An Inverse Compton Scattering (ICS) Source for High-Energy, Time-Resolved X-ray Scattering Studies of Structural Materials

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Cornell University, Ithaca, New York

Outline

1. Motivation for studying structural materials
   a. New lightweight materials
   b. New fatigue failure diagnostics and understanding
2. Characteristics of “ideal” x-ray source for characterizing structural materials
3. Basics of an Inverse Compton Scattering (ICS) hard x-ray source
4. Current capabilities of 3rd generation and XFEL sources
5. MIT concept utilizing an optical cavity
6. Combination of MIT cavity with existing Cornell ERL components
   a. Table of design parameters and performance
   b. Calculated spectral curves
   c. Floor plan/layout of source
7. Additional scientific applications

Motivation for Novel Structural Materials

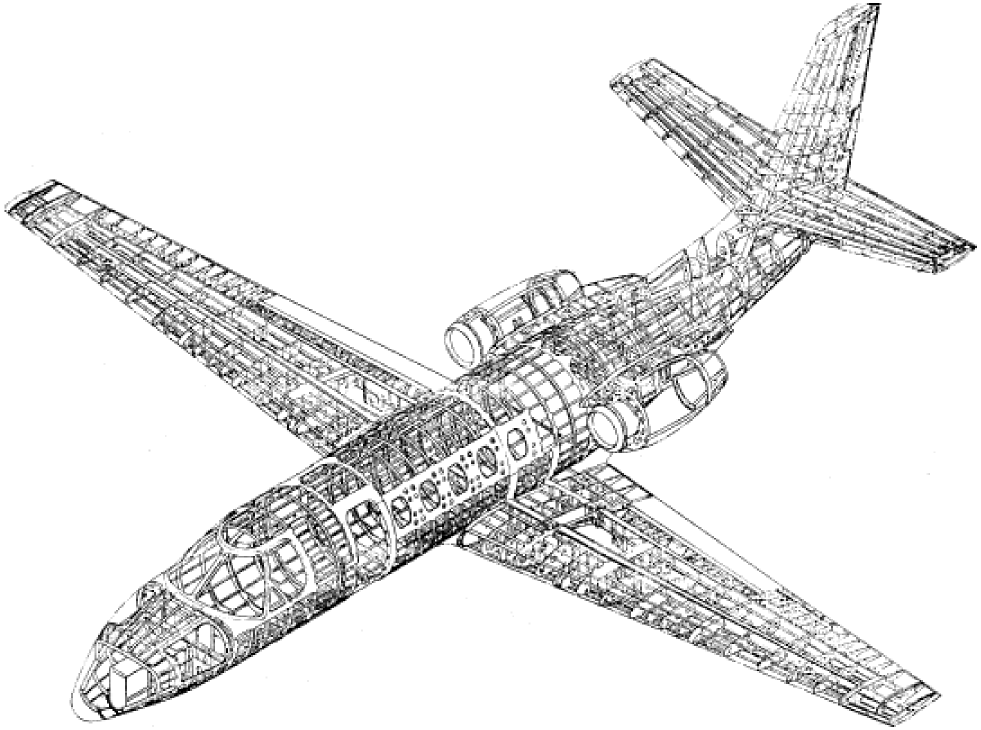
1. Lighter weight structural materials enhance fuel efficiency in airplanes, trucks, and cars.
2. Improved diagnostics and/or understanding of fatigue failure will reduce need to replace expensive parts well before expected lifetime in critical applications.
3. Improved engineering design tools.

Modern Engineering Design begins with (e.g., using finite element methods) each component (e.g., a nut or a bolt) and then couples them together to build a model of a system (e.g., an airplane). At the lowest level, materials are assumed to be homogeneous and are modeled using <u>Macroscopic</u> elasticity theory and experimentally obtained stress/strain curves, measured yield stress, etc.

Goal is to incorporate the microstructure of structural materials into the design process.

Modern Engineering Design

System



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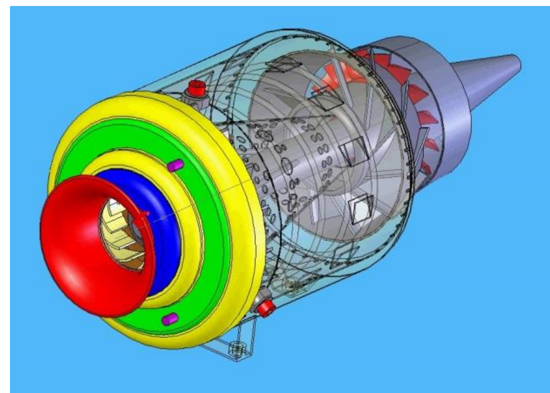
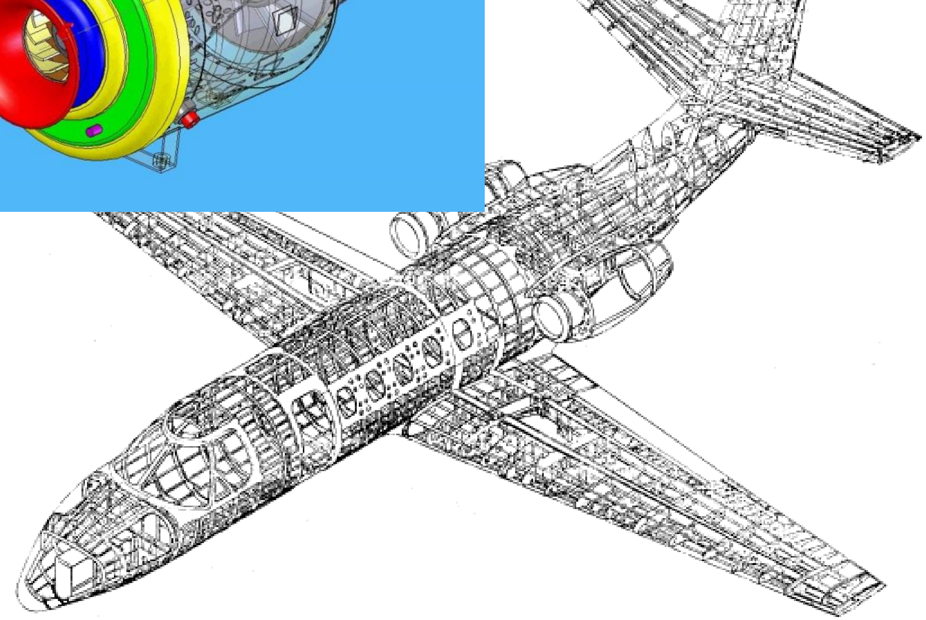


Sub-system



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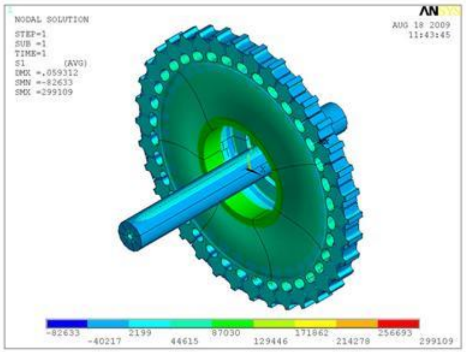
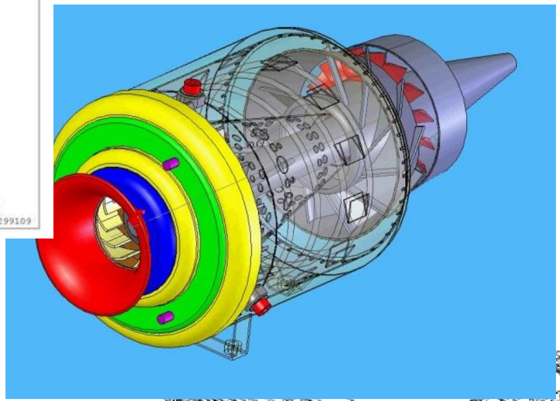


Part



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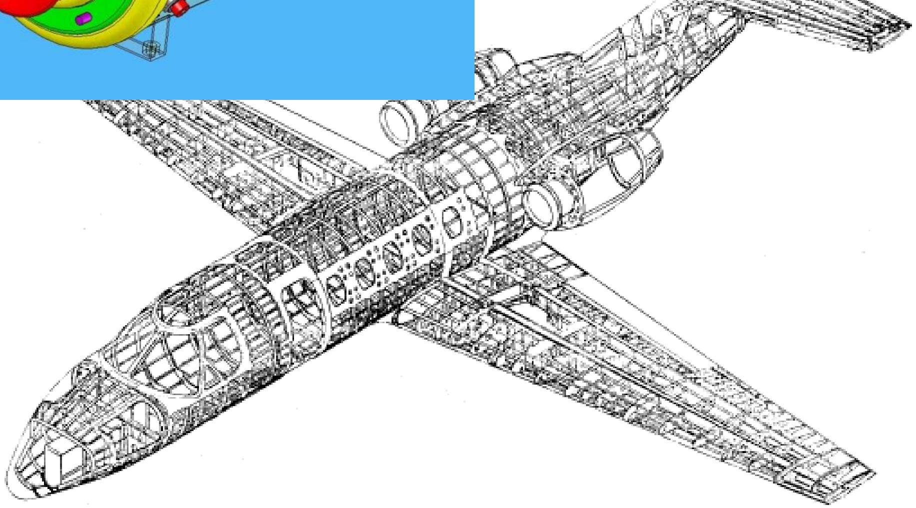

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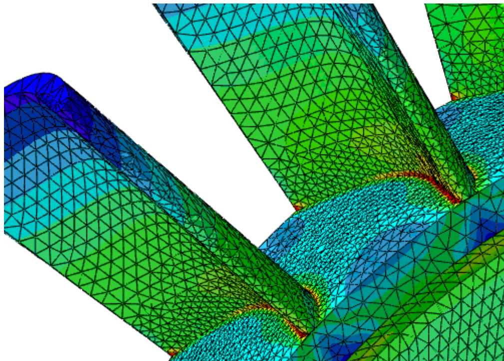
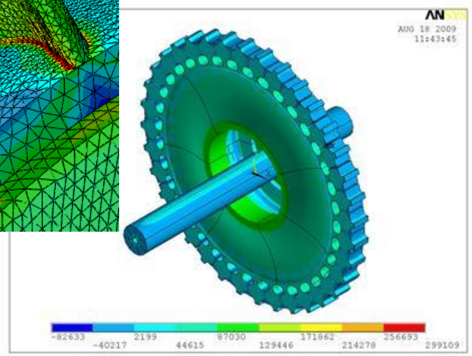


Component



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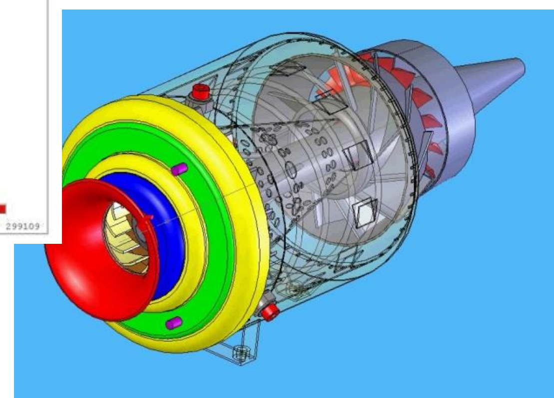

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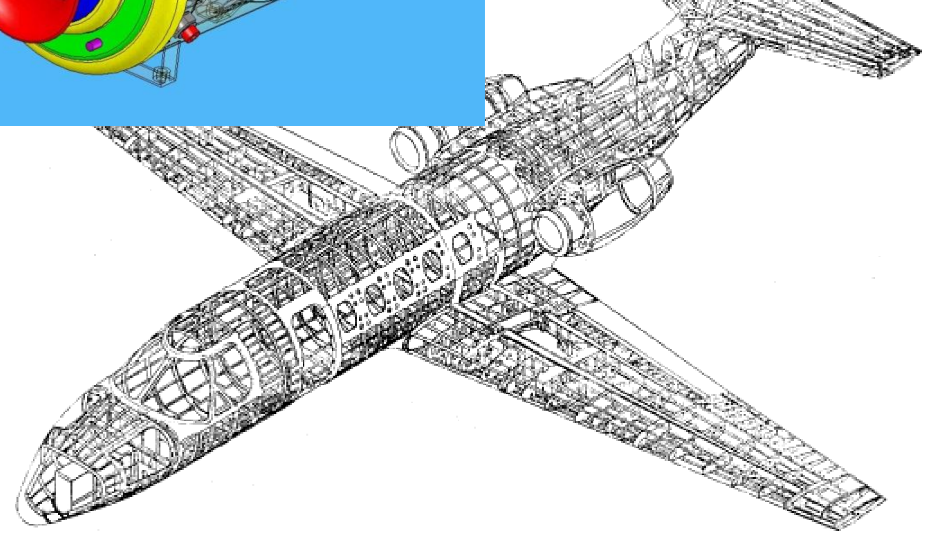

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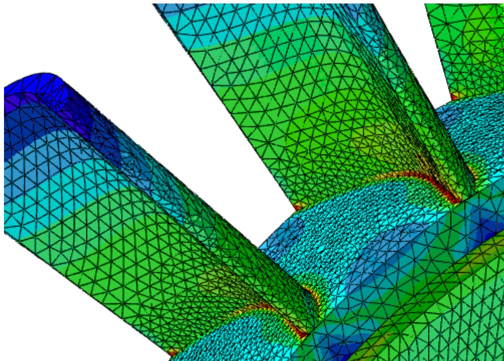
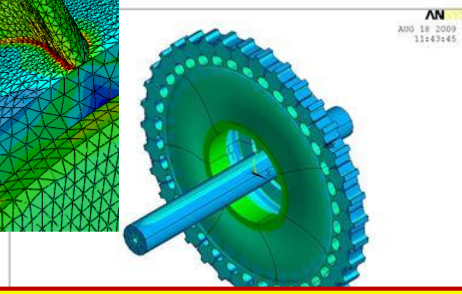
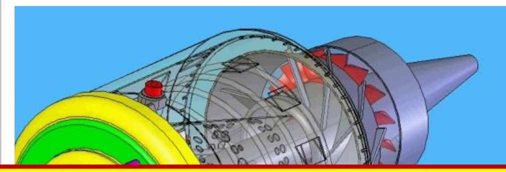
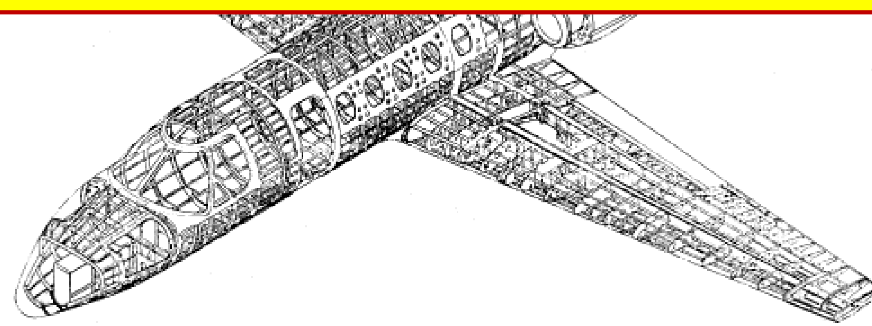






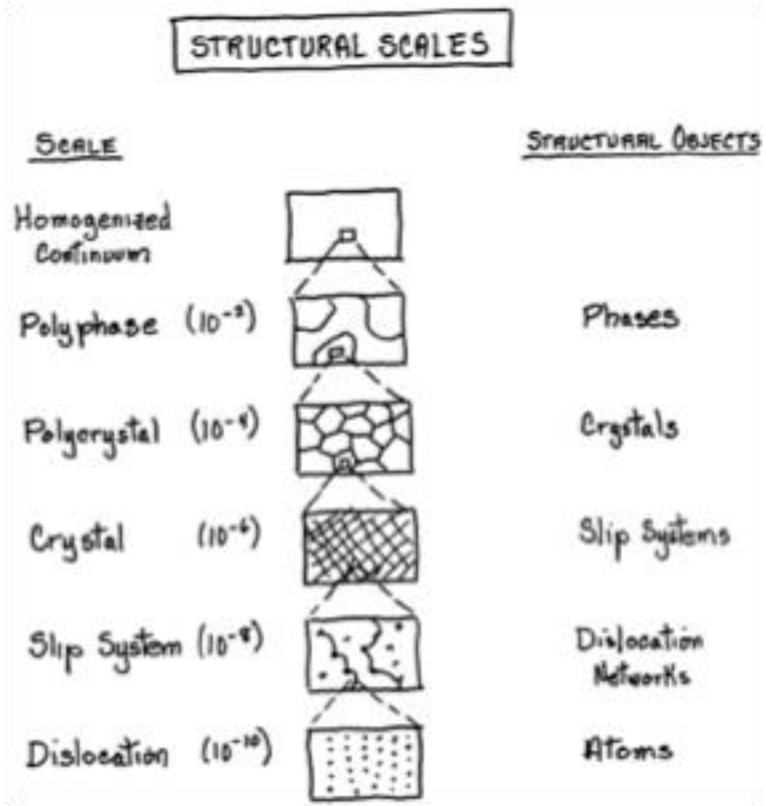
Modelling breaks down at the materials level



System

Microstructure-Based Modeling

(Owen Richmond - US Steel, Alcoa)



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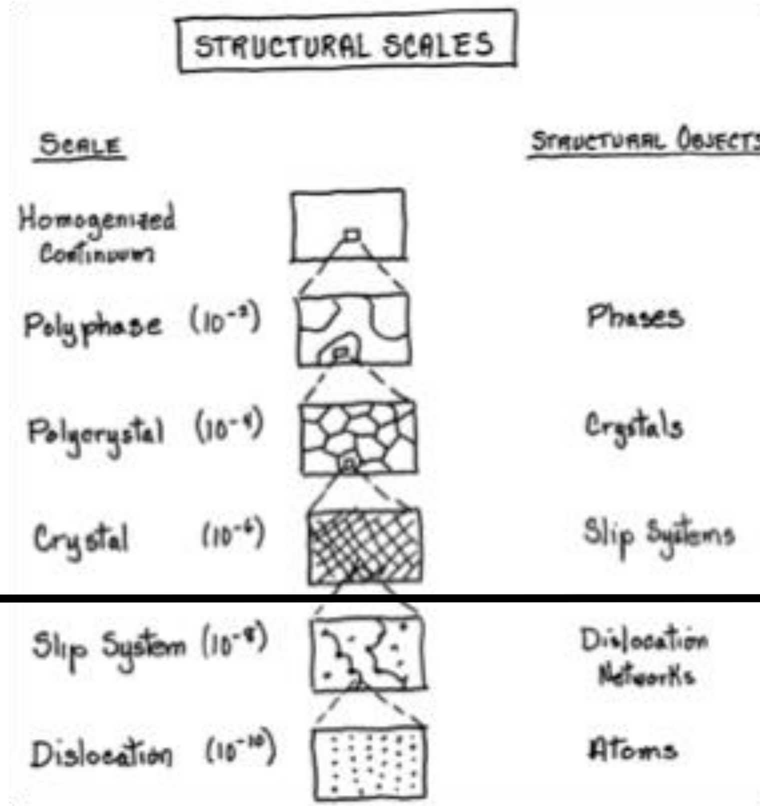

"Polycrystal" Models

Mechanical Design with Structural Alloys

- Function, Constraint, Objectives
- Constraints & Objectives based on properties
  - Strength, Stiffness, Density, Cost
- Mechanical Tests: stress-strain data
  - Extract Properties
  - Validate and Calibrate Material Models
  - Drag the model through “Gauntlet” of data
- Implement models within design methodologies - FEM
  - Understand heterogeneous deformation
- Microstructural Characterization
  - Microstructure dictates properties
  - Ever more highly resolved “images” (3D)

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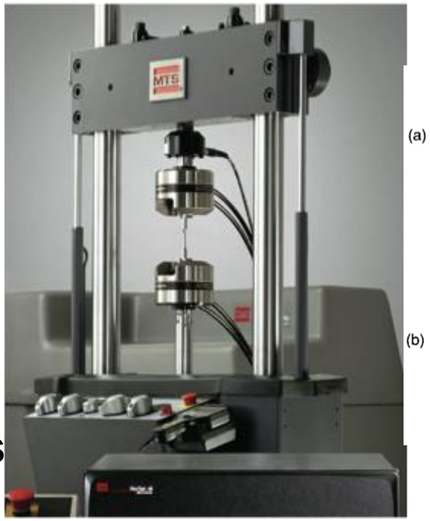

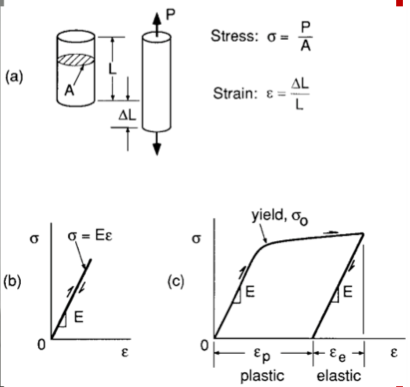

Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, Third Edition, by Norman E. Dowling. ISBN 0-13-186312-6.

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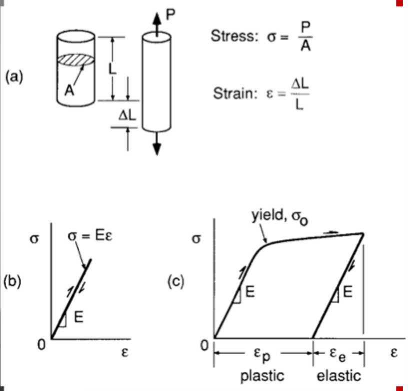

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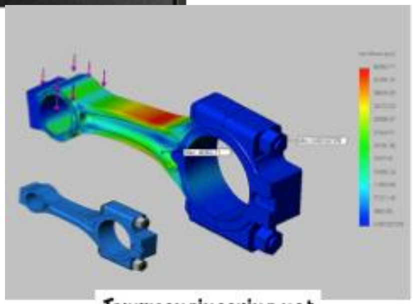

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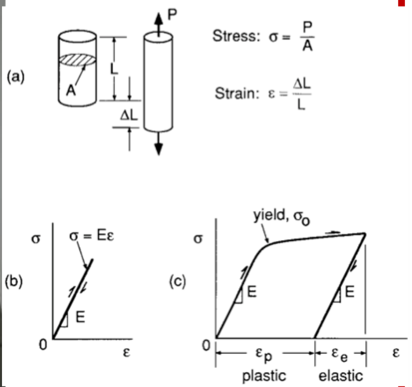

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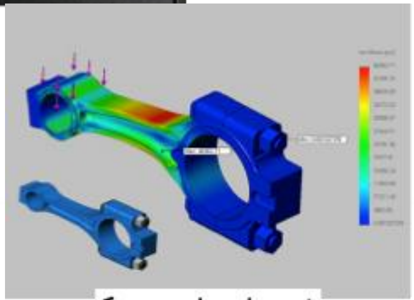

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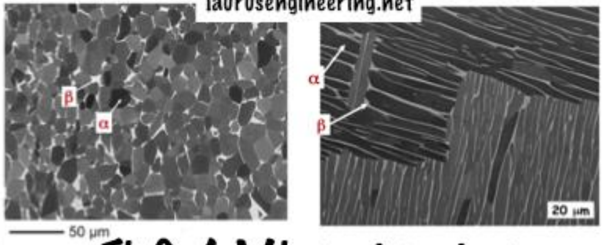


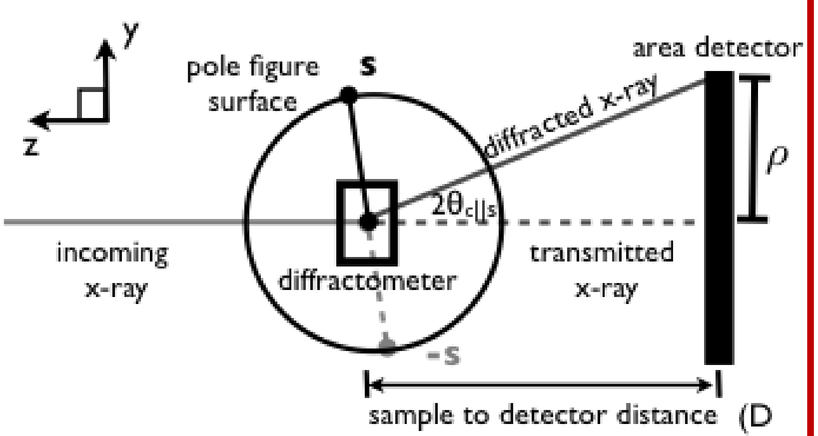
Ti-6-4 Microstructures

HEXD and FEM Modeling

HEXD

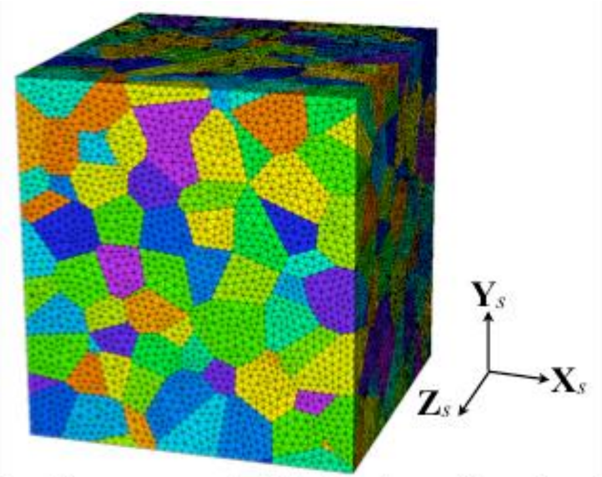
- **Transmission**
- **Near and Far Field Detectors**
  → Grain Maps
- **Evolving intensity distributions**
  - Spots – individual grains
  - Rings – distribution of grains
- **In situ loading and residual strains**

Experiment Geometry



FEM

- **Crystal scale elastoplastic deformation**
- **Assemble polycrystal**
- **Mimic loading of HEXD sample**
- **Deformation of individual grains**
- **Comparison to data: virtual diffractometer**



Neper generated finite element mesh

Experimental Challenge

What experimenters want:

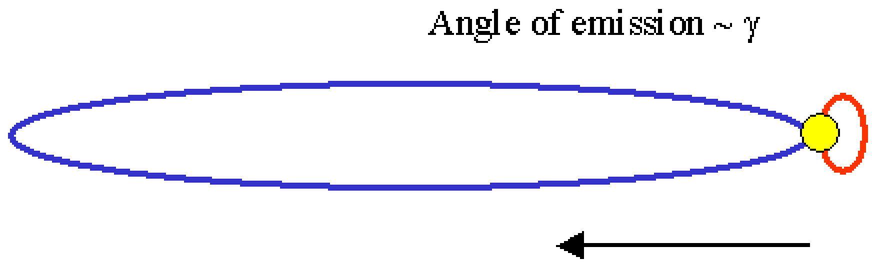
1. 50-100 keV x-rays for penetration through several mm of metal
2. Sub 1 µm spot (needs to be smaller than typical grain size)
3. Good angular collimation $(\delta k_{\perp}/k \leq 10^{-3})$
4. Narrow bandwidth $(\delta E/E \leq 10^{-3})$
5. High intensity > 10^{14} / second on sample (time resolution)
6. High-speed, high-spatial resolution, high-energy x-ray, area detectors
7. X-ray beam rastering
8. Software

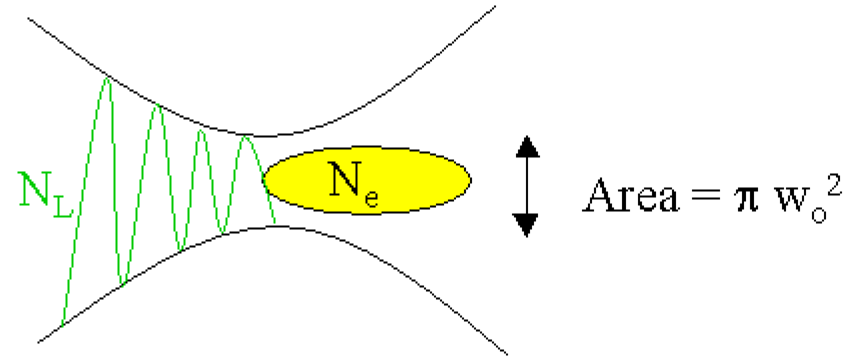
$$\mathcal{B} > 10^{20} \frac{\mathrm{ph/sec}}{(\mathrm{mm{\cdot}mrad})^2{\cdot}0.1\%\mathrm{bw}} \text{ at } \hbar\omega = 100\ \mathrm{keV}$$

Inverse Compton Scattering

W. S. Graves, W. Brown, F. X. Kaertner, and D. E. Moncton, "MIT inverse Compton source concept," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **608** (1, Supplement 1), S103-S105 (2009).

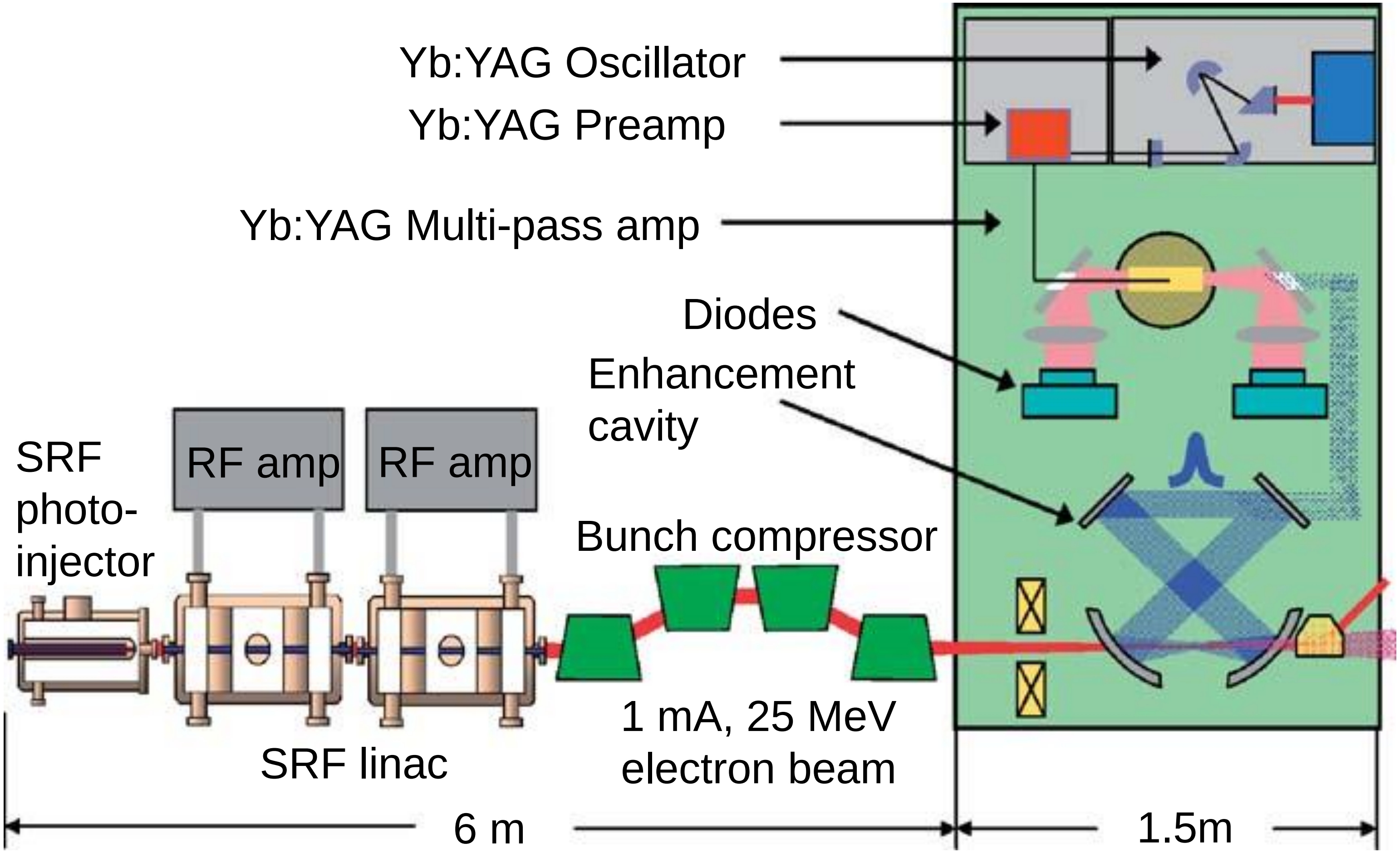
As the electron oscillates in its rest frame, it radiates (Thompson Scattering) at the same wavelength as the (doppler shifted) incident radiation. Back in the laboratory frame however this radiated electromagnetic has received another doppler shift:





Upshift: $\lambda = \lambda_0 \left(\frac{1 - v/c}{1 + v/c} \right) \approx \frac{\lambda_0}{4\gamma^2}$ (Ultrarelativistic)

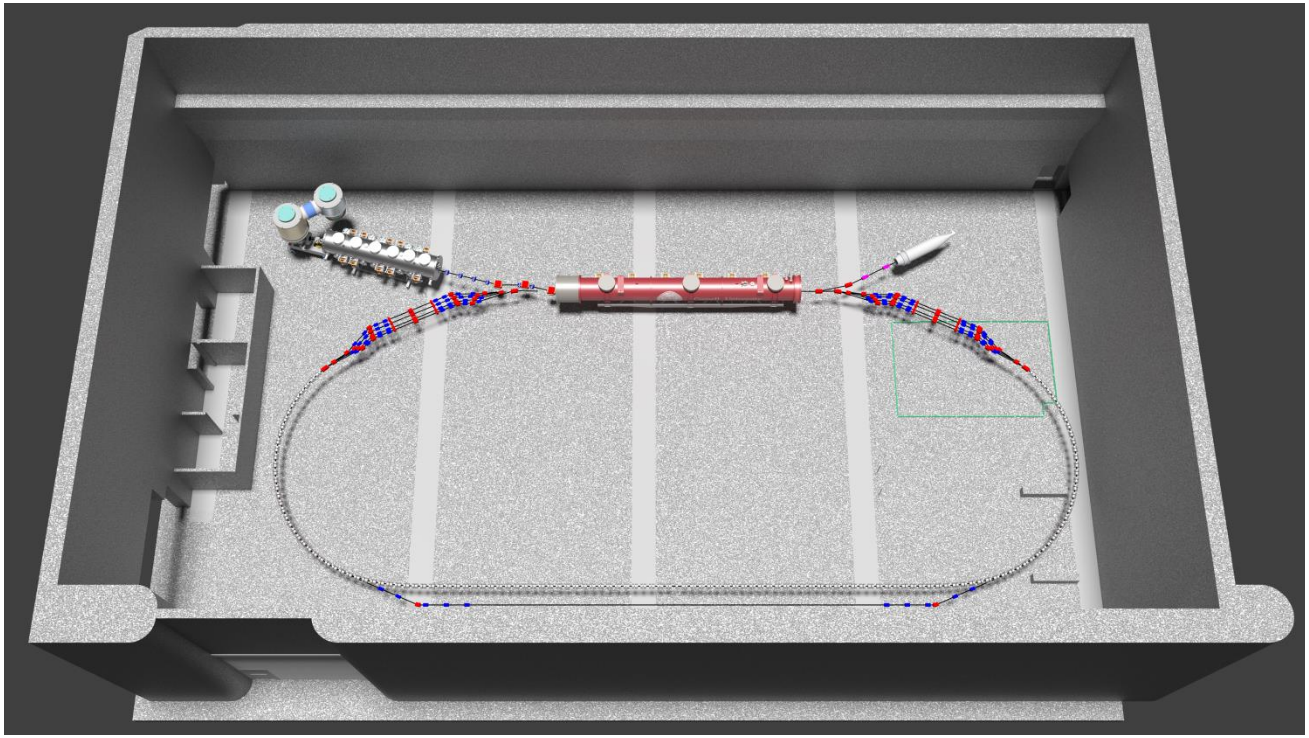
MIT Design



Yb:YAG Oscillator
Yb:YAG Preamp
Yb:YAG Multi-pass amp
Diodes
Enhancement cavity
SRF photo-injector
RF amp
RF amp
Bunch compressor
1 mA, 25 MeV electron beam
SRF linac
6 m
1.5m

Combine an Enhancement Cavity with an ERL

Higher energy beam from FFAG/ERL (to reduce angular divergence) + high average electron beam current (rep rate), plus enhancement cavity to increase flux -> high flux, high energy, time-resolved hard x-rays



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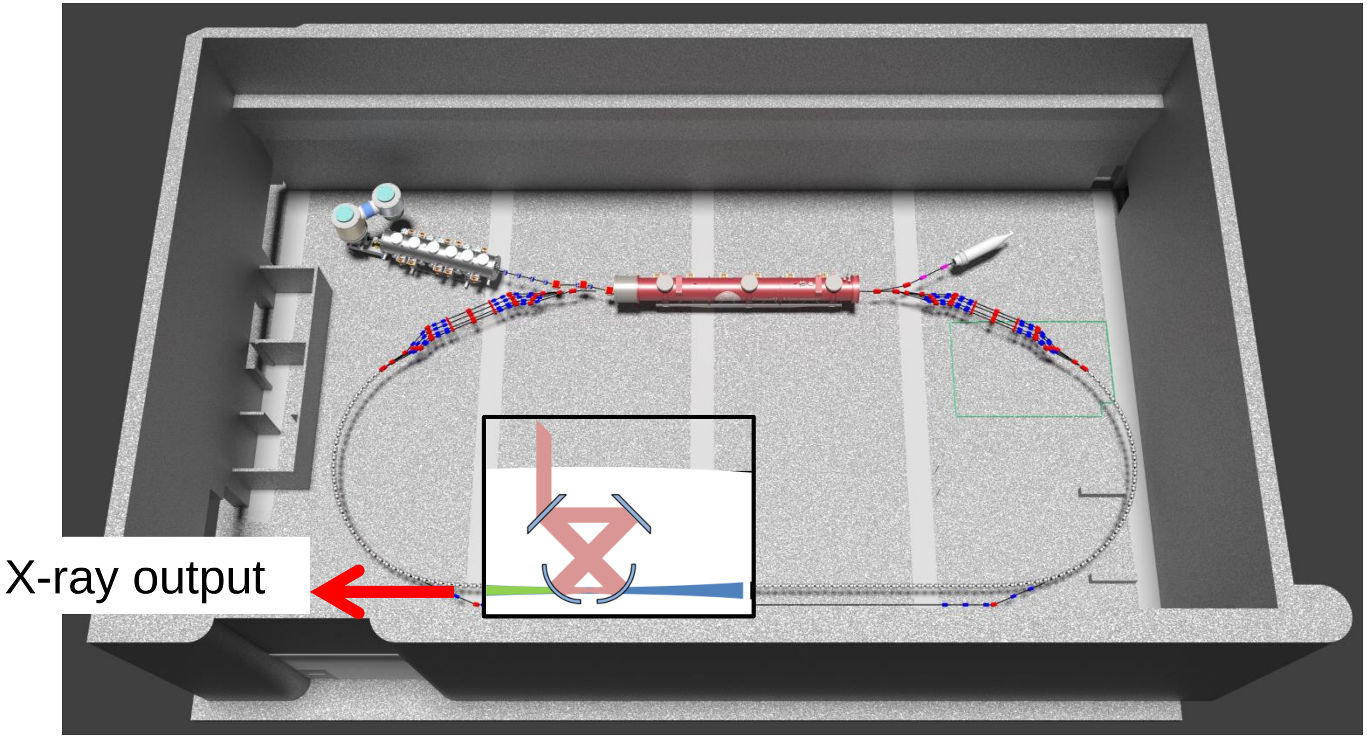


Comparison to MIT Design

of x-rays generated per pulse

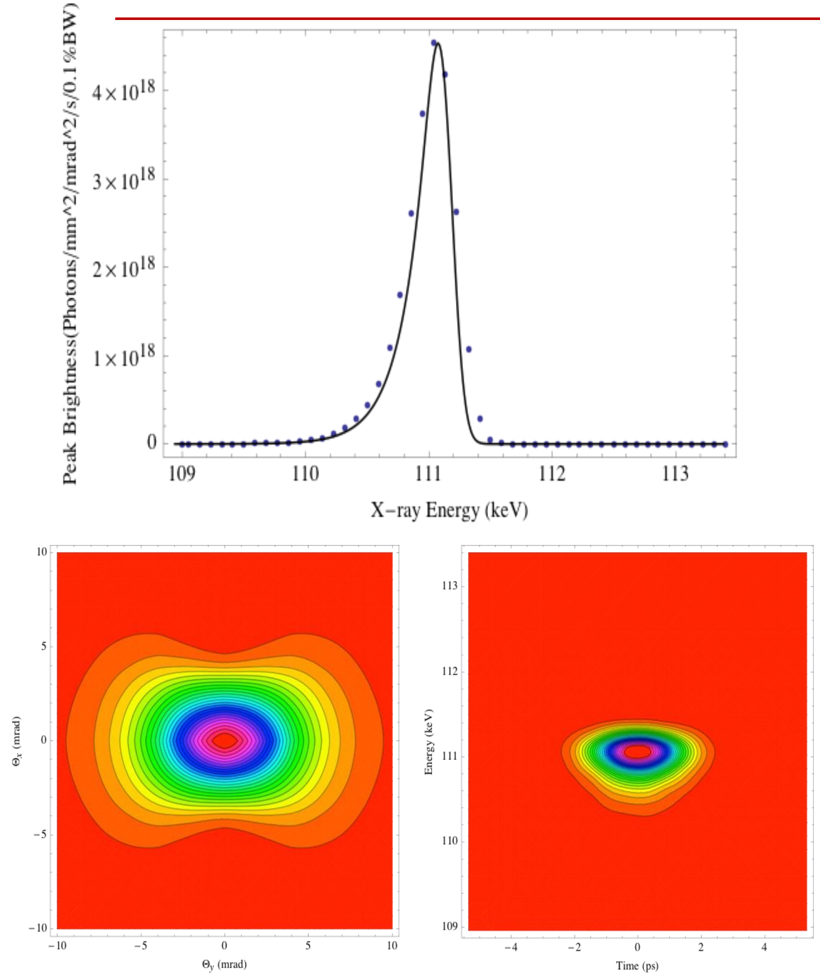
$$N_x = \frac{N_e N_\gamma \sigma_T}{2\pi(\boldsymbol{x_L}^2 + \boldsymbol{x_e}^2)} FF$$

Time-average spectral brightness

$$B_{avg} \cong 1.5 \times 10^{-3} \frac{N_e N_\gamma \sigma_T \gamma^2}{(2\pi)^3 \varepsilon_{nx}{}^2 \boldsymbol{x_L}^2} F_{rep}$$

Parameter	**MIT**	**ERL**
Tunable photon energy (keV)		
Pulse length (ps)	0.1	.05-2
Flux per shot (photons)	3.00E+06	6.00E+06
Repetition rate (Hz)	1.00E+08	1.00E+08
Average flux (photons/s)	3.00E+14	6.00E+14
On-axis bandwidth (%)	1	1.3
RMS Divergence (mrad)	1	1.8
Source RMS size (mm)	0.002	0.02
Peak Brilliance (ph/s/mm^2/mrad^2/0.1%BW)	6.00E+19	2.62E+21
Average Brilliance (ph/s/mm^2/mrad^2/0.1%BW)	2.00E+15	5.23E+17
E (MeV)	25	286
γ	48.9	559.7
photon energy (eV)	1.19E+04	1.55E+05
optical divergence (mrad)	20.4	1.8
ε_{nx} (µm)	0.1	0.15
x_e (µm)	2	10
x_e' (mrad)	1.02	0.03
Δt_e (ps)		2
x_L (µm)	2	10
Δt_L (ps)	0.3	5
λ (µm)	1	10
Q_e (pC)	10	100
W_γ (mJ)	10	5

Simulated Performance* - 76 MeV

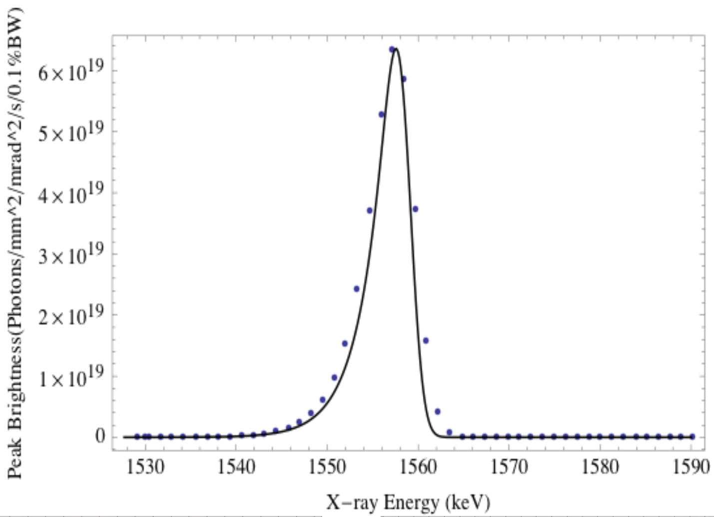


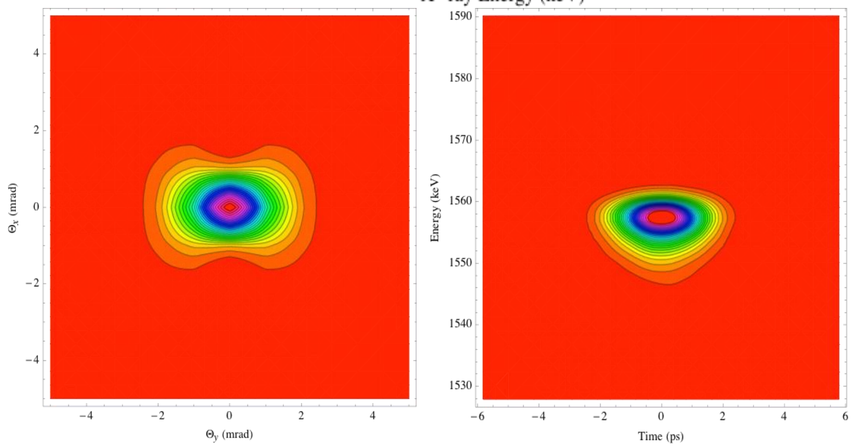
E = 76 MeV, 100 pC
1 um laser wavelength
50 mJ per pulse
100 MHz enhancement cavity

Produces a flux of over
$1x10^{13}$ photons/s

*Three-dimensional time and frequency –domain theory of femto-second x-ray pulse generation through Thomson scattering", W.J. Brown and F.V. Hartemann, Phys. Rev. STAB 7, 060703, (2004)

Simulated Performance - 286 MeV



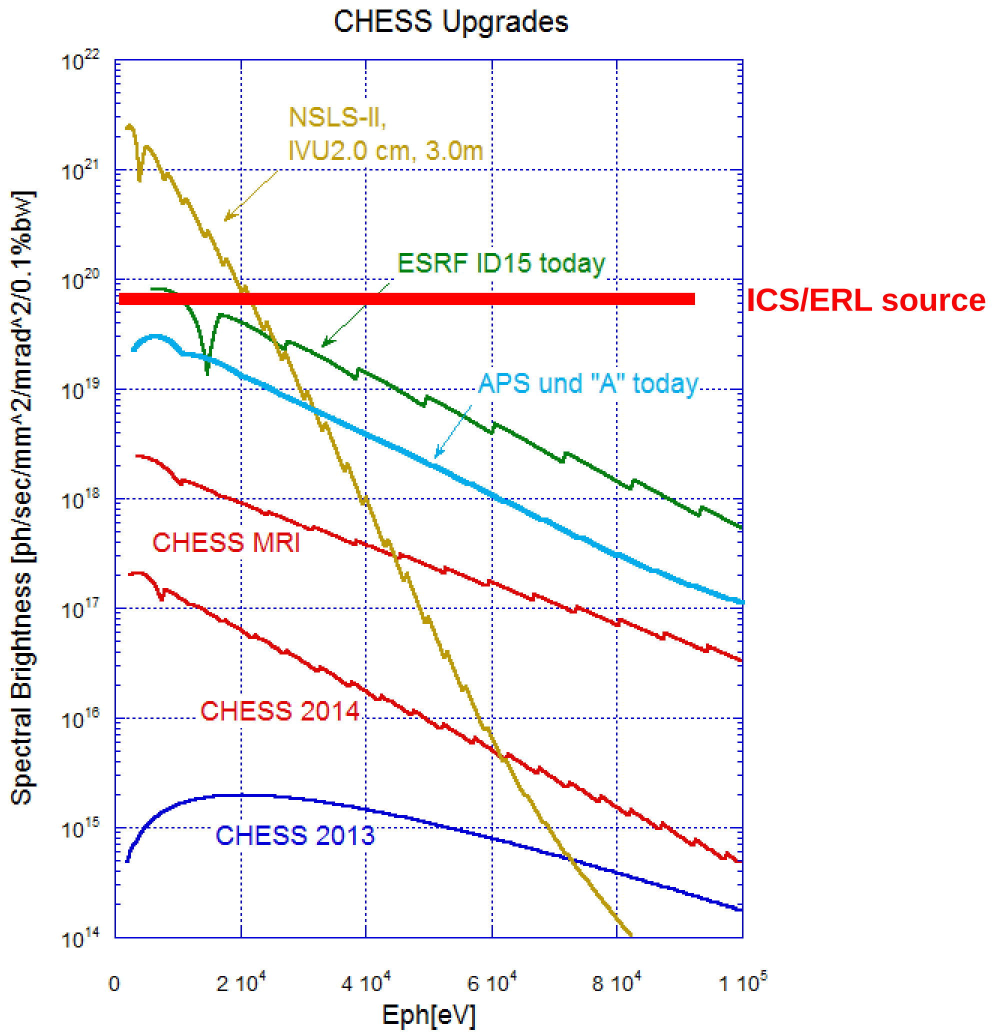


E = 286 MeV, 40 pC
1 um laser wavelength
50 mJ per pulse
100 MHz enhancement cavity

Produces a flux of over $1\text{x}10^{13}$ photons/s

With a 1 um laser, produces 1550 keV photons, so in reality we would use a 10 um laser to get 150 keV photons.

Brightness Plot with ICS Source



What else could you do with this?

1. **Structural Materials: (e.g., Matt Miller – Cornell)**
   a. If can focus to 0.1 µm spot, then can raster hard x-ray beam.
   b. Rastering eliminates grain size challenge – all materials (especially real ones) are now open for study.
2. **Time-resolved Diffraction Studies: (e.g. Aaron Lindenberg - Stanford)**
   a. Picosecond x-ray pulses (high energy, high flux) are not available anywhere else – including XFELs.
3. **Time-resolved or Spatially Resolved Pair Distribution Function Studies: (e.g., Simon Billinge – Columbia)**
   a. High energy (150 keV) x-rays
   b. Small Spots
   c. Short pulses
4. With shorter laser wavelength (or higher beam energy), we can generate gamma ray beams for nuclear physics, astrophysics and nuclear material studies.