Letter of Interest: The Path to Compact, High-Intensity Beams

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There is an ongoing need for intense proton sources for research in particle physics, medical applications, materials research, and energy research. In this Letter of Interest, we are briefly summarizing the most prevalent applications of high intensity beams and explain why we believe that in the future, compactness will play a big role for several of these. We will end with describing the IsoDAR experiment as an example of technology enabling such compact high intensity proton sources.

I MOTIVATION

Many applications of particle accelerators require high intensity beams. Examples are: 1. Spallation neutron sources like the ESS, SNS, SINQ, and MLF that provide the tools (neutron scattering) for important research in the fields of biology, medicine, chemistry, physics and overlapping areas thereof. Co-produced kaons, pions, muons, and neutrinos are also often used for experiments (e.g. CEvNS [1]). 2. Accelerator based neutrino experiments such as the FNAL Booster Neutrino Beamline, and the planned upgrade for the DUNE experiment, JPARC to HyperK, or in the past CERN Neutrinos to Gran Sasso. A comprehensive overview of the U.S. efforts is given in the 2013 Snowmass report [2]. The need for high beam intensities led to the recognition of the intensity frontier as one of the major avenues for current and future research and development in particle accelerator physics [3, 4],

There is a wide range of potential applications of high intensity particle beams outside of the fields described above. One example is in the research and development of materials for extreme environments, such as the materials used in the core of fusion energy devices and advanced nuclear reactors now being proposed. Recent scoping studies [5] and experimental activities [6] have shown that high intensity proton sources between 10 and 30 MeV provide high throughput, high fidelity methods of achieving fusion power plant or advanced fission reactor-relevant radiation damage materials responses with an order of magnitude or more less time, radioactivity, and cost as traditional irradiation methods in nuclear reactor cores. These techniques benefit substantially from recent advances in compact, superconducting proton cyclotrons [7] with the small footprint, low mass, and low operating costs enabling them to be deployed in university-scale laboratories dedicated to materials science, co-located close to post-irradiation materials testing equipment, accessible for direct participation by students and faculty at such facilities [8]. Other example applications that benefit from the same advantages of compact, intense particle sources are in accelerator-driven energy systems [9, 10] and isotope production that supplies a large fraction of the world's medical diagnostic and biological research [11],

In this Letter of Interest (LOI) we are identifying avenues of research to remedy the lack of compactness in high intensity accelerators and present IsoDAR as an example of a project that actively seeks to provide new technology to reduce the cost and footprint of high intensity proton drivers on the path to truly compact systems. It is our strong opinion that by reducing the cost and footprint of high intensity accelerators, a richer research program will ensue.

II THE PATH TOWARDS MORE COMPACT, MORE INTENSE DRIVERS

A. Technology

State-of-the-art. Typically, a medium to high energy accelerator system consists of several stages: The ion source, the pre-accelerator/buncher, main acceleration stages (often multiple). Several types of ion sources are able to provide very high currents of protons and H^- (e.g. multicusp [26]), others, like ECRIS, can provide high currents of highly charged ions [27]. Pre-acceleration and bunching of intense beams is nowadays typically done with radiofrequency quadrupoles (RFQ) [28]. Linacs can be designed compact as long as the needed energy is not very high. Beyond that, circular machines are usually more compact and cyclotrons, especially superconducting ones are a robust and reliable technology. The use of superconductivity usually helps in creating more compact machines. Beyond conventional techniques, Wakefield Acceleration (WA) both laser-driven and beam-driven promises compactness beyond what is currently

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TABLE I. A few potential uses for high current proton beams and how cyclotrons can be leveraged to reach the goals. ADSR: Accelerator Driven Sub-critical Reactors, ADS: Accelerator Driven Systems for nuclear waste transmutation. Cyclotrons can be a cost-effective alternative for tests and demonstrations at the low-power end of the spectrum (tens of mA). Adapted from [12].

Application	Field	Current	Energy	Comment
IsoDAR [13–15]	neutrinos	10 mA	60 MeV	Use $\bar{\nu}_e$ from decay-at-rest to search for sterile neutrinos.
DAEδALUS [16–20]	neutrinos	10 mA	800 MeV	A proposed search for CP violation in the neutrino sector.
ADSR [9, 10]	energy	10-40 mA	~ 1 GeV	Cyclotrons are a cost-effective alternative for demonstrator experiments.
ADS [21, 22]	energy	4-120 mA	~ 1 GeV	Cyclotrons are a cost-effective alternative for demonstrator experiments.
Isotopes [23, 24]	medicine	$1-10$ mA	3-70 MeV	E.g.: 10 mA/60 MeV can increase worldwide ^{225}Ac production by 6000 [23].
Material testing	fusion	10-100 mA	5-40 MeV	Testing of fusion materials similar to IFMIF [25], at lower power.

employed in the field. However, WA is far from tried and tested technology.

Needed Developments. To facilitate high intensity beams from compact sources, we believe that the following developments will have high impact:

- Developing LWA further and finding ways of chaining them together to achieve higher energies. Improve their duty cycle.
- Developing high power cyclotrons.
- Continuing development of high gradient RF cavities for linear and circular machines.
- Exploring how existing technology can be combined in new ways to overcome beam current limitations.

B. Computation

State-of-the-art. Much development has happened in computational accelerator physics in the past decades and it has become an indispensable tool. It is of the utmost importance for high intensity beam design to understand the interaction of beam particles with each other and their surroundings. At the forefront are advances in massively parallel multi-particle ($> 1e6$ particles) simulations that allow for relatively quick turnarounds of highly accurate simulations, spanning large parameter spaces. Typically implemented as particle-in-cell algorithms, these codes can simulate high intensity beams with space charge as well as plasma systems, beam-field interactions, beam-surface interactions and beam-gas interactions [29, 30].

Needed Developments. In order to open up new design paths for high intensity particle accelerators, we propose that the following R&D in computational accelerator physics be supported:

- Accurate treatment of pertinent physical effects and their inclusion into existing widely used simulation codes. Examples are:
  - Space charge compensation.
  - Mirror charge effects.
  - Residual gas interaction.
  - Multipacting
- Unification of codes and interfaces (e.g. to reduce the burden of translating particle distributions and externally loaded fields calculated with FEM/BEM codes from one set of units to another). An ongoing effort in this is, for example, RadiaSoft's Sirepo project [31].
- Application of Machine Learning (ML) in large scale accelerator simulations (e.g. to construct surrogate- and inverse models [32]) [1]
- Research towards realistic multiobjective optimisation with surrogate models.[1]

III AN EXAMPLE: ISODAR

The IsoDAR experiment [13–15] is an example of bringing together developments in computation and technology to enable compact high intensity sources. It will provide a highly sensitive search for sterile neutrinos, by placing a powerful source of $\bar{\nu}_e$ in close proximity to a kiloton-scale liquid scintillator detector such as KamLAND. A compact cyclotron produces a 10 mA beam of 60 MeV protons [12] that strike a neutron-producing target, these neutrons are captured in a sleeve surrounding the target, consisting of a mixture of beryllium and highly-enriched ($> 99.99\%$) ^{7}Li. The ^{8}Li neutron-capture product decays within 1 second yielding a high endpoint-energy $\bar{\nu}_e$ that is detected via inverse-beta decay (IBD) in the detector. For the most-favored parameters for sterile neutrinos, the $\bar{\nu}_e$ oscillation pattern has maxima and minima within the volume of the detector, providing exquisite sensitivity for discovery of one or more sterile neutrinos through shape analysis. Three novelties are making the leap to 10 mA possible: Accelerating H_2^+ instead of protons, inserting a radiofrequency quadrupole into the cyclotron to aggressively pre-bunch the beam and designing the compact isochronous cyclotron to utilize vortex-motion. The IsoDAR cyclotron could also be used for isotope production [11, 23, 24], and as a pre-accelerator for a 10 mA, 800 MeV - 1 GeV cyclotron that can be used for ADS(R) [9, 10, 21, 22] and particle physics, including the DAEδALUS experiment [16–20]. Potential uses are summarized in Table I.

[1] See separate LOI

IV CONCLUSION

We strongly believe that in the quest for ever higher beam intensities, compactness should be an important factor. This will enable smaller facilities to participate in much needed R&D in fields like materials-, and energy research, medical-, and particle physics. It will provide hands-on teaching opportunities for students at universities, thereby training the next generation of accelerator experts. Some experiments, like the IsoDAR experiment, will only be possible with a compact high intensity driver, due to space restrictions in an underground setting. In order to facilitate the accurate design of these compact drivers, existing computational tools must be developed further and new concepts should be explored.

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