Inverse Compton Scattering: an introductory overview

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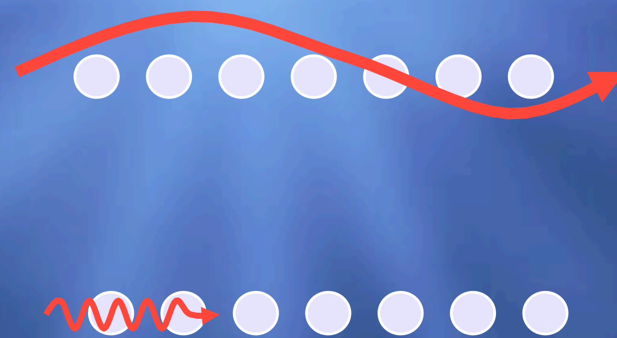
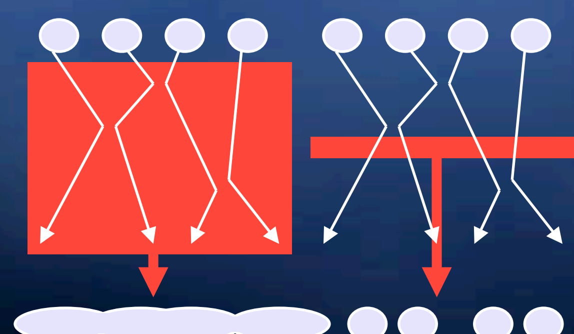
Bright Photon Sources

- Photons from keV to MeV energy critical for basic science, medicine, industry, defense apps
- Short length scales
  - atomic or below (Å)



- Fast time scales demanded
  - atomic motion in molecules and solids (0.1-1 psec)



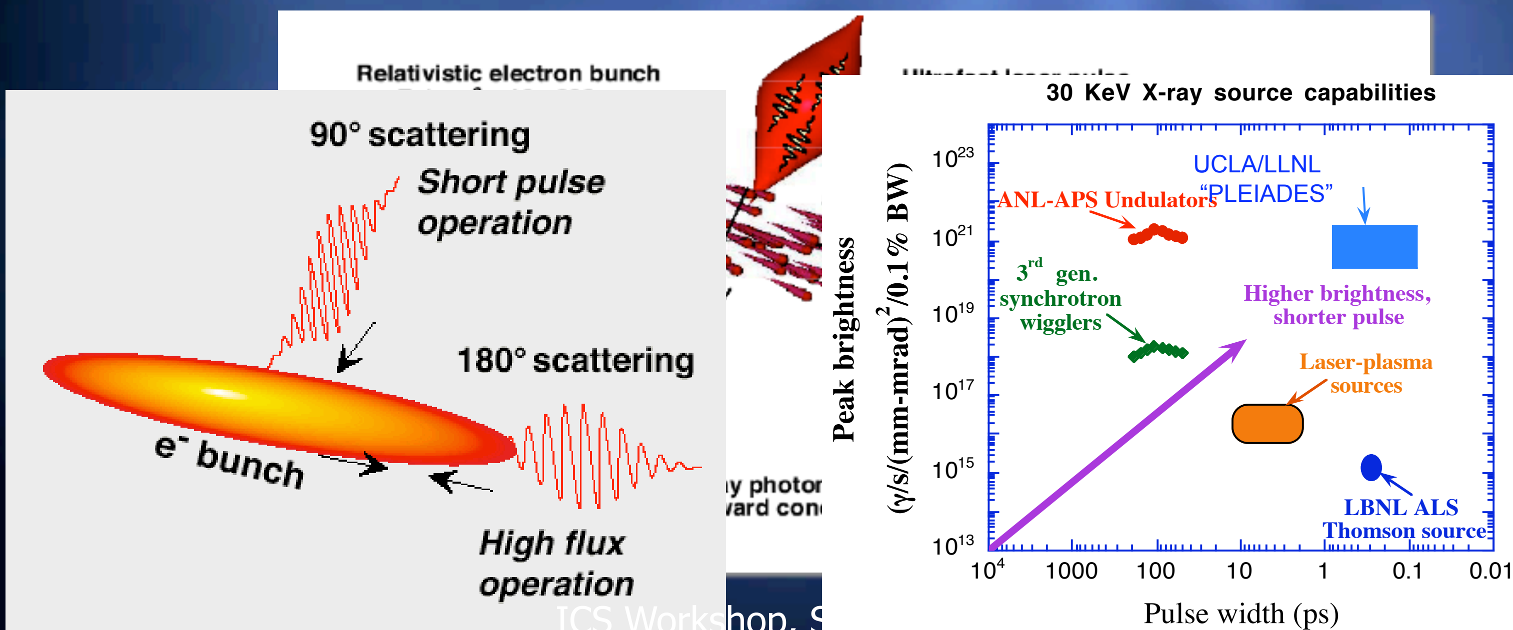
3^{rd}-4^{th} Generation Light Sources

- Synchrotron light sources: < 50 keV, > 50 ps
- X-ray FEL (LCLS): energy ≤25 (50?) keV, 1-100 fs
- K_α: energy limit ~ 100 keV, 4π emission

- New approach: inverse Compton scattering (ICS)

Inverse Compton Scattering (ICS)

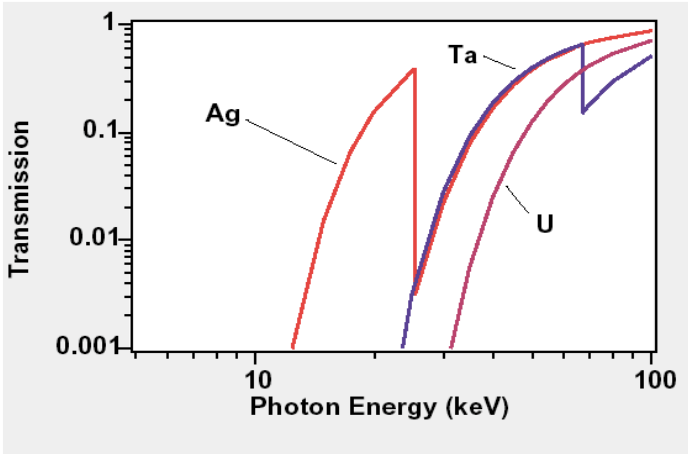
- Collision of *relativistic* electron beam bunch with intense laser pulse
- Source is *bright* (directional, ultra-fast)
- Scattered light is *~monochromatic* — new techniques enabled
- Tunable in wavelength, like FEL
- Much less expensive than XFEL. Competition bred from FEL R&D!



Applications of monochromatic ICS photons

- Ultra-fast materials characterization
  - X-rays (keV) for penetrating metals
  - Example: PLEIADES
- Biology and medicine
  - Breakthrough diagnosis/therapy
- Intermediate energy (MeV)
  - Slow positrons (for materials)
  - Nuclear materials detection
- High energy physics (GeV)
  - γγ collider, polarized e+ (see Yakimenko talk)

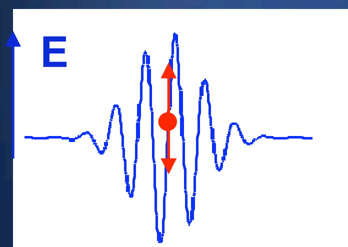
X-ray transmission through 100 μm of metal

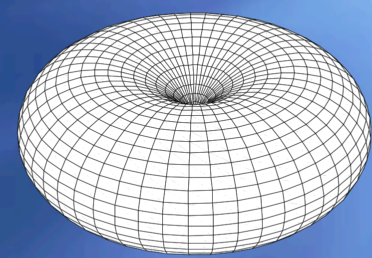


Probing macroscopic metals requires x-ray energies above 10 keV

Physics scenario

E-beam rest frame



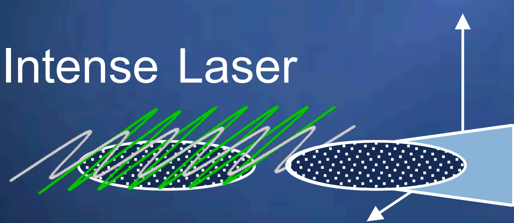


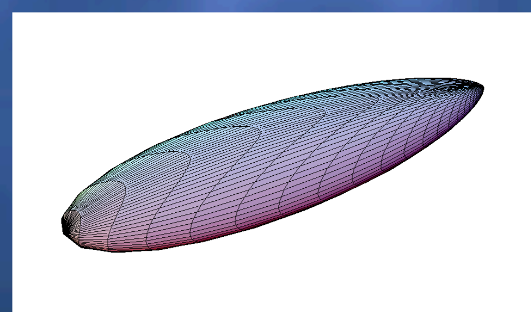
Radiated field, linear pol.

$$\omega_s' = \omega' = \gamma\omega_L\left(1+\beta\right)$$

Thomson limit
(180° ICS)

General View: Lab frame





Lorentz boosted radiation
forward directed

$$\omega_s \approx 4\gamma^2\omega_L\left(1-\frac{\left(\gamma\theta_s\right)^2}{2}\right)$$

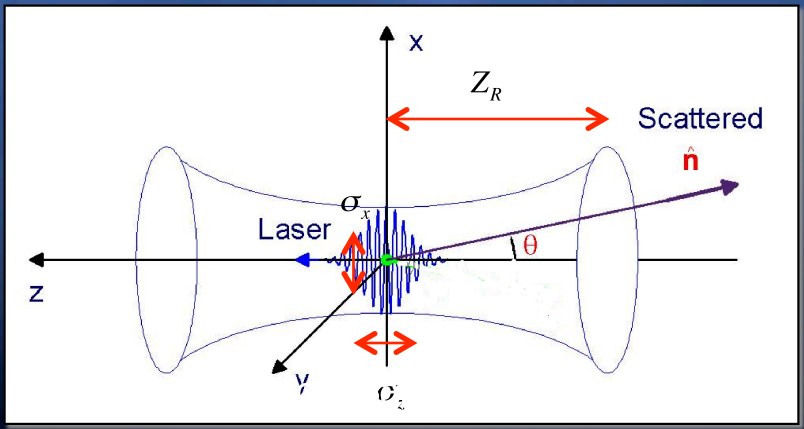
Doppler upshifted,
angular redshift

X-ray flux depends on overlapping electrons, laser photons

Scattered photons in collision

- Scattered flux $N_\gamma = \mathbf{L}\sigma_T$ $\sigma_T = \frac{8\pi}{3} r_e^2$ Thomson X-section
- Luminosity as in HEP collisions
  - Many photons, electrons
  - Focus tightly
  - Short laser pulse; <few psec (depth of focus)

$$\mathbf{L} = \frac{N_L N_{e-}}{4\pi\sigma_x^2}$$

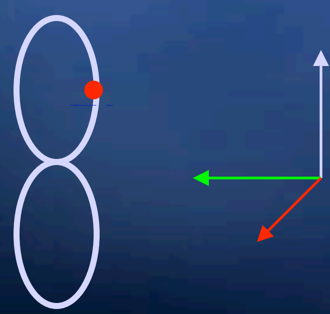


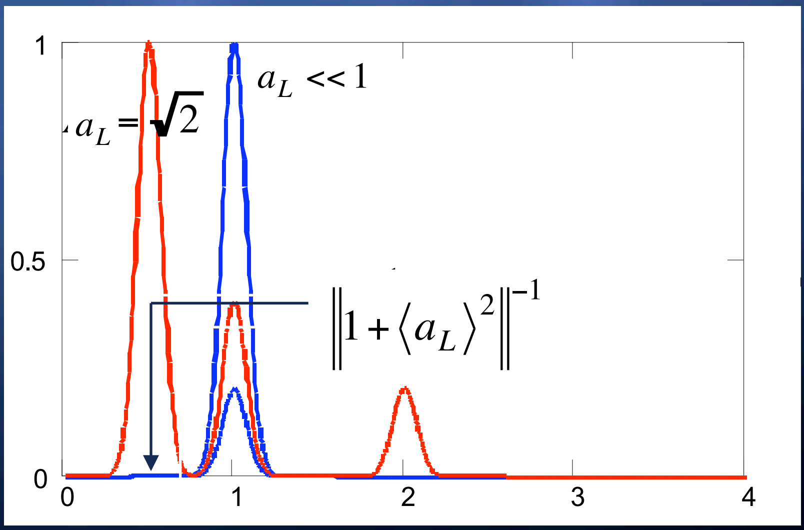
Experimental challenges: laser

- Laser system (optimize for flux)
  - Short to ultra-short pulse (0.1 - 10 psec)
  - Repetition rate (100 Hz - 10 kHz)
  - Up to ~1 J useful, limited by nonlinear effects
    - Red-shift, harmonics
- Optimum: 1 photon/electron (1% BW)

Nonlinear effects (a_L~1)

"Figure 8" in e- trajectory

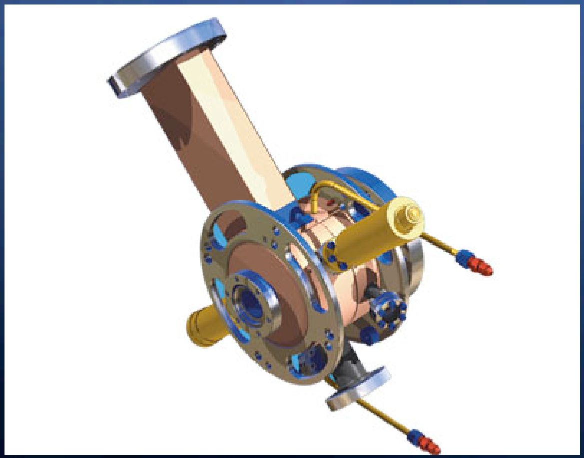




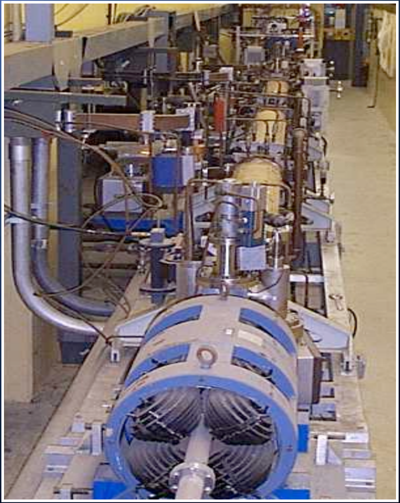
Experimental challenges: electron source

- Electron source: photoinjector
  - Cathode photoexcited by psec laser, Q=1 nC
  - Ultra-high field RF acceleration, >100 MV/m
- Post-acceleration and careful focusing
  - Controlled plasma oscillations; low emittance, ε_n=2 mm-rad

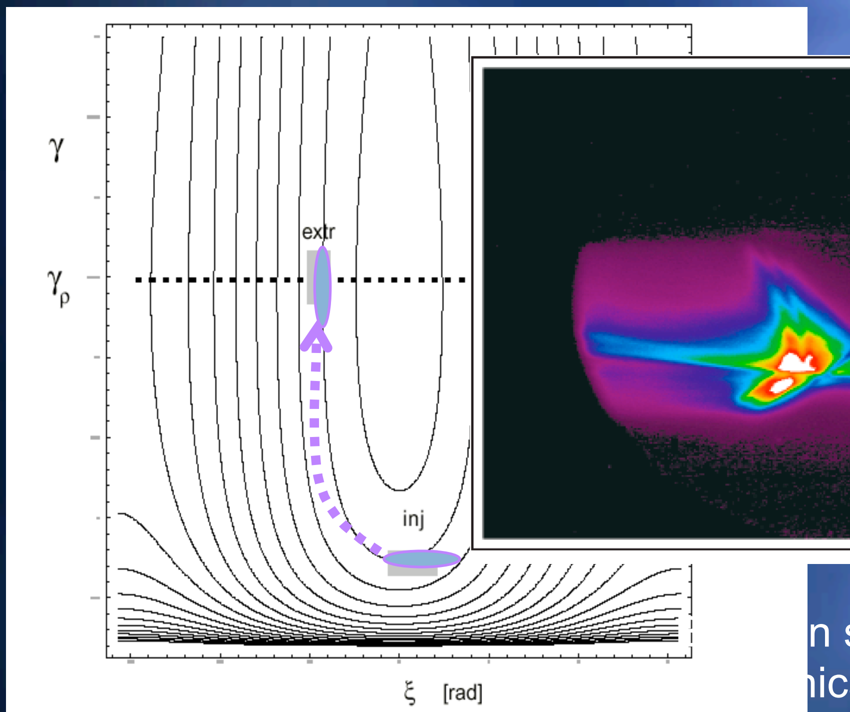
UCLA RF Photocathode Gun (5 MeV)



Linear accelerators At LLNL PLEIADES (to <150 MeV)

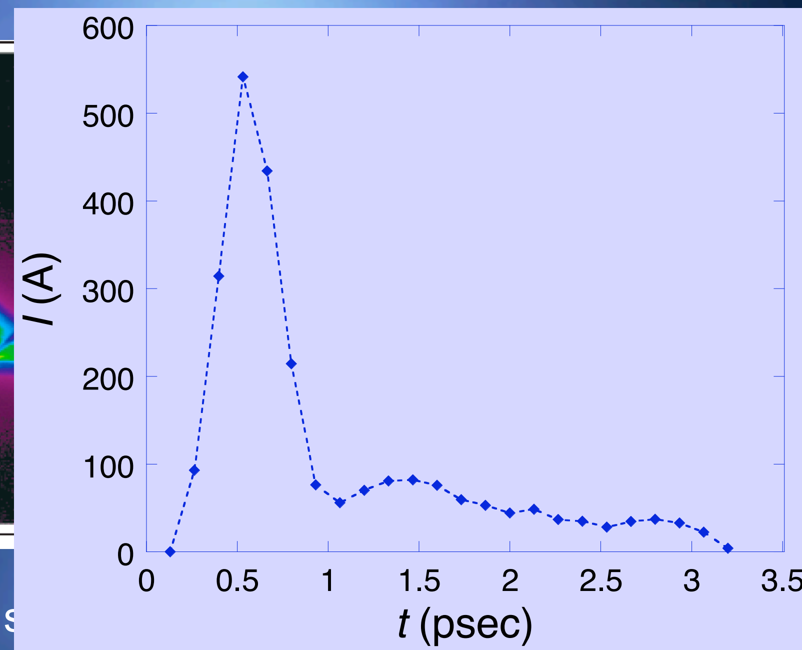


Manipulation of Electron Beam: Bunching



Longitudinal phase space schematic for velocity bunching

n s
icane bunching

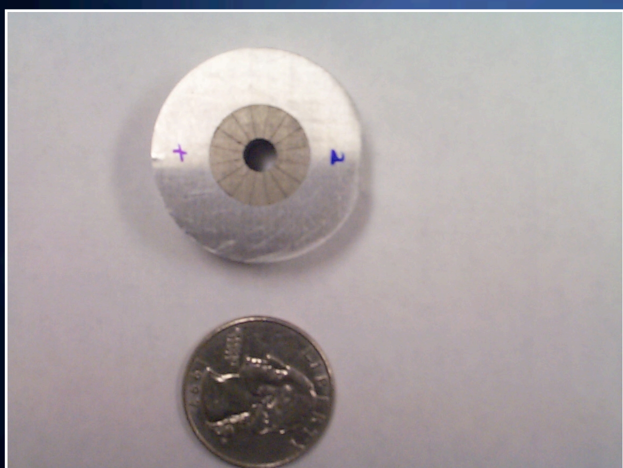


Time profile after bunching
(from coherent transition rad.)

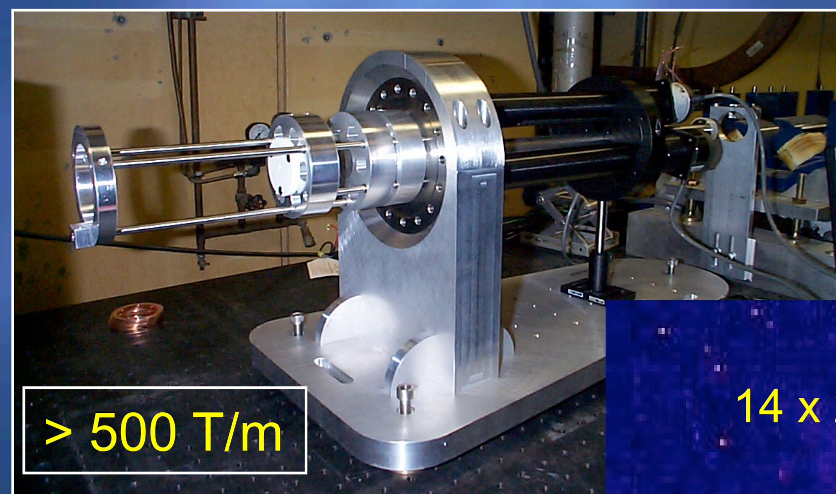
- Bunching to 0.1 psec (fight plasma expansion)
- Avoid beam self-destruction in chicane (bending)

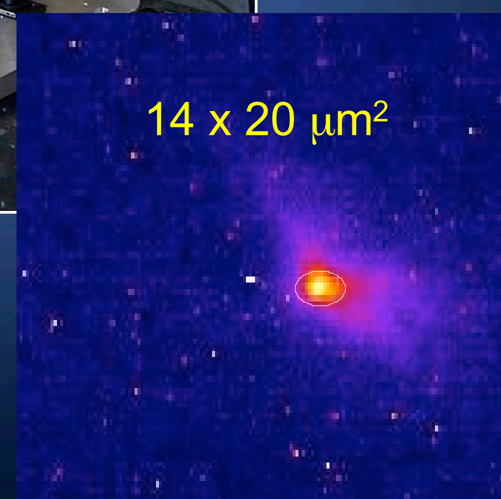
Manipulation of Electron Beam: Focusing

- Ultra-strong focusing (10 μm spots)
- World's strongest quadrupoles, "camera" triplet



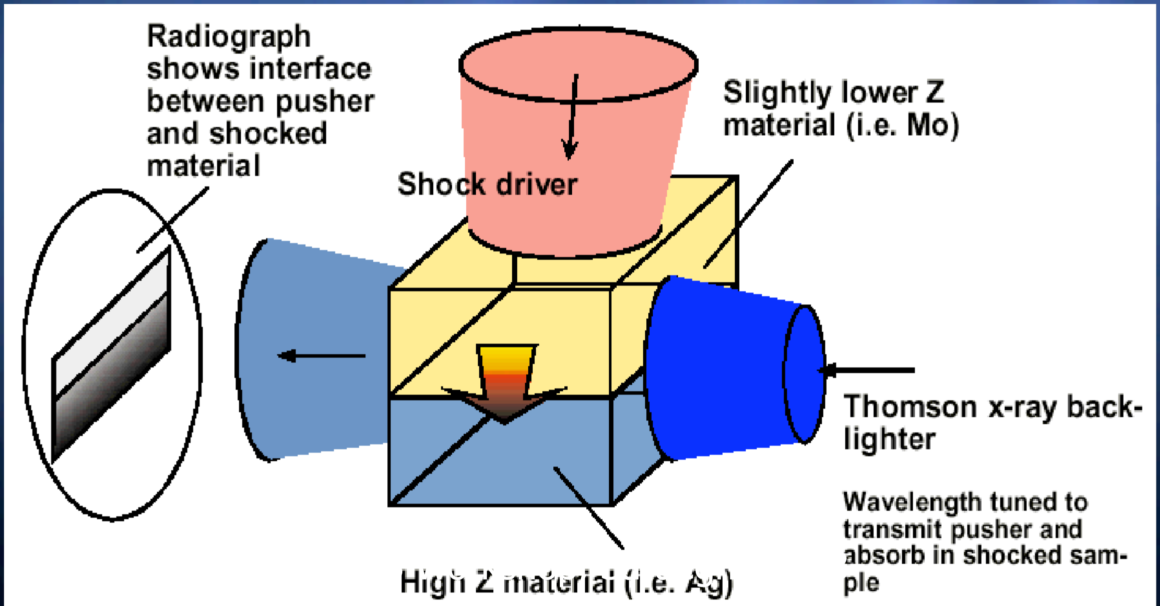
Designed and built at UCLA





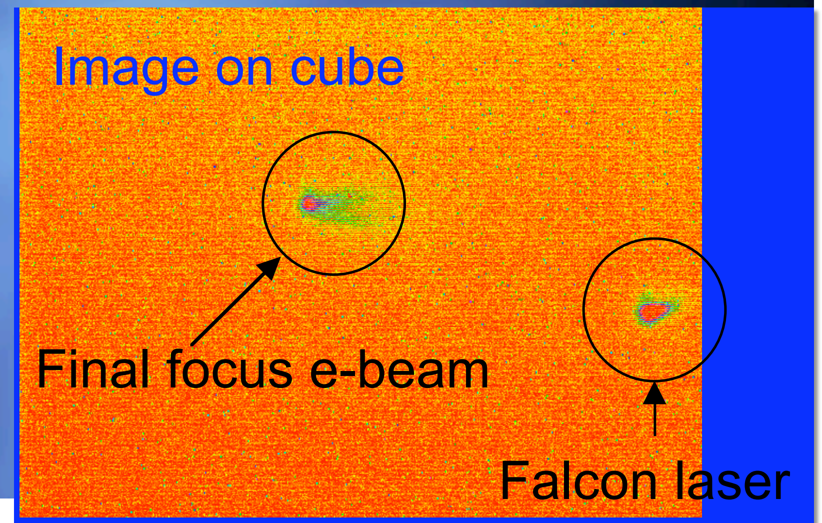
Example: PLEIADES at LLNL

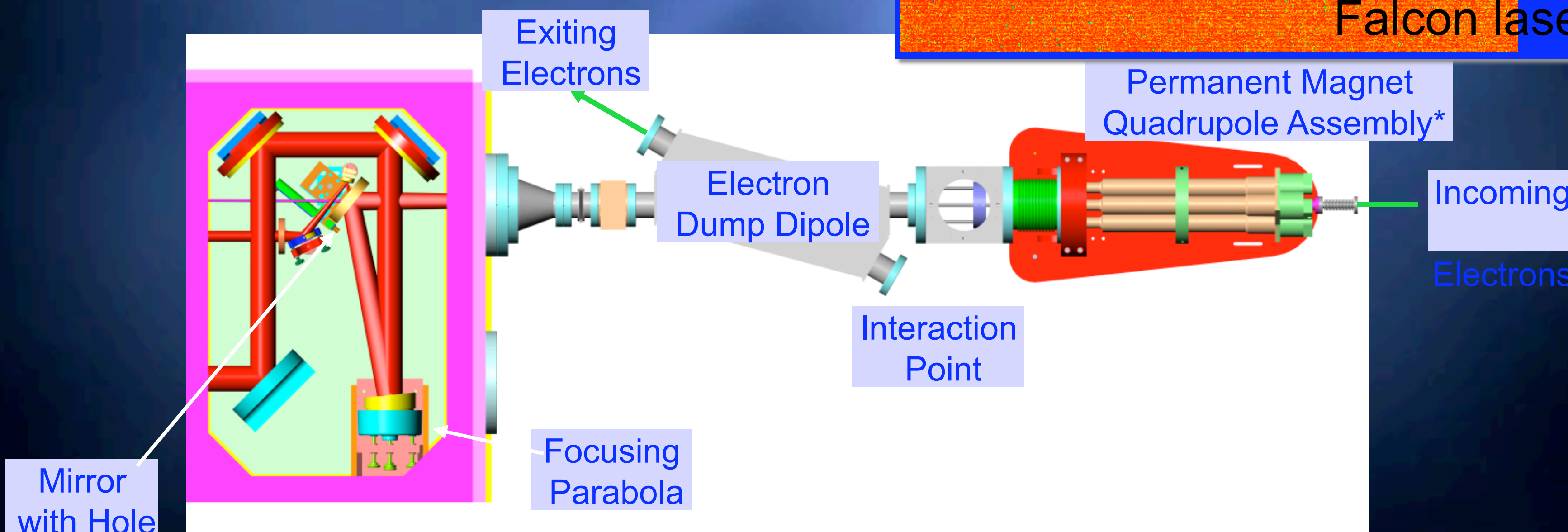
- *Ultra-fast, high energy density* physics
- Fundamental material studies for
  - Inertial confinement fusion
  - Nuclear stockpile stewardship
- Pump-probe systems with high power lasers
- EXAFS, Bragg, radiography in fsec time-scale
- Nonlinear ICS electrodynamics



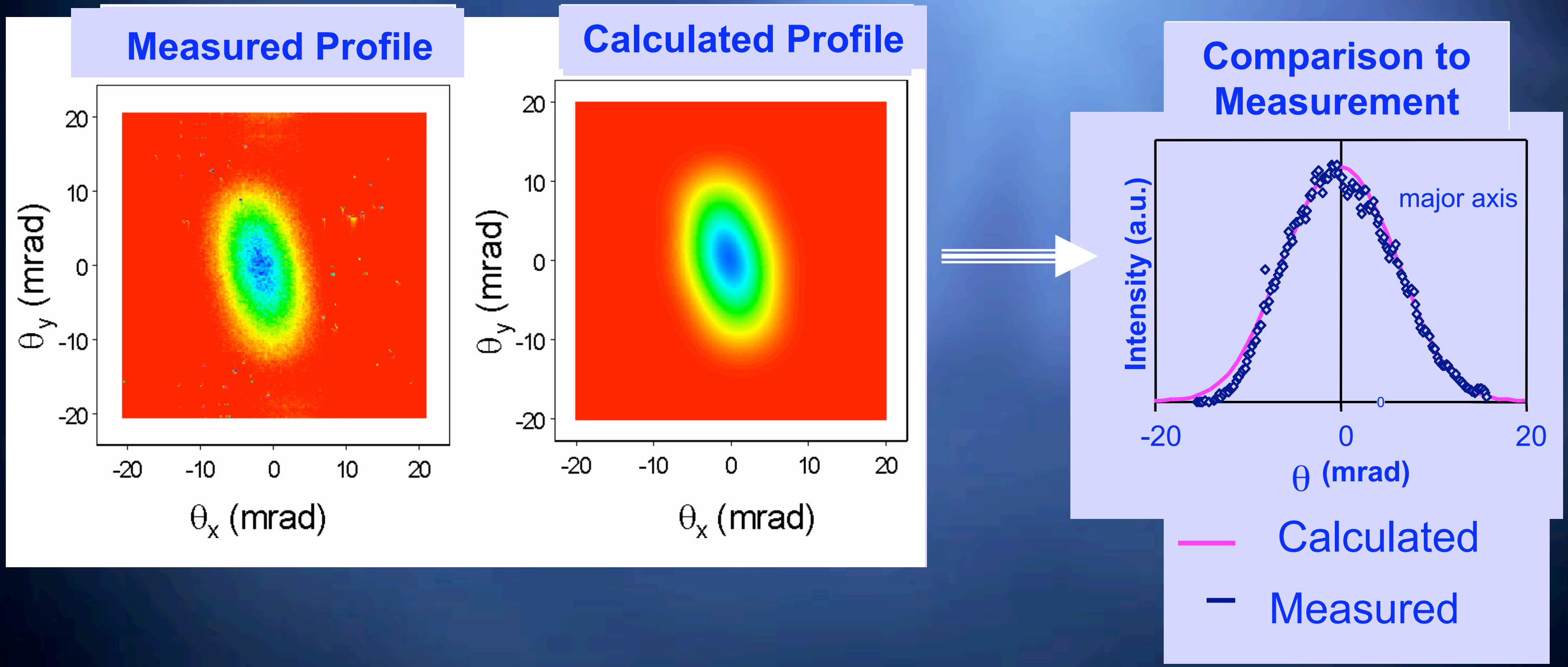
Interaction region

- Sub-picosend timing
- Micron alignment
- Low background



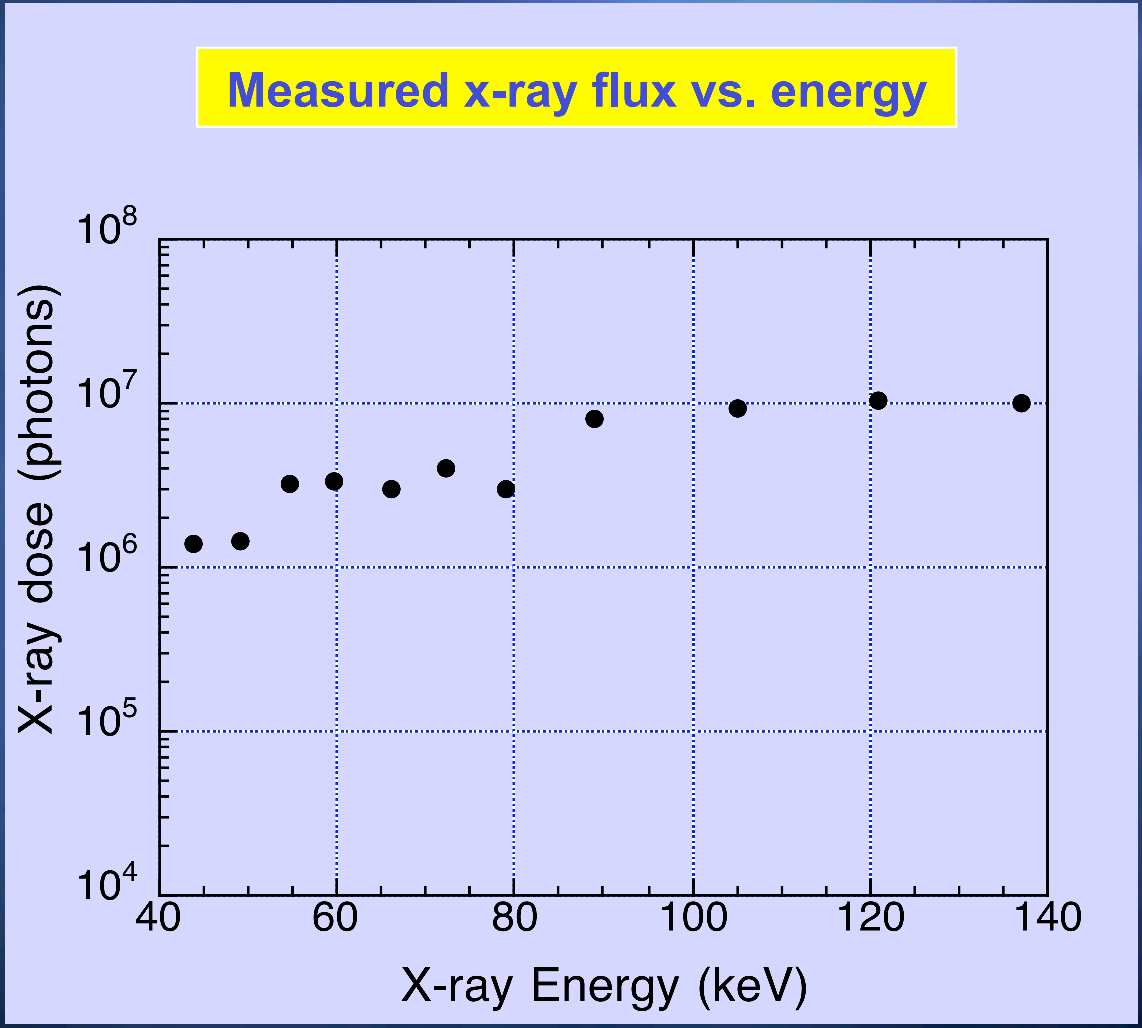


PLEIADES results: benchmark production



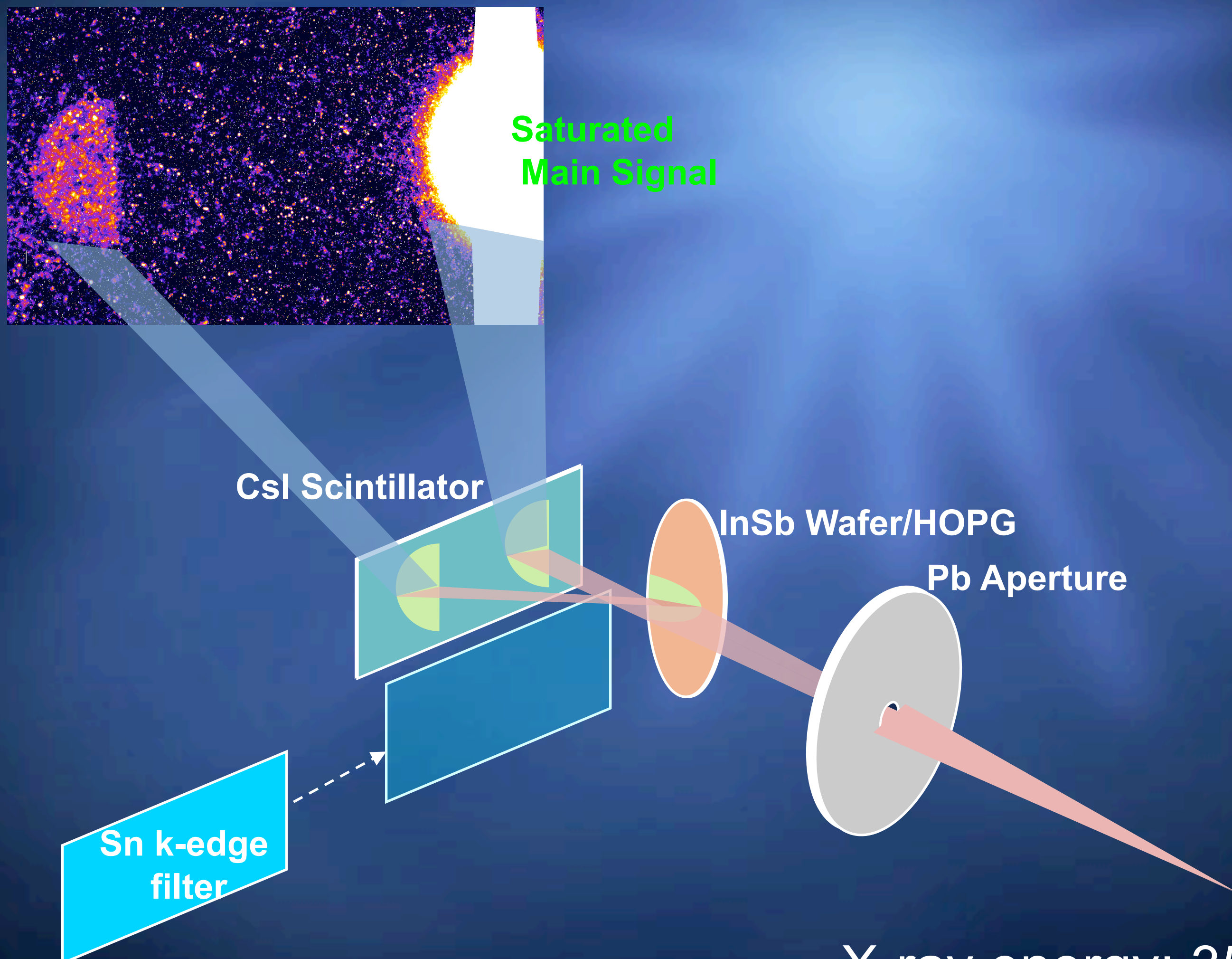
10^7 photons, $B_x > 10^{16}$ photons/s/mm^2/mrad^2/.1%bw

X-ray energy tunability



X-ray energy tuned by e-beam energy

Static diffraction demonstrated



X-ray energy: 35 keV

Beyond the science community: medical applications

- Monochromatic photons allow much better interaction specificity
  - New diagnostics
  - New therapy modes
- Promising approach
  - Funding agencies, investors interested
  - Industrial development of linac-based ICS
    - another spin-off from FEL program - Vanderbilt
  - Don't need peak flux… mini-storage ring-based solution (see Ruth talk)

Medical photons requirements

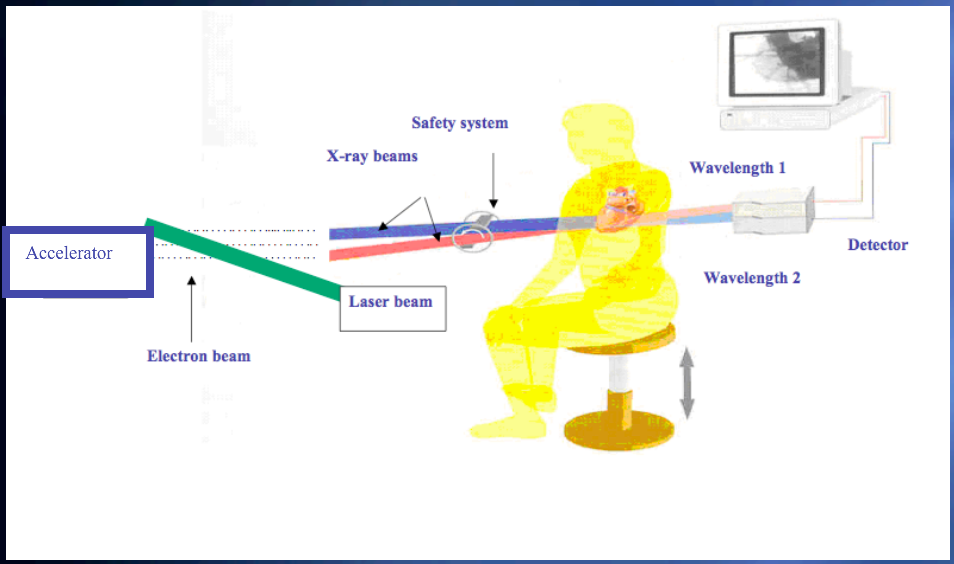
Table 1. Target specifications for NHLBI Pulsed X-ray Source

Parameter	NHLBI source (projected)
Peak flux, ph/pulse	**10^10**
Repetition rate, Hz	**1 to 10 (up to 1 kHz in the future)**
Average flux, ph/s	10^11 to 10^13
Peak brilliance, ph/(s mm^2 mrad^2 1%bw)	10^23
Wavelength range, Å	0.4 to 45
Energy range, keV	**0.28 to 30**
Energy bandwidth, %	**0.1 to 10**
Pulse width, ps	**<10**
Source size, um	**<20**
Divergence, mrad	**<2**
Tunability	**repetition rate, bandwidth, wavelength**
Coherence	partial, transverse
Suggested dimensions, m	3 x 5 x 1.5

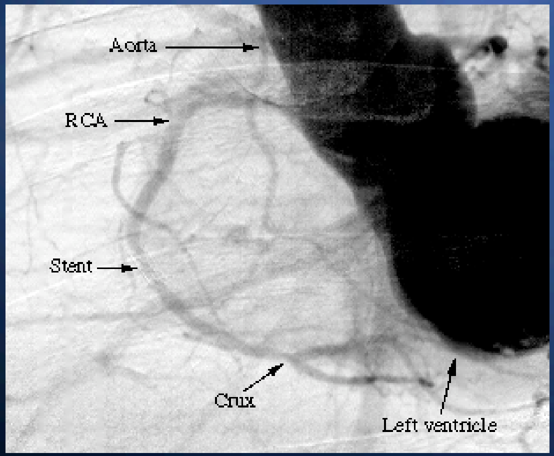
Most critical parameters are given in bold.

- Medical applications demand
  - Variable energy
  - large numbers of photons
  - Narrow bandwidth
- Example: NIH pre-solicitation
- These parameters are possible?

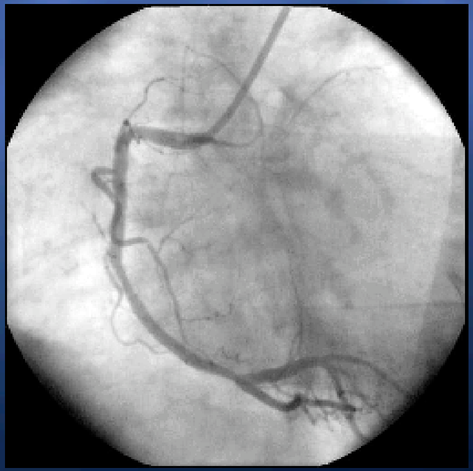
Medical applications: Dichromatic imaging



- Illuminate above and below contrast K-edge
- Digital image subtraction
- Established at synchrotrons
  - Access limited
  - Expensive ($100M's)
- Mitigate risk of angiography



Conventional angiogram



Digital subtraction angiogram (same patient, same day)

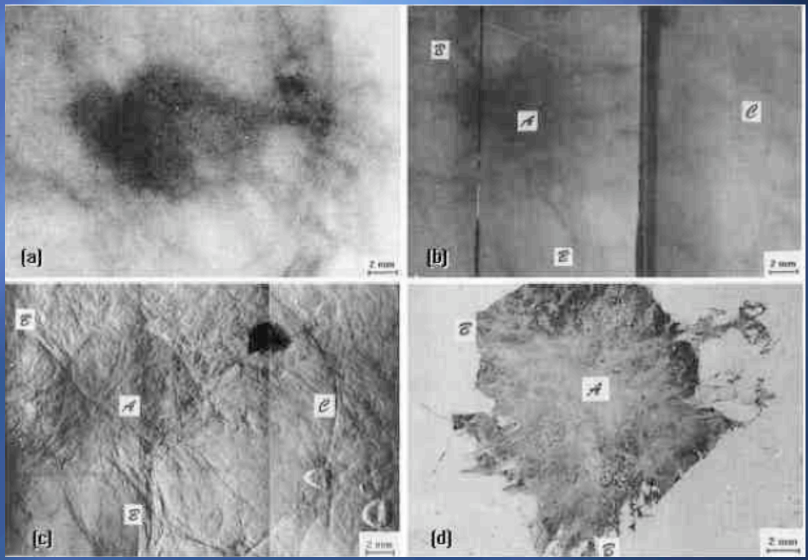
Low dose 3D imaging

- 60 images
- Total dose 74 mR

From MXISystems website

Medical applications: mammography

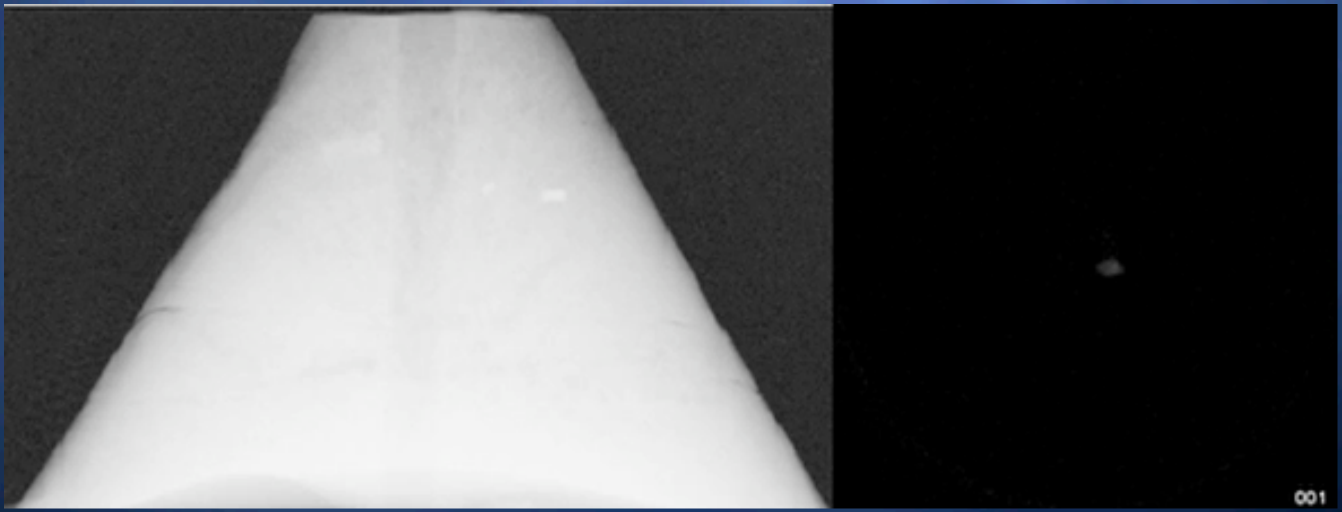
- Conventional X-ray imaging difficult in mammography
  - Soft-tissue contrast poor
- Monochromatic X-rays enable new techniques
  - Phase contrast imaging
  - 3D with low dose



Mammography images of adenocarcinoma. (a) conventional mammogram; (b) monochromatic beam at 22.2 keV; (c) phase contrast image based on monochromatic X-ray beam; (d) histological section.

Mammography in 3D

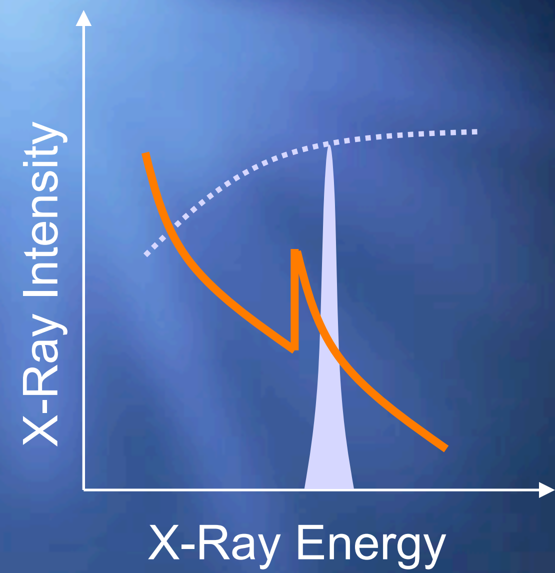
- Mammography phantom shows very fine "lesions"
- Less dose than conventional 2D



Medical uses: monochromatic cancer therapy

Tagged Agents Imaged by Noninvasive X-Ray Absorption or Diffraction Spectroscopy

Intensity Increased to Deliver Localized Radiation Dose



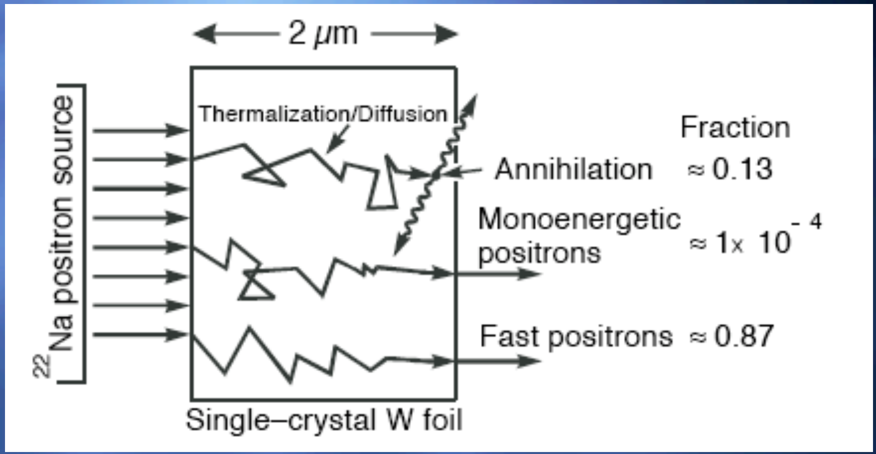
K-edge (~30 keV in iodine)

— Allows treatment of very difficult tumors

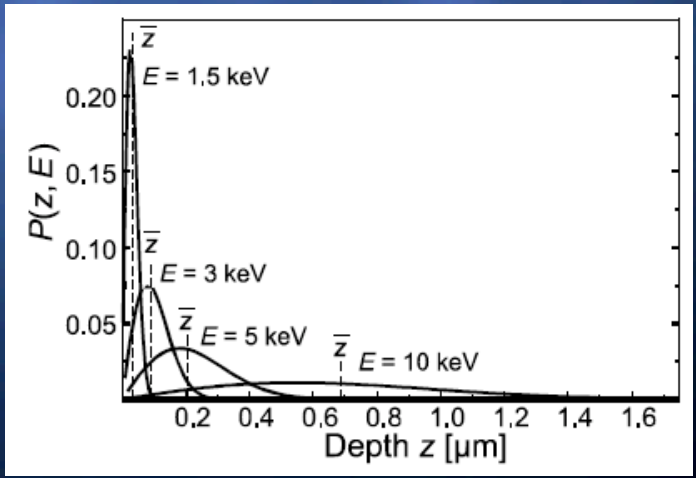
— Very successful test in mice

Higher energy application: defect profiling with e+'s

- Pair production for photon energies above threshold
  - 266 nm laser; > 148 MeV
- Moderate positrons
  - produce ultra-cold beam
  - Surface studies
- Or… create e^+e^- pairs in situ
- Positrons gather at defects
  - Directly probe material defects
  - Very promising NDT technique

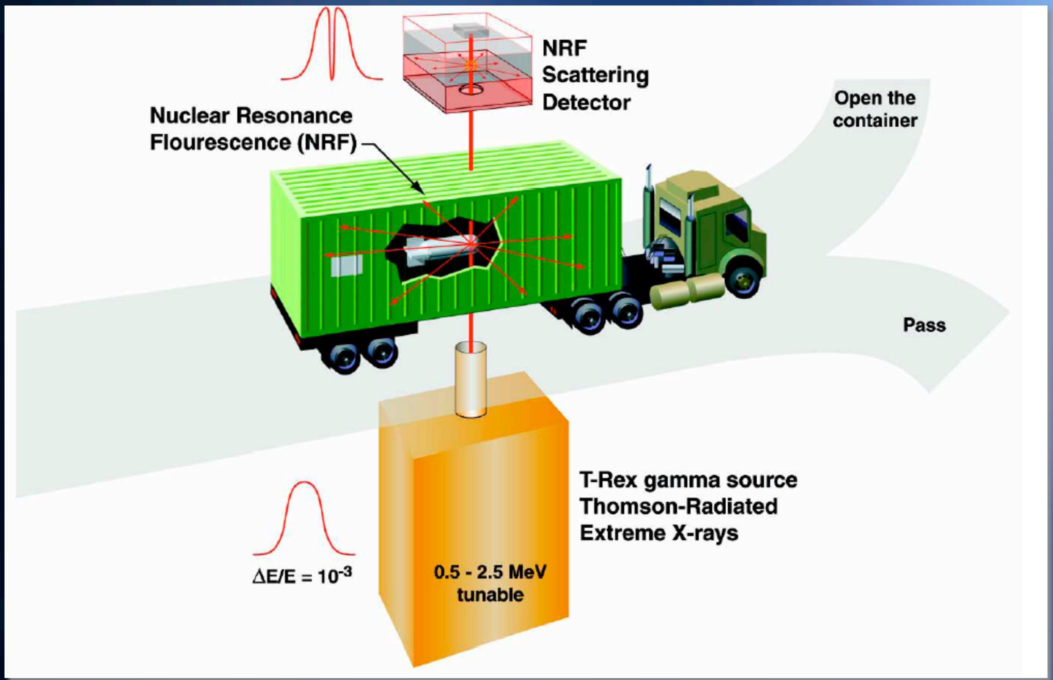


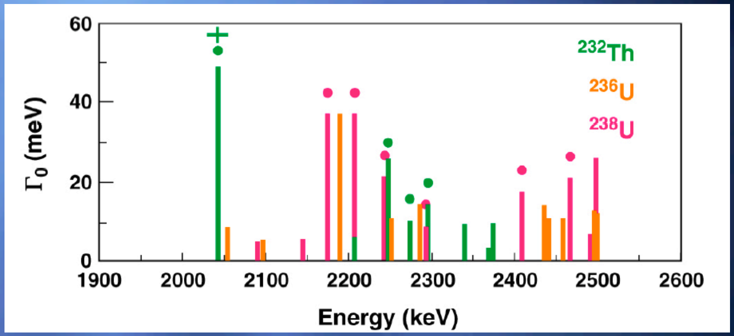
Positron moderation with standard source



Positron depth for defect profiling

High energy application: nuclear materials detection

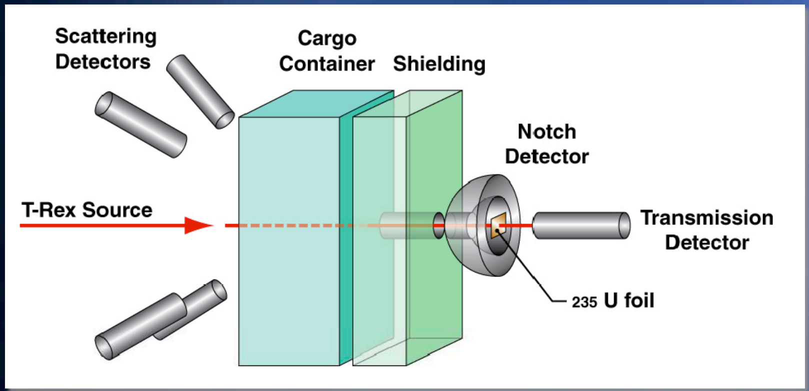


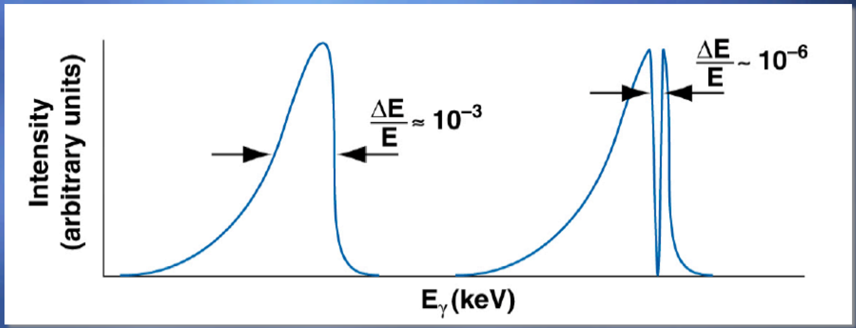


Some nuclear resonances

- Based on nuclear resonance fluorescence
- Need v. *narrow band* gammas, MeV level
- FINDER at LLNL: Fluorescence Imaging in the Nuclear Domain with Energetic Radiation
- LLNL-UCLA collaboraiton

NRF detection scheme

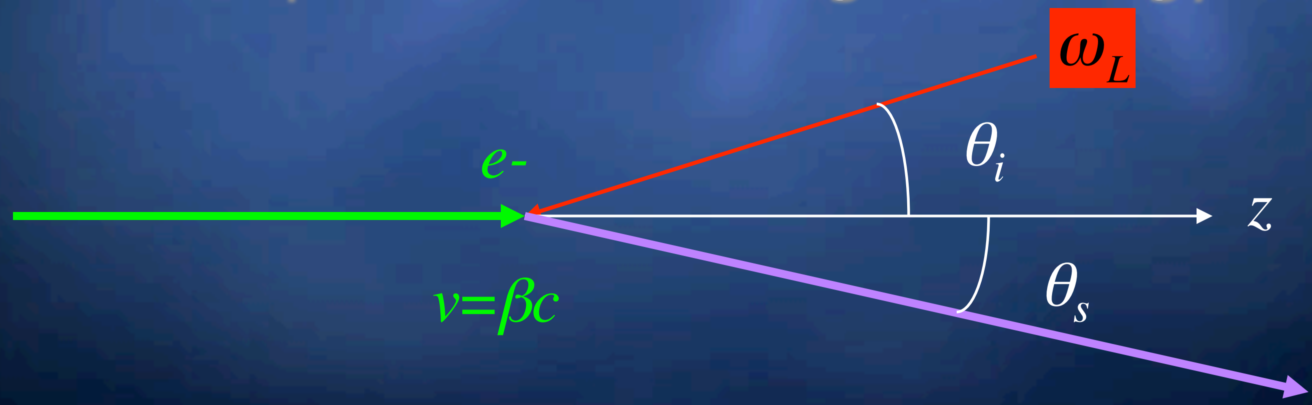




- Indirect notch detection (Bertozzi scheme)
  - Compare transmission through suspect foil to scatttering, look for discrepancy
  - *Very narrow band* photons desired
- Photon production, reported by Siders (next talk)

Physics limits to ICS brightness

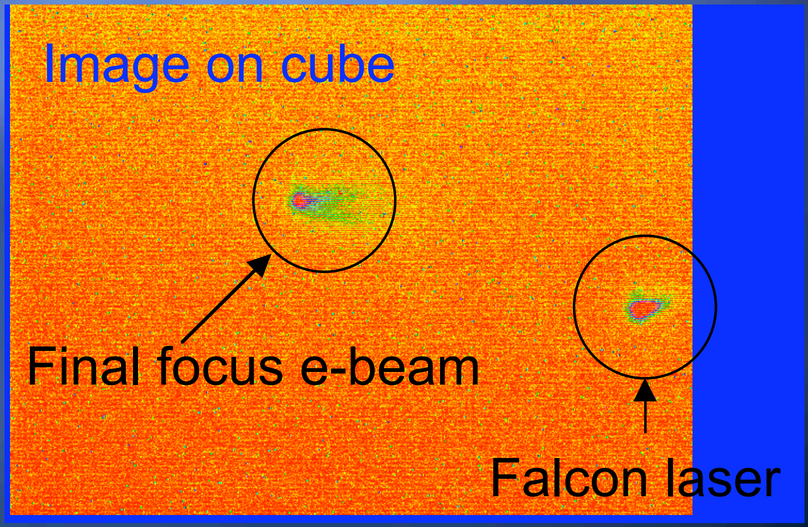
- Applications limited by brightness/BW
  - Look at spectral broadening mechanisms
  - Relate to laser intensity/photon production
- Consider nearly head-on collision
- Work in "Thomson" limit; assume quasi-linear
  - Need Compton model at higher energy



Ignoring the electron beam divergence in design

- Anecdote: even with bad final ε at PLEIADES, the e-beam was smaller at the IP than the laser…
- Laser "emittance" usually bigger than the e-beam

$$\varepsilon \cong \frac{\varepsilon_n}{\gamma} << \frac{\lambda_L}{4\pi}$$



- Example: PLEIADES design

$$\varepsilon = 1.6 \times 10^{-8}\,\mathrm{m},\ \frac{\lambda_L}{4\pi} = 6.4 \times 10^{-8}\,\mathrm{m}$$

Begin in electron rest frame

- Lorentz transformation of ω-k 4-vector

$$\omega' = \gamma\left(\omega_L + \beta c k_L \cos(\theta_i)\right) = \gamma\omega_L\left(1 + \beta\cos(\theta_i)\right)$$
$$k'_\perp = k_L \sin(\theta_i)$$
$$k'_z = \gamma\left(k_L \cos(\theta_i) + \beta\omega_0 / c\right) = \gamma k_L\left(\cos(\theta_i) + \beta\right)$$

- Blue-shifted rest frame photon scatters with negligible recoil (Thomson limit) if

$$\hbar\omega' << m_e c^2, \quad \text{or}$$
$$\hbar\omega_L\gamma\left(1 + \beta\cos(\theta_i)\right) << m_e c^2$$

BNL example:
γ=120, $h\omega_L$=0.12 eV

$$\hbar\omega_0\gamma\left(1+\beta\right) = 30\ \text{eV} << 5.11\times 10^5\,\text{eV}$$

Thomson scattering in electron rest frame

- In Thomson limit, ω is independent of emission direction in rest frame θ'

$$\omega_s' = \omega' = \gamma\omega_L\left(1+\beta\cos(\theta_i)\right)$$

- Wave-vector components

$$k_{\perp s}' = \frac{\omega_s'}{c}\sin(\theta') = k_L\gamma\left(1+\beta\cos(\theta_i)\right)\sin(\theta')$$

$$k_{zs}' = k_L\gamma\left(1+\beta\cos(\theta_i)\right)\cos(\theta')$$

- Note: Power profile in linear limit is also derived from Thomson

$$\frac{dP_s}{d\Omega'} = \frac{e^2\dot{v}^2}{4\pi c^3}\cos^2(\psi)$$

- Total Thomson cross-section Lorentz invariant

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

Back to the lab frame

- Final frequency: $\omega_s = \gamma^2 \omega_L \left(1 + \beta \cos(\theta_i)\right)\left(1 + \beta \cos(\theta')\right)$
- Wave-vector components:

$$k_{\perp s} = k_L \gamma \left(1 + \beta \cos(\theta_i)\right) \sin(\theta')$$
$$k_{zs} = k_L \gamma^2 \left(1 + \beta \cos(\theta_i)\right)\left(\cos(\theta') + \beta\right)$$

- Lab frame angle $\tan(\theta_s) = \frac{k_{\perp s}}{k_{zs}} = \frac{1}{\gamma}\left(\frac{\sin(\theta')}{\cos(\theta') + \beta}\right)$
- Small angle approximation $\theta_s \cong \frac{\theta'}{2\gamma}$

Small angle spectrum

- Approximate small angle spectrum

$$\omega_s = 4\gamma^2\omega_L\left(1-\frac{\theta_i^2}{2}\right)\left(1-\frac{(\gamma\theta_s)^2}{2}\right)$$

Maximum Doppler shift

Incident angle effect

Final angle effect

- Final angle-induced red shift familiar from FEL
  - Resonance: when emitted wave-front overtakes electron by λ_r in λ_U ($\sim\lambda_L/2$. Thomson)
  - Relative red shift always ~ $(\gamma\theta)^2/2$
  - Some subtle differences with undulator radiation

Angular "efficiency"

- Small bandwidth: small emission angles
- Write in terms of max "aperture"
- In terms of rest frame angle

$$\eta_{acc}(\theta'_{\max}) \equiv \frac{N_{acc}(\theta'_{\max})}{N_{total}} \cong \frac{3}{4}\theta'^2_{\max}$$

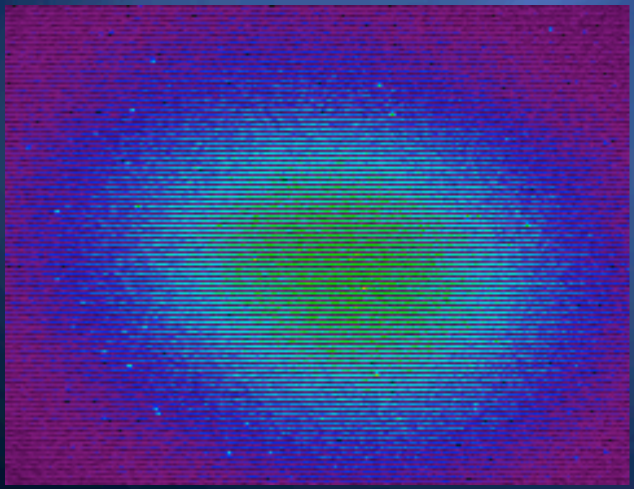
$$\eta_{acc}(\theta_s) \cong 3(\gamma\theta_s)^2$$

- In terms of *rms* bandwidth

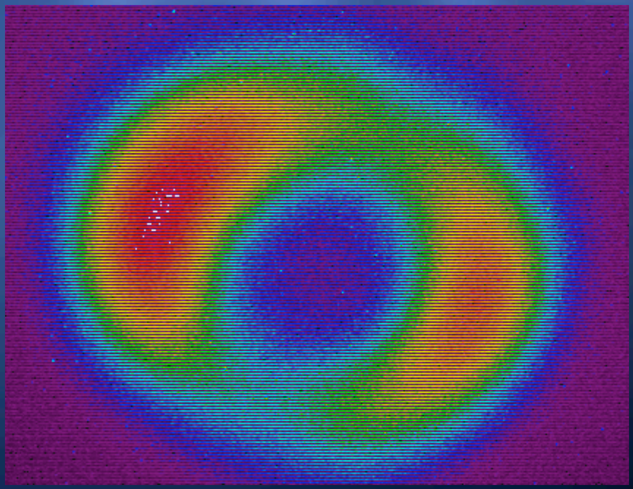
$$\eta_{acc}(\theta_{\max}) \cong 6\sqrt{3}(BW_{rms})_{acc}$$

Off-axis redshift in experiment

- New expts at BNL, 10 μm laser, ~62 MeV beam
  - Very small angles in e-beam
- Absorption of photons by Fe foil, above K-edge
  - See talk by O. Williams



No foil



Fe foil (7.1 keV K-edge)

Nonlinear red shift, pertubative limit

- Electron has angle in motion due to laser field $\theta \approx \frac{p_\perp}{p_0} \cong \frac{a_L}{\gamma}, \quad a_L = \frac{eE_L}{m_e c\omega_L}$
- Relative red shift $\frac{(\gamma\theta)^2}{2} = \frac{a_L^2}{2}$
- Result OK for small a_L only
  - Figure-8 motion
  - Harmonics… important for a_L large
- RMS BW (gaussian laser) $(BW_{rms})_{NL} \cong \frac{a_L^2}{7.7}$
- Beginning BNL studies

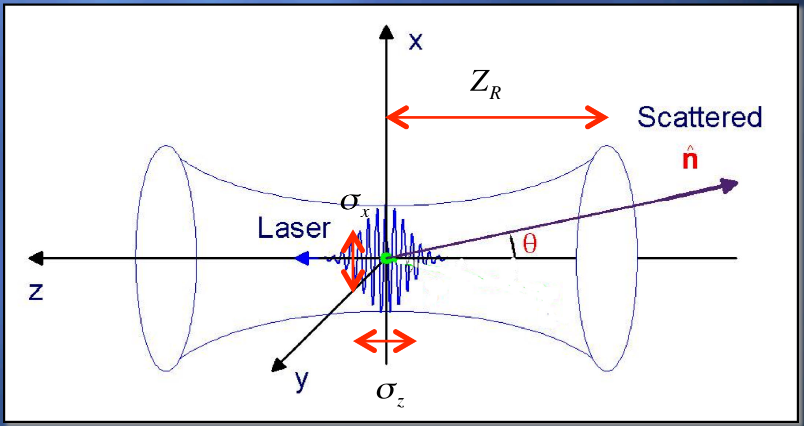
Finite pulse length and focal effects

- Fourier spread in the laser pulse from finite length

$$(BW_{rms})_{FT} \cong \left(\sqrt{2}k_L\sigma_z\right)^{-1} = \frac{\lambda_L}{\sqrt{8}\pi\sigma_z}$$

- Bandwidth smaller for longer pulse
- Practical pulse length limited by Rayleigh range

$$\sigma_z \leq Z_R = \frac{4\pi\sigma_x^2}{\lambda_L}$$



Inherent angular spread in photons…

- Away from the focus, laser phase fronts have angle, with rms spread

$$\theta_{L,rms} = \frac{\sigma_x}{Z_R} = \frac{\lambda_L}{4\pi\sigma_x}$$

$$\left(BW_{rms}\right)_\theta = \frac{\left(\theta_L^2\right)_{rms}}{2} = \left(\frac{\lambda_L}{4\pi\sigma_x}\right)^2$$

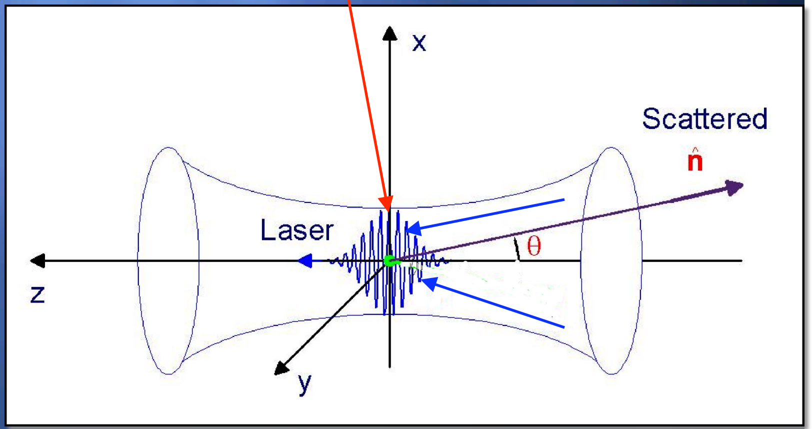
- In focus, phase fronts flatten, but Guoy phase shift changes local k_z

$$\tan(\varphi(z)) = \frac{z}{Z_R} \;\longrightarrow\; BW_{\text{shift}} = \frac{\Delta k_z}{k_z} = \frac{1}{k_z}\frac{d\varphi}{dz} \cong \frac{\lambda_L}{2\pi Z_R} = \frac{\lambda_L^2}{8\pi^2\sigma_x^2}$$

- RMS spread *same*

From dispersion relation:

$$k_z = \sqrt{(\omega_L/c)^2 - k_\perp^2} \cong \sqrt{k_L^2 - \sigma_x^{-2}} \cong k_L\left(1 - \frac{1}{2}\left(\frac{\lambda_L}{2\pi\sigma_x}\right)^2\right)$$



Photon production and luminosity

- Total scattered photons per pulse: $N_\gamma = \mathbf{L}\sigma_T$
- "Luminosity" per pulse: $\mathbf{L} = \dfrac{N_L N_{e-}}{4\pi\sigma_x^2}$
- Independent of σ_z; make beam as long as possible to mitigate FT BW: $\sigma_z = Z_R = \dfrac{4\pi\sigma_x^2}{\lambda_L}$
- *Under this assumption*, angular BW ~ the Fourier transform BW!

$$\theta_{L,rms} = \frac{\lambda_L}{4\pi\sigma_x} = \frac{\lambda_L}{4\pi}\sqrt{\frac{4\pi}{\lambda_L\sigma_z}} = \sqrt{\frac{\lambda_L}{4\pi\sigma_z}} = 2^{-1/4}\sqrt{\left(BW_{rms}\right)_{FT}}$$

→

$$\left(BW_{rms}\right)_{foc} = \theta_{L,rms}^2 = \sqrt{2}\left(BW_{rms}\right)_{FT}$$

Calculate luminosity

- Luminosity per assumption: $$\mathbf{L} = \frac{N_L N_{e-}}{4\pi\sigma_x^2} = \frac{N_L N_{e-}}{\lambda_L \sigma_z} = \frac{U_L N_{e-}}{hc\sigma_z}$$
- Look at laser pulse energy density

$$u_{\mathrm{EM}} = \frac{N_L h\nu_L}{(2\pi)^{3/2}\sigma_z\sigma_x^2} = \frac{U_L}{\sqrt{\pi/2}\lambda_L^2\sigma_z^2}$$

- Pulse intensity and field values…

$$u_{\mathrm{EM}} = \frac{\varepsilon_0 E_L^2}{2} = \frac{U_L}{\sqrt{\pi/2}\lambda_L^2\sigma_z^2}$$

or

$$E_0 = \sqrt{\frac{2u_{EM}}{\varepsilon_0}} = \sqrt{\frac{2U_L}{\sqrt{2/\pi}\varepsilon_0\lambda_L\sigma_z^2}}$$

- Put in terms of $a_{L,\max}$ to relate to NL effects

Maximum laser energy

- Laser energy
  - Linear with λ_l?

$$U_L = \frac{\varepsilon_0 E_L^2 \sigma_z^2 \lambda_L}{(2\pi)^{1/2}}$$

- Maximum in terms of $a_{L,\max}$ (BW...)

$$U_{L,\max} = \frac{k_L \sigma_z^2 a_{L,\max}^2}{4(8\pi)^{1/2} r_e} m_e c^2 \propto a_{L,\max}^2 \lambda_L^{-1}$$

- Relate to luminosity...

Maximum photon production

- Luminosity

$$\mathbf{L}_{\max} = \frac{U_{L,\max} N_{e-}}{hc\sigma_z} = \frac{\alpha a_{L,\max}^2 k_L \sigma_z}{\sqrt{8\pi} r_e^2} N_{e-}$$

- Photons per pulse
  - Now $\sim 1/\lambda_L$!

$$N_\gamma = \mathbf{L}_{\max}\sigma_T = \frac{\sqrt{8\pi}\alpha(k_L\sigma_z)a_{L,\max}^2}{6} N_{e-}$$

- Number within "acceptance" BW

$$N_\gamma = \frac{(2\pi)^{3/2}\alpha(k_L\sigma_z)a_{L,\max}^2}{6}\eta(\theta_{\max})N_{e-}$$

Relating photon production to BW

- We can cast the photon number in terms of all of the relevant bandwidths

$$N_\gamma \cong 0.76 \frac{(BW_{rms})_{acc}(BW_{rms})_{NL}}{(BW_{rms})_{foc}} N_{e-}$$

- Note: laser energy scales as $(BW_{rms})_{foc}^{-4}$

Hard to exploit larger size beam

- If NL and angular BW are chosen ~1%, and focus/FT BW is ~1E-4

$$N_\gamma \approx N_{e-}$$

How do you design laser?

- Choose a laser wavelength
  - Because of limits on NL motion $U_L \propto \lambda_L^{-1}$
- Specify the "focus" bandwidth
  - Now you know the beam dimensions
- Specify nonlinear BW
  - Now you know the laser pulse energy
- Specify angular acceptance for desired BW
- In terms of BWs

$$U_L = 0.1 \frac{(BW_{rms})_{NL}}{(BW_{rms})_{foc}^2} \frac{\lambda_L}{r_e} m_e c^2$$

A 1% RMS BW Example

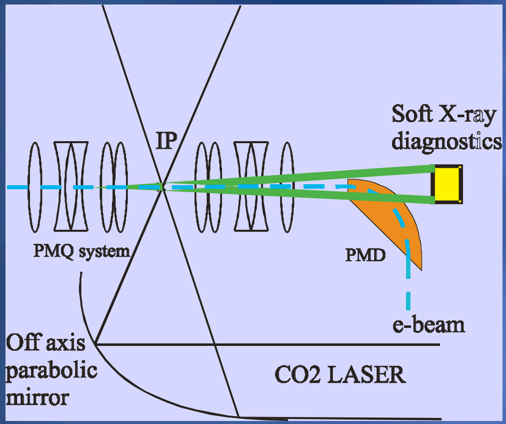
- Laser wavelength: 800 nm
- Focus BW: 1.5E-4, means

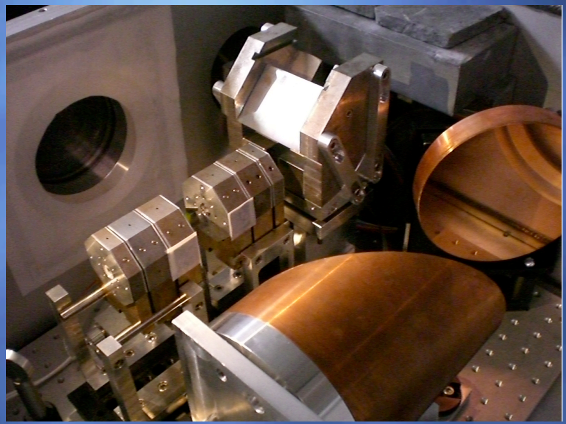
$$\sigma_z = 450\ \mu\text{m}\ (1.5\ \text{ps})$$ and $$\sigma_x = 5.3\ \mu\text{m}$$

  - Strain electron focus at moderate energy…
- NL (+ angular) bandwidth: 1%
- Looks familiar $U_L = 1\ \text{J}$
- For these choices $N_\gamma \approx 0.5 N_{e-}$
- Then… N_γ=3x10^9/nC, with OK emittance

$$\varepsilon_n << \gamma\lambda/4\pi = 5\ \text{mm-mrad}\ (38\ \text{MeV e-}/35\ \text{keV}\ \gamma)$$

ICS sources: present outlook



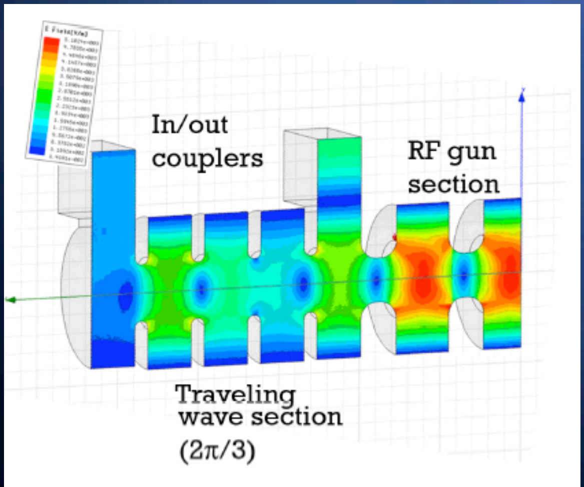


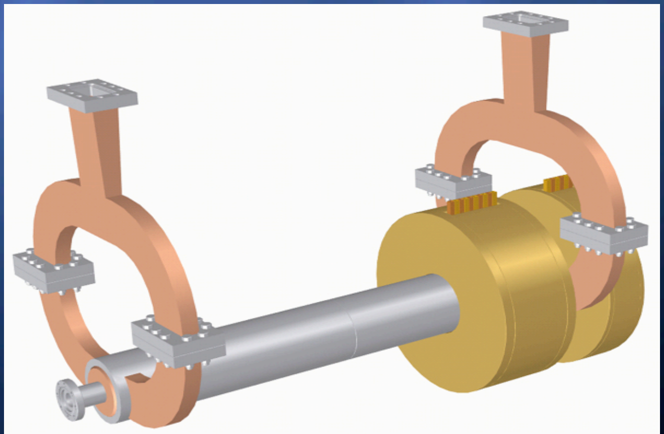
Neptune nonlinear ICS experiment

- Photon flux, tunability demonstrated
- Understand nonlinearities better
- Challenges in flux, applications
  - Better e-beams, smaller accelerator
  - Higher repetition rate, high pulse-energy lasers

Compact photoinjectors

- High frequency (X-band)
  - Better potential performance
- New device: hybrid, traveliing wave-standing wave photoinjector
  - All-in-one solution, produce 15-30 MeV beams
  - 100 fsec beams, 1 nC, good emittance!
  - Under development at UCLA and Univ. Roma

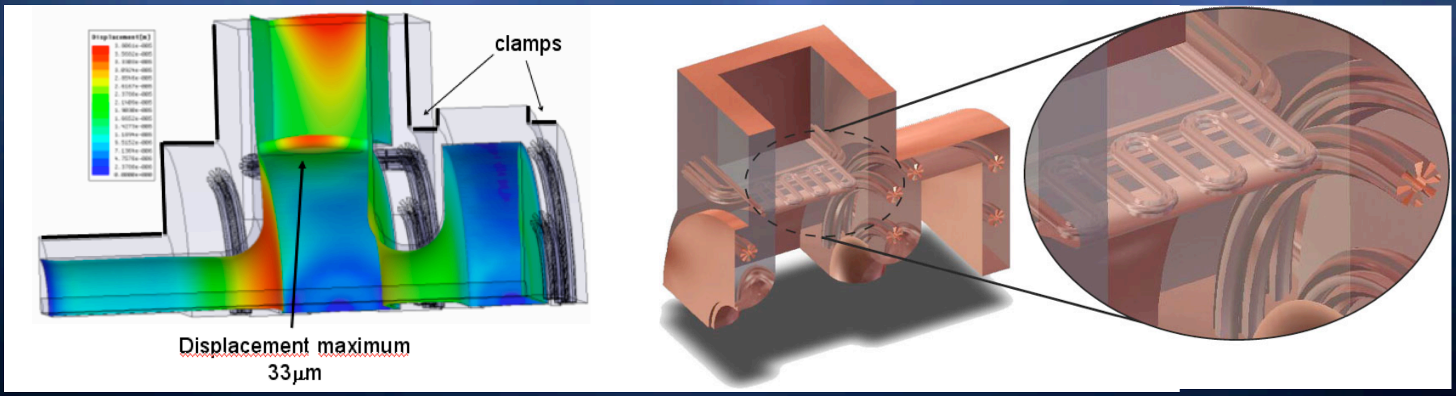




TW linac (~3 m) attached to SW gun

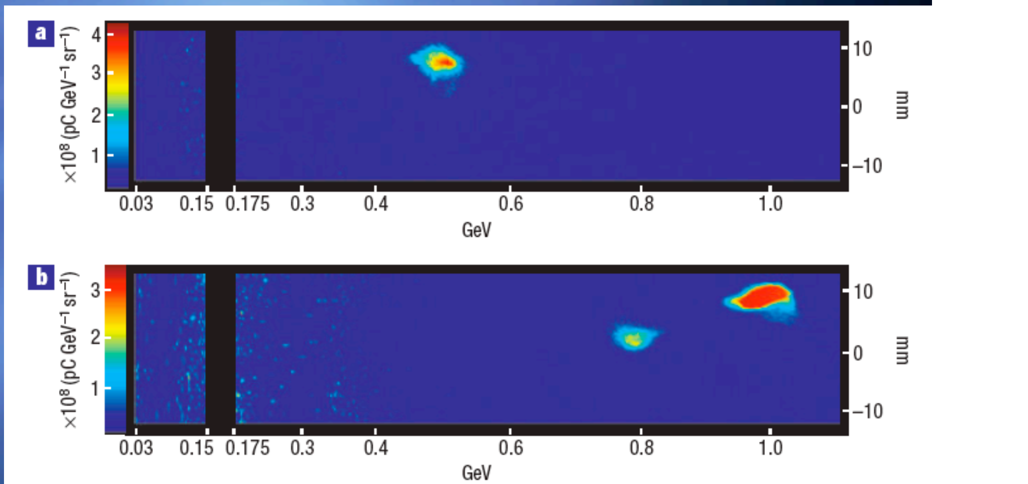
High repetition rate gun

- New lasers promise >1 KHz
- Can PI follow?
- Need new cooling approach
  - Direct metal forming (RadiaBeam patent)
  - Elaborate channels allow 1 kHz operation

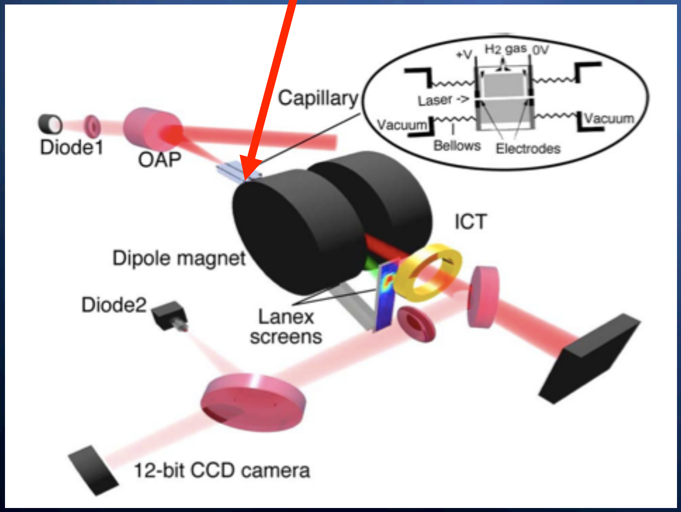


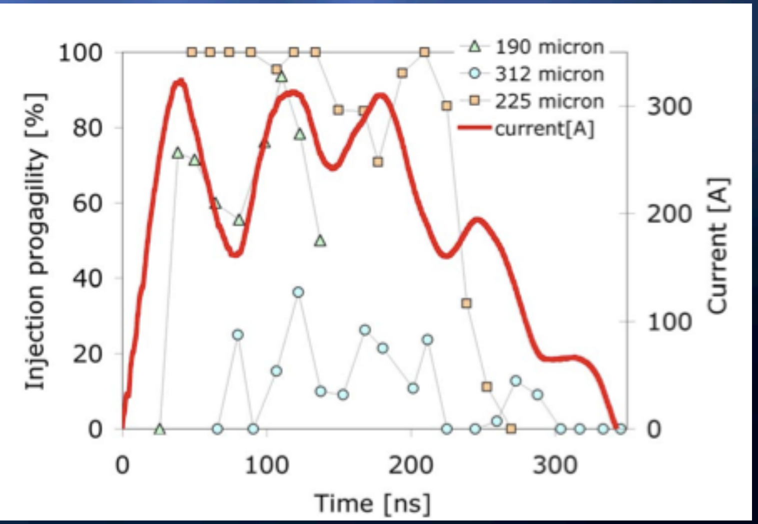
True all-in-one ICS source: Laser-Plasma Accelerator

- Up to 1 GeV (Leemans, et al.)
- Narrow band
- <100 pC, low emittance
- Reliable?
- E-beam small in plasma
- Add laser arm to have ICS



<1 GeV “monochromatic” electron beams





Starting to be reliable

Conclusions

- Monochromatic ICS sources have diverse applications from keV to TeV(?) level
- Basic physics being fleshed out
  - Limits on average and peak flux
  - Peak: use guiding? G. Travish talk
  - Average: rings or…
- Technology push still needed
  - E-beam physics now understood
  - Move to table-top (truck bed?)
  - Increase system rep rate to 10 kHz?
- Applications! Exciting reports at workshop