Summary for the Induction Linac Working Group

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July 24, 2011

The plenary session of the workshop covered different system-components e.g., injector/heavy ion source, accelerator-drivers, HIF target, chamber/interface etc. The following members participated most of the time in the working group: J. Barraza (LANL), R. Bangerter (LBNL), R. Briggs (SAIC), A. Faltens (LBNL), A. Friedman (LLNL), I. Haber (UMD), W. Herrmannsfeldt (SLAC), S. Lidia (LBNL), B. T. McCuistian (LANL), A. Molvik (LLNL), K. Nielsen (LANL), A. Radovinsky (MIT), L. Reginato (LBNL), P. Roy (LBNL), P. Seidl (LBNL), B. Smith (MIT), and I. Smith (L3 Com.).

Essentially, about one and a half days were available for the working groups to meet and deliberate - deemed not enough to deliberate in detail ALL the plausible system-combinations i.e., injector/source, accelerator and target/chamber that merit discussion for their strengths and weaknesses as integrated systems. A particular component-system concept that may stand out on its own merit may not be optimally suited for the system as a whole; as such, most appropriate use of the time was deemed to pick the most plausible scenario/layout for an induction linac based system, identify typical requirements of such a system, discuss current status of the technology, and potential issues, and provide recommendations/path forward for the identified areas.

We could envision three plausible scenarios: Multi-beam linac layout, a many-accelerator modular system, and a re-circulating beam option. We chose to limit our discussion to the first scenario i.e., multi-beam linac option. In a similar vein, three target options merit looking into. As a working group for induction linacs, we discussed the induction linac layout for an indirect drive target system only.

For an indirect-drive target, typical requirements could be summarized as: ~ 5 MJ total beam energy on the target, with ~ 1 mC delivered in ~ 10 nsec; the acceleration gain of ~ 10 – 40 MeV/amu with ~ 5 GeV at the output (for 20 MeV/amu). That would need ~ 100 beamlets (individual beams). At ~ 10 Hz duty an efficiency of about 20% or more is desirable. An acceptable beam quality would be ~ mm-scale focus on the target. Similar target and driver parameters may be found in refs. [1-3].

In a multiple-beam induction linac concept, the <u>total</u> beam current (a few to 10 kA over much of the accelerator) is made up of individual beams transported in parallel channels through a common set of "induction" modules. A typical section of a transverse focusing period of the FODO lattice is shown in figure 1, which depicts a superconducting magnet assembly at the entrance, one or more induction modules and acceleration gaps, followed by a defocusing quadrupole unit. The pattern is repeated to form a FODO accelerating lattice constituting the entire linac. The composite magnetic field-lines in the quadrupole magnets are arranged so as to provide high quality fields encompassing each of the individual beams. Each particle-beam carries about 1 Amp near the injector, and increases in current to ~50 Amp/beam at the end of the accelerator. Several insulator configuration options are possible and optimization studies need to be done for cost and acceleration efficiency of specific geometries.

The projected vacuum needs, 10^{-8} Torr at the front end gradually relaxing to 10^{-7} Torr, is considered achievable; this specification needs to be confirmed – it depends on the allowable accelerator component activation, beam loss, and relevant atomic cross sections. Alignment requirement is an issue intimately tied to the choice of the target. Constraints resulting from error analysis that fold in component errors coupled with the requirements of the specific target would determine if the state of the art alignment techniques would suffice or more innovative mitigation approach e.g., active steering is needed.

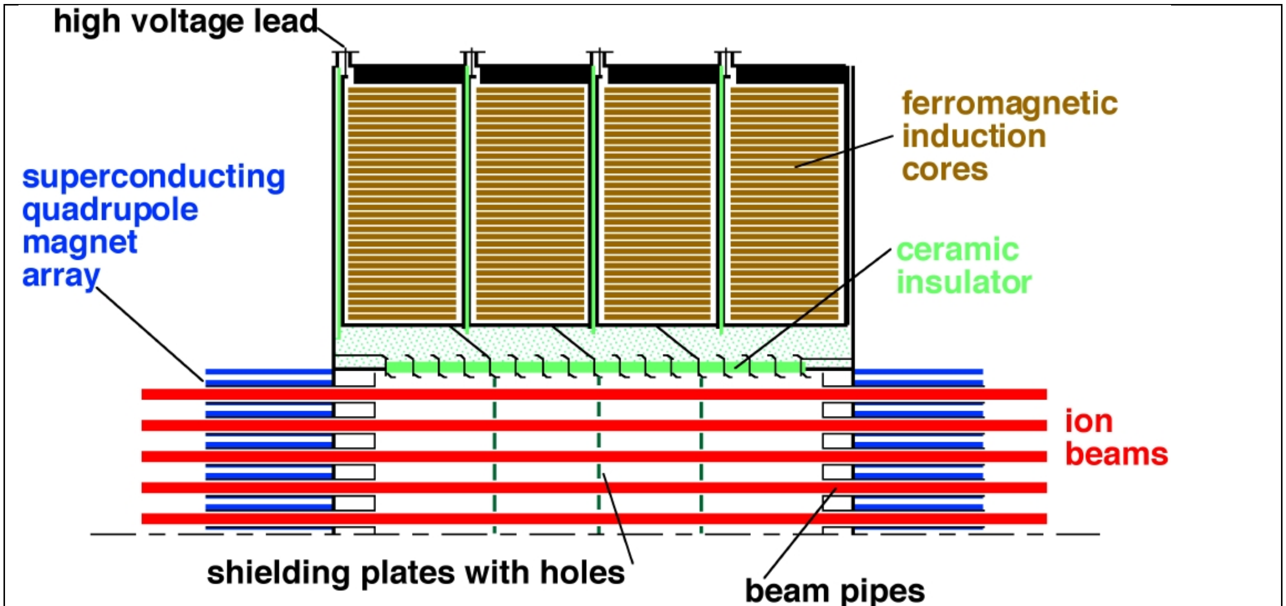

Figure 1: An induction module bracketed by quadrupole magnets at the front- and exit-end forming half of a FODO lattice period of the induction linac.

Power-feed to the accelerating modules is an important consideration that needs to be looked at carefully. Trade-off studies are needed to settle on specific systems. At the front end, i.e., around the injector region (1~ 2 MeV, ~ 20 µsec), use of silicon steel for the magnetic core and pulse forming networks (PFN) for long pulse seem to be a logical choice. In the midsection of the accelerator structure, from about 50 to 100 MeV, (and 1µsec) use of PFN's is still deemed efficient. Switching over to Metglas at ~ 5 µsec is perhaps the right transition point for the magnetic core. For cost and efficiency, trade-off studies for the use of metal-tape vs. ferrite and PFNs vs. pulse forming lines (PFL's) is most important for the remainder of the structure i.e., downstream of ~500 MeV (and ~ 200 nsec). We note that the great majority of the accelerator is downstream of ~500 MeV, so the architecture here will have the greatest impact on the driver cost and efficiency. Also, R&D efforts are needed to explore applicability and adaptability of solid-state pulsed power systems to meet demanding rise-time requirements.

A prototype module representing the high-energy end that would serve as a "prototypical module" for a demonstration driver (HIDIX/IRE) [4] is highly recommended to understand and address issues like alignment, gradient limits, efficiency, interaction impedances, fabrication and installation cost, etc.

The successful operational record of the multi-pulse DARHT facility [5] has provided the induction linac community with significant confidence in the understanding of key elements of the beam-physics, and design issues as well as operational reliability. Beam breakup instability (BBU) resulting from transverse beam-cell interactions is one of the most destructive instabilities in the electron linacs and as such had been a major consideration in their design. The "campaign" on DARHT-II to minimize the transverse impedance led to a much deeper understanding and effective control of this instability. The induction linac concept considered here will have several orders of magnitudes more induction cells. However, earlier studies for heavy-ion induction linacs indicate that the BBU amplitude growth would likely to be very slow and should not be significant for transport purposes [6]. The use of superconducting quadrupole magnets should also help by providing higher average available focusing field.

Related beam physics issues unique to the layout and deemed important are: 1) Individual beams interacting, electrically and magnetically with the module core as well as 2) mutual interaction of the beams among themselves. The group strongly recommends that comprehensive beam physics simulation studies that combine these effects should be undertaken for qualitative and quantitative understanding and look for signs of any hitherto unknown physics issues.

Opportunities exist both at LBNL and elsewhere for collaborative experimental studies on beam physics.

An outside example is University of Maryland Electron Ring (UMER) Facility. By using electrons for appropriately scaled experiments, UMER can investigate both transverse and longitudinal space-charge-dominated beam physics. Aided by 3-D simulations (using the WARP code) that accurately capture experimental results even without inclusion of the details of the "ring" characteristics, UMER can be used to simulate a long linac and to explore the "long path-length" physics.

Additional resources for experimentally examining the transverse physics important to long path space-charge-dominated transport are the Paul-Trap devices currently operational at PPPL and Hiroshima University. These devices have been used to simulate the beam dynamics, as viewed in a frame moving with the beam, by applying the appropriate time varying focusing forces to the stationary non-neutral plasma in the trap.

Collaborative effort with DARHT as well as GSI and other heavy ion accelerator facilities should be explored.

Experimental opportunities at Berkeley Lab include experiments on the HCX and NDCX-II facilities. HCX produces a single driver-scale low emittance beam, and has been applied to stray-electron control, and to both electric and magnetic quadrupole transport. Consideration should be given to upgrading HCX so that it can provide answers to important questions about driver-scale beams. Enhancement of the rep rate to 5 - 10 Hz would facilitate studies of gas build-up and e^- cloud effects. An extension would enable transport of a driver-scale beam over multiple plasma oscillation periods.

Experiments on extensions of the NDCX-II would be very valuable to explore non-neutral transverse and longitudinal compression, bending, & focusing of beams, to validate some of the key concepts in the driver-to-target-chamber geometry considered.

Too often-overlooked yet critical systems - diagnostics and controls are integral to any "complete" accelerator based system. Phenomenal advances have been made in both fields in the last decade, aided by fast computer and matching algorithms. State of the art capabilities in these areas must be taken advantage of, and be integrated into any driver scheme. Comprehensive failure mode analysis of the entire system with folded in capabilities of both would drive the necessary "redundancy" requirements.

Though outside the immediate purview of this working group, the chair of the working group would like to make two personal observations:

1. There are several options for each of the component systems such as heavy-ion sources/injector, HIF targets and accelerator drivers, none without its merits and shortcomings. A "system approach" is necessary to whittle down the "options list" to a handful of technically feasible yet practical options; that would help to draw up a couple of "down selectable," complete, end-to-end options to pursue.
2. Both RF and Induction linacs have earned the reputation of being reliable machines and hold the promise as potential drivers. However, even with the advances in the accelerating gradient of SC linacs, and demonstrated reliable operation of Inductions linacs such as DARHT, two major practical limitations remain: 1) Long machine footprint translating into high machine cost, and 2) Accelerator power-feed requirements and geometry, and power management issues. It is in this context, that an inclusive and broad view is necessary at this juncture. A hybrid that leverages the strengths of both the technologies may not only turn out to be the most attractive configuration but is a desirable path-forward with the potential of yielding a credible alternative and being taken as a serious competitor in the Fusion community at large. From a more pragmatic point of view, any driver for a demonstration system will be a billion-dollar class machine and therefore would not stand a chance of becoming a funded reality if it is not viewed as a carefully studied and laid out "**end-to end**" system. Also, the accelerator community at large would benefit to learn from the lessons of the Accelerator Transmutation of (Nuclear) Waste (ATW) national campaign in the 90's in light of the severe limitations imposed by the need of integration of the accelerator driven system to a conventional power grid as the ultimate goal.

References:

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[2] R. O. Bangerter, "*The Induction Approach to Heavy-Ion Inertial Fusion: Accelerator and Target Considerations*," *Il Nuovo Cimento* **106 A** No. 11, 1445 (1993).

[3] S. S. Yu, W. R. Meier, R. P. Abbott, J.J . Barnard, T. Brown, D. A. Callahan, C. Debonnel, P. Heitzenroeder, J. F. Latkowski, B. G. Logan, S. J. Pemberton, P. F. Peterson, D. V. Rose, G.-L. Sabbi, W. M. Sharp, and D. R. Welch, "An Updated Point Design for Heavy Ion Fusion," *Fusion Science and Tech.* **44 (2)**, 266 (2003).

[4] See slide 31 of G.L. Logan's plenary presentation in this workshop: "*The Motivation for Heavy Ion Fusion*" http://ahif.lbl.gov/plenary-presentations/01-110523Logan.pdf?attredirects=0&d=1

[5] S. Nath, "*Linear Induction Accelerators At The Los Alamos National Laboratory DARHT Facility*" Proceedings of LINAC 2010, http://accelconf.web.cern.ch/AccelConf/LINAC2010/papers/th304.pdf

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