Opportunities in Radiation Production from Light Source Injector Linacs

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Many people and groups contributed to the work I am sharing with you including...

Acknowledgments

UCLA

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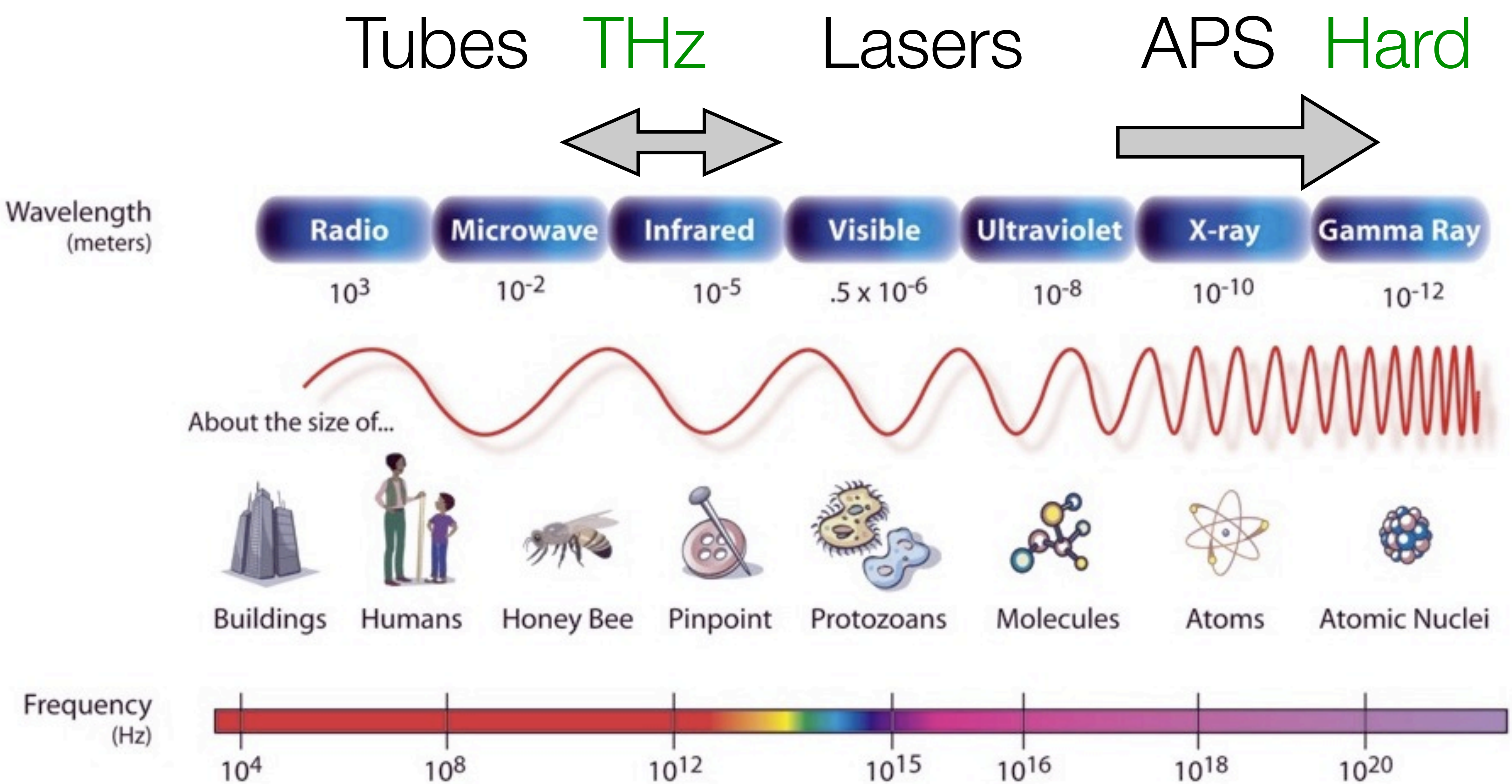
Abstract

Next generation FEL-based light sources were investigated at small scale test facilities and shown to be viable at intermediate energy linac facilities. Light sources, such as the APS, feature injector linacs with significant capabilities, including beam energies approaching 1 GeV. These facilities and their beams offer a rich opportunity to study compact radiation production schemes. These schemes can provide THz, x-ray, and gamma-ray production which are interesting in their own right, and can be complementary to existing and future light sources. In this talk, I will discuss radiation production from dielectric structures as well as Inverse Compton Scattering (ICS) sources. Selected applications, including production of positrons and detection of special nuclear materials will be mentioned. I will use examples from our work at UCLA as well as parameters that may be accessible at the APS.

Spectral regions which are still difficult to generate and produce interesting science include THz, x-ray and gamma ray



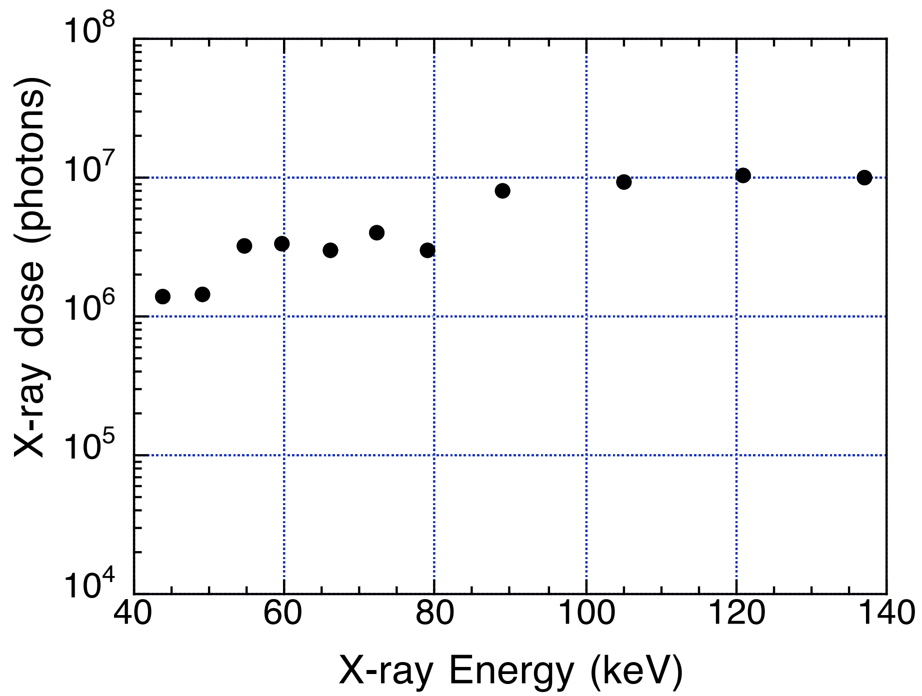
Fast, hard x-ray production (>50 keV & <50 ps) is a challenging regime

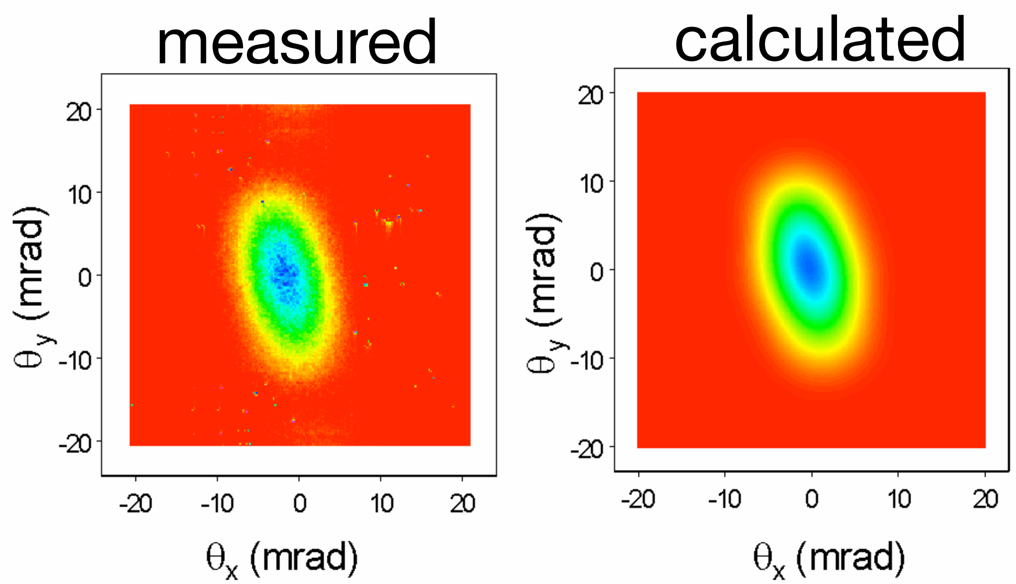
Synchrotron Light Sources:
< 50 keV, > 50 ps

LCLS:
maximum @ 24 keV

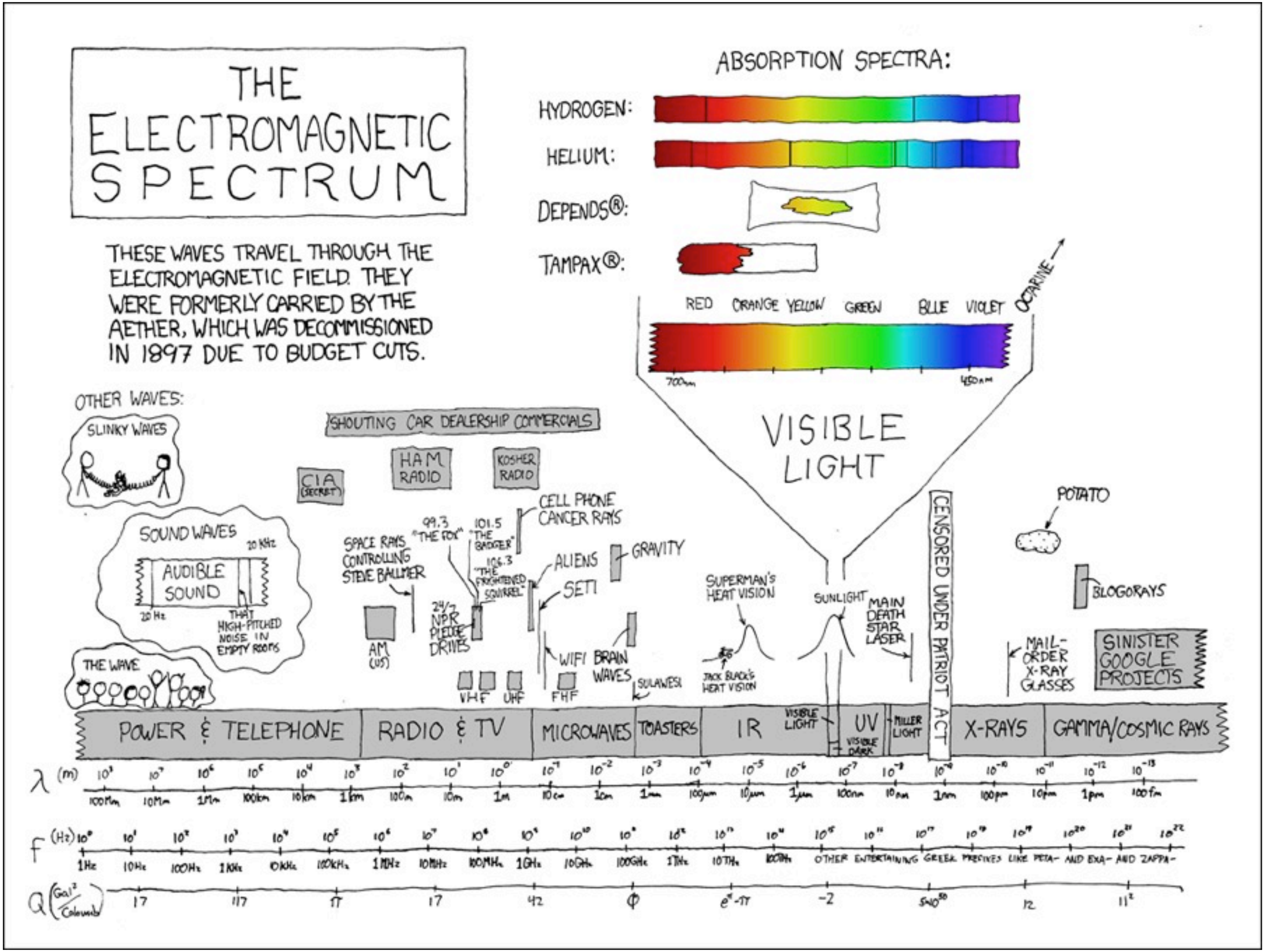
K-α:
energy limit ~ 100 keV, 4π

10^7 photons, $B_x > 10^{16}$ photons/s/mm^2/mrad^2/.1%bw



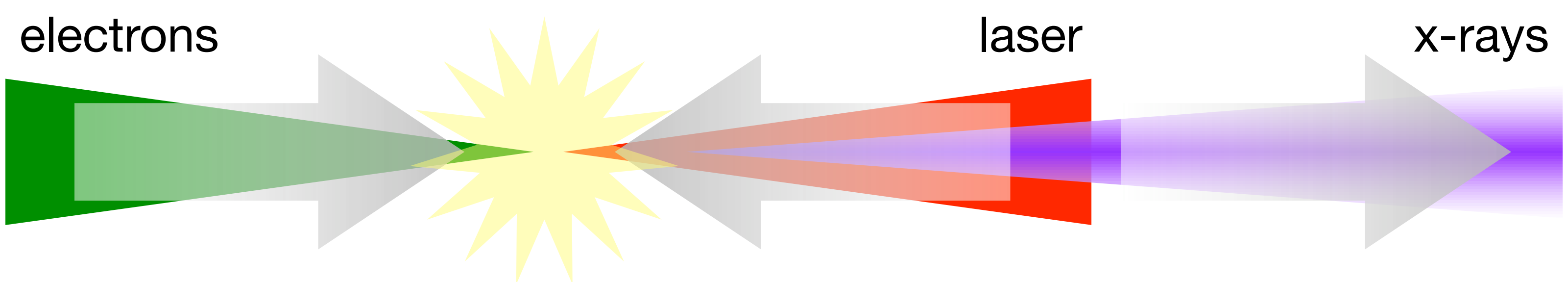


ICS: already established very high brightness at 140 keV, fs hard x-rays (PLEIADES)


THE ELECTROMAGNETIC SPECTRUM
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.
ABSORPTION SPECTRA:
HYDROGEN:
HELIUM:
DEPENDS®:
TAMPAX®:
RED
ORANGE
YELLOW
GREEN
BLUE
VIOLET
OCTARINE
VISIBLE LIGHT
OTHER WAVES:
SLINKY WAVES
SOUND WAVES
AUDIBLE SOUND
THAT HIGH-PITCHED NOISE IN EMPTY ROOMS
THE WAVE
SHOUTING CAR DEALERSHIP COMMERCIALS
CIA (SECRET)
HAM RADIO
KOSHER RADIO
CELL PHONE CANCER RAYS
SPACE RAYS CONTROLLING STEVE BALLMER
AM (US)
24/7 NPR PLEDGE DRIVES
VHF
UHF
FHF
ALIENS
SETI
WIFI
BRAIN WAVES
GRAVITY
SULAWESI
SUPERMAN'S HEAT VISION
JACK BLACK'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
POWER & TELEPHONE
RADIO & TV
MICROWAVES
TOASTERS
IR
VISIBLE LIGHT
VISIBLE DARK
UV
MILLER LIGHT
X-RAYS
GAMMA/COSMIC RAYS
λ (m)
f (Hz)
OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-
Q (Gal²/Coloumb)

The ICS process is analogous to an electromagnetic undulator

Photon is Doppler upshifted



$$h\nu_{scat} = \sim 4\gamma^2 h\nu_{laser}$$

Assume gaussians of equal length

$$N_\gamma \sim 4\times10^3 N_e \frac{E_L[\mathrm{J}]}{Z_R[\mu\mathrm{m}]}$$

$$N_\gamma \sim N_e N_L \frac{\sigma_{t,L}\sigma_{z,e}}{\sigma_{r,e}^2 + \sigma_{r,L}^2}\sigma_T$$

example: 1J laser; 1mm range; 1 nC beam

$$N_\gamma \sim 4\times10^3\left(6\times10^9\right)\frac{1}{10^3} \approx 2\times10^{10}$$

$$\sigma_T = \frac{8\pi}{3}\left(\frac{\alpha\hbar}{m_e c}\right)^2$$

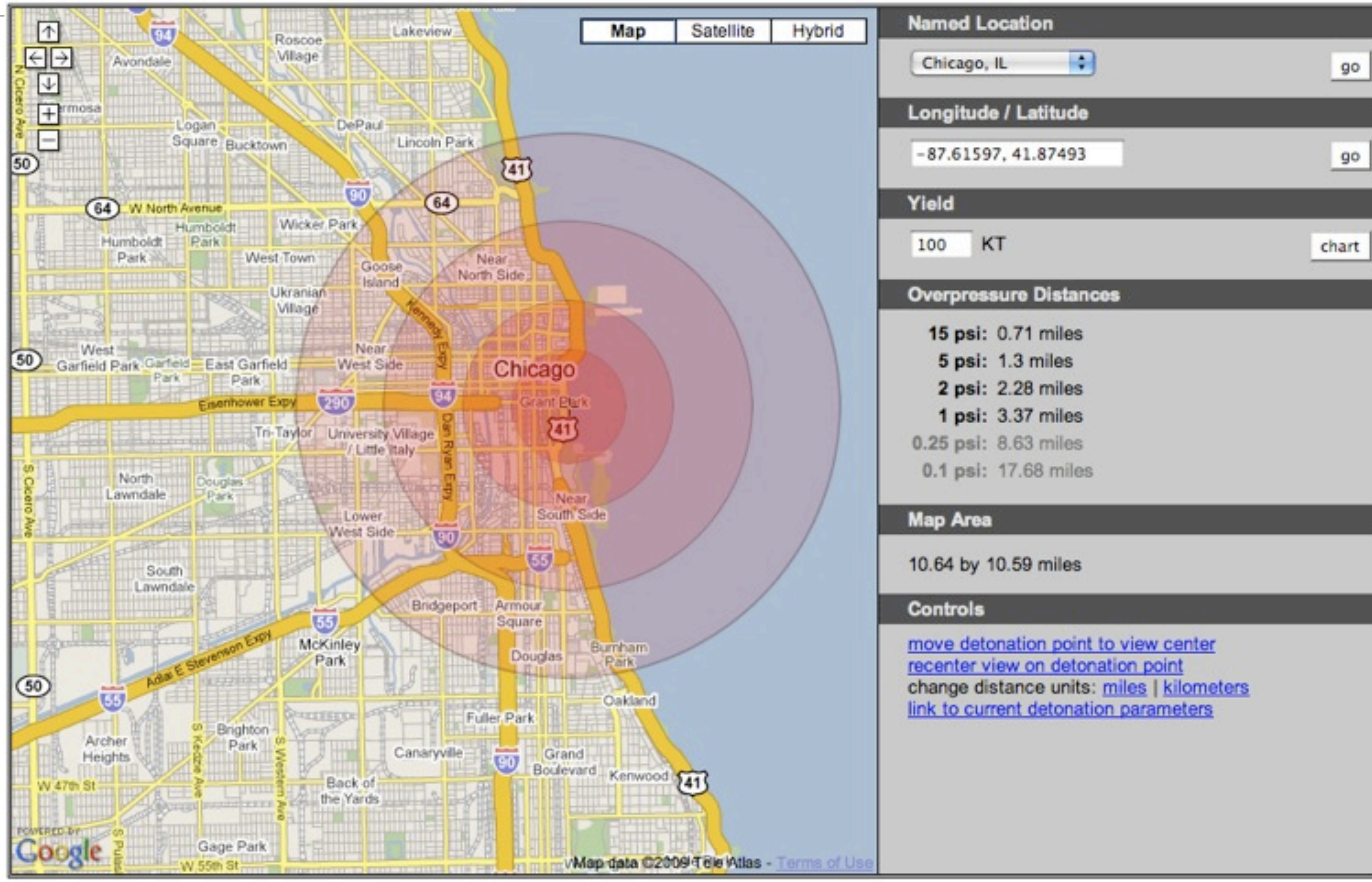
$$\sigma_T \approx 6.7\times10^{-25}\,\mathrm{cm}^2$$

good to know: normalized laser potential

$$a_0 \approx 0.85\times10^{-9}\lambda_0\left[\mu m\right]\sqrt{I_0\left[W/cm^2\right]}$$

Stand-off Detection of Nuclear Materials Using Inverse Compton Scattering Generated Gamma-Rays

“Evil doers” obtaining Special Nuclear Materials (SNR) is considered a high likelihood.



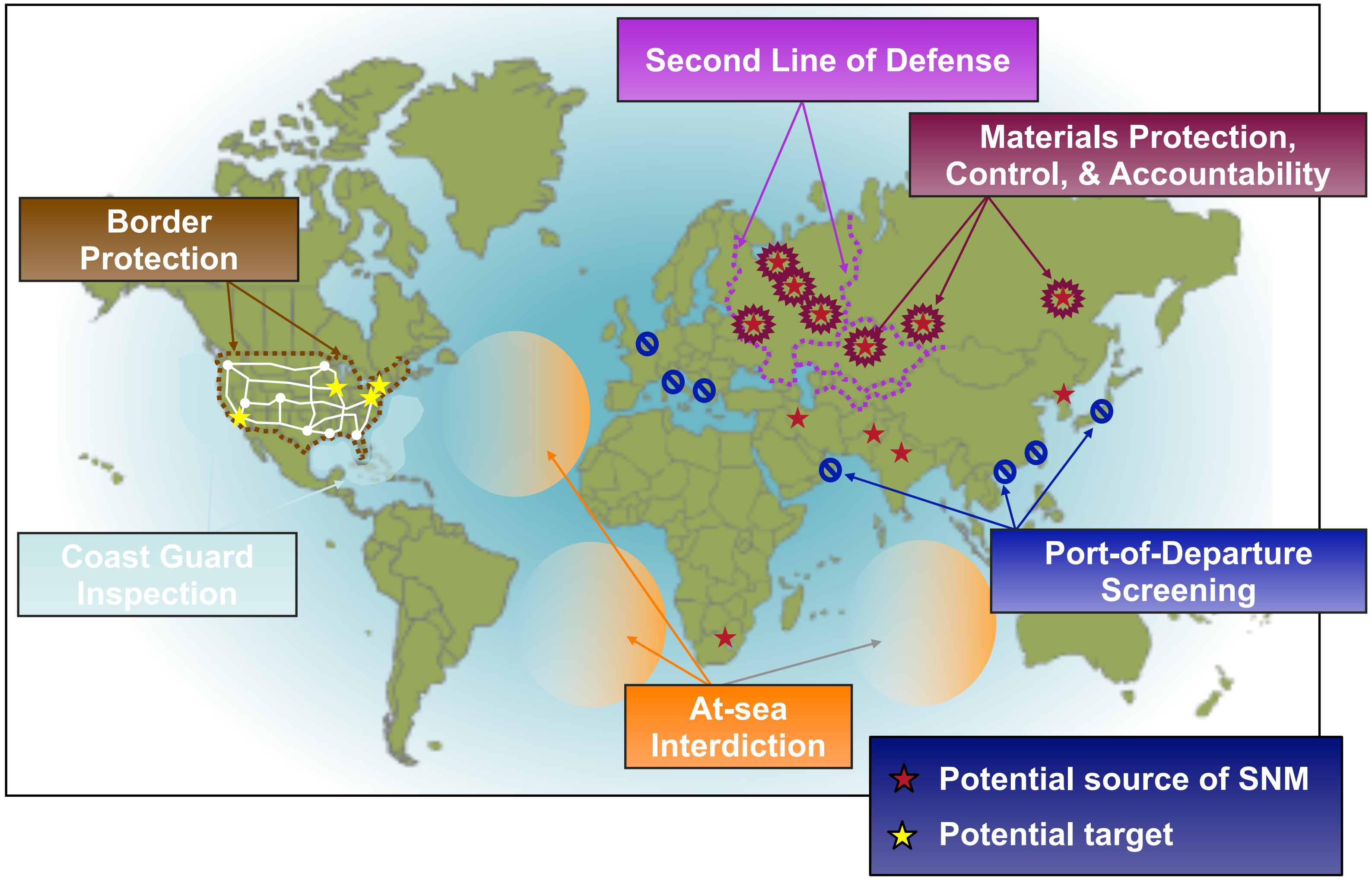
In this post-Cold War world, nuclear terrorism may be the single most catastrophic threat that any nation faces - we must do everything we can to ensure against its occurrence.

-- Joseph Krol, Associate Administrator, NNSA

The detection and tracking of SNM is a global, multifaceted effort

...nuclear materials detection is but one tool in the broad array of ongoing activities and emerging capabilities, systems, and architectures that comprise an overall strategy to counter nuclear terrorism.

-- Joseph Krol, Associate Administrator, NNSA



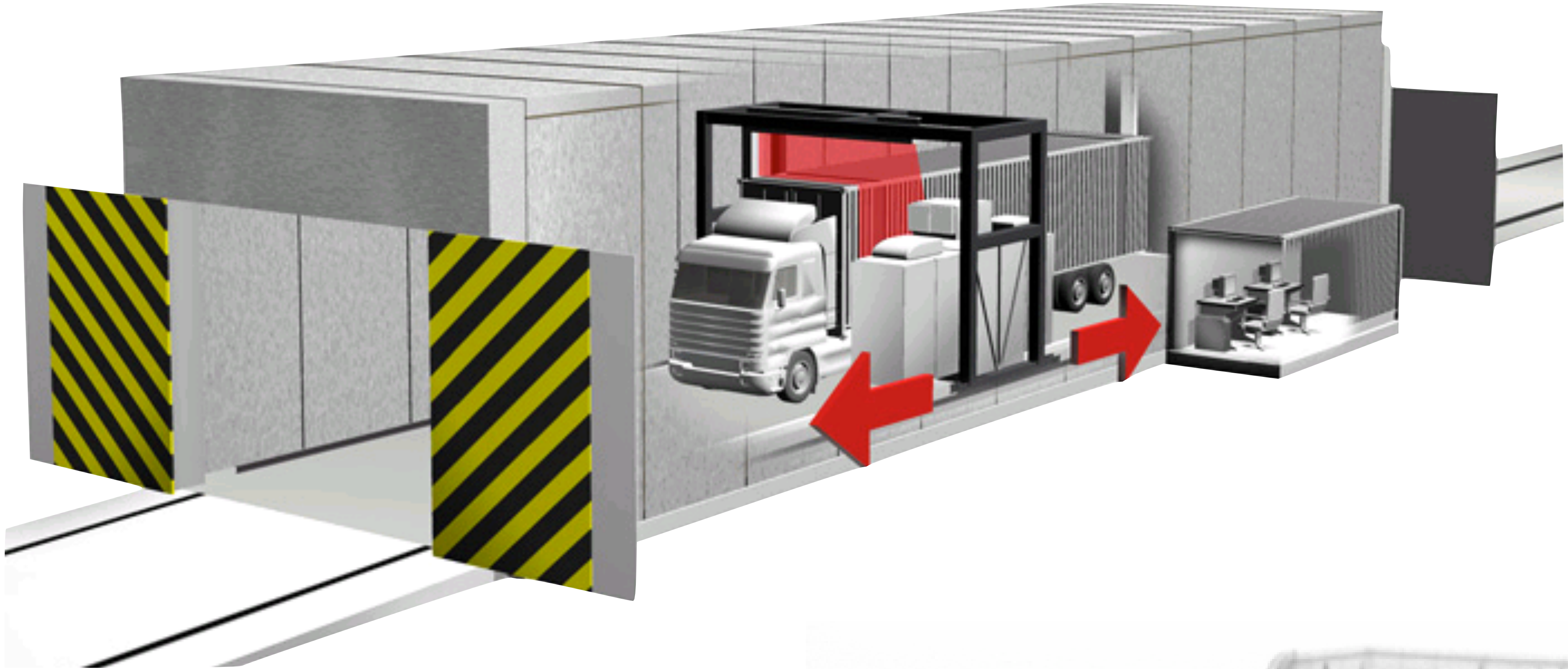
From "Progress in Nuclear Detection", Abu Bowman, DNDO, 3/23/2007

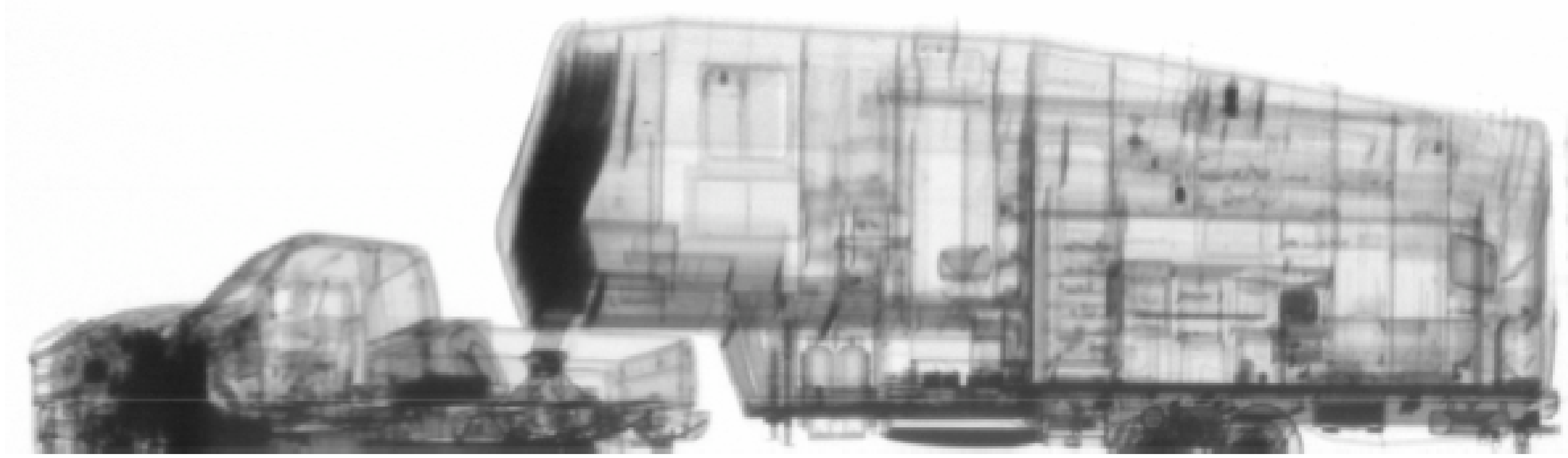
Currently employed methods of passive detection of SNM can easily be defeated

portal screening

Easy to negate with shielding
Can be masked with other isotopes
Low signal-to-noise at long-range

Radiography addresses some of the shortcomings of passive detection but is unsuited to stand-off detection





Standoff detection of SNM requires active interrogation

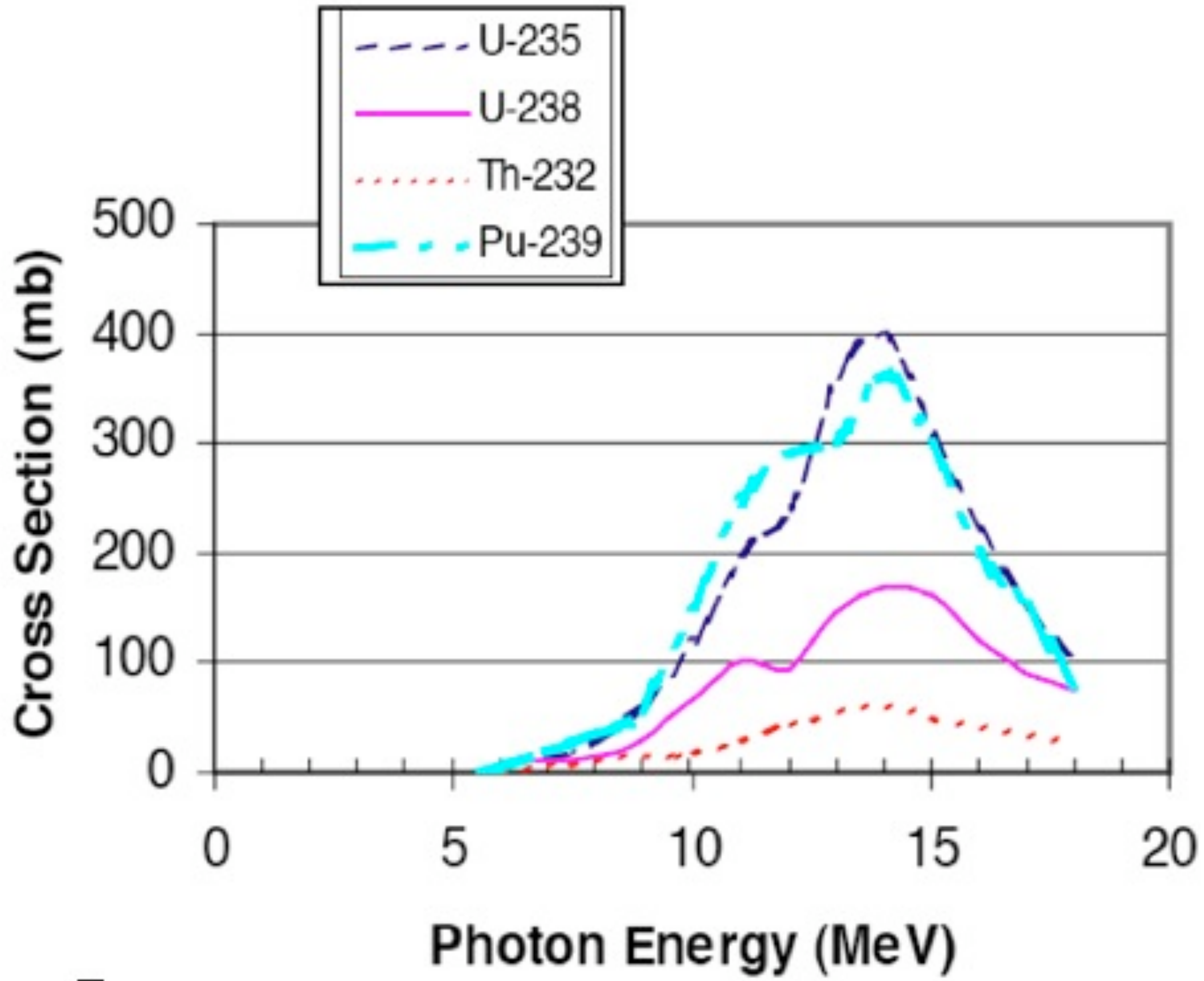
At long distances, Signal-to-Noise Ratio is low
Increasing detector size/efficiency only increases amplitude of signal, not SNR
Some tricks can be played to increase SNR, but still do not work beyond 10's of meters
Neutrons can be shielded with hydrogenous material, gammas with high-Z material

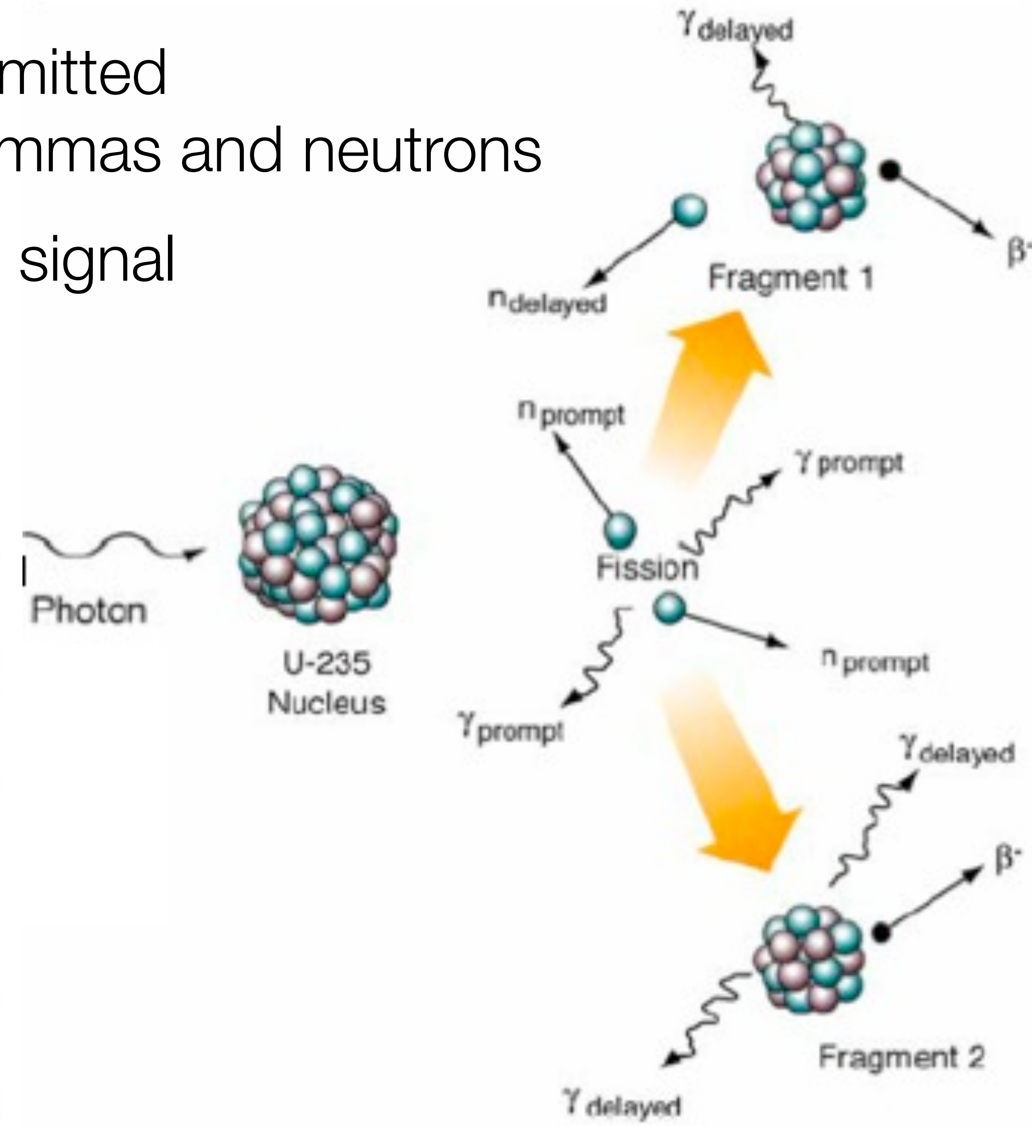
Passive	**Active**
Low S/N & Limited range	Flux determines S/N
Limited targeting	With directed source (ICS), long range and target pin pointing possible
Easy to shield against	Very difficult to mask and can be combined with neutrons
Difficult to identify materials	Specific materials can be identified

Photofission is a promising means of detecting SNM with high confidence.

❶ 6+ MeV gammas induce fission in actinides
❷ Prompt neutrons and gammas immediately emitted
❸ Fission fragments decay, emitting delayed gammas and neutrons

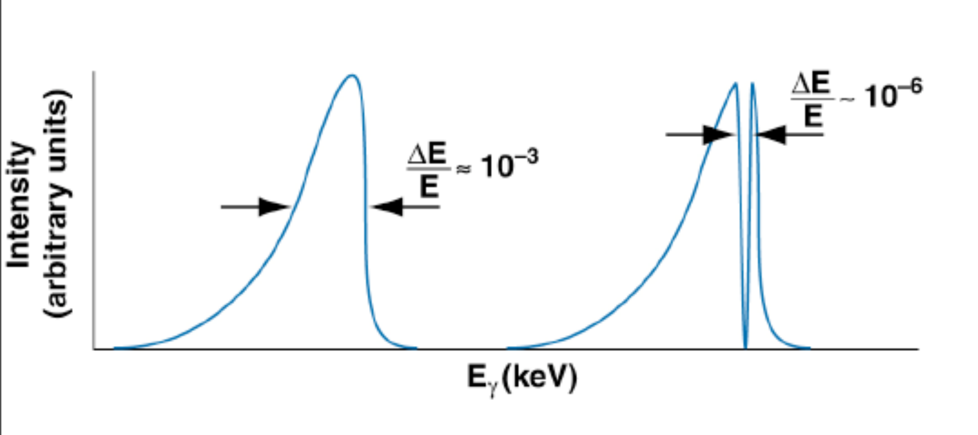
➟ Delayed gammas and neutrons are a positive signal





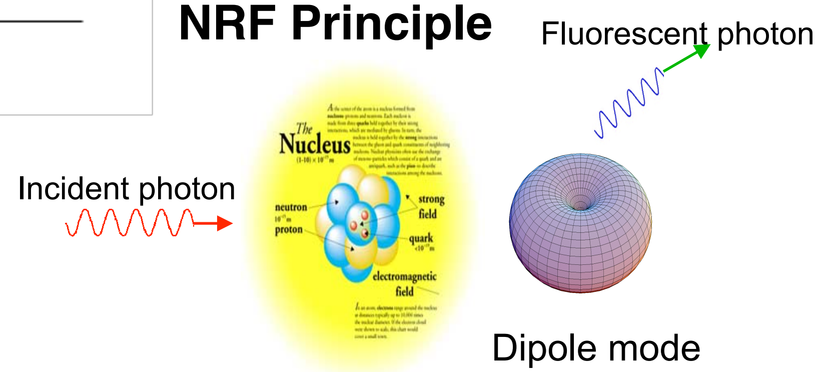
Nuclear Resonance Fluorescence (NRF) is also of interest

NRF has similar requirements...



Nuclear Resonance Fluorescence

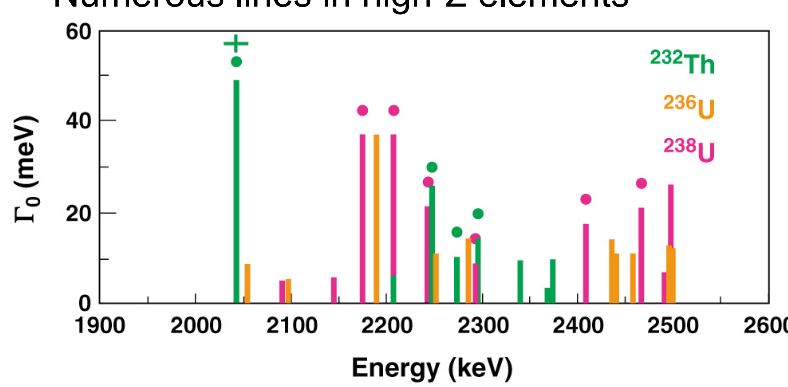
NRF Principle



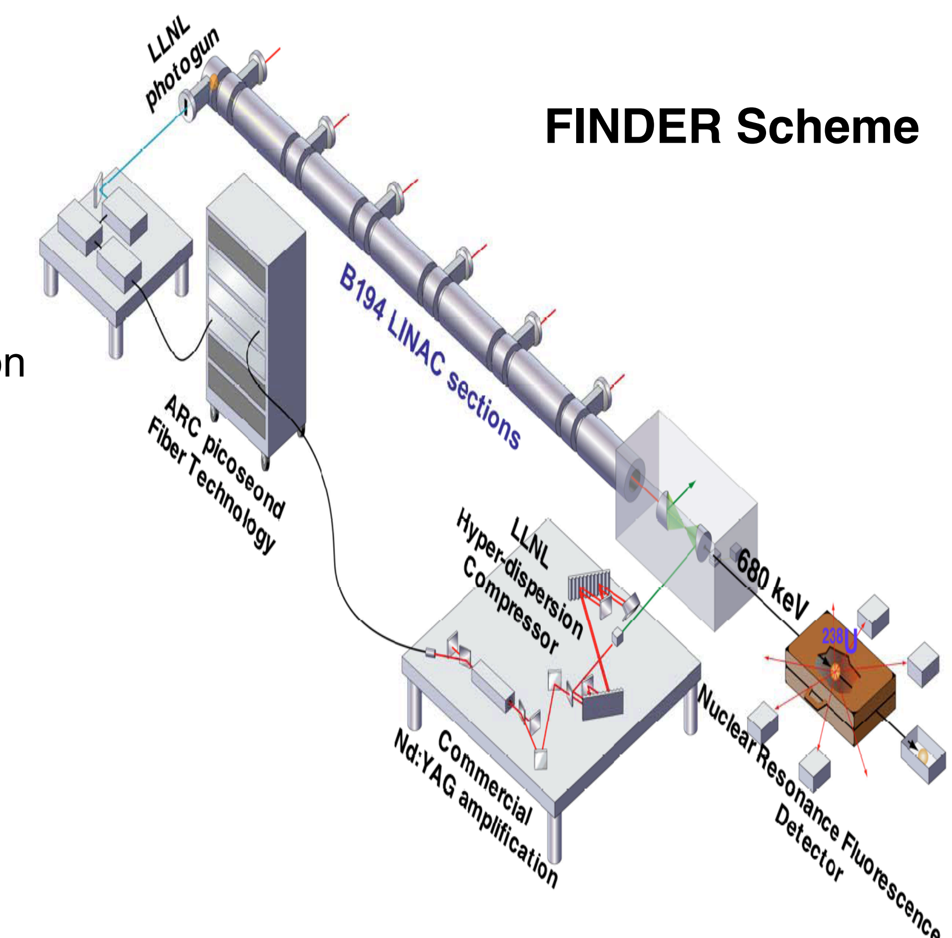
- Probability of re-radiating identical photon is exceedingly small

Observed Resonances

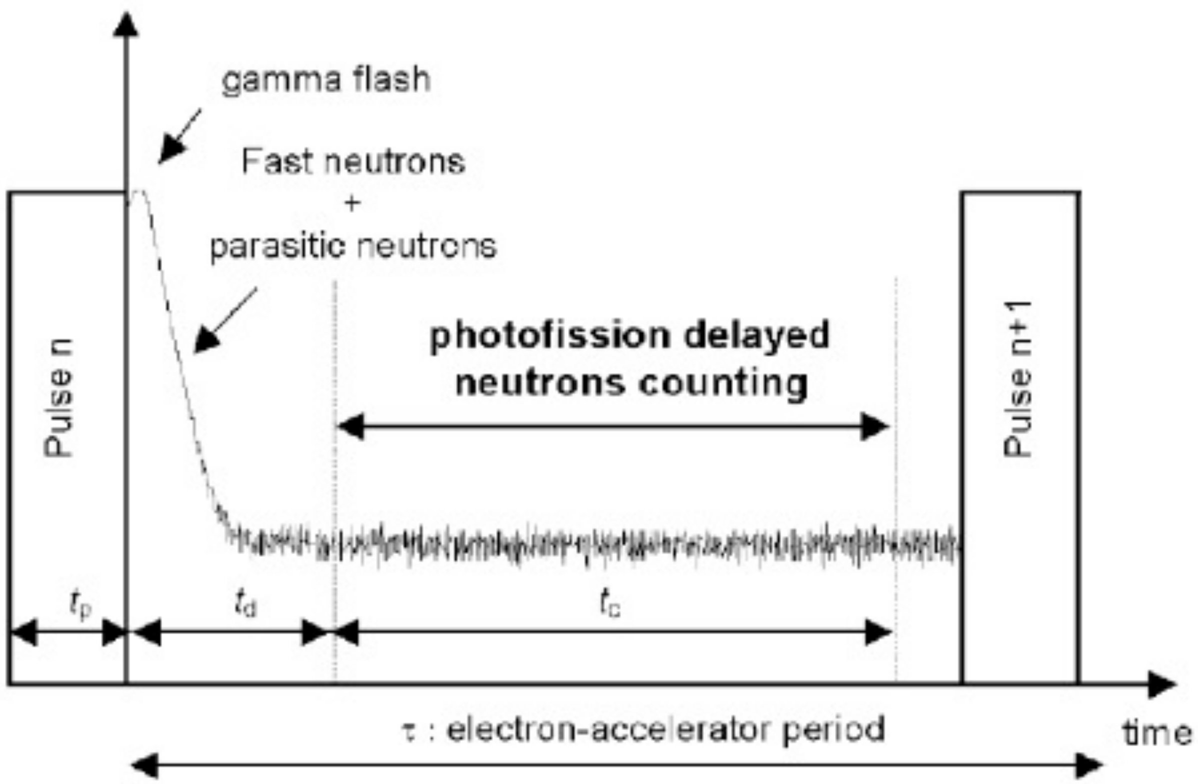
- Numerous lines in high-Z elements



- 1,733 keV line candidate in ^{235}U



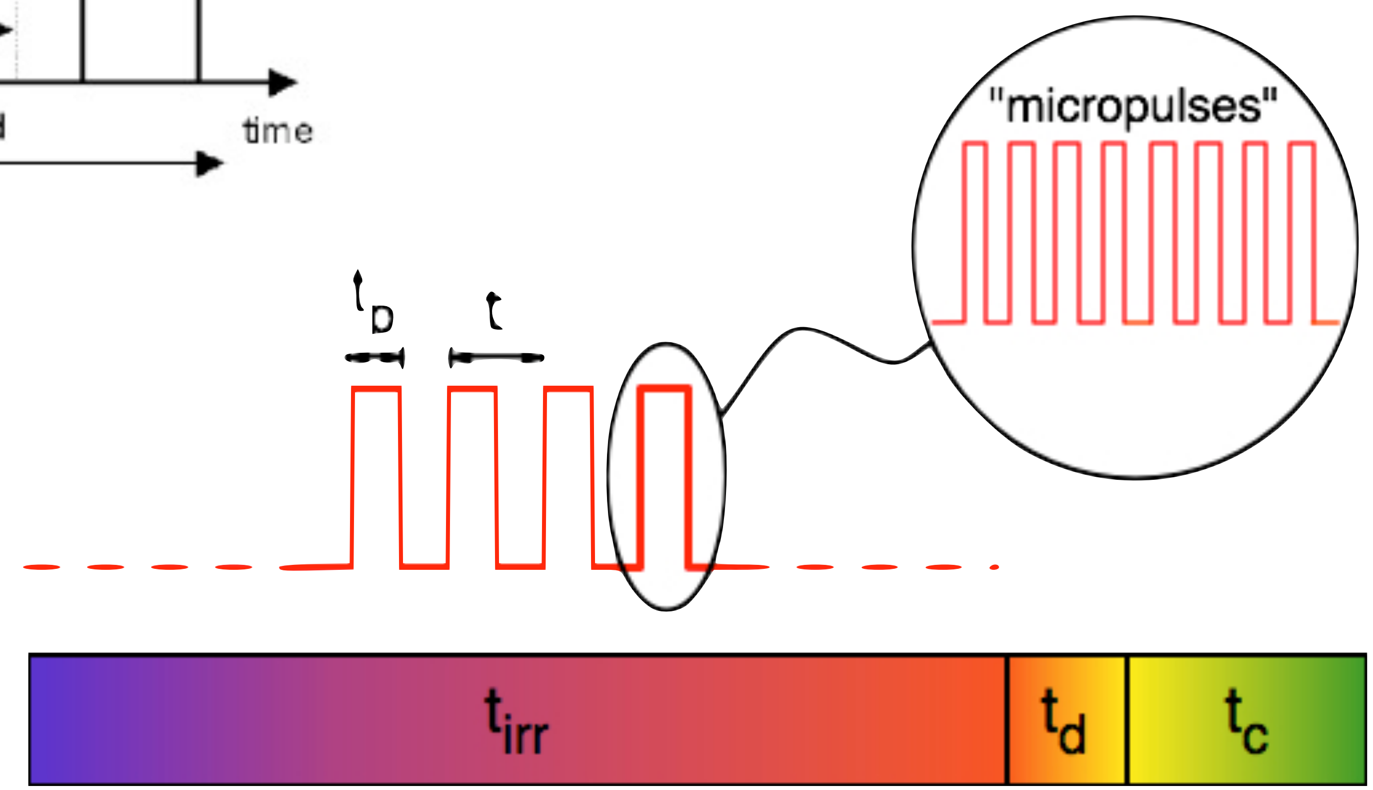
Active interrogation requires time intervals to count delayed products



$t_{irr} = 10$ s

$t_d = 5$ ms

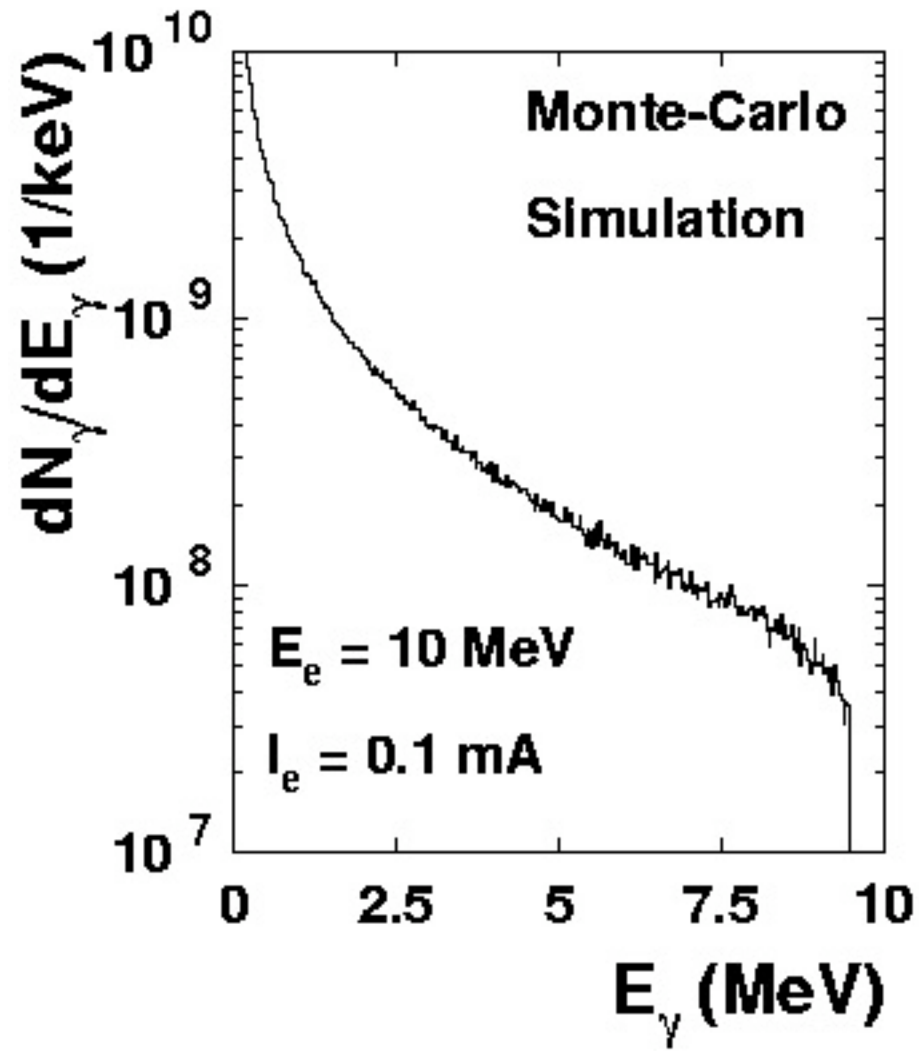
$t_c = 250$ ms



Producing gammas for photofission is easy; Producing a source with good S/N is hard

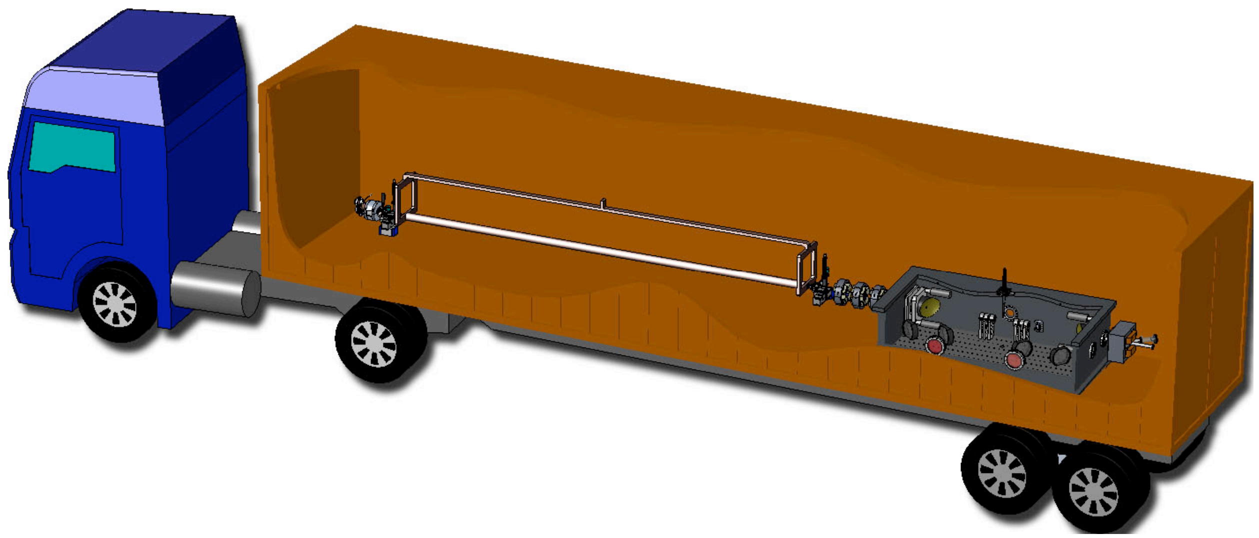
bremsstrahlung is ill suited

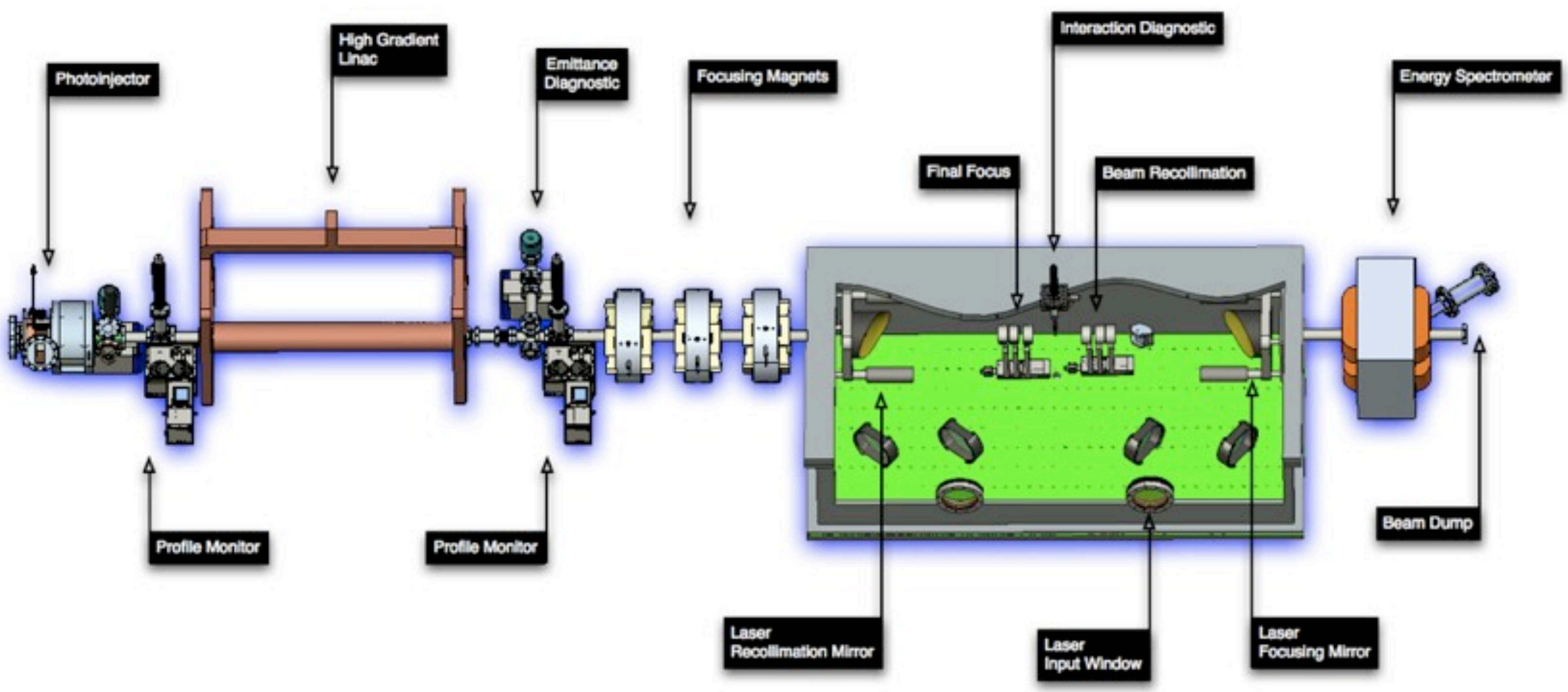
Bremsstrahlung	**ICS**
Local (target) radiation	Directed radiation beam
Low spectral density	High spectral density & brightness
High background signal	Excellent S/N
Easy to do	**Hard to do**



An ICS Gamma Source (IGS) is the best path for photofission standoff detection

fieldable source of bright monoenergetic beam of photons

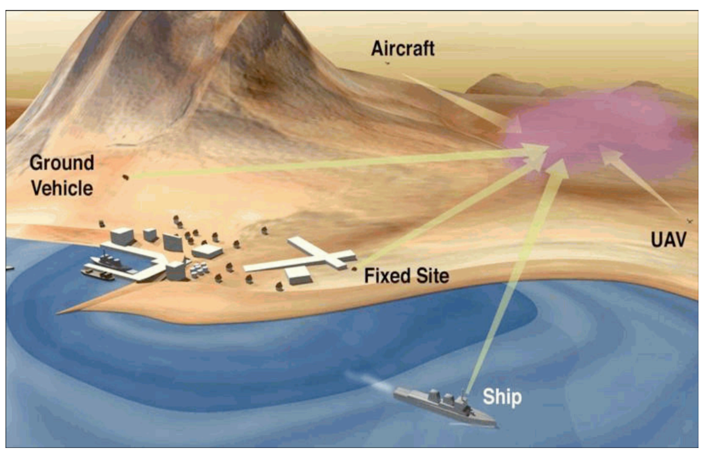


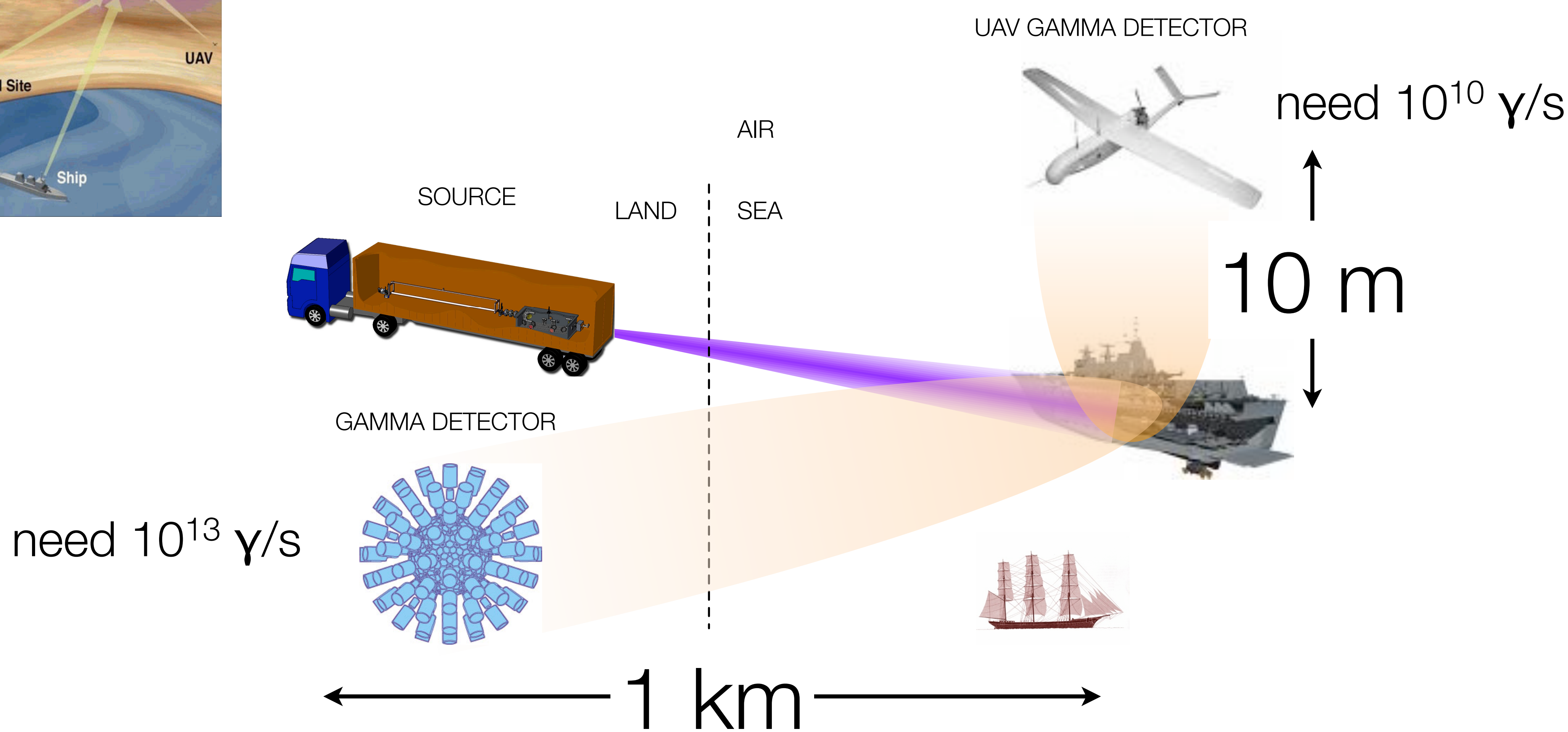


The IGS performance requirements are severe

Up to 10^{13}, 10 MeV gammas/sec

Producing 10 MeV gammas requires
~500 MeV electrons
(assuming green drive laser)



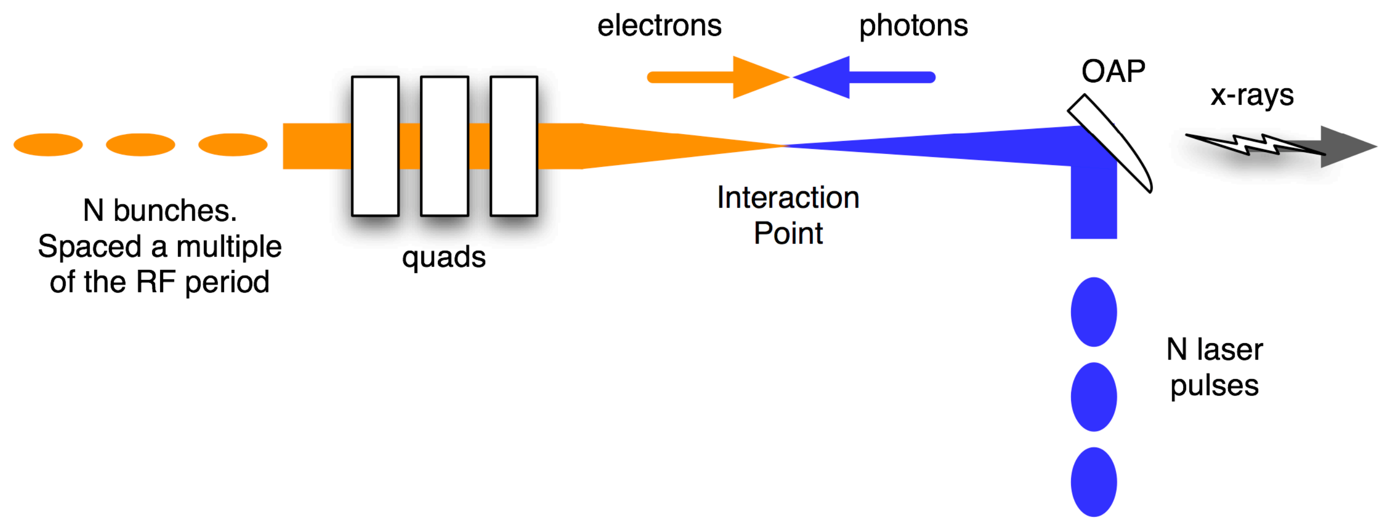


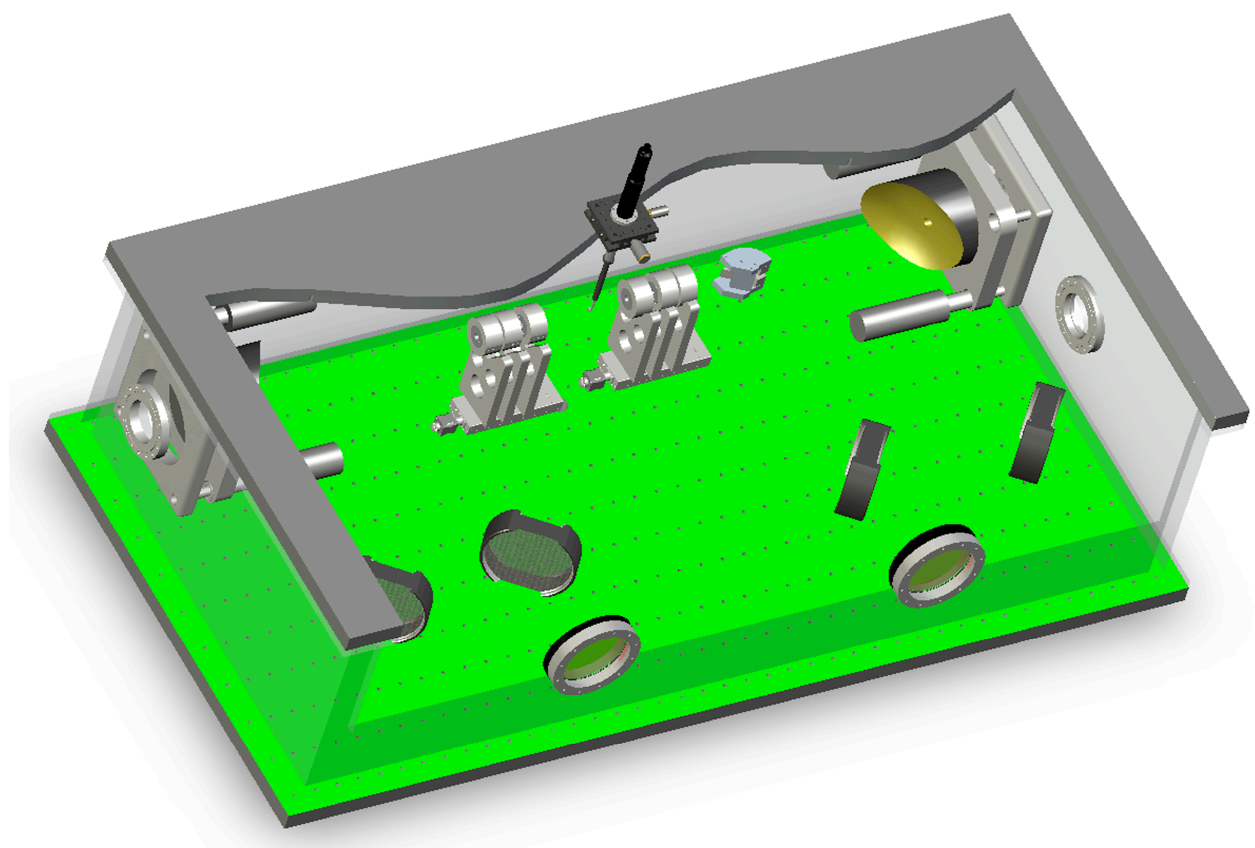
The IGS specifications are ambitious and demand advancements in several areas

Parameter	Value
Laser Pulse Length (FWHM)	10 ps
Laser Wavelength (frequency doubled)	532 nm
Laser Pulse Energy	**620 mJ**
Laser Strength Parameter (a_0)	0.06
Laser Rayleigh Range	1.28 mm
Laser/E-beam Spot Size (rms)	7.4 μm
E-beam Energy	**547 MeV**
E-beam Beta Function	29 mm
Number of Gammas per Micropulse	**1.0×10^{9}**
E-beam Charge	1 nC
E-beam Emittance	2 μm
Number of Photons per Micropulse	2.0×10^{9}
Number of Photons per Macropulse	2.0×10^{11}
Peak flux at 1 km stand-off [m^{-2}-s^{-1}]	8.9×10^{15}
Average flux at 1 km stand-off [m^{-2}-s^{-1}]	8.9×10^{12}

Multibunch operation is critical to high flux, but puts demands on the various subsystems

1kHz rep rate
100 e-bunches
100 laser recirculations
Total cavity power = 62 kW

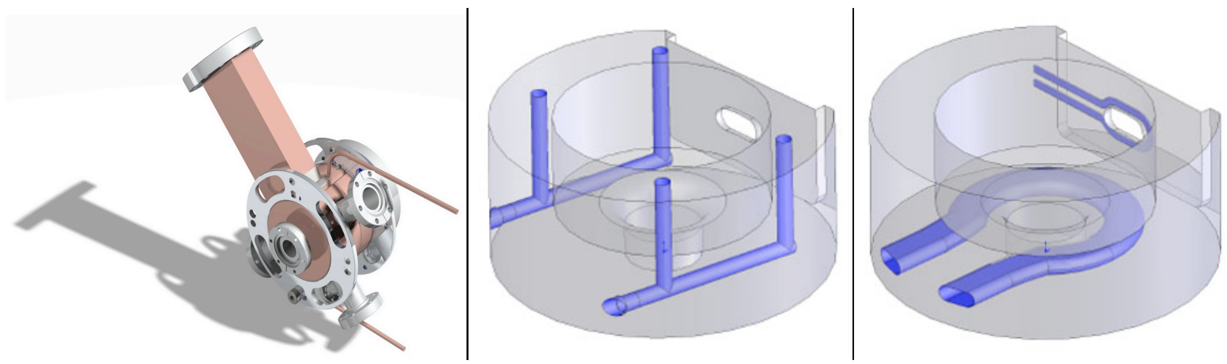




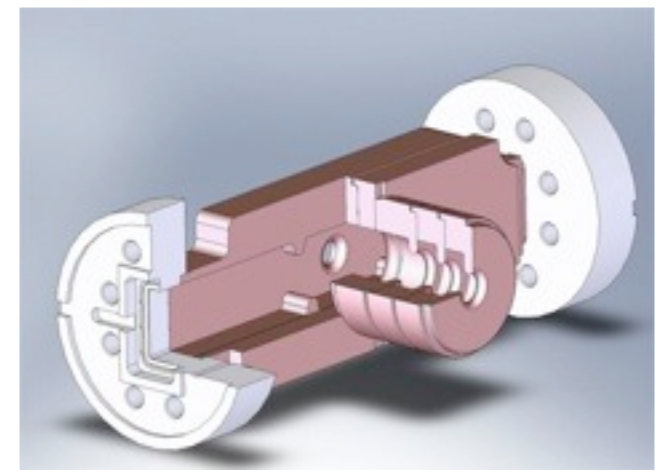
Final focus combines electron and laser optics with feedback diagnostics

The IGS effort at RadiaBeam and UCLA involves developing four core technologies

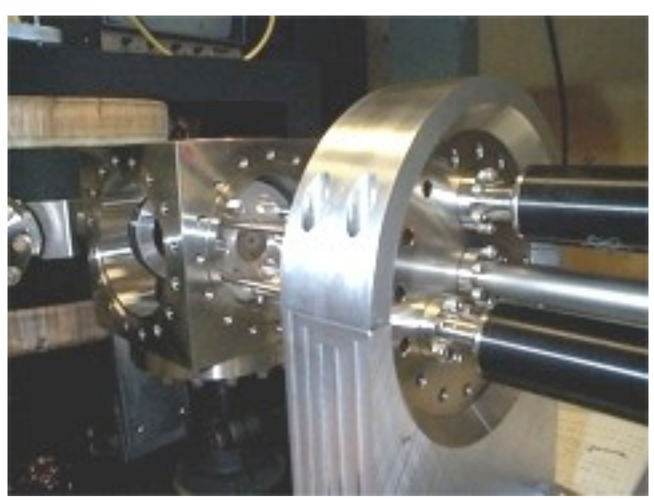
high repetition rate photoinjectors



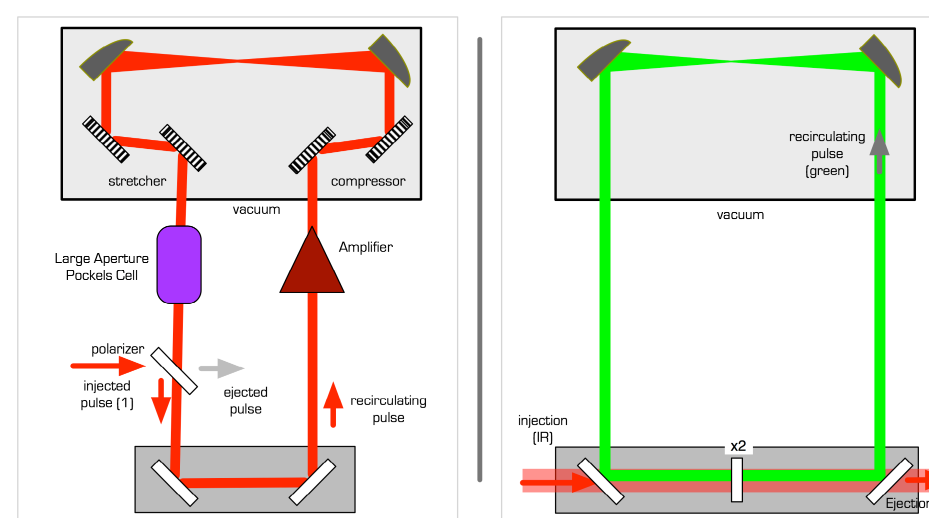
high gradient accelerator structures



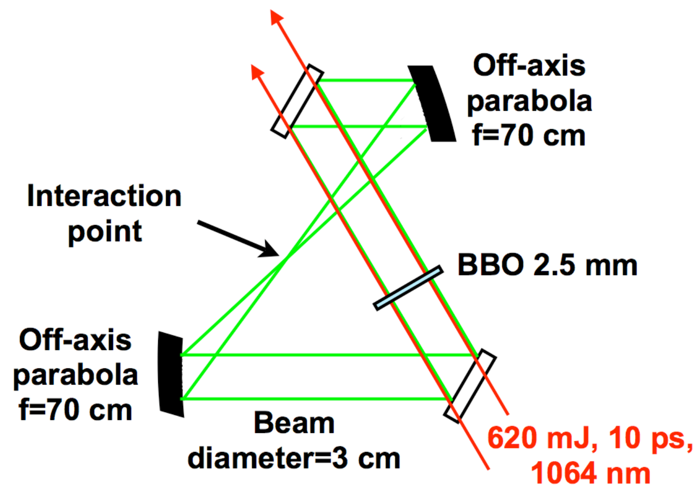
final focus systems



Multibuch interaction schemes

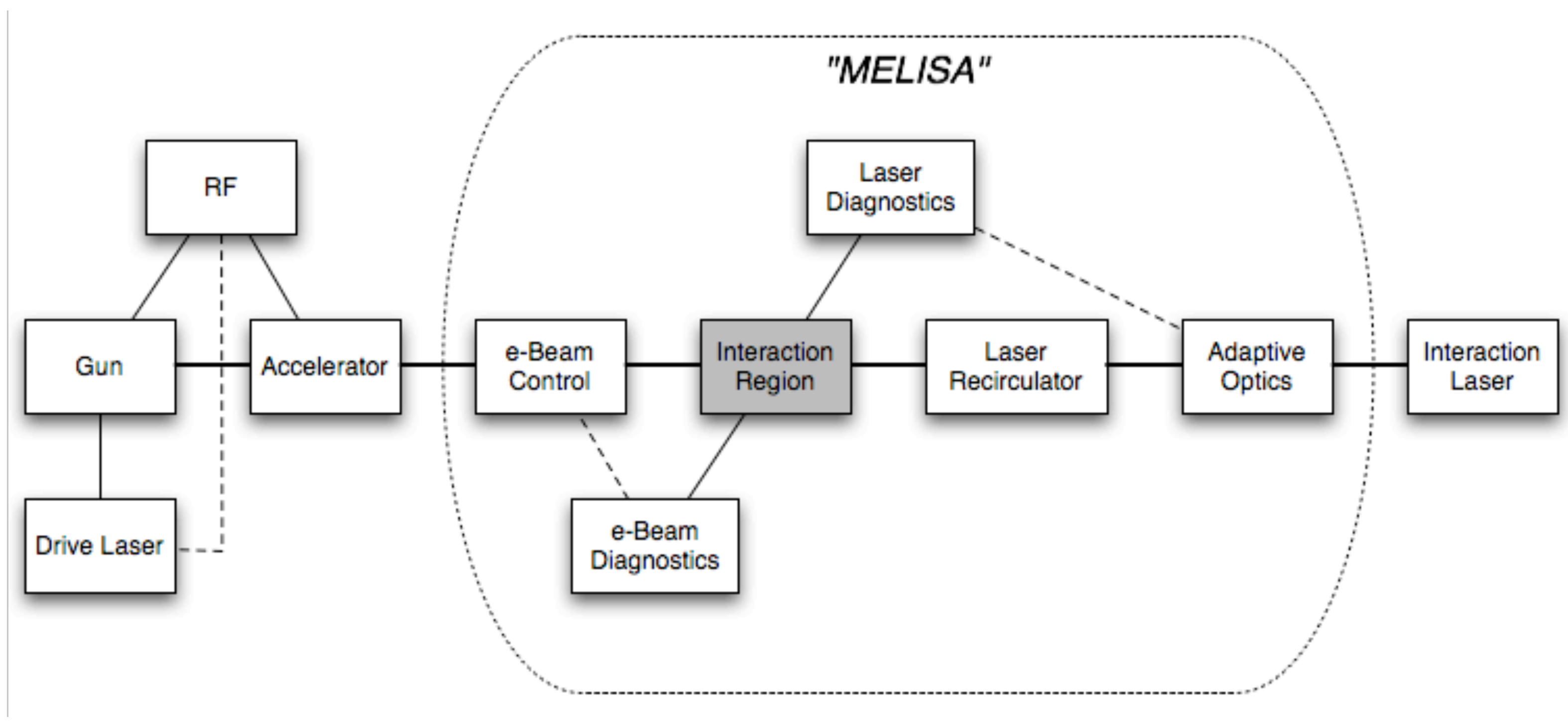


An IGS approach has not been proven to work. A POC experiment is needed



RadiaBeam is funded (DOE Phase II SBIR) to carry out a test an BNL's ATF.

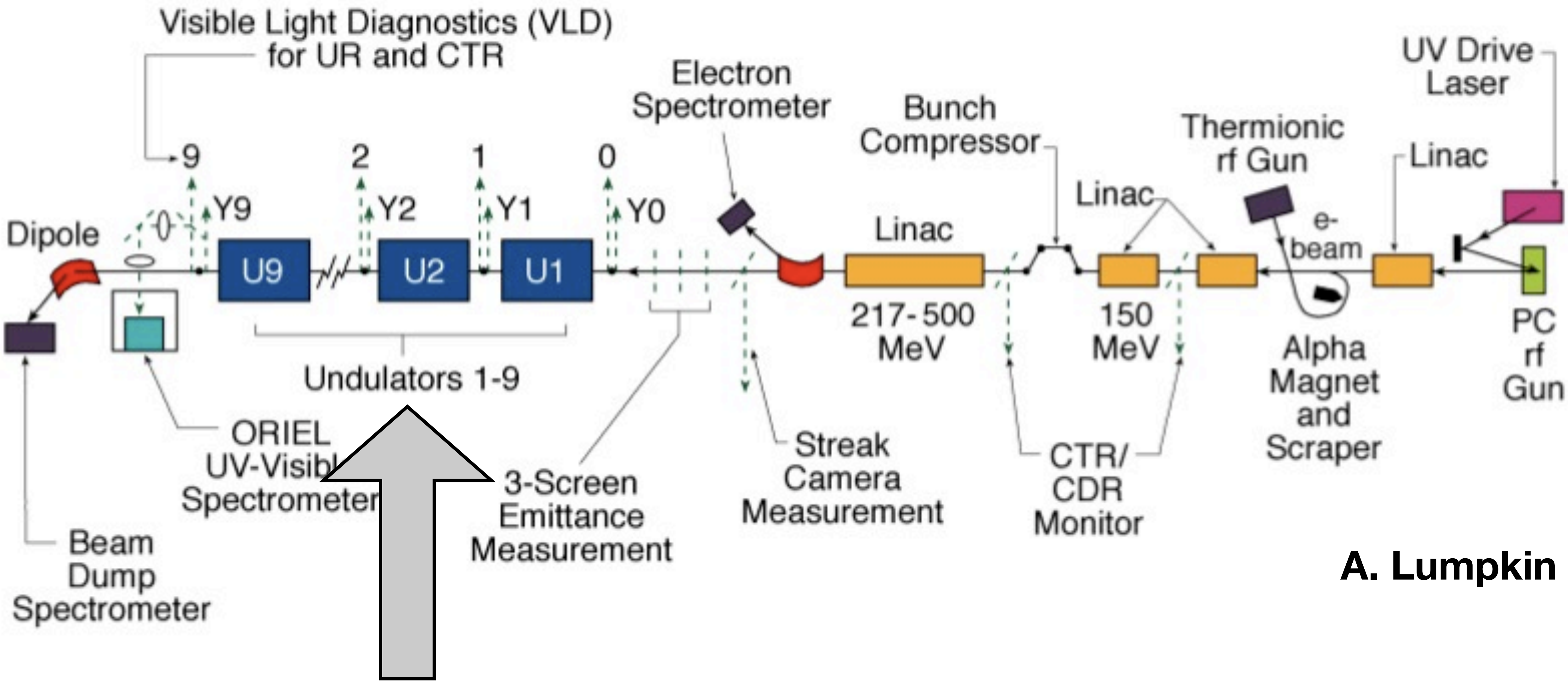
laser recirculation
adaptive optics
multibunch ICS



Proving gamma-ray production and flux levels requires >> 100 MeV beam energies

Gamma ray production at the APS

The APS Injector linac is a capable test bed



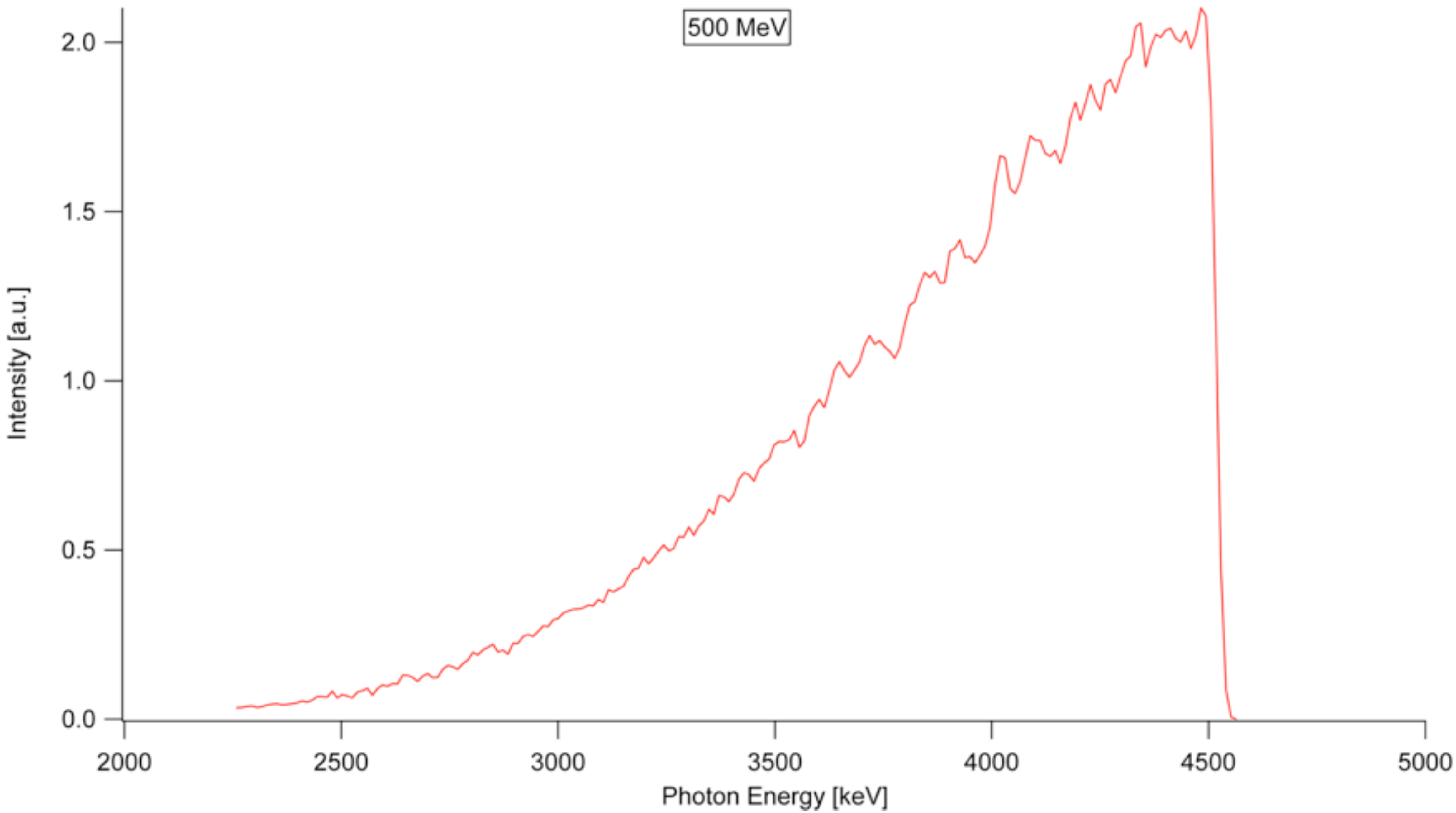
old LEUTL tunnel
good site for ICS interaction

The APS injector already possesses the necessary beam parameters for gamma-ray production

Parameter	Value
Electron Beam Energy	**500-700 MeV**
Energy Spread	0.1% energy spread
Bunch Charge	500 pC
Electron Beam Emittance	5 mm-mrad
Transverse Spot Sizes	20 micron e-beam and laser spot
Electron Beam Bunch Length	4 ps
Laser Pulse Length	6 ps
Laser Wavelength	**1053 nm**
Laser Energy	**20 mJ**

At 500 MeV, simulations show significant flux up to 4.5 MeV photons (at laser fundamental).

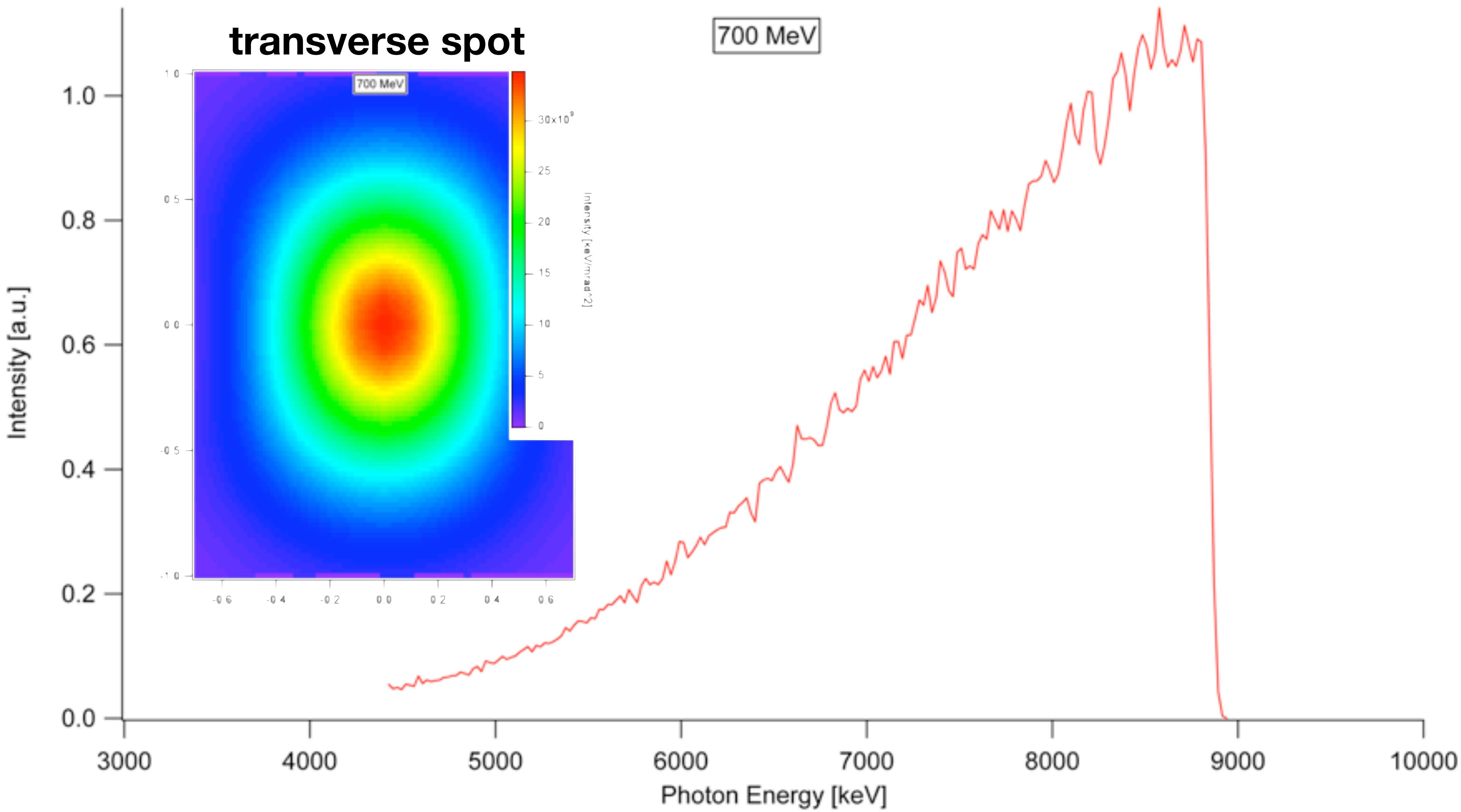
Photon Flux: 3x10^6



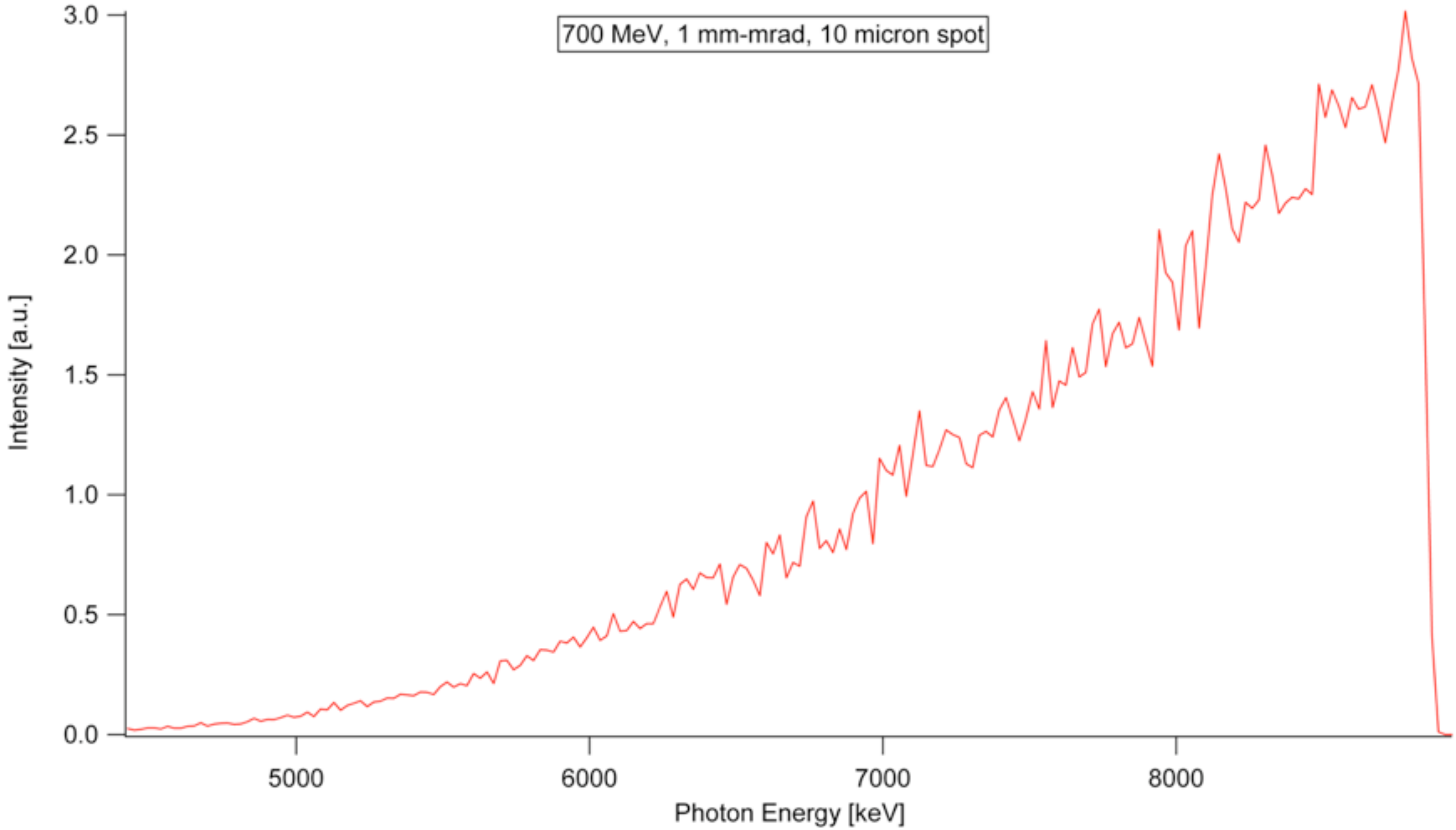
At 700 MeV, one can reach almost 9 MeV photons (at laser fundamental).

Higher brightness

Same Photon Flux: 3x10^6



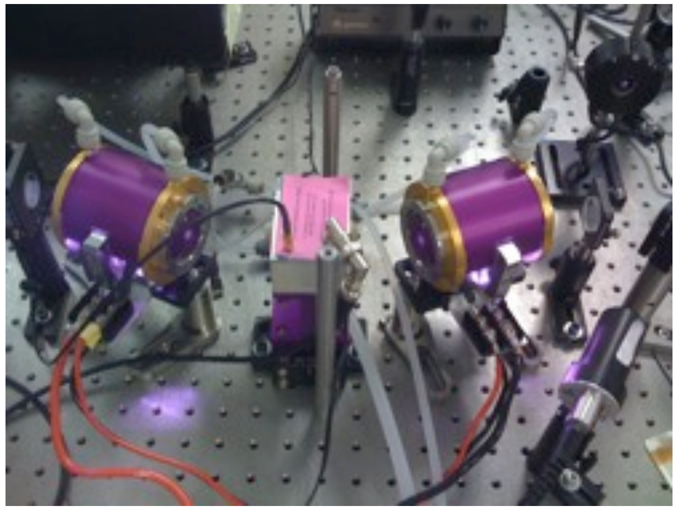
Reducing the emittance, and hence the spot size "cleans up" the spectrum



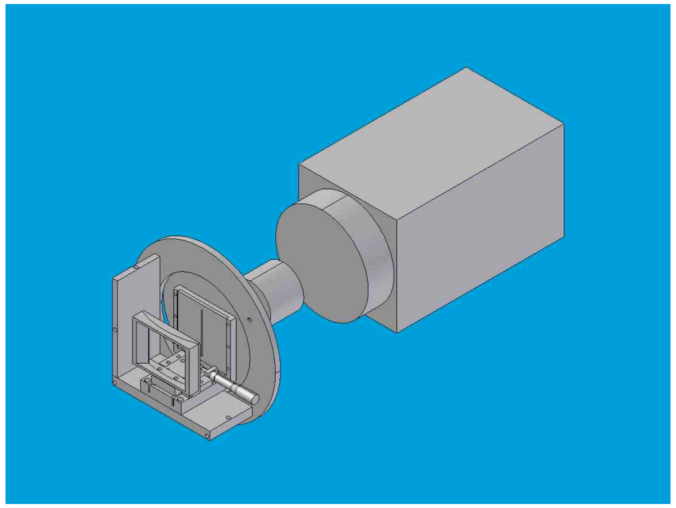
Gamma production requires some additional hardware to be installed after the linac

Ingredients:

Interaction Box



Laser amplifier

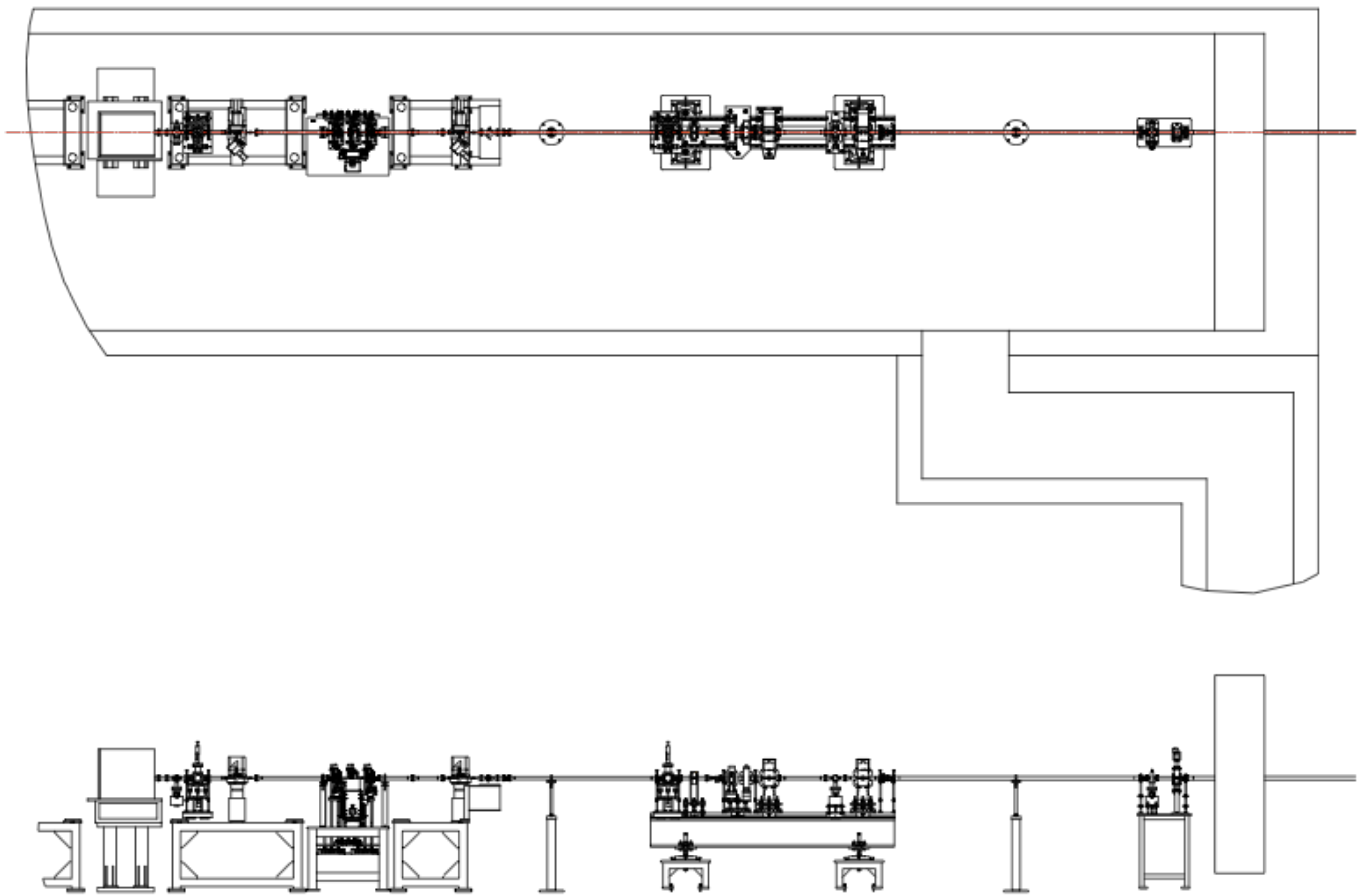


Gamma detector

Some quads

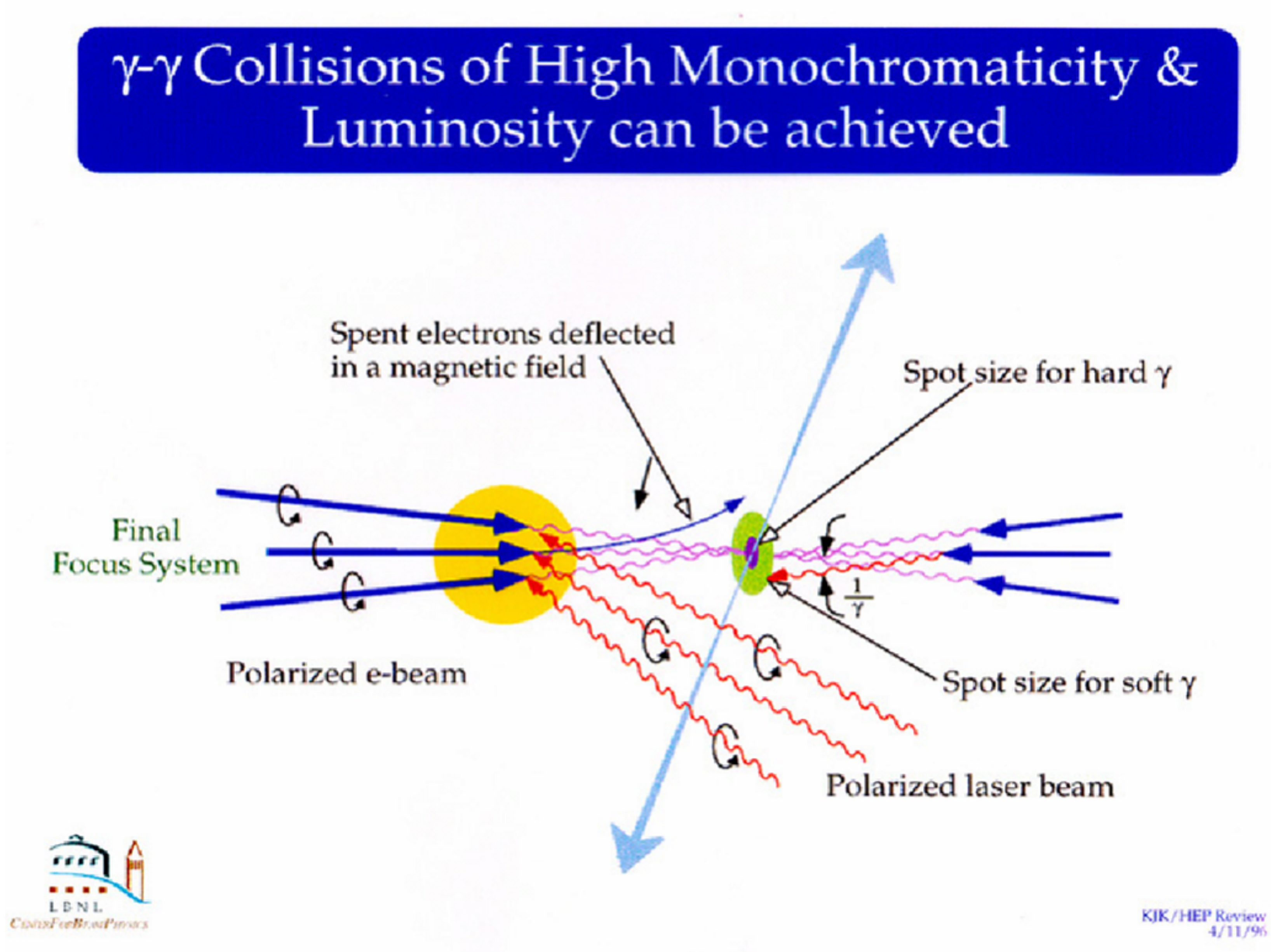
Lots of fiber

The old LEUTL tunnel can house an ICS interaction area and more

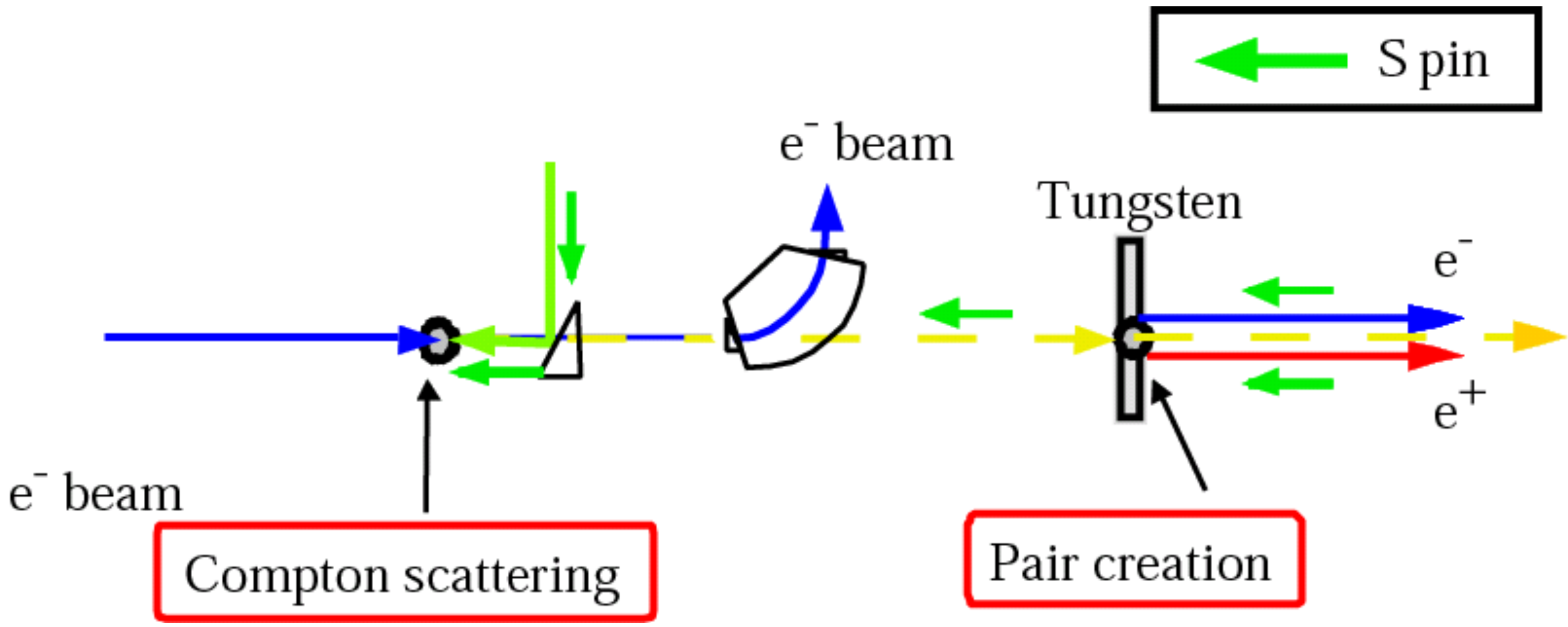


The APS Linac can be used to produce a significant gamma-ray production test

ICS based Gamma-Gamma colliders have been considered

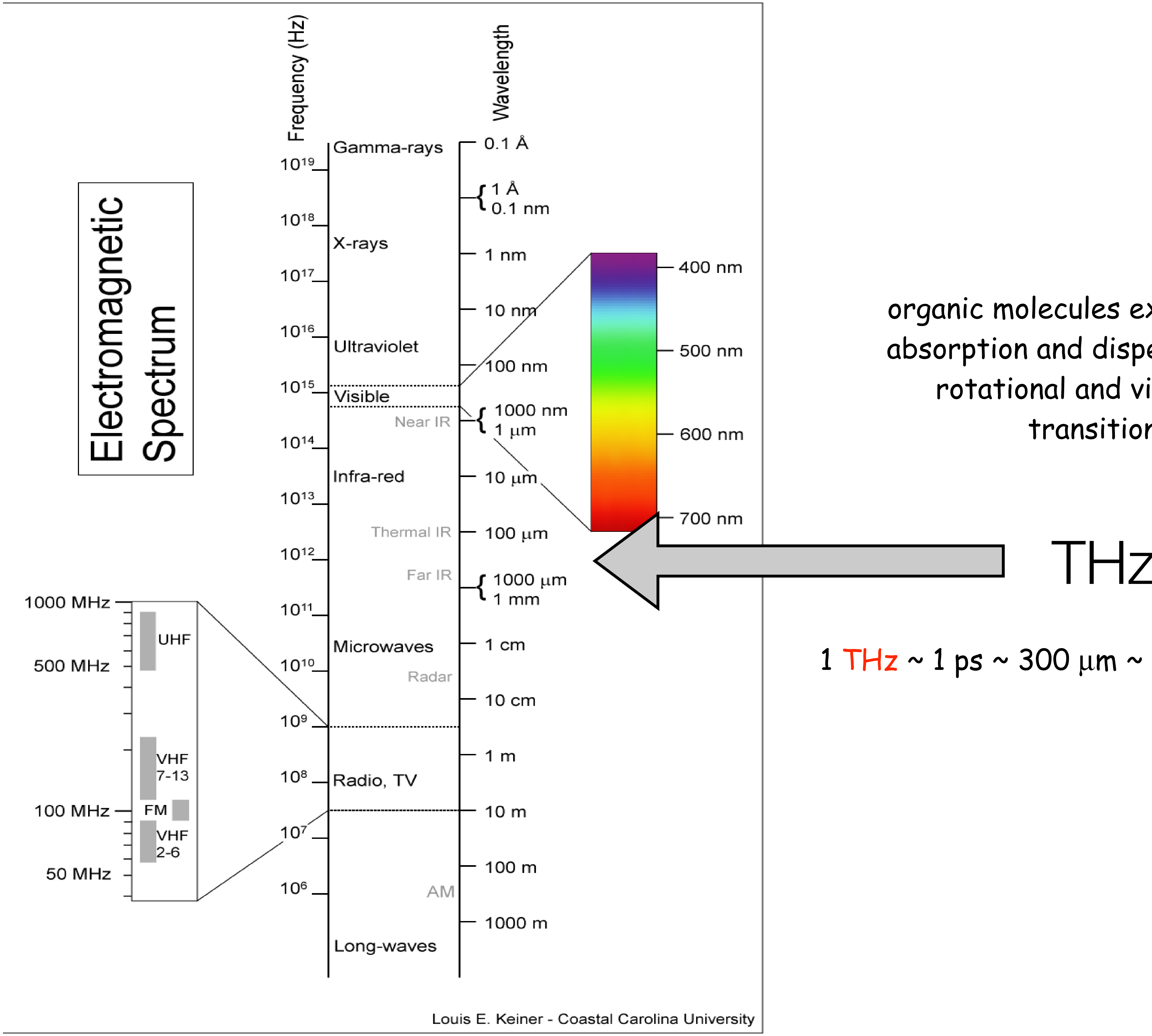


ICS based Positron production is promising



(Source: M. Fukuda, *et. al.)*

THz Production



organic molecules exhibit strong absorption and dispersion due to rotational and vibrational transitions.

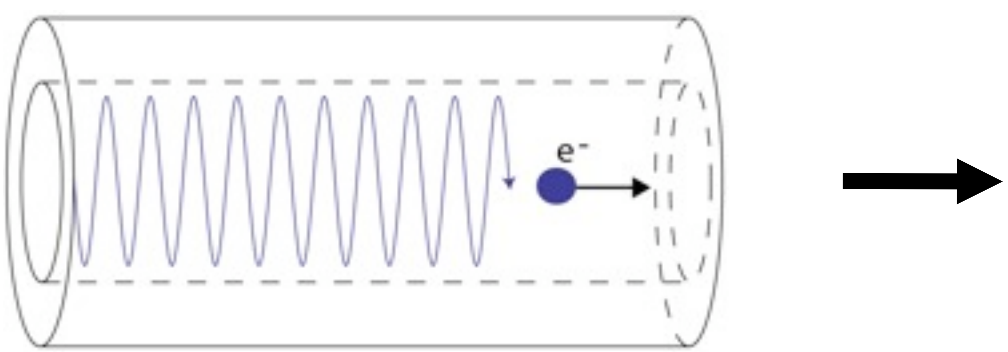
1 THz ~ 1 ps ~ 300 μm ~ 4.1 meV ~ 47.6 °K

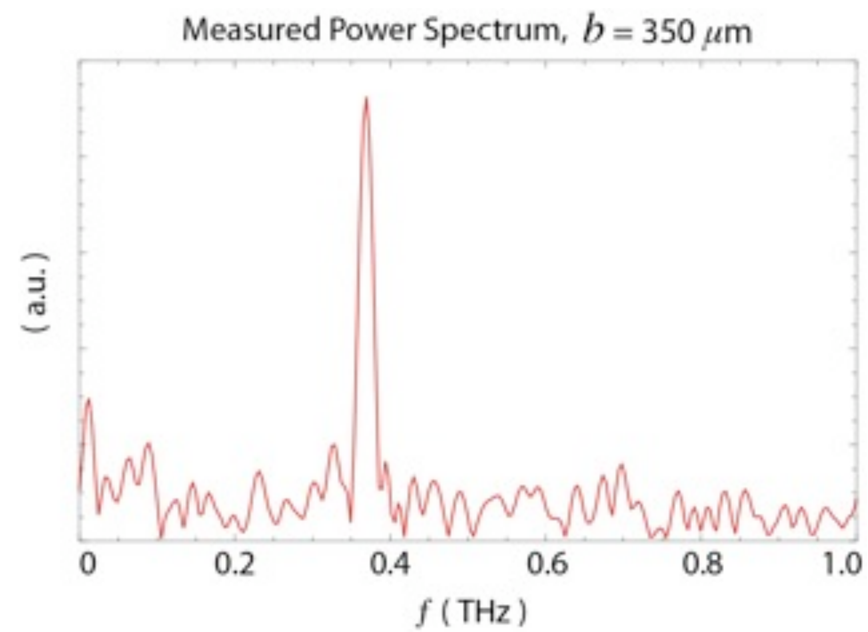
An experiment at UCLA produced narrow band THz from dielectric tubes

Alan Cook (UCLA)

Experiment

- Short beam coherently excites wakefield in capillary tube
- Only lowest-f waveguide mode excited
- Measure power spectrum and radiated energy





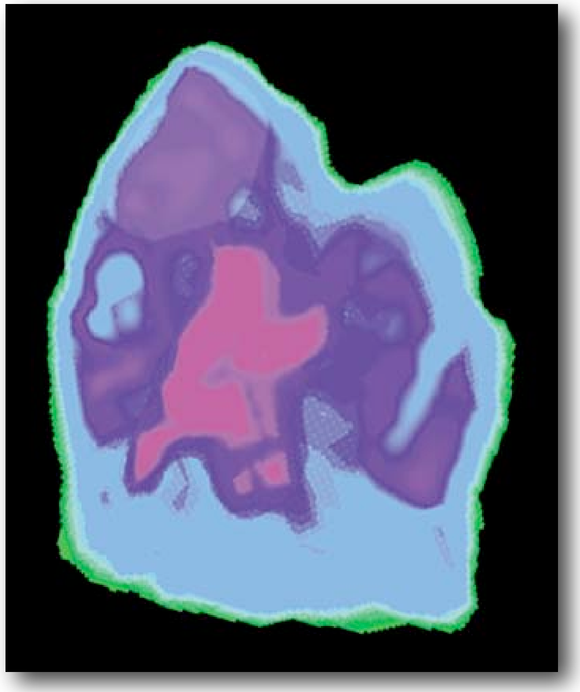
Selling Points

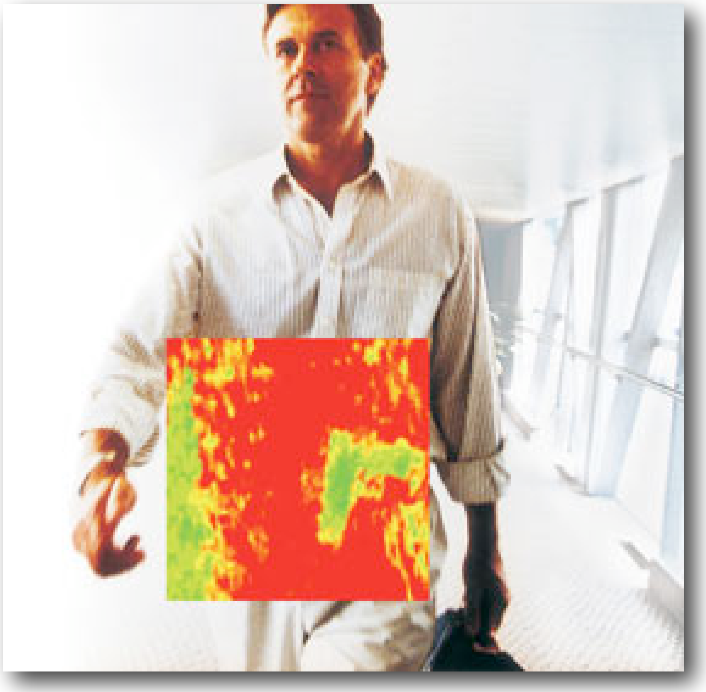
- Narrow bandwidth
- Variable pulse length
- "Tunable"
- High peak power (10^5 - 10^7 W)
- Simple, cheap structure
- Implement w/ existing beams

Production of THz is of interest for a number of fields

- **Why THz radiation?**
  - ~ 100 GHz - 20 THz
  - Imaging applications
  - Spectroscopy applications

- **Why narrow-band source?**
  - Specific *f* application
  - Efficient energy conversion

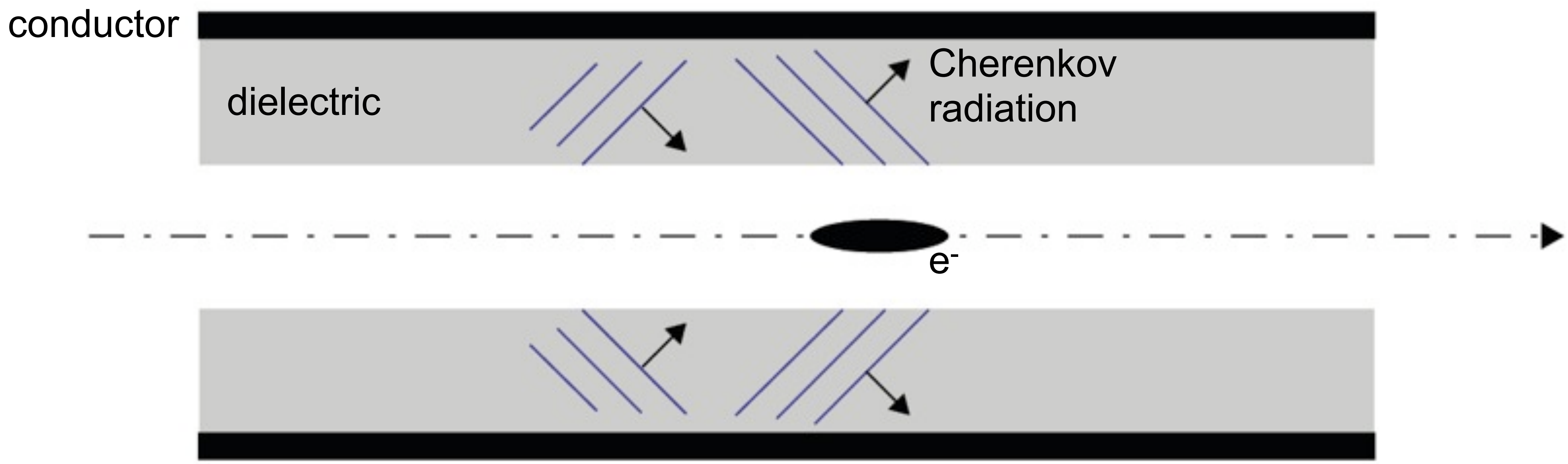




Non-beam-based THz sources: frequency mixing, quantum cascade laser, optically-pumped THz laser, etc.

THzNetwork.org

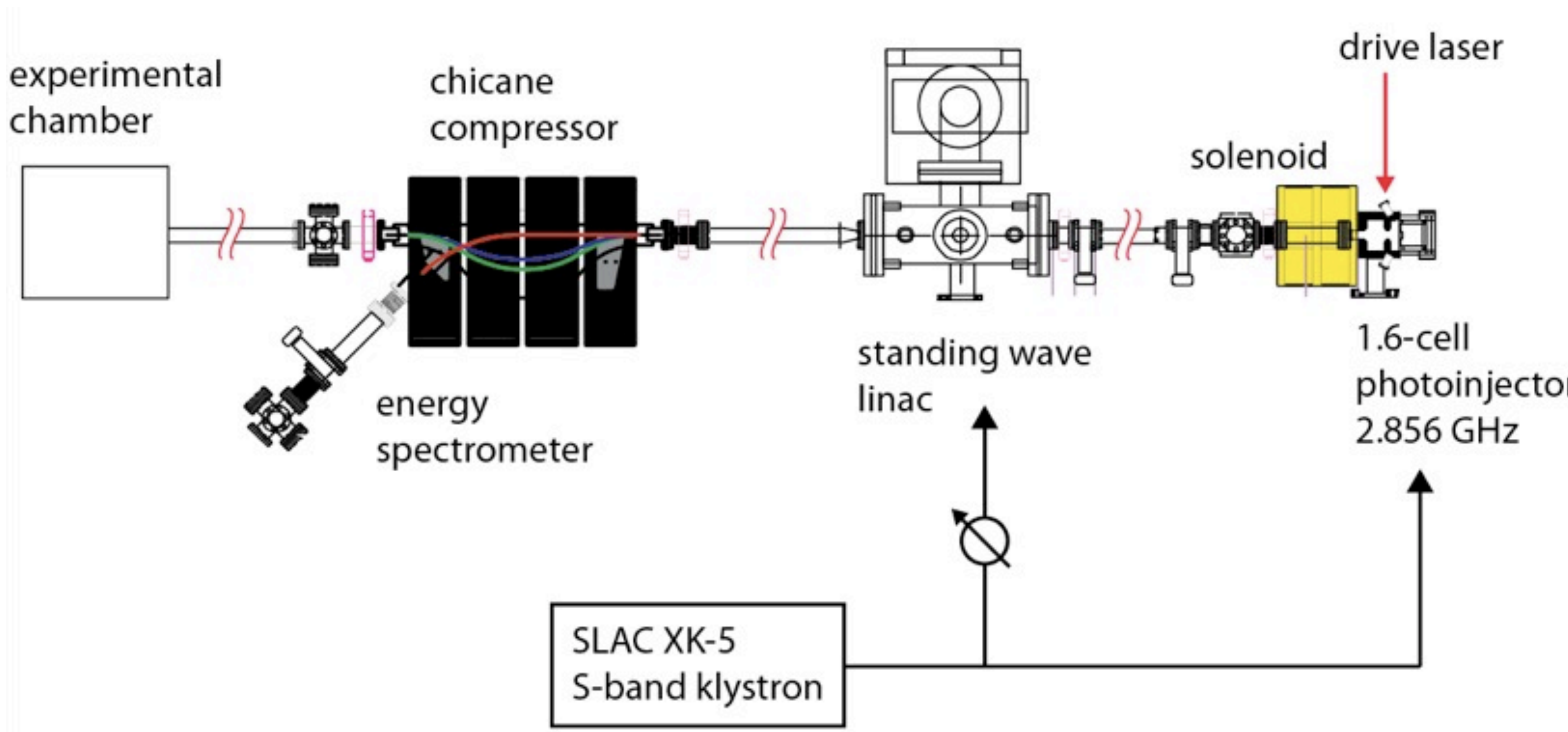
Wakefields excited by a relativistic electron beam generate THz radiation via Coherent Cherenkov.



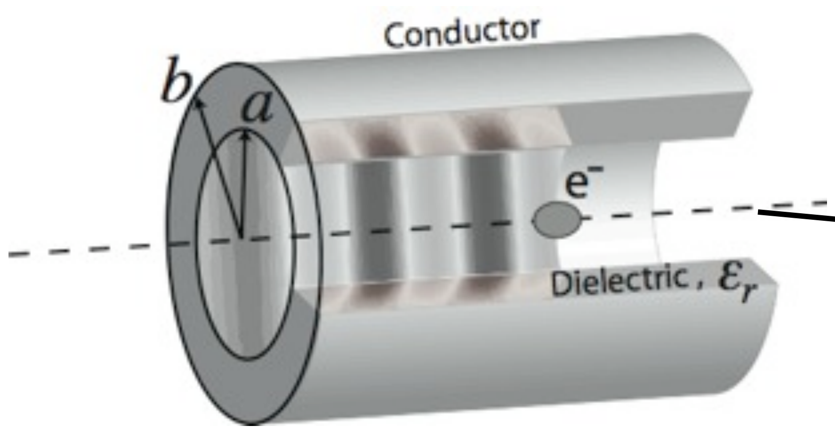
Beam couples to E_z field

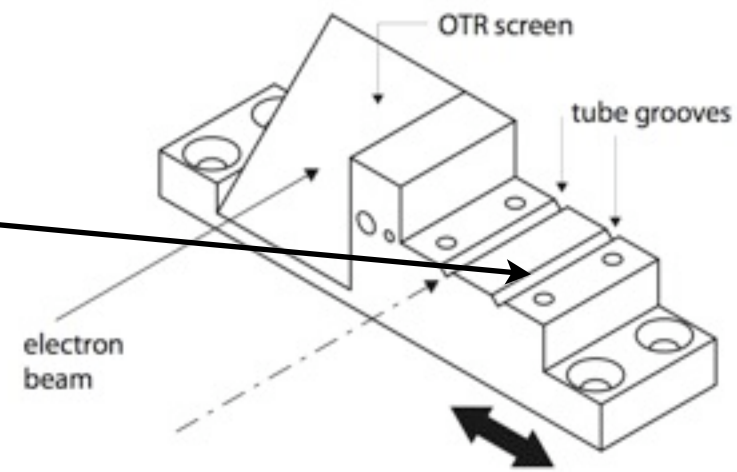
“Slow wave,” efficient beam-radiation energy exchange

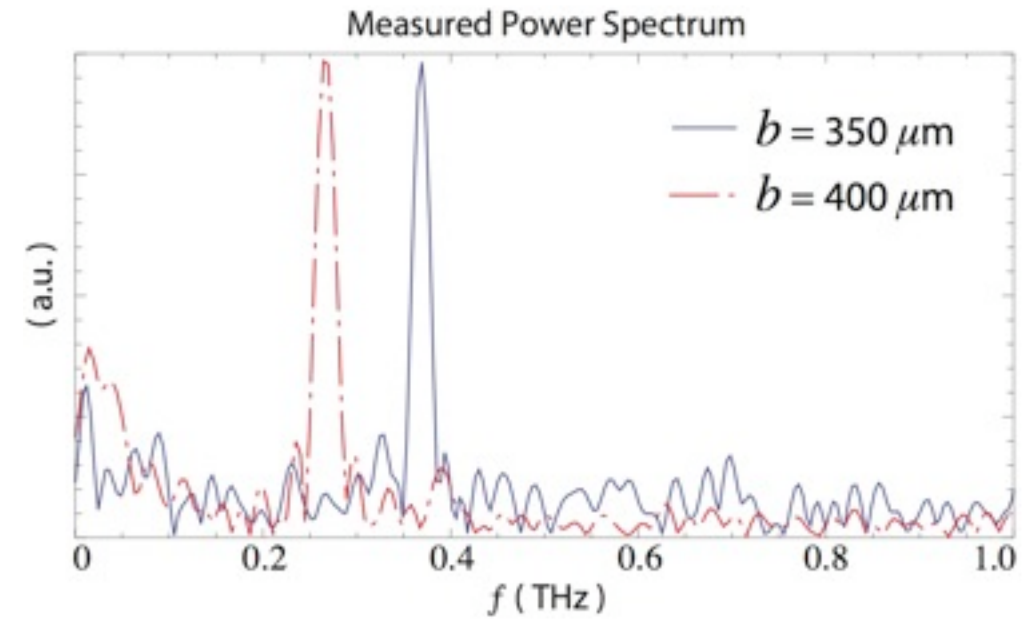
The experiment was conducted at the UCLA Neptune Lab which houses a 15MeV Photoinjector

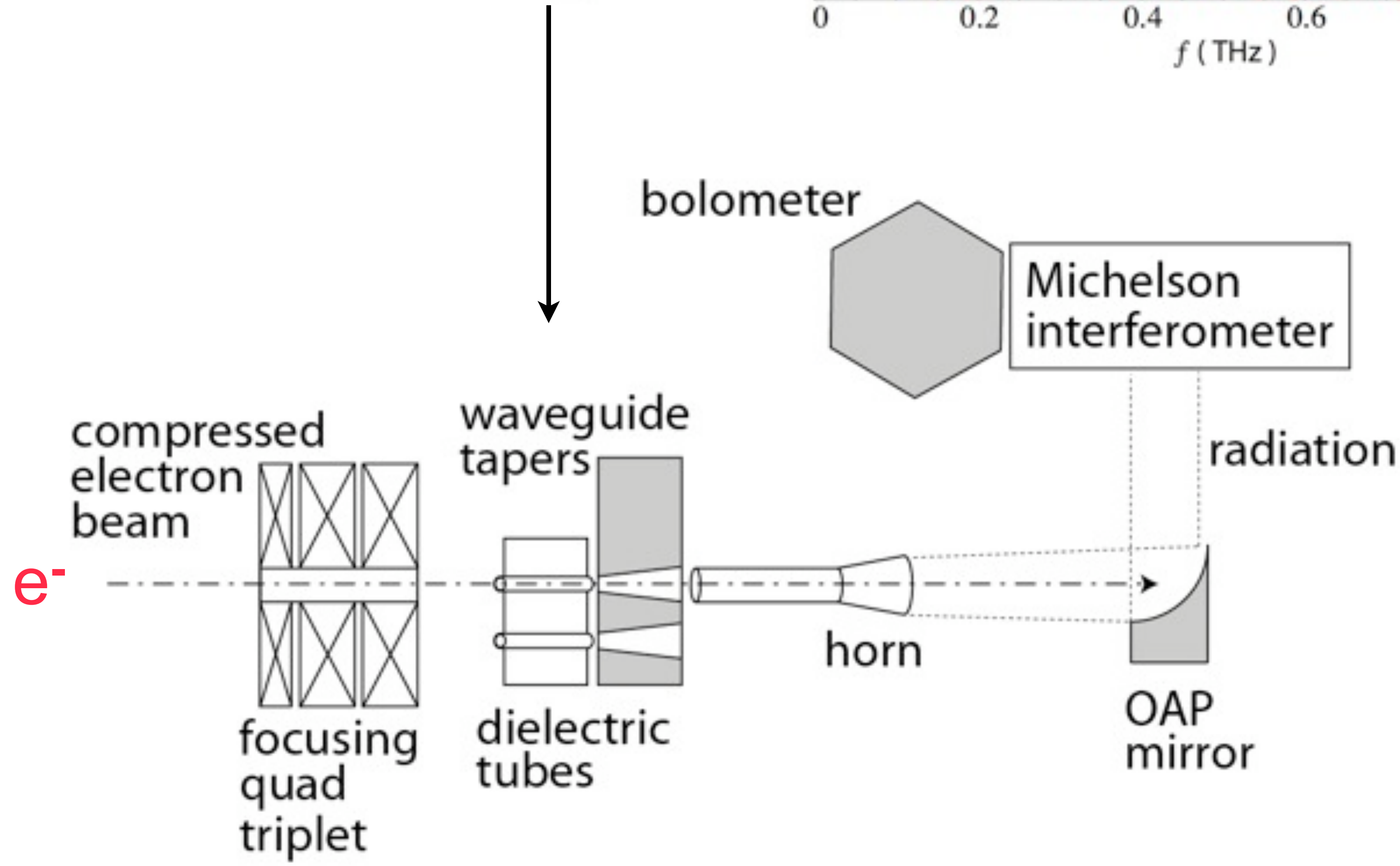


The experimental apparatus allows for detailed characterization of the emitted radiation





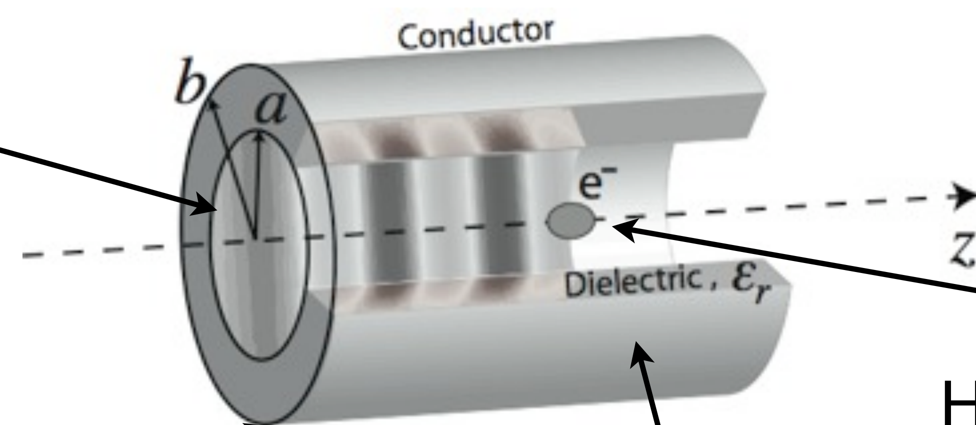




This method of THz production has simple scale laws

rules of thumb

Inner radius as small as possible: The smaller the bore, the higher the coupling field and the higher the radiation power.



Higher charge and shorter bunch length (coherence) yields higher power

The strongest knob for tuning the frequency is the wall thickness: thinner wall, higher frequency. Of course, then you need a shorter bunch to get coherence.

The dielectric constant also changes the frequency.

THz production at the APS linac

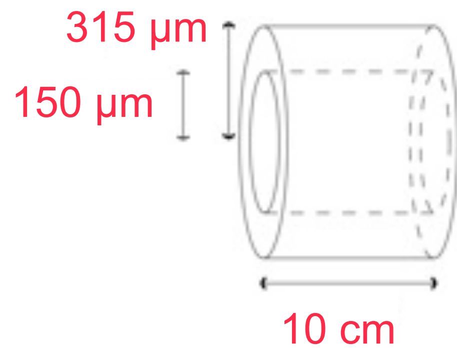
At the APS the nominal beam can reach 0.5THz at almost a MW peak power.

Case 1: nominal

Beam Parameters

σ_t = 500 fs
σ_r = 30 μm
Q = 0.25 nC
I = 500 A
γ = 1000
$\varepsilon_{x,n}$ = 5 mm-mrad
β-function = 18 cm

HDPE
(ε_r = 2.25)

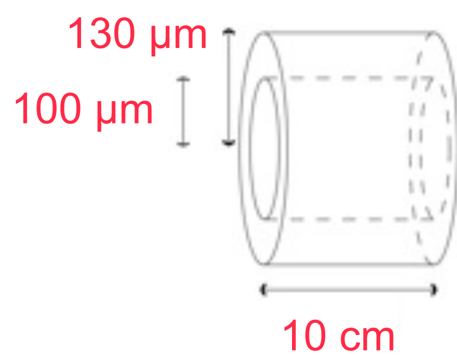


f = 400 GHz
P_{peak} ~ 650 kW
BW ~ 0.7 %
Pulse ~ 350 ps

Case 2: ultrashort bunch

Beam Parameters

σ_t = 65 fs
Q = 50 pC
I = 800 A



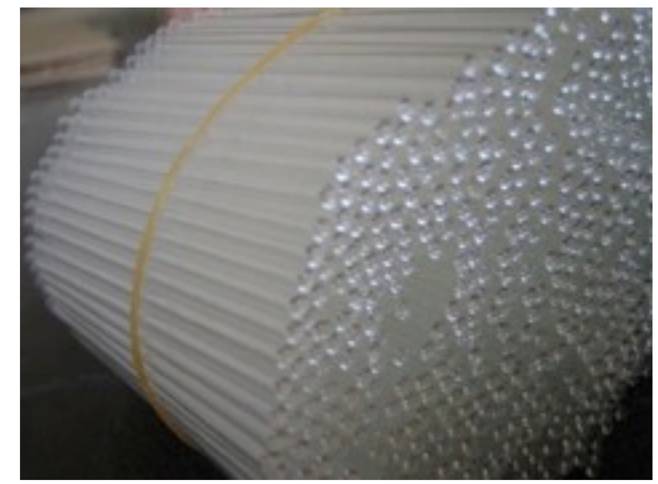
f = 1.45 THz
P_{peak} ~ 350 kW
BW ~ 0.3 %
Pulse ~ 200 ps

the thermionic gun can drive short bunches

Tunable, narrow band, ultra-high peak power THz generation at the APS linac would be straightforward

Ingredients required:

1. tube



2. holder

The APS linac, with its high energy capability and excellent instrumentation can enable many studies

IGS needs a POC experiment

The APS Linac provides unique capabilities

Dielectric tube breakdown
Dielectric tube acceleration
IFEL studies
FEL with micro undulators
short pulse hard x-rays
Positron Production
Gamma-Gamma collider studies