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

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ICFA Hamburg
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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 = 4x10^9 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

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

* 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 = $4 \times 10^9$ ph/s in 300 $\mu$m

• 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.)

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

Courtesy of Ron Ruth
Compact X-ray Sources

• Fixed Tubes and Rotating Anodes
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• Plasma Sources
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• 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
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 (γ = 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 $\hbar \omega_X < E_e$.
- The scattered photon satisfies the undulator equation with period $\lambda_L/2$ for head-on collisions:
  \[ \lambda_X = \frac{\lambda_L (1 + \gamma^2 \theta^2)}{4 \gamma^2} \]
- Therefore, the x-ray energy decreases by a factor of 2 at an angle of $1/\gamma$. 

\[ \text{energy} = E_e = \gamma m_e \]

\[ \lambda \]

\[ \lambda_X \]

\[ \lambda_L \]

\[ \theta \]
Example of Complete Calculation

\( \omega_X (\text{keV}) \)

\( \gamma_e = 100 \ (50 \text{ MeV}) \)

\( \lambda_L = 800 \text{ nm} \)


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 \( \varepsilon_{xz} = 1 \text{ mm mrad} \) focused to an rms spot size of 20 \( \mu \text{m} \) with an 800 nm, 0.5 ps bandwidth laser pulse polarized in the x direction.
Photon Distribution Has Nearly Axial Symmetry

\[ \phi = \frac{\pi}{2} \quad \text{when incident photon is polarized in the scattering plane} \]

\[ \frac{dI}{d\Omega \; dt} \propto \frac{1}{(1 + \gamma^2 \theta^2)^3} \left[ 1 - \frac{4\gamma^2 \theta^2}{(1 + \gamma^2 \theta^2)^2} \sin^2 \phi \right] \]

FWHM=1/\gamma

FWHM=0.6/\gamma
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

\[
\frac{\Delta \omega_X}{\omega_X} = \frac{\Delta \omega_L}{\omega_L}
\]

\[
\frac{\Delta \omega_X}{\omega_X} = 3 \cdot 10^{-3}
\]

for a 1 ps (300 μ) pulse of \( \lambda_L = 1 \mu \) photons
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 $\mu$m laser focus (dark blue line), 10 $\mu$m laser focus (green line), and 5 $\mu$m laser focus (light blue line).
Bandwidth and Divergence Effects

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

\[
\frac{\Delta \omega_X}{\omega_X} = 2 \frac{\Delta \gamma}{\gamma} \quad \text{typically} \quad 2 \cdot 10^{-4}
\]
Bandwidth and Divergence Effects

4) Electron Divergence

\[ \frac{\Delta \omega_x}{\omega_x} = \frac{\gamma^2}{2} (\Delta \xi)^2 \]

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

\[ \Delta x \approx 10^{-5} \text{ m for focal spot size } 10 \mu \]
\[ \Delta \xi \approx 10^{-3} \text{ rad} \]

\[ \frac{\Delta \omega_x}{\omega_x} = \frac{100^2}{2} (10^{-3})^2 \approx 5 \cdot 10^{-3} \]
Sensitivity to Electron Beam Divergence

(Focal spot fixed at 20 μ)

Emittance = 1 μ
Emittance = 2 μ

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, $k_\perp$:

$$\Delta \theta_{xL} = \frac{\Delta \omega}{\omega} \approx \Delta \theta^2 \approx \left(\frac{\lambda_0}{\pi W_0}\right)^2$$

Laser Bandwidth/Electron Energy Spread:

$$\Delta \gamma/\gamma \quad \Delta \omega_0 > 2/\Delta t_0$$

Electron Emittance:

$$\Delta \omega = \frac{\varepsilon_{nx}^2}{\chi_f^2}$$

Spectral Density (a.u.)

15 May 2006
MIT Inverse Compton Source Concept

- **Injector Power Supply**
- **Linac Power Supply**
- **Yb:YAG Power Supply**
- **Yb:YAG Oscillator**
- **Multi-pass Yb:YAG Amplifier**
- **Photoinjector Laser**
- **SRF Gun**
- **Solenoid**
- **SRF Linac**
- **Focusing Quadrupoles**
- **Collimating Chicane**
- **LHe Dewar**
- **LHe Refrigerator**

Dimensions:
- 7 m
- 3 m
- 1.5 m
Superconducting RF Electron Gun

Rossendorf design to be manufactured by Accel Instruments

1.3 GHz RF frequency, Cs$_2$ Te cathode
Current = 1 mA
Charge = 100 pC per pulse at 10 MHz
Exit energy = 8 MeV

Cryostat with cathode exchange system.
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.
Final focus is SC solenoid or quad triplet with \( f = 18 \) cm

- Spot size on mirrors large enough to avoid damage: \( 5 \text{J/cm}^2 \)
- 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

1 μm Yb:YAG
1 ps, 1μJ, 10 MHz, 10W

Laser Oscillator/Amplifier
T. Y. Fan, MIT Lincoln Labs

Cryo-cooled Yb:YAG multi-pass amplifier
1ps, 100μJ, 10 MHz 1kW

Continuous 10mJ operation

Enhancement cavity x100

Electron beam

10MHz, 0.1nc/bunch

X-ray beam

15 May 2006
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

Focal spot = 5 microns (rms)

ε_n = 0.3 μm
ε_n = 1.0 μm
Optimizing X-ray Flux and Brightness

Electron Beam Parameters

- $\varepsilon_n = 1$ mm-mrad (25 MeV)
- Rms spot size = 10 $\mu$m
- $Q = 0.1$ nC

Laser Parameters

- $\lambda = 1$ $\mu$m
- $W = 10$ mJ
- Pulse duration = 0.5 ps

Performance vs. Laser Spot Size For Different Electron Bunch Durations

![Graph showing the relationship between laser spot size and total X-ray dose and average brightness/rep. rate for different electron bunch durations.](image-url)

15 May 2006

30
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

Electron pulse too long

Electron pulse matched

Poor efficiency at head and tail
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**
- $\lambda = 1 \ \mu m$
- $W = 10 \ \text{mJ}$
- Rms Duration = 0.5 ps

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

![Graph showing the relationship between total X-ray dose and average brightness/rep. rate vs. rms laser spot size for different electron beam focus sizes.](image-url)
X-ray Performance Depends on Electron Bunch Duration

Electron Beam Parameters
- $\varepsilon_n = 0.68$ mm-mrad (25 MeV)
- Rms spot size = 4.3 $\mu$m
- $Q = 0.1$ nC

Laser Parameters
- $\lambda = 1$ $\mu$m
- $W = 10$ mJ
- Pulse duration = 0.5 ps

The graphs show the total X-ray dose and average brightness/repetition rate for different combinations of electron bunch duration and laser spot size.
Performance Enhanced by Reduced Emittance

**Electron Beam Parameters**
- $\varepsilon_n = 0.30 \text{ mm-mrad (25 MeV)}$
- Rms spot size = 2.9 $\mu$m
- $Q = 0.1 \text{ nC}$

**Laser Parameters**
- $\lambda = 1 \mu$m
- $W = 10 \text{ mJ}$
- Pulse duration = 0.5 ps

---

**Graphs**

- **Total X-ray Dose**
  - Data points for different pulse durations: 0.125 ps, 0.25 ps, 0.5 ps, 1 ps, 2 ps, 5 ps, 10 ps.

- **Avg. Brightness/Rep. Rate**
  - Data points for different pulse durations: 0.125 ps, 0.25 ps, 0.5 ps, 1 ps, 2 ps, 5 ps, 10 ps.
Intensity Profile of 12 keV X-rays With 0.01% Full Width Energy Filter

Photons/pulse = 900
## Large Time-Average-Flux Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy [keV]</td>
<td>12</td>
</tr>
<tr>
<td>Total x-ray flux per pulse (5% BW)</td>
<td>5e5</td>
</tr>
<tr>
<td>Peak spectral density per pulse [photons/eV]</td>
<td>800</td>
</tr>
<tr>
<td>Repetition rate [MHz]</td>
<td>10</td>
</tr>
<tr>
<td>Average x-ray flux @ 10 MHz (5% BW)</td>
<td>5e12</td>
</tr>
<tr>
<td>Average x-ray flux @ 10 MHz (0.1% BW)</td>
<td>2e11</td>
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<tr>
<td>On-axis spectral width FWHM [keV]</td>
<td>0.1</td>
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<tr>
<td>Spectral width FWHM [keV]</td>
<td>0.6 (5%)</td>
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<tr>
<td>Avg on-axis brilliance [photons / (mm² mrad² sec 0.1%)]</td>
<td>6e14</td>
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<tr>
<td>Peak on-axis brilliance [photons / (mm² mrad² sec 0.1%)]</td>
<td>2e19</td>
</tr>
<tr>
<td>Pulse length FWHM [ps]</td>
<td>0.1 - 3</td>
</tr>
<tr>
<td>RMS size of source [μm]</td>
<td>4</td>
</tr>
<tr>
<td>RMS opening angle [mrad]</td>
<td>3.5</td>
</tr>
</tbody>
</table>
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
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)
Applications

- Protein Crystallography
  - Rigaku FR-E produces $4 \times 10^9$ ph/sec (Cu–Kα) in a 0.3 mm aperture and is useful for $\sim 100 \ \mu m$ crystals
  - 10 $\mu m$ crystals are much more readily produced but not measurable with the FR-E
  - With ideal optics, the ICS source produces $4 \times 10^{11}$ ph/sec in a 0.03 mm aperture allowing 10 $\mu m$ crystal data to be taken
  - The diffraction intensity and quality will be similar to the FR-E/100 $\mu m$ 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); ΔE = 16 eV; R = 67%

**MAD:**  
Si (111); ΔE = 7 eV; R = 80%
Fixed Wavelength Asymm Ge(111)

$E = E_0 + \Delta E$ [meV]

- $E_0 = 10$ keV, $\Delta \theta = 100 \mu$rad, $\Delta E = 16.28$ eV, $R = 0.67$
- Crystal 1: Ge(111); $\eta = 30.3^\circ$, $\phi = 190^\circ$, $\theta = 12.981^\circ$, $l_2 = 10000 \mu$m, $b = 0.0329\times56$
- Crystal 2: Ge(111); $\eta = 30.3^\circ$, $\phi = 0^\circ$, $\theta = 10.9412^\circ$, $l_2 = 10000 \mu$m, $b = 32.5411$

Calculations by Yuri Shvyd’ko

MAD Asymm Si(111)

$E = E_0 + \Delta E$ [meV]

- $E_0 = 12.65$ keV, $\Delta \theta = 50.09 \mu$rad, $\Delta E = 7.42$ eV, $R = 0.804$
- Crystal 1: Si(111); $\eta = 8.05^\circ$, $\phi = 180^\circ$, $\theta = 9.00124^\circ$, $l_2 = 10000 \mu$m, $b = 0.056721$
- Crystal 2: Si(111); $\eta = 8.05^\circ$, $\phi = 0^\circ$, $\theta = 8.99195^\circ$, $l_2 = 10000 \mu$m, $b = 18.0508$

Calculations by Yuri Shvyd’ko

15 May 2006
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)$^3$

\[
I = 5.35 \times 10^{10} \text{ p/sec}
\]

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

\[
I = 2.92 \times 10^{10} \text{ p/sec}
\]
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

1μm Yb:YAG
10ps, 1μJ, 10MHz

Stretcher 100ps

pulse picker
@ 1-100Hz

Yb-YAG Preamplifier
10μJ x 200 = 2mJ

1 2...200

200 pulse bunch

10J loaded

Compressor 10 ps, 100mJ

Cryo-cooled Yb:YAG
multi-pass amplifier
100 mJ x 200 = 20J
Quasi-cw

10 Hz, 1nc/bunch, ε = 1 μm

X-ray beam
# High Flux-Per-Pulse Performance

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<td>Photon energy [keV]</td>
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<tr>
<td>Total x-ray flux per pulse (17% BW)</td>
<td>4e9</td>
</tr>
<tr>
<td>Peak spectral density per pulse [photons/eV]</td>
<td>2e6</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>10</td>
</tr>
<tr>
<td>Average x-ray flux @ 10 Hz [photons/sec] (17% BW)</td>
<td>4e10</td>
</tr>
<tr>
<td>On-axis spectral width FWHM [keV]</td>
<td>0.2</td>
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<tr>
<td>Spectral width FWHM [keV]</td>
<td>2 (17%)</td>
</tr>
<tr>
<td>Average brilliance [photons / (mm² mrad² sec 0.1%)]</td>
<td>1.4e10</td>
</tr>
<tr>
<td>Peak brilliance [photons / (mm² mrad² sec 0.1%)]</td>
<td>1.4e20</td>
</tr>
<tr>
<td>Pulse length FWHM [ps]</td>
<td>9</td>
</tr>
<tr>
<td>Size of source RMS [μm]</td>
<td>7</td>
</tr>
<tr>
<td>Opening angle RMS [mrad]</td>
<td>7</td>
</tr>
</tbody>
</table>

Results from 3D-code of W. Brown, MIT Lincoln Lab
APS RF Chirp Concept for Pico-second Pulses

Cavity frequency is harmonic $h$ of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is $n \times 180$ degrees

Pulse can be sliced or compressed with asymmetric cut crystal

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: $4 \times 10^9$ in 17% bandwidth, 9 ps

SPPS (Stanford)

Actual Performance

• Pulse duration: 80 fs
• Flux: $2 \times 10^6$ 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