REVIEW OF NEW DEVELOPMENTS IN THE FIELD OF INDUCTION ACCELERATORS (ELECTRONS AND IONS)*

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INTRODUCTION

Induction machines have the unique capability of delivering very high current and peak power in a pulsed mode. It was the need for high power for fusion that led Nicholas Christofilus in the 1950's to invent and build Astron, the first induction accelerator [1]. Since then, various high power applications have led to the construction of the Electron Ring Accelerator (ERA) [2], Experimental Test Accelerator (ETA) [3], Advanced Test Accelerator (ATA) [4], the flash radiography machine FXR and the high repetition rate machine, ETA II [5], which was designed to deliver high average power as well as high peak power. The largest of these machines is ATA with design goals of 50 MeV and 10 kA. All of the high current electron machines since ERA are "short-pulse" devices (~50 ns). Meanwhile, the invention of heavy ion fusion in the 70's led to the development of induction machines for ion acceleration [6]. For this application, the devices tend to have long pulses (>1 μs). The induction machines for ions and electrons operate on the same principle. The pulse length difference between electron and ion machines is historical and incidental, although long-pulse devices lead to different approaches to magnetic material and pulse power technology than short-pulse machines.

While some of the past applications, particularly those related to the Strategic Defense Initiative, have come and gone, the need for high power continues to exist in energy, environment, national defense, and basic sciences. In this paper, we will review three ongoing applications, one in fusion energy, one in defense, and one in high energy physics. Induction machines for heavy ion fusion [7], for radiography in hydrodynamic tests [8], and for relativistic-klystron two-beam-accelerators [9] are three areas of active research. Induction machines have also been considered for other applications such as treatment of nuclear wastes [10], neutron spallation sources [11], and μμ collider components [12]. These applications will not be reviewed here because of space limitations. In addition, the inductive voltage adder (IVA) technologies are described in a separate paper in these proceedings [13]. The three applications we will review were chosen to demonstrate that with vastly different goals, different machine parameters, and very different architectures, a similar set of performance objectives has led to technological advances along closely parallel paths.

In any large machine, the economic issues of cost and efficiency, and the technological issues of machine and beam performance are equally important considerations. We hope to show how these factors have affected the development paths in these three areas. We will first summarize recent activities in each one of these fields, and then proceed to describe issues and advances in the control of beam energy flatness, emittance preservation, and beam instability suppression. While these issues are common to all accelerators, the fact that we are working with very intense beams and long pulses makes the challenges of induction machines unique. For the purpose of this review, we will broadly include the induction accelerators proper, as well as their injectors.

RECENT DEVELOPMENTS

Heavy Ion Fusion

Induction linac technology has been the primary approach to the heavy ion fusion driver in the U.S. The baseline scenario [6, 7] consists of multiple beams of heavy ions, sharing common (large) induction cores. These beams are focused by electrostatic quadrupoles in the front end, and magnetic quadrupoles at the higher energies. The beams are many microseconds long in the front end, and are compressed eventually to about 10 nanoseconds at the target. To hit a target spot of several millimeters within a reactor of several meters in diameter, the ion beams must have low emittance and less than a percent of energy spread [14]. The ions are non relativistic and space-charge-dominated, and collective effects play a central role in the beam dynamics.

Early experiments at LBL had demonstrated transport of space-charge-dominated beams in electrostatic quadrupole channels (SBTE) [15] as well as the simultaneous acceleration of four beams (MBE-4) [16]. An ongoing experiment at LBL seeks to demonstrate the combining of four separate beams into one with acceptable emittance growth [17]. Beam combining is motivated by the economics of the fusion driver where attractive cost savings could be realized with many beams in the front end and fewer beams at higher energy. Small scale tests of magnetic quadrupole transport, final focusing, and beam bending are also planned in order to address the beam dynamics issues anticipated in the final driver.

An alternative accelerator architecture in a recirculating configuration [18] where induction cores and magnetic transport lines are being reused as the beam is recycled about 100 times is also being studied, both in a driver-design study [19] as well as in a small-scale recirculator experiment at Lawrence Livermore National Laboratory [20]. This scenario involves higher technical risks, but the architecture has the potential of large cost reductions for the driver. Recirculator studies have led to development of advanced technology elements such as very fast and flexible switching at high repetition rates [21].

In addition to these small scale experiments, much of the HIF engineering effort has been directed to the cost reduction of key components, such as the magnetic material, the

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electrostatic and magnetic focusing elements, alignment techniques, etc. [22]. Underlying much of these physics and engineering studies is the ultimate goal of making heavy ion fusion as competitive as the lowest cost energy options in the market.

An equally important programmatic goal is to work towards the production and control of driver-scale beams. An injector with driver-scale energy (2 MV), current (0.25 μC/m, or 800 mA of singly charged potassium ions), and emittance (normalized edge emittance of less than 1^{1} mm-mr) was constructed and successfully operated at LBL [23]. The beam parameters are required to be constant over the entire pulse of 1.5 μs. Such a demonstration was essential as a first step towards the highly controlled beam performance required for the ultimate fusion driver. Detailed measurements of beam current, energy, envelope, and transverse phase space were also essential for validating 3-D PIC codes which have been developed to model performance of fusion drivers [24]. The agreement between experiments and simulations have been excellent thus far [25]. Various experiments to transport, focus, and bend space-charge-dominated beams have been performed, using this beam, and more are planned.

Radiography for Hydrodynamic Tests

Development of induction machines for X-ray radiography are ongoing in the U.S. and in France. The goal is to design machines with 3 to 4 kA of electrons, 15 to 20 MeV and about 60 nanoseconds, low emittance ($\in_{\Omega}$~1200^{1}mm-mr) and minimal energy variation (Îp/p<1%), to impinge upon an X-ray target for the imaging of hydrodynamic events.

The DARHT (Dual Axis Radiographic Hydrodynamics Test) facility [8], under construction at Los Alamos National Laboratory, will consist eventually of two independent induction accelerators. The first arm is under construction, using technologies that are similar to the ETA II. The French machine AIRIX [26] has design goals that are quite similar to the first arm of DARHT. Full scale test stands at LANL (Integrated Test Stand, ITS) and at CESTA (PIVAIR) are addressing key engineering and beam dynamics issues. The second arm of DARHT may have multiple pulse capability over a microsecond duration, but is otherwise quite similar in current and energy to the first arm. While DARHT I and AIRIX are short pulse machines, and are based on ETA II type technologies, DARHT II has the options of ETAII-like cells with advanced 4-pulse switching, or long-pulse technologies similar to those of Heavy Ion Fusion. These options are under active study.

More advanced machines for hydrodynamics are also under study. The ETA II machine at Livermore is in fact being reconfigured to study the beam dynamics of one such advanced scheme (the Advanced Radiographic Machine ARM). The proposed scheme accelerates several long pulses each of which is “cut” into several shorter pulses at extraction by means of fast kickers. These short segments of the beam are then transported through separate beamlines to produce X-ray images at different angles and at slightly different times. These manipulations clearly require excellent control of the beam, and successful demonstration of beam chopping will undoubtedly advance the art of beam control.

Relativistic-Klystron Two-Beam-Accelerator

The relativistic-klystron two-beam-accelerator is a combination of the klystron technology with induction technology for an efficient high frequency rf power source for high gradient linear colliders. A key physics issue that has recently been demonstrated is the reacceleration of bunched beams [27]. An experiment using the ATA injector which provides a beam of 5 MeV and 1 kA was “chopped” into small bunches at 11.4 GHz by a transverse beam chopper. The chopped beam was then made to traverse three extraction cavities and two intervening reacceleration induction cells. The power levels measured at the three extraction cavities were consistent with simulations, and the measured rf phase was stable over the beam pulse.

While the ATA experiment provides a first demonstration of reacceleration, a full-scale efficient two-beam-accelerator, must of necessity be a long device with challenging drive beam dynamics issues. A new scheme recently proposed (TBNLC) [28] offers the possibility of a low cost and efficient architecture with acceptable drive beam stability. The scheme was based on the observation that the peak rf power levels of 180 MW/m required for high-gradient upgrades (100 MV/m unloaded) of the X-band linear colliders studied by SLAC (NLC) [29] and KEK (JLC) are, by induction linac standards, rather low, and can be generated by a low current (600 A) and low-gradient (300 kV/m) drive beam at an operating energy of 10 MeV. Reacceleration is provided by induction modules of 100 kV and 300 ns. This induction module has almost twice the volt-seconds of an ATA cell (250 kV, 70 ns), comparable axial lengths, but only one-half the diameter, and one-quarter the transverse area (see Figure 1). This compact cell is made out of a low-cost magnetic material (Metglas) and low-cost ferrite permanent magnet quadrupoles. In addition, the bore diameter is very small (5 cm), and is possible because of the relatively low current of 600 A, operating in a “betatron node” mode for beam break-up control. The pulse-power system consists of a low-voltage architecture with a pulse-forming-network switched by ceramic thyratrons powering a series of small 20 kV cores. This pulse power system bypasses the voltage step-up transformer of the usual klystron modulators, and the rf source requires no rf pulse compression. This simple architecture is expected to have high efficiencies. Detailed cost and efficiency estimates indicate that such a machine could be an attractive power source candidate for future colliders.

The feasibility of this new device depends critically on the ability to control beam breakup and other beam dynamics issues. Simulations to date show acceptable beam behavior, but experimental demonstration is essential. A prototype machine RTA [30] with 8 to 12 rf extraction cavities over 8 to 12 meters of reacceleration is being built at LBL to test these beam dynamics issues. Construction of this new machine also offers the opportunities for detailed engineering, costing, and efficiency checks on critical components.

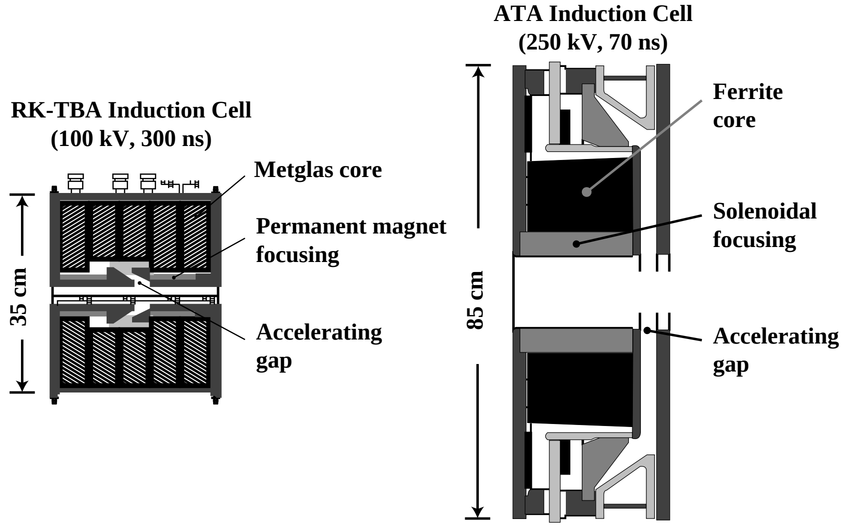

Figure 1. The RTA cell (100 kV, 300ns) is much more compact than the ATA cell (250 kV, 70 ns).

ADVANCES IN INTENSE BEAM CONTROL

While the applications and activities associated with induction accelerators have been varied and diverse, yet the quest for improved beam control is a recurring theme in most applications. In this section, we will describe advances in three areas.

Energy Flatness

The three applications share a common goal of minimal energy variation over the entire beam pulse. In heavy ion fusion, the final objective is to deliver several megajoules of heavy ions onto a small target spot several mm in diameter. Final focus requires that the energy spread from head to tail be small at accelerator exit, (Æp/p ~ 0.1%). It is therefore important to have control over the entire beam pulse at every stage from injector to target. At the LBL 2MV injector, energy flatness is attained by a combination of a flat MARX voltage pulse and a well controlled current extraction pulse. The MARX voltage was designed to have 4 to 5 µs flat-top (Æp/p~0.1%) to accommodate the entire beam pulse plus transit time through the injector column. The pulse extraction pulser has a tunable pulse forming network which was tuned to yield an energy flatness, as measured by an electrostatic energy spectrometer at injector exit, of ±0.15% over the pulse body (see Figure 2a). During the fall and rise of the beam pulse, there are strong space charge forces which lead to high energy at beam head and low energy in beam tail.

Radiography for hydrodynamic tests have similar final focusing requirements since the electron beam must hit a sub-millimeter spot on the target to produce X-ray for high resolution imaging. In both the ITS at LANL as well as PIVAIR at CESTA, spectrometer measurements have demonstrated flat-tops of less than 1% over 60 ns both at injector exit as well as after acceleration through several induction cells (see Figures 2b and 2c).

Relativistic klystron two-beam-accelerators require very good energy flatness because of r*f* phase stability requirements. In the RTA, for example, ±0.3% energy flatness is required eventually to achieve 5° phase stability over 12 meters of rf extraction and reacceleration (12 extraction cavities). This requirement must be satisfied from the gun through every stage of the RTA front-end. During 1996/97, gun construction is in progress, and we have demonstrated 1% energy flatness over 200 ns in a full-scale induction cell under a resistive load. This is a first necessary step towards an acceptable 1 MV gun which is made out of 24 such induction cells.

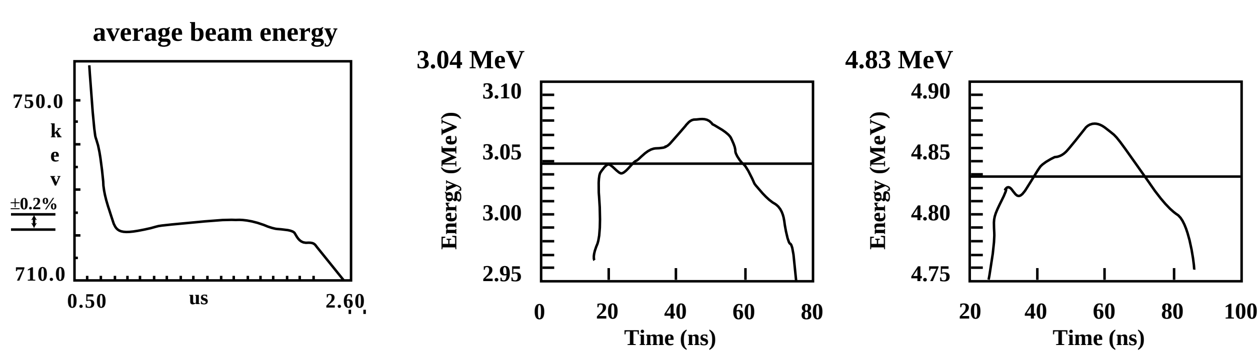

Figure 2. Energy spectrometer measurements for: (a) Ion beam from Heavy Ion Fusion Injector. (b) Electron beam from ITS at injector exit. (c) Electron beam from ITS after acceleration. Courtesy LANL for Figures 2(b) and 2(c).

Emittance Preservation

Low emittance is essential for HIF if the heavy ion beams are to hit the small target spot at the center of the fusion chamber. Although the final emittance of En ³ 10 ¹mm–mv required is a factor of 10 to 100 larger than the emittance at source (consistent with source temperature). Nevertheless, care must be taken at each step to minimize emittance growth. The issue of emittance growth has been central to experimental and theoretical beam dynamics studies at the LBL 2 MV Injector.

The LBL HIF injector column consists of four sets of electrostatic quadrupoles arranged to accelerate and focus the ion beam simultaneously (see Figure 3). The interdigital structure of the quadrupoles is intrinsically 3-dimensional with associated higher order multipoles. The beam is dominated by space charge effects. In addition, a third order kinematic effect is present when low energy beams are focused by strong electrostatic quadrupoles leading potentially to phase space distortions. All these effects can lead to emittance growth. The design of the electrostatic quadrupole injector was performed using the 3-D PIC code WARP3d, and the column geometry and voltages were optimized to minimize emittance growth at the design current and voltage. The measured phase space is in good agreement with 3-D simulations over a broad range of parameters. The normalized edge emittance of less than 1 ¹ mm-mr meets the initial design goal.

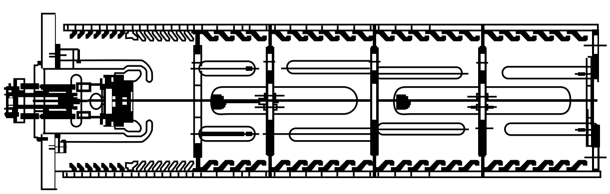

Figure 3. In an electrostatic quadrupole injector, the electrodes are arranged to accelerate and to focus the ion beams simultaneously.

While much has been learned about emittance growth mechanisms in space-charge-dominated beam, recent observations of rapid density fluctuations in the transverse plane as the ion beam propagates down a six-quad matching section beyond the injector exit was quite unexpected, and has led to further emittance growth (by another factor of two) down the transport line. Whether the observed density fluctuations are due to some space-charge instabilities, or source irregularities, or a combination of both, is still under active studies.

Radiographic machines have similar emittance requirements imposed by final focusing. ITS and PIVAIR employ a technique where the beam emittance is deduced from measurements of envelope changes after the beam exits a solenoidal lens of varying magnetic field. The measured normalized edge emittance of 1200 ¹ mm-mr is consistent with final focus requirements.

Relativistic-klystron two-beam-accelerators have tight emittance constraints which come primarily from the requirement that the beam must be transported through multiple extraction cavities. In the case of RTA, the 4 MeV, 600 A bunched beam must be able to go through 10 or 12 cavities with an inner radius of about 8 mm. The required normalized edge emittance is 800 ¹ mm-mr. Although the corresponding emittance at source is 80 ¹ mm-mr, one must again be very cautious with emittance preservation as the beam undergoes acceleration, transport, chopping and bunching. Simulations to date from extraction to chopper entrance have yielded beams with normalized edge emittance of 400 ¹ mm-mr.

Beam Breakup Instability

It is well-known that the transport of high current in induction machines is limited by the beam breakup instability. In the ATA machine, although the design current of 10 kA could be produced at the source, the beam develops large transverse oscillations, leading to the loss of beam tail long before it reaches the design energy of 50 MeV. At least three different ways of controlling BBU are known and proposed. Some are well-tested, while others are studied theoretically, with actual experimental demonstration still to be performed.

The technique of reducing BBU by de-Qing of induction cavities is well-known. The addition of ferrite dampers to reduce the Q of induction gaps is a standard technique. Every cavity design requires careful shaping of gaps to minimize the transverse impedance. The AMOS code, which calculates impedances in the presence of ferro-magnetic material, was first written to model induction gaps, and has been used quite successfully for the design of ETAII and DARHT cells. Whether AMOS could be used for the modeling of induction cores with Metglas remains an open question. But the design of induction gaps with minimal impedance is a key issue for all applications.

In addition to the reduction of transverse impedance, Landau damping is known to be an effective way of controlling transverse instabilities. Laser guiding, which allowed the transport of high current through ATA, introduces Landau damping by the nonlinear space charge forces from the non uniform distribution of ions in the channel. In TBNLC, the bunched beam is maintained in stable r*f* buckets by inductively detained r*f* extraction cavities. These r*f* buckets have a natural energy spread of a few percent. BBU simulations have shown that this amount of energy spread is enough to damp the BBU instability associated with the induction gaps to a manageable degree. Without Landau damping, transport of a 600A beam through a 300 m long two-beam-accelerator, as proposed in TBNLC, would be impossible.

There is one additional BBU mode for the drive beam of TBNLC, at a much higher frequency of 14 GHz, associated with the HEM_{11}, mode of the r*f* extraction cavities, which is quite virulent, and Landau damping alone cannot control this high frequency instability sufficiently. One additional “trick” was introduced to put it under control. The scheme involves the arrangement of the focusing channel so that adjacent extraction cavities are separated by exactly one betatron period. In this scheme, the displacement in every r*f* cavity is identical, even though the transverse kick experienced by the beam through successive cavities is additive. The growth of instability in this scheme is linear rather than exponential. We have studied the sensitivity of this scheme to errors in focusing fields and/or energy errors. The simulations indicate that errors of about 1% in either field or energy is tolerable.

While the Landau damping of the low frequency BBU, as well as the betatron node scheme for the high frequency BBU, have been shown in simulations to be effective methods of control, experimental demonstration is highly desirable. The RTA machine, a prototype two-beam-accelerator, is under construction at LBL. When operating at full-scale, this machine is capable of testing these critical BBU control mechanisms.

CONCLUSION

We have briefly reviewed recent development in induction accelerators for heavy ion fusion, radiography for hydro-dynamic tests, and for relativistic-klystron two-beam-accelerators. I have attempted to show how much of our activities has been motivated by cost reduction and improved beam control.

Control of intense beams is key to the success of the applications. Even though the architecture and parameters of the three applications are vastly different, yet the goals of energy flatness, emittance preservation, and BBU control are common to all. Significant advances have been made in these areas, although a lot more work needs to be done. Induction technology, when compared to the more conventional r*f* accelerators, is a relatively young field. Yet its unique capability for high current and high peak power merits continued aggressive development.

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