T-REX: Thomson-Radiated Extreme X-rays Moving X-Ray Science into the "Nuclear" Applications Space with Thompson Scattered Photons

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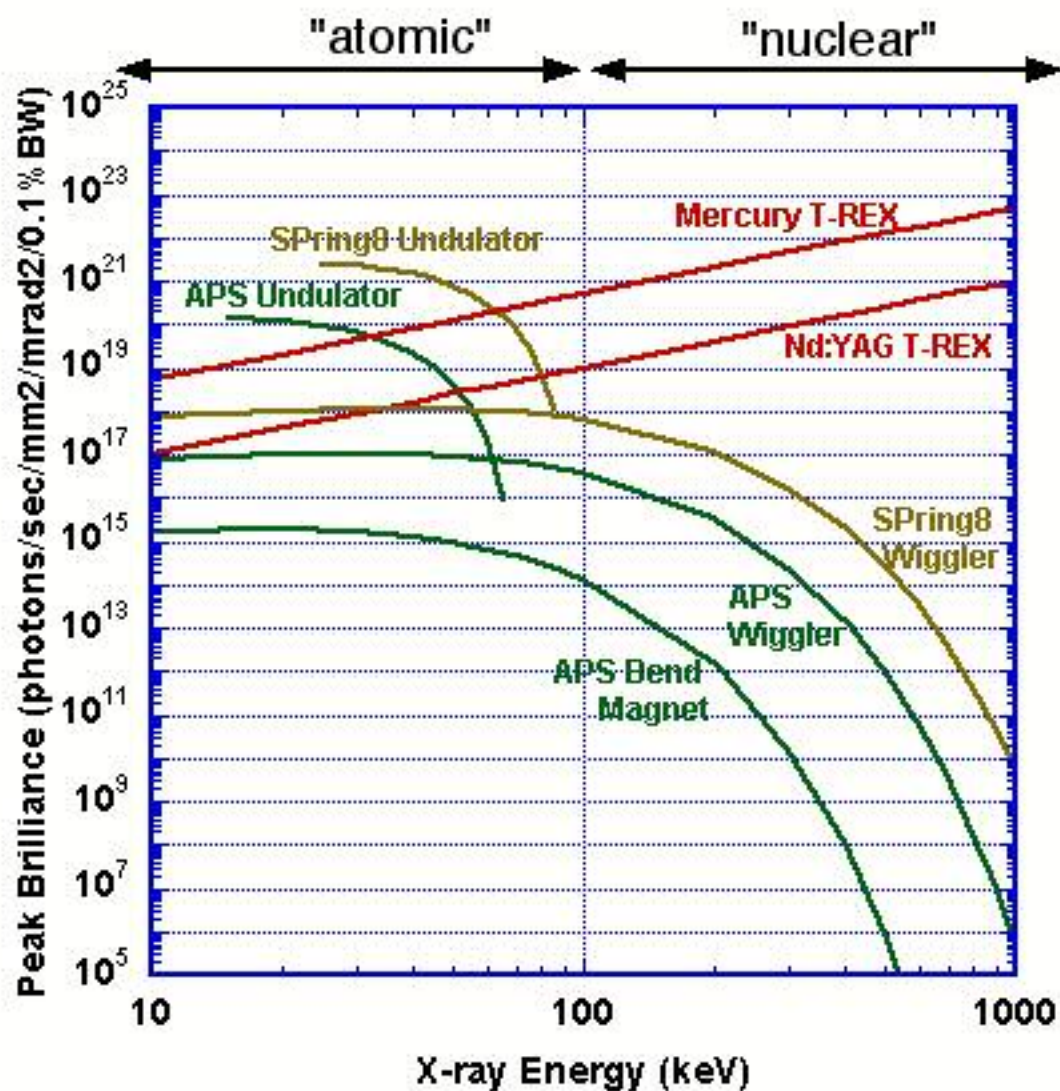
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Chris Barty (NIF) and Fred Hartemann (PAT)

Executive Summary:

The scattering of laser photons from relativistic electrons (Thomson scattering) has been demonstrated to be a viable method for the production of ultrashort-duration pulses of tunable radiation in the 10-keV to 100-keV range. Photons in this range are capable of exciting or ionizing even the most tightly bound of atomic electrons. A wide variety of atomistic scale applications are possible. For example, Thomson x-ray sources have been constructed at LLNL (PLEIADES) and LBL as picosecond, stroboscopic probes of atomic-scale dynamics and at Vanderbilt University as element-specific tools for medical radiography and radiology. While these sources have demonstrated an attractive ability to simultaneously probe on an atomic spatial and temporal scale, they do not necessarily exploit the full potential of the Thomson scattering process to produce high-brightness, high-energy photons.

In this white paper, we suggest that the peak brightness of Thomson sources can scale as fast as the 4th power of electron beam energy and that production via Thomson scattering of quasi-monochromatic, tunable radiation in the "nuclear-range" between 100-keV and several MeV is potentially a much more attractive application space for this process. Traditional sources in this regime are inherently ultra-broadband and decline rapidly in brightness as a function of photon energy. The output from dedicated, national-laboratory-scale, synchrotron facilities, e.g. APS, SPring8, ESRF etc., declines by more than 10 orders from 100 keV to 1 MeV. At 1 MeV, we conservatively estimate that Thomson-source, peak brightness can exceed that of APS (the best machine in the DOE complex) by more than 15 orders of magnitude. In much the same way that tunable lasers revolutionized atomic spectroscopy, this "Peta-step" advance in tunable, narrow-bandwidth, capability should enable entirely new fields of study and new, programmatically-interesting, applications such as: micrometer-spatial-resolution, MeV, flash radiography of dense, energetic systems (NIF, JASPER), precision, photo-nuclear absorption spectroscopy (DNT, PAT), non-destructive, resonant nuclear fluorescent imaging of special nuclear materials (NAI, DHS), dynamic, micro-crack failure analysis (aerospace industry, SSP) etc.

Concepts are presented for new Thomson-Radiated Extreme X-ray (T-REX) sources at LLNL. These leverage LLNL's world-leading expertise in high-intensity lasers, high average power lasers, diffractive optics, Thomson-based x-ray source development, and advanced photo-guns to produce tunable, quasi-monochromatic radiation from 50-keV to several MeV. Above ~100 keV, T-REX would be unique in the world with respect to BOTH peak x-ray brilliance AND average x-ray brilliance. This capability would naturally compliment the x-ray capability of large-scale, synchrotron facilities currently within the DoE complex by significantly extending the x-ray energy range over which, tunable, high-brightness applications could be pursued. It would do so at a small fraction of the cost of the purely, accelerator-based facilities. It is anticipated that T-REX could provide new opportunities for interaction of LLNL with the DoE Office of Science, DARPA, DHS etc. and would place LLNL clearly at the forefront of laser-based, x-ray generation world-wide.

Thomson Source History and Motivation:

Thomson source development has been pursued by a number of laboratories and groups over the past decade. In general these groups have been motivated by one of two desires:

a) to produce 10's of keV photons with sub-ps pulse duration for use as atomic time-scale dynamic probes or

b) to produce quasi-monochromatic tunable radiation in the 10 keV to 100 keV range for use in atom-specific radiographic applications.

Ultrashort Pulse Duration:

The use of Thomson scattering to produce sub-picosecond, 10-keV-range, x-rays for experiments was first demonstrated in the late 1990's at LBL. In this technique an energetic, short duration (typically sub-ps) laser pulse is scattered off of a single bunch of relativistic electrons. In the "head -on" geometry, the scattered photons are up-shifted in energy by a factor equal to $4\gamma^2$, where γ is the ratio of the electron kinetic energy to its rest mass energy (0.511 keV).

$$h\nu_{scattered} = 4\gamma^2 \, h\nu_{laser}$$

The LBL demonstration produced approximately 10^4, 10-keV photons per pulse. The LBL demonstration was limited in flux by the relatively low charge of the electron beam and the mismatch of repetition rates between the drive laser and the circulating electron beam. The motivation for the LBL Thomson project was to produce 100-fs to 1-ps x-ray bursts as dynamic probes of atomic scale motion. This time scale is 2 to 3 orders of magnitude shorter than that available from state-of-the-art synchrotrons. In synchrotrons, space charge limits the circulating electron bunch length and consequently the x-ray pulse duration to approximately 100 ps. This timescale, while at least an order of magnitude faster than pulsed, anode-based, x-ray sources, is still approximately 100 to 1000 times greater than the intrinsic timescale of atomic and molecular motion. Dynamic studies with synchrotrons are generally limited to large-scale systems, e.g. folding of macro-molecules etc. Depending upon the geometry of the laser and electron interaction, Thomson sources may produce sub-picosecond x-ray bursts and thus may be used to probe a much richer variety of dynamic events including the dynamics of shocked materials and energetic phase transitions of interest to many at LLNL. Via LDRD investment LLNL has gone significantly beyond the LBL demonstration and constructed in b194 a state-of-the-art, quasi-monochromatic, x-ray source based on Thomson scattering, known as PLEIADES. Unlike LBL, the LLNL source uses a dedicated, photo-conductively seeded, pulsed LINAC to generate high-charge, relativistic electron bunches. When combined with a higher-energy (0.5 J), 10-Hz, short pulse (50 fs) laser, PLEIADES has produced approximately 10^7, 70-keV photons per pulse. In this energy range, PLEIADES is the world's highest brilliance x-ray source.

Tunable Monochromatic X-rays:

The other intrinsic attribute of Thomson sources is quasi-monochromatic tunability above 10 keV. The majority of x-ray based studies today are still conducted with anode based sources similar to those first demonstrated by Roentgen over a 100 years ago. These sources produce both line radiation and quasi-continuum radiation whose range is based upon the energy of the drive electron beam. The energy of Thomson x-rays on the other hand is quasi-monochromatic

and is easily adjusted by changing the electron bunch energy or the laser photon energy. To first order, the linewidth of the x-rays is proportional to the convolution of the fractional bandwidth of the drive laser and the energy spread of the electron bunch. The tunable, relatively narrow bandwidth of these sources enables new modalities for high contrast x-ray imaging. In the PLEIADES system, the linewidth is primarily limited by the 5% fractional bandwidth of the 50-fs drive laser. Narrow linewidth increases resonance absorption, enhances imaging and increases spatial resolution in crystallographic applications. The ability to produce relatively narrow linewidth, tunable x-ray radiation has been the primary motivation for development of Thomson sources by a privately funded team at Vanderbilt University. This group is associated with the radiology department of the Vanderbilt medical school. While absolute yield has not been accurately measured, this believes it has produced up to 10^{10} photons per pulse tunable from 15 keV to ~50 keV. The Vanderbilt Thomson source consists of a commercial 50 MeV LINAC and photo-gun (~$1.5M) and a 1 picosecond, commercial, 10-J, single-shot laser system (~$1.5M). The Vanderbilt team has used this source for a wide variety of medical radiographic demonstrations in which the x-rays are tuned above and below an inner-shell, ionization resonance for a particular atomic species. In this way image contrast can be dramatically improved for a given dose or conversely dose can be dramatically reduced for a given image quality. Record spatial resolution, low-dose, 3-D mammography has been demonstrated. The same team has also demonstrated the benefits of monochromatic tunability for oncology applications. In this experiment the Thomson source is tuned to ionization resonance of a specific heavy element that has been attached to a cancer-seeking drug. Such drugs can be designed to selectively bind to the DNA of cancerous cells. The resulting ionization and Auger electron production is thus localized at the cancer cell. This significantly increases the effective dose to the cancerous cells without increasing the dose to the surrounding healthy tissue. The team is currently seeking outside funding to produce a 10-Hz commercial system for the medical community. The challenge for this venture is primarily the reduction of costs and complexity associated with generation of high-repetition, high-energy laser pulses.

Observations from Previous Source Development:
   Before discussing possible future Thomson sources, it is instructive to catalog some of the lessons that have been learned from previous source development and use. The following comments can be made with respect to Thomson source development at LBL, LLNL and/or Vanderbilt University.

   a) Source brilliance drives applications and should be optimized. This is of course the same conclusion which drives synchrotron machine design. Brilliance depends linearly upon the number of photons produced, and inversely on the time over which they are produced, the size of the emission area, the solid angle of the emission, and bandwidth of the emitted radiation.
   b) The head on geometry is preferred for Thomson scattering. Higher energy photons are produced, and generally speaking the yield is higher and the experimental effort of overlapping the electron and laser pulse in both space and time is dramatically reduced relative to a 90-degree interaction geometry. The potential advantages of the 90-degree geometry are shorter pulse duration and the lack of optics in the beam path, both of which can be addressed in other ways.

c) Pulse duration of the x-rays is set by the duration of the interaction of the laser and electron pulse. In the case in which the laser pulse is significantly shorter duration that the electron pulse, the 90-degree interaction geometry produces the shortest duration x-rays. In the case in which the electron bunch is shorter duration than the laser pulse, the head-on geometry can produce equally short duration x-rays. It is interesting to note that state of the art accelerator structures like that will be incorporated in the injector system for the Linear Coherent Light Source may potentially produce, high current, 100-fs time-scale electron bunches.

d) Thomson sources are cross section driven.   The number of x-rays generated is increased rapidly by making the transverse dimensions of the interaction region small. The electron beam and not the laser beam has limited the transverse dimensions of the interaction to date. Electron foci which are 20 times that of the laser diffraction limit are typical. Higher quality electron bunches and smaller interaction volumes can be obtained from optimized photo-guns. Photo-gun R&D is important. Smaller electron foci may also be produced at higher electron bunch energy.

e) X-ray yield is optimized when the pulse duration of the laser pulse is matched to the electron beam and the geometry of the interaction. Space charge limits the electron bunch number density.   In principle one may increase the number of electrons and x-rays by increasing the bunch length. This is true up to the "bucket" length of the accelerator structure. 5 ps is about optimal for a standard S-band LINAC structure.

f) Laser pulse energy cannot be increased arbitrarily for linearly polarlized laser electron interactions. At high intensity (>10E17 W/cm2 for 1 micron light) the laser field strength is sufficient to perturb the electron bunch energy and thus increase the bandwidth of the generated x-rays.

g) There is little or no benefit to be obtained in making the laser pulse duration extremely short. X-ray bandwidth is proportional to the convolution of the laser bandwidth and the electron energy spread. Short duration laser pulses generate wider bandwidth x-ray emission. If short duration is required it is better to make the electron bunch length short. Many dynamic studies may not require sub-picosecond x-ray bursts but will benefit from narrow x-ray bandwidth.

h) 5 ps laser pulses can be produced by a wide variety of solid state laser materials. Ideally one produces a transform limited laser pulse. Making a 5 ps pulse by stretching a 50-fs pulse just adds unwanted bandwidth and decreases source brilliance unnecessarily. Chirped pulse amplification compressor dispersion is proportional to the inverse of the pulse bandwidth.   Grating separations from 'conventional' compressor structures would require 10's of meters if 5 ps bandwidths were used.   Compact, high dispersion compressor structures have recently been invented at LLNL (IL-11362 and IL-11709). These structures could reduce compressor footprints by at least an order of magnitude and thus make 5 ps CPA with narrow bandwidth materials practical.

i) Optimally the laser and accelerator technology should have approximately the same footprint and should be located in as close proximity to one another as physically possible.

j)   S-band LINAC technology is reliable, reasonably compact and inexpensive and can be commercially obtained. LINAC technology can scale to higher repetition rate than 10 Hz. The LCLS injector LINAC is designed for 120 Hz.

High Energy Scaling:

With respect to x-ray sources in the 10 keV to 100 keV range, the state of the art is light from bending magnets, undulators and wigglers at 3rd generation synchrotron facilities such as the Advanced Photon Source (APS) in the US, the European Synchrotron Radiation Facility (ESRF) in France or Spring8 in Japan. These sources typically run in a quasi-cw mode with low-number density electron bunches at 350 to 500 MHz repetition rates. The two attributes that are most commonly used as metrics for 3rd generation devices are the peak brilliance and average brilliance or average flux. Peak brilliance, i.e. photons per unit time per unit area per unit solid angle per unit bandwidth, impacts directly to quality of image, quality of x-ray diffraction, quality of absorption spectra etc. Average flux or average brilliance determines data acquisition time. Because of the high repetition rate of 3rd generation devices and their intrinsic 100-ps pulse duration, the difference between peak and average brilliance is typically only a factor of about 20 (2ns/100ps). Previous Thomson sources (LBL, PLEIADES, Vanderbilt) can produce peak brilliance on scale with 3rd generation devices but have many orders of magnitude less average brilliance. For these devices it is either the unique pulse duration of the x-rays or the laboratory scale of the device that provides the appropriate niche. The majority of synchrotron applications are "static". Dynamic studies are hindered by the intrinsic 100-ps duration of the x-rays and by the need to pump or initiate the dynamics at high repetition rate (350 to 500 MHz). Nonetheless techniques for "slicing" portions of the x-ray pulse have been developed and dynamic studies have been conducted with these machines. The effective peak brilliance in this mode of operation is reduced by the "slicing" efficiency, typically < 10 %. The average brilliance is further reduced by the ratio of slicing frequency, typically 1 kHz or less, and the bunch frequency.

While the 3rd generation machines provide high peak and average brilliance in the 10 to 100 keV range, their output diminishes rapidly above 100 keV, dropping by more than 10 orders of magnitude in the range between 100 keV and 1 MeV. A machine's peak energy at high brigthness is set by the energy of the circulating electron bunch. Spring8, which has the highest electron bunch energy at 8 GeV, has the highest output above 100 keV. APS and ESRF which operate at 7 GeV and 6 GeV respectively have outputs above 100 keV that are significantly lower.

Thomson sources on the other hand become more "brilliant" at higher x-ray energy and do so rapidly as a function of the electron beam energy and consequently x-ray energy. Several factors conspire to make this the case. In the head on geometry, the number of x-rays produced by Thomson scattering of a focused laser pulse from a focused electron pulse is optimized when the laser focal spot and electron bunch focus are similar in size. In this case the x-ray output can be approximated by.

$$N_{x\text{-}ray} = (\sigma/\pi\omega_O^2)\, N_{laser}\, N_{electron}.$$

Where σ is the Thomson scattering cross section (i.e. 6.25×10^{-25} cm^2) and ω_O is the larger of the laser beam waist or the electron beam focal spot diameter. Typically it is harder to focus the electron beam than the laser and thus the laser is set to match the electron beam focus. It is, however, possible to focus the electron beam more tightly as the electron beam energy increases. Roughly the electron beam focal spot diameter scales as one on the electron beam energy. Therefore the number of x-rays produced scales at the square of the electron energy. In principle, since these x-rays are emitted from an area that is proportional to the inverse square of

the electron energy, the peak brilliance of the source scales as at least the 4th power of the electron beam energy. Brilliance from Thomson-based sources can be further improved by working with longer duration laser and electron pulses. Longer duration allows more charge in the electron bunch and thus more x-rays to be produced. The practical upper limit is the effective acceleration "bucket" for the RF accelerator, or approximately 5 ps for a common S-band device. Longer duration also allows the laser bandwidth to be reduced, thus potentially reducing the bandwidth of the generated x-rays and increasing the monochromaticity and brilliance of the source.

Above 100 keV, Thomson source output could be unique. They could potentially produce peak and average brilliance many orders of magnitude beyond that available from 3rd generation synchrotrons. The facts that they would be easily tunable and intrinsically narrow bandwidth warrants special note. Unlike at lower energies, convenient methods for production of narrow bandwidth radiation from continuum sources in the 100 keV and above range to not currently exist.

Thomson-Radiated Extreme X-ray source (T-REX):

Let us consider two examples for Thomson-radiated extreme x-ray (T-REX) machines based on LLNL's advanced laser and accelerator technology. In one case we suggest optimizing average brilliance of the machine through use of LLNL's state-of-the-art, diode-pumped, kW-average -power, inertial-fusion-energy, concept laser, Mercury as the short pulse drive laser. In the other we suggest minimizing cost through use of common, flashlamp-pumped, relatively-narrow-bandwidth, laser materials and new, LLNL-proprietary, chirped-pulse-amplification technologies that have been developed over the last 3 years via LDRD investments. Schematically these sources are similar and consists of 8 sub-systems (see Figure 1):

1. The seed pulse laser system. (mJ-level, wide-bandwidth, chirped-pulses that aresplit, delayed appropriately relative to one another and sent either to the photo-gun pulse generator or to the main laser amplifier)
2. the photo gun pulse generator. (precision, UV pulse generation)
3. the photo gun. (low emittance, copper photocathode)
4. the accelerator. (commercially available S-band LINAC)
5. the electron beam focusing assembly. (superconducting focusing magnets)
6. the main laser amplifier. (either high average power or low cost)
7. the pulse main laser pulse compressor (LLNL hyper dispersion compressor)
8. the laser beam transport and focusing system (beam shaping and parabolic focusing)

In order to reach the MeV range, it is suggested that photo-generated electrons be accelerated to ~250 MeV prior to interaction with a 1 micron wavelength, ~ 5 ps duration laser pulse. 250 MeV electrons may be produced from common S-band accelerator sections. Since modern S-band LINACs are capable of sustaining acceleration gradients of >50 MeV per meter, the minimum footprint of the devices would of order 6 meters. The Vanderbilt Thomson project has demonstrated that S-band accelerator sections may be obtained commercially and operated with long mean time to failure. Preliminary inquiries and scaling from the Vanderbilt experience, suggest an accelerator cost in the range of $2M or less. For the seed pulse system, we suggest leveraging the significant ongoing institutional investment in short pulse fiber laser technology. The principle R&D aspects of this short pulse fiber laser technology are currently being developed at LLNL under the High Energy Short Pulse Strategic Initiative and under the High
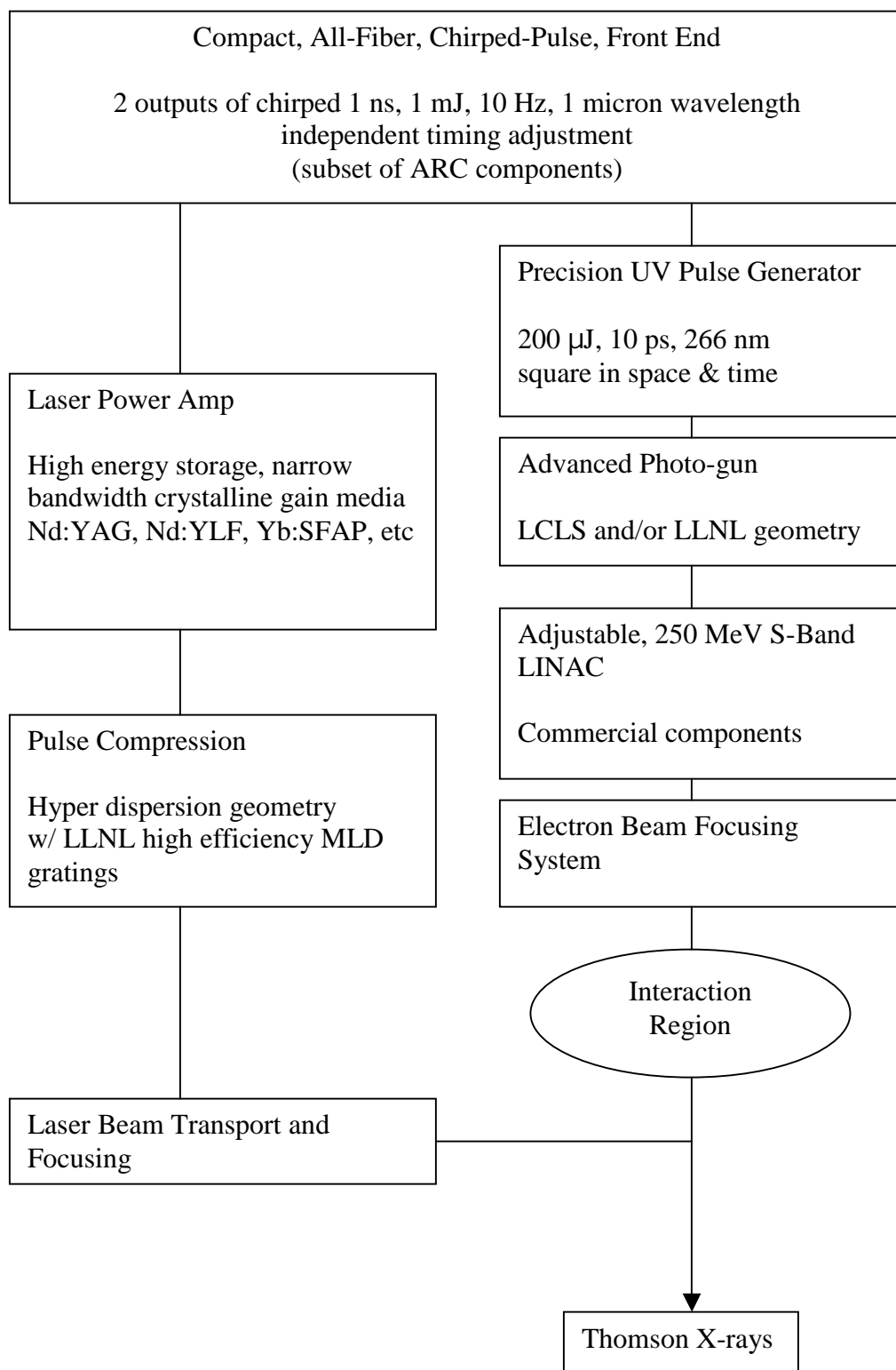
Compact, All-Fiber, Chirped-Pulse, Front End

2 outputs of chirped 1 ns, 1 mJ, 10 Hz, 1 micron wavelength
independent timing adjustment
(subset of ARC components)

Precision UV Pulse Generator

200 μJ, 10 ps, 266 nm
square in space & time

Laser Power Amp

High energy storage, narrow
bandwidth crystalline gain media
Nd:YAG, Nd:YLF, Yb:SFAP, etc

Advanced Photo-gun

LCLS and/or LLNL geometry

Adjustable, 250 MeV S-Band
LINAC

Commercial components

Pulse Compression

Hyper dispersion geometry
w/ LLNL high efficiency MLD
gratings

Electron Beam Focusing
System

Interaction
Region

Laser Beam Transport and
Focusing

Thomson X-rays

Figure 1. Schematic of T-REX components and subsystems. 1st generation versions of these components have been constructed, designed and/or tested as part of the PLEIADES SI, the High Energy Short Pulse SI or the Vanderbilt University monochromatic x-ray system.

Average Power Fiber Laser Exploratory research project. The benefits of a fiber-based front end for T-REX are superior pulse stability, system robustness, reduced component count and significantly lower costs. It is estimated that the fiber-based component costs required for the seed pulse laser system could be as low as ~$100k. Furthermore these components are nearly identical to those presently planned as part of the Advanced Radiographic Capability ARC project on NIF. Many of the designs that will be developed for that project could be directly copied for T-REX. The photo-gun pulse generator consists of a small diode pumped bulk amplifier to boost the mJ fiber output to ~10-mJ. These pulses are then compressed, frequency quadrupled and temporally and spatially shaped to produce 10-ps-duration, ~265-nm square pulses in space and time of approximately 200 micro-Joules in energy. Pulses of this kind will minimize the emittance of the generated electron beam and thus maximize the brilliance of the Thomson scattered x-rays. Similar sources are desired elsewhere, in particular the UV drive laser requirements for the photo-gun of the ongoing Linear Coherent Light Source (LCLS) project at the Stanford Linear Accelerator Center (SLAC) are nearly identical to those desired for T-REX.   The photo-gun illuminated by the UV laser pulses, is based on copper anode technology and is similar to that developed for PLEIADES and is identical to that planned for deployment on LCLS.

Case 1: T-REX with a Commercial Laser Amplifier and LLNL Proprietary Short Pulse Technology.

One of the principle cost drivers for the PLEIADES Thomson source was the joule-level, 50-fs, Ti:sapphire drive laser. This system occupies several optical tables, consists of dozens of optics and components and was constructed at a cost of >$2M. By relaxing the pulse duration requirements on the laser system it is possible to consider, significantly simpler laser architectures based on narrower bandwidth, flashlamp-pumpable gain media such as Nd:YAG and Nd:YLF.   Commercial, flashlamp-pumped Nd:YAG lasers costing <$150k routinely produce >2J, Q-switched pulses of several nanoseconds in duration at a 10-Hz repetition rate. 5-ps, Joule-level pulses could be produced from these components via chirped pulse amplification. Such a system would use the mJ-level, wide-bandwidth, chirped-pulse output of an LLNL fiber laser system as the seed and would require newly developed compact compressor designs (IL-11362) and LLNL dielectric grating technology for pulse compression.   In principle the component cost of the Nd:YAG amplifier and compressor components would be of order <$100k. Using the same models for Thomson x-ray production that have been benchmarked on the PLEIADES project, it is estimated that a system based on 1-J, 10-Hz, Nd:YAG drive laser and a 250 MeV LINAC would produce a peak brilliance at 1.2 MeV of 1×10^{21} (photons/sec/mm2/mrad2/0.1%BW). As a comparison the peak brilliance from the Advanced Photon Source wiggler at Argonne National Laboratory at 1 MeV is ~ 5×10^{5} (photons/sec/mm2/mrad2/0.1%BW) (see Figure 2). It is important to note that this estimate for T-REX performance is very conservative in several ways. It assumes a 5 ps electron bunch length and no improvement in electron beam emittance over that already demonstrated in PLEIADES project. The LCLS photo-gun for example is required to produce nano-coulomb bunches with an emittance that is at least an order of magnitude lower than PLEIADES. Furthermore the LCLS pulse duration at 250 MeV will be of order ~100 fs. In addition no attempt has been made to optimize the laser beam shape in the interaction region.   The combined optimization of these effects could increase T-REX source brilliance by several additional orders of magnitude.

Case 2: High Average Power T-REX with Mercury.

Both peak and average brilliance from Thomson sources could maximized by leveraging LLNL's world leading expertise diode-pumped, high average power laser technology. The Mercury laser located in b381 is currently being constructed to evaluate scalable concepts for possible future inertial fusion energy drive lasers. Based on a novel, LLNL-developed, gain media, Yb:S-FAP, Mercury is designed to produced 100-J, 1040-nm pulses at a 10 Hz repetition rate with a 10% wall plug efficiency. While the IFE goals for the project aim to produce shaped nanosecond pulses, the bandwidth of Yb:S-FAP is capable of easily supporting 5-ps pulses if used in a chirped pulse amplification mode. As a short pulse laser, Mercury would be by at least an order of magnitude the highest average power short pulse laser in existence. Peak and average brilliance of a T-REX source would scale relative to our previous example by the ratio of the pulse energy and laser average power. Predictions suggest that >2 x10^{12}, 1.2 MeV x-rays per pulse could be produced. Peak x-ray brilliance would be 5x10^{22} or more than 17 orders of magnitude greater than that produced by the APS wiggler. Besides the boosts in x-ray output that are possible with Mercury as a drive laser, it is important to note that significant infrastructure has been put in place over the course of Mercury's construction and that this infrastructure could be leveraged to form the basis for a future, world-class, state of the art experimental facility.
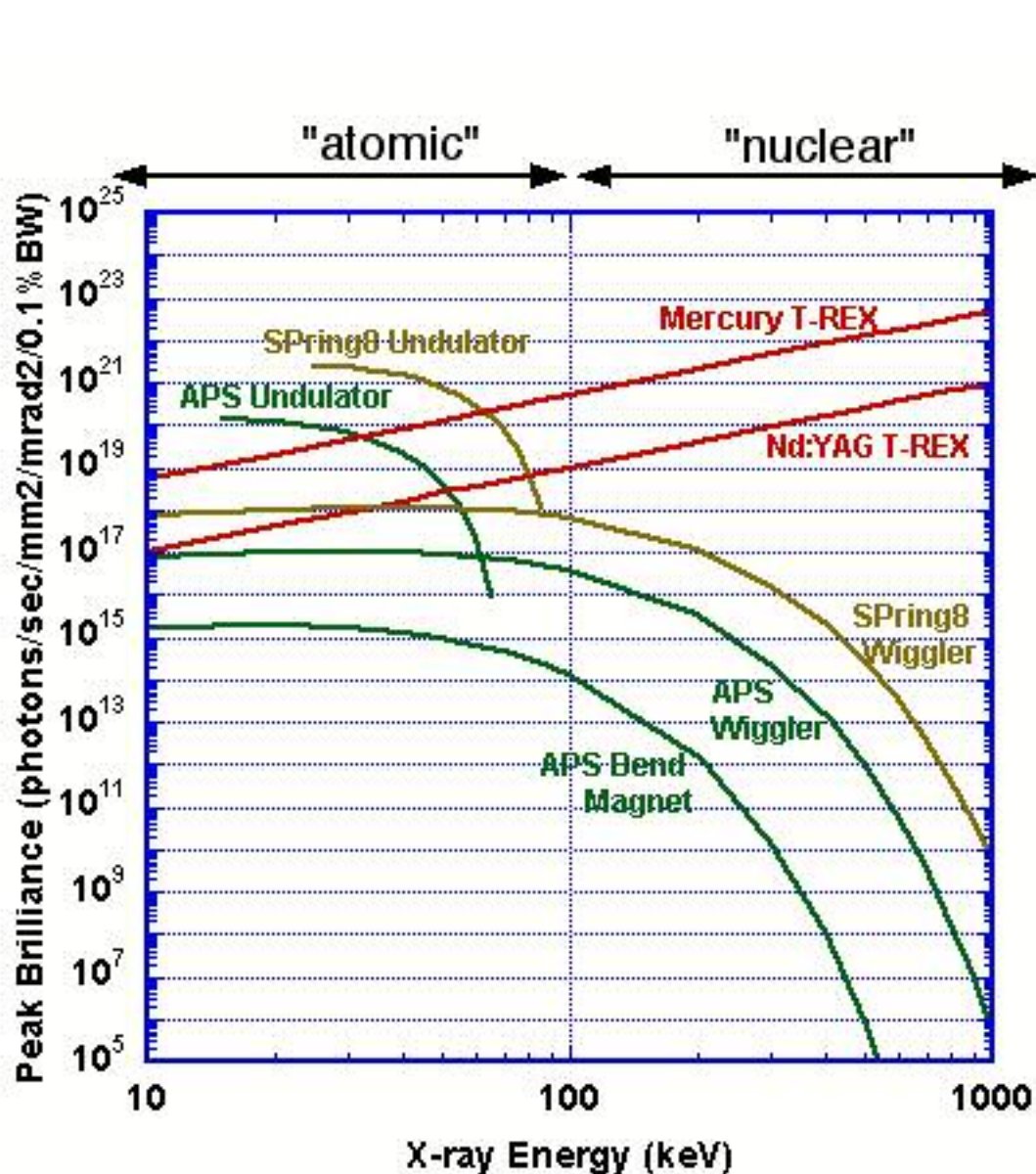
Figure 2. Comparison of peak x-ray brilliance possible from T-REX to that presently available from the highest brightness source in the USA, the Advanced Photon Source at ANL and highest brightness source outside of the US, the Spring8 synchrotron in Japan. Note in the range below 100 keV, harmonics of the APS and Spring8 undulators produce output in excess of both T-REX and either the APS or Spring8 wiggler. It is also important to note that above 100 keV, synchrotron output is broadband. In this region it is extremely difficult to "mono-chromatize" broadband output. Thus the peak "monochromatic" brilliance available to the experimentalist is actually lower by 1 or 2 orders of magnitude than that depicted above.

Some Potential Applications:

The development of synchrotron x-ray machines is well established. Numerous sources of 1-keV to 30-keV radiation now exist world wide. The science performed with these machines is generally atomistic, i.e. aims to study or determine the positions of atoms in molecules or solids or to determine the nature of electrons bound to the atom. The favorable scaling of Thomson scattering with energy combined with the very poor performance of synchrotron technology at x-ray energies above 100 keV would suggest that the "nuclear" x-ray regime is a fertile applications space for future Thomson-based, high energy radiation sources. At least two generic classes of applications are foreseen. In the first traditional radiography or x-ray shadowgraphy is extended to thicker or denser material systems. The high energy of the photon is useful simply for its penetrating nature. High spatial resolution (micron scale) radiography of dense energetic materials is of fundamental interest to high-profile, planned experiments on NIF and is also potentially applicable to gas gun experiments such as those conducted at the JASPER facility. In situ metrology of crack formation for the aerospace industry is an ongoing issue which could potentially be addressed by a high brightness, MeV-class x-ray source. In the second class of applications, one takes advantage of the photons interaction with the nucleus. Most high-resolution nuclear spectroscopy to date has been based on broadband excitation of an ensemble of nuclei by energetic electrons, neutrons, gammas or alpha particles followed by measurement of subsequent decay products with precision pulse height detectors. Alternatively direct photo access and study of individual transitions could be conducted with a T-REX source. For example polarization studies of transition strengths and characterization and assignment of weakly allowed transitions would be possible. T-REX could potentially do for precision gamma-ray spectroscopy of the nucleus what the laser did for precision spectroscopy of the atom. Among the interesting, possible nuclear spectroscopic applications of T-REX is nuclear resonance fluorescent imaging of materials, particularly special nuclear materials. The ground state nuclear spectra of all heavy elements is rich in transitions between 100 keV and several MeV. While these transitions do not result in alternation of the nuclei they may be potentially be used as a diagnostic of material composition. Radiation which has been tuned to the energy of a particular nuclei's transition will be isotropically scattered by the nuclei. Therefore by placing detectors around to an illuminated test subject, one may determine if the elemental composition of that object includes a particular nuclei simply by illuminating the object with an appropriately tuned T-REX beam. The detectors in this case need not be energy resolving. Because of the highly penetrating nature of MeV-class photons, it may be possible to probe for small quantities of material that would otherwise be hidden by shielding. Of course optimization of a Thomson-based machine for production of MeV-class radiation does not preclude that same machine from producing sub-100-keV photons as well. This may be accomplished by simply turning off sections of the overall accelerator structure to produce lower energy electron bunches prior to the interaction region.

Conclusions:
The generic endeavor of utilizing intense laser-matter and/or laser-electron interactions to create new and unique sources of x-rays is in its relative infancy compared to the billion-dollar-scale of investment that has been made in synchrotron technology. Only a handful of Thomson-based sources have been developed to date. These machines have been constructed to fill niche regions of the sub-100-keV applications space, i.e. shorter pulse duration or more compact tunability, that are ill-served by synchrotrons or anode sources. It is clearly possible for correctly designed Thomson-based sources to compete with alternative approaches and to fill these needs.

However, the strong positive scaling of Thomson source brilliance with energy combined with the even stronger decline of existing machine output above 100 keV, suggests that the applications space above 100-keV could be uniquely served by Thomson-based machines. One can easily imagine an evolution of ever more capable Thomson-based sources in much the same way that synchrotron sources have advanced. Advancement of these sources will be dependent upon the successful marriage of ever more advanced laser and accelerator technology. At this juncture it is clearly the case that the laser (both the photo-gun laser and the main drive laser) and not the accelerator is the least mature of the required technologies. LLNL is clearly the logical place for the required laser technology and advanced photo-gun technology to be developed, promoted and advanced. It has the technology, programmatic needs and expertise to do so. Development of sources such as T-REX will establish LLNL as the leader of laser-based x-ray sources and will allow both the continuation of programmatically relevant, sub-100-keV short pulse science as well as development of entirely new applications in the "nuclear" photon regime.