Ultracompact Accelerator Technology for a Next-Generation Gamma-ray Source

Presented by

Roark Marsh

Lawrence Livermore National Laboratory

International Particle Accelerator Conference 2012

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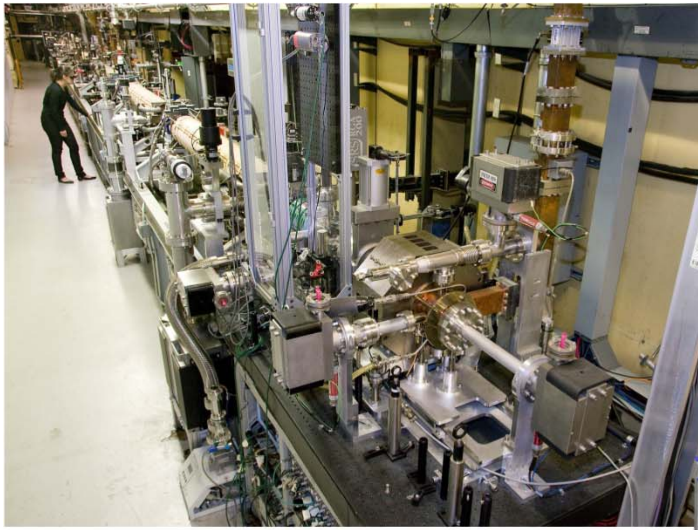
Lawrence Livermore National Laboratory Collaborators

- Felicie Albert
- Gerry Anderson
- Scott Anderson
- Paul Armstrong
- Chris Barty
- Andy Bayramian
- Glenn Beer
- Shawn Betts
- Gina Bonanno
- Sam Chu*
- Rick Cross
- Gary Deis
- Chris Ebbers
- Scott Fisher
- David Gibson
- Fred Hartemann
- Tim Houck
- Mike Messerly
- Matt Prantil
- Miro Shverdin
- Sheldon Wu

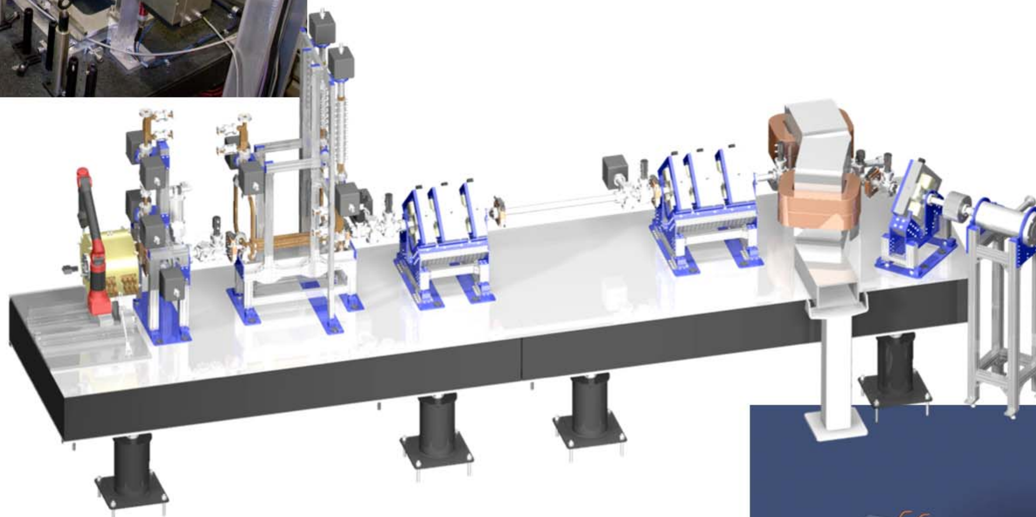
SLAC National Accelerator Laboratory Collaborators

- Chris Adolphsen
- Karl Bane
- Arno Candel*
- Mike Fazio
- Norbert Holtkamp
- Erik Jongewaard
- Zenghai Li
- Cecile Limborg-Deprey
- Tor Raubenheimer
- Sami Tantawi
- Faya Wang
- Juwen Wang
- Arnold Vlieks
- Feng Zhou

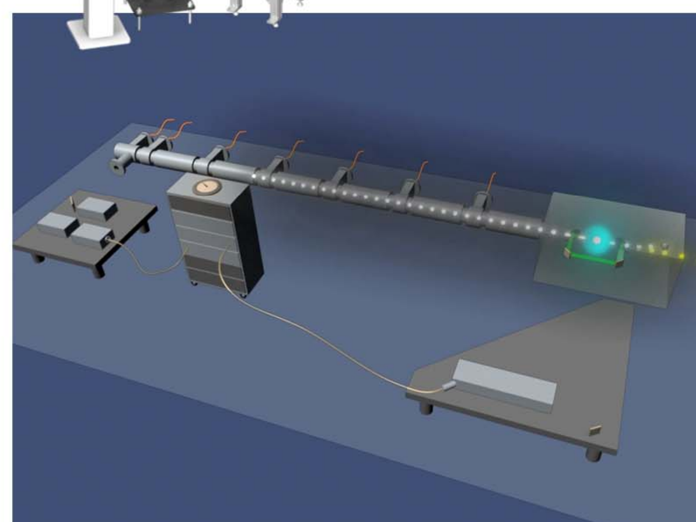


- **Introduction**

- **X-band Test Station**



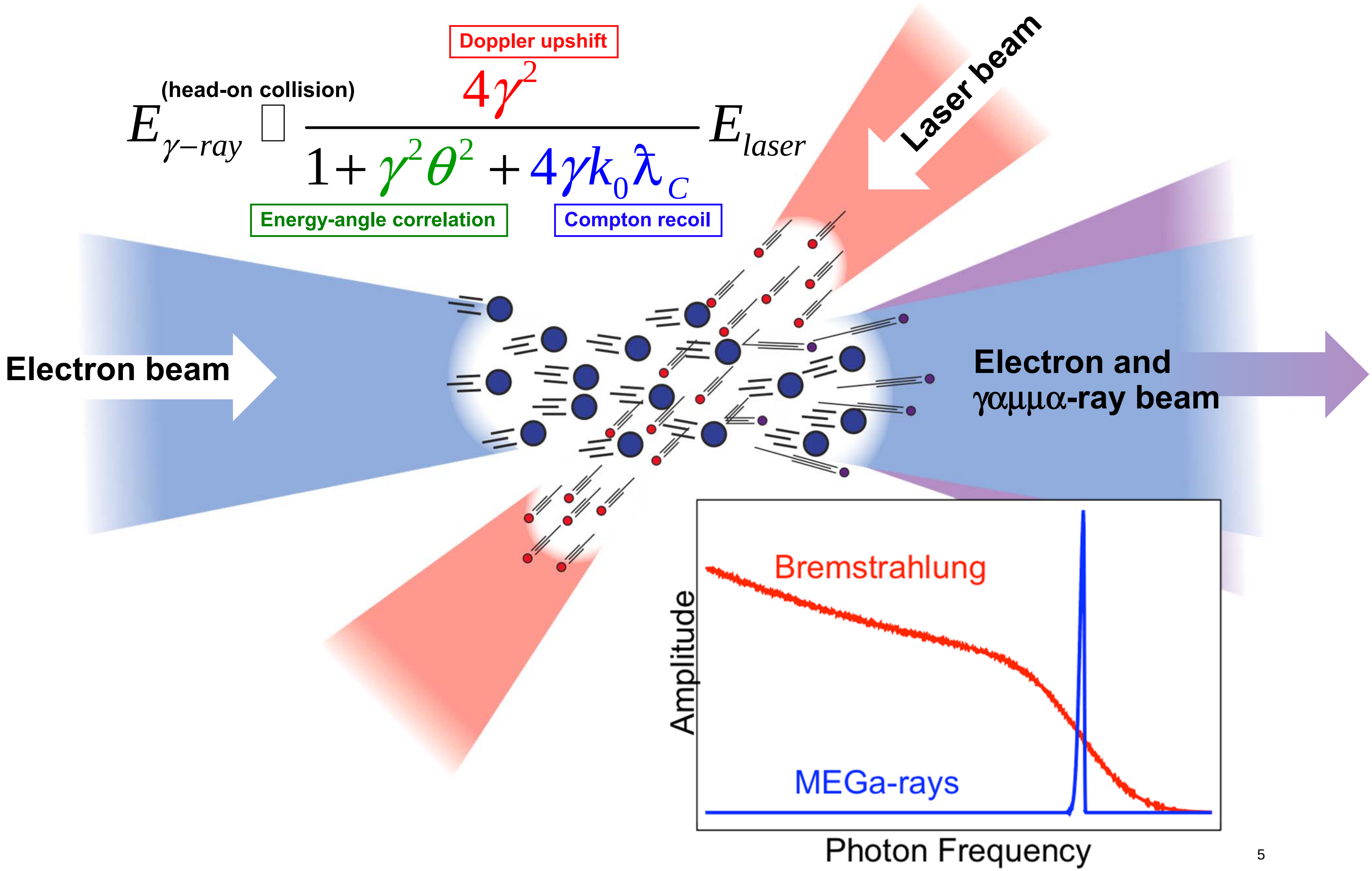
- **Ongoing Exploratory Research**



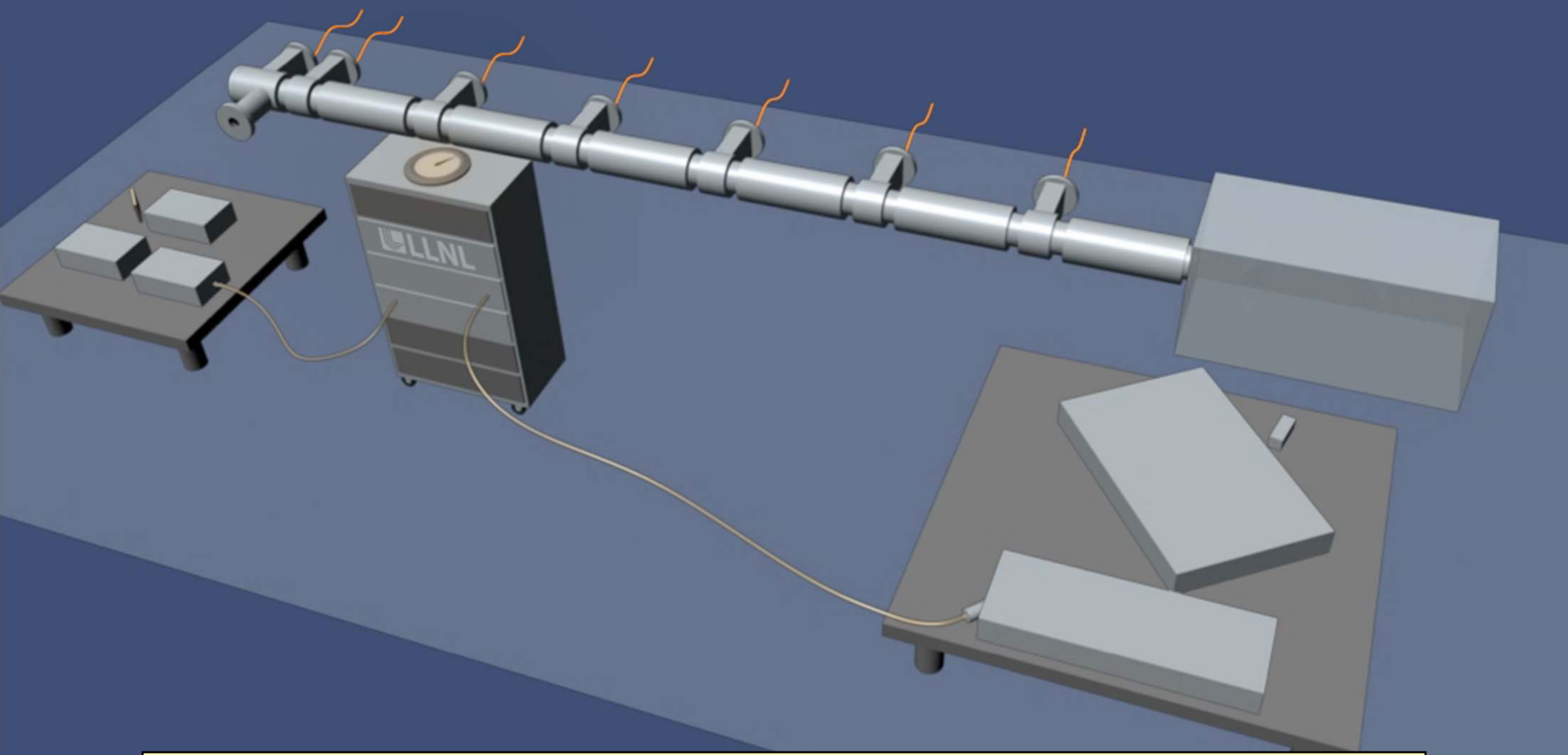
Scattering optical photons off electron beam generates a keV-MeV photon beam.

(head-on collision)

$$E_{\gamma-ray} \approx \frac{4\gamma^2}{1+\gamma^2\theta^2+4\gamma k_0 \lambdabar_C} E_{laser}$$

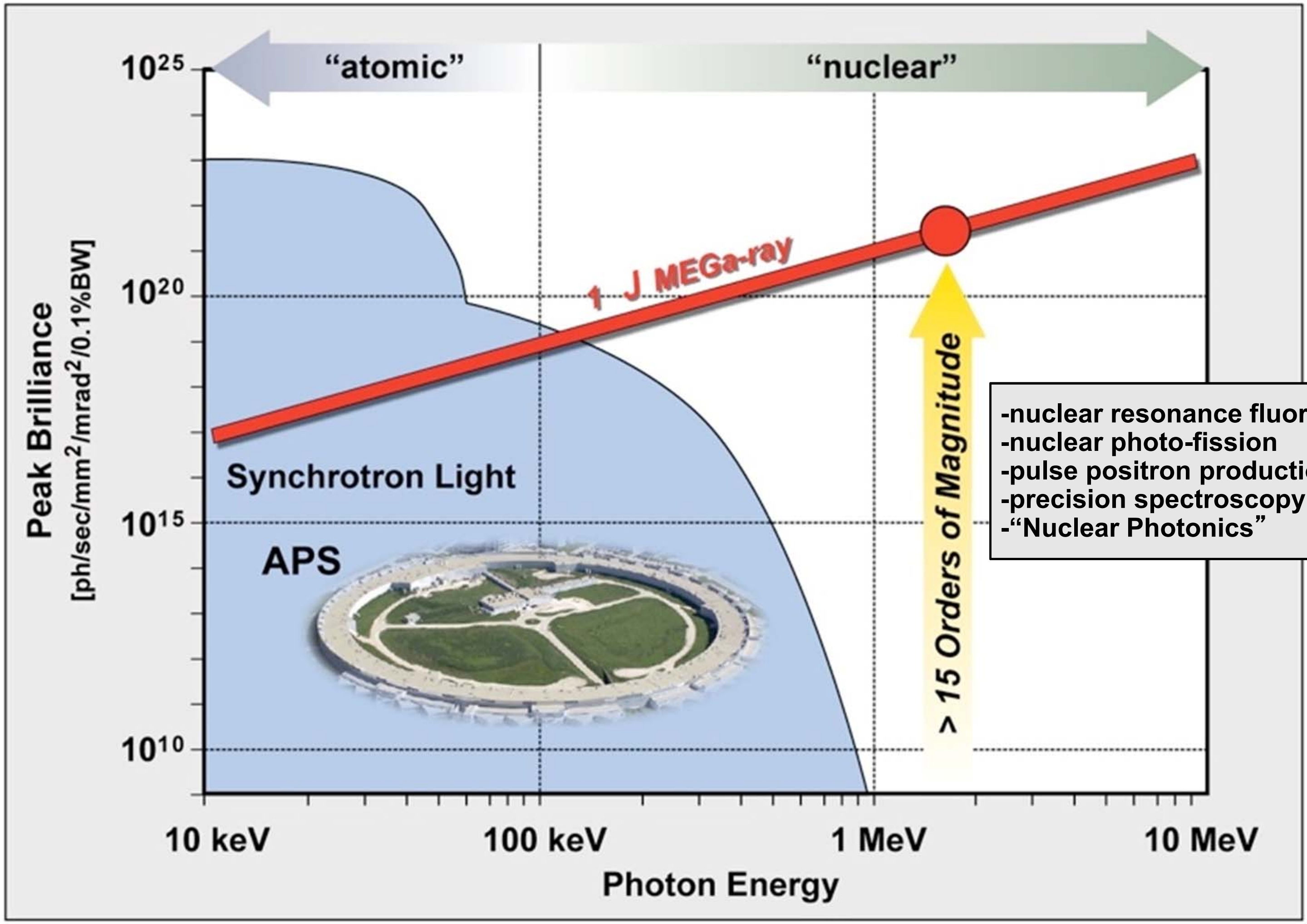


The optimized scattering of laser pulses off of relativistic electrons can create beams of ultra-bright, Mono-Energetic Gamma-rays (MEGa-rays)



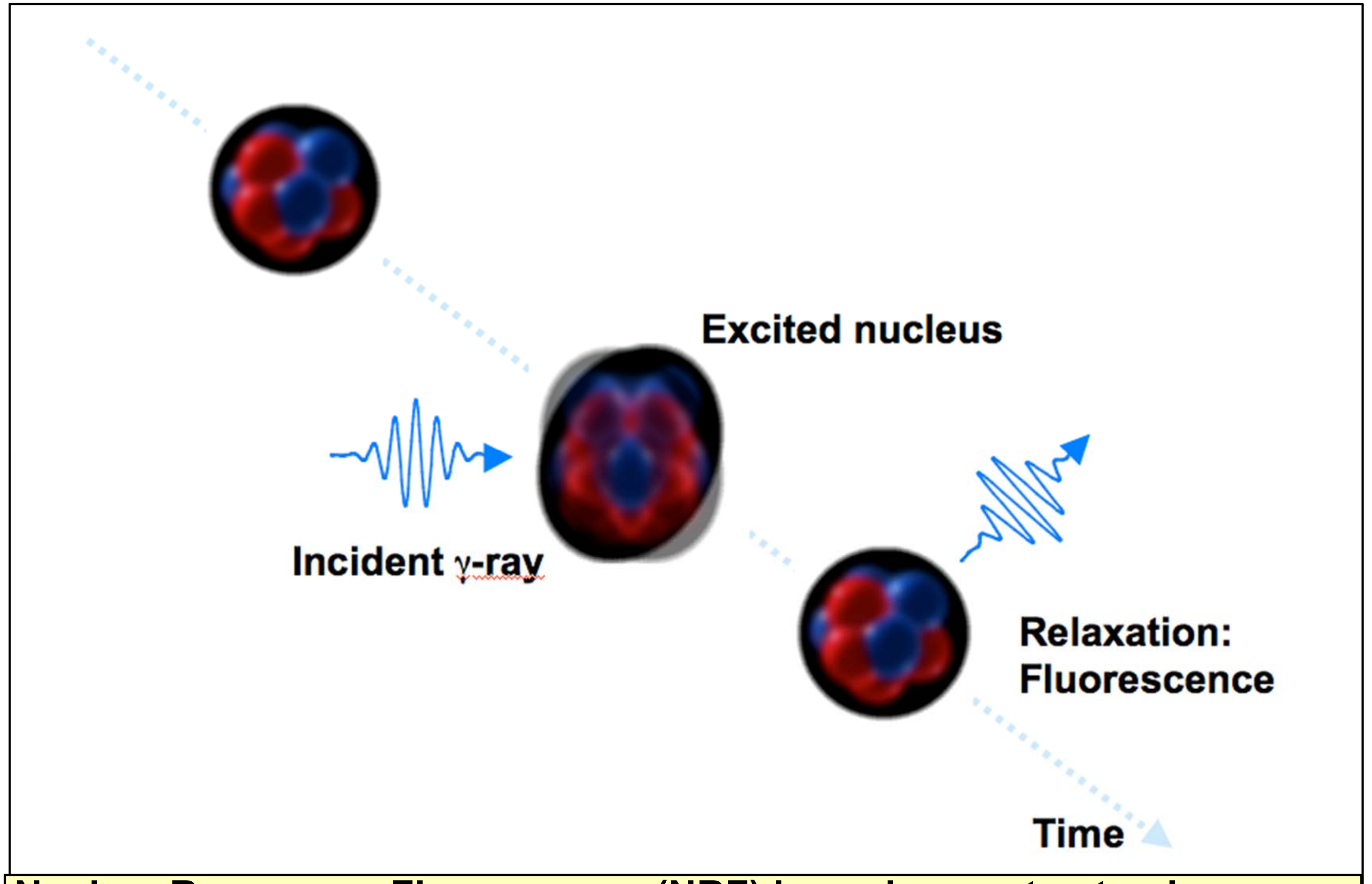
Scattered radiation is Doppler upshifted by more than 1,000,000x and is forwardly-directed in a narrow, polarized, tunable, laser-like beam

The peak brilliance & bandwidth of an optimized MEGa-ray source is revolutionary & transformative



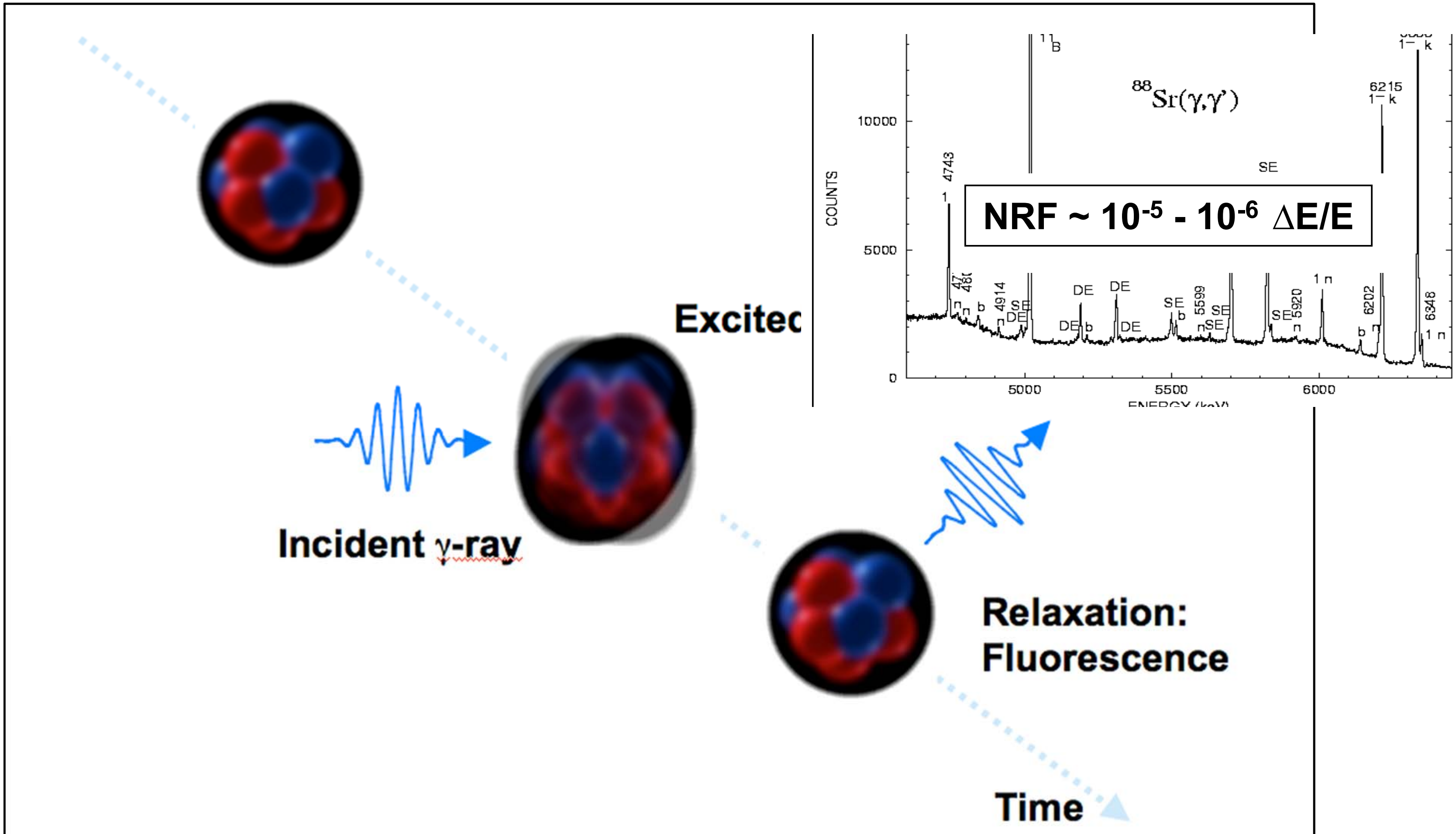
- -nuclear resonance fluorescence
- -nuclear photo-fission
- -pulse positron production
- -precision spectroscopy
- -“Nuclear Photonics”

Gamma-ray absorption & radiation by the nucleus is an "isotope-specific" nuclear signature



Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus

Gamma-ray absorption & radiation by the nucleus is an “isotope-specific” nuclear signature



Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus

MEGa-ray Enabled Isotope-Specific Nuclear Photonics

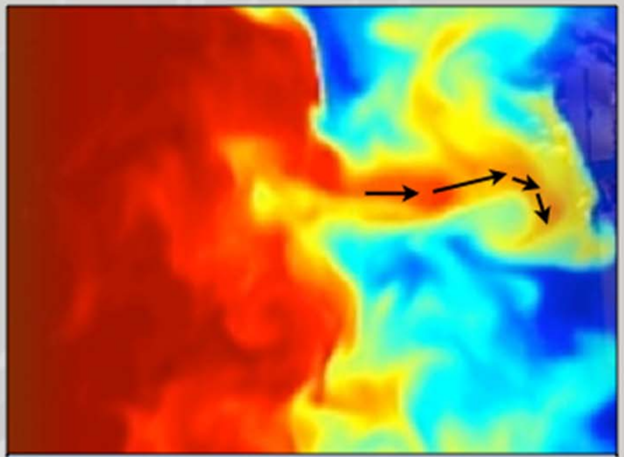
HEU Grand Challenge
detection of shielded material

Nuclear Fuel Assay
100 parts per million per isotope

Waste Imaging & Assay
non-invasive content certification

Stockpile Surveillance
micron-scale & isotope specific

Medical Imaging
low density & isotope specific



HED Science
isotope mass, position & velocity

US patent #7,564,241

MEGa-ray Enabled Isotope-Specific Nuclear Photonics

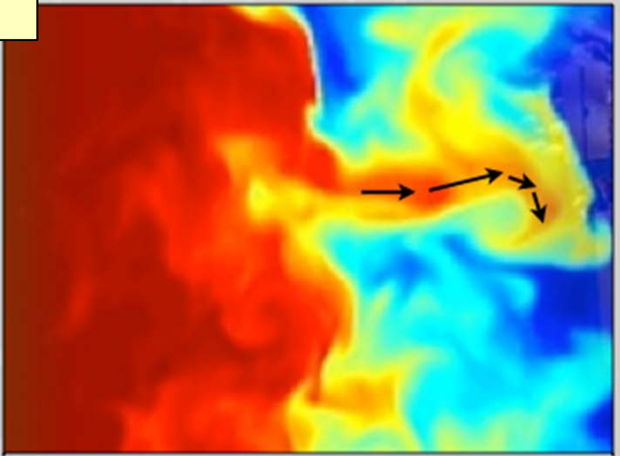
HEU Grand Challenge
detection of shielded material

Waste Imaging & Assay
non-invasive content certification

- **Spectral Flux: photons/s/eV**
- **Bandwidth**
- **Real world architecture**

Stockpile Surveillance
micron-scale & isotope specific

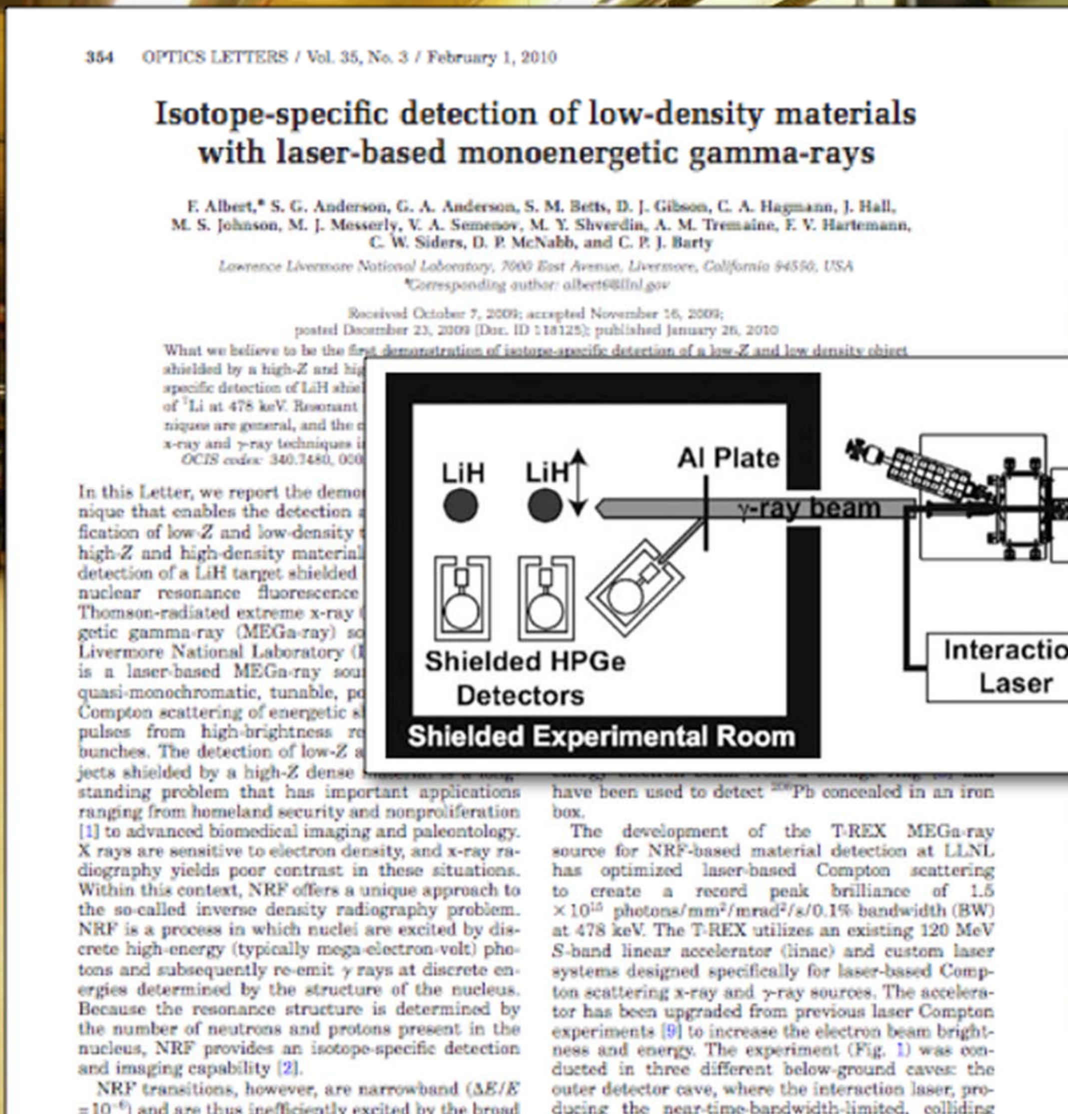
Medical Imaging
low density & isotope specific



HED Science
isotope mass, position & velocity

US patent #7,564,241

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



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Isotope-specific detection of low-density materials with laser-based monoenergetic gamma-rays

F. Albert,* S. G. Anderson, G. A. Anderson, S. M. Betts, D. J. Gibson, C. A. Hagmann, J. Hall, M. S. Johnson, M. J. Messerly, V. A. Semenov, M. Y. Shverdin, A. M. Tremaine, F. V. Hartemann, C. W. Siders, D. P. McNabb, and C. P. J. Barty

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550, USA

*Corresponding author: albert6@llnl.gov

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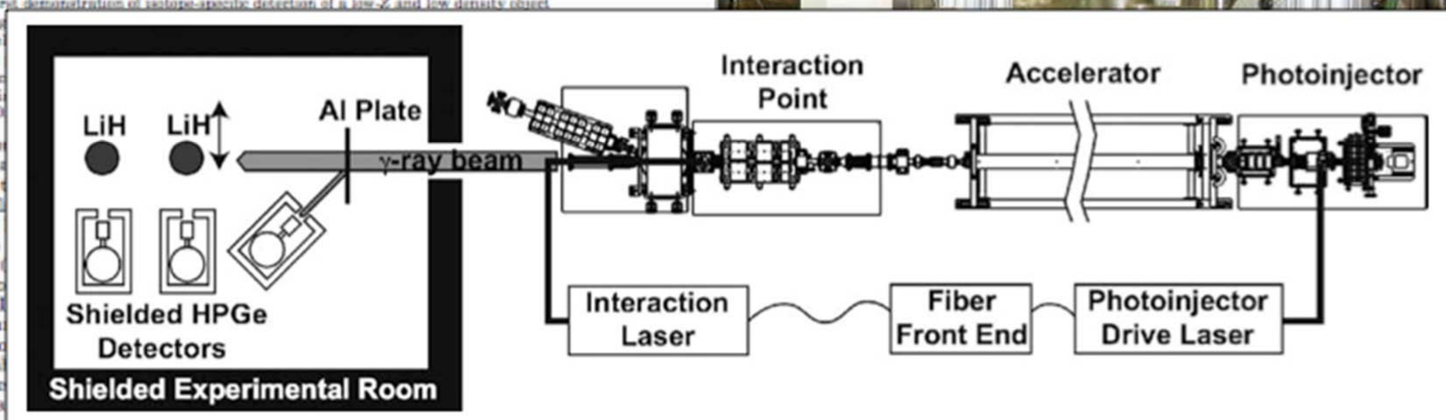
What we believe to be the first demonstration of isotope-specific detection of a low-Z and low density object
shielded by a high-Z and hig
specific detection of LiH shie
of ^{7}Li at 478 keV. Resonant
niques are general, and the c
x-ray and γ-ray techniques i
OCIS codes: 340.7480, 000

In this Letter, we report the demo
nique that enables the detection a
fication of low-Z and low-density t
high-Z and high-density material
detection of a LiH target shielded
nuclear resonance fluorescence
Thomson-radiated extreme x-ray (
getic gamma-ray (MEGa-ray) so
Livermore National Laboratory (I
is a laser-based MEGa-ray sou
quasi-monochromatic, tunable, po
Compton scattering of energetic sl
pulses from high-brightness re
bunches. The detection of low-Z a
jects shielded by a high-Z dense
standing problem that has important applications ranging from homeland security and nonproliferation [1] to advanced biomedical imaging and paleontology. X rays are sensitive to electron density, and x-ray radiography yields poor contrast in these situations. Within this context, NRF offers a unique approach to the so-called inverse density radiography problem. NRF is a process in which nuclei are excited by discrete high-energy (typically mega-electron-volt) photons and subsequently re-emit γ rays at discrete energies determined by the structure of the nucleus. Because the resonance structure is determined by the number of neutrons and protons present in the nucleus, NRF provides an isotope-specific detection and imaging capability [2].

NRF transitions, however, are narrowband ($\Delta E/E = 10^{-6}$) and are thus inefficiently excited by the broad

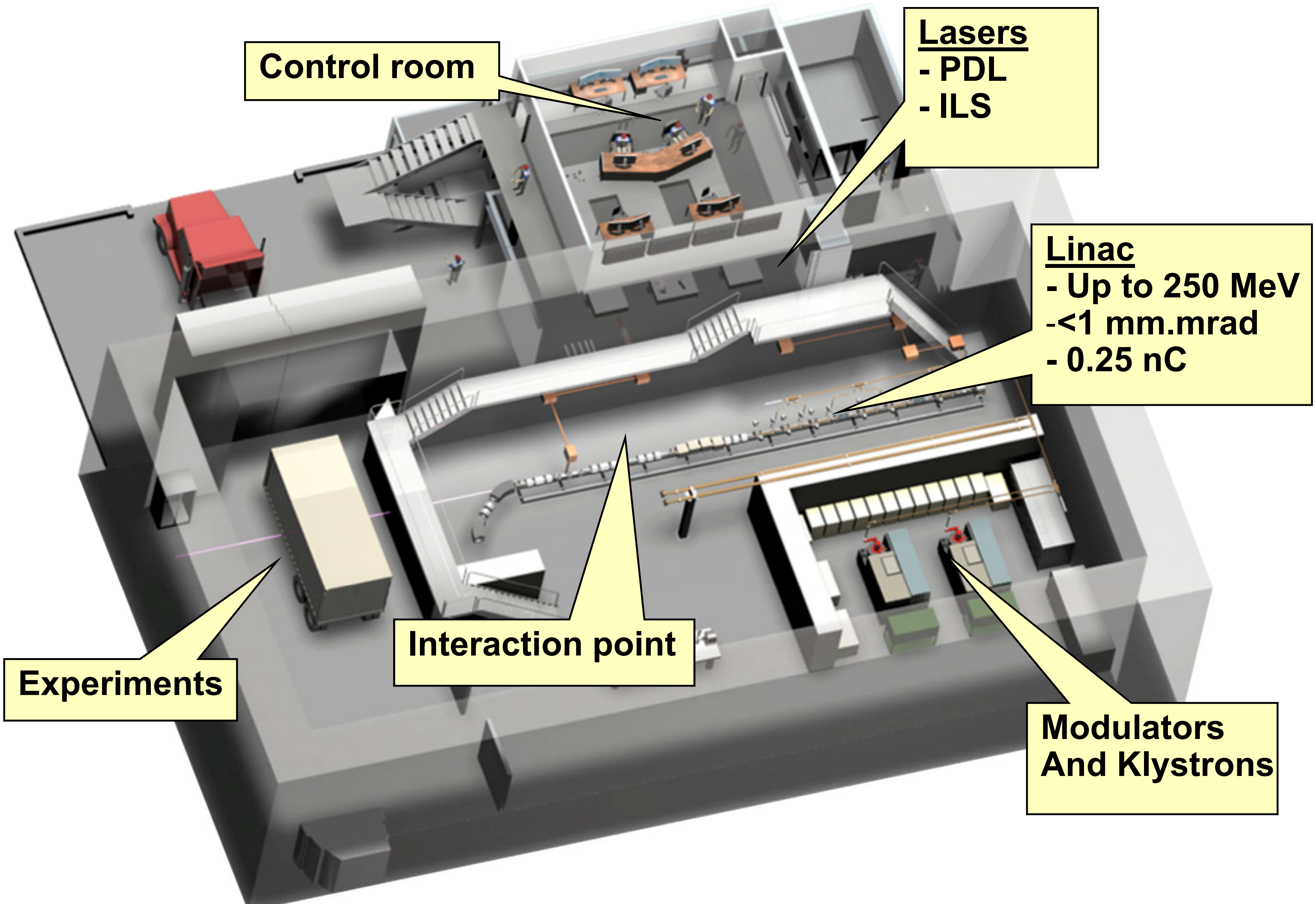
have been used to detect ^{208}Pb concealed in an iron box.

The development of the T-REX MEGa-ray source for NRF-based material detection at LLNL has optimized laser-based Compton scattering to create a record peak brilliance of 1.5×10^{15} photons/mm^2/mrad^2/s/0.1% bandwidth (BW) at 478 keV. The T-REX utilizes an existing 120 MeV *S*-band linear accelerator (linac) and custom laser systems designed specifically for laser-based Compton scattering x-ray and γ-ray sources. The accelerator has been upgraded from previous laser Compton experiments [9] to increase the electron beam brightness and energy. The experiment (Fig. 1) was conducted in three different below-ground caves: the outer detector cave, where the interaction laser, producing the near-time-bandwidth-limited, colliding

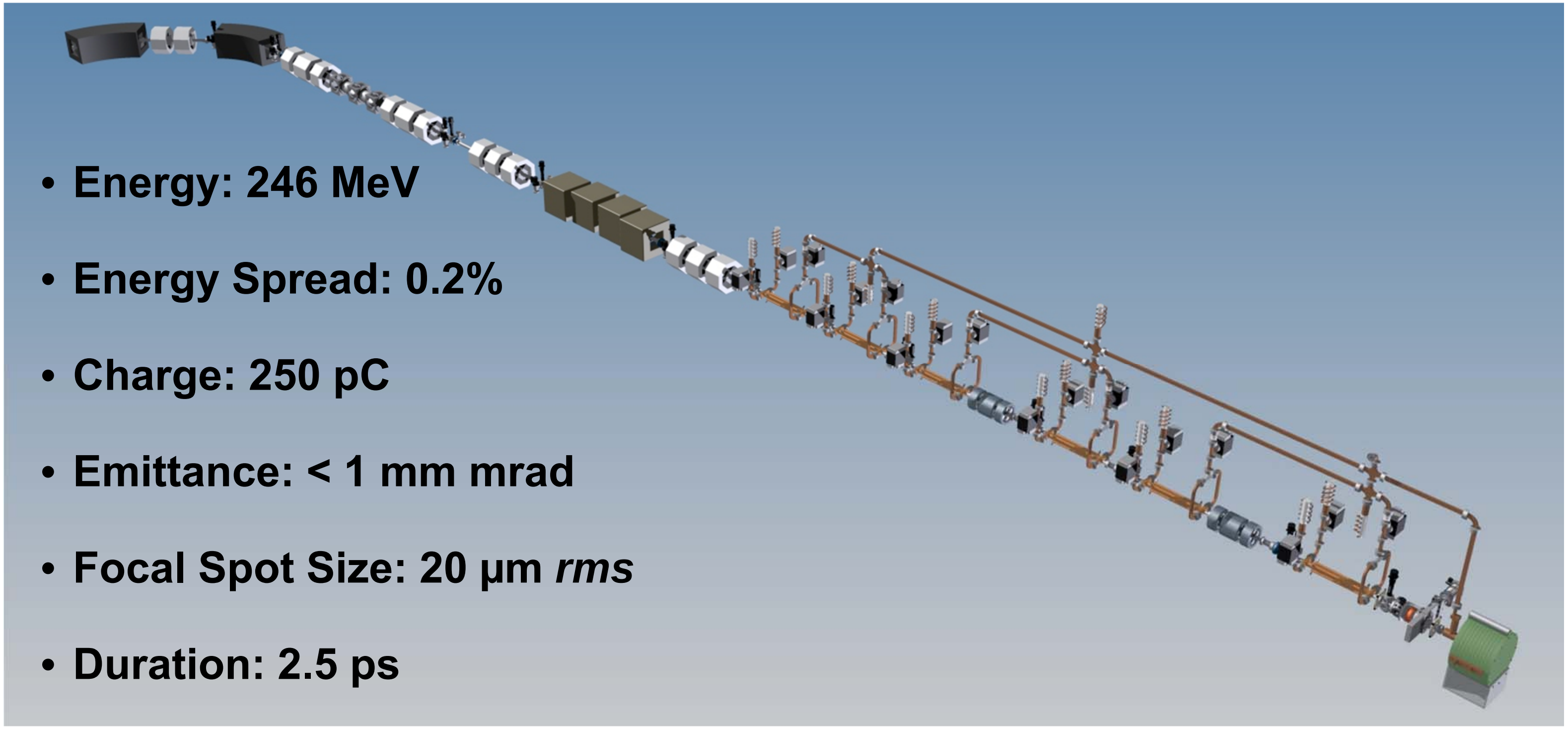


2008 World's highest peak 'brilliance'
0.5 MeV - 1 MeV beam

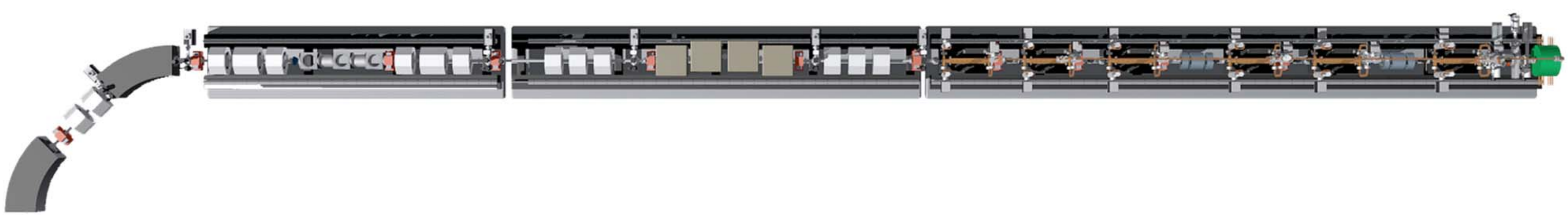
To achieve precision gamma-rays we need a robust laser and linac platform



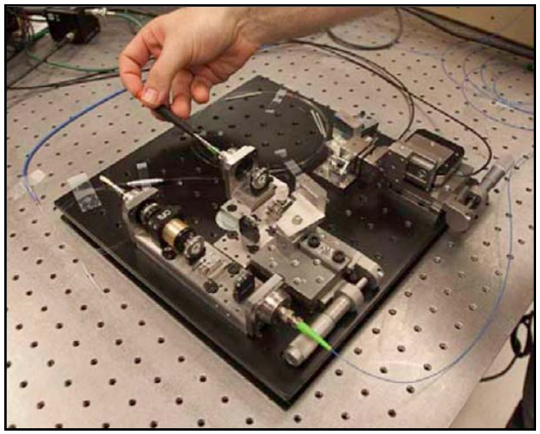
VELOCIRAPTOR 250 MeV X-band Linac

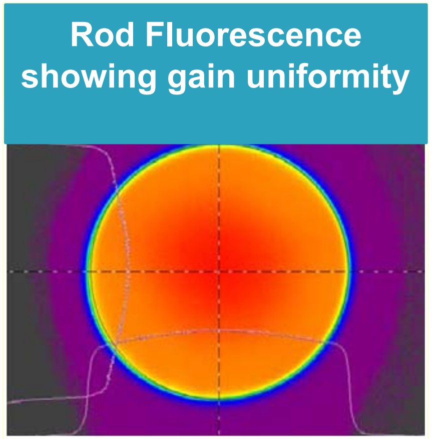


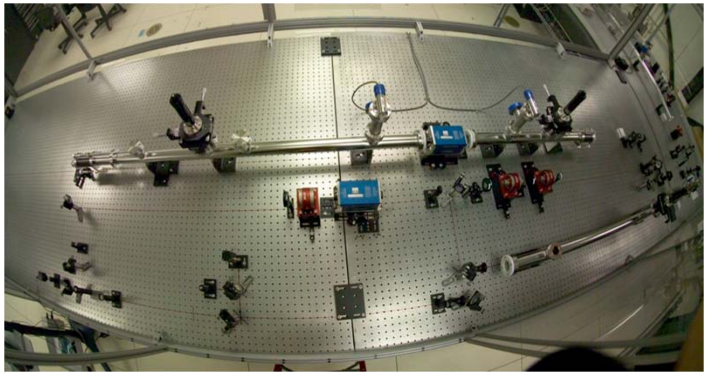
- **Energy: 246 MeV**
- **Energy Spread: 0.2%**
- **Charge: 250 pC**
- **Emittance: < 1 mm mrad**
- **Focal Spot Size: 20 µm *rms***
- **Duration: 2.5 ps**

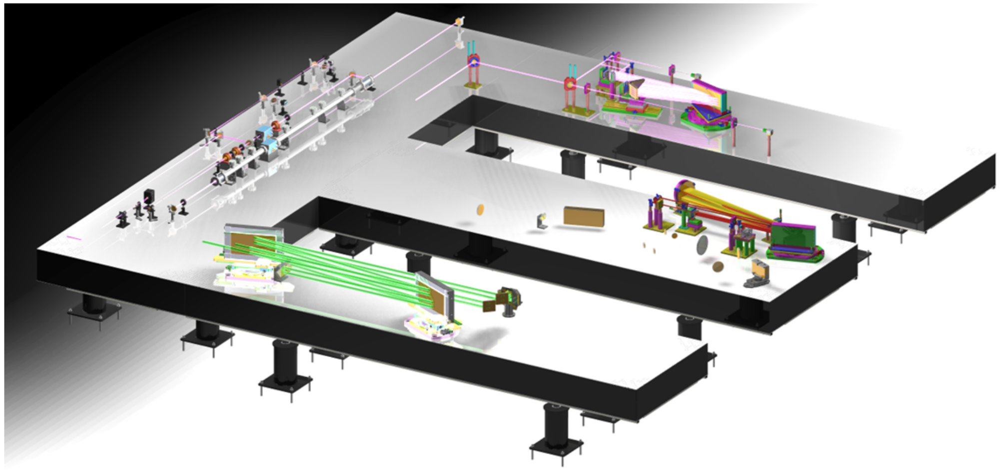


Current status of Nuclear Photonics laser systems

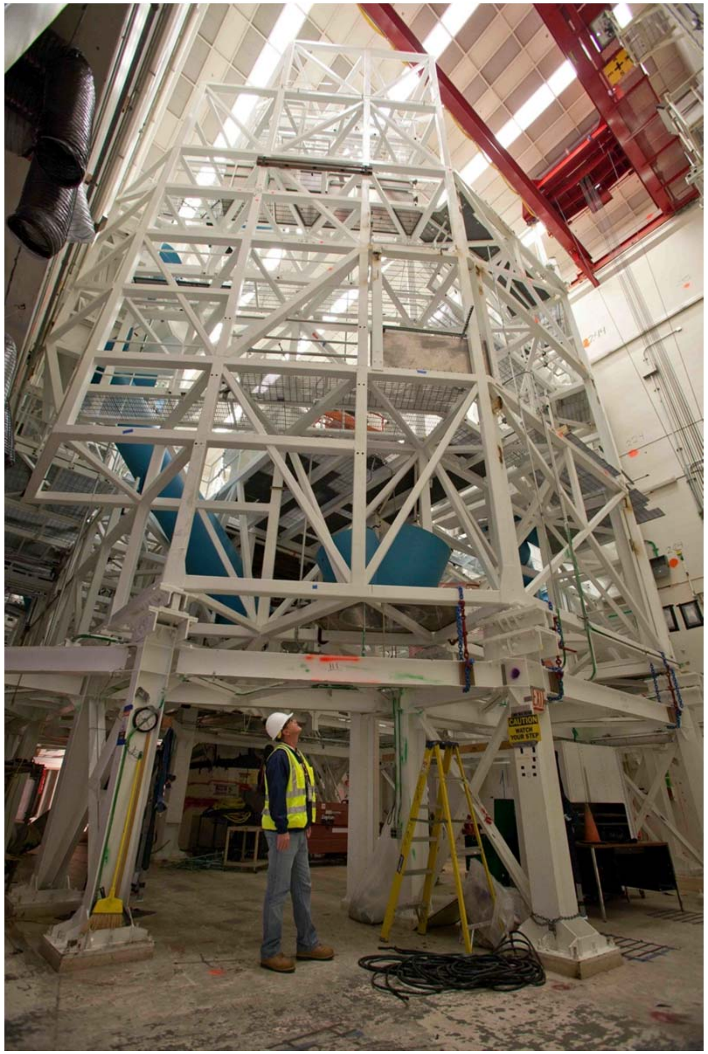


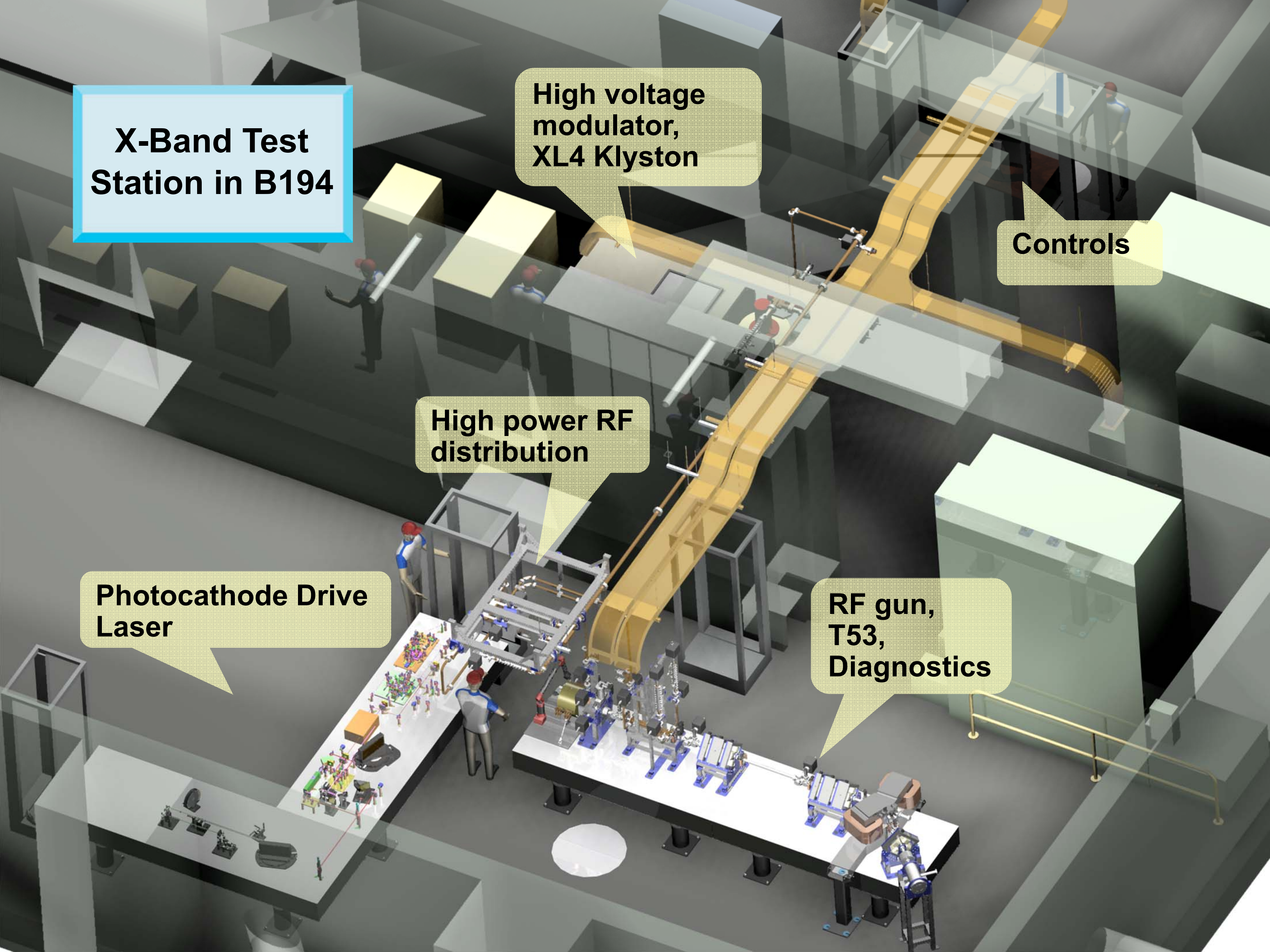




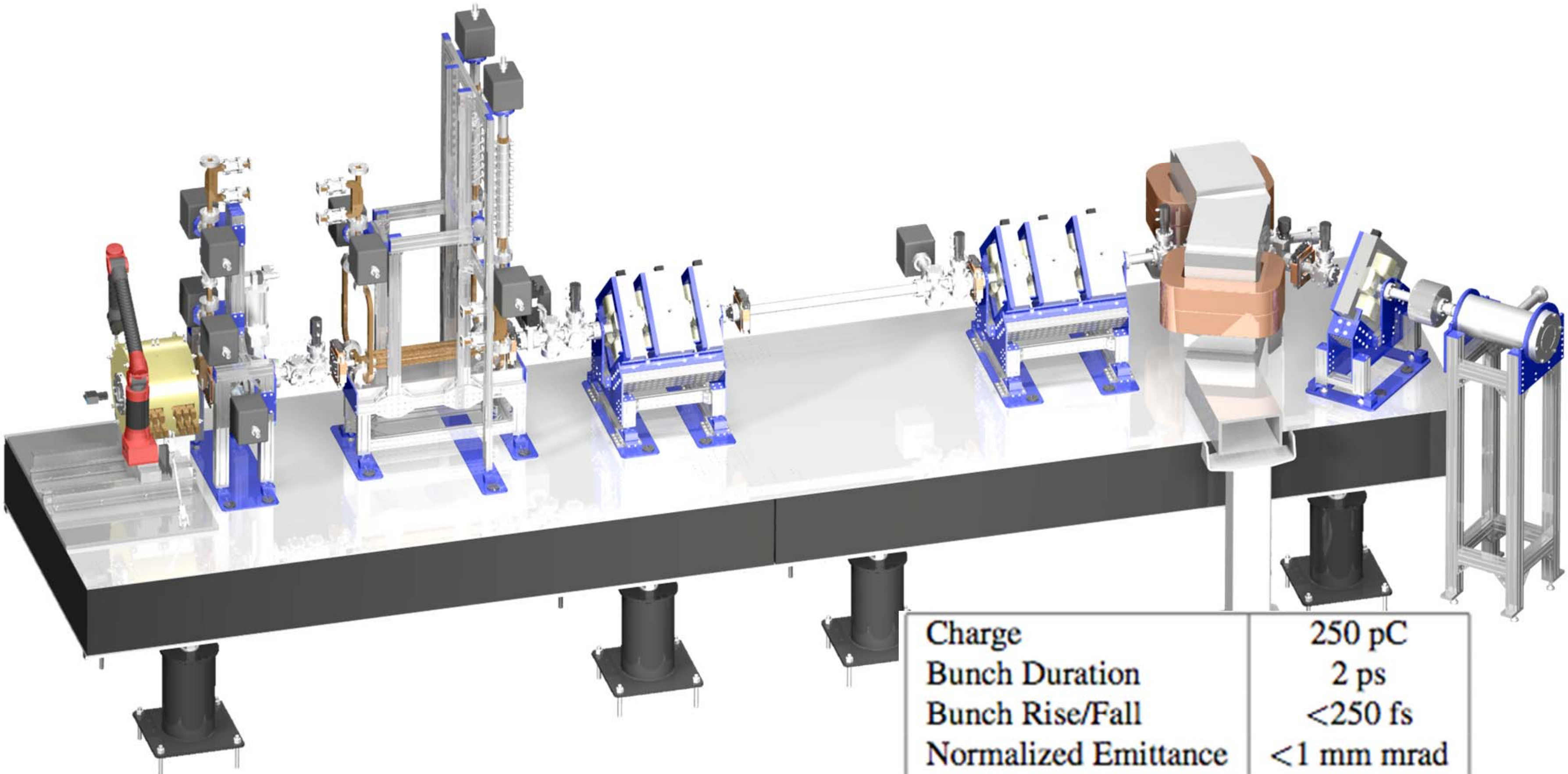


High Bay Decontamination and Demolition



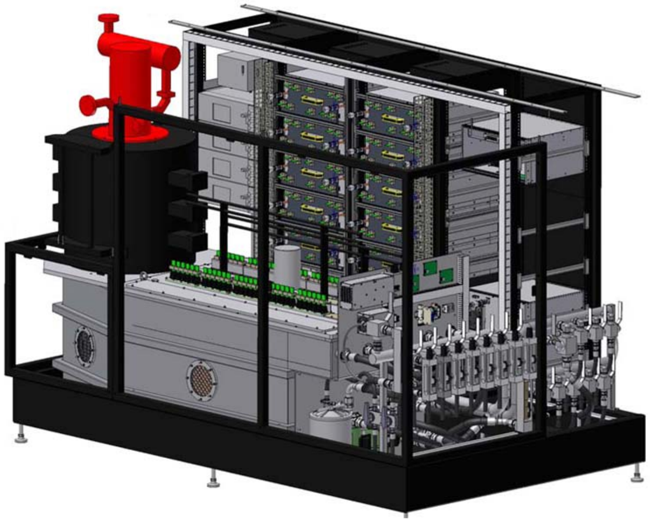

X-Band Test Station in B194
High voltage modulator, XL4 Klyston
Controls
High power RF distribution
Photocathode Drive Laser
RF gun, T53, Diagnostics

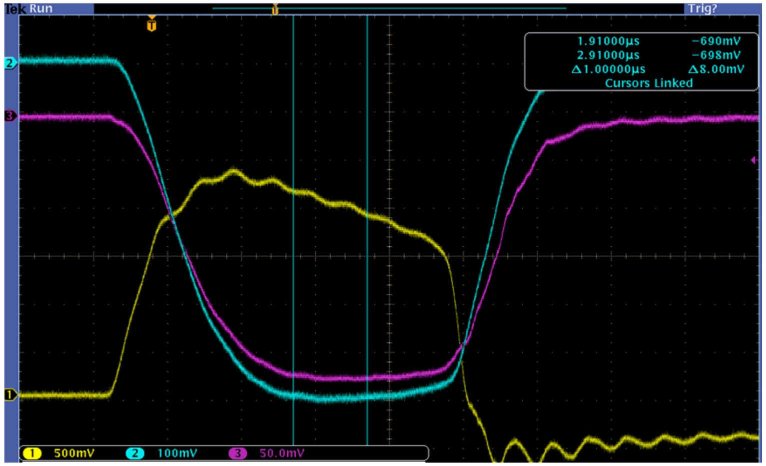
X-band Test Station



Charge	250 pC
Bunch Duration	2 ps
Bunch Rise/Fall	<250 fs
Normalized Emittance	<1 mm mrad
Gun Energy	7 MeV
Cathode Field	200 MV/m
Coupling β	1.7
Section Gradient	~70 MV/m
Final Energy	30–50 MeV

Solid-state modulator has been installed and tested into low average power load at LLNL





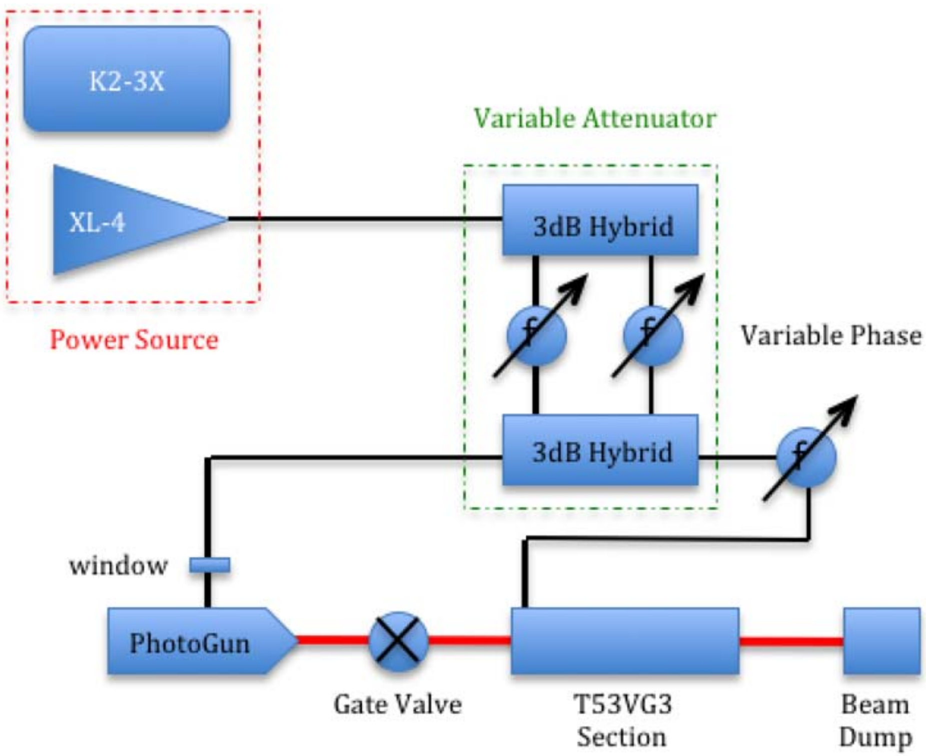
LLNL XL4 fabricated, commissioned and tested at SLAC, and has now been delivered to LLNL

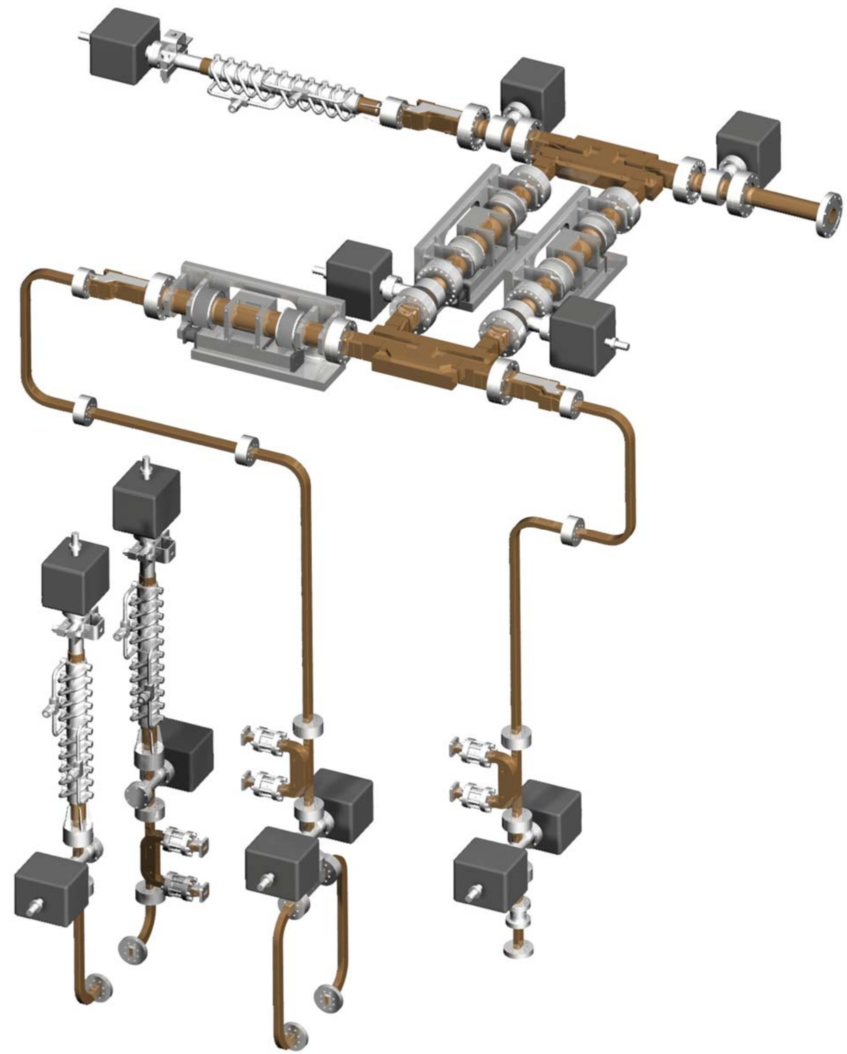
Klystron installation begins this week: lift, dress, move, install

Frequency	11.424 GHz
Beam voltage	427 kV
Perveance	1.09 $\mu A/V^{3/2}$
Max RF pulselength	1.5 μs
Saturated power	50 MW
RF drive	700 W
Gain	49 dB
Efficiency	41%
-3dB bandwidth	50 MHz
Cathode heater current	22 A
Vacuum level	10^{-9} Torr

Flexible RF Distribution will use a single RF source to power both the RF gun and T53 linac

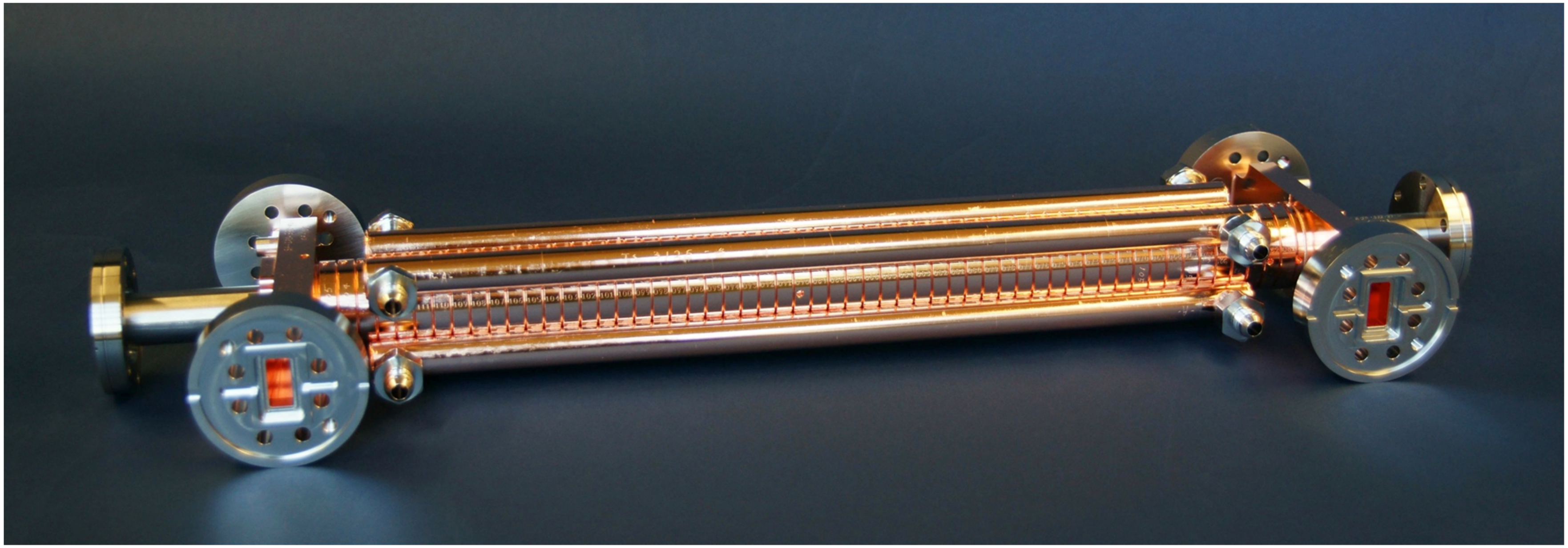
All major parts designed, fabricated, and awaiting installation





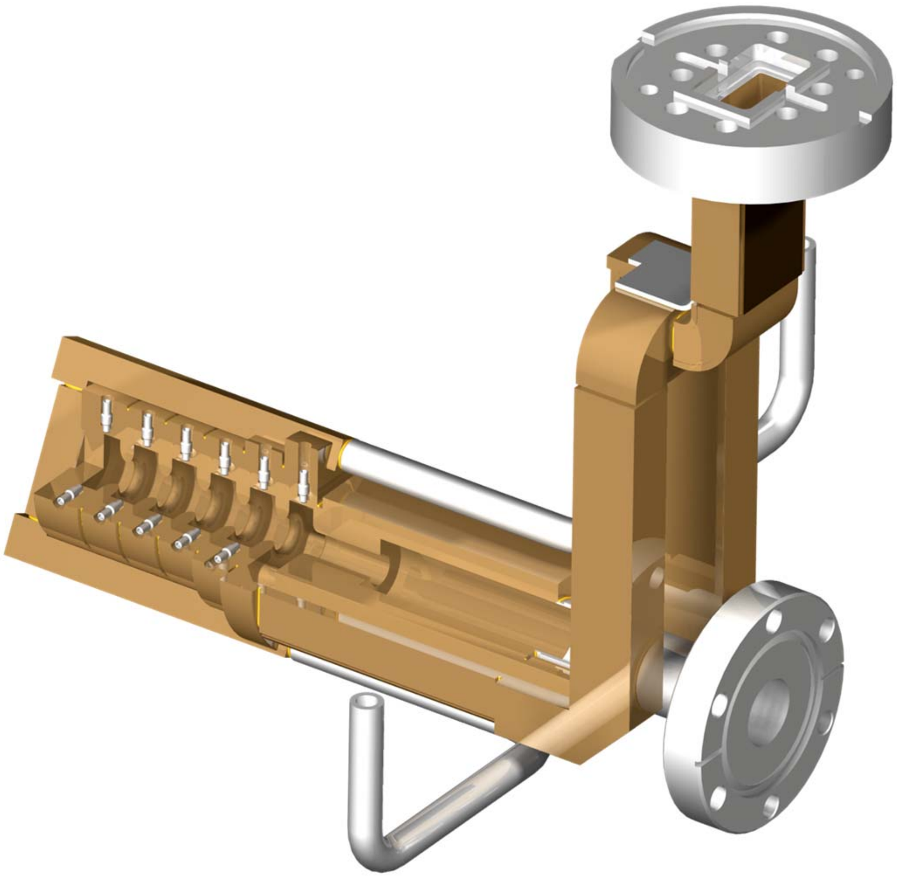
T53 Accelerator section had coupler redesign for lower emittance operation, and is completed

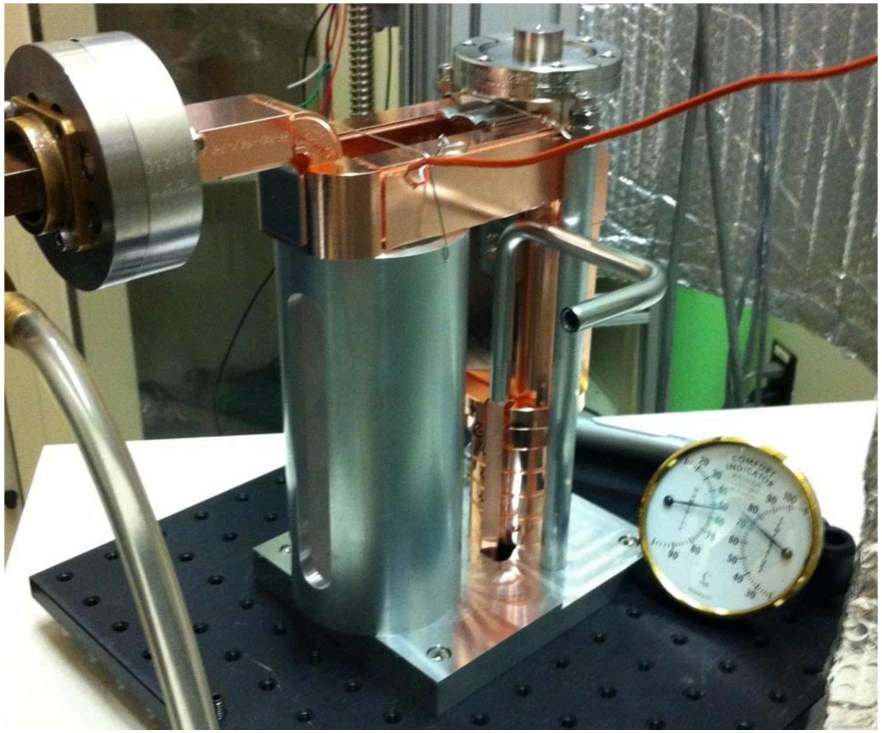
Achieved over 90 MV/m gradient with very low breakdown rates



LLNL/SLAC developed single bunch high brightness RF photoinjector

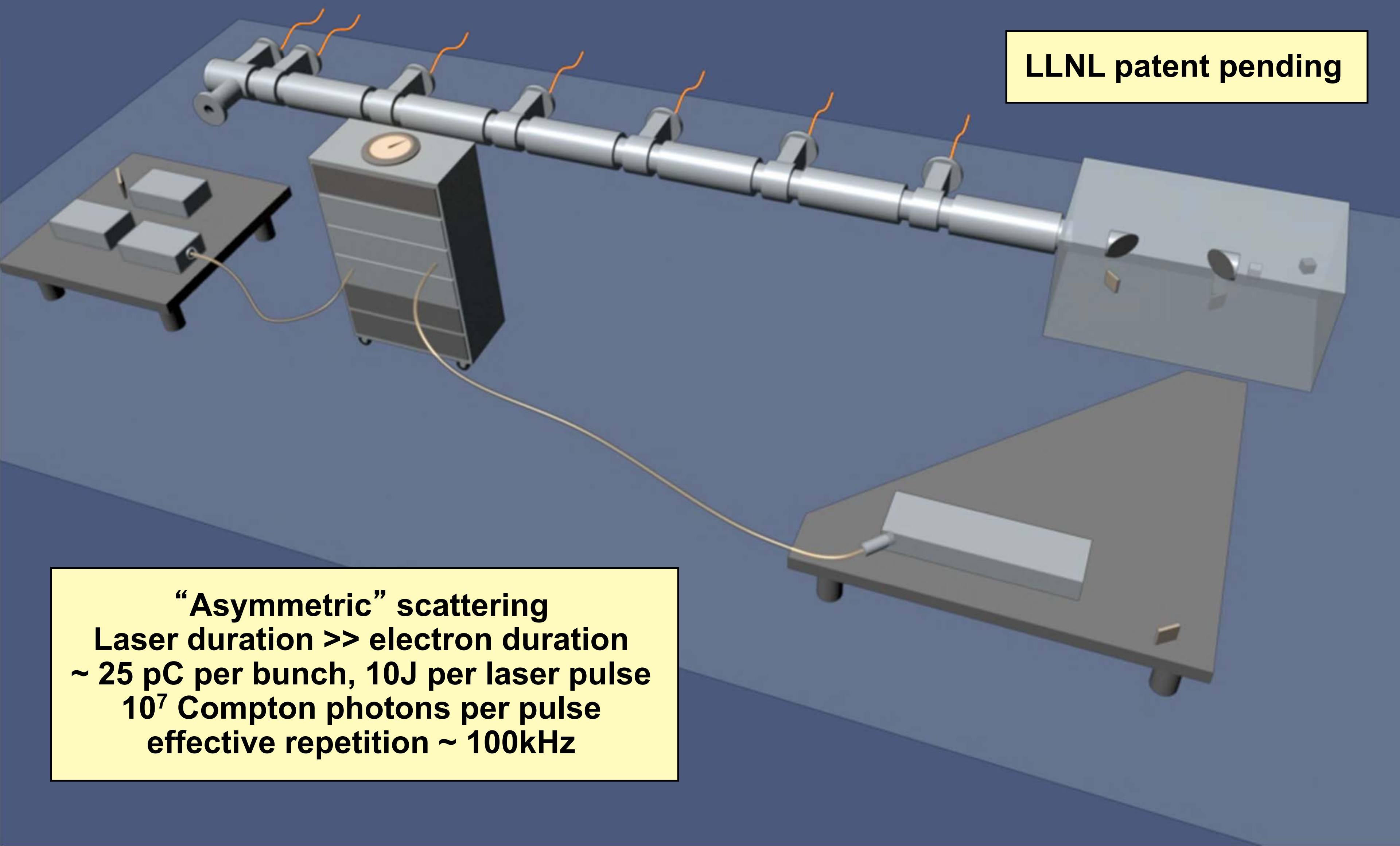
X-band RF gun has been fabricated, tuned, vacuum baked and delivered to LLNL





LLNL's asymmetrical laser-electron Compton scattering configuration further reduces the bandwidth & increases flux of MEGa-ray sources

LLNL patent pending



"Asymmetric" scattering
Laser duration >> electron duration
~ 25 pC per bunch, 10J per laser pulse
10^7 Compton photons per pulse
effective repetition ~ 100kHz

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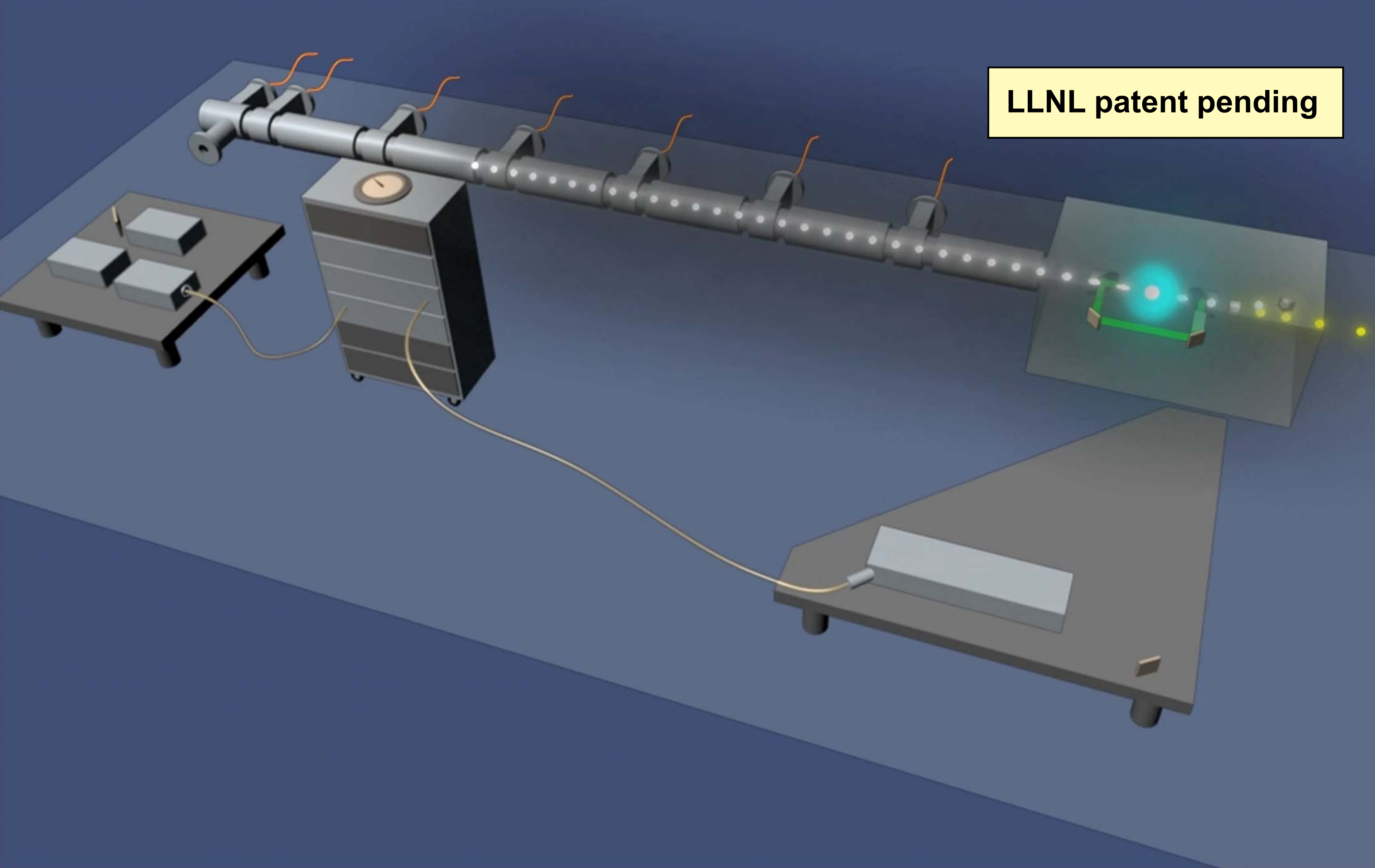

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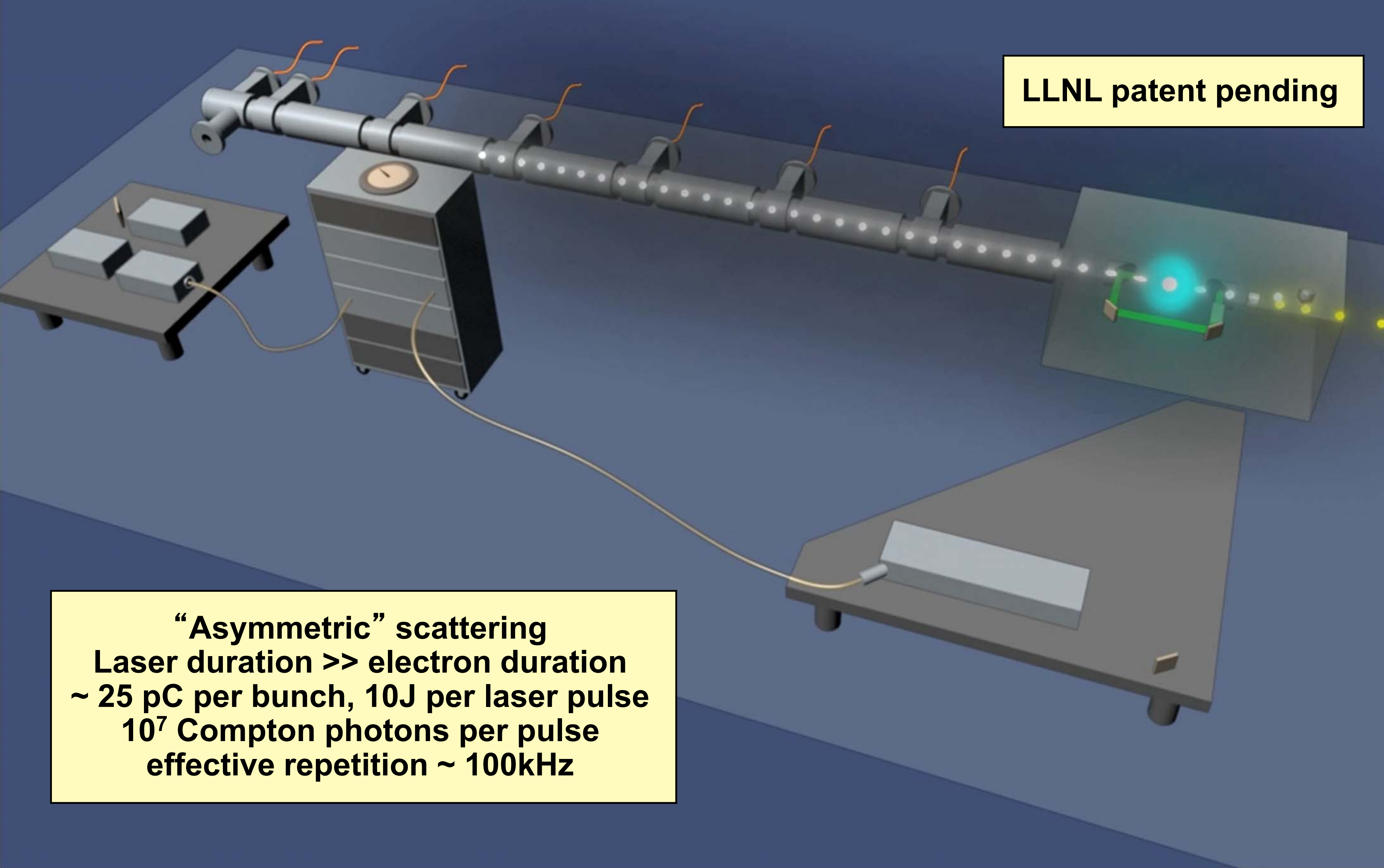

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Photocathode Drive Laser Specifications

Parameter	Cu cathode (baseline)	Mg cathode (high efficiency)
Micro-pulses per macro-pulse	1,000	1,000
Beam quality, M^2	< 1.1	< 1.1
Micro-pulse specifications		
Repetition rate	11.424 GHz	11.424 GHz
Duration	250 fs	250 fs
Energy @ 260 nm	5 µJ	0.5 µJ
Energy at 1040 nm	50 µJ	5 µJ
Macro-pulse specifications		
Repetition rate	120 Hz	120 Hz
Duration	87.5 ns	87.5 ns
Energy @ 260 nm	5 mJ	0.5 mJ
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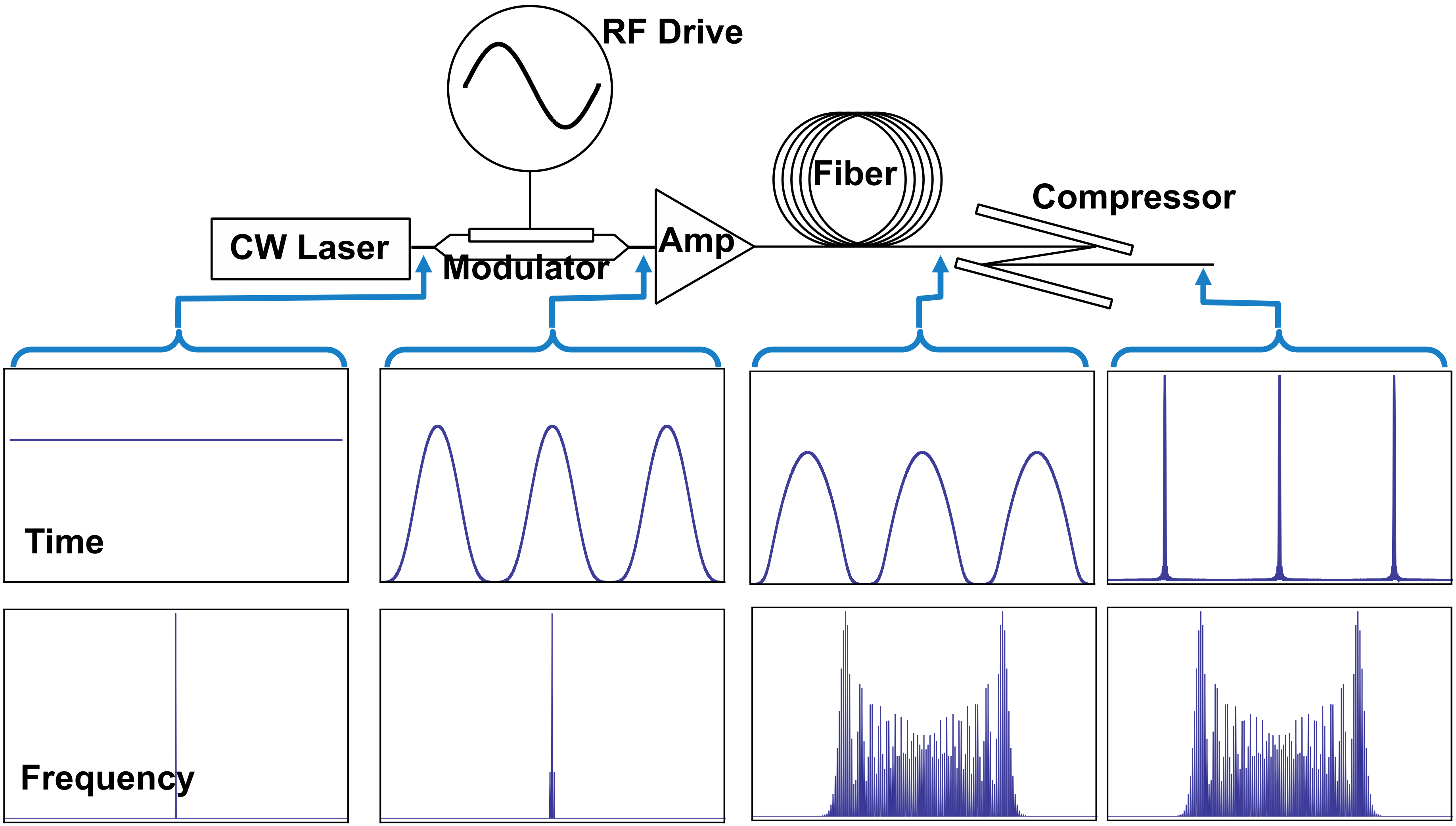
really hard

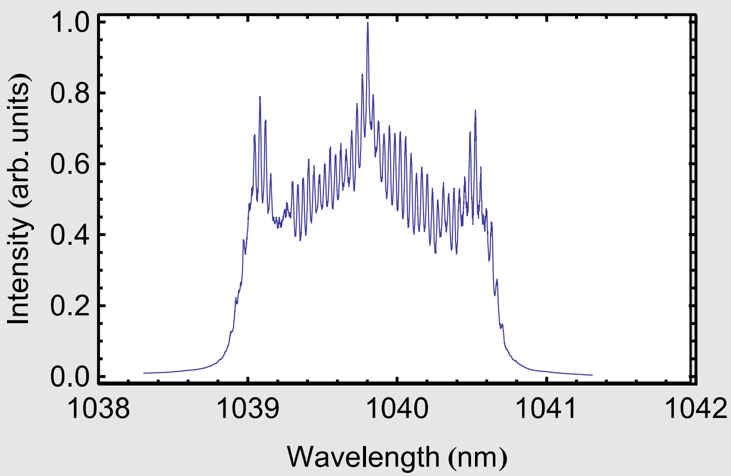
demonstrated at 1MHz

11.424 GHz Photocathode Drive Laser concept: generate bandwidth using self phase modulation



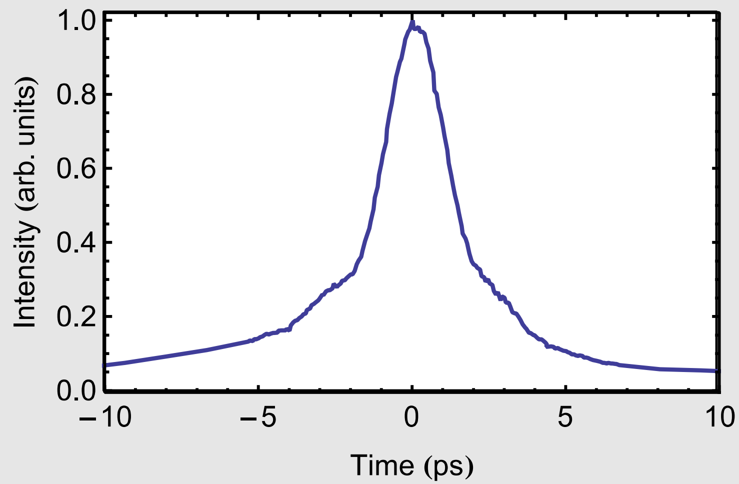
GHz laser demonstration status

Pulse train spectrum



Generated 1.5 nm of bandwidth

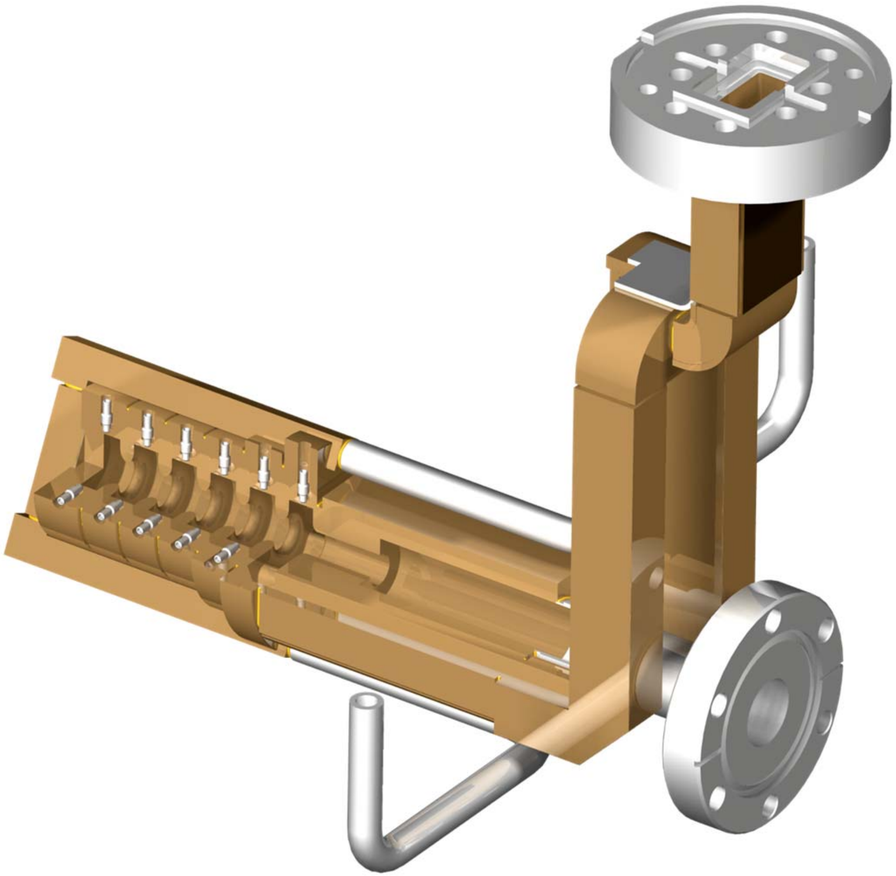
Pulse train autocorrelation

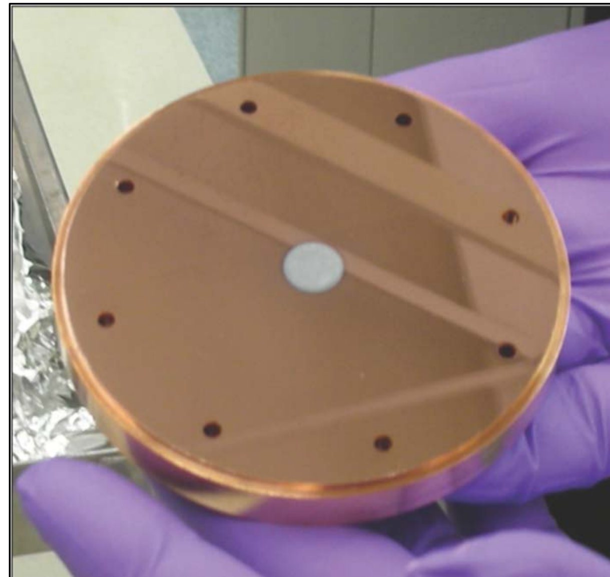


Compressed pulse to ~2 ps

- **Current specs: 1.7 nJ in 2 ps at 10 GHz, 100 ns macropulses at 20 kHz.**
- **Currently finishing comparison of ps pulses and verifying SPM models.**
- **Next step: add more amplification to increase both the energy and bandwidth at the system output.**

LLNL/SLAC developed a single bunch high brightness RF photoinjector for X-band test station



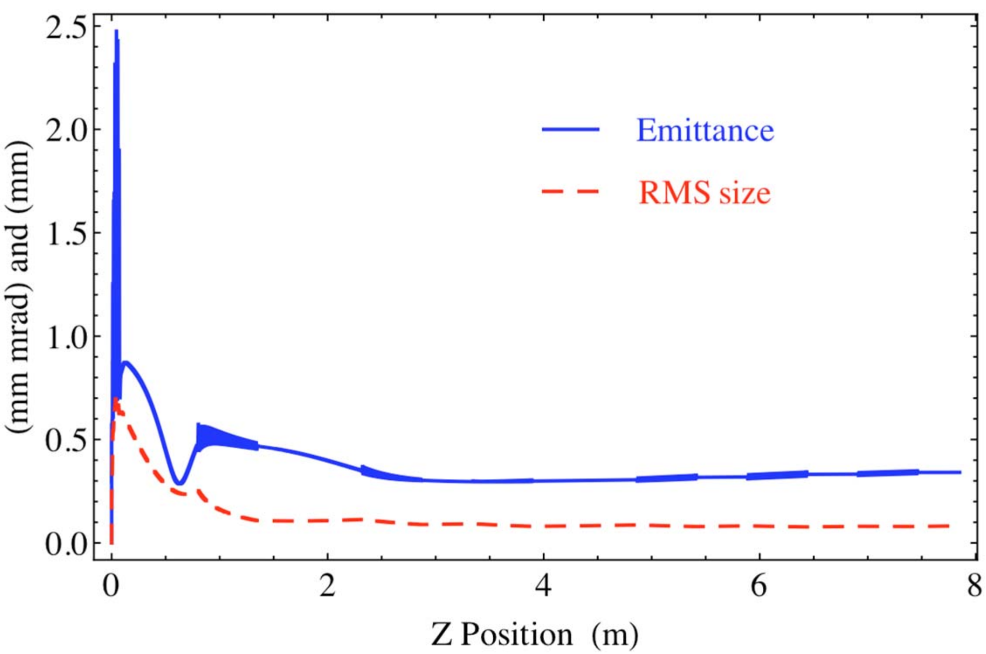


2 μm of Mg is sputtered in a 1 cm diameter spot on the Cu back plane of the photoinjector

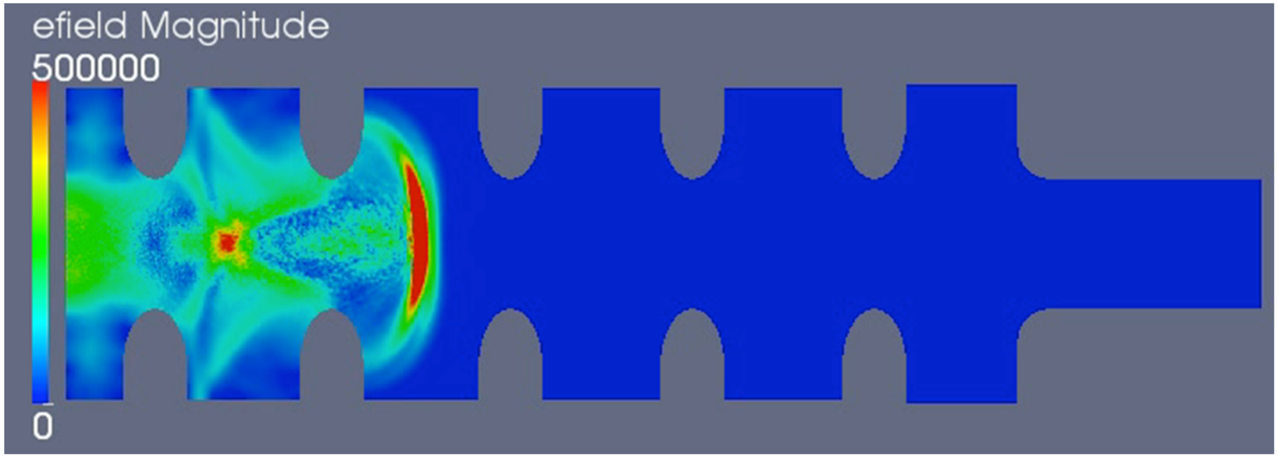
The next step is to test this RF gun and design a removable photocathode version so that we can change the cathode material

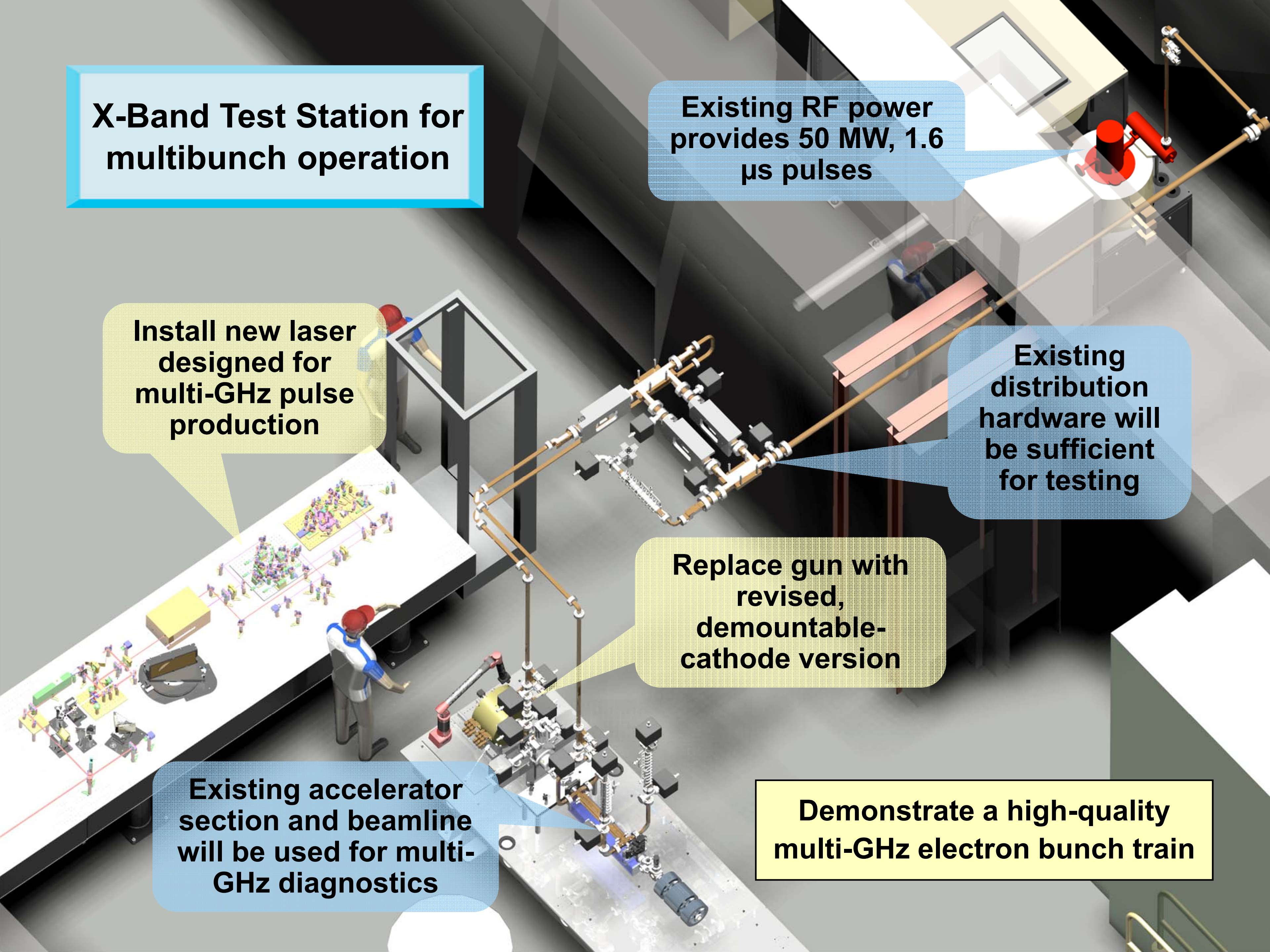
Dropping the per-bunch charge from 250 pC to 25 pC will lower the emittance and energy spread

PARMELA modeling of full 250 MeV linac with reduced charge show promising scaling

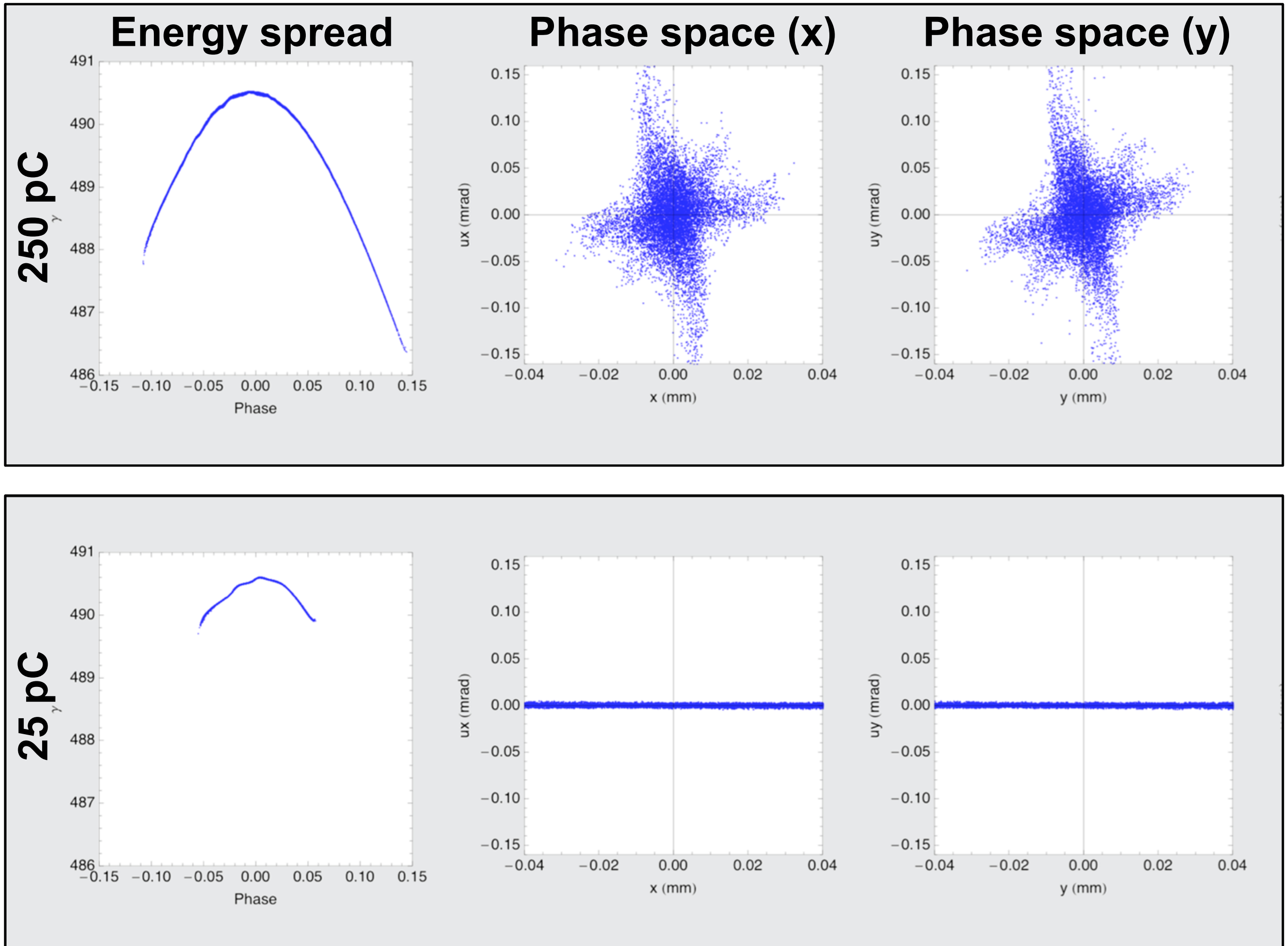


ACE3P Results using both: times domain (T3P), and Particle-in-cell (PIC3P) codes




X-Band Test Station for multibunch operation
Existing RF power provides 50 MW, 1.6 μs pulses
Install new laser designed for multi-GHz pulse production
Existing distribution hardware will be sufficient for testing
Replace gun with revised, demountable-cathode version
Existing accelerator section and beamline will be used for multi-GHz diagnostics
Demonstrate a high-quality multi-GHz electron bunch train

PARMELA: low charge electron bunches yield lower normalized emittance and energy spread

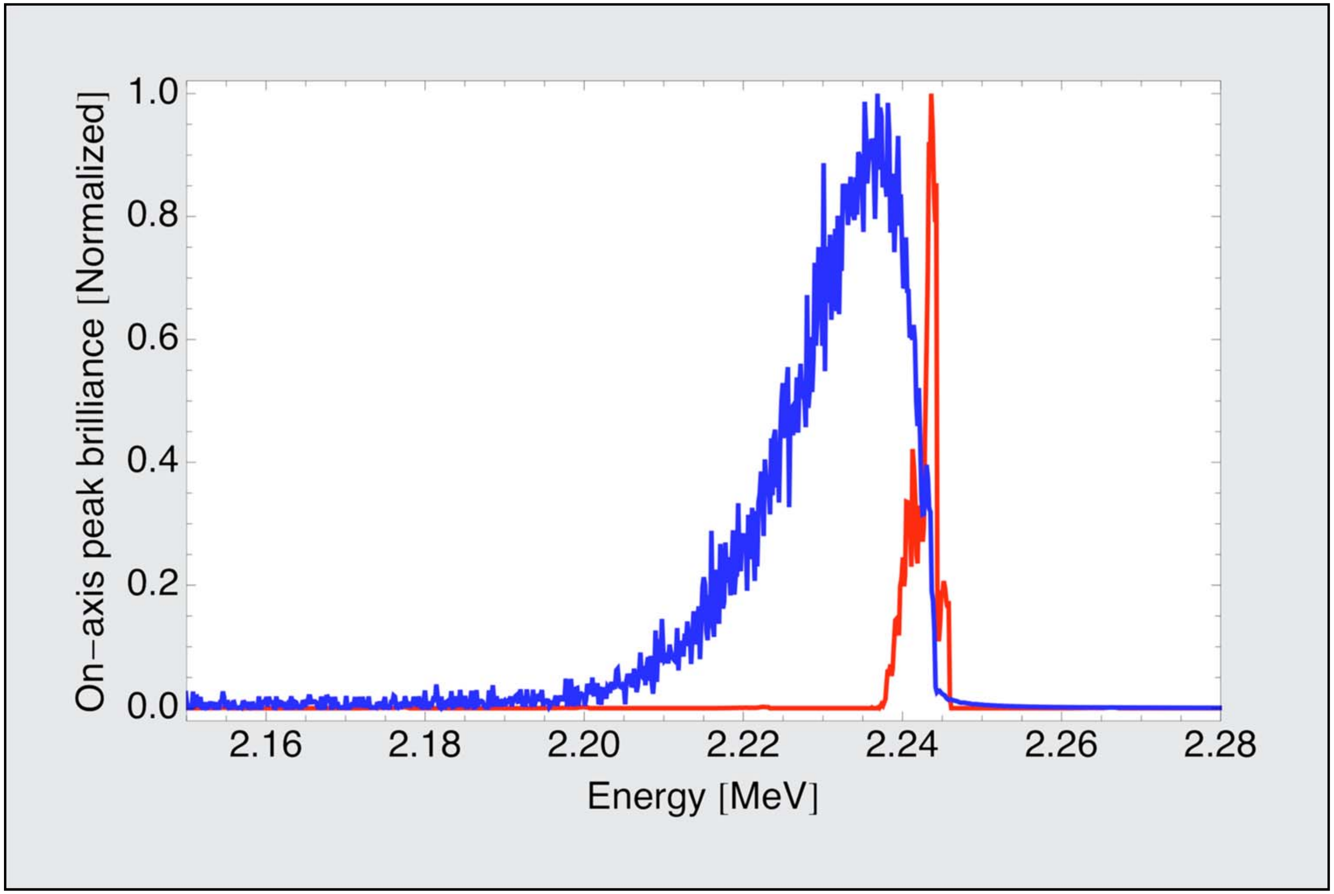


⊗©/© = 0.16%
$\sum_n$= 0.35 mm.mrad

$\theta/\sum_n^2$= constant

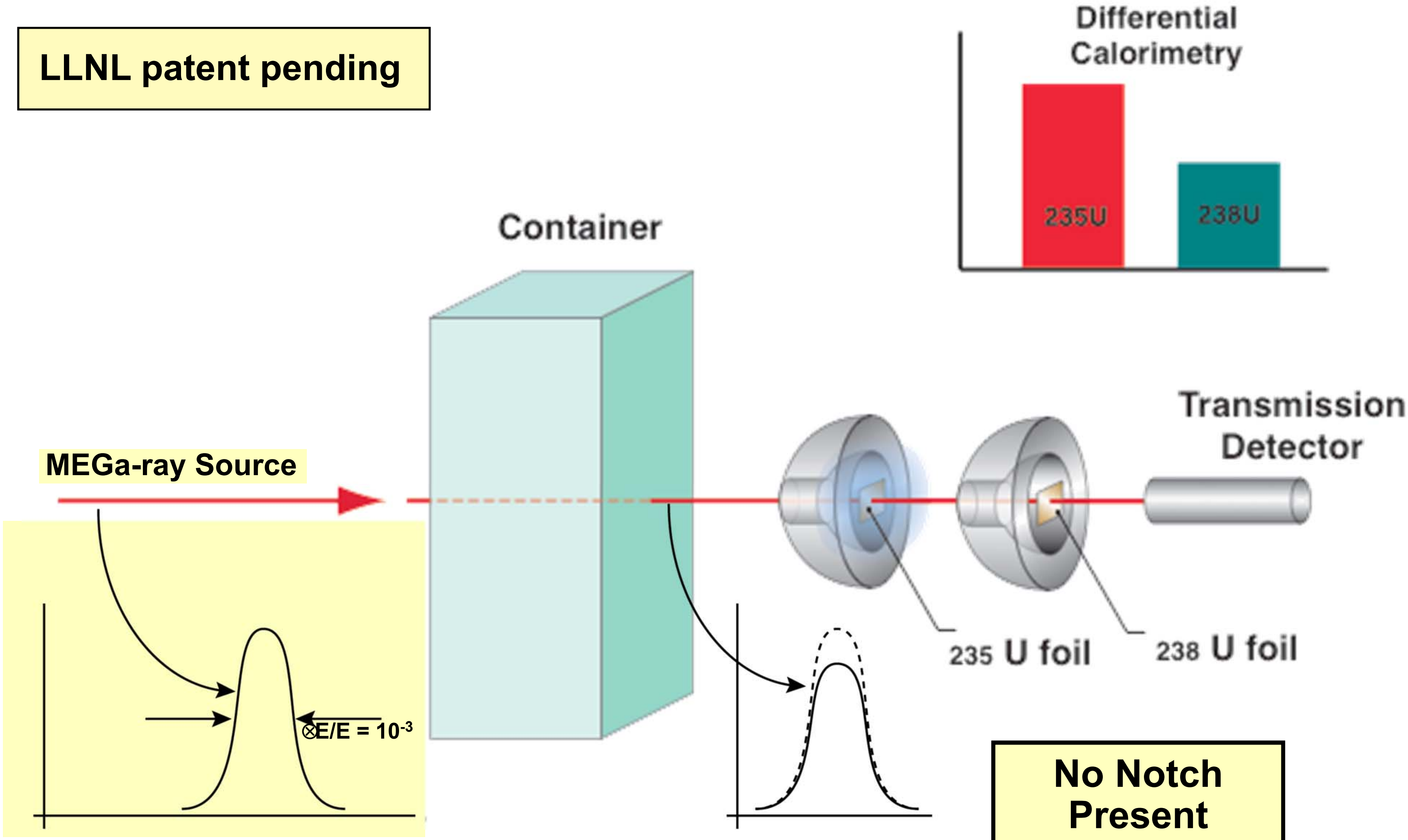
⊗©/© = 0.03 %
$\sum_n$= 0.1 mm.mrad

Electron bunches with lower charge reduce the bandwidth



Dual Isotope Notch Observation (DINO) eliminates the need for high resolution spectroscopy

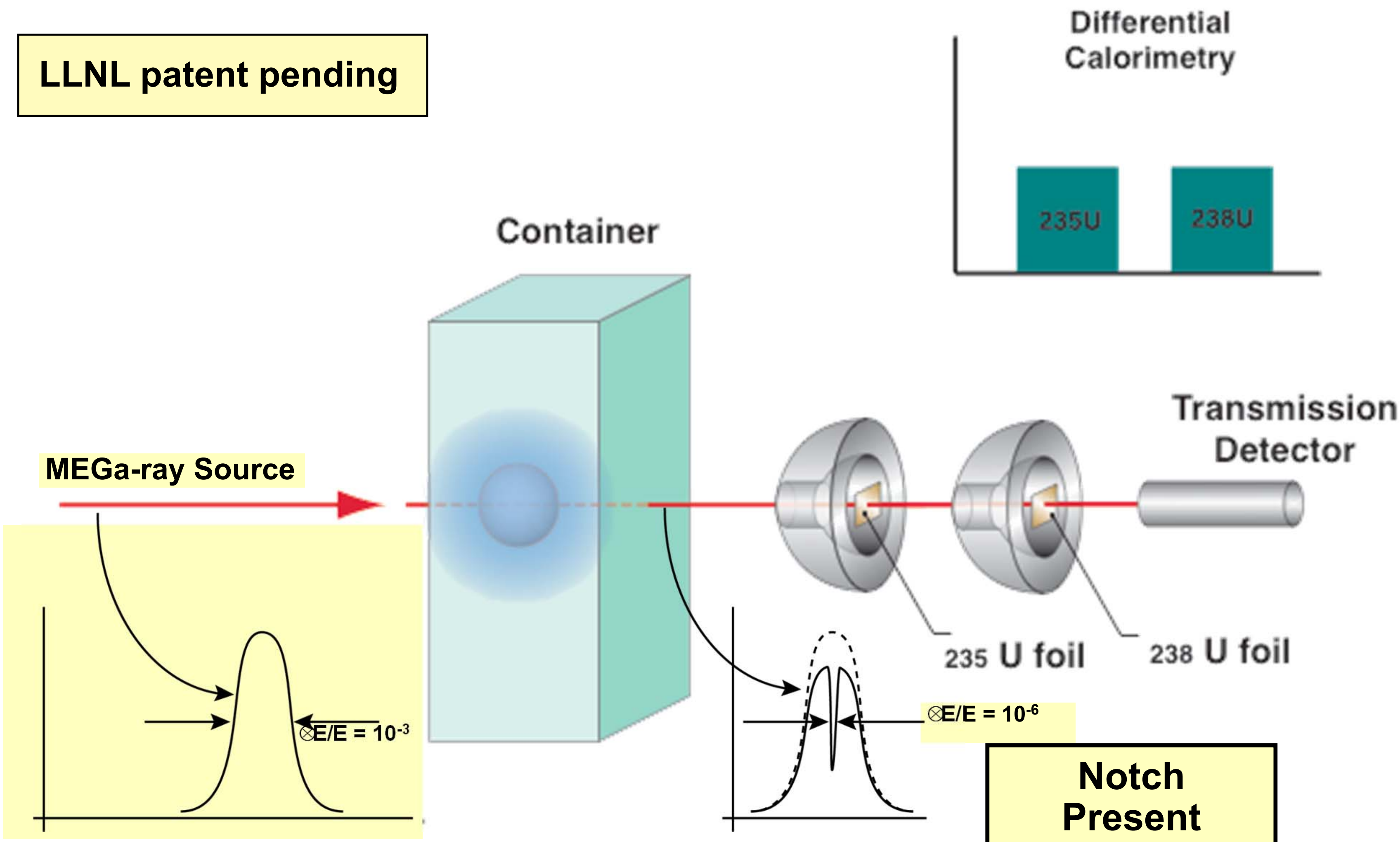
LLNL patent pending



No Notch Present

Dual Isotope Notch Observation (DINO) eliminates the need for high resolution spectroscopy

LLNL patent pending



Notch Present

Other Presentations at IPAC 2012

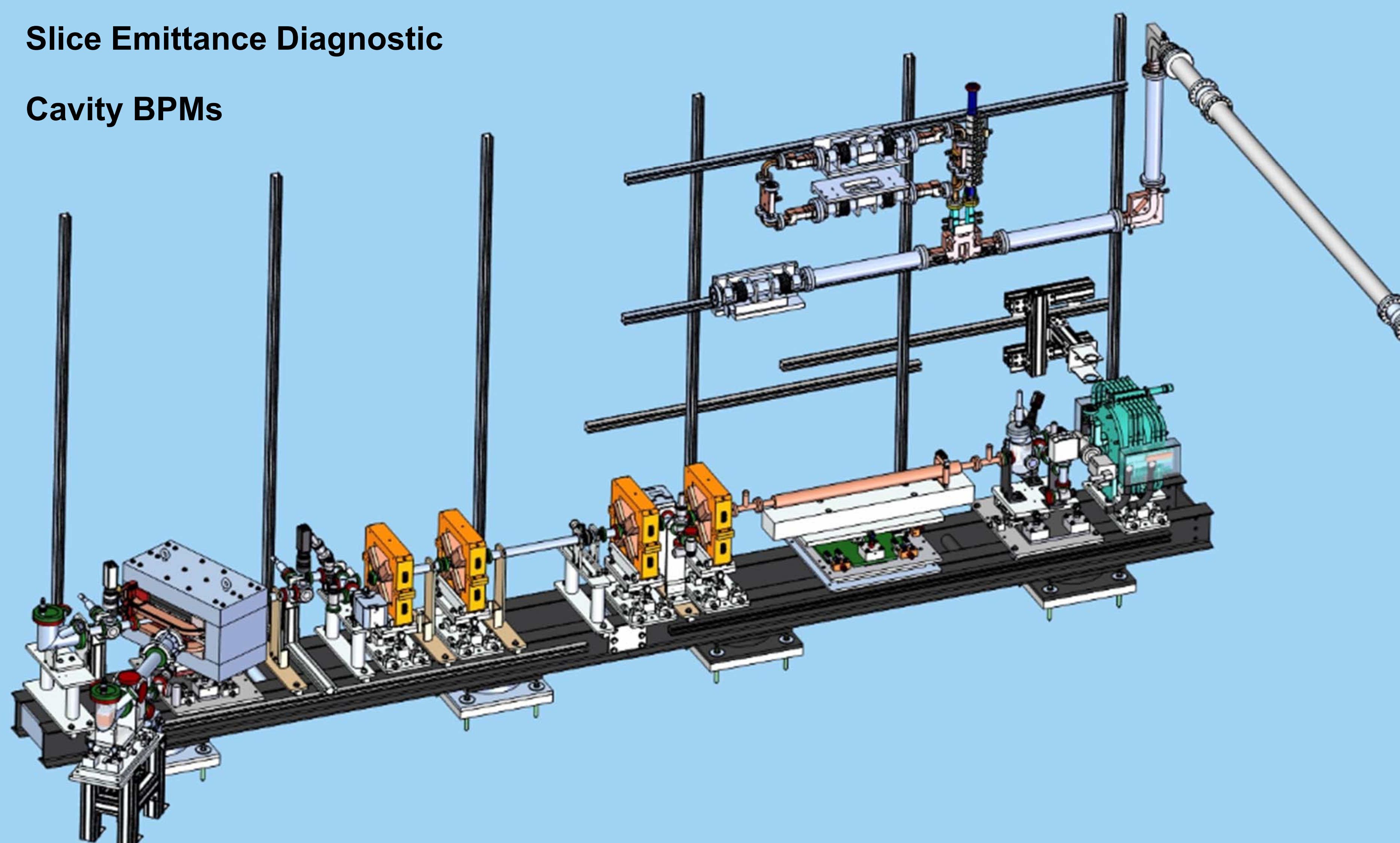
- F. Albert: MOPPP011, “Narrow Band Optimization of a Compton Scattering Gamma-ray Source Produced from an X-band Linac”
- D.J. Gibson: WEPPD060, “A Drive Laser for Multi-bunch Photoinjector Operation”
- R.A. Marsh: MOPPP042, “Modeling Multi-bunch X-band Photoinjector Challenges”, THPPD018, “Precision Magnet Measurements for X-band Accelerator Quadrupole Triplets”
- A.E. Vlieks: WEPPB007, “Initial Testing of the Mark-0 X-band RF Gun at SLAC”

SLAC NLCTA X-band Test Area

T105 Accelerator

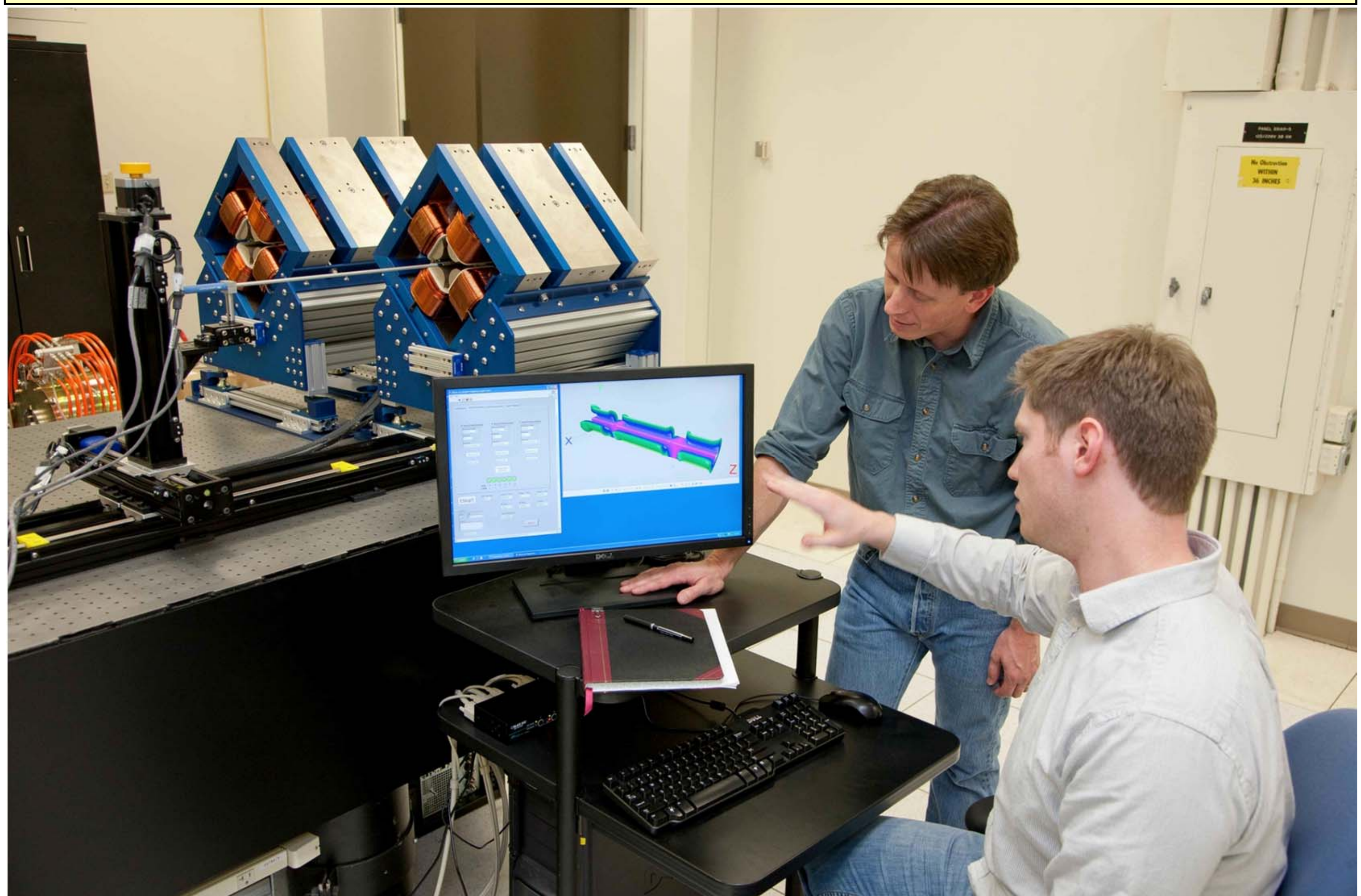
Slice Emittance Diagnostic

Cavity BPMs



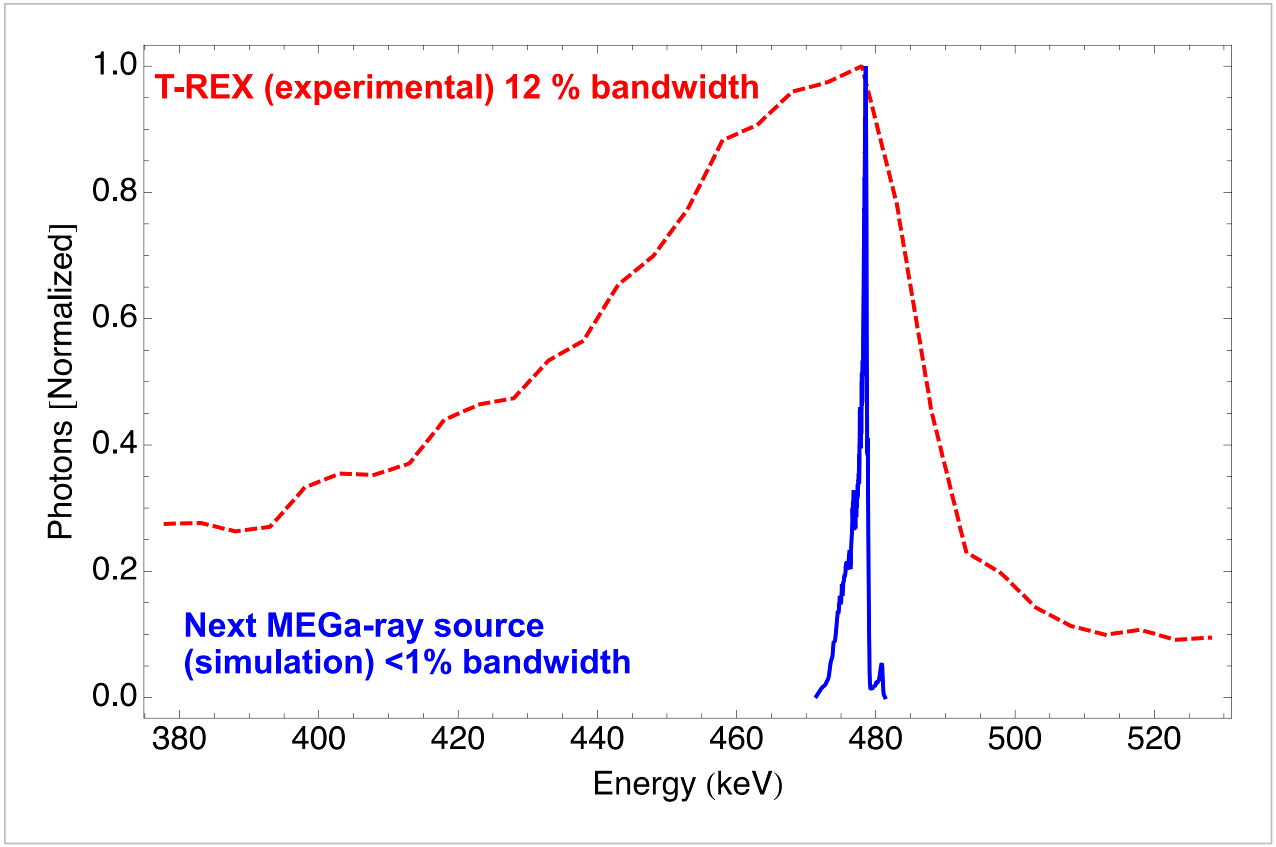
Ancillary systems: controls, diagnostics, and magnets have been designed and delivered

Magnet measurement of quadrupole focusing triplets for alignment



Comparison with results from T-REX at 478 keV

- We expect to do faster detection than T-REX (mins vs. hours)
- Source optimized depending on applications
- The source can be optimized for a given energy



Outline

- Introduction
  - Compton Scattering Overview
  - Nuclear resonance fluorescence
  - Nuclear Photonics Facility and VELOCIRAPTOR
- X-band Test Station
  - Mod
  - Klystron
  - Components
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  - Gun
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  - Narrowband
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