BNL-93896-2010-TECH

EIC/33;BNL-93896-2010-IR

On the future of BNL user facilities

I. Ben-Zvi,

August 2010

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

BNL-93896-2010-IR

C-A/AP/#402
August 2010

On the future of BNL User Facilities

Ilan Ben-Zvi
Brookhaven National Laboratory, Upton, NY 11973, USA

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

PREFACE

The following document was written in June 2000 as an attempt to assess the impact of an emerging technology, high-brightness and high-power electron beams. It has been circulated widely but not published. The progress on this subject made over the past decade has been gratifying. Given the need to make references to this document, it is published now as a C-AD AP report with no modifications.

On the future of BNL User Facilities

Ilan Ben-Zvi, NSLS, September 2000, Version 2

Table of Contents

1. Introduction

The purpose of this document is to portray the emerging technology of high-power high-brightness electron beams. This new technology will impact several fields of science and it is essential that BNL stay abreast of the development. BNL has a relative advantage and vital interest in pursuing this technology that will impact its two major facilities, the NSLS and RHIC. We have a sensible development path towards this critical future technology, in which BNL will gradually acquire a strong basis of Superconducting Radio Frequency (SRF) technology while executing useful projects.

The technology of high-power AND high-brightness (HPHB) electron beams is based of the convergence of two extant, but relatively recent technologies: Photoinjectors and superconducting energy-recovering linacs. The HPHB technology presents special opportunities for the development of future BNL user facilities for High-Energy and Nuclear Science (HE-NP) and Basic Energy Science (BES). In HE-NP this technology makes it possible to build high-energy electron cooling for RHIC in the short range and a unique linac-based electron-ion collider (eRHIC). In BES, we can build short pulse, coherent FIR sources and high flux femtosecond hard x-ray sources based on Compton scattering in the short range and, in the longer range, femtosecond, ultra-high brightness synchrotron light sources and, ultimately, an X-ray Free-Electron Laser (FEL).

2. The Science and Technology of High-Power, High-Brightness Electron Beams

High power electron beams are the basis for all current synchrotron light sources. Consider that the NSLS X-ray ring has a circulating electron beam power of about one gigawatt. This makes it possible to extract a high flux of synchrotron radiation. The energy of the electron beam is not wasted after a turn by circulation. The price we pay for circulation is a limited emittance and a long bunch length. However, using current standards in electron beam physics, storage rings are not high-brightness devices (compared with photoinjector based linacs). This is the reason why x-ray FEL, which need high-brightness beams for achieving gain, are based on linacs and not on storage rings.

Linacs usually dump the beam after one pass. Thus there is no problem of beam lifetime, and ultra short bunches are possible. Short pulses of hard x-rays are a new frontier and among the most exciting aspects of X-ray FELs. High brightness electron beams became possible in linacs with the advent of the photocathode RF gun, or photoinjector. This relatively new science and technology makes it possible to build very short wavelength FELs. High average current linacs became an accessible technology with the demonstration of the energy recovering SRF linac of the Jefferson Lab kW power IR FEL.

Combining photoinjectors and energy-recovering superconducting linacs opens up a new technological frontier of high-brightness, high average power electron accelerators, with the possibilities mentioned above.

The following sections describe a few projects that should be pursued at BNL:

- A light source based on a HPHB electron linac (a major project).
- Electron – ion collider in RHIC (also a major project).
- Electron cooling for RHIC (an intermediate size project).
- Femtosecond Radiation sources (FIR and x-rays) (small projects).

3. Energy Recovering Linac – a New Light-Source Paradigm.

Conventional wisdom has it that a synchrotron light source has to be based on a storage ring. The enormous success of storage-ring based light sources led to a proliferation of these facilities. However storage-ring light sources cannot support either very short bunches (picosecond and sub-picosecond) or an x-ray FEL. Consider a superconducting linac, with energy of several GeV with an average current of the order of 100 to 200 mA. The electron source for this machine would be a photoinjector. With energy recovery, the RF power consumption is just a few megawatt while the beam power is at the gigawatt level, similar to that of a storage ring light source. The advantages that such a machine has over storage rings is the elimination of most beam instabilities, a photoinjector level of emittance, an inherent picosecond length electron bunch and the ability to compress the beam to the femtosecond range. The optics of the machine allows for very long insertion devices. The current does not decay, as it would be in a storage ring operating in a top-off mode. The bunch timing and charge can be programmed arbitrarily, to suit various experimental needs. The energy stability of superconducting linacs is excellent, but the charge stability, which depends on the laser energy stability, needs improvement. With a long insertion device (say 50 to 100 meter long undulator) the average brightness is extremely good compared to any existing light source. With a short pulse at the sub-picosecond level, the peak brightness would be spectacular, falling short only of a Free-Electron Laser. However, the clear advantage of this machine is in its unique ability to provide extremely short bunches. Both peak-brightness and short pulse will open up new avenues in science.

The need to produce pulses on the femtosecond timescale cuts across many disciplines in fundamental and applied sciences, the main reason being that many electronic processes occur in this timescale. Electron transfer reaction dynamics in atomic and molecular systems, providing information about the most basic reaction mechanisms (e.g. forming and breaking chemical bonds) in chemistry, biology and condensed matter physics are on the femtosecond scale. For example, molecular vibrations have typical lifetimes of a few hundred femtoseconds. With probing pulses of under 50 fs these excitations will appear basically as frozen. This will facilitate and make it possible to study fundamental, dynamical excitation mechanisms in conjunction with, for instance, structure determinations.

Synchrotron radiation is used by a very broad scientific community and the time structure provided (from the infrared to hard x-rays) is an important aspect for many applications. However, it is very hard to get pulses shorter than 30-50 ps without seriously sacrificing other performance parameters of the synchrotron radiation. A multi-GeV energy-recovering linac may provide pulses as short as 50 fs or below, thus three orders of magnitude shorter than the state-of-the-art of the most modern synchrotron radiation sources. This, in combination with the high peak brilliance, full coherence and energy tunability, make the energy-recovering linac a unique photon source.

4. An upgrade to the NSLS

An energy recovering superconducting linac may be used to recirculate an electron beam through the existing NSLS x-ray ring. Assume 3 GeV beam energy. The average current, the bunch spacing, bunch length, emittance and the charge would all be variable, as can be seen below. This upgrade path maintains all the current capabilities and beam lines of the NSLS and preserves the considerable investment in NSLS beam lines. It will capitalize on the strong user program and will not require a long shutdown to implement. Following the upgrade the large NSLS user community will enjoy a light source that improves the vertical emittance to somewhat better than the APS or ESRF, will better the horizontal emittance of these sources by two orders of magnitude and provide a pulse length shorter by three orders of magnitude.

In this new operational mode, the maximum average current will be of the order of 200 mA. In one particular operational more, the emittance at 200 mA can be about 0.07 nm in both vertical and horizontal (surpassing **any** existing light source), and the bunch length under 100 fs. This is an **unprecedented** performance for a light source. In this mode the bunch spacing will be 0.77 ns. An increase in the bunch spacing will require operation at a lower average current. Since the beam is NOT STORED in the x-ray ring (essentially the x-ray ring will serve as a beam transport only), this will be no current decay and no fills.

The linac will be placed in a new building adjacent to building 725. A shielded passage for the input and exit beam will have to be constructed, and this may impact one or two existing beam lines. The beam will be introduced into the NSLS x-ray ring by turning off one or two bend magnets. The magnet(s) where beam will enter and exit will require a modified vacuum chamber. These modifications should have a minimal impact on the existing scientific program. In addition, the current injection system will be preserved, and operations in the extant mode can alternate with the new mode at will.

Besides providing the NSLS x-ray ring beam lines with an ultra-high performance beam, the energy recovering linac transport can be designed to support many additional beam lines outside the NSLS building. If this option is to be realized, the building has to be designed accordingly. These beam line may operate independently of the x-ray ring (while beam is provided to the x-ray ring or when the x-ray ring operates in the old mode, i.e. storage of beam from its injector. In addition, the facility may support an HGHG soft x-ray FEL.

The linac may be based on TESLA type structures. These 9-cell superconducting cavities can operate up to 25 MV/m. We will specify 20 MV/m, thus the linac length will be about 150 m (not including beam transport).

- Extremely well known cavities (JLAB, DESY, Stanford, industry)
- R/Q=1036W, L=1.038m.
- Take conservatively Q_0=1.5x1010 at 2K, 20MV/m.
- Refrigeration power 26 W/structure at 20 MV/structure.
- 150 cavities require a refrigeration power of 4 kW.

The beam may be produced by a photocathode gun. For a bunch spacing of 0.77 ns, each accelerator bucket will be filled with 0.15 nC. At this low bunch charge the normalized emittance is expected to be under 0.4 microns, leading to an emittance of 0.7Å at 3 GeV. Emittance growth due to coherent synchrotron radiation is also negligible at this low charge even at 100 fs bunch length.

To get a notion of the photocathode laser power requirements, let us consider the following. The laser power in watts, P, is related to the electron current in amperes, I, through

$$P=I*E/Qe$$

Where E is the energy of a photon in electron volts and Qe is the quantum efficiency.

For a quantum efficiency of 10% and an IR photon of 1 eV, which is typical of the widely used gallium arsenide (GaAs) photocathodes, then P is 2 watt for the 200 mA of current. This is an extremely modest power in the IR, since mode-locked lasers are available with upwards of 50 W average power. However this cathode requires an ultra high vacuum environment. Cesium telluride (Cs_2Te) cathodes are more robust and can tolerate less than UHV vacuum, then the need is for UV light (photon energy about 5 eV) and the quantum efficiency is at 2 to 10 %. This requires perhaps 10 watt per 200 mA in green, which requires now about 50 watts IR laser (to make up for the quadrupling efficiency). This cathode, which is used routinely in a number of photocathode RF guns, will use the maximum power available in a pulsed laser today.

The exact choice of the gun depends on the state of the art of lasers, which is advancing rapidly. An RF gun with a semiconductor cathode can provide the necessary average current with currently available lasers. The Los Alamos L band RF gun and the Boeing 500 MHz gun have been designed for CW operation. Both have the capability of providing a good emittance with the required low bunch charge.

Measurements at the Jefferson lab energy recovering linac have shown that the energy spread for a 1 ps bunch at a charge of 0.08 nC is 0.25% rms, with a very gradual slope, which extrapolates to 0.35% rms at 0.15 nC. This is at energy of less than 50 MeV. Thus the longitudinal phase space area is .175 MeV-ps, or 1.75 MeV rms energy spread for compressing down to 100 fs, which is 0.06% at 3 GeV.

Bunch compression may be done at a few intermediate energies yet to be determined. First bunch compression will be done at the exit of the gun. A second one at about 100 MeV, following which the bunch length will be brought down to about 1 or 2 ps. Final bunch compression, to 100 fs, may be done after the linac, at 3 GeV, or at an energy of the order of 1 GeV. In the second case, higher order power loading in the cavity will be under 8 watts for the cavities following the bunch compressor, adding about 800 watts to the refrigerator load. Intermediate energy bunching simplifies the bunch compressor.

For timing experiments that require a larger spacing between the x-ray pulses, the bunch repetition frequency may be decreased. For the ultimate in emittance and short bunches the charge per bunch will be maintained. However, now there is another adjustment that can be done. The bunch charge may be increased, within certain limits, to maintain the average current, but that will come at the cost of increased emittance. The emittance increase from the gun can be assumed (based on experience) to scale linearly with the charge. However, as we increase the charge wake fields and CSR will start playing a role. A lot of computations must be done to estimate these effects with confidence.

The x-ray ring will operate in the new mode with the sextupoles turned off, and the quadrupoles set to produce a low momentum compaction factor α. With a 100 fs bunch length and energy spread (after bunching) of 0.06%, α has to be set to about 10^{-4}, (smaller than the nominal 5.6×10^{-3}, but doable.)

5. An X-ray FEL

The high-brightness of the energy-recovering linac is sufficient to drive a hard x-ray Free-Electron Laser. The x-ray FEL will take the peak and average brightness of the spontaneous emission source discussed above to new records. The potential of X-ray FELs has been discussed at length, and it is generally accepted that a user facility x-ray FEL will be based on a superconducting linac. It follows that unlike a machine like the proposed 120 hertz Linear Coherent Light Source (LCLS) at SLAC, the bunch repetition rate will be in the tens of megahertz. The work on the LCLS is considered a proof-of-principle x-ray FEL and a precursor to future x-ray FEL user facilities. It is generally accepted that a user facility FEL should have a much higher throughput than the LCLS. BNL participates in the national LCLS R&D project, but ought to prepare for the competition that will surely take place for the location of a user facility FEL.

The natural advantage that BNL would have in such a competition is having RHIC, (besides the NSLS), its refrigeration facility and the possible site of eRHIC. The disadvantage (to be corrected) is the lack of SRF work at BNL.

6. A Polarized Electron – Ion Collider, eRHIC

Interest continues to grow among theorists and experimentalists in the physics of collisions between electrons and heavy ions and between polarized electrons and polarized protons.

At BNL, it is natural to consider adding polarized electrons to the RHIC repertoire. An accelerator physics study group studied this possibility. One of the options that were considered was a superconducting linac with energy recovery for the production of the electrons. The RHIC cryogenic refrigeration plant already installed has enough spare capacity to run such a linac.

The considerable energy which is stored in the electron beam is not thrown away after each single pass collision, but is recovered by recirculating the electron beam back through the linac. The accelerating and decelerating electron beams travel in the same direction along the linac in order to avoid collisions. The planned linac energy and current are 10 GeV at 130 mA.

The natural advantages of a linac (over an electron storage-ring) are in the ability to vary the energy over a very wide range without affecting the polarization or beam quality and in its high beam quality (low emittance and energy spread). It is easy to build a linac with energy of 10 or 15 GeV and to provide polarized electrons at up to 80% polarization. The linac may be constructed of niobium superconducting cavities, for example 1.3 GHz TESLA cavities that may be operated at over 20 MV/m. Thus a full energy linac for eRHIC would be rather short, about 500 meters long.

Why is a linac attractive for a collider?

- A linac is that it avoids the limitation of beam-beam tune shift inherent in a storage ring. That allows one to reduce (by cooling) the beam size of the ion storage ring and increase its charge per bunch considerably.

- Another aspect of the above point is that a given luminosity is obtained at a much smaller electron beam current (up to an order of magnitude) relative to an electron storage ring, thus reducing the synchrotron radiation loading of the interaction point detectors.
- The fact that the electrons are used only once means that complicated spin rotation conditions are relaxed. Thus a linac based collider can provide a polarized electron beam at any energy, while a storage ring is limited to a very narrow energy range.
- The interaction point optics of the linac is much simpler (since the polarization may be prepared well in advance and the beam has a small emittance) thus the bending radii are larger.
- A linac can operate over a wide energy range without sacrificing performance.
- The polarization of a linac is high and can be alternated rapidly at will.
- A linac produces a naturally round beam, which matches well with the RHIC beam.
- A linac can be extended to higher energies with a cost that is linear in length whereas an storage ring faces an increase in RF power that goes with the fourth power of its energy.
- Last, but not least, a linac will double up as a unique light source, as discussed above.

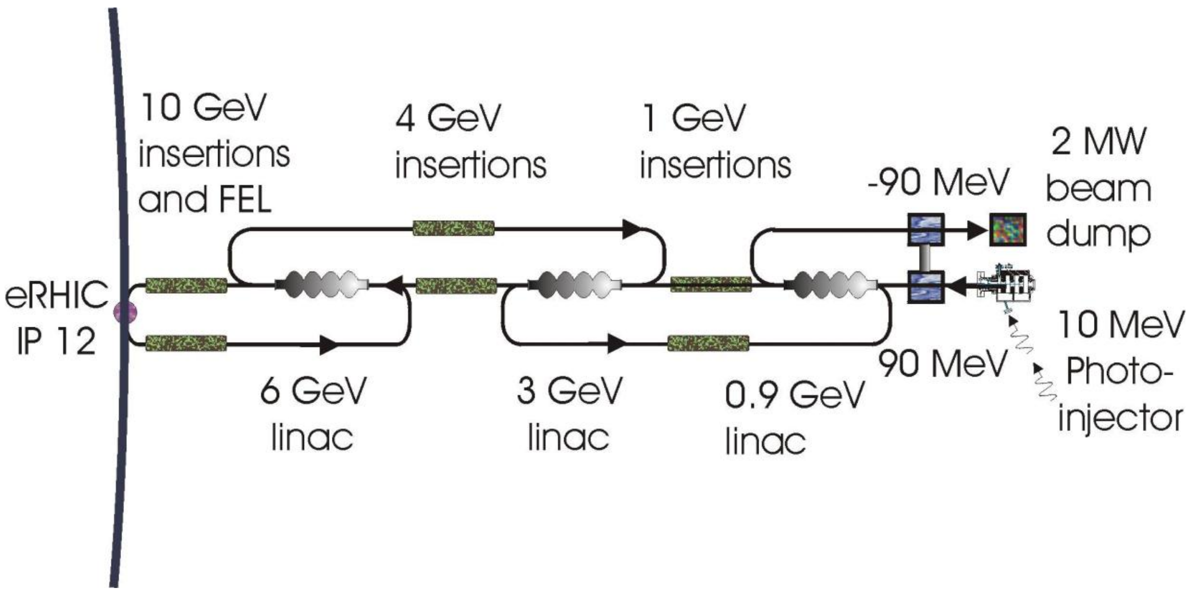

Figure 1. A schematic layout of a combined femtosecond, ultra-high brightness synchrotron radiation facility combined with eRHIC.

7. RHIC Electron Cooler

A high beam quality, high current superconducting linac with energy recovery is the machine of choice to provide electron beams for cooling a highly relativistic ion beam. The cooling beam energy ranges from about 50 MeV for gold beams at 100 GeV/A to about 130 MeV for 250 GeV/A protons. Cooling the ion beam of RHIC may increase the integrated luminosity of RHIC (in ion-ion collision mode) by about an order of magnitude by some estimates. On top of that, electron cooling may allow the operation of the collider at larger than usual beam-beam tune shifts. As mentioned above, in the context of linac-based eRHIC, electron cooling of the RHIC ion beam takes on a special significance. Note that any reduction of the ion emittance would be detrimental to an eRHIC electron storage ring due to the beam-beam tune shift.

An MOU has been signed with the Budker Institute of Nuclear Physics in Novosibirsk to collaborate in the design of an electron cooler for RHIC.

8. Radiation Sources Based on a RHIC-Cooler Class Linac

An energy-recovering linac, like the RHIC cooler linac can be used for a number of radiation-sources, all with a tremendous potential:

1. A femtosecond hard x-ray source based on Compton scattering high-power diode-lasers on the high-average-current electron beam.
2. A single-pass, far IR, femtosecond, coherent-emission-source. Such a source will use a tightly bunched (“microbunched”) electron beam and produce coherent emission in the very far IR in a single-pass through a wiggler.
3. A high power FEL, in the IR (for a 50 MeV linac energy) or UV (for the 130 MeV class), similar to the TJNAF present and planned machines.

The first two sources are low cost items and have no competition at the present time. The third, the high-power IR FEL, has been built at TJNAF. These sources can initially start by sharing the same SRF facility as the RHIC electron cooler / SRF test facility. If desired, they may be replicated in the NSLS for pump-probe capabilities with the present NSLS sources.

The 1994 study of the National research Council on FELs was most supportive of the scientific need of a very short pulse FIR source. In its range of coherent emission (approximately where the wavelength is longer than twice the electron bunch length), the single-pass FIR source will surpass the intensity of storage-ring based sources by many orders of magnitude. It also would have some other unique features: The format of the radiation pulse can be varied on command by altering the strength and number of periods of the wiggler (by using an electromagnet wiggler). Control of the current of individual periods can lead to the generation of a variable length and waveform FIR pulse, including a chirped pulse.

The Compton source will produce a high flux of femtosecond hard x-rays, a radiation that is currently unmatched by any source. It would complement nicely the NSLS longer-pulse sources.

9. Related SRF Projects

SRF technology has other potential applications at BNL, not necessarily related to high brightness. Examples are a linac-based spallation source, an improved heavy-ion injector for RHIC, muon collider (or neutrino source) and SRF cavities for RHIC or the NSLS.

10. A Path Towards Establishing High-Brightness High-Average Power Electron Beam Technology at BNL

The relative advantages of BNL in pursuing the technology of High-Brightness High Power electron beams and its applications is in the following:

- Leading expertise in high-brightness electron sources.
- Expertise in radiation sources such as FELs and Compton sources.
- Having both RHIC and the NSLS and their staff.

The proposed path towards the goals outlined above would center about establishing the high-power SRF technology, starting with the smaller applications, building up experience and prestige and recognition. Key to this development would be an immediate construction of a SRF test facility, equipped with radiation shielding and interlocks, a supply of liquid helium and other necessities. This SRF test facility may be located at RHIC, making use of the available cryogenic system and potentially house a future RHIC electron cooler.

A superconducting photoinjector is a key device in producing a high-brightness, high-average-power electron beam. It should be noted that a normal-conducting version has been under development at Boeing for some time, and a 25% duty factor has been demonstrated. However this is a brute-force, limited performance device. The development of SRF photoinjectors have been attempted unsuccessfully in the past. A significant expertise that has been accumulating at BNL on metal photocathode photoinjectors (at the ATF and in the Instrumentation Division). This expertise has been the basis of photoinjectors at the ATF, DUV-FEL and LEAF facilities at BNL and most other US laboratories and universities as well as internationally. Based on this expertise we have suggested to a local small-business (Advanced Energy Systems, or AES) to submit an SBIR for the development of a SRF photoinjector based on a pure niobium photocathode. The expectations were that the quantum efficiency of the niobium cavity material might be enhanced (using techniques developed at the Instrumentation Division) to make such a device practical. The results of quantum efficiency tests were spectacular and AES just won the phase II SBIR. It has been agreed that the built device will be used at a test facility at BNL.

The immediate plan is to construct a new SRF laboratory near RHIC, (making use of RHIC refrigeration) in which we may pursue several investigations:

1. Test the SRF photoinjector.
2. Use the SRF PI to inject to a SRF linac and study energy recovery for a RHIC electron cooler.

3. Use the beam to develop novel radiation sources.
4. The same facility will be located in such a place that it will be ready to house a RHIC cooler.
5. Other uses of the laboratory could be testing SRF cavities for RHIC and RHIC high-power normal-conducting cavity testing.

This will be followed up by constructing the larger applications, RHIC electron cooling and radiation sources. The goal is to get a major facility, eRHIC and / or a linac based light-source.