MW-CLASS 800 MeV/n H_2^+ SC-CYCLOTRON FOR ADS APPLICATION, DESIGN STUDY AND GOALS*

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Abstract

This paper addresses an attempt to start investigating the use of the Superconducting Ring Cyclotron (SRC) developed for DAEδALUS experiment for ADS application [1, 2], focusing on the magnet design and its implication for lattice parameters and dynamic aperture performance.

INTRODUCTION

Accelerator Driven Sub-critical (ADS) fission is a promising candidate basis for nuclear waste transmutation and for nuclear power generation. ADS can use Thorium or depleted Uranium as fuel, operate below criticality, and consume rather than produce long-lived actinides. ADS systems offer several interesting advantages in comparison to traditional critical reactors :

1. ADS provides greater flexibility for the composition and placement of fissile, fertile, or fission product waste within the core, and require less enrichment of fissile content;

2. The core can be operated with a reactivity k_{eff} that cannot reach criticality by any failure mode.

3. Coupling the fast neutron spectrum of the spallation drive to fast core neutronics offers a basis for more complete burning of long-lived actinides.

4. ADS designs can provide sufficient thermal mass that meltdown cannot occur from radioactive heat after fission is stopped. Furthermore, if a liquid Thorium fuel is used, much less nuclear waste will be generated and the fuel can be recycled continuously without stoppage of the operation.

A modular reactor capable of delivering few hundred MW of electrical power is considered to be one possible type of application of immediate use. In order to drive a $\sim$GWe fission core, a CW proton beam of $>$800 MeV and $\sim$15 MW beam power is sufficient. A previous study of the accelerator performance required for ADS systems [3] concluded that present accelerator performance is approaching those requirements, but accelerator system cost and reliability remain particular concerns. The obvious candidates that can provide intense CW proton beams are isochronous cyclotrons and superconducting linacs.

The target system, reactor interface, neutronics performance, and reliability are also important concerns. At current technology level, a target system in the range of 3 to 5 MW can be developed in few years time for deployment in an ADS facility. Our previous study [4] indicates that a configuration consisting of 3$\sim$5 high power cyclotrons and associated target systems can best meet the requirement of a medium size power generation facility.

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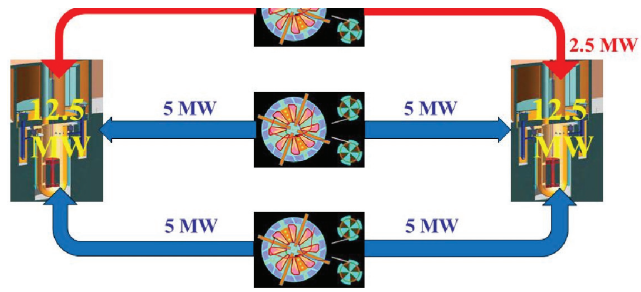

Figure 1: Possible arrangement of a pair (out of a series) of 12.5 MW beam power sub-critical units, based on a 10 MW SRC and its two 60 MeV/amu injectors. In case of failure in a cyclotron, it is possible to increase the beam power from the others and maintain a total 12.5 MW per unit [1, 2].

Table 1: Parameters of the SRC.

Ion type		H_2^+
Ion mass	MeV/c^2	1876.635
Injection-extraction energy	MeV/amu	60.44 – 800
Inj.-extr. $B\rho$	T.m	2.283 – 9.809
$B\rho_{xtr}/B\rho_{inj}$		4.2969
Inj.-extr. $\beta\gamma$		0.3647 – 1.567
Injection-extraction radii	m	1.99 – 4.90
Orbit excursion	m	2.935
Max. field on orbit, inj.-extr.	T	4 – 5.8
Lattice type		spiral sector
Spiral angle	deg.	< 12
Number of sectors		8
Q_r range (min.-max.)		1.085 – 1.927
Q_z range (min.-max.)		0.486 – 1.161
Number of RF cavities		> 6
RF frequency	MHz	49.2
Peak voltage	MV	1
Energy gain per turn	MeV	4.6

The present paper addresses an attempt to start investigating the use of the cyclotron developed for DAEδALUS experiment for ADS application, focusing on the magnet design and its implication for lattice parameters and dynamic aperture performance. The Multi-MegaWatt Superconducting Ring Cyclotron (SRC), which has to supply the few MW beam for the DAEδALUS experiment, is shown in Fig. 1. Preliminary parameters are presented in table 1.

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The cyclotron complex consists of an injector cyclotron, which accelerates molecular H_2^+ from injection energy 50 keV/amu about, up to 60 MeV/amu. Raising the injector energy to 80∼120 MeV/amu according to DAEδALUS concerns is now in discussion. The beam is then injected into the SRC along a valley, by one or more superconducting injector magnets and one electrostatic deflector, and accelerated up to 800 MeV/amu by means of a series of 6 RF cavities, 4 single-gap and 2 double-gap. The extraction is performed by insertion of a pyrolytic graphite stripper foil with thickness less than 2 mg/cm^2. It is possible to use one or two stripper foils depending on the power limitations of the beam dump.

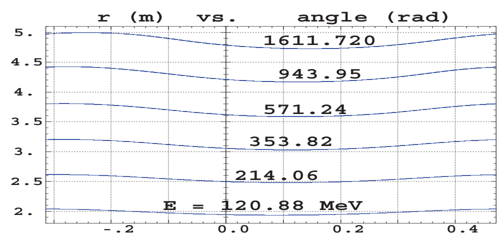

Figure 2: Closed orbits across one of the eight cells of the cyclotron, at six different energies.

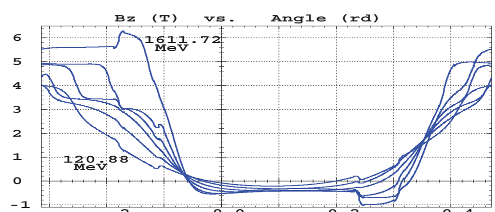

Figure 3: Field on closed orbits across a cell, featuring ”shimming” bumps.

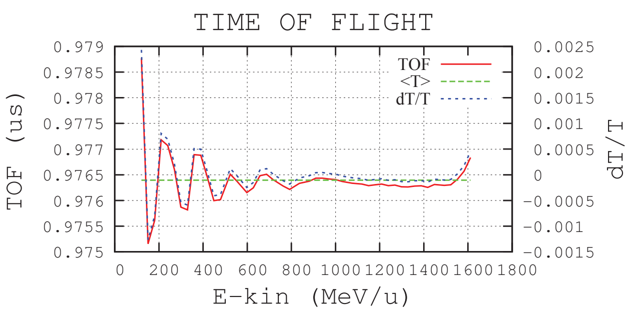

Figure 4: Time of flight (left axis), its average value $<T>$, and (right axis) the relative difference $(T- <T>)/ <T>$.

The superconducting coils are simply wound around the hills, like in the RIKEN SRC [5]. The shape of the iron of the hill and consequently the shape of the coils has been chosen to assure the isochronism as well as the focalization of the beam. A preliminary study has been carried out along the past two years, including evaluations using 3-D magnet code, and it proved the feasibility of the Cyclotron.

To accelerate the H_2^+ we need a good vacuum, preliminary evaluation shows that with a vacuum of 2×10^{-8} Torr the beam losses should be lower than 4 μA along the total acceleration path. This value of beam losses is lower than the estimated beam losses at the TRIUMF cyclotron (520 MeV) and the required vacuum is achieved in the latter which is also larger (6 m extraction radius) than the presented solution.

OPTICS ASSESSMENTS

We essentially focus here on lattice parameters and dynamic aperture performance in relation with the design of the SRC 45 degrees spiral sector superconducting magnet.

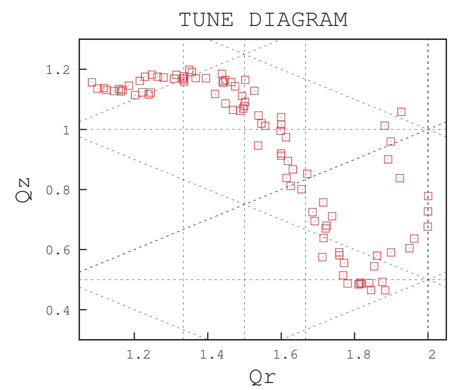

Figure 5: Beam path in tune diagram, from injection (upper left end) to extraction energy (upper right end). Resonance lines up to 3rd order, normal multipoles, random, are shown.

Orbits, Time of Flight

Orbits at various energies from injection to extraction, across a single 45 degree sector, are shown in Fig. 2. Fig. 3 shows the magnetic field (purely vertical) on these orbits. Note the presence of overshoots on the downstream end of the hill and of the valley ; these are an artifact and result from the following : the original, smooth, OPERA field map yielded about $\pm 0.5\%$ isochronism defect. In order to perform acceleration simulations including space charge effects, it is necessary to ensure isochronism at a level of 0.01%. In the present stage of the studies however, refined 3-D field simulations are not needed, the engineering of the magnet still has to be done and serious changes will occur. For this reason isochronism in this first approach has been obtained by “shimming” the field map at radii and at azimuthal locations as necessary, namely, around the boundary of the hills. In doing so, care has been taken not to spoil the vertical focusing. A smooth OPERA design, including lower stray fields in the central region, is in progress.

The time of flight evolution so obtained is displayed in Fig. 4. It is still far from optimal and more work is needed to achieve $dT/T < \pm 0.01\%$ departure from isochronism.

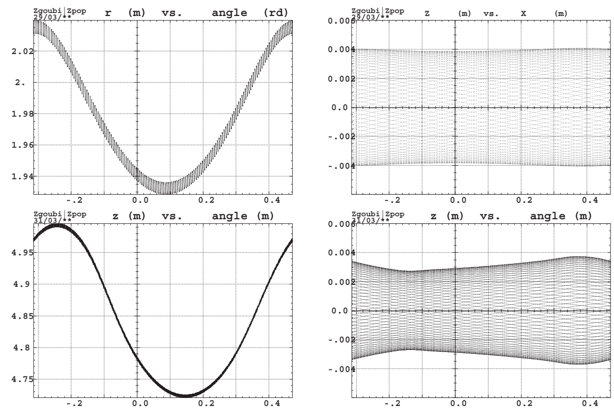

Figure 6: Beam envelopes on injection orbit (top row) and extraction orbit (bottom row), horizontal (left col.) and vertical (right). Emittance value is 3.35π mm.mrd, normalized, in both planes.

First Order

Paraxial tunes along the acceleration range are displayed in Fig. 5, the beam path crosses the $Q_r = 1 + 1/3$, $Q_r = 1 + 2/3$ lines and the Walkinshaw resonance. Given the strong acceleration rate, this should not be harmful but will be investigated with tracking simulations.

The variation of the tunes with motion amplitude (“amplitude” de-tuning) is further addressed below.

BEAM ENVELOPES

Figs. 6 show the beam envelopes on the injection and extraction orbits. Horizontal betatron functions (not shown here) at extraction energy have about 50% larger value than at injections, whereas $\beta\gamma$ is a factor about 4.3 larger. Hence envelopes at extraction are smaller by a factor about $\sqrt{\epsilon_{xtr}\beta_{xtr}/\epsilon_{inj}\beta_{inj}} \approx \sqrt{(1 \times 1.5)/(4.3 \times 1)} \approx 0.6$ (left column in Fig. 6).

Vertical betatron functions at extraction energy are about 3 times greater than injection. Hence a small difference of a factor about $\sqrt{\epsilon_{xtr}\beta_{xtr}/\epsilon_{inj}\beta_{inj}} \approx \sqrt{(1 \times 3)/(4.3 \times 1)} \approx 0.84$ (right col. in Fig. 6).

Dynamical Acceptance

The dynamical acceptance (DA) is the limit of stable motion in phase space (tracked at fixed energy over 500 turns here), resulting from misalignments, field defects, nonlinearities, and is normally expected to exceed the geometrical acceptance, tracking results in Figs. 7, 8.

Comparison with envelopes in Fig. 6 shows that the DA well exceeds $\epsilon_{r,z} = 3.35\pi$ mm.mrd normalized emittance, in both radial and axial planes.

The DA gives an idea of possible radius values in the ring where some local shape of the field could excite strong resonant motion causing particle loss after a small number of turns, which is not desirable. Variation of tunes with motion amplitude, either radial or axial, is an outcome of

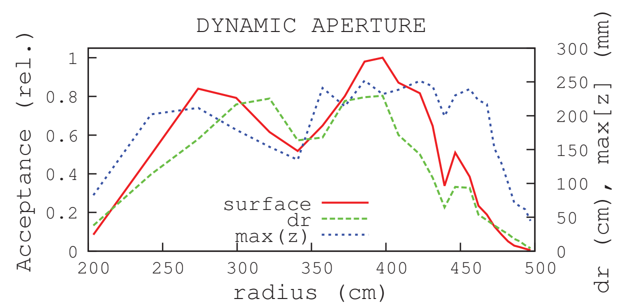

Figure 7: Left axis : r-dependence of the surface of the DA window in physical (r,z) space. Right axis : Radial (dr, cm) and vertical extent (max[z], mm) of the acceptance.

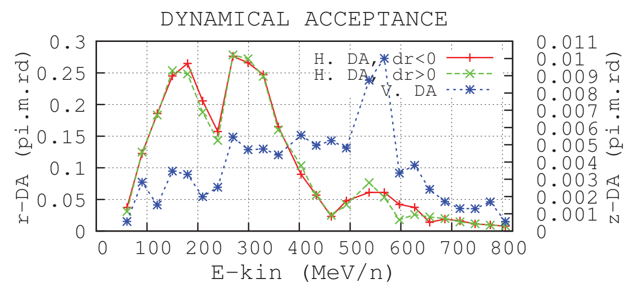

Figure 8: 500-turn DA (normalized) as a function of energy. Left axis : Horizontal DA, for either $dr < 0$, or $dr > 0$, wrt. closed orbit. Right axis : Vertical DA.

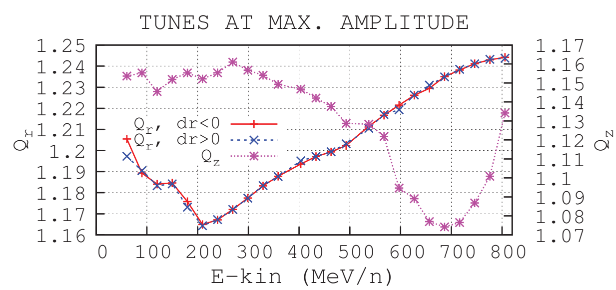

Figure 9: Tunes at stability limit, as a function of energy. Left axis : Q_r, for either $dr < 0$, or $dr > 0$, wrt. closed orbit. Right axis : Q_z. The amplitude detuning effect is visible by comparison with paraxial tunes, Fig. 5.

DA computation. Fig. 9 shows that the effect is substantial. This will be investigated further.

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