Compact X-ray Sources: Addressing the Limitations of Large User Facilities

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Motivation for Compact X-ray Light Sources

- X-rays are the light which enables us to see deep into natural and man-made materials, into manufactured components, and of course into the human body, with the ability to determine structural details down to the atomic level.

?

- Emerging technology based on inverse Compton scattering is enabling much brighter x-ray beams to be available from laboratory-scale systems, opening up a remarkable array of new applications.

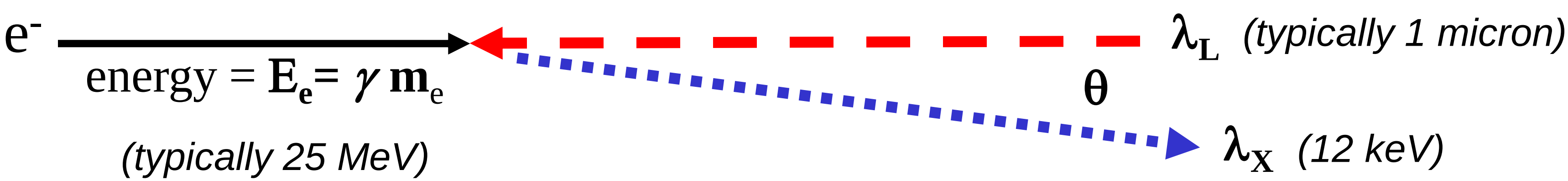
Applications Requiring Compact Sources

- QA on the semiconductor fab line
- Medical phase-contrast imaging
- X-ray studies in high magnetic field
- Studies of extremely precious cultural heritage objects
- Instant turnaround for structure-based drug design
- Studies of highly pathogenic samples such as viruses
- Simultaneous neutron and x-ray studies
- Studies of highly radioactive nuclear materials and fuels
- Providing high-brilliance x-rays in nano-centers not at a synchrotron
- Training of students in preparation for use of major XFELs
- Additional capacity for ps time resolved experiments

The Technical Opportunity

Inverse Compton Scattering (ICS)

- Head-on collision between a relativistic electron and a photon



- Normal Compton scattering the photon has higher energy than the electron
- The inverse process has the Thomson cross-section when $\hbar\omega_X < E_e$
- 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 $1/\gamma$

ICS Demonstration Experiments with Linacs

Laboratory	Geometry	Energy	Rep. Rate	Photons/pulse
LBNL	90^0	30 keV	2 Hz	10^4-10^5
BNL	180^0	6 keV	< 1 Hz	10^7-10^8
LLNL (PLEIADES)	180^0	40-140 keV	10 Hz	10^7
NRL	180^0	0.4 keV	?	10^7(macro-pulse)
Vanderbilt Univ.	180^0	10-50 keV	0.01 Hz	10^9-10^{10} **
Univ. Tokyo, UTNL*	180^0	40 keV	?	10^9(macro-pulse)
LLNL(T-REX)	180^0	0.1-1 MeV	10 Hz	10^9

*** Under Development**

**** Design value**

Matching Laser Pulse Length and Focus Size

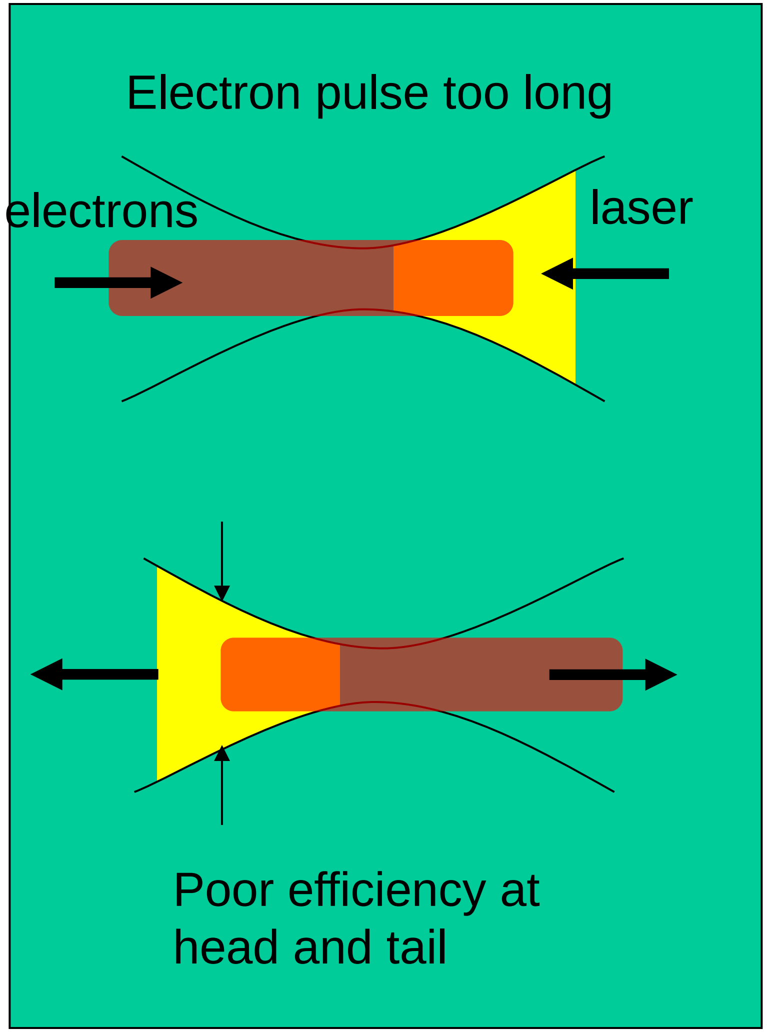
Laser pulse length matched to focus size (Rayleigh length).

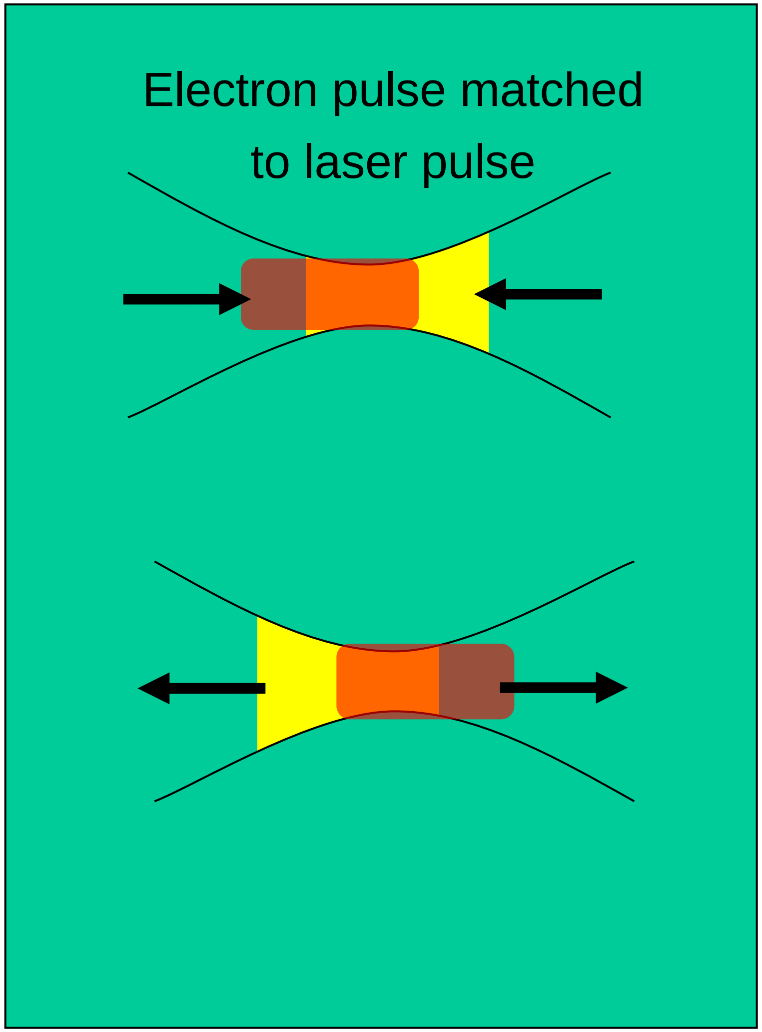
Laser pulse too long for small focus size.

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

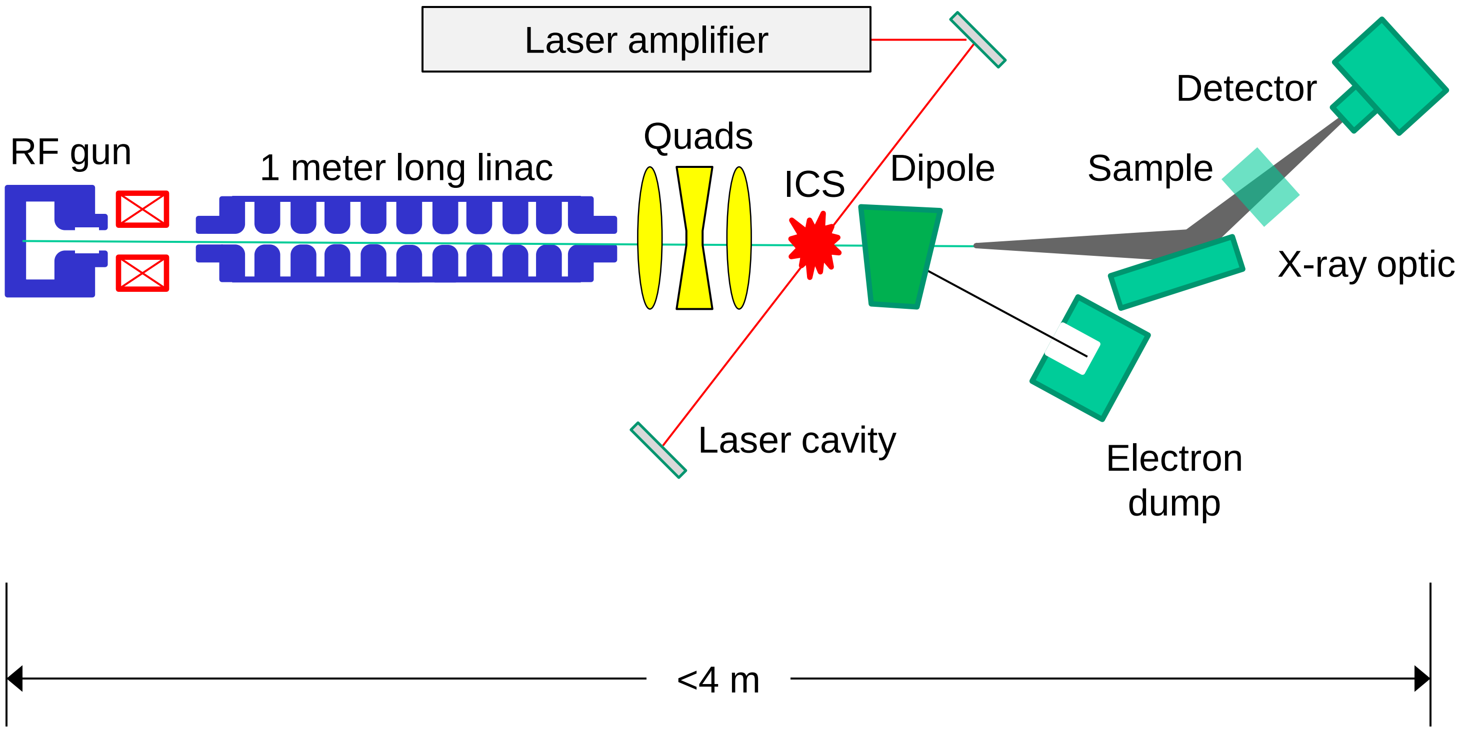
Laser may be shorter than Rayleigh length, but less than 0.5 ps is not practical, and could lead to non-linear effects.

Electron Bunch Length Matched to Rayleigh Length





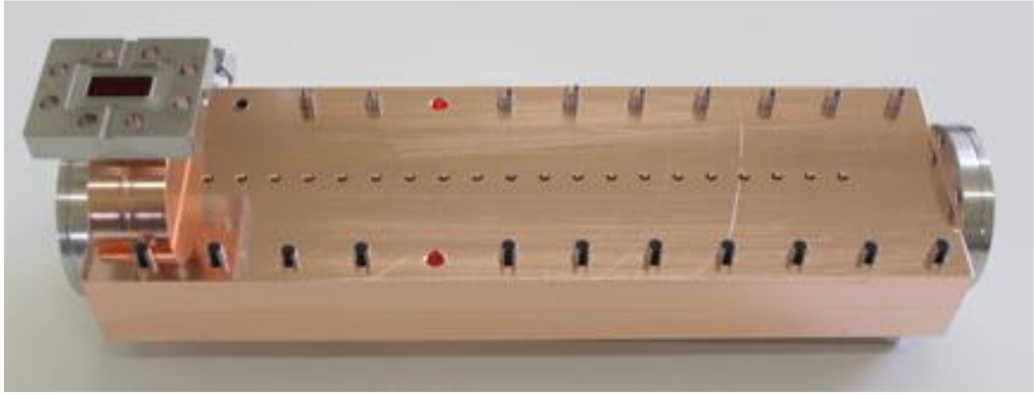
Basic Layout for ICS



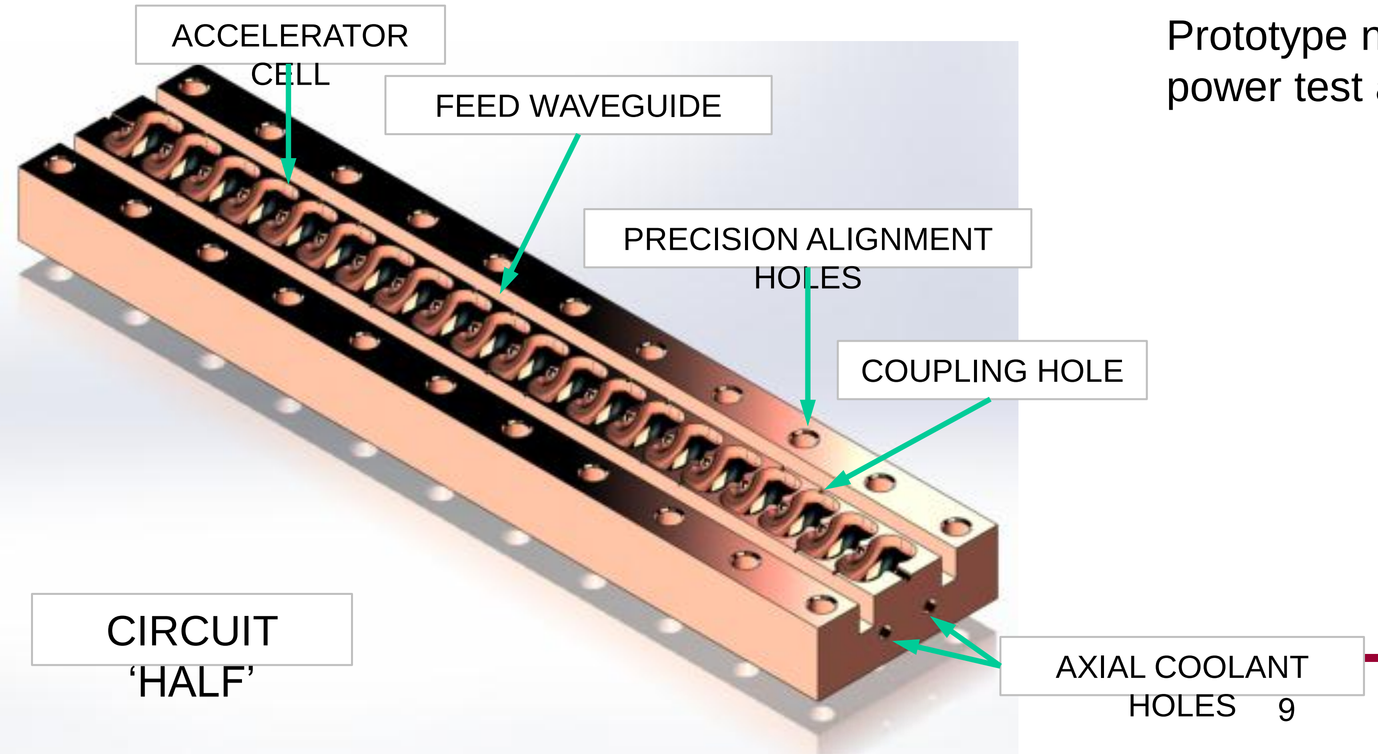
Novel 9.3 GHz (x-band) Linac Structure

S. Tantawi, SLAC

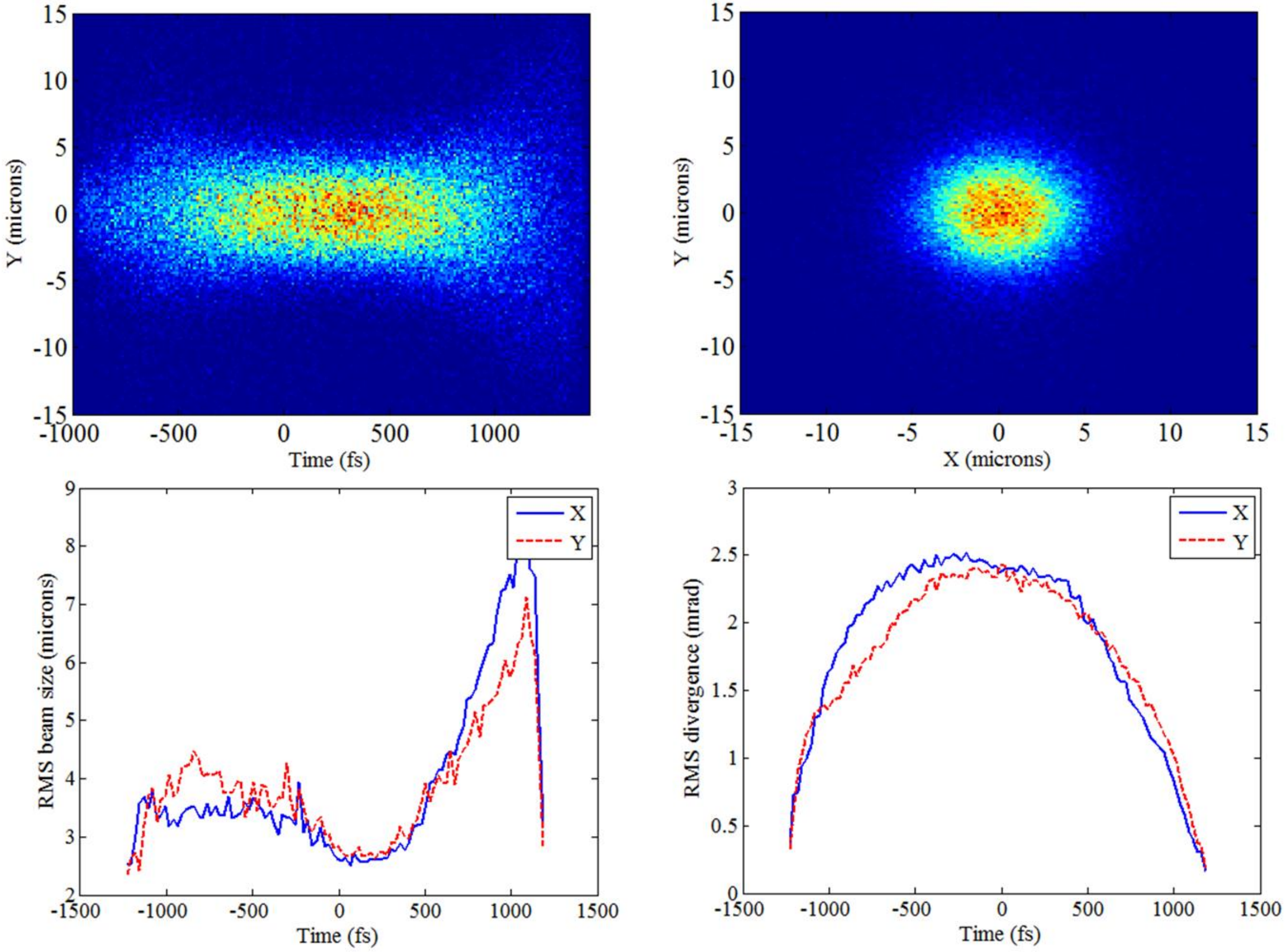
- Very high efficiency standing wave structure at 9.3 GHz
- 1 kHz rep rate
- Every cell coupled from waveguide
- Inexpensive to build



Prototype now under high power test at SLAC



Electron Beam at IP



Laser Systems

ICS Laser

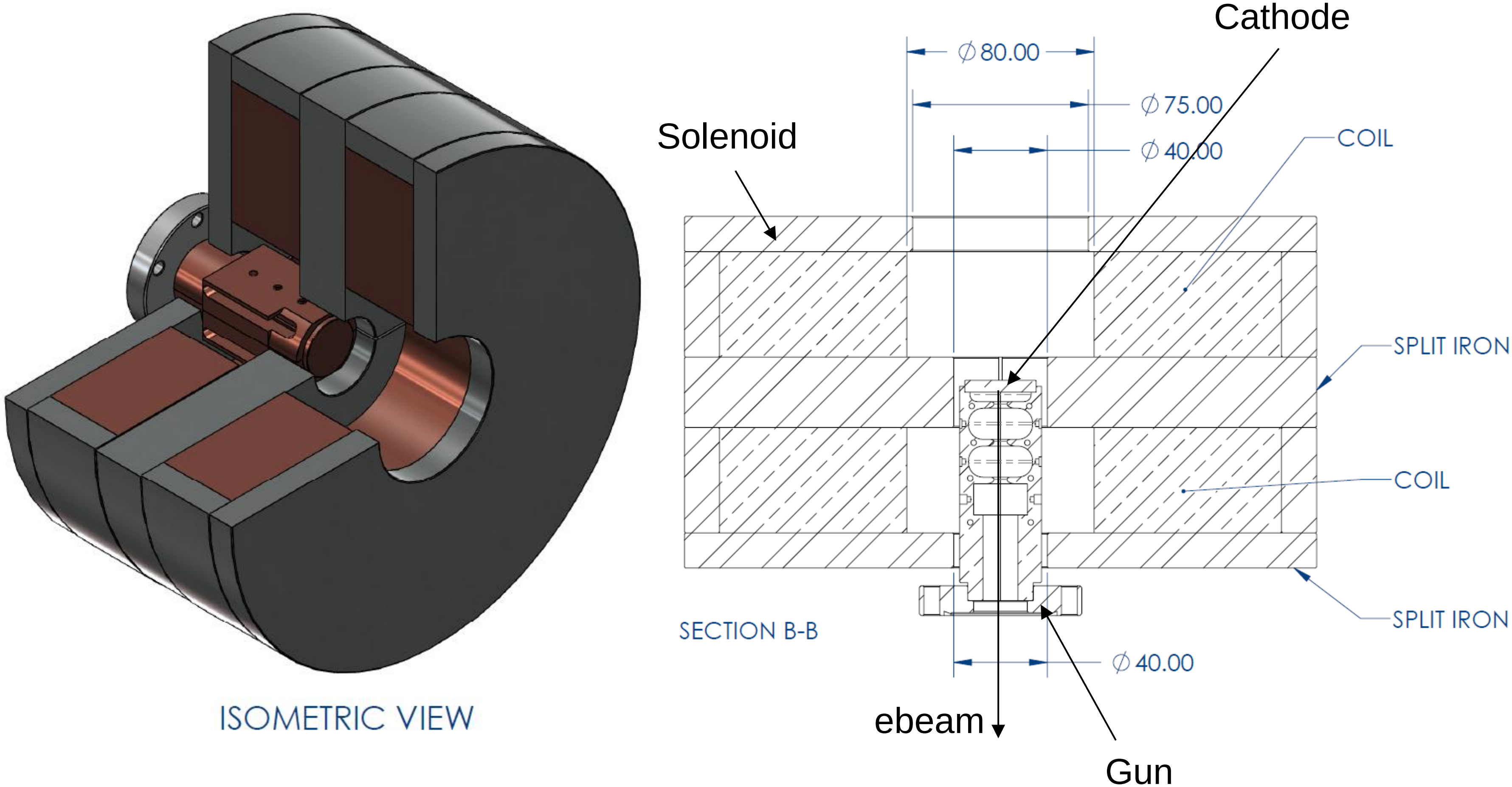
200 mJ, 1.9 ps, 1 kHz Yb:YAG

Photocathode Laser

1 mJ, 190 fs, 1 kHz Yb:KGW

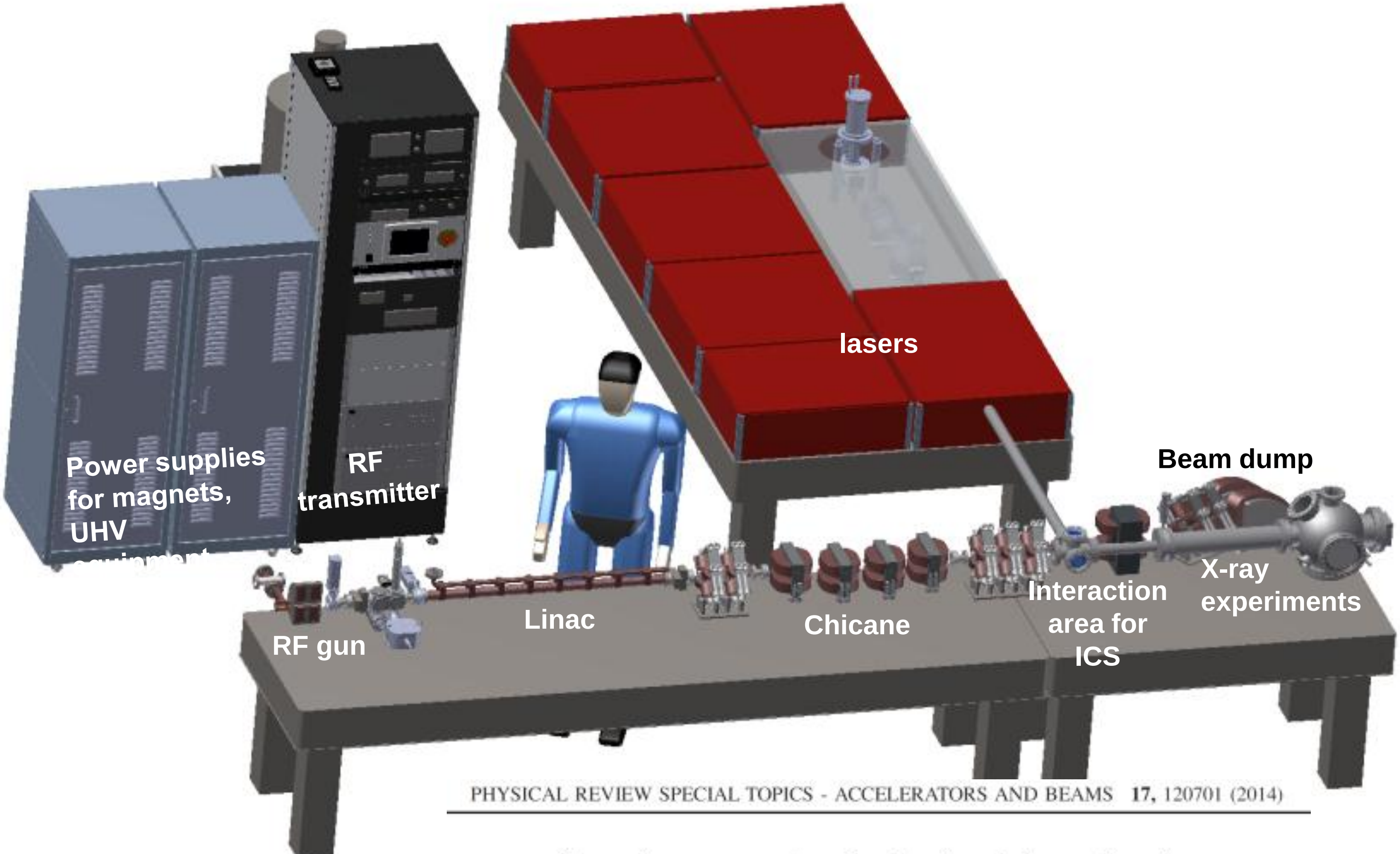
9.3 GHz RF photoinjector

Dolgashev (SLAC), Borchard (Dymenso), Graves



“Disposable” photoinjector. Inexpensive and easily replaced.

Compact X-ray Source Layout



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 120701 (2014)

Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz

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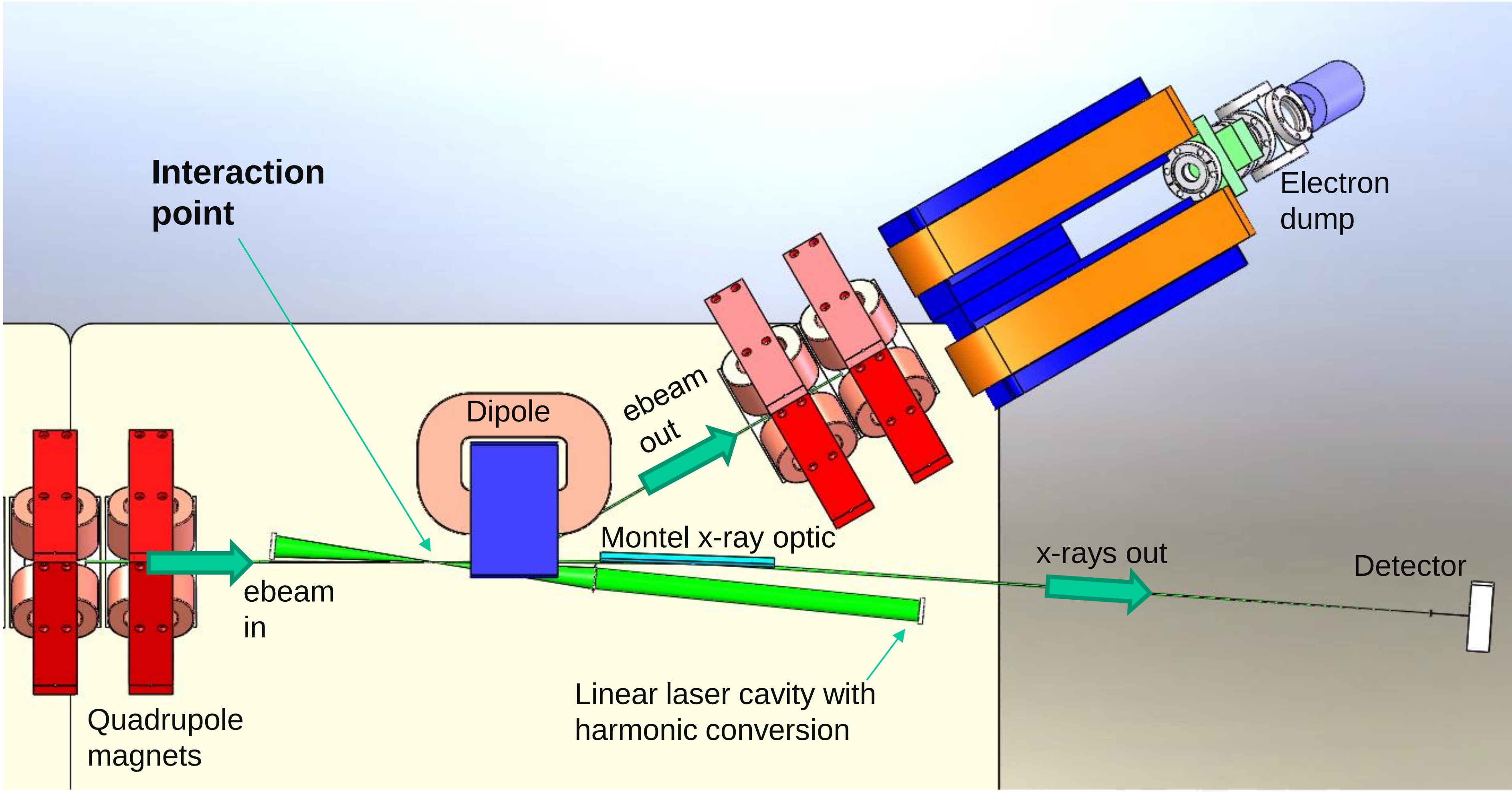
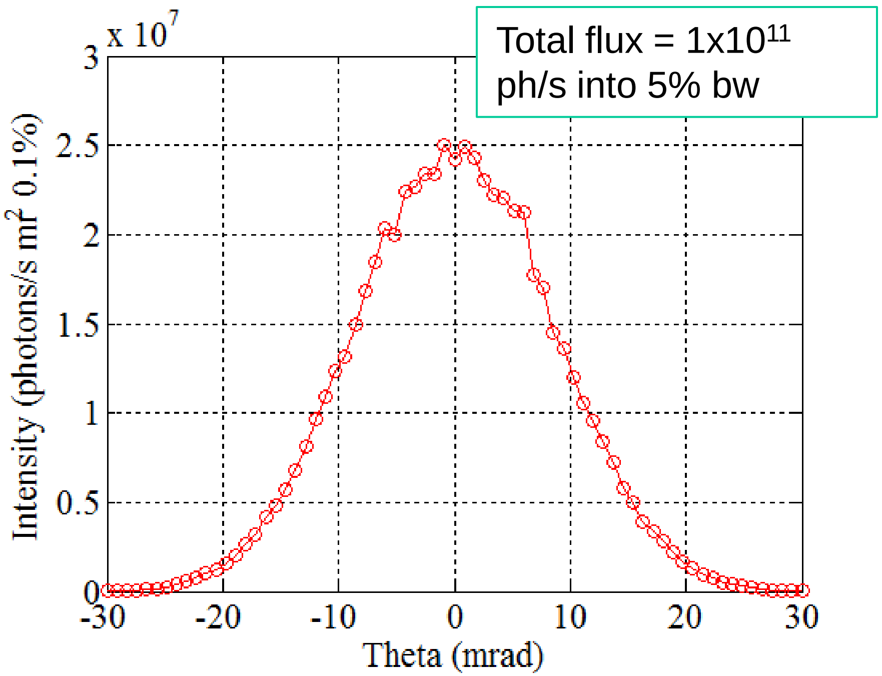
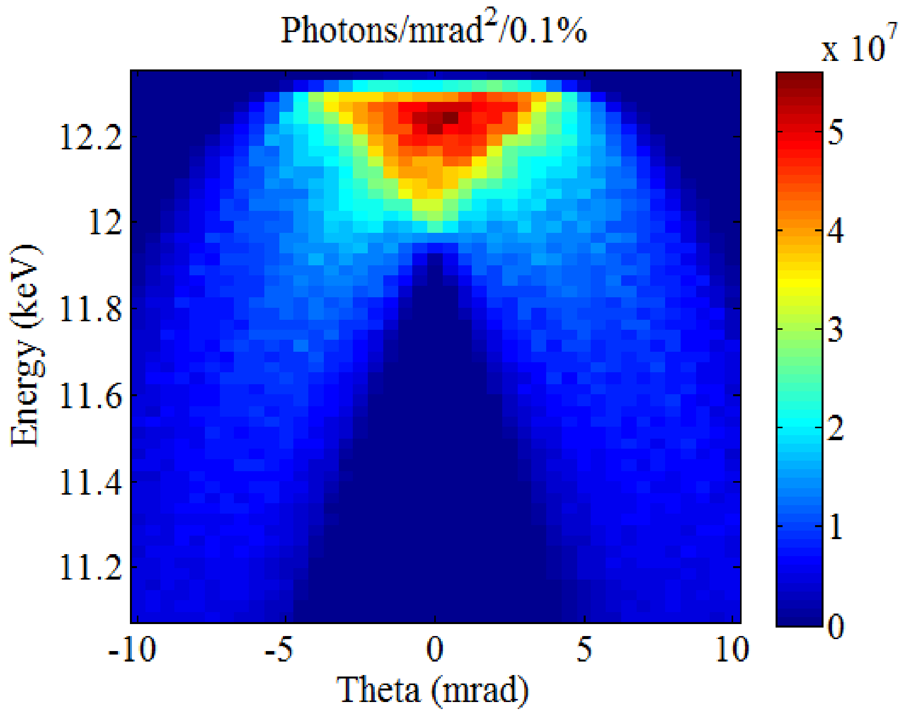
ICS Interaction Point (IP)



X-ray Performance for 12.4 keV

Note: e-beam energy is 17.8 MeV





Photon intensity vs emission angle.

Photons at large angle are lower energy than on-axis.

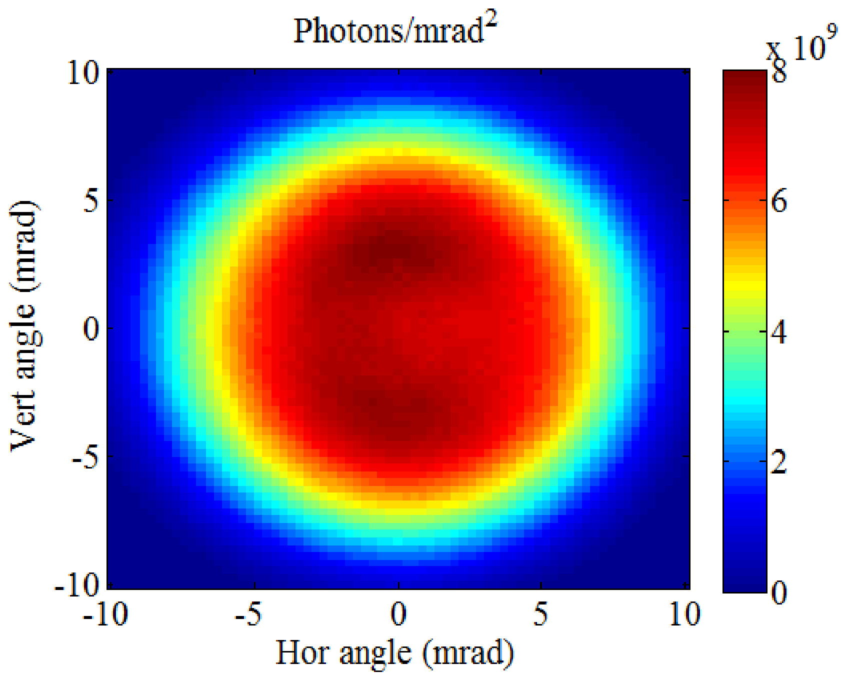
Color indicates intensity vs photon energy and angle.

Off-axis photons are lower energy relative to on-axis.

Divergence of 12.4 keV Radiation

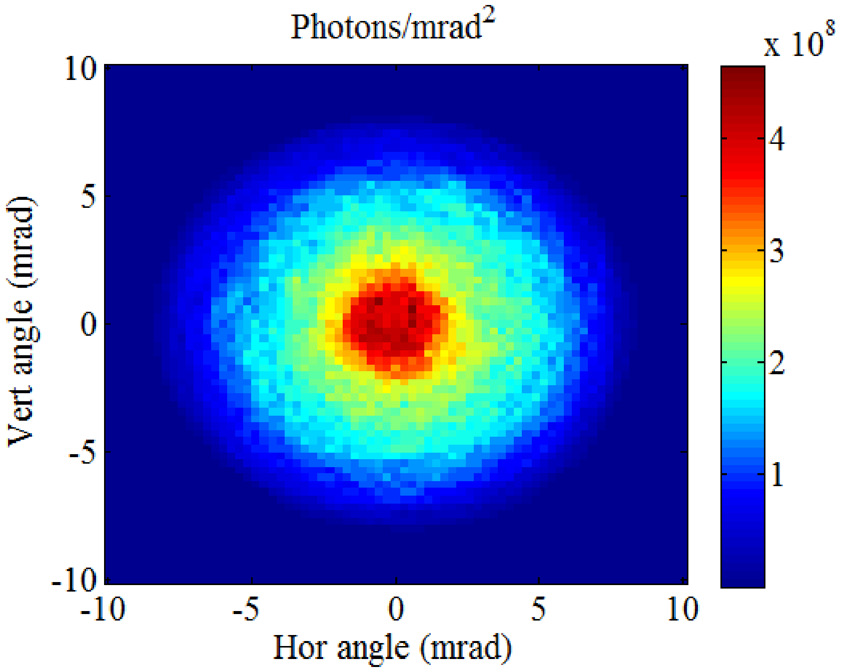
Intensity vs angle for 5% bandwidth

Flux is 1×10^{11} per second



Intensity vs angle for 0.1% bandwidth

Flux is 5×10^{9} per second



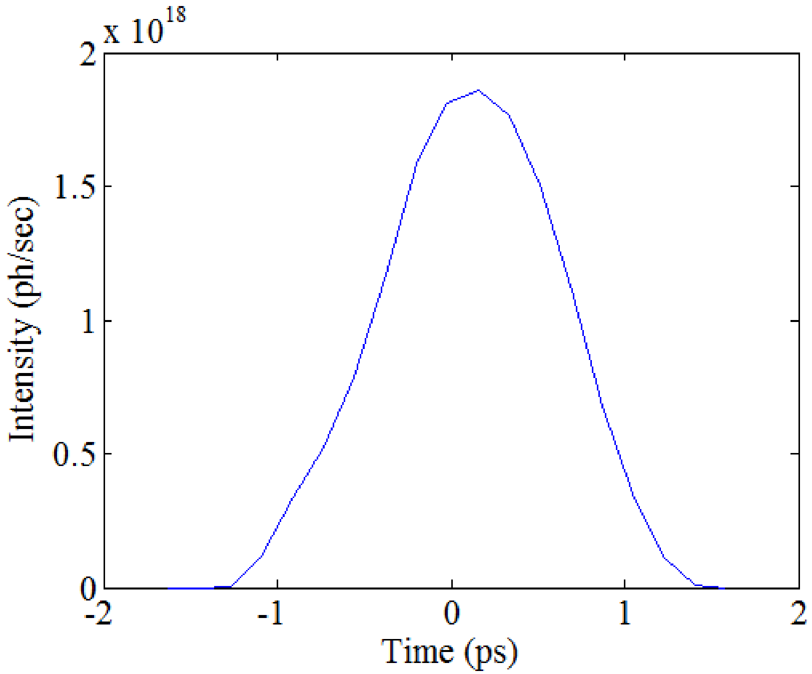
Summary of 12 keV parameters

(incoherent ICS, undulator-like radiation)

Parameter	**0.1% Bandwidth**	**5% Bandwidth**	**Units**
Average flux	$5x10^{9}$	$1x10^{11}$	photons/s
Average brilliance	$2x10^{12}$	$5x10^{12}$	photons/(s .1% $mm^2 mrad^2$)
Peak brilliance	$3x10^{19}$	$9x10^{18}$	photons/(s .1% $mm^2 mrad^2$)
RMS horizontal size	2.4	2.5	microns
RMS vertical size	1.8	1.9	microns
RMS horizontal angle	3.3	4.3	mrad
RMS vertical angle	3.3	4.3	mrad
Photons per pulse	$5x10^{6}$	$1x10^{8}$	
RMS pulse length	490	490	fs
Repetition rate	1	1	kHz

Pulse Duration

X-ray intensity vs time



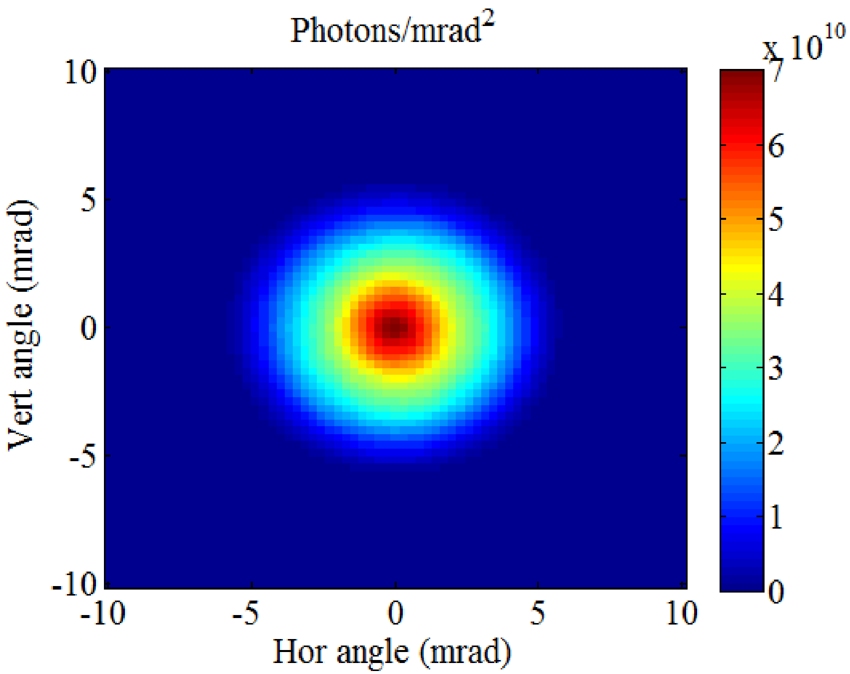
RMS pulse length is 490 fs without compression

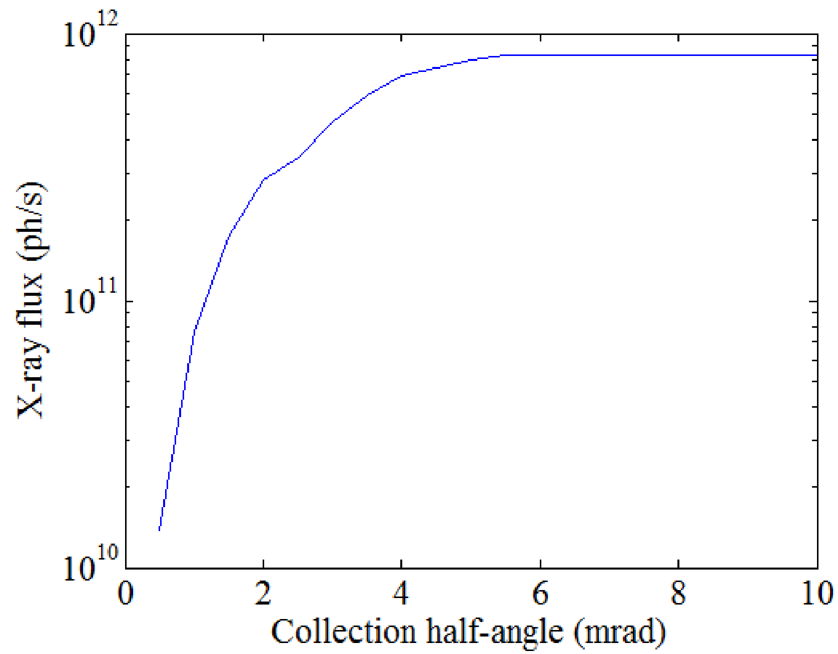
Can be compressed factor of 2-3 without loss of flux via electron bunch compression

Can be compressed <100 fs at lower flux

X-ray Performance for 65 keV

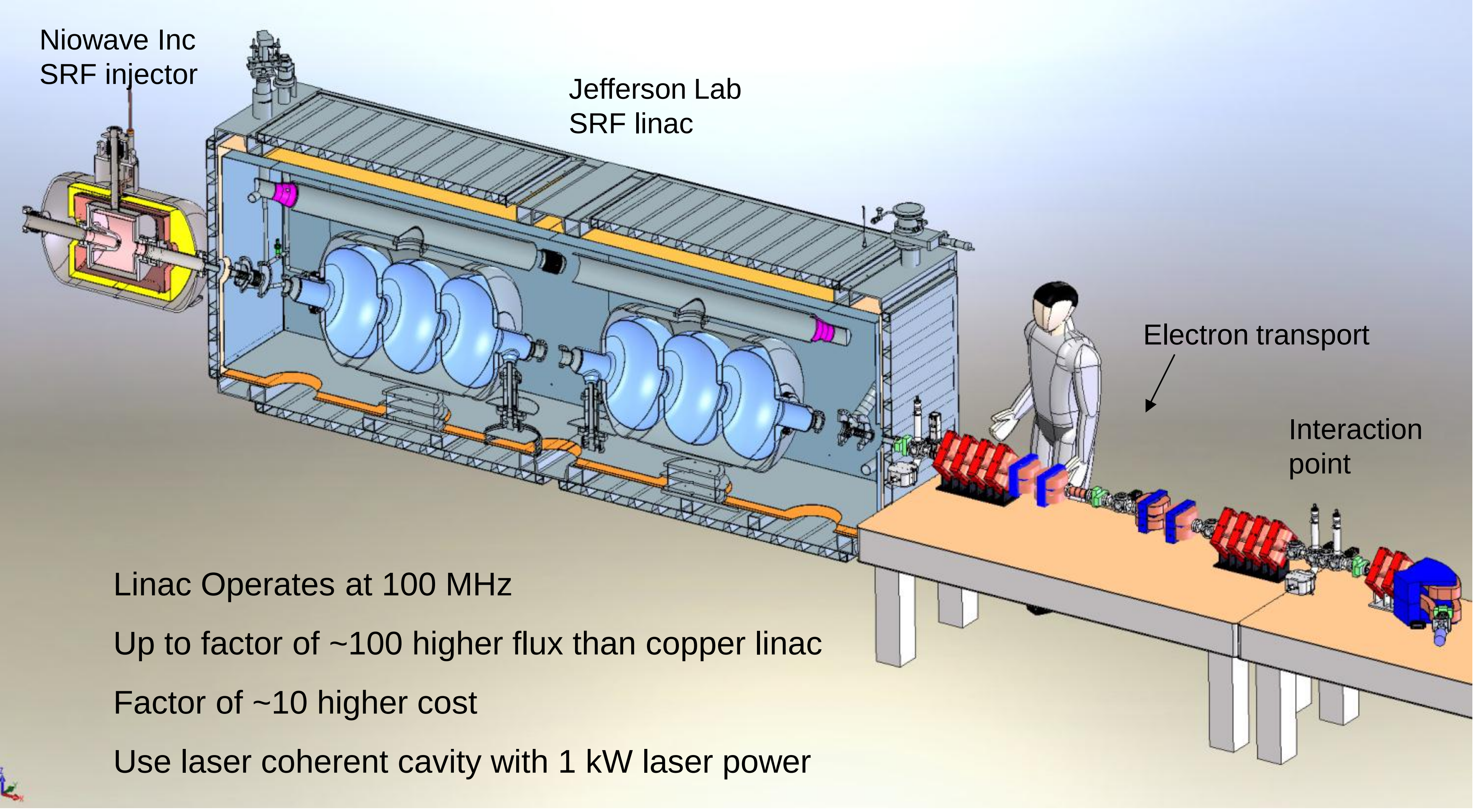
Intensity vs angle for 5% bandwidth





Note: e-beam energy is 35 MeV

Superconducting Gun and Linac



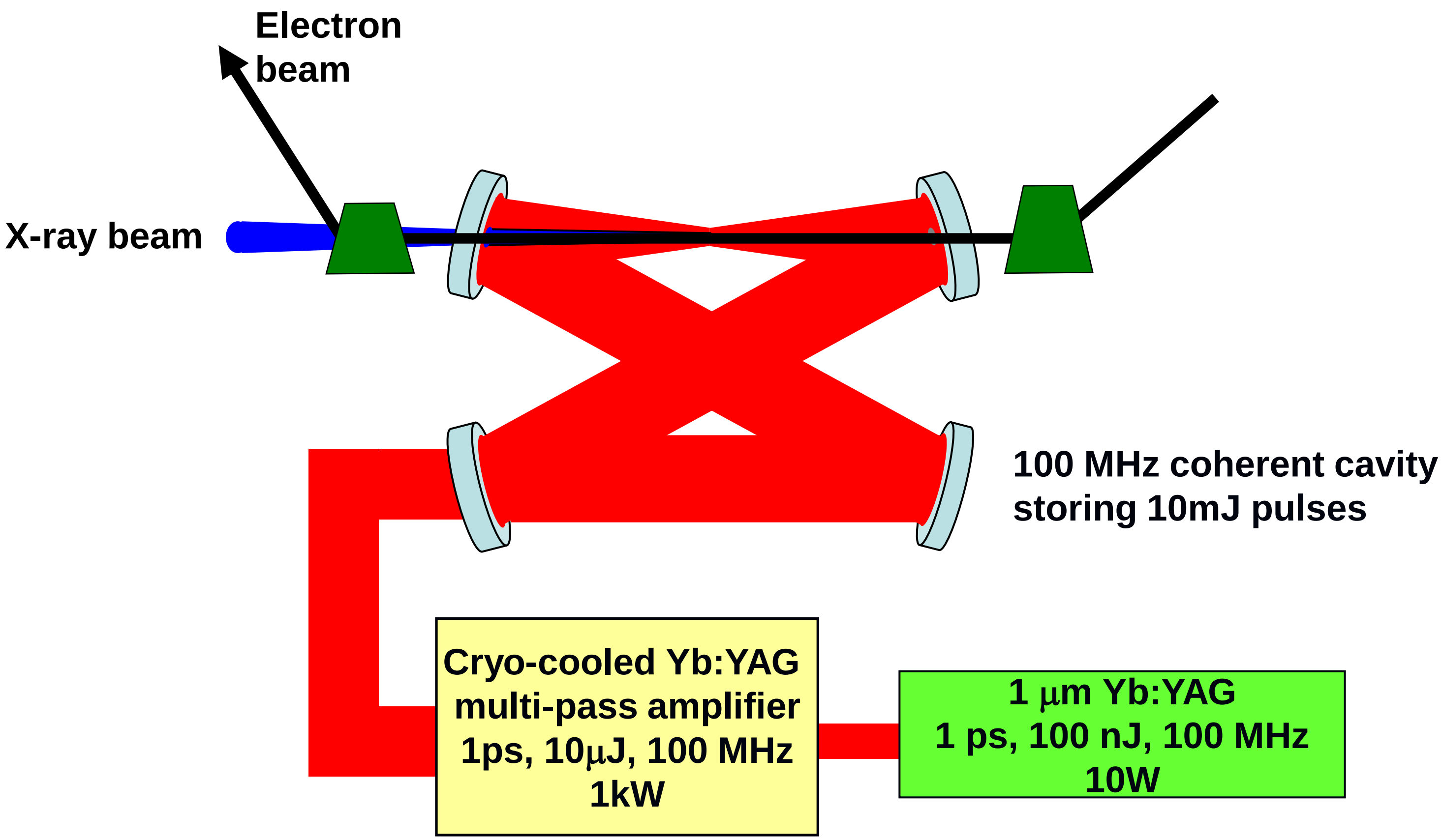
Linac Operates at 100 MHz

Up to factor of ~100 higher flux than copper linac

Factor of ~10 higher cost

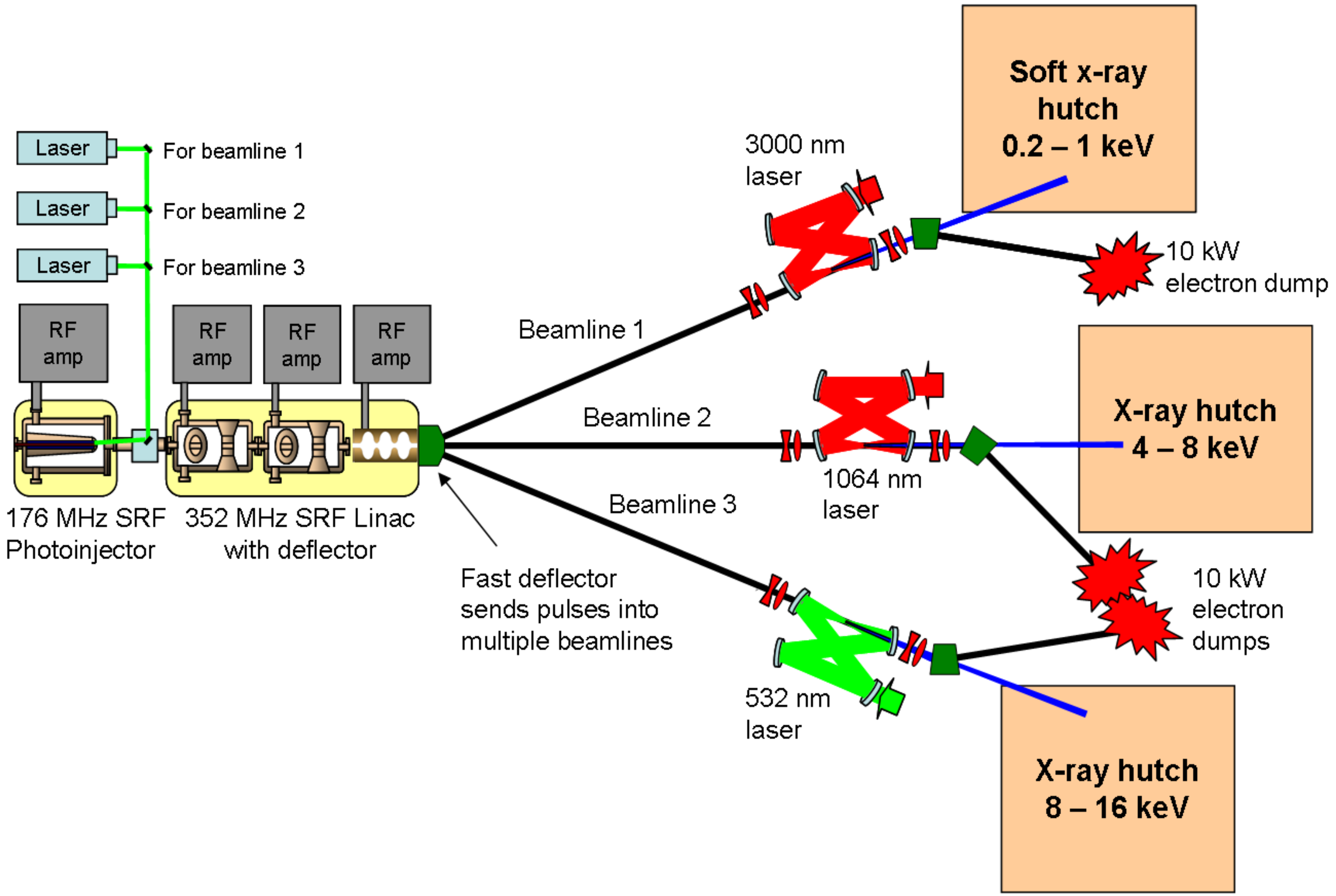
Use laser coherent cavity with 1 kW laser power

Coherent Laser Cavity



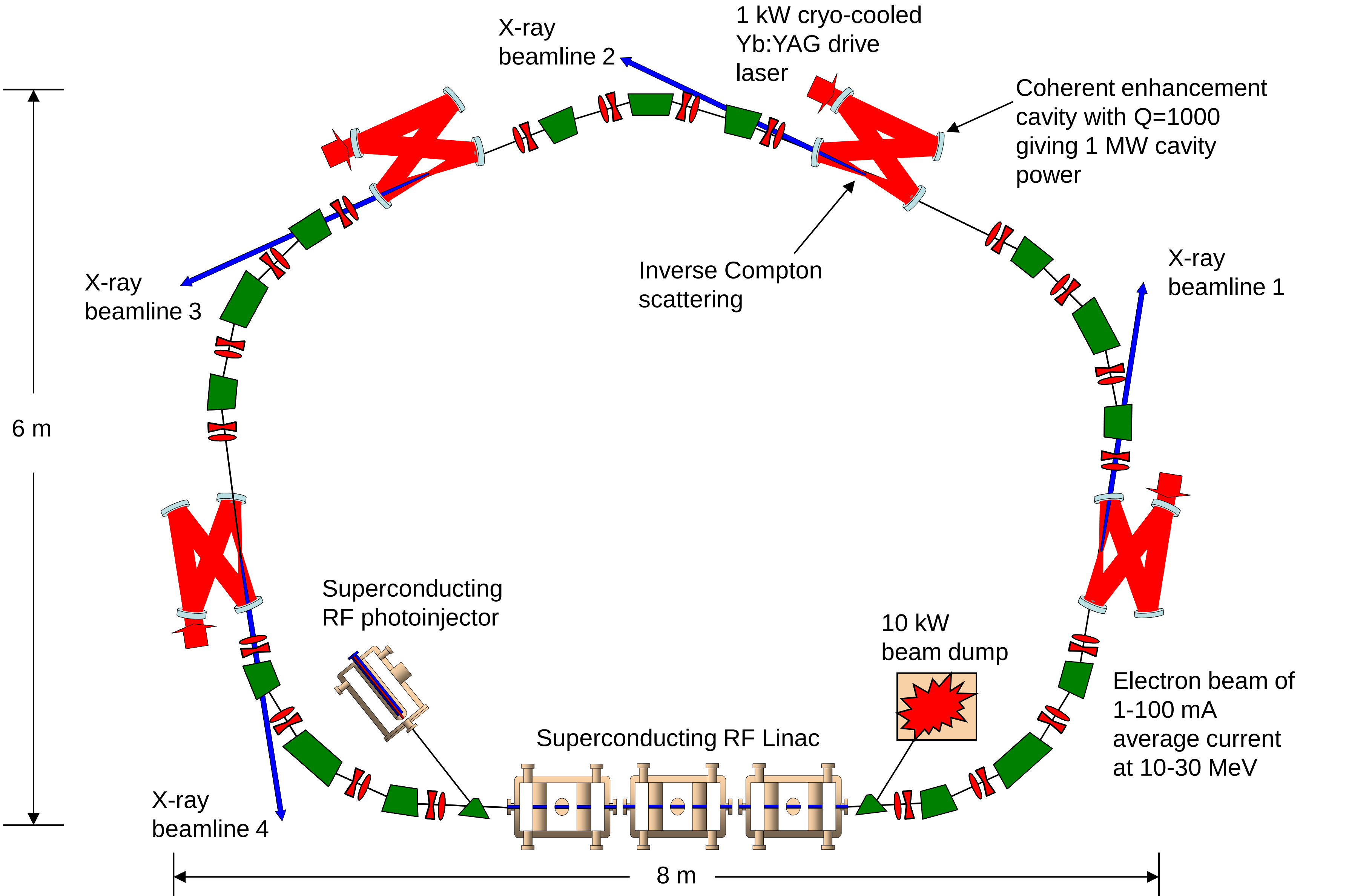
High power lasers developed by T.Y. Fan group at MIT LL and Franz Kaertner’s group at DESY and MIT

Potential for Multiple Beamlines



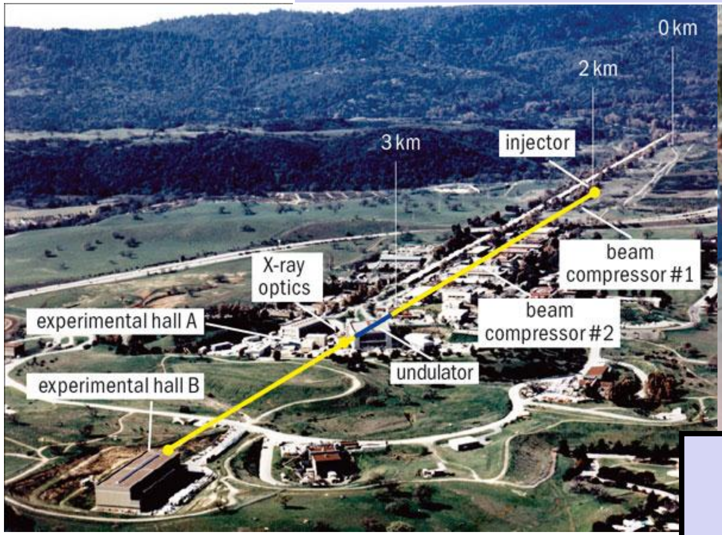
Use 3 photocathode drive lasers with different arrival times to generate pulses into multiple beamlines each with independently tunable energy.

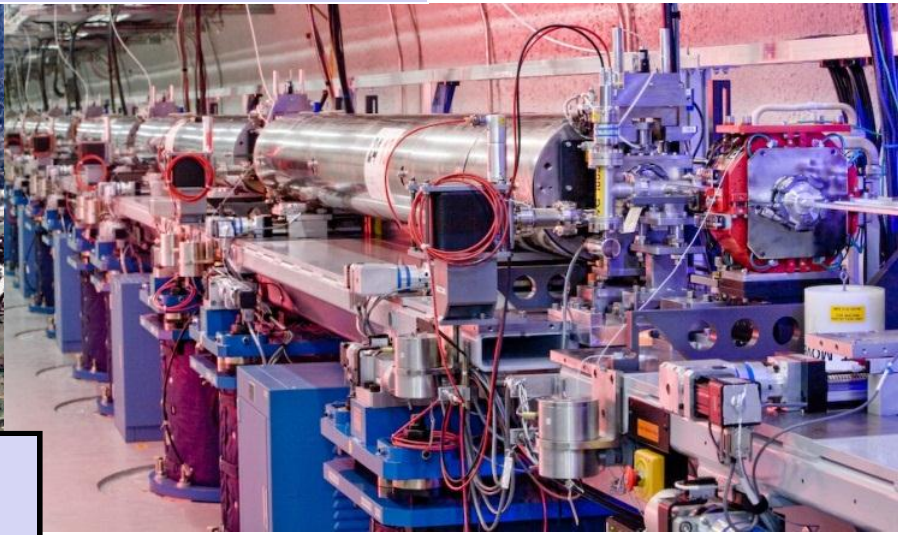
Conceptual Multi-User Facility Based on ICS



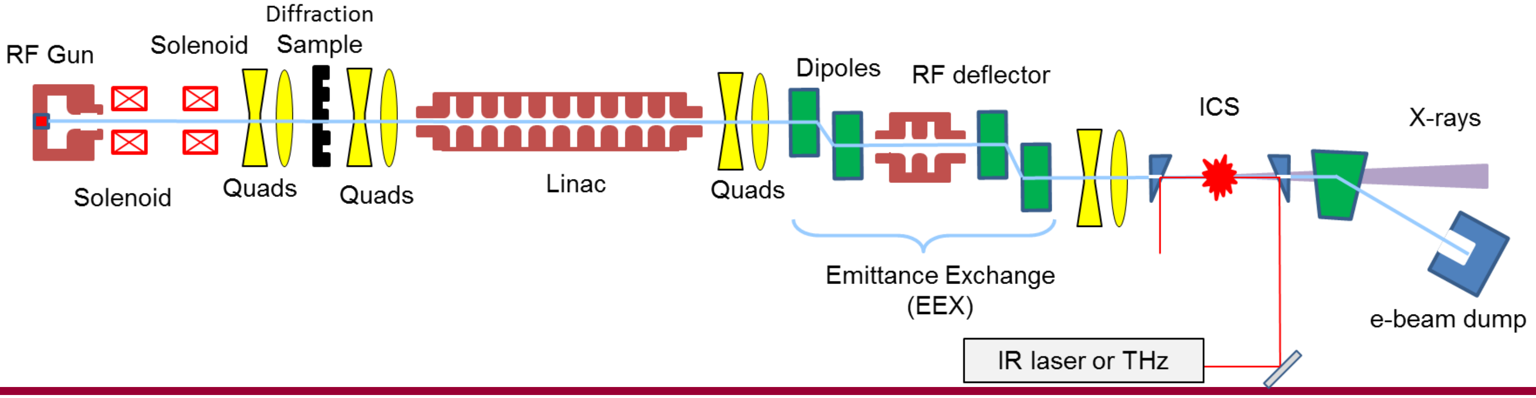
X-ray Lasers

Coherent emission from LCLS (2009)





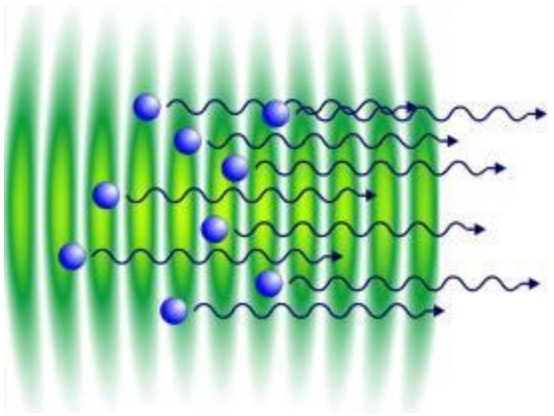
Tabletop X-ray Laser



Toward an XFEL using coherent ICS

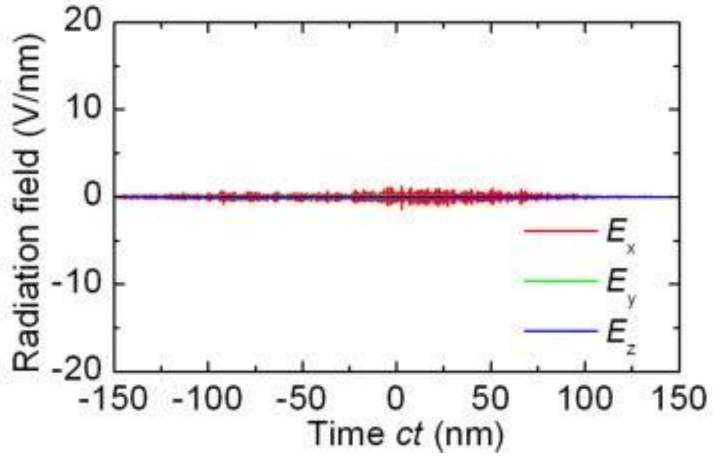
- **Randomly distributed electron beam**

Graves et al, Phys Rev Lett 108, 263904 (2012)

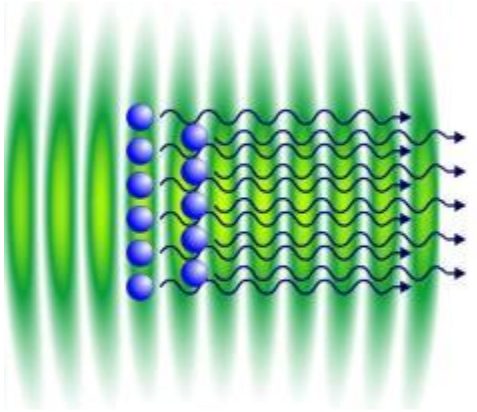


Regular:

$I_{\text{x-ray}} \sim N$



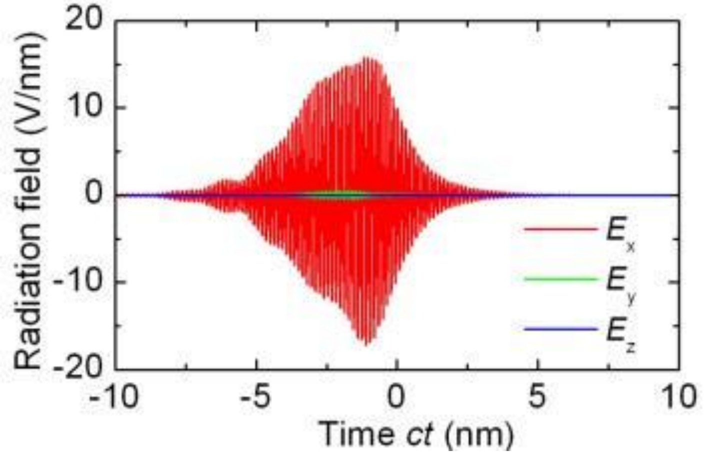
- **Bunched electron beam**



Coherent:

$I_{\text{x-ray}} \sim N^2$

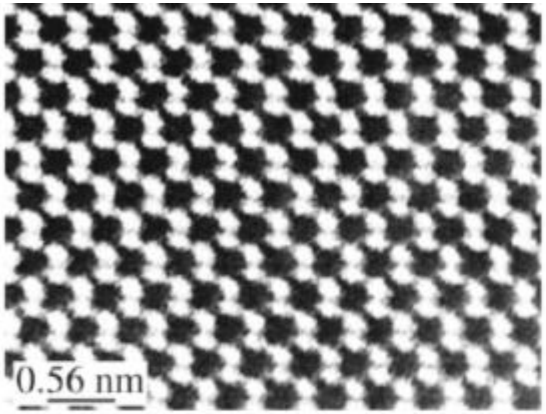
$N > 10^6$



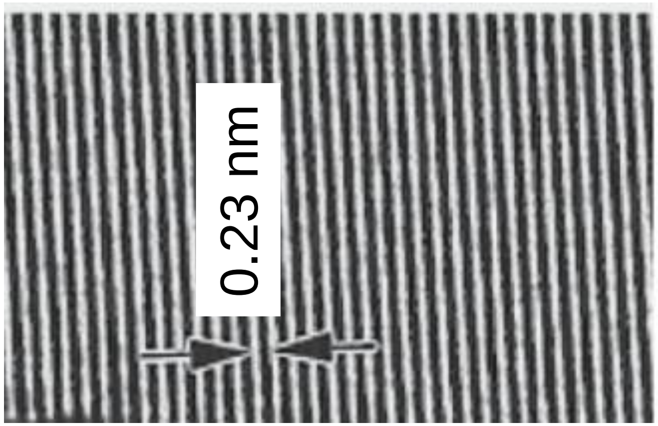
Transmission Electron Microscopy (TEM)

TEMs routinely achieve sub-nanometer resolution (density modulation) with electron energy < 1 MeV

Perfect Si Crystal

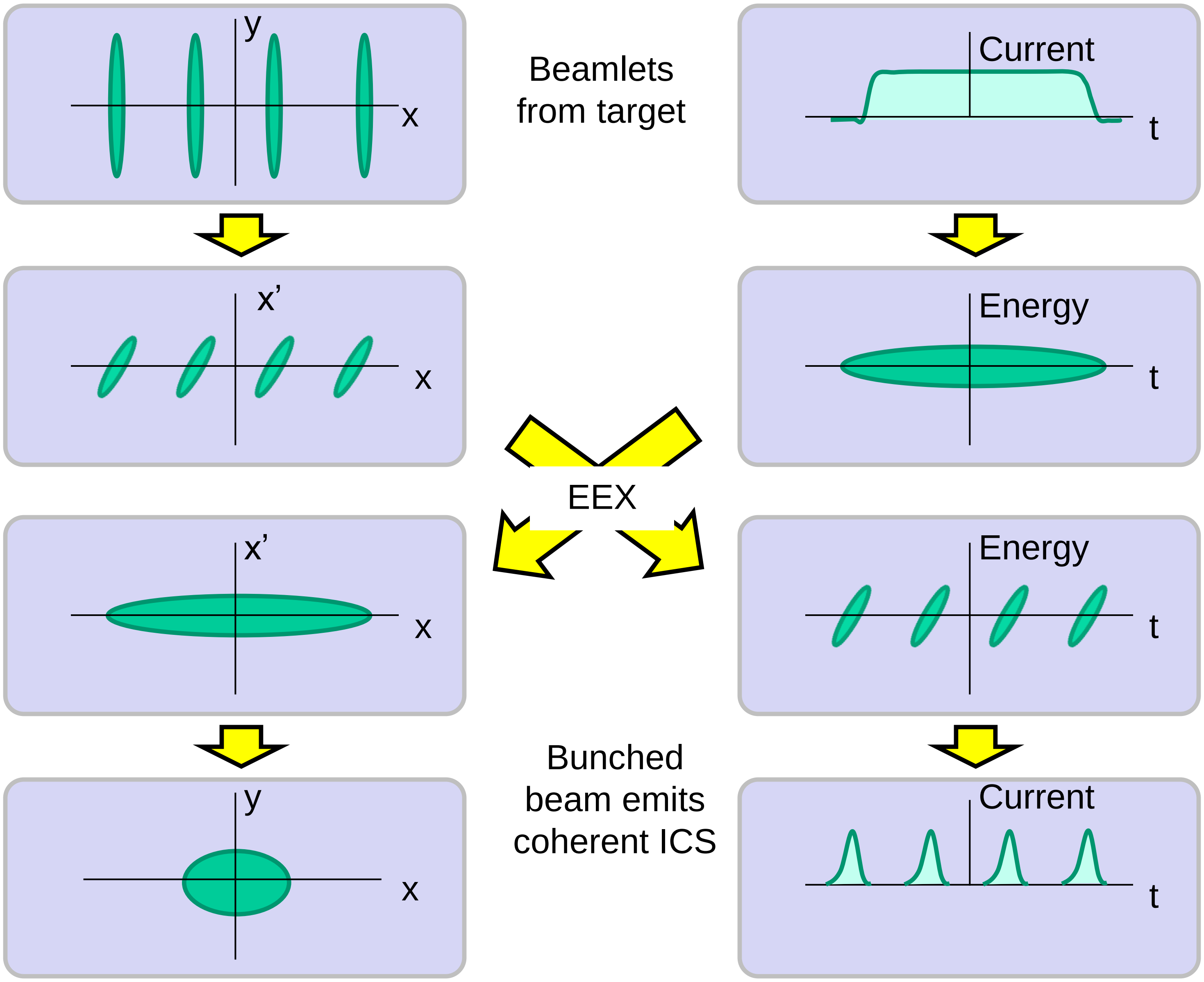


Fringes from Stacking Faults in Al-Cu-Mg-Ag



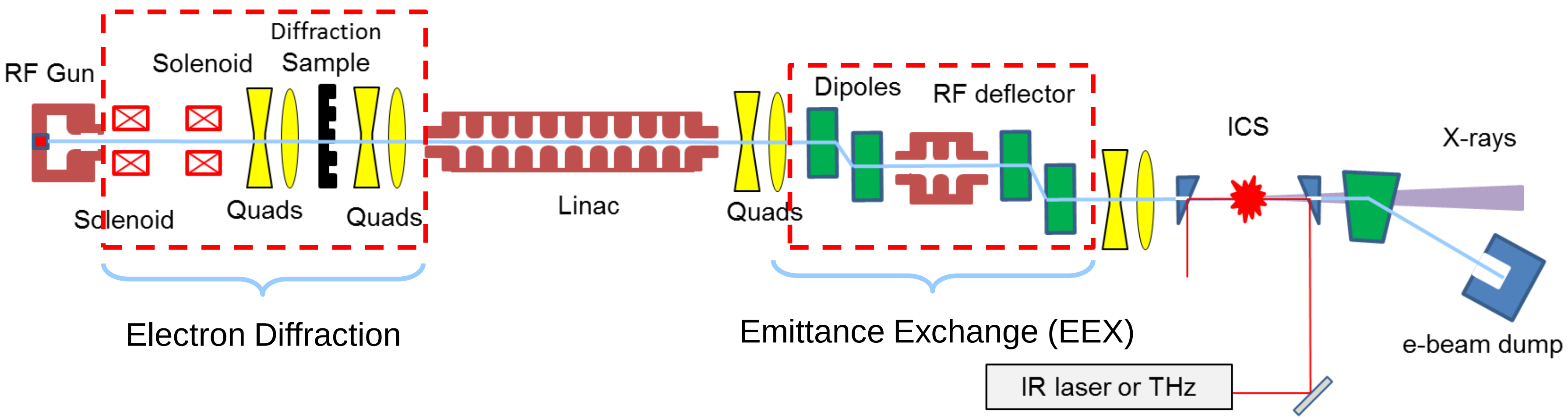
Need to arrange for the periodic structure to be in the longitudinal direction

Emittance Exchange (EEX)



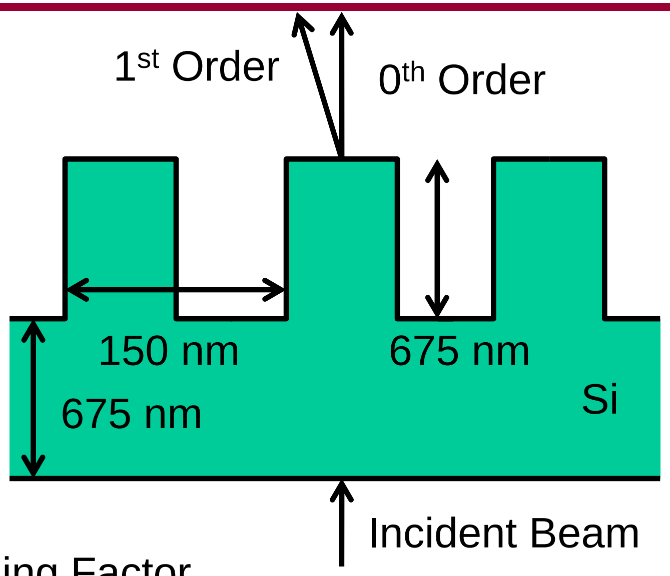
Compact XFEL Layout

- Major components unchanged from incoherent ICS source
- Electron bunch modulation generated with electron diffraction
- Emittance Exchange (EEX) requires RF deflector cavity and additional magnets
- Operate with 1 pC electron bunch from RF gun to improve emittance

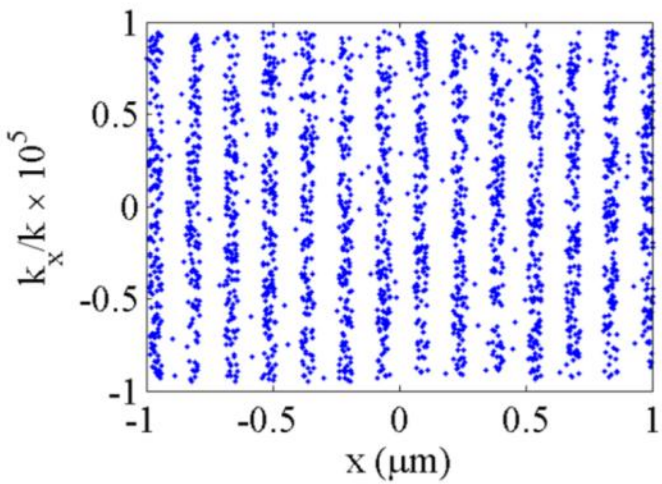


Diffraction Contrast Image

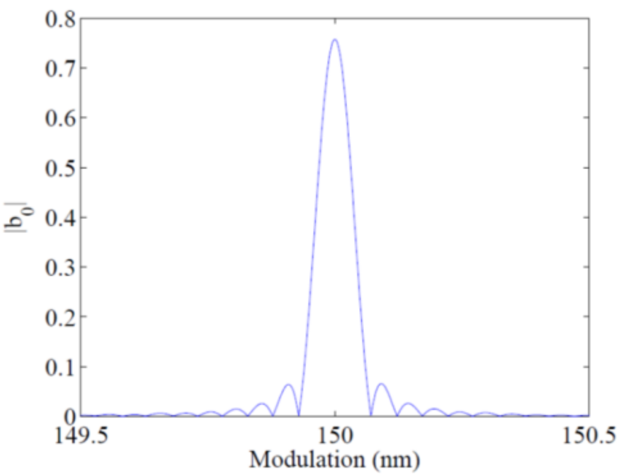
- Tune the modulation spacing of the diffracted beam with patterned Si substrate



Modulated Electron Beam



Bunching Factor



~2000 Modulations

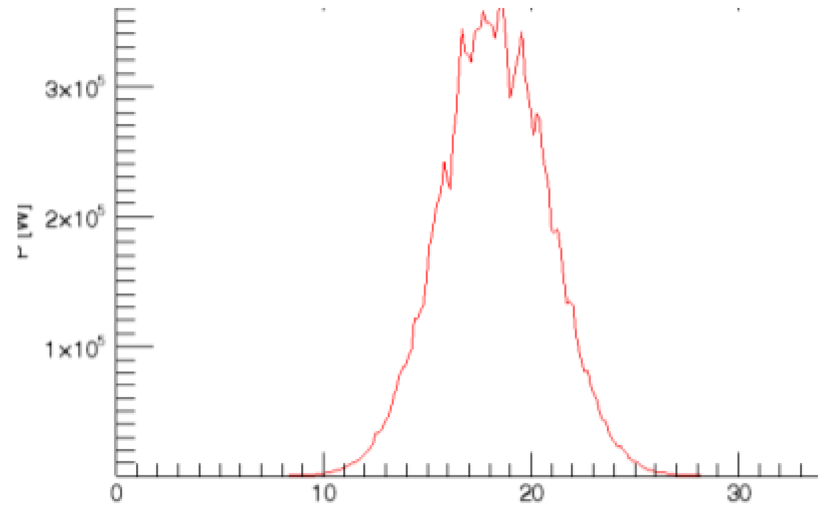
Simulation Results

1.24 nm Modulation – 1 keV X-ray

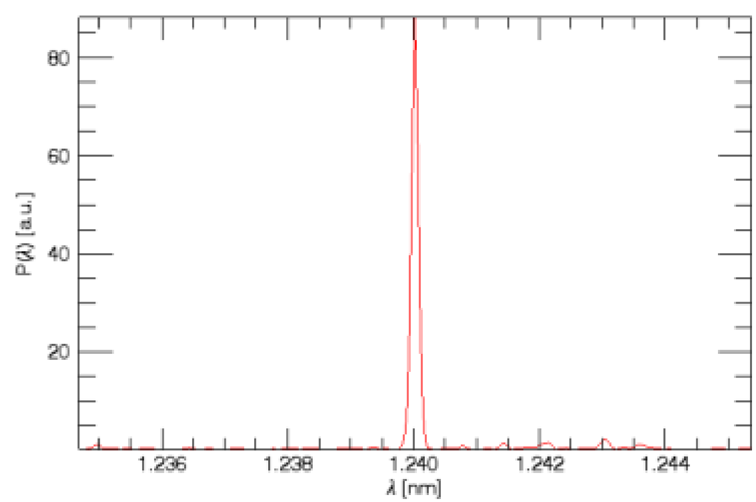
Parameter	Value	Units
Photons per pulse	3.1×10^{7}	
Pulse energy	5.0	nJ
Average flux*	3.1×10^{12}	photons/s
Bandwidth (FWHM)	0.1	%
Average brilliance*	10^{18}	#
Peak brilliance	10^{28}	#
Opening angle	0.5	mrad
Source size	0.5	µm
Pulse length	28	fs
Repetition rate	100	kHz
Average current	50	nA

*average values for 100 kHz rep rate
#photons/(s .1% mm^{2}mrad^2)

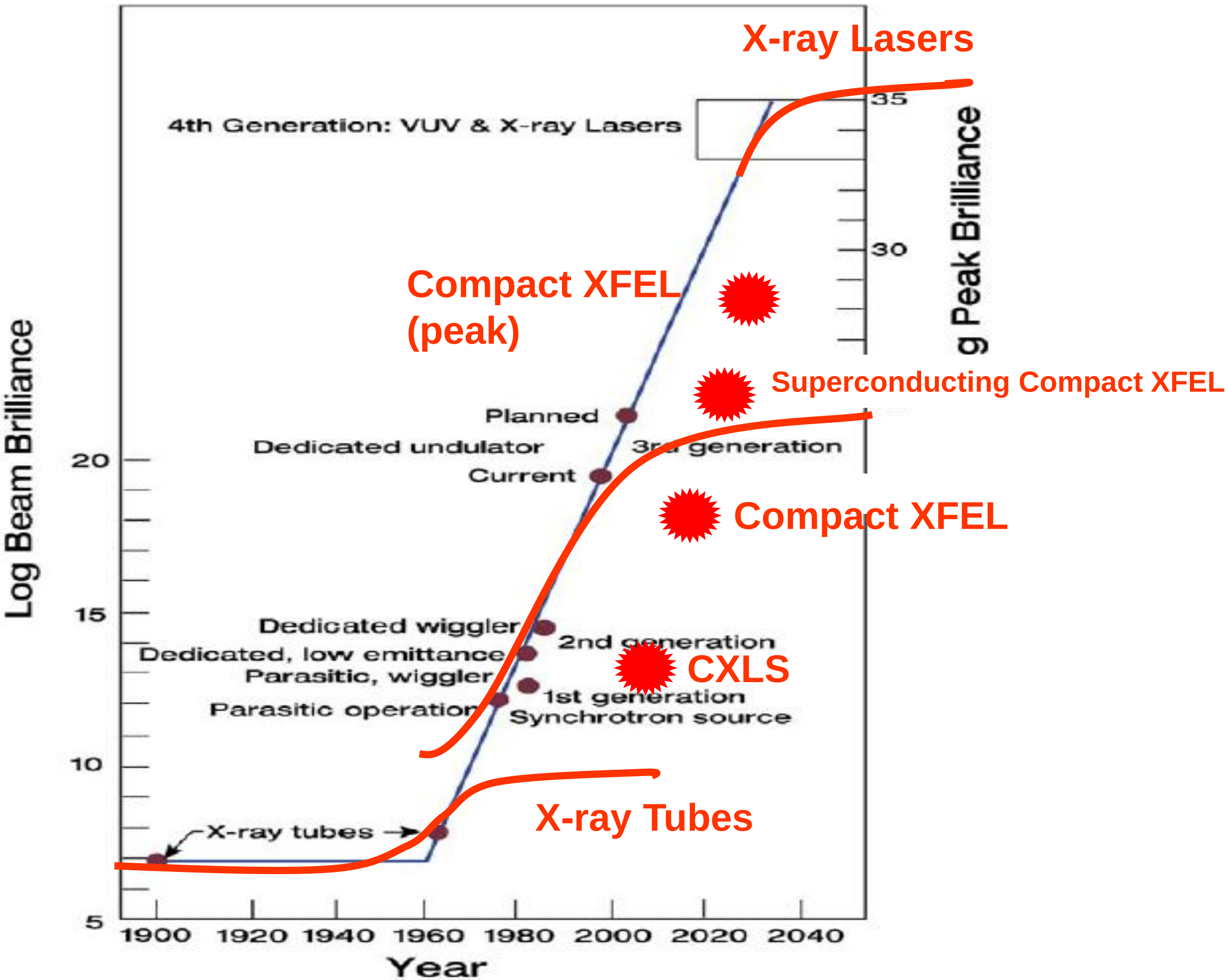
Pulse in Time



Spectrum



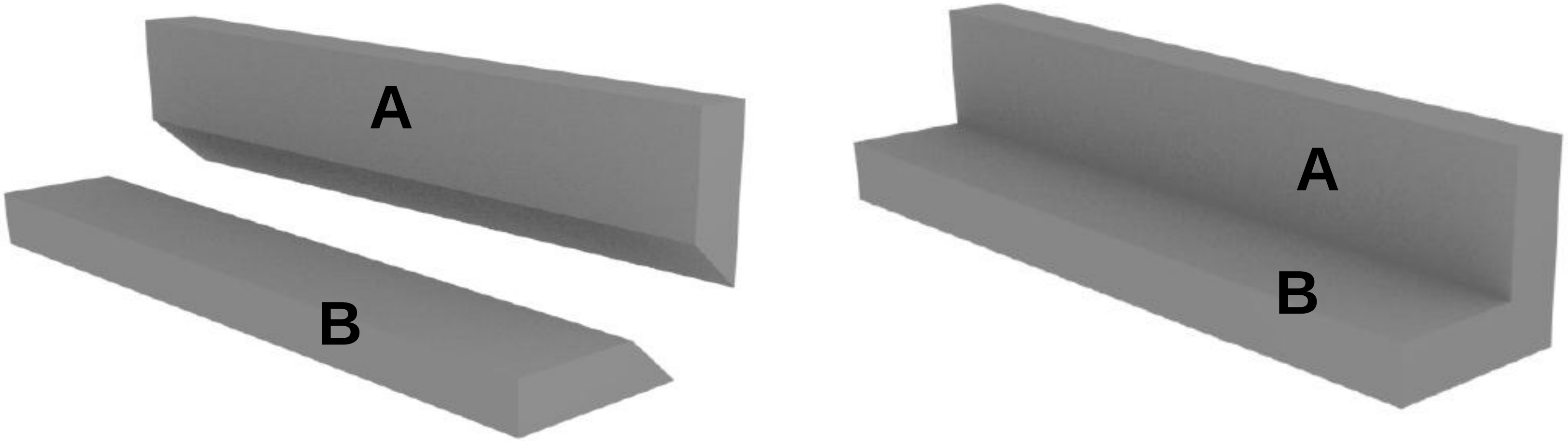
Brilliance of Compact Light Sources



Using X-rays from an ICS Source

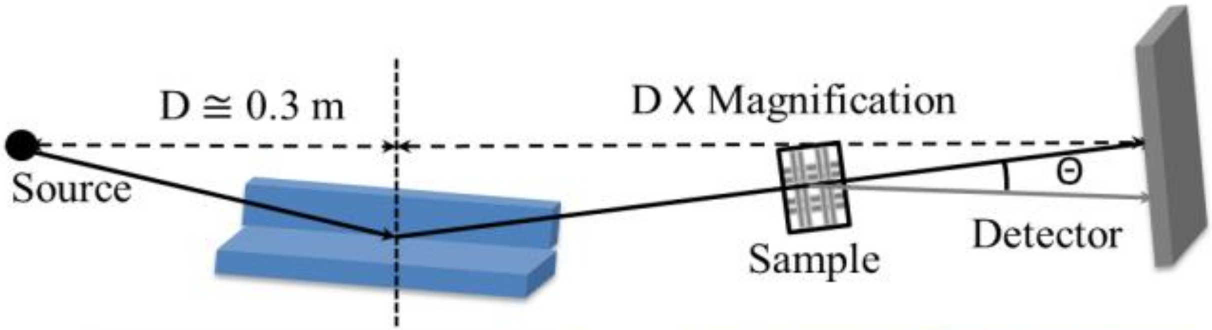
Montel Mirror Concept

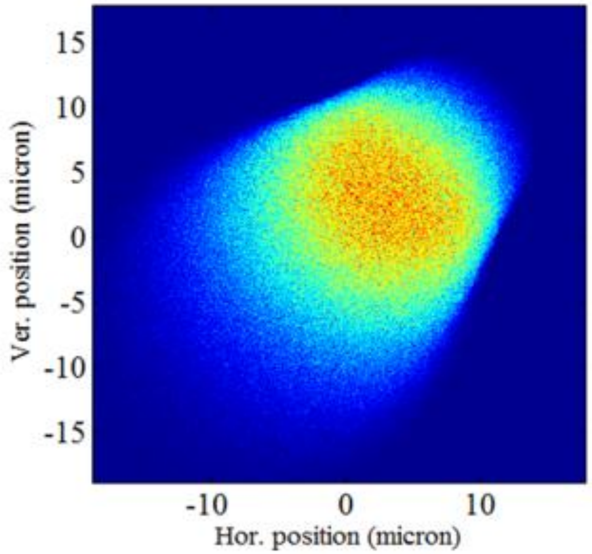
The best solution to collimating ICS beams is the "Montel" implementation of the Kirkpatrick-Baez parabolic mirror geometry, used in reverse to provide focusing in synchrotron micro-probe beamlines

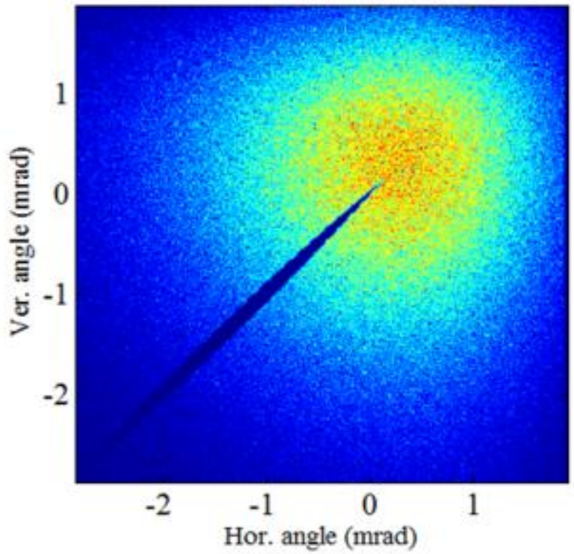


- Both surfaces are shaped to the same parabolic surface figure
- Approximately half the beam strikes surface A first, and half strikes surface B first
- If each parabola is aligned optimally for intercepting unreflected beam, then the resulting output beam is bifurcated into two distinct bunches separated by a divergence gap
- Our group at MIT has developed a new ray-tracer for Montel optics and found excellent solutions, which require precise cutting and joining of the two mating surfaces

Focusing Optics







RMS source size and divergence are 2 microns and 4 mrad

Nested Si K-B optic with graded multilayer magnifies factor of 3

Optic collects 84% of light within 5% bandwidth.

Detector is ~1.2 m from source.

Collimating Optics

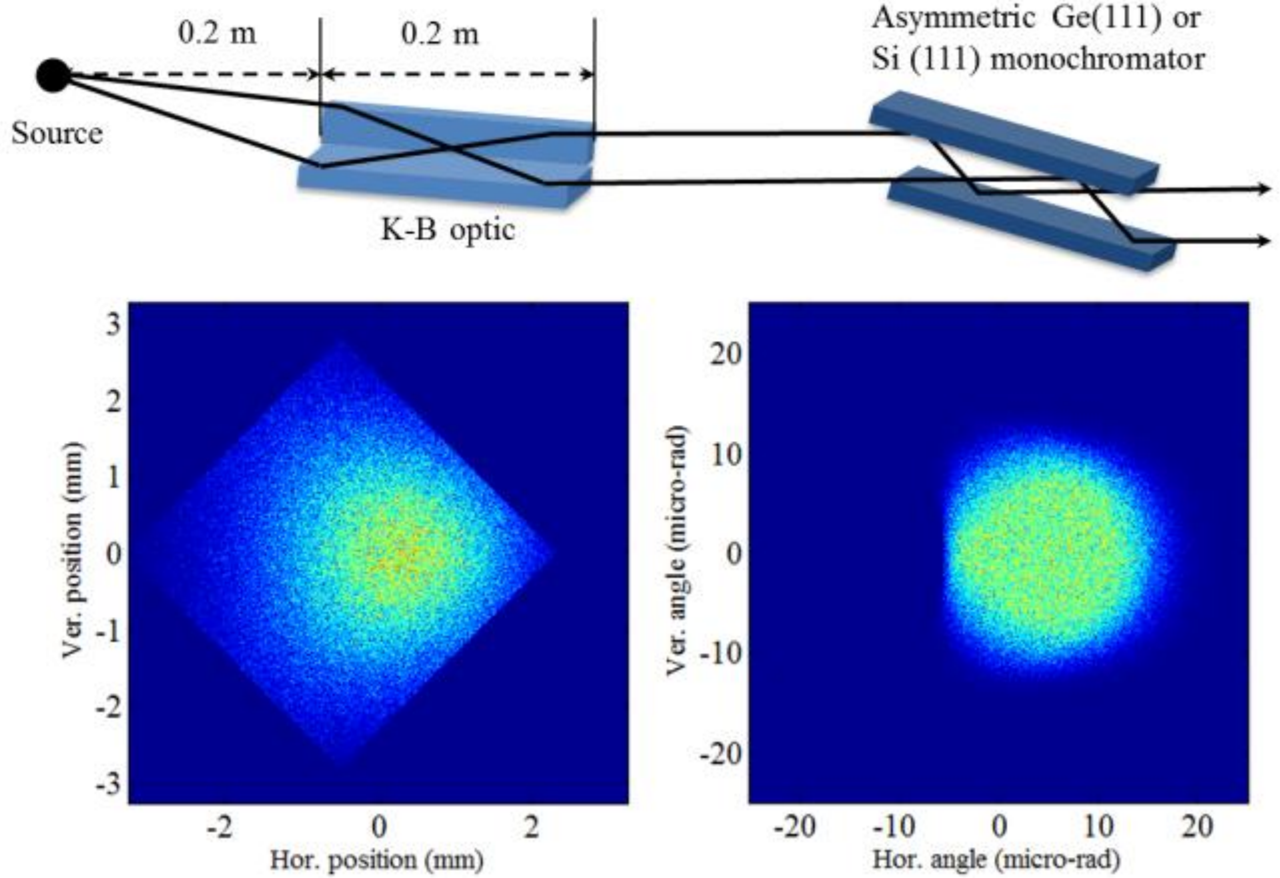
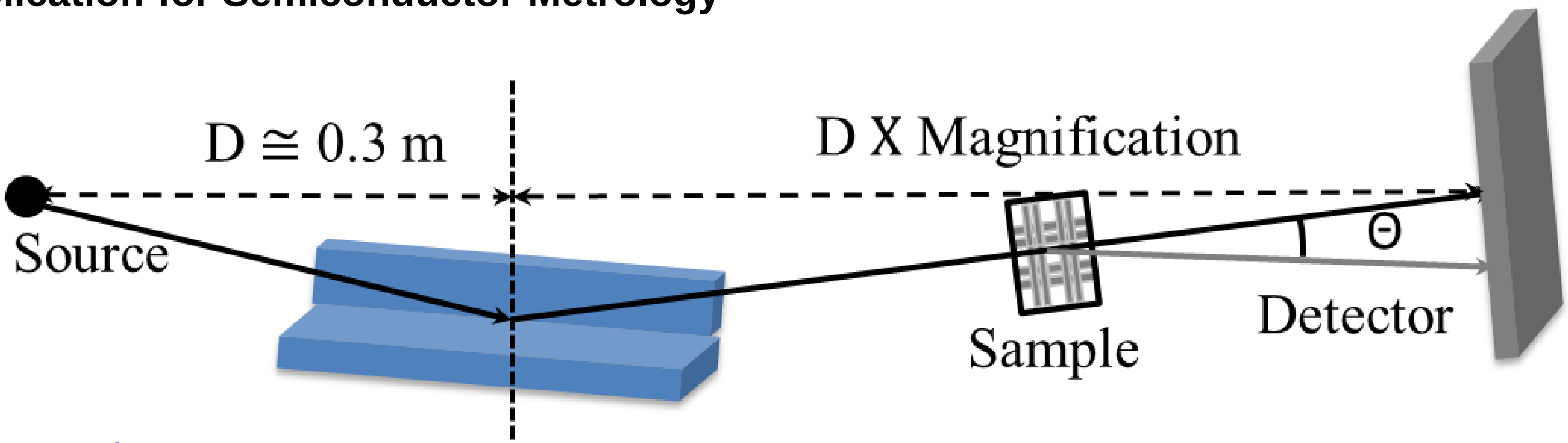


FIG. 8. Geometry and simulation results for collimating optics. A nested KB mirror with graded multilayer coating collects 5% bandwidth radiation at 24 mrad grazing angle. The ICS source size (2 μm) and opening angle (4 mrad) are converted to a synchrotron-like beam with output rms beam size of 0.94 mm and rms divergence of 5.6 μrad. Total efficiency is 40% including 80% collection efficiency and 70% surface reflectivity.

Critical Dimension-SAXS

Application for Semiconductor Metrology



Requirements:

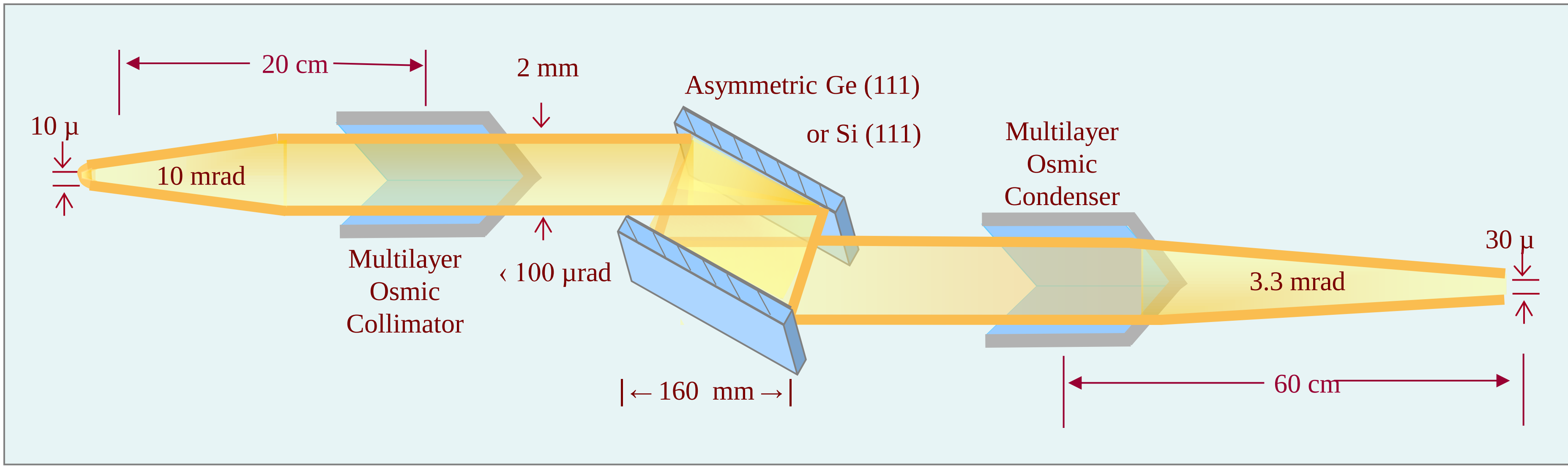
Place the sample where the beam diameter ~ 80 μm
Mirrors collect most of the beam divergence from the source, ~ 10 mrad
X-ray energy E = 17 keV
Sample periodicity d = 22 nm

Solution:

Magnification M=3, the optic-detector distance =1.2 m,
sample-to-detector distance of 24 mm.
Separation between diffraction orders (72 μm) > pixel size (10 μm)

Small Crystals with Fixed Wavelength and MAD

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



Fixed Wavelength: Ge(111); ΔE = 16 eV; R = 67%

MAD: Si (111); ΔE = 7 eV; R = 80%

Medical Applications

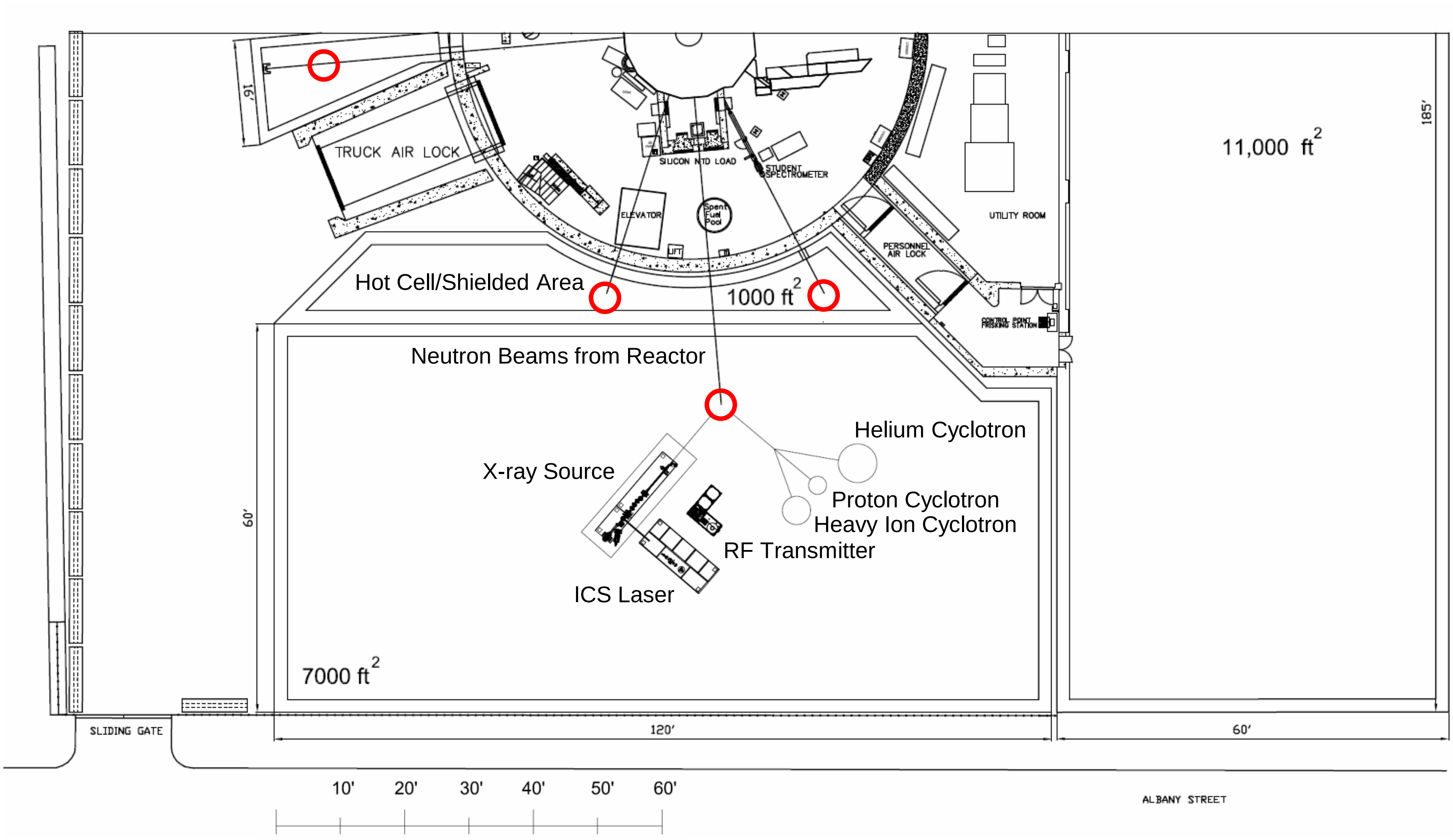
- **Medical Imaging—Phase Contrast Method**
  - Few micron circular source is ideal
  - Many milli-radian divergence illuminates large objects in short distance
  - Few percent bandwidth can be fully utilized and presents no limitation
  - Would improve medical imaging for soft tissue while reducing 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

Medical Applications

- **Medical Imaging—Improved Absorption Images**
  - Current radiographs use 5-75 keV Bremsstrahlung 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

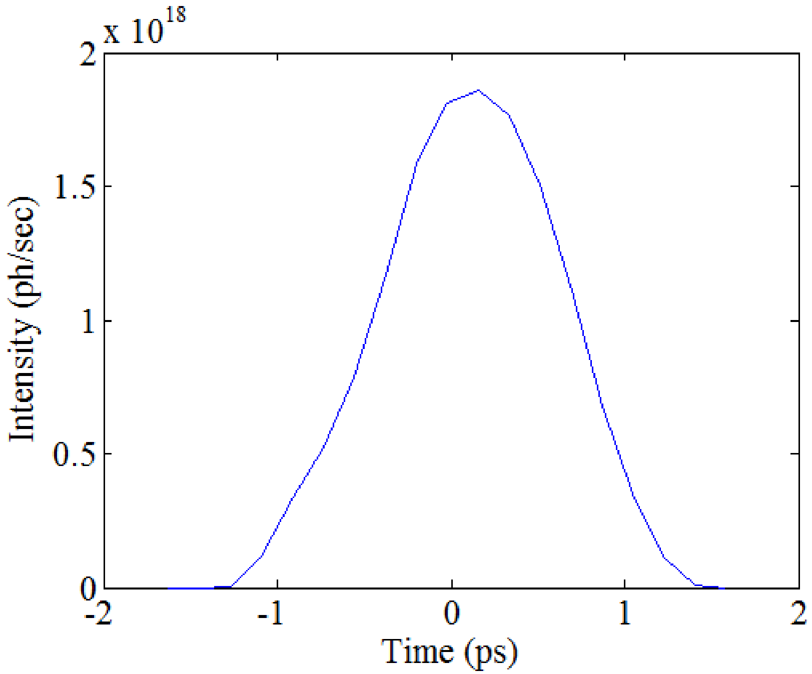
- **Medical Imaging/Therapy—Tuning Wavelength**
  - Iodine contrast agent for blood imaging
  - Gd or Pt based cancer therapy

Irradiation and In-situ Imaging of Nuclear Materials



Pulse Duration

X-ray intensity vs time



RMS pulse length is 490 fs without compression

Can be compressed factor of 2-3 without loss of flux via electron bunch compression

Can be compressed <100 fs at lower flux

Ultrafast 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 $>10^8$ photons in a 5% 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 exceeds storage ring pulse chopping schemes
  - Would be a stepping stone to the big FELs

Conclusions

- Inverse Compton Scattering offers low risk and low cost options for high performance compact x-ray sources greatly exceeding conventional x-ray tube sources
- Such sources would open a wide range of applications not possible with large central facilities
- Characteristics of micron source size and short pulse duration are attractive versus large synchrotron facilities
- With further development, x-ray performance could approach second generation synchrotron fluxes and brilliance
- There appear to be interesting technical paths to a coherent compact x-ray source, which would exceed third generation sources and provide a stepping stone to the large FEL sources