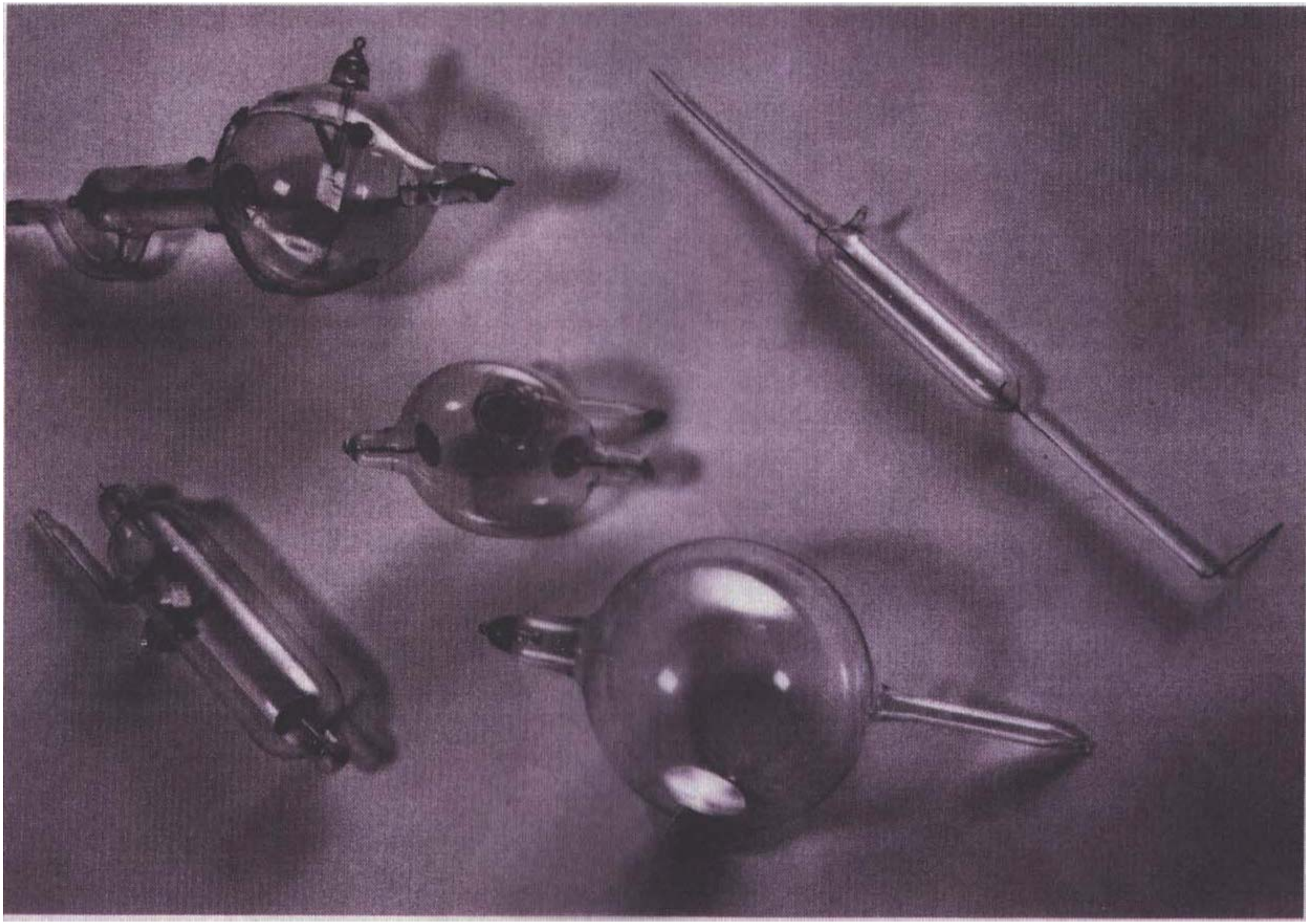
Inverse Compton Scattering: A Small Revolution in X-ray Sources and Applications

David E. Moncton
Massachusetts Institute of Technology

ICFA Hamburg
May 16, 2006

In collaboration with Franz Kaertner, William Graves, and Winthrop Brown

Electron Accelerators: Roentgen's X-ray Tubes 1895-1896



Big Accelerators are Proposed

Use of Synchrotron Orbit-Radiation in X-Ray Physics*

L. G. Parratt

Cornell University, Ithaca, New York

(Received December 1, 1958)

In the design and use of synchrotrons to date, so far as the author is aware, the very costly orbit radiation is a waste product. The proposed use of this radiation in x-ray physics would, therefore, be essentially free. Certainly, if the stability of the x-ray intensity were good to a percent or better, the orbit radiation would be a boon in many aspects of x-ray physics.

Big Accelerator Facilities Now Cost $1 Billion

Compact X-ray Sources

- Fixed Tubes and Rotating Anodes
  - Electron beam colliding with metal target—well known
  - Rigaku FR-E Model for PX has flux = 4×10^9 ph/s in 300 μm
- Plasma Sources
  - Laser beam colliding with fixed metal target
  - Very low time average flux, but short (fs) pulses
- Inverse Compton Sources
  - Laser beam colliding with electron bunch
  - Various demonstrations with warm linacs and large conventional storage rings

Inverse Compton X-ray Sources

Laboratory	Geometry	Energy	Rep. Rate	Photons/pulse
LBL	90^o	30 keV	2 Hz	10^4-10^5
BNL	180^o	6 keV	0.03 Hz	10^7-10^8
LLNL (PLEIADES)	180^o	40-140 keV	10 Hz	10^7
NRL	180^o	0.4 keV	~0.01 Hz	10^7/macro-pulse
FESTA	$90^o/180^o$	2.3/4.6 keV	10 Hz	$10^4/10^5$
Vanderbilt Univ.	180^o	10-50 keV	~0.01 Hz	10^9-10^{10} **
Univ. Tokyo, UTNL*	180^o	40 keV	10 Hz	10^8/macro-pulse**
LLNL(T-REX)*	180^o	0.1-1 MeV	10 Hz	10^8-10^9 **
Kharkov Institute*	$170^o/30^o$	6-900 keV	40-700 MHz	10^5**

*** Under Development**

**** Design value**

Compact X-ray Sources

- Fixed Tubes and Rotating Anodes
  - ➢ Electron beam colliding with metal target—well known
  - ➢ Rigaku FR-E Model for PX has flux = 4×10^9 ph/s in 300 μm

- Plasma Sources
  - ➢ Laser beam colliding with fixed metal target
  - ➢ Very low time average flux, but short (fs) pulses

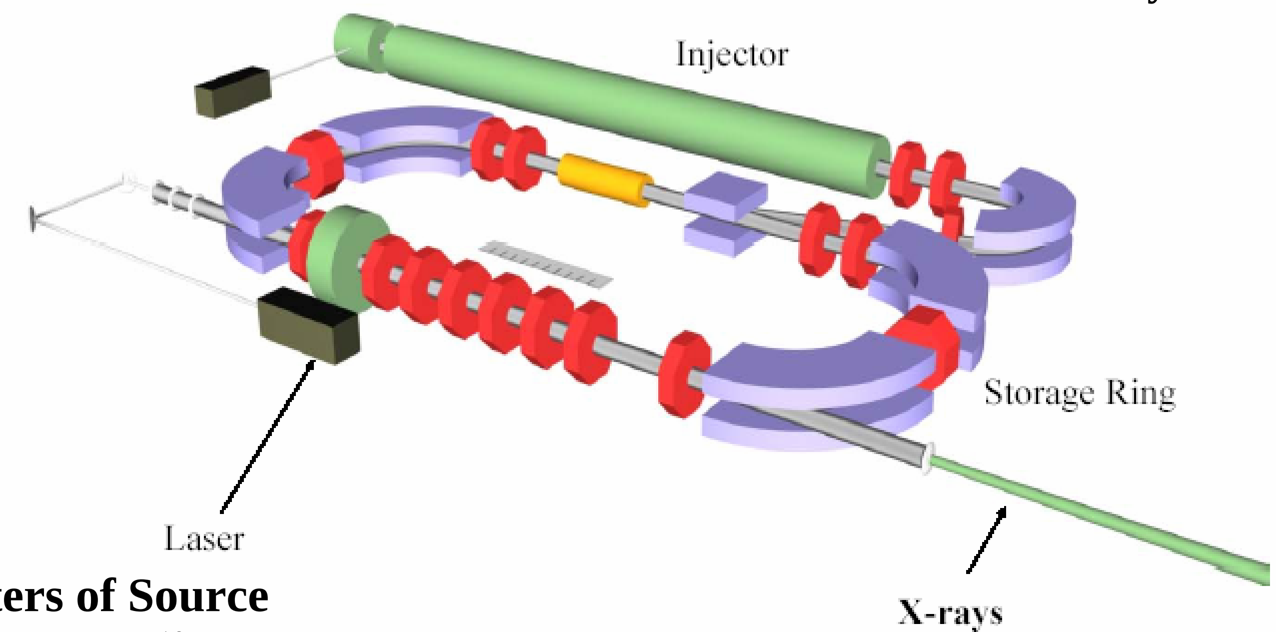
- Inverse Compton Sources
  - ➢ Laser beam colliding with electron bunch
  - ➢ Various demonstrations with warm linacs and large conventional storage rings
  - ➢ Lyncean Technologies developing "table-top"synchrotron-driven source

Lyncean Technologies Compact Source Concept

A Conceptual Picture of the CLS

(The 30 cm ruler in the middle is shown for scale.)

Courtesy of Ron Ruth



Parameters of Source

Average flux 10^{12} photons/sec
Source size 100 microns

"This is not a good time now for us to present results because we are in the middle of tune up"—5/11

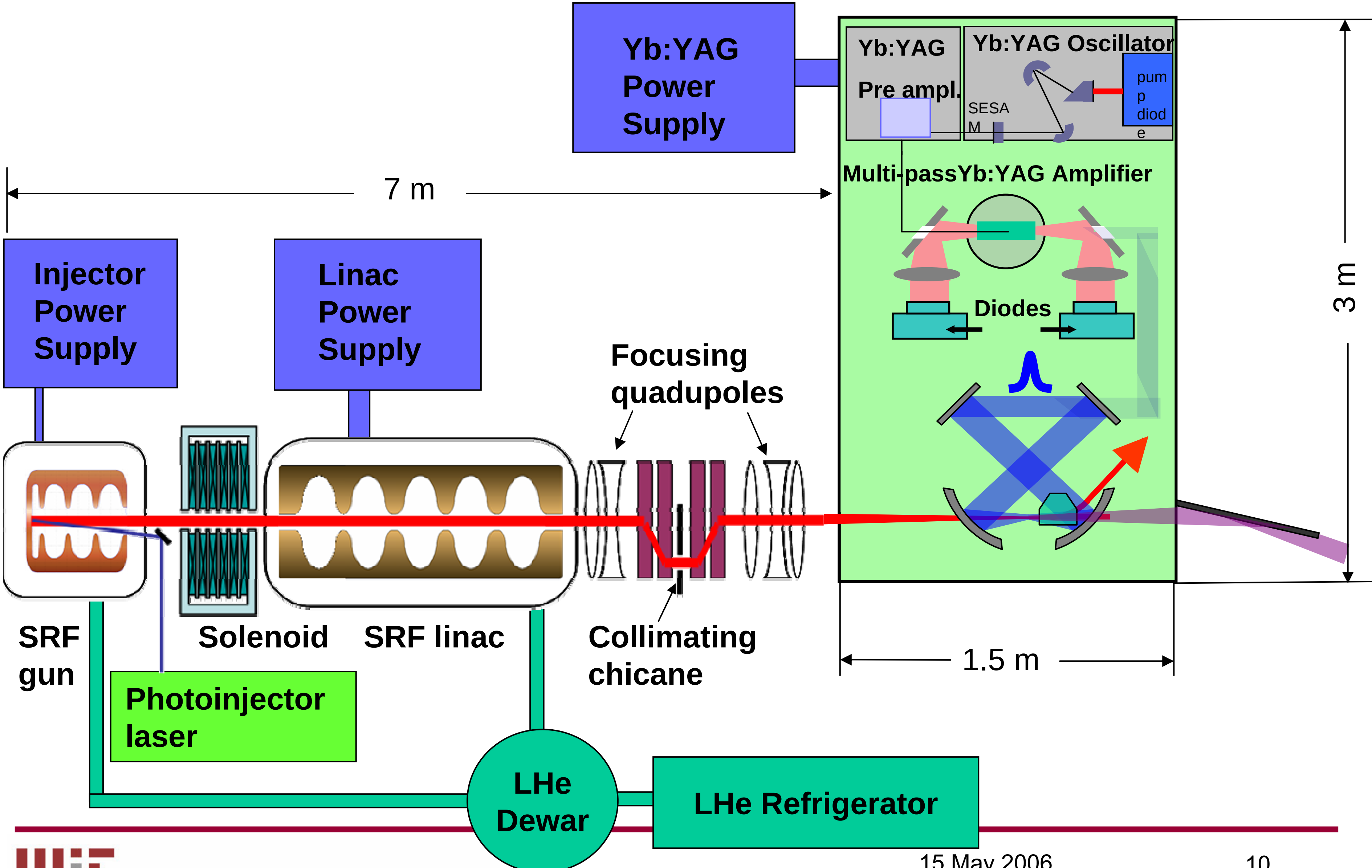
Compact X-ray Sources

- Fixed Tubes and Rotating Anodes
  - ➢ Electron beam colliding with metal target—well known
  - ➢ Rigaku FR-E Model for PX has flux = $4\text{x}10^9$ ph/s in 300 μm

- Plasma Sources
  - ➢ Laser beam colliding with fixed metal target
  - ➢ Very low time average flux, but short (fs) pulses

- Inverse Compton Sources
  - ➢ Laser beam colliding with electron bunch
  - ➢ Various demonstrations with warm linacs and large conventional storage rings
  - ➢ Lyncean Technologies developing "table-top"synchrotron-driven source
  - ➢ At MIT we are studying a SC linac-driven source

MIT Inverse Compton Source Concept

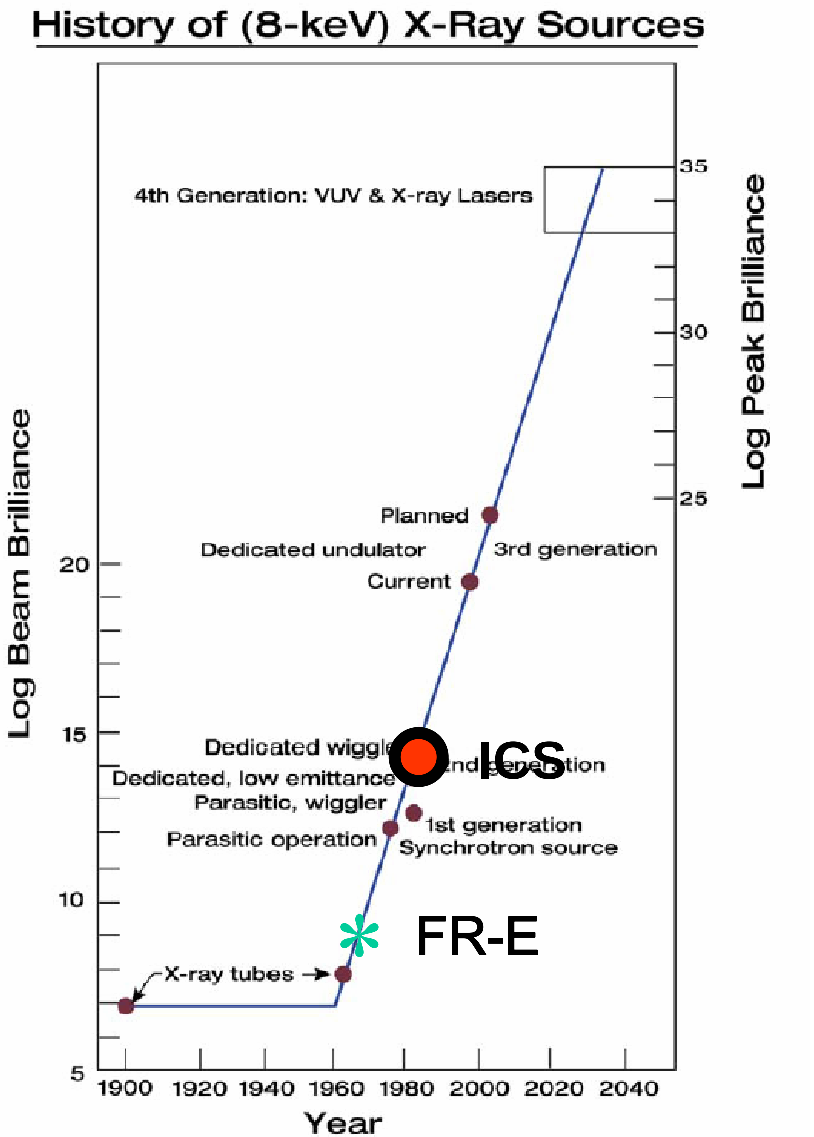


Advantages of an SC Linac: Low Emittance, Short Pulses, High Rep Rate

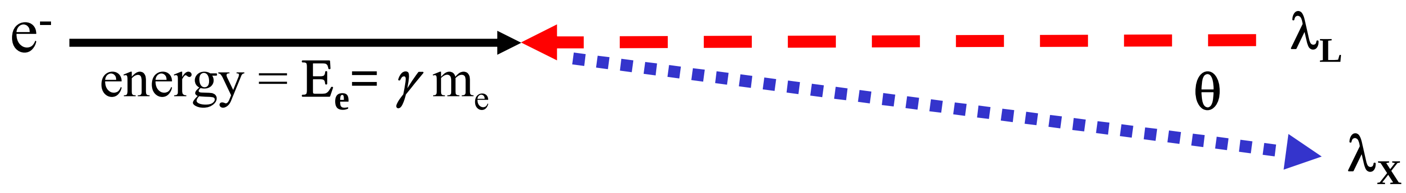
- Like conventional synchrotron beams, the figures of merit for Inverse Compton Sources will be flux and brilliance (brightness).
- High performance will depend on achieving low electron emittance, short pulses, and high time-average currents (and excellent laser properties as well).
  - **Low Emittance:** Normalized electron emittance may approach 0.3 μm. With electron energies of 25 MeV ($\gamma = 50$) the electron beam emittance would be 6 nm—comparable to APS (3 nm)!
  - **Short Pulses:** Pulse durations below 1 ps will enable full advantage to be taken from the low emittance beams
  - **High Current:** Superconducting linac-driven Inverse Compton Sources will employ photo-cathode guns operating at 10 MHz with 0.1 nano-coulomb charge. Currents of 1 milli-amp are generated.
- SC linacs outperform storage rings, and are more reliable.
- They are the next generation ICS after the Lyncean machine

X-ray Science Driven by Beam Brilliance

- X-ray sources have made extraordinary scientific contributions over 100 years
- Over a dozen Nobel Prizes
- The structure of virtually every material is determined by x-rays
- Medical Imaging and the CAT scan
- About a thousand protein structures per year
- Source brilliance increasing at 2x Moore's



Inverse Compton Scattering

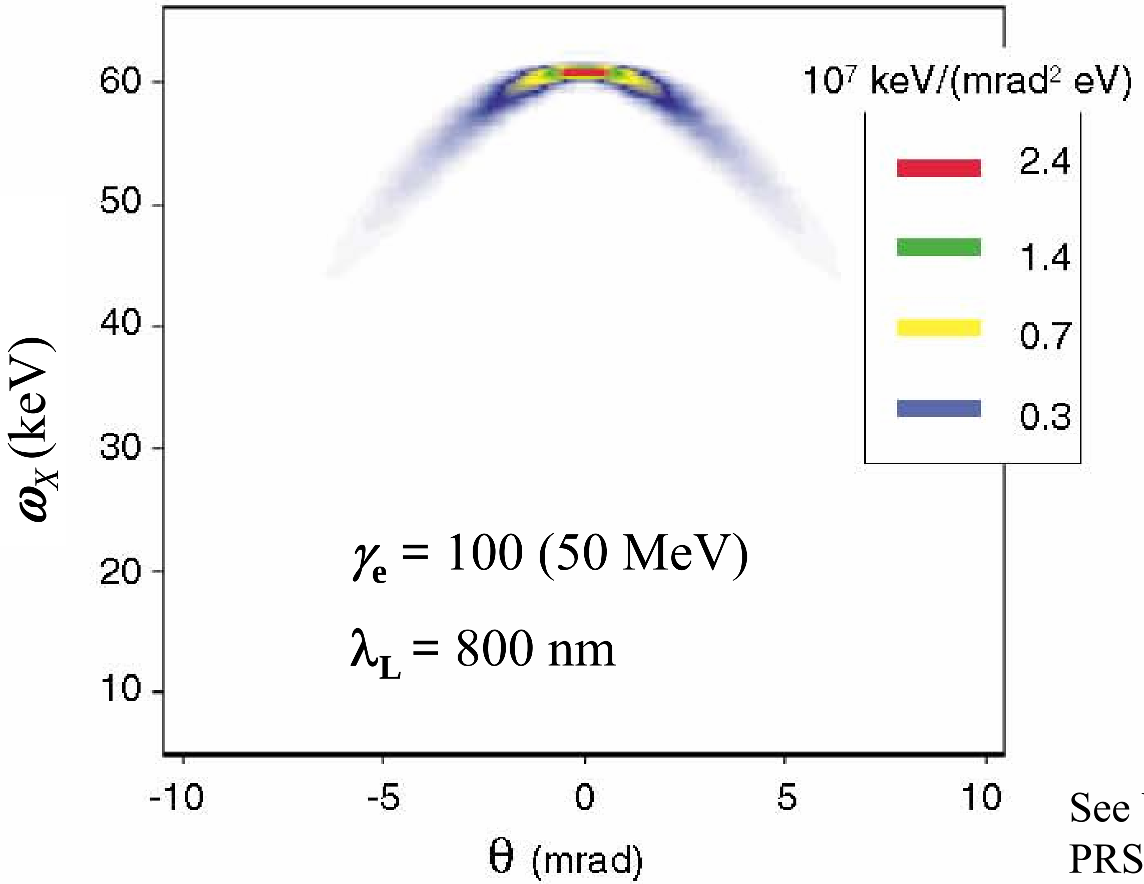


- Normal Compton Scattering the photon has higher energy than the electron
- The inverse process has the Thomson cross-section when $\hbar\omega_X < \mathbf{E_e}$
- The scattered photon satisfies the undulator equation with period $\lambda_L/2$ for head-on collisions

$$\lambda_X = \lambda_L \frac{(1+\gamma^2\theta^2)}{4\gamma^2}$$

- Therefore, the x-ray energy decreases by a factor of 2 at an angle of $1/\gamma$

Example of Complete Calculation



See W.J. Brown et al.
PRST **7,** 060702 (2004)

FIG. 10. (Color) False color plot of the spectral density of scattered x rays in the y-z plane resulting from the head-on collision of a 50 MeV electron bunch with $\varepsilon_{nx} = 1$ mm mrad focused to an rms spot size of 20 μm with an 800 nm, 0.5 ps bandwidth laser pulse polarized in the x direction.

Photon Distribution Has Nearly Axial Symmetry

$\phi = \dfrac{\pi}{2}$ when incident photon is polarized in the scattering plane

$$\frac{dI}{d\Omega\, dt} \propto \underbrace{\frac{1}{(1+\gamma^2\theta^2)^3}}_{\text{FWHM}=1/\gamma}\left[1-\frac{4\gamma^2\theta^2}{(1+\gamma^2\theta^2)^2}\sin^2\phi\right]$$

FWHM=0.6/γ

High Level of Spectral Control

- Photon energy
  --Depends on electron energy—easy to change
- Polarization
  --Determined by the laser polarization
- Source size
  --Determined by interaction area—the smaller of the electron or laser beam size
- Bandwidth
  --Determined primarily by electron beam divergence

Bandwidth and Divergence Effects

1) Laser Bandwidth

$$\frac{\Delta\omega_X}{\omega_X} = \frac{\Delta\omega_L}{\omega_L}$$

$$\frac{\Delta\omega_X}{\omega_X} = 3\cdot 10^{-3} \quad \text{for a 1 ps (300 μ) pulse of } \lambda_L = 1\ \mu \ \text{ photons}$$

Bandwidth and Divergence Effects

2) Laser Divergence Negligible down to focal spot size of 10 microns

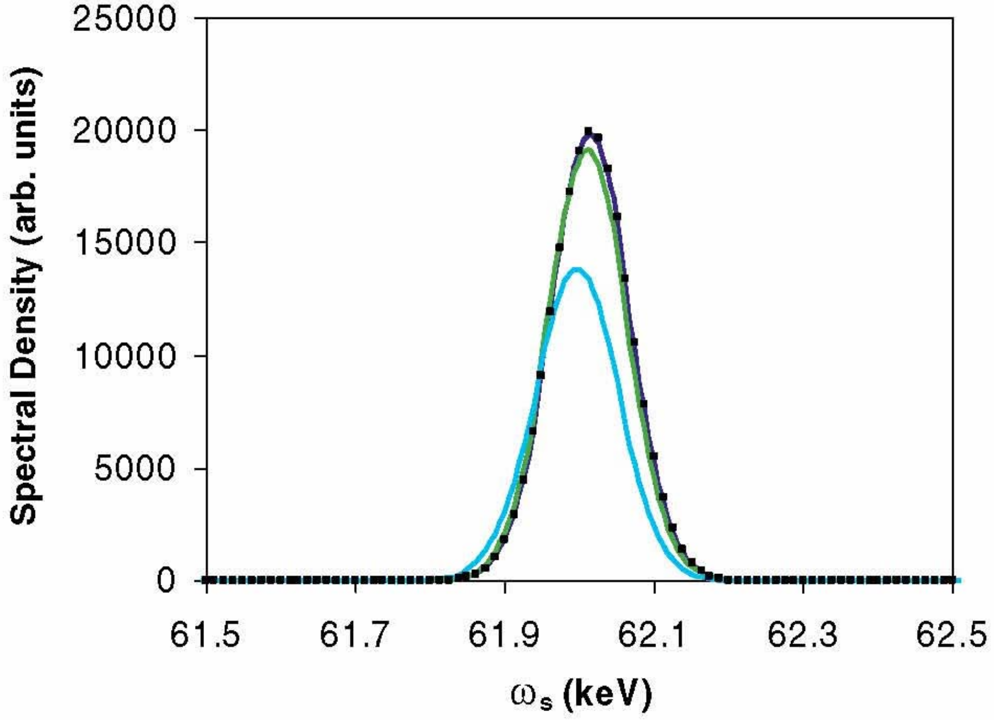


FIG. 7. (Color) On-axis x-ray spectrum produced by a $\gamma = 100$ electron colliding *head on* with an 800 nm laser pulse with a bandwidth corresponding to a 0.5 ps $1/e^2$ pulse width for the case of a plane wave (dots), 20 μm laser focus (dark blue line), 10 μm laser focus (green line), and 5 μm laser focus (light blue line).

Bandwidth and Divergence Effects

3) Electron Bandwidth (i.e. energy spread)

$$\frac{\Delta\omega_X}{\omega_X} = 2\frac{\Delta\gamma}{\gamma} \quad \text{typically} \;\; 2\cdot 10^{-4}$$

Bandwidth and Divergence Effects

4) Electron Divergence

$$\frac{\Delta\omega_X}{\omega_X} = \frac{\gamma^2}{2}(\Delta\xi)^2$$

Emittance $\varepsilon = \Delta x \cdot \Delta\xi \quad (\varepsilon \approx 10^{-8}\ \text{m}\ \text{for linac with}\ \gamma = 100)$

$$\left.\begin{array}{l} \Delta x \approx 10^{-5}\ \text{m for focal spot size 10}\ \mu \\ \Delta\xi \ \approx 10^{-3}\ \text{rad} \end{array}\right\} \varepsilon \approx 10^{-8}\ \text{m}$$

$$\frac{\Delta\omega_X}{\omega_X} = \frac{100^2}{2}(10^{-3})^2 \approx 5 \cdot 10^{-3}$$

Sensitivity to Electron Beam Divergence

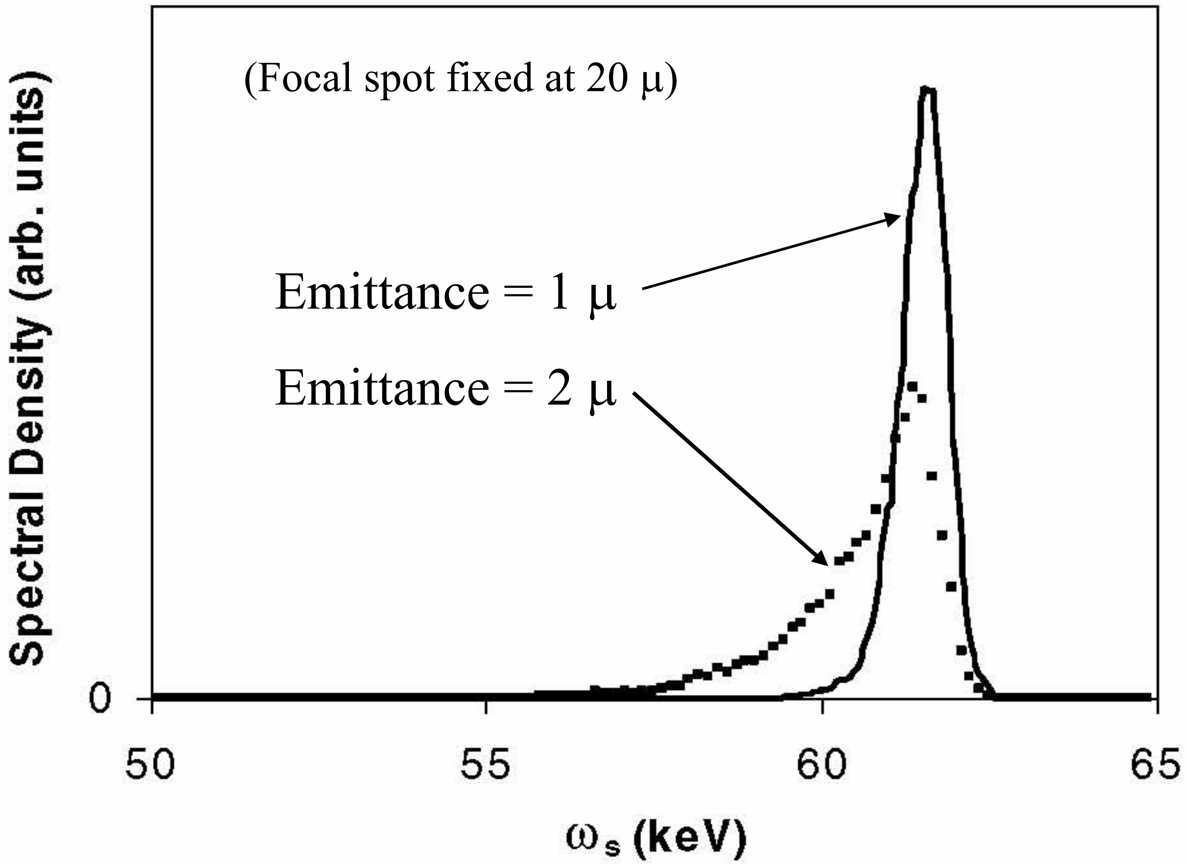
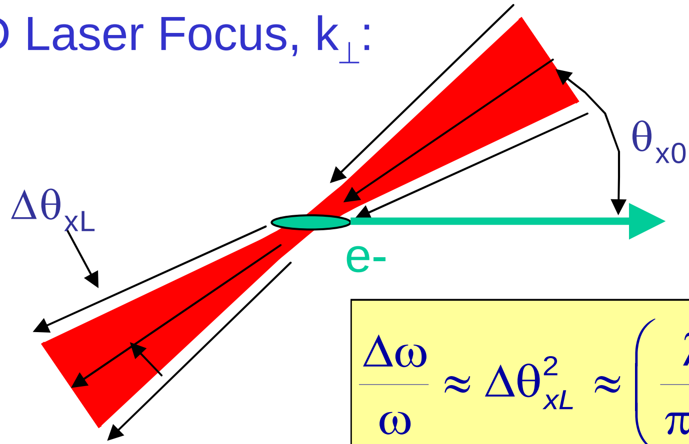


FIG. 9. On-axis x-ray spectrum resulting from a head-on collision of a 50 MeV electron beam with an 800 nm laser pulse for the case of an rms normalized emittance of 1 mm mrad (line) and 2 mm mrad (dots).

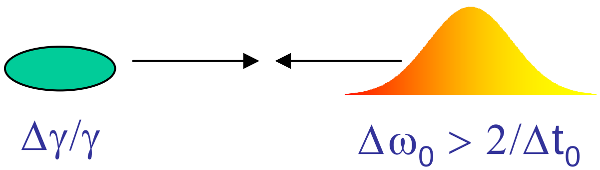
Bandwidth and Divergence Effects

3D Laser Focus, $k_\perp$:



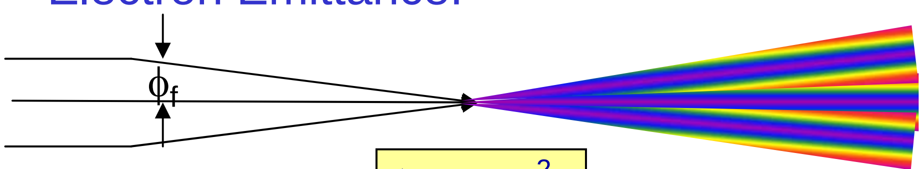
$$\frac{\Delta\omega}{\omega} \approx \Delta\theta_{xL}^2 \approx \left(\frac{\lambda_0}{\pi w_0}\right)^2$$

Laser Bandwidth/Electron Energy Spread:

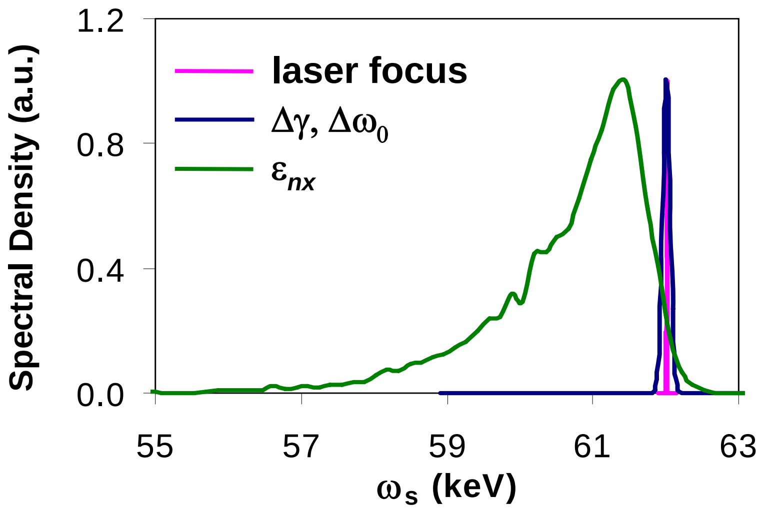


$$\frac{\Delta\omega}{\omega} \approx 2\sqrt{\frac{\Delta\omega_0^2}{\omega_0^2} + \frac{\Delta\gamma^2}{\gamma^2}}$$

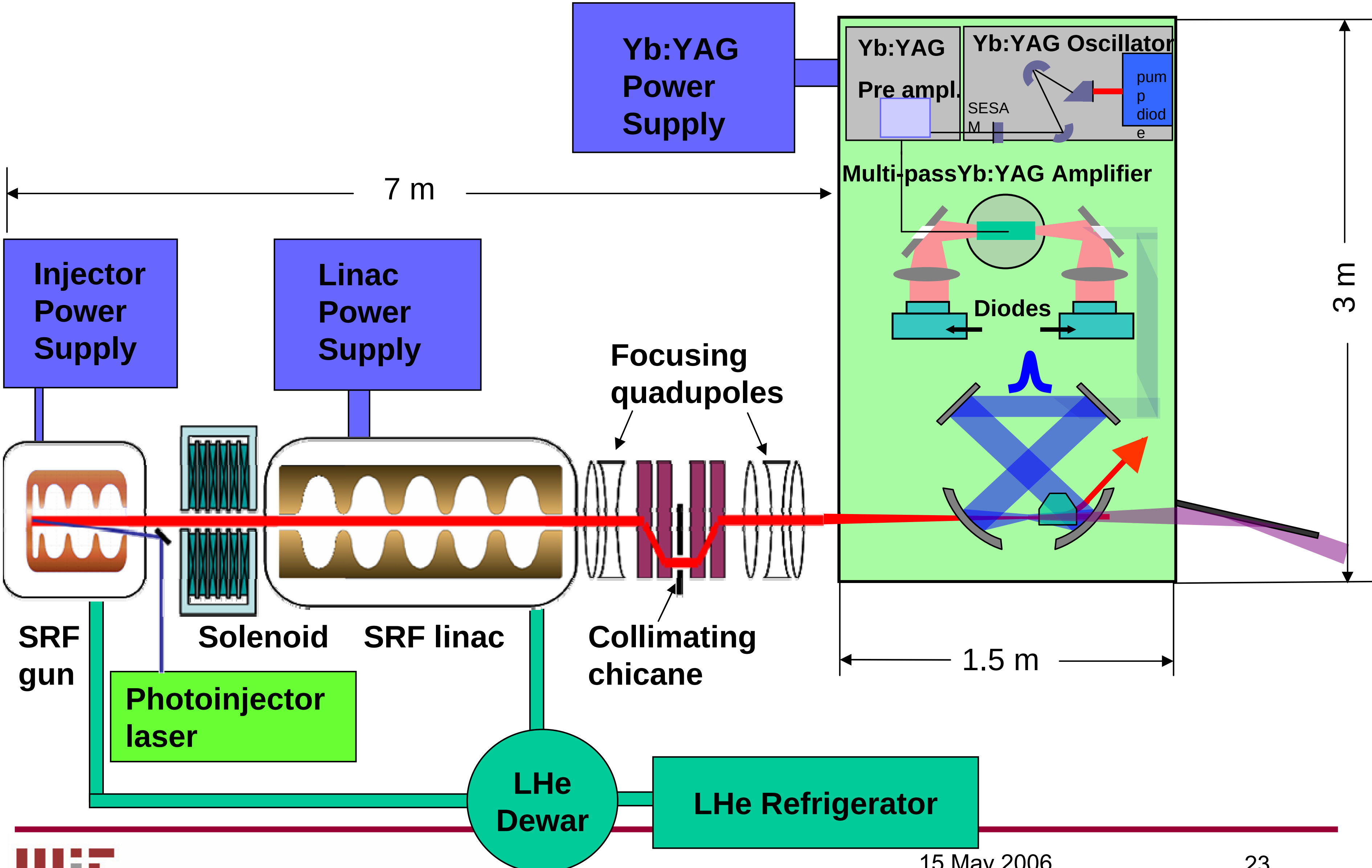
Electron Emittance:



$$\frac{\Delta\omega}{\omega} \approx \frac{\varepsilon_{nx}^2}{x_f^2}$$

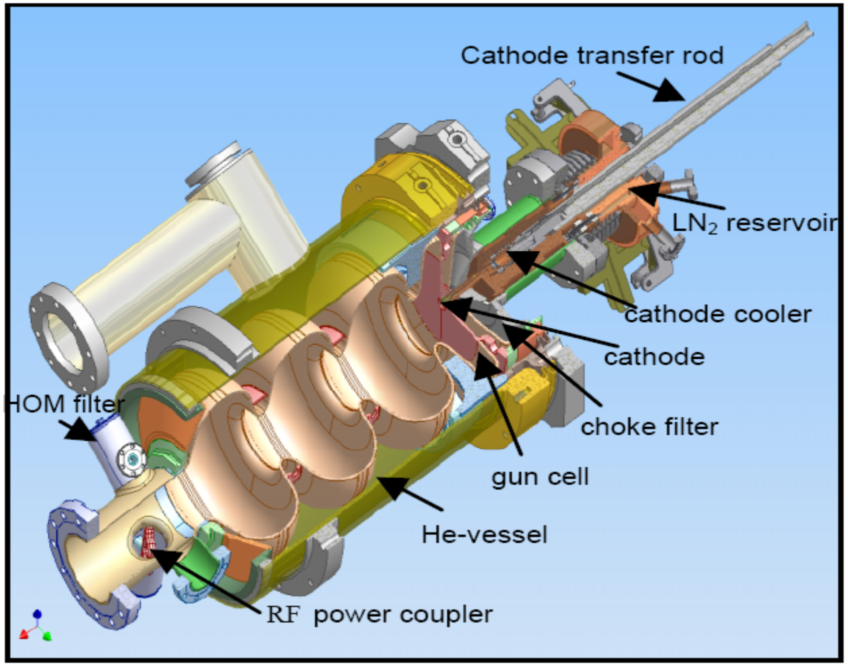


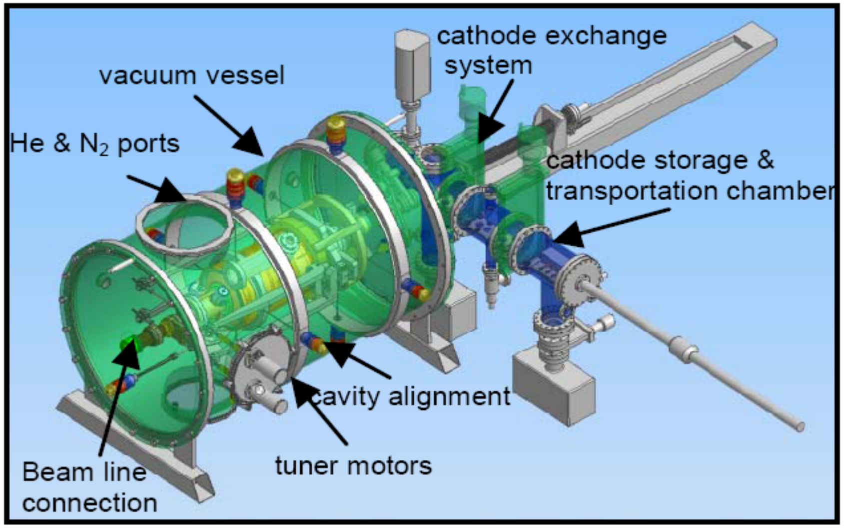
MIT Inverse Compton Source Concept



Superconducting RF Electron Gun

Rossendorf design to be manufactured by Accel Instruments





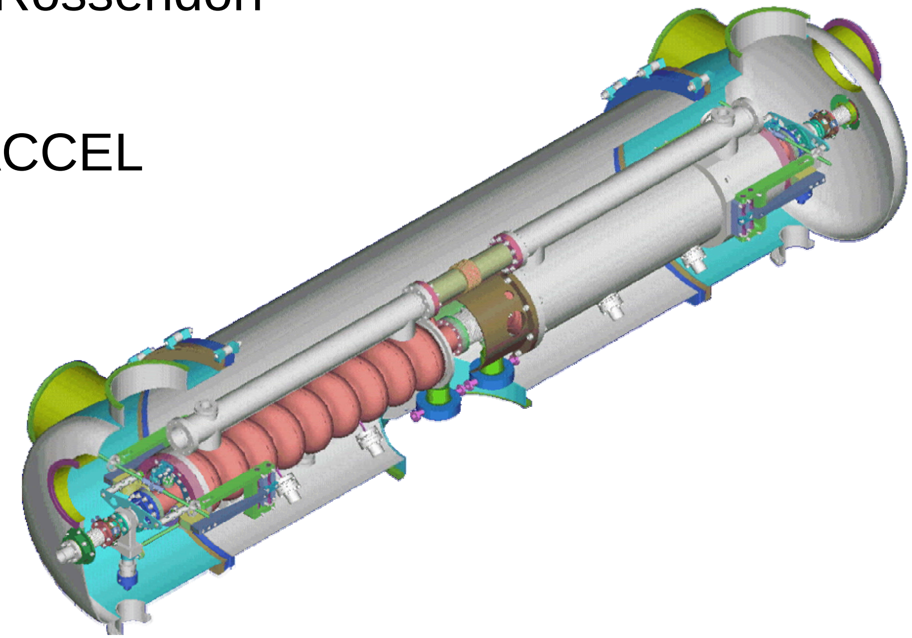
Cryostat with cathode exchange system.

1.3 GHz RF frequency, Cs_2Te cathode
Current = 1 mA
Charge = 100 pC per pulse at 10 MHz
Exit energy = 8 MeV

Superconducting Linac 15-50 MeV

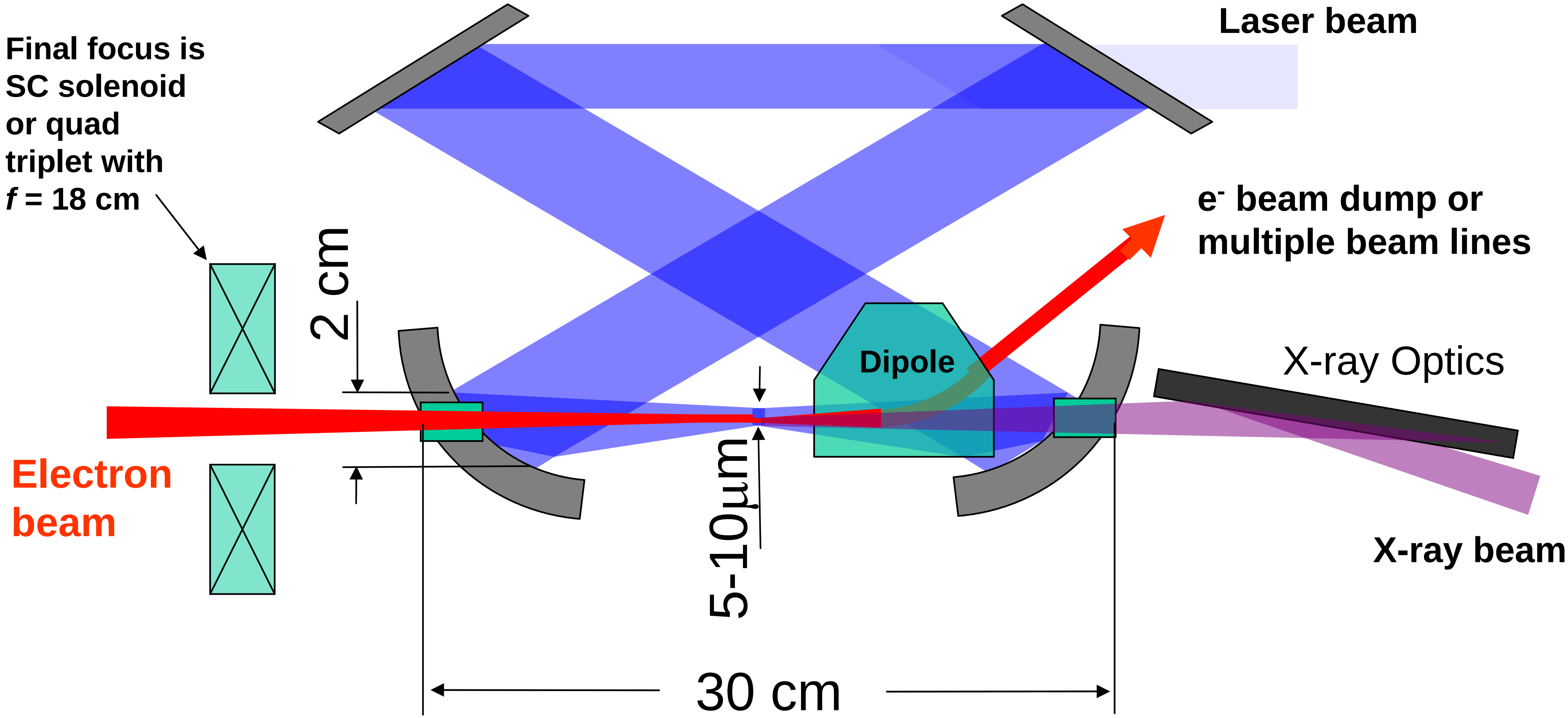
Developed by Rossendorf and DESY

Produced by ACCEL



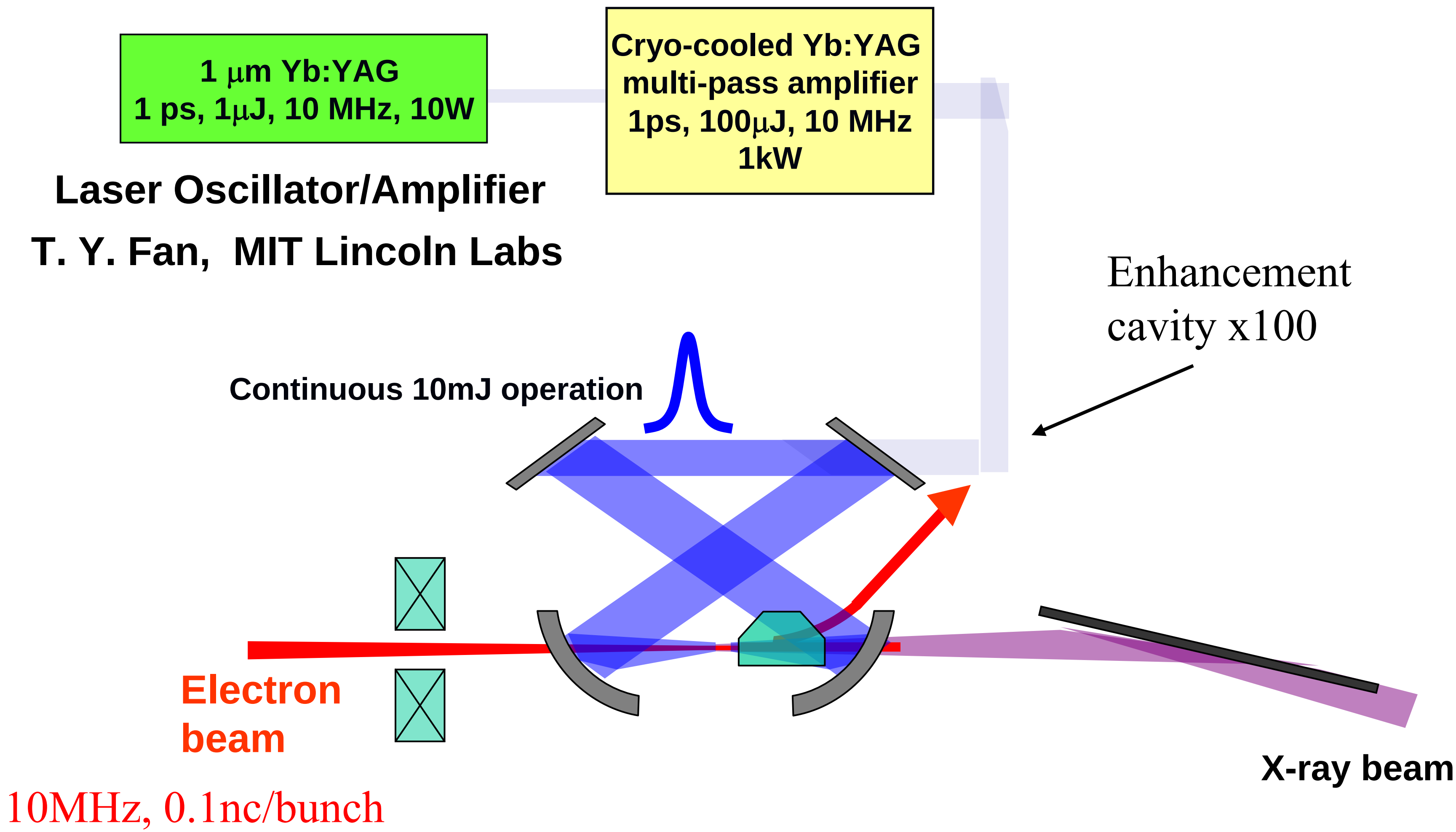
- Superconducting cryomodule containing 2 RF accelerating cavities.
- This module is used to reach a final electron beam energy of 15-50 MeV.

Interaction Region



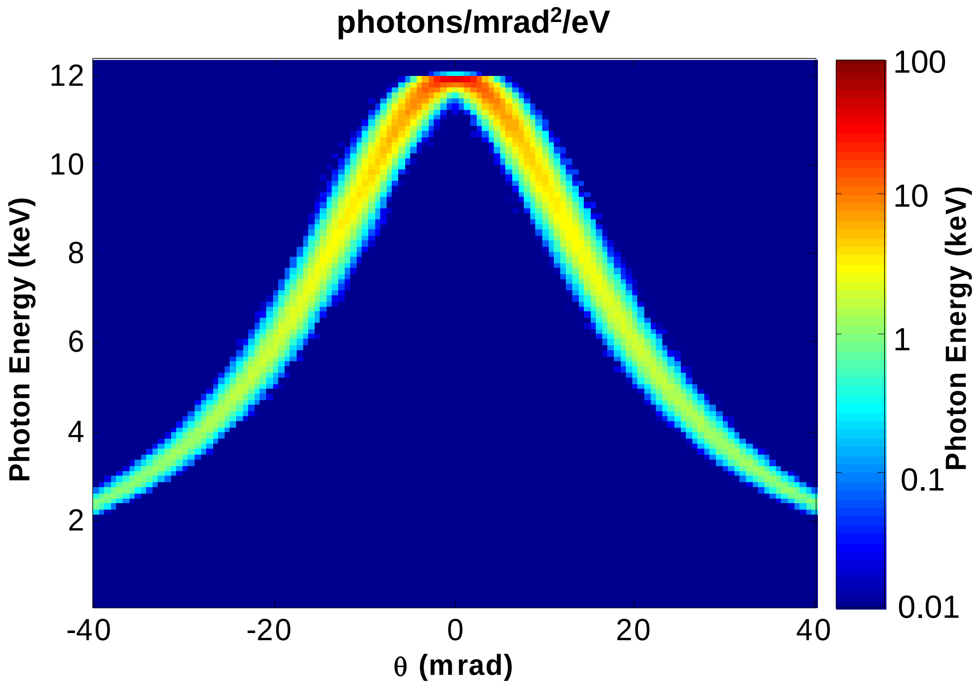
- Spot size on mirrors large enough to avoid damage: 5J/cm^2
- Holes in mirrors (1-2mm) for x-ray output and to avoid damage

High Repetition Rate, High Total Power Laser System For Large Time-Average Flux

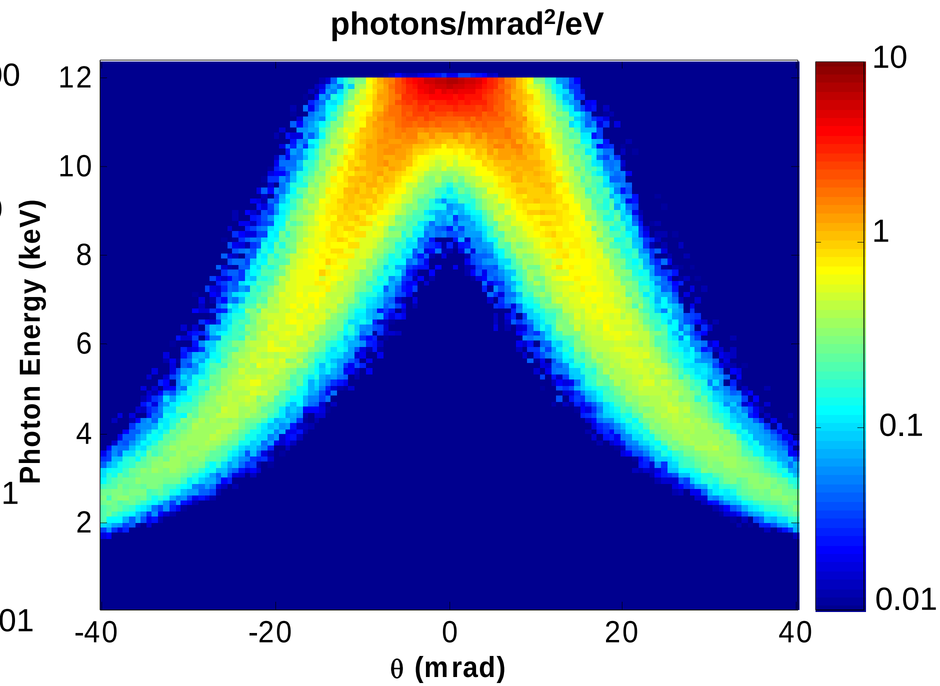


Angular Dependence of the Photon Spectrum

Normalized emittance = 0.3 μm

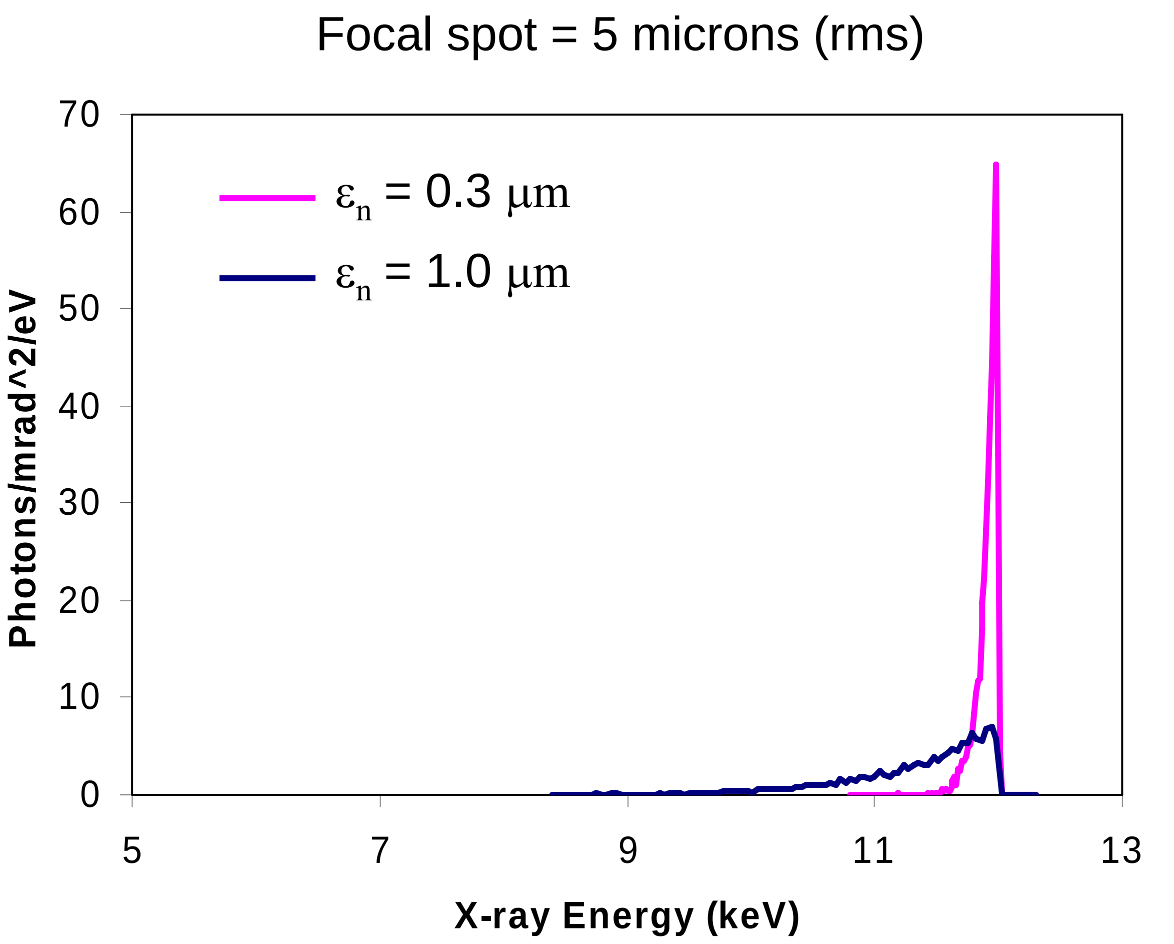


Normalized emittance = 1.0 μm



Note: Plane Perpendicular to Laser Polarization

Sensitivity to Electron Beam Emittance



Optimizing X-ray Flux and Brightness

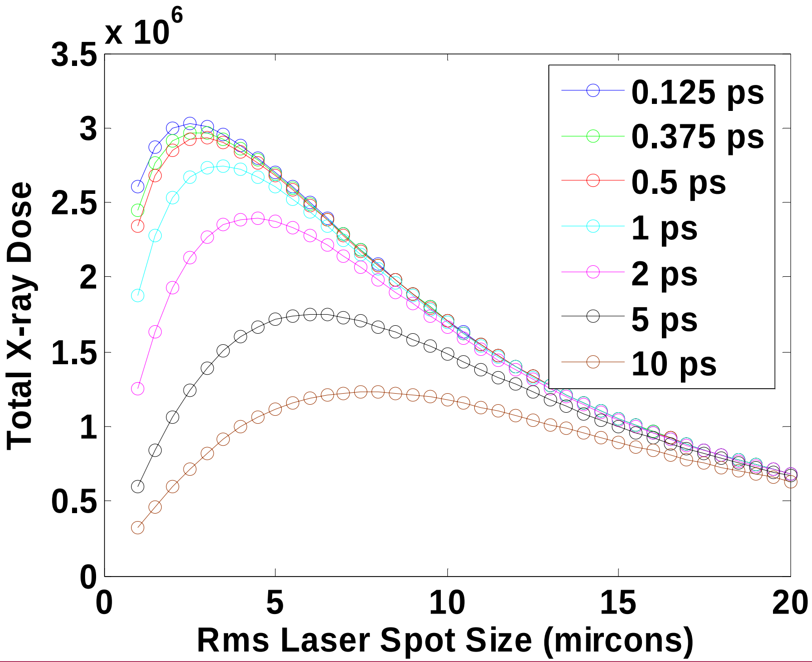
Electron Beam Parameters

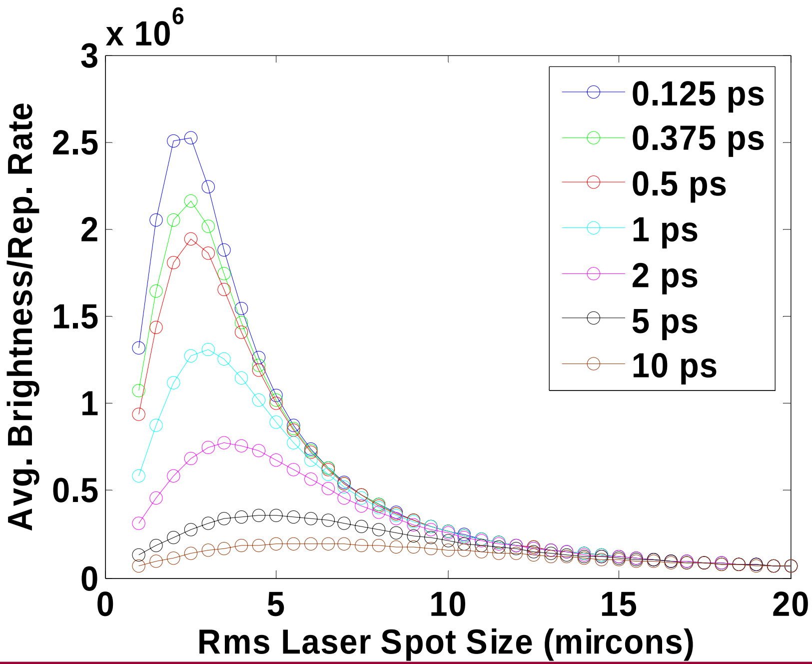
- ε_n = 1 mm-mrad (25 MeV)
- Rms spot size = 10 μm
- Q = 0.1 nC

Laser Parameters

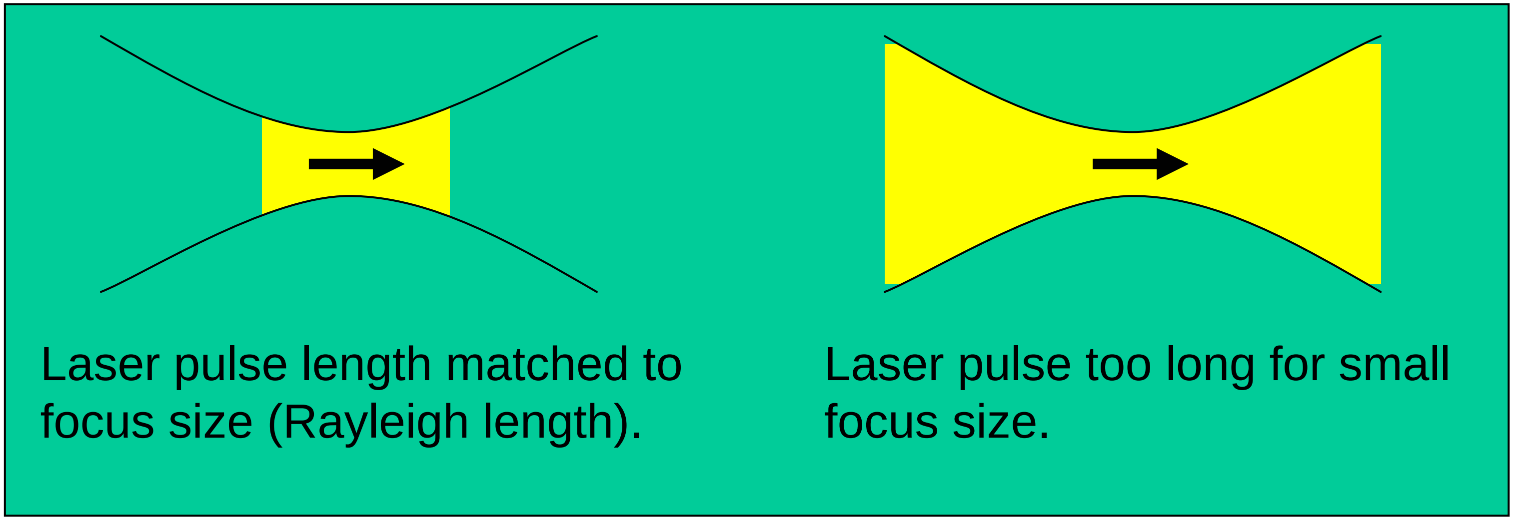
- λ = 1 μm
- W = 10 mJ
- Pulse duration = 0.5 ps

Performance vs. Laser Spot Size For Different Electron Bunch Durations





Matching Laser Pulse Length and Focus Size

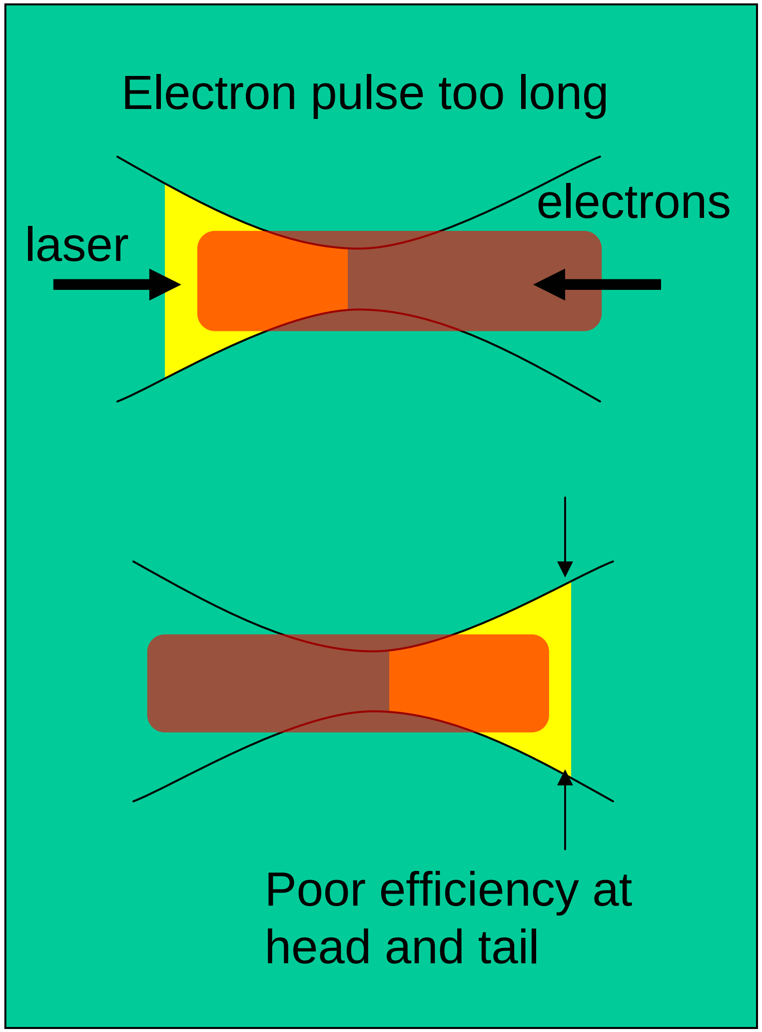


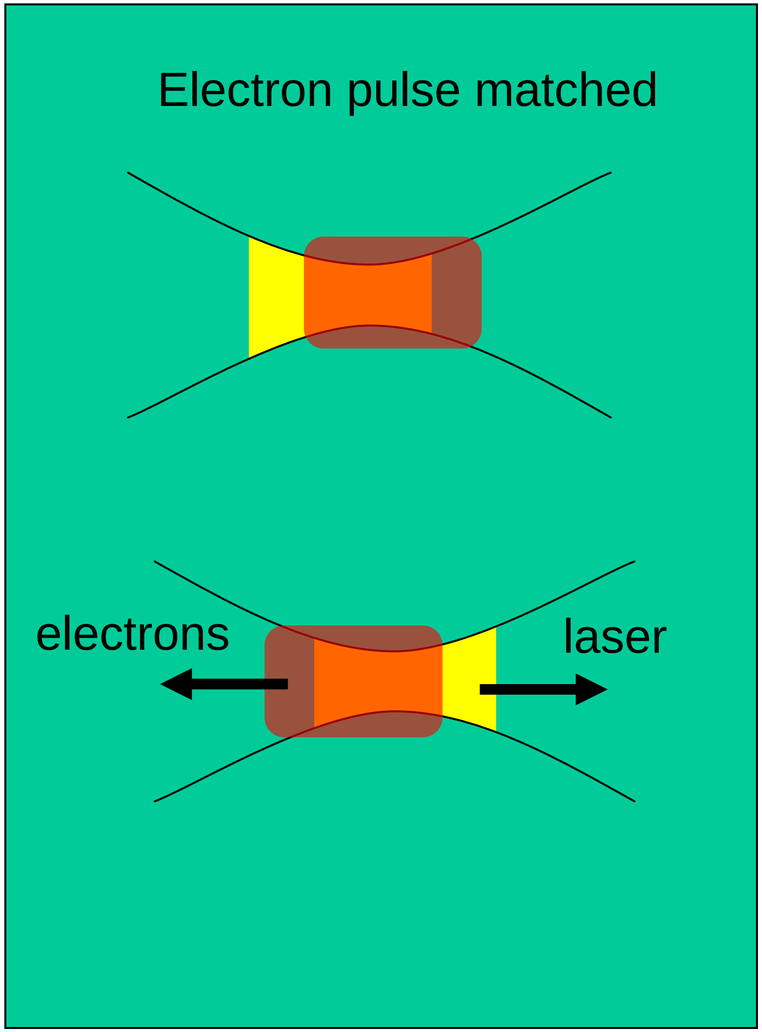
Laser pulse must be short compared to Rayleigh length so that whole pulse is focused simultaneously.

Laser may be shorter than Rayleigh length, but not so short that vector potential $a_0 \sim 1$.

Matching Electron Bunch Length to Laser Focus

Electron bunch length must be matched to Rayleigh length for best x-ray flux





X-ray Performance Depends on Electron Beam Focus

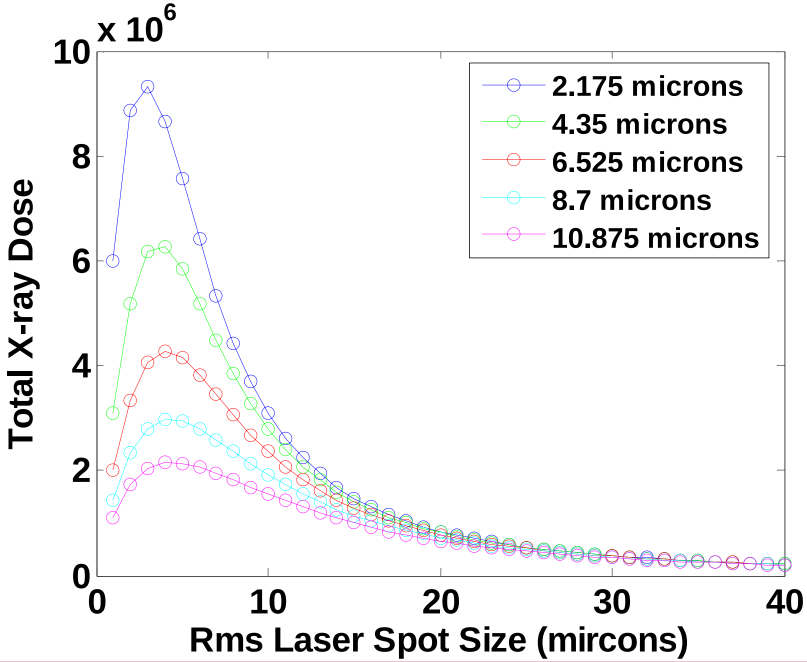
Electron Beam Parameters (25 MeV)

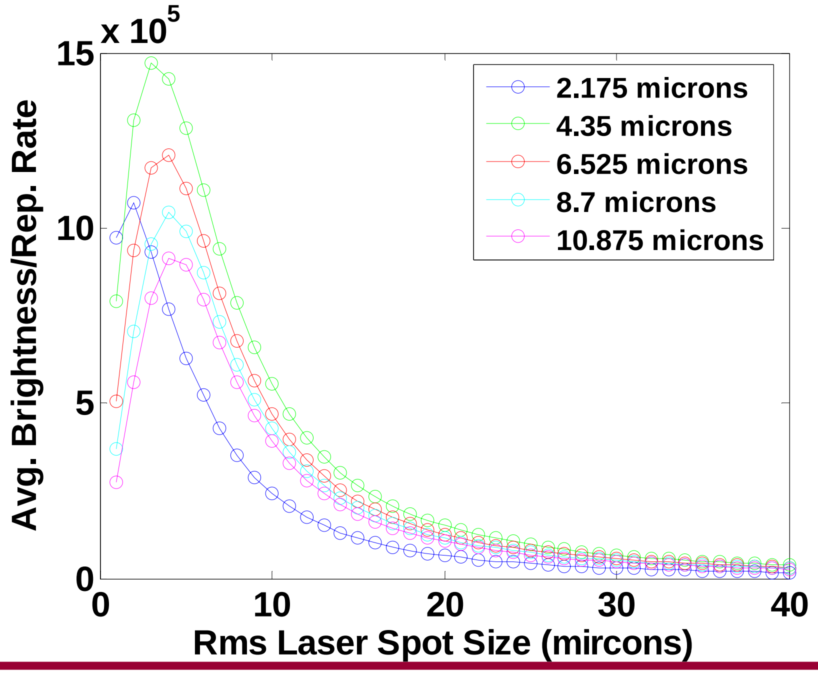
- Emittance = 0.68 mm-mrad
- Q = 0.1 nC
- Rms Duration = 2.1 ps
- Energy Spread = 0.01%

Laser Parameters

- λ = 1 μm
- W = 10 mJ
- Rms Duration = 0.5 ps

Performance vs. Laser Spot Size for Different Electron Beam Focus Sizes





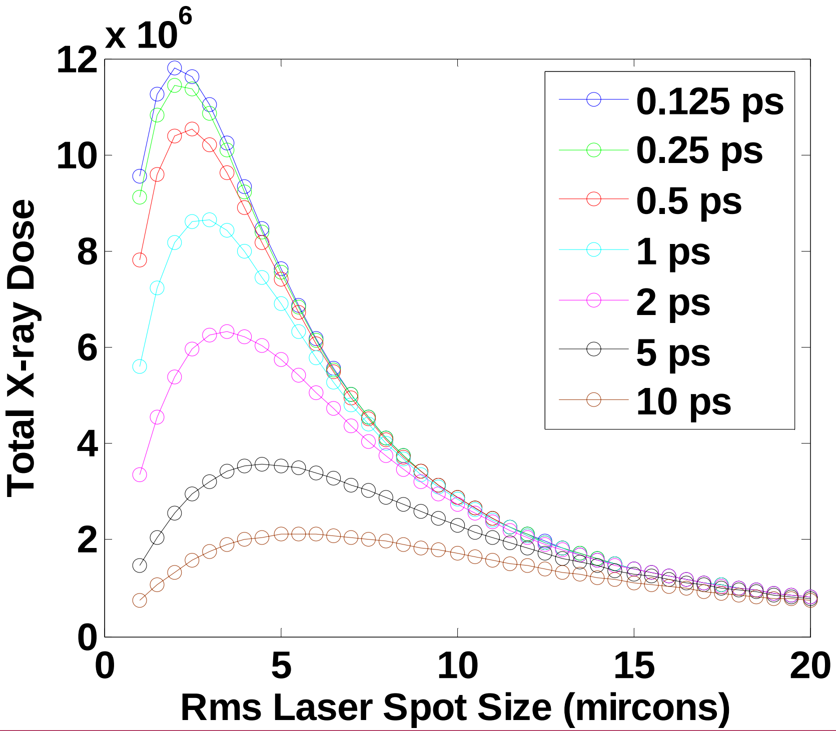
X-ray Performance Depends on Electron Bunch Duration

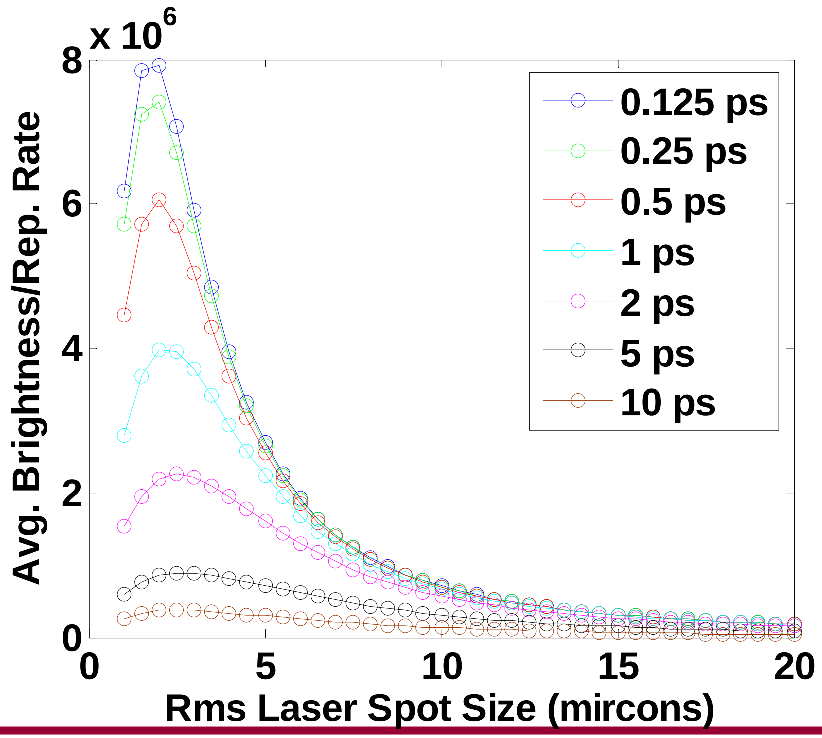
Electron Beam Parameters

- ε_n = 0.68 mm-mrad (25 MeV)
- Rms spot size = 4.3 μm
- Q = 0.1 nC

Laser Parameters

- λ = 1 μm
- W = 10 mJ
- Pulse duration = 0.5 ps





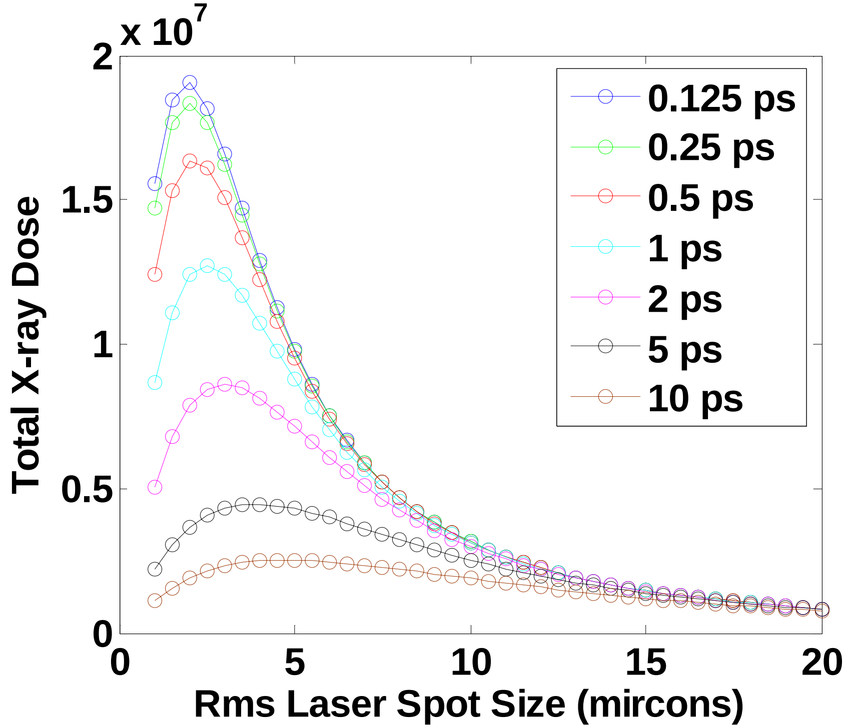
Performance Enhanced by Reduced Emittance

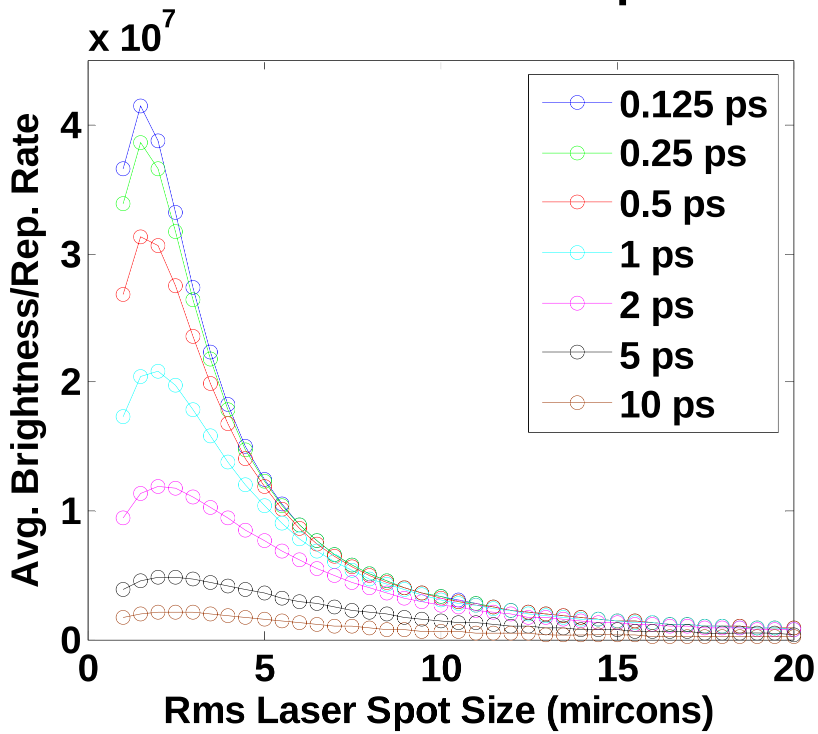
Electron Beam Parameters

- ε_n = 0.30 mm-mrad (25 MeV)
- Rms spot size = 2.9 μm
- Q = 0.1 nC

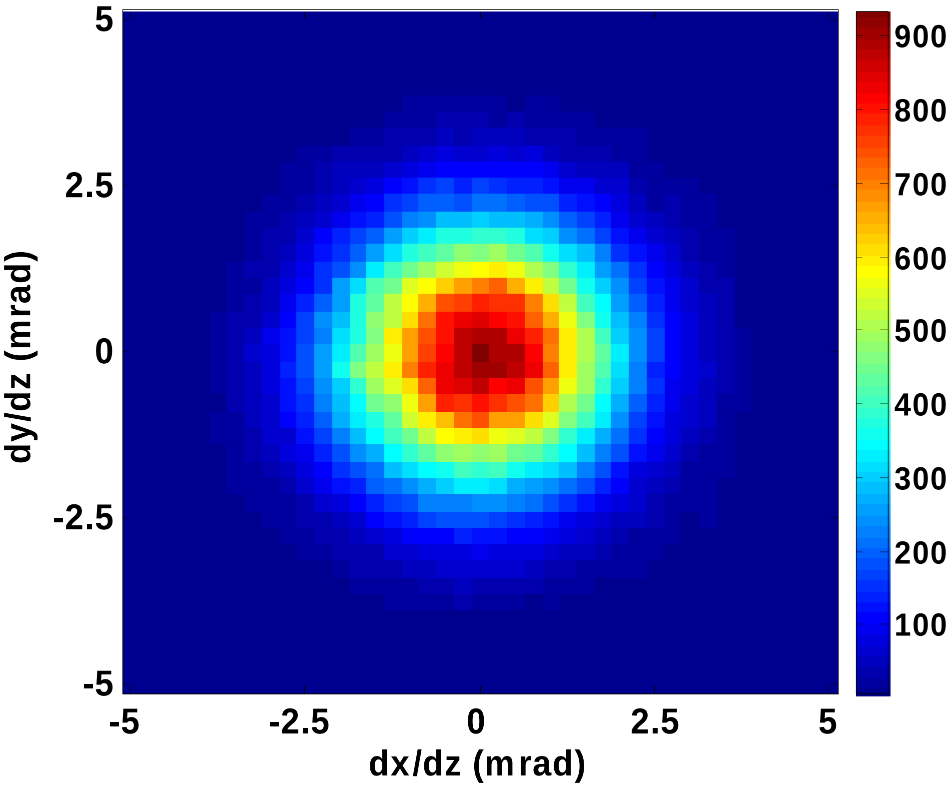
Laser Parameters

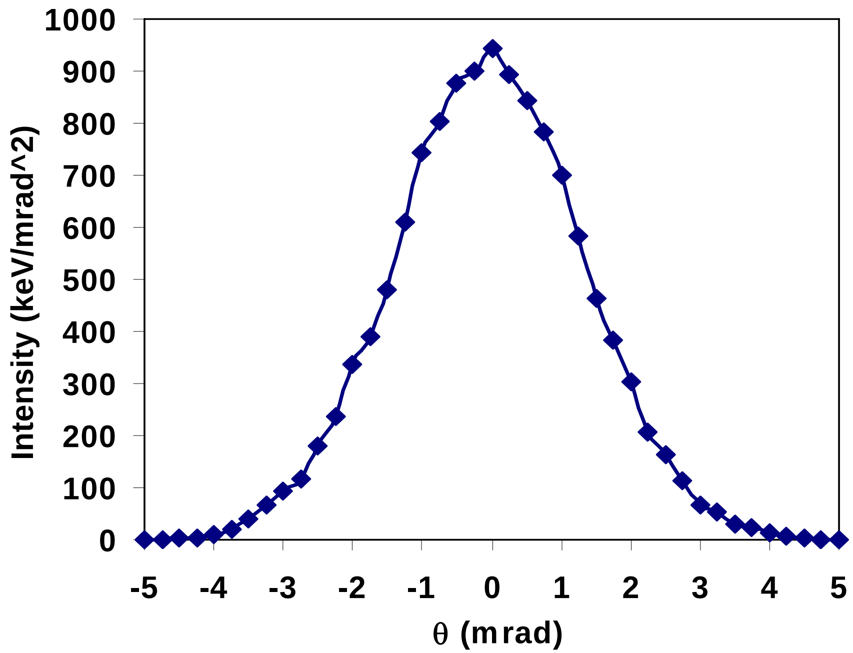
- λ = 1 μm
- W = 10 mJ
- Pulse duration = 0.5 ps





Intensity Profile of 12 keV X-rays With 0.01% Full Width Energy Filter





Photons/pulse = 900

Large Time-Average-Flux Performance

Photon energy [keV]	12
Total x-ray flux per pulse (5% BW)	5e5
Peak spectral density per pulse [photons/eV]	800
Repetition rate [MHz]	10
Average x-ray flux @ 10 MHz (5% BW)	5e12
Average x-ray flux @ 10 MHz (0.1% BW)	2e11
On-axis spectral width FWHM [keV]	0.1
Spectral width FWHM [keV]	0.6 (5%)
Avg on-axis brilliance [photons / (mm^2 $mrad^2$ sec 0.1%)]	6e14
Peak on-axis brilliance [photons / (mm^2 $mrad^2$ sec 0.1%)]	2e19
Pulse length FWHM [ps]	0.1 - 3
RMS size of source [μm]	4
RMS opening angle [mrad]	3.5

Applications

- Small Angle X-ray Scattering
  - Bandwidth of 5% is ideal for SAXS
  - 4 micron spot too small for most samples, and the few mrad divergence is too large, but…
  - Magnifying optics could reduce divergence to 100 μrad
  - Photons/sec of $>10^{12}$ possible into a 140 μm aperture
  - This is comparable to 2nd generation sources

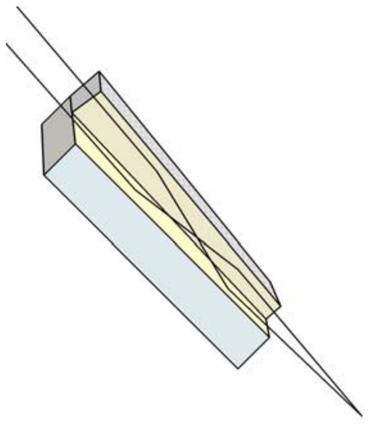
Focusing Optics for SAXS: Kirkpatrick-Baez Case

Magnification: 35

Beam size
source: 4 microns (rms)
focus: 140 microns

Divergence
source: 3.5 mrad (rms)
focus: 100 micro-rad

Distance to focus: 7 meters
(assuming mirrors are 20 cm from source)



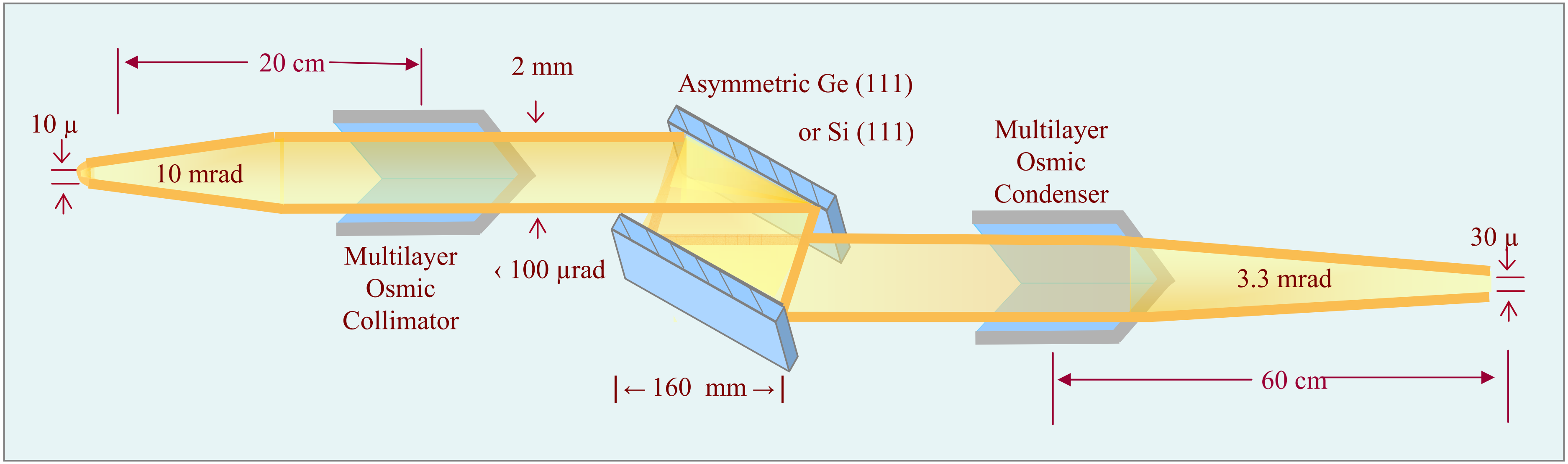
Courtesy of Gene Ice

Applications

- Protein Crystallography
  - Rigaku FR-E produces 4×10^{9} ph/sec (Cu–Kα) in a 0.3 mm aperture and is useful for ~100 µm crystals
  - 10 µm crystals are much more readily produced but not measurable with the FR-E
  - With ideal optics, the ICS source produces 4×10^{11} ph/sec in a 0.03 mm aperture allowing 10 µm crystal data to be taken
  - The diffraction intensity and quality will be similar to the FR-E/100 µm crystal case if optics are >10% efficient
  - This flux is smaller than an APS undulator by up to 2 orders of magnitude, but comparable to 2nd generation sources
  - Also, the ICS is tunable allowing MAD analysis

Protein Crystallography for Small Crystals with Fixed Wavelength and MAD

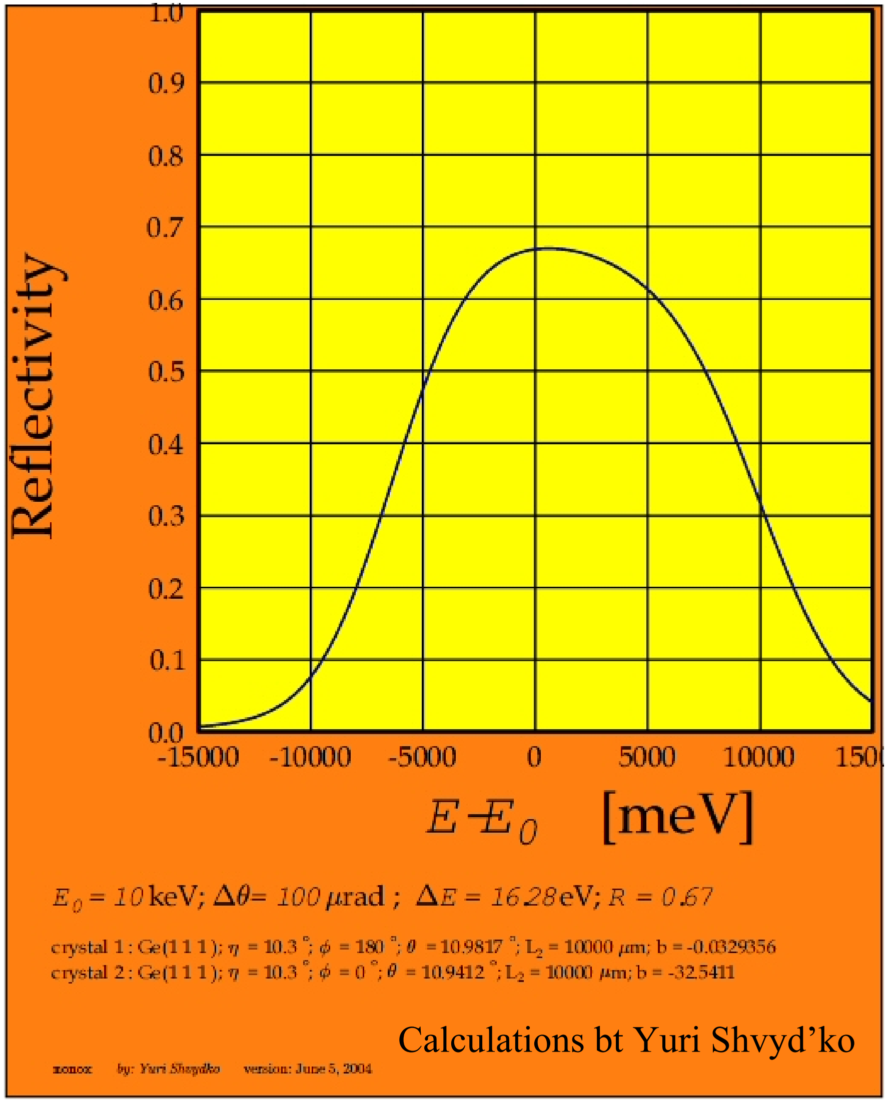
- Goal: Achieve ICS images with 10 µm crystals of equal or better quality compared to FR-E with 100 µm crystals.



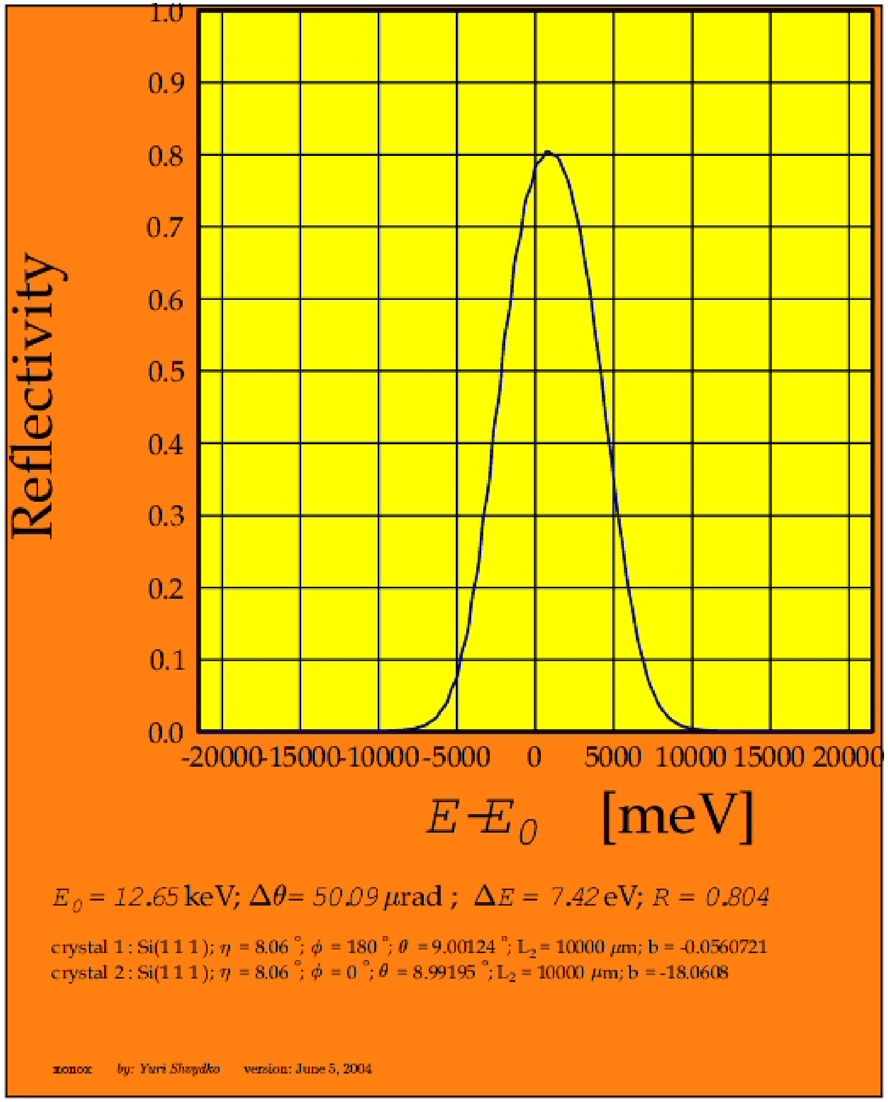
Fixed Wavelength: Ge(111); $\Delta E = 16$ eV; $R = 67\%$

MAD: Si (111); $\Delta E = 7$ eV; $R = 80\%$

Fixed Wavelength Asymm Ge(111)



MAD Asymm Si(111)



Photon Flux Calculation

- Fixed Wavelength—Ge(111)
  - 800 p/sec/eV
  - 10 MHz
  - 16.28 eV bandwidth
  - Reflectivity of monochromator 0.67
  - Reflectivity of multilayers $(0.85)^3$

$I = 5.35 \times 10^{10}$ p/sec

- MAD—Si(111)
  - 800 p/sec/eV
  - 10 MHz
  - 7.42 eV bandwidth
  - Reflectivity of monochromator 0.80
  - Reflectivity of multilayers $(0.85)^3$

$I = 2.92 \times 10^{10}$ p/sec

Applications

- Medical Imaging
  - Improved absorption images
  - Tuning to specific wavelengths
  - Phase contrast method
  - Optics considerations

Applications

- Medical Imaging—Improved Absorption Images
  - Current radiographs use 5-75 keV Bremstahlung spectrum
  - Low energy range causes skin dose, no contrast
  - High portion cause tissue dose with low contrast
  - Only the range of energies around 30 keV useful
  - ICS spectrum is ideal at 30 keV with 5-15% bandwidth
  - Image quality improved and dose reduced
  - We would establish collaboration with local radiologists to further study these factors in detail
- Medical Imaging—Tuning to specific wavelengths
  - Iodine contrast agent for blood imaging
  - Gadolinium-based cancer therapy

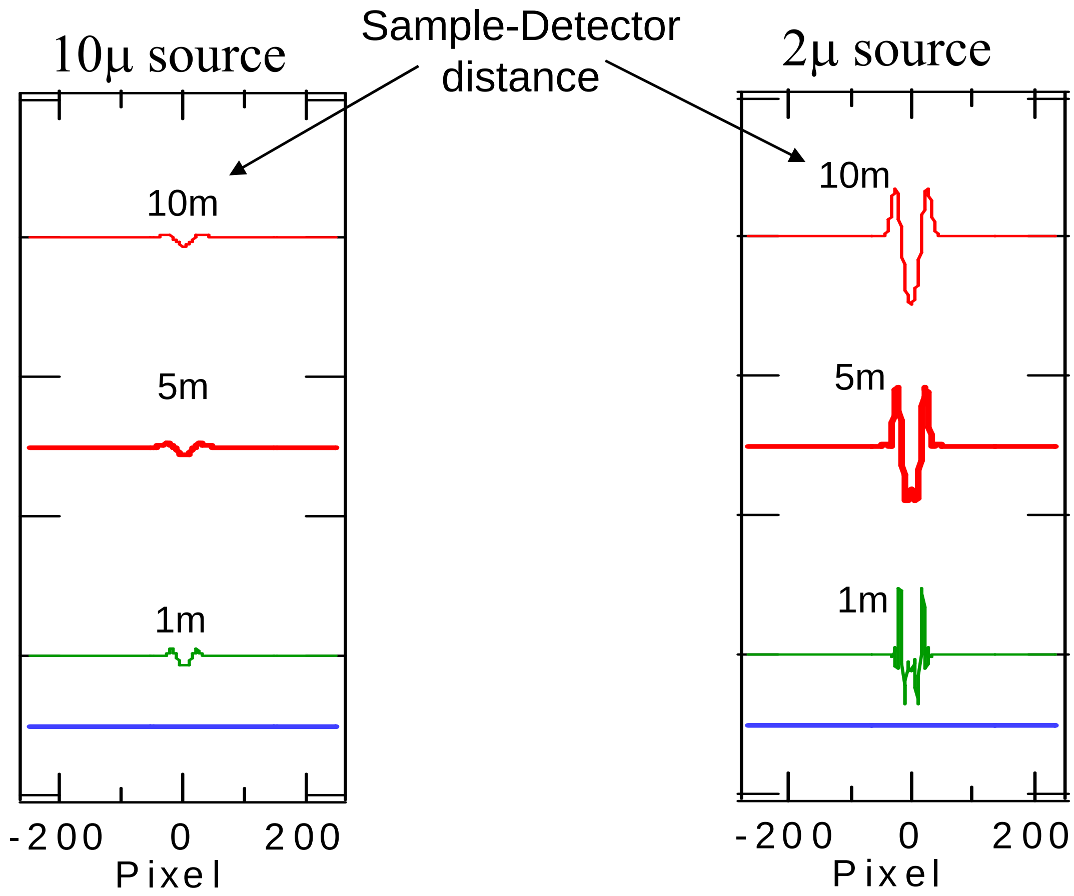
Applications

- Medical Imaging—Phase Contrast Method
  - Few micron circular source is ideal
  - Many milli-radian divergence illuminates large objects in short distance
  - Few percent bandwidth can be fully utilized and presents no limitation
  - Would improve medical imaging for soft tissue while reducing dose
  - Could also utilize the single-shot mode for time-resolved images
  - Simplest approach requires no optics
  - But optics could reduce spot size, increase coherence, and increase illuminated area

Phase Contrast Imaging 1D Simulations: Source Size Matters

Sample:
20μ dia C fiber

Source: 31 keV
@ 1 m from sample

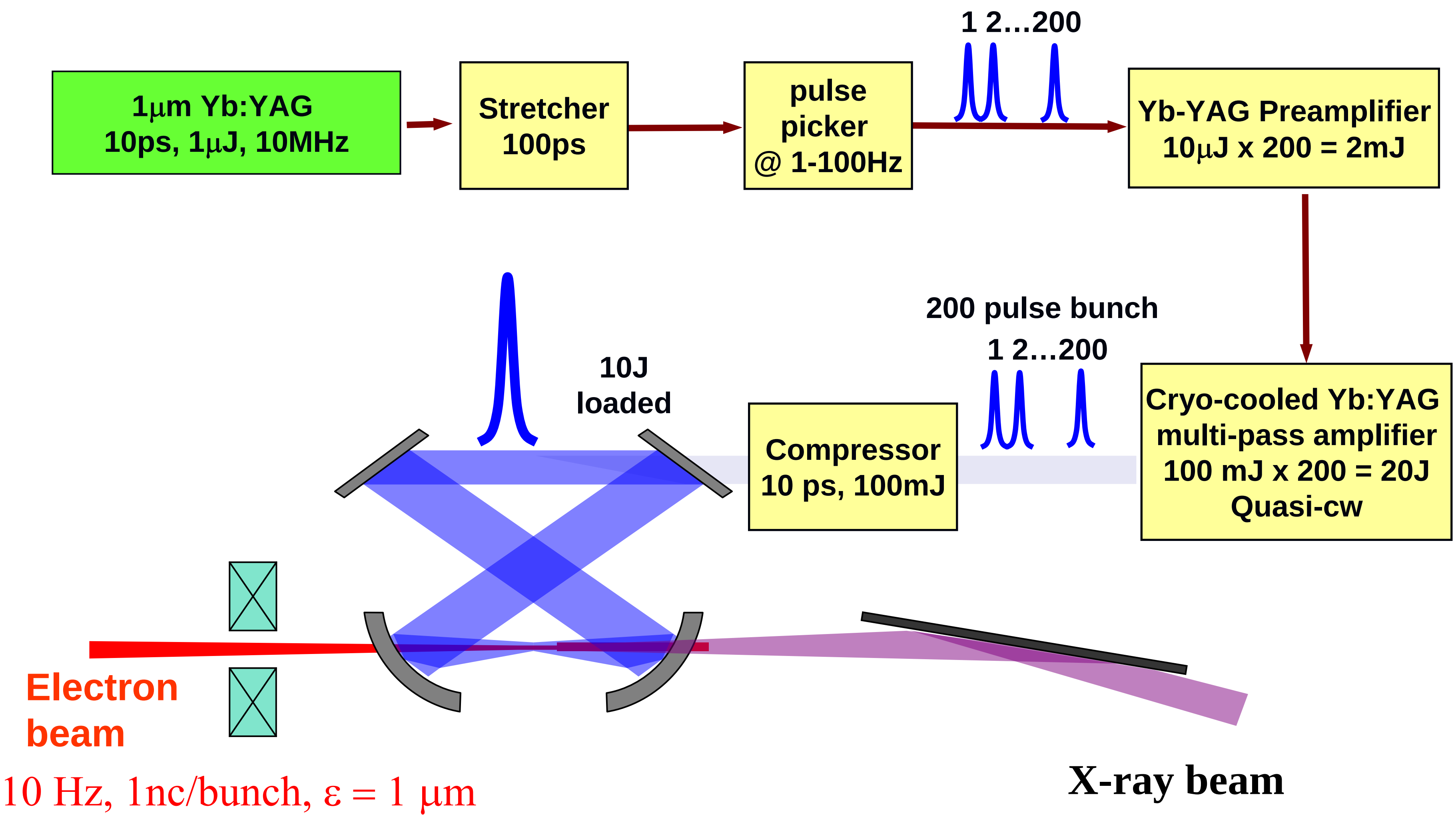


Courtesy of Wah Keat Lee, ANL

Science Opportunities

- Pico-second Science
  - Synchrotron sources have 50-100 ps pulse lengths
  - ICS source may have pulse lengths down to 100 fs
  - At 1 ps the single-shot flux could be 10^{10} photons in a 6% bandwidth
  - Large bandwidths are appropriate for Laue method as pioneered by Wulff and co-workers at ESRF
  - ICS could be run in a kHz mode for repetitive experiments
  - Both diffraction and PC imaging modes possible
  - Flux exceeds plasma sources by many orders of magnitude
  - Flux similar to APS RF chirp concept and exceeds SPPS performance

Low Repetition Rate, High Pulse Power Laser System For High Flux Per Pulse

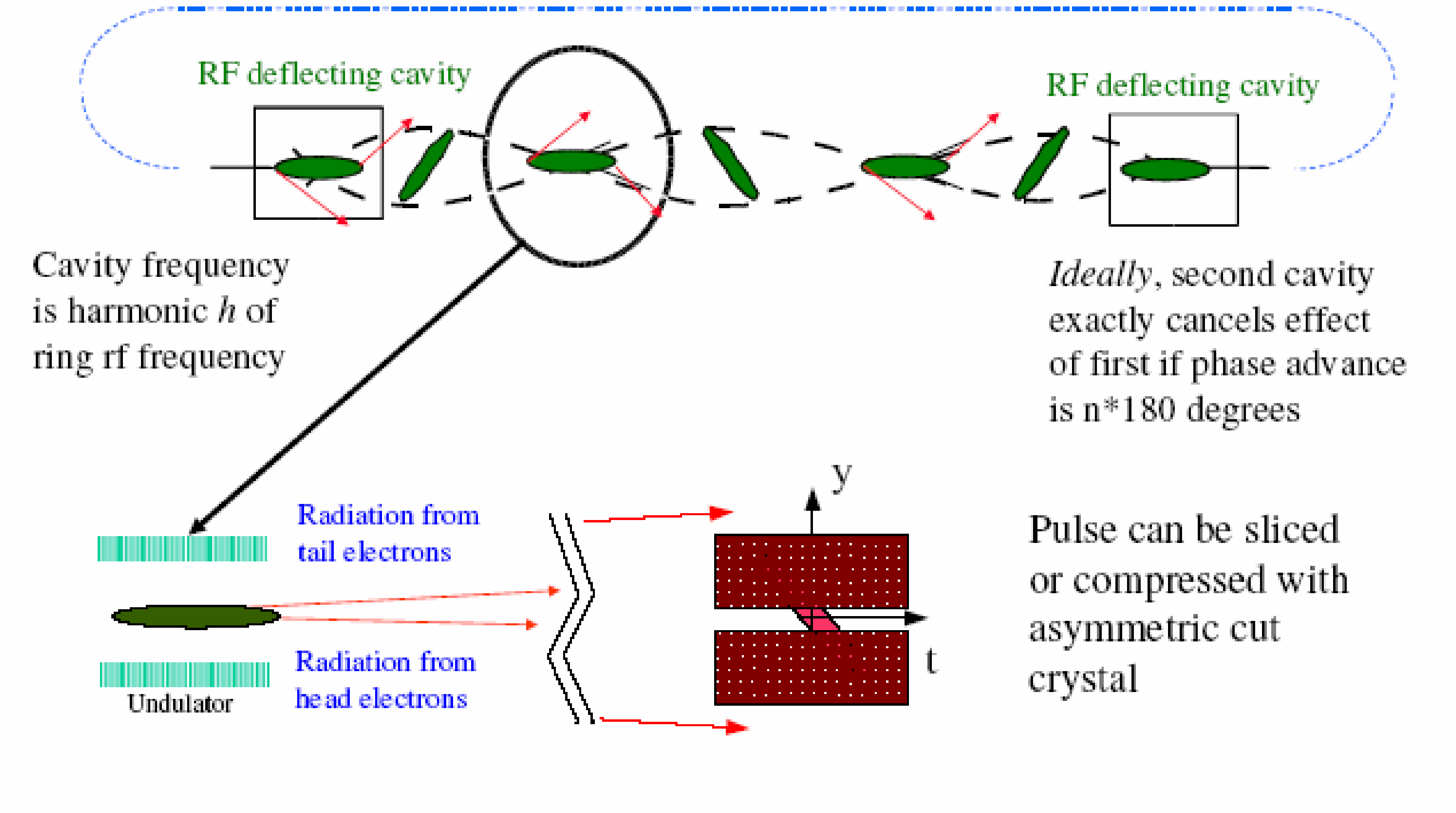


High Flux-Per-Pulse Performance

Photon energy [keV]	12
Total x-ray flux per pulse (17% BW)	4e9
Peak spectral density per pulse [photons/eV]	2e6
Repetition rate [Hz]	10
Average x-ray flux @ 10 Hz [photons/sec] (17% BW)	4e10
On-axis spectral width FWHM [keV]	0.2
Spectral width FWHM [keV]	2 (17%)
Average brilliance [photons / (mm^2 $mrad^2$ sec 0.1%)]	1.4e10
Peak brilliance [photons / (mm^2 $mrad^2$ sec 0.1%)]	1.4e20
Pulse length FWHM [ps]	9
Size of source RMS [μm]	7
Opening angle RMS [mrad]	7

Results from 3D-code of W. Brown, MIT Lincoln Lab

APS RF Chirp Concept for Pico-second Pulses



Conceived by A. Zholents and applied at APS by M. Borland

APS RF Chirp Concept

Performance Expected

- Pulse duration: 1.5 ps
- Compression efficiency: 15%
- Flux: 10^8 photons per pulse (1% bandwidth)

Compare with ICS: $4\text{x}10^9$ in 17% bandwidth, 9 ps

SPPS (Stanford)

Actual Performance

- Pulse duration: 80 fs
- Flux: 2 x 10^6 photons per pulse (1.5% bandwidth)

Technical Challenges

- Electron beam
  - SC gun: high charge and rep rate (10-100 amp peak, 1milli-amp average)
  - Low emittance, high stability, repeatability
  - Focussing optics (5microns or less)
- Laser beam
  - 1 kW average power
  - x100 enhancement cavity
  - Mirrors
  - Stability
- Timing
  - 100 fs
- X-ray Optics
  - Large collection angles
- Other
  - Refrigerator
  - Photoinjector drive laser

Conclusions

- Linac-driven compact sources can outperform laboratory rotating anode sources by 10^3 in flux and 10^6 in brilliance, and they are tunable
- Linac-driven sources also have advantages of small focal spot and short pulse duration over synchrotrons
- Protein crystallography, SAXS, phase contrast imaging, and pico-second science are major applications and business opportunities