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COMPARISON OF ACCELERATOR TECHNOLOGIES FOR USE IN ADSS*

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Abstract

Accelerator Driven Subcritical (ADS) fission is an interesting candidate basis for nuclear waste transmutation and for nuclear power generation. ADS can use either thorium or depleted uranium as fuel, operate below criticality, and consume rather than produce long-lived actinides. A case study with a hypothetical, but realistic nuclear core configuration is used to evaluate the performance requirements of the driver proton accelerator in terms of beam energy, beam current, duty factor, beam distribution delivered to the fission core, reliability, and capital and operating cost. Comparison between a CW IC and that of a SRF proton linac is evaluated. Future accelerator R&D required to improve each candidate accelerator design is discussed.

INTRODUCTION

ADS fission has interesting potential for electric power generation and also for destruction of long-lived actinide waste produced by conventional critical reactors. ADS systems offer several interesting advantages in comparison to critical reactors:

- 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;
- The core can be operated with a reactivity k_{eff} that cannot reach criticality by any failure mode.
- When the beam is shut off fission ceases in the core;
- Coupling the fast neutron spectrum of the spallation drive to fast core neutronics offers a basis for more complete burning of long-lived actinides.
- ADS designs can provide sufficient thermal mass that meltdown cannot occur from radioactive heat after fission is stopped.

In order to drive a ~GW_e fission core a CW proton beam of >700 MeV and ~15 MW beam power is required. A previous study of the accelerator performance required for ADS systems [1] concluded that present accelerator performance is approaching those requirements, but accelerator system cost and reliability remain particular concerns. The obvious candidates for accelerators that can provide intense CW proton beams are isochronous cyclotrons (IC) and superconducting linacs.

We have examined a case study using a hypothetical ADS core configuration to guide our thinking in evaluating those two accelerator technologies for use in ADS systems. Issues of accelerator power, multiplicity of accelerators, and options for core neutronics and fuel form are discussed.

FUEL OPTIONS FOR ADS CORE

The fertile/fissile fuel can be arranged as fuel pins, configured within a molten lead moderator/heat exchange medium, or it can be prepared into a molten salt eutectic. The fuel pin option carries a significant challenge for even momentary interruptions of beam power. Each such interruption causes fission to stop abruptly, so the heat generated within each pin stops abruptly, so the temperature difference across the thin metal cladding of the pin drops from its ambient value (typically several hundred degrees C) to zero with a relaxation time of <ms. This constitutes a thermal shock to the cladding tube, and if repeated many times will induce fatigue and cracking.

In a molten salt eutectic core there is no fuel cladding and so there is no risk that momentary interruptions of beam power would damage cladding. This consideration is an important one for the choice of ADS core design.

BEAM RELIABILITY

Unscheduled interruptions of beam are a fact of life in accelerators. Such interruptions arise from a multitude of issues, *e.g.* hardware failure, beam instabilities, beam losses. Many studies have been made of the origins and frequency, and improving reliability is of course a major priority at all operating accelerators. The duration of interruptions spans from seconds to days, but all such interruptions would shock fuel pins. This interruption plot is quite similar for the PSI IC [2] and for SNS. For some ADS applications there should be less than 2500 beam trip per year with off time between 10 second and 5 minutes.

Since many authors are developing designs for fuel pin-based ADS cores, the interruption problem is of primary significance. It is with this in mind that the following study was undertaken.

SINGLE BEAM VS. MULTIPLE BEAMS

ADS concepts have typically assumed a single drive beam. This places extreme requirements upon the accelerator, both for its CW power (the current world record is 1.3 MW from the PSI IC, far less than required for ADS), and for the reliability problem discussed above.

Here we examine the option of using multiple drive beams, first proposed by McIntyre and Sattarov [3]. The concept is illustrated in Figure 1, which shows a top view of the arrangement of spallation targets (white), moderator/coolant, and neutron reflector (blue). For a molten salt eutectic core the red regions are filled with fuel salt and the green regions are moderator/heat exchanger medium. For a fuel pin core the fuel pin bundles and lead modera-

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tor fill the red regions and the green regions are heat exchange channels.

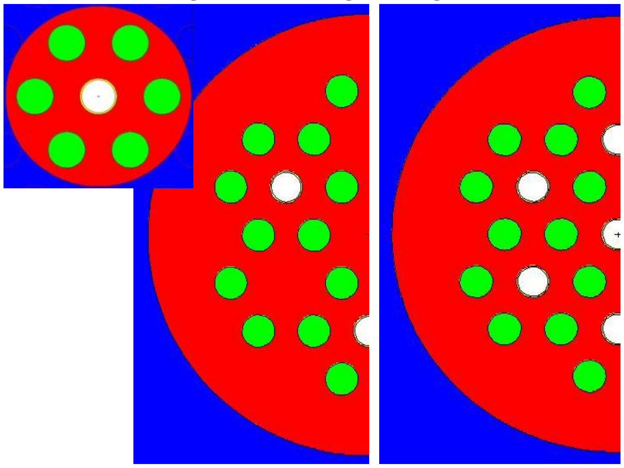

Figure 1. ADS core configuration with a) 1 drive beam; b) 3 drive beams; c) 7 drive beams.

Table 1. Fractional change in fission power density as a function of radius when one beam is interrupted.

r (cm)	1 beam	3 beams	6 beams
9		0	0
26		0.12	0.05
44	1.0	0.29	0.14
61	1.0		
78	1.0	0.42	0.22
96	1.0	0.39	0.19
114	1.0	0.37	0.16
131	1.0	0.34	0.15

Provision of multiple spallation targets yields three important benefits for a fuel-pin-based ADS core. First, it reduces proportionately the temperature shock to the fuel pin cladding, since when the beam from one accelerator is interrupted remaining beams should still operate. Second, the fast neutron flux from multiple symmetrically placed spallation targets can be optimally tuned to match the core neutronics, improving the achievable k_{eff} for a given core composition. Third, the accumulation of fission products occurs more uniformly throughout the core, eliminating the requirement to shuffle pins during the life cycle.

CASE STUDY

The proton beam is assumed to have an energy of 1 GeV, and the target material is natural lead, which is also the coolant for the reactor assembly. Three proton beam arrangements are considered: a concentric single beam, and symmetric configurations of three and six beams.

Several figures of merit are considered in our evaluation of these scenarios. First, we estimate the change in thermal stress induced in the fuel pin cladding following a sudden interruption of one proton beam. Second, we calculate the variation of k_{eff} with time as the reactor operates, Third, we calculate the variation of the required accelerator beam power to maintain a constant thermal power output from the ADS core. Lastly we are simulateing the materials degradation (dpa) and gas production (H and He) in the spallation target materials.

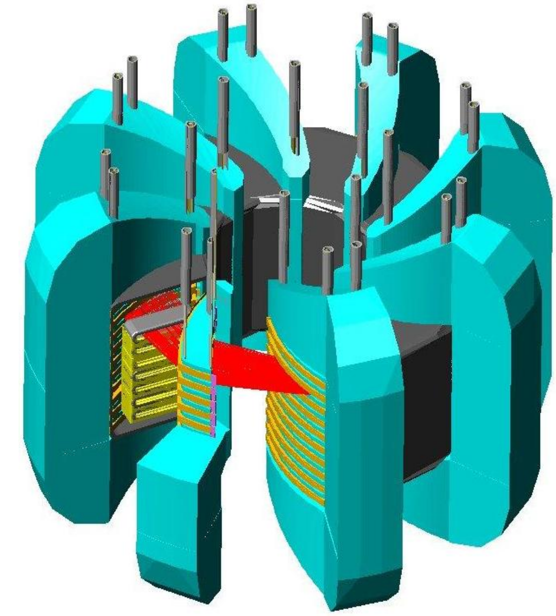

Figure 2. Isotropic cutaway view of a flux-coupled 7-stack of isochronous cyclotrons. The proton orbits in the top IC are shown in red.

The calculated results [4] is summarized in Table 1 and it shows that with a single proton beam the maximum fractional change occurs, which is 100% at all locations. This induces the maximum stress in the various mechanical components including the fuel within the fuel pins. Introducing three beams, delivered to three spallation targets in the target/blanket assembly, results in a maximum fractional change of 42%. Introducing six beams results in a maximum fractional change of 22%.

The peak/average energy deposition is a measure of the overall power distribution within the blanket assembly. The peak/average for the single beam, 3-beam, and 6-beam configurations are 1.58, 1.35, and 1.36 respectively.

With a flatter distribution implied for the multi-beam arrangements, more of the blanket is involved in the transmutation processes, so the efficiency of proton spallation for driving the ADS core would improve.

FLUX-COUPLED STACK OF ISOCHRONOUS CYCLOTRONS

From the performance records of existing high power proton accelerators, it is our opinion that a CW isochronous cyclotron, similar to that of PSI, is closest to fulfill the requirements of an accelerator for ADS applications. Based on the current performance of the PSI Cyclotron [2] and the improved understanding of beam dynamics in high intensity isochronous cyclotrons [4], we consider a reference design which uses the flux-coupled stack of isochronous cyclotrons shown in Figure 2. We consider a 3-stack, in which each IC delivers 800 MeV, 3 mA beam to provide 2.4 MW beam power to its spallation target.

PSI now operates routinely at 590 MeV, 2 mA, 1.3 MW for spallation neutron physics research and has a plan to reach 1.8 MW with component upgrades. To operate the 800 MeV IC at 3 mA, all the lessons learned at PSI must be implemented with care, including:

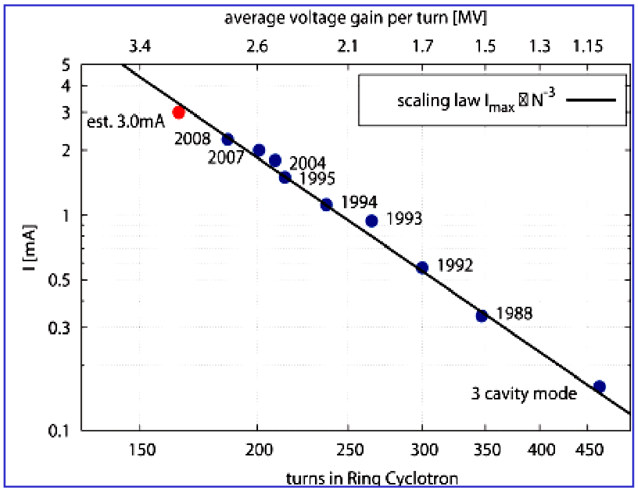

Figure 3. Relation of beam current and voltage gain at PSI

- Prepare the optimum phase space distribution of the injected bunches. It has been found that due to strong transverse-longitudinal coupling in the cyclotron, a round beam is a stationary distribution over the acceleration cycle with little emittance degradation and beam loss [5].
- Provide large enough energy gain per turn of about 3.2 MV to reduce number of turns to less than 170 to achieve 3mA, as shown in Figure 3.
- Provide enough beam separation at extraction to maintain beam loss $<10^{-4}$.
- Provide appropriate beam collimation and scraping to assure beam loss $<10^{-4}$during acceleration.
- Assure accelerator reliability of better than 90% with trip rate less than 5 per hour.

The multiple ICs are configured in a flux-coupled stack to reduce the construction cost. The multiplicity of accelerators can be located in about the same footprint as a single one. All systems for injection, extraction, and rf (which are the most important contributors for reliability) are provided separately for each IC, so that if one fails the others continue to function. The superconducting sector magnets share a common warm-iron flux return (light blue in the figure), the field distribution for each gap is created by a steel flux plate with a superconducting winding boned to its outer boundary. RF acceleration is provided by cavities similar in design to those of PSI but bent 90^{o} so that the lobes lie in the plane of the IC just above and below the beam aperture. An improvement would be to replace the copper cavities by superconducting cavities to improve the energy efficiency. The three beams are separately extracted and transported to the three spallation targets. The total beam power delivered is 7.2 MW, sufficient to drive a high-power fission core. If more power is needed, we can either increase operating current or add ICs to the stack.

SC LINAC ADS DRIVER

The progress in SRF linac technology has made it a possible choice for ADS application. The SNS linac at ORNL routinely operates at 1 GeV, delivering 1.0 MW beam at 60 Hz. FNAL proposes to design and build PX, a 3 GeV CW linac for few-MW operation. In comparing the SRF linac approach to the stacked IC design, there are few observations worth mentioning: a. Currently, there is no MW CW SRF proton linac in operation, b. To be useful, a system of more than 10 MW is needed, which would require a longer time to develop, c. It is harder to resolve the neutron distribution and material fatigue problem with a single spallation target, d. The reliability of a single SRF linac cannot meet the ADS requirement for a fuel-pin core configuration, e. The spallation target for ~10 MW would require aggressive development.

Another important issue needs attention is the construction and operation cost of the facility. Without a reliable design on either accelerator technology, it is impossible to provide a detail cost of construction and operation of an ADS facility. To guide our thinking and provide direction for future work, we still need some rough but useful cost comparisons. Based on historical records, it appears that the cost of one 8 MW CW SRF linac (or three 3 MW SW SRF linacs) would cost ~ three times that of a 3-stack 8 MW IC system. In addition, the corresponding operating power consumption and cost would likely be considerably higher due to its RF system and cryogenic installation.

At this moment, the isochronous cyclotron appears to be closest to meeting all requirements for ADS applications, using realistic and achievable improvements to the technology proven at PSI. A collaboration has been formed to identify a realistic first application of the stacked-IC accelerator system, and we are planning an aggressive R&D program for the accelerator, spallation target, and ADS core.

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