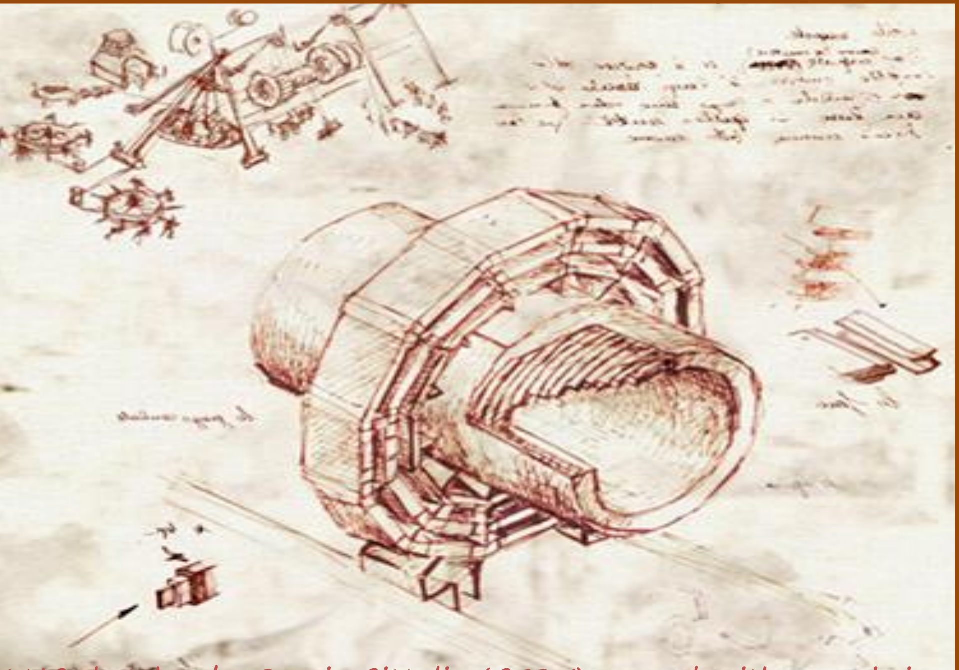
John Adams Institute for Accelerator Science

Unifying physics of accelerators, lasers and plasma



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John Adams Institute

Lecture 7: Light sources

USPAS 16

June 2016

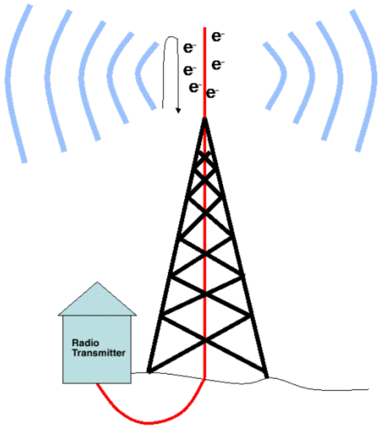
Light sources

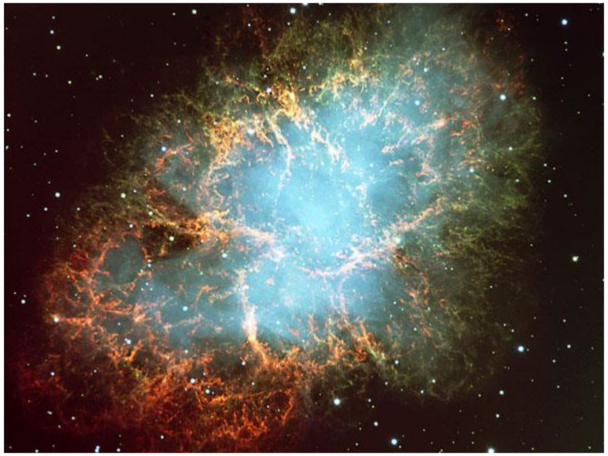
- Synchrotron radiation light sources
  - Why SR useful and history
  - Equilibrium emittance, damping time
  - Brightness
  - Examples

- Compton light sources
  - Basic formulae
  - Overview of existing projects

What is synchrotron radiation

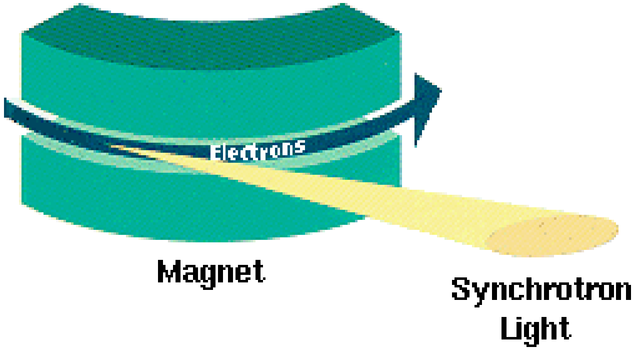
- Electromagnetic radiation is emitted by charged particles when accelerated

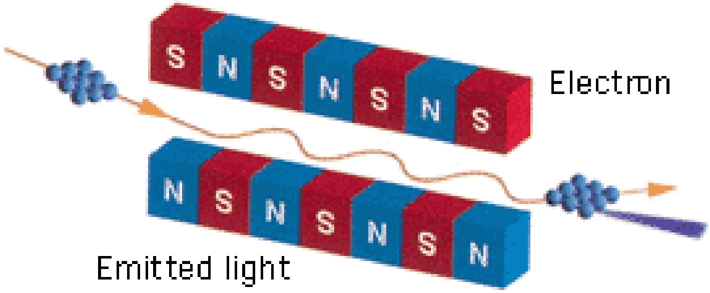




The electromagnetic radiation emitted when the charged particles are accelerated radially (v ⊥ a) is called synchrotron radiation

It is produced in the synchrotron radiation sources using bending magnets undulators and wigglers



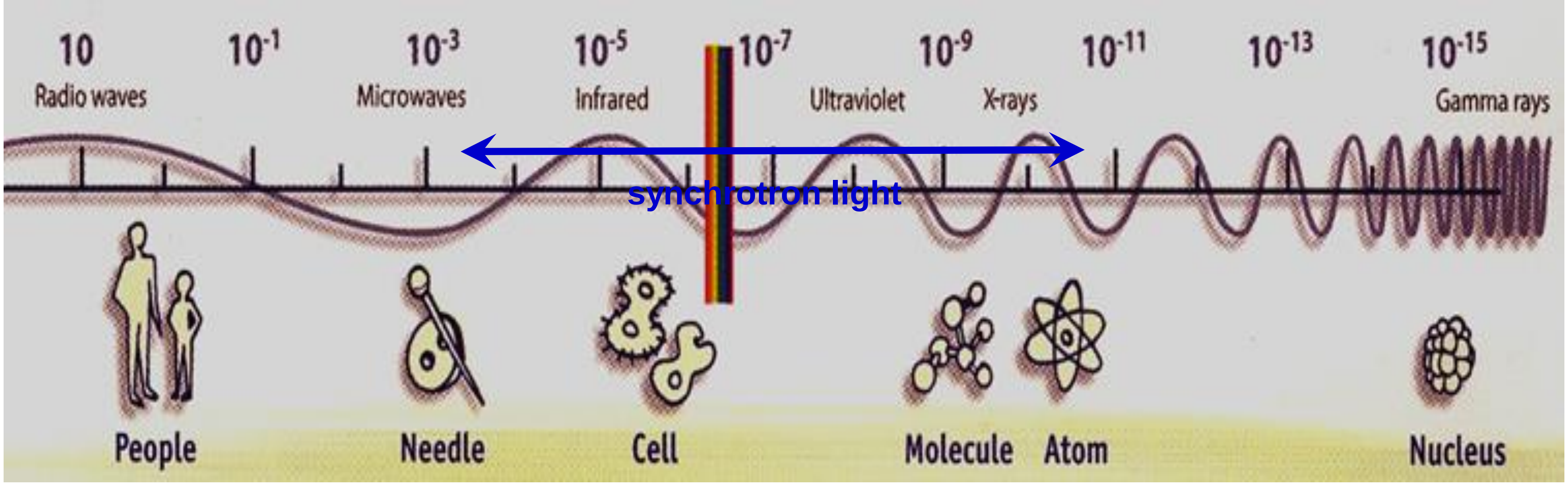


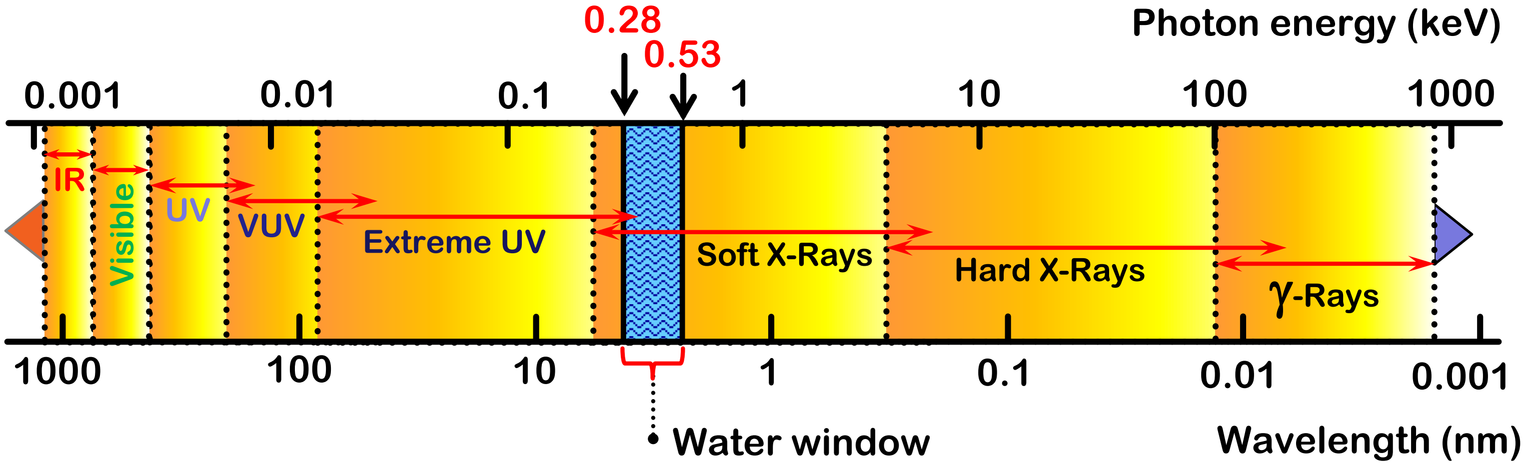
Synchrotron radiation sources properties (I)

Broad Spectrum which covers from microwaves to hard X-rays:

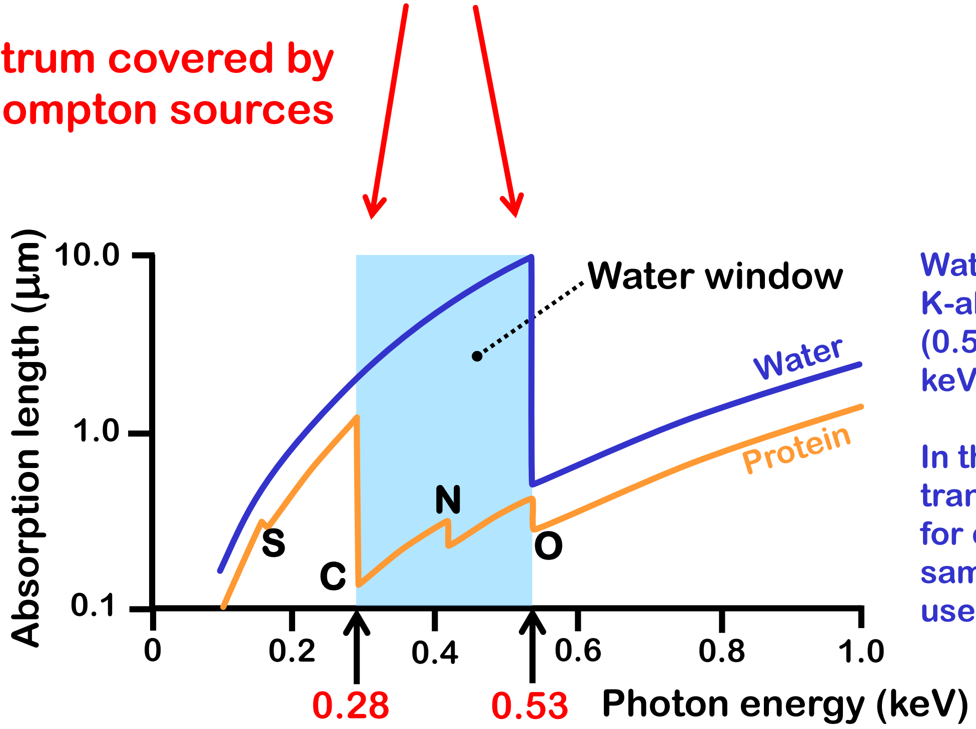
The user can select the wavelength required for experiment;

either with a monochromator
or adjusting the emission wavelength of insertion devices





EM spectrum covered by SR and Compton sources



Water window – range between K-absorption edges of oxygen (0.53 keV) and carbon (0.28 keV)

In this range water is relatively transparent and this is useful for experiments with biological samples that often need to be used as water solutions

Photon attenuation in water in comparison with a typical protein

Synchrotron radiation sources properties (II)

High Flux: high intensity photon beam, allows rapid experiments or use of weakly scattering crystals;

Flux = Photons / (s • BW)

High Brilliance (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source

Brilliance = Photons / (s • mm^2 • mrad^2 • BW)

Partial coherence in SRs

Full T coherence in FELs

Polarisation: both linear and circular (with IDs)

Pulsed Time Structure: pulsed length down to

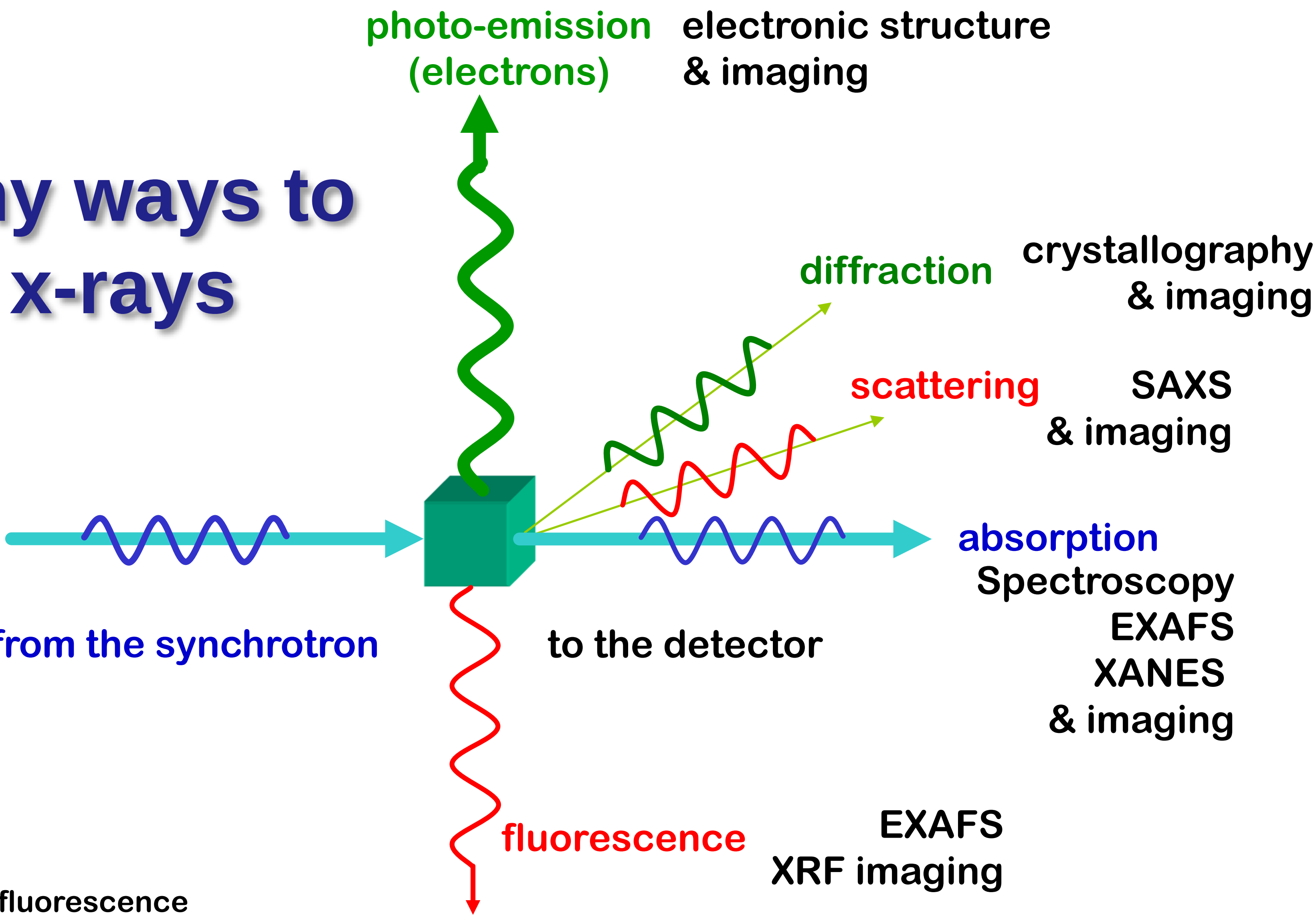
10s ps in SRs

10s fs in FELs

High Stability: submicron source stability in SR

… and it can be computed!

Many ways to use x-rays



XRF=X-ray fluorescence

SAXS=Small-angle X-ray scattering

XANES=X-ray Absorption Near Edge Structure

EXAFS=Extended X-ray absorption fine structure

Life science examples: DNA and myoglobin

Photograph 51
Franklin-Gosling

DNA (form B)

1952

Franklin and Gosling used a X-ray tube:

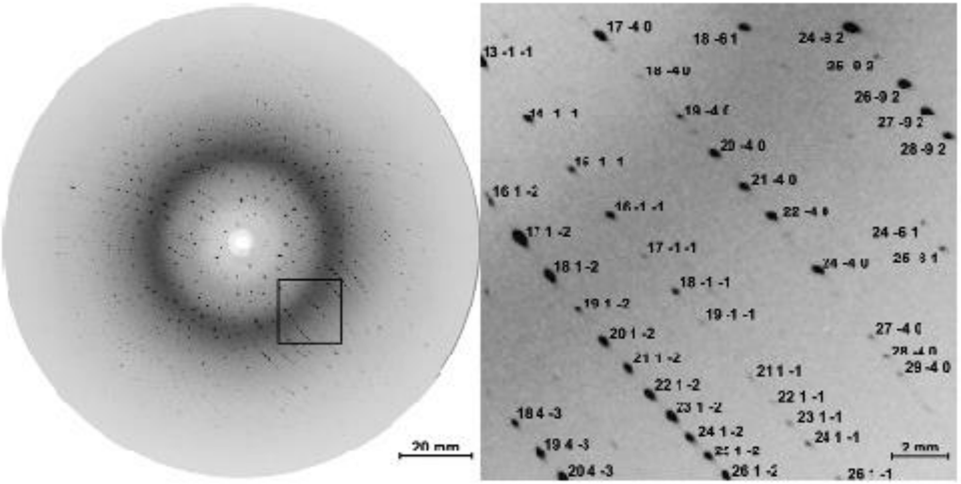
Brilliance was 10^8 (ph/sec/mm^2/mrad^2/0.1BW)

Exposure times of 1 day were typical (10^5 sec)

e.g. Diamond provides a brilliance of 10^{20}

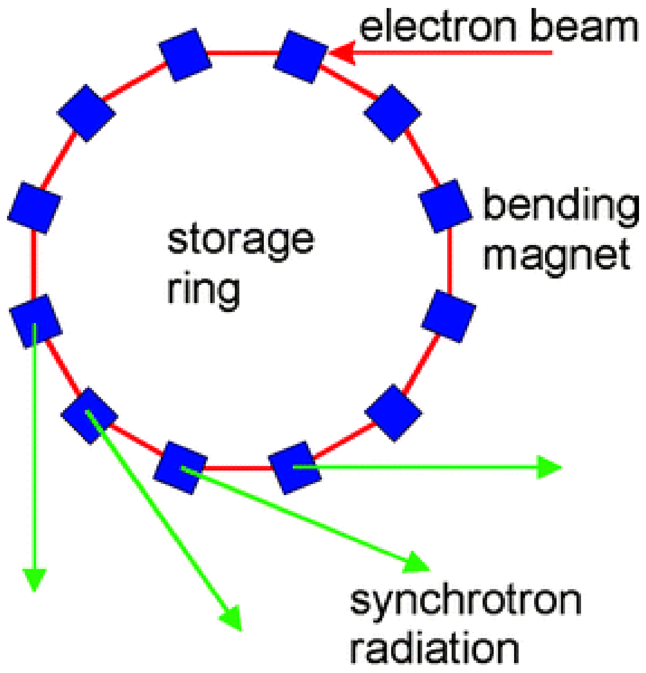
100 ns exposure would be sufficient

Nowadays pump probe experiment in life science are performed using 100 ps pulses from storage ring light sources: e.g. ESRF myoglobin in action



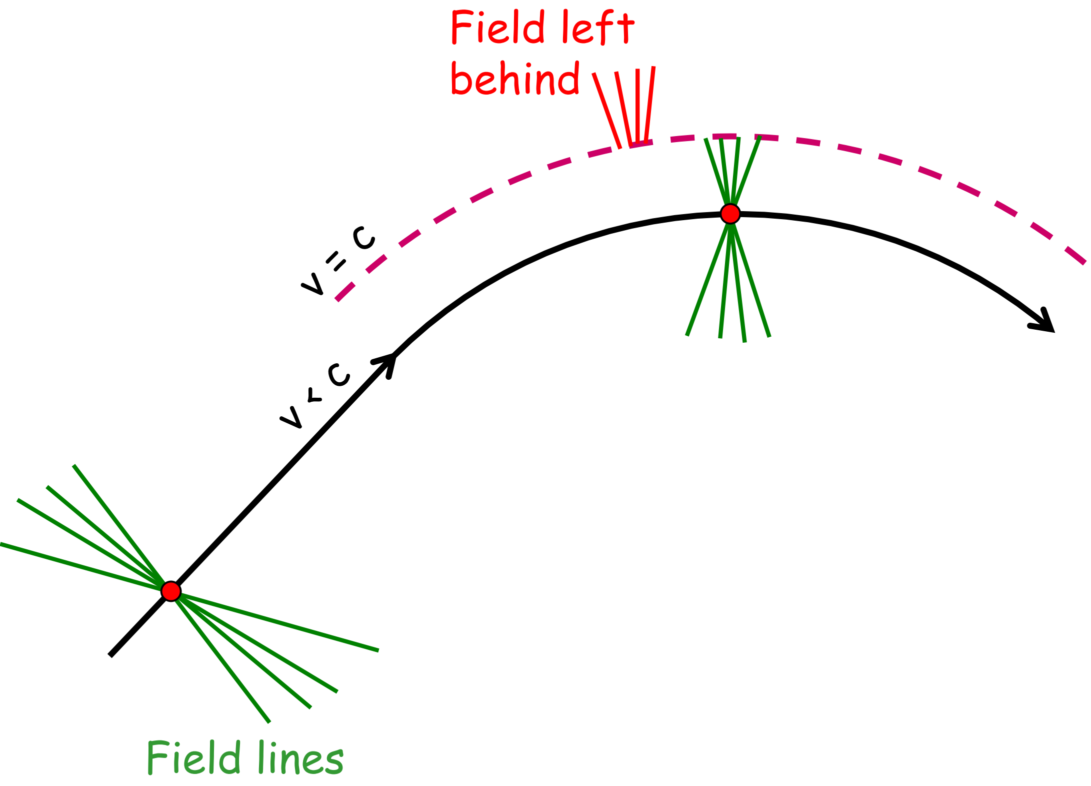
Basic parameters of SR sources

- Let's
  - Recall simple treatment of SR
  - Estimate cooling time
  - Estimate equilibrium emittance
  - Estimate brightness



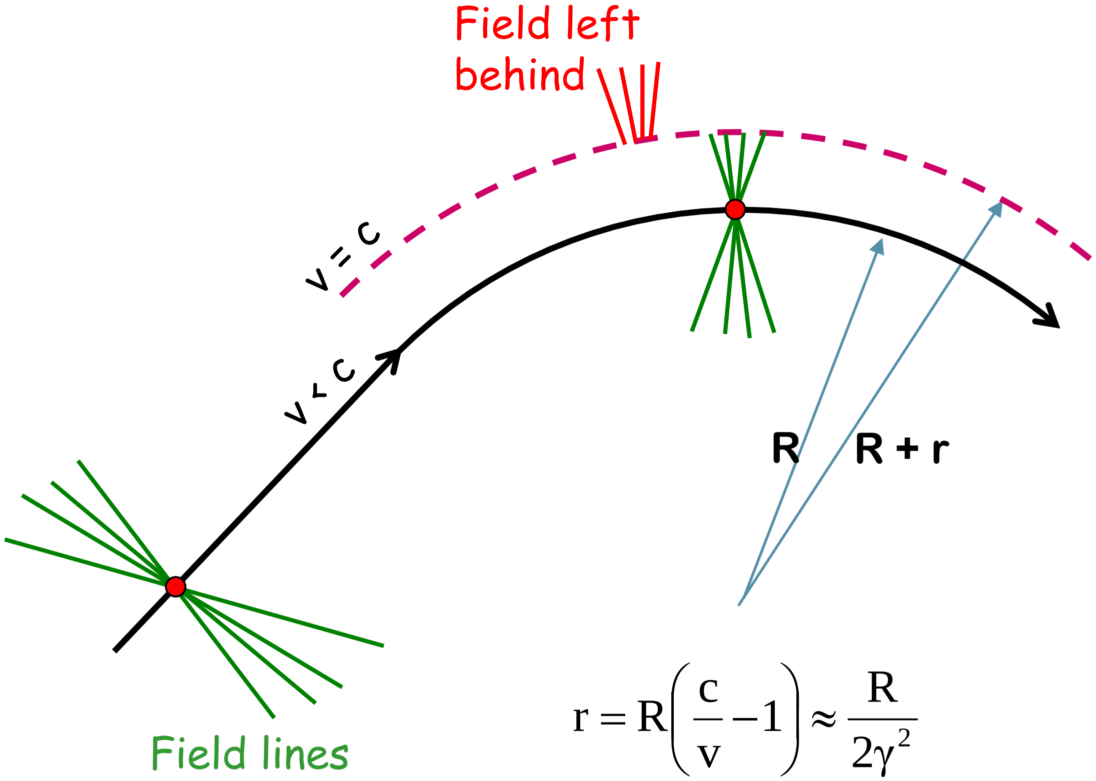
We will start considerations from SR sources of 2nd generation, where radiation emitted in bending magnets

Basics: Synchrotron Radiation



- Simplistic picture – SR caused by leaving part of the fields behind
- Can be useful as it
  - Creates high brightness radiation source
- Can be harmful as it
  - Creates additional energy spread
  - Creates additional emittance growth

Synchrotron radiation – power loss



$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2\, dV$$

The field $E \approx \frac{e}{r^2}$ **the volume** $V \approx r^2\, dS$

Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \frac{R}{2\gamma^2}$ **and get an estimate:**

$$\boxed{\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}}$$

Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$

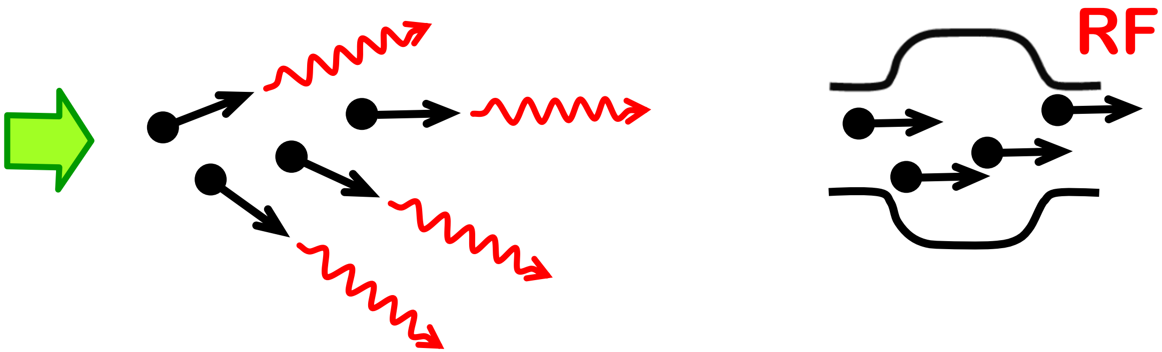
Gaussian units on this page!

Let’s estimate cooling time

We estimated that losses per unit length are: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$ **or** $\frac{dW}{dS} = \frac{2}{3}\frac{r_e\gamma^4}{R^2}mc^2$

Thus losses per turn are: $U_0 = \frac{4\pi}{3}\frac{r_e\gamma^4}{R}mc^2$

When electron radiate a photon, its momentum decrease



RF cavity restores only longitudinal momentum, thus other degrees of freedom cooled

Estimate cooling time τ as E_0T_0/U_0 : $\tau \approx \frac{2\pi R}{c}\frac{\gamma mc^2}{U_0}$ **or** $\tau^{-1} \approx \frac{2}{3}\frac{c\, r_e\gamma^3}{R^2}$

Cooling time & partition

So, we estimated cooling time as $\tau^{-1} \approx \frac{2}{3} \frac{c\, r_e\, \gamma^3}{R^2}$

Usually, there is factor of 2 in the definition: $\tau = 2E_0 T_0/U_0$ => $\tau^{-1} = \frac{1}{3} \frac{c\, r_e\, \gamma^3}{R^2}$

The evolution of emittance under SR damping is given by $\varepsilon(t) = \varepsilon_0 \exp(-2t/\tau)$

Both transverse planes and longitudinal motion in rings are usually coupled
Thus we can expect that the damping will be distributed between these degrees of freedom in some proportion depending on details of the optics

Distribution of cooling is defined by so called partition numbers J_x, J_y, J_E

Cooling time of a degree of freedom is $\tau_i = \frac{\tau}{J_i}$

Total radiated power fixed => $\sum \tau_i^{-1} = const$

Mentioned to you without derivation

Usually $J_x \approx 1, \quad J_y \approx 1, \quad J_E \approx 2$

Partition theorem $\sum J_i = 4$

Equilibrium emittance

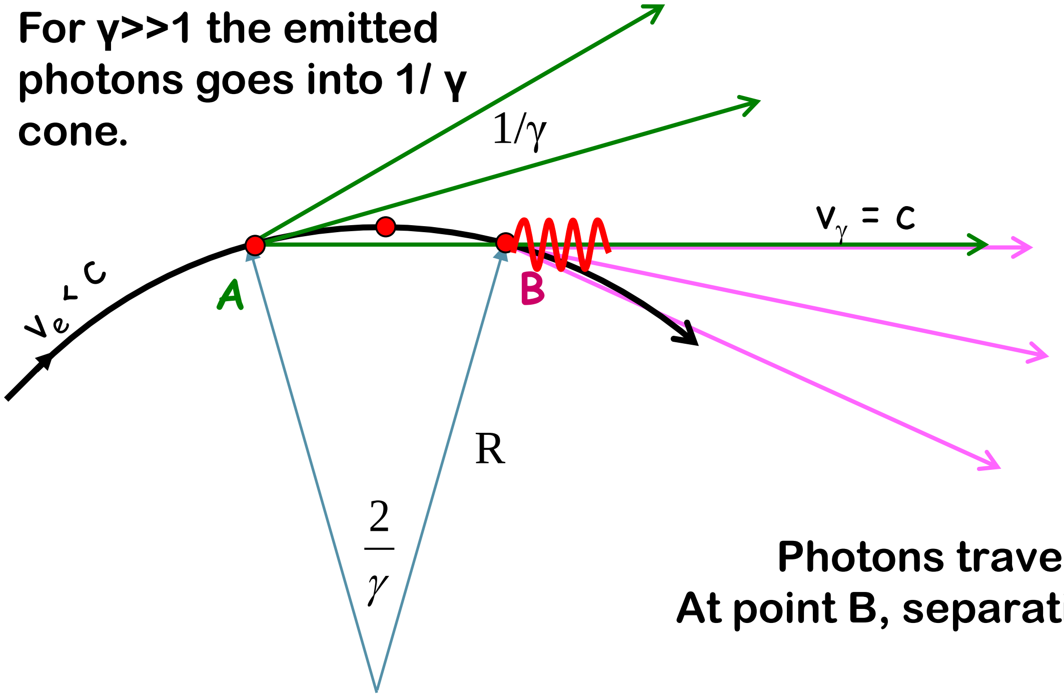
- Have SR cooling – would beam emittance reduce to zero?

- No, as there are quantum fluctuations

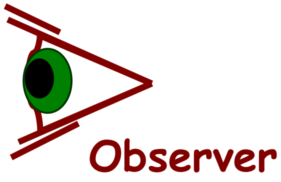
- Let’s make simple estimations of the effects

Recall SR – photon energy

For γ>>1 the emitted photons goes into 1/ γ cone.



During what time Δt the observer will see the photons?



Photons emitted during travel along the 2R/γ arc will be observed.

Photons travel with speed c, while particles with v. At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1-\frac{v}{c}\right)$$

Therefore, observer will see photons during

$$\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$$

Estimation of characteristic frequency

$$\boxed{\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}}$$

Compare with exact formula:

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$$

Synchrotron radiation – number of photons

We estimated the rate of energy loss: $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ **And the characteristic frequency:** $\omega_c \approx \frac{c\gamma^3}{R}$

&

The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ **where** $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

=>

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ **(per angle** θ**:** $N \approx \alpha\gamma\theta$ **)**

Gaussian units on this page!

Let's estimate energy spread growth due to SR

We estimated the rate of energy loss: $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ **And the characteristic frequency:** $\omega_c \approx \frac{c\gamma^3}{R}$

The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R} \lambda_e mc^2$ **where** $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c} \frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ **(per angle θ:** $N \approx \alpha\gamma\theta$ **)**

The energy spread ΔE/E will grow due to statistical fluctuations ($\sqrt{N}$**) of the number of emitted photons :**

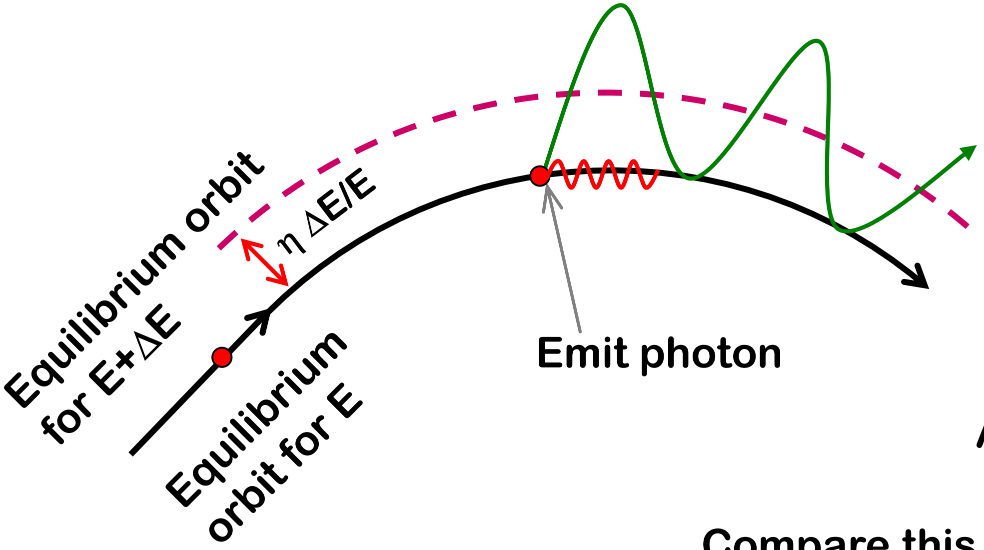
$$\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \varepsilon_c^2 \frac{dN}{dS} \frac{1}{\left(\gamma mc^2\right)^2}$$

Which gives:

$$\boxed{\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \frac{r_e \lambda_e \gamma^5}{R^3}}$$

Compare with exact formula: $\frac{d\left((\Delta E/E)^2\right)}{dS} = \frac{55}{24\sqrt{3}} \frac{r_e \lambda_e \gamma^5}{R^3}$

Let’s estimate emittance growth rate due to SR



Dispersion function η shows how equilibrium orbit shifts when energy changes

When a photon is emitted, the particle starts to oscillate around new equilibrium orbit

Amplitude of oscillation is $\Delta x \approx \eta\, \Delta E/E$

Compare this with betatron beam size: $\sigma_x = (\varepsilon_x \beta_x)^{1/2}$

And write emittance growth: $\Delta\varepsilon_x \approx \dfrac{\Delta x^2}{\beta}$

Resulting estimation for emittance growth:

$$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x}\,\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \boxed{\frac{\eta^2}{\beta_x}\,\frac{r_e\,\lambda_e\,\gamma^5}{R^3}}$$

Compare with exact formula (which also takes into account the derivatives):

$$\frac{d\varepsilon_x}{dS} = \underbrace{\boxed{\frac{\left(\eta^2 + (\beta_x \eta' - \beta_x' \eta/2)^2\right)}{\beta_x}}}_{=\mathcal{H}}\,\frac{55}{24\sqrt{3}}\,\frac{r_e\,\lambda_e\,\gamma^5}{R^3}$$

Equilibrium emittance

We estimated the rate of emittance growth:

$$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x} \frac{d\left(\left(\Delta E/E\right)^2\right)}{dS} \approx \frac{\eta^2}{\beta_x} \frac{r_e \lambda_e \gamma^5}{R^3}$$

SR cooling gives $\frac{d\varepsilon}{ds} = -\frac{2}{c\tau}\varepsilon$ **with** $\tau^{-1} = \frac{1}{3}\frac{c\, r_e \gamma^3}{R^2}$

The equilibrium emittance is thus: $\varepsilon_{x0} \approx \frac{c\tau}{2}\frac{\eta^2}{\beta_x}\frac{r_e \lambda_e \gamma^5}{R^3}$ **or** $\varepsilon_{x0} \approx \frac{3}{2}\frac{\eta^2}{\beta_x}\frac{\lambda_e \gamma^2}{R}$

(these are estimations –> for accurate formulas need to take into account average values <1/R^2> and <1/R^3> over the orbit period)

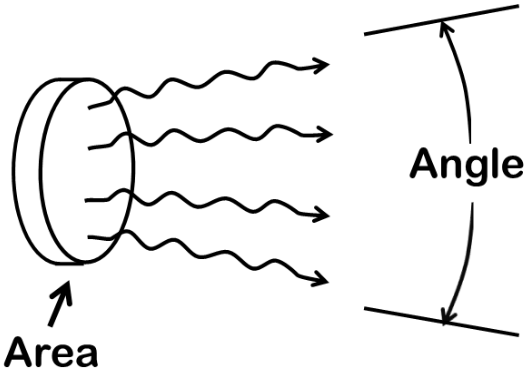
In vertical plane, SR contribution to emittance is only due to 1/γ angles of photons, and this effect is usually very small

Vertical emittance usually defined by coupling coefficient k (<<1) of x-y planes:

$$\varepsilon_{y0} \approx k\, \varepsilon_{x0}$$

Brightness

- Now we have almost everything to estimate brightness of synchrotron light sources



Brightness
photons / (s m^2 rad^2 (%bandwidth))

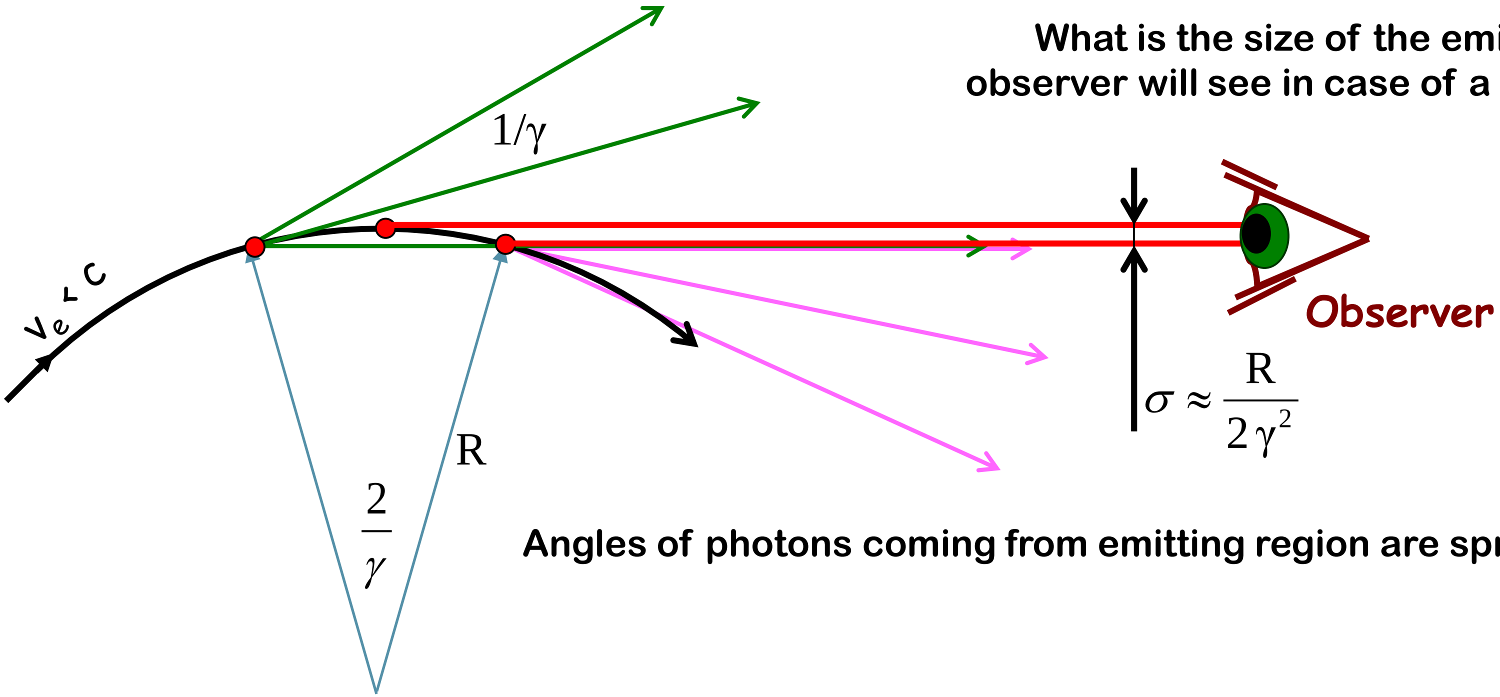
- And know how we can increase brightness
  - Smaller size of emitting area
  - Smaller angular divergence

To a certain limit,
as single photon has "emittance" –
diffraction limited sources

- We will discuss it in future lectures

Emittance of single photon radiation

What is the size of the emitting region the observer will see in case of a single electron?



Angles of photons coming from emitting region are spread over σ'~1/ γ

Estimate emittance of SR photon from single electron as $\varepsilon_{ph} = \sigma\sigma'$ **=>** $\varepsilon_{ph} \approx \frac{R}{2\gamma^3}$

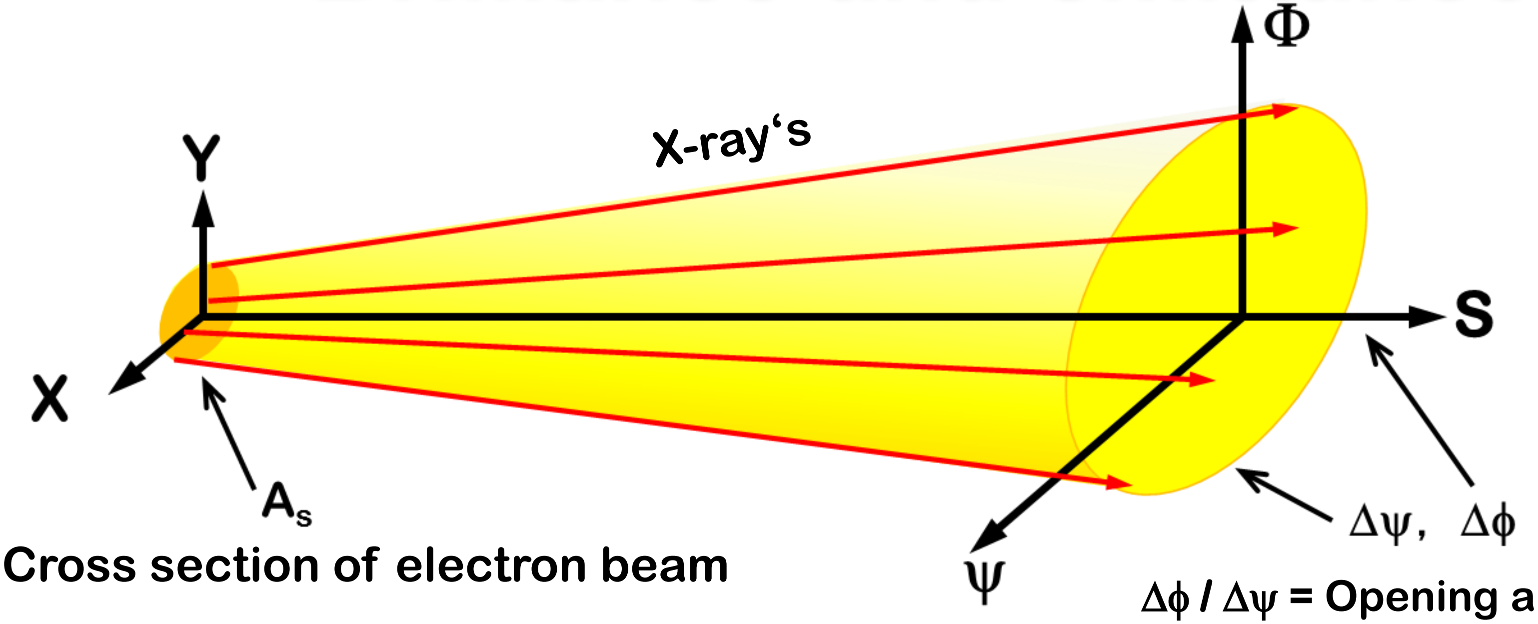
Recall $\omega_c = \frac{2\pi c}{\lambda_c} \approx \frac{c\gamma^3}{R}$ **=>** $\varepsilon_{ph} \approx \frac{\lambda_c}{4\pi}$

We see that emittance of synchrotron radiation is directly connected to its wavelength. This is not a coincidence in a single example, but general property.

$$\varepsilon_{ph} = \frac{\lambda}{4\pi}$$

(In a similar way one can estimate beta function of photons as β=σ / σ')

Brilliance and emittance



Cross section of electron beam

$\Delta\phi$ / $\Delta\psi$ = Opening angle in vert. / hor. direction

Flux = Photons / (s • BW)

Brilliance = Flux / (A_s • $\Delta\Phi$ •$\nabla\psi$) , [Photons / (s • mm^2 • $mrad^2$ • BW)]

Need to use total effective size & divergence - of electrons and photons:

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2} \qquad \sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph,e}} \qquad \sigma_{x'} = \sqrt{\varepsilon_x \beta_x + (D'_x \sigma_\varepsilon)^2}$$

Brilliance - number of photons per second emitted in a given bandwidth

Ultimate brightness

Electron beam distribution must be convolved with single-electron distribution:

Overall effective emittance: $\sqrt{\sigma_e^2+\sigma_{ph}^2}\ \sqrt{\sigma_{e'}^2+\sigma_{ph'}^2}$

Smallest photon beam emittance obtained when:

$$\varepsilon_e=\sigma_e\sigma_{e'}\leq\varepsilon_{ph}$$

Diffraction-limited source

Modern SR rings - radiation typically 100 eV to 100 keV

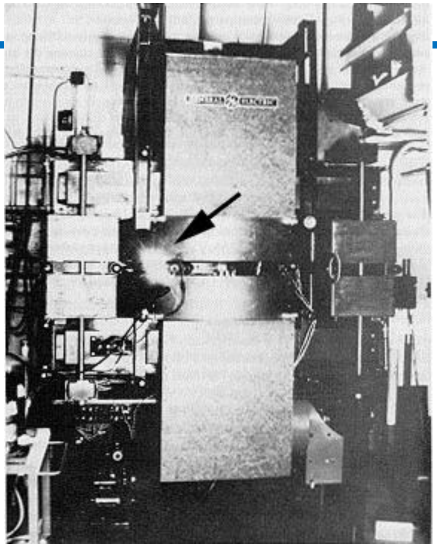
Take example of 12.4 keV

$$\lambda\approx 1\overset{o}{A} \quad \Rightarrow \quad \varepsilon_{ph}\approx 8\text{pm}$$

For typical 3rd-generation rings ε_x : [1,5]nm, ε_y: [1,40]pm

Close to ultimate performance in vertical but many orders of magnitude away from diffraction limited performance in horizontal plane

A brief history of storage ring synchrotron radiation sources



- **First observation:**

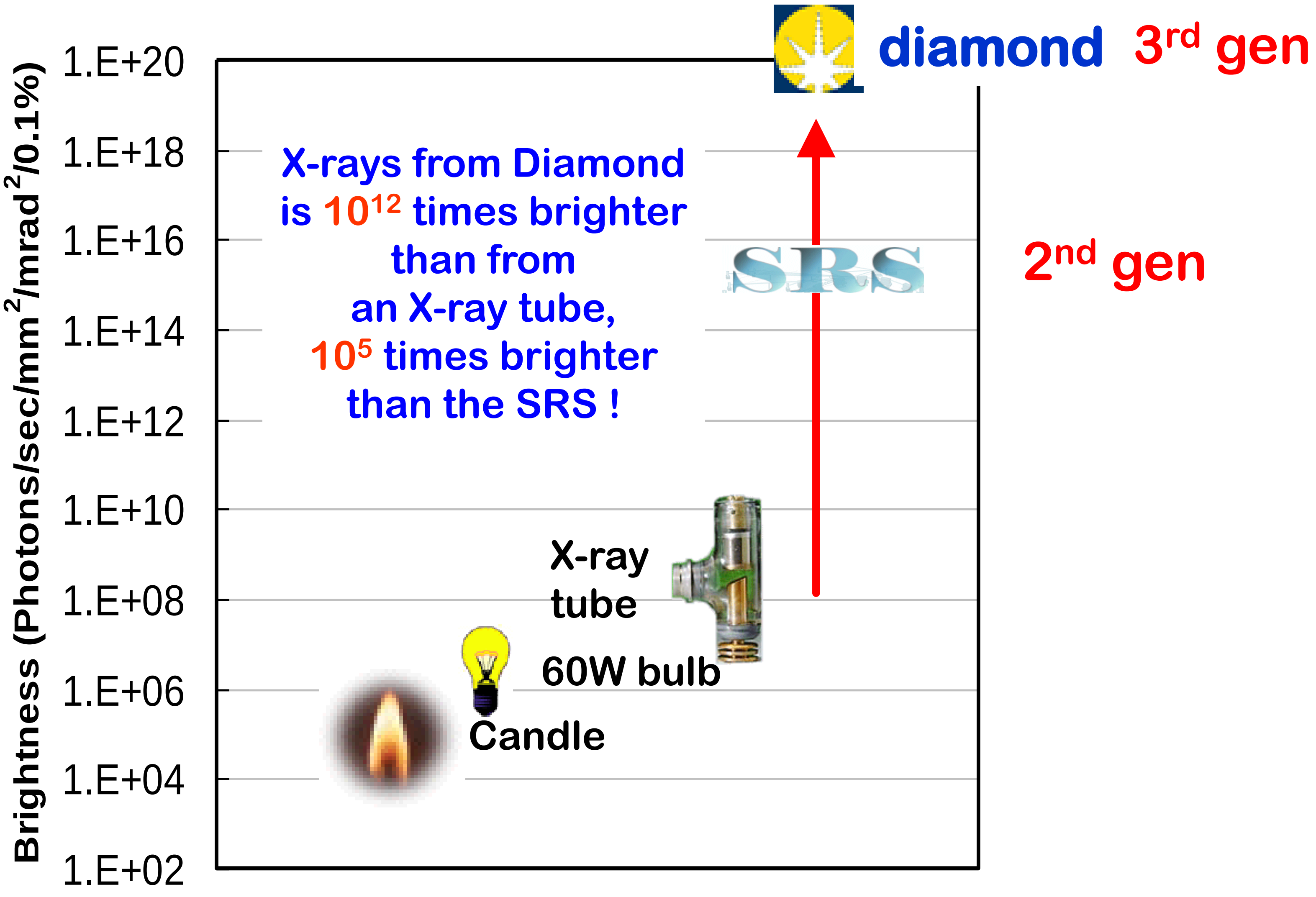
  1947, General Electric, 70 MeV synchrotron

- **First user experiments:**

  1956, Cornell, 320 MeV synchrotron

- **1st generation light sources:** machine built for High Energy Physics or other purposes used parasitically for synchrotron radiation
- **2nd generation light sources:** purpose built synchrotron light sources, SRS at Daresbury was the first dedicated machine (1981 – 2008)
- **3rd generation light sources:** optimised for high brilliance with low emittance and Insertion Devices; ESRF, Diamond, …
- **4th generation light sources:** photoinjectors LINAC based Free Electron Laser sources; FLASH (DESY), LCLS (SLAC), …

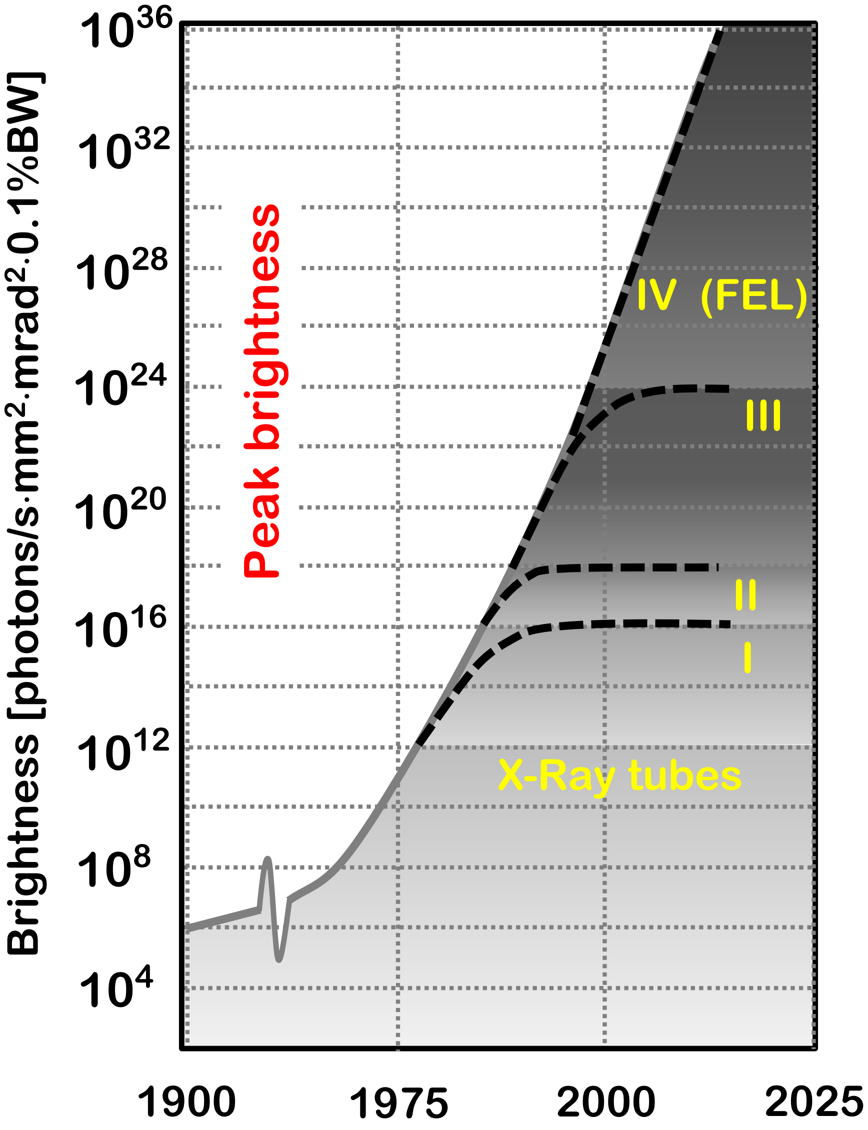
Peak Brilliance



X-rays from Diamond is 10^{12} times brighter than from an X-ray tube, 10^{5} times brighter than the SRS !

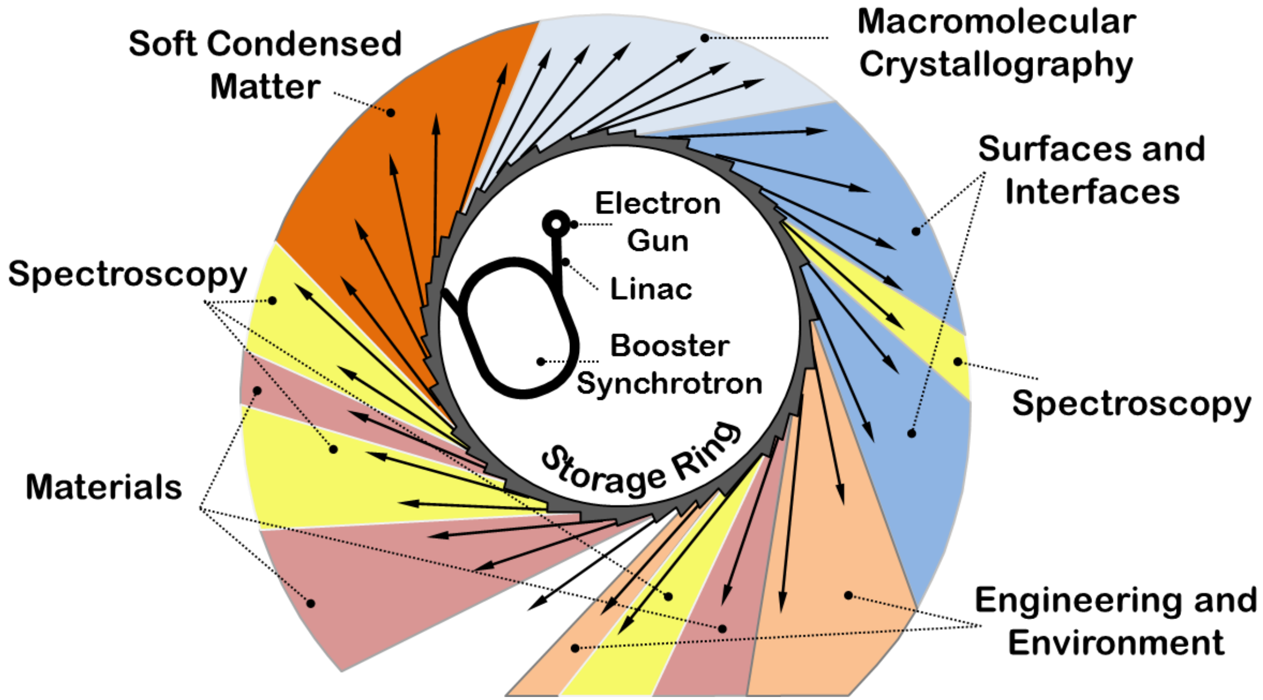
Peak Brilliance & SR sources generations

- I – SR from bends
- II – SR from insertion devices – wigglers
- III – SR from insertion devices – undulators
- IV – Free Electron Lasers

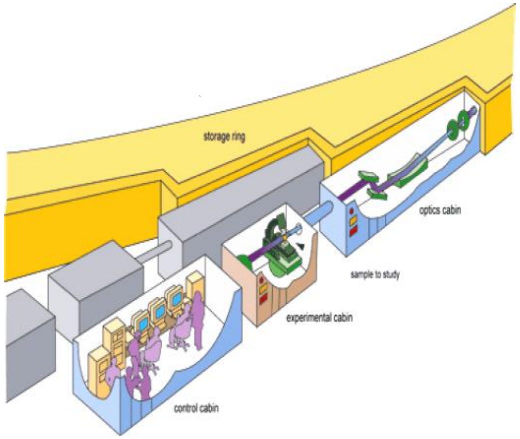


Layout of a synchrotron radiation source (I)

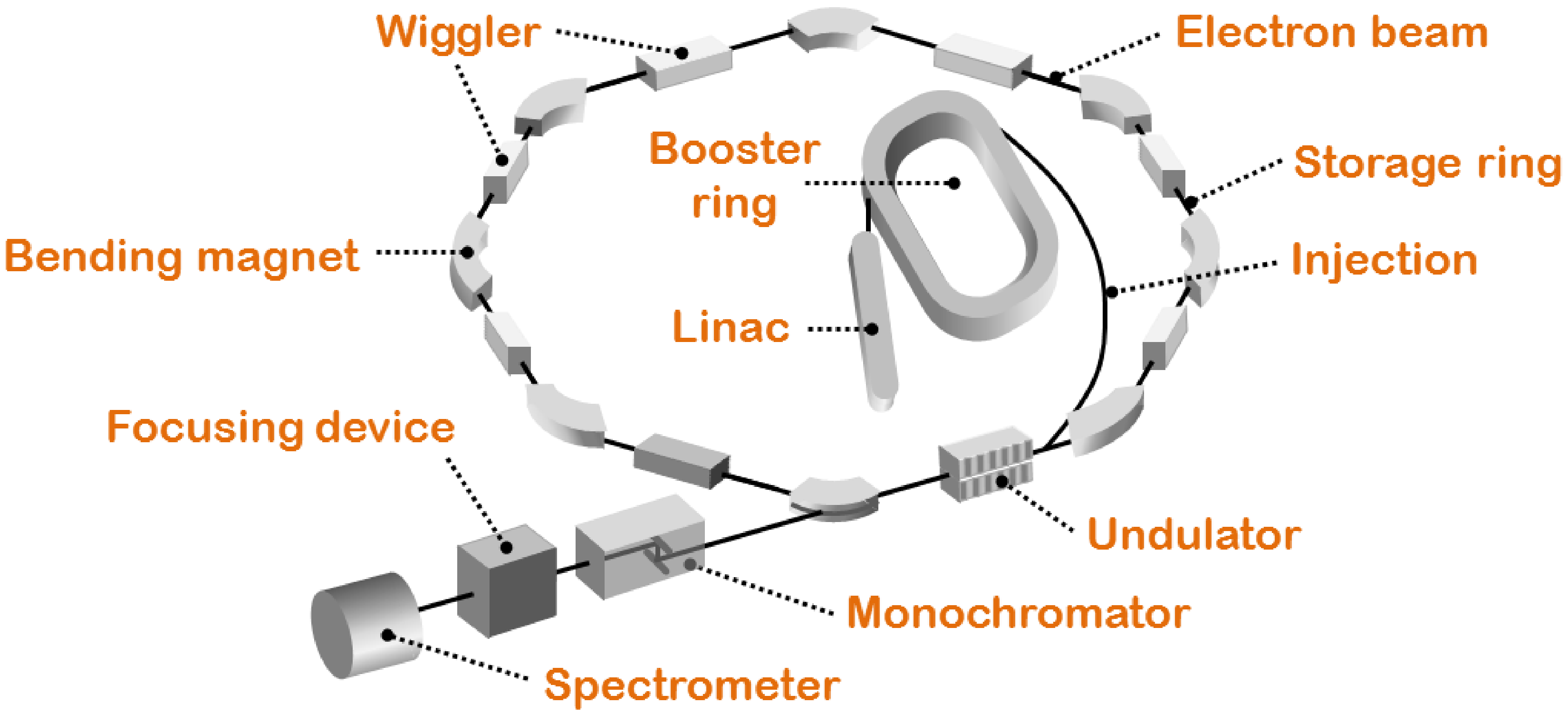
Electrons are generated and accelerated in a linac, further accelerated to the required energy in a booster and injected and stored in the storage ring



The circulating electrons emit an intense beam of synchrotron radiation which is sent down the beamline

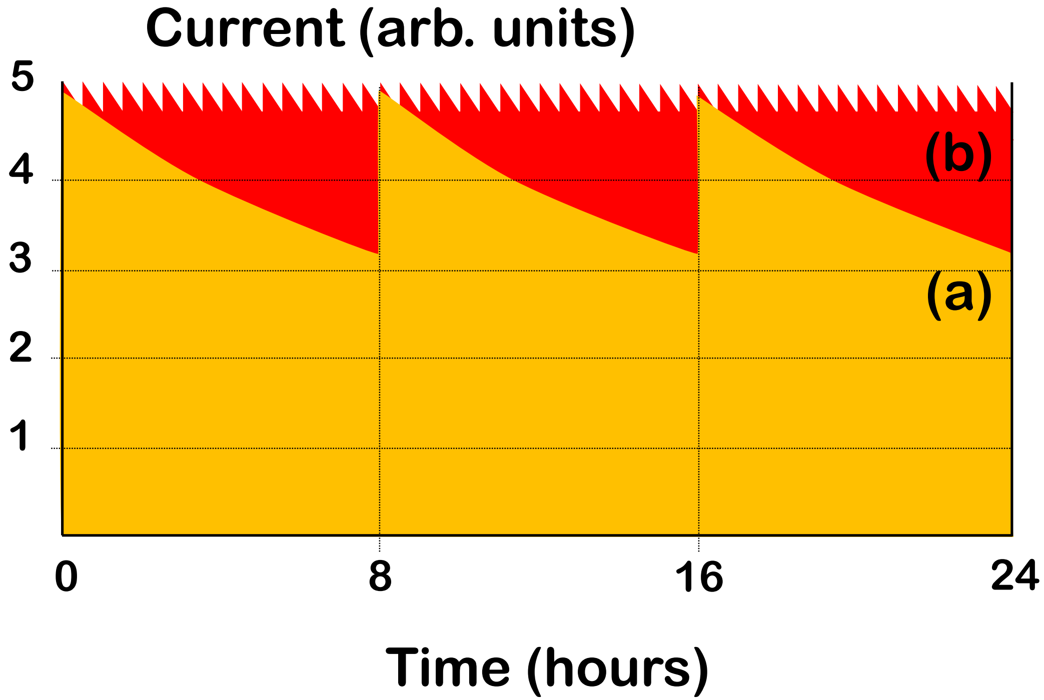


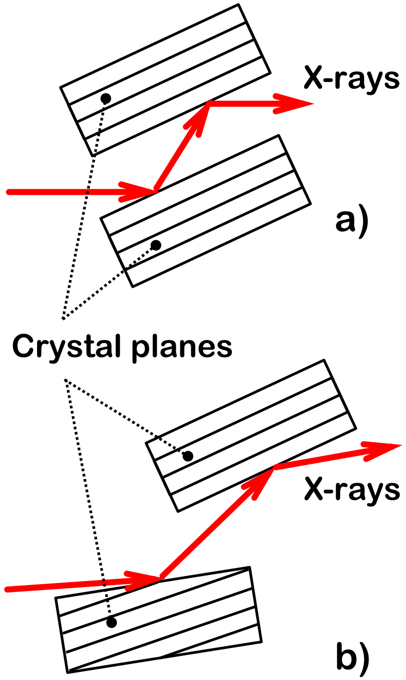
Layout of a synchrotron radiation source (II)



Synchrotron storage ring

T stability ; Monochromators

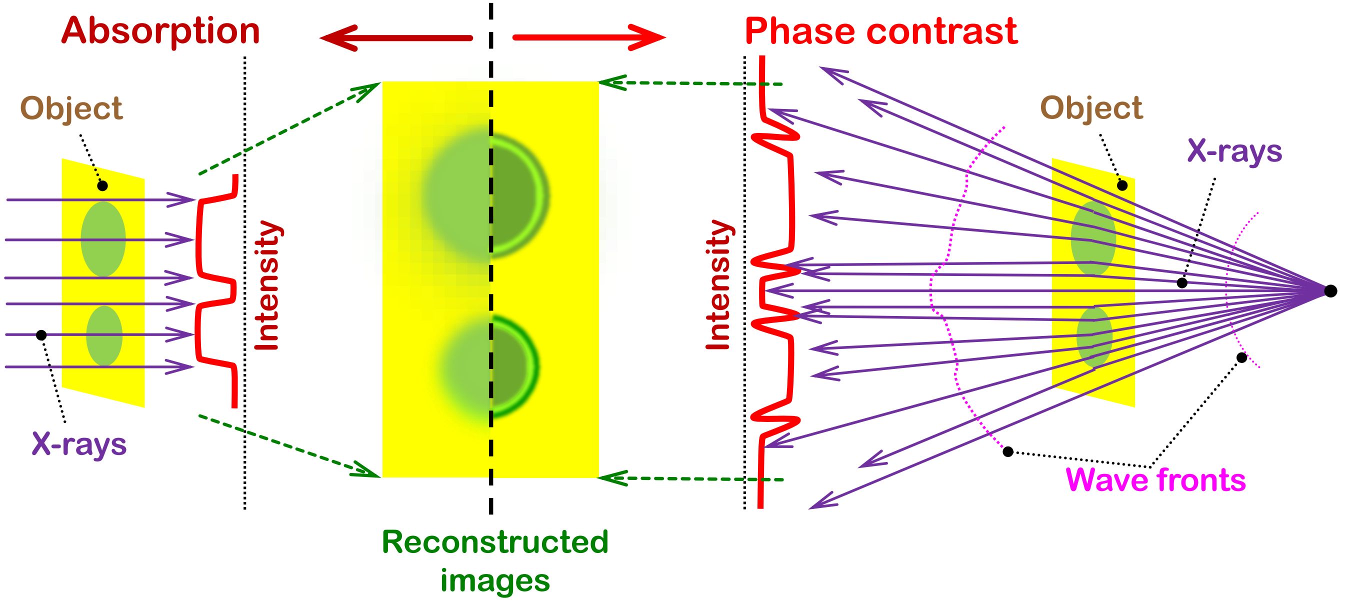




Top off injection

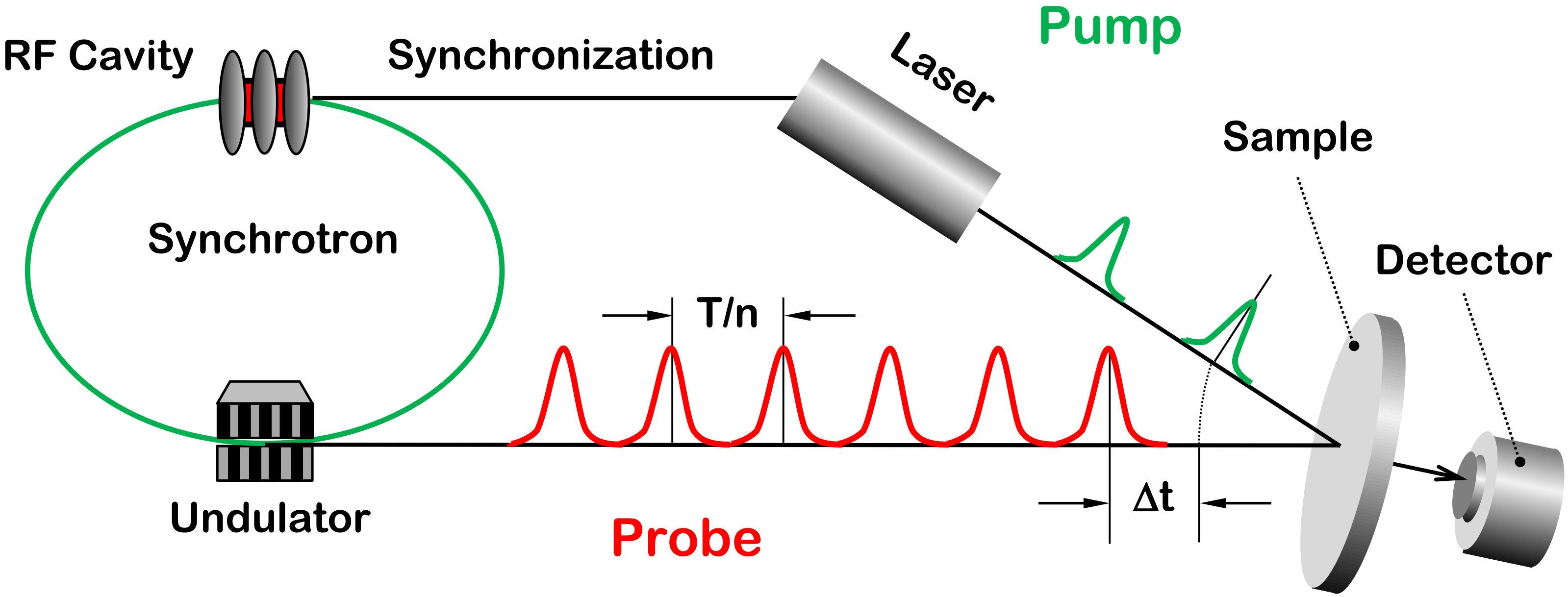
Use crystals and Bragg condition

Phase contrast imaging



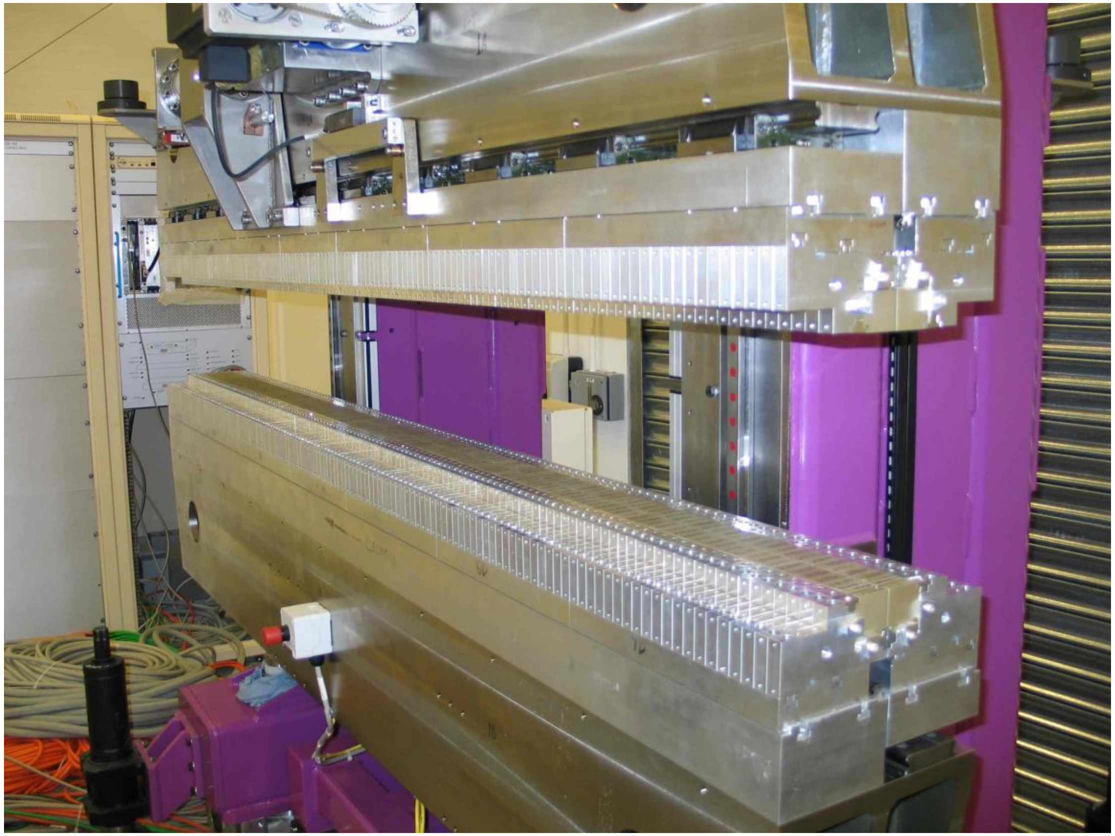
- Absorption (left) and phase contrast (right) X-ray imaging
  - – and comparison of reconstructed image (middle)

Pump-probe experiments



Main components of a storage ring

Insertion devices (undulators) to generate high brilliance radiation



Insertion devices (wiggler) to reach high photon

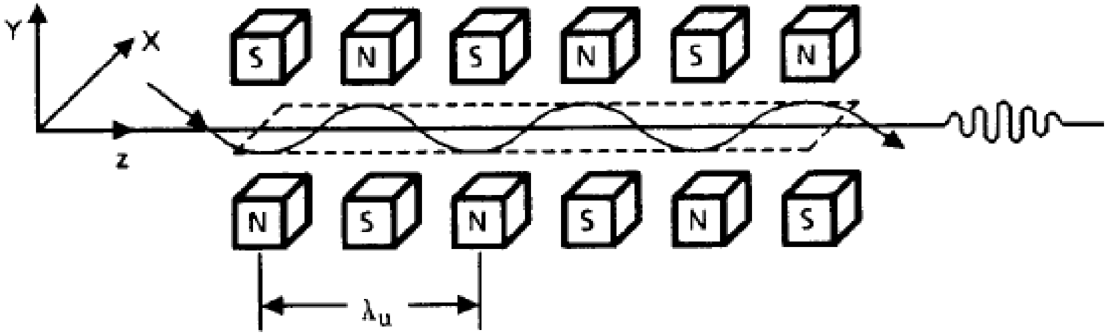
3rd generation storage ring light sources

1992	ESRF, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	TLS, Taiwan	1.5 GeV
1994	ELETTRA, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	APS, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	Spring-8, Japan	8 GeV
1998	BESSY II, Germany	1.9 GeV
2000	ANKA, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	SPEAR3, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	SOLEIL, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	SSRF, China	3.4 GeV
2009	PETRA-III, D	6 GeV
2011	ALBA, E	3 GeV

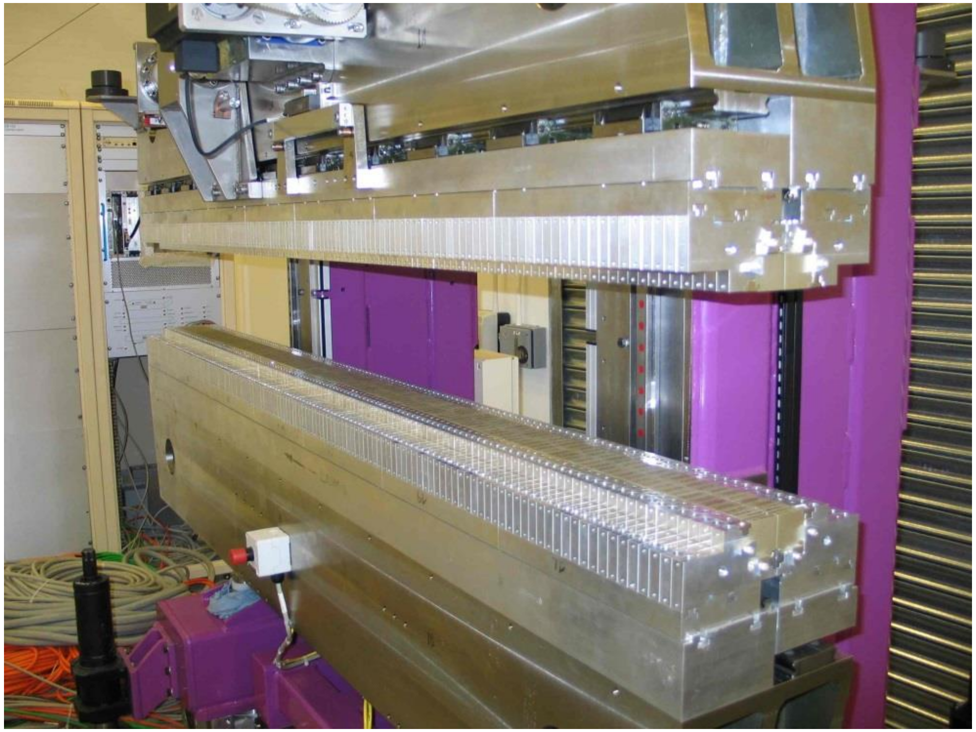
How to increase brightness - undulators & wigglers

Periodic array of magnetic poles providing a sinusoidal magnetic field on axis:

$$B = (0, \quad B_0 \sin(k_u z), \quad 0,)$$

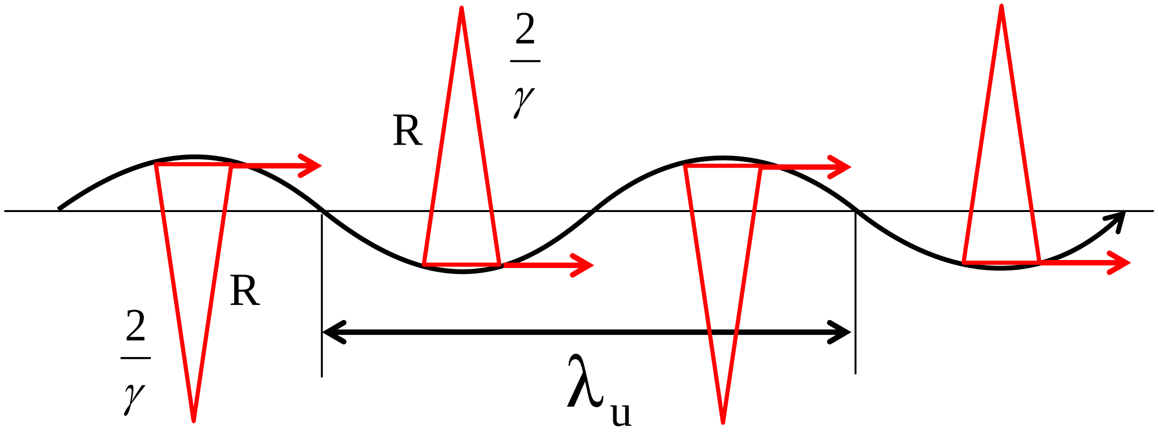


Insertion devices (undulators) to generate high brilliance radiation



Recall L3: Radiation from sequence of bends

Assume that bends are arranged in sequence with +-+-+- polarity with period λ_u, so that trajectory wiggles:



Observer will see photons emitted during travel along the arc 2R/γ

If $2R/\gamma \ll \lambda_u/2$, then radiation emitted at each wiggle is independent

If $2R/\gamma \gg \lambda_u/2$ => regime where entire wiggling trajectory contribute to radiation

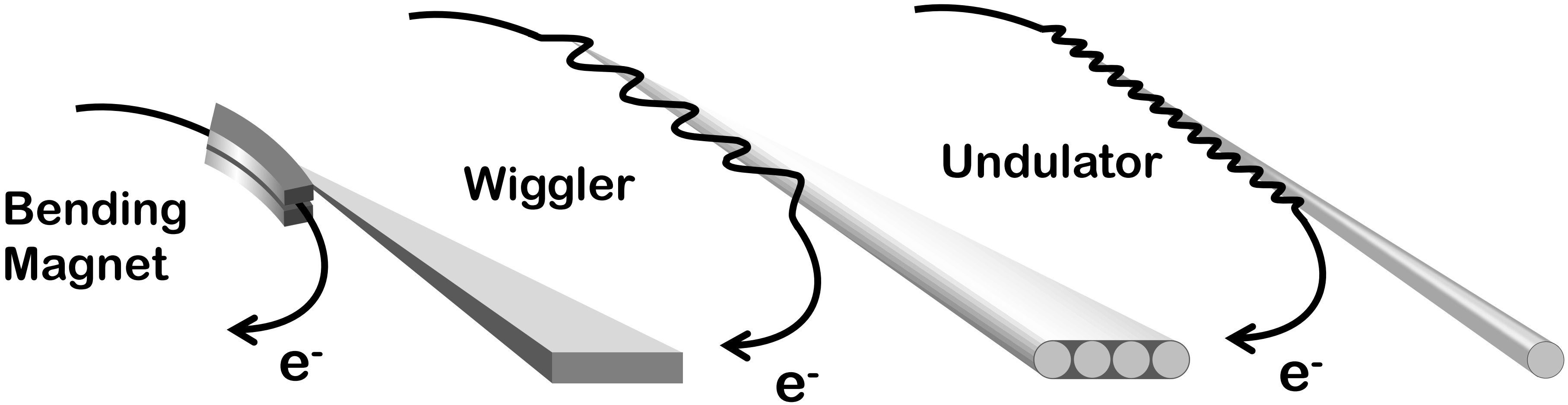
Define $K \sim \gamma\, \lambda_u/R$

$K \gg 1$ – wiggler regime

$K \ll 1$ – undulator regime

Wiggler and undulator radiation

Parameter $K \sim \gamma\ \lambda_u/R$ defines different regimes of synchrotron radiation

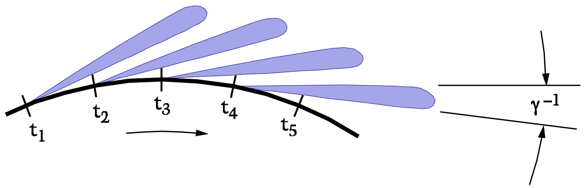


$K \gg 1$
wiggler
regime

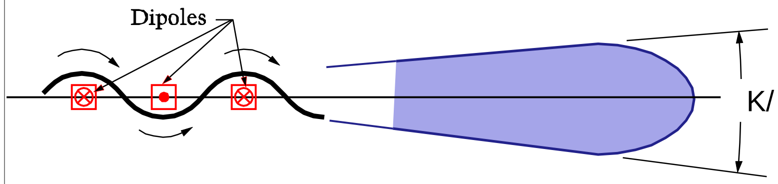
$K \ll 1$
undulator
regime

We will consider this in more details in the lecture about light sources

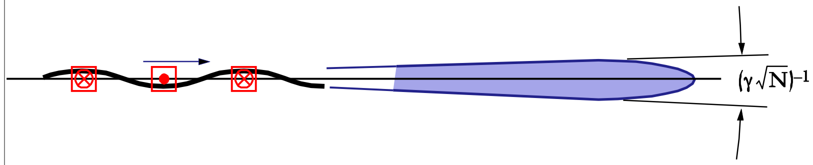
Synchrotron radiation from undulators and wigglers



bending magnet - a “sweeping searchlight”



wiggler - incoherent superposition K > 1



undulator - coherent interference K < 1

Bends and wigglers:

Continuous spectrum characterized by ε_c = critical energy

ε_c(keV) = 0.665 B(T)E^2(GeV)

eg: for B = 1.4T E = 3GeV ε_c = 8.4 keV

(bending magnet fields are usually lower ~ 1–1.5T)

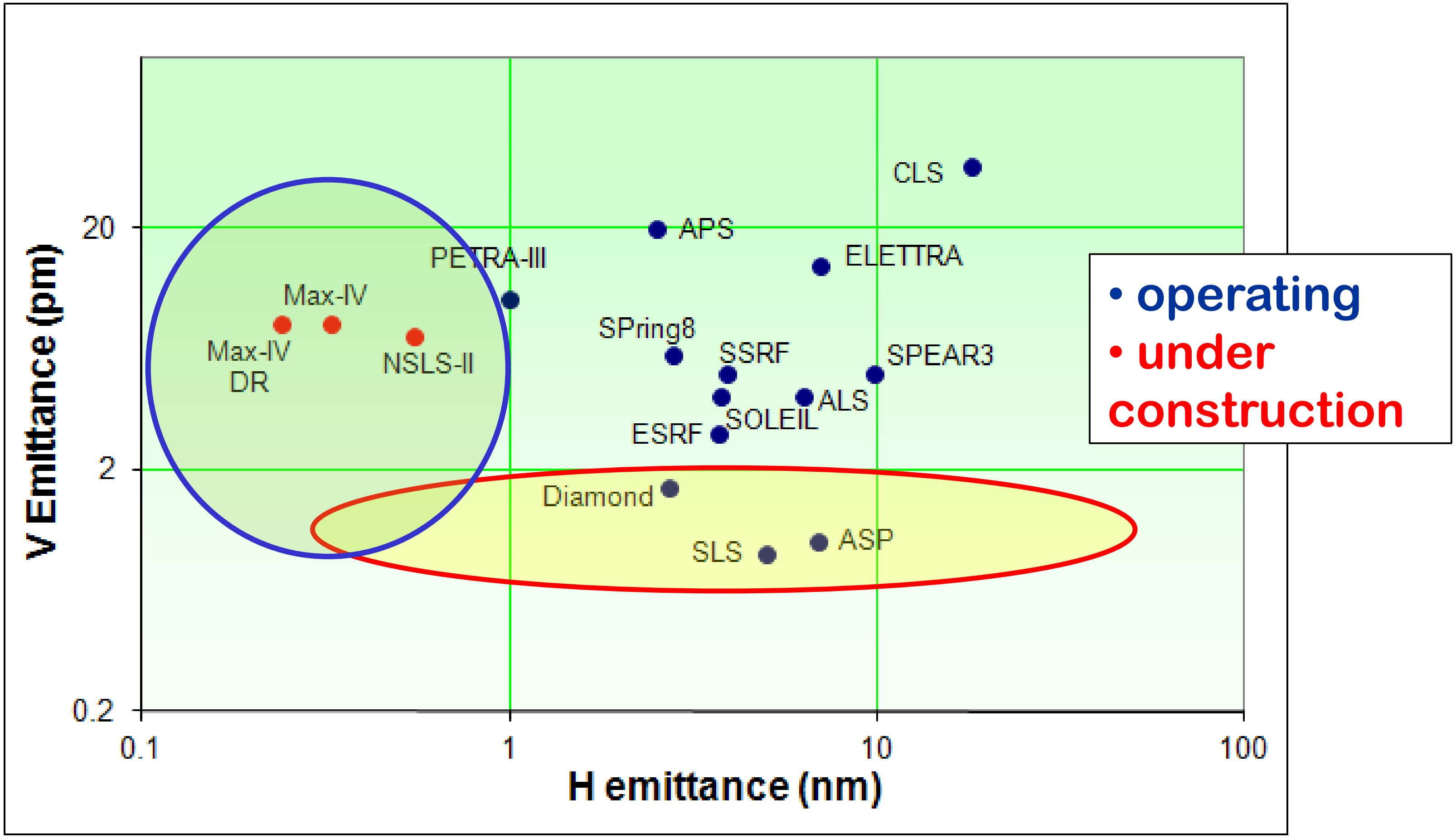
Undulator:

Quasi-monochromatic spectrum with bandwidth of $\Delta f/f \sim 1/N$ (where N is number of periods)

(We will discuss K and wavelength of undulator radiation in the FEL lecture)

Emittance of third generation light sources

The emittance in the vertical plane however has been reduced to the pm range in several light sources. This radiation is diffraction limited in the vertical plane up to the hard X-rays



Compton sources

- – Basic formulae
- – Review of existing projects

Thomson scattering

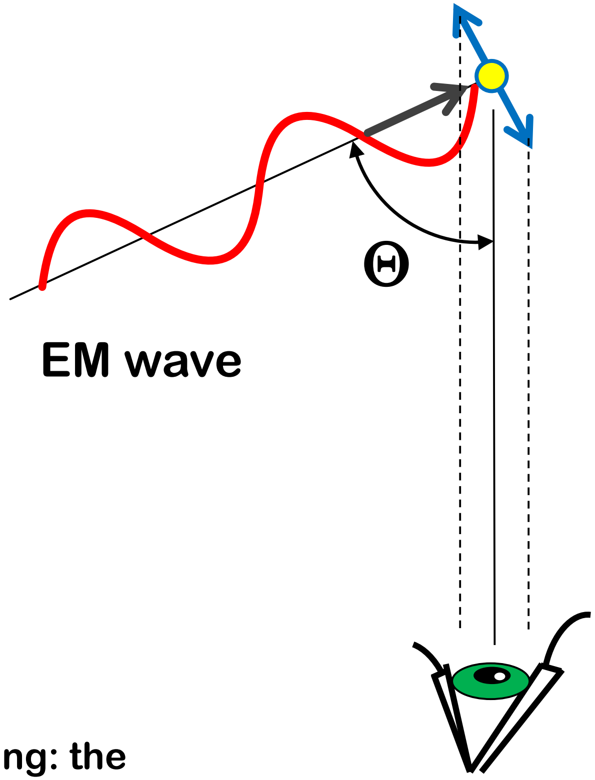
Elastic scattering of an EM plane wave by an electron at rest (or low E), with mass m_e and charge q, is a process known as "Thomson scattering"

The classical Thomson cross section is

$$\sigma_{Th} = \frac{8\pi}{3} r_e^2 = 0.665 \cdot 10^{-28} [m^2]$$

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(1 + \cos^2 \theta\right)$$

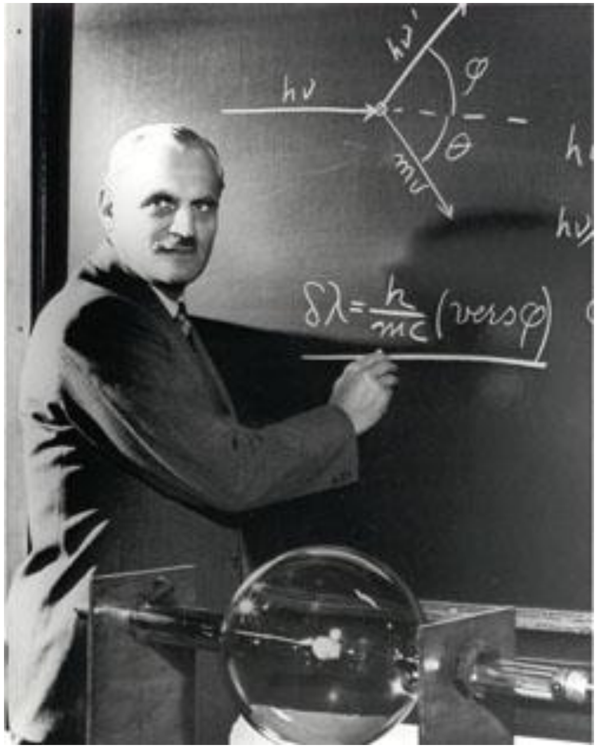


Thomson scattering is the low-energy limit of Compton scattering: the energies of the particle and photon are the same before and after the scattering, i.e. recoil of the electron can be neglected

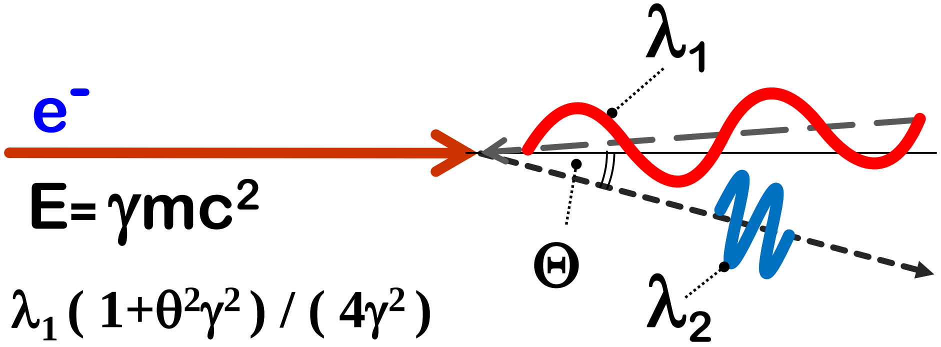
Compton scattering

In collision between a high E free electron and a low energy photon a substantial fraction of the electron energy can be transferred to the photon As a result, in the observer frame, the photon is backscattered with a significant energy boost .

This process is known as Compton backscattering



Inverse Compton scattering:
photon gains energy after interaction

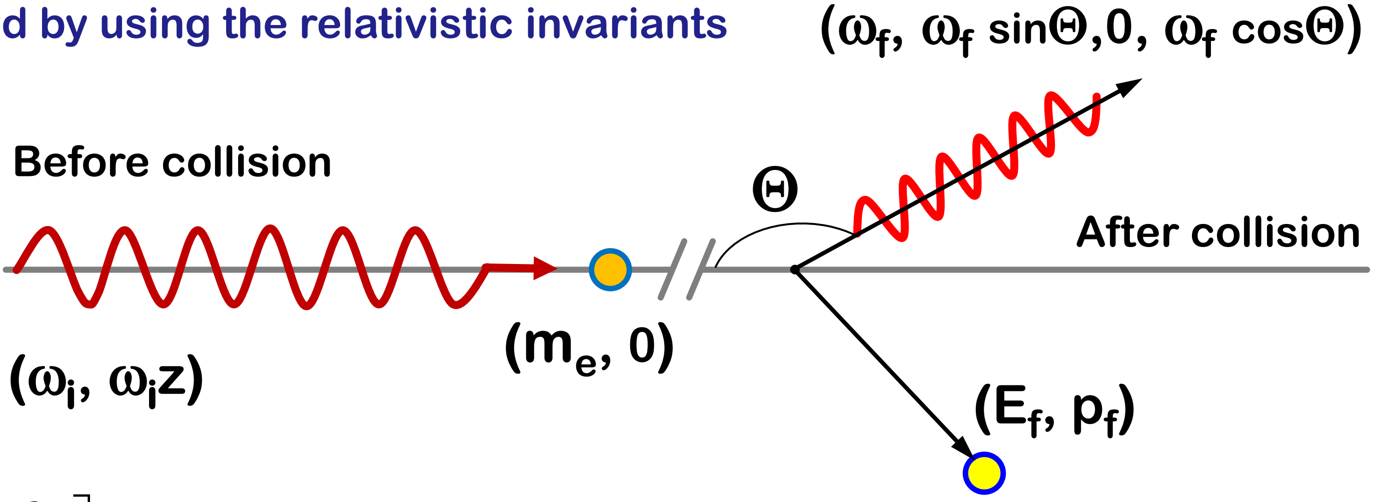


$$\lambda_2 = \lambda_1 \, (1+\theta^2\gamma^2) \,/\, (4\gamma^2)$$

- Examples for λ_1= 532 nm (2.33 eV)
  - e- 5.11 MeV (γ =10), λ_2= 1.33 nm (0.93 keV)
  - e- 18.6 MeV (γ =36.5), λ_2= 0.1 nm (12.4 keV)

Compton scattering

An expression of the total Compton scattering cross section in the centre-of-mass frame can be obtained by using the relativistic invariants



$$\sigma_{tot} = \frac{2\pi\, m_e^2\, r_e^2}{E_{cm}^2} \mathrm{Log}\left[\frac{E_{cm}^2}{m_e^2}\right]$$

where $E_{cm} = m_e^2 + 2 p_f \omega_f (1 - \cos\theta)$

differential and the total cross section in the laboratory frame:

$$\sigma_{TOT} = \frac{2\pi\, r_e^2}{x_1}\left\{\left(1 - \frac{4}{x_1} - \frac{8}{x_1^2}\right)\ln(1 + x_1) + \frac{1}{2} + \frac{8}{x_1} - \frac{1}{2(1 + x_1)^2}\right\}$$

$$\frac{d\sigma}{d\Omega} = 2 r_e^2 \left(\frac{\omega_f}{m_e x_1}\right)^2 \left(4y(1 + y) - \frac{x_1}{x_2} - \frac{x_2}{x_1}\right)$$

where $x_1 = 2\gamma \frac{\omega_i}{m_e}(1 - \beta\cos\varphi_1)$; $x_2 = -2\gamma \frac{\omega_f}{m_e}(1 - \beta\cos\varphi_2)$; $y = \frac{1}{x_1} + \frac{1}{x_2}$

Where β is the relativistic factor and angles φ_1 and φ_2 are defined as shown in the figure in next slides

Following THOMX CDR, A.Variola, et al, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010. Assume c=1 here.

Compton scattering approximation

If $x_1 << 1 \quad (\gamma\, \omega_1 << m_e)$ **then** $\sigma_{TOT} = \frac{2\pi\, r_e^2}{x_1} \underbrace{\left\{ \left(1 - \frac{4}{x_1} - \frac{8}{x_1^2}\right) \ln(1+x_1) + \frac{1}{2} + \frac{8}{x_1} - \frac{1}{2(1+x_1)^2} \right\}}_{=>\ 4x_1/3}$

Recall examples for λ_1= 532 nm (2.33 eV)

e- 5.11 MeV (γ =10), λ_2= 1.33 nm (0.93 keV)

e- 18.6 MeV (γ =36.5), λ_2= 0.1 nm (12.4 keV)

=> 4x$_1$/3

thus $\sigma_{TOT} = \frac{8\pi\, r_e^2}{3}$

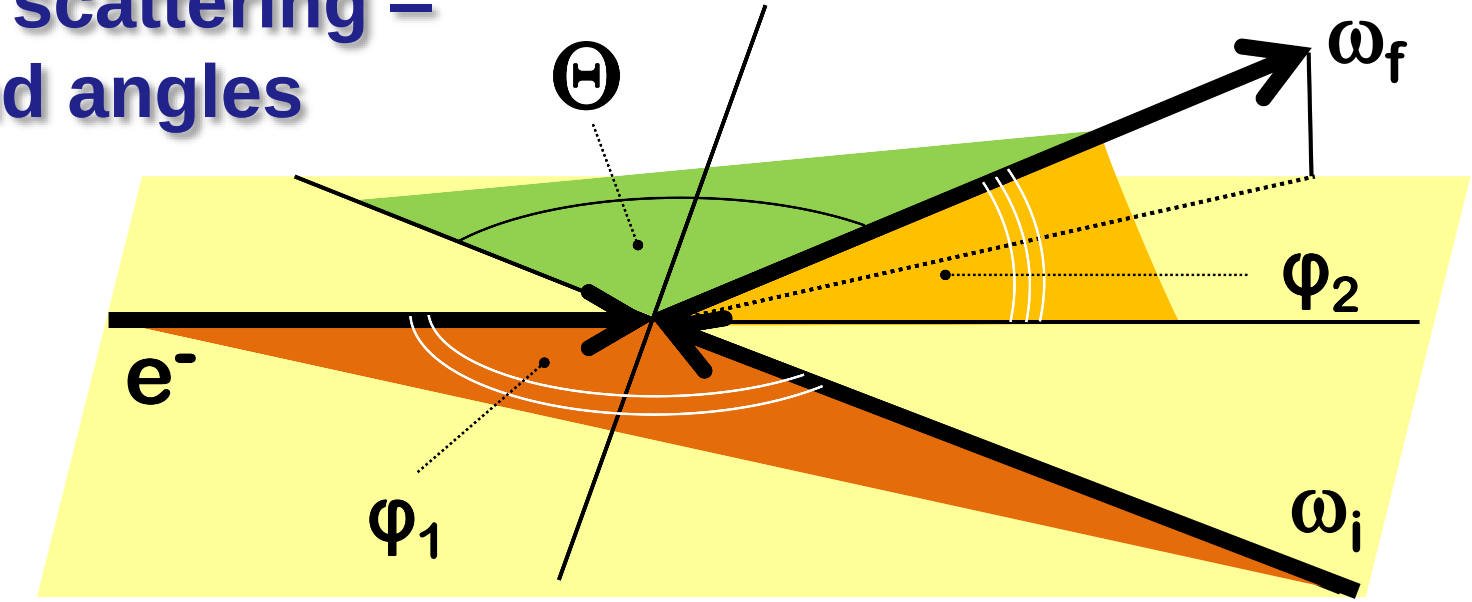
Then the total scattering cross section is very close to the Thomson one

Therefore, in this approximation, one can evaluate the emitted rate as the product of the Thomson cross section and the luminosity L

Assuming head-on collision: $L = \frac{N_e N_\gamma f}{2\pi\, \sigma_x \sigma_y}$

Where sizes are convolution of e and γ sizes: $\sigma = \sqrt{\sigma_e^2 + \sigma_\gamma^2}$

Compton scattering – ω shift and angles



When γ >>1 =>

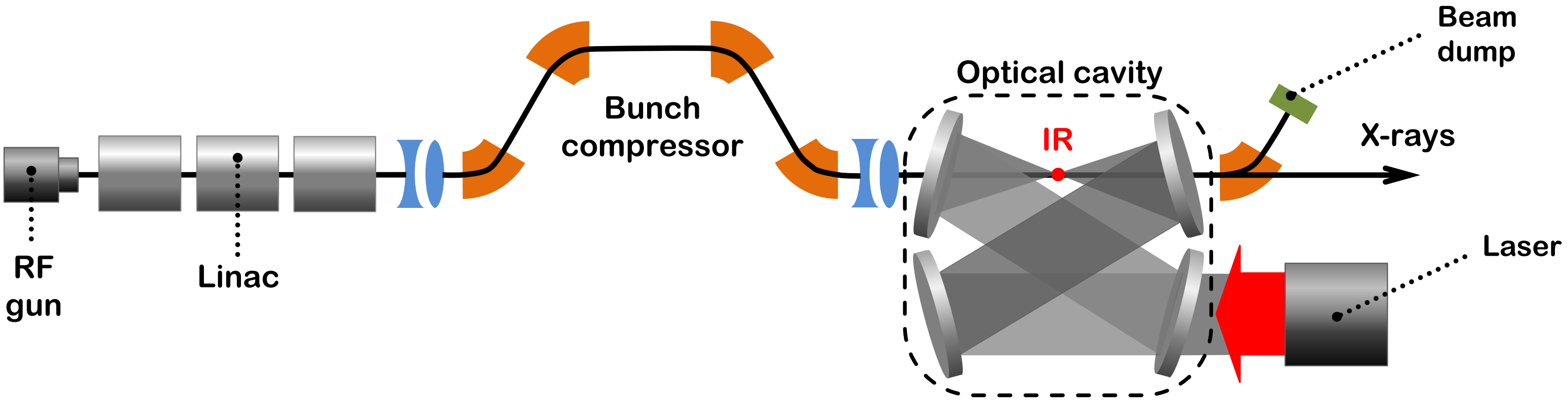
$$\omega_f \approx \frac{2\gamma^2\omega_i(1-\cos\varphi_1)}{1+(\gamma\varphi_2)^2+2\gamma\frac{\omega_i}{m_e}(1-\cos\varphi_1)}$$

Characteristics of Compton scattering:

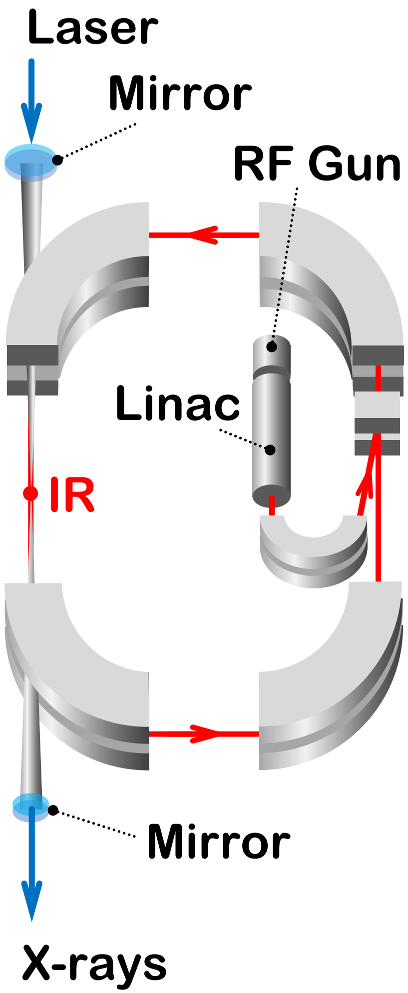
1. **Clear dependence between scattered photon energy and its angle – useful for selection of monochromatic beam using diaphragms**
2. **All flux is emitted into a cone of 4/γ**
3. **Photons of max energy $\omega_c=4\omega_i\,\gamma^2$ come from head-on collision ($\varphi_1=\pi$), and photons of half-max energy come from $\varphi_1=\pi/2$ collision**

Following THOMX CDR, A.Variola, et al, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010. Assume c=1 here.

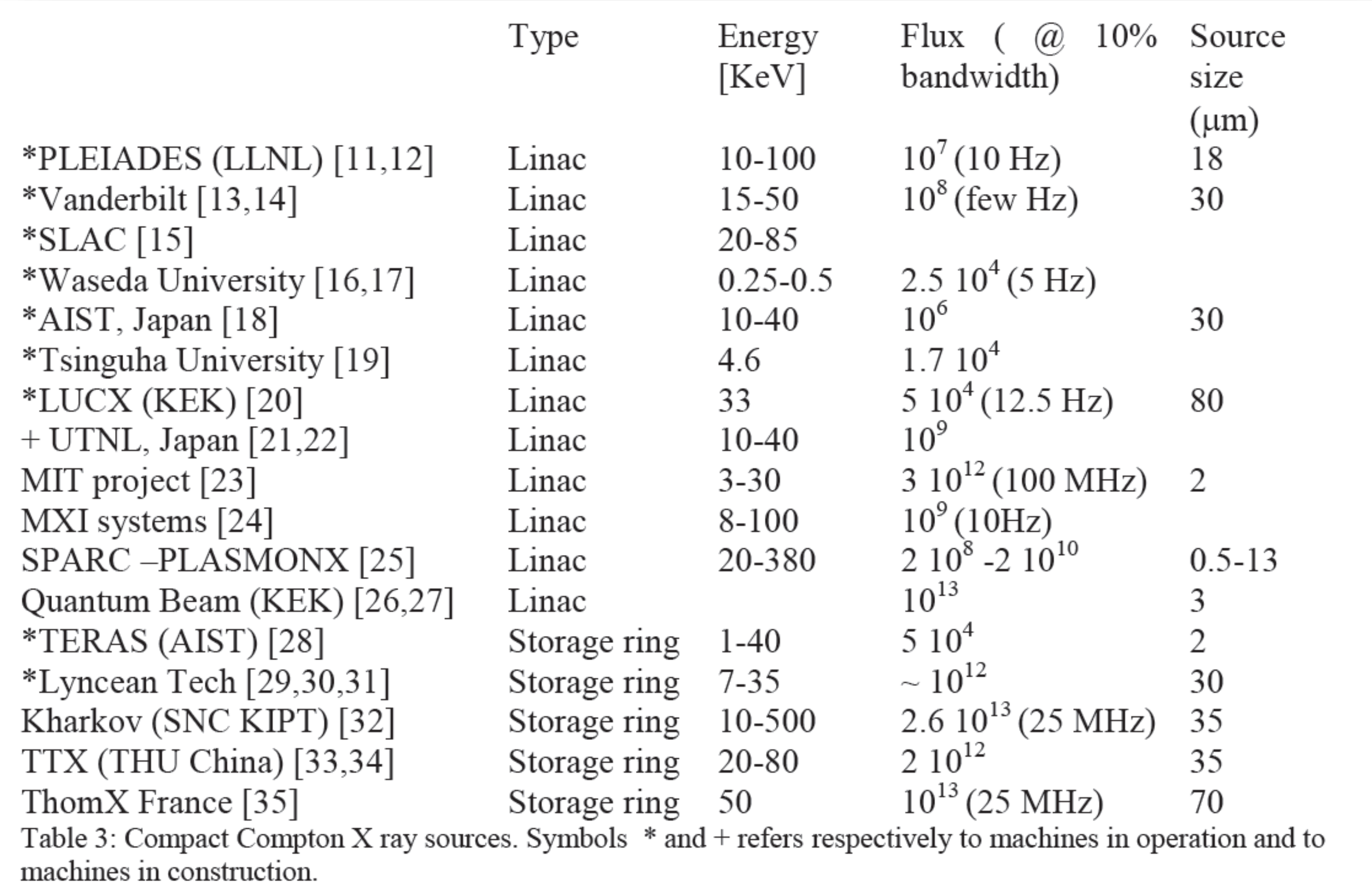
Generic linac based Compton source



Generic ring based Compton source



Existing and planned Compton sources



	Type	Energy [KeV]	Flux (@ 10% bandwidth)	Source size (μm)
*PLEIADES (LLNL) [11,12]	Linac	10-100	10^7 (10 Hz)	18
*Vanderbilt [13,14]	Linac	15-50	10^8 (few Hz)	30
*SLAC [15]	Linac	20-85		
*Waseda University [16,17]	Linac	0.25-0.5	$2.5\ 10^4$ (5 Hz)	
*AIST, Japan [18]	Linac	10-40	10^6	30
*Tsinguha University [19]	Linac	4.6	$1.7\ 10^4$	
*LUCX (KEK) [20]	Linac	33	$5\ 10^4$ (12.5 Hz)	80
+ UTNL, Japan [21,22]	Linac	10-40	10^9	
MIT project [23]	Linac	3-30	$3\ 10^{12}$ (100 MHz)	2
MXI systems [24]	Linac	8-100	10^9 (10Hz)	
SPARC –PLASMONX [25]	Linac	20-380	$2\ 10^8$ -$2\ 10^{10}$	0.5-13
Quantum Beam (KEK) [26,27]	Linac		10^{13}	3
*TERAS (AIST) [28]	Storage ring	1-40	$5\ 10^4$	2
*Lyncean Tech [29,30,31]	Storage ring	7-35	~ 10^{12}	30
Kharkov (SNC KIPT) [32]	Storage ring	10-500	$2.6\ 10^{13}$ (25 MHz)	35
TTX (THU China) [33,34]	Storage ring	20-80	$2\ 10^{12}$	35
ThomX France [35]	Storage ring	50	10^{13} (25 MHz)	70

Table 3: Compact Compton X ray sources. Symbols * and + refers respectively to machines in operation and to machines in construction.

Following THOMX CDR, A.Variola, et al, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010. Assume c=1 here.

Lyncean Technologies, Inc.

Compact X-ray light source

25 MeV accelerator

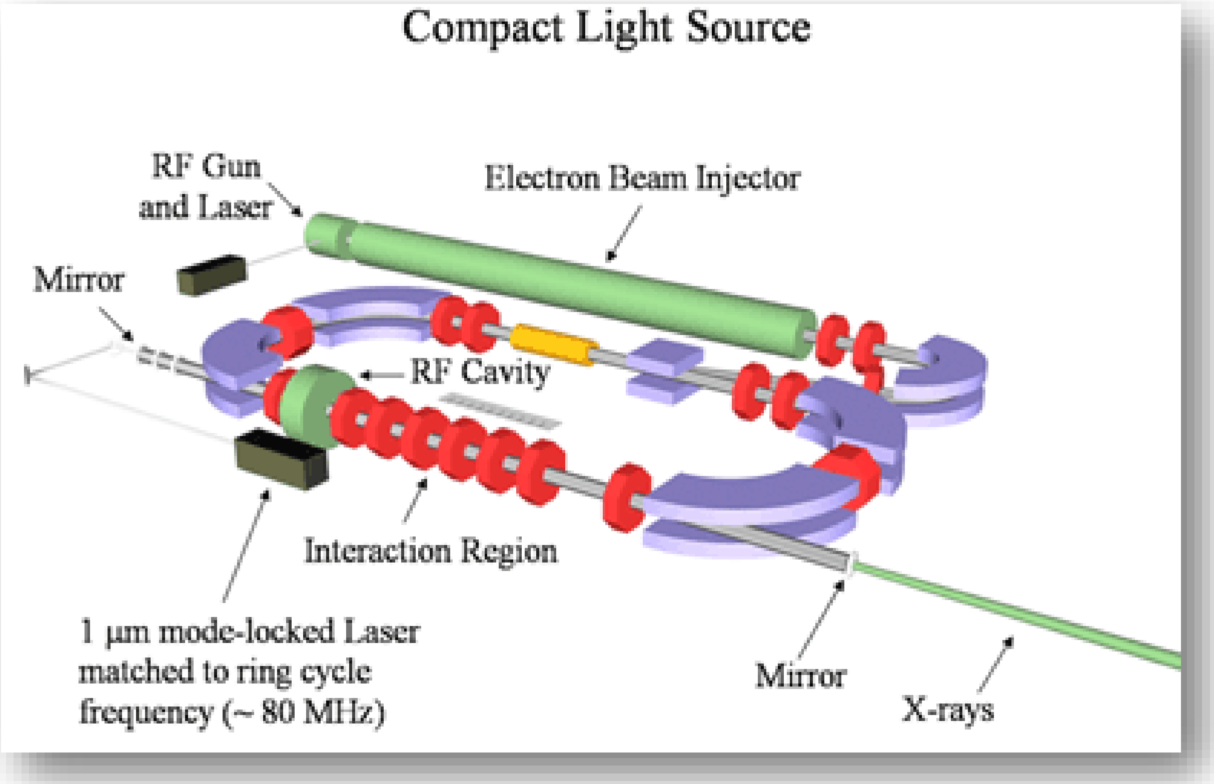
X-ray tuneable from a few keV up to 35 keV

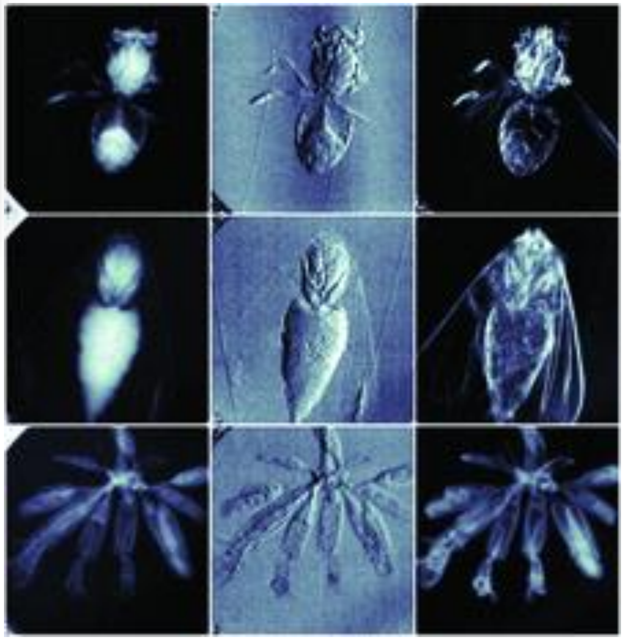
Fits in a 10x25 ft room

Clinical High Resolution Imaging System

Micro-tomography

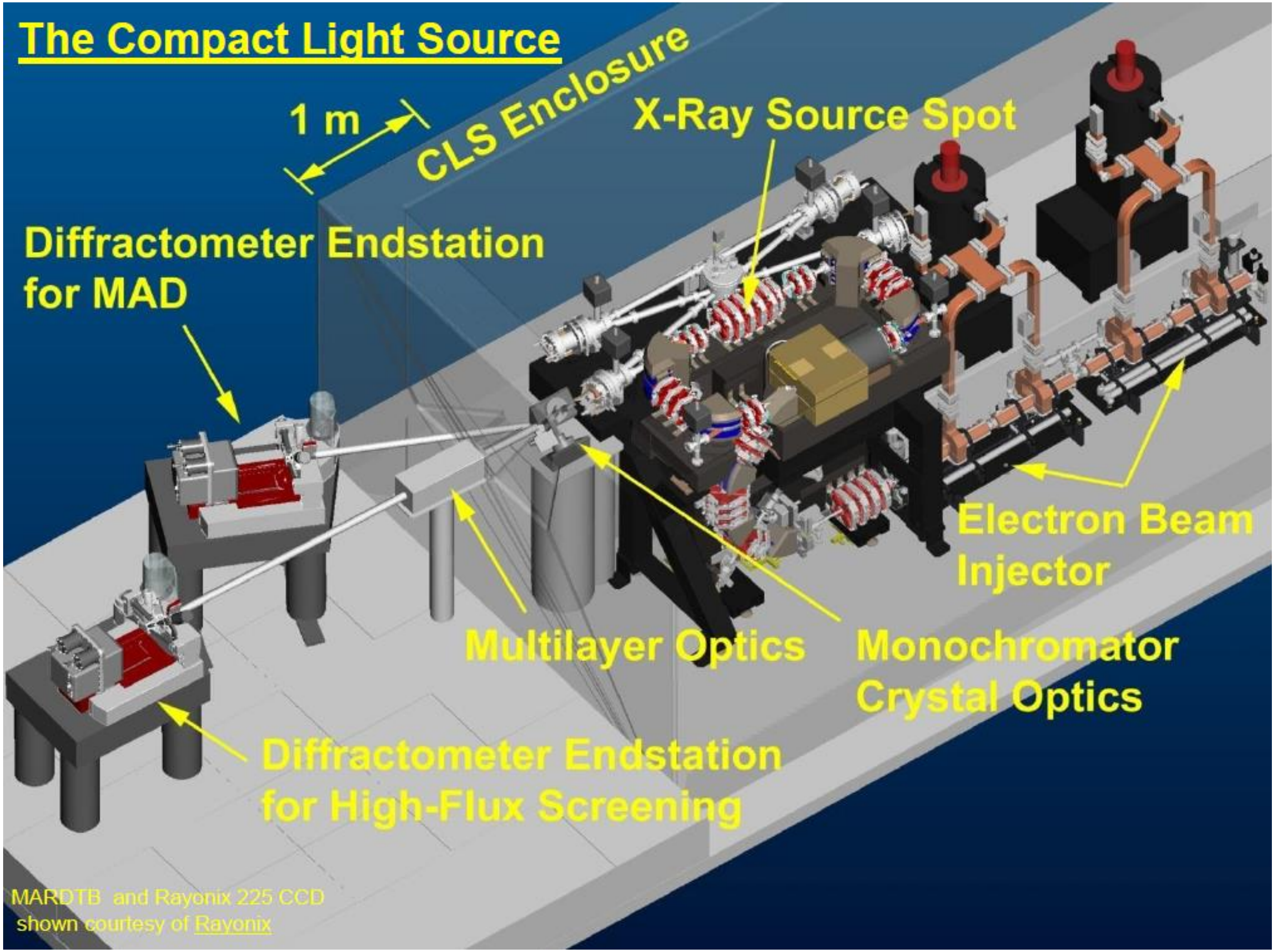
Protein crystallography





Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays,
M. Bech, O. Bunk, C. David, R. Ruth, J. Rifkin, R. Loewen, R. Feidenhans'l and F. Pfeiffer
et al, *J. Synchrotron Rad.* (2009). **16**, 43-47

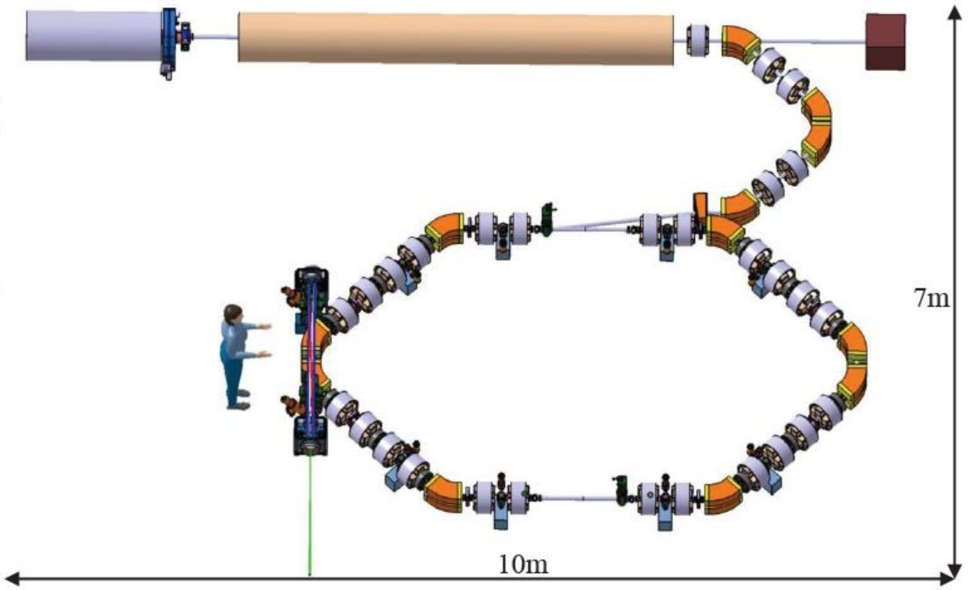
The Compact Light Source



MARDTB and Rayonix 225 CCD shown courtesy of Rayonix

R. Ruth, SLAC / Lyncean Technologies

THOMX – Compton source



X-ray energy 50-90 keV

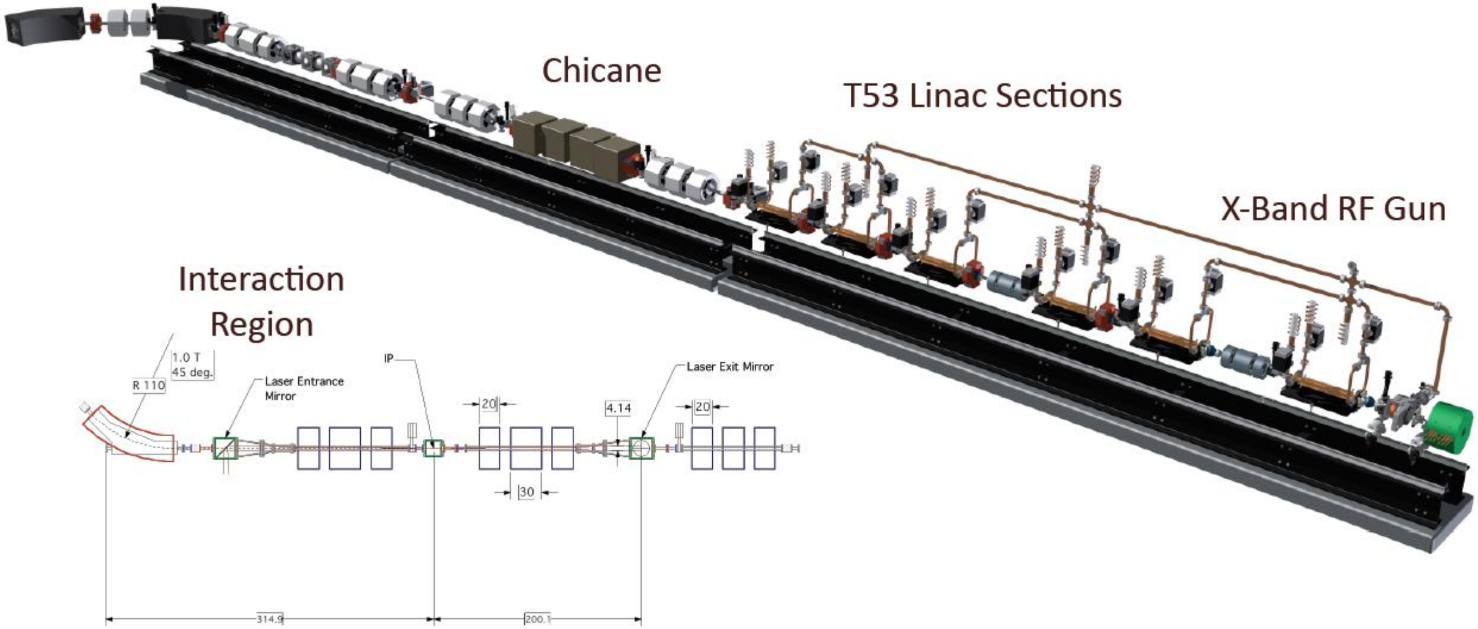
Flux 1E11-1E13 ph/s

Ring energy 50 MeV

A.Variola, A.Loulergue, F.Zomer, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010

- Scientific case
  - Cultural heritage application
  - Bio-Medical applications
  - X-ray crystallography

Mono-Energetic Gamma-Ray (MEGa-Ray) Compton light source (LLNL & SLAC)



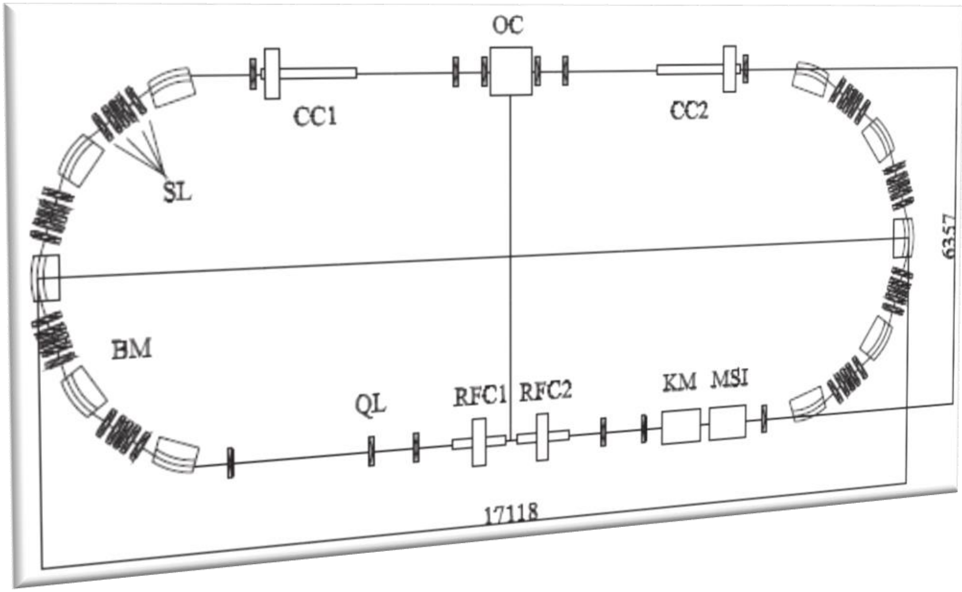
Nuclear resonance fluorescence

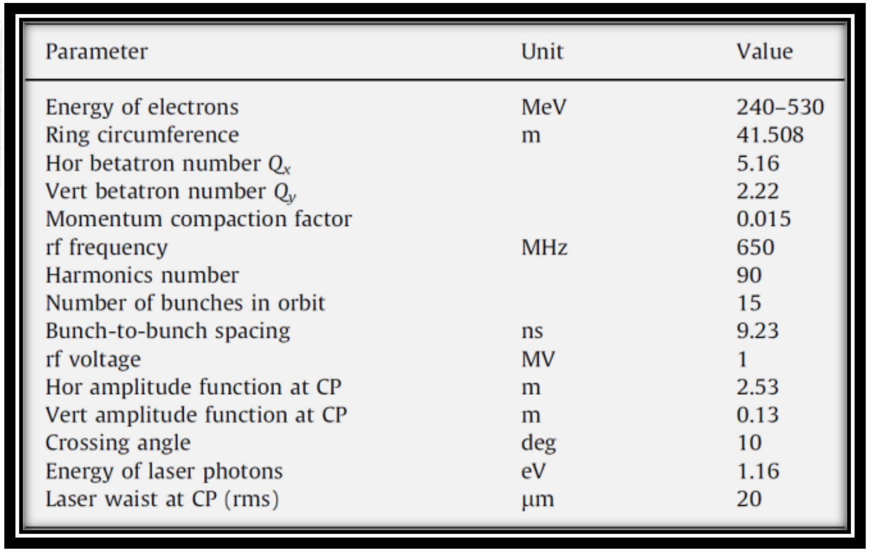
Isotopic sensitivity

RF gun:	5.59 cells, 11.424 GHz, 200 MV/m
Photocathode laser:	Fiber-based, 4th harmonic, 50 uJ
Linac:	250 MeV, 11.424 GHz, > 75 MV/m
Interaction laser:	0.5 J, 1.064 nm, 10 ps; 0.1 J, 2ω
Nominal rep. rate:	60-120 Hz
Dose:	10^7-10^8/shot
Flux:	10^{10}/s
Energy range:	0.5 – 2.2 MeV
Spectral bandwidth:	0.5%

F.V. Hartemann (LLNL) et al, ICFA FLS 2010

Compton ring for nuclear waste management





Parameter	Unit	Value
Energy of electrons	MeV	240–530
Ring circumference	m	41.508
Hor betatron number Q_x		5.16
Vert betatron number Q_y		2.22
Momentum compaction factor		0.015
rf frequency	MHz	650
Harmonics number		90
Number of bunches in orbit		15
Bunch-to-bunch spacing	ns	9.23
rf voltage	MV	1
Hor amplitude function at CP	m	2.53
Vert amplitude function at CP	m	0.13
Crossing angle	deg	10
Energy of laser photons	eV	1.16
Laser waist at CP (rms)	μm	20

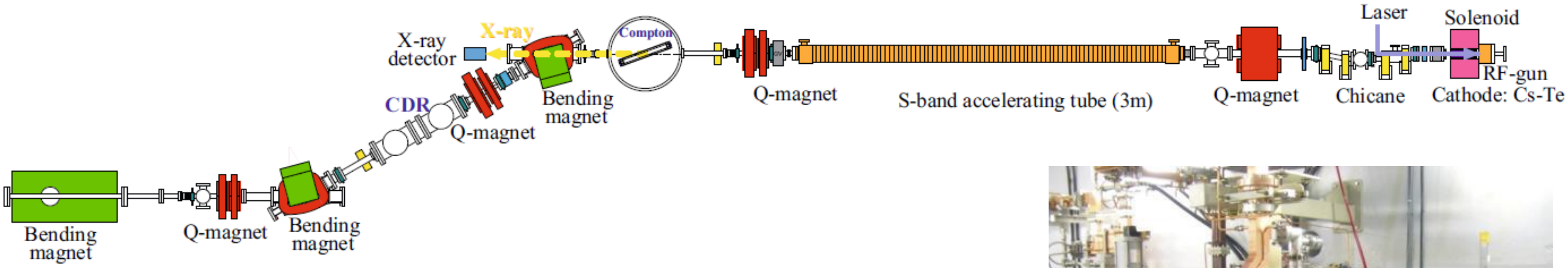
E. Bulyak, J. Urakawa, et al., Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.06.215

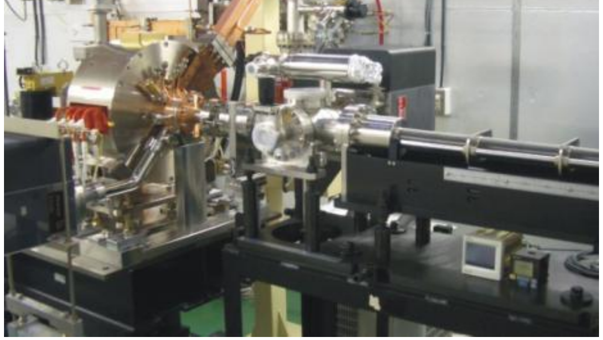
- **Intense gamma-ray source**
- **Energy of electrons 240-530 MeV**
- **Gamma-ray energies in the range from 1 to 5 MeV.**

•Detect practically all of the isotopes present in nuclear waste, based on nuclear resonance fluorescence method –suitable for express nuclear waste management

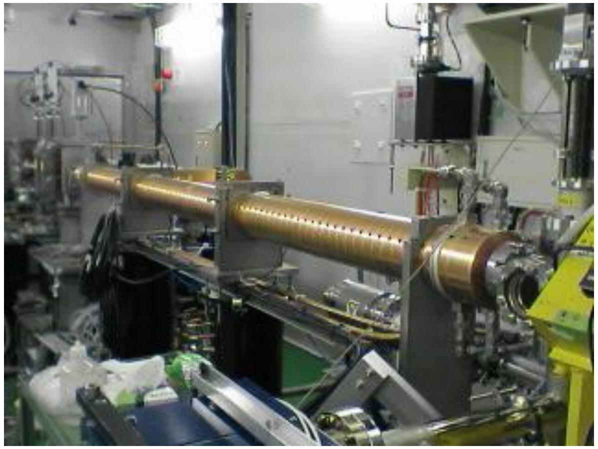
- **Crab-crossing scheme helps to reach gamma-beam intensity of up to 5E13 γ/s**

Laser Undulator Compact X-ray Source Facility (LUCX) at the Accelerator Test Facility (ATF), KEK



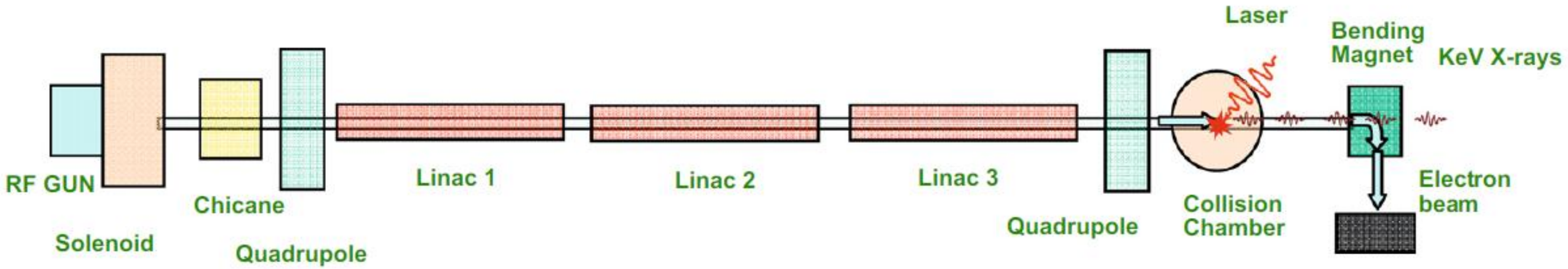


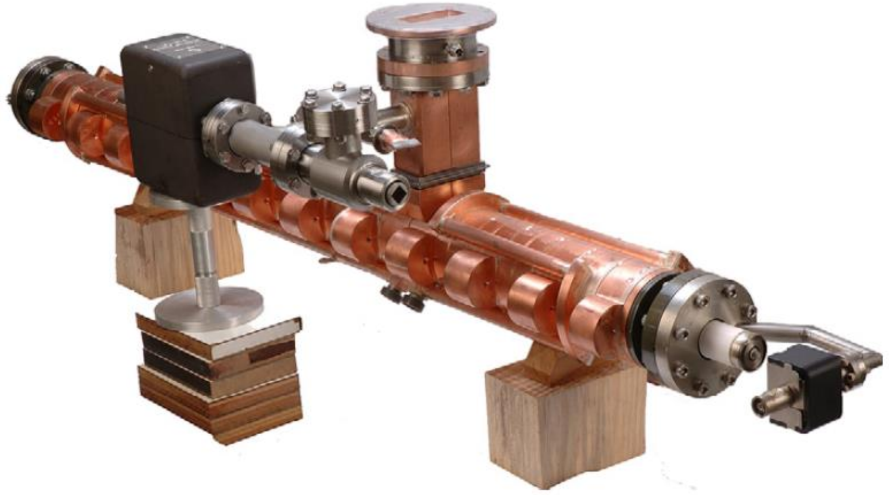
50 MeV beam, trains with 100 bunches,
bunch spacing of 2.8 ns,
a maximum total charge of 250 nC
multi-bunch electron linac mode-locked
1064 nm laser
Flux 1.2E5 photons/s
A first step toward “Quantum beam project”



Development of a compact X-ray source based on Compton scattering using a 1.3 GHz superconducting RF accelerating linac and a new laser storage cavity, J. Urakawa, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.02.019

S-band linac-based X-ray source

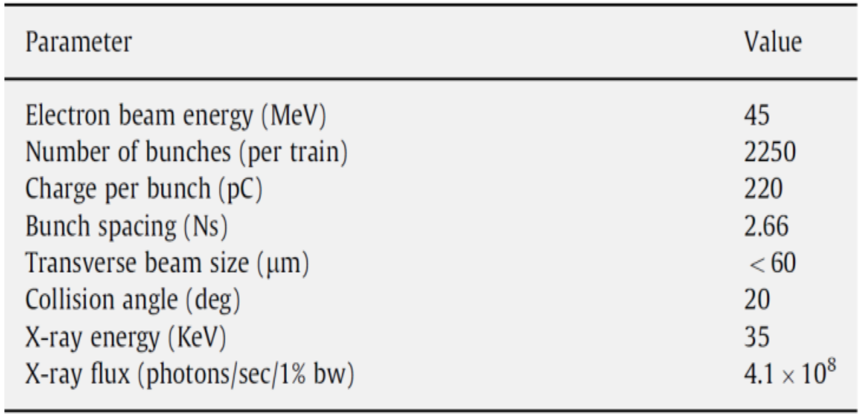




Side-coupled linac tube built at SAMEER, Society for Applied Microwave Electronic Engineering and Research (SAMEER), India

45 MeV electrons, 35keV X-rays
Aiming to develop a low-cost, high-performance tuneable X-ray source very useful for small research groups, small industry setups, and hospitals

S-band linac-based X-ray source with p/2-mode electron linac, A. Deshpande, et al., Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.02.023

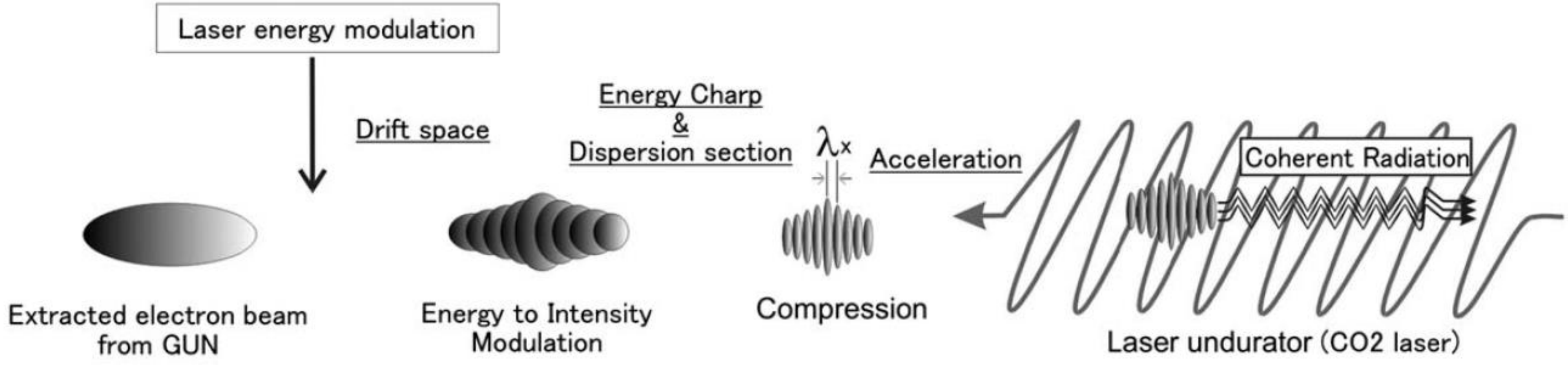


Parameter	Value
Electron beam energy (MeV)	45
Number of bunches (per train)	2250
Charge per bunch (pC)	220
Bunch spacing (Ns)	2.66
Transverse beam size (μm)	<60
Collision angle (deg)	20
X-ray energy (KeV)	35
X-ray flux (photons/sec/1% bw)	4.1×10^8

KEK- SAMEER (India) collaboration

Compact coherent Compton EUV source

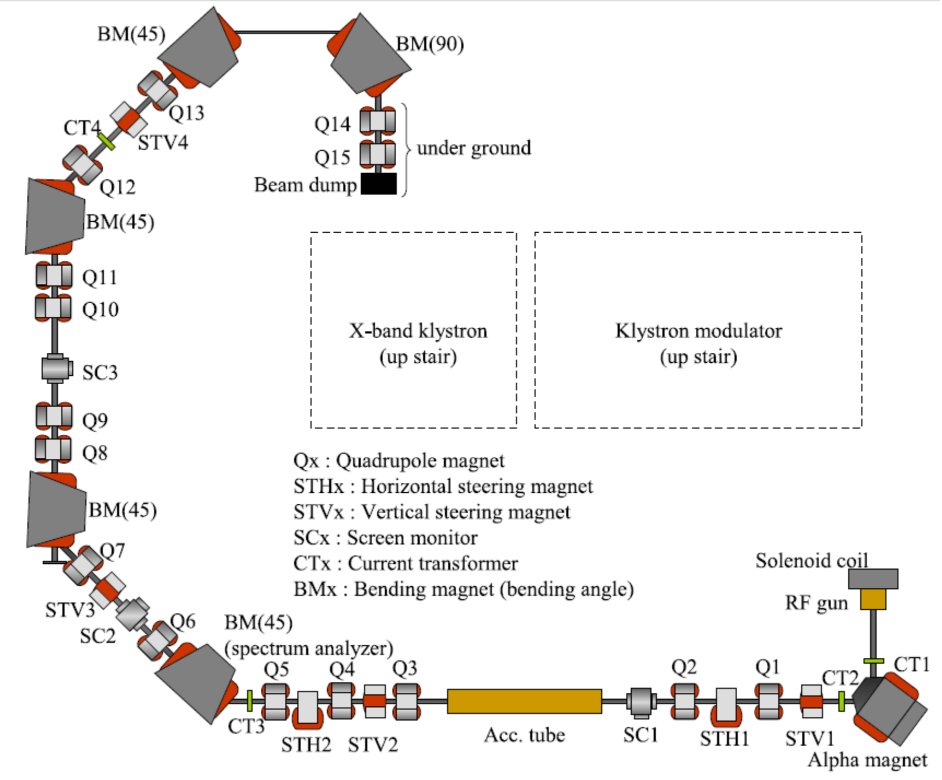
- Extreme ultra-violet (EUV) lithography at λ=13.5nm – strongest candidate of the next generation processing of Large Scale Integration circuits
- FEL schemes are possible, but require ~GeV scale facilities
- Compact EUV Compton source with 7 MeV micro-bunched electron beam and a high-intensity CO2 laser pulse – a possible solution
- Necessary high flux can be achieve using coherent effect, when the pre-bunched beam is applied to the laser Compton scheme



S. Kashiwagi et al. / Radiation Physics and Chemistry 78 (2009) 1112–1115

Compton X-ray source at University of Tokyo

- **X-rays 10–40 keV for medical science, biology, and materials science**
- **Multi-bunch electron beam and a long-pulse laser for higher flux**
  - **Electron beam: 200 mA peak & 2 mA average under 10 Hz operation, multi-bunch (10^4 bunches in 1 ms)**
  - **Laser: energy 1.4 J, duration 10 ns at a wavelength of 532 nm.**
- **30 MeV X-band (11.424 GHz) linac**
- **3.5-cell thermionic cathode RF-gun**
- **Have demonstrated the 2MeV electron beam generation from the RF-gun**



F. Sakamoto et al, Nuclear Instruments and Methods in Physics Research A 608 (2009) S36–S40

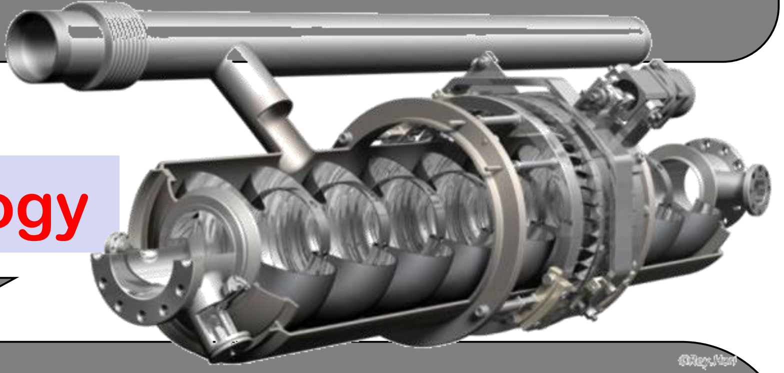
Quantum beam project

Characteristic of proposed machine

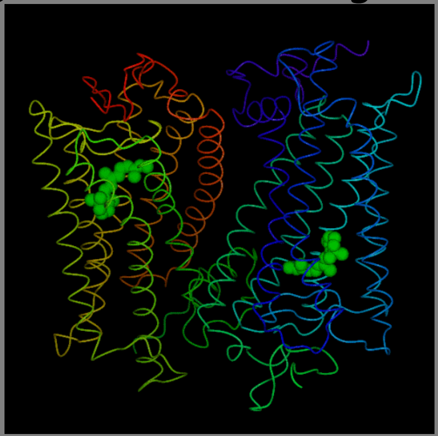
Compact (less than 10m) **quasi-monochromatic** (less than 1%)
High Flux (100 times than Compact normal Linac X-ray : 10^{11} photons/sec 1% BW)
High Brightness (10^{17} photons/sec mrad^2 mm^2 0.1% b.w.)
Ultra-short pulse X-ray (40 fs ~)

J. Urakawa, Quantum Beam Project

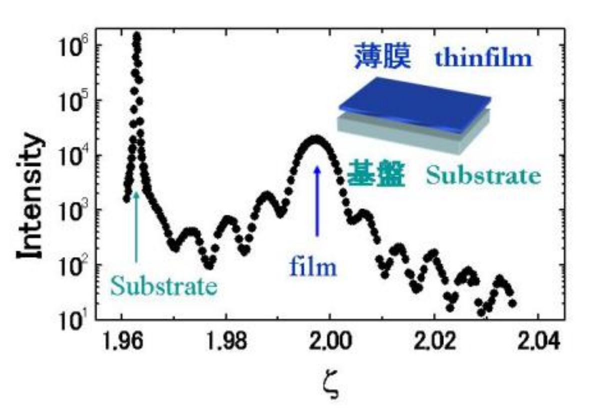
Key: SCRF acceleration technology



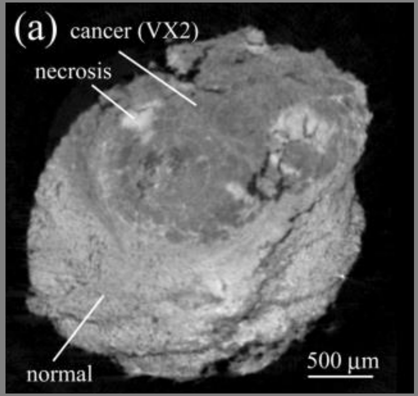
Structural genetic analysis,



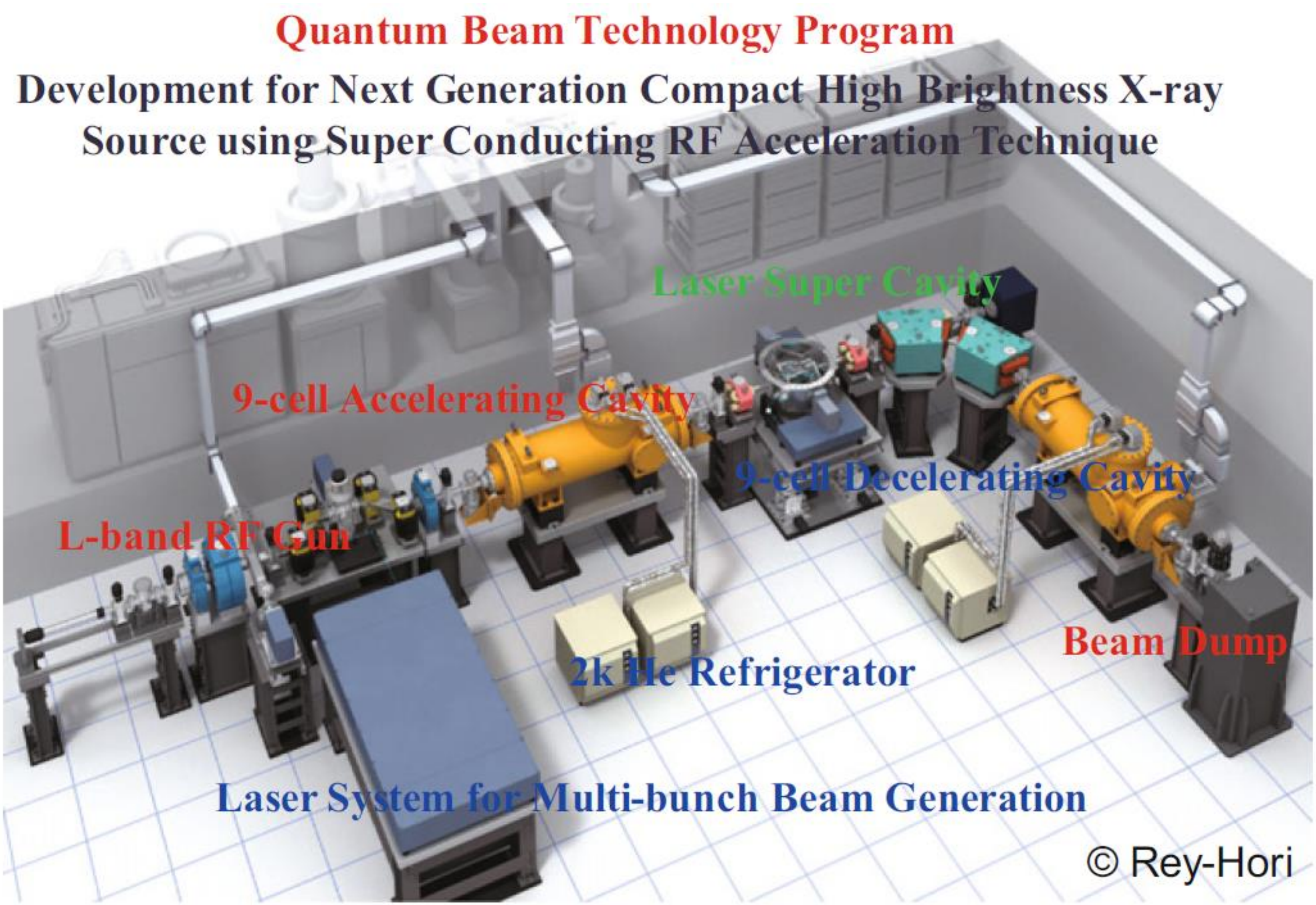
Nano-material evaluation,



Highly fine X-ray Imaging



http://mml.k.u-tokyo.ac.jp/

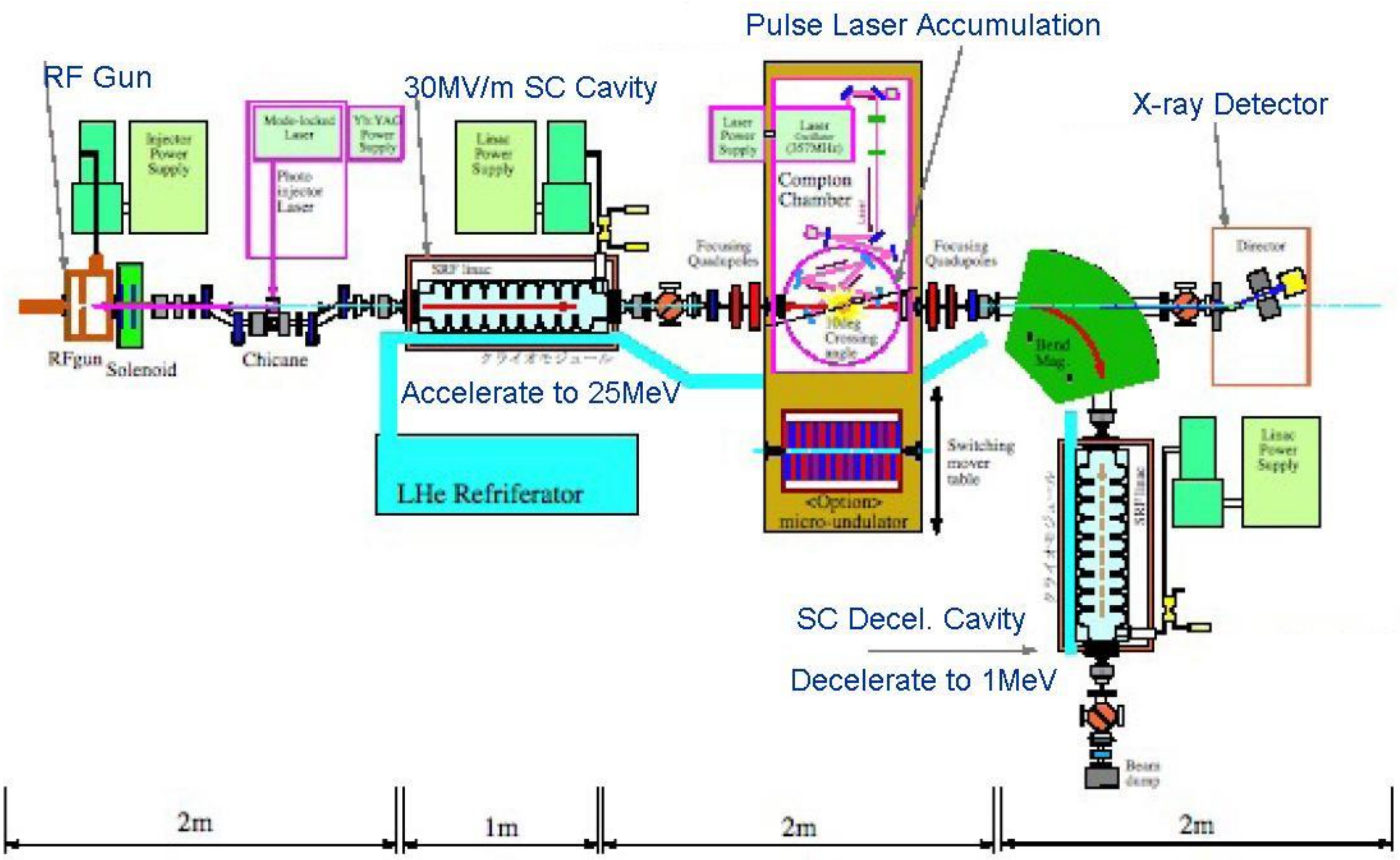


Quantum Beam Technology Program

Development for Next Generation Compact High Brightness X-ray Source using Super Conducting RF Acceleration Technique

J. Urakawa, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.02.019

High-Intensity Compact X-ray Source



RF Gun

30MV/m SC Cavity

Pulse Laser Accumulation

X-ray Detector

Accelerate to 25MeV

SC Decel. Cavity

Decelerate to 1MeV

J. Urakawa, et al, Quantum Beam Project

High-Intensity Compact X-ray Source

Technology	Present status	Target	Key points
Electron source	300 nC/pulse 10,000nC/pulse (2008-2009)	48,000 nC/pulse (2010-2012)	Pulse laser, new photo-cathode, 1 msec pulse length
SC Cavity	Pulse: 25 MV/m CW: 12 MV/m	Pulse: 30 MV/m CW: 20 MV/m	Non-defect and clean surface, Precise electron beam welding, High precision forming, Non-contamination material
Pulsed laser storage	0.5 mJ/pulse, Waist: 30 μm	50 mJ/pulse, Waist: 8 μm	4-mirror optical cavity
Colliding control	μm beam orbit control	Sub-μm beam orbit control	Minimizing environmental effect, Fast feedback control

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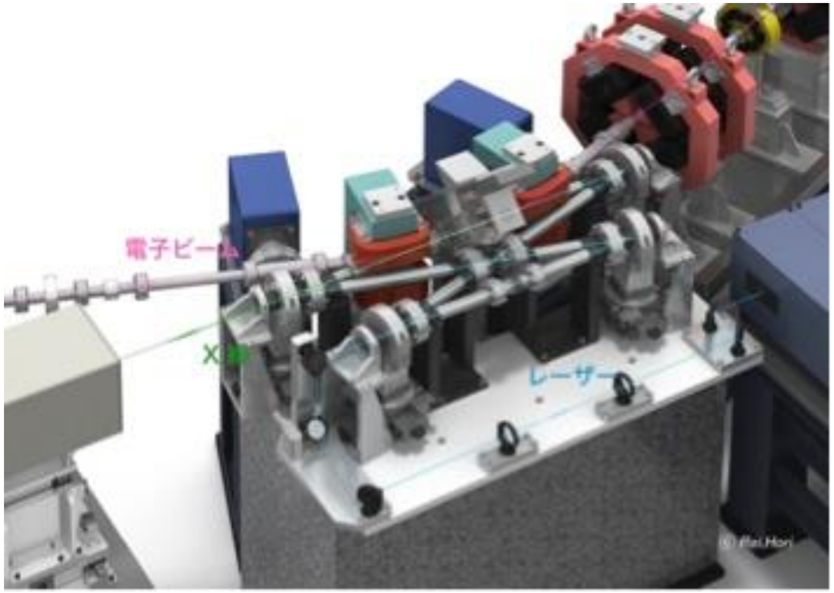
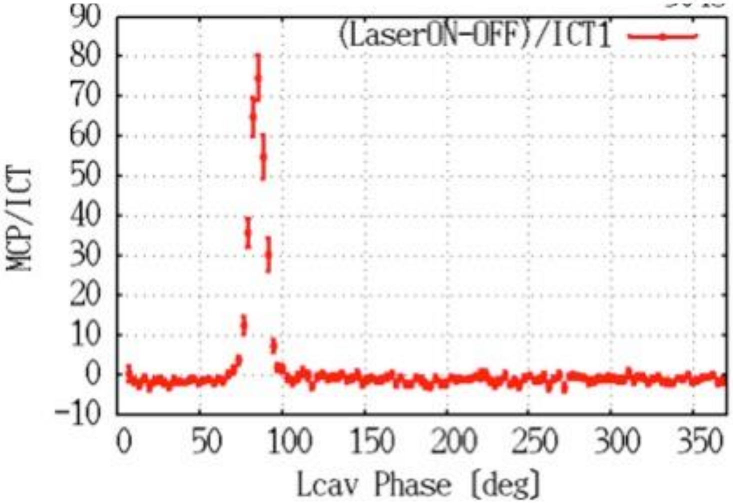
Quantum beam status, 2014

- Actual installation =>
- Results – first gen of Compton x-rays with SRF technology





http://newsline.linearcollider.org/2013/04/04/a-spin-off-of-ilc-technology-already/

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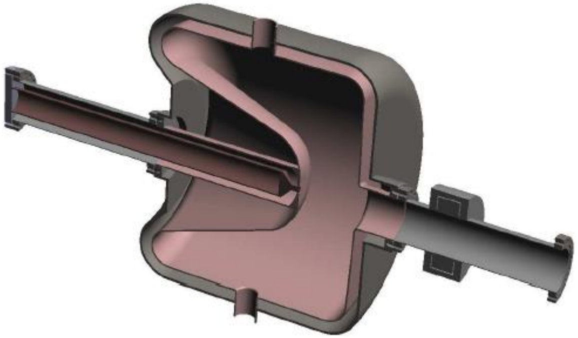
SRF Compact Light Sources @ 4K

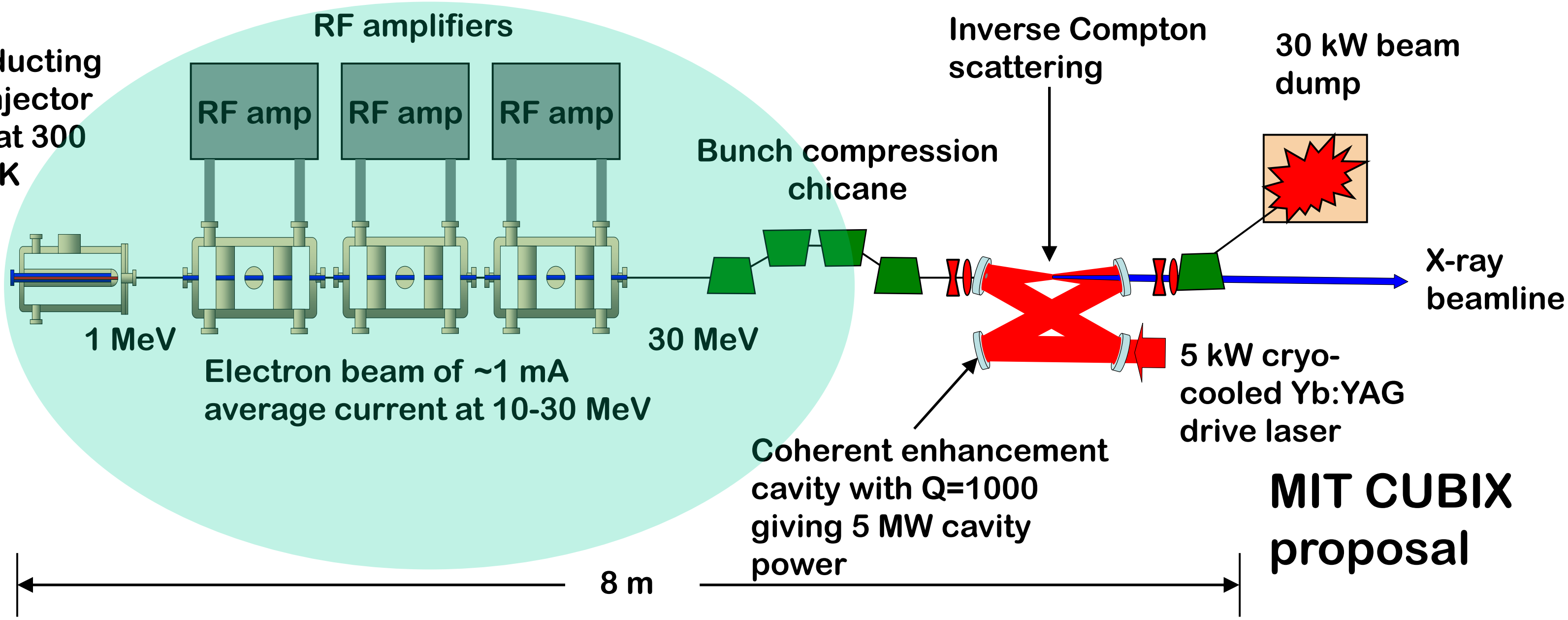
- **Most existing SRF cavities require or benefit from 2K operation**
  - Too complex for a University or small institution-based accelerator
  - Cryogenics is a strong cost driver for compact SRF linacs
- **Spoke cavities can operate at lower frequency**
  - Lower frequency allows operation at 4K
  - No sub-atmospheric cryogenic system
  - Significant reduction in complexity

- **Next generation of SRF injectors**
  - 200-500 MHz, 4k, 4MeV, 1mA
  - Naval Postgraduate School, Niowave Inc, and UW-Madison



Jean Delayen, Old Dominion Univ. & Thomas Jefferson National Accelerator Facility
P. Ostroumov and K. Shepard, ANL, W. Graves, MIT

SRF Compact Light Sources @ 4K



Superconducting RF photoinjector operating at 300 MHz and 4K

RF amplifiers

Electron beam of ~1 mA average current at 10-30 MeV

Bunch compression chicane

Inverse Compton scattering

30 kW beam dump

X-ray beamline

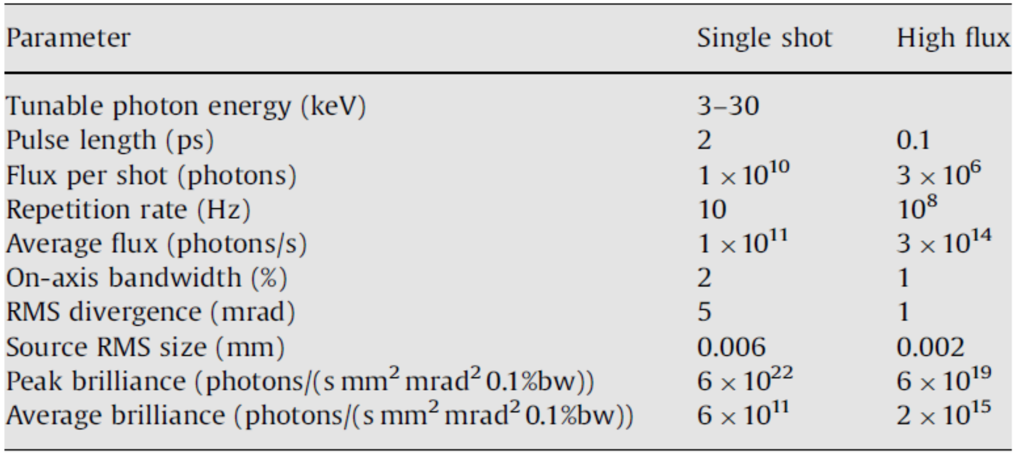
5 kW cryo-cooled Yb:YAG drive laser

Coherent enhancement cavity with Q=1000 giving 5 MW cavity power

MIT CUBIX proposal

SRF Linac Parameters	
Energy gain [MeV]	**25**
RF frequency [MHz]	**352**
Average current [mA]	**1**
Operating temperature [K]	**4.2**
RF power [kW]	**30**

Jean Delayen CAS, Old Dominion University and Thomas Jefferson National Accelerator Facility



Parameter	Single shot	High flux
Tunable photon energy (keV)	3–30	
Pulse length (ps)	2	0.1
Flux per shot (photons)	1×10^{10}	3×10^{6}
Repetition rate (Hz)	10	10^{8}
Average flux (photons/s)	1×10^{11}	3×10^{14}
On-axis bandwidth (%)	2	1
RMS divergence (mrad)	5	1
Source RMS size (mm)	0.006	0.002
Peak brilliance (photons/(s mm^2 mrad^2 0.1%bw))	6×10^{22}	6×10^{19}
Average brilliance (photons/(s mm^2 mrad^2 0.1%bw))	6×10^{11}	2×10^{15}

W.S. Graves et al. / NIM A 608 (2009) S103–S105

Summary of the lecture

- In this lecture we discussed
  - Synchrotron radiation light sources
    - Why SR useful and history
    - Equilibrium emittance, damping time
    - Brightness
    - Examples
  - Compton light sources
    - Basic formulae
    - Overview of existing projects