Development of Advanced Modulators for Recirculating Heavy-Ion Accelerators

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INTRODUCTION

Heavy-ion accelerators are considered to be one of the promising driver alternatives for inertial fusion.[1] In a heavy-ion inertial-fusion driver, multiple beams of heavy ions are accelerated to the kinetic energies needed to ignite a fusion target. During acceleration, the beams of heavy ions are compressed from initial pulse durations of 10's to 100's of microseconds to a final pulse duration in the reactor of approximately 10 nanoseconds. The compressed beam of heavy ions is focused on the target in a reactor chamber where the energy released from the fusion reaction is converted to thermal energy and eventually to electricity.[2] Several approaches for accelerating heavy-ions have been proposed including RF accelerators, conventional linear induction accelerators, multi-pulse linear accelerators and recirculating induction accelerators (recirculators).[3]

A recirculator is an induction accelerator which accelerates the particles and bends them in a closed path with dipole magnetic fields. A single beam traverses the same accelerating cavities many times (50-100) to acquire its final energy. The primary motivation to evaluate recirculators is the potential for significant cost reduction over conventional linear induction accelerators. This results from re-using many of the most expensive accelerator components, e.g. induction cells, pulsers, and focusing magnets, many times during one acceleration sequence. The idea of recirculation is not new, but only recently has a thorough investigation of this concept been conducted.[4]

One of the areas of technology that is critical to the feasibility of a recirculator is the modulator system which generates the pulses that accelerate the ion beams. System studies were conducted which helped identify the desirable modulator characteristics. The following section will briefly describe the system studies.

OVERVIEW OF SYSTEMS STUDIES

A system model was developed to evaluate cost and efficiency in a complex recirculator system. This model uses the appropriate physics and engineering relationships to identify a self-consistent configuration for a recirculator given certain input parameters such as ion species, ion mass, output energy etc. Cost algorithms have been derived to estimate the cost of each recirculator sub-system. Energy losses are also calculated to estimate the overall system efficiency. Using this model, different accelerator parameters can be varied, such as accelerator cell voltage, dipole magnet field strength etc., to determine their effect on the overall system cost and efficiency.

The induction cell modulator system was identified in the studies as having a large impact on the cost and efficiency of a recirculator. The cost of the modulator/cell system in a recirculator can be as much as 25% of the cost of the recirculator if the estimates are based on today's technology at today's costs. The cost of such a modulator, using FETs as the opening/closing switch, in today's dollars has been estimated to be approximately .05 ¢/watt of peak power.[5] At 25%, the modulator/cell system would be the most expensive system in the recirculator. Modest improvements in technology and cost through investment in development can reduce this percentage to around 10% which is more in balance with the other system costs. The system studies indicate that an FET modulator would need to cost approximately .01 ¢/watt peak to be a feasible and attractive choice for a recirculating heavy-ion driven power plant. This is certainly plausible considering the time scales of fusion energy and the trends in solid state technology over the last couple of decades.

Figure 1 is a breakdown of the power consumption in a recirculator system. The figure shows that approximately 30% of the total losses in a recirculator are in the acceleration system (modulators and induction cells).

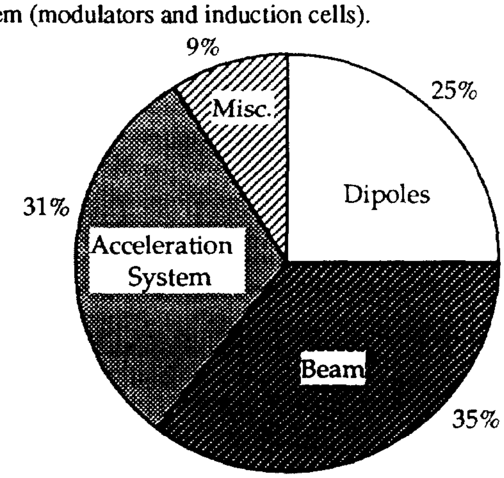

Figure 1. Breakdown of power consumption in a recirculator.

As will be discussed in a later section, the power consumption in the acceleration system is a strong function of the pulse format that is used to accelerate the ion beam. It is apparent that one of the highest leverage areas for reducing cost and increasing the efficiency of a recirculator is the induction cell/modulator system.

MODULATOR SYSTEM REQUIREMENTS

In a recirculating heavy-ion accelerator, the induction cell modulator must generate a voltage pulse capable of driving a load consisting of the magnetic material in the induction cell and the ion beam. The characteristics and performance requirements for the modulator system are influenced by a number of factors including system efficiency, beam energy, recirculator configuration and beam dynamics.

Efficiency

The driver efficiency is dependent on the type of pulse format used to drive the induction cells. The energy dissipated in the magnetic material of the induction cells is the largest loss in the recirculator system. The induction cell losses, assuming the magnetic material is Metglas 2605 S-2, can be expressed by the empirical relationship shown in equation 1 where K=140, m=-.8, n=1.8, V is the magnetic material volume, ΔB is the flux density and Δt is the pulse width. A comparison of energy loss in the induction cells for three different acceleration pulse formats is shown in figure 2.

$$E = VK\Delta t^m \Delta B^n \qquad (1)$$

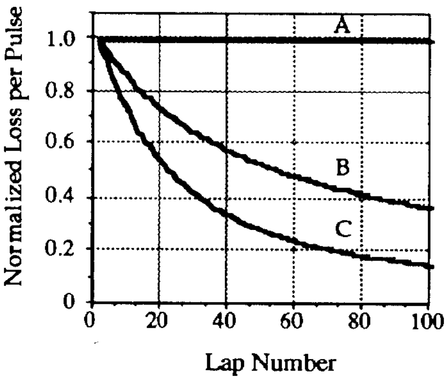

Figure 2. Magnetic losses per lap for different pulse formats.

Plot "A" is a plot of the energy lost in the induction cores for each pulse in a 100 pulse acceleration sequence where the pulse width and pulse amplitude are maintained constant. As one would expect, the losses are the same for each pulse.

Plot "B" represents an acceleration sequence where the pulse duration is directly proportional to the velocity of the beam (constant pulse length acceleration) and the acceleration pulse amplitude is constant. The induction cell losses on each successive pulse decrease. This is because less flux ø, (=∫ V dt) is required for each successive acceleration pulse. Since the cross-sectional area, A, of the induction cores does not change between pulses, ΔB (= ∫ ø dA) decreases.

Plot "C" is a plot of the losses for an acceleration sequence where the ion beam is compressed in both time and space. In this particular plot the pulse duration is decreased approximately proportional to the square of the velocity. Note that with this acceleration sequence the loss per pulse is even less. The total loss for the "C" case is approximately 30% of the losses for the constant pulse duration acceleration schedule of plot "A". Case "C" is the preferable pulse format based on efficiency.

Repetition Rate

The repetition rate of the acceleration pulses must vary because the heavy ions are sub-relativistic and increase in velocity as they are accelerated. The repetition rate varies from a few kilohertz initially, to greater than 50 kilohertz for the last few pulses in one acceleration sequence.

The pulse repetition rate, f_o, is determined by the energy of the particles and the circumference of the recirculator as :

$$f_o = \frac{\beta c}{L} \qquad (2)$$

where L is the circumference of the recirculator ring, c is the velocity of light in a vacuum and

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \qquad (3)$$

where

$$\gamma = 1 + \frac{E}{mc^2} \qquad (4)$$

E is the particle energy in joules and m is the particle rest mass in kilograms. In general, the circumference of the recirculator is determined by the maximum field that can be generated by the dipole magnets which bend the beam. A typical recirculator requires a peak dipole field of ≈ 2T, resulting in a circumference of approximately 2 km and a peak repetition rate of ≈ 50 kHz for mass = 200, charge state = +1 ions. Figure 3 shows how the modulator repetition rates vary as a function of particle energy for various particle masses. The repetition rates plotted assume a circumference of 2 km. Repetition rates for a different circumference can be easily obtained by dividing the repetition rate by the appropriate scale factor (L/2 km).

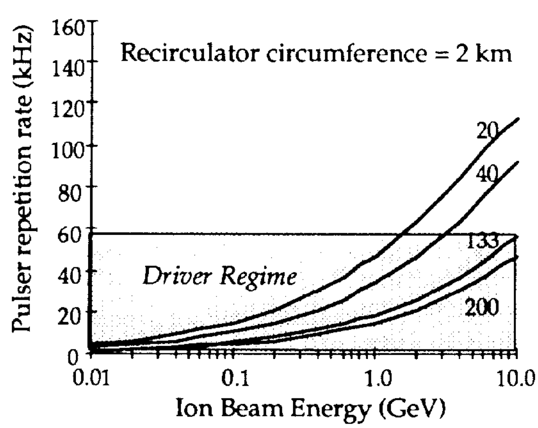

Figure 3. Modulator rep-rate vs. particle energy

Reset

The induction cell core material is a magnetic material which must be reset between acceleration pulses. The modulator that drives the induction cell must provide an inverse voltage to reset the core material before the next pulse. Insufficient reset or no reset would allow saturation of the induction cell core material resulting in little or no acceleration voltage appearing at the gap after the first few pulses. The amplitude of the reset pulse is dependent on the time available for reset because the $\int Vdt$, where V is the amplitude of the modulator output, must be equal for the main accelerating pulse and the reset pulse.

Beam Dynamics

From the standpoint of accelerator physics, a modulator with pulse to pulse agility using an on/off switch is desirable for two reasons. The first reason is that pulse agility allows a constant and more gentle compression of the beam during the acceleration sequence. Elimination of abrupt changes in beam size and velocity eases some of the physics issues associated with maintaining the ion beam quality. The second reason is that on/off switching capability allows a modulator configuration that provides for very low drive impedance for the cells which helps alleviate longitudinal instabilities in the beam.[6] The growth rate of these instabilities is proportional to cell impedance which can be made very low if the source is a large capacitor bank being switched by a device with on/off capability.

Figure 4 shows what a typical pulse format might look like if all of the considerations mentioned in the previous sections are taken into account. The main accelerating pulse (shown as positive) is followed by a reset pulse (shown as negative). In this particular scenario, the main accelerating pulse width varies from approximately 2.5 µs to about 250 ns while the repetition rate varies from approximately 10 kHz to 50 kHz. The time available for reset ranges from less than 100 µs to less than 20 µs.

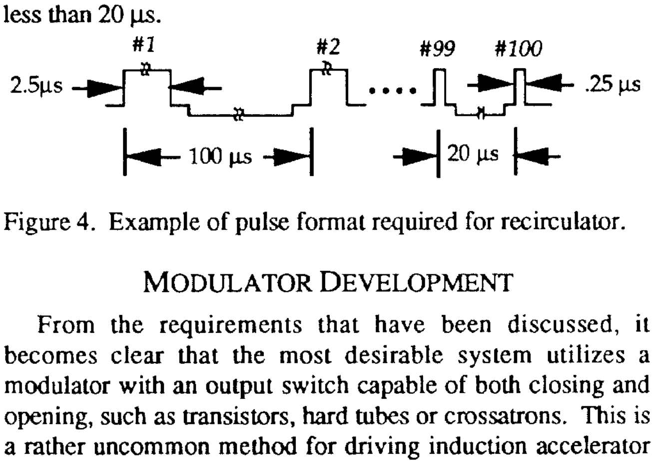

Figure 4. Example of pulse format required for recirculator.

MODULATOR DEVELOPMENT

From the requirements that have been discussed, it becomes clear that the most desirable system utilizes a modulator with an output switch capable of both closing and opening, such as transistors, hard tubes or crossatrons. This is a rather uncommon method for driving induction accelerator cells, but for a recirculating accelerator there are significant advantages. This type of modulator would meet all of the desired requirements mentioned previously, enabling the continuous compression of the beam throughout the acceleration sequence increasing the overall machine efficiency.

There are several possible future applications for this type of modulator, i.e. recirculator and multi-pulse linear accelerators, but the most immediate need may be a small recirculator experiment on LBL's ILSE accelerator. The recirculator experiment, if built, would provide the first test of recirculating technology in an integrated system. A development plan has been defined that will provide the information necessary to design the modulators for a recirculator on ILSE and develop a database of information and experience to guide future development efforts.

The first investigations have focused on modulator topologies that rely on switches with on/off capability. Small-scale, solid-state models have been built to experimentally evaluate the feasibility of driving an induction cell with an on/off switch. The issues of magnetic material reset and maintaining pulse to pulse voltage regulation at repetition rates in excess of 50 kHz are being addressed. Our first objective is to achieve > 50 kHz operation at a few kilovolts to prove the concept and provide a basis for understanding the limitations on high repetition rate operation of an induction accelerator. Preliminary tests of single solid-state devices driving a Metglas load have been conducted and the design of the first small-scale modulator is in progress.

CONCLUSIONS

The choice of modulator configurations is a complex process that must consider the entire system. The systems studies that have been performed to date have identified very strong advantages for a modulator with agile pulse generation capability. Solid state devices , such as field effect transistors, appear to be a viable choice for this application. The present capabilities of arrays of solid state devices are not far from meeting some of the switching requirements such as repetition rate, voltage and current needed for the modulators. However, the modulators must also deliver a precisely tailored and well regulated acceleration pulse to the induction cells as well as provide a reset pulse for the induction core material. At present the cost of such a modulator is too high for a commercially viable power plant, but relatively modest improvements in the technology and cost would make this a plausible approach.

Modulator development work has begun at LLNL, to evaluate concepts and limitations of these concepts for agile high-repetition rate modulators. A small scale model is being used to evaluate different network topologies that may be used in the design of our first field effect transistor modulator which will be tested later this year.

REFERENCES

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