FLUX-COUPLED CYCLOTRON STACK: OPTIMIZATION FOR MAXIMUM BEAM POWER AND MINIMUM LOSSES*

Peter McIntyre[#] and Akhdiyor Sattarov, Texas A&M University, College Station, TX 77843 USA

Abstract

A flux-coupled stack of isochronous cyclotrons has been proposed as a driver for Accelerator-Driven Subcritical Systems (ADSS) for thorium-cycle fission power. The issues that limit beam current and phase space brightness are evaluated, including space charge tune shift, synchro-betatron coupling, orbit separation at injection and extraction, RF parasitic modes and propagation within the accelerator envelope, and stability of electrostatic septum operation.

INTRODUCTION

Accelerator-driven subcritical ADS fission offers a basis for green nuclear power technology [1]:

It is not a critical reactor; it is a subcritical core, and no failure mode can make it go critical.

It cannot melt down, even if cooling to the core were stopped indefinitely.

It operates at ambient pressure and cannot develop an explosive pressure of gases.

It burns any of the fertile nuclear fuels: U, Th, or spent nuclear fuel. There are sufficient reserves to provide Man's energy needs for 3000 years.

It burns all of the fertile fuel inventory, breeding it into fissile isotopes and fissioning them in a continuous process until nothing is left but spent non-fissile waste.

It burns the long-lived actinide isotopes rather than breeding them. Fission is driven by fast neutronics, so that the waste isotopes that are left all have half-lives of less than a century and so can be disposed of safely.

A critical enabling element for ADS fission is a reliable, affordable CW proton accelerator that is capable of delivering a beam with 800 MeV energy and >3 mA current. The highest-power proton accelerator in this energy range today is the isochronous cyclotron (IC) at PSI [2], which delivers 1.3 MW of beam power at 590 MeV energy. Comparing tan IC and superconducting linac for ADS applications, the IC delivers more power, for lesscost, with comparable reliability.

These considerations have motivated us to examine the elements of IC design that limit its efficiency, beam current, beam losses, and reliability. We set out to develop a conceptual design for an ADS-appropriate IC modelled closely upon the PSI IC, while addressing ways to optimize it to ADS applications.

Each sector magnet of the PSI IC has a warm-iron flux return and normal-state Cu windings. For ADS we replace those by a flux-coupled stack of cold-iron flux plates, each with a superconducting winding, which form the magnetic field regions for a vertical stack of independent ICs. The stack is supported within a warm-iron flux return as shown in Fig. 1. This approach makes it possible to deliver multiple beams, each with its own RF injection and extraction, thus providing reliability through redundancy in driving an ADS core: if any one beam trips due to hardware failure or beam losses, the other beams should continue to operate.

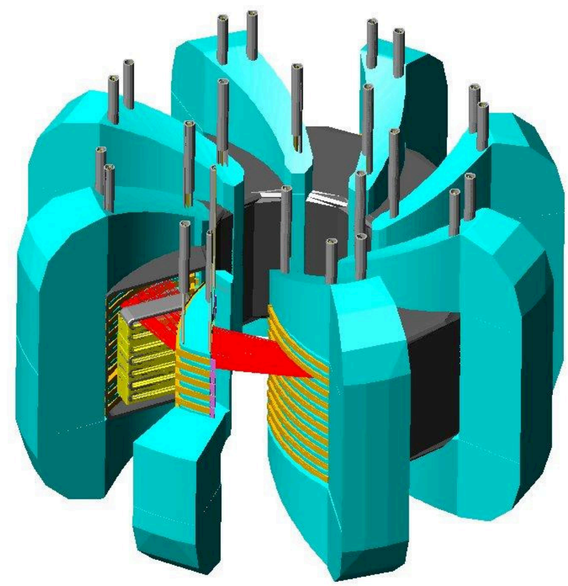

Figure 1: Flux-coupled stack of seven ICs, showing dielectric-loaded superconducting RF cavities, cold-iron flux plates, and envelope of 150 orbits for in the top IC.

We have developed two designs for compact 50 MHz cavities that make it possible to accommodate 1 MV cavities for each IC in a 0.5 m vertical spacing in the flux-coupled stack. We devised a method to couple RF power into each cavity in a fashion that naturally suppresses excitation of parasitic modes and makes it possible to match RF power injection to the power consumed to accelerate beam in the successive orbits.

We are modelling how to optimize the rest-frame phase space distribution in each bunch to minimize emittance dilution from the strong synchro-betatron mixing in an IC.

In what follows we describe each of these design elements and its potential importance to increase beam current, reduce beam losses, and improve reliability.

COMPACT RF CAVITIES

The PSI group have demonstrated that the achievable CW beam current in an IC increases $\propto N^{-3}$ with the number N of orbits in the IC aperture. Energy gain per turn is therefore at a premium, and 4 MV/turn is desirable. The 50 MHz Cu cavities used in the PSI IC [2] are 3.25 m tall,

*Work supported by US Dept. of Energy, grant DE-FG03-95ER40924.
mcintyre@physics.tamu.edu

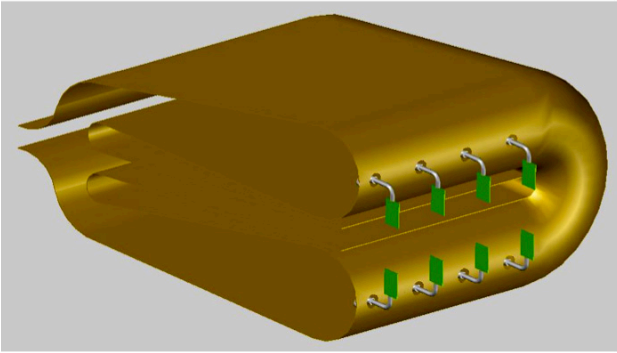

Figure 3: Sliced section of 50 MHz Cu cavity, designed to fit in staggered 0.5 m spacing of flux-coupled IC stack.

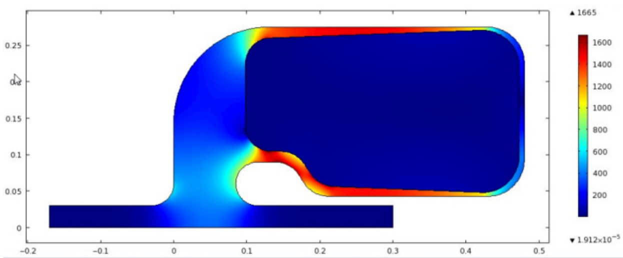

Figure 2: 50 MHz dielectric-loaded superconducting cavity (top half). Rutile dielectric is shown in dark blue; color scale shows local electric field in vacuum regions.

and would not be compatible with placement in the confined vertical spacing in a flux-coupled stack. We have considered two options: a morphing of the PSI Cu-cavity structure in which the two lobes are bent 90^o so that they flank the plane of the IC orbits, and a dielectric-loaded superconducting cavity that would fit in an even more compact IC spacing.

The Cu cavity version is shown in Fig. 2; the cavity has been sliced to show the accelerating gap and internal configuration. The structure contains four innovations. First, the two lobes are morphed from the vertical alignment used in the PSI cavities, each lobe is bent 90^o close to its coupling to the accelerating gap, and the shape is morphed to reduce the width of the far lobe. The overall cavity has an overall height of 0.9 m, and will fit within the 0.5 m space between ICs providing the cavities on alternate layers are placed in alternate gaps between sectors; (the cavities for ICs #1, 3, 5, 7 in gaps 1, 3, 5, 7, and the 4 cavities for ICs #2, 4, 6 in gaps 2, 4, 6, 8). Second, the ends of the two lobes at the radial inner and outer ends are connected by U sections, so the problems associated with end termination literally disappear. Third, RF power is generated on board-level RF power amplifiers and locally coupled into the cavity by a row of loop couplers located on the far lobe as shown. This has the effect of driving RF current to flow in the exact pattern associated with the desired accelerating mode of the cavity; any longitudinal or diagonal parasitic modes are naturally suppressed by this coupling.

Suppression of parasitic modes is important, both to prevent transverse bunch growth and to prevent propagation of RF within the accelerator envelope. The latter appears to occur occasionally in the PSI IC, where it can initiate plasma discharge in the wire comb of the extraction septum. This in turn can cause high-voltage breakdown and beam trip. Although each RF insertion in the PSI IC has a long, narrow aperture that strongly cuts off the accelerating mode from propagating, the aperture does not cut off longitudinal modes. The longitudinal modes are coupled readily from the cylindrical waveguide input coupling at the end wall of the PSI cavity lobe.

We suppress the coupling of such modes in two ways. First, input coupling is provided by a row of loop couplers, located along the far lobe as shown in Fig. 2. Each coupler is driven locally by a board-level solid-state power amplifier (green in Fig. 2). The loop couplers drive RF currents that propagate in the z-ϕ plane only – the radially oriented currents that would be associated with longitudinal modes cannot couple to the loops.

Second, the inner and outer ends of the top and bottom lobes are coupled to one another by U-segments (see Fig. 2), so the cavity ends disappear and the two halves behave electromagnetically as a deformed toroid. This removes the perturbation to the accelerator mode that would otherwise deform it if the ends were terminated in a conductive wall as is the case for the PSI cavities; the end perturbation is likely a source of cross-coupling and mixing between accelerating and longitudinal modes.

Interestingly the distributed direct drive of an array of coupling loops is only possible because high-power high-efficiency (up to 80%) board-level RF power amplifiers are now feasible with power up to 25 kW/board using current-generation RF transistors. With a row of 20 couplers on each lobe of the cavity, a total of 1 MW can be coupled into each of the 4 cavities on each IC, sufficient to accelerate 2 MW of beam with Cu cavities or 4 MW of beam with superconducting cavities (discussed below). Distributed power coupling offers a more robust method to couple RF power with excellent VSWR, phase control, and mode selection. Finally the linear array of couplers can be spaced to match the power density that is coupled into cavity to the (radially increasing) power density that is coupled into the beam. (The orbits are more closely spaced for the high-energy orbits, so the power density dP/dr is correspondingly higher).

We have also devised a dielectric-loaded superconducting cavity [1], which would eliminate the RF wall losses in the Cu-cavity and improve the overall power efficiency. The cavity design respects established limits on RF surface fields, but would approach them for 1 MV accelerating gradient. The rutile (Ti_2O_3) dielectric exhibits minimum loss tangent and ε~100 at liquid nitrogen (LN) temperature. RF losses would be predominantly in the rutile, so we would contemplate operating it at 80K and the cavity walls at 4 K. This would require a tricky cryostat structure to integrate LN refrigerant flow through support stems to the rutile.

We plan to implement the room-temperature Cu cavity option structure in our first prototype of the ADS IC, (it is simpler and involves less risk), and plan to develop the

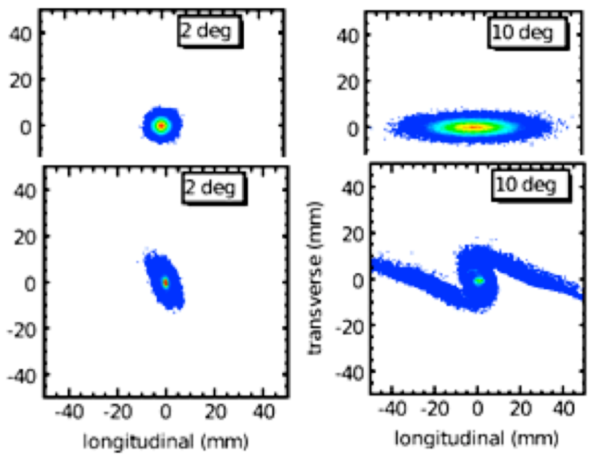

Figure 4: Phase space distributions, at injection and extraction orbits, for two cases of longitudinal phase spread at injection: 2° and 10° (from Ref. 3).

superconducting option as an R&D effort for further improvement.

POLE FACE WINDINGS ON FLUX PLATES

We plan to implement a pattern of pole face windings on the flux plates that magnetically define each IC, as shown in Fig. 5b. Following the procedure at PSI, the trim windings will be used to trim the field integral as a function of radius to enforce isochronicity of all orbits.

PHASE SPACE DISTRIBUTION AT INJECTION

Yang *et al*. [3] present an excellent analysis of the effect of the phase space distribution at injection upon the subsequent filamentation and emittance growth during acceleration. The effect is illustrated dramatically in Fig. 4 extracted from their paper. When a bunch is injected with a spherical distribution in horizontal/longitudinal phase space, the sphere is self-preserving even in the strong mixing of horizontal betatron and longitudinal phase space that is intrinsic with large voltage gain/turn and strong bending. But if the injected bunch is elongated, it will filament and wrap up, resulting in significant phase space dilution by the time it reaches the extraction orbit.

Yang *et al*. calculate that this dilution is present in the PSI IC, and is caused by phase expansion in the long transfer line from the injector cyclotron to their IC. We plan to locate the injector cyclotron very close to the IC, so that transfer is essentially ballistic and the spherical distribution that is intrinsic at the injector extraction is still intact when it is injected into the IC. The filamented tails are likely closely related to the bunch tails that limit the losses on the extraction septum, so we expect that optimizing the injection bunch should reduce bunch tails and make it possible to accelerate larger beam current with lower losses.

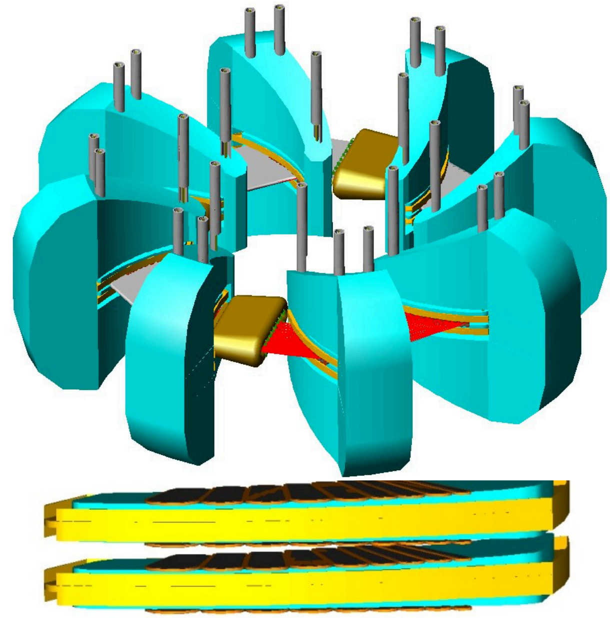

Figure 5: Single-IC configuration for a prototype ADS driver, showing placement of Cu RF cavities; b) a pair of flux plates showing the pole face windings.

CONCLUSIONS

We have reported the development of a set of concepts for how to reduce losses, increase beam current, and improve reliability by controlling beam phase space more effectively. Options for compact RF cavities that are compatible with the close spacing required in a flux-coupled stack of ICs are presented. It appears that it may be possible by these measures to significantly increase beam power, and to thereby improve the performance of ICs as a driver for ADS nuclear power systems. A detailed design is being prepared for a single-IC prototype that is compatible with the flux-coupled stack design, shown in Figure 5a. We plan to build this prototype and use it to study the effects that limit beam current and losses and to optimize the approaches discussed above.

REFERENCES

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