Laser and Accelerator Tech for High-Brightness Laser-Compton Light Sources

KEK Satellite Meeting
Tokai-mura, Japan

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The MEGa-ray and Nuclear Photonics efforts described in this presentation represent contributions from 11 institutions

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Matt	**Prantil**	**LLNL**
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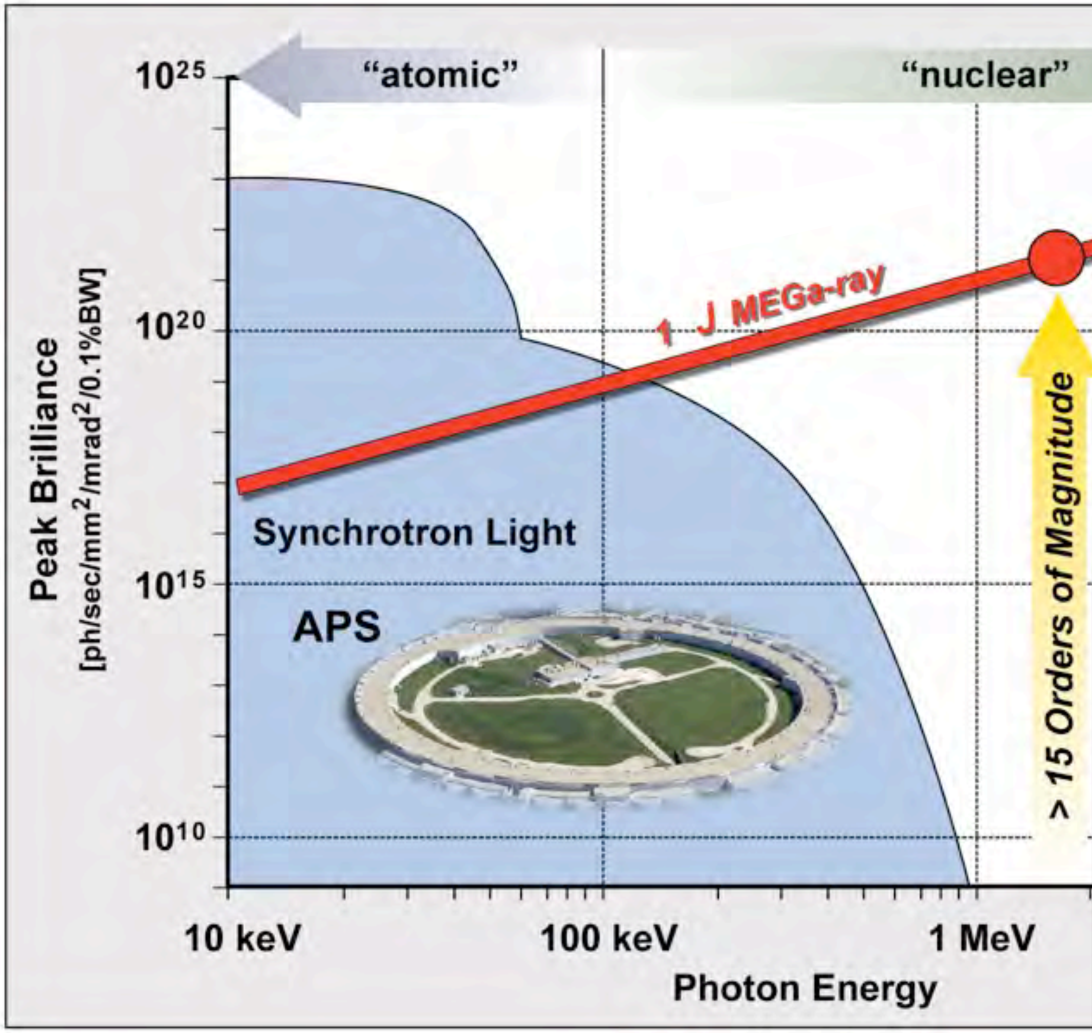
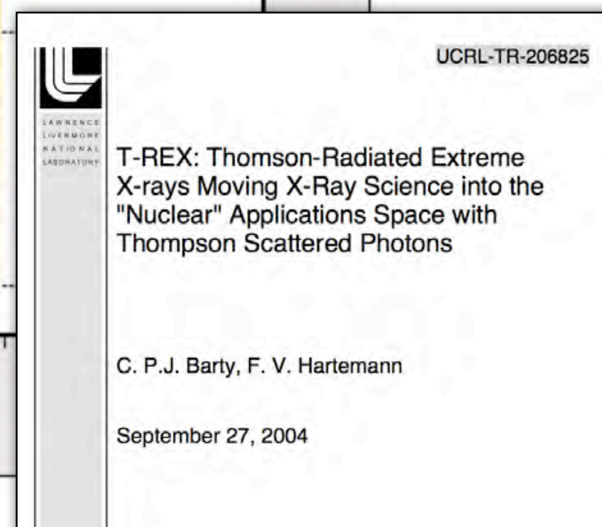
The characteristics of optimized laser-Compton gamma-ray sources enable "nuclear photonics"





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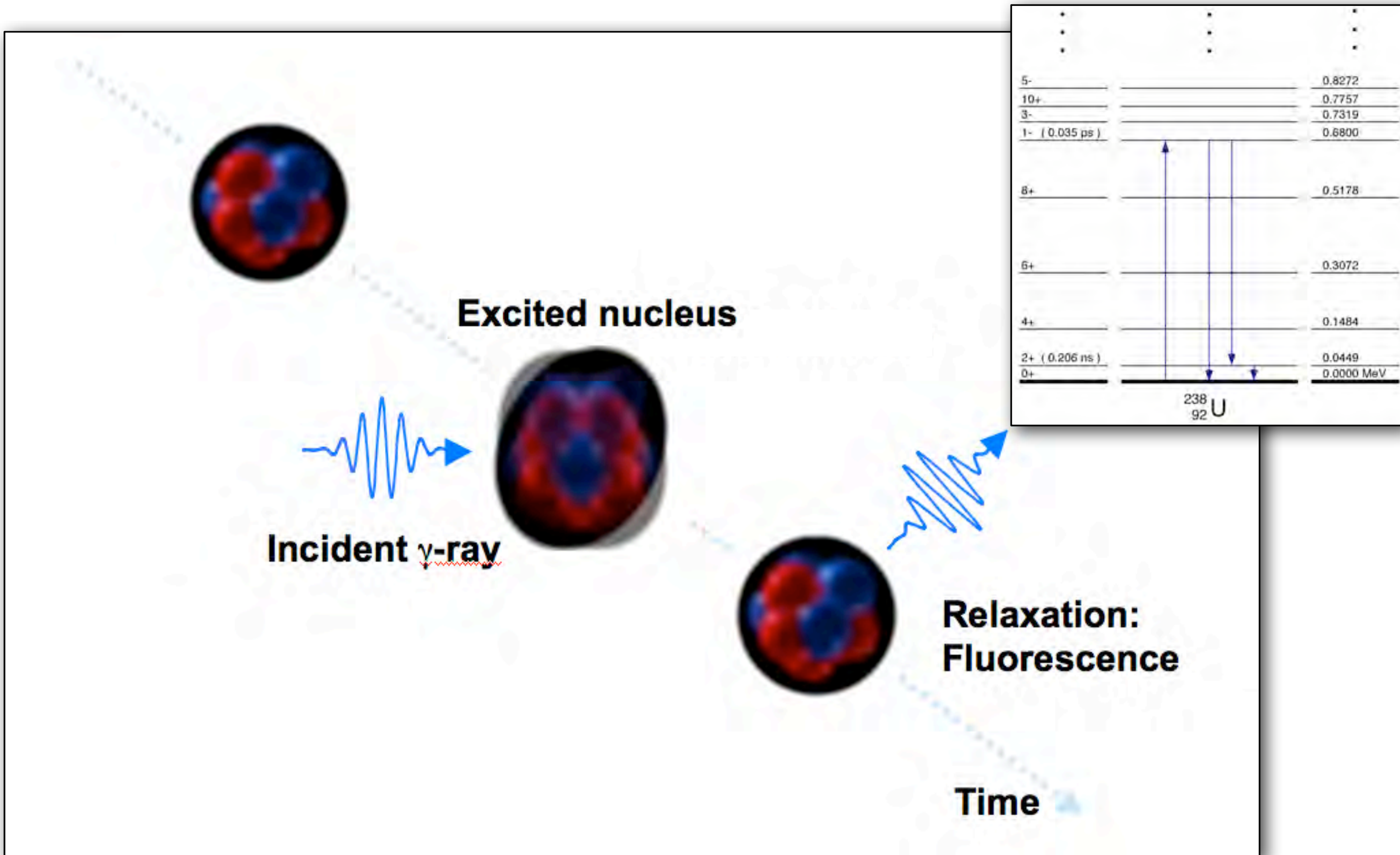
T-REX: Thomson-Radiated Extreme X-rays Moving X-Ray Science into the "Nuclear" Applications Space with Thompson Scattered Photons

C. P.J. Barty, F. V. Hartemann

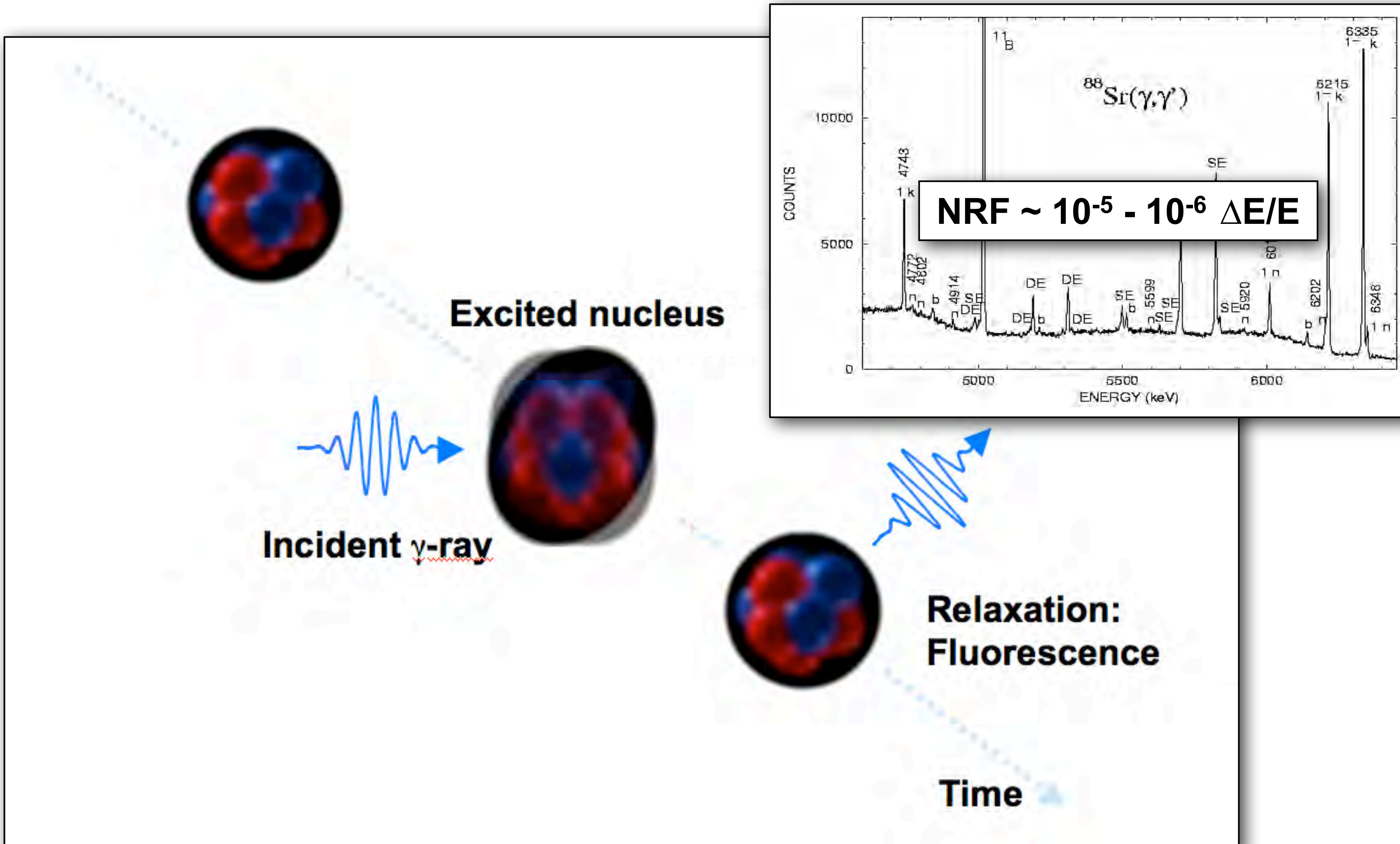
September 27, 2004

Nuclear resonance fluorescence is easily excited narrowband laser-Compton sources



Nuclear Resonance Fluorescence depends upon the number of protons and the number of neutrons in the nucleus and is an isotope-specific material signature

Intrinsic NRF widths are of order meV but are thermally (Doppler) broadened to of order eV



Selective excitation of NRF transitions is possible with laser-Compton gamma-ray source bandwidths of order $\Delta E/E \sim 10^{-3}$

Potential NRF-based Applications of Bright Gamma Sources are Numerous

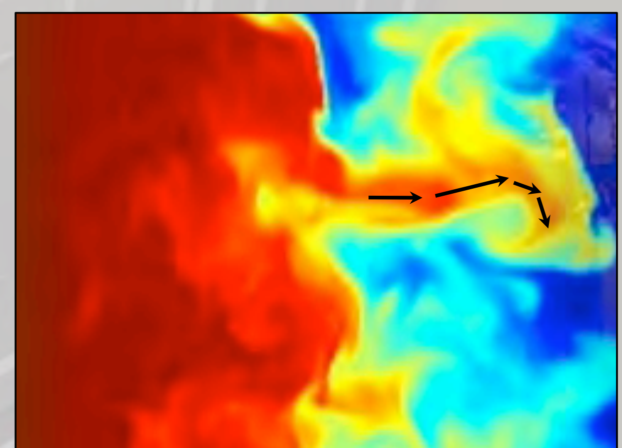
HEU Grand Challenge
detection of shielded material

Nuclear Fuel Assay
100 parts per million per isotope

Waste Imaging & Assay
non-invasive content certification

Industrial NDE
micron-scale & isotope specific

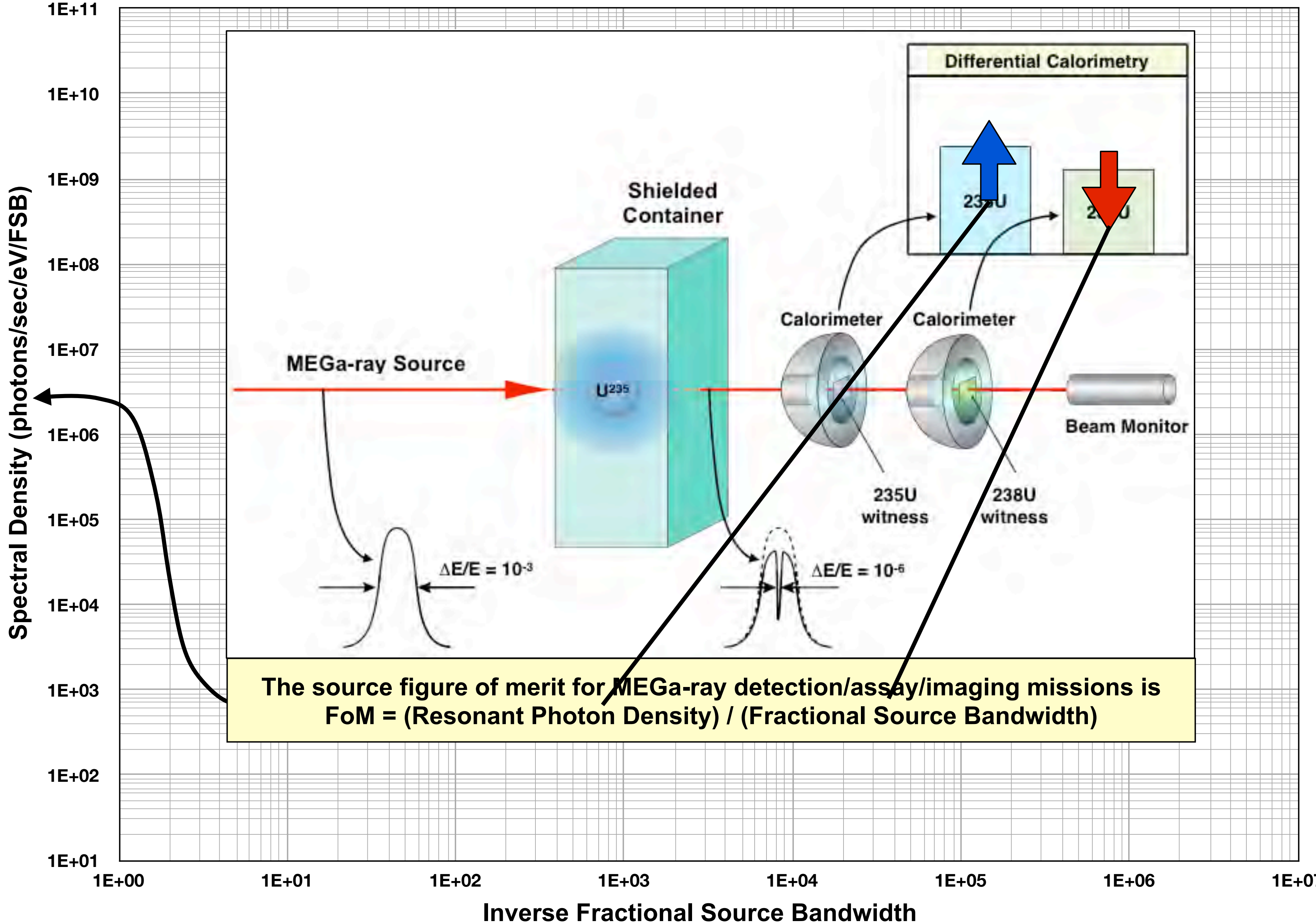
Medical Imaging
low density & isotope specific

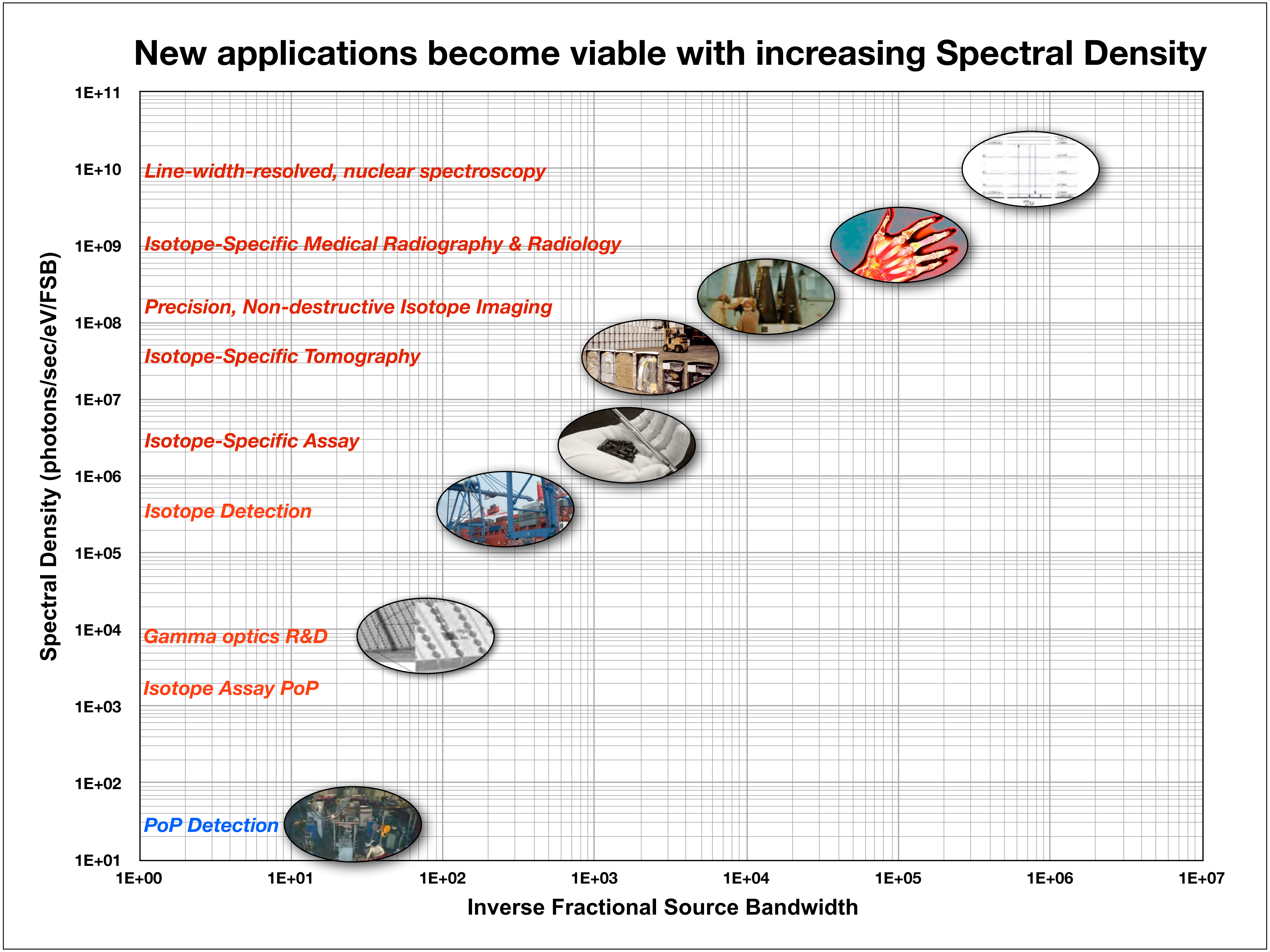


Dense Plasma Science
isotope mass, position & velocity

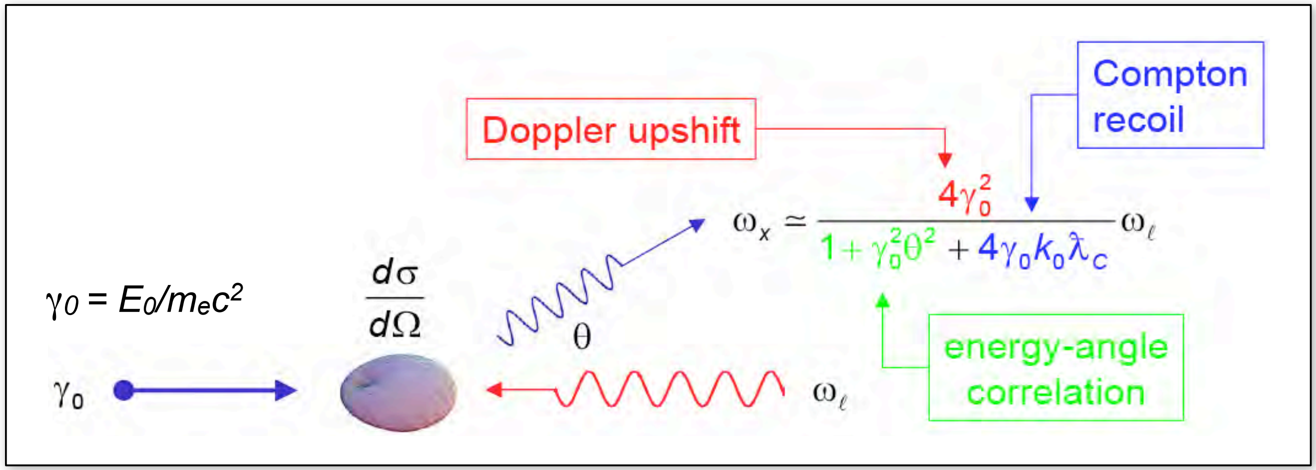
US patent #7,564,241 Barty, Hartemann, McNabb & Pruet - detection, assay and imaging with MEGa-rays

Spectral Density is the key source metric for most NRF applications




New applications become viable with increasing Spectral Density
Spectral Density (photons/sec/eV/FSB)
Inverse Fractional Source Bandwidth
1E+11
1E+10
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
1E+01
1E+02
1E+03
1E+04
1E+05
1E+06
1E+07
Line-width-resolved, nuclear spectroscopy
Isotope-Specific Medical Radiography & Radiology
Precision, Non-destructive Isotope Imaging
Isotope-Specific Tomography
Isotope-Specific Assay
Isotope Detection
Gamma optics R&D
Isotope Assay PoP
PoP Detection

Laser Compton back scattering off of high energy electrons can produce tunable x-ray & gamma-rays



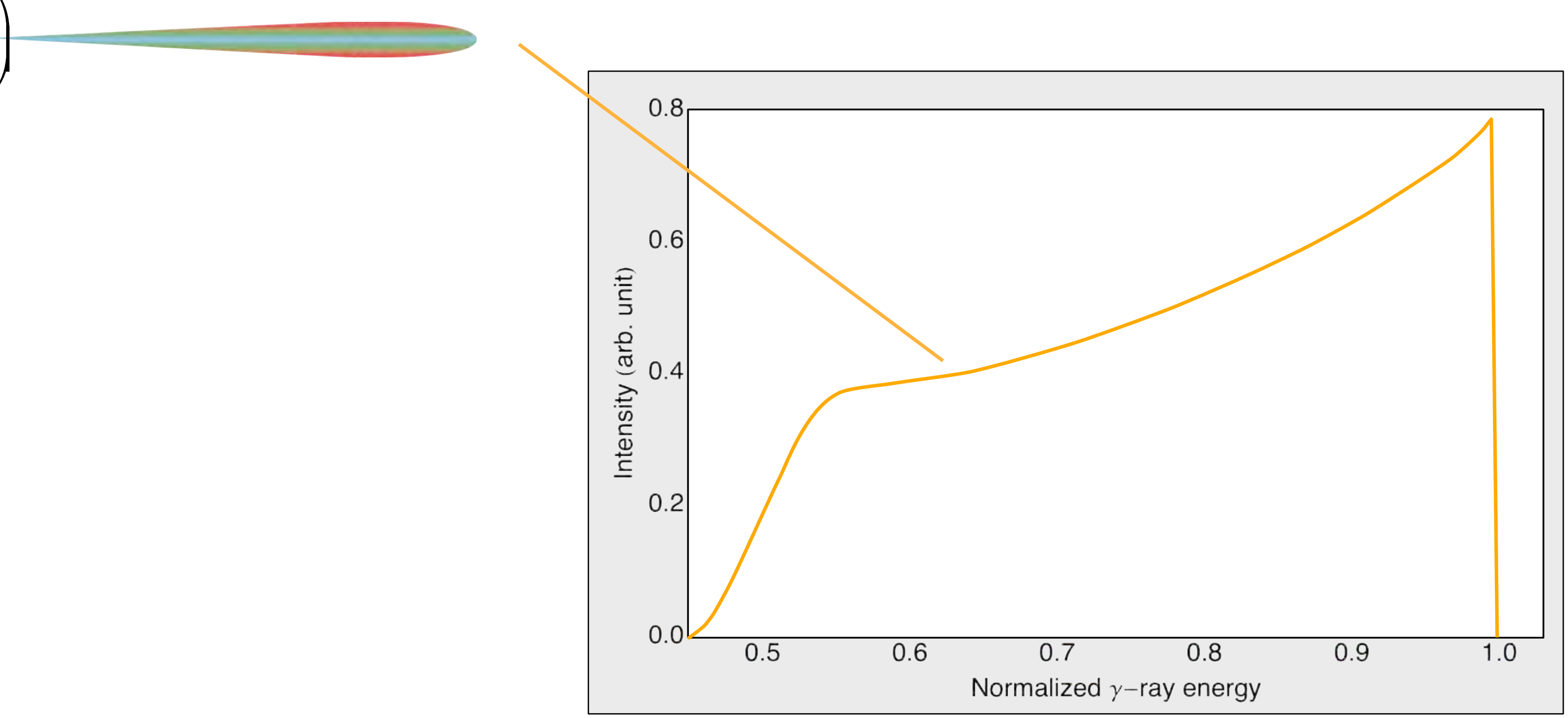
A photon flux of 1.7 x 10^{24} ph/cm^2 = "unity" efficiency

1.7 x 10^{24} ph/cm^2 @ 532 nm in a 100 micron spot = 44 J!

Overall Compton scattering is broadband, but it is highly angle correlated and is ‘narrowband’ on axis

$\Delta\Omega \; ; \; \pi\left(\frac{1}{\gamma}\right)^2$

few mrad



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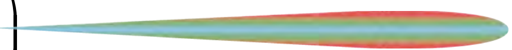
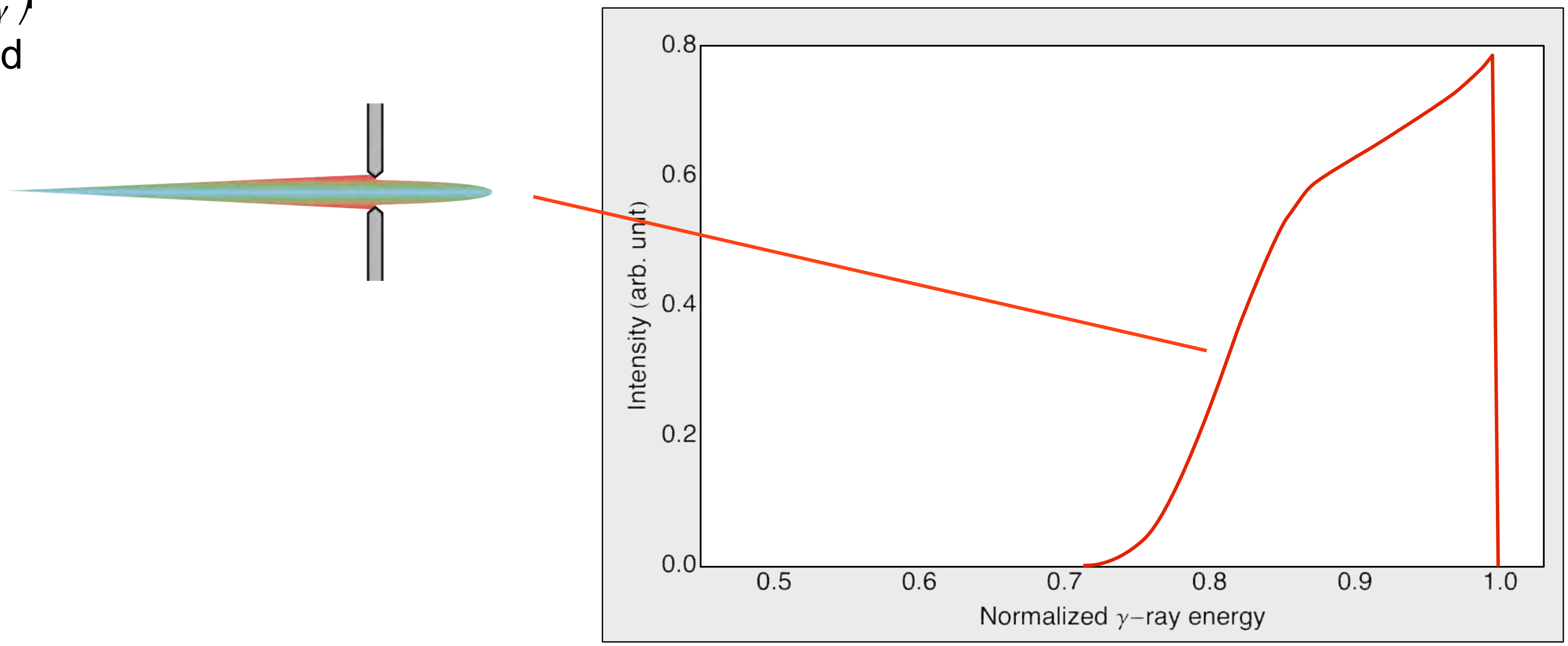


few mrad



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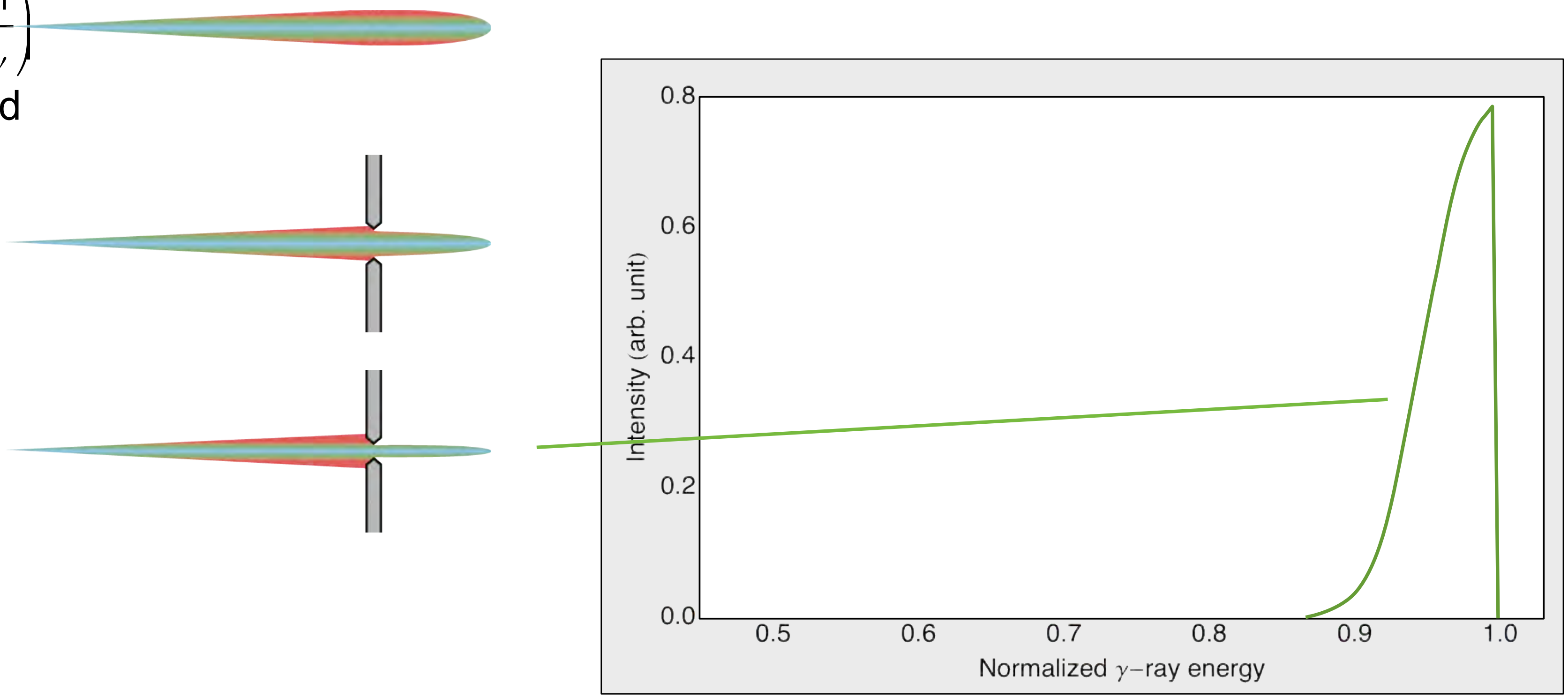

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$\Delta\Omega \; ; \; \pi\left(\frac{1}{\gamma}\right)^{2}$

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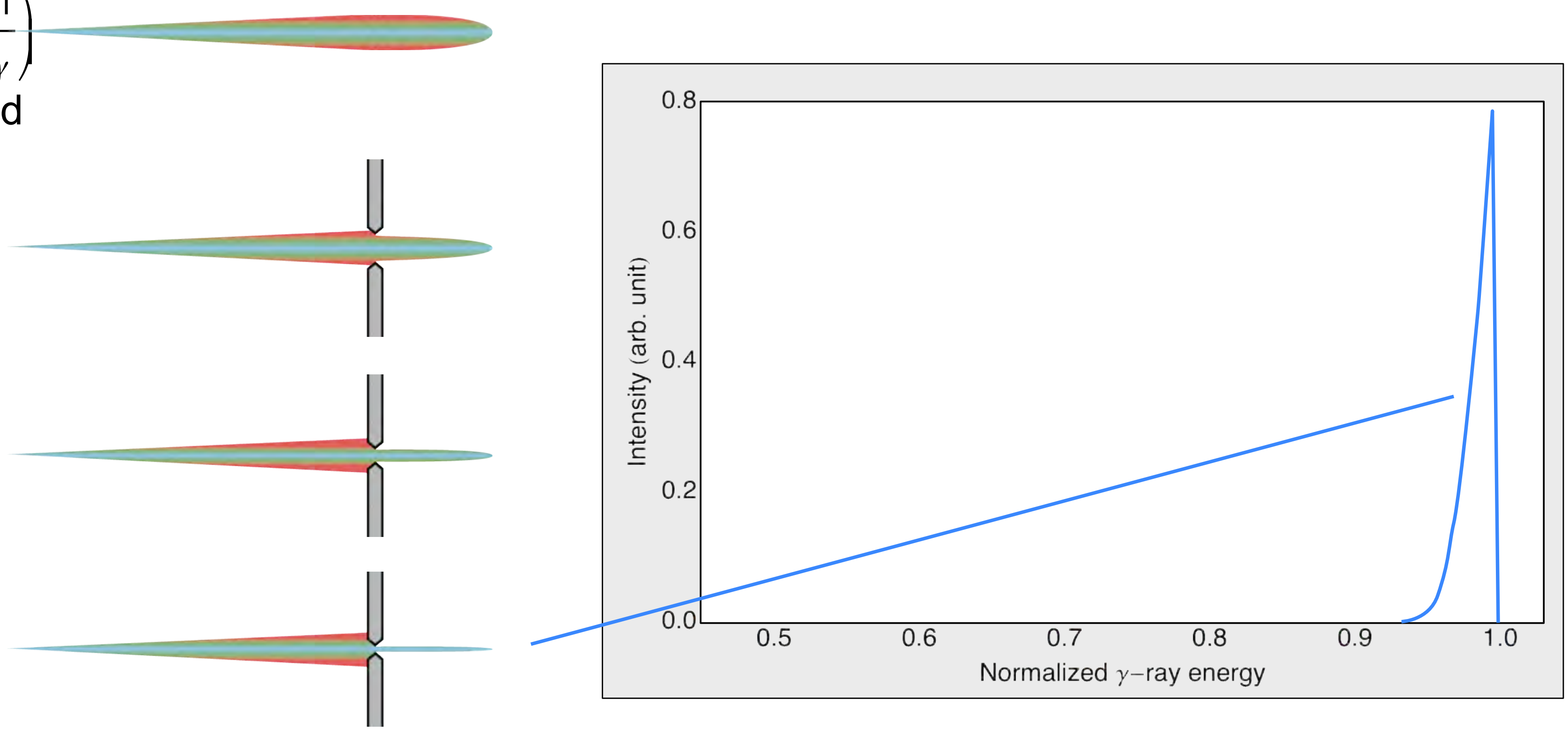

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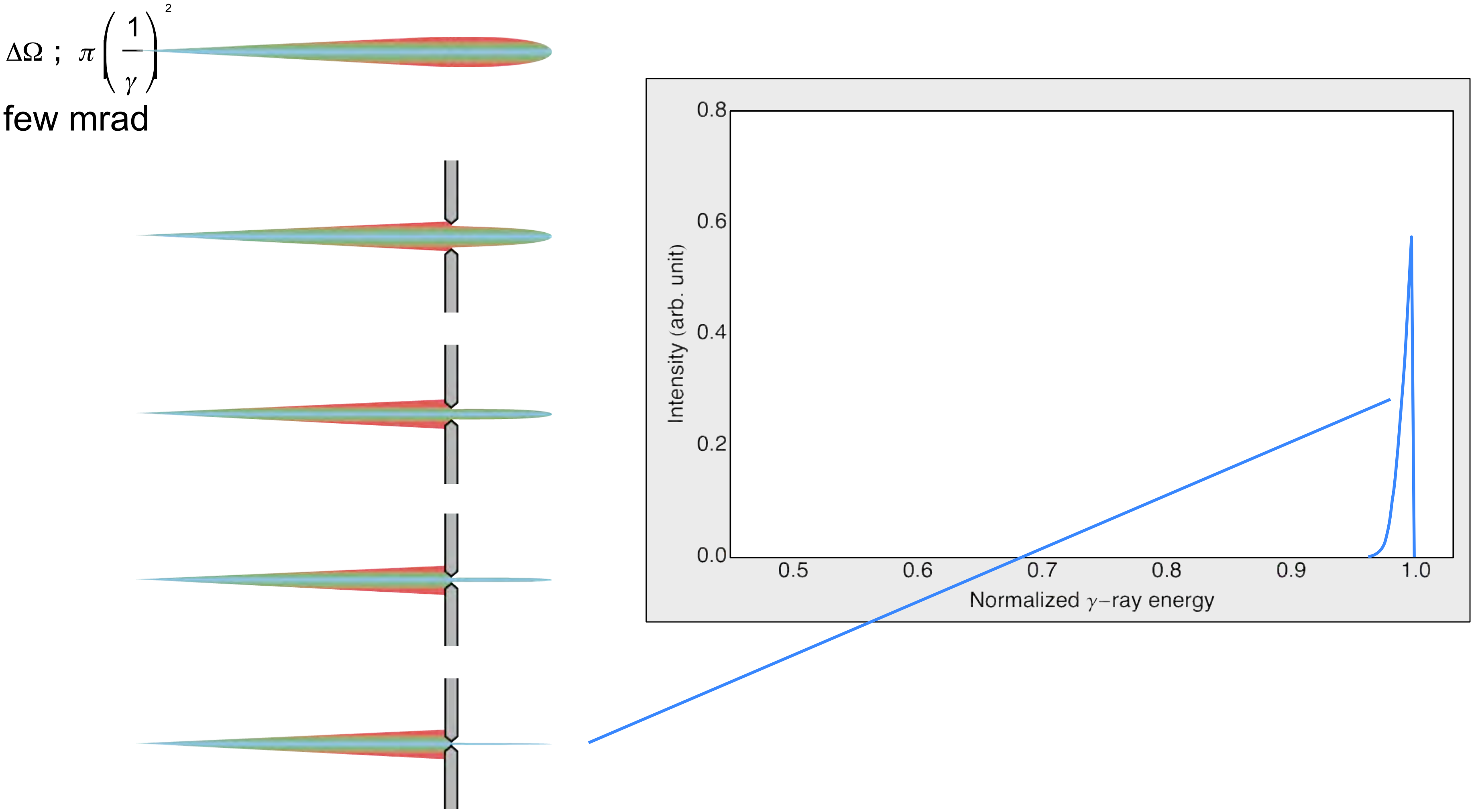
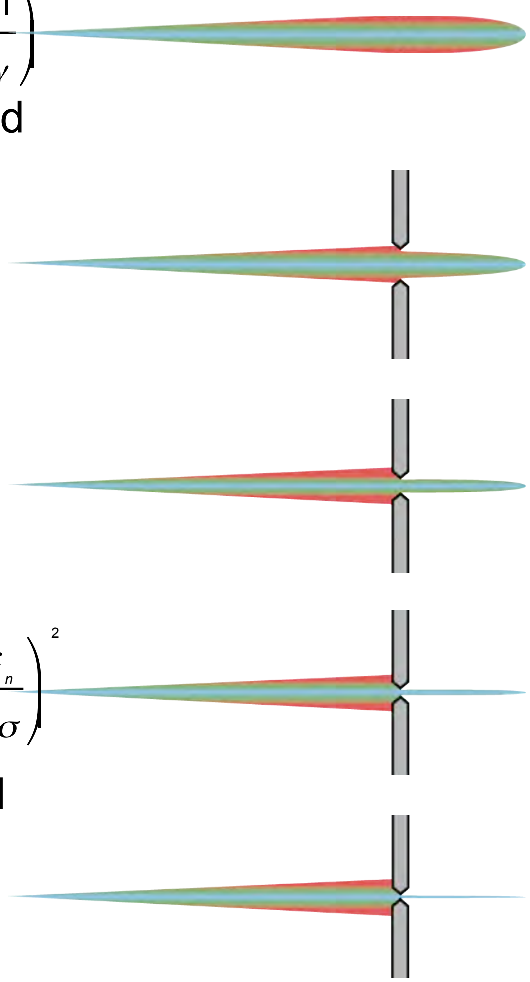


Overall Compton scattering is broadband, but it is highly angle correlated and is 'narrowband' on axis

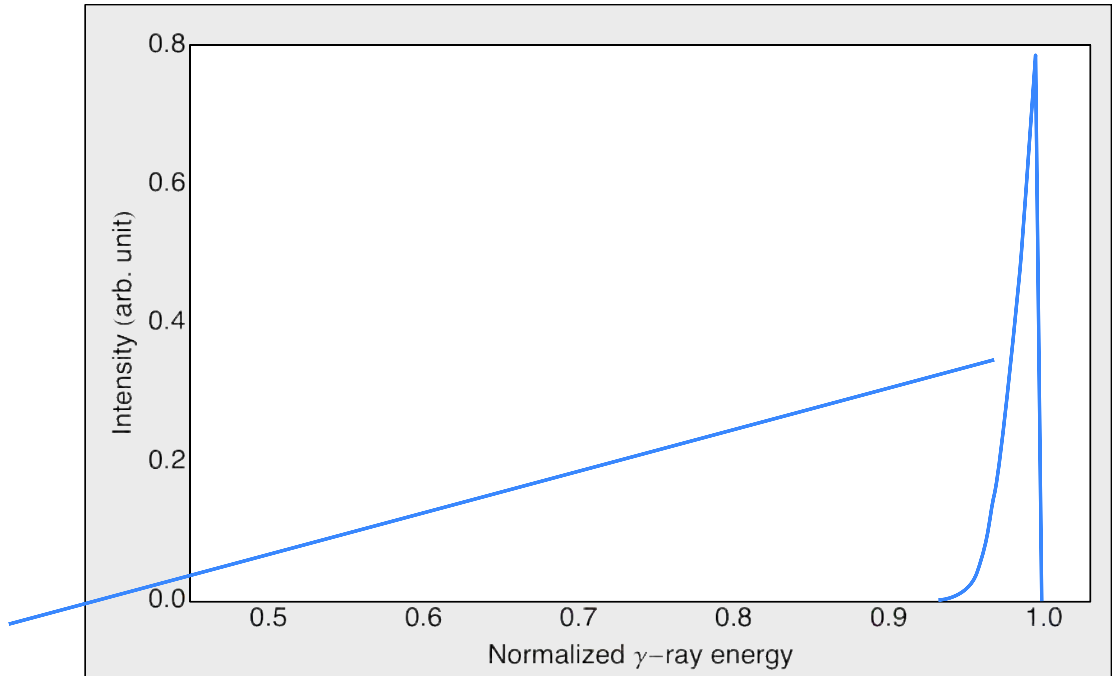
$\Delta\Omega \; ; \; \pi\left(\frac{1}{\gamma}\right)^2$

few mrad



$\Delta\Omega \; ; \; \pi\left(\frac{\varepsilon_n}{\gamma\sigma}\right)^2$

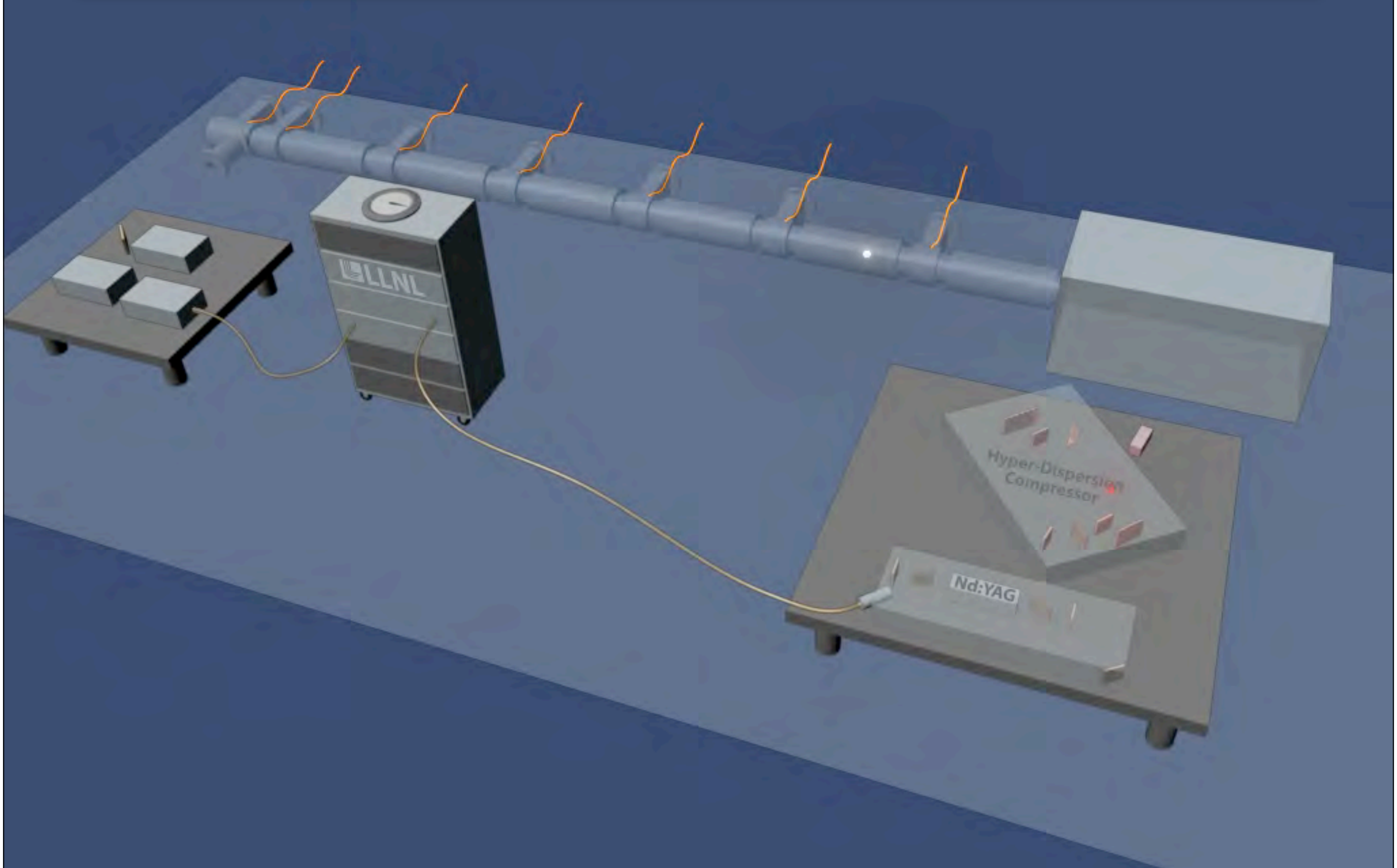
few μrad



"**Mono-Energetic Gamma-rays" - MEGa-rays**

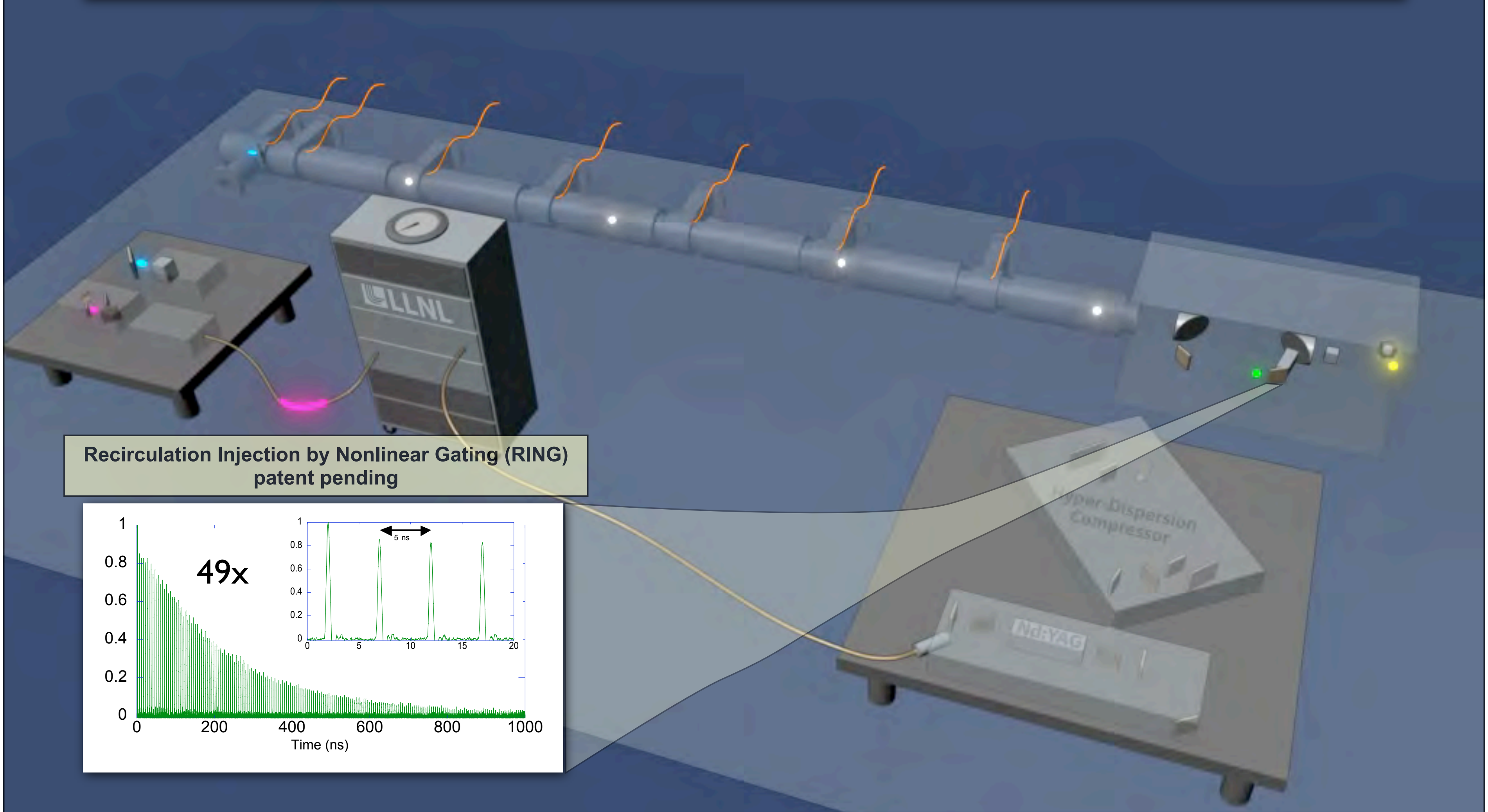
Optimally designed sources can have fractional bandwidths of ~10^{-3} FWHM

High-flux, laser-Compton scattering arrangements aim to produce high photon & electron densities at a common focus



US patent #8,068,522 Barty - Hyperdispersion Chirped Pulse Amplification and Compression

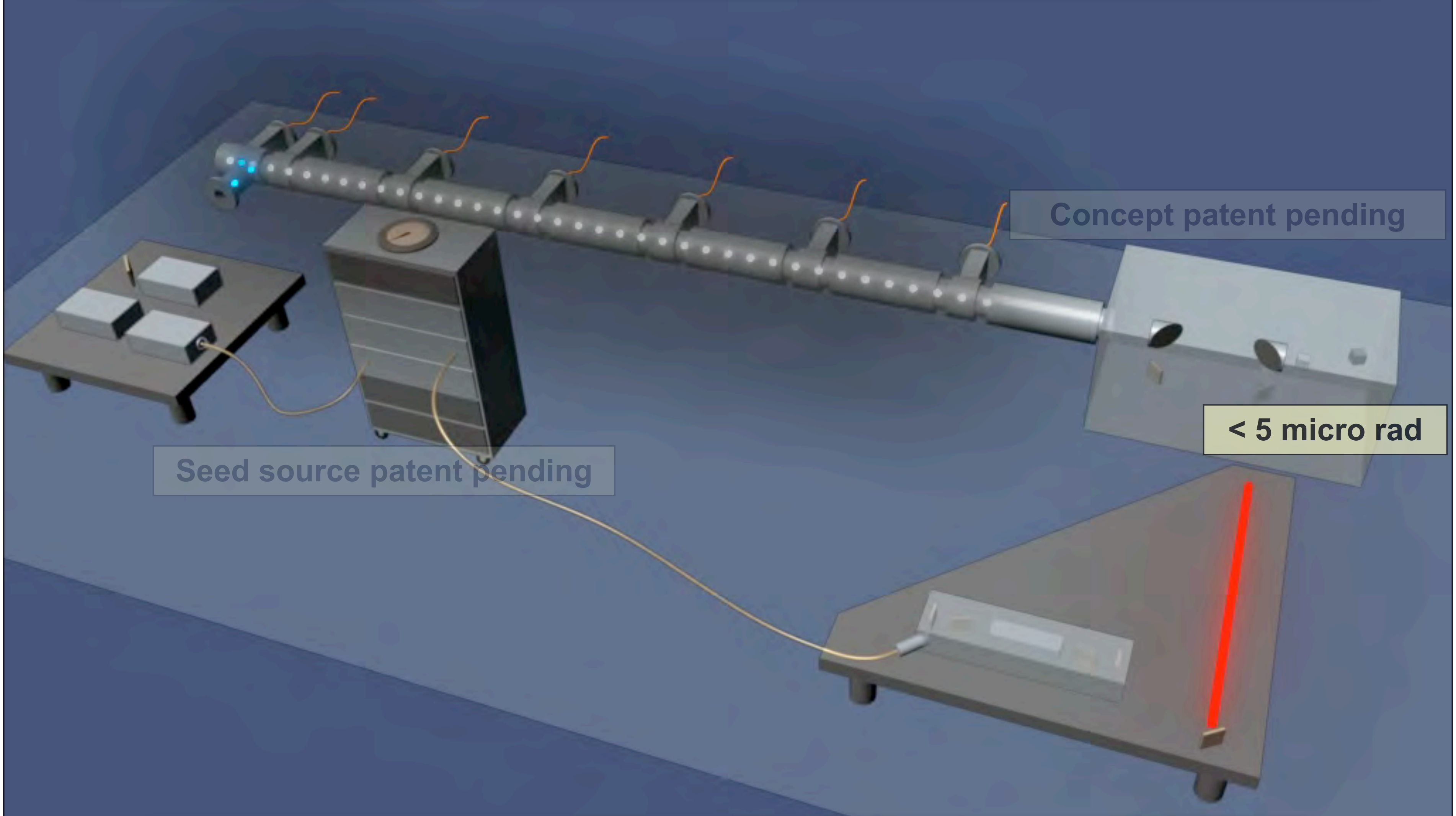
High-flux, laser-Compton scattering arrangements perturb the laser pulse energy very little during the interaction



Recirculation can give > 20x increase in Compton photon production for "free"
RING positioning requirements are 10,000x less stringent than Cavity schemes

US patent #8,068,522 Barty - Hyperdispersion Chirped Pulse Amplification and Compression

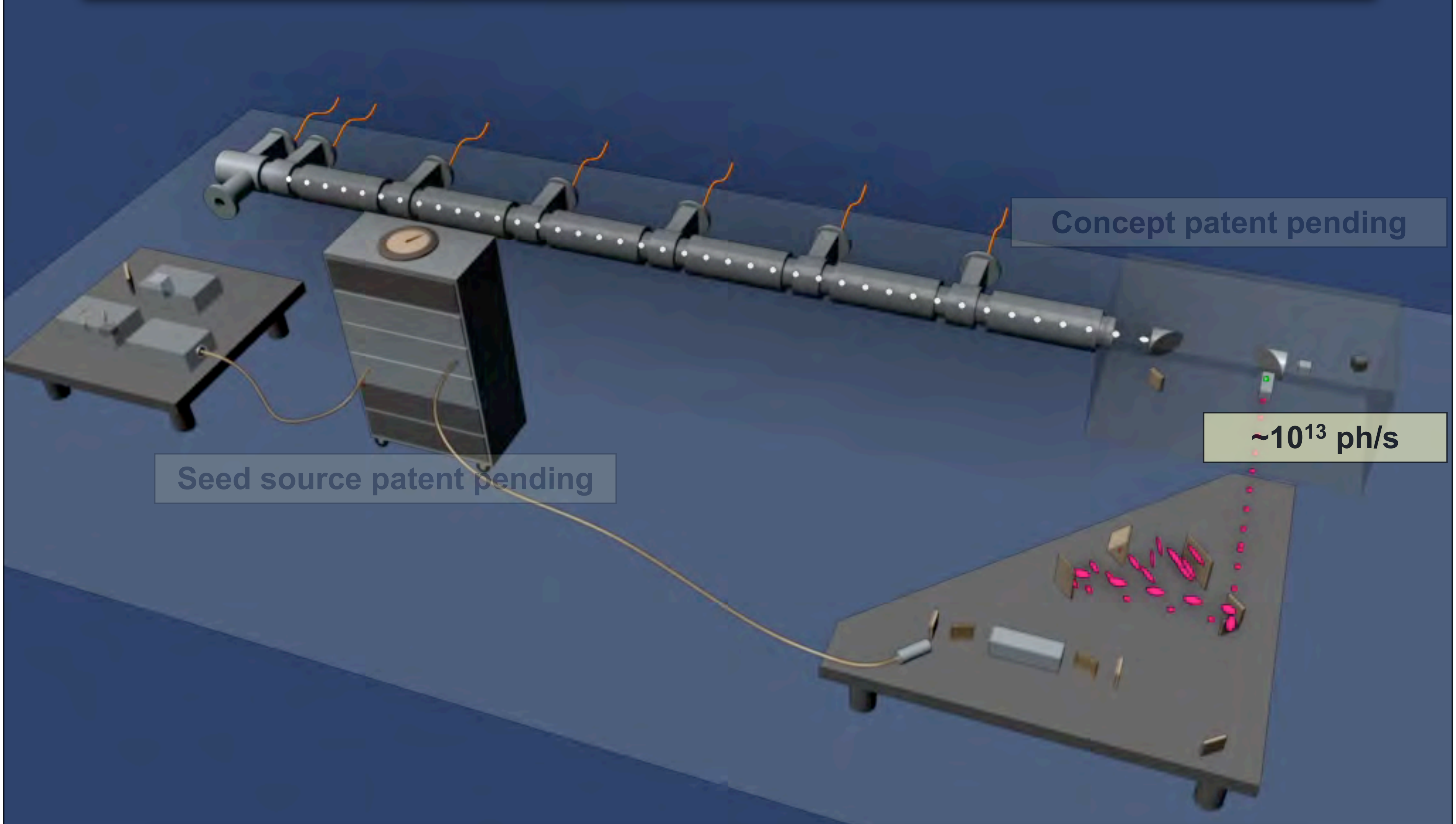
2011 multi-GHz, multi-bunch laser-Compton source concept



Highly collimated - reduces bandwidth, complexity of photon gun drive laser, interaction laser and system timing but requires high energy laser

patents pending

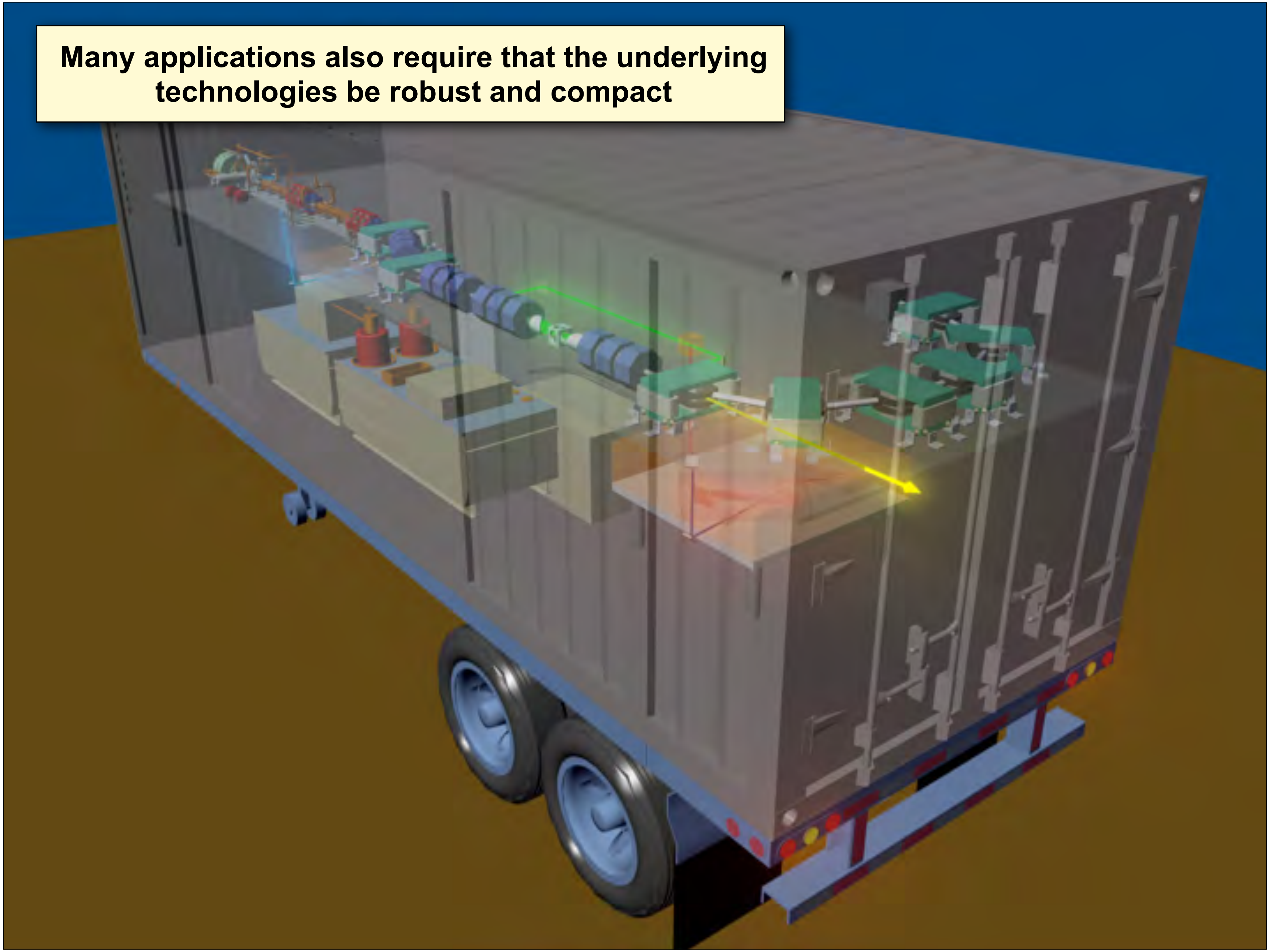
LLNL's "Picket Fence" multi-GHz, laser-Compton source concept



This configuration enables near "unity" efficiency, operates with high beam current, minimizes bandwidth and is intrinsically synchronized to RF clock

patents pending

Many applications also require that the underlying technologies be robust and compact

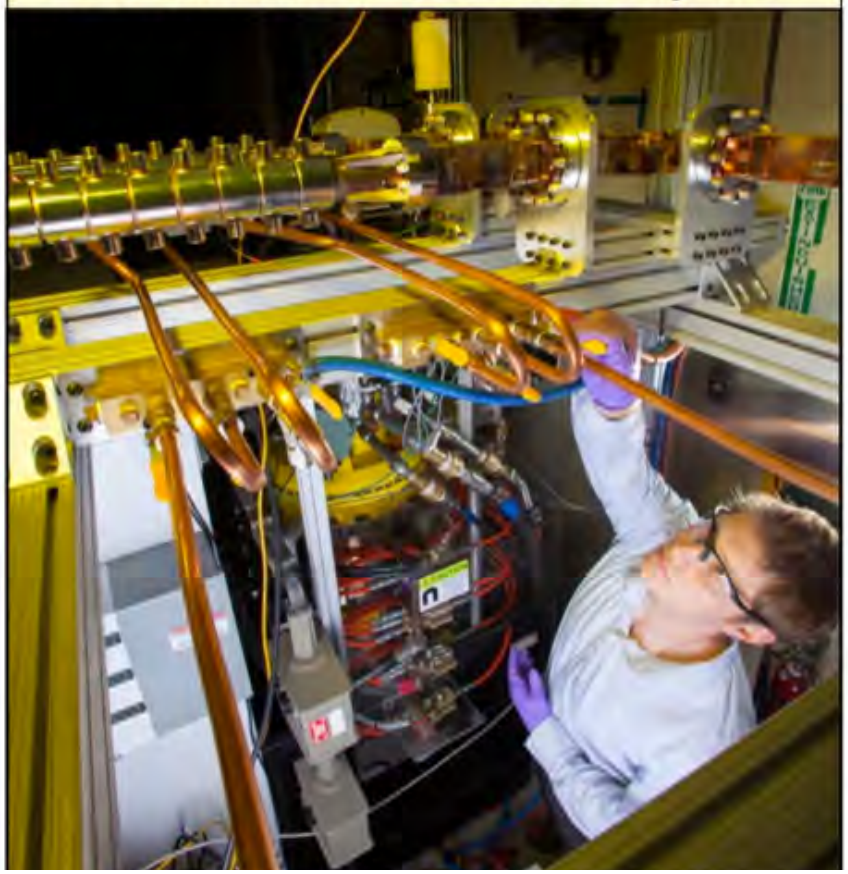


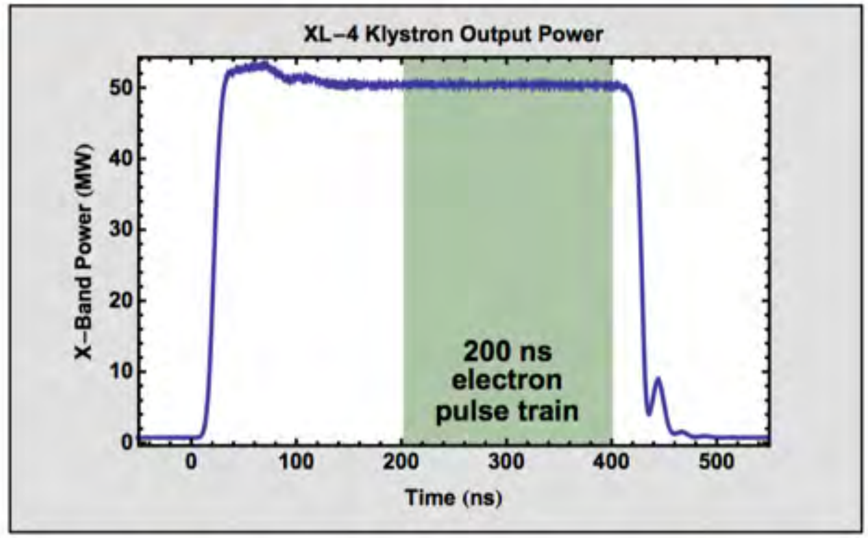
B194 X-Band Test Station

LLNL has designed & constructed a compact x-band accelerator in order to develop & demonstrate advanced, high-flux, laser-Compton x-ray & gamma-ray architectures

RF Power combines the best of SLAC klystron technology & commercial solid state modulators

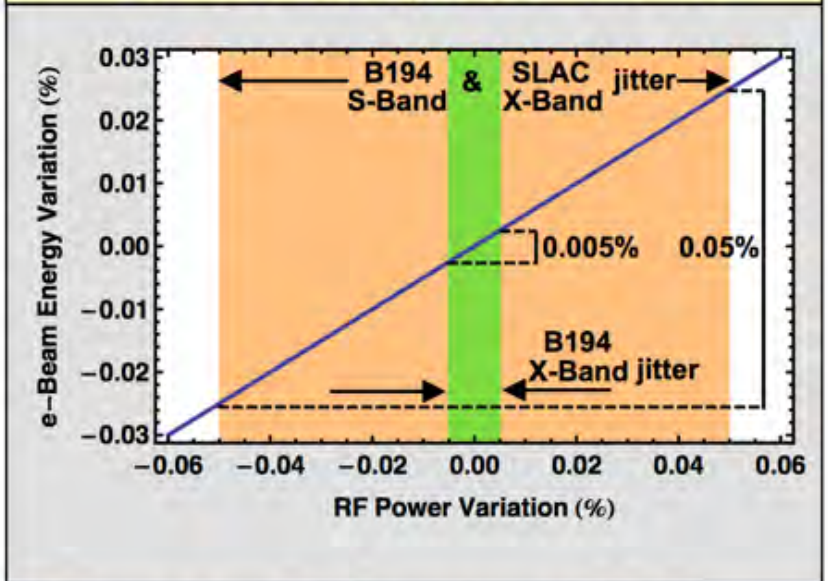
State-of-the-art solid-state, 420 kV, 300 A Modulator and 50 MW Klystron





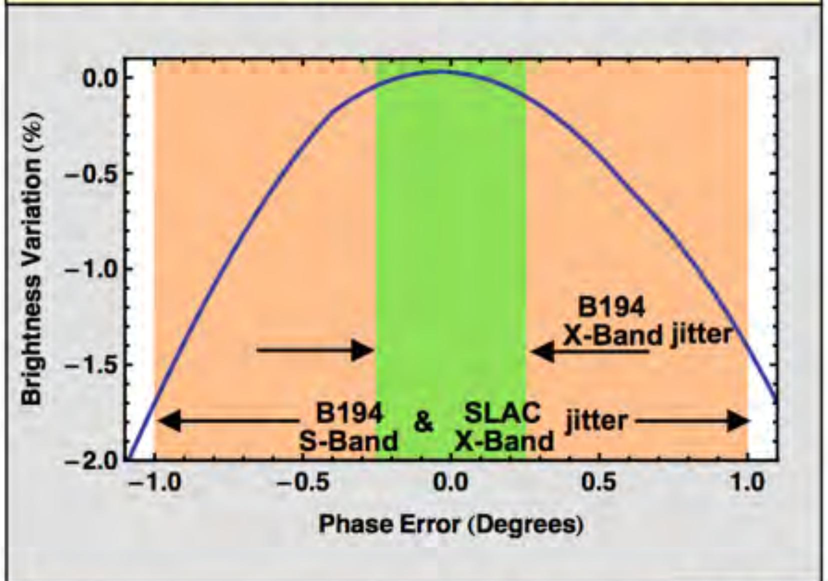
Performance of the XL4 klystron and ScandiNova modulator exceed all of our requirements

E-Beam Energy vs. RF Power



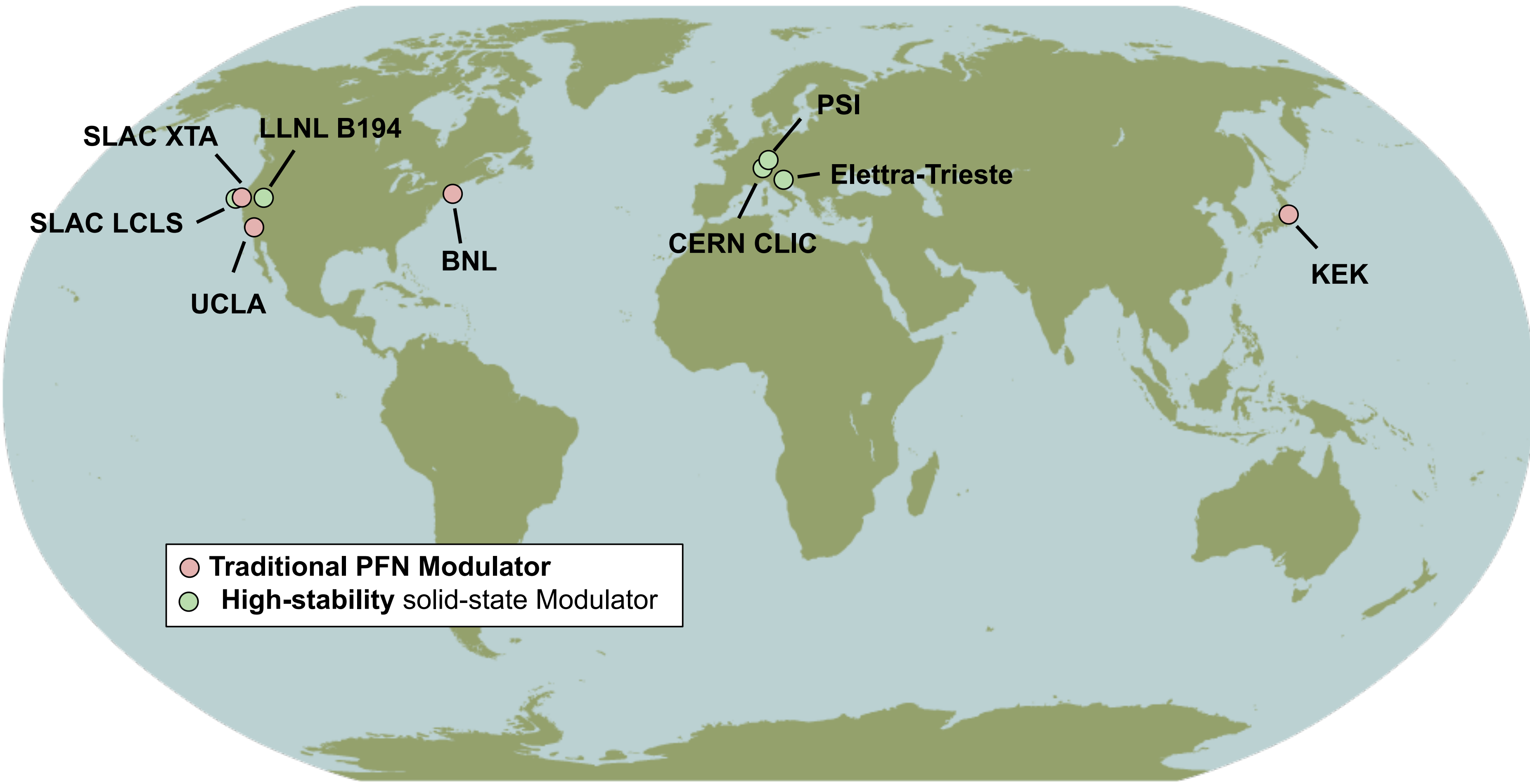
This system is 10x more stable in amplitude than existing SLAC and LLNL sources.

E-Beam Brightness vs. RF Phase

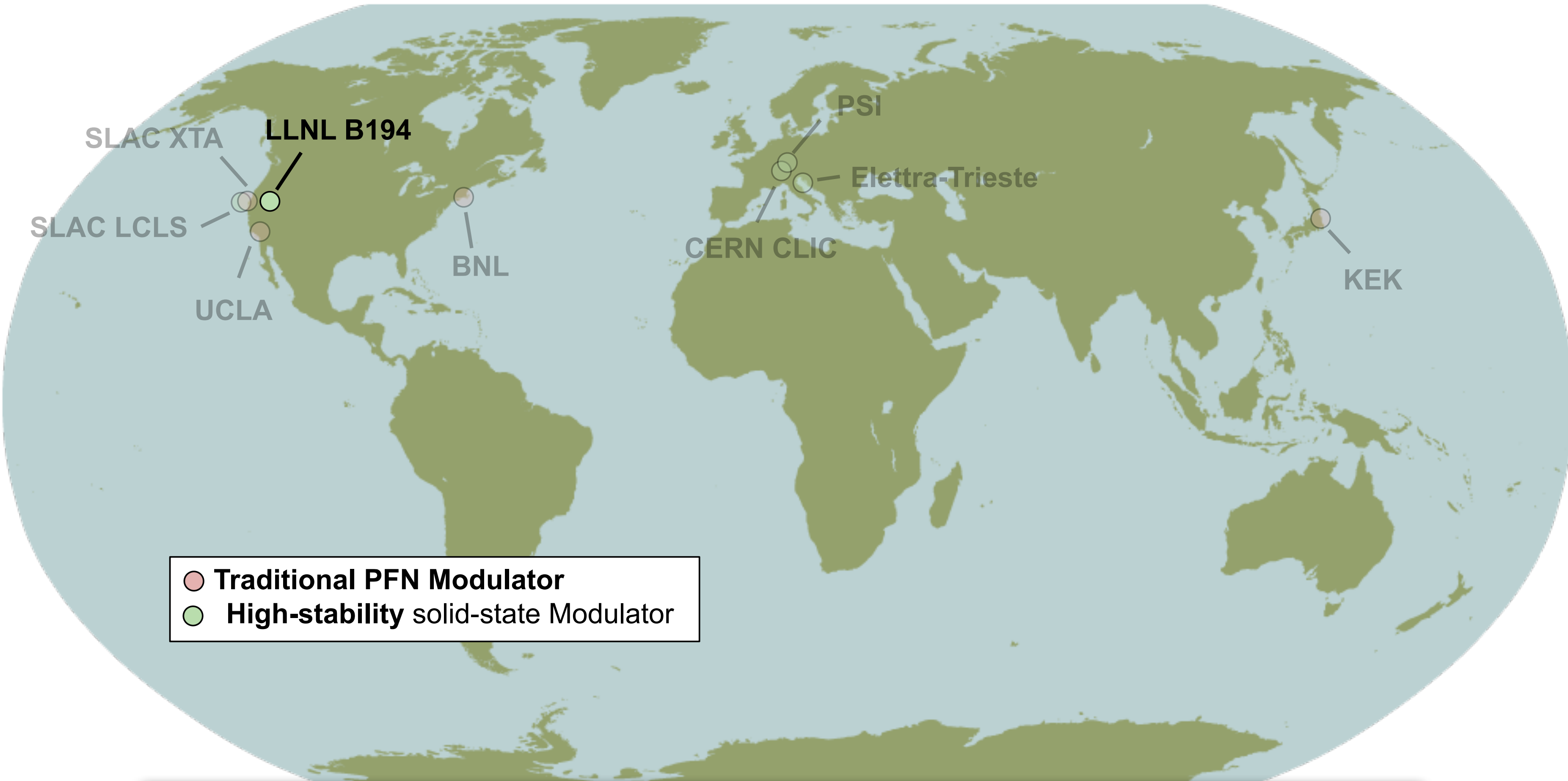


4x improvement in RF phase stability corresponds to 10x improvement in brightness stability.

Worldwide high power x-band sources

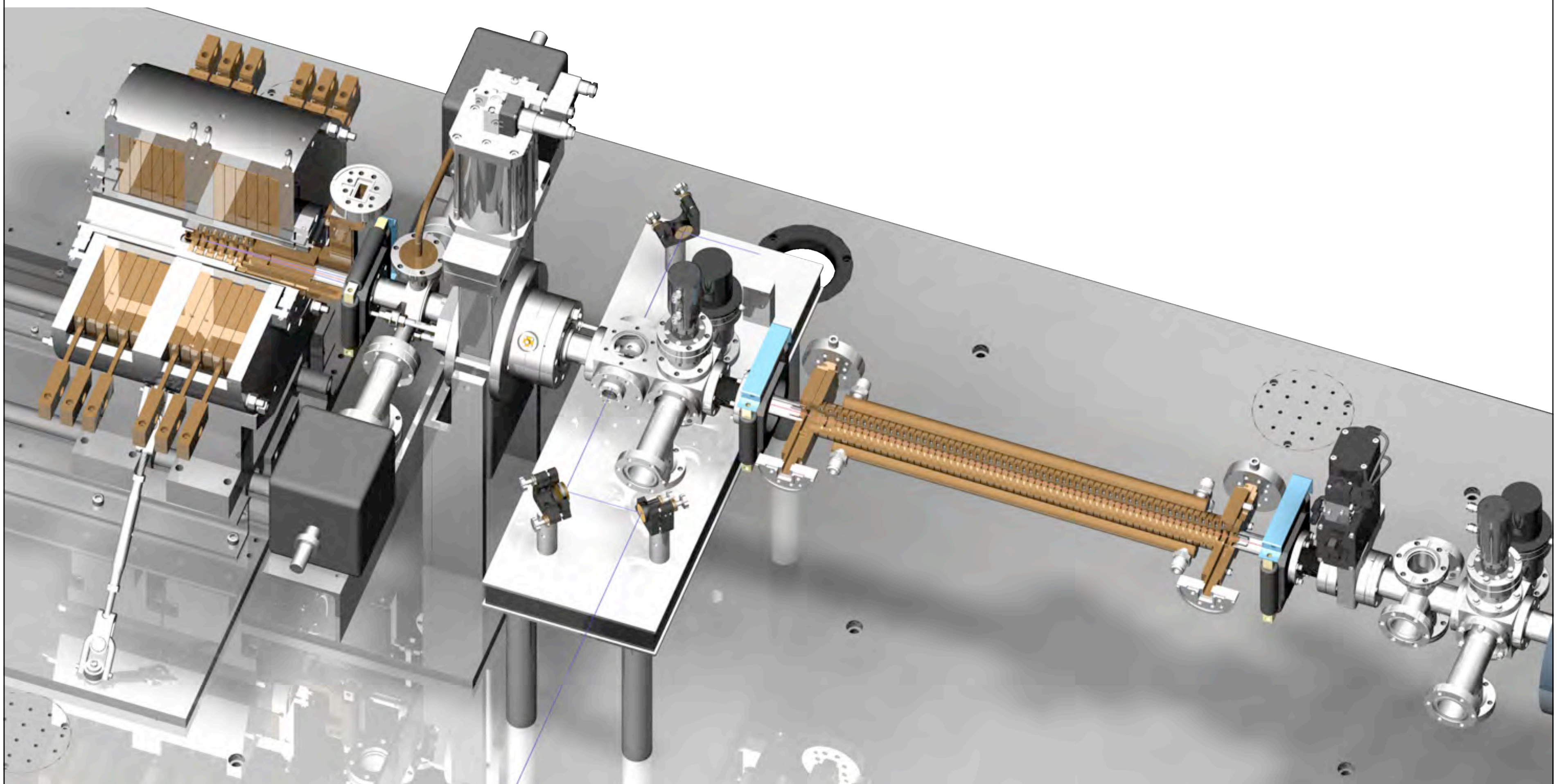


Worldwide high power x-band sources



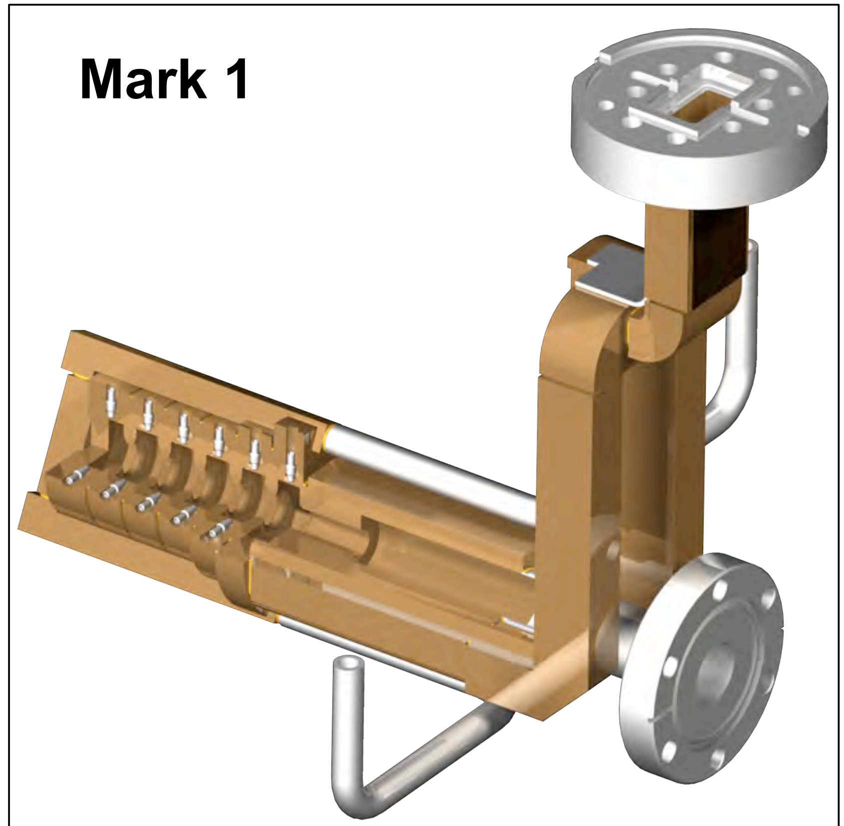
LLNL set up is currently the only facility where high quality x-band RF is coupled with state-of-the-art structures to produce beam

Photo-gun and first section



X-band photo-gun evolution

SLAC 5.5 cell x-band gun
designed by Arnold Vlieks (SLAC)

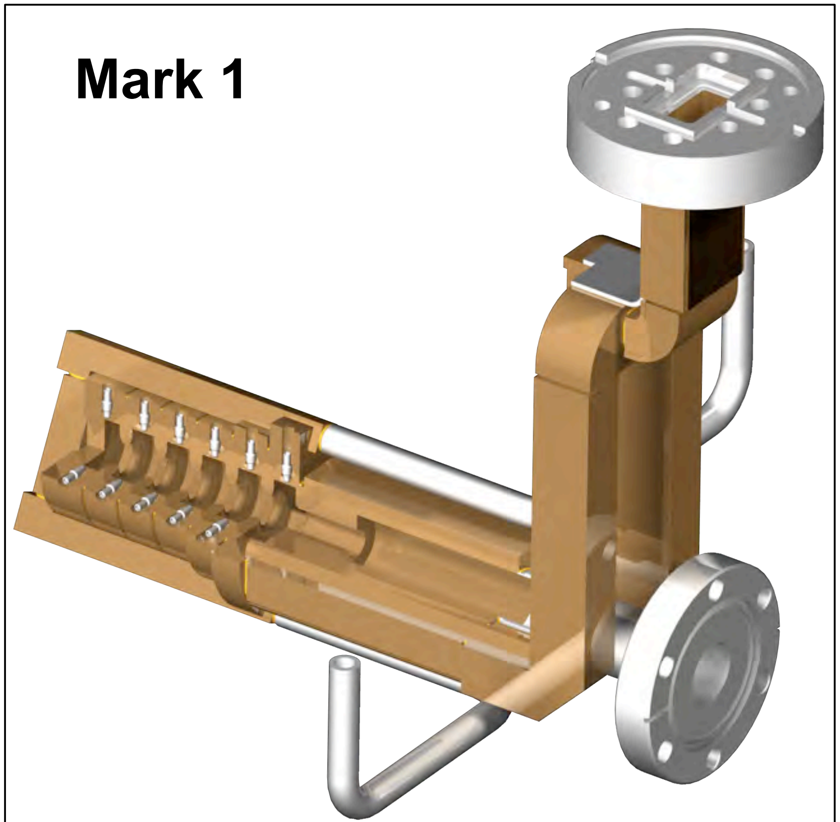


LLNL/SLAC 5.59 cell x-band gun
design lead - Roark Marsh (LLNL)

X-band photo-gun evolution

- Longer Half cell for lower final emittance
- Better mode separation for less mode beating on cathode surface
- Elliptical irises for lower peak surface electric field
- Dual feed racetrack coupler for minimized RF quadrupole kick
- Optimized beta for a balance of fast gun fill time and low pulsed heating

Mark 1



LLNL/SLAC 5.59 cell x-band gun design lead - Roark Marsh (LLNL)

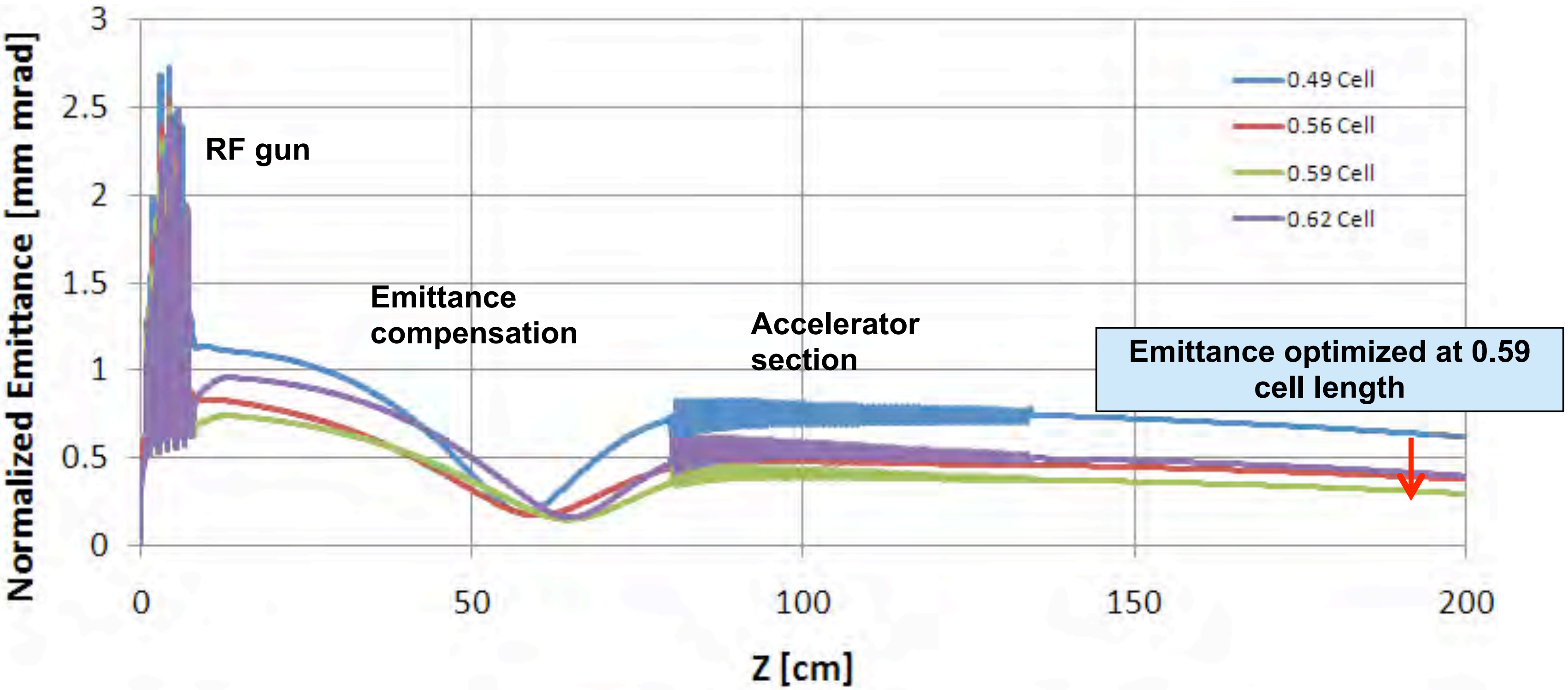
Multiple Codes were used to design and verify the Mark 1 x-band RF photo-gun

- Pro/Engineer and Solidworks
  - Mechanical design
- Superfish
  - Fast 2D axially symmetric gun optimization
- PARMELA, GPT, ASTRA, Impact-T
  - Beam dynamics
- Ansoft HFSS
  - Full 3D microwave design, frequency domain
- ACE3P
  - Suite of 3D parallel SLAC codes
  - CUBIT mesher, Omega3P, S3P, T3P, PIC3P, ParaView postprocessing
  - Final benchmark and verification

PARMELA results

Redesigned longer half cell for optimized brightness

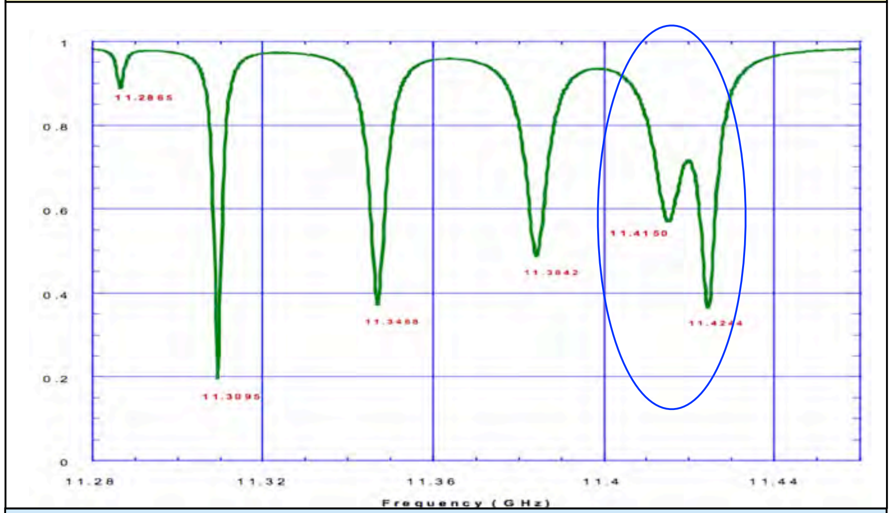
Optimized launch phase and solenoid strength
Beam parameters: Q = 250 pC, τφ = 10 deg.
200 MV/m cathode field



Calculated mode separation is greater than Mark 0

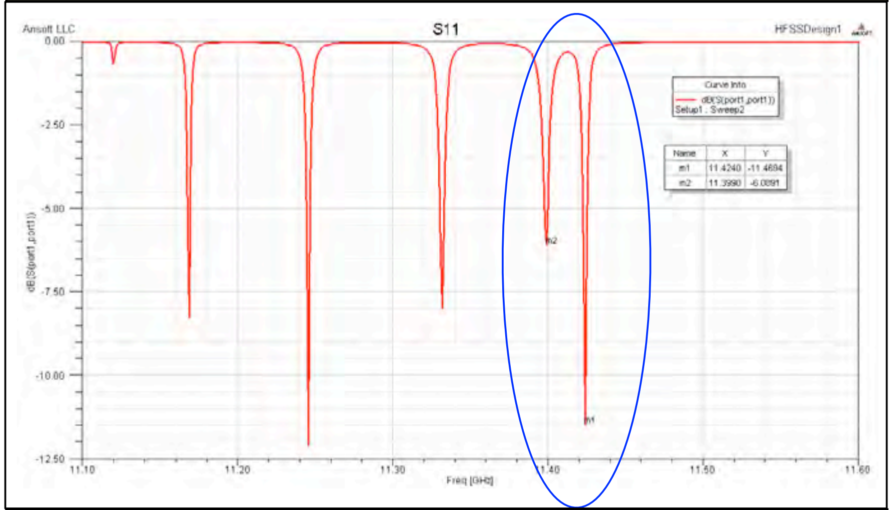
- Original Mark 0 design provided <10 MHz separation
- Redesign of iris geometry achieves 25 MHz spacing

Mark 0 Measurement



9 MHz separation: Clear co-excitation

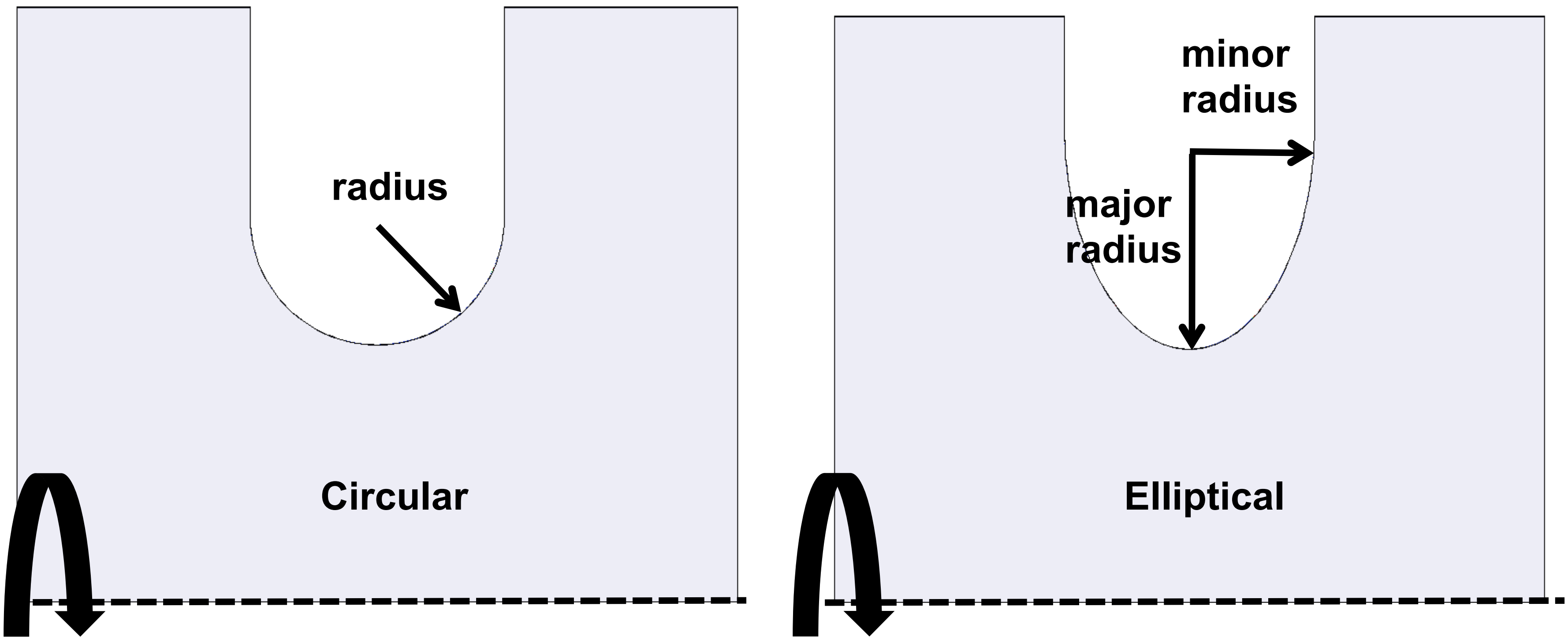
Mark 1 Design



25 MHz separation: Distinct modes

Iris geometry was changed from circular to elliptical and optimized

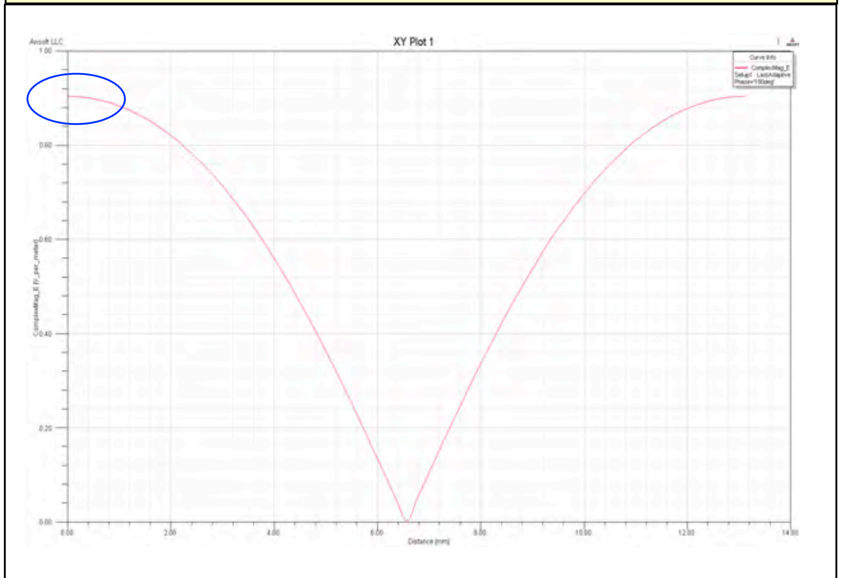
- Ellipticity for Mark 1 RF gun: major/minor = 1.8



Electrical performance difference

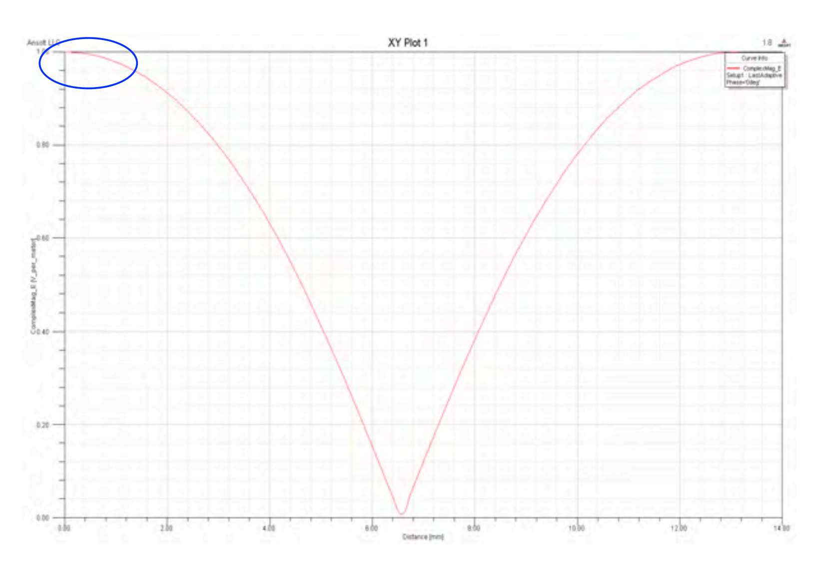
- **Figure of merit: ratio of peak axial electric field to peak surface electric field on iris**

Axial Field for Circular Iris



Ratio of 0.92

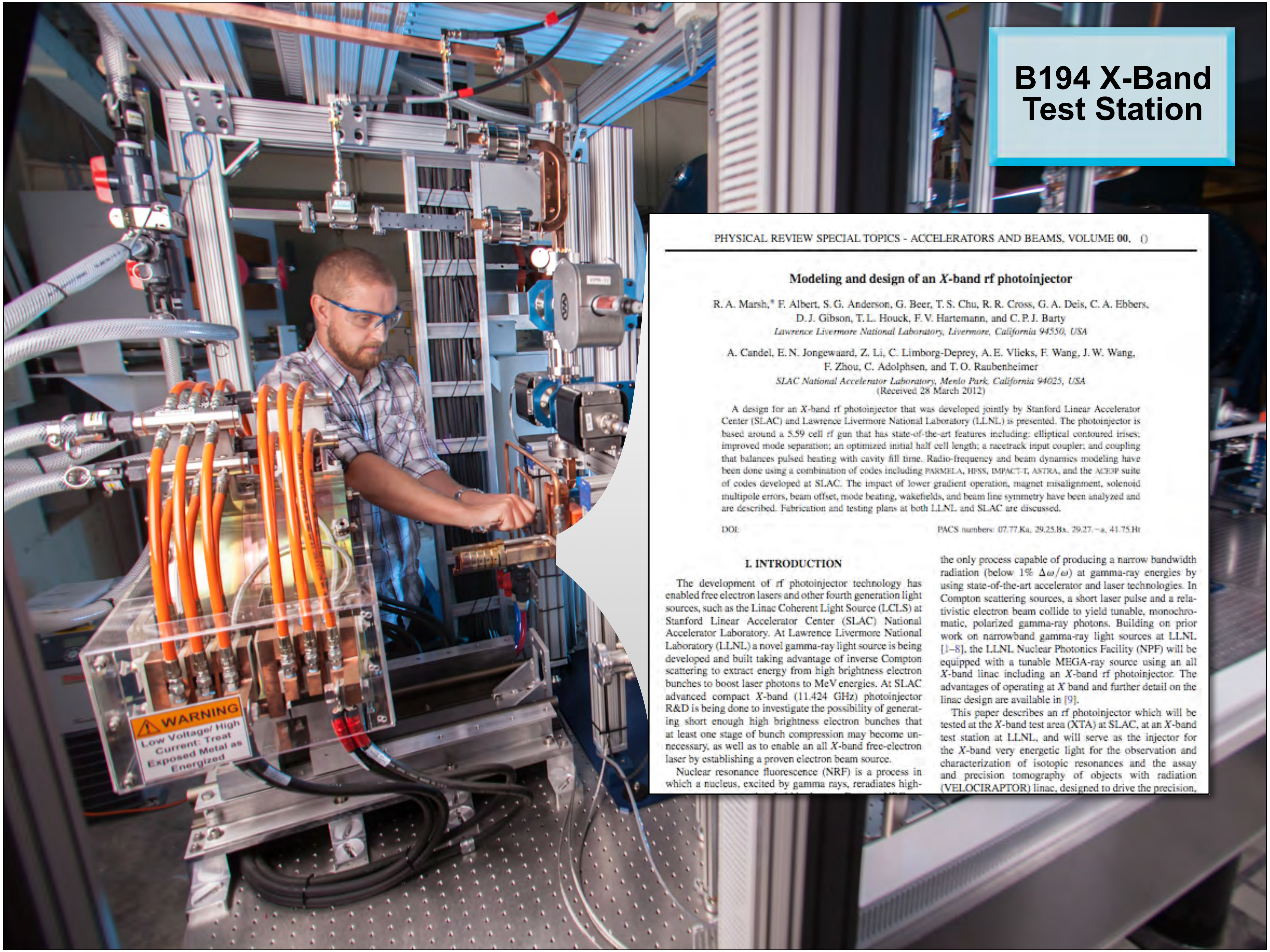
Axial Field for Elliptical Iris



Ratio of 1.04

Peak axial field improvement of >10% for the same peak surface electric field

B194 X-Band Test Station



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **00**, ()

Modeling and design of an *X*-band rf photoinjector

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(Received 28 March 2012)

A design for an *X*-band rf photoinjector that was developed jointly by Stanford Linear Accelerator Center (SLAC) and Lawrence Livermore National Laboratory (LLNL) is presented. The photoinjector is based around a 5.59 cell rf gun that has state-of-the-art features including: elliptical contoured irises; improved mode separation; an optimized initial half cell length; a racetrack input coupler; and coupling that balances pulsed heating with cavity fill time. Radio-frequency and beam dynamics modeling have been done using a combination of codes including PARMELA, HFSS, IMPACT-T, ASTRA, and the ACE3P suite of codes developed at SLAC. The impact of lower gradient operation, magnet misalignment, solenoid multipole errors, beam offset, mode beating, wakefields, and beam line symmetry have been analyzed and are described. Fabrication and testing plans at both LLNL and SLAC are discussed.

DOI:

PACS numbers: 07.77.Ka, 29.25.Bx, 29.27.−a, 41.75.Ht

I. INTRODUCTION

The development of rf photoinjector technology has enabled free electron lasers and other fourth generation light sources, such as the Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory. At Lawrence Livermore National Laboratory (LLNL) a novel gamma-ray light source is being developed and built taking advantage of inverse Compton scattering to extract energy from high brightness electron bunches to boost laser photons to MeV energies. At SLAC advanced compact *X*-band (11.424 GHz) photoinjector R&D is being done to investigate the possibility of generating short enough high brightness electron bunches that at least one stage of bunch compression may become unnecessary, as well as to enable an all *X*-band free-electron laser by establishing a proven electron beam source.

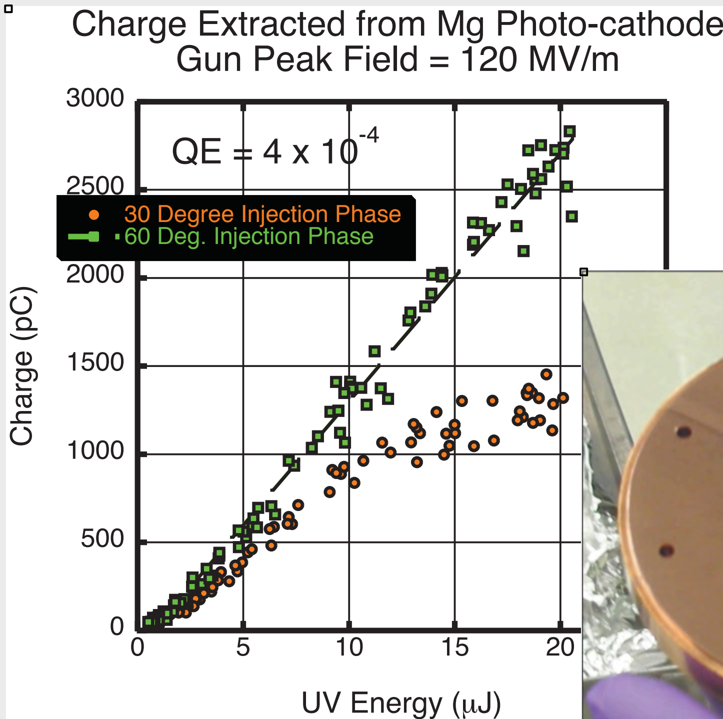
Nuclear resonance fluorescence (NRF) is a process in which a nucleus, excited by gamma rays, reradiates high-

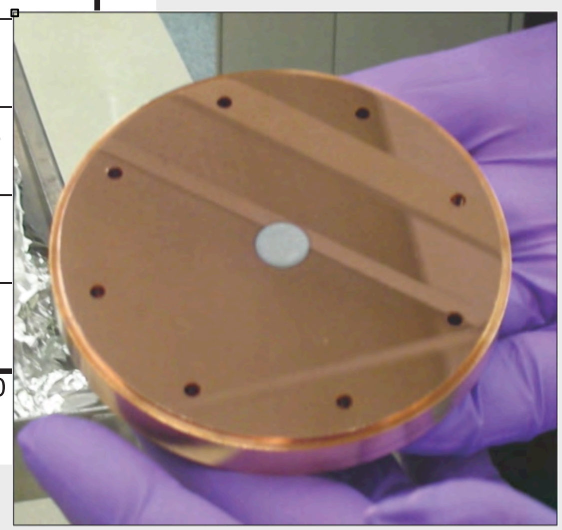
the only process capable of producing a narrow bandwidth radiation (below 1% $\Delta\omega/\omega$) at gamma-ray energies by using state-of-the-art accelerator and laser technologies. In Compton scattering sources, a short laser pulse and a relativistic electron beam collide to yield tunable, monochromatic, polarized gamma-ray photons. Building on prior work on narrowband gamma-ray light sources at LLNL [1–8], the LLNL Nuclear Photonics Facility (NPF) will be equipped with a tunable MEGA-ray source using an all *X*-band linac including an *X*-band rf photoinjector. The advantages of operating at *X* band and further detail on the linac design are available in [9].

This paper describes an rf photoinjector which will be tested at the *X*-band test area (XTA) at SLAC, at an *X*-band test station at LLNL, and will serve as the injector for the *X*-band very energetic light for the observation and characterization of isotopic resonances and the assay and precision tomography of objects with radiation (VELOCIRAPTOR) linac, designed to drive the precision,

High efficiency cathode materials reduce the requirements for the photo-gun drive laser

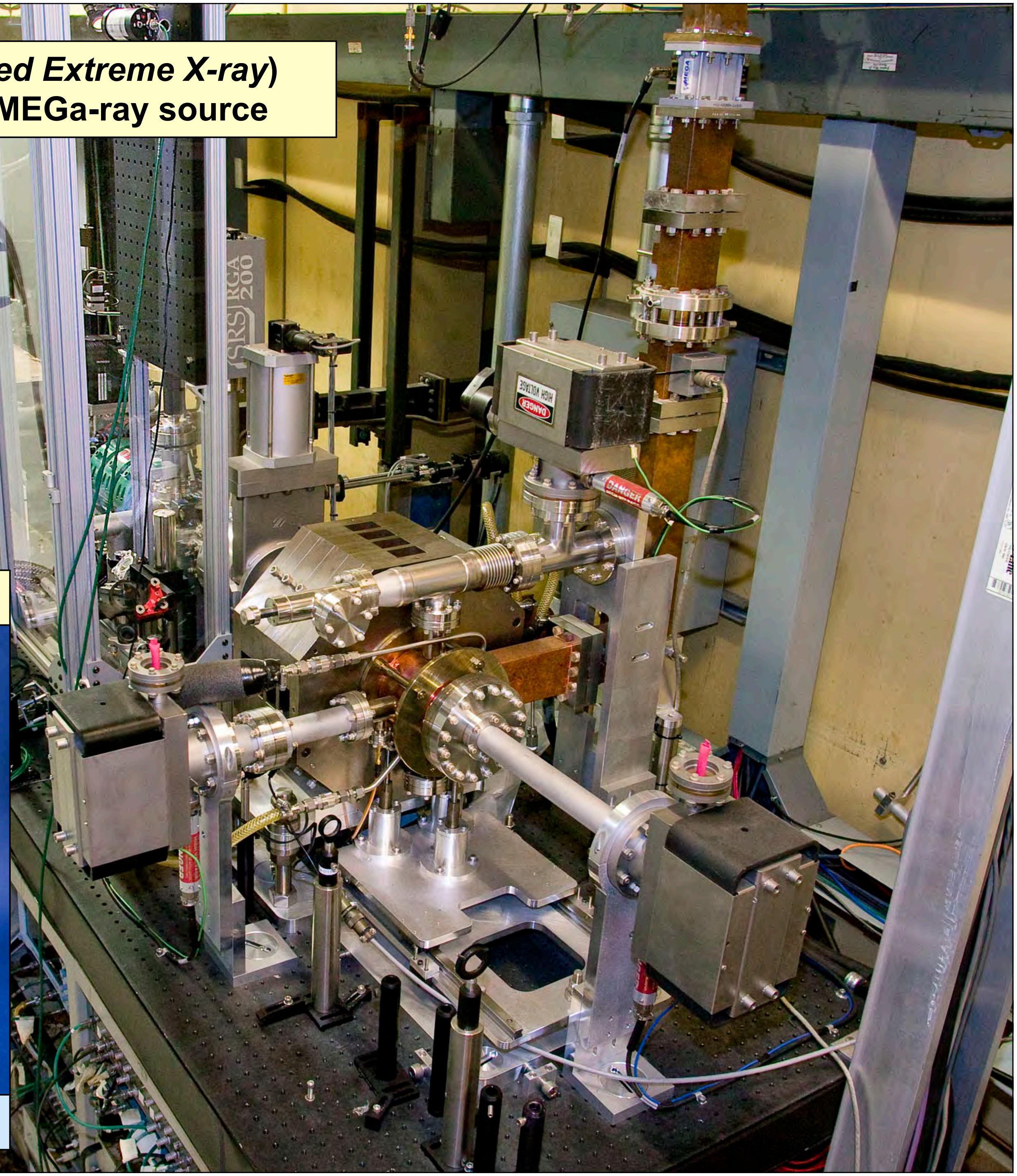
Mg QE Demonstration



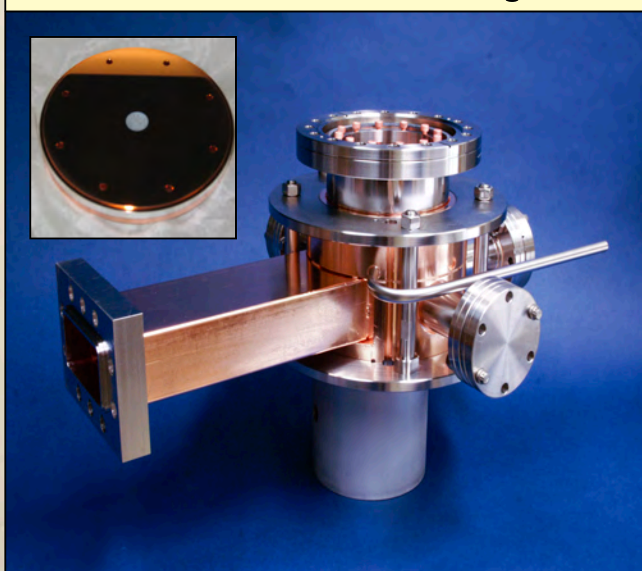


10^{-4} QE demonstrated in S-Band gun

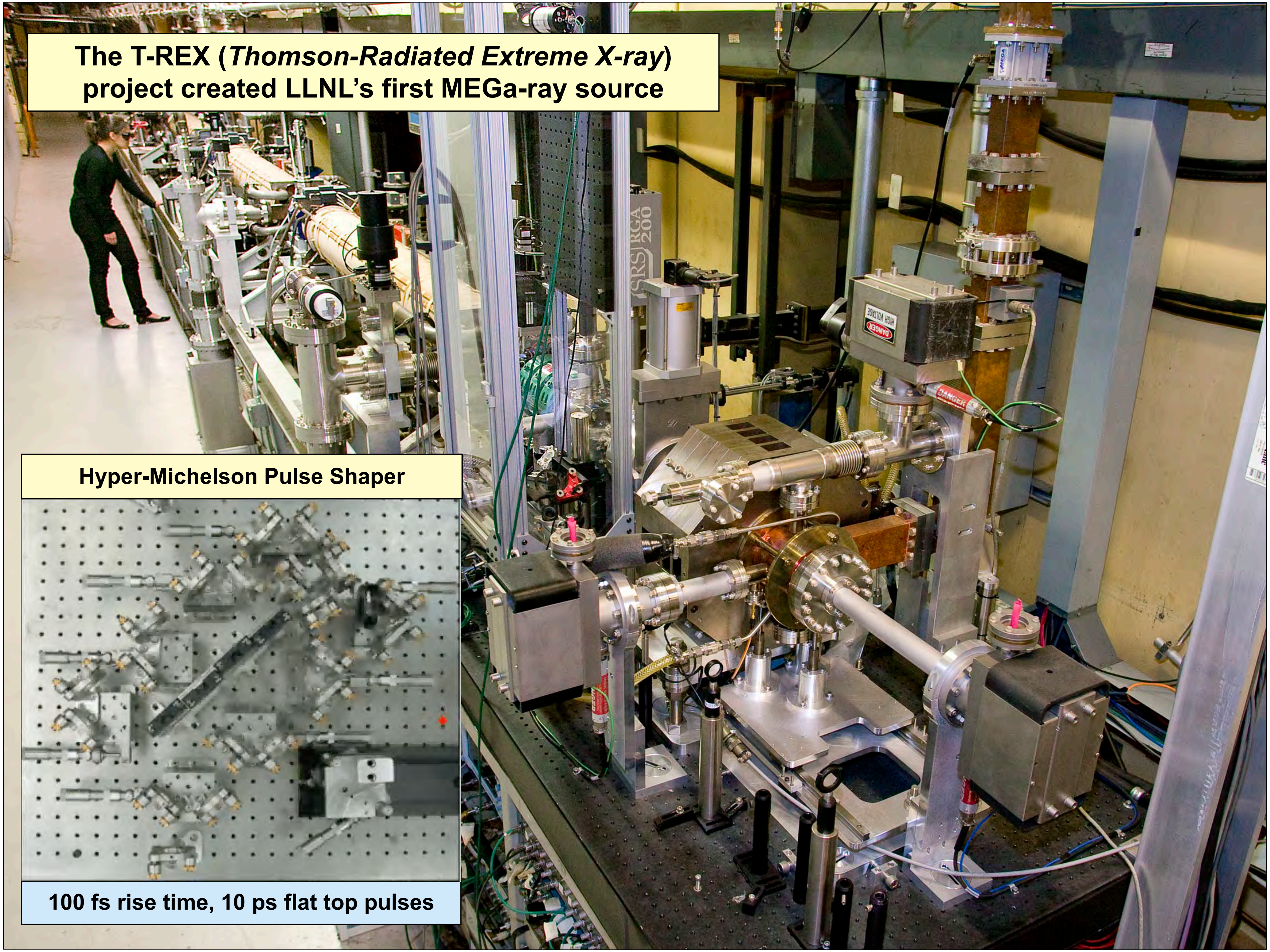
The T-REX (*Thomson-Radiated Extreme X-ray*) project created LLNL's first MEGa-ray source



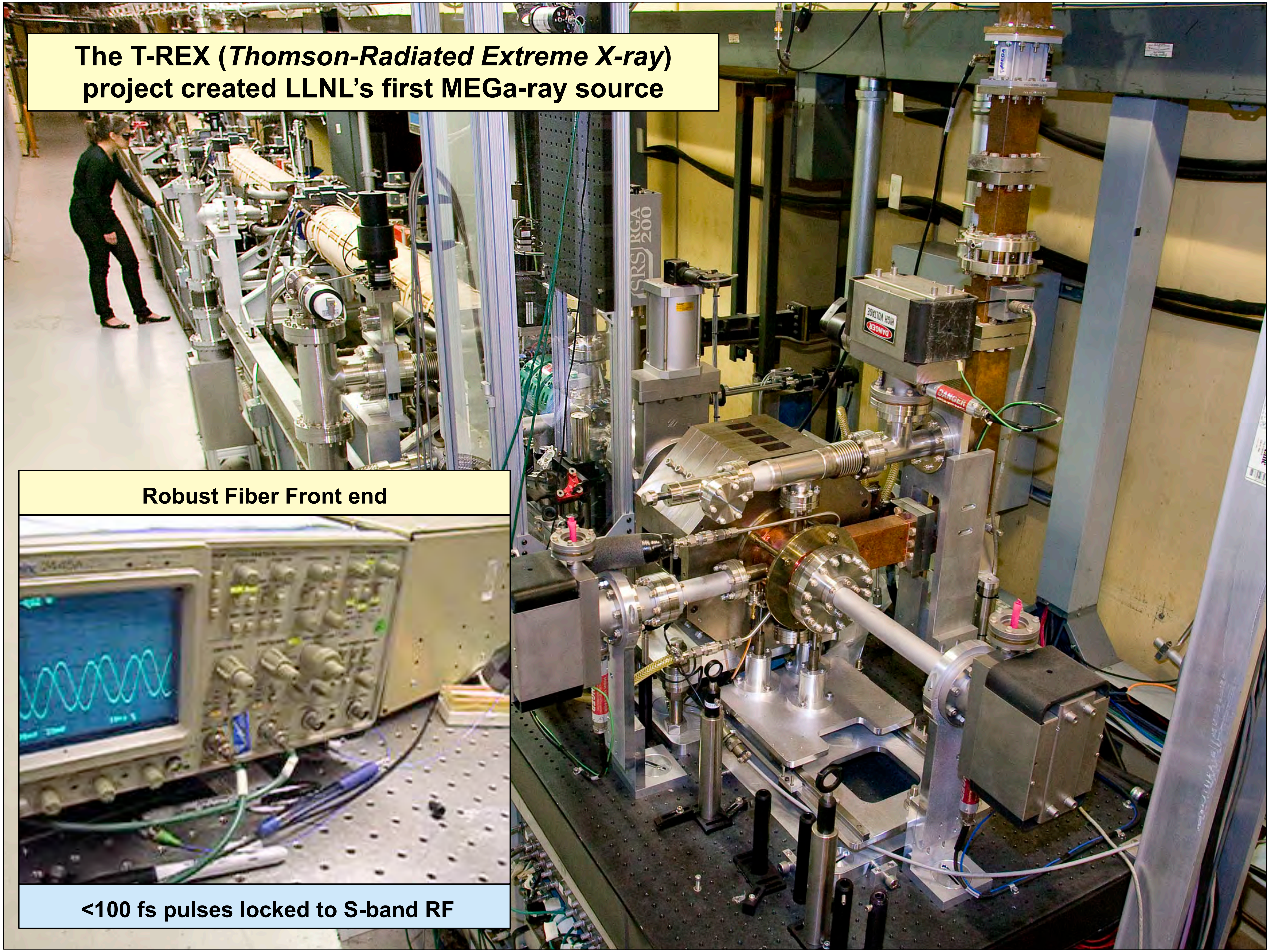
Ultra-low Emittance Photogun



Fully Symmetrized w/ Mg Cathode


The T-REX (*Thomson-Radiated Extreme X-ray*) project created LLNL's first MEGa-ray source
Hyper-Michelson Pulse Shaper
100 fs rise time, 10 ps flat top pulses

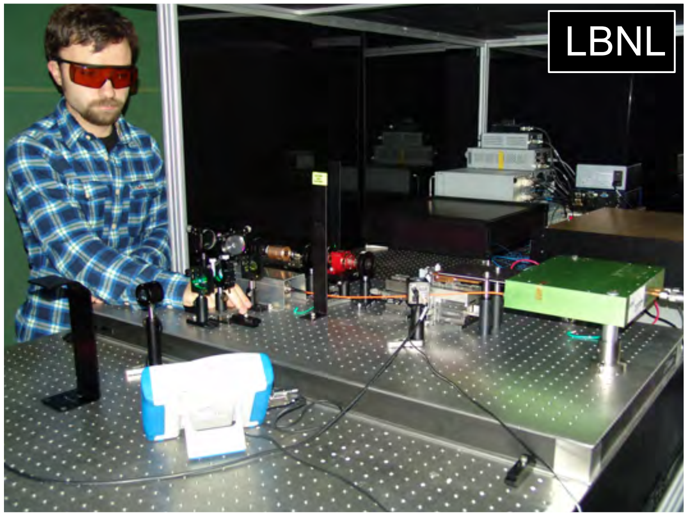
The T-REX (*Thomson-Radiated Extreme X-ray*) project created LLNL's first MEGa-ray source

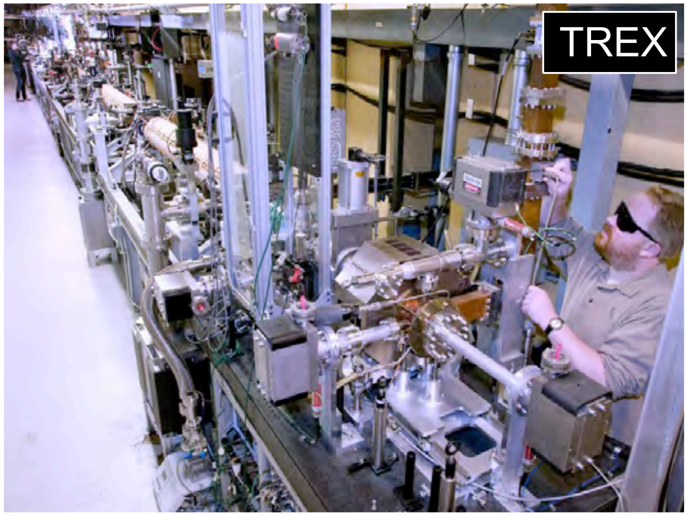


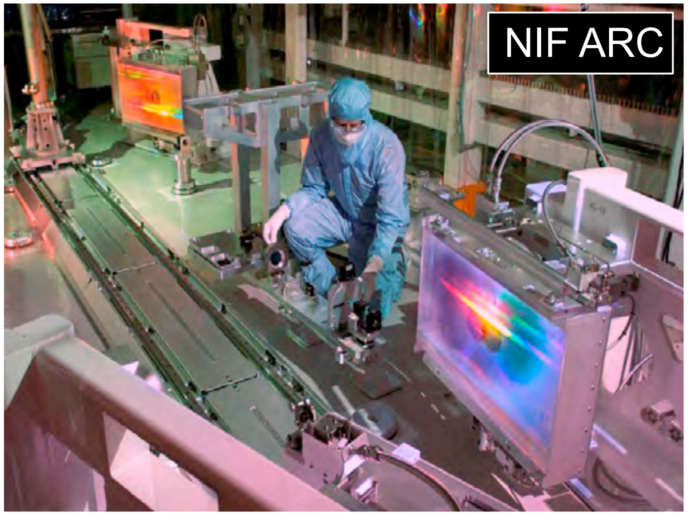
Robust Fiber Front end

<100 fs pulses locked to S-band RF

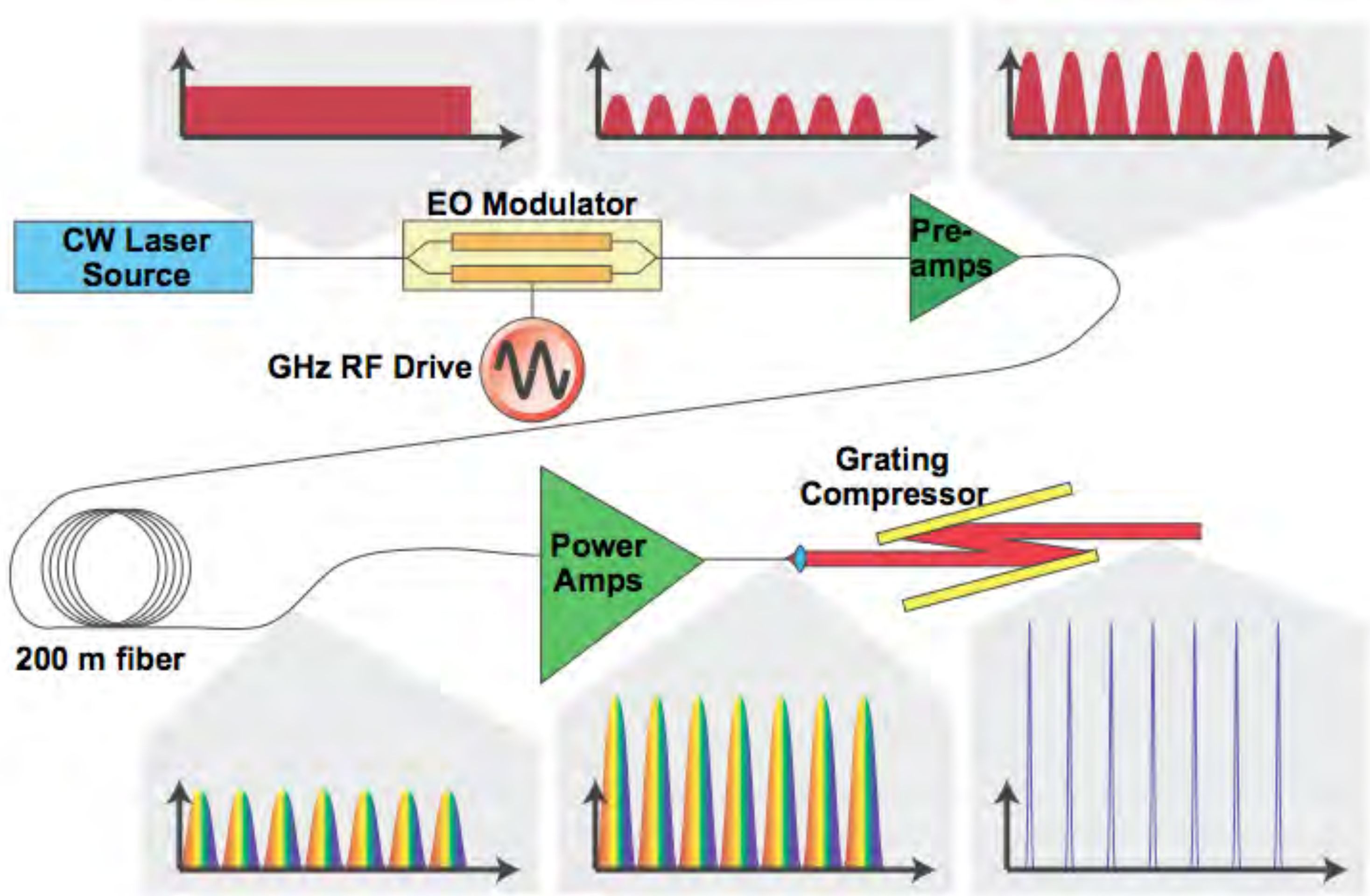
Fiber lasers at LLNL





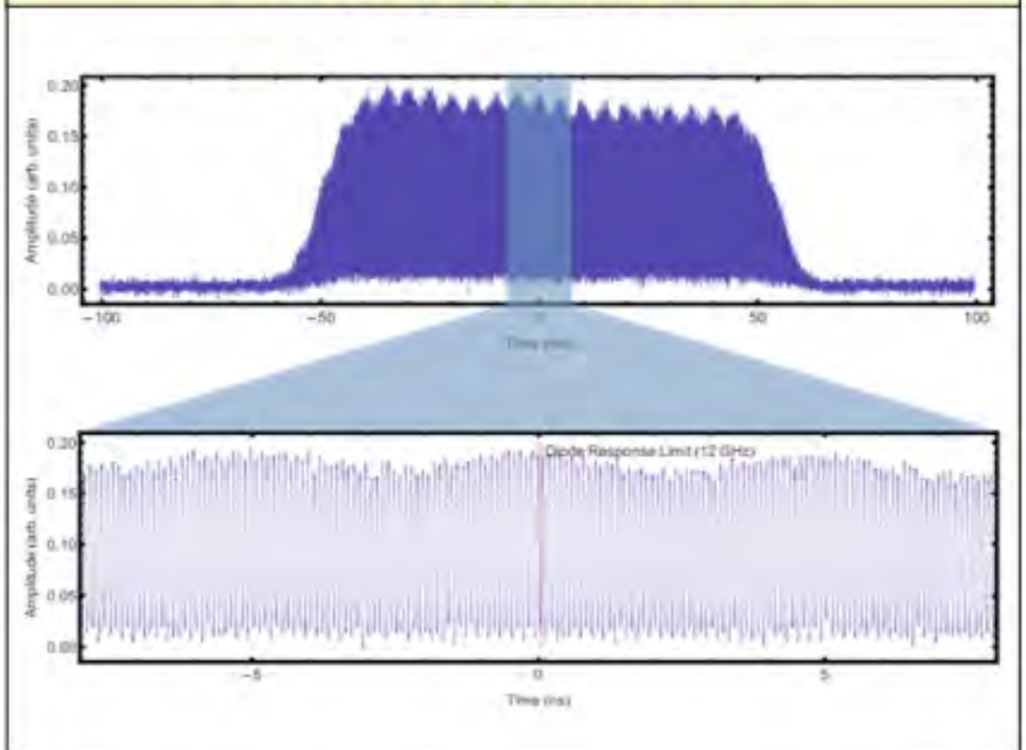


"CW" method for generation of 11.424 GHz, synchronized train of picosecond IR pulses

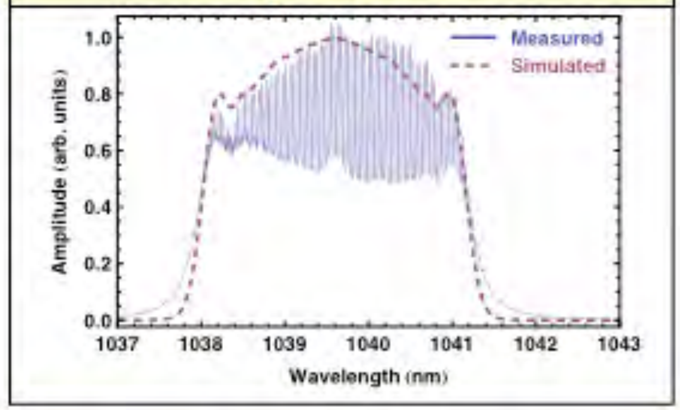


“CW” method for generation of 11.424 GHz, synchronized train of picosecond IR pulses

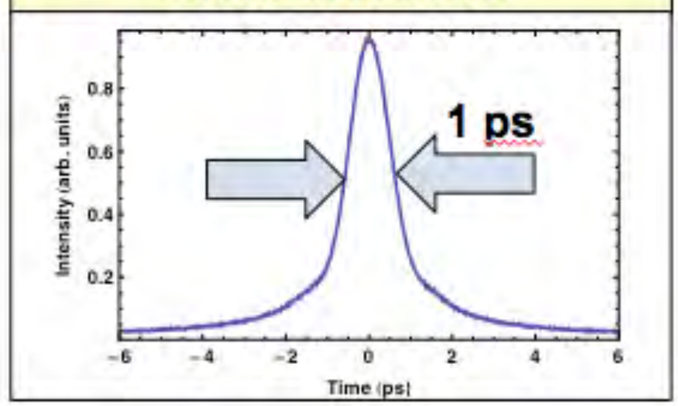
Burst Temporal Profile



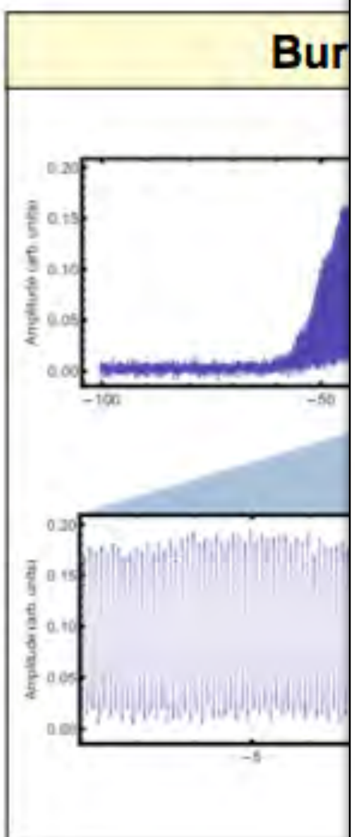
Spectrum



Autocorrelation



“CW” method for generation of 11.424 GHz, synchronized train of picosecond IR pulses



Widely tunable 11 GHz femtosecond fiber laser based on a non-modelocked source

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An 11 GHz fiber laser built on a modulated CW platform is described and characterized. This compact, vibration-insensitive, fiber based system can be operated at wavelengths compatible with high energy fiber technology, is driven by an RF signal directly, and is tunable over a wide range of drive frequencies. The demonstration system when operated at 1040 nm is capable of 50 ns bursts of 575 micro-pulses produced at a macro-pulse rate of 83 kHz where the macro-pulse and micro-pulse energies are 1.8 μJ and 3.2 nJ respectively. Its micro-pulses are compressed to a duration of 850 fs.

OCIS Codes: 060.3510, 140.7090

Very-short-pulse laser sources (in the range of picoseconds to femtoseconds) with high repetition rates (100 MHz to tens of GHz) are needed to drive short-wavelength high-energy photon sources via higher-order nonlinear optical parametric interactions, and as photo-cathode illuminators to create photo-electrons in high frequency particle accelerators. Other applications of these ultrafast pulse laser systems include materials processing, 3-D lithography, high-data-rate laser communication, and remote sensing systems. The system architecture described here is wavelength compatible with high energy fiber technology, is driven directly by an RF source (and thus sidesteps synchronization issues), and allows for amplification to materials-processing pulse energies. Moreover, the ability to modify electronically the temporal pulse shape, in amplitude and phase [1, 2], offers the possibility of controlling various complex photochemical processes and quantum control of interactions on molecular time scales.

We generate a laser pulse train by modulating a continuous-wave (cw) laser with an RF source. Several groups [2, 3] have converted cw lasers to sub-ps, high frequency pulse trains; however, these groups have relied on "time-lens" techniques [4] to generate ps-level bandwidths, then used soliton compression at 1550 nm in specially optimized fibers to generate further bandwidth while simultaneously compressing the pulse. At the 1030-1070 nm wavelengths where we wish to work, the soliton compression scheme is not feasible because the dispersion in standard fibers has the opposite sign from dispersion at 1550 nm. In the demonstration of this cw-modulation concept reported here, we rely on self-phase modulation (SPM) [5] to generate 3.2 nm of bandwidth and compress the pulse with a grating-pair compressor. To reduce allow high pulse energies at modest average laser power, we

the groups (macro-pulses) occur at mult-kHz rates while the individual pulses (micro-pulses) are at multi-GHz rates. Alternatively, the micro-pulses might be directly amplified to modest energies for a clock-distribution scheme, or driven to micro-joule energies to create tens of kilowatts of power for machining or supercontinuum sources.

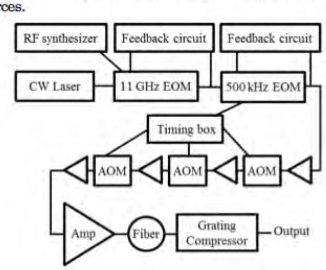
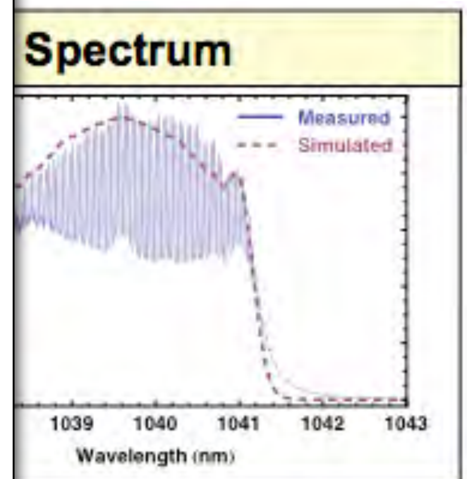
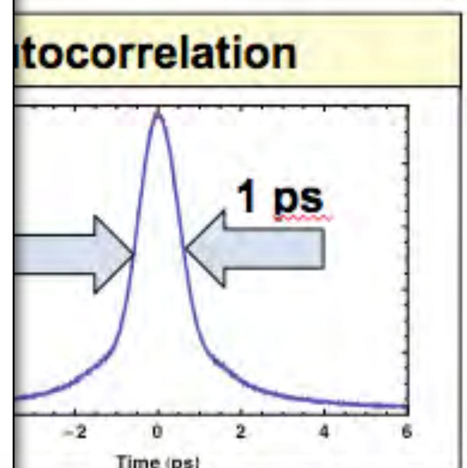


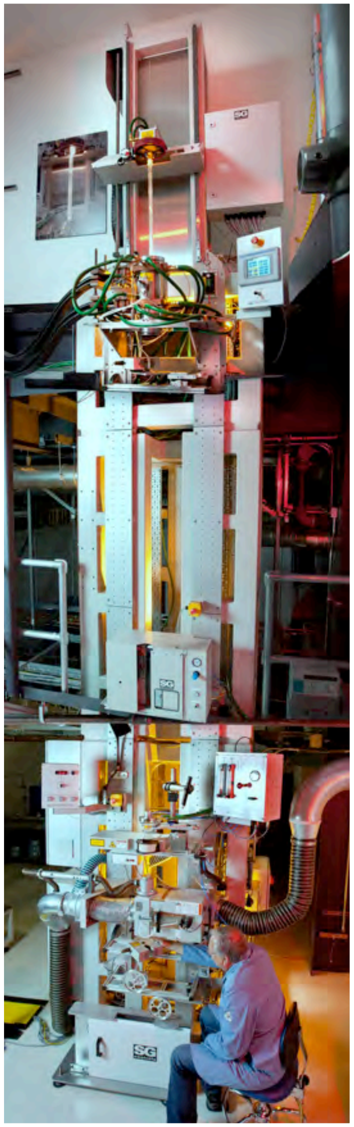
Figure 1 Schematic diagram of the experiment.

The architecture, shown in Figure 1, begins with a cw laser: a New Focus Velocity laser set to provide a 1040 nm beam. The beam is sent through an EOSPACE-brand, Z-cut, 20 GHz, dual drive Mach-Zehnder electro-optic modulator (EOM) monitored by a control circuit (YY Labs, Inc.) to keep the modulator null-biased – that is, biased to block light when the RF drive is off.. This modulator is driven with 20.1 dBm of 5.7 GHz RF power. Because of the null bias, the RF creates an 11.4 GHz laser pulse train with 44 ps pulse length and no cw component as shown in Figure 2; the latter prevents stimulated Brillouin scattering from damaging subsequent fiber amplifiers. A second EOM temporally slices macro-pulses at a 500 kHz rate with 50 ns

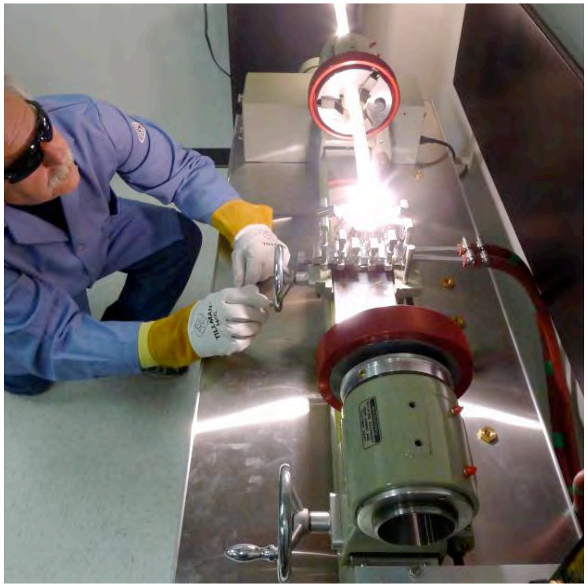




LLNL fiber facilities

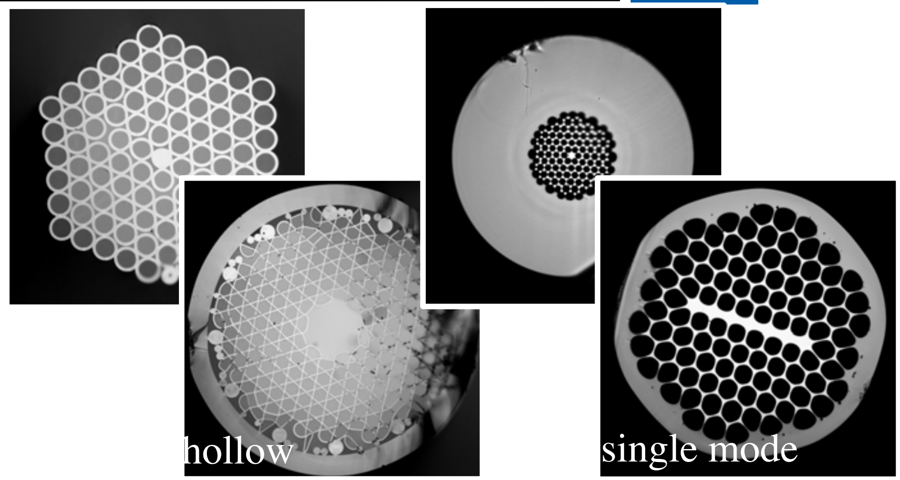


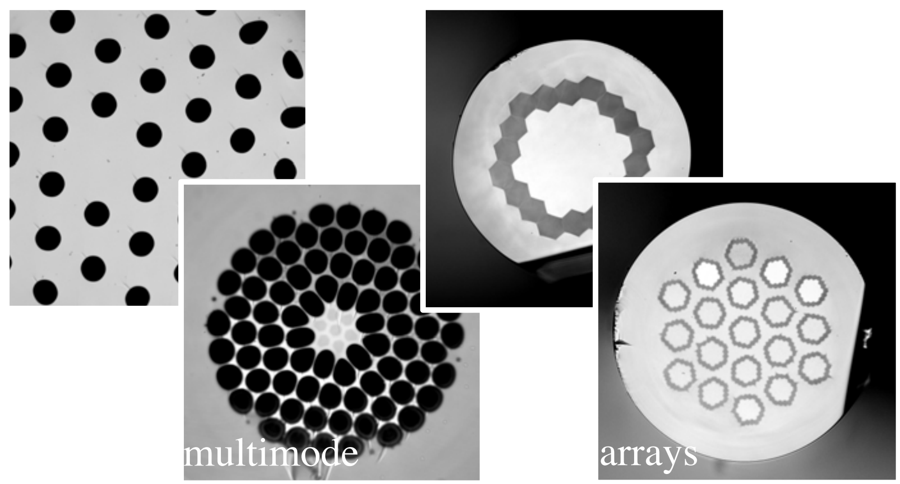
- Fiber fabrication
  - 8.2m draw tower
  - Preform assembly fixtures
  - Glass working lathe



Recent work

- Discerned laser limits[1]
- Fabricated ribbon fiber[2]
- Launched high-order modes[3]
- Built, tested lasers[4]
- Designed new type of fiber[5,6,7]

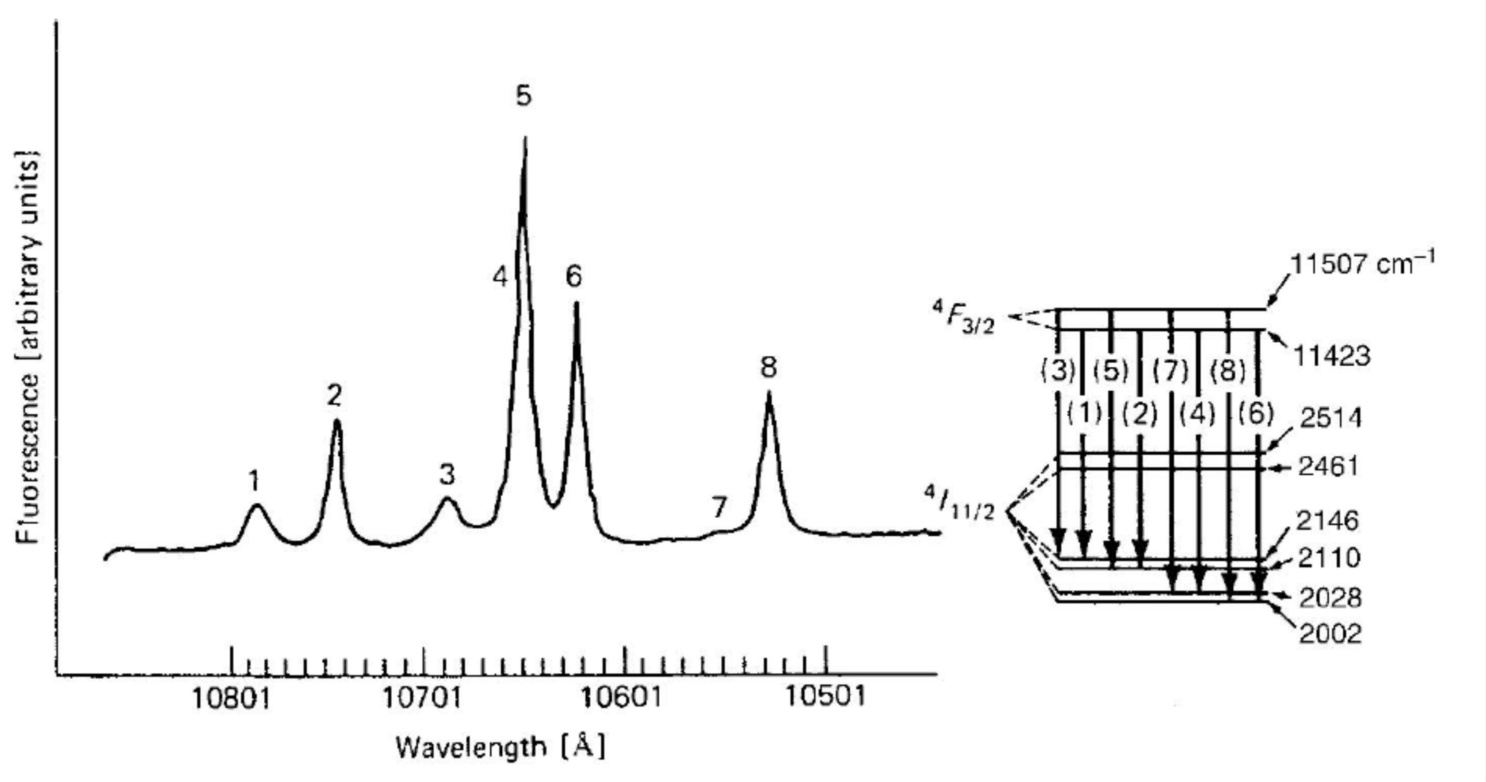




1. J. Dawson et al, Opt. Exp. 16 13240-13266 (2008).
2. D. Drachenberg et al, Opt. Exp. 21 11257-11269 (2013).
3. A. Sridharan et al, Opt. Exp. 20 28792-28800 (2012).
4. D. Drachenberg et al, submitted to Opt. Express (2013).
5. M. Messerly et al, Opt. Exp. 21 12683-12698 (2013).
6. M. Messerly et al, Optics Letters 38 3329-3332 (2013).
7. P. Pax et al, submitted to Optics Letters (2013).

Nd:YAG could be ideal for a drive laser

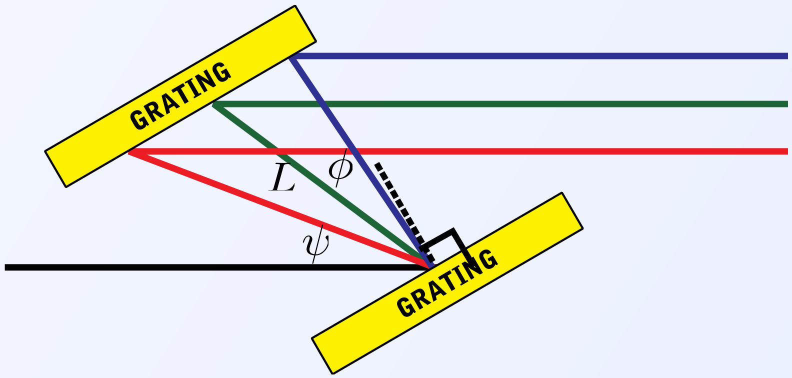
- Routinely used to produce few-ns long multi-Joule laser pulses
- Sufficient bandwidth for ps pulses: 120 GHz (~0.5 nm)
- Requires stretching < 1 nm to a few ns



Koechner and Bass, *Solid-State Lasers*, Springer-Verlag, New York (2003)

CPA with narrow-band pulses requires very large dispersion

Standard Compressor



$$\frac{d\tau}{d\lambda} = \frac{2L\lambda}{cd^2\cos^2\phi} = 6000\ \frac{\text{ps}}{\text{nm}}$$

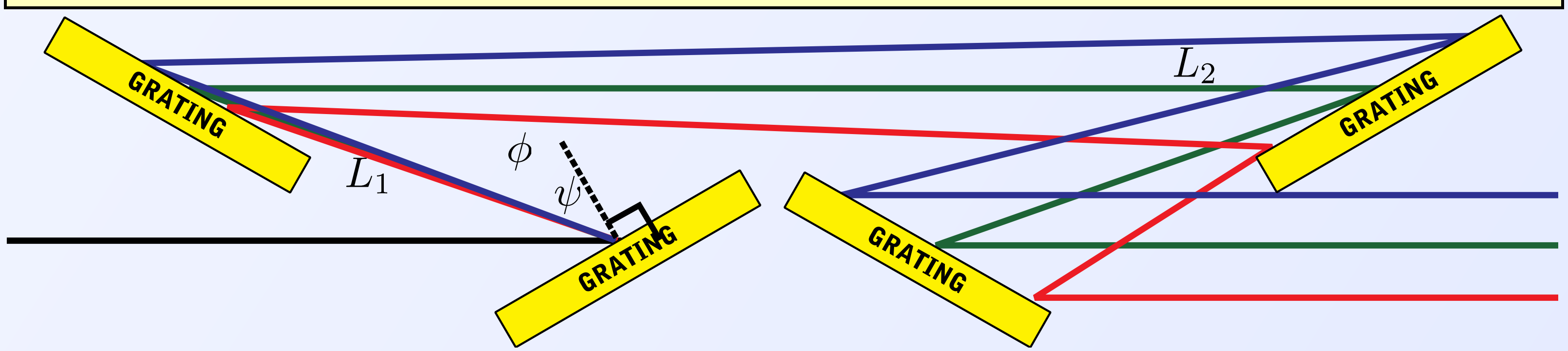
$$\frac{1}{d} = 1740\ \frac{\text{lines}}{\text{mm}}$$

$$\psi = 65^\circ$$

$$\lambda = 1064\ \text{nm}$$

$$L \approx 30\ \text{m}$$

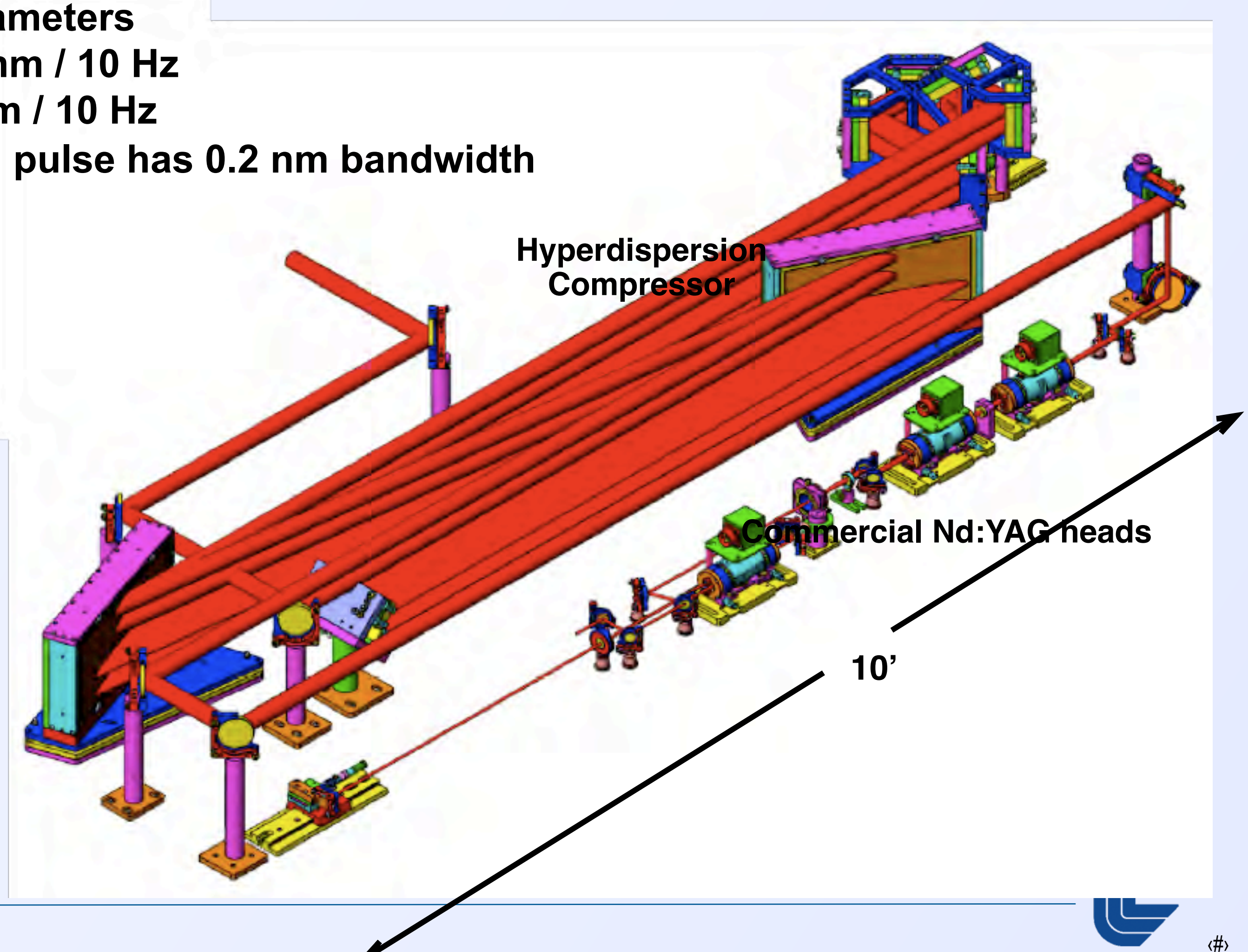
Hyperdispersion Compressor



T-REX Interaction Laser demonstrated Hyperdispersion Stretcher/Compressor

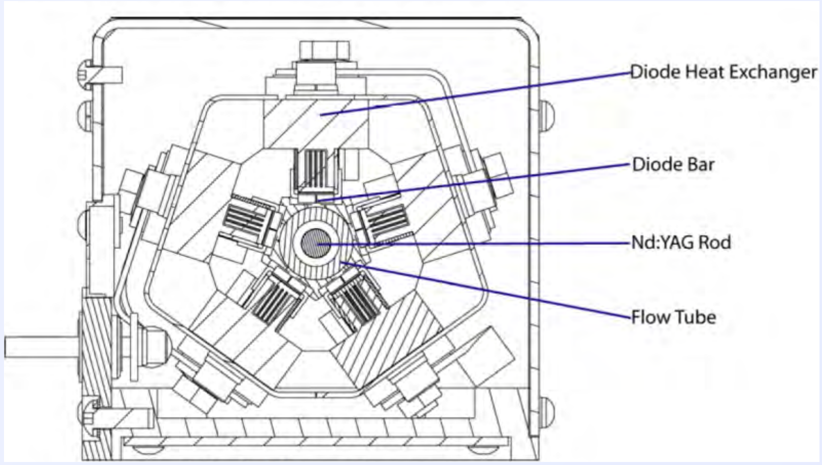
- Commercial flashlamp-pumped heads
- Seeded with fiber system similar to PDL front end
- Laser System Parameters
  - 0.8 J / 1064 nm / 10 Hz
  - 0.3 J / 532 nm / 10 Hz
- Amplified 1064 nm pulse has 0.2 nm bandwidth

Three Continuum Amplifier Heads

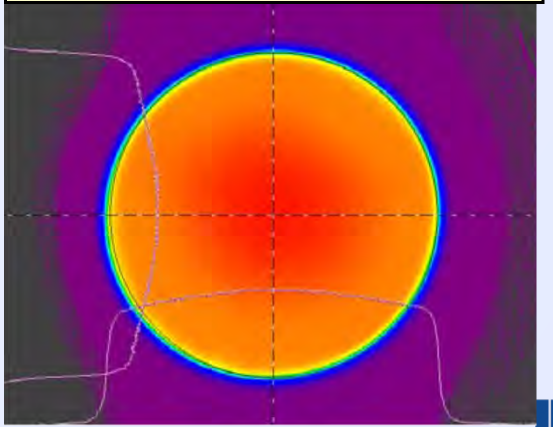


Commercial diode pumped laser heads are now capable of several 100 W cw operation

Diode pumped amplifier head w/ 1 cm diameter x 14.6 cm long Nd:YAG rod



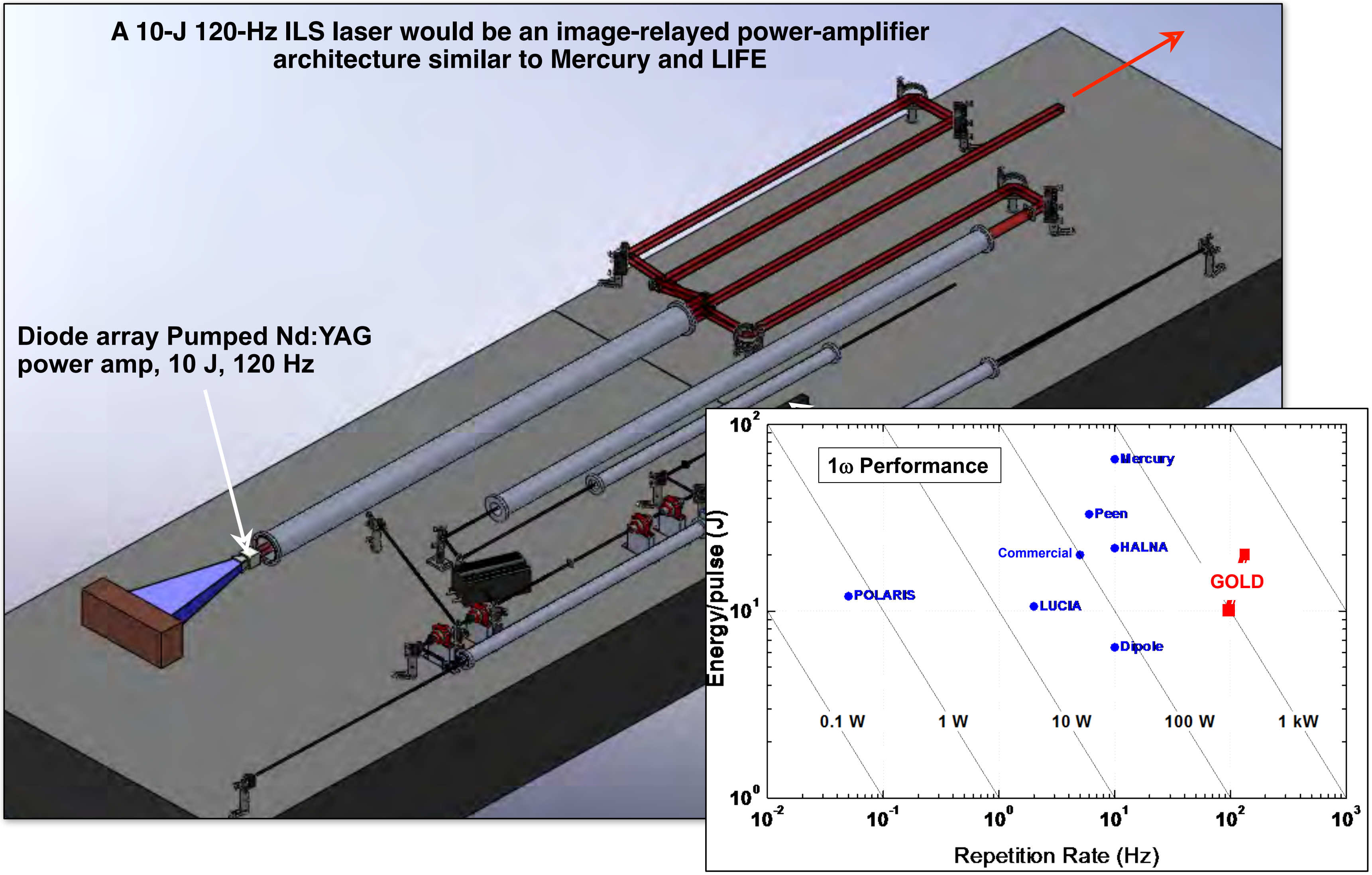
Rod Fluorescence showing gain uniformity

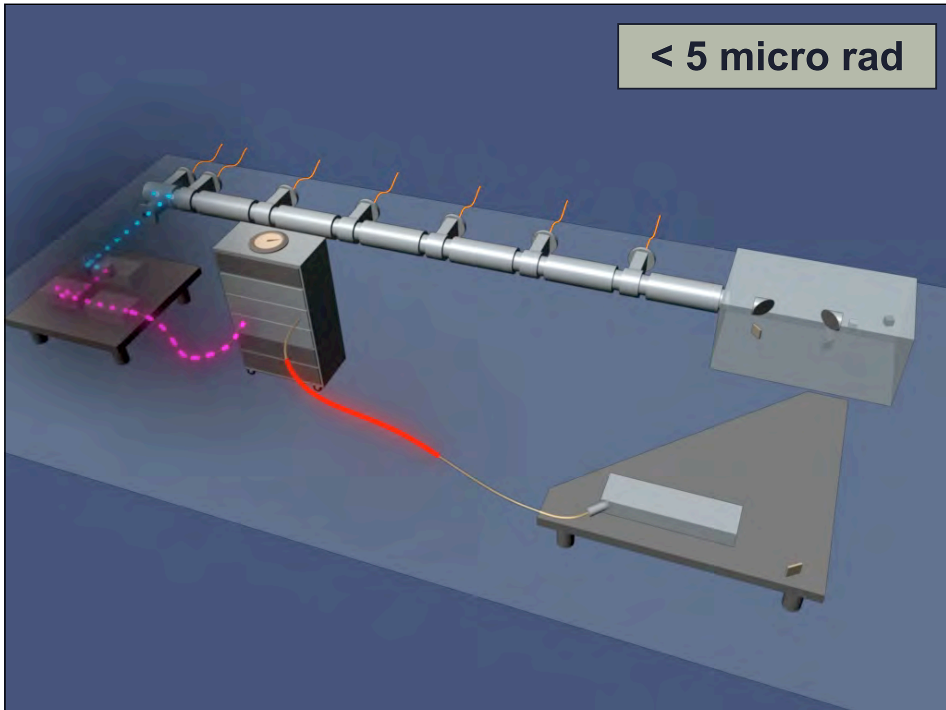


In pulsed mode these heads should be capable of joule level operation

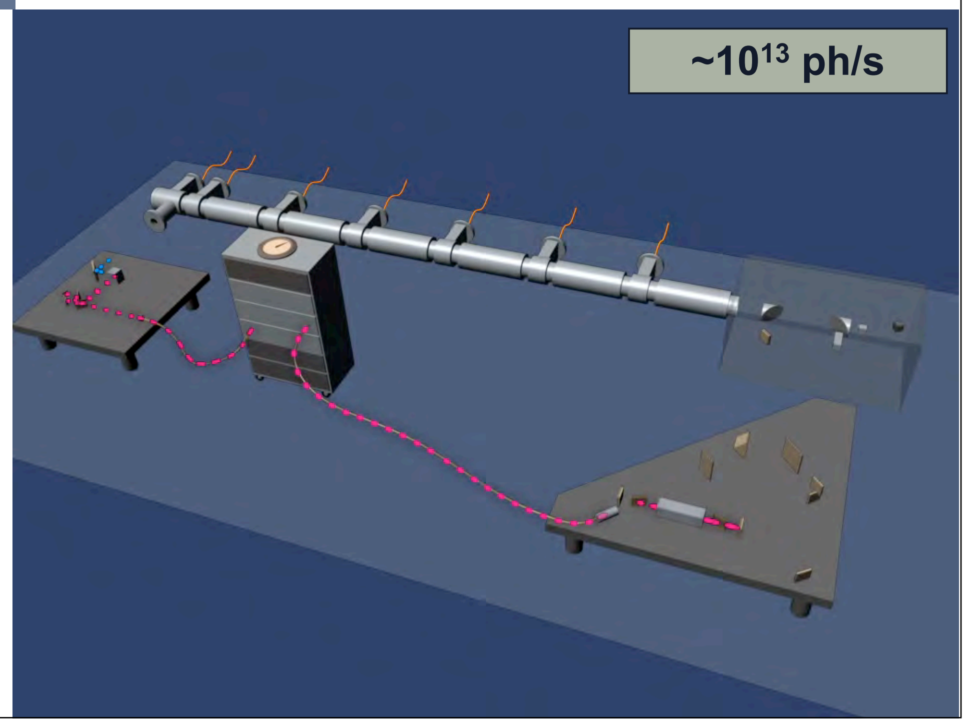
Our custom, diode-pumped solid state laser architecture is capable of > 1J per pulse @ 120 Hz

LLNL is currently constructing a 120 Hz, 10 J, Nd:YAG laser for fusion optic lifetime studies





100% overlap
"Unity"
Conventional mirrors
NO interferometry required
Any color interaction
Intrinsically synchronized



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National Laboratory