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HIGH REPETITION RATE PULSER CONCEPTS FOR A RECIRCULATING HIF DRIVER†

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Recently a study on recirculating induction accelerator drivers for HIF was initiated to address feasibility and cost. One of the major engineering issues associated with designing and building a recirculating induction accelerator is the method used to drive the accelerating cells. High-repetition-rate pulsers (≤ 50 kHz) are required to accelerate the ion beams in a recirculating scheme. Different accelerating schemes have been evaluated to reduce cost and technical risk in the pulser design. This paper will describe the pulser requirements and concepts. The issues of cost, efficiency and feasibility will be addressed.

1 INTRODUCTION

The use of induction accelerators as drivers for heavy ion fusion power plants has been studied extensively for several years.[1] A natural extension of the linear accelerator technology is to re-use the accelerator systems multiple times by recirculation of the ion beam. One of the motivations for looking at recirculating schemes for accelerating heavy ions is the potential for significant cost reductions in some of the more expensive linear accelerator systems. In many cases, however, the cost reductions realized by recirculation in one accelerator system can be offset by increased costs in another system due to the added complexity of a recirculator. One of the systems that is significantly more complex is the set of induction cell drivers that provide the accelerating potential for the heavy ions. The system requirements are more demanding and require the use of more expensive hardware. The following sections will describe and discuss the accelerating system requirements and conceptual designs for the induction cell drivers.

2 SYSTEM POINT DESIGN

The point design evaluated in this study was a 4-MJ driver composed of four separate rings for accelerating the heavy ions to a final energy of 10 GeV. The injection ring (IR) accelerates the beam from 2 MeV to 10 MeV, after which the ions are extracted and injected into the low energy ring (LER) where they are accelerated to 100 MeV.

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TABLE 1
System Parameters for Recirculating Accelerator Design

		IR	LER	MER	HER
Atomic mass	200				
Charge state	1				
Charge per beam (μC)	100				
Initial Energy (GeV)		0.002	0.01	0.1	1
Final Energy (GeV)		0.01	0.1	1	10
Initial Pulse Width (μs)		67	27	3.5[a]	0.55[a]
Final Pulse Width (μs)		27	3.5	0.55	0.1
Number of beams		4	4	4	4
Initial beam current per beam (A)		1.5	3.7	28.6	182
Final beam current per beam (A)		3.7	28.6	182	1000
Circumference (meters)		156	278	921	2592
Number of acceleration laps		50	50	50	50

[a] Constant-pulse-duration acceleration with pulse compression after acceleration.

The medium energy ring (MER) and the high energy ring (HER) accelerate the ions to 1 GeV and 10 GeV, respectively. Table 1 below summarizes the point design used for this study.

3 INDUCTION CELL PULSER SYSTEM REQUIREMENTS

Induction cell pulsers provide the accelerating potential to accelerate the heavy ions. Each pulser in the system must generate a pulse with the appropriate waveform at the appropriate time and deliver it to an induction cell. The ion beam is accelerated as it traverses the gap with the potential provided by the pulser. The specific system requirements for the induction cell pulsers are a result of evaluating tradeoffs among physics requirements, pulser feasibility, system cost, and system efficiency. In this study, existing technology was used as a basis for evaluation of pulser feasibility and cost. Technology development (and its impact on the induction cell pulser systems) was not addressed but certainly will be in the future.

The pulser system and the load characteristics must be defined before a conceptual design can be chosen. The system requirements for the induction cell pulsers in each of the four rings are summarized in Table 2. Note that the pulser requirements for each of the rings are significantly different. The amplitude, shape and duration of the accelerating pulses vary from ring to ring in the recirculator. The required pulse width decreases by greater than two orders of magnitude and the required pulse amplitude increases by a factor of 30. This wide dynamic range necessitates the use of multiple pulser types to drive the various induction cells.

The repetition rate requirements and the average power requirements for the induction cell pulsers in a recirculating accelerator differ significantly from the requirements for induction cell pulsers in a linear machine. In the recirculator, the same pulsers are used multiple times to accelerate a beam to the desired energy. The

TABLE 2
Induction Cell Pulser System Requirements

	IR	LER	MER	HER
Initial pulse repetition rate (kHz)	9	12	10	12
Final pulse repetition rate (kHz)	20	38	35	37
Induction cell voltage (kV)	5[a]	10[a]	40	150
Estimated peak drive current/cell (A)	150	160	300	1300
Average input power of total system (MW)	1	5.3	13	88
Pulse duration (μs)	67–27	27–3.5	3.5	0.55
Average repetition rate (Hz)	500	500	500	500
% pulser energy delivered to beam	4	8	35	53

[a] Average cell voltage.

recirculator pulsers must be capable of producing pulses every time the beam passes through the cell during the acceleration sequence. The time period between laps is determined by the energy of the beam and the circumference of the individual rings. The maximum repetition rates for the pulsers in each of the rings in this point design are listed in Table 2.

The first two rings in the recirculator, IR and LER, require pulses that vary in amplitude, shape and duration from pulse to pulse during a single accelerating sequence. The output pulses are very long ($67\ \mu\text{s} > \text{pulse width} > 3.5\ \mu\text{s}$) and the amplitudes are relatively low (< 10 kV average). This requires a very "agile" induction cell pulser with a switch that is capable of operation in the linear mode. The final two rings of the recirculator have been configured to utilize a fixed pulse duration and amplitude to accelerate the ion beam. This allows the use of a simpler and less expensive pulser design than is required for the first two rings. In both cases, the size and cost of the pulser systems is dependent on a number of different factors. These factors include the peak repetition rate, average power, acceleration requirements and load characteristics.

The pulser systems for a recirculating accelerator must also be capable of high-average-power operation. The average repetition rate is equal to nf_0, where n is the number of laps that a beam will make around a ring and f_0 is the average repetition rate required at the reactor chamber. In the point design described in this paper ($n = 50$, $f_0 = 10$ Hz), the average repetition rate is 500 Hz. Table 2 summarizes the average power requirements for the induction cell pulser systems for each of the rings.

Pulser load characteristics are more difficult to define because the load consists of two components: the ion beam current and the magnetization and loss current of the magnetic material in the induction cell. The percentage of energy delivered to the induction cell that is used to accelerate the beam varies in each ring of the recirculator and depends on the ion beam current, pulse width, and amplitude, as well as the induction cell configuration. The predominant component of the load is due to the magnetic material in the induction cell, whose exact characteristics depend on the choice of magnetic material and the geometry of the induction cell. Metglas 2605 S-2 was chosen for this study because of its low cost and acceptable loss characteristics. A comprehensive comparison to other materials has not been done. The magnetic losses of 2605 S-2 were estimated using published experimental data.[2] The percent of pulser output energy delivered to the beam is summarized in Table 2.

4 INJECTION AND LOW ENERGY RING PULSERS

The induction cell pulsers for the IR and LER must have the flexibility to generate a wide spectrum of pulse shapes and amplitudes. Controlling the waveform that is delivered to each cell in a very precise manner requires the use of a device capable of operation in the linear mode. There are several possible devices that could be used for this application. Some of the possible devices include series/parallel combinations of bipolar transistors or field effect transistors, as well as vacuum tubes. Vacuum tubes were evaluated for this study because of the relatively high voltages needed at the cells.

A simple schematic of the hard-tube modulator is shown in Figure 1. The hard tube is simply used as a series element which can vary pulse widths, amplitudes and pulse shapes. The bandwidth of vacuum tubes is more than adequate to provide any intrapulse shaping that might be necessary.

In addition to generating the acceleration pulse, the pulser system must also provide pulses of opposite polarity to reset the magnetic material in each induction cell. The condition that must be met for cell reset is $\int v_{\text{reset}}\,dt \geq \int v_{\text{acceleration}}\,dt$. This condition can be satisfied with a fixed duration pulse and does not require the agility needed for the accelerating pulse. There are several possible methods for resetting the induction cells, but the most straightforward method would be to use a separate fixed-pulse-length pulser.

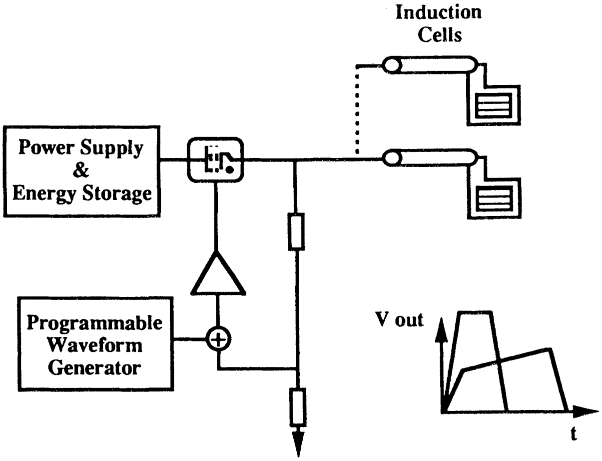

FIGURE 1 Conceptual design for induction cell pulsers in injection and low-energy rings.

The efficiency of this type of induction cell driver depends on the actual operating requirements. The more pulse tailoring required, the more inefficient the pulser system becomes on account of power dissipated in the switch. The efficiency with which energy is transferred to the beam in the overall pulser system in the IR and LER is very small. The reason is that the magnetization current of the magnetic material in the induction core is greater than the ion beam currents in these two rings. Fortunately these two rings only provide a small fraction (1%) of the 4 MJ of beam energy, so inefficient operation can be tolerated. The cost of the hard tube modulators were estimated to be about \$0.04 per watt of peak power delivered to the induction cell. This estimate is based on the component costs and labor estimates required to build a single hard-tube modulator.

5 MEDIUM AND HIGH ENERGY RING PULSER

A fixed pulse format was adopted for the two higher-energy rings, MER and HER, to enable the use of fixed-length pulse-forming lines or pulse-forming networks. This type of pulser is much less expensive than the linear type of drivers used in the IR and LER, although the repetition rate and average power required present some significant challenges.

The peak repetition rate for the pulsers in the two higher energy rings is <40 kHz. Multiple parallel channels of switching circuits are employed on the primary side of the step-up transformer in order to achieve the high repetition rates. A magnetic switch was chosen for the output switch because of its high repetition rate capability.[3] A schematic of the conceptual design is shown in Figure 2.

Four channels of thyratron switching are used to achieve the 40 kHz repetition rates in the PFL charging circuits. Thyratrons were chosen for this study because they are relatively inexpensive at a cost of approximately 10^{-5} $\$/w_{\text{peak}}$. The S1 thyratrons are used to resonantly charge the intermediate storage capacitors, C2. These capacitors are then alternately discharged with thyratrons, S2, into the primary of a dual resonant transformer, T1, with a coupling coefficient of 0.6, to resonantly charge the Blumlein[4,5,6]. As the voltage on the Blumlein reaches its peak, the magnetic switch S3 saturates and discharges the Blumlein into the induction cell load, delivering the appropriate pulse width and amplitude.

There are several advantages to using this type of configuration for the induction cell pulsers. One of the advantages is that all of the magnetics in the system are reset during the Blumlein charge cycle. The magnetic material in the induction cells is reset by the Blumlein charge current, which flows through the induction cell. The magnetic material in the magnetic switch, S3, is reset by the bipolar voltage waveform on the secondary of the resonant transformer. This waveform is shown in Figure 3 for a dual resonant charging system where the leakage inductance of the circuit is external to the transformer. It can be seen from Figure 3 that the integral of the voltage over one complete charge cycle, $\omega t = 4$, is equal to 0. This means that the magnetic material in the magnetic switch ends up at the same flux state where it started. As a result, with this type of configuration, there is no need for an additional

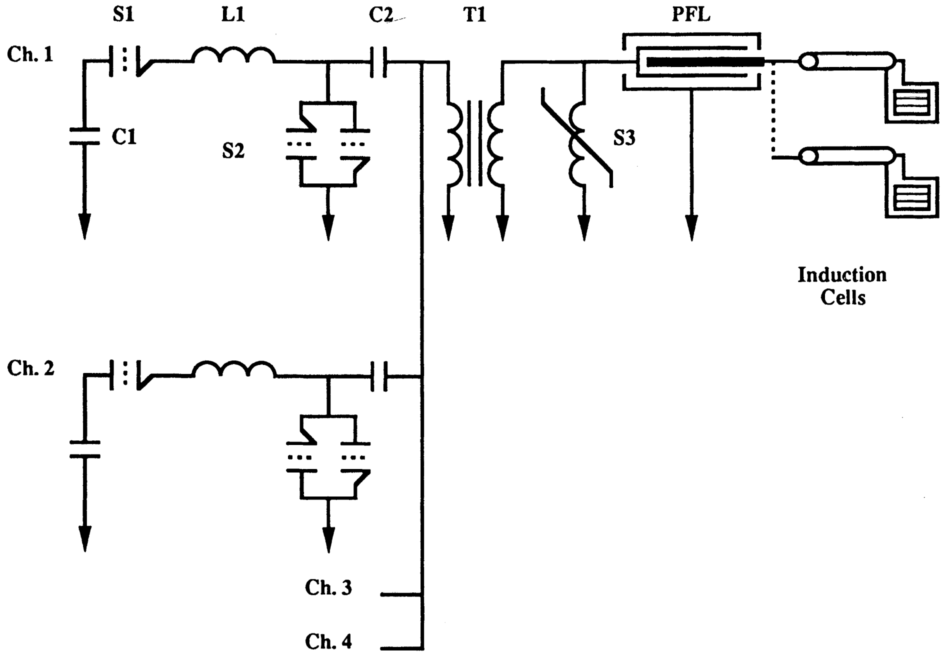

FIGURE 2 Conceptual design for induction cell pulsers in medium-energy and high-energy rings.

pulser circuit to reset the cell magnetic material or the magnetic switch between pulses.

The efficiency of this pulser concept was estimated by calculating the losses of each of the components in the conceptual design. The efficiency of this type of pulser has been estimated to be 75–80% with the primary losses being in the magnetic switch

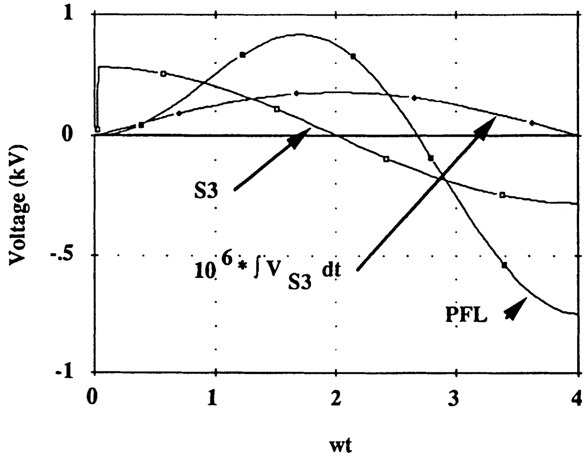

FIGURE 3 Secondary circuit voltages for dual resonance charging of PFL.

and the thyratrons. The cost of this type of a pulser was estimated to be approximately $240 per joule of output energy. This estimate was based on the component costs and labour estimates required to build a single pulser. The predominant cost component of this design is the thyratron switching followed by the cost of the magnetic switch. This particular conceptual design has not been optimized to minimize losses or cost.

6 CONCLUSIONS

These conceptual designs are based on a non-optimum point design for a recirculator system and are limited by the use of existing technology. There is considerably more work required to explore the possibilities of future development work and how it might impact the induction cell driver designs as well as the overall system design. The conceptual designs presented here all appear to be feasible using existing technology, but the impact of advanced pulser technology on the driver system must also be evaluated.

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