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Nuclear Photo-Science and Applications with T-Rex Sources

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LINAC 2006
Knoxville, TN, United States
August 24, 2006 through August 25, 2006

Disclaimer

Nuclear Photo-Science & Applications with T-REX Sources

- Motivation
- Nuclear Resonance Fluorescence
- Compton scattering
- Electron beam technology
- Laser technology
- LLNL’s T-REX source
- Nuclear applications

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Team

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Motivation: Mission-Driven R&D

T-REX R&D is mission-driven:

Homeland Security top priority list includes the development of novel imaging technologies for fast, accurate, & reliable cargo container screening

Inverse density radiography (DNT)

Flash MeV radiography (NIF)

Motivation: The Cargo Container Problem

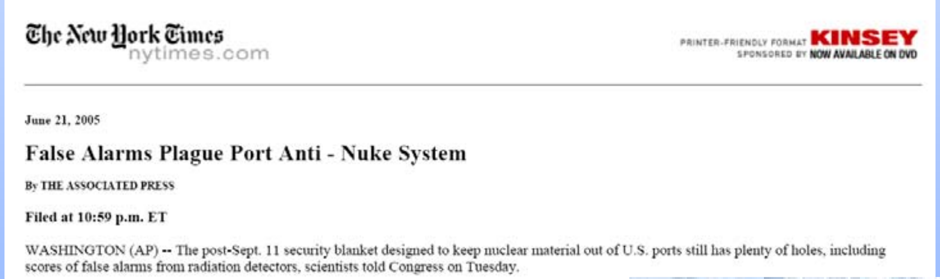
Worldwide sea-faring cargo container traffic: 48,000,000/year

3 containers shipped/received every 2 seconds!

5 kg of concealed SNM = a very bad day!

Current inspection techniques are inadequate:

- Weight/manifest
- Radiation Counters
- Radiography



The New York Times
nytimes.com

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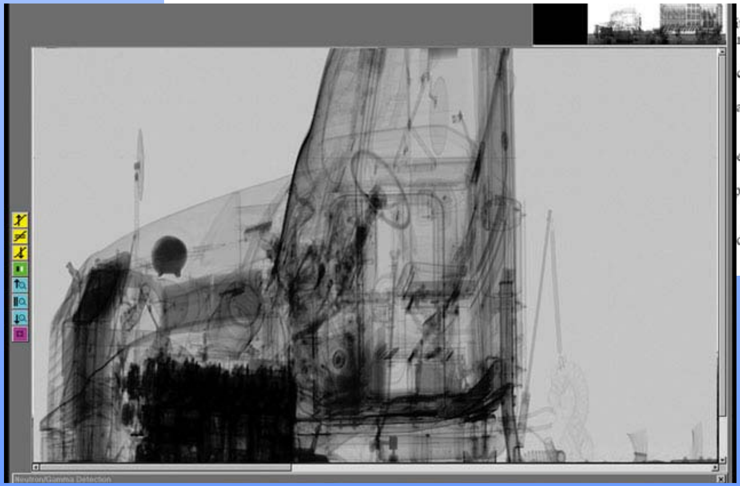
June 21, 2005

False Alarms Plague Port Anti - Nuke System

By THE ASSOCIATED PRESS

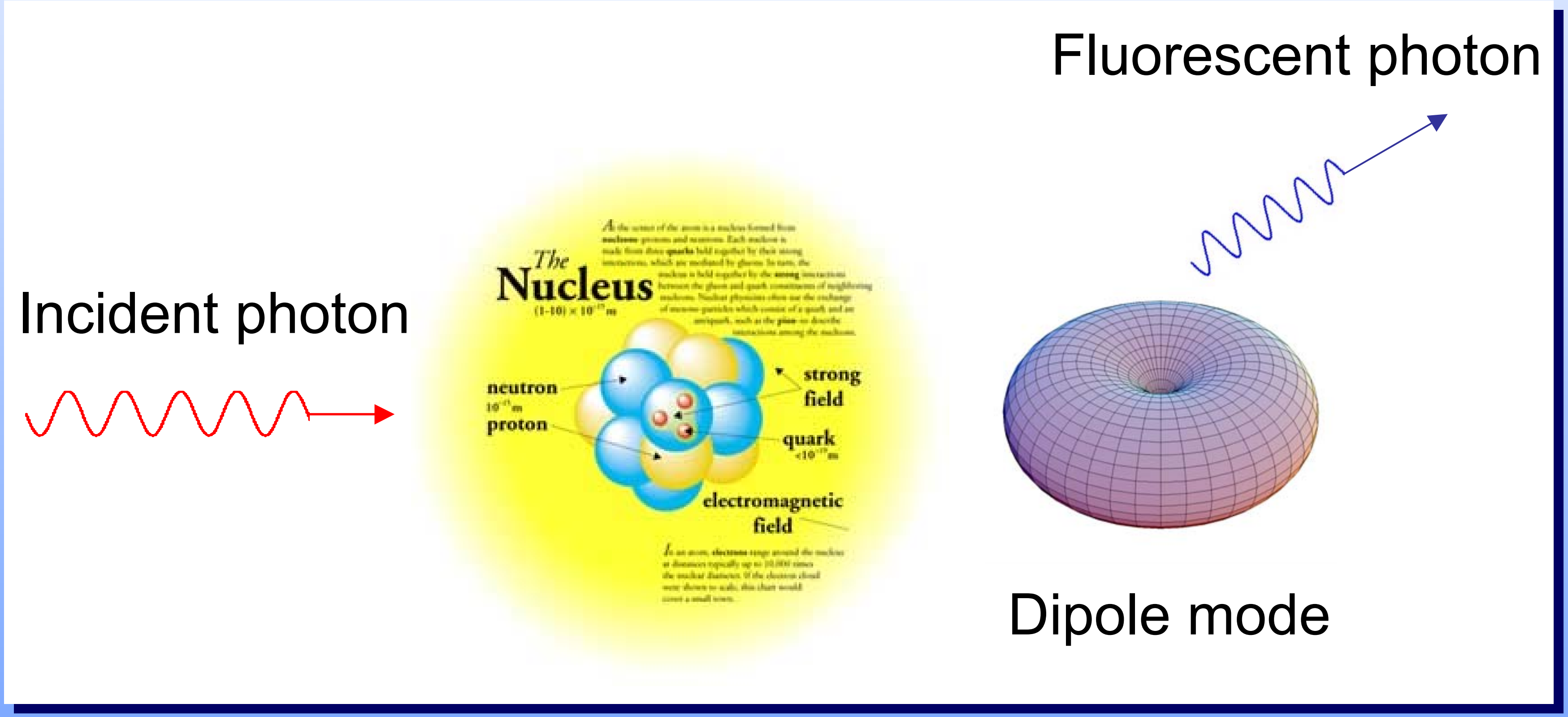
Filed at 10:59 p.m. ET

WASHINGTON (AP) -- The post-Sept. 11 security blanket designed to keep nuclear material out of U.S. ports still has plenty of holes, including scores of false alarms from radiation detectors, scientists told Congress on Tuesday.



NRF in Theory

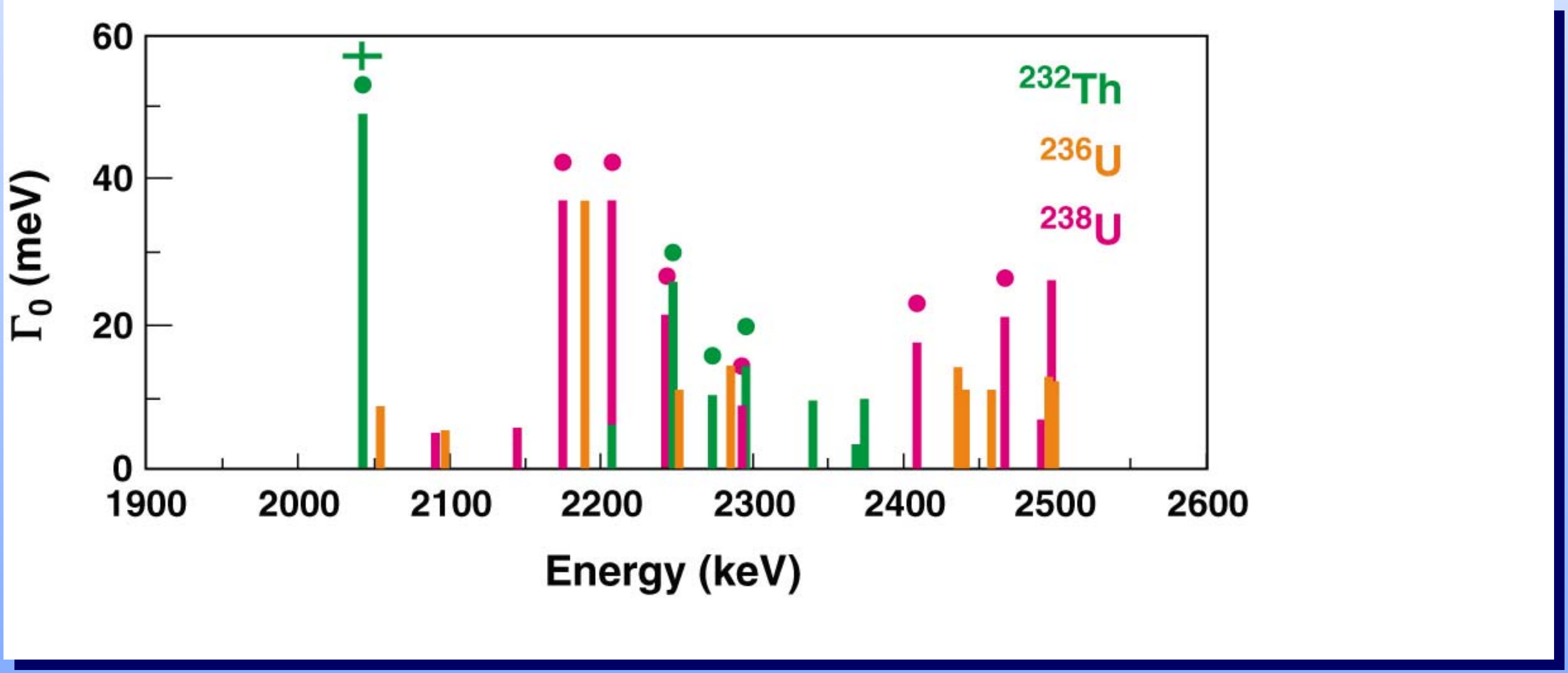
Nuclear Resonance Fluorescence



NRF Lines

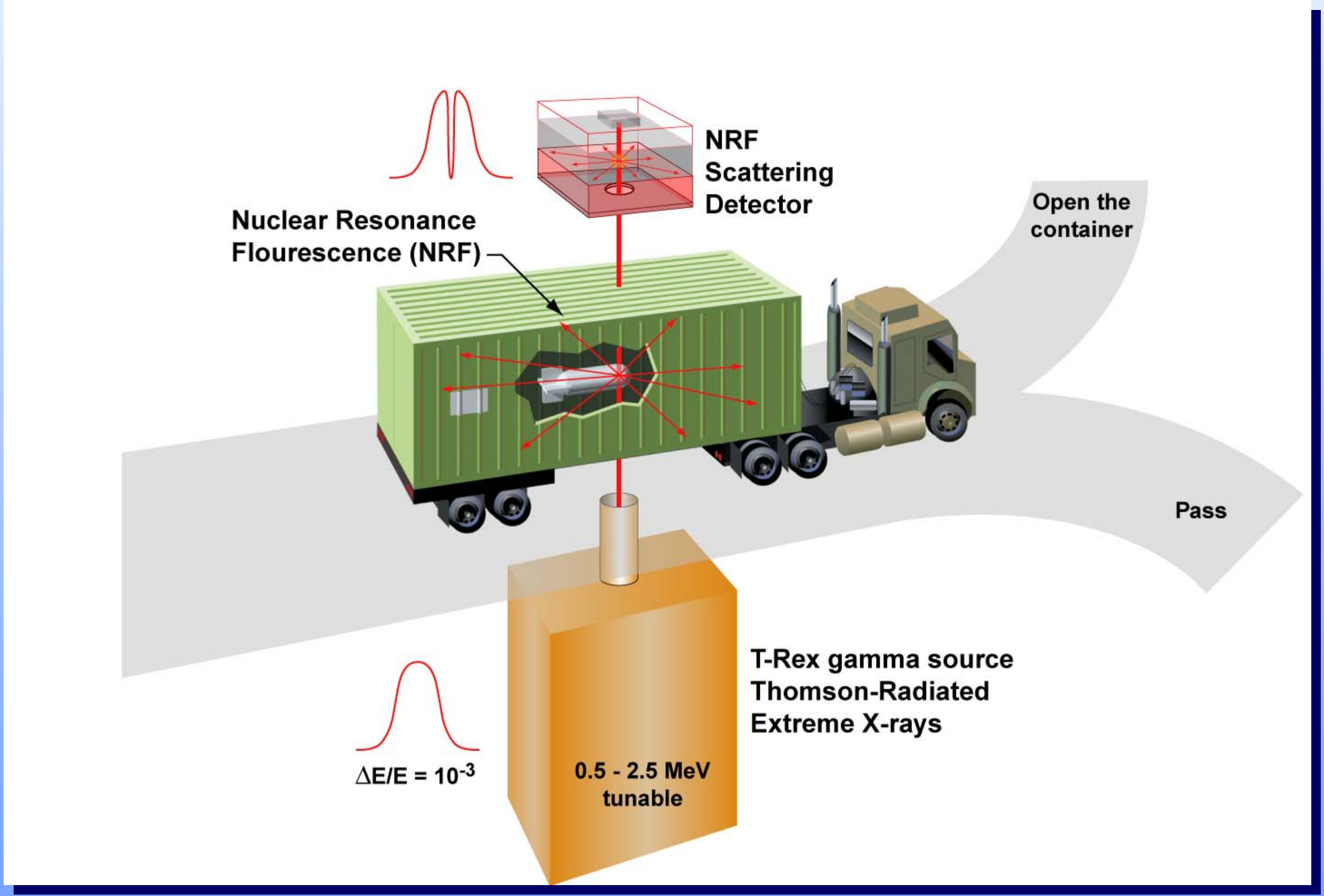
Numerous lines in high-*Z* elements, at penetrating wavelengths

Doppler-broadened to ~ 1 eV



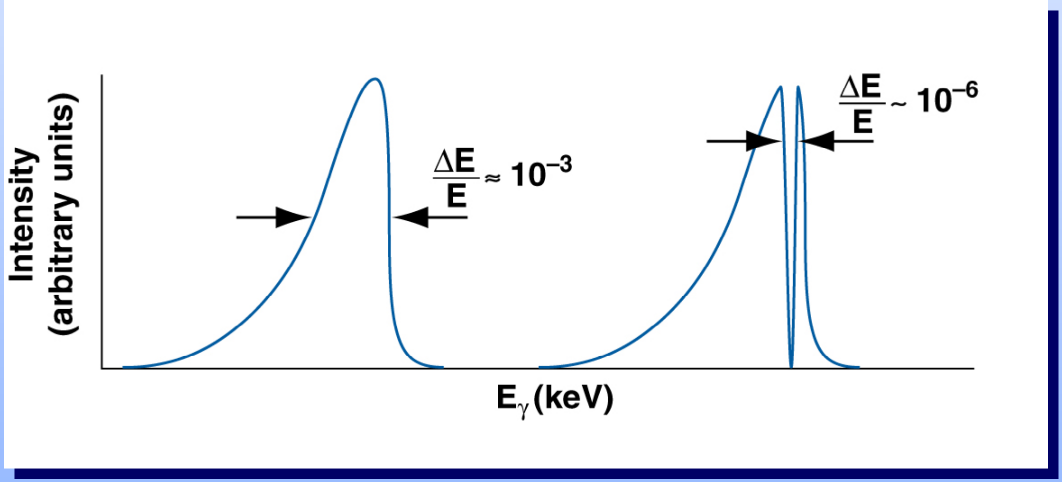
Strong MeV line in ^{235}U

NRF in Practice: FINDER



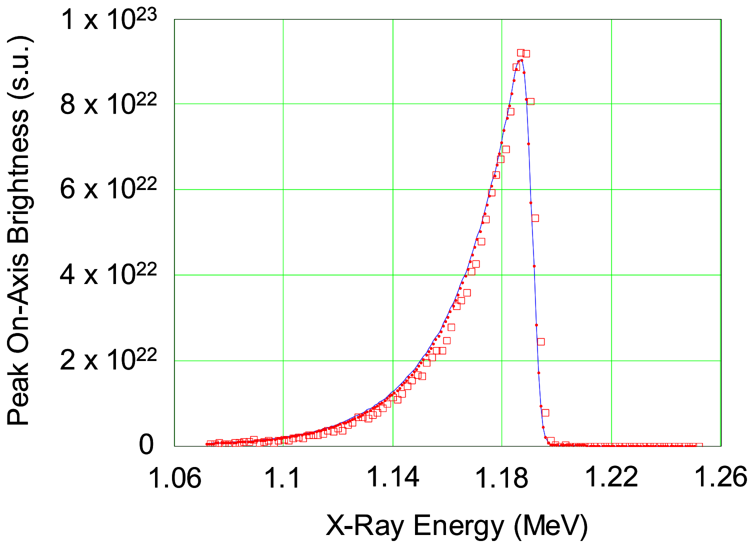
NRF Spectrum

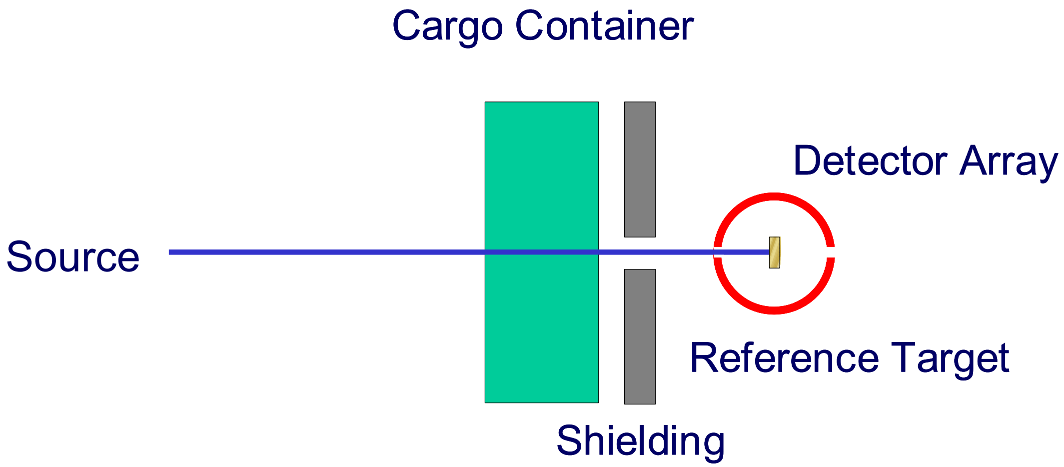
FINDER NRF signature would be unmistakable…

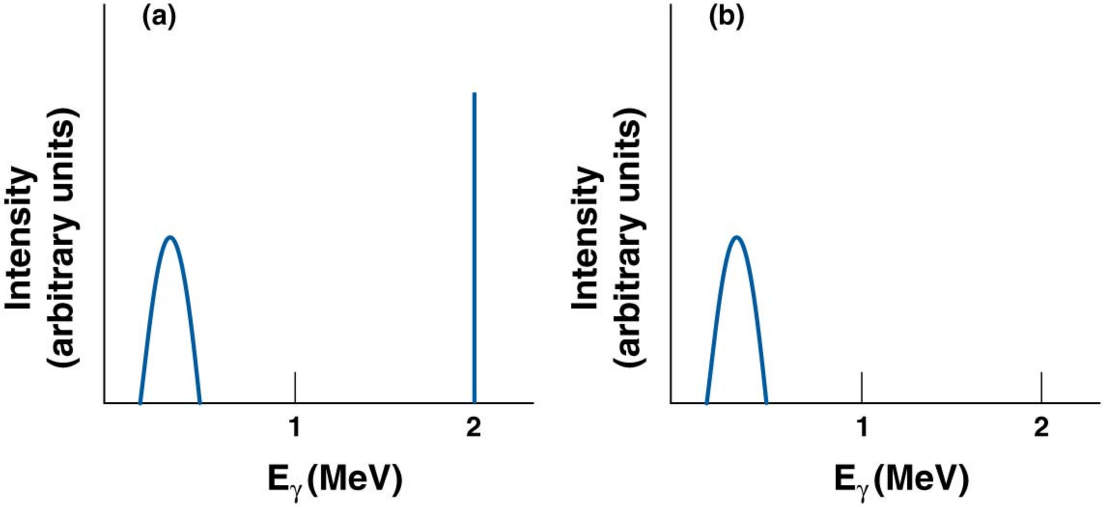


… but how can we detect such a narrow notch?

“Bertozzi’s Trick”







Isotopic Imaging Requires Novel γ-Ray Sources

To become a practical technology, isotopic imaging using nuclear resonance fluorescence (NRF) requires the development of very bright, nearly monochromatic photon sources operating in the MeV range

For NRF detection of a 1 cm^2 target located 10 m away, with high confidence (6σ), and a short acquisition time (s), one requires:

Photon energy	1 – 5 MeV (good transparency, strong NRF lines)
Beam divergence	< 1 mrad (good pixel resolution)
Av. spectral brightness	10^{10} photons/0.1% bandwidth/s/mrad^2

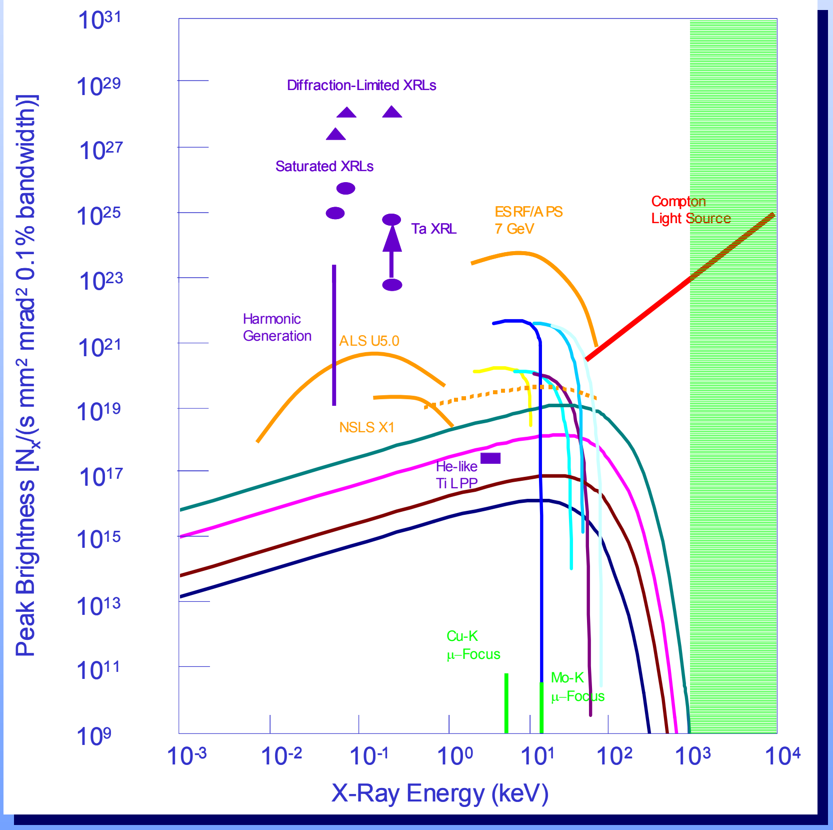
Energetic Photon Sources

High-energy (MeV) photons are deeply penetrating

Flux & brightness required for imaging applications are high

No ideal light source for detection:

- X-ray laser (keV)
- X-ray FEL (10 keV)
- Synchrotron (100 keV)
- Laser-driven (116 keV U)
- Bremsstrahlung ($\Delta\omega_x/\omega_x$), dose
- Radioactive (weak)



Compton Scattering

Compton scattered photon energy scales as γ^2

MeV photons can be produced with laser & modest e-beam energies (~100’s MeV)

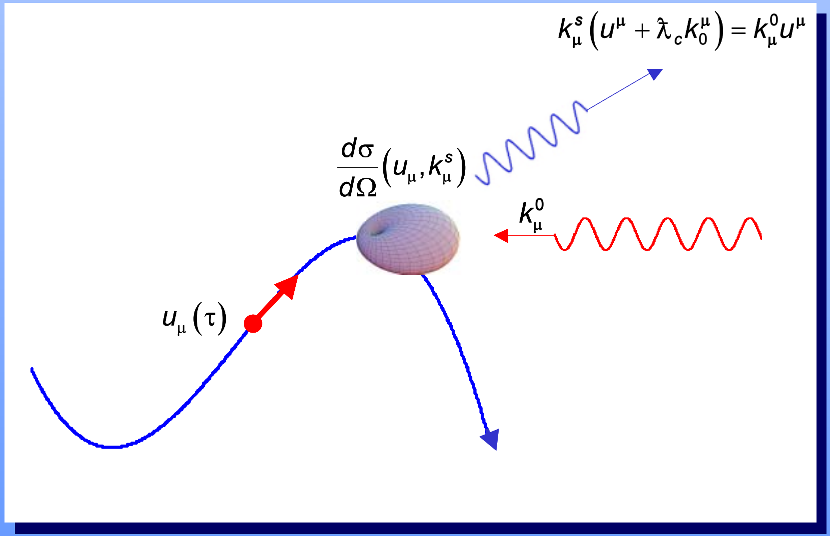
Compton scattering source brightness scales as γ^2

X-ray phase space ~ e-beam phase space; $(\gamma/\varepsilon)^2$

Small cross-section: $8\pi r_0^2/3$

Requires high electron and photon densities at focus

Compton formula: 4-momentum conservation $\boxed{\hbar\omega_x \simeq \hbar\omega_0 4\gamma^2}$



Thomson scattering is the recoil-free limit of Compton scattering

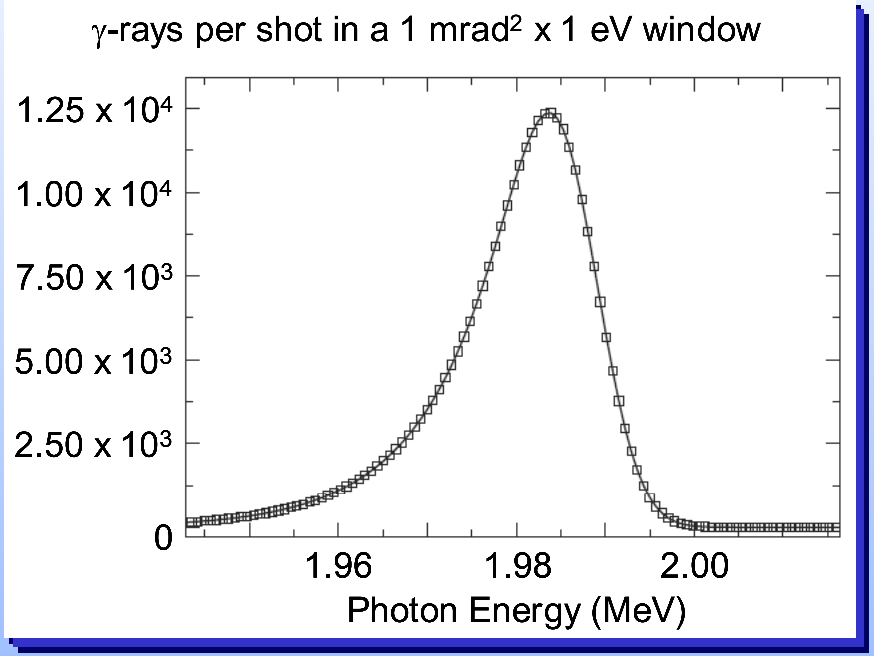
LLNL Thomson-Radiated Extreme X-rays Example

E-beam parameters:

E-beam energy	235 MeV
Bunch charge	1 nC
Energy spread	0.1%
Emittance	1 mm.mrad
Bunch duration	3 ps

Laser parameters:

Laser pulse energy	5 J
Laser pulse duration	5 ps
Wavelength	532 nm
Spot size	20 μm



Above 1 MeV, the peak brightness of T-REX sources is > 15 order of magnitudes larger than that of a 3rd-generation synchrotron

FINDER with T-REX Advantages

Photon energy range near absorption minimum (MeV)

Large NRF cross-section (deep notch) relative to atomic processes

Low false positive/negative rates

Highly accurate; very high-resolution (μm)

Isotopic imaging (!)

Low dose

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YSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 100702 (2005)

High-energy scaling of Compton scattering light sources

temann, W. J. Brown, D. J. Gibson, S. G. Anderson, A. M. Tremaine, P. T. Springer, A. J. Wootton,
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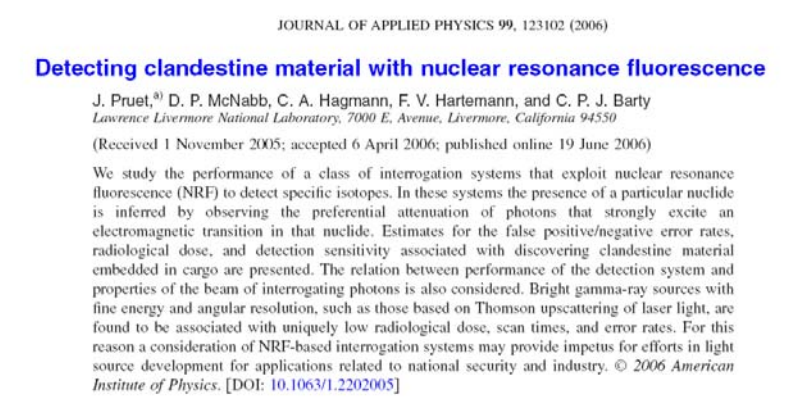
(Received 11 November 2004; published 31 October 2005)

No monochromatic ($\Delta\omega_x/\omega_x < 1\%$), high peak brightness [$> 10^{20}$ photons/(mm^2 × mrad^2 × s × 0.1% bandwidth)], tunable light sources currently exist above 100 keV. Important applications that would benefit from such new hard x-ray and γ-ray sources include the following: nuclear resonance fluorescence spectroscopy and isotopic imaging, time-resolved positron annihilation spectroscopy, and MeV flash radiography. In this paper, the peak brightness of Compton scattering light sources is derived for head-on collisions and found to scale quadratically with the normalized energy, γ; inversely with the electron beam duration, $\Delta\tau$, and the square of its normalized emittance, ε; and linearly with the bunch charge, eN_e, and the number of photons in the laser pulse, N_γ: $\hat{B}_x \propto \gamma^2 N_e N_\gamma / \varepsilon^2 \Delta\tau$. This γ^2 scaling shows that for low normalized emittance electron beams (1 nC, 1 mm · mrad, <1 ps, >100 MeV), and tabletop laser systems (1–10 J, 5 ps) the x-ray peak brightness can exceed 10^{23} photons/(mm^2 × mrad^2 × s × 0.1% bandwidth) near $\hbar\omega_x = 1$ MeV; this is confirmed by three-dimensional codes that have been benchmarked against Compton scattering experiments performed at Lawrence Livermore National Laboratory. The interaction geometry under consideration is head-on collisions, where the x-ray flash duration is shown to be equal to that of the electron bunch, and which produce the highest peak brightness for compressed electron beams. Important nonlinear effects, including spectral broadening, are also taken into account in our analysis; they show that there is an optimum laser pulse duration in this geometry, of the order of a few picoseconds, in sharp contrast with the initial approach to laser-driven Compton scattering sources where femtosecond laser systems were thought to be mandatory. The analytical expression for the peak on-axis brightness derived here is a powerful tool to efficiently explore the 12-dimensional parameter space corresponding to the phase spaces of both the electron and incident laser beams and to determine optimum conditions for producing high-brightness x rays.

DOI: 10.1103/PhysRevSTAB.8.100702 PACS numbers: 41.60.Ap, 41.60.Cr, 52.59.Px, 07.85.Fv



JOURNAL OF APPLIED PHYSICS 99, 123102 (2006)

Detecting clandestine material with nuclear resonance fluorescence

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(Received 1 November 2005; accepted 6 April 2006; published online 19 June 2006)

We study the performance of a class of interrogation systems that exploit nuclear resonance fluorescence (NRF) to detect specific isotopes. In these systems the presence of a particular nuclide is inferred by observing the preferential attenuation of photons that strongly excite an electromagnetic transition in that nuclide. Estimates for the false positive/negative error rates, radiological dose, and detection sensitivity associated with discovering clandestine material embedded in cargo are presented. The relation between performance of the detection system and properties of the beam of interrogating photons is also considered. Bright gamma-ray sources with fine energy and angular resolution, such as those based on Thomson upscattering of laser light, are found to be associated with uniquely low radiological dose, scan times, and error rates. For this reason a consideration of NRF-based interrogation systems may provide impetus for efforts in light source development for applications related to national security and industry. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2202005]

FINDER with T-REX Key Requirements

The specific application we target has strong implications in terms of source parameters

Requires high average brightness

High-quality, bright electron beam

- Beercan UV, 8 ps
- High-charge gun (nC)
- Very low emittance

Low linac noise (dump, dark current, etc.)

Need sufficient electron beam energy

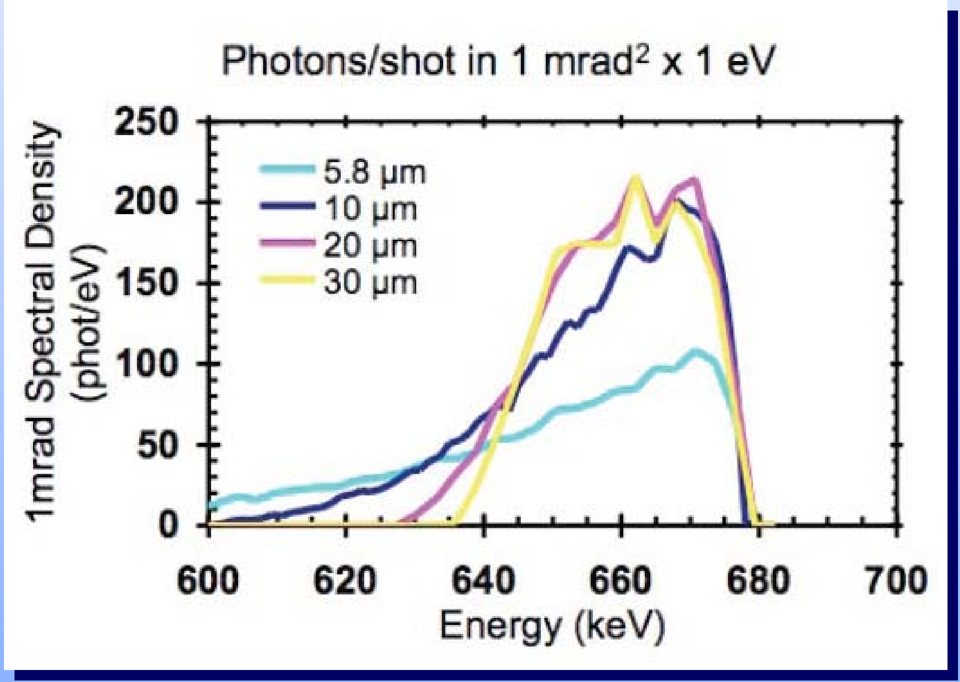
680 keV T-REX Source for ^{238}U Demonstration

E-beam parameters:

E-beam energy	112 MeV
Bunch charge	0.3 nC
Energy spread	0.1%
Emittance	2 mm.mrad
Bunch duration	8 ps

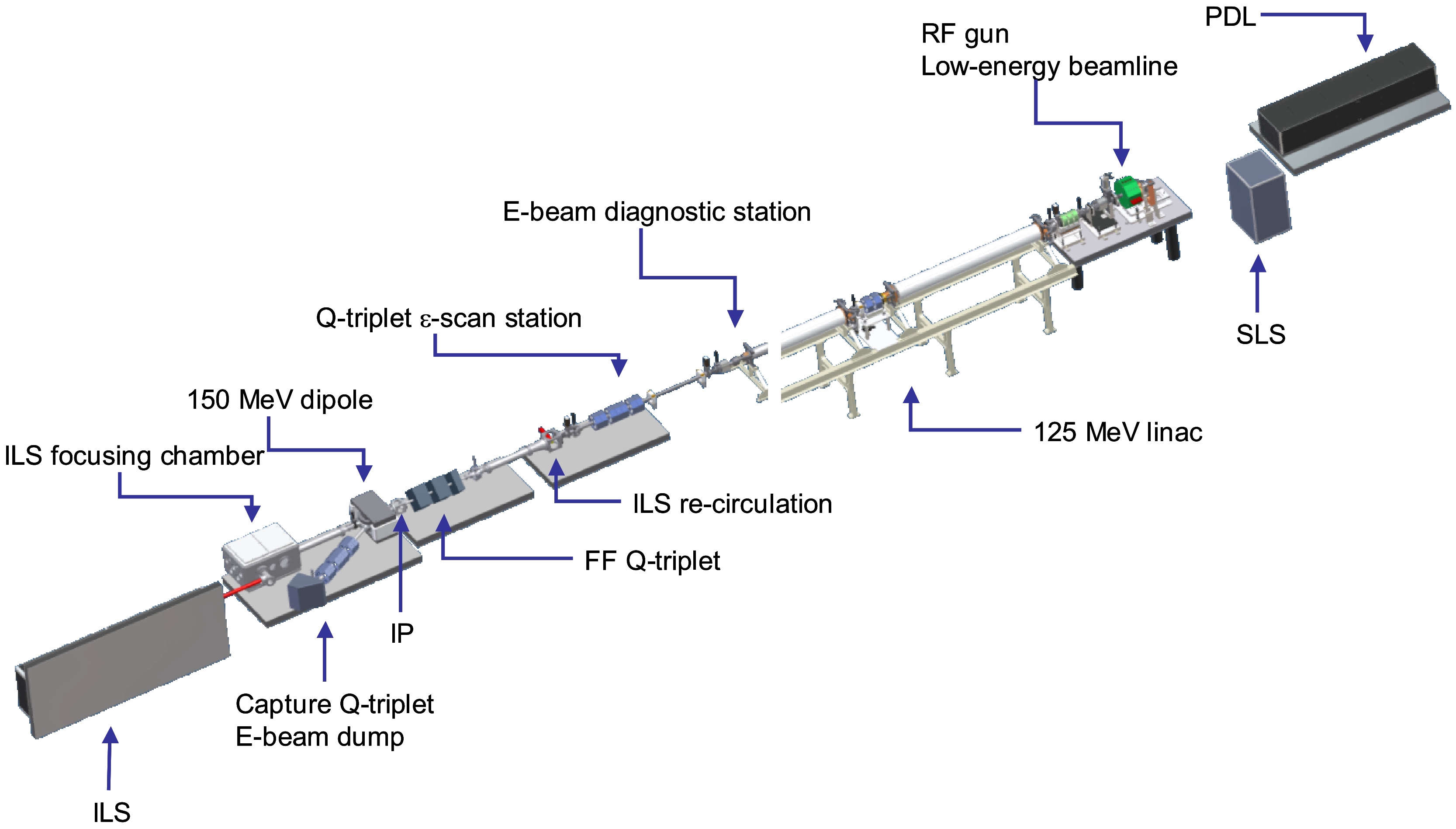
Laser parameters:

Laser pulse energy	0.5 J
Laser pulse duration	5 ps
Wavelength	355 nm
Spot size	20 μm



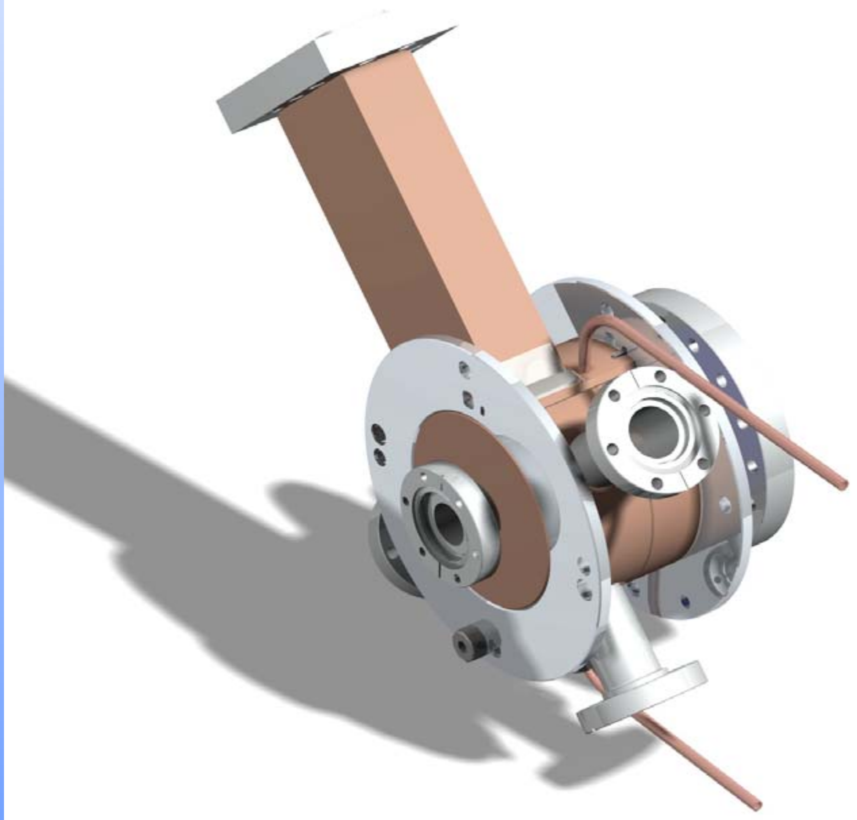
Photons/shot in 1 mrad^2 x 1 eV

LLNL T-REX CAD



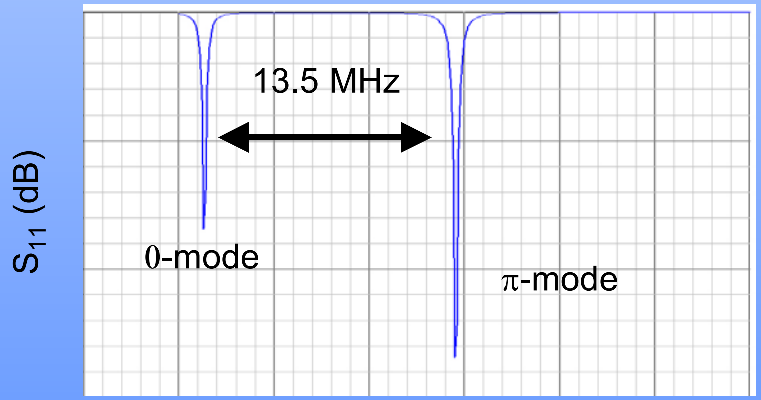
LLNL/UCLA Gun Design

Gradient	120 MV/m
Emittance	0.7 mm.mrad
Charge	1 nC
Energy	6 MeV
Energy spread	0.17%


3-D model of LLNL/UCLA RF gun

LLNL/UCLA RF Gun

- Cold tests have been performed successfully
- Key upgrades include:
  - Wider frequency separation between the 0 and π-modes
  - No tuners (to allow high-gradient operation > 120 MV/m)
  - No 70^o laser input windows (fully symmetrized half cell)
  - Solenoidal magnetic field symmetrized up to quadrupole



Low-Energy Beamline

Fully emittance-compensated setup

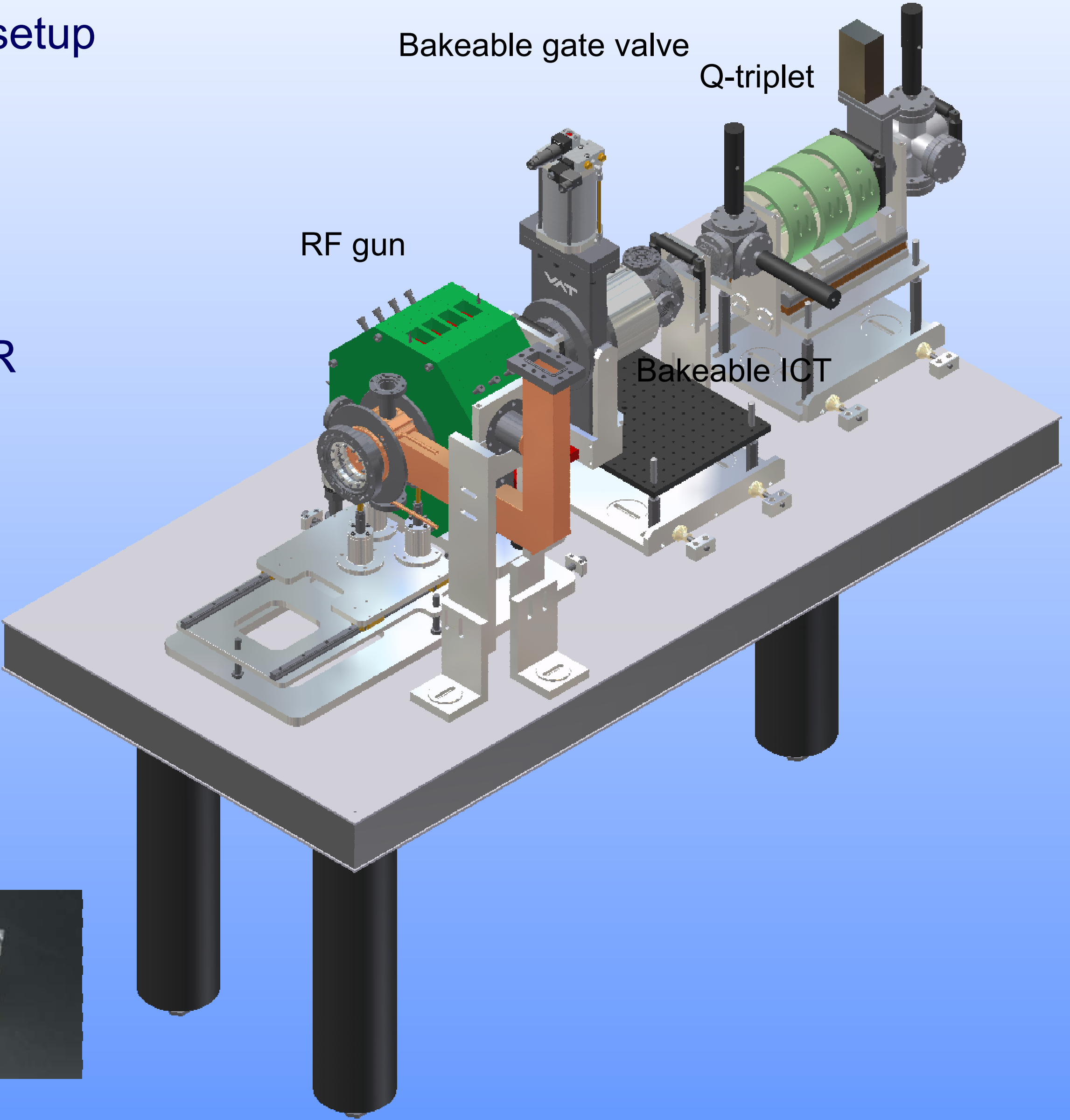
Precision diagnostics included

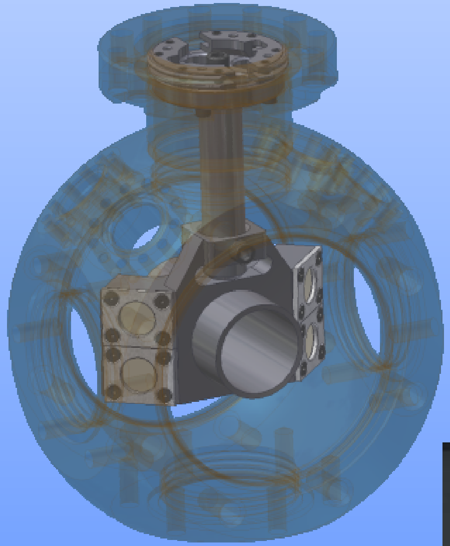
Optimized gun/linac interface

UHV for photocathode lifetime

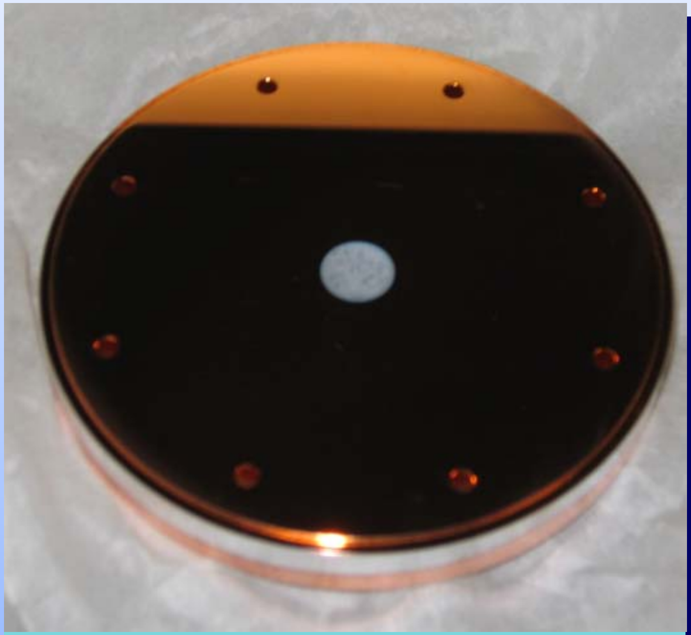
Symmetrized beamline for CSR

Symmetrized UV coupling box



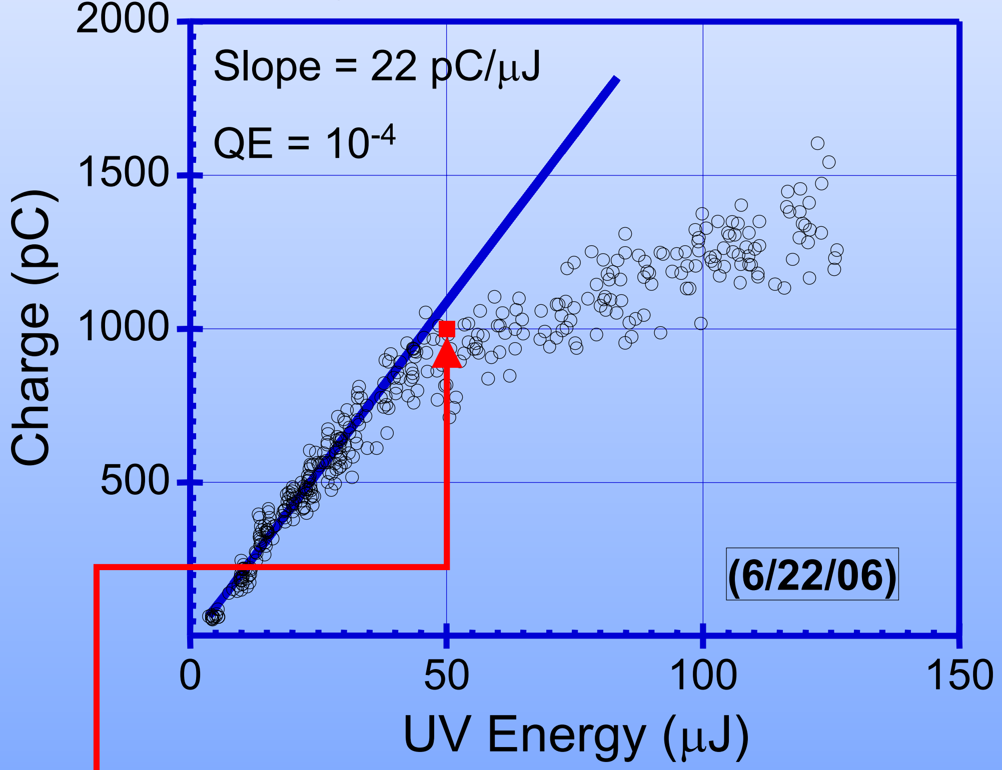


Sputtered Mg Photocathode Enables Fiber-Based UV Laser



2 μm of Mg is sputtered on a 1 cm diameter spot on the polished Cu back plane of the photoinjector. A 2 mm diameter UV laser strikes the Mg spot, generating photoelectrons

Gun peak field: 80 MV/m
Injection phase: 40°



50 μJ of UV light can be produced readily with custom LLNL fiber laser system

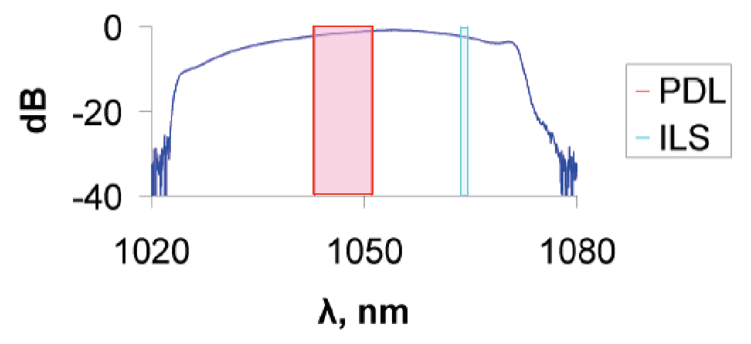
LLNL Fiber Laser System

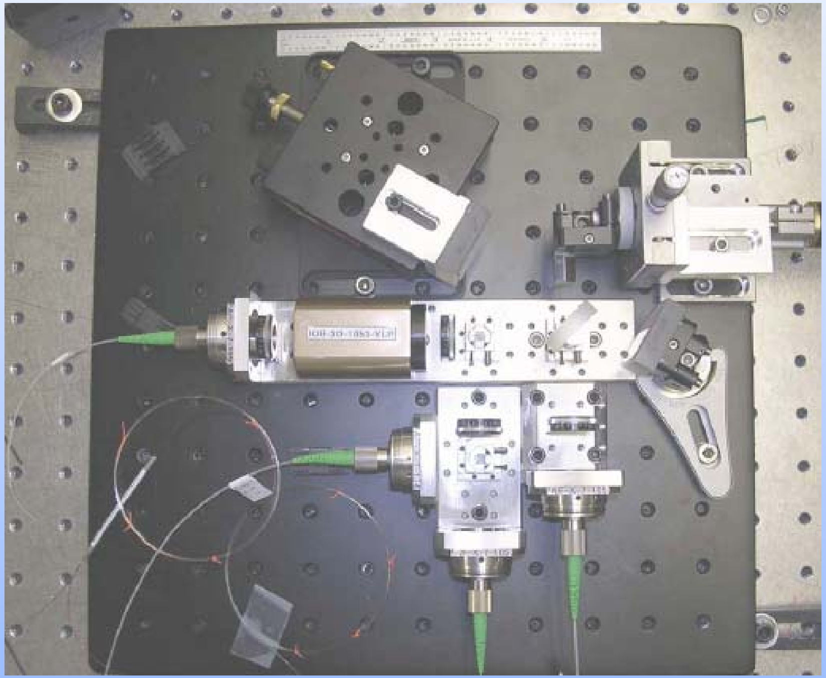
Modelocked pulses:

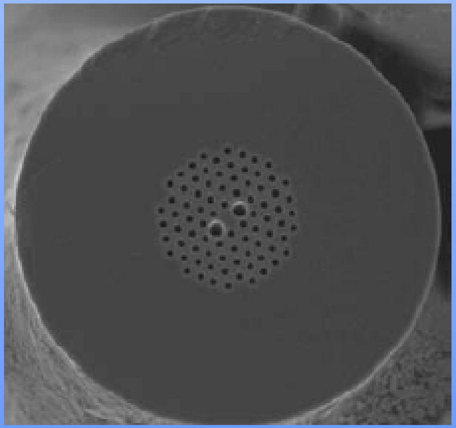
1 nJ

150 fs FTL

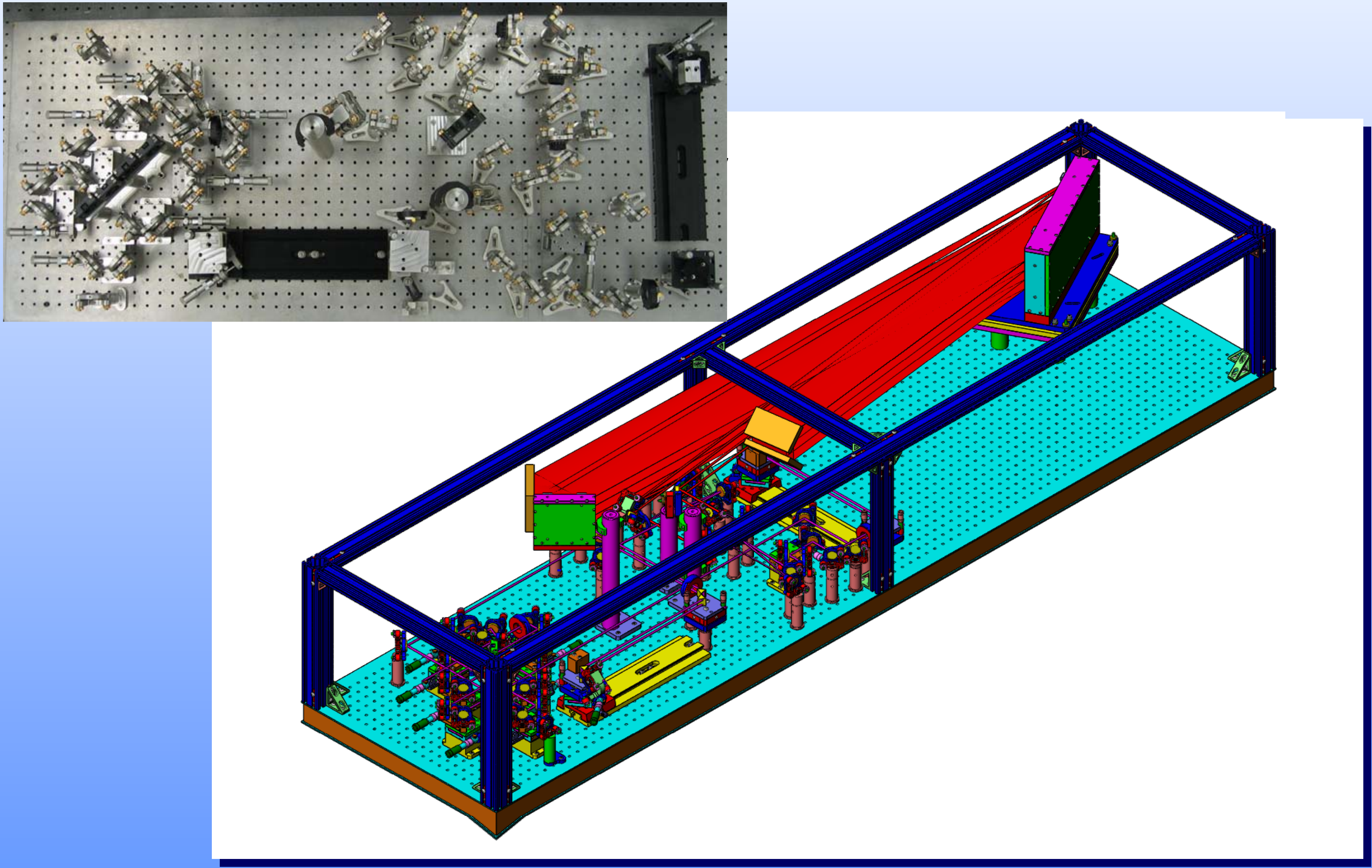
40.7785 MHz



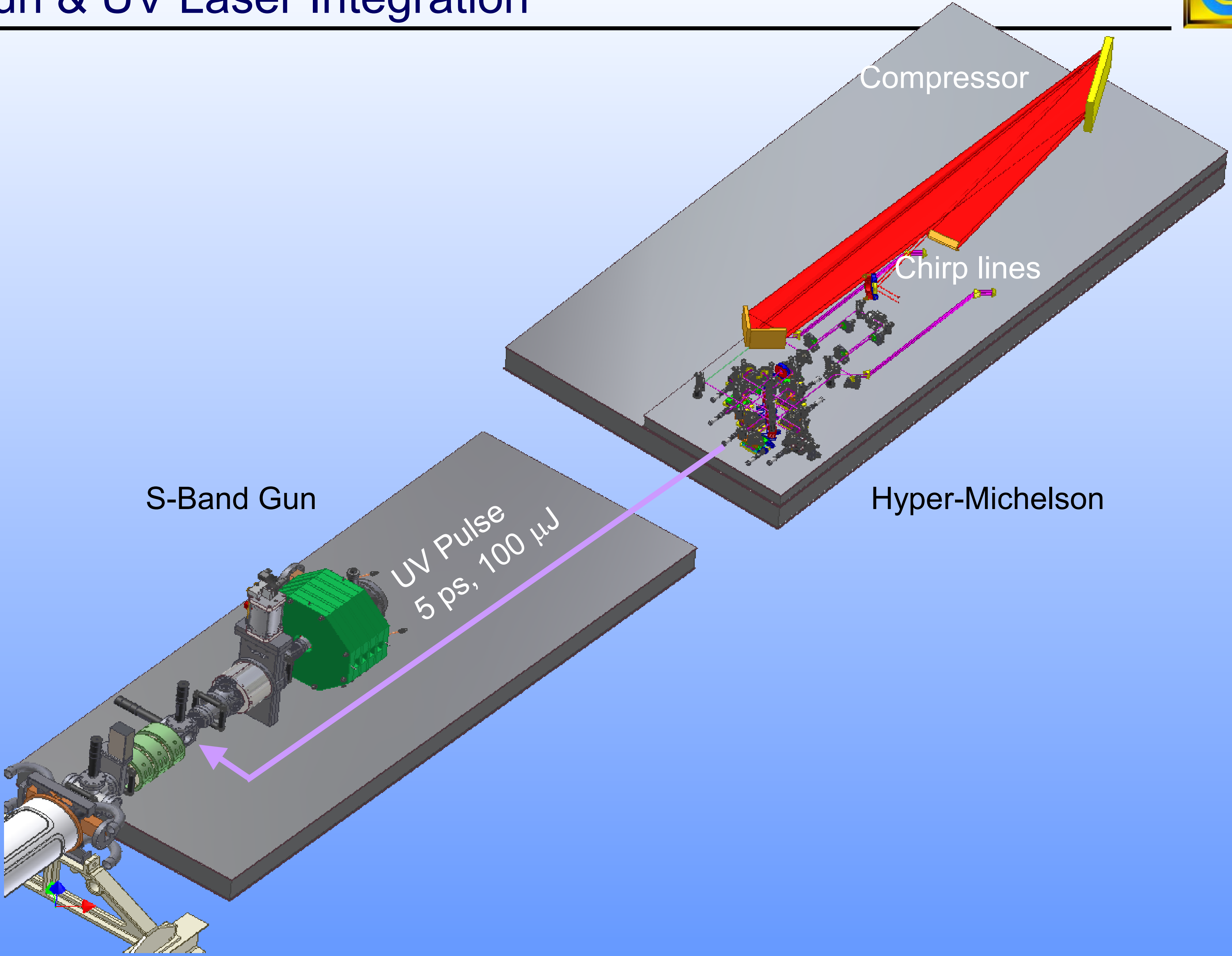




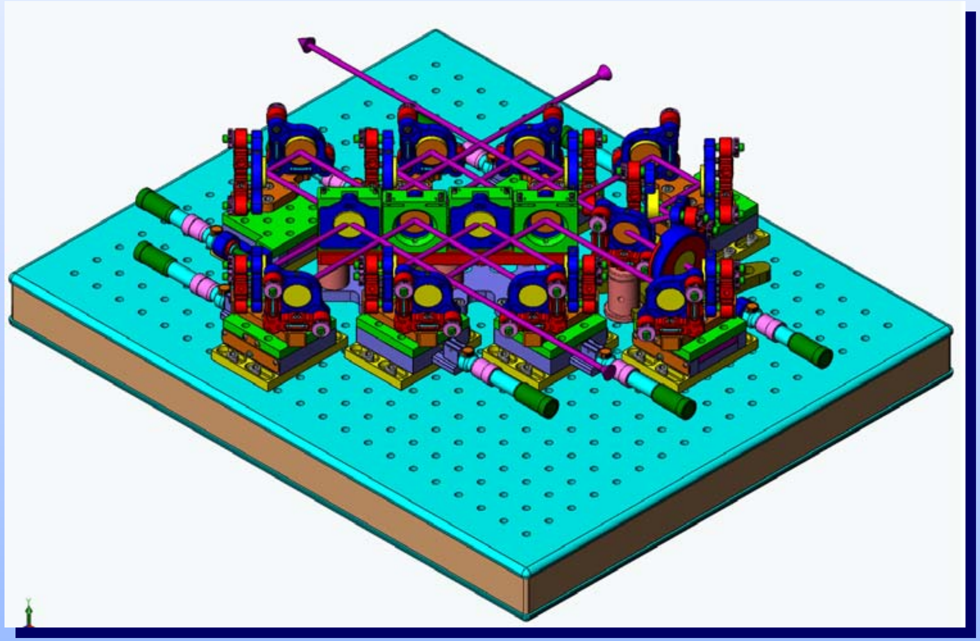
LLNL Photocathode Drive Laser

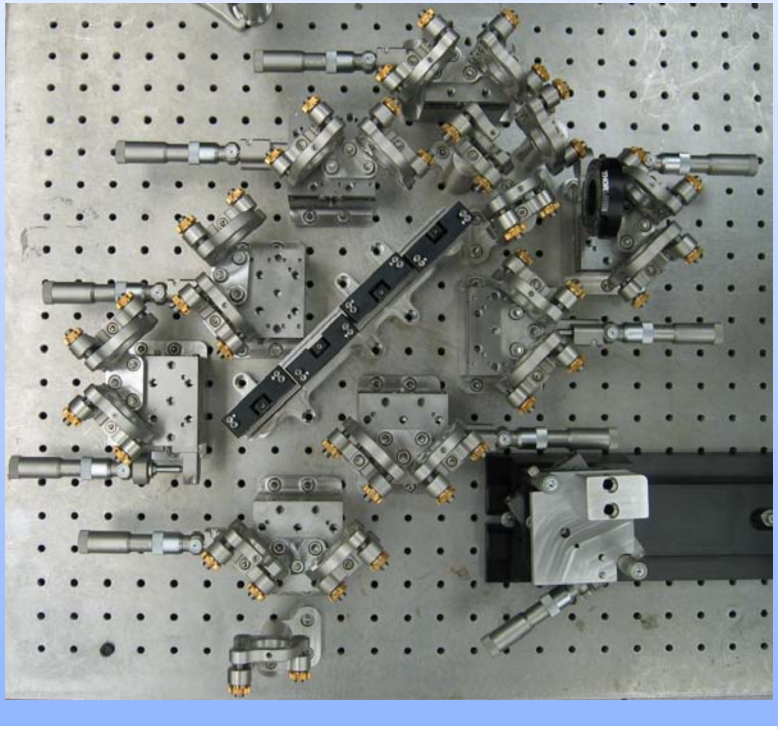


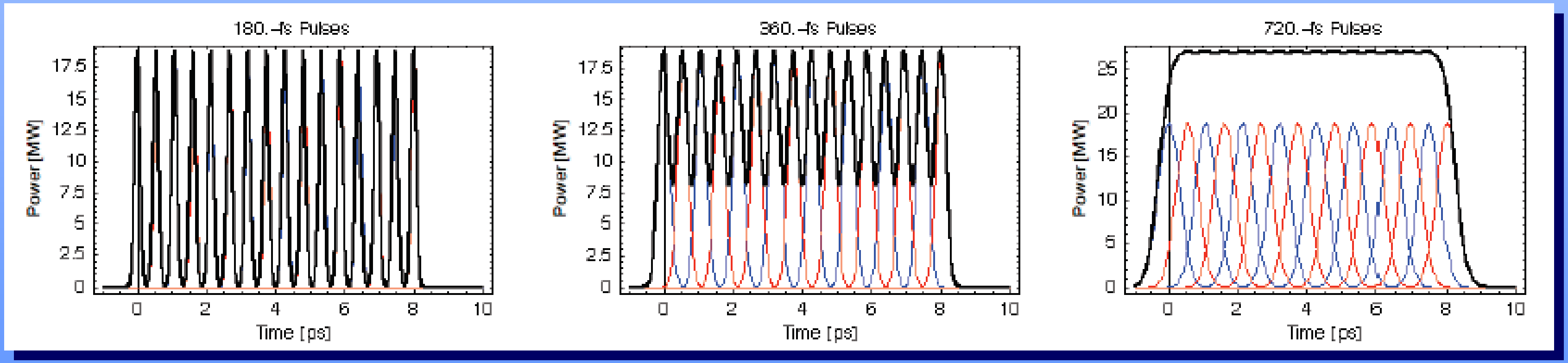
Gun & UV Laser Integration



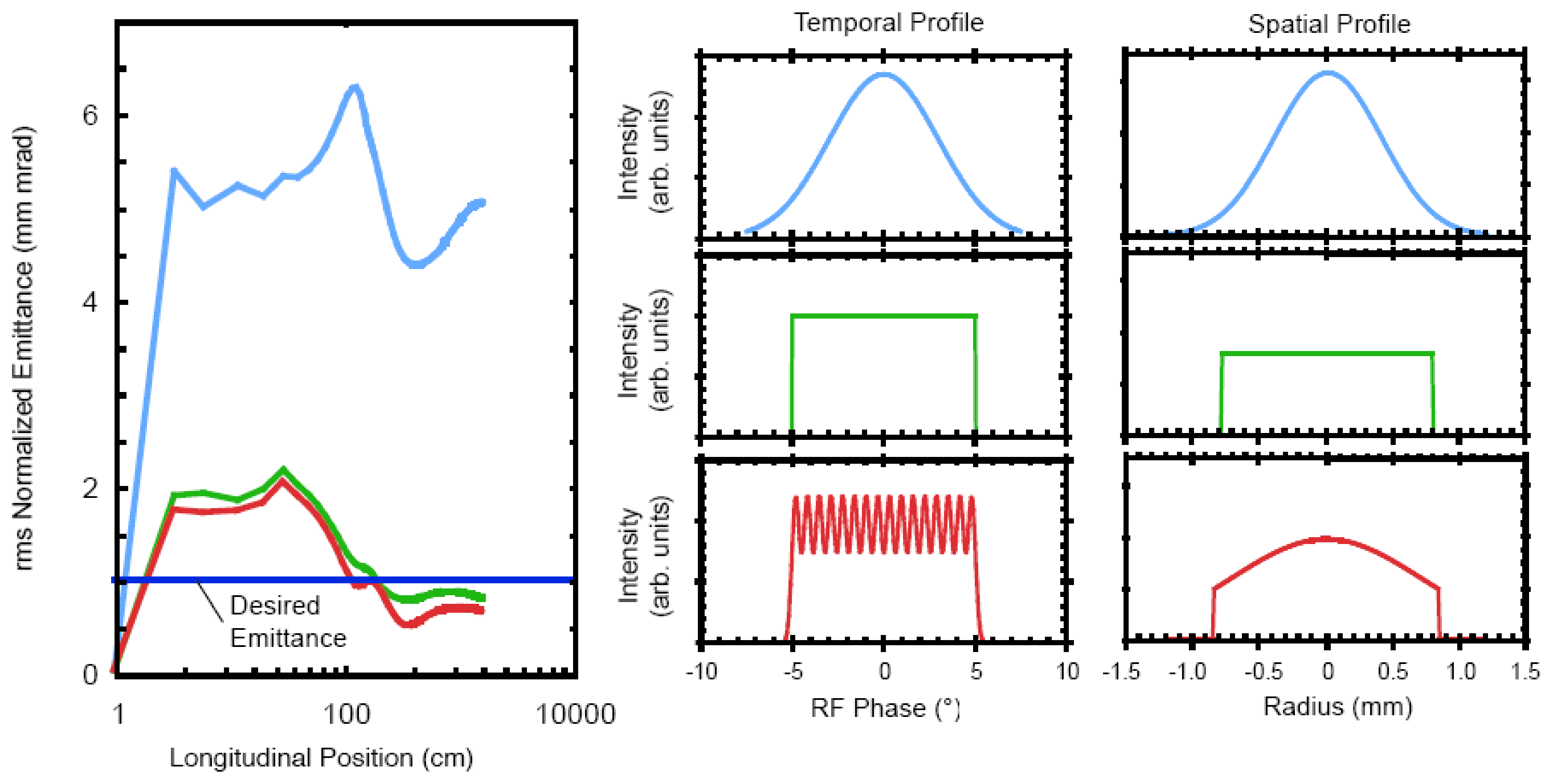
LLNL Hyper-Michelson Pulse Stacker/Shaper



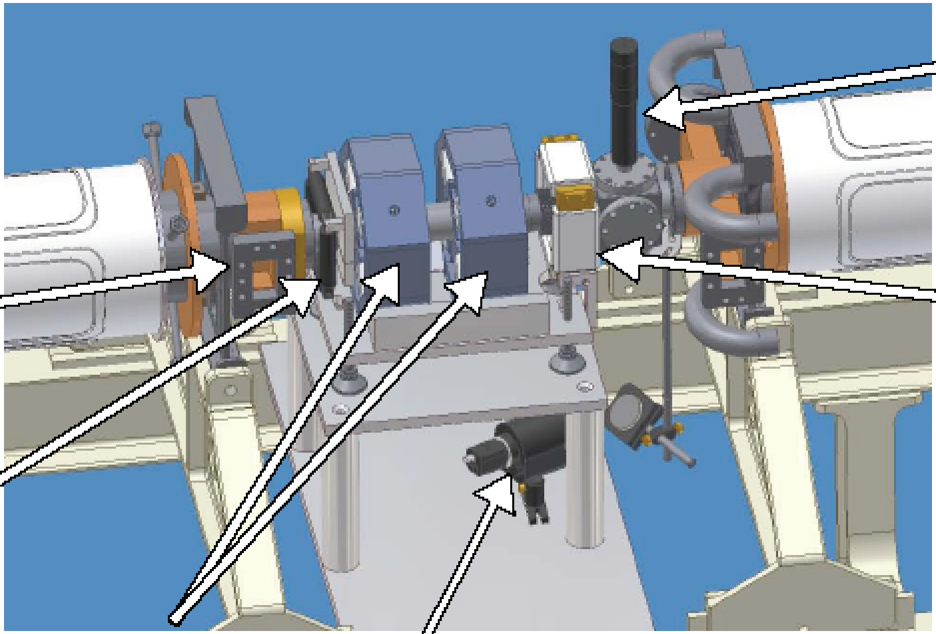


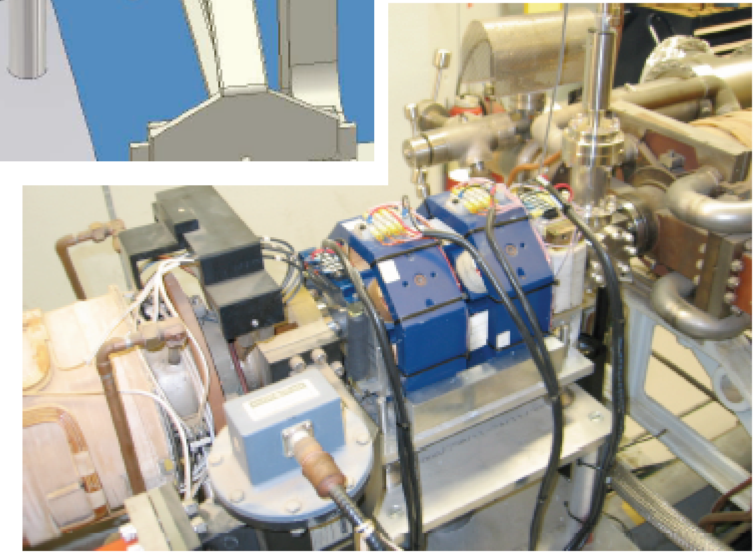


Emittance Optimization & Preservation



Electron Beamline Designed to Preserve Emittance

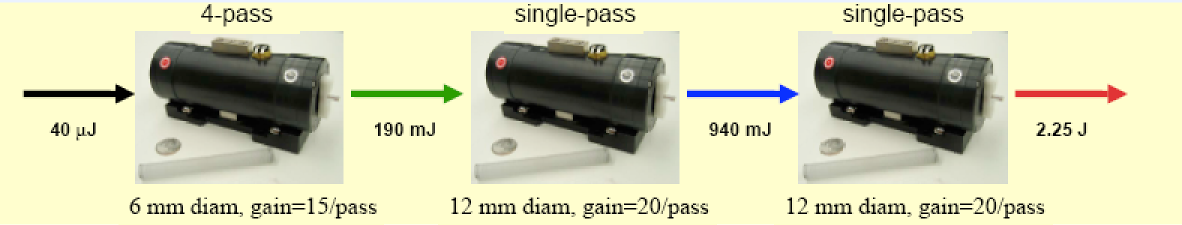


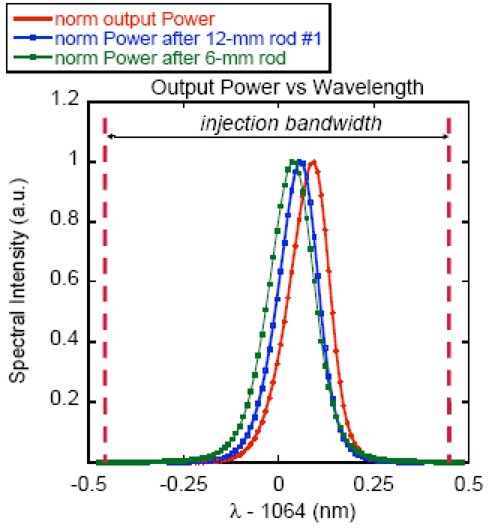


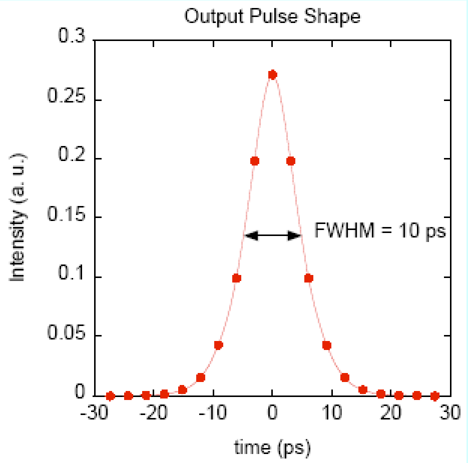
Solenoids and long steerers, which can induce emittance growth, will not be used.

Quadrupoles and short steerers will be used instead.

LLNL Drive Laser System

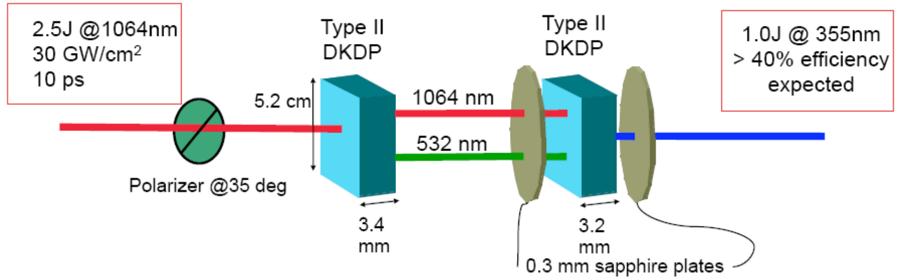




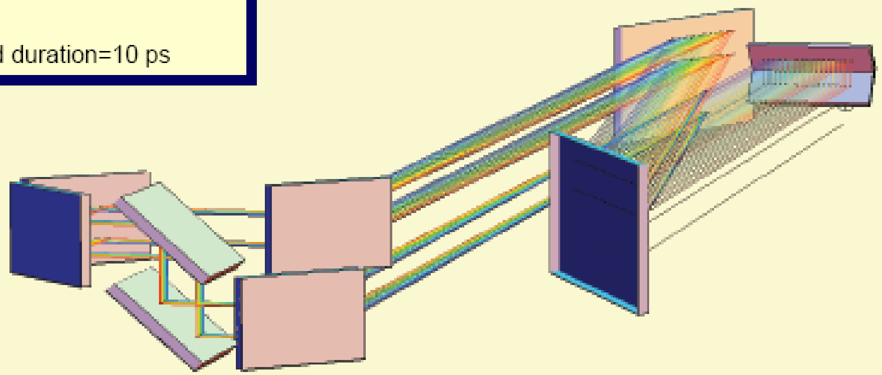


Input pulse: energy = 40 µJ, bandwidth > 0.8 nm

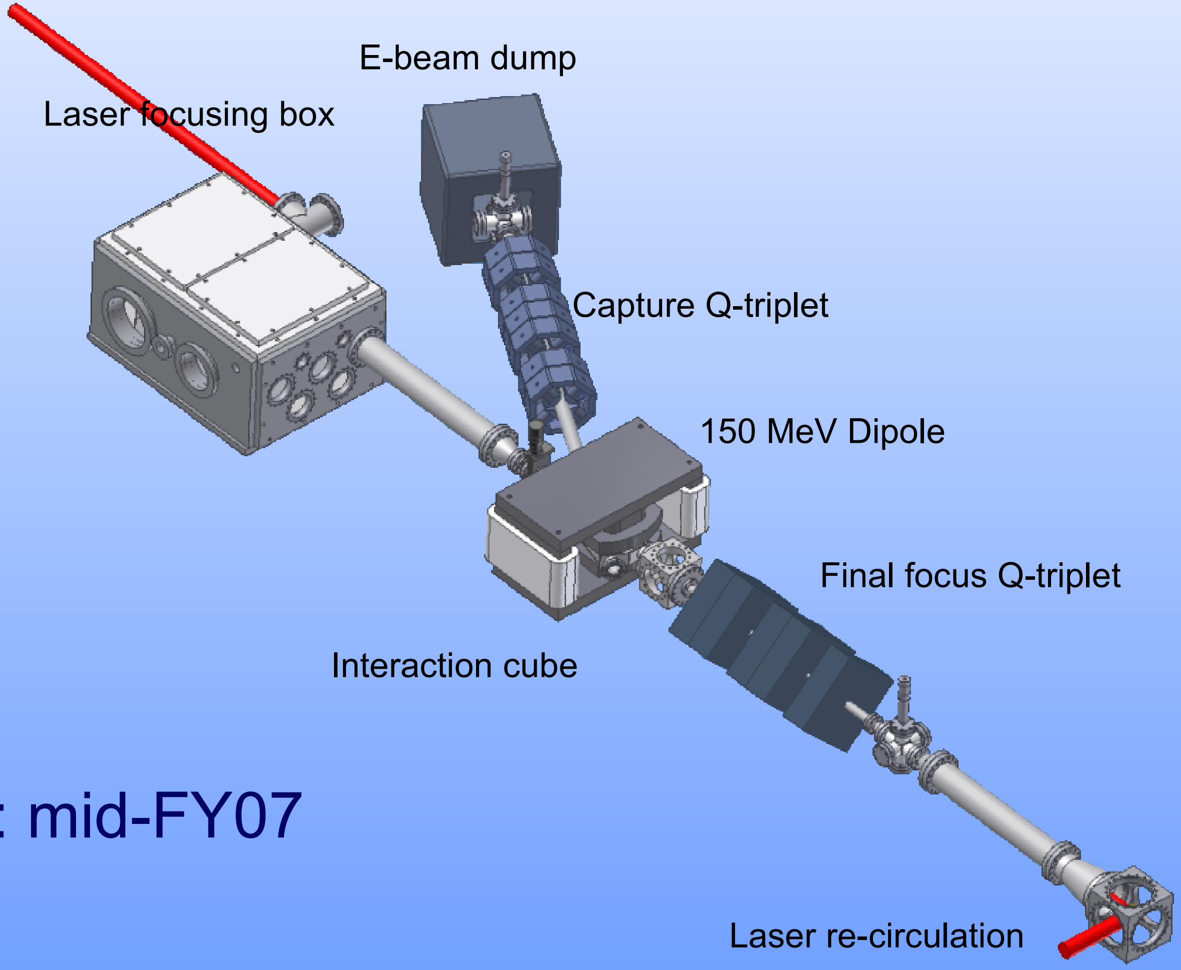
Output pulse: energy = 2.25 J, 10 dB bandwidth=0.25 nm, transform limited duration=10 ps



HDC compressor



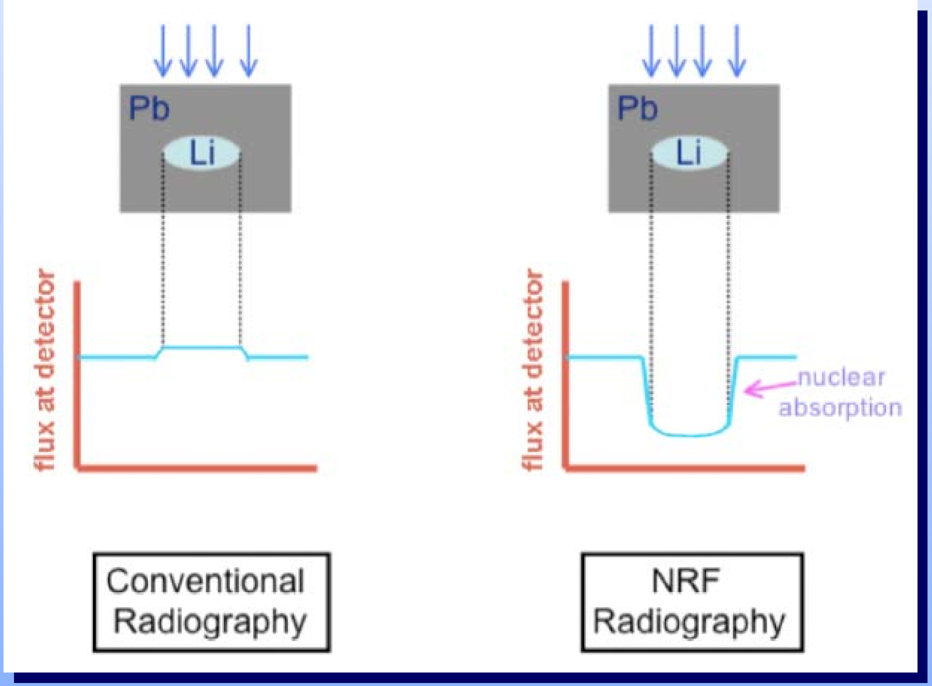
T-REX Interaction Region

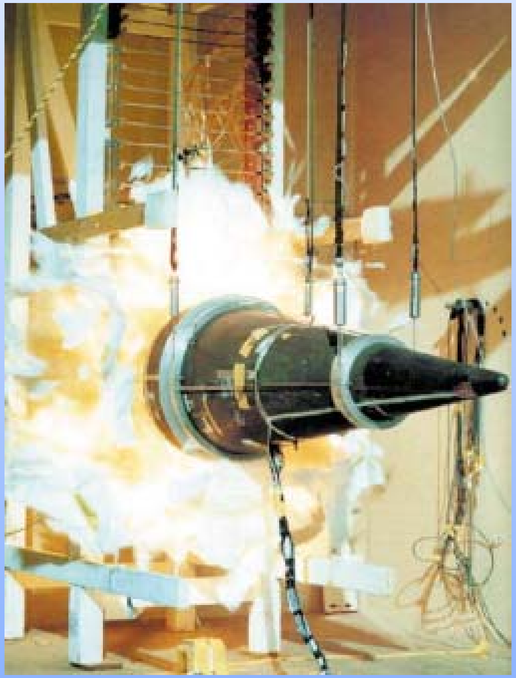


1st Light: mid-FY07

Applications: Stockpile Surveillance

Isotopic imaging enables inverse density radiography





Applications: Waste Evaluation

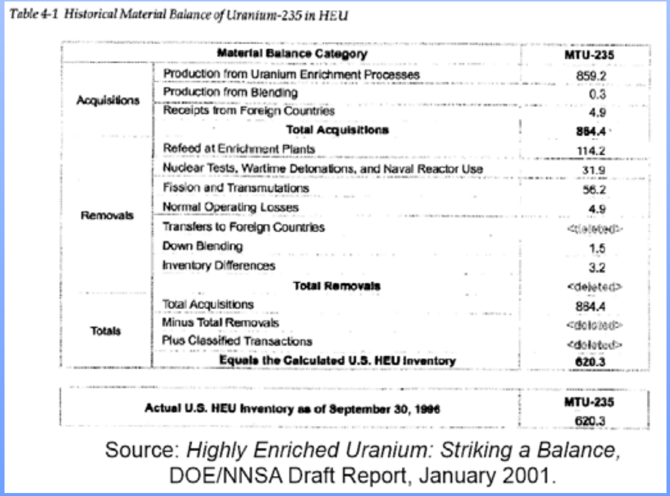
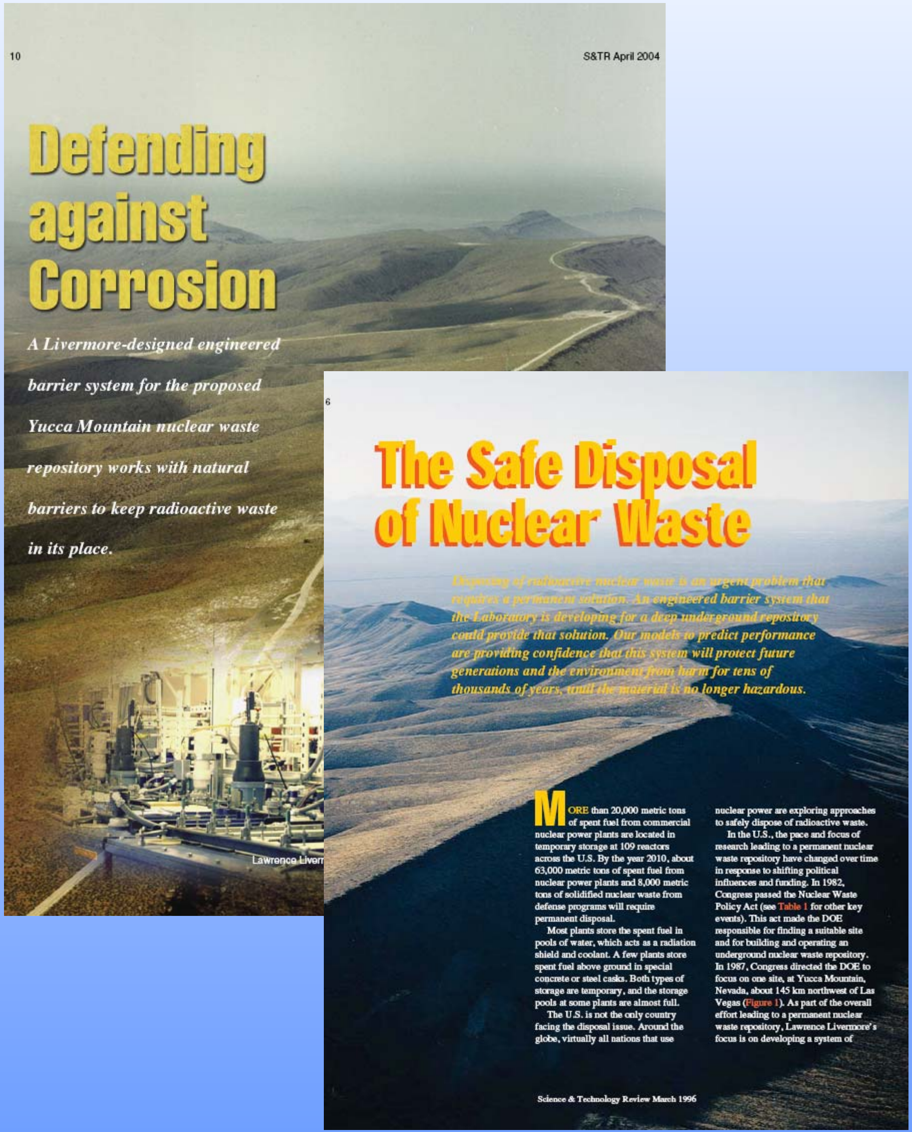


Table 4-1 Historical Material Balance of Uranium-235 in HEU

Material Balance Category		MTU-235
Acquisitions	Production from Uranium Enrichment Processes	859.2
	Production from Blending	0.3
	Receipts from Foreign Countries	4.9
	Total Acquisitions	**864.4**
Removals	Refeed at Enrichment Plants	114.2
	Nuclear Tests, Wartime Detonations, and Naval Reactor Use	31.9
	Fission and Transmutations	56.2
	Normal Operating Losses	4.9
	Transfers to Foreign Countries	<deleted>
	Down Blending	1.5
	Inventory Differences	3.2
	Total Removals	<deleted>
Totals	Total Acquisitions	864.4
	Minus Total Removals	<deleted>
	Plus Classified Transactions	<deleted>
	Equals the Calculated U.S. HEU Inventory	**620.3**

	MTU-235
Actual U.S. HEU Inventory as of September 30, 1996	620.3

Source: *Highly Enriched Uranium: Striking a Balance,* DOE/NNSA Draft Report, January 2001.



Defending against Corrosion

A Livermore-designed engineered barrier system for the proposed Yucca Mountain nuclear waste repository works with natural barriers to keep radioactive waste in its place.

The Safe Disposal of Nuclear Waste

Disposing of radioactive nuclear waste is an urgent problem that requires a permanent solution. An engineered barrier system that the Laboratory is developing for a deep underground repository could provide that solution. Our models to predict performance are providing confidence that this system will protect future generations and the environment from harm for tens of thousands of years, until the material is no longer hazardous.

MORE than 20,000 metric tons of spent fuel from commercial nuclear power plants are located in temporary storage at 109 reactors across the U.S. By the year 2010, about 63,000 metric tons of spent fuel from nuclear power plants and 8,000 metric tons of solidified nuclear waste from defense programs will require permanent disposal.

Most plants store the spent fuel in pools of water, which acts as a radiation shield and coolant. A few plants store spent fuel above ground in special concrete or steel casks. Both types of storage are temporary, and the storage pools at some plants are almost full.

The U.S. is not the only country facing the disposal issue. Around the globe, virtually all nations that use nuclear power are exploring approaches to safely dispose of radioactive waste.

In the U.S., the pace and focus of research leading to a permanent nuclear waste repository have changed over time in response to shifting political influences and funding. In 1982, Congress passed the Nuclear Waste Policy Act (see Table 1 for other key events). This act made the DOE responsible for finding a suitable site and for building and operating an underground nuclear waste repository. In 1987, Congress directed the DOE to focus on one site, at Yucca Mountain, Nevada, about 145 km northwest of Las Vegas (Figure 1). As part of the overall effort leading to a permanent nuclear waste repository, Lawrence Livermore's focus is on developing a system of

Applications: Nuclear Photo-Science

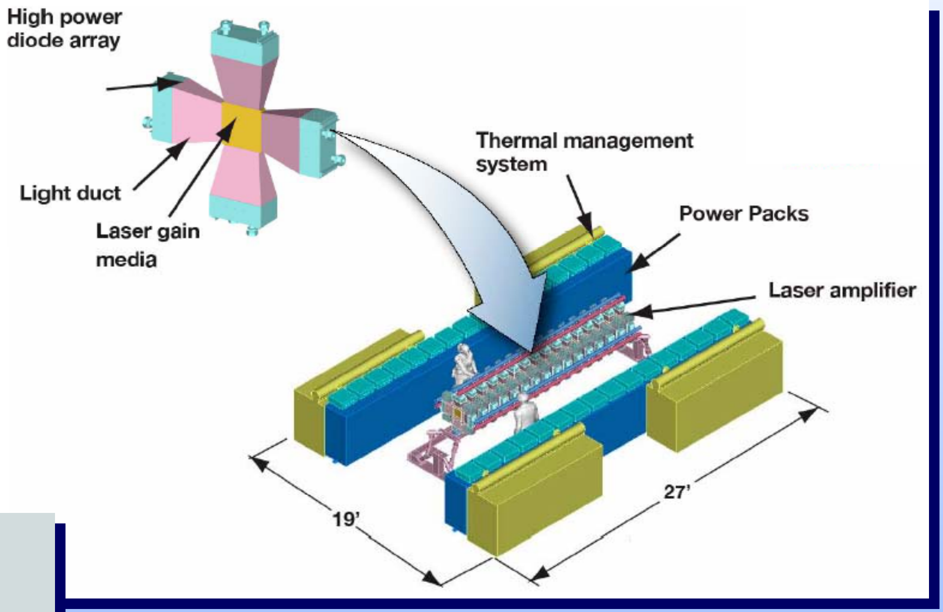
Energy-recovery linacs

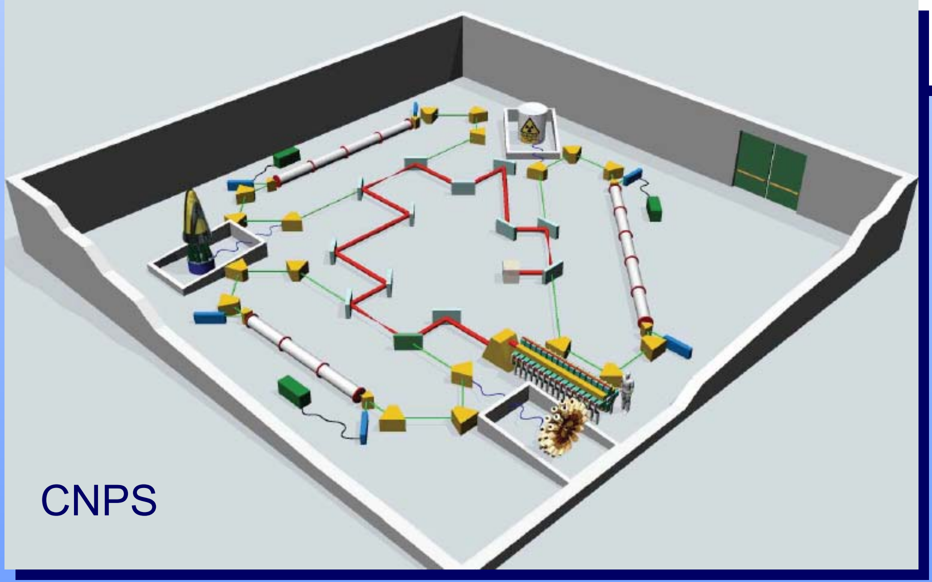
Superconducting linacs

Superconducting rf guns

Tailor-aperture ceramic lasers

Nonlinear trapping




CNPS

kW-average γ-ray flux

Isotopic imaging

Inverse density radiography

γ-induced fission

Parity measurements

Conclusions

- There are a number of bright γ-ray missions within the DoE complex and beyond
- T-REX sources will generate γ-rays with unprecedented brightness
- LLNL's laser and electron beam technology are key components for the development of T-REX sources
- The future of T-REX sources is closely tied to advanced accelerators, as the γ-ray phase space maps onto the electron beam phase space
- In particular, energy-recovery superconducting linacs, coupled to LLNL's high average power lasers may yield a path to kW γ-ray beams