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# ACCELERATOR DRIVEN SYSTEMS FOR ENERGY PRODUCTION AND WASTE TRANSMUTATION

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*Abstract*

Due to their inherent safety features and waste transmutation potential, accelerator driven subcritical reactors (ADSRs) are the subject of research and development in almost all countries around the world. The neutrons needed to sustain fission are generated by the spallation process resulting from high energy protons impacting a target element installed at the centre of the core. In the present paper the possible benefits of FFAGs as accelerator drivers for ADSR systems are analysed. FFAGs afford fast acceleration as there is no need of synchronization between RF and magnets, high average current with large repetition rate and large acceptance. The present study also focuses on the Monte Carlo studies of the reactor core design. The impact of the subcriticallity, target material and proton beam energy on the ADSR performance was also examined. Entirely novel ADSR configurations involving multiple accelerator drivers and associated spallation targets within the reactor core have also been considered. Calculations were carried out using the GEANT4 simulation code.

## INTRODUCTION

Accelerator Driven Systems (ADS) for transmutation of nuclear waste typically require accelerators with proton beam energy between 350 MeV and 1 GeV and delivering proton fluxes of 5-10 mA for demonstrators, and 20-50 mA for large industrial systems [2]. Up to now, only sector-focused cyclotrons and linear accelerators are able to provide proton beam currents in the mA region. Recent studies have shown that a Fixed Field Alternating Gradient (FFAG) accelerator could meet these requirements and would also be more cost-efficient to build and operate than a linac.

The first part of this paper shows some preliminary studies on the design of a non-scaling FFAG prototype that could be used to accelerate the proton beam to energies suitable for an ADSR. The second part is focused on the neutronic aspect of the problem. It starts from a fast neutron ADSR design, using pure lead as spallation target, coolant and reflector in the framework of the ADSR proposed by C. Rubbia [1]. The simulation data is used to see if one can improve the reactor design by changing the target position and considering whether different designs with multiple targets would improve the reactor performance.

## ACCELERATOR STUDIES FOR AN FFAG DRIVEN ADSR

An FFAG would be used to boost protons from a 70 MeV cyclotron, as used at PSI, to sufficient energies of up to 1 GeV. An FFAG's magnetic fields stay constant during the acceleration cycle. It is therefore possible to run it in a continuous mode.

It has been suggested [3] that it may be possible to design an FFAG lattice based on a synchrotron, with the dispersion minimised and the apertures wide enough to accommodate a wide range of energies.

A lattice with 30 × 1 m cells, each with a focusing quadrupole, a dipole, a defocusing quadrupole and a drift has been studied. The magnetic element lengths were constrained to 200 mm, with 50 mm gaps and a 300 mm drift. The lattice was optimised to reduce the maximum distance between low and high energy closed orbits, and to reduce the time of flight variation.

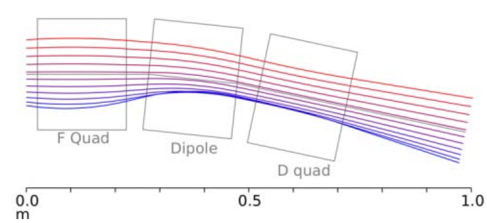


Figure 1: Tracks for energies from 70 (blue) to 500 MeV (red).

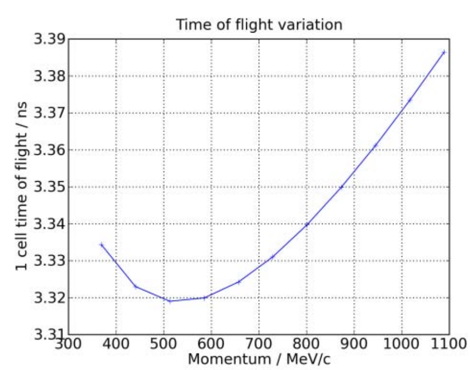


Figure 2: Time of flight variation.

Particle tracking was done using Zgoubi [4]. It follows each particle for many steps though the magnets, and re-

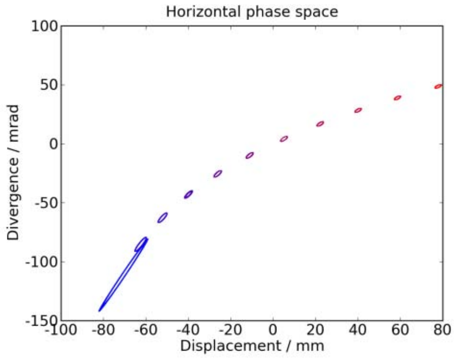


Figure 3: Horizontal phase space for 10000 cells, after 1 mm displacement, for energies from 70 MeV (Blue) to 500 MeV (Red).

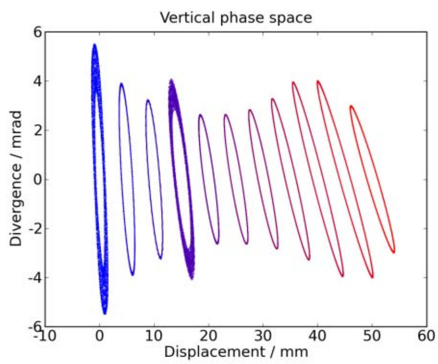


Figure 4: Vertical phase space for 10000 cells, after 1 mm displacement, for energies from 70 MeV (Blue) to 500 MeV (Red). Plots are artificially separated in displacement.

evaluates the field and forces at each step. This is needed as trajectories are non-paraxial.

The final values achieved were, dipole strength of 2.7142 T, focusing gradient of 28.604 T/m and defocusing gradient of 19.398 T/m. The time of flight variation was 0.0674 ns, and the maximum separation of beams was 157.76 mm. Fig. 1 shows how the closed orbits say close to the centres of the magnets.

Fig. 2 shows the time of flight variation, this must be small so that the RF frequency can remain constant.

To confirm that the closed orbits are stable, the starting coordinates were offset by 1 mm horizontally and vertically. These particles were tracked for 10000 cells. Figures 3 and 4 show the coordinates traced out in phase space. The particles remained confined to stable orbits in both cases.

## REACTOR CORE STUDIES

The reactor geometry for the proposed Accelerator Driven System has been implemented into a GEANT4 simulation code [5].

In GEANT4 there are two intra-nuclear cascade models that could describe the neutron spallation processes: the Bertini and Binary cascade models and they both have been previously validated against data from Los Alamos experiments. The validation plots of the Binary cascade model are shown in Fig. 5 for different target materials including Pb.

The validation plots for the Bertini model are shown in Fig. 6 for the same target materials.

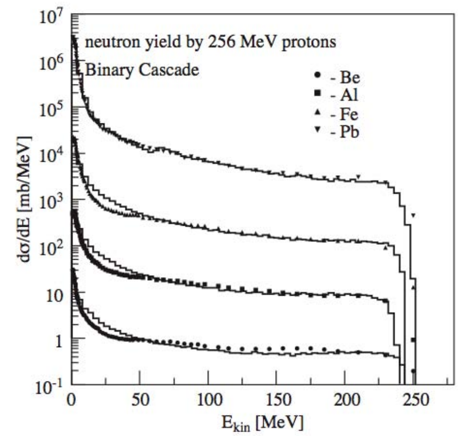


Figure 5: Neutron yield produced by 256 MeV protons. Histograms - Binary Cascade predictions, points - data [6].

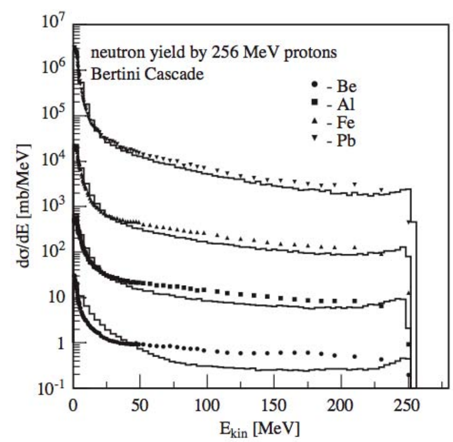


Figure 6: Neutron yield produced by 256 MeV protons. Histograms - Bertini Cascade predictions, points - data [6].

Binary Cascade reproduces the data rather well for all targets for energies above 50 MeV, while below 50 MeV the neutron evaporation becomes important for light targets (Fig. 5). For Pb targets there is very good agreement between the data and the model predictions over the whole energy range. In contrast to Binary Cascade, the Bertini model reproduces only the general trend of the data above 50 MeV (Fig. 6), but does well below 50 MeV for all targets.

The Binary Cascade model has been used in our code to describe the nucleons and pions interactions at intermediate

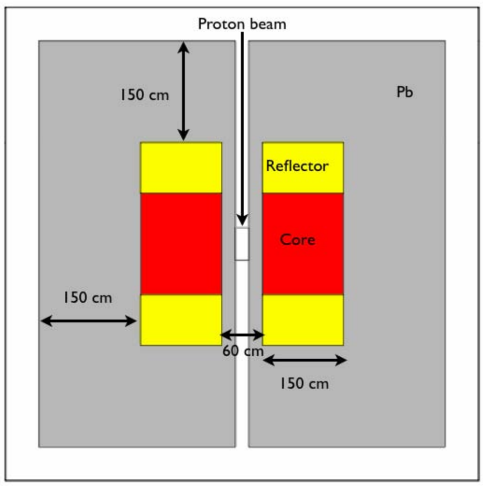


Figure 7: Longitudinal section through the lead-cooled subcritical reactor. The target is made of lead, and the reactor is surrounded by a Pb reflector. The 1 GeV proton beam of 10 cm radius hits the target from the top.

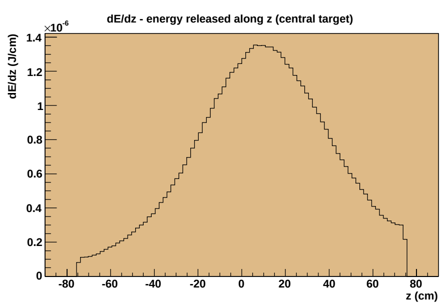


Figure 8: $z$-dependence of the energy released inside the core for a central target position.

energies (65 MeV - 6.1 GeV) and the pre-equilibium model for lower energies (20 MeV -70 MeV).

As already indicated the model of the subcritical reactor is based on the Energy Amplifier proposal by C. Rubbia [1]. It consists of a reactor with $Th^{232}/U^{233}$ fuel, with lead as the coolant, moderator and reflector material. Also the target is made of lead and has a diameter of 20 cm and a length of 48 cm. The longitudinal section is shown in Fig. 7. The core is surrounded by $ZrO_2$ and Pb reflectors. The z-axis is defined as the axis along the direction of the incoming proton beam (Fig. 7).

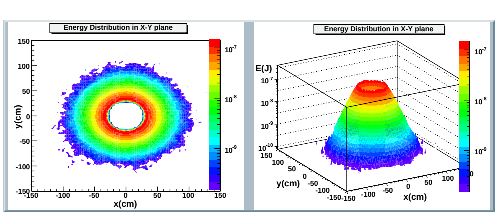


Figure 9: Energy distribution inside the core - transversal plane.

The z-axis dependence of the energy released inside the core is shown in Fig. 8, for a central position of the target. The maximum of the energy distribution is at $z \approx 10$ cm. Therefore, lowering the Pb target by 10 cm will result in an optimum energy distribution inside the core.

The energy distribution within the transverse plane (X-Y) is shown in Fig. 9 and it shows that the largest fraction of energy released inside the reactor core region is released in the central part of the core and that very few fission neutrons reach the outer regions.

## CONCLUSION

The first part of the paper showed preliminary studies for the design of a non-scaling FFAG which is believed to be the best candidate for an ADSR unit. It has been shown that the FFAG design can stably hold beams of a sufficient range of energies, however variables such as magnet lengths, positions and face angles, the existing lattice could be further optimised. It may be possible to use an optics code to give quick approximate parameters before using the more complete tracking code. It will also be necessary to add acceleration in to the model.

The second part of this paper describes a first attempt to use the GEANT4 simulation code to simulate an Accelerator Driven Subcritical Reactor, and presents few attempts to improve the initial design proposed by Rubbia [1], which was based on the idea of using a standard nuclear reactor design. This study showed that by lowering the Pb target one can get a better energy distribution inside the core. It also showed that the energy output inside the reactor is localised in the central part of the core and therefore the design could be improved by considering multiple targets inside a homogeneous core, leading to a more uniform energy distribution inside the reactor.

After implementing the multiple-targets geometry into the code, the next steps would be to simulate the reactor power output distributions for the $Th^{232}/U^{233}$ fuel reactor and for different fuel enrichment values, and though different initial values of the criticality $k_{eff}$.

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