Design Considerations for a Tunable, Laser-based, Compact Mono-energetic Gamma-ray source

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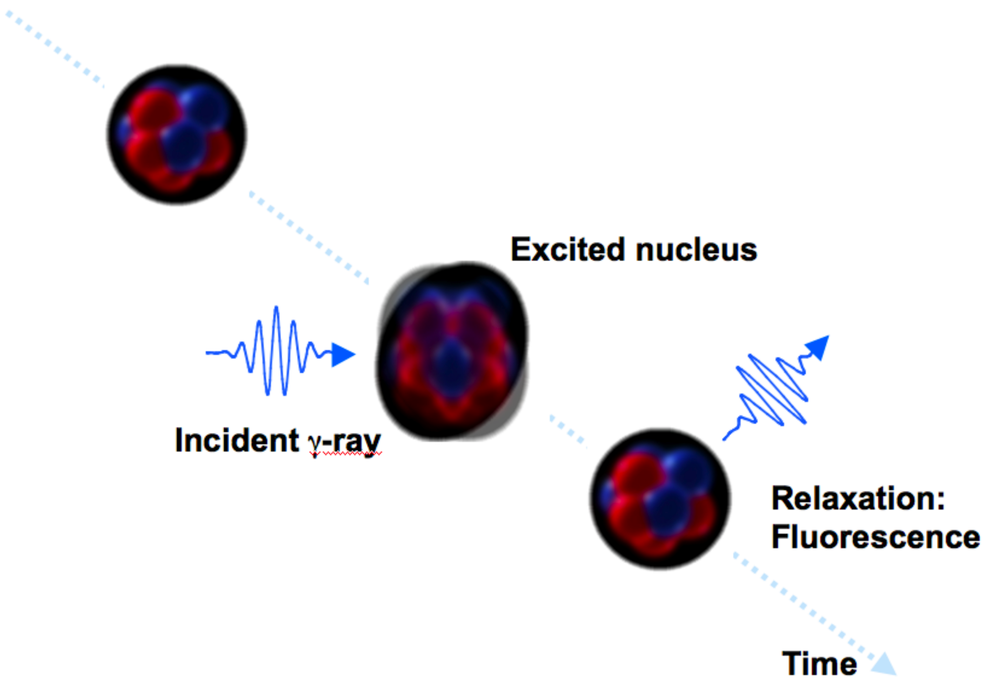
Outline

- Background and motivation
  - Nuclear resonance fluorescence
  - Source Bandwidth Requirements
  - Compton Scattering Overview
- The Next Nuclear Photonics Gamma-ray source: Engineering design and theoretical modeling
  - General architecture
  - Linac
  - Lasers
  - Weakly nonlinear Compton Scattering code
  - Electron beam and gamma-ray simulations
  - Comparison with T-REX results
- Preliminary design of a GHz Gamma-ray source
  - Electron beam and gamma-ray simulations
  - 11.424 GHz photo-injector design

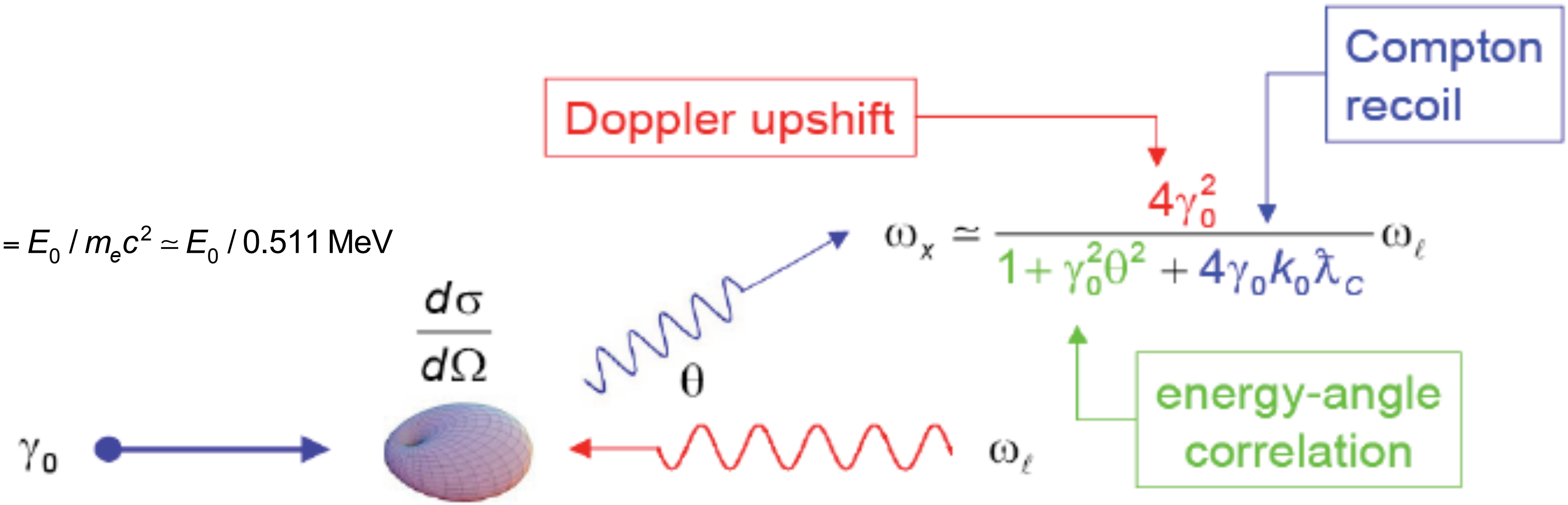
Nuclear Resonance Fluorescence (NRF) can provide isotope-specific contrast



- Incident photon excites nucleus
  - MeV
  - Discrete energies
  - Isotope specific
- Nucleus subsequently re-radiates photons
  - NRF lines very sharp (1 eV)
  - Need high brightness narrow band source to detect them
- Applications
  - Isotope specific detection
  - Special Nuclear Materials detection (Homeland security)
  - Nuclear waste assay and detection

Narrowband gamma-rays are produced by Compton Scattering

$$\gamma_0 = E_0 / m_e c^2 \simeq E_0 / 0.511\,\text{MeV}$$

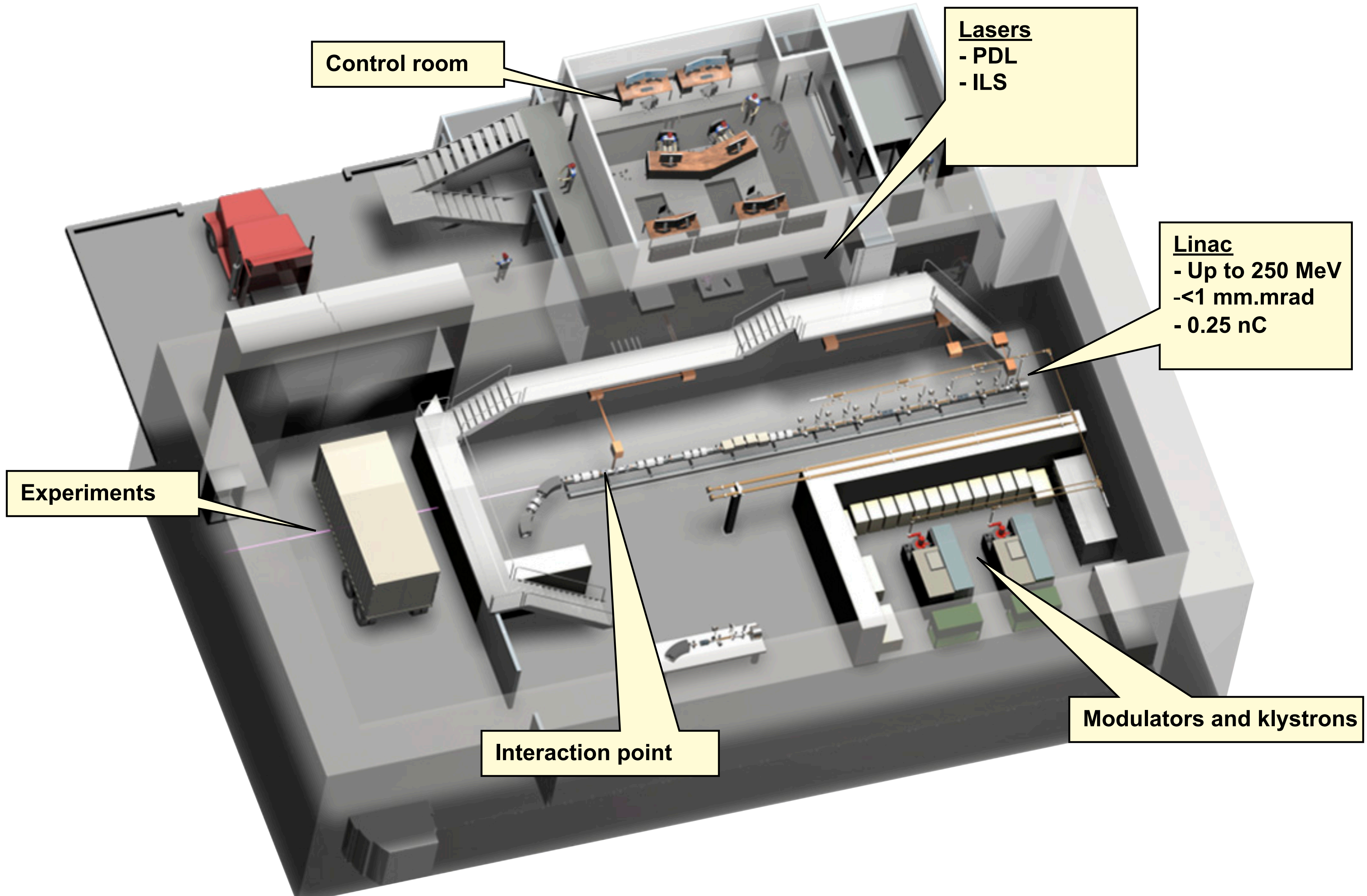


Energy-momentum conservation yields $4\gamma^2$ Doppler upshift

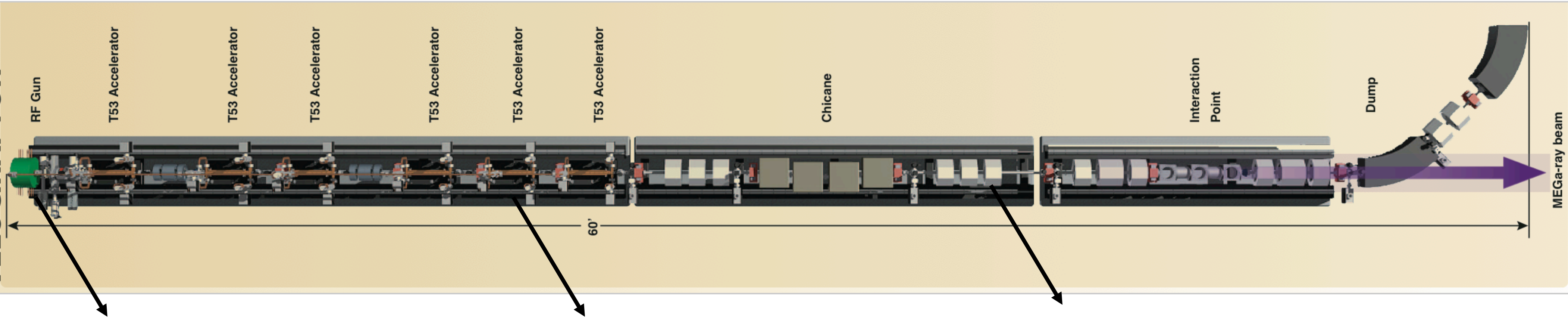
The Thomson scattering cross section is very small (6×10^{-25} cm^2)

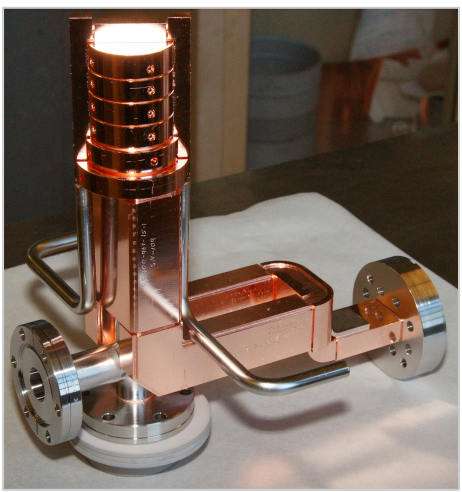
High photon and electron densities are required

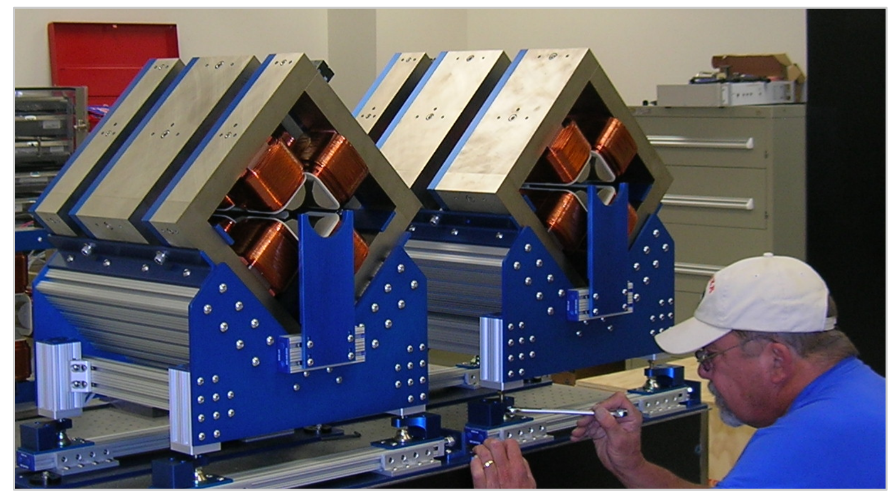
To achieve precision gamma-rays we need a robust laser/linac platform



X-band linac technology will provide high brightness electron beams



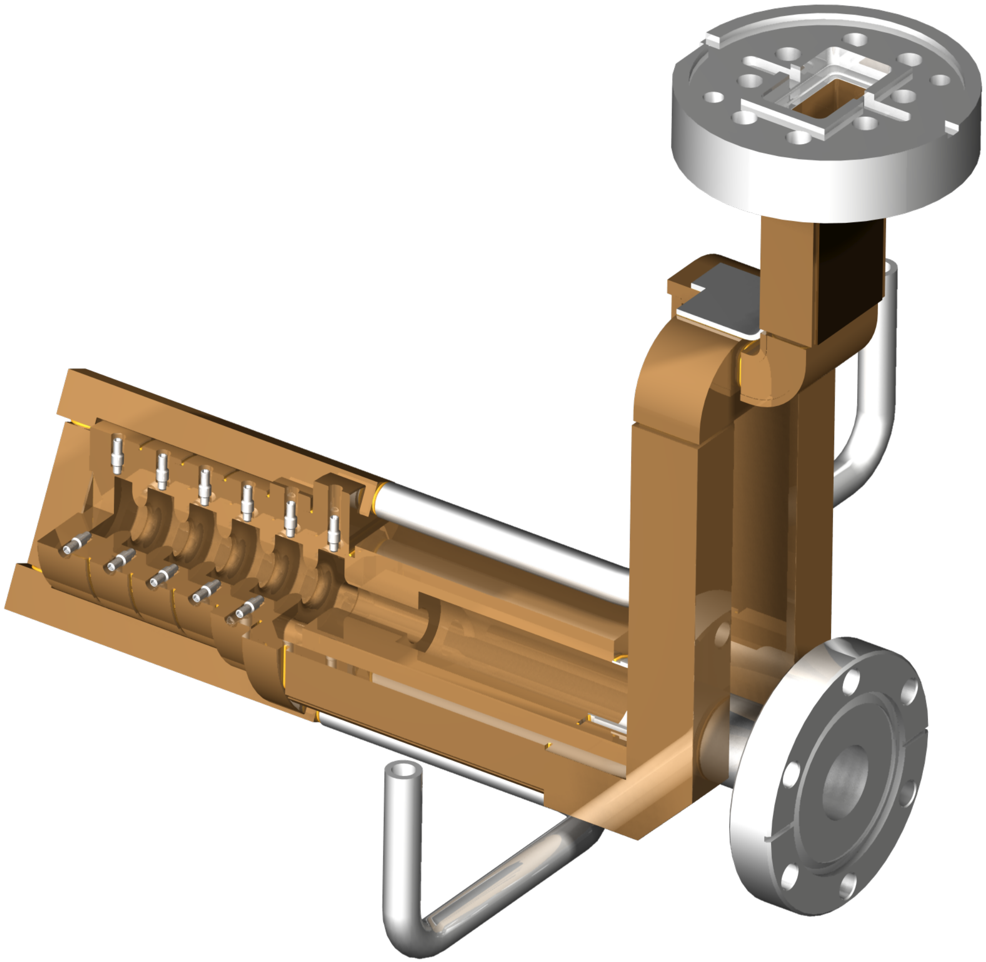




250 MeV, 0.25 nC, 70 MeV/M X-band linac

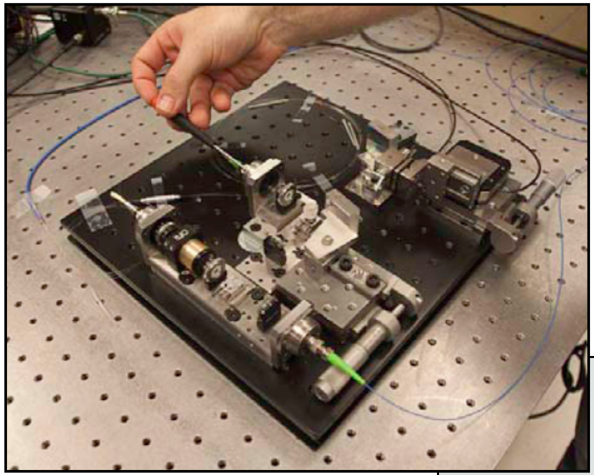
LLNL/SLAC developed a single bunch high brightness RF photoinjector

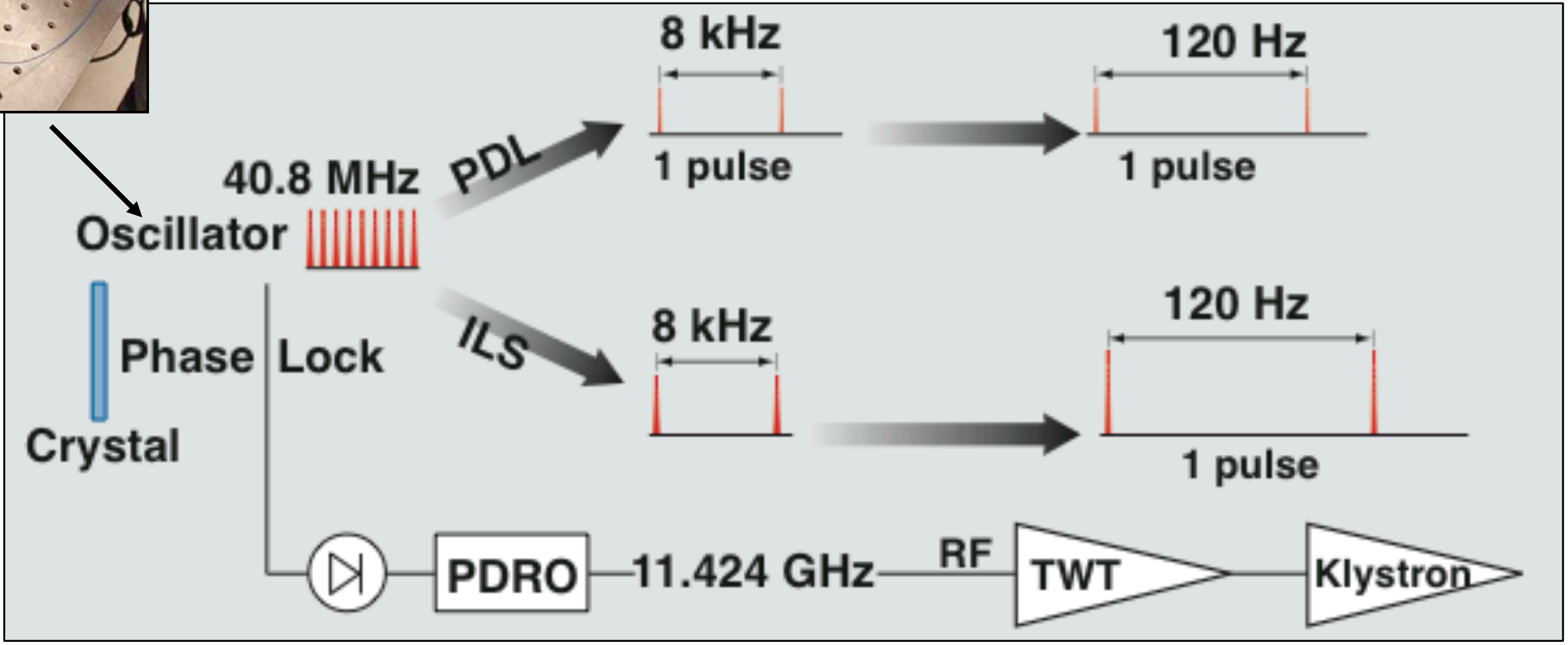
- **Longer Half cell**
- **Better mode separation**
- **Elliptical irises**
- **Dual feed racetrack coupler**
- **Optimized beta**
- **Compatible with 250 pC, 0.35 mm-mrad emittance, 250 MeV MEGa-ray machine**



This state of the art X-band photoinjector is our starting point

Laser systems

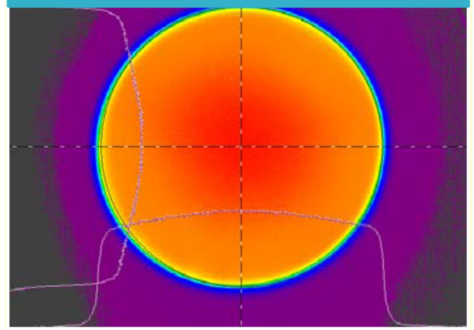


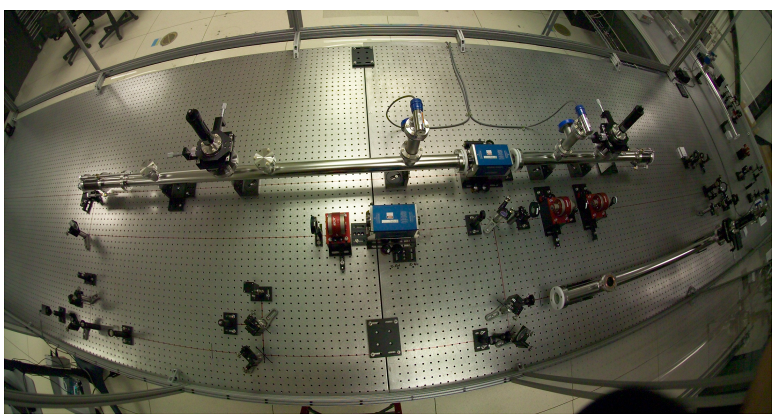


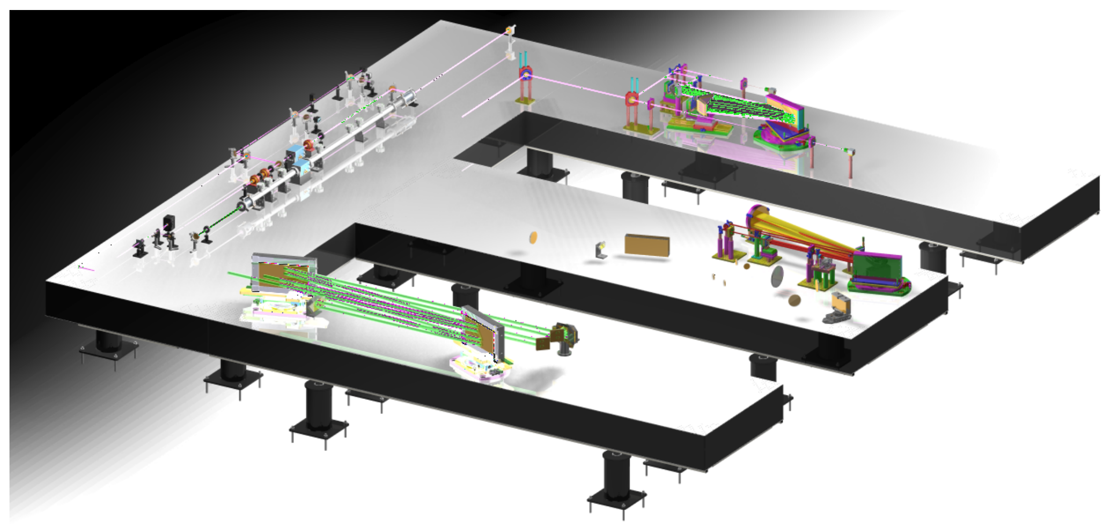
Interaction Laser System (ILS) and Photocathode Drive Laser (PDL) seeded by the same oscillator

Current status of laser systems

Rod Fluorescence showing gain uniformity



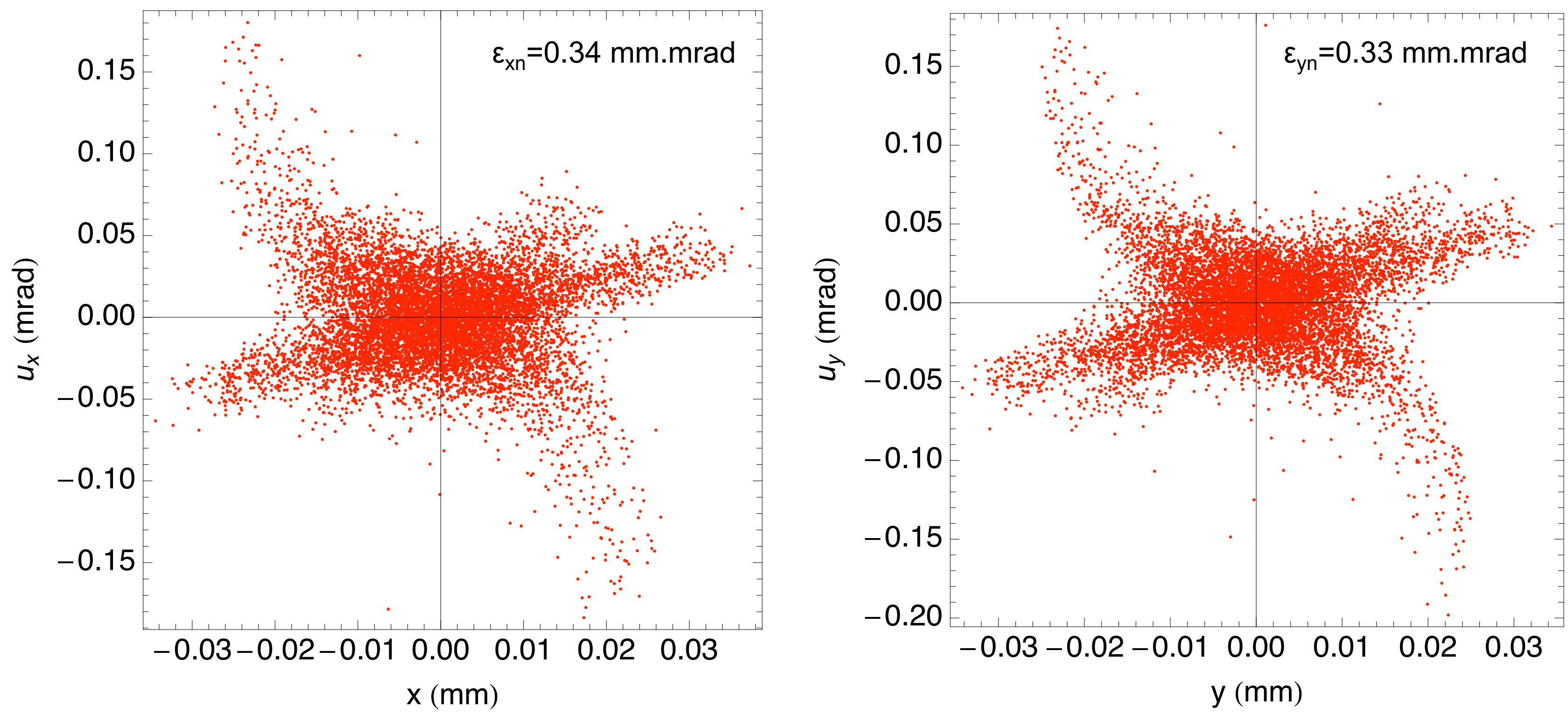




We have modeled the x-band linac output

- Simulations done with PARMELA and ELEGANT
- 10,000-100,000 particles

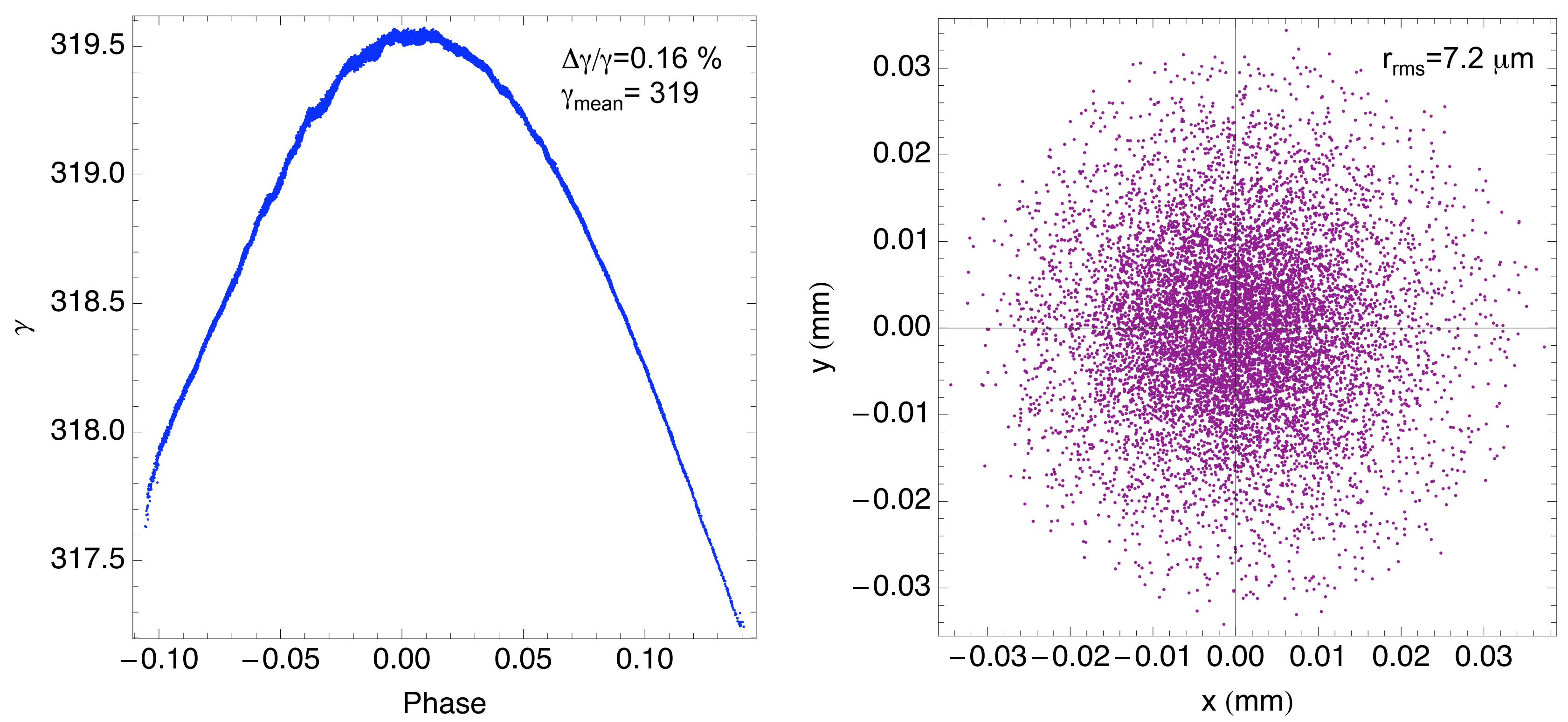
E-beam phase space at the interaction point



Electron beam simulations (2)

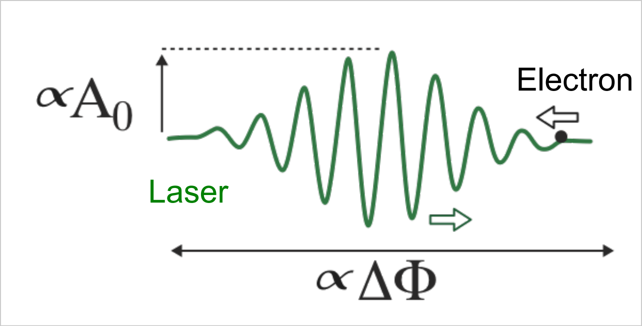
- **Energy optimized for 478 keV gamma ray production**

E-beam energy and focal spot at the interaction point

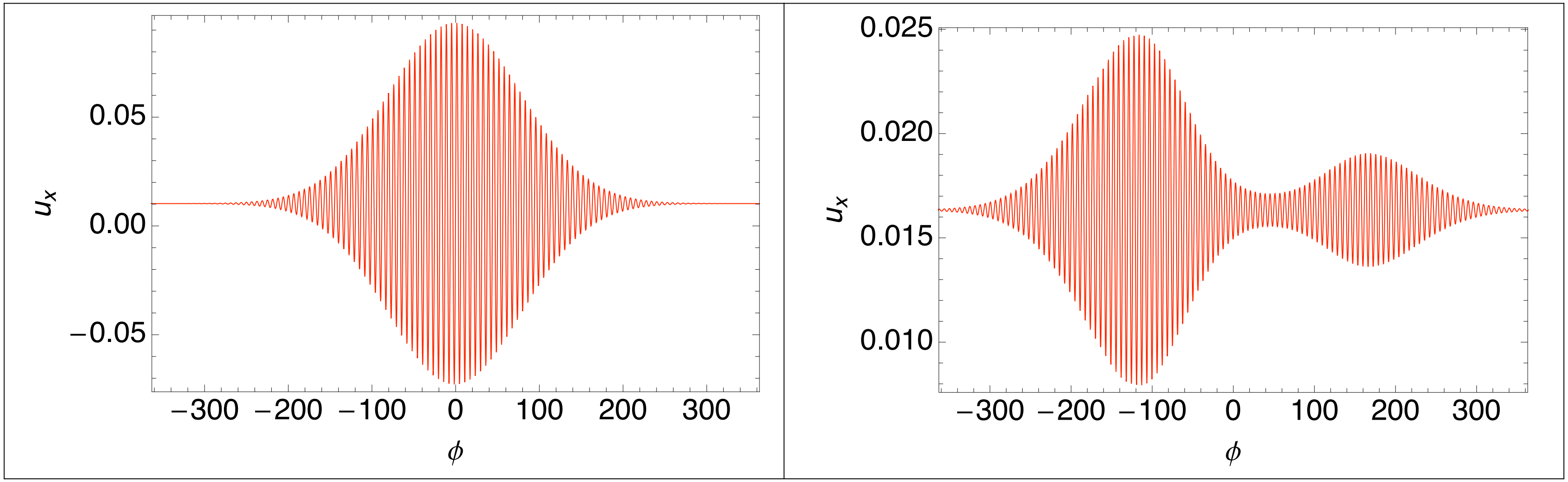


Weakly nonlinear Compton scattering code: trajectories

- **For a single electron, calculated trajectory in laser E-Field**
  - **SWEA**
  - **Ballistic approximation**
  - **Electron (x,y,z) and (u_x, u_y, u_z)**



Analytical trajectories of single electron in laser E-field



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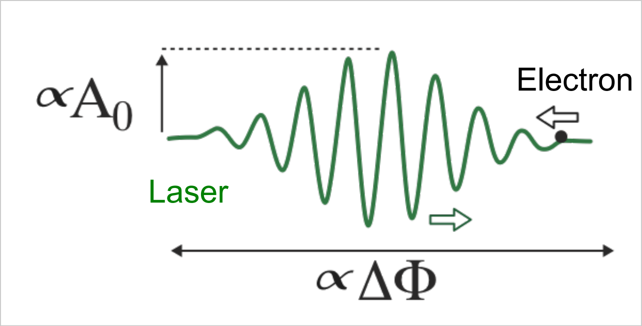
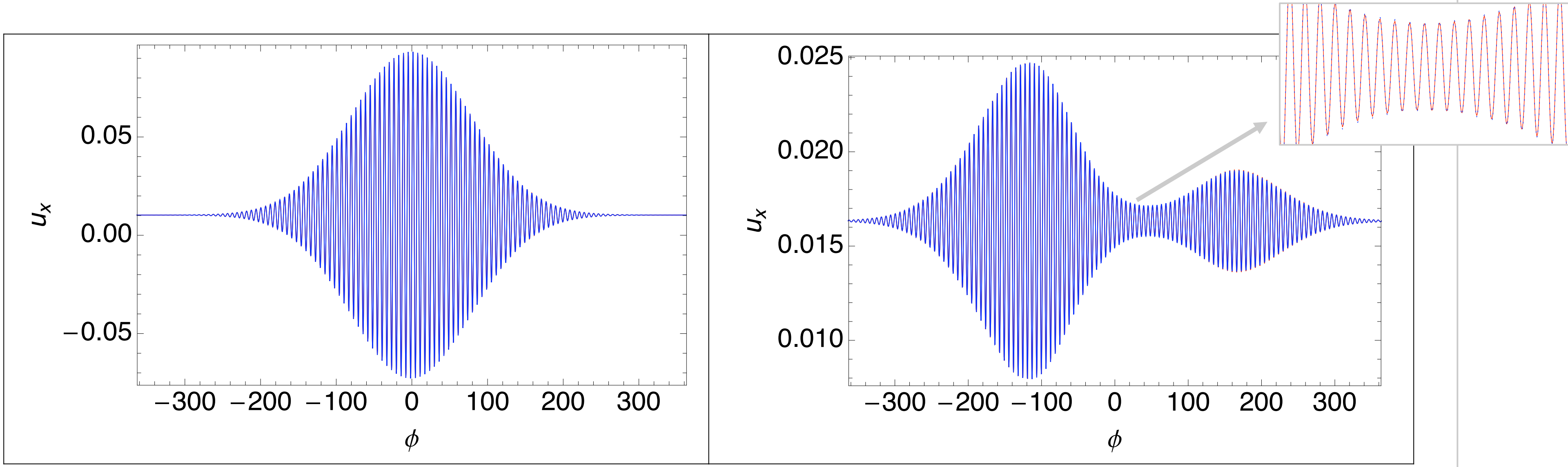


Analytical trajectories benchmarked against numerical calculations



Weakly nonlinear Compton scattering code: radiation

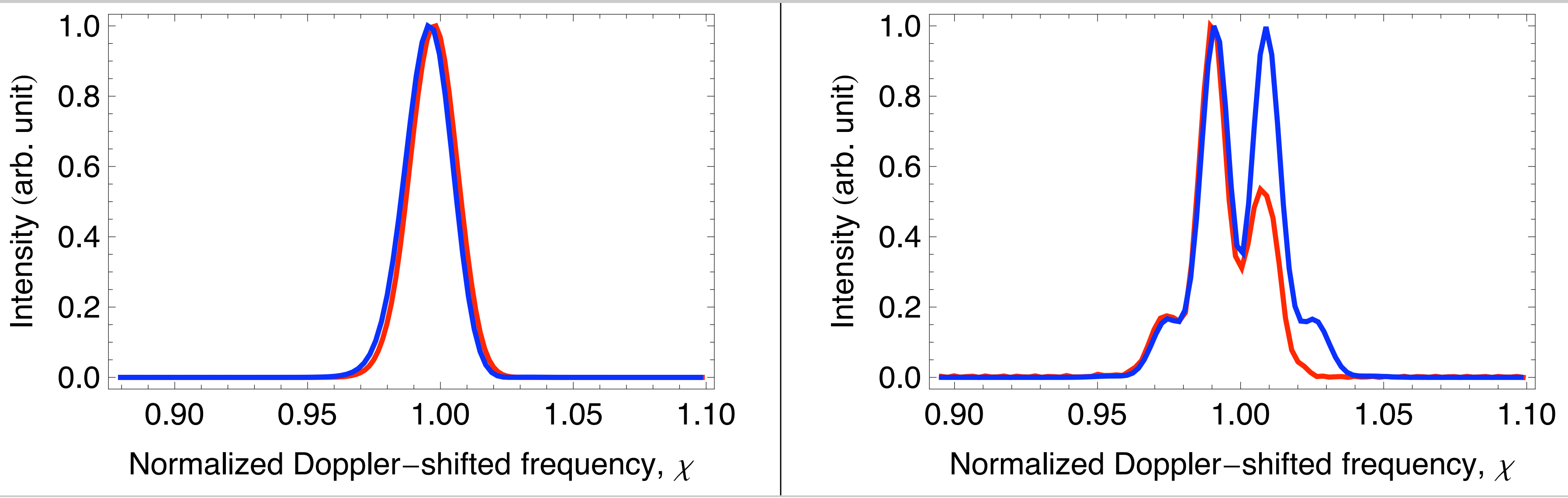
- **Single electron spectrum calculated from electron trajectory**

Radiation formula: $$\frac{d^2N}{dq\,d\Omega} = \frac{\alpha}{4\pi^2} q \left| \int_{-\infty}^{+\infty} \pi_\mu u^\mu e^{-iq_\nu x^\nu} d\tau \right|^2$$

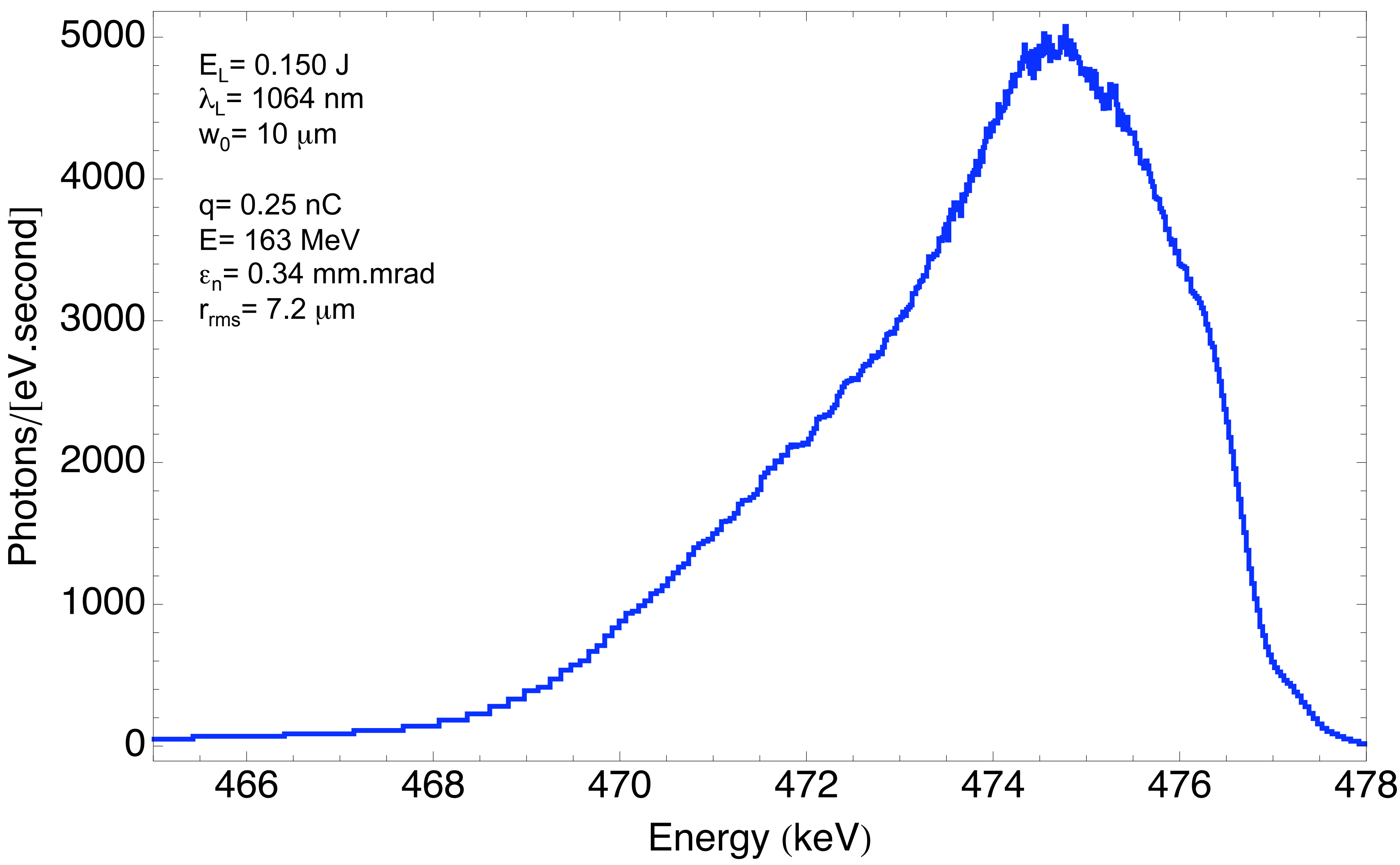
Radiation formula after approximations:

- **The code works for long laser pulses (>ps) and weak nonlinear effects (A_0 <<1).**

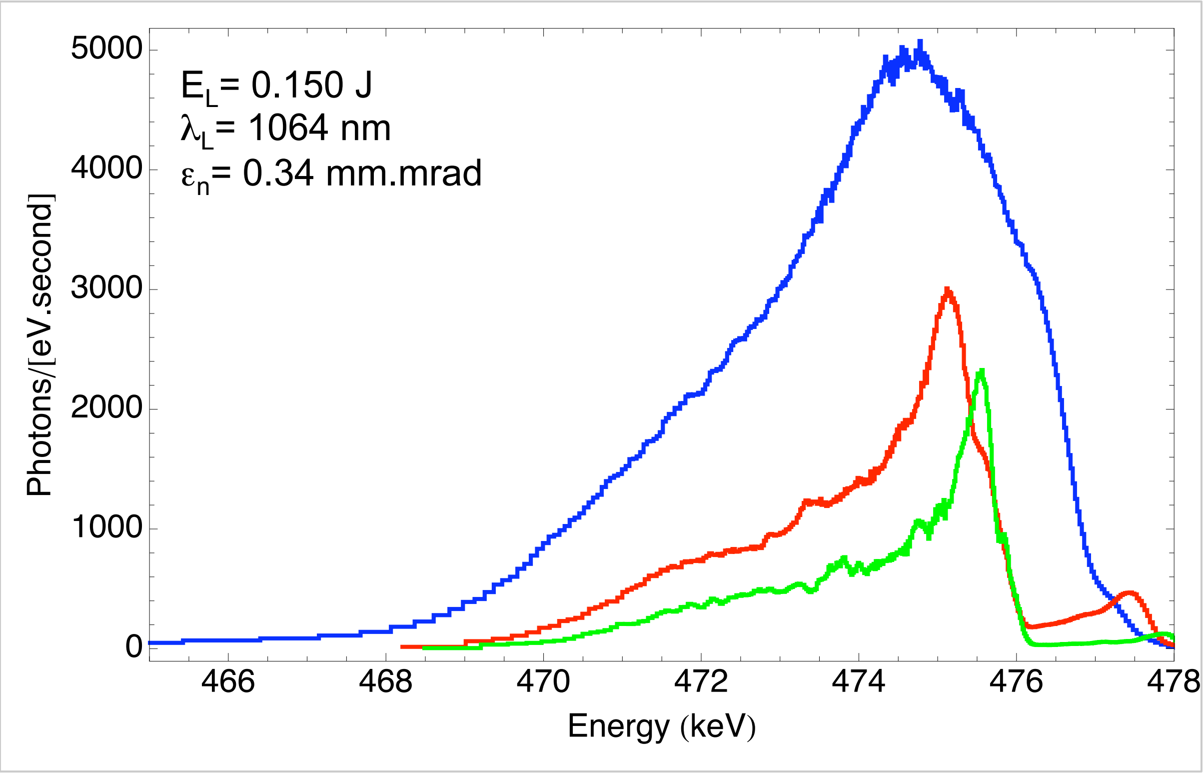
Analytical and numerical single electron spectra



Single electron spectra are added to yield the gamma-ray source spectrum on axis

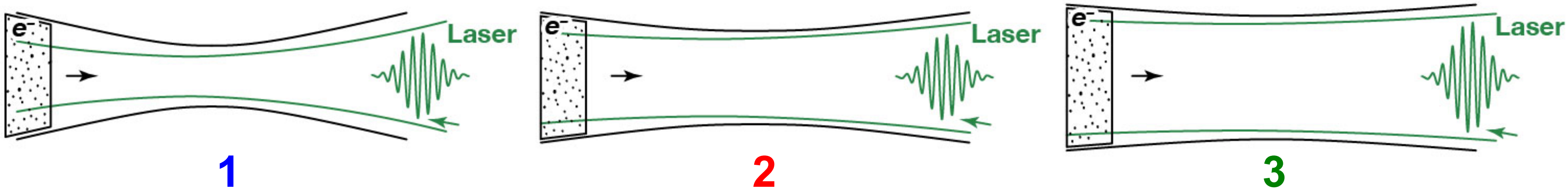


Influence of focusing geometry



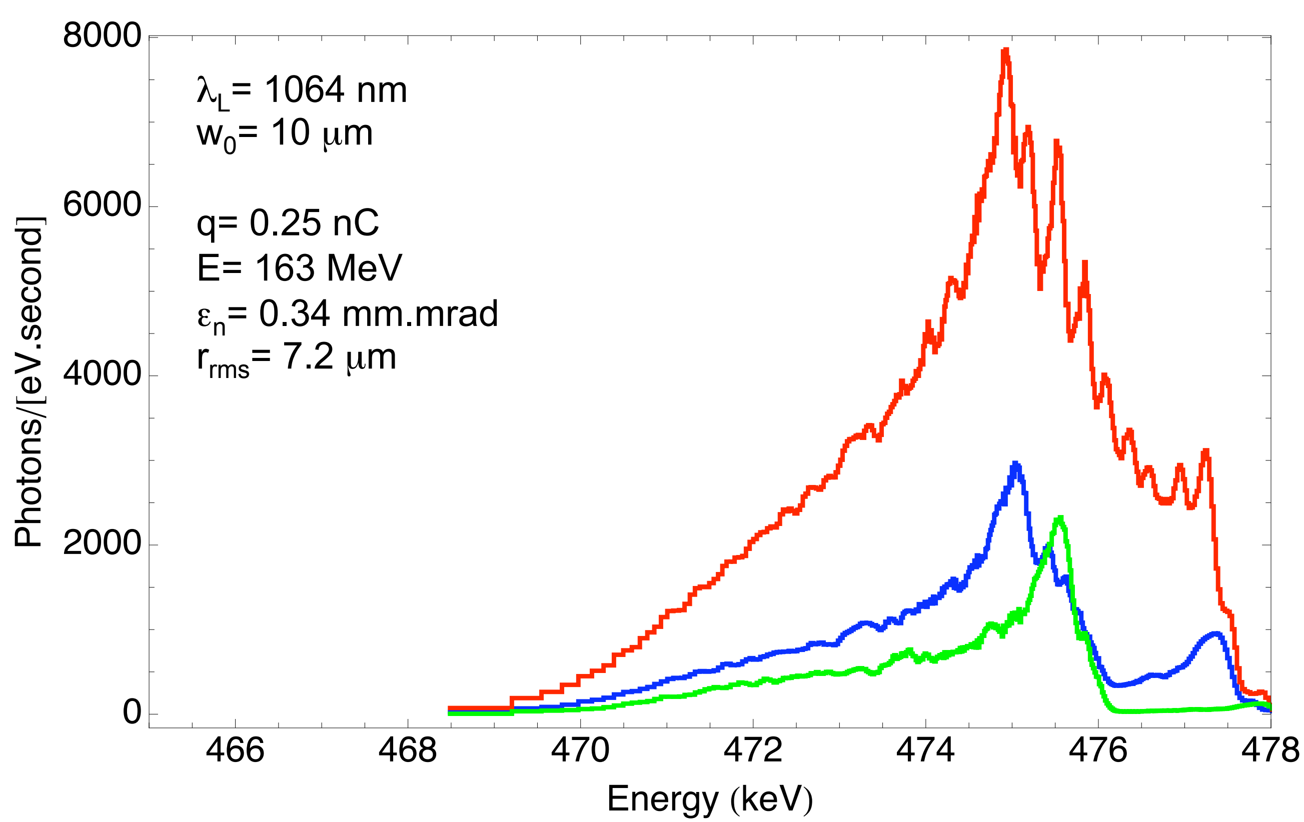
Parameters

Parameters
1: w_0= 10 μm, r_{rms}= 7.2 μm, a_0=0.06
2: w_0= 15 μm, r_{rms}= 14.5 μm, a_0=0.04
3: w_0= 18.6 μm, r_{rms}= 28.9 μm, a_0=0.03



Tight electron and laser focus: broader bandwidth and more nonlinear effects

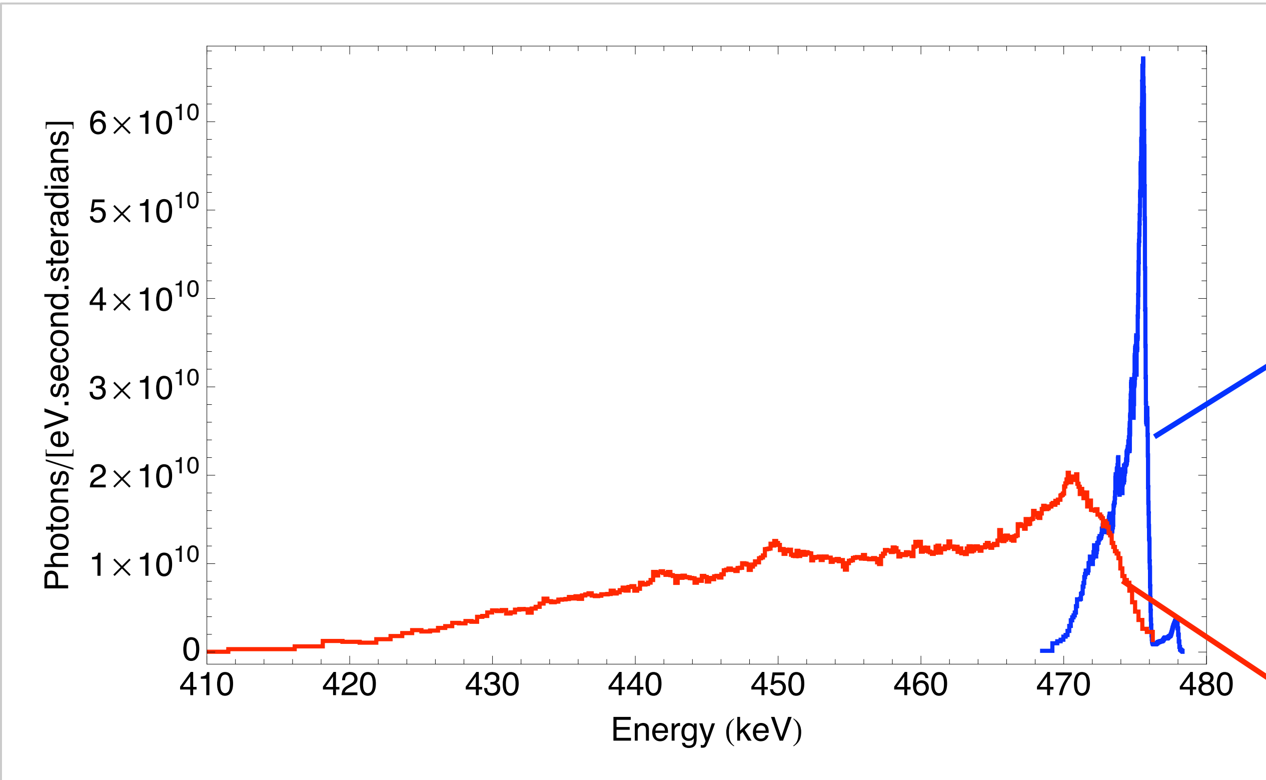
Influence of laser energy: nonlinear effects



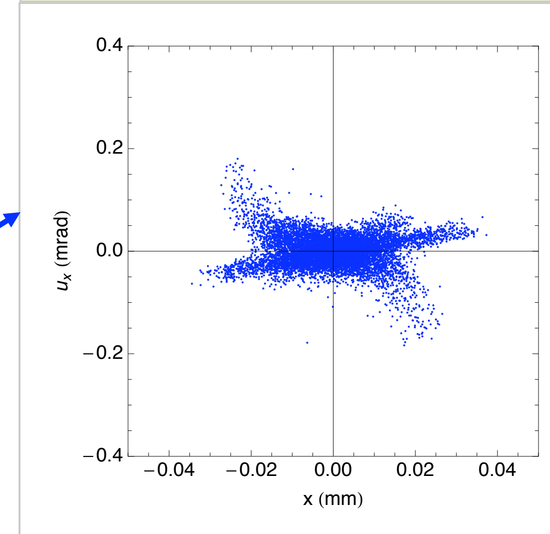
Parameters
EL= 0.15 J
EL= 0.3 J
EL= 1 J

Higher laser energy means higher spectral bandwidth

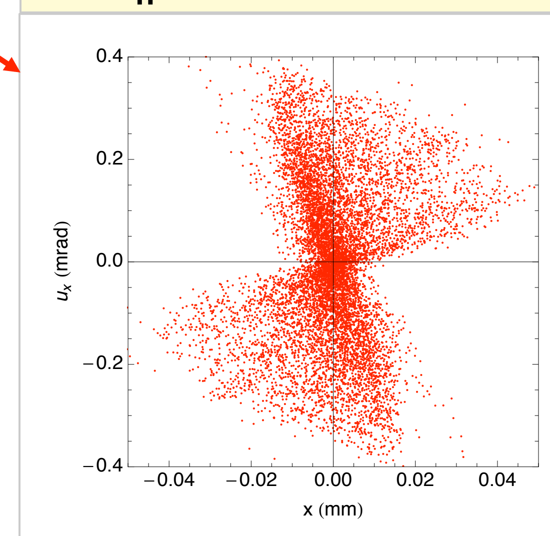
Influence of electron beam emittance



ε_n=0.34 mm.mrad

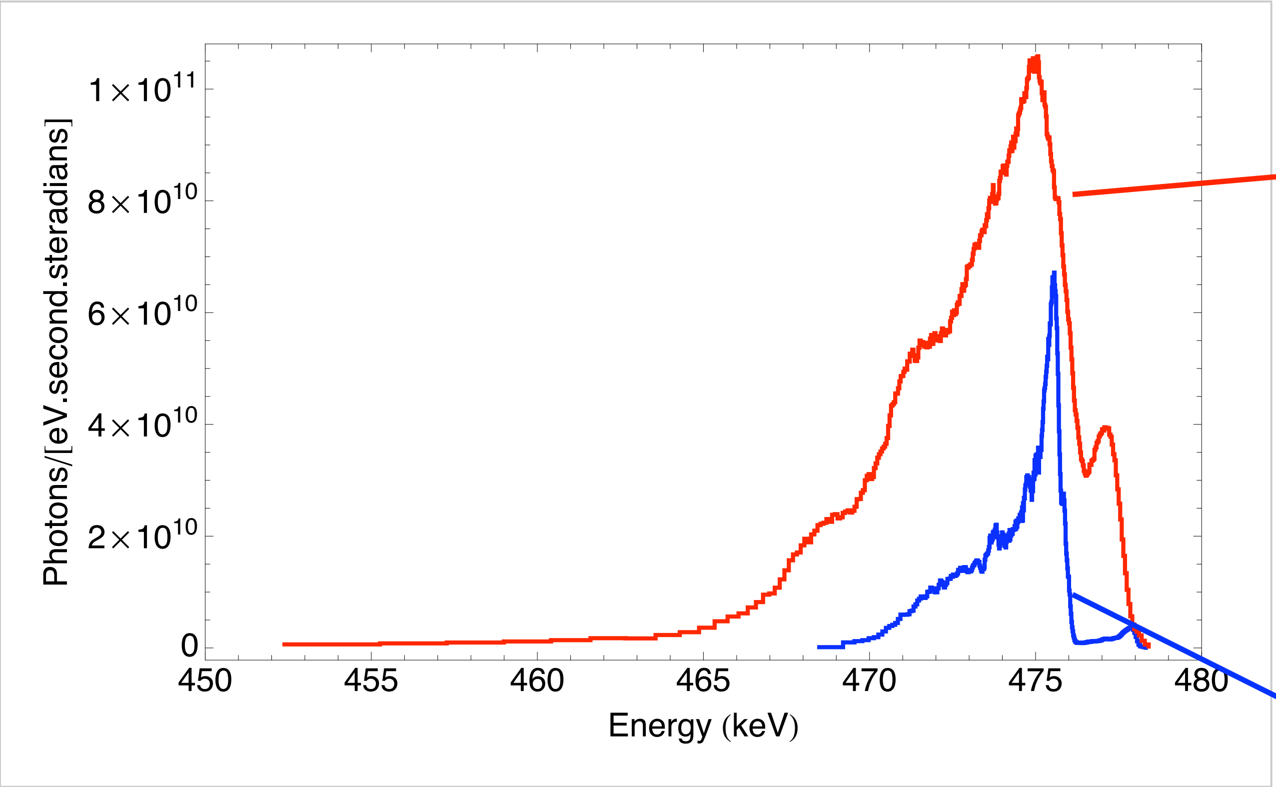


ε_n=1.6 mm.mrad

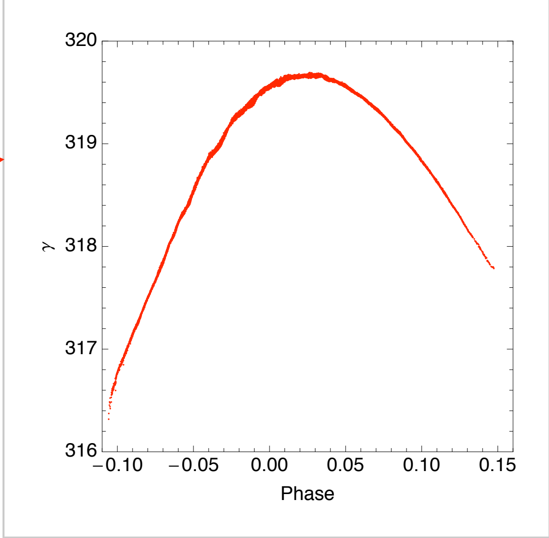


A small emittance increase considerably broadens the bandwidth

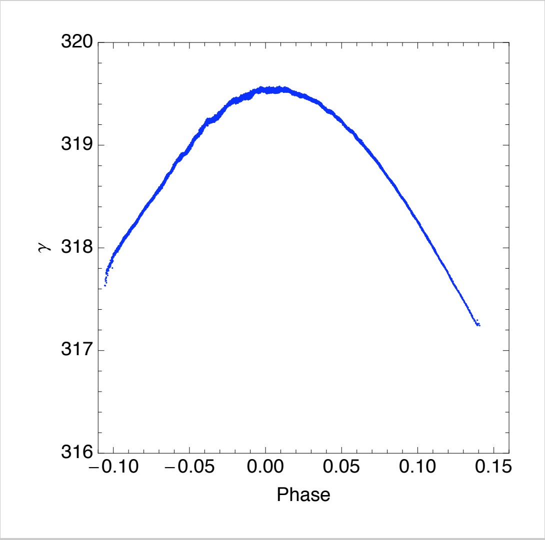
Influence of electron beam energy spread



$\Delta\gamma/\gamma$=0.25 %

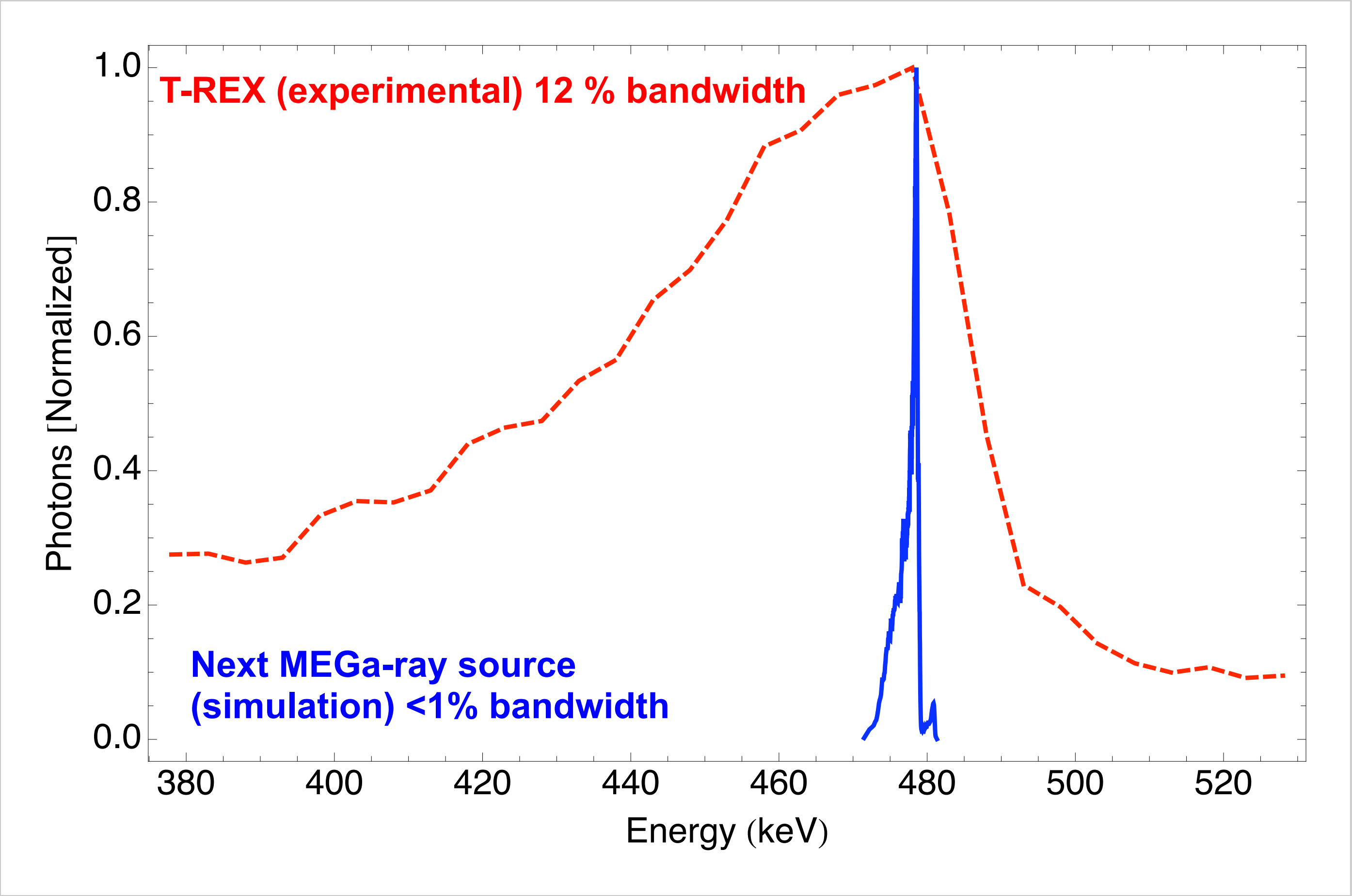


$\Delta\gamma/\gamma$=0.16 %



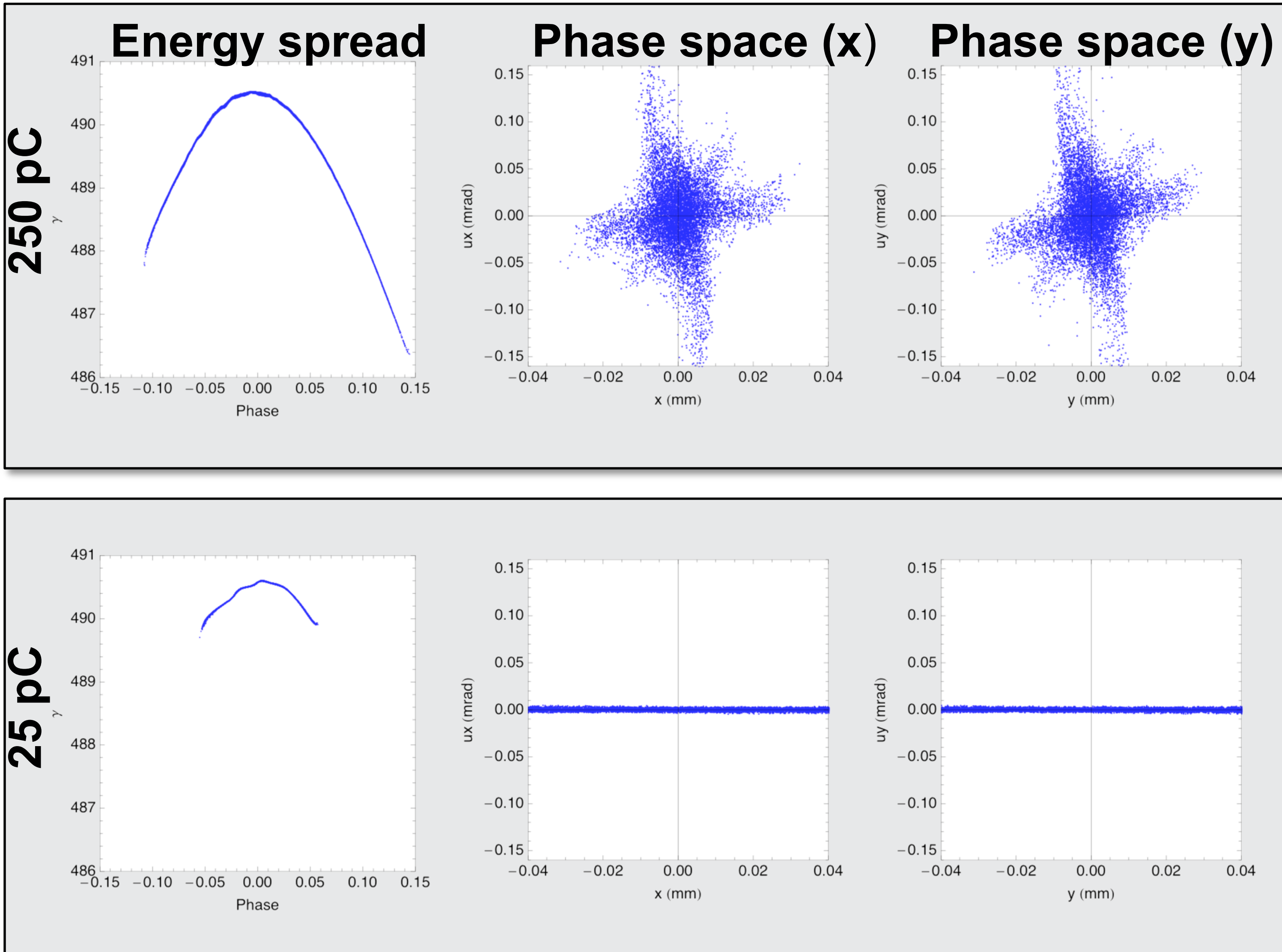
The gamma-ray bandwidth directly depends on the electron beam energy spread

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

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

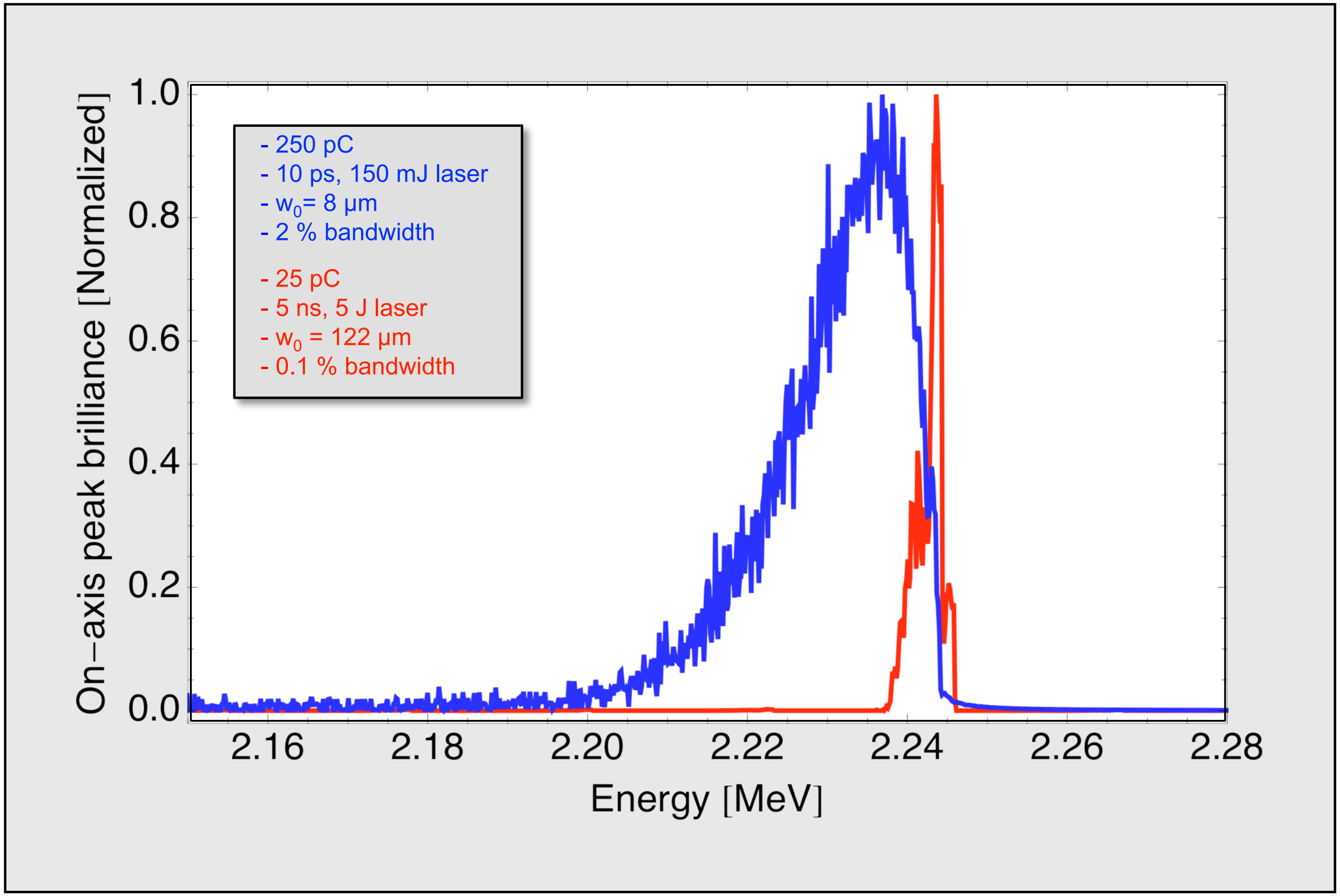


$\Delta\gamma/\gamma = 0.16\%$
$\varepsilon_n = 0.35$ mm.mrad

$$\frac{q}{\varepsilon_n^2} = \text{constant}$$

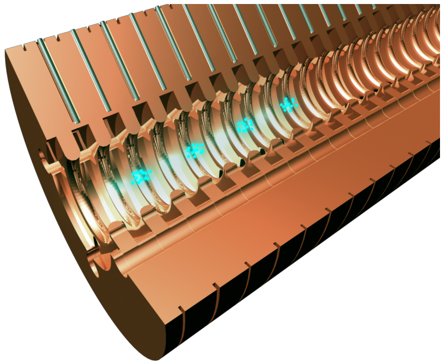
$\Delta\gamma/\gamma = 0.03\ \%$
$\varepsilon_n = 0.1$ mm.mrad

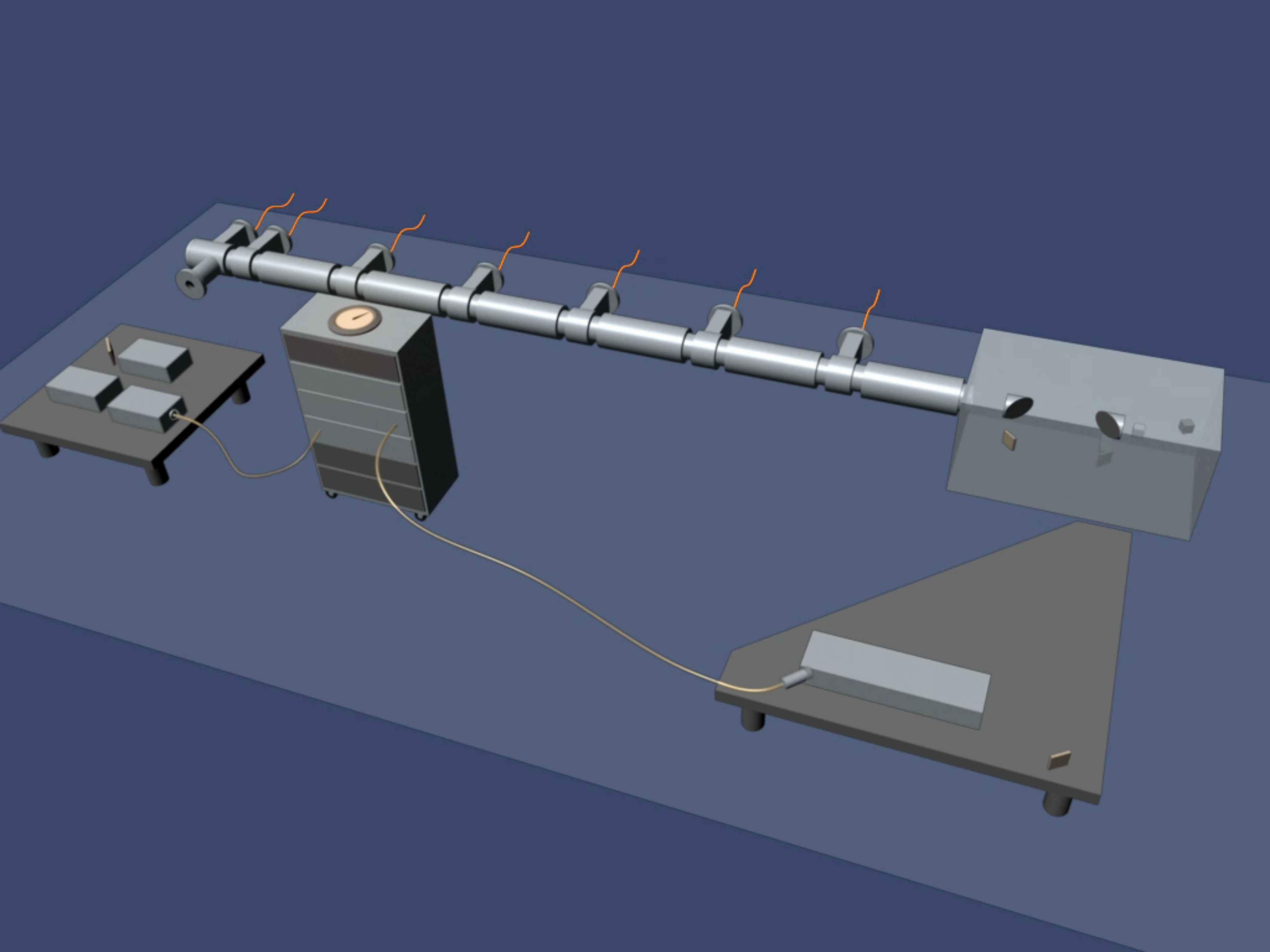
Electron bunches with lower charge reduce the bandwidth



Spectral broadening mitigation and bandwidth reduction strategy

- **The normalized emittance is the biggest contributor to on-axis spectral bandwidth**
- **Charge over normalized emittance square is a conserved quantity**
- **To both reduce bandwidth and maintain/increase number of photons, distribute interaction over a large number of bunches**
- **This leads to a "fill every (rf) bucket" (FEB) approach**





FEB leads to considerable spectral flux improvement and system simplifications

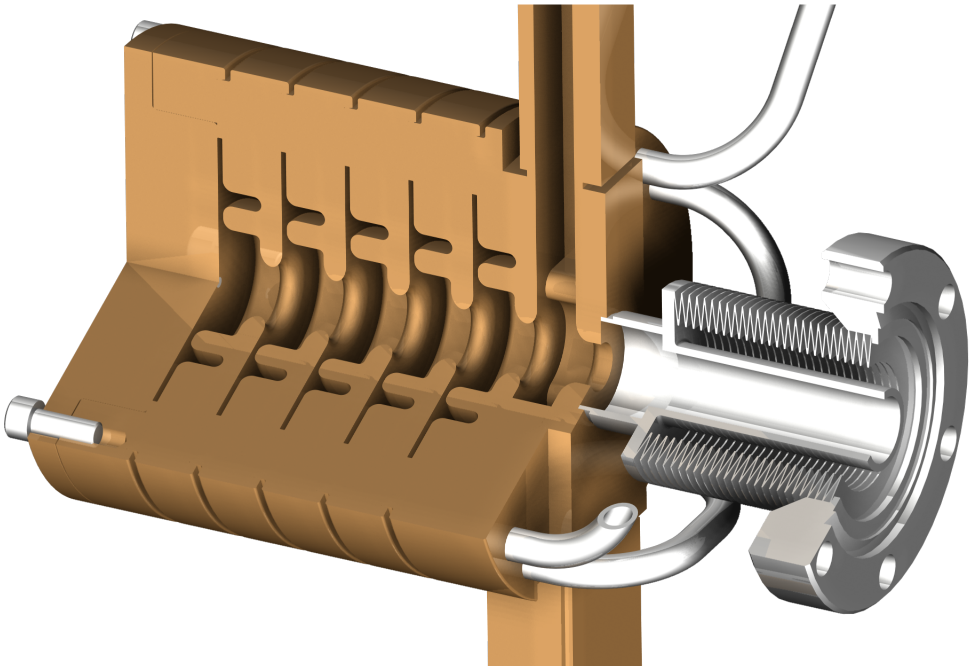
- FEB at 11.424 GHz distributes charge optimally (more buckets per unit time)

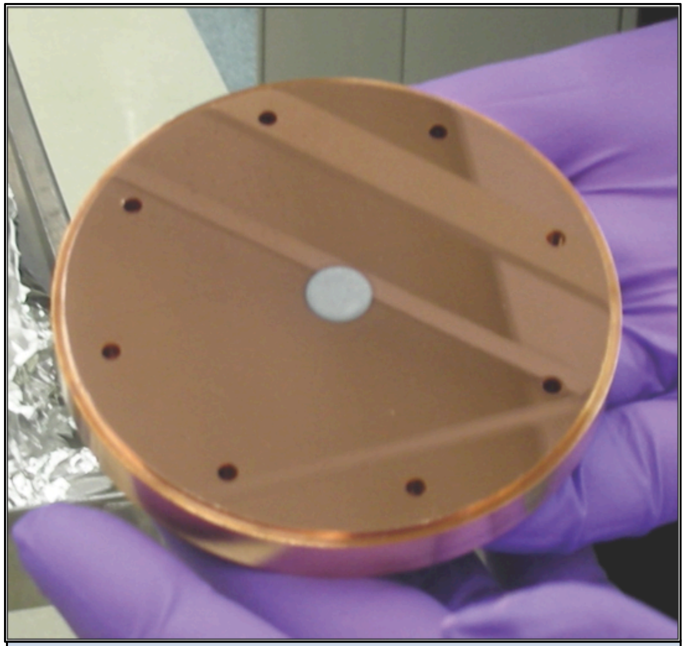
- All e-beam detrimental effects scale as q^2:
  - Coherent synchrotron radiation
  - Wakefields
  - Space-charge

- The interaction laser becomes a long (ns) pulse system
  - No hyper-dispersion CPA
  - No damage issues
  - Commercial-like interaction laser

Requirements for Multi-GHz high brightness photoinjector

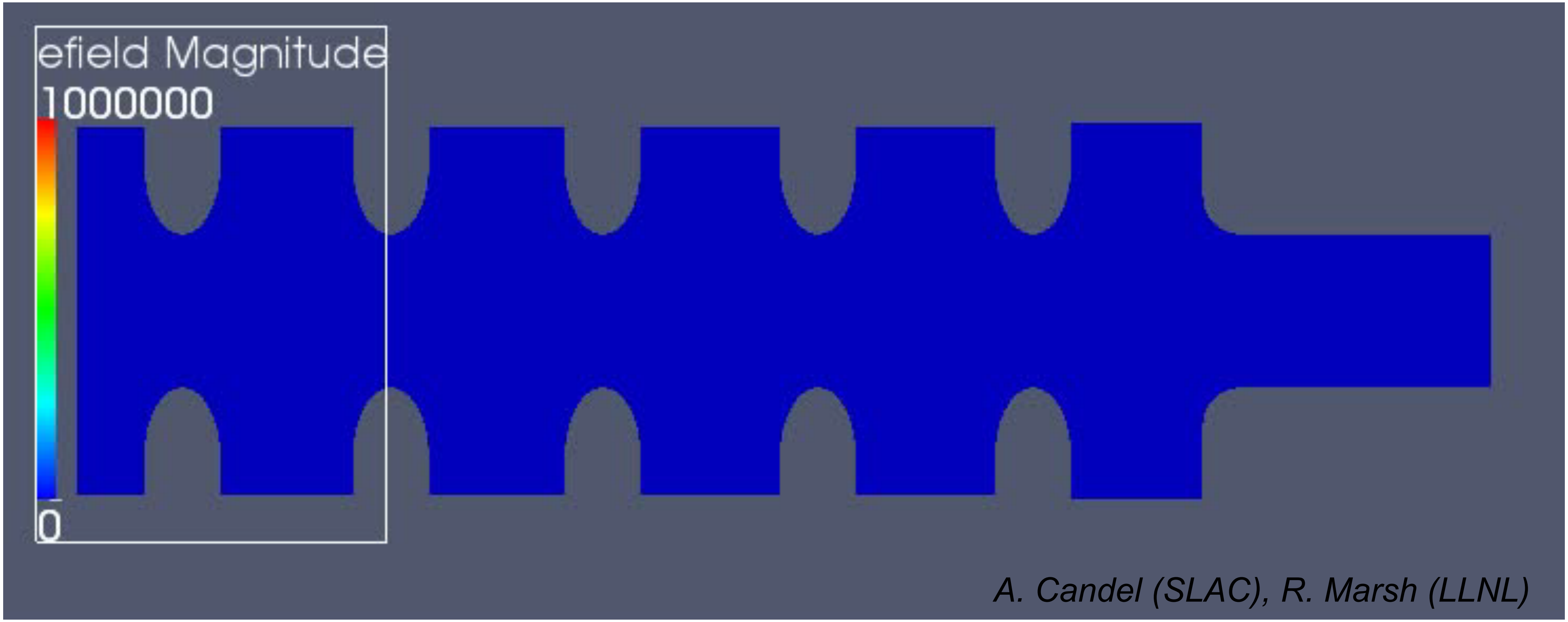
- Removable photocathode
- 1000 equivalent electron bunch operation
  - DE/E , 0.1%
  - 0.1 mm-mrad emittance
  - Maximize charge





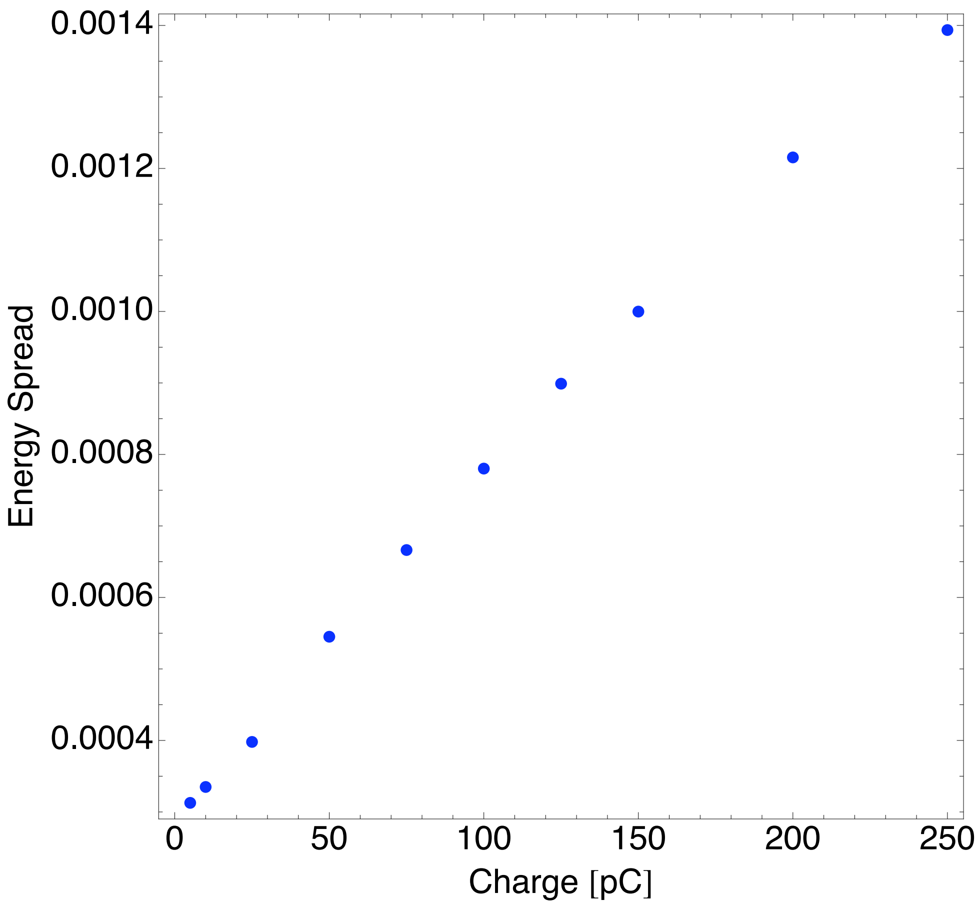
2 μm of Mg is sputtered in a 1 cm diameter spot on the Cu back plane of the photoinjector

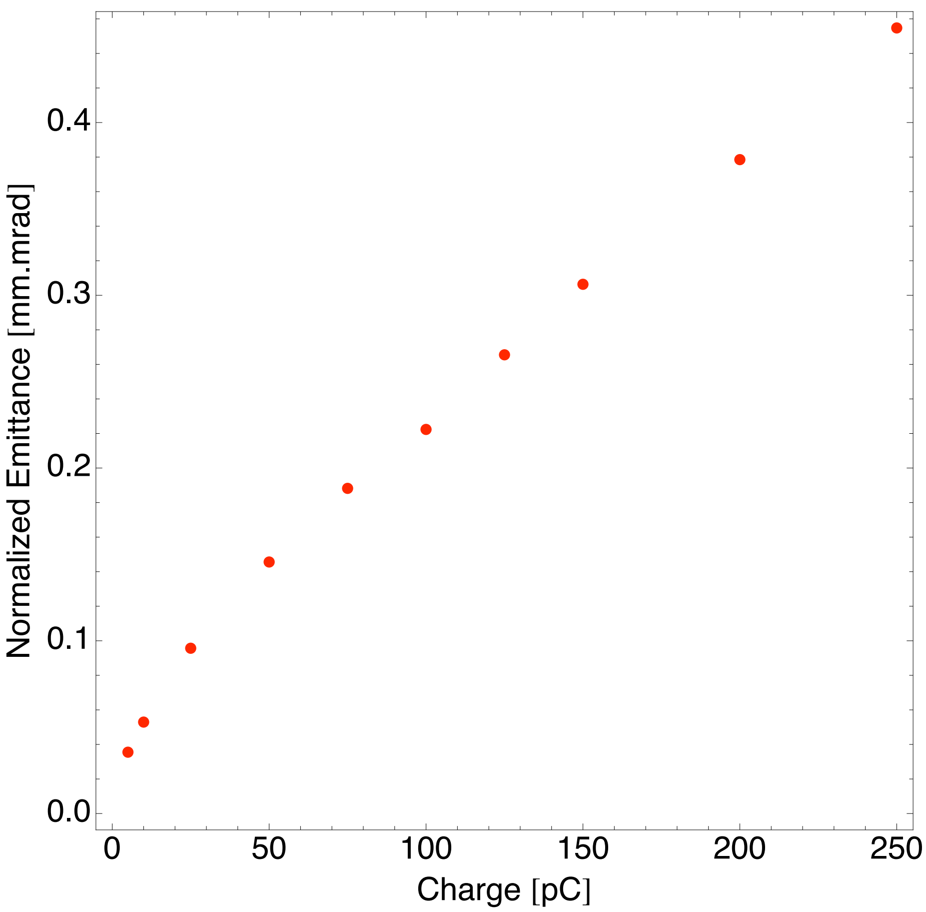
Dropping the per-bunch charge from 250 pC to 25 pC will lower wakefield effects



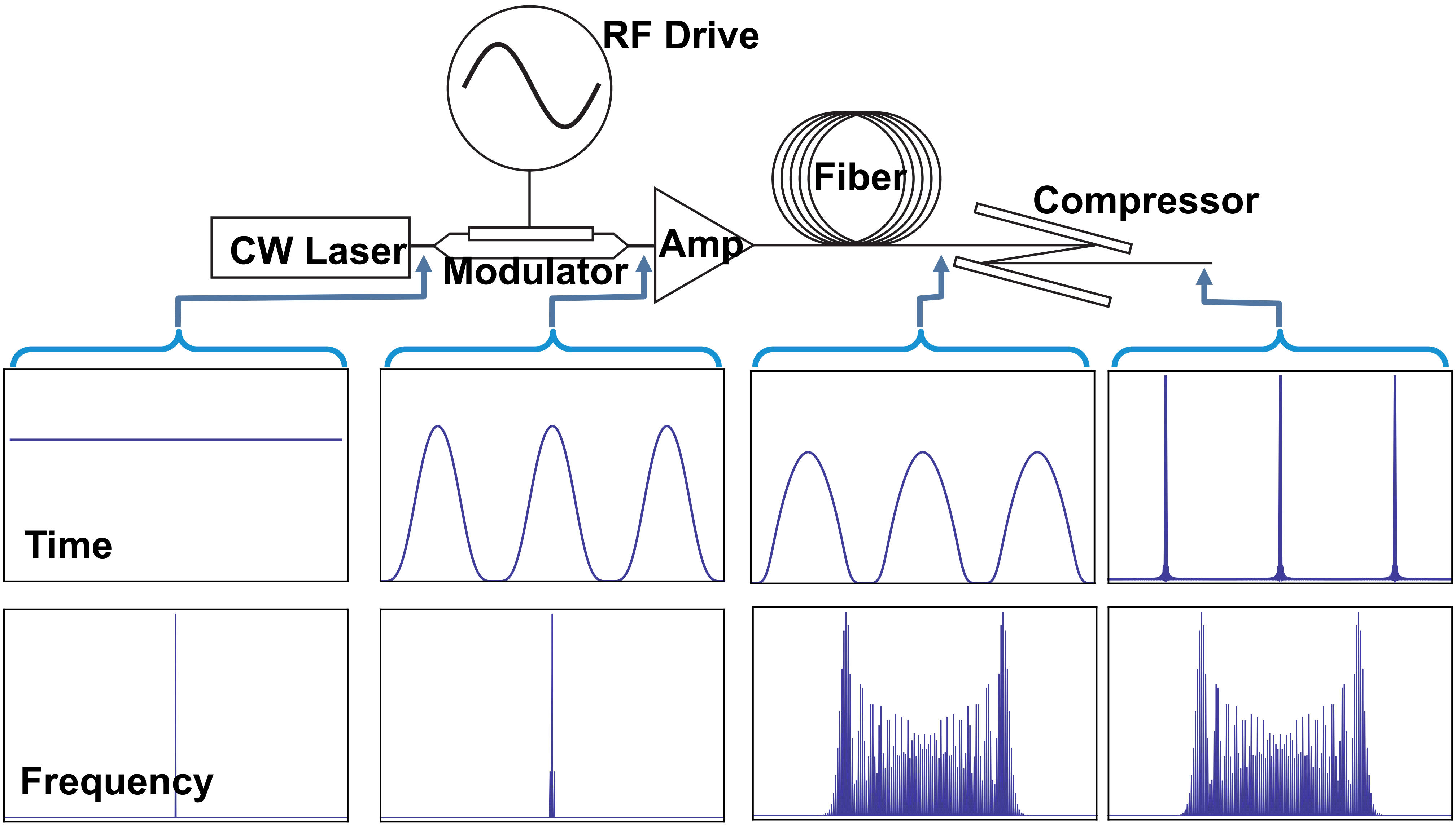
200 MV/ meter accelerating field
1 MV/ meter wakefield scale

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





11.424 GHz Photocathode Drive Laser concept

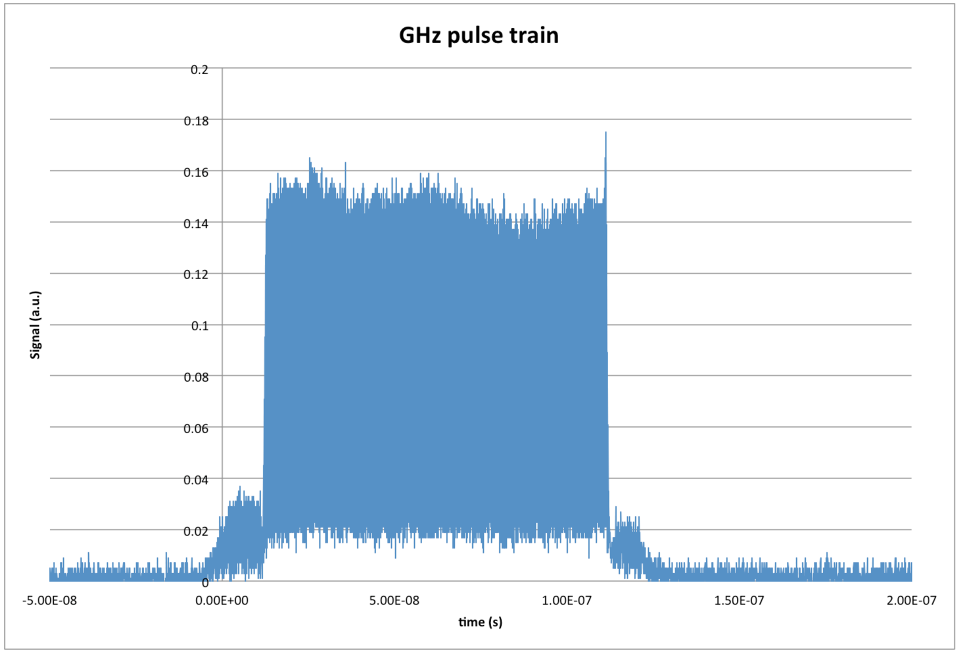


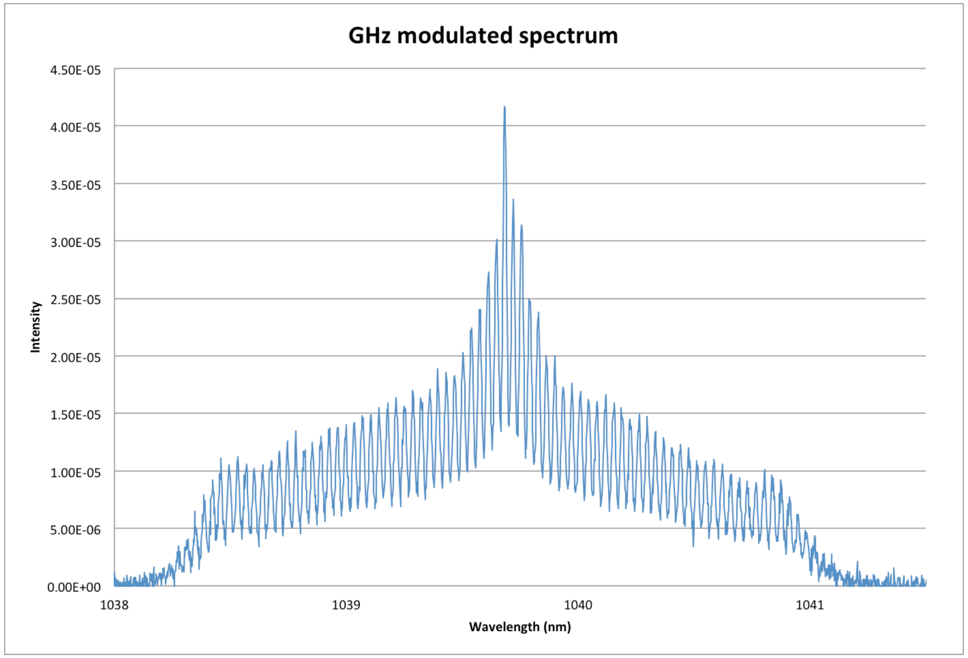
Photocathode Drive Laser Specifications

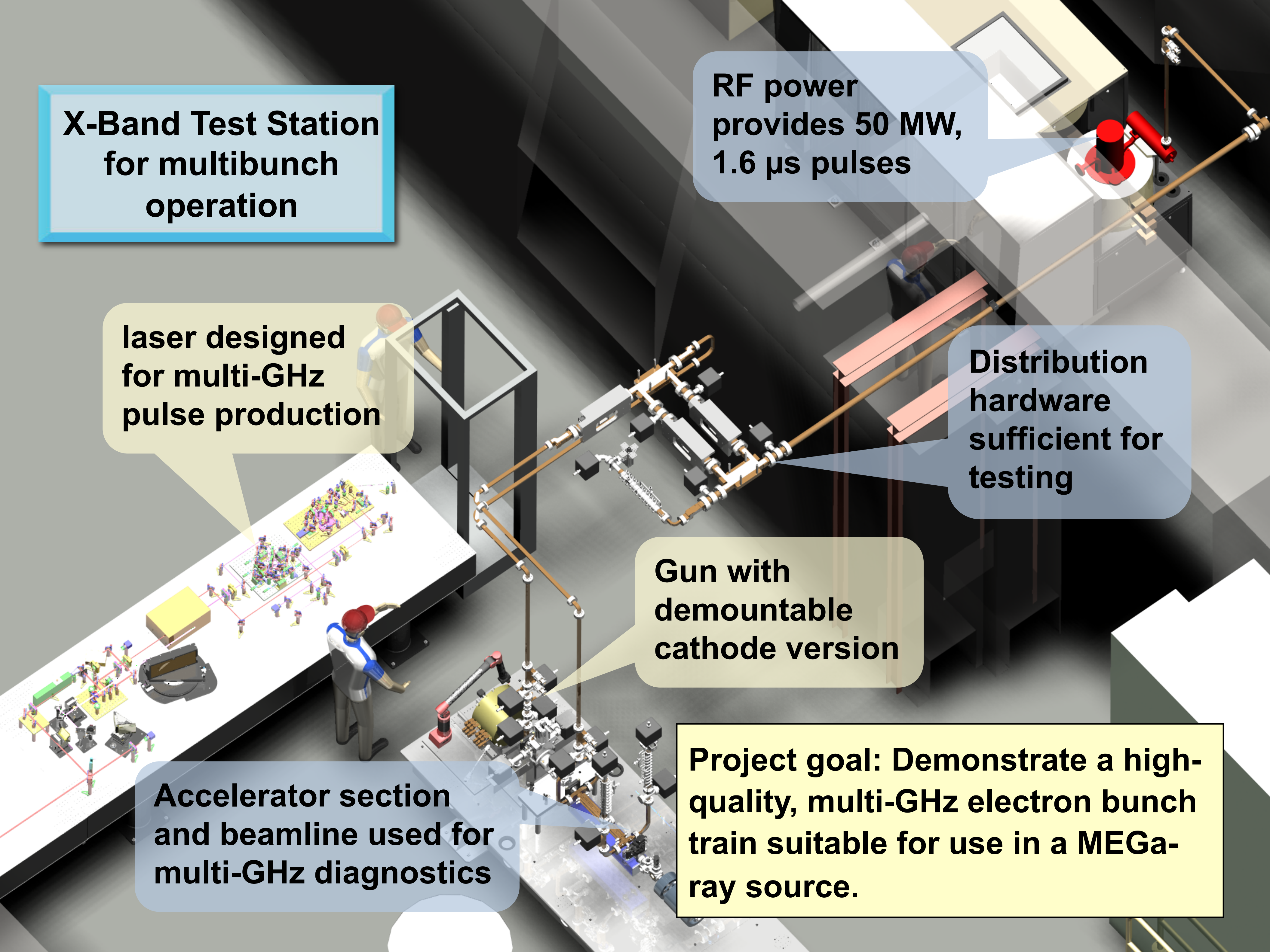
Parameter	Mg cathode (high efficiency)
Micro-pulses per macro-pulse	1,000
Beam quality, M^2	< 1.1
Micro-pulse specifications	
Repetition rate	11.424 GHz
Duration	250 fs
Energy @ 260 nm	0.5 µJ
Energy at 1040 nm	2.5 µJ
Macro-pulse specifications	
Repetition rate	120 Hz
Duration	87.5 ns
Energy @ 260 nm	0.5 mJ
Energy @ 1040 nm	2.5 mJ

Photocathode Drive Laser experimental status

- Modulated CW laser and sliced out bunch trains
- Generated ~3 nm bandwidth (~ ps pulse length)
- Working on compression
- Next step: 5x increase in bandwidth







X-Band Test Station for multibunch operation
RF power provides 50 MW, 1.6 µs pulses
laser designed for multi-GHz pulse production
Distribution hardware sufficient for testing
Gun with demountable cathode version
Accelerator section and beamline used for multi-GHz diagnostics
Project goal: Demonstrate a high-quality, multi-GHz electron bunch train suitable for use in a MEGa-ray source.

Related publications

T-REX Experiments:

- F. Albert et al Isotope-specific detection of low density materials with laser-based monoenergetic gamma-rays, **Opt. Lett, 35, 3 354 (2010).**
- F. Albert et al Characterization and applications of a tunable, laser-based, MeV-Class Compton scattering gamma-ray source, **Phys. Rev. ST Accel. Beams, 13, 070704 (2010)**.

T-REX Source design:

- D. J. Gibson et al, **Phys. Rev. ST Accel. Beams 13, 070703 (2010).**
- M.Y. Shverdin et al, Chirped-pulse amplification with narrowband pulses, **Opt. Lett. 35, 14, 2478-2480 (2010).**

Source development (Theory):

- F. V. Hartemann et al, Low intensity nonlinear spectral effects in Compton scattering, **Phys. Rev. Lett, 105, 130801 (2010).**
- F. Albert et al Design of narrow-band Compton scattering sources for nuclear resonance fluorescence, **Phys. Rev. ST Accel. Beams 14, 050703 (2011)**.
- F. Albert et al Three dimensional weakly nonlinear theory of Compton scattering**, Phys. Plasmas, 18,013108, (2011).**
- F. Albert et al**.** Precision Linac and Laser Technologies for Nuclear Photonics Gamma-ray Sources, **Phys. Plasmas, In press, (2012).**
- R.A. Marsh et al**,** Modeling and Design of an LLNL/SLAC X-band RF Photoinjector, submitted to **Phys. Rev. ST Accel. Beams (2012).**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