Survey of Proposed High Intensity Accelerators and their Applications*

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Abstract

Many interesting applications are being considered for high intensity accelerators. Implications of the technology developments that are enhancing these opportunities, or making them possible, will be covered in context of the applications. Applications include those for research (in areas such as material science, biological sciences, nuclear and high energy physics), accelerator-driven transmutation technologies, defense, and medicine. Specific examples will be used to demonstrate the impact that technology development can have and how transfer of this technology to industry can have an impact in the consumer and commercial arenas. Technology development in rf power, controls, beam optics, rf structures, magnets, injectors, and beam halos will be considered. *

1. INTRODUCTION

The discussion in this paper serves as an introduction to the "Special Session on High Intensity Issues". Following papers, covering beam dynamics by I. Hofmann, sources by A. J. T. Holmes, injectors by A. Schempp, design issues by G. P. Lawrence, rings by G. Rees, spallation sources by H. Lengeler and factories by M. S. Zisman, provide the details of the technology, scientific and engineering issues, and specific opportunities. A brief description of some of these issues will be provided in the following for the sake of completeness.

Accelerators have been developed to the point that they are now having impacts for many applications, and in many different fields of research, study and investigation. They are having an influence on our quality of life, the safety of our environment and the capability of society to move forward in a productive manner. Users of accelerators and related technologies are placing more emphasis on reliability, availability, maintainability and inspectability (RAMI), and on the economic considerations for installation and operation of a facility. Other user concerns have to do with time schedules and associated approvals from government oversight agencies.

"Big science" employing accelerators is no longer supported by "patrons". It requires not only good justifications for the research activities, but must have some indication of spin-offs for the technology being developed and for the investments made in the underlying research. Fortunately accelerator development has had this capability and a direct connection into the economic sectors for many years. We need to ensure that this continues and that we, as an accelerator community, continue to strive for excellence and for other uses of the capabilities we develop. We also need to ensure that we inform the general public of our activities and their applications, as well as the decision makers and decision influencers.

The following sections will cover applications and examples of high intensity accelerators in a number of different areas. A summary of what these applications require will then be provided. A survey of the technical, scientific and engineering issues will be discussed followed by a few comments on their associated needs.

This paper will not show equations, formulas or develop theories, it will not show block diagrams or system layouts, and it will not provide the underlying theories or justifications for the comments made. That information can be found in the rest of this conference publication and in earlier reports.

2. HIGH INTENSITY ACCELERATORS

Accelerators with an average beam intensity to a target system in excess of 1 MW will be considered within this discussion of high intensity systems. Injectors for these powerful devices usually consist of two types -- rf-based or induction-based. This is the case for either electron or ion accelerators. Following the injector can be a ring with many different types under consideration -- accumulators, synchrotrons, storage, stacking, cooling, damping, etc. G. Rees in a following paper gives an excellent account of the technical implications and the state of the art for rings.

When a beam with multi-MW of beam power impinges on a target, a considerable amount of damage, erosion, melting, shock or destruction can occur if the design doesn't clearly consider the impact and the pulse conditions of the beam. Is the beam continuous or is it pulsed with short very intense "shocks" to the target? All of these effects have important consequences to the target and the integration of associated components to the entire system. For these reasons, it is very important that the design include all system aspects when optimizing the geometry and selecting beam parameters. The experience at RAL with the targets for ISIS, as described by I. Gardner at this meeting, is a case in point. The targets don't have very long lifetimes if the parameters for operation are not chosen carefully.

Accelerators considered in the following discussion will, in general, have energies of about a GeV, have average currents in the range of 50 to 500 mA, and require normalized beam emittances of less than 0.1 π cm·mrad. Some of them will not fit the three areas

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precisely, but will have enough of an overlap in parameters that they will be covered in the following discussion

3. APPLICATIONS

3.1 Defense Examples

Investments in Directed Energy Weapons as part of the USA Strategic Defense Initiative have had a significant impact on the capabilities of accelerators and the underlying technology. Research and development pushed hard at the barriers and frontiers of what was considered possible and reasonable for particle beam systems. Two major accelerator initiatives were the Neutral Particle Beam (NPB) program and the Free Electron Laser. (FEL) These were developed in the anticipation that they could be used as SDI assets in the future. With the advent of budget cuts, resetting of priorities and the change of the mission to Ballistic Missile Defense, these two programs were no longer supported by the BMD office. Before the programs were canceled, the related technologies had been developed to the level that many other accelerator programs were benefiting from developments in bright sources, an understanding of emittance growth and the means to control growth, materials and new accelerating structures, and higher order optic systems necessary to transmit the bright beams.

The FEL was based on either an induction linac or an rf-based linac driving a wiggler to produce the laser frequency of interest. Beam currents were very intense with very small emittances in order to achieve good coupling between the electron beam and the laser oscillations in the wiggler region. Powers of interest in the beam were in the multi-MW level for an application that had a laser effect on re-entry vehicles or the boosters. Technology was developed to the stage that a competition between a TRW-Livermore team and a Boeing-Los Alamos team was underway to determine the best technology route to follow for a powerful FEL. The Boeing-Los Alamos rf-based team won the competition but the program was canceled shortly thereafter. The highest average power demonstrated by an FEL is less than a kW and this was accomplished by Vanderbilt University with their medical FEL facility.

The NPB was based on an intense H^- accelerator that used a beam neutralizer after the beam had been accelerated to about 100 MeV and had been expanded in a telescope to aid propagation of the beam over large distances without effects from magnetic fields. Again the application was to interact with re-entry vehicles and to make them inoperable. Demonstrations of the technology reached the point that industries, such as Grumman, Lockheed, Westinghouse and McDonnell-Douglas, were involved in system design as well as technical developments. The program demonstrated an accelerator system in space and the relevant necessary elements. Technology developed for the NPB program has been incorporated into many other accelerator systems; intense beam formation, intense beam transmission, acceleration with control of emittance growth, use of accelerator codes, and related technologies such as controls, rf power and diagnostics.

The above two examples of technology development and their associated spin-offs required the development and enhancement of rf power systems. RF power systems were also developed for applications in such areas as electronic upset and system saturation. In all of these applications the technology enhancements led to interesting developments that have had an impact in the accelerator business.

Over all, because of investments made in technology by pushing at the boundaries of what was considered possible, significant advancements were realized and this will be the legacy of the SDI program for accelerator designers and builders. Developments couldn't have happened at a better time, presenting an opportunity to improve our standards of living and our environment.

3.2 Research Applications

There are many relevant papers at this conference that describe advancements being made in accelerator science and technology, many which relate to high power applications mentioned in this paper. The installation and commissioning of the CEBAF facility in Virginia is just one example. This cw electron beam will be one of the most powerful for research purposes and one that uses a new technology. Superconducting structures can now be considered for major facilities at accelerating gradients leading to possible cost and space savings. Other facilities that have or are being put into operation with intense beams are colliders such as those at CERN, DESY and Fermilab. GSI with their 25% duty factor accelerator meets many of the criteria for intense beam operation and they have assisted in technology development over the years that they have been in operation. Although the energies are higher and the currents less, the beams circulating in these machines are very powerful.

Other examples that will be seen in the near future are radioactive beam accelerators, relativistic heavy-ion colliders and possibly kaon factories.

Proposals that fit the high power criteria very well are the spallation sources being considered in Europe, Asia and North America. They all use an rf-based H^- accelerator followed by a ring of one of the types discussed by G. Rees at this conference. In Europe, a study described by H. Lengeler in this conference has a 5 MW beam as the design parameter with an energy of about 1 GeV. This study is supported by the European community and uses expertise from a number of areas. Collaborations on the target, experimental halls and accelerator are underway. The proton beam will impinge on targets designed using information gleaned over the years from operation of the ISIS facility at Rutherford, the PSI facility at Zurich and the LANSCE facility at Los Alamos. A lower power spallation source study, AUSTRON, is underway incorporating interests from some eastern European countries with most of the support from Austria. Studies are underway for a 1 to 5 MW facility to be located somewhere in the USA. Organizations looking into possible use of a spallation facility include Los Alamos, Argonne, Brookhaven and Oak Ridge.

3.3 Medical Applications

There are a number of challenging applications for high power accelerators in medicine. One that is once again being considered in a number of countries, particularly in the USA, is the production of radioisotopes from an accelerator with up to a MW of beam power and with an energy around 100 MeV. Most of the facilities being considered are based on a pulsed rf linac. Such a device would be able to produce a host of isotopes of interest to the medical community and would be able to provide services to a large customer clientele because of the available beam power. Some of the proposals suggest using such a facility for other purposes that would be parasitic during operations. One such possibility would be to use the facility for proton therapy.

Another application consists of the PET sources that are being located in many hospitals. They are showing that attention to simplicity in design, operation and reliability are important factors.

The last example given here is Boron Neutron Capture Therapy (BNCT). In this application, a patient is given a boron chemical that is particular in the site it accumulates in the body. Slow neutrons from an accelerator beam on a target such as Li are captured by the boron and create radiation damage in a very localized area of the body. Accelerators for this application are only a few MeV in energy, but have cw currents in excess of 100 mA for some of the designs.

3.4 Fusion Applications

In the fusion area, there are a number of accelerator applications that fit within materials research needs, heavy ion fusion studies and neutral beam injectors. The international materials community recognizes that new materials and effects for present materials are needed in order to move ahead with some of the future fusion reactor designs. An international effort is underway with Europe, Japan, Russia as an observer and the USA to study the design of a (D,Li) source that will eventually have about an ampere of deuteron beam on a flowing liquid Li target. Again all of the high power aspects are present in the design of a machine for this purpose, because initiation of a high intensity beam must be accomplished very carefully.

Reactors will continue to be used for material research and development, as can appropriate spallation sources. The spectrum and the ratio of displacements to He production may not be exactly correct for these devices, however these variables are close enough to understand many of the processes affecting materials under the stressful environments of a fusion device.

Neutral beam injectors have many of the attributes for the injectors of a high intensity accelerator. Quiet plasmas, beam transport, good emittance and long lifetimes are just a few of the necessary requirements. These injectors need to address RAMI implications and need to be efficient in materials use, gases and costs.

Heavy ion fusion is being addressed in Japan and Germany by studying different aspects of an rf-based, stacking rings design. Within the USA, the approach being pursued at LBL is an induction machine under a development program called ILSE. These applications will require interesting gymnastics of the beams, bright beam generation, controlled beam transport and code development.

3.5 Accelerator Driven Transmutation Technologies

There are a number of areas that fit within this category and they include material production, waste transmutation and energy production. These are interesting applications requiring intense proton beams of about a GeV in energy for efficient production of neutrons from the spallation process. All of the devices have bright beam injectors, funneling to increase the current carrying capabilities, new structures for stability and performance, large bore holes for minimizing lost beam, improved rf systems, advanced control and diagnostic systems and beam emittance control procedures. Operation of the MW LAMPF facility over the past 20 years at Los Alamos has provided the background information to move forward on these initiatives, as well as the spallation sources mentioned earlier.

In the materials production area, possibilities of producing T, Pu and U are being considered by a number of countries. In the past, Canada has taken a lead role in studying materials production using the spallation process. Pioneering work was undertaken with their Intense Neutron Generator program in the mid 1960s.

Although world events have changed so that we no longer live under the mantle of what was known as the MAD or Mutually Assured Destruction scenario, there will be a need to support a small number of nuclear weapons in the future. This will be necessary to ensure world stability and to ensure against terrorist threats, proliferation or renegade regimes threatening the world. In order to support the material needs of this small number of nuclear weapons, it will be necessary to provide a source of tritium because it decays 5% per year. Producing tritium from an intense spallation source has many features that make it an attractive alternative to a nuclear reactor. The accelerator-based system has many safety features, is economic, can be scaled in production output easily and has a small waste stream associated with its operation.

In the past, a number of countries have pursued the possibility of producing 239 Pu and 233 U from the vast uranium and thorium resources to augment power producing capabilities of nuclear power systems. Most of this activity has been in paper studies, however a few institutions such as the Chalk River Laboratories in Canada funded technology projects that demonstrated some of the feasibility issues.

Studies are underway in Russia and the USA on the use of an intense spallation source to destroy Pu resources that exist in the world today and those that are being generated by commercial nuclear power systems in operation. The Pu resources that exist as a consequence of the weapons activities in Russia and the USA in the form of "pits" and production streams are overshadowed by the amount that exists in spent fuel from commercial power reactors. Any solution that addresses weapons Pu removal needs to consider the material from commercial activities as well. Destruction of Pu is safer than secure storage from a long term proliferation point of view. One of the advantages for burning Pu in an accelerator-based system is that the Pu resource can be used to produce electricity (a valuable commodity) while burning the fission products in situ, resulting in a small waste stream.

Intense spallation sources are also being considered in a number of countries for transmutation of the radioactive wastes that are a legacy from defense production complexes and those that are associated with spent fuel from commercial reactors. In the former case, it is a matter of cleaning up the environment after many years of operations that stored the waste material in anticipation of future solutions. In the latter case, it is a matter of meeting regulatory requirements and offering an alternative that enhances considerations for long and deep storage of the material.

Very interesting studies are underway in many institutions that demonstrate the attributes to be realized from coupling a high power accelerator to a reactor-like system for generating electricity. The accelerator provides extra neutrons from the spallation process that assist the overall system to run more safely (with a keff of about 0.9 to 0.95 -- neutron multiplication of 10 to 20). Such a coupled system appears to have economic benefits, burns most of the generated actinides and fission products, can run on relatively simple fuel cycles, eliminates fuel fabrication and reprocessing, and does in-line separations. There are many potential benefits from such an accelerator-based device and a number of crucial experiments are being planned to demonstrate the critical elements of the system.

3.6 Miscellaneous Applications

There are many other examples of possible applications for high power accelerators and a few of these will be mentioned here. One that is intriguing because of the possibility of a hundreds of millions of dollars per year business is recharging satellites from an earth station. Laser light from an FEL at the correct frequency for propagation through the atmosphere and for high absorption by the solar panels can extend the life of failing satellites by at least five years. As the satellite passes over the station the laser beam is directed to the solar panels that have been damaged from many years in a space environment. Coupling of solar radiation to the panels is not as good as originally designed because of panel aging in space. Without a recharging capability the satellites would fail to operate.

Intense beams and plasmas are being used to modify the surface of materials and to make them last much longer under wear conditions and other applications. These beams and plasmas must pay attention to many of the issues that are important for high power accelerators and employ many of the technical innovations.

Soil remediation with high power microwaves is another area that is being pursued, as is the use of microwaves for drying, altering chemical bonds, aiding various processes and treating effluents.

High power beams and associated processes are being used for waste treatment of solids and liquids. Powerful radiation units for sterilization are becoming an industry standard.

High power photon sources and FELs are being considered for lithography applications in the future that will significantly reduce the size of computer elements.

4. NEEDS FOR ALL APPLICATIONS

All of the applications need attention paid to a few important issues that can make a significant difference to design, construction, commissioning, operation and long term maintenance. These issues include well thought out designs that consider safety and operating margins. Cost, power and operating efficiency need to be factored into all aspects of the facility, as does attention to RAMI. Intense beam generation, intense beam transport and minimal beam spill will be important considerations. Matching of the beam parameters to all parts of the system including targets and transition sections will need to be considered. Power systems should be improved for an impact on facility design and operation. It would be better to achieve 80% conversion from ac power to beam power as compared to the 50% expected today.

Consideration should be given to preventative maintenance, scheduled replacements and keeping down times to less than 8 hours. Surprises can be minimized if adequate attention is paid to cooling systems and components such as magnets that will be in high radiation fields. Design needs to factor in the desire for turning on the machine within a minute.

5. TECHNOLOGY IMPLICATIONS

Because the technology material will be covered in other presentations, only a brief summary with points for consideration is provided for some of the key technology areas.

* Injectors -- high current, high emittance, adiabatic changes, matching, focusing periodicity, reliable, minimal fluctuations, easily replaceable, long lifetime, understand beam initiation processes, materials, brightness >250 A/(cm2*mrad2).

* Beam properties -- size, halo, charge per microbunch, stability, image charges, wakefields, painting schemes, instabilities, funneling .
* Structures -- size and pulse constraints, frequency and mechanical constraints, joining techniques, room temperature versus superconducting (input couplers for MW/m inputs), radiation damage, beam loading, new DTL concepts (BC DTL and CC DTL), new RFQ concepts, HILBILAC.
* Power -- size and cost, efficiency for ac to beam, phase and amplitude control, supplies, materials and voltage standoff, fast switches and crowbars, rf breakdown, higher order modes.
* Magnets and cores -- materials, saturation, design and codes, lattice designs, beam pipe and loss, injection schemes, funneling.
* Beam optics -- higher order optics, aberration control, bench marked codes, large/small bore optics, permanent magnets, 3D codes, mapping and alignment.
* Controls and automation -- simplification and visual aids, sharing and exchanging information, tool-kit approach, "smart" and "learning" systems, coupling to diagnostics and data analysis.
* Diagnostics -- fast response and small size, innovative solutions, large bandwidths/operating ranges/signal to noise, non-interfering, multiple measurements.
* Beam halos -- beam loss less than one part per million total, understand driving mechanisms, experiments and verification of theories, injectors and rings, activation, beam bore sizes.

* Miscellaneous -- alignment, tolerance build-ups, turn-on, "burps", discharges, transients, vacuum requirements, thermal management, x-ray and UV background, radiation resistant material, off-normal operation envelope, 1 mA cw beam loss converts to 2000 l/s pumping at 10-7 Torr, 1 mA cw beam loss on structure walls converts to one angstrom coating per 100 hours for average dimensions.

6. SUMMARY

The physics, engineering and technology for accelerators has come a long way over the past decade; many innovative advances have been realized. We still need integrated high-power demonstrations, high-efficiency and low-cost ac to beam converters, continued development on theory and simulation, continued work on materials and "forgiving" designs, and continued information exchanges. The impacts on industry and consumers has been significant and will continue to increase as more applications and systems are completed. Many of the solutions being pursued should lead to safer and cost-effective activities, a cleaner environment, improvements to life style, a better understanding of processes, and new products and capabilities.

Accelerator science and engineering provides an exciting and demanding environment that leads to interesting challenges, partners, missions, demonstrations and symbiotic connections. A lot can be accomplished by our community and we will experience some of this in the near future.