The Abdus Salam
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School on Synchrotron and Free-Electron-Laser Sources and their Multidisciplinary Applications

26 April - 7 May, 2010

Production of synchrotron and
Production of synchrotron and FEL radiation
Part 2

Emanuel Karantzoulis
Sincrotrone Trieste, S.C.p.A.

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ICTP

Emanuel Karantzoulis

Sincrotrone Trieste S.C.p.A

Overview

- Characteristics of SR
- SR sources
- Insertion devices
- The FEL process
- FEL sources
- Elettra, EuFos and FERMI@Elettra

Angular and Spectral properties

$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c}\frac{|n\times\{(n-\beta)\times\dot{\beta}\}|^2}{(1-n\beta)^5}$$

The angular power distribution when velocity and acceleration are parallel

$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c^3}\left|\dot{\vec{v}}\right|^2 \frac{\sin^2\Theta}{(1-\beta\cos\Theta)^5}$$

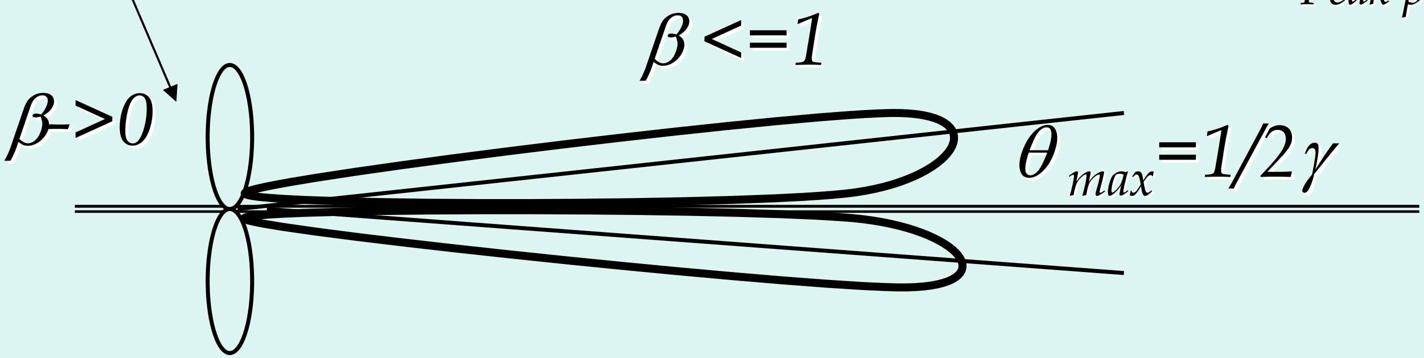
1/2γ is the angle for which the intensity is at maximum

Larmor

$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c^3}\left|\dot{\vec{v}}\right|^2 \sin^2\Theta$$

$$\frac{dP}{d\Omega} = 5.42E^4(GeV)B(T)I_b(A) \qquad W/mrad^2$$

Peak power on- axis

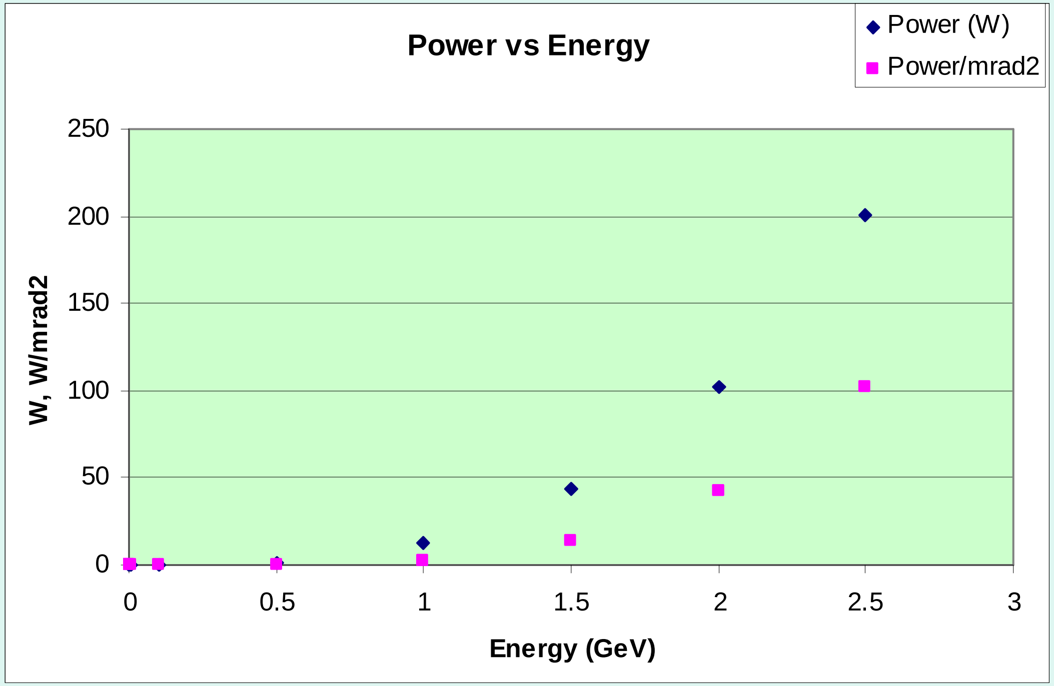


The Power is concentrated in a small angle, for Elettra 2 GeV is 130 mrad

Energy (GeV)	Energy loss (keV)	Power (kW)	W/mrad^2	Angle(deg)
0.0001	3.2065E-11	1.2826E-11	2.62328E-16	143.3121019
0.001	3.2065E-08	1.2826E-08	2.62328E-12	14.33121019
0.01	0.000032065	1.2826E-05	2.62328E-08	1.433121019
0.1	0.032065	0.012826	0.000262328	0.143312102
0.5	4.008125	1.60325	0.163955	0.02866242
1	32.065	12.826	2.62328	0.01433121
1.5	108.219375	43.28775	13.280355	0.00955414
2	256.52	102.608	41.97248	0.007165605
2.5	501.015625	200.40625	102.471875	0.005732484

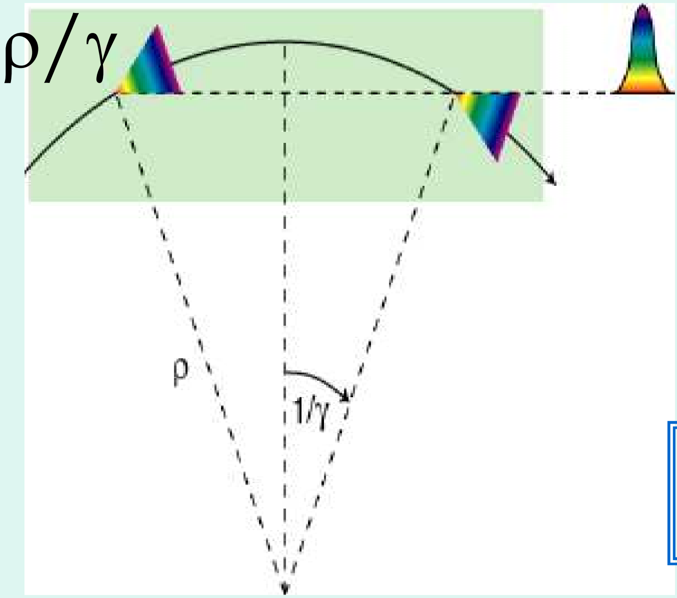
Taking B=1.21 T and 0.4 A current

For comparison potent conventional X-ray tubes of 60 kW electron beam power strike a rapidly rotating anode, radiate a total of about 10 W or 2mW/mrad^2



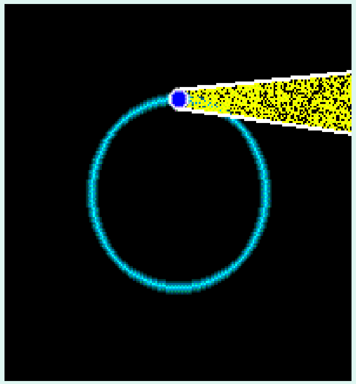
Pulse length and harmonics

$l = 2\rho/\gamma$



Due to extreme collimation of light the observer sees only a small portion of electron trajectory

Light comes in extremely short flashes and the harmonics can reach very high frequencies



$$\Delta t \approx \frac{l}{\beta c} - \frac{l}{c} = \frac{l}{\beta c}(1-\beta)$$

$$(1-\beta) \approx \frac{1}{2\gamma^2} \quad for\, \beta \to 1$$

$$\Delta t \approx \frac{\rho}{\gamma^3 c}$$

$$\omega \approx \frac{1}{\Delta t} = \gamma^3 \omega_0$$

γ=2000

ω_0= 1.15MHz

Pulse length: difference in times it takes an electron and a photon to cover the "l" distance

Spectral Distribution

The total energy received per solid angle during the passage of the electron past the observer is

$$\frac{dW}{d\Omega} = \int \frac{dP}{d\Omega} dt = \frac{c}{4\pi} \int |RE|^2 dt$$

Performing a Fourier transform to frequency

$$\frac{dW}{d\Omega} = \frac{c}{4\pi} \int \left| R\tilde{E}(\omega) \right|^2 d\omega$$

$$\tilde{E}(\omega) = \frac{1}{\sqrt{2\pi}} \int \vec{E}(t) e^{i\omega t} dt$$

$$\frac{d^2W}{d\Omega d\omega} = \frac{1}{8\pi^2 c} \left| \int_{-\infty}^{\infty} (RE(t)) e^{i\omega t} dt \right|^2$$

And one should now insert the expression for E

Peak Intensity

The variation of the peak intensity on-axis as a function of the frequency is given by:

The spectral range is very broad and peaks near the critical frequency

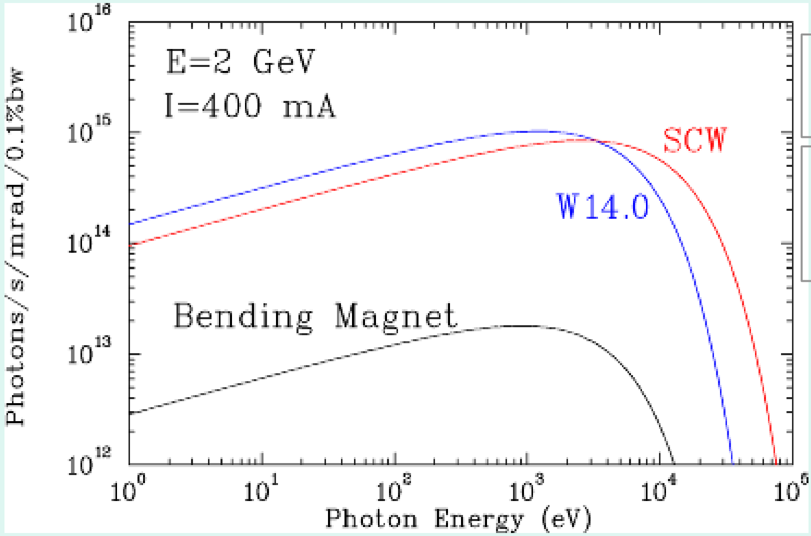
$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2}{16\pi^3\varepsilon_0 c}\gamma^2 H_2\left(\frac{\omega}{\omega_c}\right)$$

$$H_2\left(\frac{\omega}{\omega_c}\right) = \left(\frac{\omega}{\omega_c}\right)^2 K_{2/3}^2\left(\frac{\omega}{2\omega_c}\right)$$

In fact the critical frequency divides the power in two equal halves

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

$$\varepsilon_c = \hbar\frac{3}{2}\frac{\gamma^3 c}{\rho}$$



$$\varepsilon_c(keV) = 2.218E^3(GeV)/\rho$$

$$\lambda_c(\mathring{A}) = 5.589\rho/E^3(GeV)$$

For Elettra 2 GeV
ε_c is 322 eV

Quantum nature

Finally one should consider that photons are produced in a discrete way and not continuously (Quantum effect)

The total number of photons emitted per electron per second is

$$Np = \frac{5}{2\sqrt{3}} \frac{e^2 c}{4\pi\varepsilon_0 \hbar} \frac{\gamma}{\rho}$$

And the total number of photons for a beam of electrons is

$$\frac{dF}{d\theta} = 1.3\times10^{17} E(GeV) I(A)$$

Photons/sec/mrad (horizontal)

For E=2 GeV and I=0.3 A

$0.8x10^{17}$ p/s/mrad

Generations and Brilliance

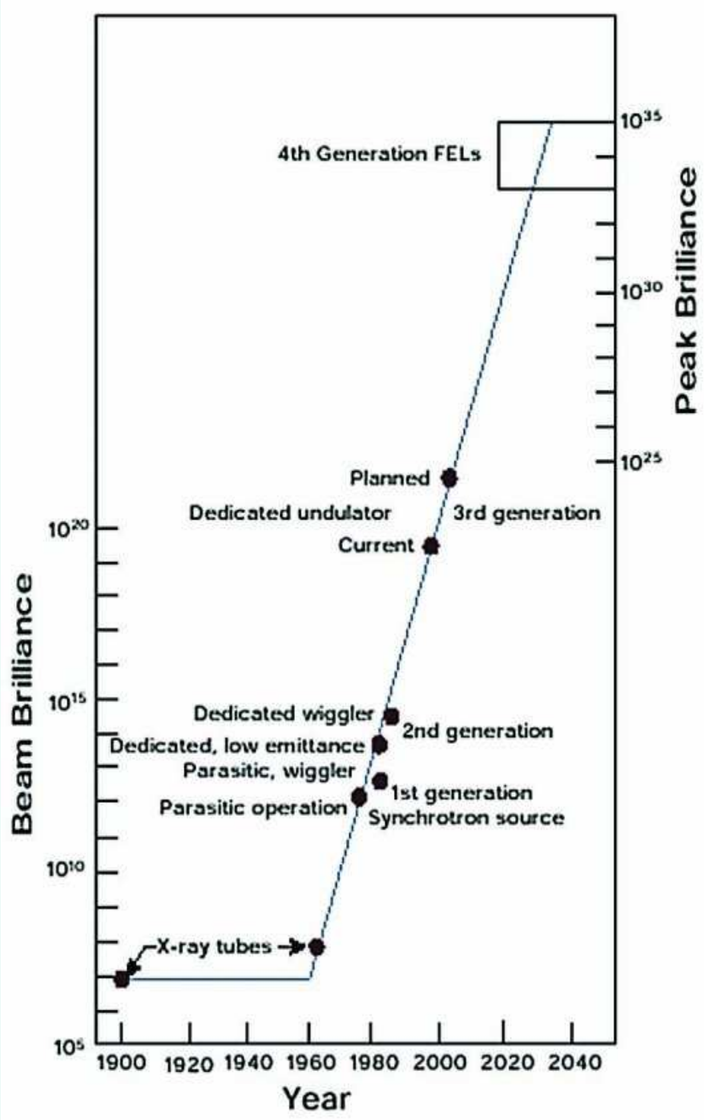
1950s it was understood that SR was a important source of radiation for experiments. Following the work at Cornell (proved that radiation power scales with the 4power of energy) it was pointed out that SR could be a useful source for absorption experiments and as a standard for calibration of instruments in VUV. First experimental program at Tantalus (240 MeV) Madison Wisconsin 1968.

First generation synchrotron sources were high energy physics accelerators, where the synchrotron radiation was an unwanted by-product and it was used in parasitic mode.

In the 1960s, physicists and chemists began to use the radiation from several of these accelerators in a "parasitic mode". The second generation of synchrotron radiation facilities, such as the Photon Factory in Japan, were constructed expressly to provide synchrotron X-rays for research.

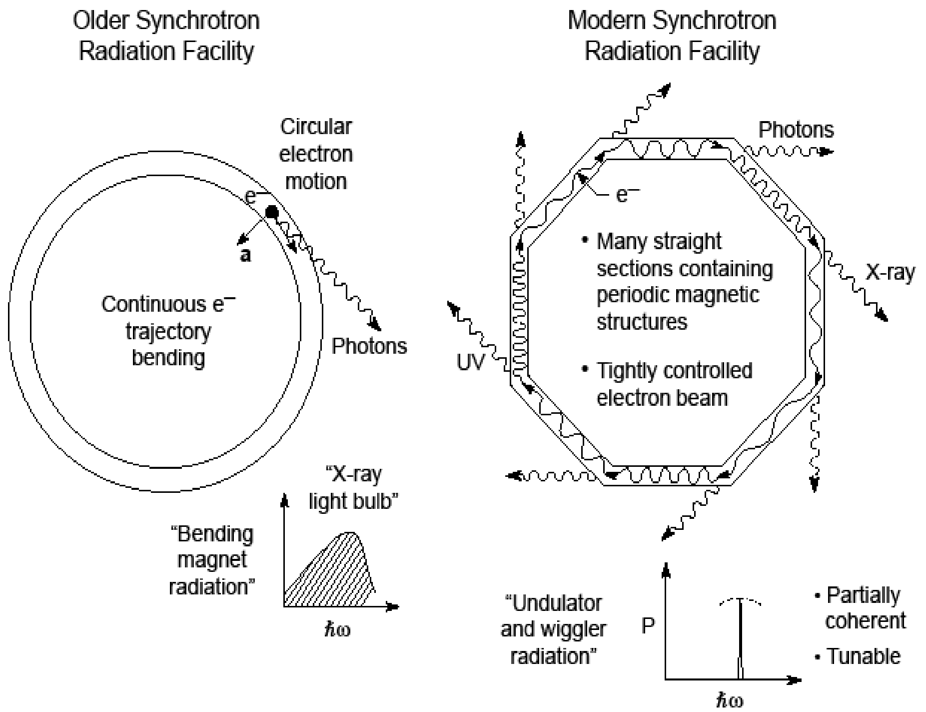
The third generation of facilities were build and used to provide even higher brightness X-ray beams, about 10,000 times higher than those of the second generation.

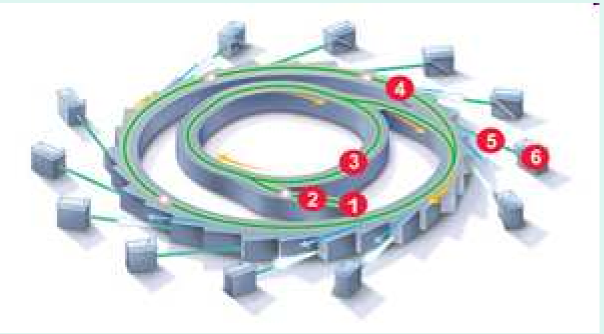
The fourth generation are FELs that provide except even higher brilliance also ultra short pulses (fs range)

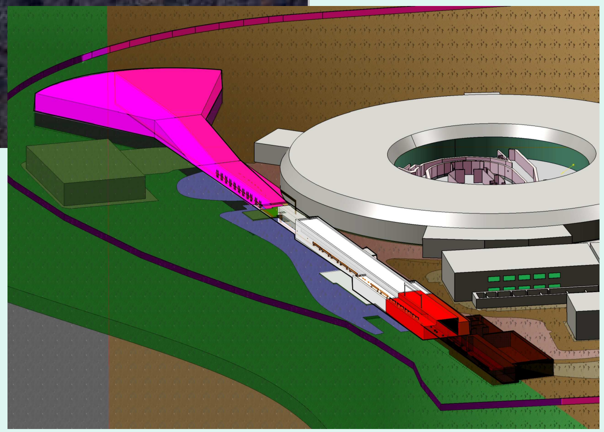


Old and new generations

In the past SR was a byproduct. In modern days it is also produced by dedicated devices called insertion devices (wigglers and undulators) so that the design of modern sources is greatly influenced by those devices.



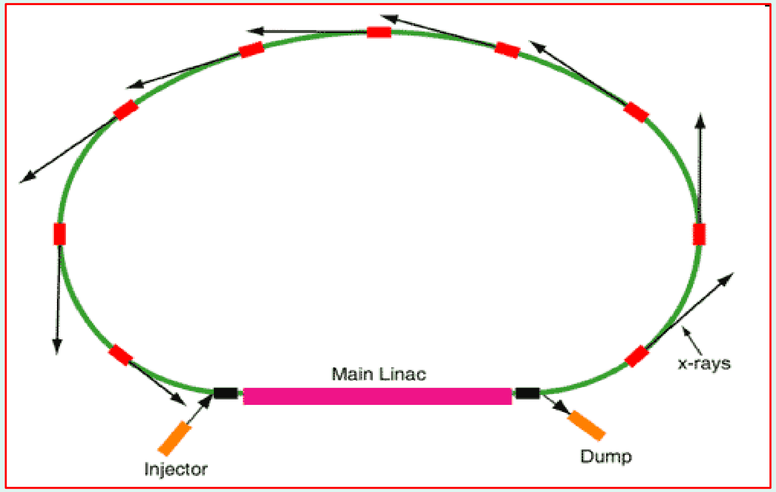




SR Sources

- Storage rings
- FELs
- Energy Recovery Linacs
- Table top sources (Inverse-Compton-scattering)

But most of them use Insertion Devices (undulators and wigglers)



ERL can achieve 3 orders of mag. in brightness to storage rings

Small x-ray device 3x8 m with no mechanical undulator

IR photon E λ~1 um

e with γ about ~ ?

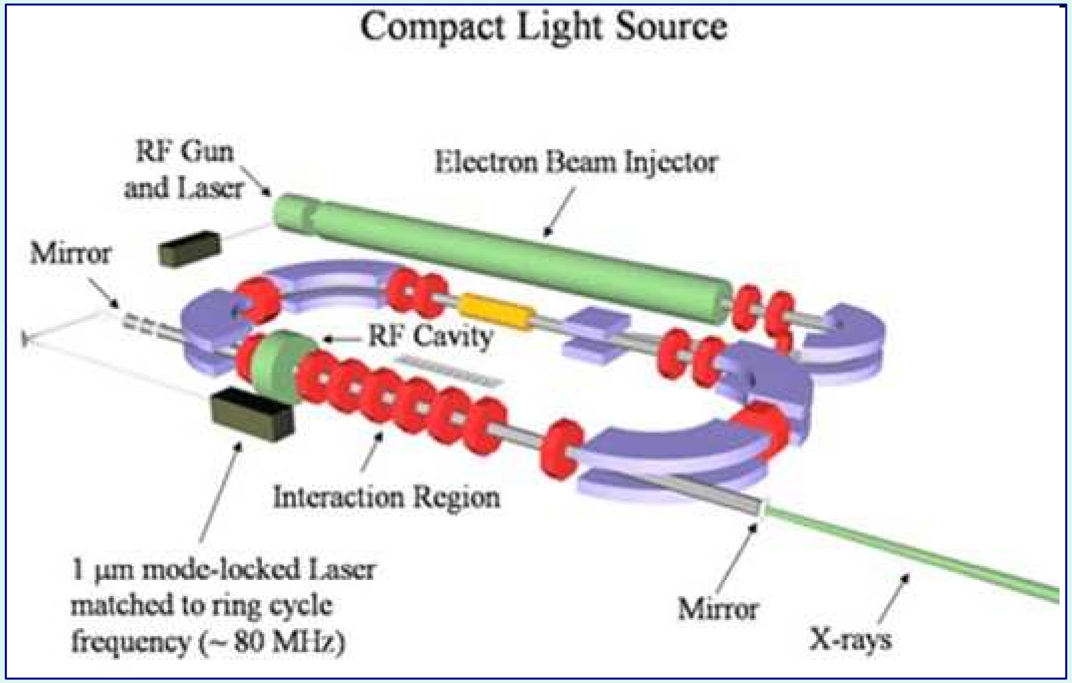
$E_p' \sim 4\gamma^2 E_p$ λ~1 Å

$$\gamma = \frac{1}{2}\sqrt{\frac{\lambda}{\lambda'}}$$

$$\gamma \approx \frac{10^2}{2}$$

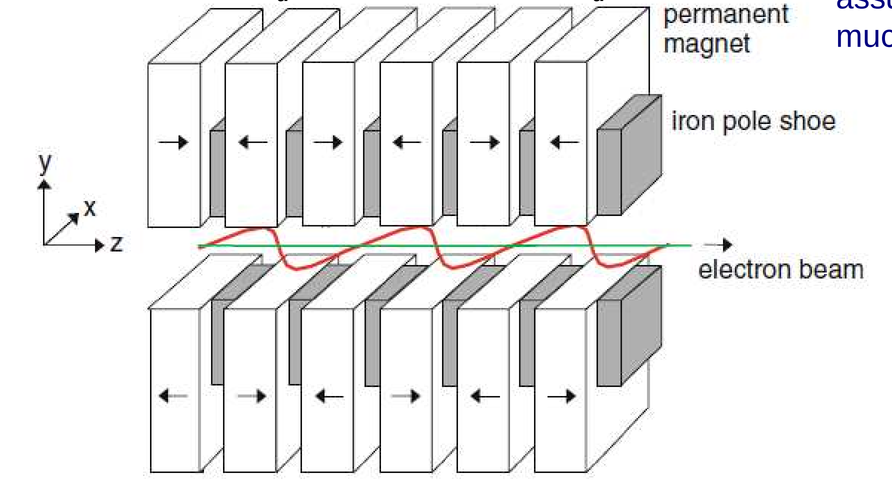
E_e=0.5 x 1000/2 MeV

= 25 MeV



Insertion devices

The distance between two equal poles is called the undulator period λ_u. A typical value is λ_u = 30 mm



Neglect x dependence assuming pole in x much larger than in z

$$\nabla \times B = 0 \qquad B = -\nabla \Phi_{mag}$$

Laplace eq. $\nabla^2 \Phi_{mag} = 0$

Since the field on the axis is approx. harmonic assume:

$$\Phi_{mag}(y,z) = f(y)\sin(k_u z) \Rightarrow \frac{d^2 f}{dy^2} - k_u^2 f = 0 \qquad k_u = \frac{2\pi}{\lambda_u}$$

With the solution $f(y) = c_1 \sinh(k_u y) + c_2 \cosh(k_u y)$

The vertical field is

$$B_y(y,z) = -\frac{\partial \Phi_{mag}}{\partial y} = -k_u\left(c_1 \cosh(k_u y) + c_2 \sinh(k_u y)\right)\sin(k_u z)$$

Demanding By symmetric to y=0 plane the potential is

$$\Phi_{mag}(x,y,z) = \frac{B_0}{k_u}\sinh(k_u y)\sin(k_u z)$$

So we get the components

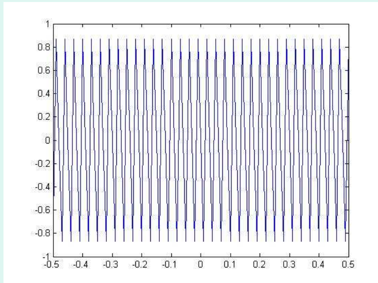
$$B_x = 0$$

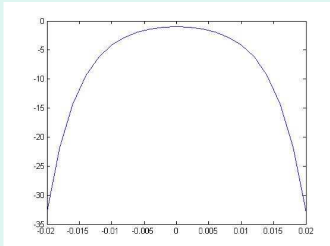
$$B_y = -B_0 \cosh(k_u y)\sin(k_u z)$$

$$B_z = -B_0 \sinh(k_u y)\cos(k_u z)$$

And for y=0 only the By component exists

$$B_y = -B_0 \sin(k_u z)$$





Insertion devices @ Elettra

A range of insertion devices has been designed, built and installed in Elettra. Most of them employ the permanent magnet technology, usually blocks of NdFeB . The only exception is one electromagnetic variably polarized wiggler.

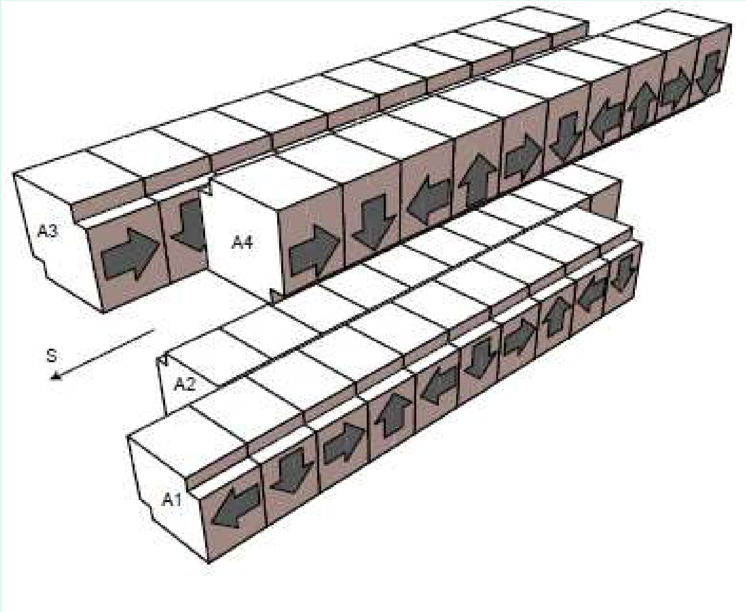
Conventional (vertical field) undulators and wiggler. They represent the 'first generation' of magnets built for ELETTRA, and provide fixed polarization.

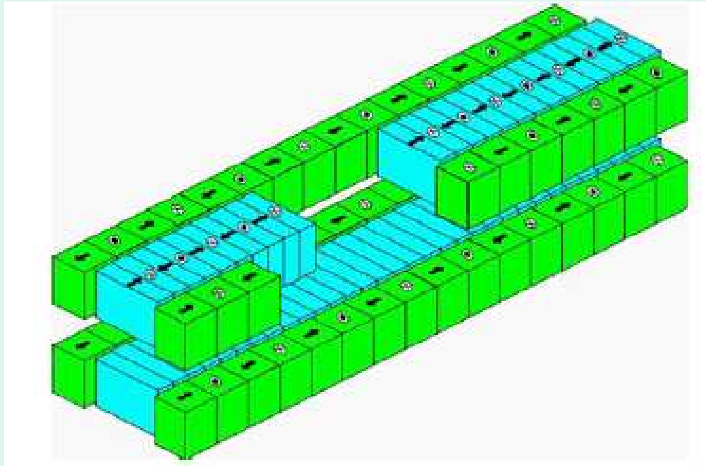
(EEW). Designed to allow circular polarization with fast helicity switching.

The development of these 'second generation' devices was stimulated by strong users' demand for variable polarization sources.

(FEU), a source of low energy (5 eV) photons with reduced on-axis power compared to a conventional device.
It will be used for Inelastic UV Scattering experiments.

(SCW), which will extend the useful spectrum at high energies (>10 KeV) for X-Ray Diffraction applications.

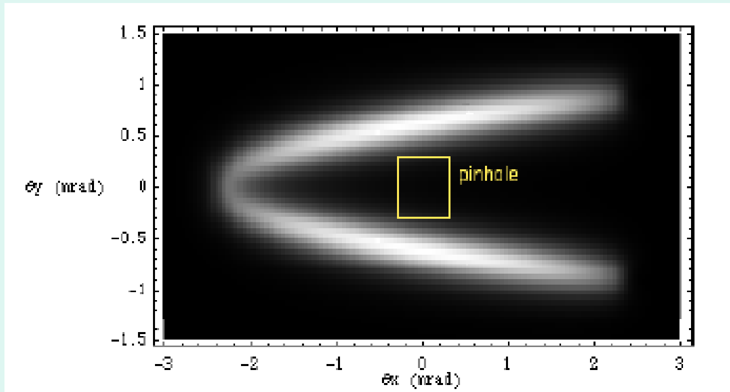




Energy loss is given by

$\Delta E(\mathrm{keV})=0.6333\ E^2\ (\mathrm{GeV})\ B^2\ (\mathrm{T})\ L\ (\mathrm{m})$

A 4 m wiggler of 1.5 T at 2 GeV loses 22.7 keV or assuming 400 mA 9kW All this radiation is directed to the experimental stations. Note that in case of a bending magnet only a fraction of the produced radiation is used



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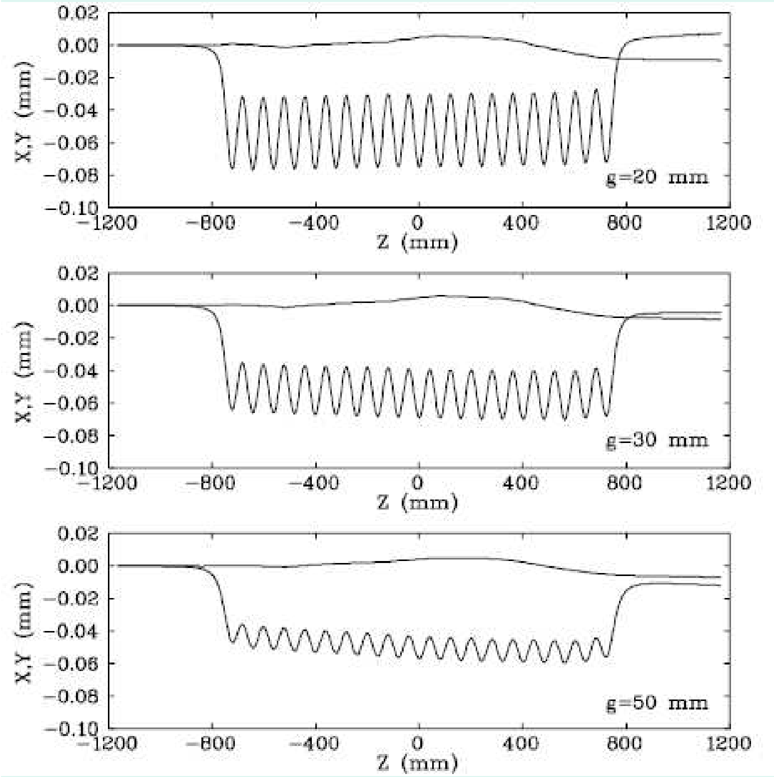
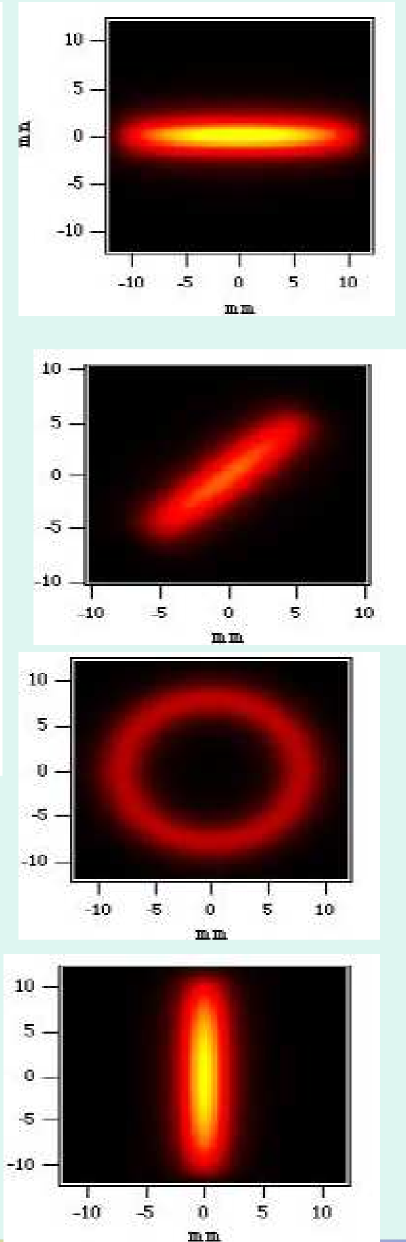
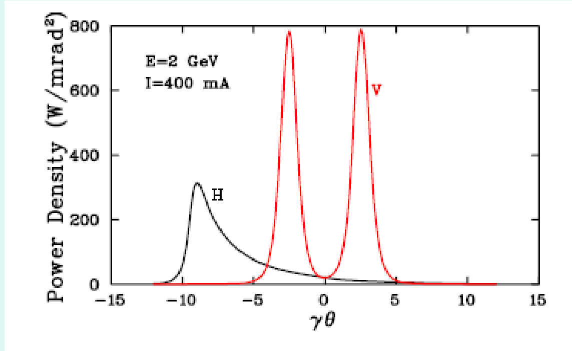
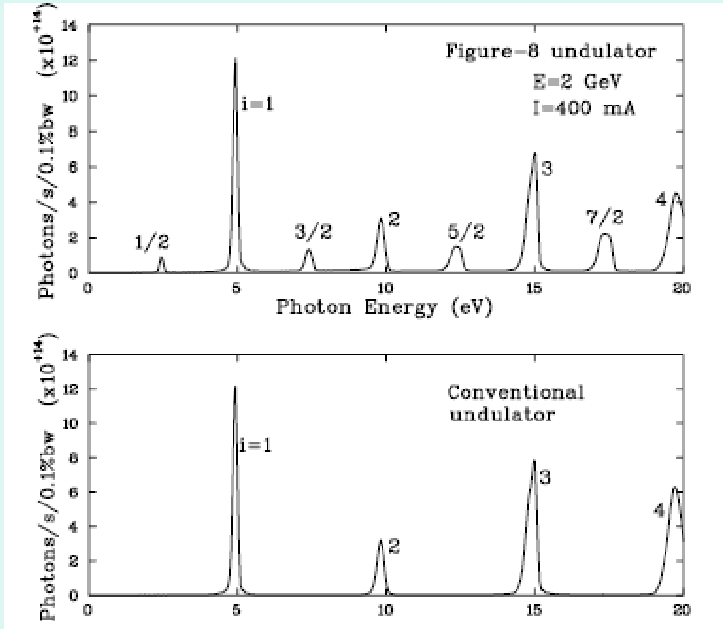
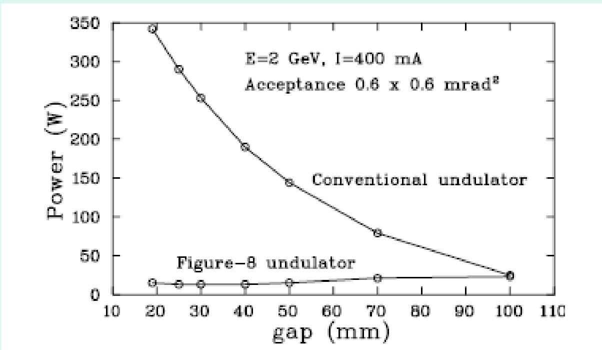




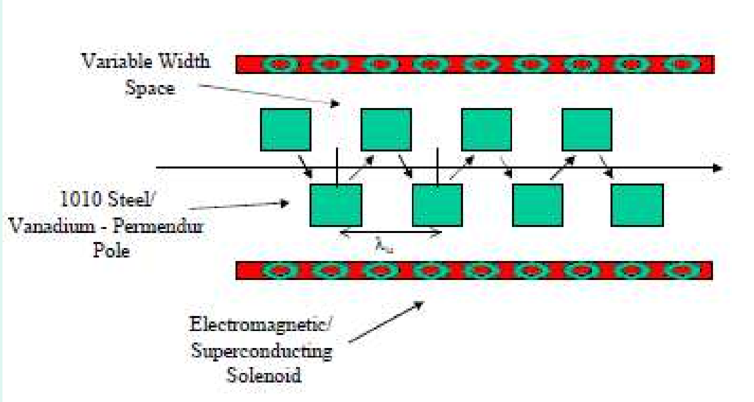


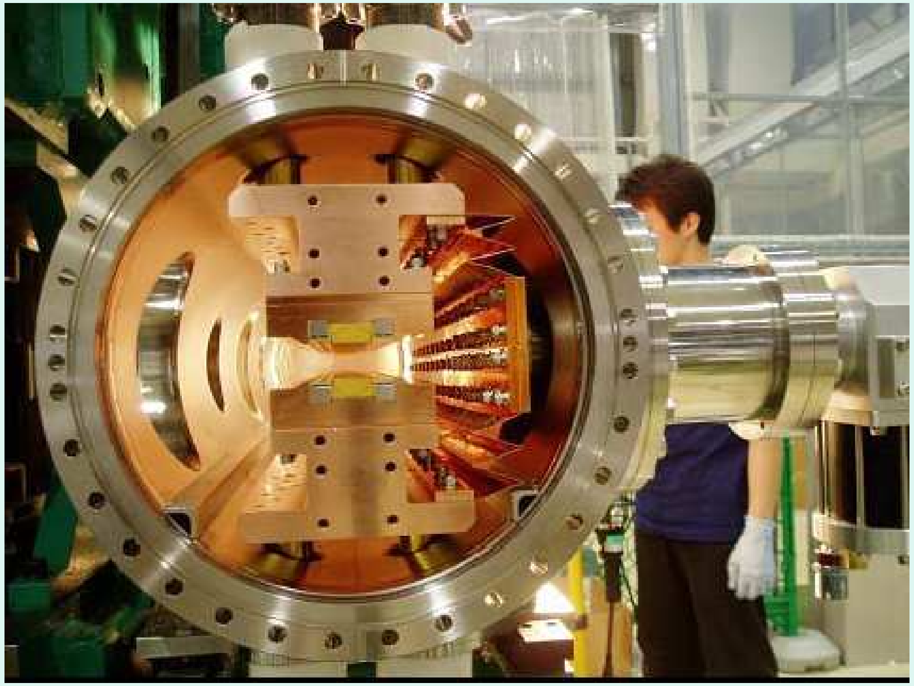


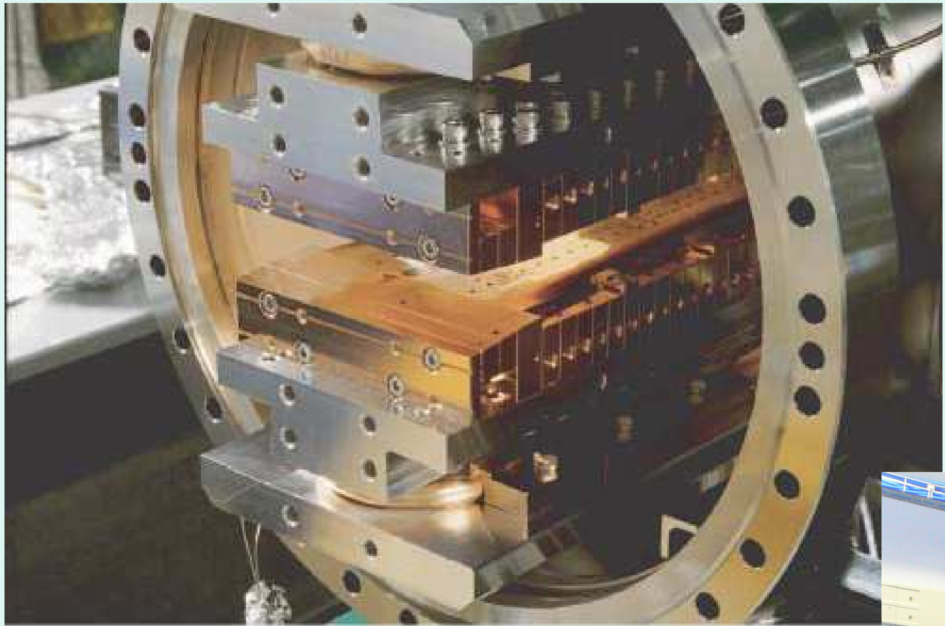


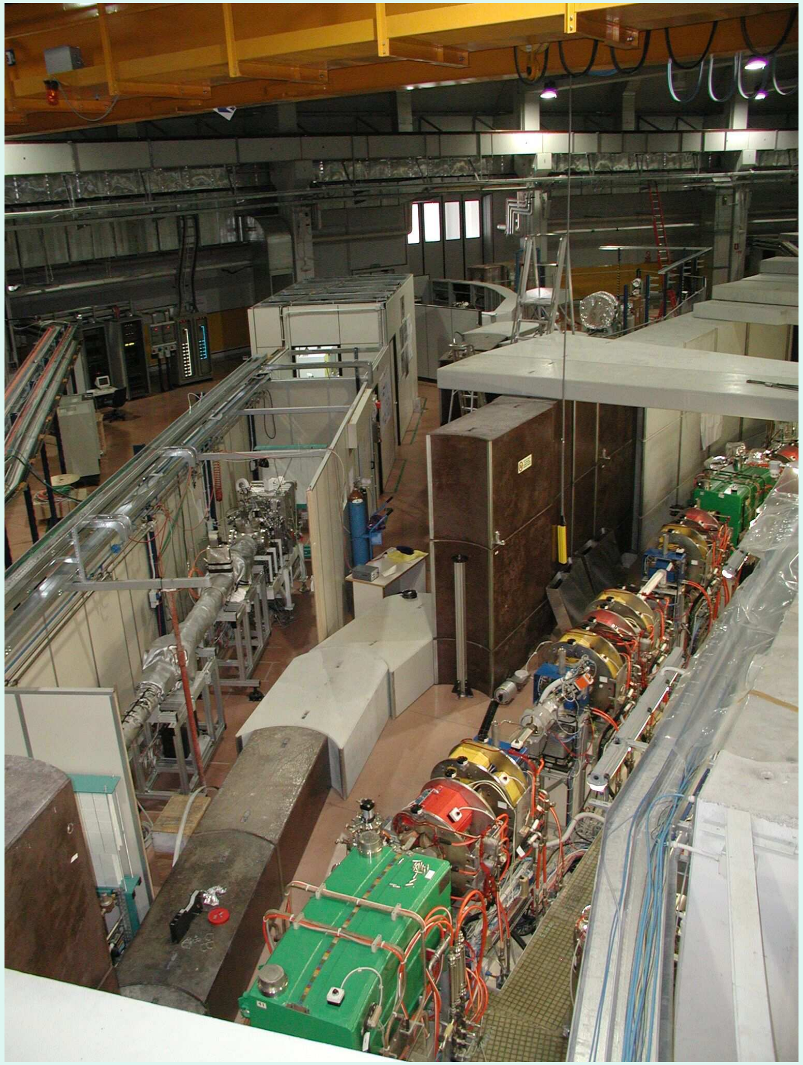
(courtesy B. Diviacco)

Other types: Revolving , hybrid Cryo-Permanent Magnet, In-vacuum Undulators etc

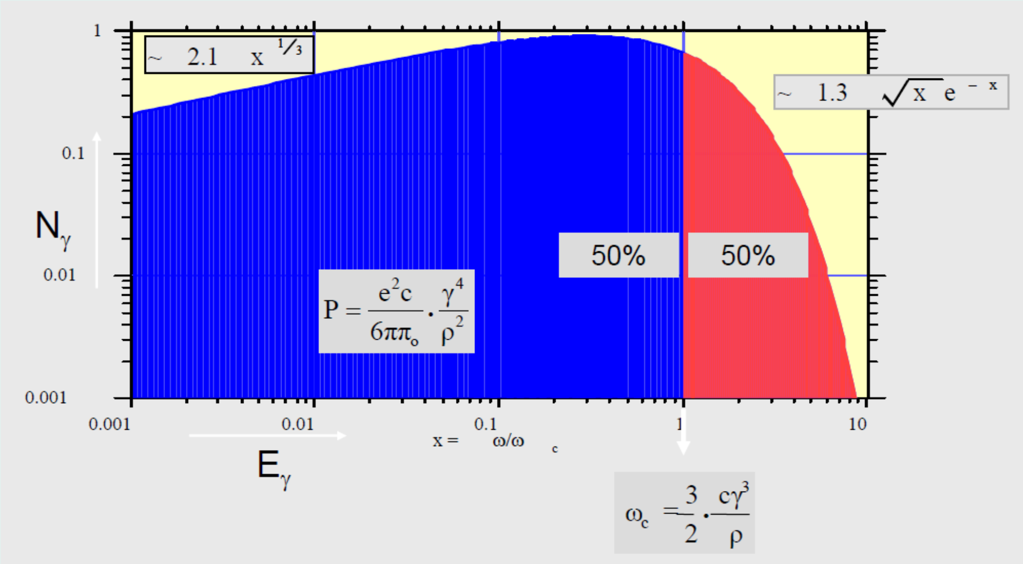


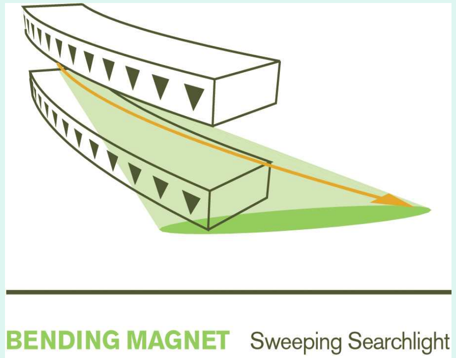






Bending magnet radiation



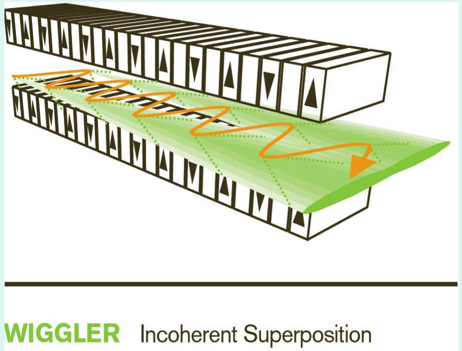


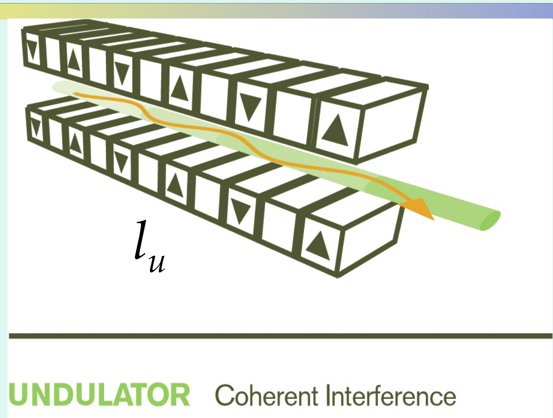
$$E_c(keV) = 0.665 B(T) E^2(GeV)$$

$$\lambda_c(nm) = 1.864 / B(T) E^2(GeV)$$

$$E_c = \hbar \frac{3}{2} \frac{\gamma^3 c}{\rho}$$

ID characteristic radiation





$$\lambda = \frac{l_u}{2\gamma^2}(1 + K^2_{rms} + \gamma^2\theta_{axis}^2)$$

$$E_c(keV) = \frac{0.9496E^2(GeV)}{l(1+K^2+\gamma^2\theta^2)}$$

$$\lambda = \frac{l_u}{2\gamma^2}(1 + \frac{K^2_{peak}}{2})$$

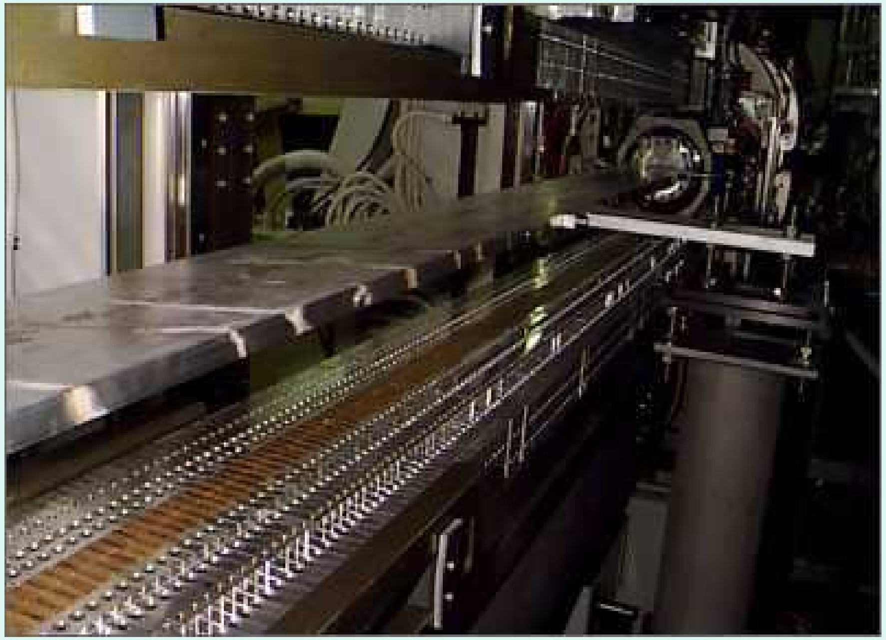
Non dimensional magnetic deflection parameter K

$$K >> 1$$

$$K = \frac{eBl_u}{2\pi mc} = 0.9337B(T)l_u(cm)$$

$$E_c(keV) = 0.665B(T)E^2(GeV)\sqrt{1-(\frac{\vartheta\gamma}{K})^2}$$

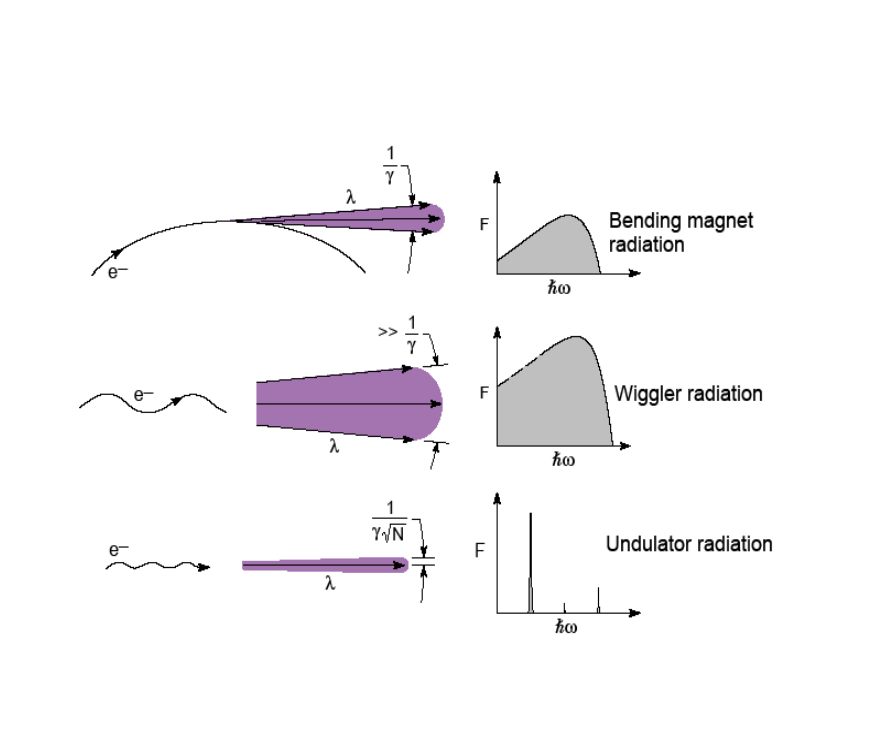
Flux=2NF$_{bend}$



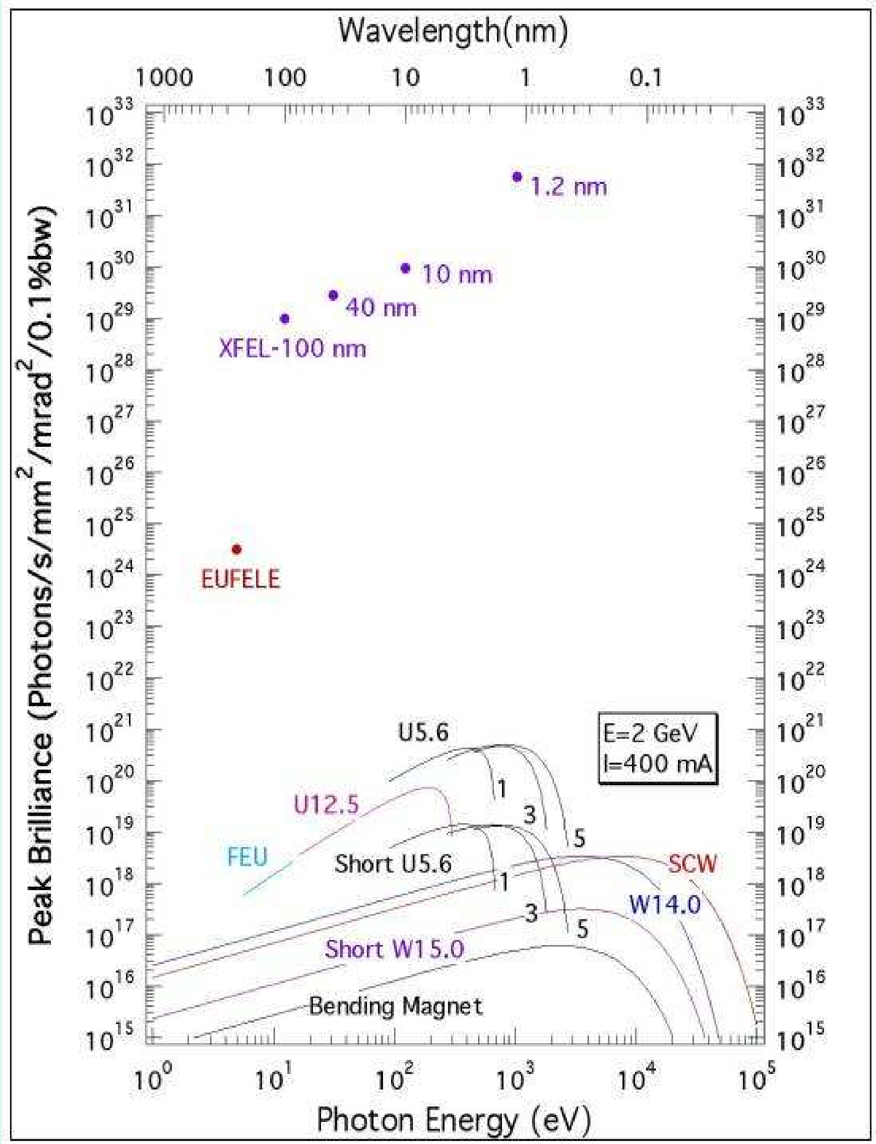
$$\theta_{light} \approx \frac{1}{\gamma\sqrt{N}}$$

Typical 50 µrad

Typical values: l_u 0.5 to 25 cm, K 1 to 20, B 0.1 to 3.5 T, N from 10 to 50



At K>> 1** the radiated energy appears in very high harmonics and at rather large horizontal angles K/γ that tend to merge the harmonics. The result is a continuum at high photon energies **similar to the bending magnet radiation** but increased by **2N



SR from 3° rd generation

- High brightness and high intensity, many orders of magnitude more than with X-rays produced in conventional X-ray tubes
- High level of polarization (linear or elliptical)
- High collimation, i.e. small angular divergence of the beam
- Low emittance, i.e. the product of source cross section and solid angle of emission is small
- Wide tunability in energy/wavelength by monochromatization (meV to KeV)
- High brilliance, exceeding other natural and artificial light sources by many orders of magnitude: 3rd generation sources typically have a brilliance larger than 10^{18} photons/s/mm^2/mrad^2/0.1%BW where 0.1%BW denotes a bandwidth $10^{-3}\,\omega$ centered around the frequency ω.
- Pulsed light emission (pulse durations up to ps 10^{-12} s but can be as short as femto seconds 10^{-15} s)

Free Electron lasers

In SR in general power scales with N. However there are cases that one can exploit the N^2 rule i.e. to use the coherence. This is already happening in SR partially in undulators but it can better be exploited using FELs

FELs are devices producing coherent radiation from free electrons rather than electrons bound to atoms or molecules (conventional lasers)

Motz 1950, Phillips ~1960, Madey 1970)

Special version: starting from noise (no input needed) Single pass saturation (no mirrors needed)

Self-Amplified Spontaneous Emission (SASE)

(Kondratenko, Saldin 1980, Bonifacio, Pellegrini 1984)

Their other big advantage is their tunability. Unlike the conventional lasers that one is tied to the natural frequency of the atom or molecule, here all frequencies are possible!!!

FEL Basics

The typical opening angle of the wavelength integrated radiation is

$$\frac{1}{\gamma} = \frac{m_e c^2}{E}$$

In the undulator, the deflection of the electrons from the forward direction is comparable to the opening angle of the synchrotron radiation cone. Thus the radiation generated by the electrons while travelling along the individual magnetic periods overlaps. This interference effect is reflected in the formula for the wavelength of the first harmonic of the spontaneous, on-axis undulator emission.

$$\lambda_{rad} = \frac{\lambda_0}{2\gamma^2}(1+\frac{K^2}{2})$$

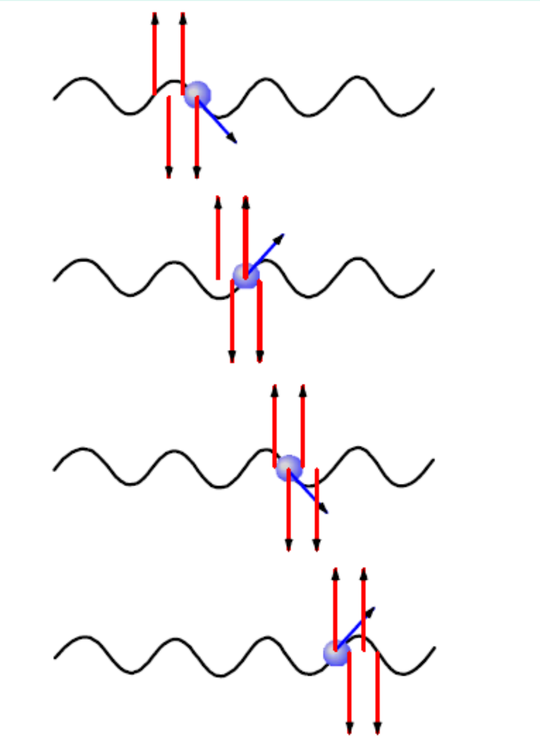
K gives the ratio between the average deflection angle of the electrons and the typical opening cone of the synchrotron radiation. B_0 is the peak magnetic field.

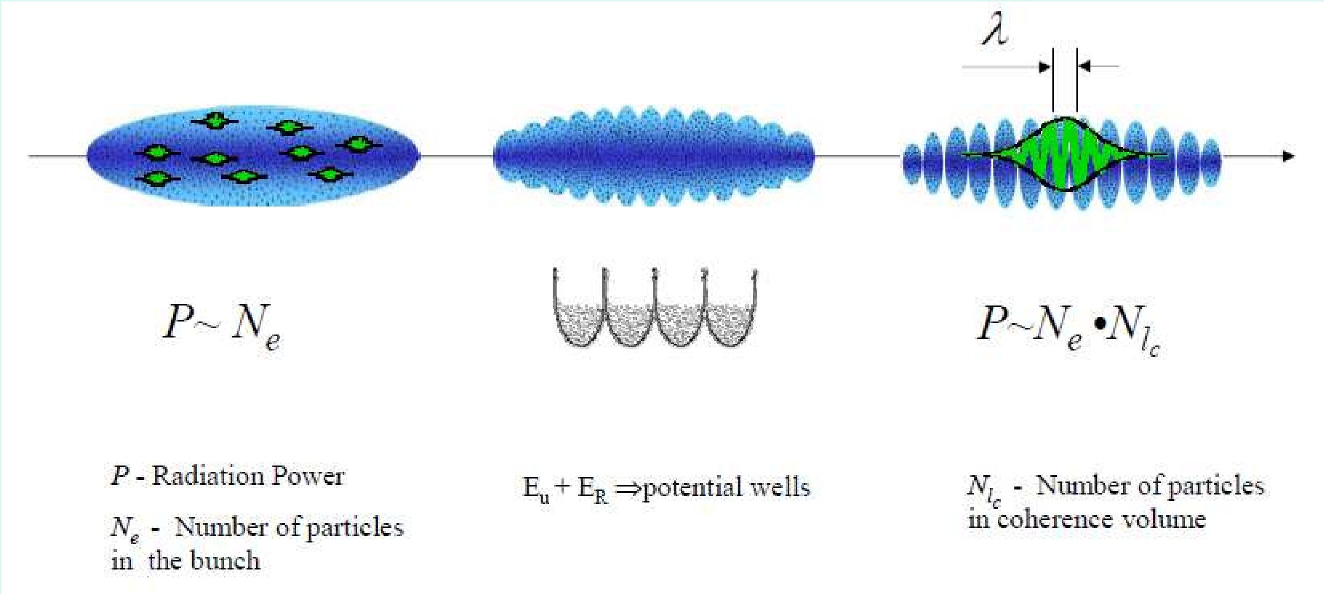
$$K = \frac{eB_0\lambda_0}{2\pi m_e c}$$

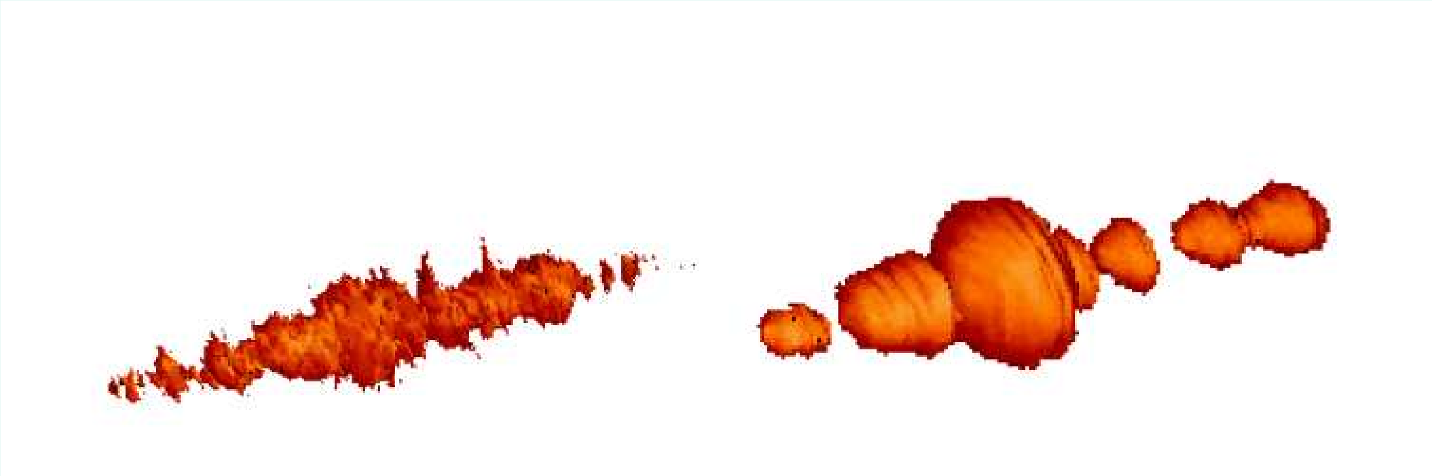
The interference condition basically means that, while travelling along one period of the undulator, the electrons slip by one radiation wavelength with respect to the (faster) electromagnetic field. This is one of the prerequisites for the SASE process of the FEL. To obtain an exponential amplification of the spontaneous emission present in any undulator, some additional criteria have to be met

FEL principle

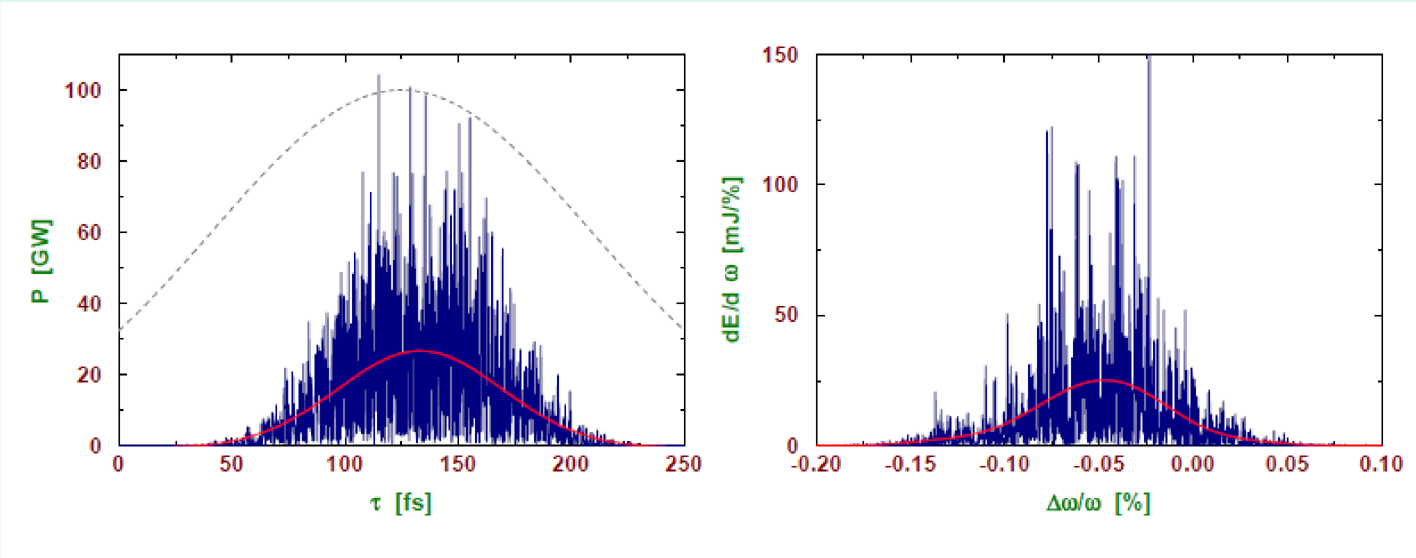
The interaction of electrons with the EM field of the light creates micro-bunching (when distribution of electrons not homogeneous) . The micro-bunches emit coherently SR with intensity orders of magnitude higher than the incoherent synchrotron radiation







Example of the buildup of coherence along the undulator. The left figure shows the radiation intensity profile half way through the undulator, the figure to the right close to saturation.



Typical temporal (left) and spectral (right) structure of the radiation pulse from a SASE XFEL at a wavelength of 1 Å. The red lines correspond to averaged values. The dashed line represents the axial density profile of the electron bunch. The radiation pulse length of 100 fs (FWHM) is about a factor of two shorter than the electron bunch.

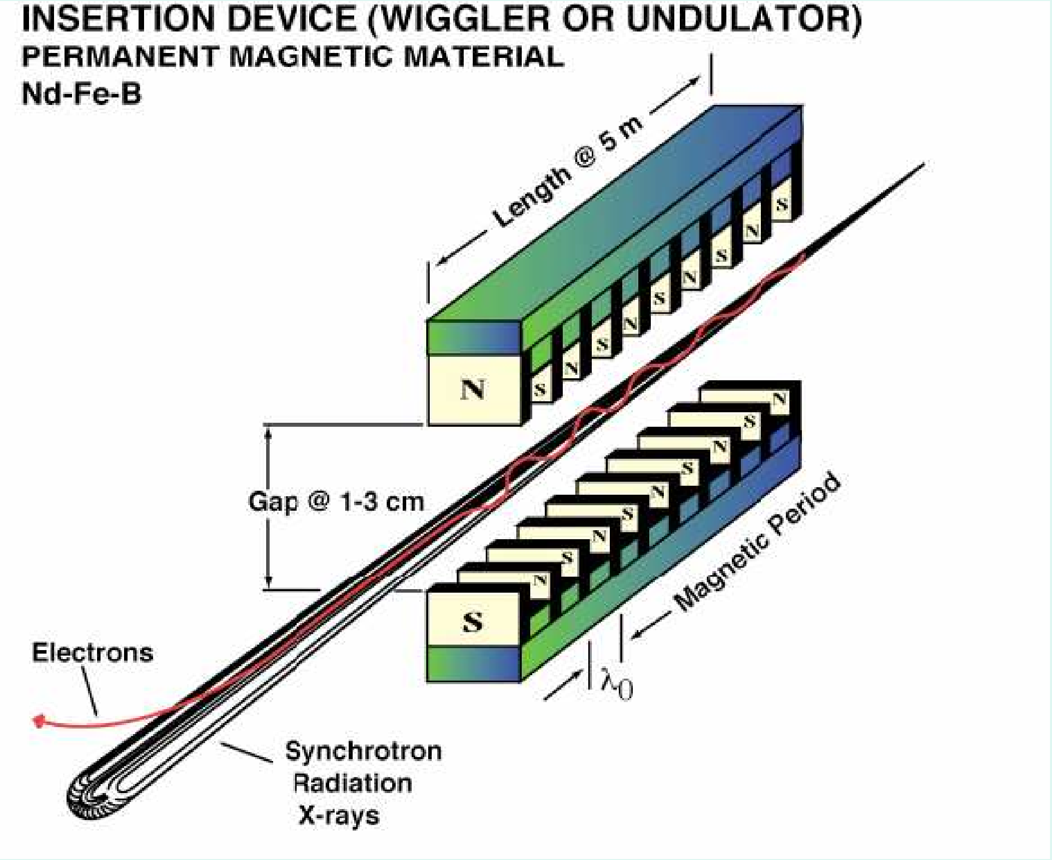
FEL tunability

To have a FEL one needs undulators , light and the resonant condition

$$\lambda_{rad} = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = 0.934\lambda_0 B_0 (cmT)$$

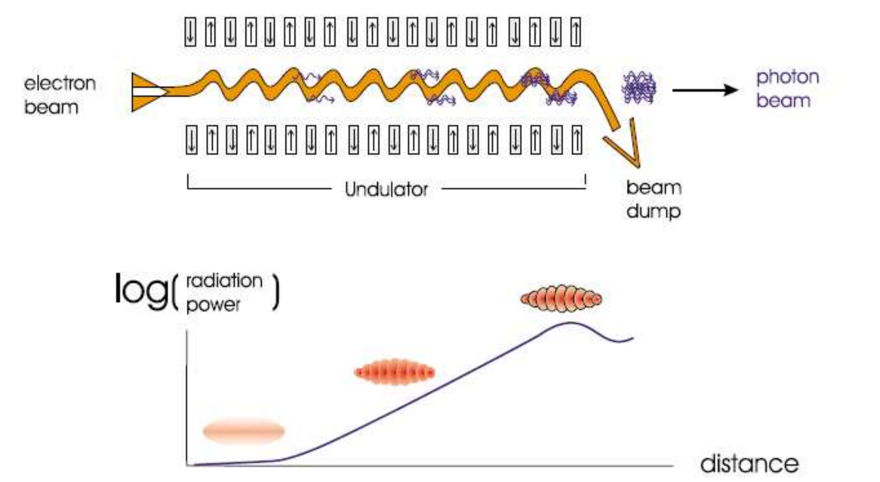
Easy Tunability



FEL requirements

Due to the progressing micro-bunching, the radiation power $P(z)$ of a SASE FEL grows exponentially with the distance z along the undulator:

$$P(z) = AP_{in}e^{2z/L_g}$$



Gain Length (power e-folding): $L_g = \frac{1}{\sqrt{3}}\left[\frac{2mc\,\gamma^3\sigma_r^2\lambda_u}{\mu_0 e \quad K^2\hat{I}}\right]^{1/3}$

A good electron beam quality and a sufficient overlap between radiation pulse and electron bunch along the undulator should be established.
To achieve that, a low emittance, low energy spread electron beam with an extremely high charge density in conjunction with a very precise magnetic field and accurate beam steering through a long undulator are necessary.

Beam size:
$\sigma_r \approx 50\ \mu m$ ⇔ high electron desity for maximum interaction with radiation field
Emittance $\varepsilon \leq \lambda/4\pi$
need special electron source & accelerate the beam before it explodes due to Coulomb forces

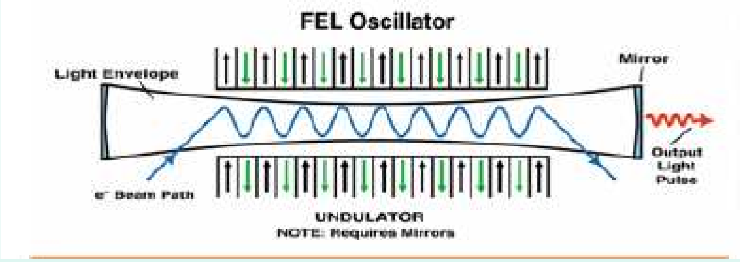
Peak current inside bunch:
$\hat{I} > 1$ kA
feasible only at ultrarelativistic energies, otherwise ruins emittance
⇒ bunch compression

Energy width:
Narrow resonance → $\sigma_E/E \lesssim 10^{-3}$
⇔ Small distortion by wakefields etc.

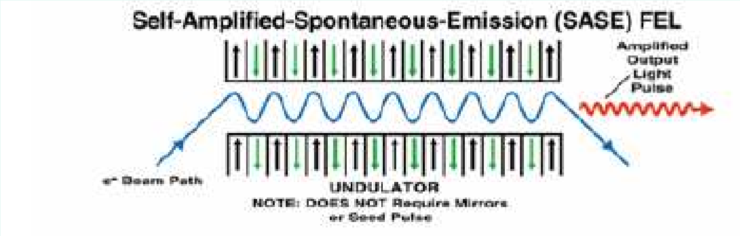
Straight trajectory in undulator
to guarantee overlap electron beam – photon beam:
typically < 10 μm over >10 m

FEL systems

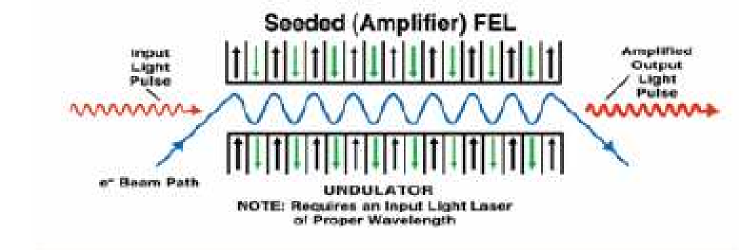
Variation of FELs based however on the same physical principle



Shorter chain of undulators

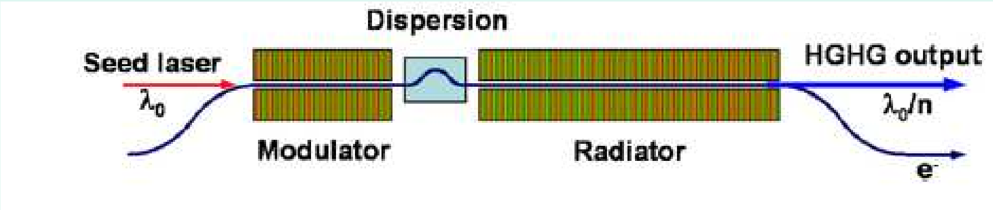


Longer chain of undulators



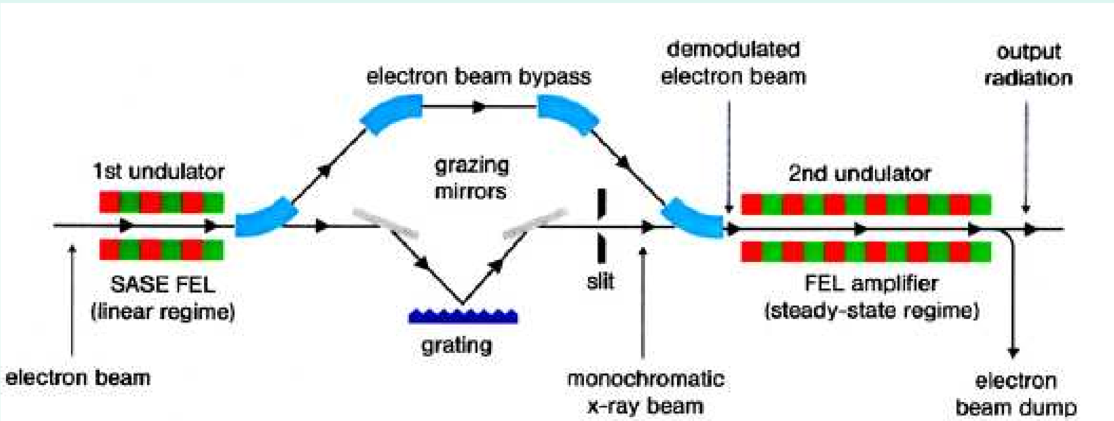
HGHG FEL systems

It would be much more elegant if the FEL process could be controlled in such a way that Fourier-limited radiation pulses with adjustable duration could be produced. This is straightforward, in principle, if the FEL is used not in the SASE mode (where it amplifies the shot noise in the electron beam), but rather as an amplifier seeded by coherent radiation. Since seed pulses of sufficiently intense, coherent radiation are not now available at very short wavelengths, two different routes to achieve coherent seeding have been investigated

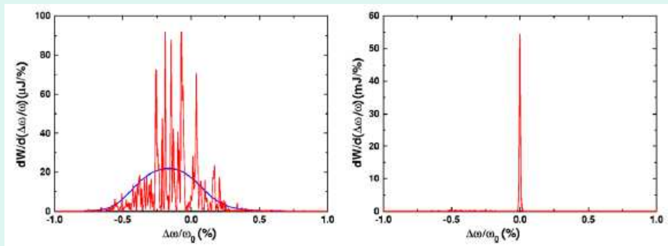


CHG / HGHG

The laser is focused into the first undulator (called the modulator, and tuned at the seed wavelength), and synchronized with the incoming electron bunch. The laser-electron interaction in the modulator leads to a modulation of the electron energy. When the beam crosses the magnetic chicane, the energy modulation is converted into a spatial micro-bunching of electrons at the period of the seed wavelength. As this micro-bunching is non-sinusoidal, when analyzed in the frequency domain it contains significant harmonics of the fundamental. Finally, these micro-bunched electrons radiate coherently in the second undulator (called the radiator), which is tuned at a harmonic of the first. The extracted power is proportional to the square of number of seeded electrons.



Self-seeding (no external laser needed)



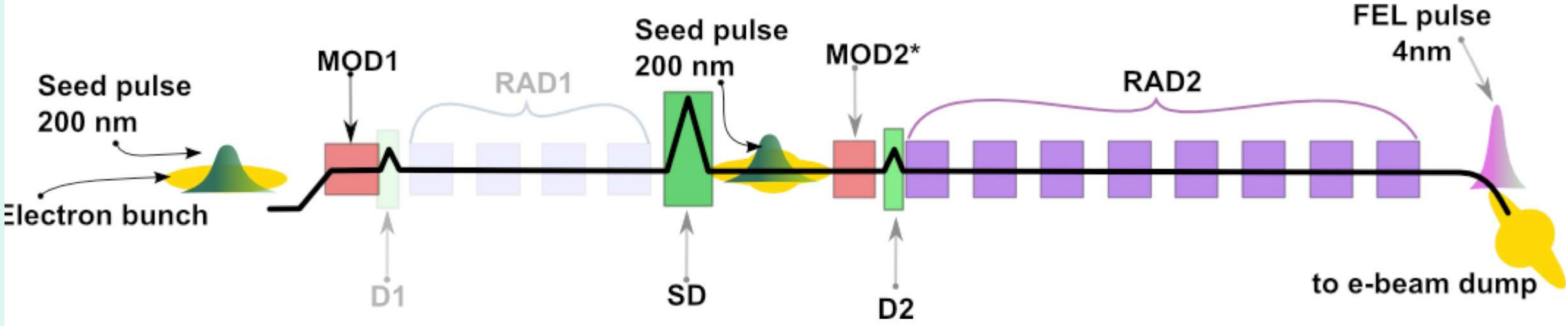
EEHG FEL systems

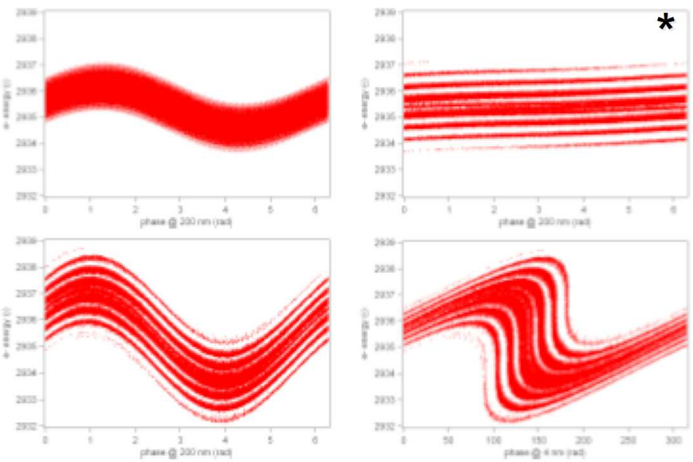
The possibility to implement the EEHG scheme with the FEL-2 layout with small modification has been studied*.

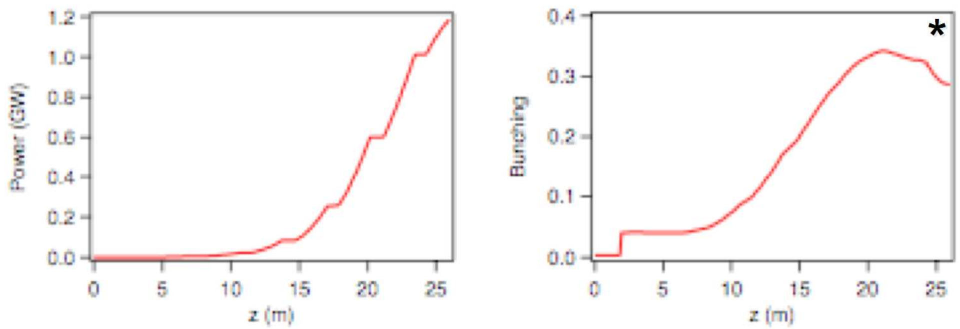
The strong dispersive section (R56~mm) can be obtained from the standard delay line of the current scheme.

The second modulator would be changed to be resonant at 200nm

Electron Beam Energy	1.5 GeV
Peak current	800 A
Normalized emittance	0.8 mm mrad
Slice energy spread	150 keV
λ_{seed}^{MOD1}	200 nm
$Power_{seed}^{MOD1}$	20 MW
λ_{seed}^{MOD2}	200 nm
$Power_{seed}^{MOD2}$	150 MW

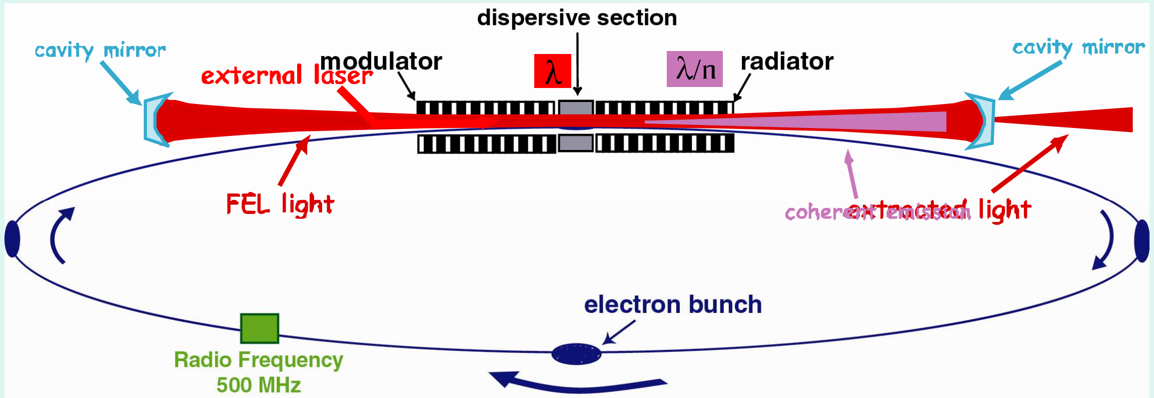




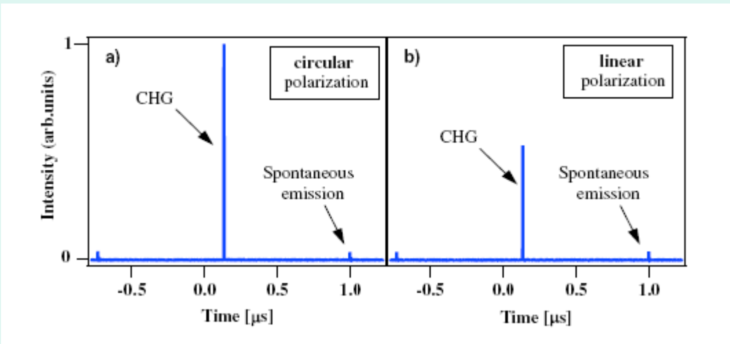


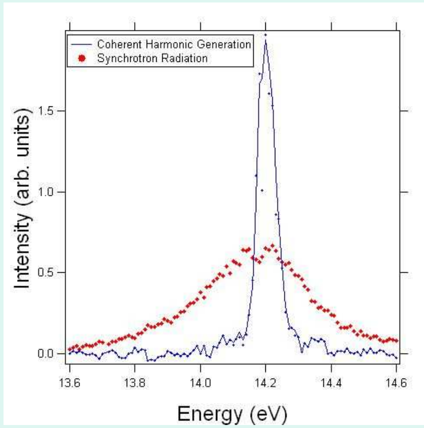
*D.Xiang et al. **MOPC02**, FEL09

EuFos

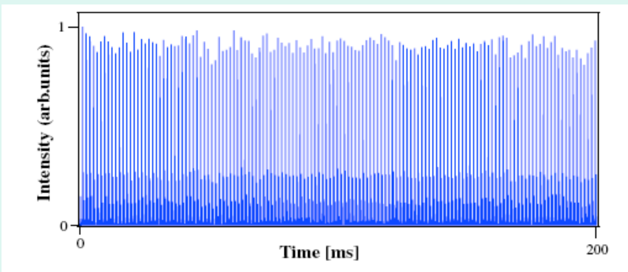


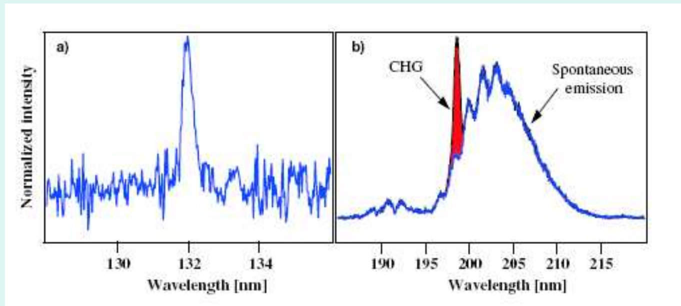
Using the Elettra storage-ring free-electron laser, we have implemented a light source generating sub-picosecond (ps) coherent optical pulses in the VUV spectral range. The setup relies on the frequency up-conversion of a high-power external signal (provided by a Ti:Sapphire laser) and makes use of a relativistic electron bunch as resonating medium. The produced VUV pulses have peak power in MW range, variable polarization, high shot to shot stability and control of the timing parameters at the ps level. The radiation can be exploited for new experiments in the fields of dynamical phenomena, non-linear physics, magnetism and biology.





87 nm



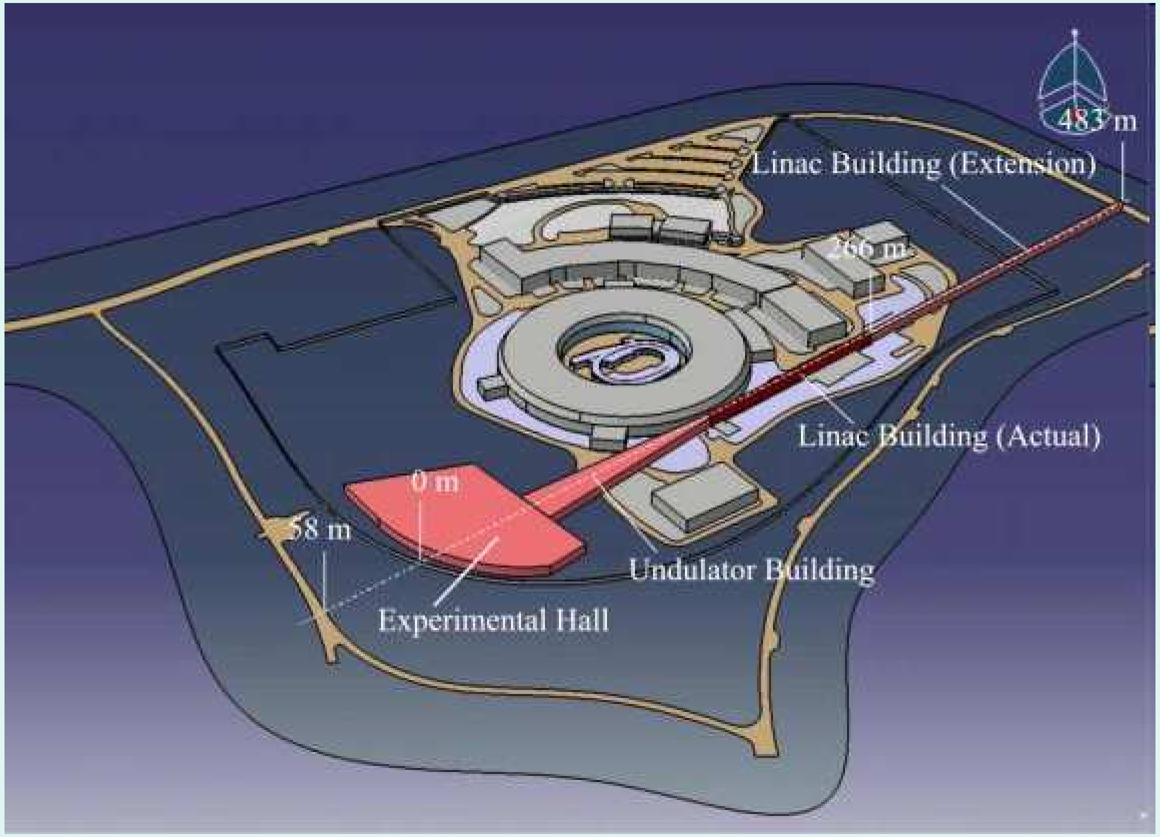


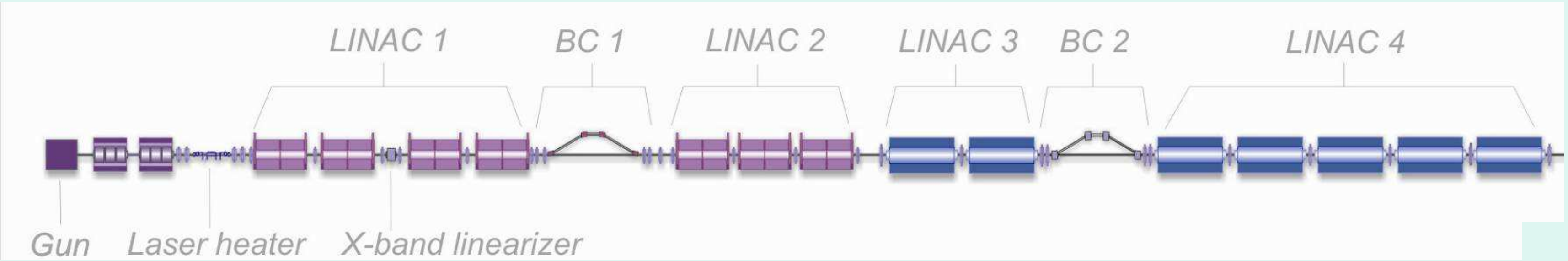
FELs provide laser like source (both transversely and longitudinally) tunable from IR to x-ray wavelength and with peak intensities many orders of magnitude higher than other existing sources

Sincrotrone Trieste has an SR based source EuFos and currently constructing a seeded FEL source FERMI@ELettra capable of producing wavelengths from 100 to 2 nm

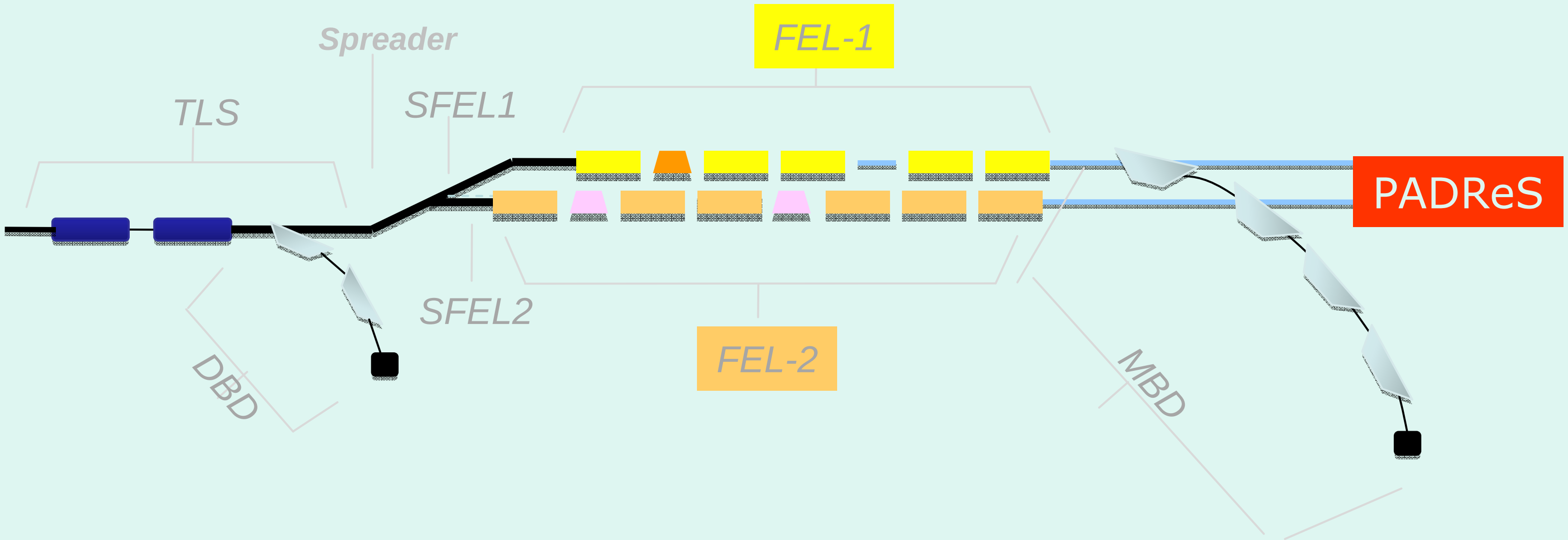
The Elettra complex

Combines a 3 rd generation storage ring and Storage Ring based FEL in operation and a linac based FEL light source in construction





APLEII type, 50 mm period, L=1.5 m



FERMI@Elettra is a single-pass FEL user-facility covering the wavelength range from 100 nm (12 eV) to 10 nm (124 eV) to 2 nm (621 eV)

Main Characteristics

- **High peak power (~ GW) both long (~1 ps) and short (~100 fs) optical pulses with synchronization to external laser sources. Generation of shorter pulses (sub fs) will also be explored.**
- **APPLE II type undulators to enable flexible tuning of both photon wavelength and polarization.**
- **Implementation of seeded harmonic cascade FEL schemes for tunable and controlled short-wavelength photon pulse production.**
- **Advanced feedback and feed-forward systems to improve output stability.**

Nominal Electron beam and FEL parameters

Parameters	*Value at 40 nm*	*Value at 10 nm*	*Units*
Electron beam energy	1.2	1.2	GeV
Peak current	800	500	A
Emittance (slice)	1.5	1.5	μm, rms
Energy spread (slice)	150	150	keV
Bunch duration	700	1400	fs, FWHM
Repetition rate	10 (50)	10 (50)	Hz
FEL peak power	2.5	0.6	GW
FEL pulse duration	200	400	fs, FWHM
# of photons/pulse	10^{14}	10^{12}	
Bandwidth Brilliance	17 $\sim 10^{31}$	4 $\sim 10^{31}$	meV ph/s/mm^2/mrad^2/0.1%BW

FEL-1 and FEL-2 expected performance

Parameter	***FEL-1***	***FEL-2***
Wavelength range [nm]	100 to 40	40 to 10 to 2
Output pulse length (rms) [fs]	≤ 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	Variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~ 2	~ 0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	≤ 30 %	~50 %
Pointing stability [μrad]	< 20	< 20
Virtual waist size [μm]	250 (at 40 nm)	120
Divergence (rms, intensity) [μrad]	50 (at 40 nm)	15 (at 10 nm)

FELs vs SRs

FELS

- Higher Brilliance and peak power
- Low repetition rate
- Lower reproducibility
- Very short pulses high intensity pulses
- Can serve few beam lines
- Specimens get easely destroyed

SRs

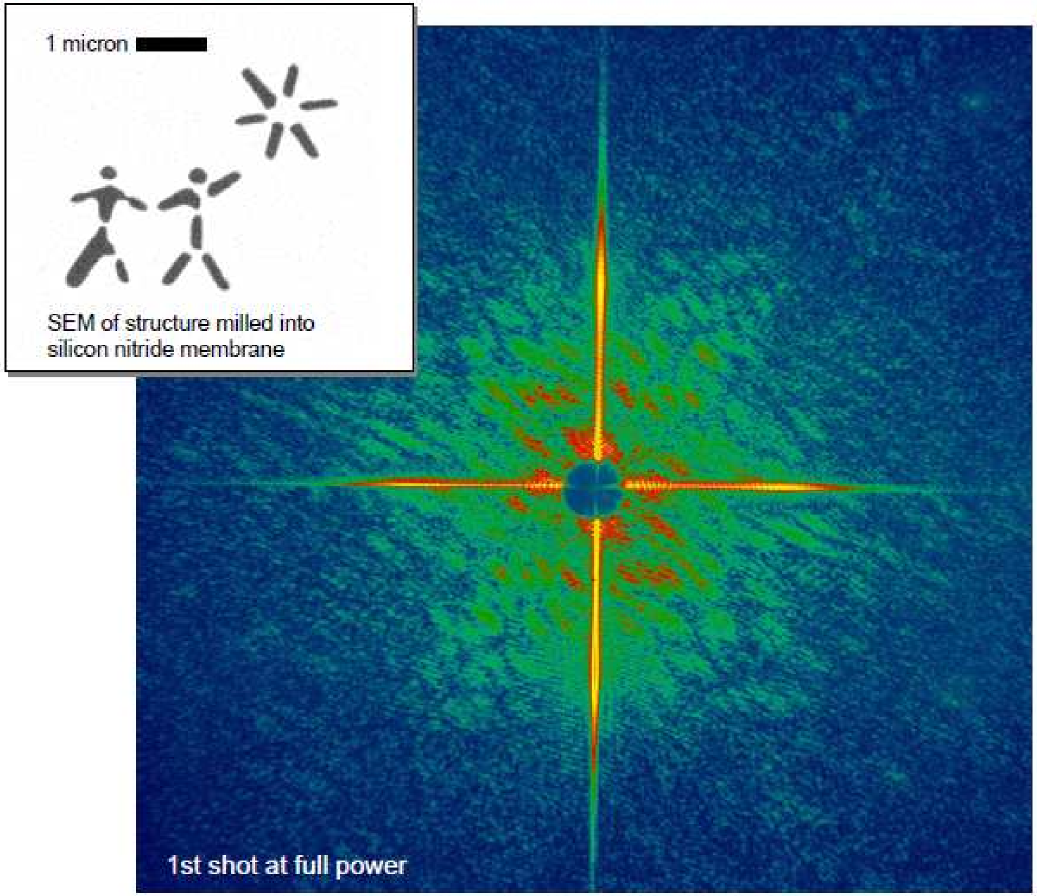
- High Brilliance
- Very high repetition rate
- High reproducibility
- Short pulses
- Very short but lower intensity
- Serve many beam lines

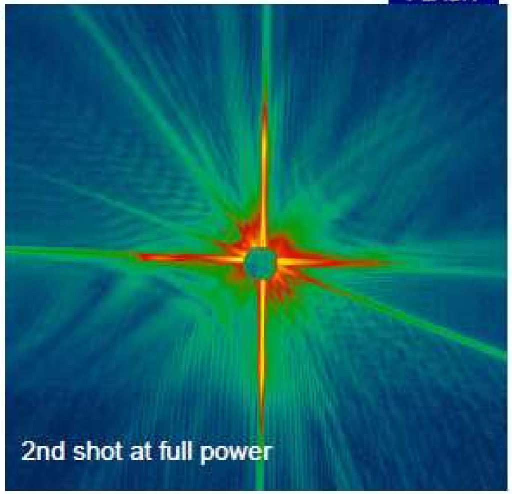
Many call FELs 4 th generation sources, to my opinion are complementary to SRs not a replacement.

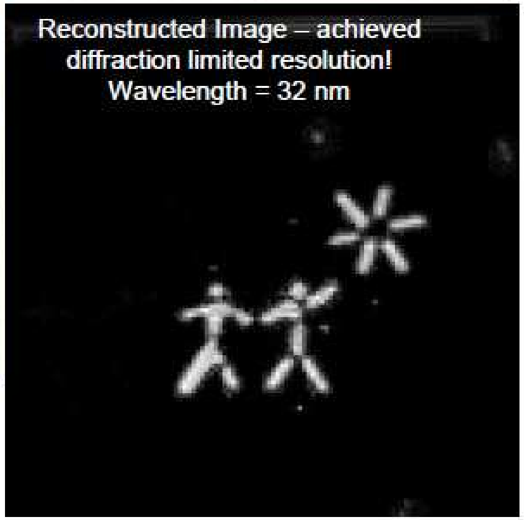
If SRs produce “photos” in material science , FELs produce “films” and one needs both!

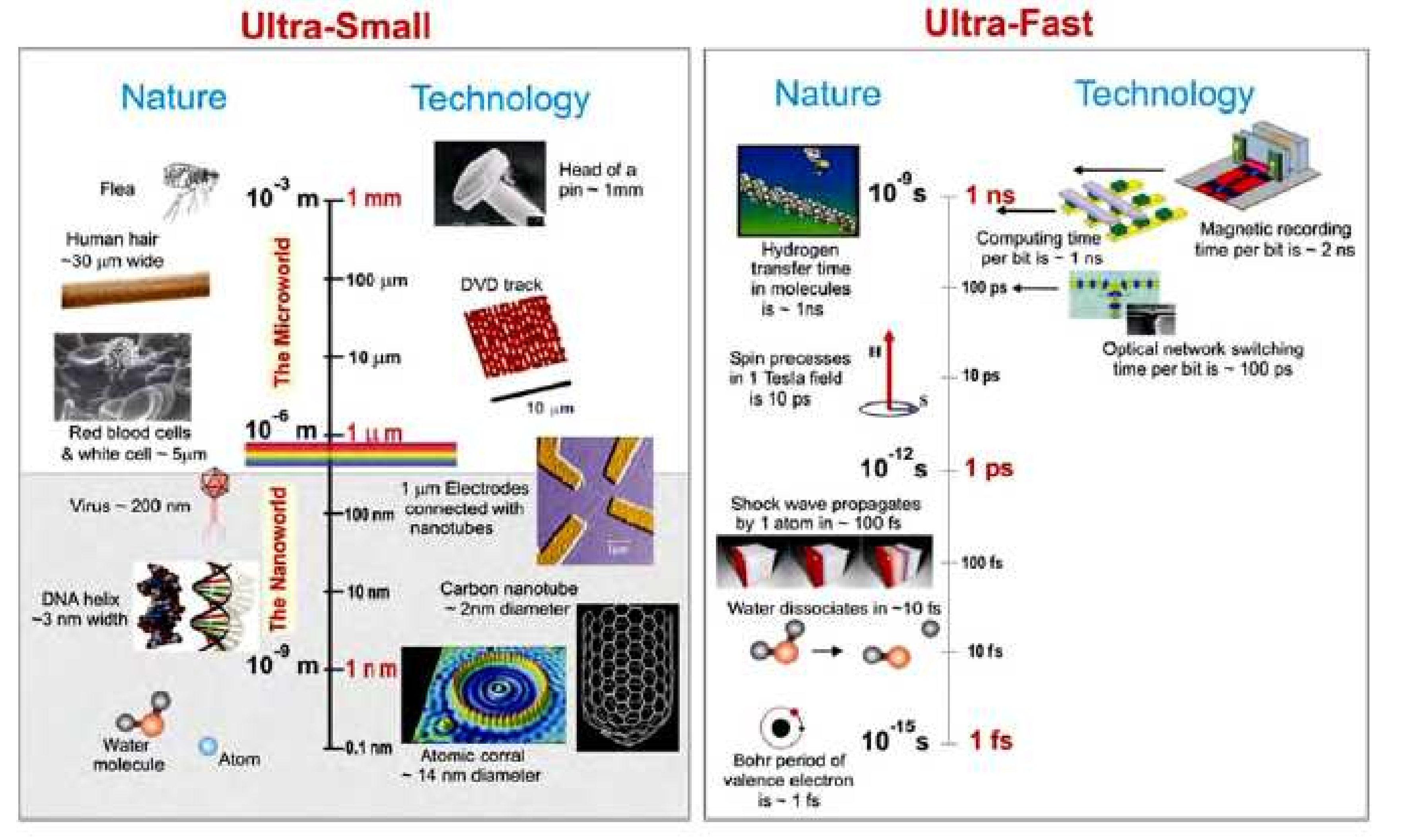
First demonstration of coherent diffraction imaging with a soft-X-ray FEL (Hajdu, Chapman)

FLASH









Initially x-rays have opened the ultra-small world. FELs open both the ultra-small and ultra-fast worlds. Graphic courtesy of J Stoehr.