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Title: New Energy Recovery Linac Source of Synchrotron X-rays

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Introduction

Cornell University and Jefferson Laboratory physicists have been studying the properties of a new type of synchrotron radiation machine, called an Energy Recovery Linac (ERL), based on a superconducting linac configured for energy recovery with a return ring. A high energy, high current ERL could produce electron beams of order 10 microns in diameter. These could be used as an ultra-high brilliance x-ray source with many desirable characteristics, including: transversely coherent, diffraction-limited hard x-ray beams, very short (~100 fs) frequent (1 – 2 GHz) pulses, no limits on beam lifetime, and very flexible modes of operation. This combination of characteristics opens up new possibilities and could significantly advance the state of the art in x-ray research.

A Cornell University goal is to eventually build a hard x-ray ERL machine at Cornell University. The feasibility of the machine design was explored in a Machine Physics workshop held at Cornell on August 11 & 12, 2000 [1]. A subsequent X-ray Science workshop was held at Cornell on December 2 & 3, 2000 with about 80 persons participating [2]. In this brief note we describe the ERL machine and the exciting conclusions from the two workshops. We believe that this new concept of building a synchrotron radiation source should be considered for future generation light sources.

ERL Concept

Maury Tigner (Cornell Univ.) first described the ERL concept in a 1965 paper of machines for colliding beam experiments [3]. Current interest has been catalyzed by the successful demonstration of an ERL-based IR Free Electron Laser (FEL) at Jefferson Laboratory working with a 48 MeV, 5 mA electron beam [4]. In a storage ring, important electron beam characteristics, such as emittance and bunch length, are determined by process that need thousands of passes around the ring to reach their (large) equilibrium values. By contrast, linacs can be used to accelerate bunches without degrading emittance or pulse length, thereby preserving the desirable characteristics of a brilliant photoinjector.

High energy linacs usually operate at low current and low duty cycle because of prohibitive energy costs. For example, an ERL model discussed at the Cornell workshops would operate at 7 GeV and 100 mA, i.e., a beam power of 700 MW, which is the power output of a very large electrical generating station if the energy were not recovered. [This is not a problem in a storage ring because the electrons are accelerated once and then reused many times by trickling in RF power to replace relatively minor synchrotron radiation losses.] By way of contrast, in an linac with energy recovery, the kinetic energy of the electron beam is recycled by reinjecting it into the linac out of phase with the traveling RF wave, its energy recovered, and the now energy-depleted electrons are steered to a dump at the other end, Figure 1. The recovered energy is used to accelerate new electron bunches ariving from the injector; in fact, accelerating and decelerating bunches can be interleaved at GHz rates while maintaining continuous beams. The key technological advance which has enabled ERLs is the development of the high-Q superconducting linacs which are required for efficient energy recovery.

There are numerous advantages of recycling the beam energy, instead of the electrons: no Touschek effect to limit the beam lifetime, flexible bunch patterns that are determined by a laser flashing at a photocathode, no lattice radiation equilibrium which limits emittances, and opportunities to use very short length bunches down into the 100 fs regime. The emittance of the x-ray undulator sources can be designed to be dominated by the emittance of the injector. Unlike a conventional storage ring, just improving the injector emittance will result in a lower emittance (smaller diameter) beam through the undulators. And unlike present day storage rings, lowering the injector emittance will increase the brilliance of the x-ray beams produced by the ERL light source. In other words, the limiting characteristics are set more by the injector, a relatively small device, than by the entire machine.

Since the bunches in the ERL are continuously injected at GHz rates, the proposed machine looks like a nearly DC source of x-rays with a constant beam current. There is no lifetime limit to the x-ray beam because the electrons are not stored. Since all the beam position monitors and optics operate at one current, the time varying non-linearities of position monitors and optics are minimized, suggesting that the ERL technology will be capable of delivering extraordinarily stable beams. This will be essential for effective utilization of the resultant very brilliant beams.

August Machine Physics Workshop

In the August workshop [1], Sol Gruner (Cornell Univ.) overviewed the limitations of storage rings and the advantages of ERLs. Maury Tigner (Cornell Univ.) and Ivan Bazarov (Cornell Univ.) summarized the essentials of ERL configurations for synchrotron radiation and Don Bilderback (Cornell Univ.) discussed insertion devices (IDs) and characteristics of the x-ray beams which might thereby be produced. Charles Sinclair (Jefferson Lab) discussed injector issues and concluded that the initial ERL design value of 77 pC/bunch at 2 mm-mrad gun emittance was not far away from the 60 pC/bunch delivered presently at the IR FEL at Jefferson Lab, with 1.65 mm-mrad emittance measured at the gun. Table 1 shows the rest of the tentative ERL design parameters. The repetition rate can be increased by about 20x to reach the desired 100 mA current. Sinclair and his working group (convened by Gerry Dugan of Cornell Univ.) concluded that there were no fundamental obstacles and that the technical changes needed in current hardware designs are straightforward.

Lia Merminga (Jefferson Lab) gave an overview of the accelerator physics issues in an ERL, including beam stability, multibunch beam breakup (BBU), emittance growth during acceleration and rf control. It was pointed out that better high order mode damping of CEBAF or TESLA style cavities will be needed for the ERL and Hasan Padamsee (Cornell Univ.) stated that this is achievable. In the end, Merminga and her working group (convened by Joe Rogers of Cornell Univ.) concluded that there were no unreasonable obstacles to overcome and that the technical changes needed in current hardware designs are possible to achieve.

A third machine physics talk was given by Geoff Krafft (Jefferson Lab) on tentative parameter choices, lattice and single particle dynamics and transverse and longitudinal quantities. Geoff and his working group (convened by Richard Talman of Cornell Univ.) concluded that the high energy ERL machine was possible and that the next steps would be to design linac and turn around ring optics and then to run beam breakup codes to estimate the threshold of the expected BBU instabilities.

December X-ray Science Workshop

There are many possible variants of ERL-based machines. The charges given to the x-ray science workshop participants were based on expected properties of the ERL model outlined in [6]. Sol Gruner (Cornell Univ.) set the stage for the discussion by noting that the ERL concept opens new science opportunities stemming from low emittance (in *both* transverse dimensions to beam travel), unprecedented brilliance, ultra-short bunches, flexible bunch structures, stable beams, high x-ray flux, and extreme flexibility. With transverse beam sigmas of 3 to 40 microns (values that depend on the machine beta function and the ID lengths), the ERL will be a splendid source for making microbeams of x-rays and will overcome the relatively large horizontal source sizes of conventional storage rings. Gruner then enunciated the charges to the workshop participants: What are the best science opportunities? What machine parameters should be optimized to realize the best science?

Maury Tigner (Cornell Univ., see Figure 2) followed with details about ERL machine opportunities, including an explanation of why ERLs and storage rings are subject to different emittance limitations and photoinjector considerations.

Don Bilderback (Cornell Univ.) followed with further illustrations of how an ERL machine may exceed current 3rd generation machine performance. By reducing the injector current from 100 to say 10 mA, we are hoping to lower the emittance of the recirculator by as much as a factor of 15 (in a storage ring the emittance is fairly constant with current during normal types of operations). Assuming no further dilution upon acceleration, a diffraction limited light source can then be achieved at 8 keV and the brilliance actually increases over the 100 mA case as the source size is made significantly smaller. Many more experiments involving the use of coherent x-ray beams become possible.

With small beam sizes (~3 to 40 microns) comes the possibility to optimize the ID with short gaps down to 2 mm or so. When such a machine is optimized from the ID point of view, the bottleneck becomes the emittance produced by the injector. For making 10 keV x-rays, a machine with lower energy of 3 to 5 GeV would be well matched to short period IDs of under a cm in period length, but these devices are not yet routinely manufactured and regularly used in present day storage rings. The way the ERL machines make low emittance is to start with a low gun emittance. If the emittance is not diluted by the linac, then the final machine (geometric) emittance is just the gun emittance divided by gamma, the ratio of the machine energy to the rest mass energy of the electron. Thus, the higher the beam energy, the smaller the emittance of the electron beam. [This is the same principle that 4th generation machines also depend upon for making low emittance electron beams at much higher energies.]

Other laboratories are thinking about extending this type of technology as well. There is general interest at Jefferson Laboratory for not only upgrading the current IR FEL but considering other types of machines [7]. The Budker Institute has a concept of 4th generation light source based on a Multipass Accelerator-Recuperator Source (MARS) [8]. As discussed by Peter Siddons (Brookhaven National Laboratory) below, NSLS could be upgraded with a single-pass ERL type of machine and LBNL is thinking about a version that is designed as a dedicated femtosecond x-ray source. [All of these machines, including the Cornell one will be discussed in a future one day workshop at SRI2001 titled: Energy Recovery Linac Sources of Synchrotron Radiation. Organizers: Don Bilderback & Sol Gruner (Cornell Univ.), Chi-Chang Kao (Brookhaven National Laboratory) and Gwyn Williams (Jefferson Laboratory).]

Pascal Elleaume (ESRF) spoke about possible insertion devices for an ERL machine using an in-air set of magnets with 5 m long sections to make up a 25 m total length. He also described a 7 GeV, 500 mA Ultimate Storage Ring [9], a 2.2 km circumference ring which may have an emittance low enough to rival the ERL in brilliance and flux.

ERL Science Opportunities

The workshop then turned to specific science opportunities enabled by an ERL. Chris Jacobson (SUNY Stony Brook) and Janos Kirz (SUNY Stony Brook) reminded us of the state of the art of working with coherent beams in the soft x-ray domain. The possibility is good to use diffraction from non-periodic specimens down to near atomic resolution, but considerable more development work is needed. Imaging biological samples may require the even greater instantaneous brilliance of a 4th generation FEL in order to collect the data before the sample is destroyed by the strong x-ray beam.

John Arthur (Stanford Univ.) spoke of beam spatial coherence and concluded that the smaller ERL source size will have some advantages. One part in 100,000 of the present beam at APS is coherent. The ERL could produce 100 times more coherent x-rays of the sort that could drive non-linear x-ray optics experiments. On the other hand, LCLS and Tesla will both far surpass these numbers during SASE lasing, but the ERL might be the more effective source for coherence experiments above about 50 keV in energy.

Sow-Hsin Chen (MIT) spoke of his work on the collective dynamics of fully hydrated phospholipid bilayers using inelastic x-ray scattering spectroscopy. He showed that the collective motions of supramolecular liquids and bilayers could be extracted from data taken from the ESRF when using an analyzer resolution of better than 650 micro-eV and the use of an

Eigenmode Theory of data analysis. This information is vital to understanding the damping of heat diffusion, the dispersion relation of propagating density waves in bilayers and the damping of density waves. More detailed information about dynamics is presently hidden near the strong central elastic peak, so an ERL type of machine with higher brilliance and higher energy resolution is needed to reveal the next level of rich detail that is waiting to be observed (and seen presently as small bumps on the side of the central peak).

Steve Dierker (U. of Michigan) spoke about the prospects for X-ray Photon Correlation Spectroscopy (XPCS) using an ERL source. At present 3rd generation synchrotron sources, XPCS probes the arrangements of domains in a sample on a time scale of 10e-5 to 100 seconds at large wave-vector resolution. The speckle patterns "twinkle" depending on the exact arrangement of domains that provide random constructive and destructive interference terms to the x-ray detector and requires a partially coherent beam. With a sufficiently brilliant source, a number of scientific problems could be addressed such as studying the transition from the hydrodynamic to the kinetic regime in simple liquids; the entanglement and reptative dynamics of polymers, order fluctuations in alloys, liquid crystals, and polymer mixtures; the nature of phason and phonon dynamics in quasicrystals; the dynamics of adatoms, island, and steps during growth and etching; magnetic strip domain dynamics in magnetic systems; etc. Full transverse and increased longitudinal coherence is needed at even higher brilliance than available at existing 3rd generation sources. One to two orders of magnitude improvement over present brilliances will be significant for the field, said Dierker.

Al Sievers (Cornell Univ.) spoke of the opportunity to use infrared radiation emitted by the ERL to study localized vibrational and spin wave modes in nonlinear periodic lattices in condensed matter physics situations involving domain walls, kinks and solitons. Theories have been advanced in many physically exciting contexts such as non-linear crystal dynamics, magnetic systems, electron-phonon systems, reaction dynamics, and biological matter where an experimental program making use of 300 fs long (100 micron) intense coherent far-infrared radiation produced by the ERL could be used to determine the universal properties of localized dynamical structures in strongly driven periodic lattices.

John Parise (SUNY Stony Brook and Geophysical Research Laboratory, Washington) reminded us that high pressure studies span the range from vacuum to the center of a giant star. Most high pressure experiments are brightness limited and higher pressure generally means that a smaller sample size is needed. By providing quality microbeams, the ERL will be able to make an impact, especially for those situations where it may reduce experimentation time from a day to an hour.

Bob Suter (Carnegie Mellon University) spoke of the opportunities to study the useful properties of polycrystalline materials in bulk quantities. Using Three Dimensional X-ray Diffraction Microscopy (3DXDM) at the ESRF with a 1 micron beam size, the dynamics of structure evolution can be currently followed on a minute time scale with 40 to 80 keV x-rays. Many technologically important materials require small grain size and the dynamics can be expected to be different from large grains. These are complex materials; not trendy, but vital. Therefore there is large payoff waiting for pushing the resolution limits downward in both time and spatial resolution. The ERL should improve the quality of experiments possible on both of these fronts.

Phil Heimann (Lawrence Berkeley National Laboratory) spoke of time-resolved research at LBNL using a fs laser as pump and probe in the 100 eV to 10 keV regime with a 10 kHz repetition rate of a laser synchronized to the 100 fs x-ray pulses from the ALS linac. The science opportunity is to study atomic disordering on the time scale of a vibrational period. For instance, the LBNL group wants to use fs x-ray pulses to observe the response of atoms in a InSb crystal being melted/disordered from the incident laser pulse; to study coherent acoustic phonons generated by a 100 fs laser pulse or even to observe the evolution of a simple photochemical reaction with 100 fs resolved x-ray absorption spectroscopy. The LBNL group is exploring the possibility of building a 2 GeV ERL dedicated to fs x-ray probe efforts [10,11]. Lasers of higher repetition rate and experiments that are reproducible with each flash will be needed to maximally use this type of ERL source.

Ben Larson (Oak Ridge National Laboratory) reminded us that impressive picosecond and sub-picosecond experiments have been performed, but they have been limited by source intensity, resolution, triggering and/or detection capabilities. Examples given included Pulsed Laser Deposition and film growth where the crystallization phase has not been yet resolved in diffraction studies. For crystal truncation rod studies of surfaces, the ERL will provide capability to study microsecond resolved deposition as well as the aggregation phase of pulsed thin-film growth. Microbeam focusing with a brilliant ERL beam will provide enough intensity for single-terrace surface studies.

APS microbeams have provided a revolutionary new technique for mesoscale materials physics with its white/monochromatic microbeams produced with Kirpatrick-Baez (KB) mirrors. The present white microbeam resolution is about 0.5 micron x 0.5 micron. The ERL with 10 to 50 times higher brilliance may provide 0.05 micron x 0.05 micron resolution. Thus 3D nanoscale materials structure and evolution investigations will become possible.

Gene Ice (Oak Ridge National Laboratory) built on Larson’s talk and went on to describe the new regime of material science possible with the ERL: better spatial resolution for studying nanoscale materials, the local environment of fracture, nucleation and growth, and fine grain mosaic materials; better signal-to-noise on fluorescing materials and highly deformed/mosaic materials; better 3D resolution in high Z materials at high x-ray energies. However, more perfectly made x-ray optics will be needed to take advantage of this kind of new source.

Mark Rivers (University of Chicago) spoke on using an ERL for microfluorescence, microspectroscopy and microtomography applications. The increased brilliance from an ERL source can increase the flux in a 1 micron size by a factor of 100 to 1000 or to reduce the spot size to 100 nm or less. The flux can be used to compensate for the low efficiency of wavelength dispersive high-energy resolution detectors. Rivers also noted the need for KB mirrors with sub-microradian slope errors in order to fully utilize an ERL type of source.

The ERL will also greatly increase the speed of fluorescence tomography experiments as well. Rivers also suggested that the bending magnets of the ERL not be neglected. Special high-field bending magnets with 40 keV critical energy with a wide fan could be used for microtomography of large high-Z objects producing 100x the flux at 200 keV of other bend magnet sources.

Mark Sutton (McGill Univ.) and Joel Brock (Cornell Univ.) showed speckle patterns taken from both aerogel and latex spheres on an APS beamline. A phase separation image of AlLi was presented from Troika beamline at the ESRF. The speckle experiments allow kinetic measurements to be made which are particularly important for material science. These experiments are brilliance driven and having a very small, round ERL source size is a great advantage. There is also opportunity to go to 100 keV with substantial spatial coherence. The 'CW' like nature of the source suggests that a time-resolution can be increased in the measurement by several orders of magnitude. For sub-microsecond time scales, the pulse structure of the typical storage ring can get in the way. The ERL can also generate pseudo-random pulse trains which might be of use in overcoming this problem.

Ercan Alp (Argonne National Laboratory) spoke of using inelastic scattering as a tool for studying the dynamic behavior of condensed matter and biological systems. For these experiments the ERL offers enhanced flux, brilliance and high-energy x-rays. Ercan noted that the lower divergence of an ERL source is better matched to angular acceptance of high-resolution monochromators (2 to 4 microradians at 30 keV with higher order reflections) than current 3rd generation sources.

Rich Matyi (National Institute Standards & Technology) suggested using the ps time-resolved analysis of forbidden cubic crystal reflections during the early stage of an ion-solid reaction. The idea is to modulate an ion beam with a fs laser to divert an ion pulse to the surface of a crystal and to monitor forbidden reflections such as 200, 211, etc for changes of intensity vs. time. Such measurements could be compared to the model calculations of Morehead and Crowder.

Jens Als-Nielsen (Copenhagen Univ.) pointed out that with a round ERL beam, the undulators could be rotated by 90 degrees about the beamline direction making vertically polarized rather than horizontally polarized x-rays as is currently done with storage rings. The benefit: a horizontal diffraction plane as is currently used with neutron diffraction – a real benefit when studying samples at extreme conditions in bulky cryostats, heavy furnaces, etc. A second advantage comes in flexibility in beamline layout. With an ERL and rotated undulators, efficient use of single transparent crystals in series is possible, simplifying the division of a single beamline into many branch lines using a "spokes-around-hub" model.

At the end of the formal presentations, the session was open for brief 5 minutes presentations from anyone. Ivan Bazarov (Cornell Univ.) spoke on the good prospects for obtaining a better than 2 mm-mr emittance from the ERL injector at 77 pC/bunch and the possibility of considerable improvement in emittance for injector operation at a fraction of the designed 100 mA current. His conclusion: there is room for substantial improvement!

Peter Siddons (Brookhaven National Laboratory) mentioned a possible ERL type machine as a possible upgrade plan for the NSLS as well as simultaneously obtaining new SR capability for the BNL community. John Galayda (Argonne National Laboratory) talked about the prospects of improving APS in the future including lowering the horizontal emittance to 3.5 nm-rad, increasing the current to 300 mA, doubling the undulator lengths to 4.8 m, and shortening the bunch length. Gopal Shenoy and John Arthur put together a table showing comparisons of 3rd generation rings, ERL, and proposed XFELs which helped to emphasize the complementary nature of the new planned sources to current storage rings. Don Bilderback showed how to possibly make 10 nm diameter x-ray beams created by tapered glass capillaries and Geoff Krafft gave an overview of the accelerators (IR FEL and CEBAF) at Jefferson Lab and how they serve as a knowledge base for the future designs of ERL type of machines.

The final activity was to put together a summary statement of experimental beamline needs. Table 2 displays the results including the important parameters for the various types of experiments planned.

All in all, machine physicists and x-ray scientists learned of the tremendous possibilities of ERL technology. The workshop concluded with a realization that the community is entering an era when new types of synchrotron-radiation-producing machines will open up whole new areas of science!

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Figures:

Figure 1. Energy Recovery Linac schematic (not to scale). A laser driven photocathode produces a brilliant electron beam that is accelerated to 5 MeV and bent into the one-turn storage ring by a weak bending magnet. [Note: There are many possible configurations for the layout of an ERL. This sketch is for conceptual purposes only. An exact layout has not yet been made.] Upon entering the linac, the electron bunch rides a crest of the traveling RF wave down the linac and is brought up to full energy (5 to 7 GeV). Subsequently, the beam passes nearly undeflected through another weak bending magnet. The electrons are then guided by a magnetic lattice for one turn in a similar fashion as they would in a storage ring. As they pass through 2 to 25 m long undulators, bright beams of x-rays are produced. Here is where the similarity with a storage ring ends. The circumference of the machine is arranged so that when the beam comes around to the entrance of the linac, the electron beam is made to be 180 degrees out of phase with respect to the 1300 MHz traveling RF wave that accelerated the bunch to high energy in the first place. Now the electrons dwell in the trough of the traveling wave and they are decelerated. The kinetic energy of the electron beam is extracted and the energy is stored in the oscillating field of the superconducting cavity. The beam after extraction has an energy of 5 MeV and is then steered into the beam dump.

The RF cavities for the ERL machine have high Q’s and thus the energy recovery can be higher than 99% as demonstrated in the Jefferson Lab IR FEL [5] . In addition, the electron beam power to be disposed of at the dumps and the associated radioactivity would also be too great to handle without efficient energy recovery.

Figure 2: Maury Tigner of Cornell Univ. explaining the principles of an energy recovery linac source of synchrotron radiation to the x-ray science workshop group.

Tables

Table 1. Tentative Energy Recovery Linac parameter list.

Machine Energy: 5 to 7 GeV
Machine Current: 1 to 100 mA
Photocathode gun emittance: 0.1 to 2 micron
Emittance at full energy: 150 pm @ 100 mA, 10 pm @ 10 mA (x or y)
Bunch length: 100 fs to 10 psec
Max. bunch repetition rate: 1.3 GHz
RF frequency: 1.3 GHz - superconducting RF
Beam lifetime: infinite (continuous injection)
Insertion device gaps: >2mm
Undulator lengths: <25 m
Bend magnet critical energy: 10 to 20 keV
Electron beam sizes (sigma x or y): 3 to 40 microns (depends on current, beta, ID length)
X-ray beam divergences: 3 to 10 microradians
Natural beam size: round
Flux from undulators: 10^{16} x-rays/sec/0.1%bw
Brilliance from undulators: $>10^{22}$ x-rays/sec/mm**2/mr**2/0.1% bw

note: not all parameters can be achieved simultaneously

Table 2. Summary of experimental beamline needs from December, 2000 workshop.

Experiment Type	*Important Machine Parameters*	*Undulator Needs*	*Special Concerns*
Microbeam Diffraction	Source size 5 to 50 µm Tapered undulator Scan quickly	10 to 20 keV polychromatic 40 – 40 keV Riso approach Brilliance 100 to 1000 fold improvement	Beam Stability of 10% of source size Thermal stability Long term reproducible beam position
Microbeam Fluorescence	Source size 5 to 50 µm	4.5 to 20 keV Scan quickly, Tapered undulator	
High Pressure Diffraction	Same as Microprobes above	20 to 70 keV Most often: 30 to 35 keV	
High Pressure Spectroscopy		4 to 10 keV pink beams polarized (circular)	
Femtosecond Spectroscopy and Diffraction of Solids and Molecules	100 fs flux of 10^{10}/0.1% bw at 10 kHz	100 eV to 10 keV Most often: 3 to 10 keV	At sample want 50 µm spot and 100 µrad divergence synchronizing to laser
Femtosecond Diffraction of Proteins	100 fs to 1 ps flux of 10^8/0.1% bw/pulse	10 to 14 keV Tapered undulator	separation between pulses of 1 µs synchronizing to laser
Spectromicroscopy Coherent tomography Holograpy & Diffraction with zone plates Single molecule imaging	Need average brilliance Beyond 1x10^{18} to 1 x 10^{19} Short pulse ~ 50 fs Large bunch charge at kHz rep rate	x-ray of ~ 2 to 4.5 nm, also 0.3 nm Tapered undulator for spectroscopy with 50 eV range Circular polarization for magnetics	Beam stability, especially for scanning Need enough info from 1 pulse to align sample
Photon Correlation Spectroscopy	As much brilliance as possible Repetition rate > 10 MHz	5 to 12 keV pink beam high energy opportunity at 100 keV	Sample coherence diameter: 10 to 50 υm δE/E ~10^{-4} to 10^{-2}
Nuclear Resonant Scattering	Bunch to bunch separation of 20 to 200 ns High brilliance in the vertical and horizontal for polarizer/analyzer experiments Variable bunch structure	First harmonic tunable between 6 and 18 keV	Large transverse coherence for quasi-elastic scattering
Inelastic x-ray scattering (sub meV to eV resolution) Time-resolved phonon measurements Quasi-elastic scattering	Brilliance Flux Low horizontal emittance	First harmonic in the 30 keV range	π polarized for horizontal scattering spectrometer note: 1 THz= 4 meV
Normal Incidence Diffraction x-ray metrology x-ray interferometry microfocusing at 10^4 to 1 demag	Low emittance		stability
Polarized Beam Experiments Resonant scattering* Faraday rotation Circular Magnetic Dichroism*	Round Beams - give uniform angular size and high throughput for 0.1 eV optics	5 to 100 keV Undulator rotatable about beampipe (or use Apple II type undulator) Standard short period Novel ID designs	That tuning ID doesn't affect other users

Notes: brilliance in units of x-rays/sec/mm**2/mr**2

* Polarization switching on input (as opposed to low signal end).

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ENERGY RECOVERY LINAC