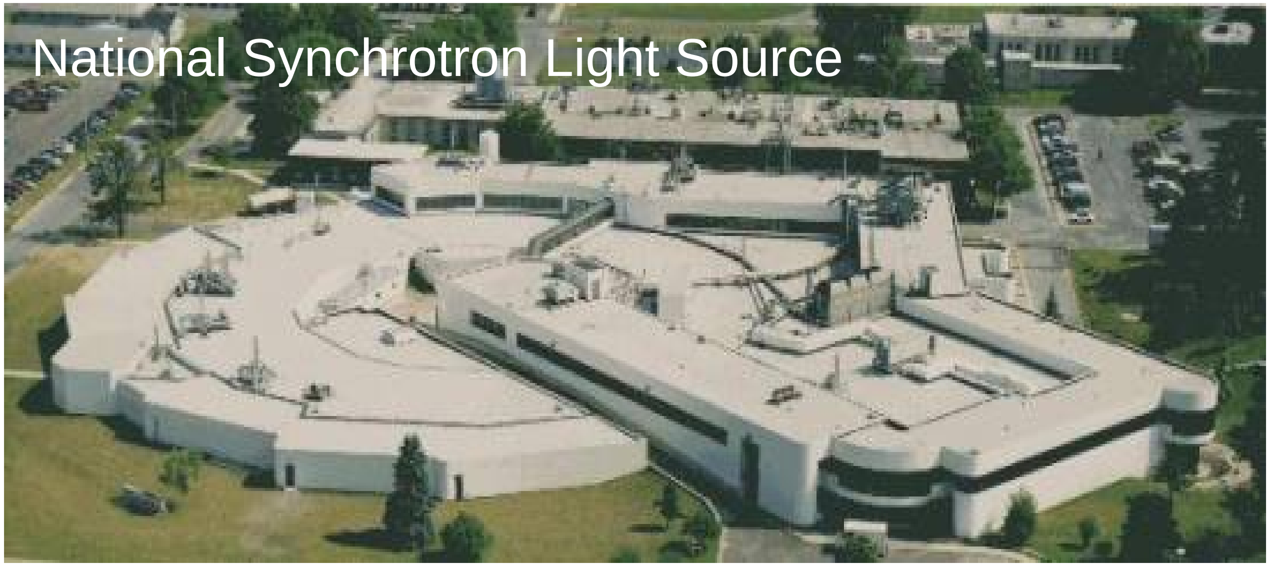
HBCU Workshop



NSLS Machine Introduction

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July 23, 2008

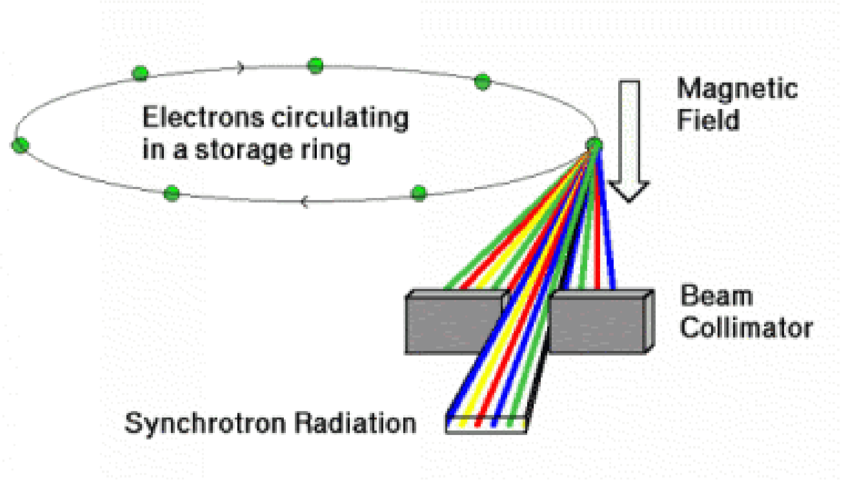
Outline

- Synchrotron Radiation (SR) Primer
  - SR definition & properties
  - Generation of SR
  - How to build a Synchrotron Light Source
- NSLS Machines
  - VUV ring
  - X-ray ring
  - Insertion Devices
  - ~~Injection System, Vacuum, RF, power supplies, controls, …~~
  - ~~Beamlines and SR User Applications (talks to follow)~~
- Conclusions and outlook

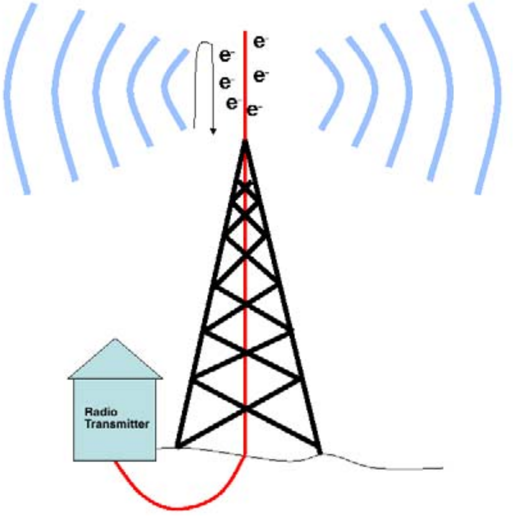
Thanks to many NSLS staff & F. Sannibale (ALS) for material used in this talk

Synchrotron Radiation

SR is EM radiation emitted when charged particles are radially accelerated (move on a curved path).



Electrons accelerating by running up and down in a radio antenna emit radio waves

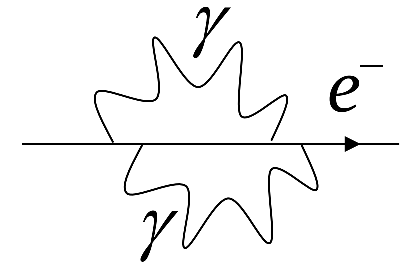


Both cases are manifestation of the same physical phenomenon:

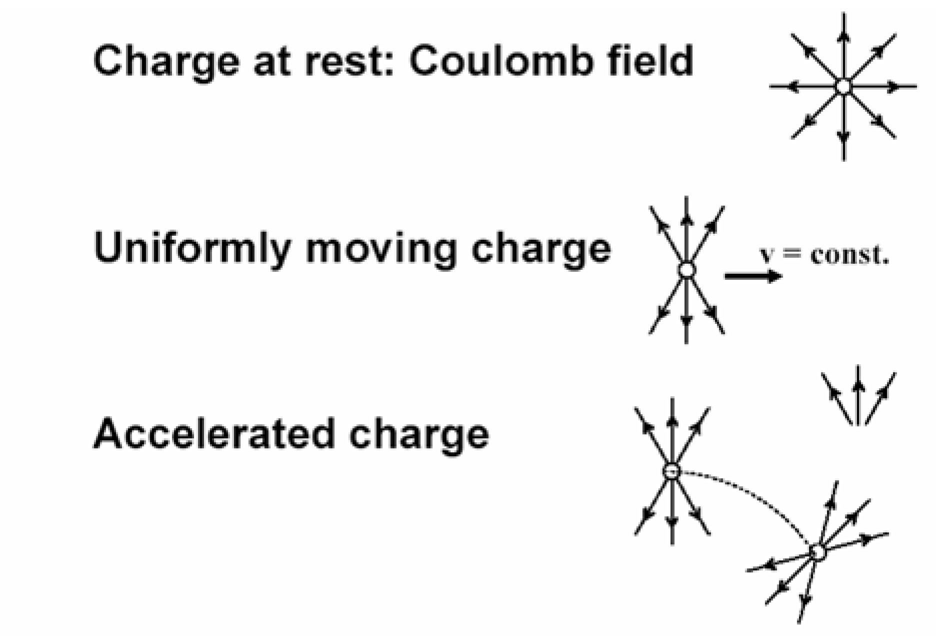
Charged particles radiate when accelerated.

Why Do Particles Emit SR?

• A charge moving in free space is "surrounded" by a cloud of virtual photons that indissolubly travel with it.

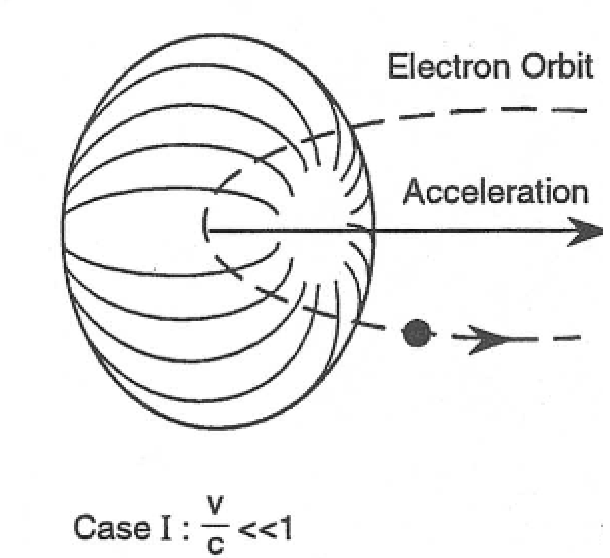


• When accelerated, the particle receives a "kick" separating it from the photons that become real and independently observable.
•Lighter particles are easier to accelerate so they radiate photons more efficiently
=> light sources use electrons

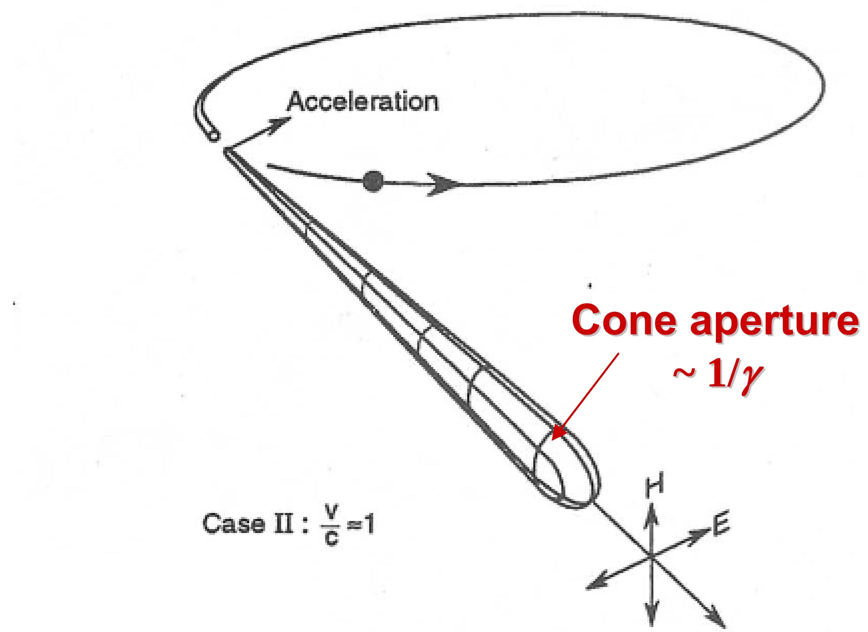


In a light source electrons follow curved trajectories in bend magnets and insertion devices. The transverse acceleration creates e^- - γ separation generating ***synchrotron radiation***.

SR Angular Distribution



At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern



When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward.

Radiation becomes more focused at higher energies.

SR Bandwidth

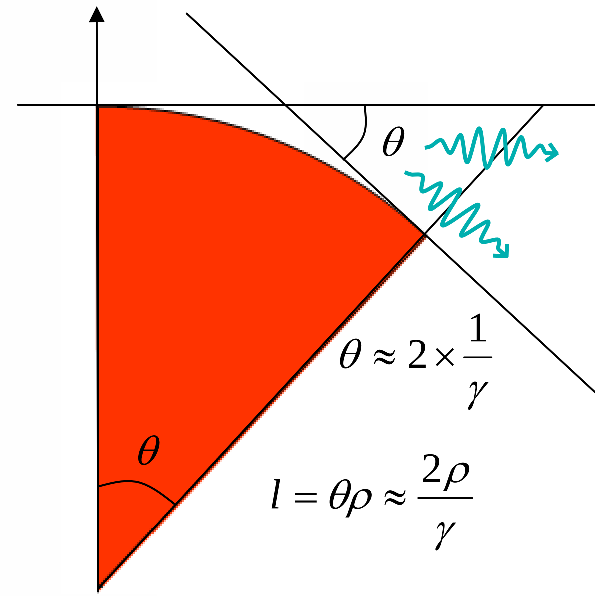
Due to extreme collimation of light

- observer sees only a small portion of electron trajectory **(a few mm)**

$$l \sim \frac{2\rho}{\gamma}$$

- Pulse length: difference in times it takes an electron and a photon to cover this distance

$$\Delta t \sim \frac{l}{\beta c} - \frac{l}{c} = \frac{l}{\beta c}(1-\beta) \quad \Longleftrightarrow \quad \Delta\omega = \frac{1}{\Delta t}$$



X-ray Ring Bend Magnet (ε_c=7.1 keV):

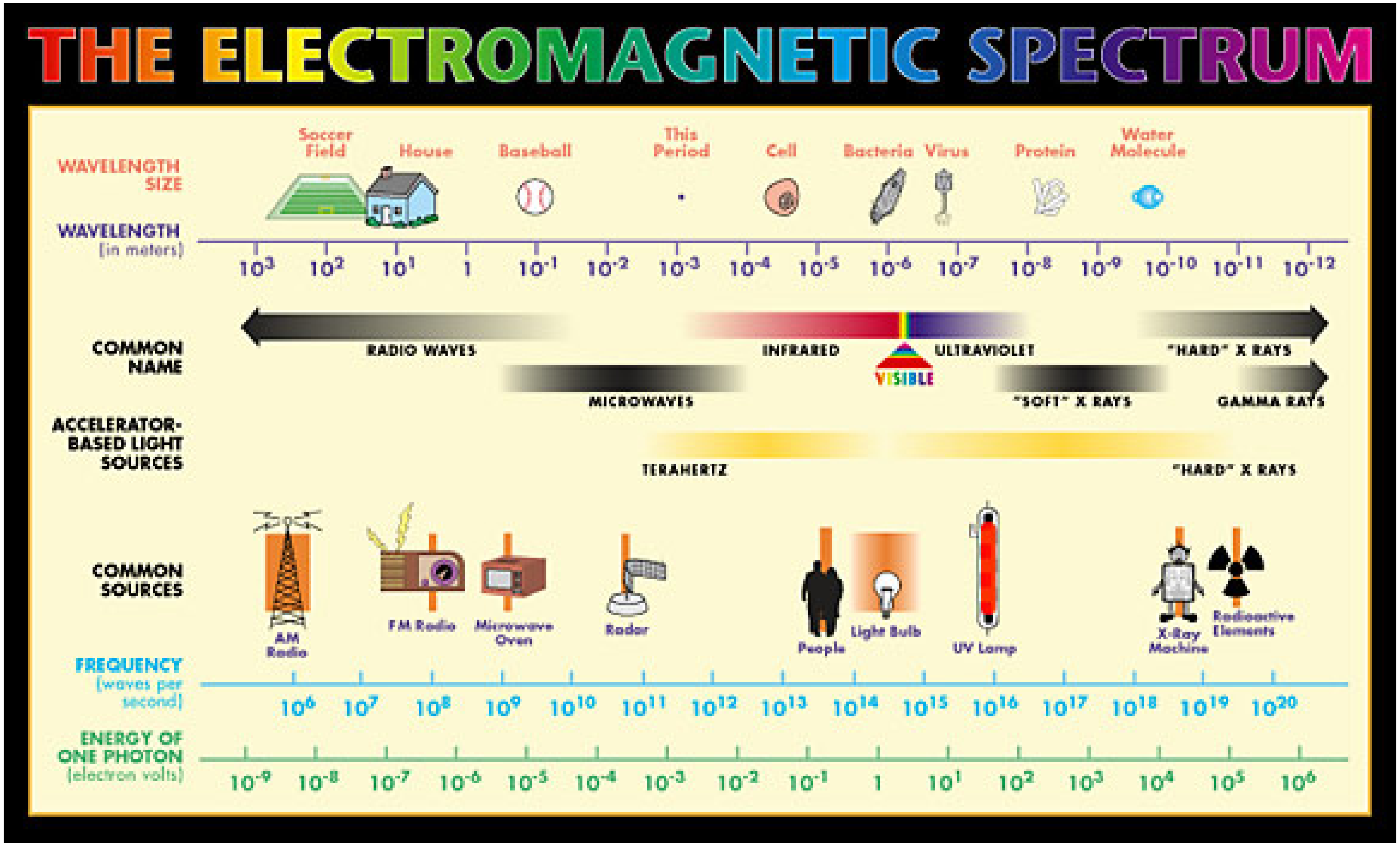
E=2.8 GeV (γ=5479, 1-β=1.7×10^{-8}), ρ= 6.875 m:

$$l \cong 2.5\ mm \ \Rightarrow\ \Delta t \cong 1.4\times10^{-19}\ s \ \Rightarrow\ \Delta\omega \cong 7.2\times10^{18}\ \ s^{-1}$$

$$\omega \approx \Delta\omega \cong 7.2\times10^{18}\ \ s^{-1} \quad \Leftrightarrow \quad \varepsilon \approx \Delta\varepsilon = \hbar\,\omega \cong 4.7\,keV$$

Very broad-band

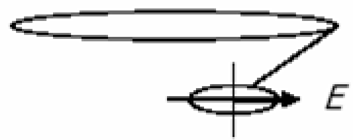
SR Spectrum



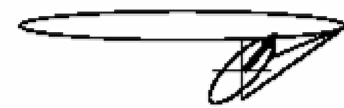
NSLS ranges from 0.12 meV (U12 IR) to 100 KeV (X17 SCW)

SR Polarization

Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal

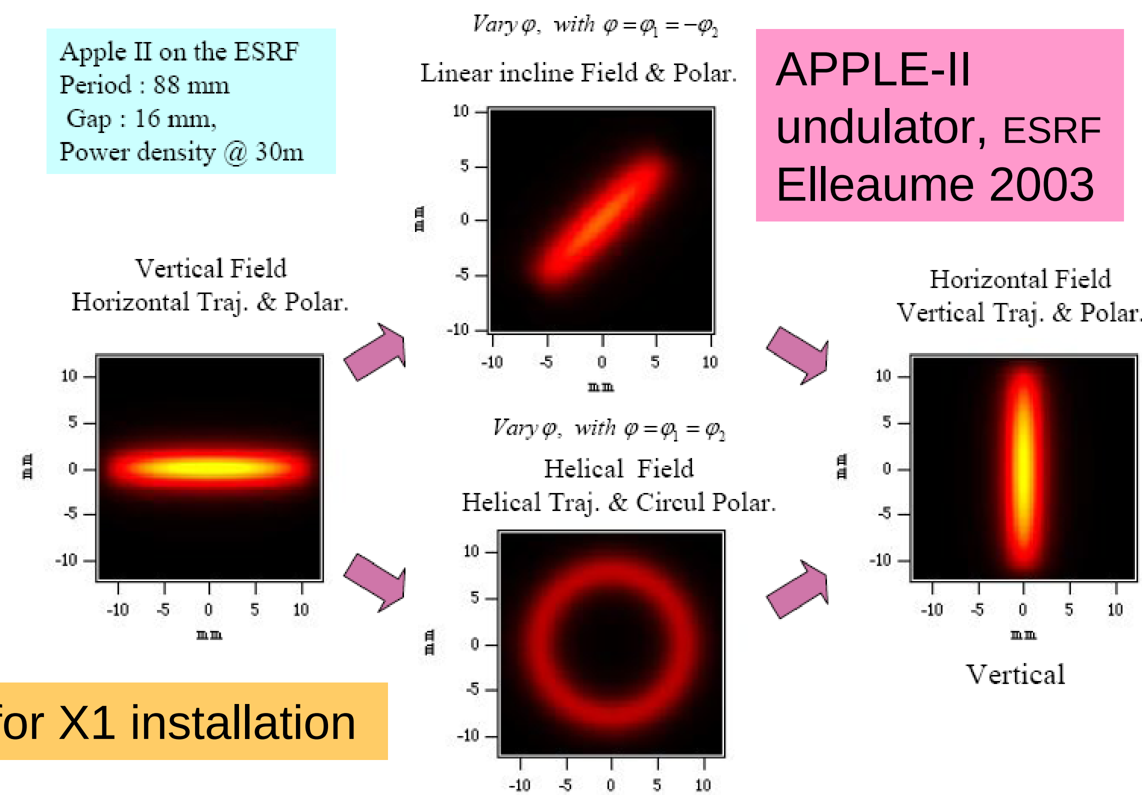


Observed out of the horizontal plane, the radiation is elliptically polarized



Specialized IDs apply “twists” to electron trajectory and make any desired (often variable) polarization

APPLE-II undulator, ESRF Elleaume 2003



Apple-II is being considered for X1 installation

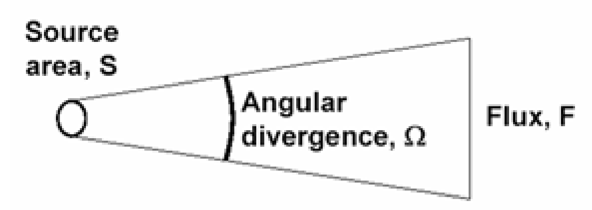
Brightness

• **brightness** is the key parameter of any particle source, incl. SR sources

• **brightness** is defined as 6-D phase space (x, p_x, y, p_y, t, E) density of particles

• **The same definition applies to the photon case**;
taking into account that the Pauli exclusion principle does not apply to bosons
=> no limitation to achievable photon brightness exists from Quantum Mech.

Brightness = $\dfrac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$



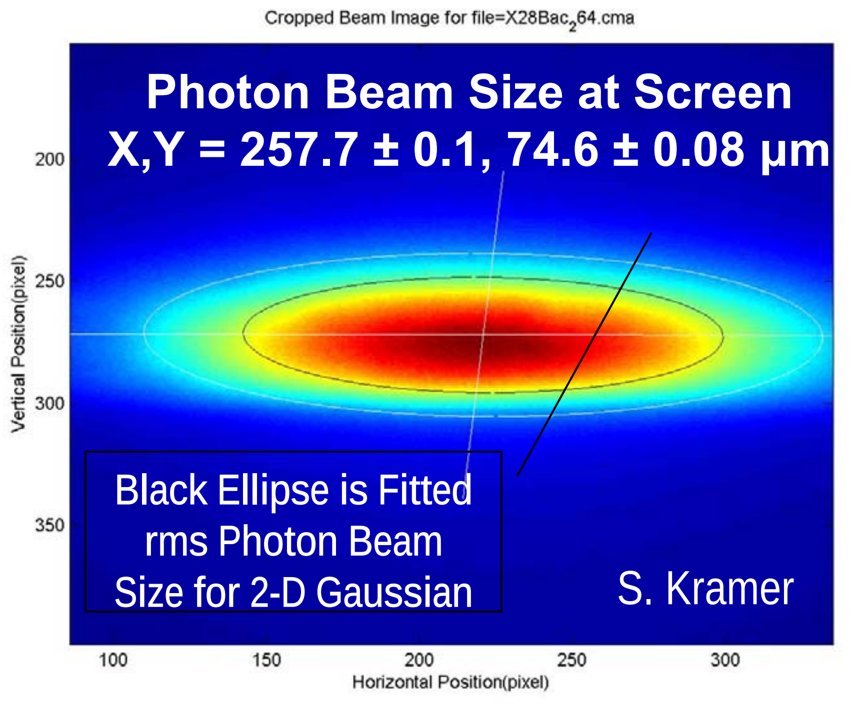
Flux = $\dfrac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec}}$

$$Flux = \frac{d\dot{N}}{d\lambda} = \int Brightness\, dS\, d\Omega$$

•**For a given flux, smaller emittance** (transverse phase space area) **sources have larger brightness**

How Do We Know the Emittance?

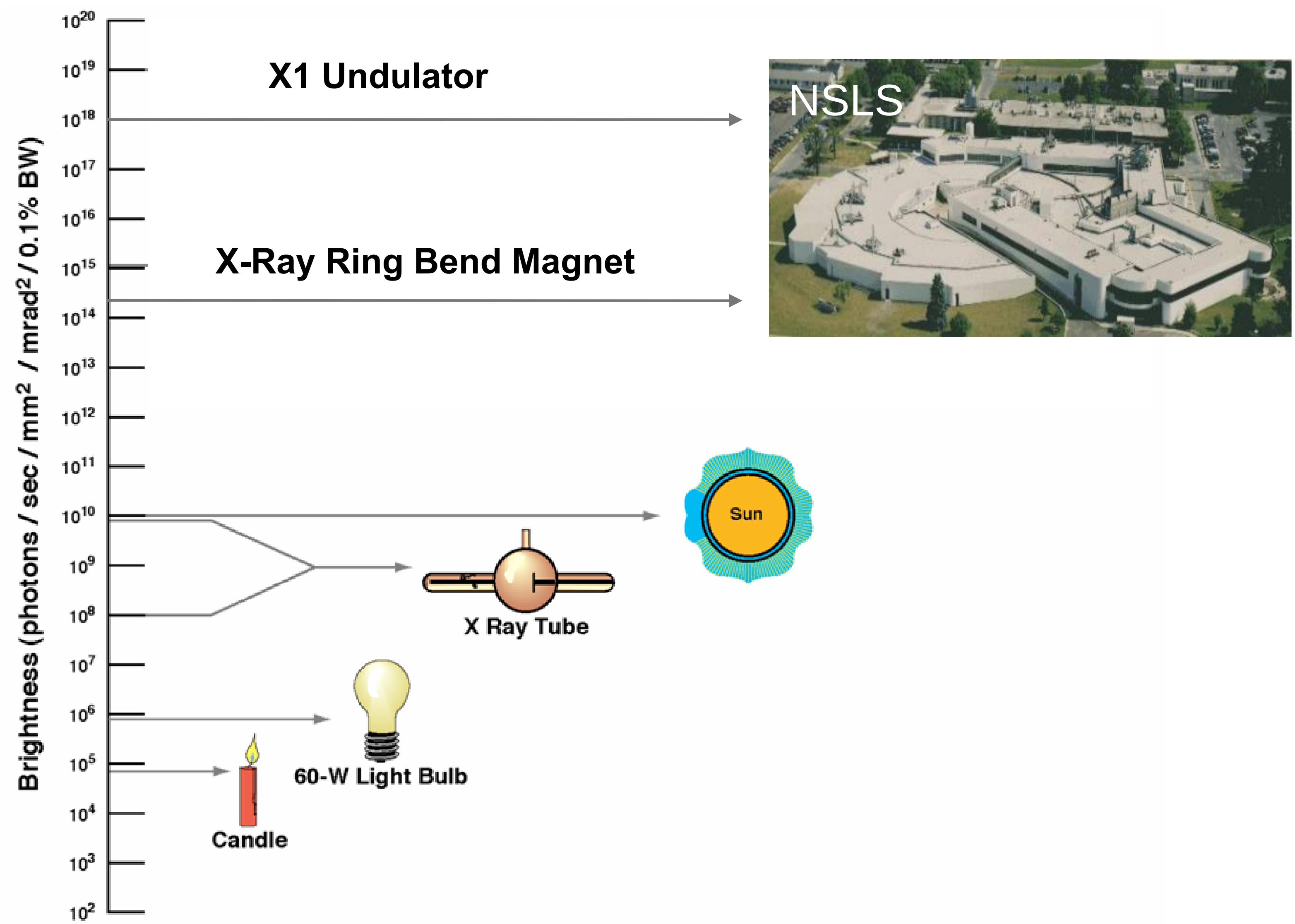
X-28 Emittance Meter: X-Ray Pinhole Camera



Emittance: $\varepsilon_{x,y}$ = 67.9 ± 3 , 0.36 ± 0.05 nm

Coupling: χ ~ 0.53 ± 0.08 %

How Bright Are We?



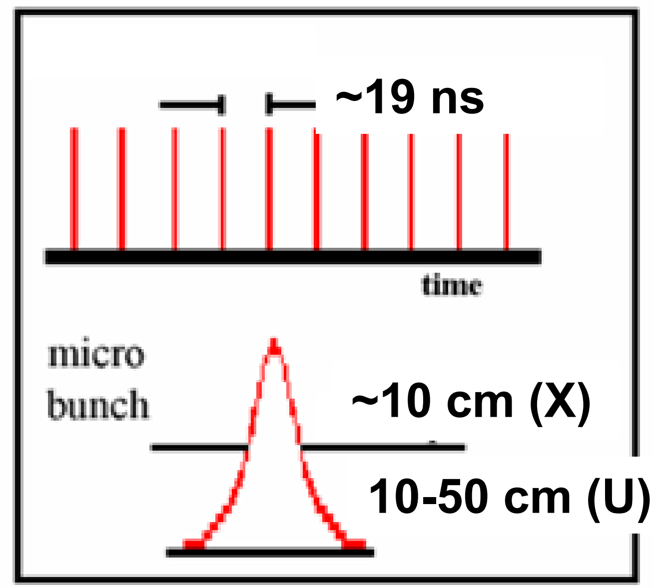
Properties of SR that Make It Useful

- High brightness and flux
- Very broad energy spectrum
- Highly polarized and short pulses

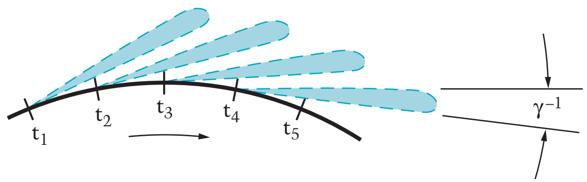
SR extends many useful properties of conventional lasers into x-ray regime!

- Partial coherence
- High stability

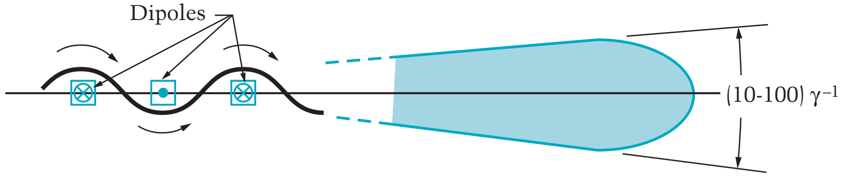
Time structure @ NSLS



SR Sources in Storage Rings



bending magnet



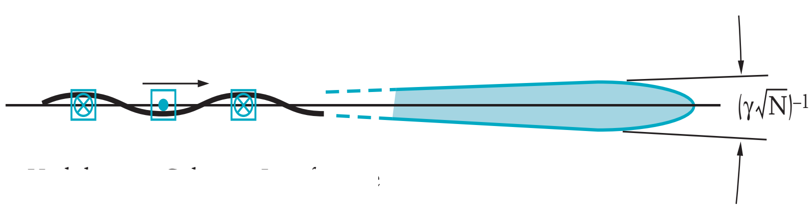
wiggler - incoherent superposition

Continuous spectrum characterized by critical energy, ε_c

ε_c(keV) = 0.665 B(T) E^2(GeV)

B = 1.4 T E = 0.8 GeV ε_c = 0.6 keV

B = 1.4 T E = 2.8 GeV ε_c = 7 keV



undulator - coherent interference

Quasi-monochromatic spectrum with peaks at

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_U}{\gamma^2} \textbf{ (fundamental)}$$

$$\varepsilon_1 \text{ (keV)} = \frac{0.95\, E^2 \text{ (GeV)}}{\lambda_u^{\text{(cm)}} \left(1 + \frac{K^2}{2}\right)}$$

K ~1 is undulator parameter

+ harmonics at higher energy

Building a Storage Ring Light Source 101

1) Take evacuated beam pipe

ADD:

2) Bends (dipoles) to form e-beam trajectory (& as SR sources)

3) Quadrupole magnets to focus e-beam transversely

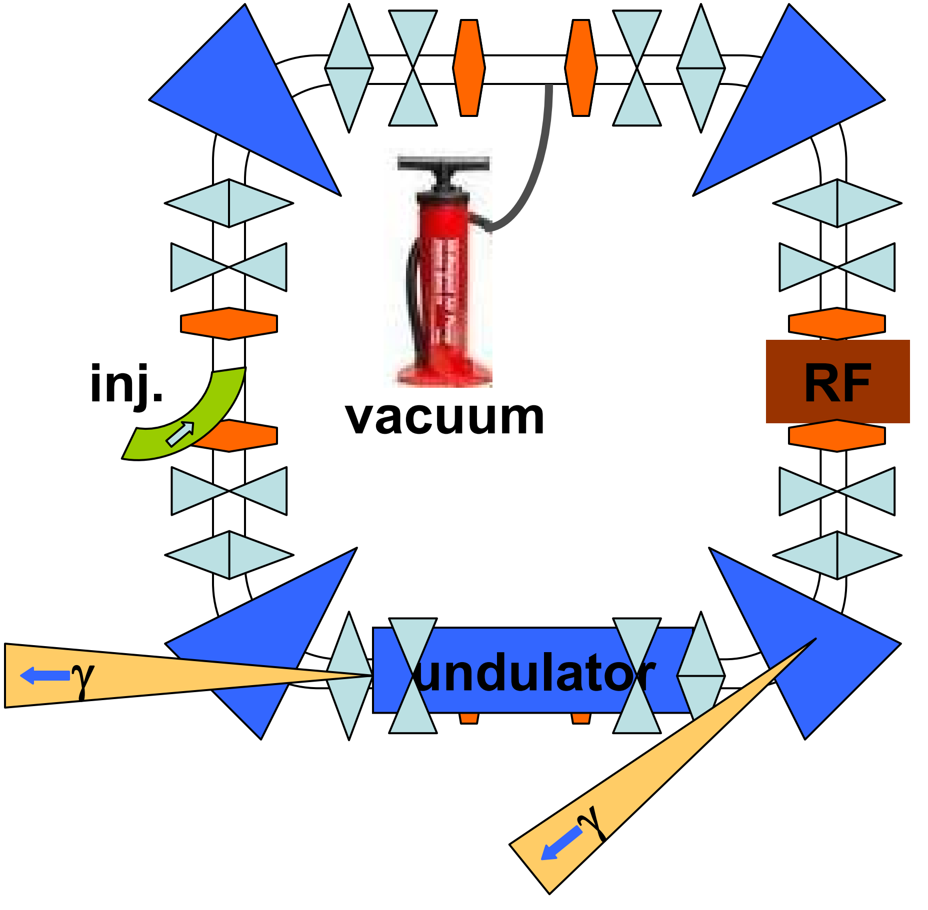
4) Sextupoles for achromatic focusing

5) RF to make up for energy loss; also provides longitudinal focusing (bunching)

6) Injection system

7) IDs into avail. straight sections

8) Beamlines to deliver photons to the Users



Essential Elements of a Light Source

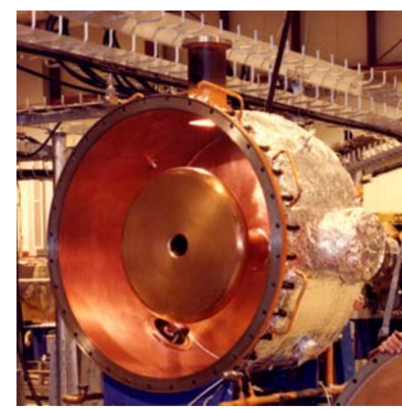
VUV Ring Construction ~1980

Sextupoles

Bend magnet

Quadrupoles

Beamline ports



53 MHz RF cavity

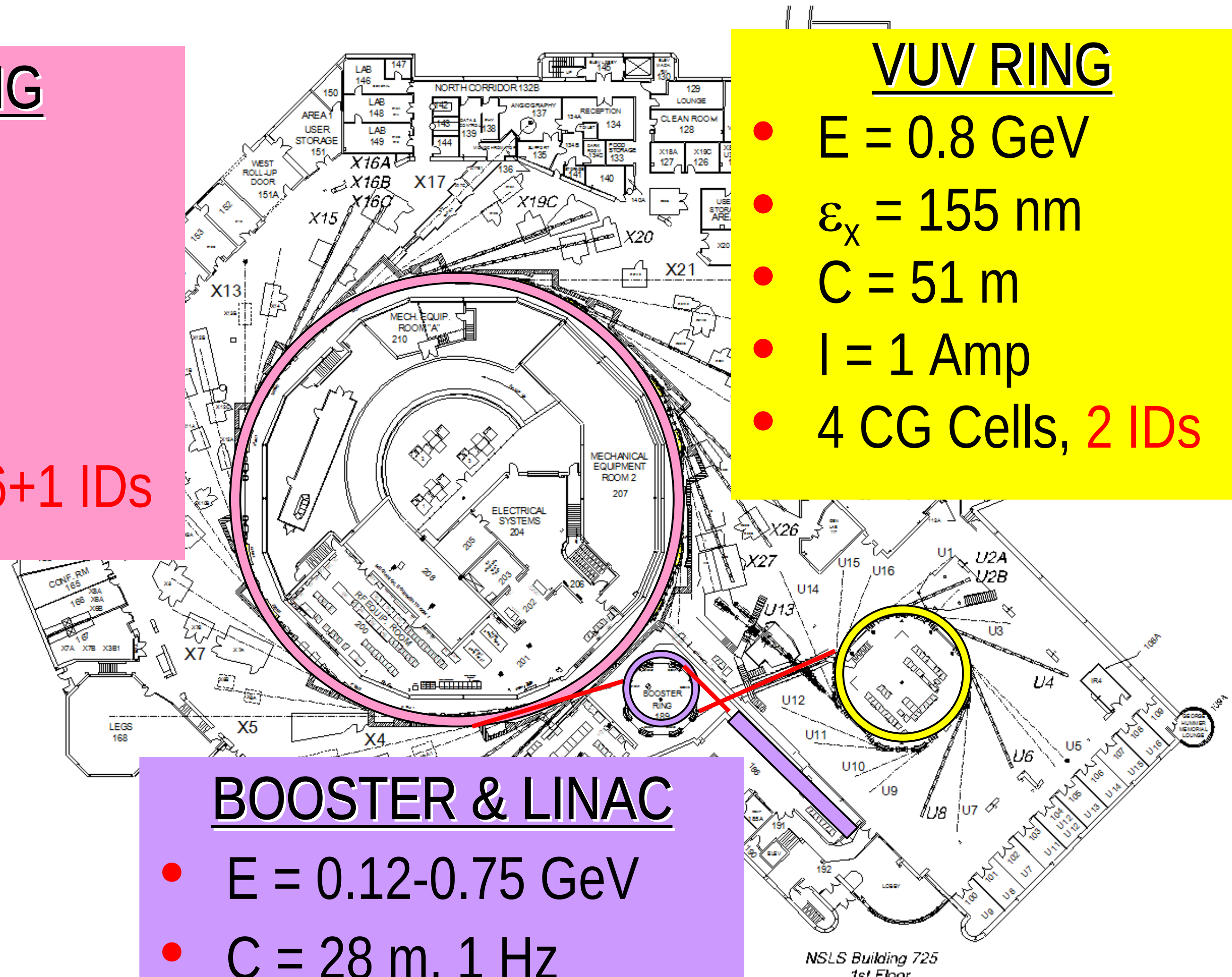
NSLS Accelerators Today

XRAY RING

- E = 2.8 GeV
- ε_x = 65 nm
- C = 170 m
- I = 0.3 Amp
- 8 CG Cells, 6+1 IDs

VUV RING

- E = 0.8 GeV
- ε_x = 155 nm
- C = 51 m
- I = 1 Amp
- 4 CG Cells, 2 IDs



BOOSTER & LINAC

- E = 0.12-0.75 GeV
- C = 28 m, 1 Hz
- I = 0.03 Amp

NSLS VUV Ring

Essential Parameters

- Critical energy: 622 eV (λ_c=19.9 Å)
- Emittances: ε_x~160 nm, ε_y~4 nm
- Beam sizes

  Bends: (σ_x, σ_y) : 540-570 μm, 170-200 μm

  IDs: (σ_x, σ_y) : 1240 μm, 220 μm

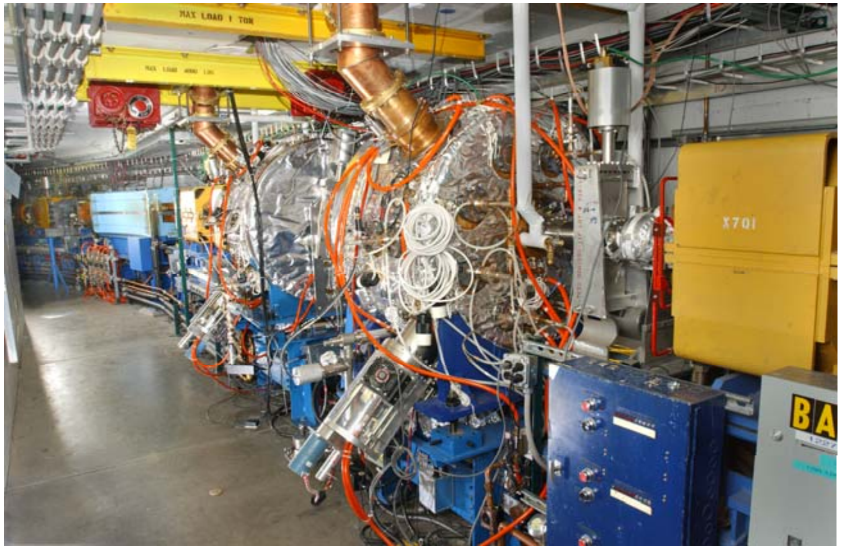
Operations

- Reliability exceeding 95% at 808 MeV
- High Current ~ 1 Amp in 7/9 bunches
- 4th Harmonic Cavity for beam lifetime
- Both Straights have IDs
- Longitudinal Coupled Bunch Feedback
- H&V Global Orbit Feedback
- 90 x 90 mrad IR ports

R&D

- Bursting CSR & Microwaves
- Laser Slicing & Coherent IR

NSLS X-Ray Ring



Essential Parameters

•Critical energy 7.1 keV (λ_c=1.75 Å)

•Emittances: ε_x~60 nm, ε_y~ 0.3 nm

•Beam sizes

Bends: (σ_x, σ_y) : 260-460 μm, 60-90 μm

IDs: (σ_x, σ_y) : 310 μm, 11 μm

Operations

•Reliability of 90-95% at 2.8 GeV

•High Current ~ 0.3 Amp in 25/30 Bunches

•Inject @ 0.75 GeV and Ramp Up

•Four New RF Cavities Provide 1 MV

•Six of Eight Straight Sections have IDs

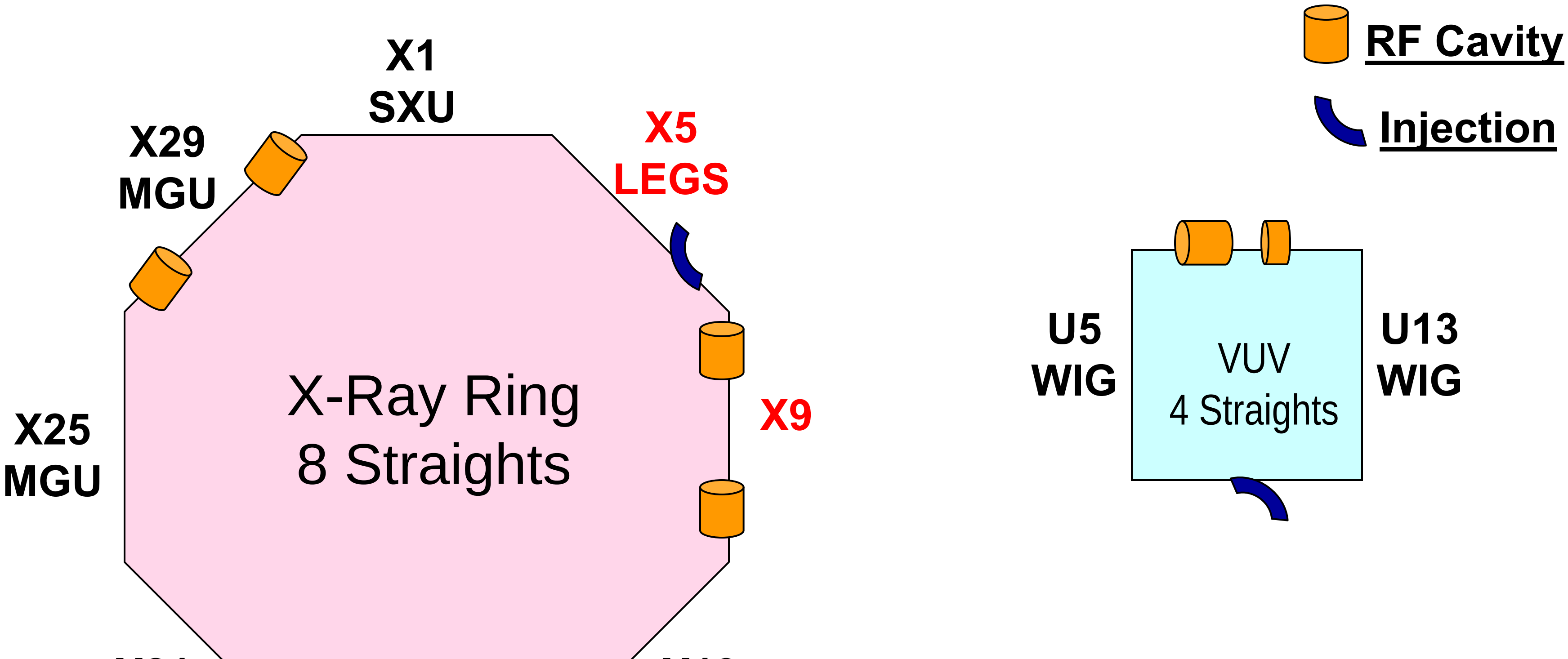
•H&V Global Orbit Feedback

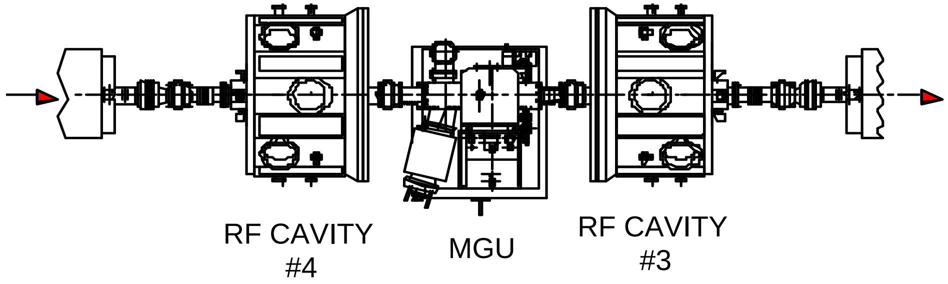
R&D

•Small Gap Insertion Devices

•Dynamic Aperture with EPU + IDs

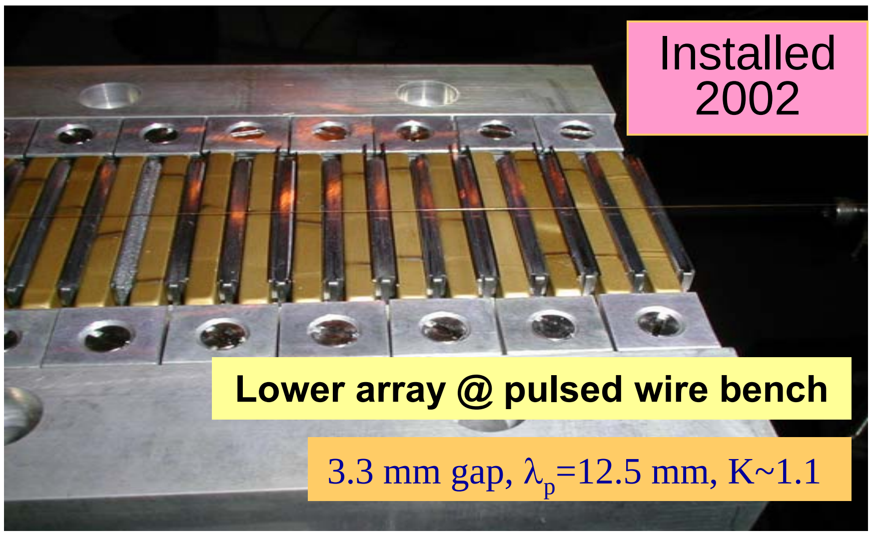
NSLS Insertion Devices: Near Capacity





Mini-Gap In-Vacuum Undulators

NSLS X13 MGU



Installed 2002

Lower array @ pulsed wire bench

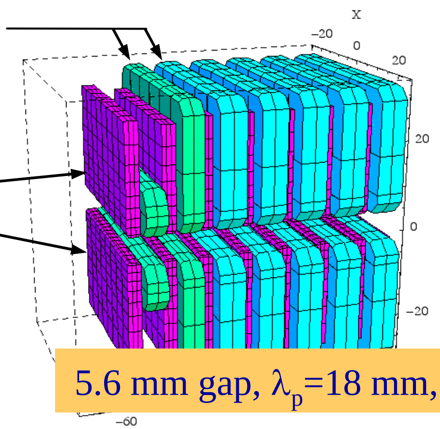
3.3 mm gap, λ_p=12.5 mm, K~1.1

- MGUs are one of greatest successes at NSLS
- Provide hard X-ray photons on the cheap
- Paved the way for Intermediate Energy Light Sources
- Will be heavily used at NSLS-II

NSLS X25 MGU

NdFeB Magnets:
new "hybrid car motor" grade

Vanadium Permendur Poles



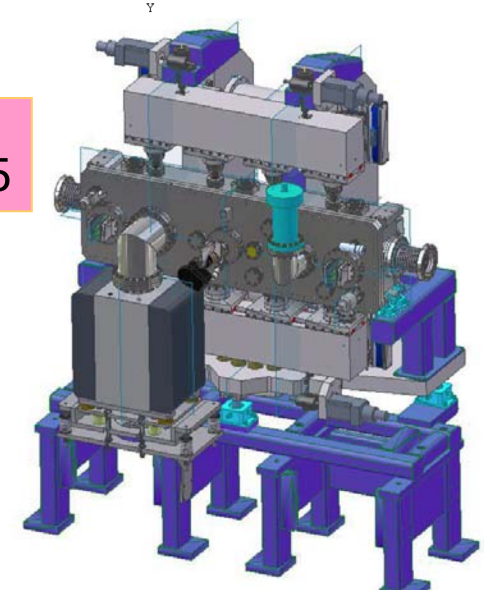
Design:

NSLS (magnetic)

ADC, Inc (mech.)

5.6 mm gap, λ_p=18 mm, K~1.5

Installed Dec. 2005



Conclusions and Outlook

NSLS Storage rings are highly optimized but still improving

- In Place: Mini-gap & variable polarization IDs, digital feedback, 4th harmonic cavity, EPICS-like controls …
- To Be Done: New IDs, improved injection, stability & reliability, …

NSLS-II Storage ring is the future of NSLS

- Will Provide: much higher brightness, many straight sections filled with advanced IDs, high beam stability, unprecedented energy resolution, etc
- Many Potential Synergies with Present NSLS

A wealth of Research Opportunities at NSLS & NSLS-II

- User Techniques & Applications: talks and the rest of this workshop
- Accelerator R&D: NSLS Rings & SDL provide a wealth of opportunities for advanced accelerator R&D

Contact me boris@bnl.gov if you want to learn more and/or participate