FRONTIER ACCELERATOR TECHNOLOGIES

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Although accelerator technology is more than a half century old, the application of new technologies is enabling continuing advances in performance and capabilities. These new capabilities as applied are driving advances in accelerator physics, condensed matter physics, nuclear and atomic physics, molecular physics, and even biological and medical research. The field is as vital and growing today as it has ever been. Examples include ultra high gradient acceleration by lasers and wakefields for compact systems, advances in superconducting rf technology (single crystal niobium and approaching theoretical gradient limits in high purity niobium) driven by the desires of the Next Linear Collider, high average current and high brightness in Energy Recovering Linacs, two approaches to 4th generation light sources, electron – ion colliders based on the use of high collision frequencies and crab-crossing, spallation neutron generation, Muon factories and radioactive ion beams. Supporting technologies have made significant advances, too. RF generation by IOTs and solid state is growing in efficiency and power capability. Photo injectors are producing high brightness, high average current and highly polarized beams at high reliability. This talk will present a survey of the most advanced accelerator programs and highlight some of the exciting possibilities for the future..

I. INTRODUCTION

The field of accelerator technology is exciting and dynamic. Many of the technologies which are in use today were not even conceived of only 5 years ago. As a result the accelerator community is able to provide brighter light sources, higher collision rates in particle generation, and more precise measurements of physical properties of everything from quarks to nuclei to macroscopic materials. Further advances are on the horizon in all of these areas. This paper will present a snapshot of a few of the recent technology advances.

II. ACCELERATOR SYSTEMS

Accelerator system development is driving toward higher average beam brightness, shorter pulses, higher energy in shorter lengths, and generation and acceleration of more exotic particles such as rare isotopes, muons, etc. A key figure of merit is beam brightness, the charge density in 6 dimensional phase space, which can be characterized on an average or peak basis.

II.A. High Average Brightness

One major driving application for higher average brightness and shorter pulses is photon generation. The use of third generation light sources has grown into a sizeable international research activity. It is estimated that there are 20,000 users on 39 synchrotrons worldwide, running typically 4000 hours each and supplying an average of about 30 beamlines, and producing on the order of 5000 publications per year in reviewed journals (Ref. 1). There are at least 12 third generation sources which are specifically designed for the addition of wigglers and undulators to enhance the brilliance at specific wavelength bands. A typical third generation facility such as the Advanced Photon Source at Argonne National Laboratory (Ref. 2) has ~50 beamlines some of which are general purpose but many of which are designed by collaborations to have special capabilities for study of biological, condensed matter, or basic atomic physics research. Despite the successes of these devices and a steady flow of research output from them they are widely viewed as the end of a development line. The reason for this is that fundamental limits will prevent improvements of device performance in machines such as these by more than a factor of 50, or so. This is because stochastic heating of the circulating electron beam will set limits on the minimum emittance achievable at the high energies and currents these systems run.

An additional limitation to synchrotrons is that the pulse lengths from these systems are too long to probe most issues of molecular dynamics. The Touschek effect will limit the pulse lengths in normal operation to ~ 10 ps. One group has developed a technique to pulse slice a very short electron bunch from the circulating pulse to allow the measurement of rapid activity (Ref. 3 – see discussion later in this paper) and there may be other approaches which permit bunch length manipulations to a greater extent (Ref. 4) but substantial progress in this area is not anticipated.

An approach to overcome such limitations has been developed based on the success of high average current energy recovery in the Jefferson Lab IR Demo Free Electron Laser (Ref. 5). Energy recovery from an electron beam involves taking the beam after FEL lasing or other use of the beam and sending it back through the accelerator again ~180^{o} out of rf phase so the beam is decelerated rather than accelerated. (See Figure 1) Using same cell energy recovery in a srf linac the process can be exceptionally efficient. One can then consider running very high average currents through the system without the concomitant expense of high average power rf and its associated energy use. It has the additional advantage that in decelerating the beam below the neutron threshold eliminates to a large degree activation of accelerator components. It was first suggested in 1976 (Ref. 6) and subsequently demonstrated in a system without an FEL at Stanford University (Ref. 7). Recently it has been extended to high average currents during FEL operation (Ref. 5).

The demonstration of such same cell energy recovery of high average current in an srf accelerator has opened the door for application in a number of areas, FELs, synchrotron light sources, electron coolers for ion beams, and electron ion colliders.

There are three operational energy recovering linac (ERL) high average power FELs. The Jefferson Lab FEL has now produced over 14.3 kW CW of outcoupled laser power at 1.6 microns. The electron beam for this was running at 9.3 mA CW in a 74.7 MHz train 300 femtosecond pulses. A group at Budker Institute in Novosibirsk has an 18 MeV, 22 mA, beam in a recirculating system that lases producing 400W of 60 micron light (Ref. 8). A third group at JAEA has an infrared FEL producing 22 micron light from a 17 MeV, 8 mA beam (Ref. 9). All groups intend major upgrades and new facilities are expected to take advantage of these successes.

As a second possible application of the technology considers high power energy recovering linacs as next generation synchrotron light sources. Advancements in CW injector performance yield beams with higher brightness than available in third generation sources. The possibility of long straight sections in the energy recovery lattice transport makes it feasible to use very long wigglers or undulators while retaining large numbers of user ports. Fundamental differences in the performance result because while an electron storage ring stores the same electrons for hours in an equilibrium state, an ERL stores only the energy of the electrons. In an ERL, electrons spend little time in the accelerator (~1 ms), therefore they never reach an equilibrium state; pulse lengths can be very short and emittances not limited by equilibrium levels of stochastic heating from photon emission. In common with linacs: In an ERL the 6-D beam phase space is largely determined by electron source properties which can be of significantly lower emittance than storage ring equilibrium In common with storage rings: An ERL possesses high average current-carrying capability enabled by the ER process, thus promising high efficiencies and high average brightness.

A number of organizations are considering construction of these devices and two proposals and white papers for construction of such systems have been produced (Ref. 10, 11, 12). This technology will likely be a major driver in the construction of new light sources over the next decade. Beam powers under consideration are huge, currents on the order of 0.1 A average and beam energies of up to 5 GeV. Essentially all the technology

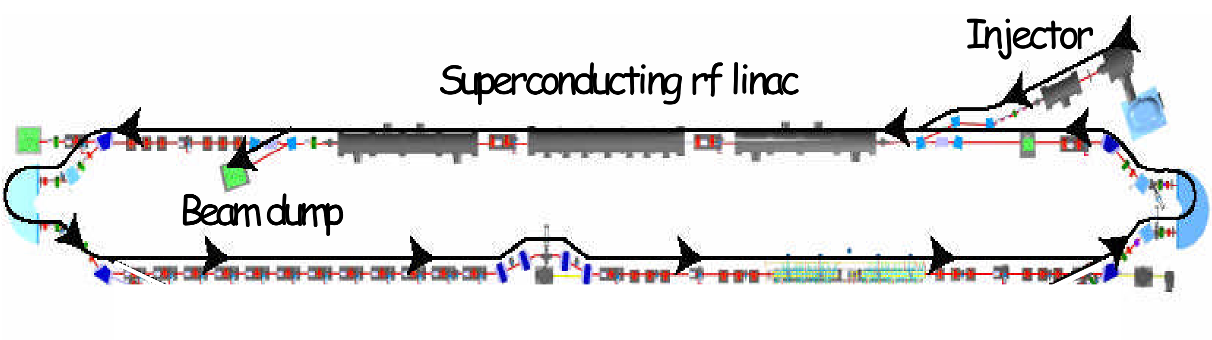

Fig. 1. A layout of the JLab IR Upgrade Free Electron Laser illustrating the path of the electrons in energy recovery. They are produced in the injector, get accelerated in the superconducting rf linac, do a 180 degree bend and after a chicane pass through the FEL wiggler. Another 180 degree bend follows after which they arrive at the linac 180 degrees out of rf phase and decelerate to the injection energy where they are sent to the beam dump.

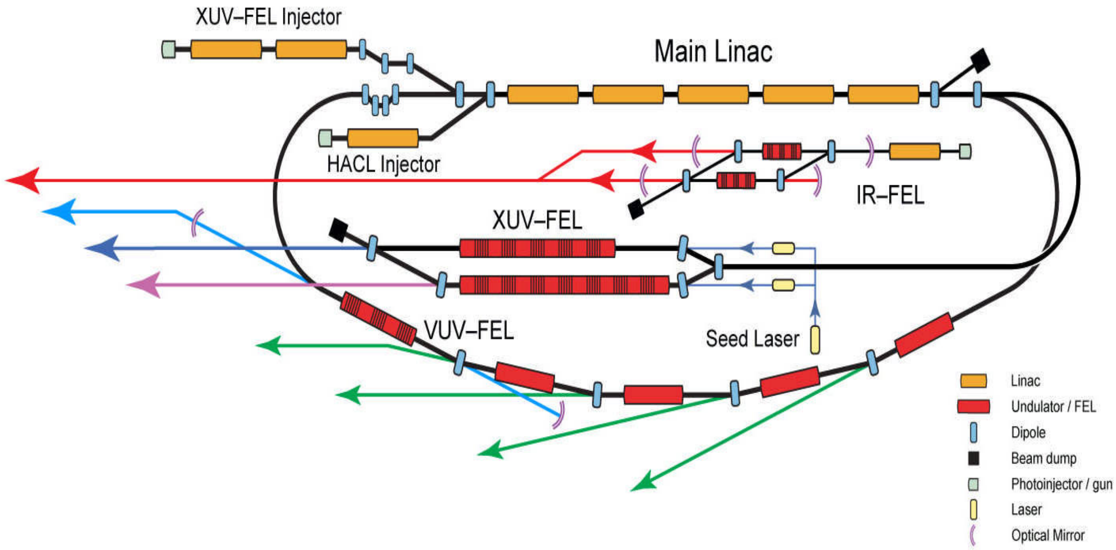

Fig. 2. An illustration of the Daresbury 4GLS. A true 4th generation light source, it utilizes synchrotron ports, collective amplification of light for the XUV region, and VUV and IR FELs and THz to permit a variety of pump probe experiments.

exists for such a system except the injector which has been designed but awaits experimental validation. Perhaps the most ambitious and best example to show the range of possibilities of such devices is the 4GLS of Daresbury Lab (Ref. 13). It is illustrated in Figure 2. The system has been designed with multiple FELs, two operating as oscillators and one as an XUV amplifier as well as a number of undulators for synchrotron ports. The XUV system does not utilize energy recovery because it operates at high peak but low average current negating the advantage of energy recovery in this case. The group is presently submitting the full proposal for consideration by the UK Science Council.

ERLs can also produce average current electron beams which can be used to cool (Ref. 14) or collide with ion beams (Ref. 15). The advantage of being able to determine the electron beam characteristics primarily from the injector source is a huge advantage in achieving the highest performance from such devices. Key to applying this technology in the future will be the development of high brightness CW injectors (see below) and carefully managing the capital and operating costs associated with large linacs.

To further develop and benchmark this technology test beds are in assembly and test at Jefferson Lab, Cornell, Daresbury, and KEK in Japan. Others are expected to soon follow.

II.B. Very High Gradient Acceleration

While ERLs push to high average currents the push to extremely high acceleration gradients has been built around wakefield acceleration (Ref. 16, 17, 18). Substantial progress has been made in the last few years in understanding the mechanisms behind such acceleration and getting good agreement between models and experiment. The process works by using a laser or electron beam to ionize a channel in a low pressure gas. A relativistic electron pulse then travels through the ion channel expelling the low energy ionized electrons and creating a strong accelerating electric field at the tail of the pulse. Energy is extracted from electron in the earlier parts of the pulse and some electrons at the end of the pulse are accelerated to very high energies. Programs are underway at LBNL, Oxford and Strathclyde University collaboration and elsewhere (Ref. 17). The Strathclyde group intends to use the accelerated electrons to drive an FEL among other applications. A recent demonstration at SLAC accelerated electrons to 42 GeV in an 80 cm long gas channel (Ref. 18). Efforts to extend the channel met with limited success due to what is believed to be defocusing of the electrons in the initial part of the pulse.

II.C. Acceleration of ion beams

Progress in ion accelerators has not been quiet either. The Spallation Neutron source has become a very productive facility and the results are sufficiently encouraging that upgrades are already envisioned. Plans for RIA have been revitalized by the DOE and the redesigns for the superconducting rf facility are underway under a new name FRIB, the Facility for Rare Isotopes Beams (Ref. 19). It is listed as the second priority for construction by DOE. And the major program on the horizon is the ILC which will demand very high gradients in a pulsed srf machine (Ref. 20, 21, 22). Key work is underway to improve the performance and reproducibility while significantly reducing fabrication costs. Significant international collaborations have formed with Fermilab taking the lead in the US.

III. ELECTRON SOURCES AND CAVITY TECHNOLOGY

To support advances in a broad range of electron accelerator technologies it is required to have major improvements in the source performance. This has not been a quiet area either with progress on both the peak brightness front and in producing high average electron currents, polarized or not.

III.A. Pulsed injectors for highest peak brightness

One of the most demanding applications for high brightness electron beams is for SASE FELs and the most aggressive programs for X-ray FELs is the LCLS at Stanford Linear Accelerator Center (Ref. 23). Designed to produce lasing at 0.15 nm with 2 mJ of output (Ref. 10^{12} photons/pulse) the peak brightness of the FEL is so many orders of magnitude brighter than the previous sources that entirely new techniques will have to be developed to deal with the intense flux. A laser cannot produce an optical beam brighter than the electron beam that generates it. Because of this, even though the electron beam energy is 15 GeV at the output of the 1/3 of the SLAC accelerator used for the project, the injector must produce nanocoulomb levels of charge at slice emittances of less than 1 micron. The resulting beam ends up being bunched in three stages to over 4 kA peak current. In order to achieve such high brightnesses the beam must be produced in a very high gradient gun with minimal high order fields. Furthermore the pulse profile, both temporal and transverse, must be contoured to meet exceptionally high tolerances. The development of the control on the UV drive laser for this effort exceeded by a large margin what is commercially available but after a development program is now beginning to operate and approach the demanding specifications. Recent results show the beam's slice emittance is approaching the required level.

III.B. CW injectors for average current

The quality of electron beam than can be delivered at high charge is less in CW systems because the gradients that can be achieved in CW systems are considerably less than pulsed machines. Nevertheless significant improvements in performance have been achieved in the last few years and a number of possible advances are on the horizon. A number of groups are pursuing the development of DC guns; Cornell, JLab, Daresbury Lab, KEK. All of these have the goal of high average current at high brightness. The best emittances are achieved for the production of low charges at high repetition rate. This is due to the minimization of space charge effects. The group at Cornell has led the way in multi-parameter design optimization. They have set up a massively parallel system to optimize the strength and position of all injector components running PARMELA thousands of times and scoring results based on the beam qualities. The result yields a system design which is projected to provide 100 mA beams of 77 picocoulomb charge at 0.1 mm-mrad normalized emittances. At that level the remaining emittance is dominated by the electron temperatures in the cathode itself, 0.025 eV (Ref. 24).

An additional challenge is presented when the application require polarized electrons. In DC guns using GaAs photocathodes such electrons have traditionally been produced from strained GaAs layers and long wavelength excitation. A 38% improvement in the figure of merit for such cathodes has been achieved by using a superlattice structure: Layers of GaAs on GaAsP. Such cathodes demonstrate long life with quantum efficiencies of around 1% at 780 nm excitation and yield polarizations of 85% (Ref. 25). It is worth mentioning that advances in laser technology are providing significant benefits to photoinjection. Conversion of the CEBAF injector to a fiber laser driver decreased lost runtime by a factor of 2 by eliminating required realignment and driver failures.

Maintaining good emittances when space charge comes into play is more difficult but aided by high acceleration gradients in the gun. DC guns operate in the 6 to 10 MV/m range. Two groups are presently pursuing the development of srf photoinjectors, Dresden and an AES/BNL collaboration. The Dresden group has constructed and is testing a 1300 MHz 3 ½ cell photoinjector destined to power their srf linac at multi-mA levels (Ref. 26). The AES/BNL collaboration is more ambitious (Ref. 27). They are constructing a 703 MHz srf gun to provide beam for a 100 mA electron cooler ERL. Significant challenges exist in marrying the cathode with the srf cavity: the rf field generates high currents in the cathode stalk; the cathode material must be compatible with the srf environment; significant rf power must be fed into the cavity; heating due to rf losses and conduction must be kept to a minimum; etc.

III.C. Superconducting rf cavities

Significant benefits to accelerator designs over the last decade have resulted from improvements in delivered SRF cavity gradients. These improvements have been due to improved understanding of the fundamental physics as well as advances in surface processing and material handling. At the cutting edge of advancing this technology are predictions by Gurevich that coating thin layers on a superconducting material can yield significant benefits in the ultimate field capability (Ref. 28). Specifically, he predicts that a single 50 nm layer coating of Nb3Sn on a base of niobium should yield breakdown fields on the order of 100 MV/m. These predictions have yet to be experimentally confirmed.

Nonetheless, what is being achieved is very impressive. The use of single crystal and large grain Nb combined with care in processing is yielding single cell CW gradients up to 46 MV/m (Ref. 29). Work at KEK, JLab, and DESY is aimed at establishing reliable, reproducible protocols for cavity processing. Once the cavities are assembled and under vacuum, experience has been very positive regarding lifetime and reliability. Multicell cavities offer special challenges because they are harder to process and are limited by the single worst cell in the chain. Typically CW gradients of 20 to 25 MV/m are possible in the 1300-1500 MHz band although Jefferson Laboratory has produced 40 MV/m multicell cavities. Pulsed gradients can be 20% to 30% higher. Significant engineering challenges are ahead for projects such as the ILC which desire very high pulsed gradients and lowered production costs.

IV. LIGHT SOURCES TECHNOLOGY

A number of accelerator technology advances are aimed at improving the performance for a specific set of needs. In a couple of examples below I touch on three technologies extending the source characteristics of light sources.

IV.A. Compton Sources

The availability of very high peak power laser pulses and short, high charge relativistic electron bunches makes feasible significant brightness from Compton scattering. Photons from a conventional laser with photon energies on the order of 1 eV get upshifted proportional to γ^2 as they scatter off the relativistic electrons. X-ray photons with energies from 1 keV up to MeV levels have been produced in this manner at useful fluxes. For example, peak brightnesses as high as 8 x 10^{22} in standard units have been achieved for MeV X-rays. (Ref. 30) The key factors governing the performance are the fluxes of both electrons and photons and how tightly they are focused in the interaction region. For back scattering the X-ray pulse length is determined by the electron bunch length so it is very possible to produce sub-picosecond pulses. An advantage of this sort of source is that a relatively inexpensive and compact machine can produce quite useful brightnesses for individual researchers.

IV.B. Pulse slicing

While huge fluxes will be available when coherent sources such as the LCLS become fully operational, techniques utilizing conventional lasers have been developed to produce femtosecond X-ray pulses. Seminal work in this area was being performed at Lawrence Berkeley National Laboratory where a 300 fsec pulse from a high power laser was used to modulate the energy of a short pulse out of a 100 ps pulse circulating in the ALS synchrotron (Ref. 3). At a subsequent energy-dispersed location a fsec pulse of synchrotron light is produced. This source now has a dedicated beamline and can be used to perform molecular dynamics experiments and fast X-ray diagnostic development. This work has now been extended and applied at a number of locations around the world including among others the SLS at PSI and UVSOR-II. (Ref. 31, 32). The short pulse structure can also be used to produce THz pulses as discussed below.

IV.C. THz Production

THz radiation lies at the interface of electronics and photonics. Narrow-band THz radiation can be produced by free-electron lasers (Ref. 33) and fast diodes(Ref. 34,35), while low power broadband THz radiation can be produced by thermal sources and more recently by table-top laser-driven sources (Ref. 36-38). It can also be produced by short electron bunches in accelerators (Ref. 39). The mechanism for this production is easy to grasp. As is well known, individual electrons radiate synchrotron light when accelerated. The transverse acceleration of a relativistic electron around a bend produced by a magnetic field is the source of synchrotron emission used in light sources. If many electrons go around a bend their radiation adds incoherently and the power scales linearly with the number of particles. This is the case unless all the electrons radiate in optical phase. Such occurs for wavelengths of light much longer than the electron bunch length. In that circumstance then the electric field from every electron adds together linearly and the resulting power scales as N^2 where N is the number of electrons. Since N in this case is on the order of 109, the increase in power is very large. Production of broadband THz radiation with an average power of nearly 20 watts was accomplished at Jefferson Lab with 500 fs, 135 pC electron bunches of originally 40 MeV (Ref. 40) but now the work has been extended beyond 100 MeV. Such THz power production is 4 orders of magnitude higher than other sources and creates new opportunities and applications. Since the absorptive and dispersive properties of materials in this spectral range are rich in structure, they can be utilized to provide contrast which reveals unique features in images. For example one can image the distribution of specific proteins or water in tissue, or buried metal layers in semiconductors (Ref. 41, 42). The present Jefferson Lab source would allow full-field, real-time capture of such images. High peak and average power THz sources are also critical in driving new non-linear phenomena with excellent signal to noise, and for pump-probe studies of dynamical properties of novel materials (Ref. 43, 44).

IV.D. System timing

The final point I want to touch on in this discussion is the necessity of synchronizing all the elements of accelerators and possibly associated diagnostic equipment, lasers, etc. to extremely high precision without drift. In the past this has been typically accomplished by using a master source distributed around the linac system on phase stabilized transmission lines. Picosecond or larger drifts and significant jitter between components was routine. A new optical approach is now yielding impressive results by performing optical to optical synchronization. Jitter and drift levels as low as 380 attoseconds have been demonstrated using this technology. (Ref. 45) Use of such systems allows precise and reproducible setup and control of accelerators to levels impossible only a few years ago.

V. SUMMARY

The field of accelerator technology is diverse and dynamic. I have discussed a few of the exciting technologies emerging in the last few years. There are others that I was unable to discuss in this forum. Examples include beam tomography, electro-optic bunch length measurement, coherent synchrotron radiation induced emittance growth, the emergence of IOTs as a viable rf source for high power accelerators, etc. I hope the wide range of this technology and the exciting recent progress encourages the reader to contribute to the growth of this field for the benefit of accelerator users around the world.

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