). Its underlying goal is to improve reliability by reducing accelerator units and increasing redundancy.

An OSC uses superconducting multi-cell RF cavities in each period and combined function magnets resulting in a spiral beam orbit with only several turns. The magnets have a common yoke, but separated poles for each orbit. Each magnet is subdivided for triplet focusing with adjustable gradients, bending angles and bending radii. Although the beam energy changes in every period, synchronous acceleration is achieved by using orbit length adjustments, reverse bending, and harmonic number jumps. A schematic layout of an OSC arc is shown in Figure 1. A detailed description of the OSC concept is given in [1] and [3].

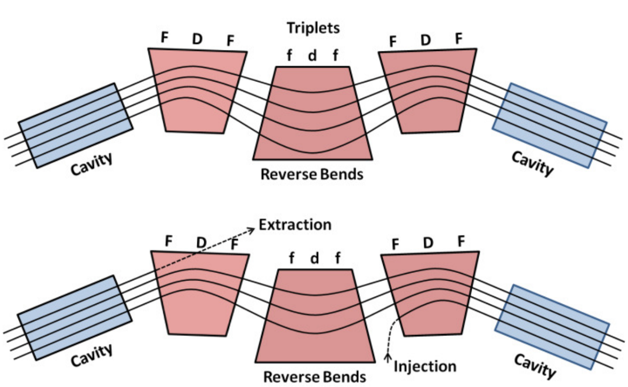

Figure 1: Schematic layout of a typical OSC arc (top), as well as the injection and extraction section (bottom).

Using the OSC concept, a 10 MW acceleration scheme has been designed as a potential ADSR proton driver. The accelerator uses a 250 MeV linac followed by two OSC rings. The first ring accelerates the beam to 500 MeV, while the second to the final energy of 1 GeV (Figure 2). The accelerator operates in CW mode and the beam current is 10 mA. An RF frequency of 324 MHz is used throughout.

ACCELERATOR MODEL

The second OSC ring is further detailed. It has four turns with separated orbits. This is sufficient to double the beam power from 5 to 10 MW. Each turn uses eight superperiods, with cavities placed in each long straight section (eight in total). For comparison, employing the linac for the same energy and power interval, would require four times more superconducting cavities. The average length of a superperiod is ~20 m, while the average ring radius is ~25 m. A schematic ring layout is shown in Figure 2.

From a beam dynamics point of view, an OSC can be regarded as a wrapped-up linac and therefore a linac-based modelling approach has been adopted. Simulation

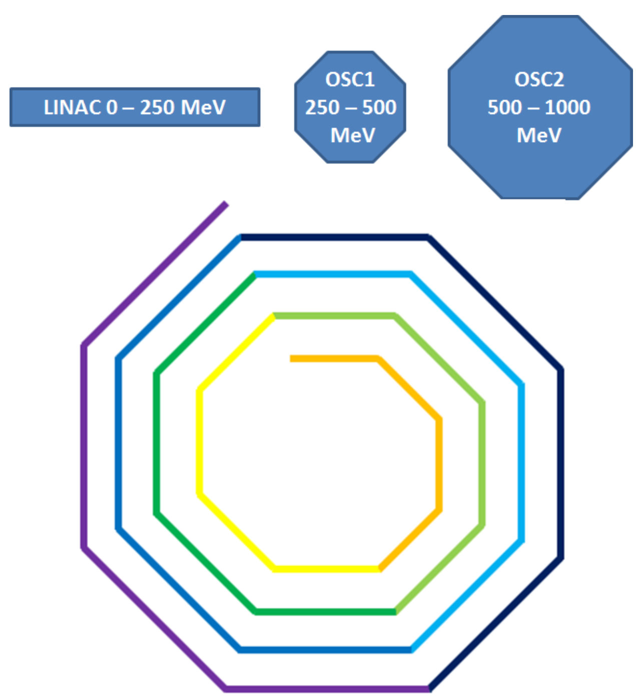

Figure 2: Potential 10 MW accelerator chain (top) and details of the four-turn OSC2 (0.5-1.0 GeV). Colours represent groups of four equal length periods.

codes like Trace3D [4], Parmila [5] and TraceWin [2] have been used. One of the advantages of using these codes is the readily available inbuilt analytical accelerator elements that allow a rapid development of simulation models without the need of producing complex field maps for magnets and RF cavities. Consequently, a simple model was developed used both as design and tracking tool. The total model length is ~633 m, four times the average ring circumference.

However, several limitations were soon recognized. As the beam travels through the cavity on four different paths, 6 cm apart (-9, -3, 3, 9 cm off-axis), to correctly estimate the energy gain and the time of flight on each path, using an approximation of the cavity voltage is no longer sufficient. Detailed knowledge of the off-axis field levels and the transit time factors across each path is needed. This required the development of 2D and 3D RF cavity models using Superfish [6] and CST MicroWave Studio [7] (Figure 3), as well as additional tools to calculate off-axis transit time factors. When taking these additional effects into account differences in energy gain of up to 2% in each cavity have been found between on and off-axis beams. If not corrected, this error is sufficiently large to quickly compromise the machine synchronicity.

Transverse deflecting fields in the cavities also have to be taken into account. For the first and fourth turn orbits (9 cm off-axis), a transverse kick left uncorrected will lead to major beam loss within the first superperiod. As a result, a correction mechanism was put in place and the OSC design method was modified to take this effect into account [3].

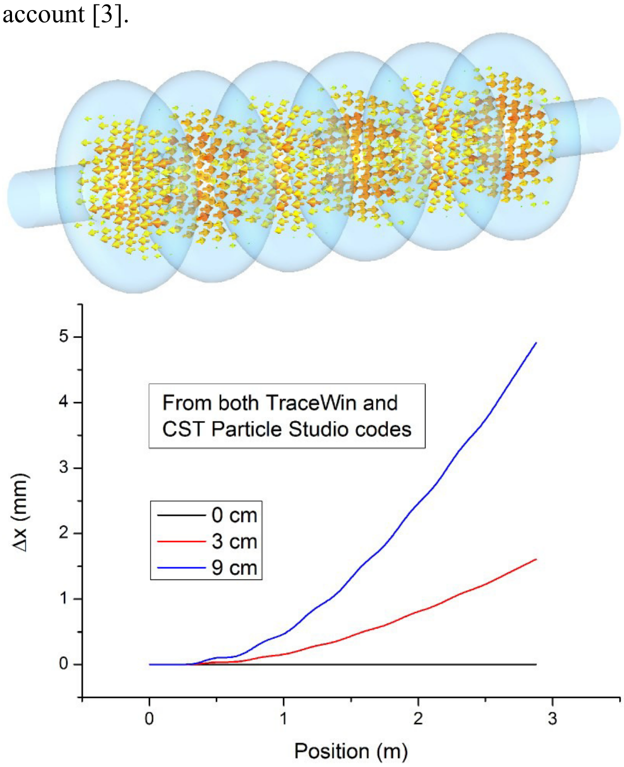

Figure 3: Beam centroid horizontal displacement (bottom) when travelling on and off-axis through a six-cell superconducing RF cavity (top).

An additional key modelling difficulty comes from the intrinsic nature of the linac codes used in these simulations, in which the coordinate system is chosen such that it follows the central orbit. To correctly track the beam on the off-axis orbits (-9, -3, 3, 9 cm), one option is to shift the beam's horizontal position at the cavity entrance. This results in the beam also entering the following magnetic elements at a shifted position. This is a working solution as long as complex 3D field maps are also employed for the magnets.

However, in the absence of field maps, when using magnetic elements, in order to see the correct magnetic fields, the beam has to travel on axis through the combined function magnets. Therefore another horizontal beam position change would be required at the cavity exit to bring the beam back on the magnet axis. This process would have to be repeated for each cavity passing and results in a method that is both tedious and inept.

To overcome this problem, a more elegant solution has been found in which the beam is kept on axis, but the 3D field map of the cavity is shifted horizontally by the correct amount. With this technique, tracking the full OSC ring becomes less complicated and can be done in a single step. In addition, the method also works when using the inbuilt gap element to model the cavity, rather than field maps. By using one of TraceWin's many error study features, the gap position can be shifted horizontally and the tracking process repeated as above, thus correctly calculating the deflections and the change in energy gain. Finally a small rematch is needed as the "transfer matrix" is slightly different when travelling off-axis.

SIMULATION RESULTS

With a functional simulation model complete, end to end particle tracking was performed in OSC2 with the aim of verifying the design and identifying any potential bottlenecks. A 10 mA 6D Gaussian input beam distribution with 10^5 macroparticles was used, with 0.4 π.mm.mrad transverse and 0.23 π.deg.MeV longitudinal normalised rms emittance. Beam envelopes in a single OSC arc can be seen in Figure 4, while Figure 5 shows

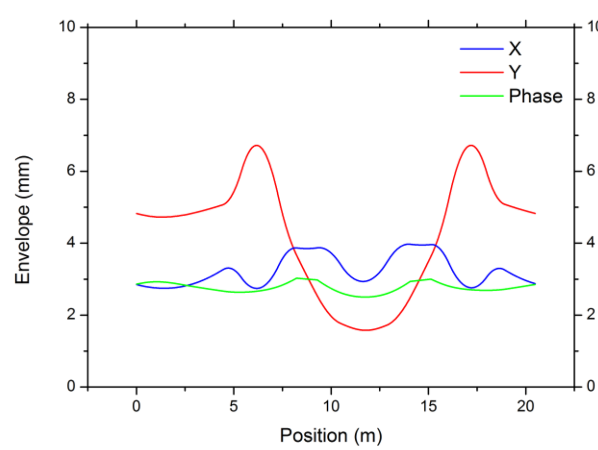

Figure 4: 5*RMS emittance beam envelopes in a single OSC2 period.

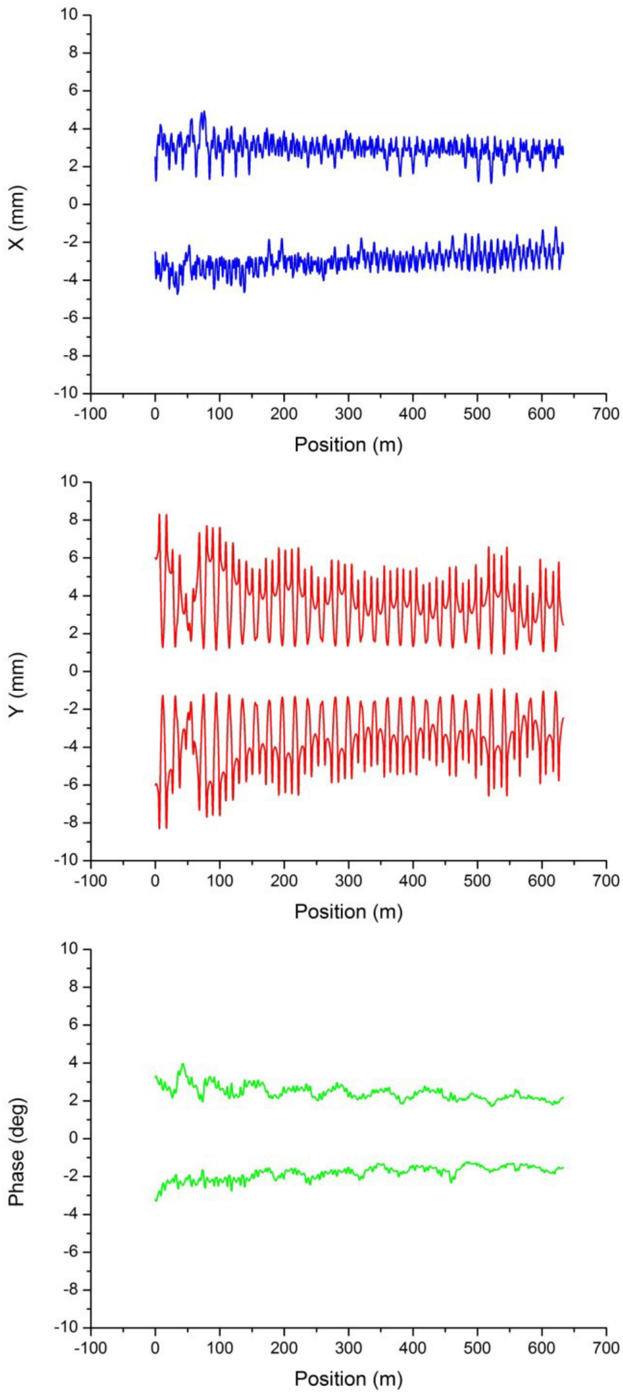

Figure 5: 5*RMS emittance beam envelopes through OSC2.

a matched and smooth envelope evolution throughout the entire acceleration cycle. The RMS emittance development is shown in Figure 6, with almost negligible growth in the longitudinal and vertical planes and ~10% increase horizontally. Figure 7 shows the beam density along the four turns being well within the minimum physical accelerator aperture, with no obvious beam loss and bottlenecks. This is an important machine feature, as for high power operation it is imperative to avoid beam loss as it can lead machine activation, maintenance difficulties and component damage.

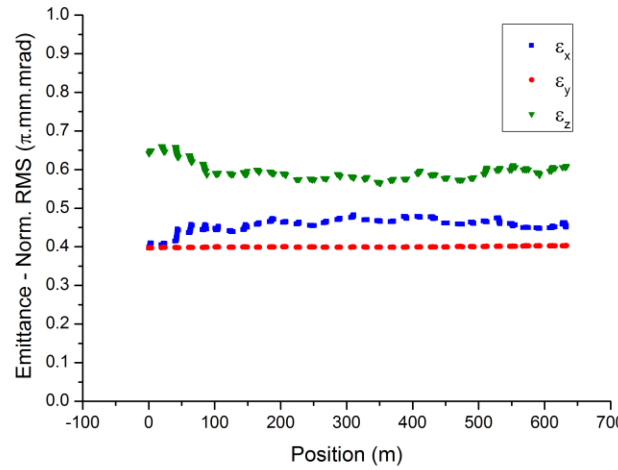

Figure 6: Emittance evolution in OSC2.

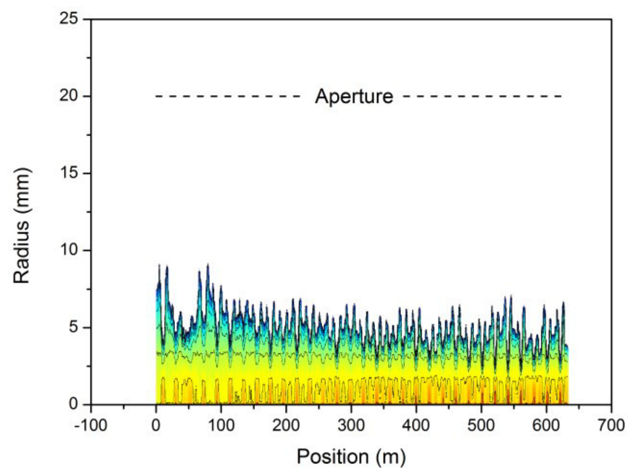

Figure 7: Particle density evolution in OSC2.

CONCLUSION

The development of a functional accelerator model for an orbit separated cyclotron using linac specific methods illustrates the versatility of linac codes such as TraceWin. This approach is particularly suitable for applications where acceleration occurs over several turns and for which sophisticated cavity models as well as suitable space charge routines are necessary.

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