The Injector Summary Report

Martin Stockli[1] and Joe Kwan[2]
[1]Oak Ridge National Laboratory
[2]Lawrence Berkeley National Laboratory
July 26, 2011

Introduction

Heavy ion driven inertial fusion is a very difficult challenge, but it is not unlike all other attempts to harness the power of fusion for energy production. It actually has some advantages over other methods, especially in terms of the high efficiency and reliability of accelerators that has been achieved with high-power accelerators over the last few decades.

Heavy Ion Fusion requires ion beams with several MJ energy to compress and heat the fuel pellets to the required density and ignition temperature. For the induction linac approach, this requires heavy ion beams of ~10 ns with tens of thousands of Amps (total charge ~ 1 mC) and several GeVs at the target. This charge can be generated by combining the 0.5 to 1 amp beams from ~100 sources and longitudinally compressing the 10 to 20 μs long pulses (at the sources) after being accelerated.

Light ions are much easier to produce in large quantities, but their lower stopping power limits their useful energy range between ~10 MeV for H, ~100 MeV for Li, and a few hundred MeV for Ne. The lower kinetic energy would have to be made up by increasing the beam charge (or beam current), which becomes very unpractical. Most likely heavy ions of ~200 amu are best suited to meet such requirements. Nevertheless, lighter ions can provide opportunities to study certain aspects of the injector or driver early on during the development phase [1].

The ion beam's normalized transverse emitttance requirement is determined by the need to compress the beam diameter down to the mm-size target. Typically, this means the beam brightness at the ion source should have a current of ~ 1A and an emittance of less than 1 π·mm·mrad (for induction linacs). The goal is to have simultaneously high current and high brightness.

Inventive approaches to produce beams with lower emittance (approaching the fundamental limit given by the size and temperature of the emitted ions) allows for perhaps better emittance at the fusion target. This is not essential if the past successes for single beams can be replicated in a multi-beam geometry, but it could help target performance.

Development history and "state of the art"

An accelerator facility of unusually high reliability (as drivers for fusion power) requires ion sources that are remarkably stable and rugged. In the first HIF workshops of the late 1970's, the ion source was an immediate concern. A survey of the state of the art found that some ion sources produced currents in the microampere scale, at hundreds of kV; other ion sources demonstrated many Amperes but at only a few kV extraction voltage. The periodic table was scoured for candidate ions, and a few emerged as likely candidates: The heavy alkali ions (Cs, Rb) were good candidates because of the ease of producing a single ionization state (q=1). Mercury is another ion that is easy to produce in a unique charge state, but occurs naturally in a wide range of isotopes. Isotopic separation should be considered in cases of significant isotopic admixtures.

An example of high current beam was the ion thruster based on contact ionizer using Cs^+ [2]. It had produced beams for thousands of hours continuously, with a high total current from multiple-beamlets, but relatively low voltage. It represented – and still does – a highly developed sub-area of ion sources that overlaps with HIF in reliability and beam intensity. At the start of the HIF program many years ago, Berkeley had a Heavy Ion Linear Accelerator (HILAC) and experts on r.f. accelerator sources. The high current Xenon source [3] worked satisfactorily, producing 30 mA at 22.5 kV. It was given to BNL, and was used for a long time there. A multiple-ribbon beam array was designed [4]. The design included focusing by einzel lenses at low energy.

Today, single ion beams with the required emittance, current, and energy have been produced, suitable for injection into an induction linac [5]. The repetition rate for these sources was low due mostly because of the cost of building HV pulsers capable of the higher rep-rate, and the experiments at the time did not require it. The total operating hours was still well below the number of pulses required in a HIF driver in one year. The neutral beam injectors (for Tokamaks) can produce up to tens of Amperes of H^+ or H^- by merging multiple beamlets from a gas discharge ion source. Likewise, Xenon ion thrusters have been used on satellites [2].

The most recent HIF injector development was done for a multi-beam quadrupole array driver design. One beam of such an array is the 2 MV injector in the existing HCX experiment at LBNL using Alumino-silicate thermionic source [6]. A similar (current, emittance) beam was produced in the multi-beamlet injector Argon gas plasma source (STS-500) [7].

Ion sources for RF accelerator approach

In contrast to the induction linac approach to build a heavy ion beam driver, the RF (linac) approach will use longer pulse, lower current ion sources (because induction linac has a much lower impedance than RF linac). For example, one design is to use U^{4+} ion source [8] in a 200 MV RF linac (~ 1 km) injecting into a storage ring (of many km in circumference). The beam current at the ion source is ~ 10's mA each and pulse length > 100 µs.

In another RF accelerator scheme, accumulation of the 1 mC beam charge is done by "funneling" multiple beams (some designs have different isotopes), i.e, by stacking beam pulses in time. Here each ion source will produce 100 mA, ~ 20 µs, of singly charged ions [9]. Up to 640 ion sources will be used for producing the compression beams and another 384 ion sources for the ignition beams.

TIT had demonstrated the acceleration of two C^{2+} beams simultaneously, each 50 mA, within a single RF cavity which has two RFQ beam channels [10]. A laser ion source was used with direct plasma injection scheme (DPIS) which was invented by the BNL laser ion source group in 2006 [11].

High Charge State Ions

The ease of production and the low space charge cause singly charged ions to be the dominant charge state that is normally extracted from ion sources. Heavy ion accelerators often use a stripper foil or gas to drastically boost the ion charge state in order to boost the energy of the accelerated ions or to lower the cost of the accelerator required for the desired energy. Stripping generates distributions of charge states. A well designed stripper can limit the widths to a few charge states if the ion of interest is a highly charged ion with a full shell. However, when stripping lower-charged heavy ions at low energy, the less structured ions yield only ~10% in the dominant charge state due to the distributions covering ~20 charge states [12]. While stripping could reduce the cost of acceleration, the associated loss in intensity is prohibitive for reaching the heavy ion fusion requirements.

The MEVVA source that is currently used to produce these high charge state heavy ions is still considered unreliable with problems related to current fluctuation and high emittance [8].

There are several examples of laser ion sources. Those based on CO_2 lasers can be used to produce high charge state ions, but normally suffered from life time and instability issues. Using a YAG laser at low target intensity can produce multiple charge state ions that are not very high in the charge states and with a narrow distribution, but with adequate life time and stability. BNL is planning to install a YAG laser ion source to provide low charged state ion beams to an EBIS injector to feed heavy ion beam to RHIC and NSRL for daily operation. TIT had produced Cu^+ and Cu^{2+} ions using laser intensity at 10^8 – 10^9 W/cm^2 [13]. More recently BNL had observed Bi^{2+} current density of ~ 10 mA/cm^2 at 1 m of a plasma drift length. [14]. This experiment is indicating that more than 1 A of Bi^{2+} beam can be achieved by a compact table top YAG laser. More work is needed in tailoring the laser ion source design and characterizing the beam emittance in order to meet the specific requirements for HIF.

Furthermore, gas discharge ion sources with strong confinement and/or powerful plasma generators naturally output multiply charged ions with a rather narrow distribution of charge states. In some cases, the ion source can be tuned to optimized a desired charge state, thus significantly lower the cost of the accelerator without reducing the beam current available from the source. Multiply charged ions can provide unique opportunities that need to be continued to explore.

The unwanted charge states, as well as other ion species, have to be dumped in a controlled fashion before they are accelerated to high energies and cause excessive activation of the accelerator. Even at low energy, the dumps for the unwanted beams have to be carefully designed to handle the high peak power and possible emittance growth, although the low duty factor keeps the average thermal load modest.

Future work

In developing an HIF R&D plan for the next several years, one often frames the discussion in terms of a development path that leads to a believable scientific and technical case for a large intermediate step (such as HIDIX [15]). For such an accelerator and target physics facility that is likely to cost in the range of $1B, we need R&D early on to show that at least one design for the injector for a multiple beam accelerator driver will work. Seven or nine beams might be considered a fundamental unit of an injector that would require ~100 beams. There are no fundamental showstoppers here. The merging of many ion beams, which are created from sources that are larger than the unit cell size of a multiple beam induction linac array (~0.1-0.2 m), requires dipole as well as focusing fields to match the induction linac. Another requirement would be to explore and show control of gas buildup, electron clouds, and reliability at 5-10 Hz.

In summary, there is a way forward for the HIF ion source and injector. Based on demonstrated single beam sources, future effort must demonstrate scaling up to many beams, repetition rate, and reliability. These are significant and necessary next steps, but amenable to significant progress on a 5-year timescale.

References:

[1] J.W. Kwan, "*High Current ion sources and Injectors for Induction Linacs in Heavy Ion Fusion*," IEEE Trans. On Plas. Sci., 33 (2005) 1901.

[2] J. Sovey et al., "*A Synopsis of Ion Propulsion Projects in the United States: SERT I to Deep Space I*," NASA/TM--1999-209439 (1999) http://www.scribd.com/doc/46736439/A-Synopsis-of-Ion-Propulsion-Development-Projects-in-the-US-SERT-1-to-Deep-Space-I

[3] W. Chupp et al., "*Operation of a high-current Xenon source*," PAC (1979) http://accelconf.web.cern.ch/AccelConf/p79/PDF/PAC1979_3036.PDF

[4] W.B. Herrmannsfeldt, "*A Multi-Ampere Heavy Ion Injector for Linear Induction Accelerators Using Periodic Electrostatic Focusing*," HIF Workshop 1978, Argonne National Laboratory (ANL-79-41) http://ahif.lbl.gov/selected-references/files/Herrmannsfeldt-HIF78-p273.pdf?attredirects=0&d=1

[5] A. Faltens and D. Keefe, "*Ion Induction Linacs: Reference Design and Proposed Test-Bed*," http://www.slac.stanford.edu/cgi-wrap/getdoc/hif79-016.pdf

[6] F. M. Bieniosek, et al., "*2-MV electrostatic quadrupole injector for heavy-ion fusion*," Phys. Rev. ST Accel. Beams 8, 010101 (2005). http://prst-ab.aps.org/abstract/PRSTAB/v8/i1/e010101

[7] J. W. Kwan, et al., "*Compact multibeamlet high-current injector for heavy-ion fusion drivers,*" Rev. Sci. Instruments 77, 03B503 (2006).

[8] P. Spadtke, "*U4+ Mevva source and outlook for HIF sources*," Nucl. Instrum. And Meth. A464 (2001) 388, and M. Weber, P. Beller, R. Hollinger, A. Maaser, K. Volk, H. Klein, "*Development of a Bi+ Ion Source*" in The HIDIF-Study, GSI-98-06 Report (1998) 18.

[9] J.M. Watson, J.M. Bogarty, R.J. Burke, R.L. Martin, "*A High Intensity 1.5 MegaVolt Heavy ion Preaccelerator for Ion Beam Fusion*," IEEE Trans. on Nucl. Sci. NS-26 (1979) 3098.

[10] T. Ishibashi, N. Hayashizaki and T. Hattori, Phys. Rev. ST Accel. Beams 14, 060101 (2011).

[11] M. Okamura, et al, Rev. Sci. Instrum. 77, 03B303 (2006).

[12] P. Seidl and J.L. Vay, "*Formation of high charge state heavy ion beams with intense space charge,*" Proceedings of the Particle Accelerator Conference, (PAC 11), http://www.jacow.org

[13] M. Yoshida et al, "*Development of a high-current laser ion source for induction accelerators,*" Rev. Sci. Instrum., 71, p1216, (2000).

[14] T. Kanusue, et al, presented at HIF conference in Darmstadt (2010).

[15] See G. Logan's slide # 31 http://ahif.lbl.gov/presentations/

Ion sources and Injectors Working Group Participants:

Martin Stockli	*ORNL*	*stockli@ornl.gov*
Joe Kwan	*LBNL*	*jwkwan@lbl.gov*
John Verboncoeur	*Michigan State Univ.*	*johnv@msu.edu*
Lionel Prost	*Fermi Lab*	*lprost@fnal.gov*
Masahiro Okamura	*BNL*	*okamura@bnl.gov*
Anton Stepanov	*PPPL*	*astepano@pppl.gov*
*John Staples**	*LBNL*	*JWStaples@lbl.gov*
*Jean-Luc Vay**	*LBNL*	*jlvay@lbl.gov*
*Molvik Art**	*LBNL*	*akmolvik@comcast.net*

* *roaming participants*