Australian Government

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Future Light Sources

Asia Oceana Forum for Synchrotron Radiation 2024

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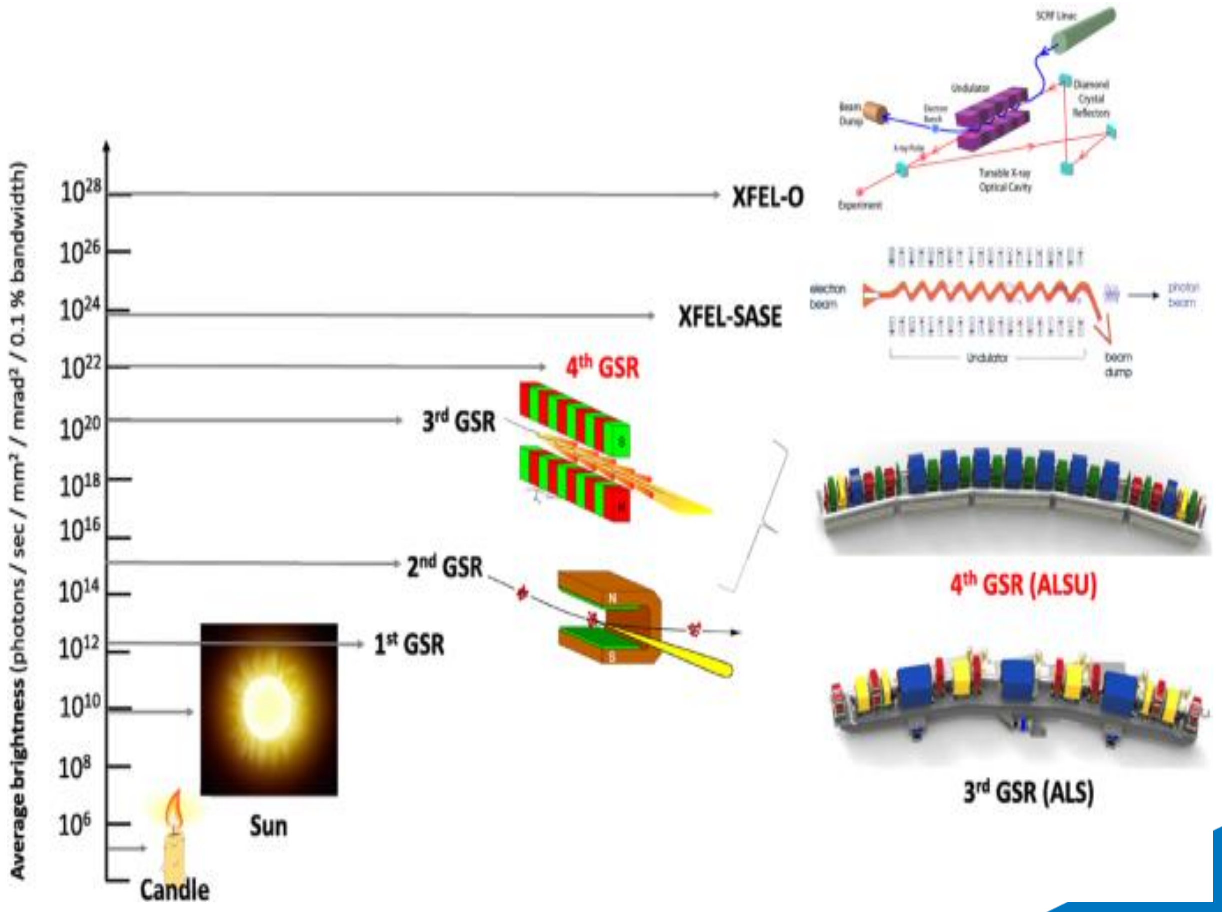
Science. Ingenuity. Sustainability.

Overview

- What do we mean by future light sources?
- Making a 4^{th} generation storage ring light source
- Other types of light sources
- Some Technology challenges

Light source generations

- 'Generation' is a loose term, denotes:
  - The brightness of the light source
  - The technology used to achieve it.
- Each (storage ring) light source generation is ~2 orders of magnitude brighter than the last.
- X-ray free electron lasers (XFELs) now sit on their own.



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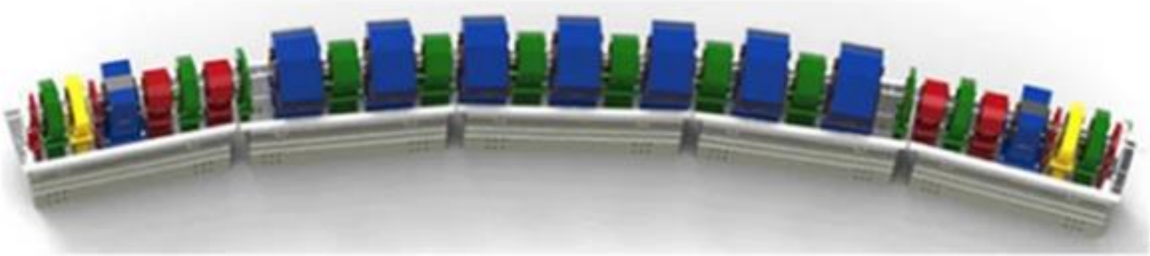
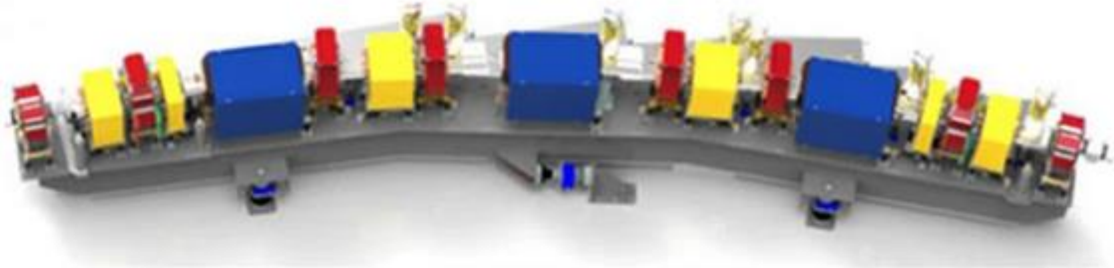
3rd vs 4th generation

- 2015 marked the start of the 4th Generation era for Light sources
- Many 3rd Gen sources currently upgrading or planning to.
- ~2 order magnitude brighter, with semi coherent beams,
- Will there be a 5th Gen?



4th GSR (ALSU)



3rd GSR (ALS)

Revisiting Brightness

Brightness:

Photon flux at wavelength, λ

$$B(\lambda) = \frac{F(\lambda)}{4\,\pi^2\,\Sigma_x\Sigma_y\;\Sigma_{x'}\Sigma_{y'}}$$

Unit source area

Unit solid angle

$$\Sigma_{x,y}^2 = \sigma_{x,y}^2 + \sigma_R^2$$

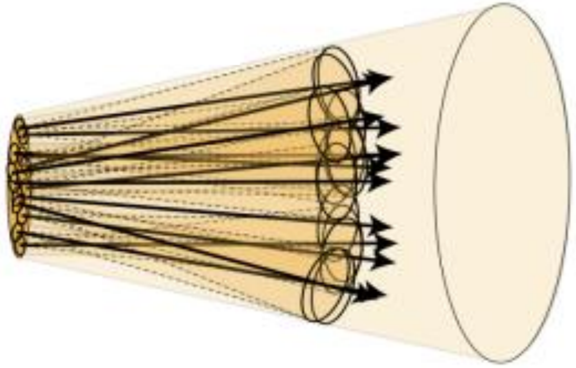
$$\Sigma_{x',y'}^2 = \sigma_{x',y'}^2 + \sigma_{R'}^2$$

Diffraction limit

$$\sigma_{x,y} \ll \frac{\lambda}{4\pi}$$

Single electron

3rd Gen electron bunch



4th Gen electron bunch

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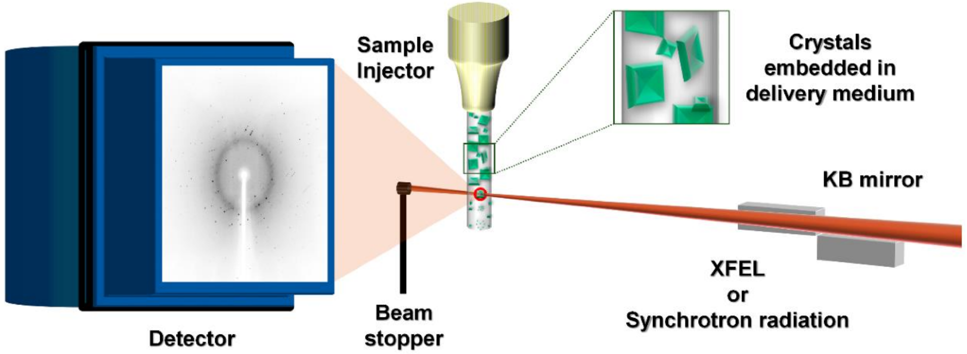
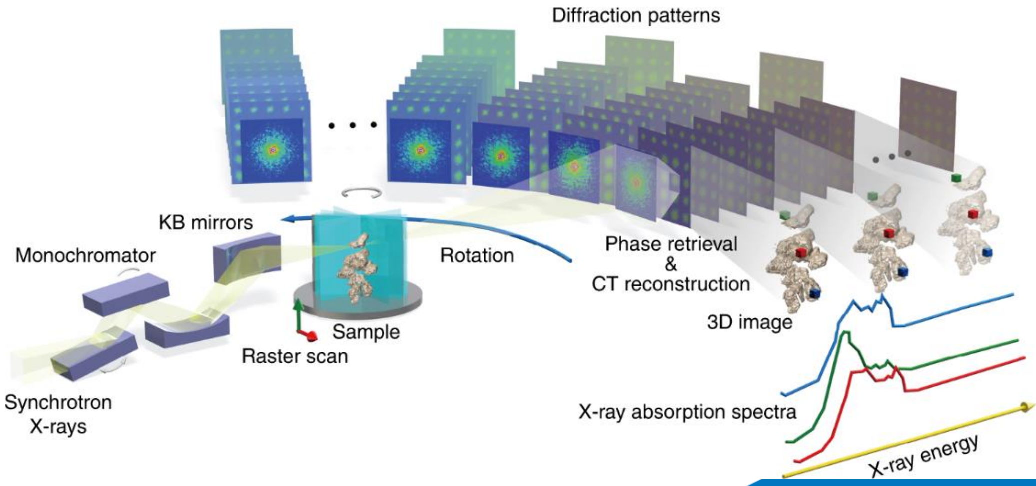
Why are we chasing Brightness?

- Smaller beams can be focussed onto smaller spots
  - Microscale –> Nanoscale
  - More detail of fine structures

- More photons means shorter integration times needed
  - Can start to explore dynamics of chemical processes
  - Less damage to structure from the X-rays
  - Unfeasibly long experiments become possible

- Coherent beams
  - Phase information -> phase contrast imaging





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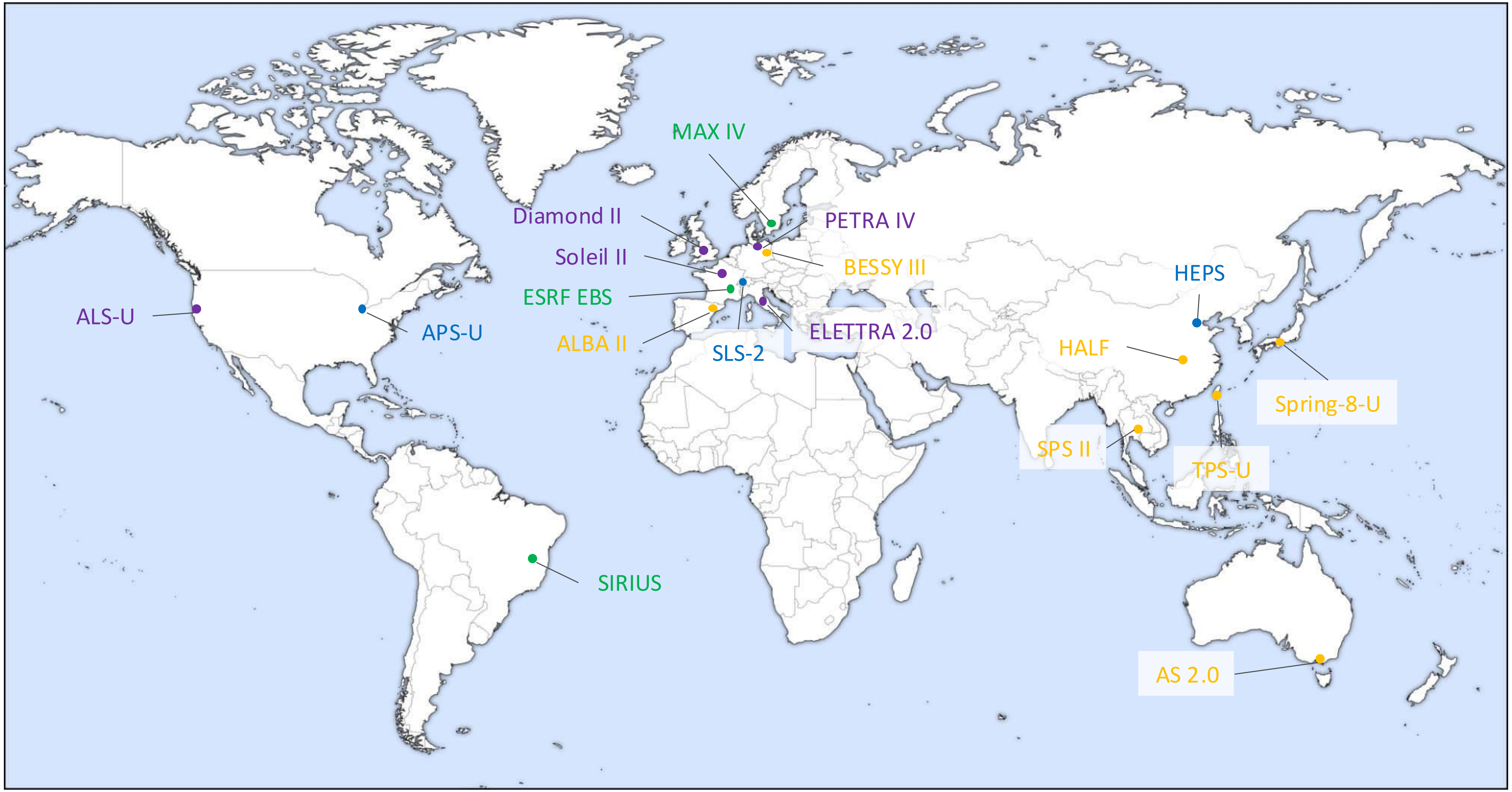
4^{th} gen synchrotron light sources



- Operating
- Commissioning
- TDR/CDR
- Planning

Making a 4th Generation Light Source

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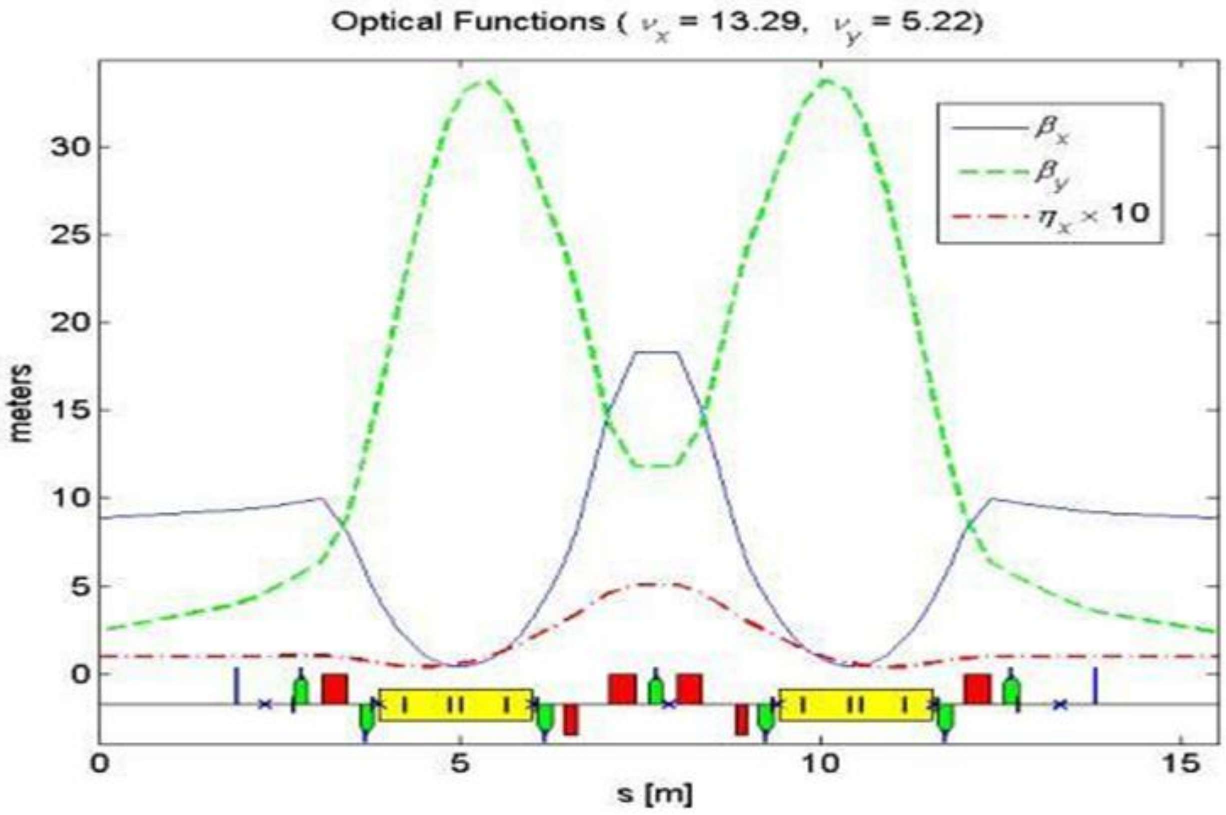
The Magnetic Lattice

- Repeating series of focusing, and bending magnets
- Each sector is identical
- Beam optics and entry of sector is identical to exit.
- Defines the minimum possible emittance that can be achieved
- Beam Size: $\boxed{\sigma^2 = \varepsilon\beta + \eta^2 (\Delta E/E)^2}$



To minimise beam size, we want to minimise emittance and dispersion

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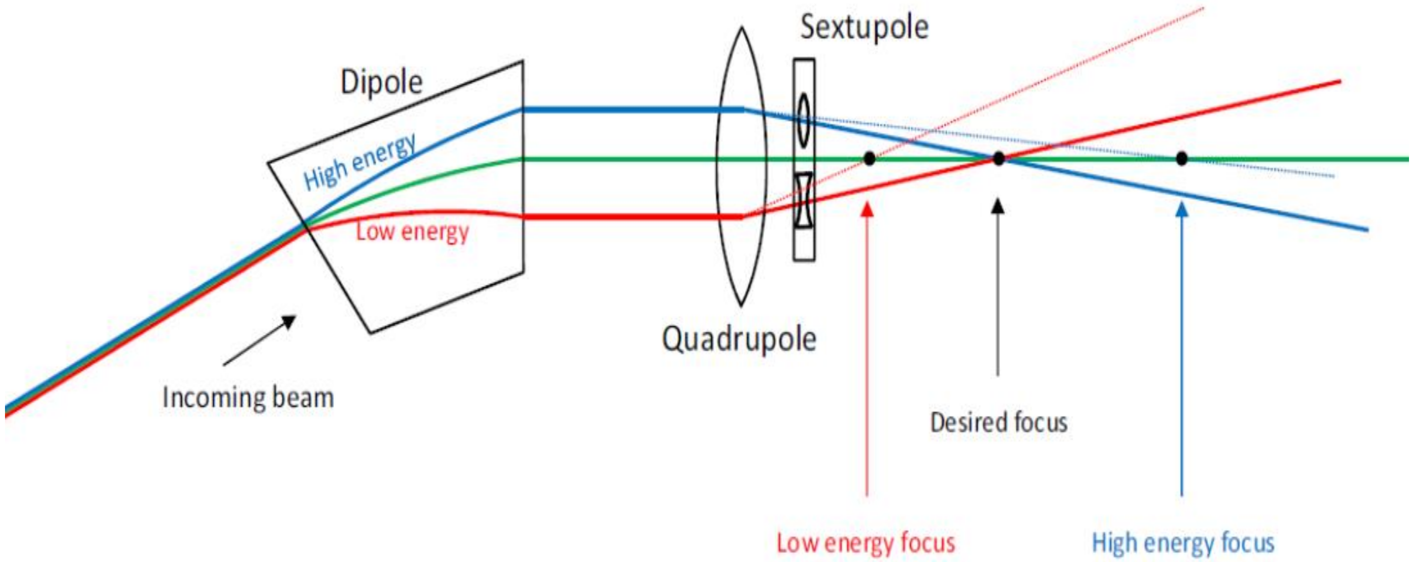
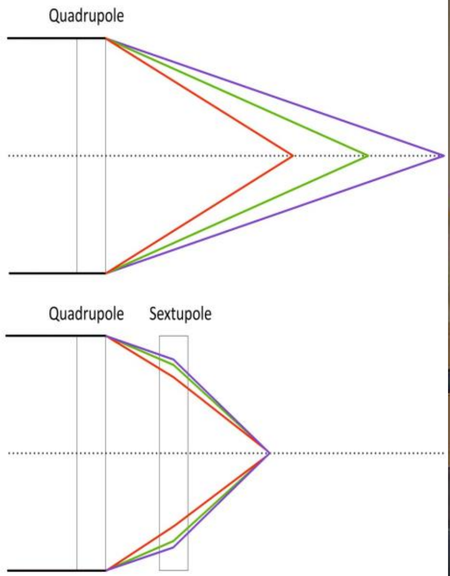
Dispersion

Different energy particles will be deflected by a bend magnet by different amounts.

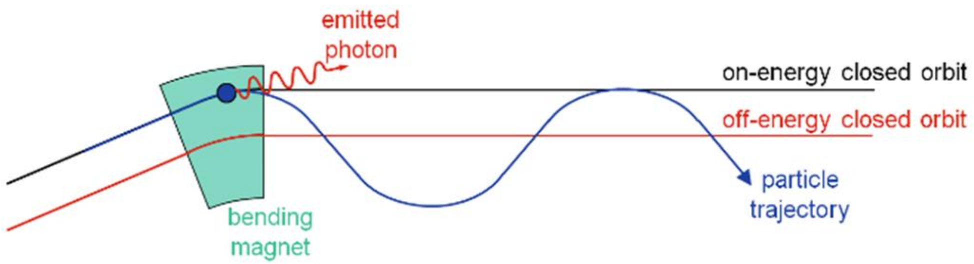




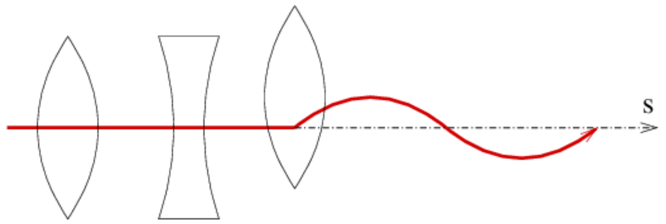
- Sextupole magnets provide different amounts of focusing on each side to correct for the spread of beam energy

Emittance drivers

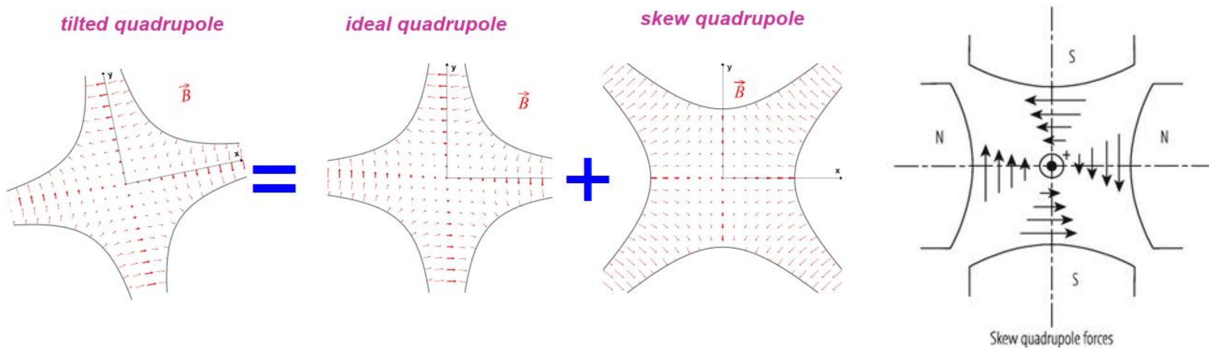
- Radiation emission through a bend
  - Dominates horizontal emittance in a storage ring



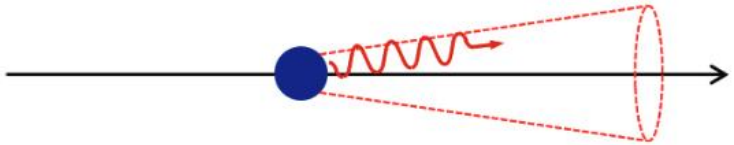
- Misalignments



- Coupling from other planes
  - Dominates vertical emmitance
  - Primarily magnet misalignments

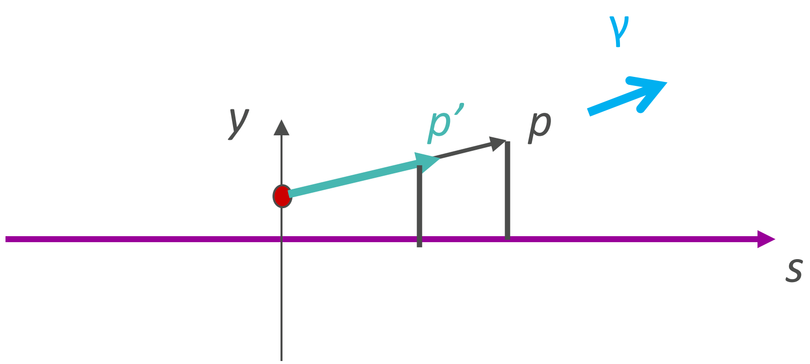


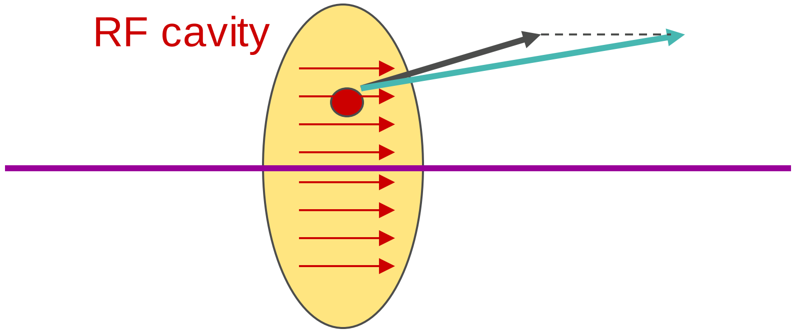
- ‘Quantum’ emmitance
  - Intrinsic opening angle of radiation

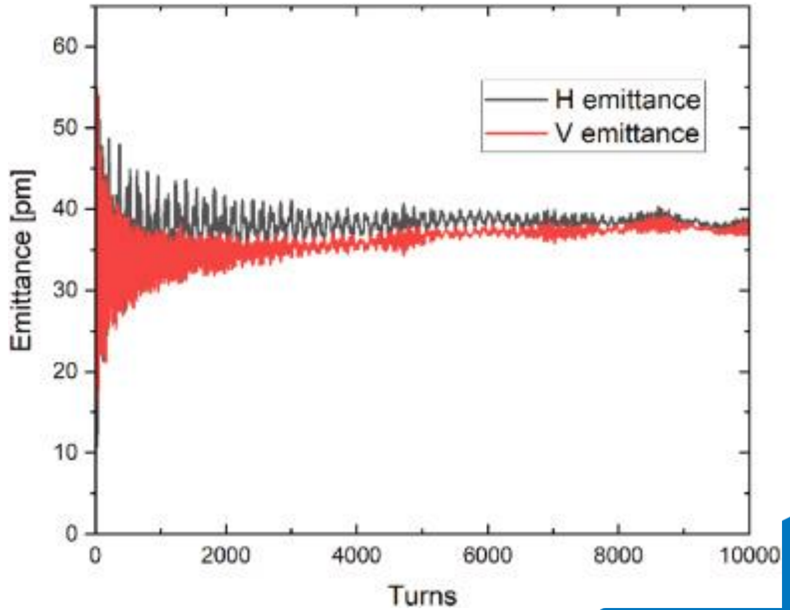


Damping Emittance

- Emission of synchrotron radiation will 'Damp' the transverse motion and hence reduce the emittance.
- This emission is mainly in Dipoles, but wigglers and other IDs can have an effect.
- Emittance in a (electron) ring will reach an equilibrium value as a balance between the driving terms and radiation damping.







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Minimising emittance

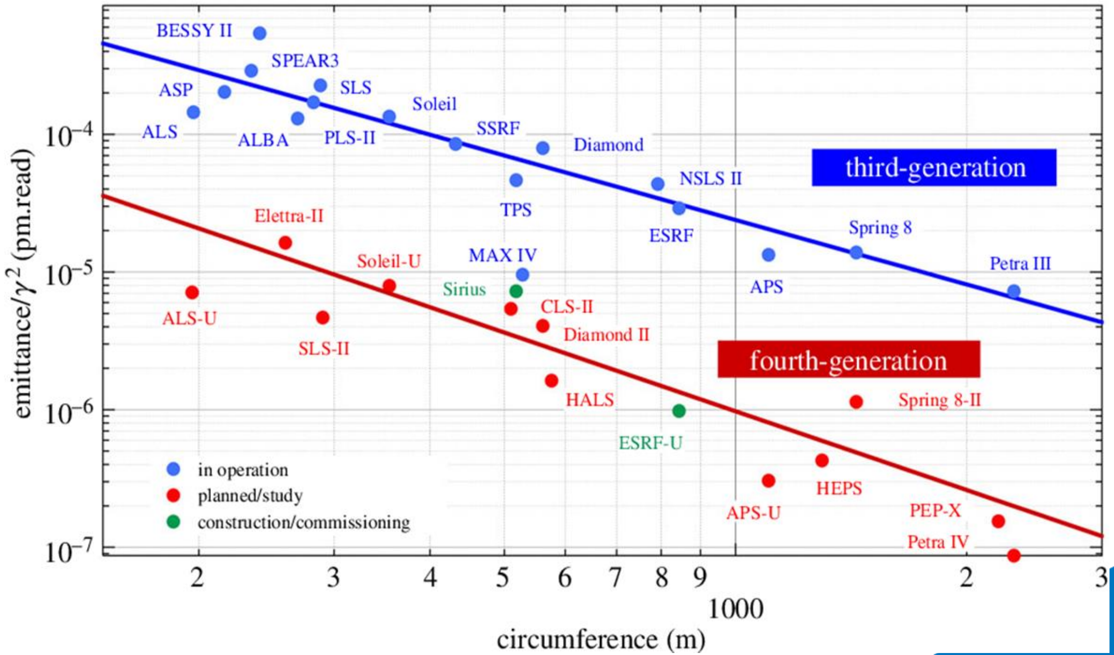
- Emittance can be reduced by minimising:
  - the bend angle - $1/\rho$
  - values of 'curly H' inside bend magnets
- Multi bend achromat (MBA) designs do both
  - Many shallower bends minimises $1/\rho$
  - optics minimises curly H (mainly through dispersion)

$$\varepsilon_x = C_q \frac{\gamma^2}{\mathcal{J}_x} \frac{\boxed{\oint \mathcal{H}/\rho^3 \mathrm{d}s}}{\boxed{\oint 1/\rho^2 \mathrm{d}s}}$$

Lattice optics

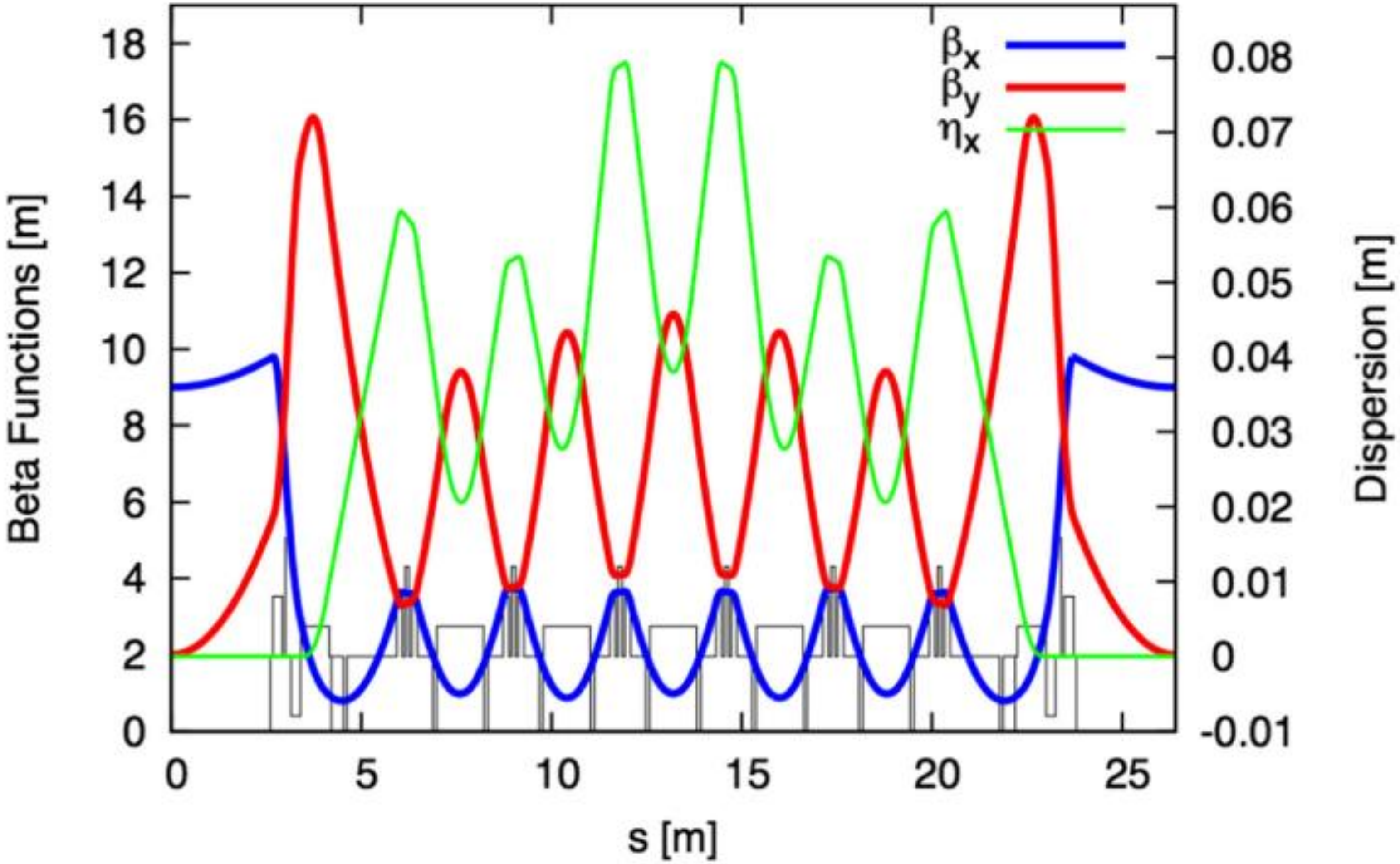
Bend angle (beam energy /circumference)

$$\mathcal{H} = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$



4th Gen – minimising 'Curly H'

$$\mathcal{H} = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$



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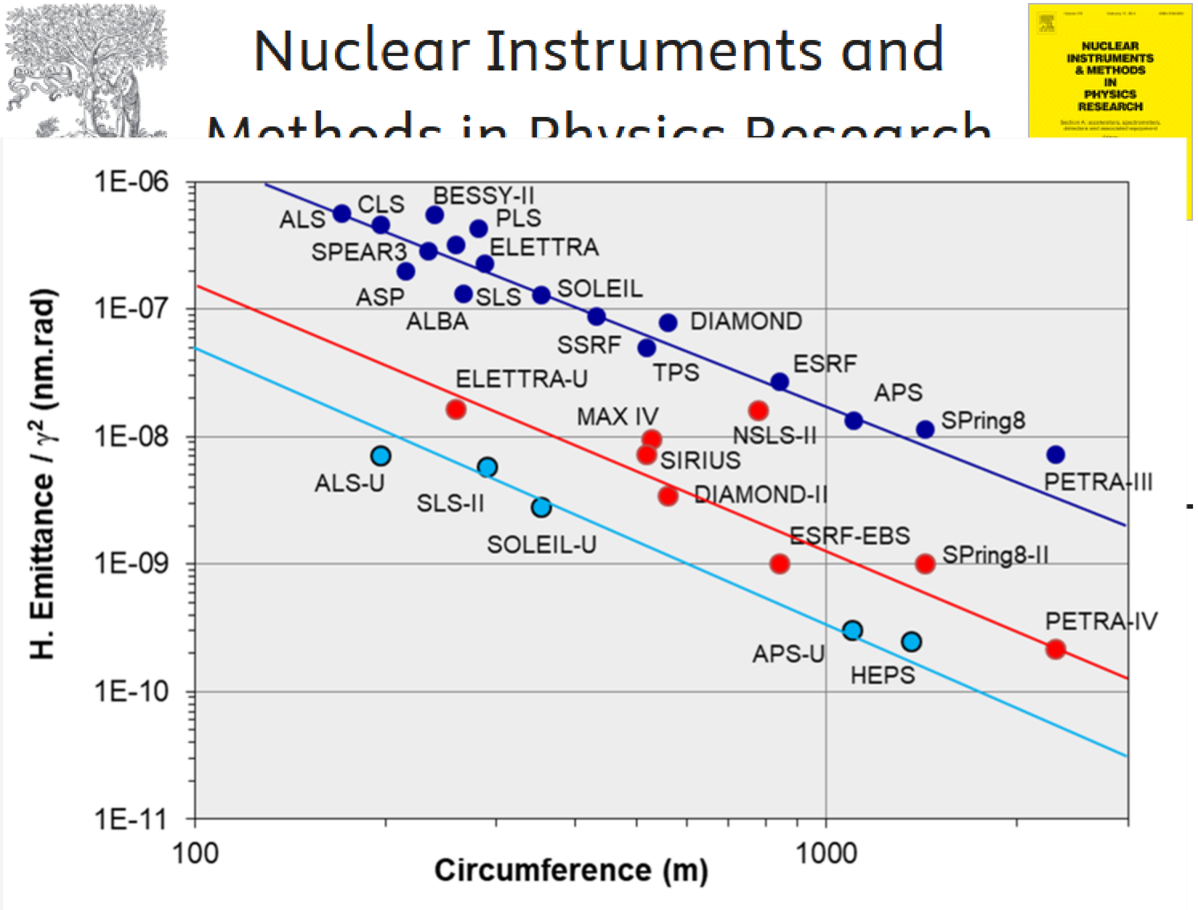
Bending Backwards?

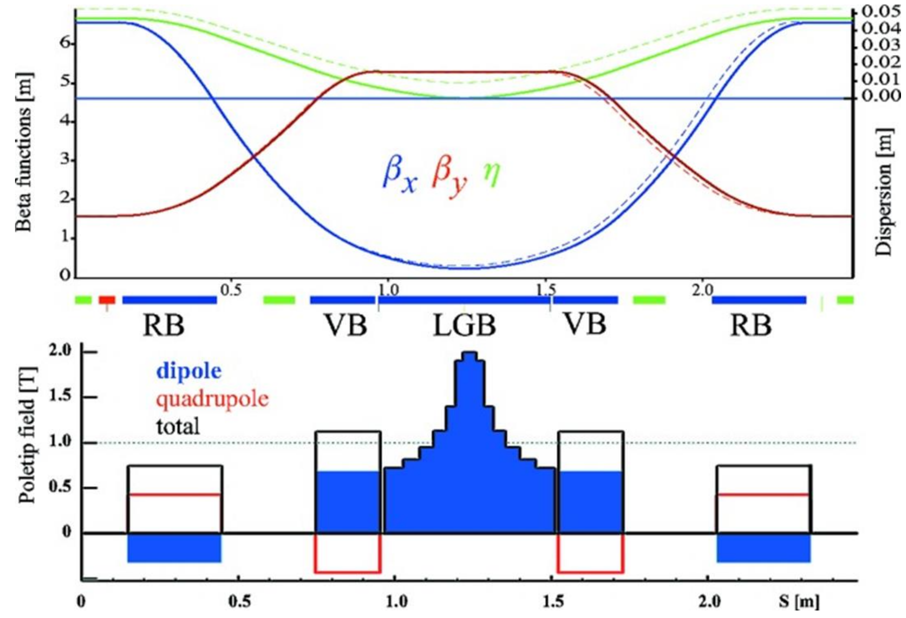
- New design concept in 2014 for SLS-2 adopted dipoles that bend the beam in the opposite direction.
- Allows more control over the beam dispersion
- Beam ends up bending more than 360 degrees – more synchrotron radiation
- Adoption of 'reverse bends' has created mini generation (gen 4.5?)



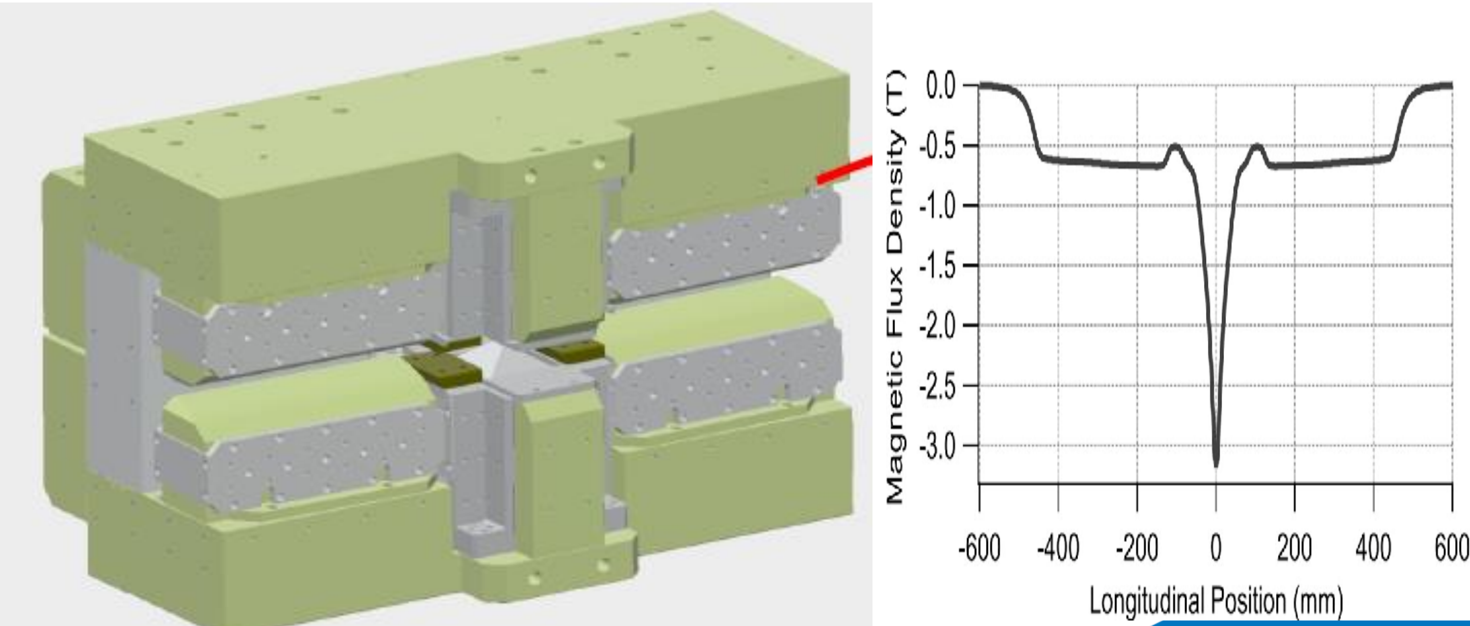
A. Streun

Gradient Dipoles

- Bending field changes along the length of the magnet. Peak field can be up to 3-4 Tesla.
- Reduces emittance by concentrating bend force at low $\mathcal{H}$ area
- Raises the critical energy of SR photons from the dipole



Longitudinal gradient dipoles of the SLS2 design



Sirius Superbend

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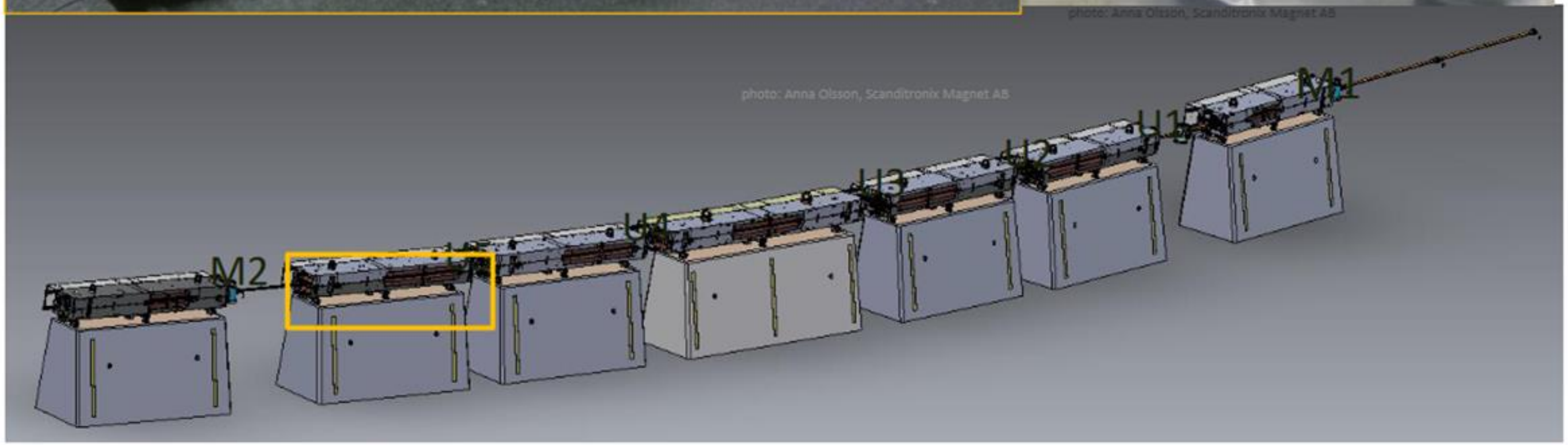
Exa

- 3 GeV

a MAX IV magnet block:

- a U5 bottom half →
- ↓ an assembled U5



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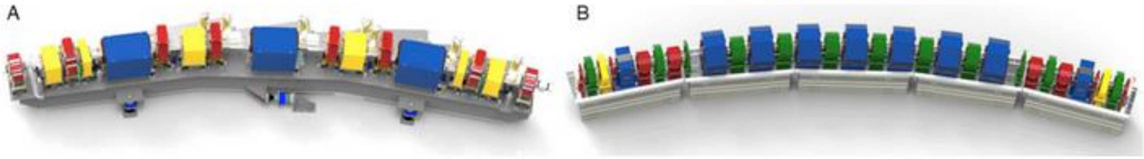
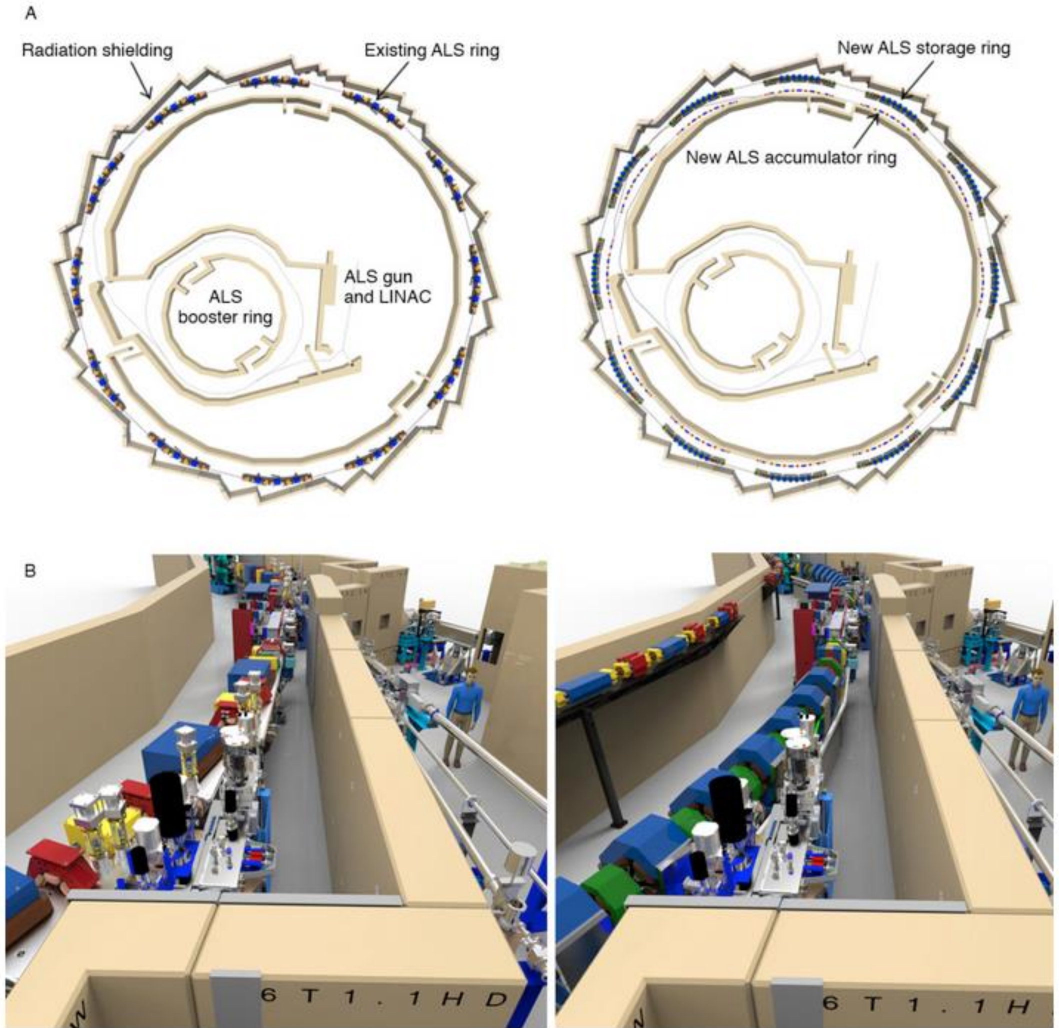
Examples: ALS-U

- 2 GeV, 197 m, 50 pm H emmittance

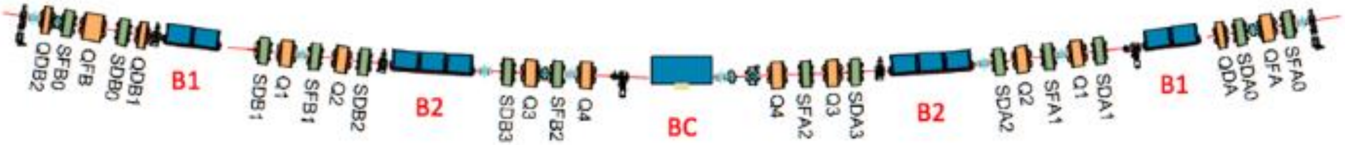


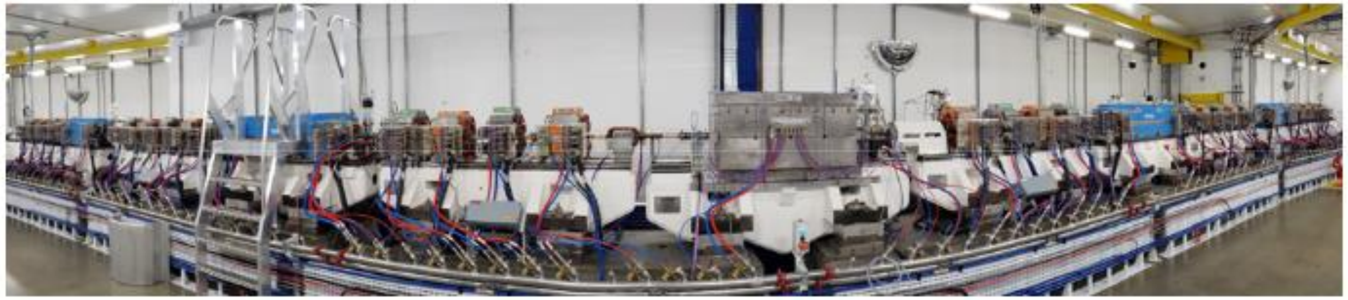
(A) The existing ALS triple-bend achromat. (B) The ALS-U multibend achromat. The bend magnets are shown in blue



Examples: irius

- 3 GeV, 518 ... itt.





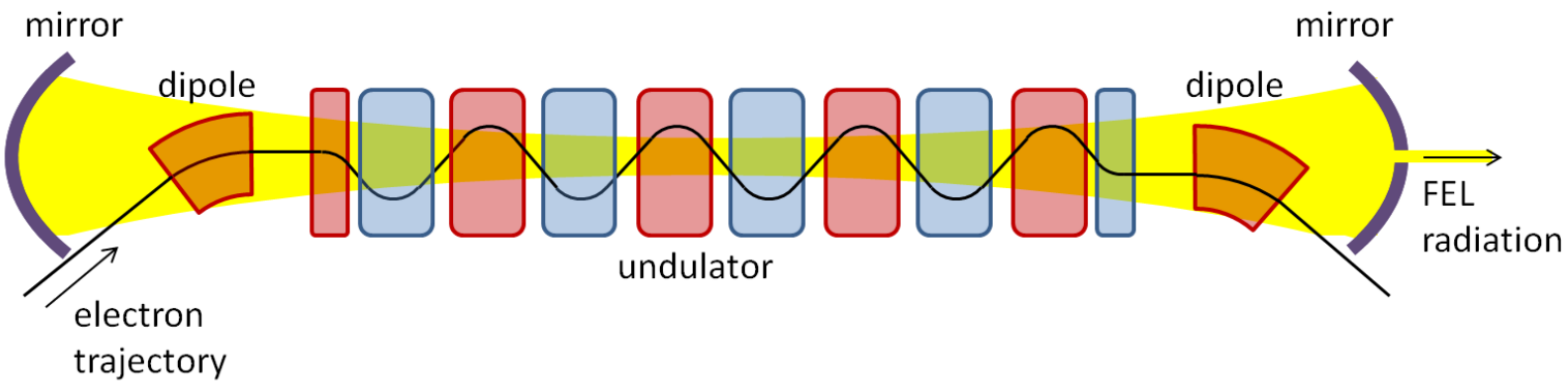
Other Types of Light source

Other types of Light Sources

- Ring based light sources are likely to dominate for the short to medium term as they:
  - Provide bright and high repetition rate (MHz) light pulses
  - Service many experiments and wavelengths at once
  - Can achieve the diffraction limit
- However Linear accelerator based light sources do have distinct advantages in certain areas.
- Ideal situation is to have access to a mix of sources.

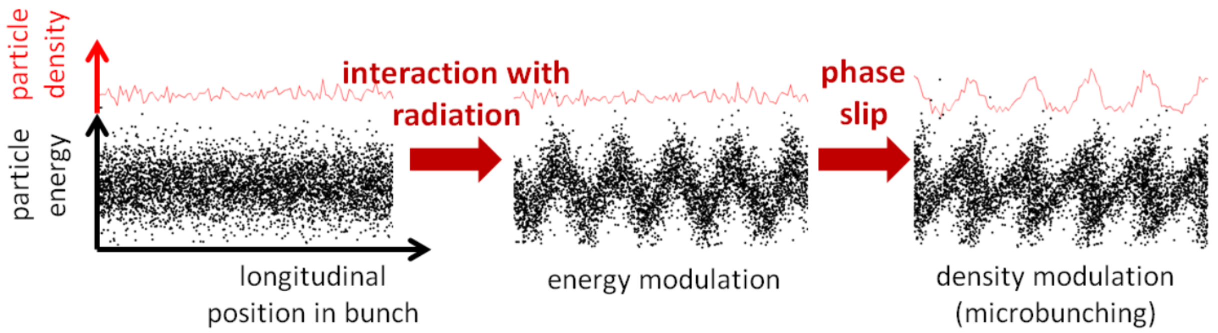
Free Electron Laser

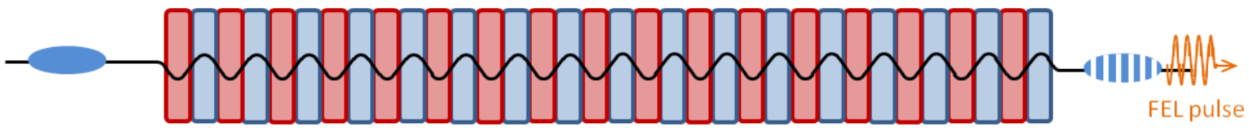
- Simplest form is an optical cavity across an undulator.
- Electron beam acts as the lasing medium.
- Needs reflective optics to work, cannot use for X-rays

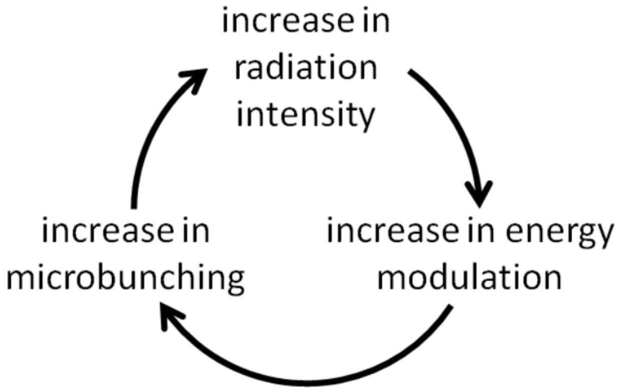


Self Amplified Spontaneous Emission (SASE)

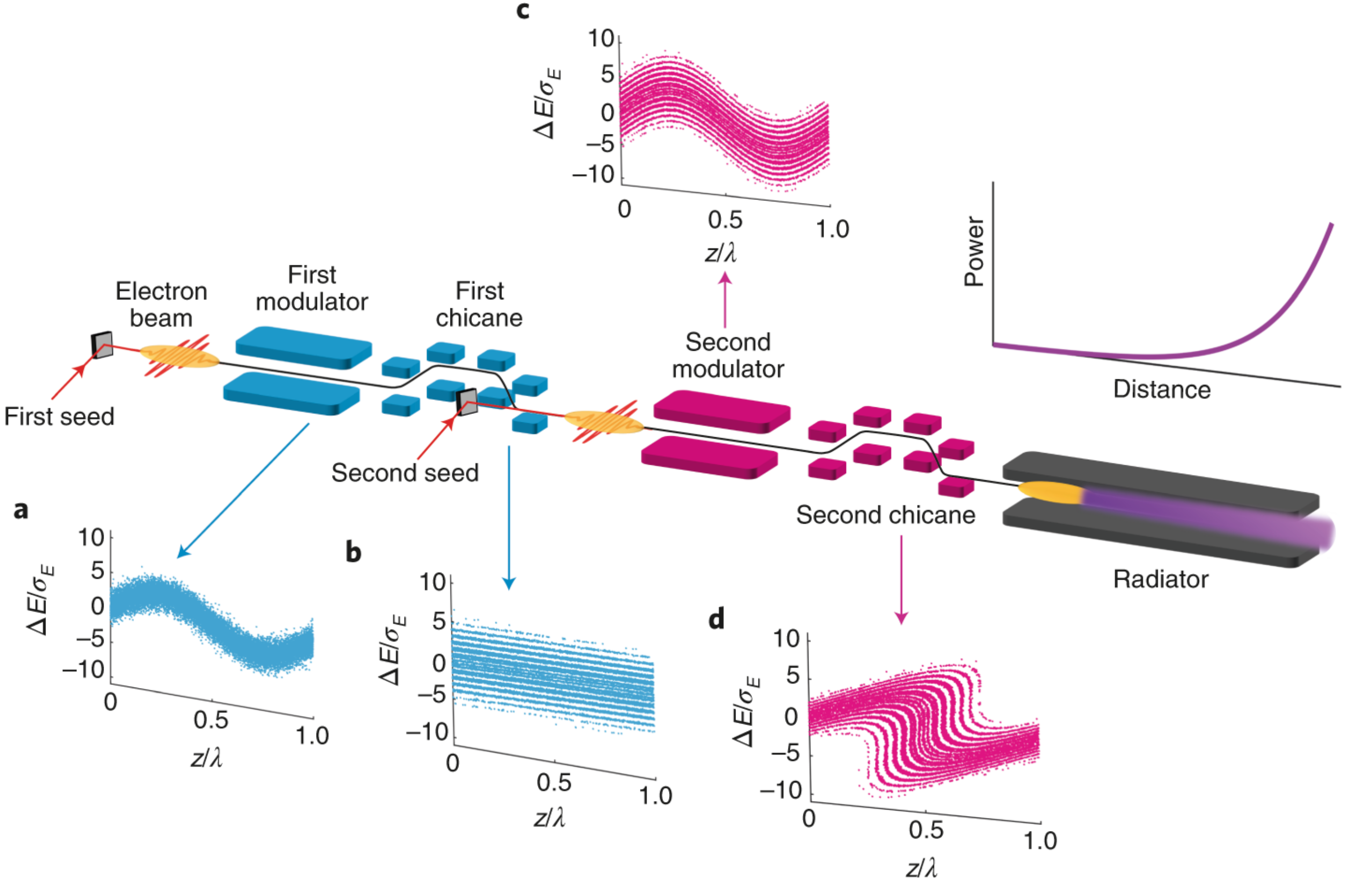
- Beam interacts with its own radiation
- Energy modulation builds up
- Density modulation -> microbunching
- 'Gain length' α emittance



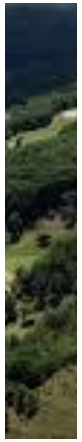


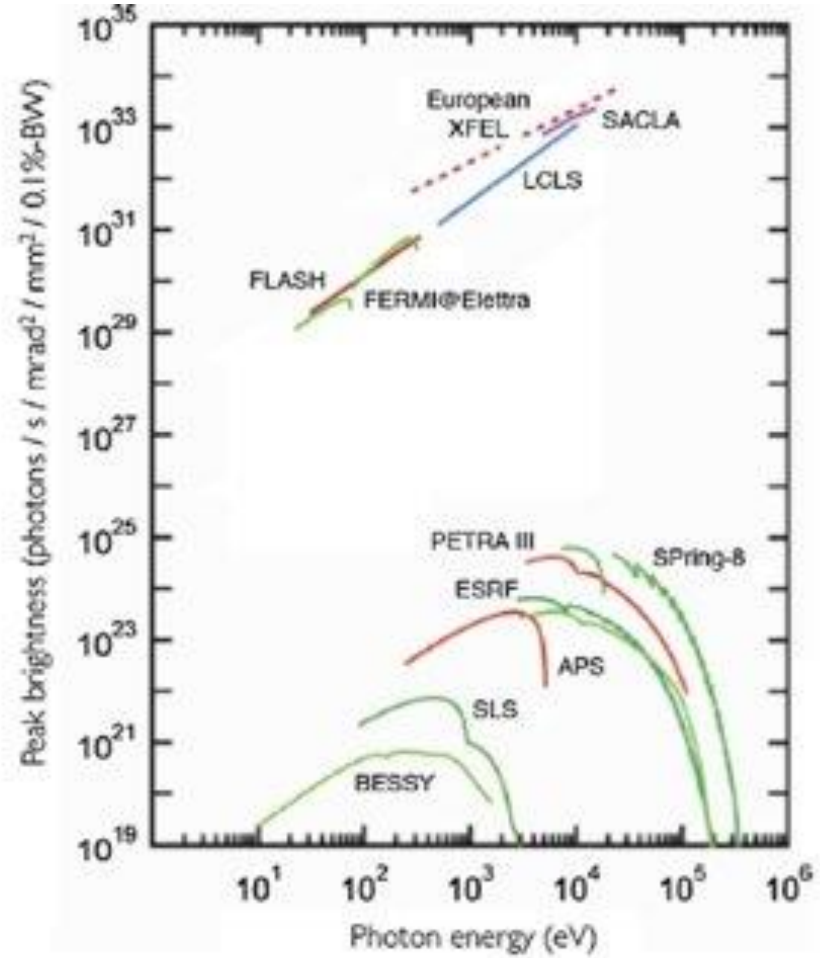


Seeded FELs



c
10
5
0
−5
−10
ΔE/σ_E
0
0.5
1.0
z/λ
Power
Distance
Electron beam
First modulator
First chicane
Second modulator
First seed
Second seed
Second chicane
Radiator
a
b
d





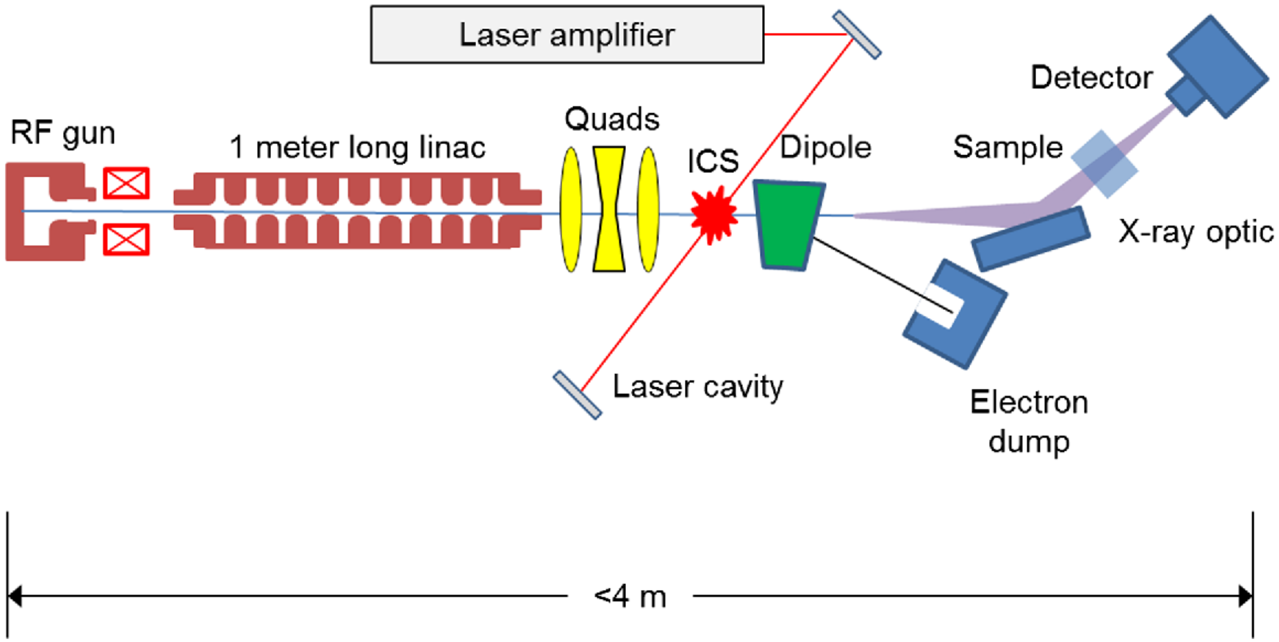
Peak brightness (photons / s / mrad² / mm² / 0.1%-BW)
Photon energy (eV)
European XFEL
SACLA
LCLS
FLASH
FERMI@Elettra
PETRA III
SPring-8
ESRF
APS
SLS
BESSY

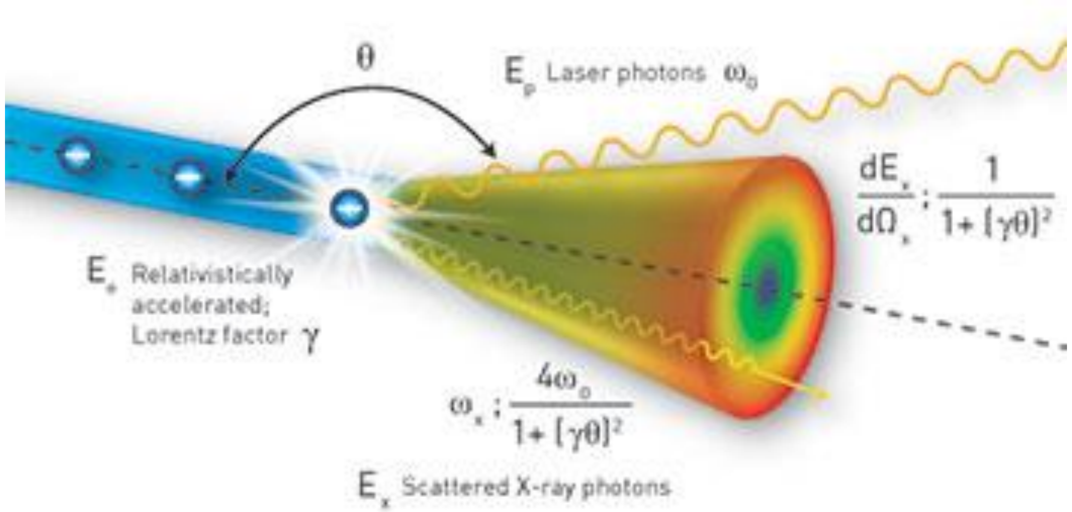
FEL properties

- Often large and expensive. Massive shot-to-shot flux, but not very high repetition rate compared to Storage ring.
- Limited applications?
- Limited beamlines – rep rate goes down with more beamlines
- Complementary but does not replace a SR source.

	3rd Gen.	SASE-FREE-ELECTRON LASER	Short pulse SASE-FREE-ELECTRON LASER
Wavelength range, nm	1-0.1		
Emittance, nm rad	2	0.03	0.03
Pulse length, ps	15-30	0.06	0.01
Average brightness	10^{20}	10^{22}	10^{21}
Peak brightness	10^{23}	10^{33}	10^{33}
Peak power, W	10^{3}	10^{10}	10^{10}

Inverse Compton Light Sources





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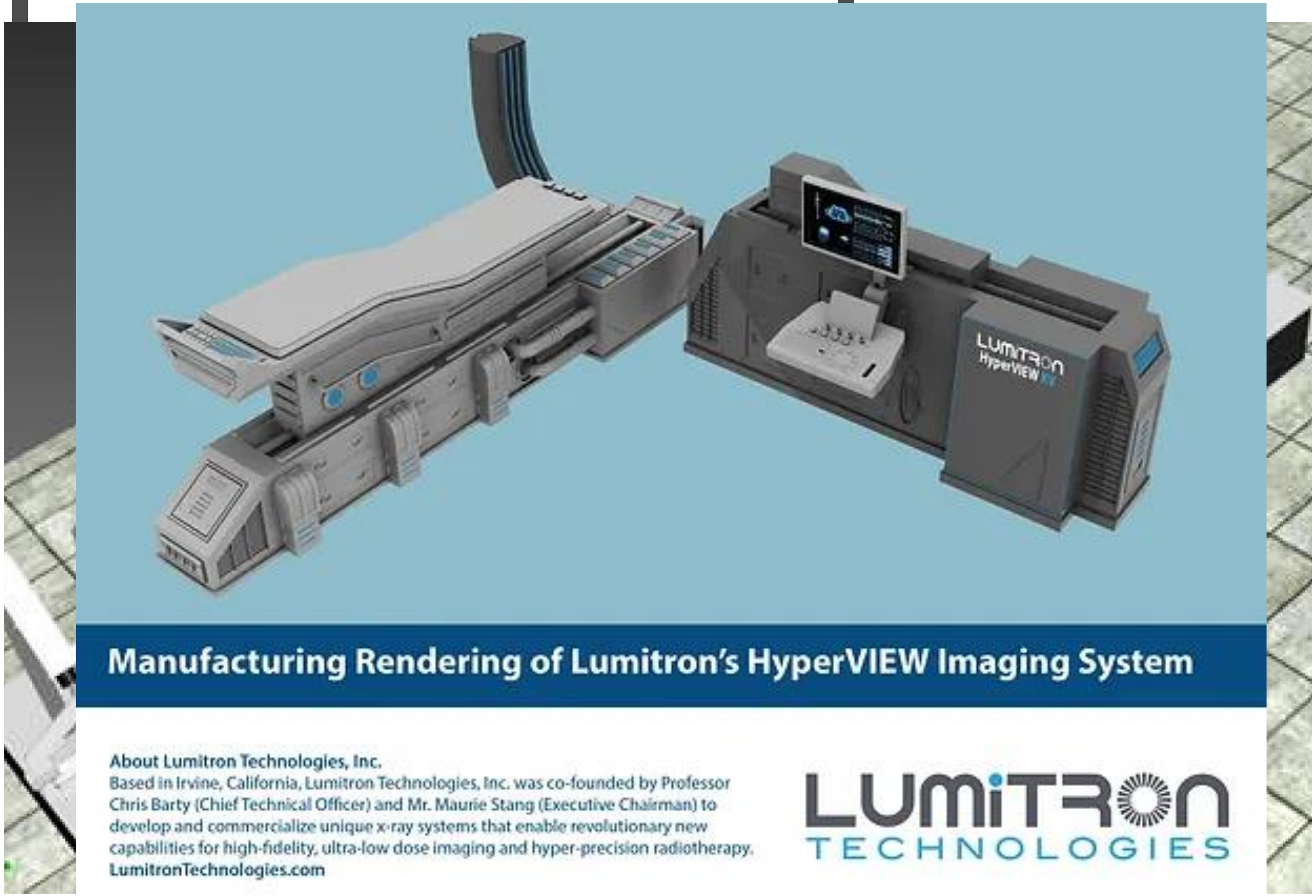
Inverse Compton Light Sources

- Potential to be smaller, cheaper versions of FELs, but flux is not there yet
- Emerging technology for hard X-ray, Gamma energies.
- Huge potential if can be miniaturised to room sized.

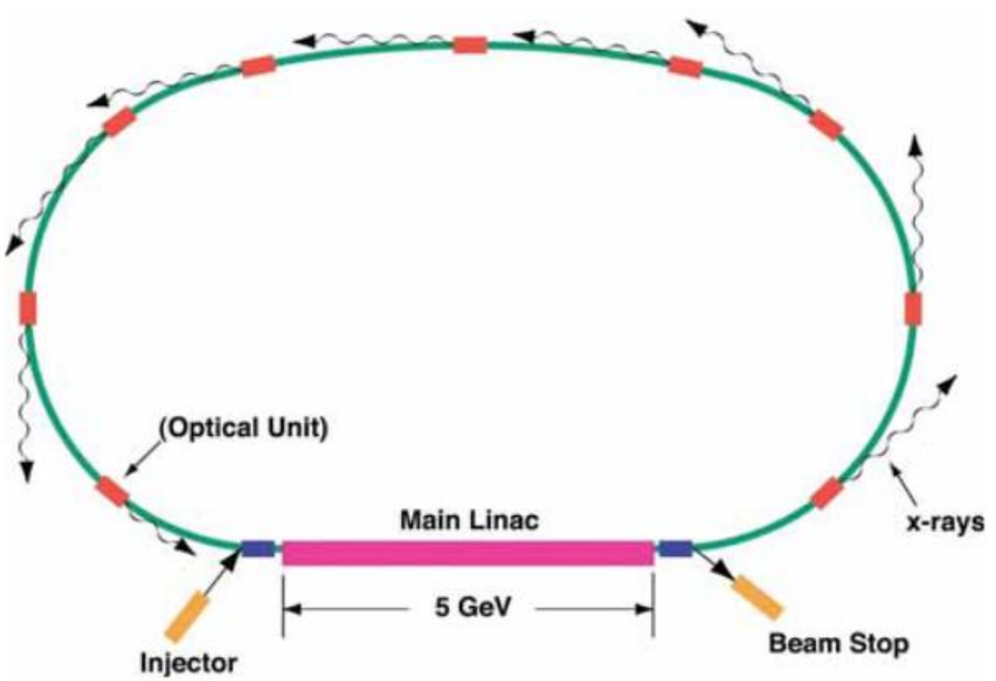
Project	Type	E_x (keV)	Ph/s	Ph/(s-mrad^2 -mm^2-0.1%BW)	σ_γ (μm)
Lyncean at Munich [4, 16, 19]	SR	10-20	10^{11}	10^{11}	45
TTX [20]	SR	20-80	10^{12}	10^{10}	50
LEXG [21]	SR (SC)	33	10^{13}	10^{11}	20
ThomX [22]	SR	20-90	10^{13}	10^{11}	70
KEK QB [23]	Linac (SC)	35	10^{13}	10^{11}	10
KEK ERL [24]	Linac (SC)	67	10^{13}	10^{11}	30
NESTOR [25]	SR	30-500	10^{13}	10^{12}	70
ASU (MIT) [14]	Linac	12	10^{13}	10^{12}	2
ODU (12 microns)	**Linac (SC)**	**12**	$\mathbf{10^{13}}$	$\mathbf{10^{14}}$	**3**
ODU (3.2 microns)	**Linac (SC)**	**12**	$\mathbf{10^{14}}$	$\mathbf{10^{15}}$	**2**

Compactness of a Compton Source



Energy Recovery Linac (ERL) Light Source

- Beam from a very low emittance linac injected into ring and accelerated in main linac
- Performs one turn, emitting SR along the way
- Arrival time tuned so that it is decelerated in linac and energy is recovered and used to accelerate next beam
- Produces diffraction limited X-ray beams
- Problems getting enough charge in beam
- Problems getting repetition rate
- Challenges in main linac design



Technology Challenges

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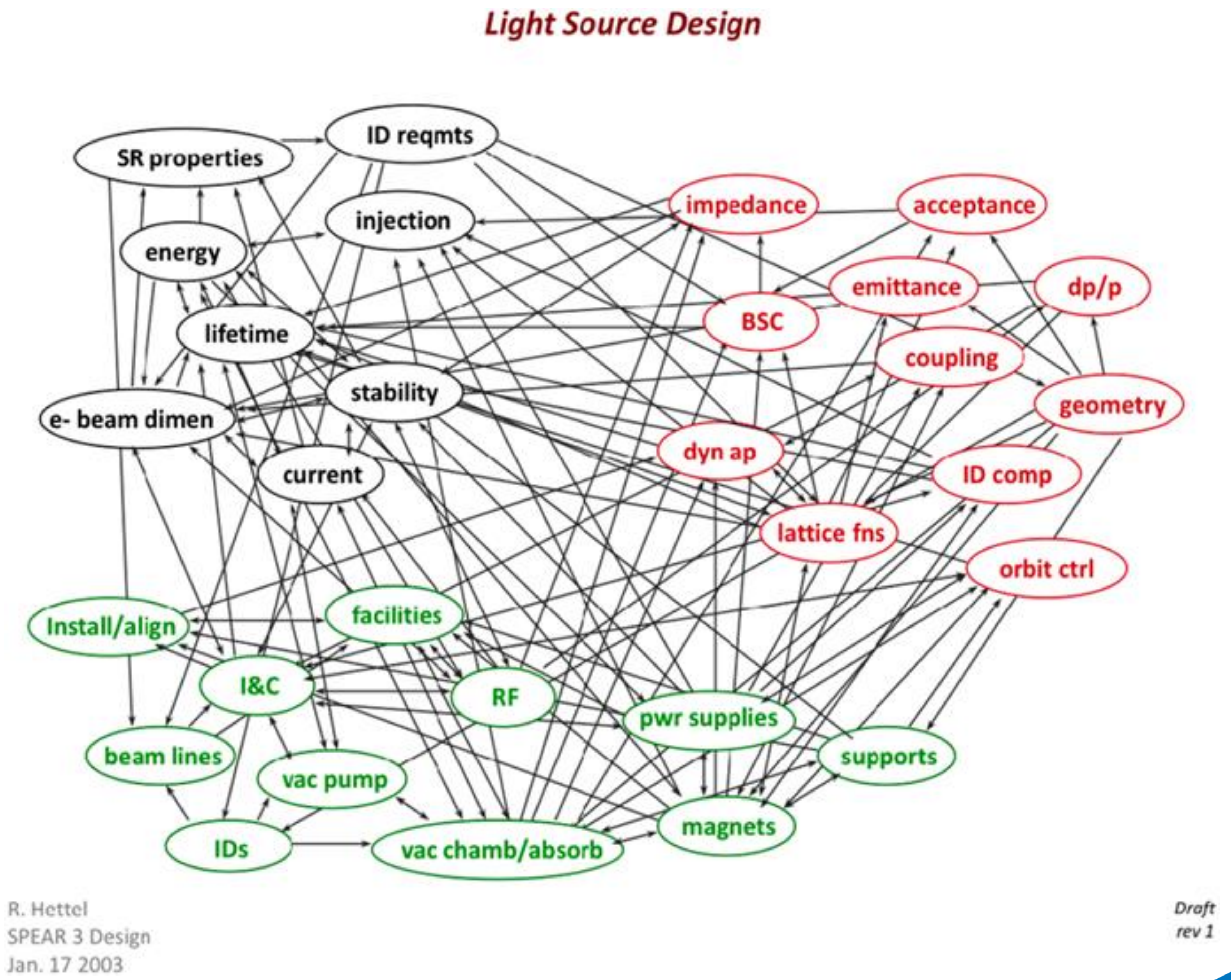
Light Source Design
SR properties
ID reqmts
injection
energy
lifetime
stability
e- beam dimen
current
impedance
acceptance
emittance
dp/p
BSC
coupling
geometry
dyn ap
ID comp
lattice fns
orbit ctrl
Install/align
facilities
I&C
RF
pwr supplies
supports
beam lines
vac pump
magnets
IDs
vac chamb/absorb
R. Hettel
SPEAR 3 Design
Jan. 17 2003
Draft
rev 1

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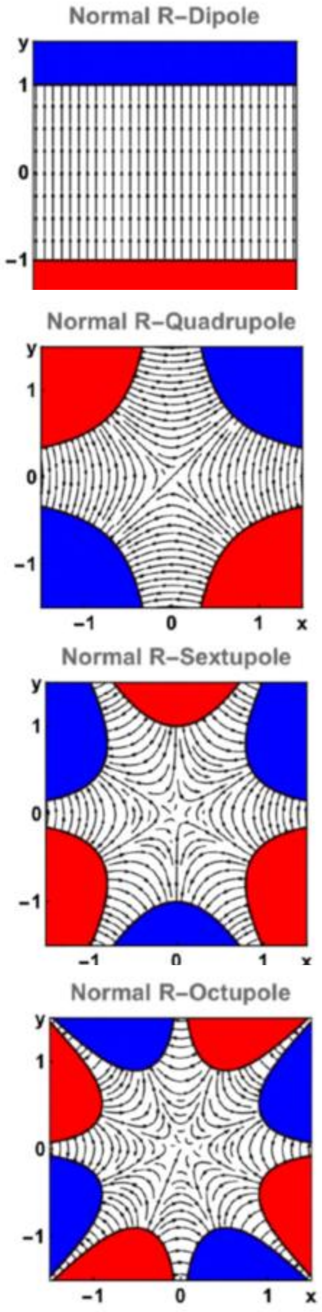
Magnets

- Field strength for multipole (Quads, Sextupoles, Octopoles) are significantly higher in a 4th Gen source
  - Need to demonstrate we can achieve required fields and physically fit all the magnets in the ring.
  - Current spacing between magnets can be as low as 50 mm!
  - Stronger magnets required = smaller vacuum chamber

- Longitudinal gradient dipoles required for 'superbends'
  - Design can be challenging, will need prototyping

- Alignment tolerances
  - Strong magnets = more sensitivity to errors
  - Order of magnitude jump in sensitive compared to 3rd gen



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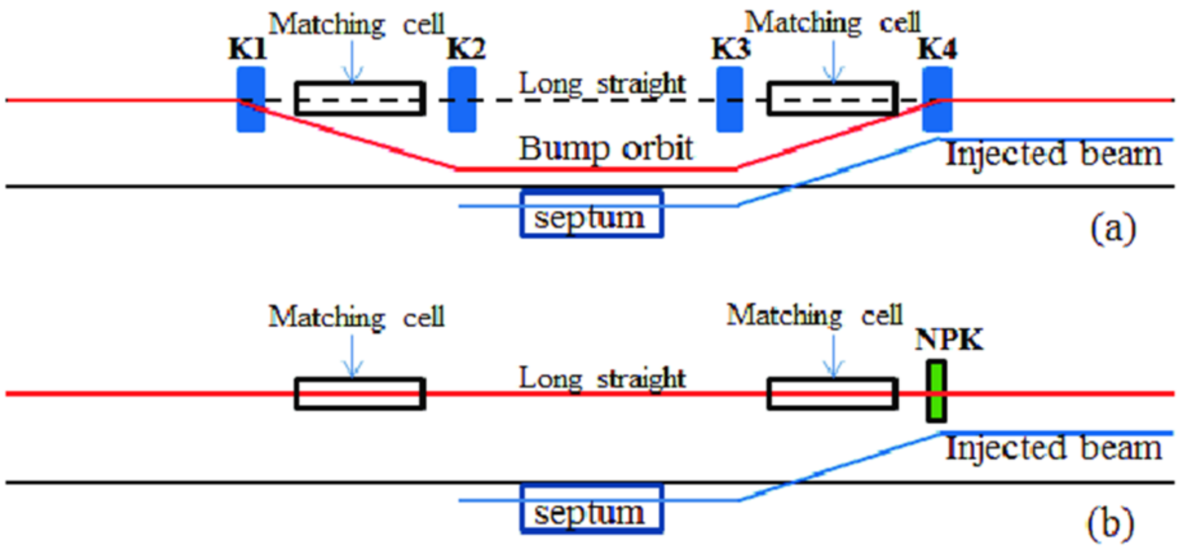
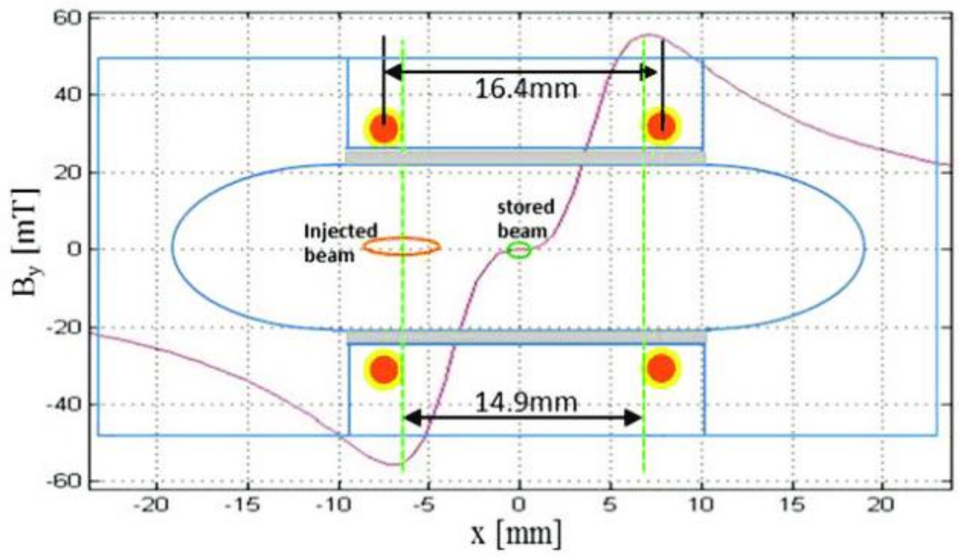
Injection

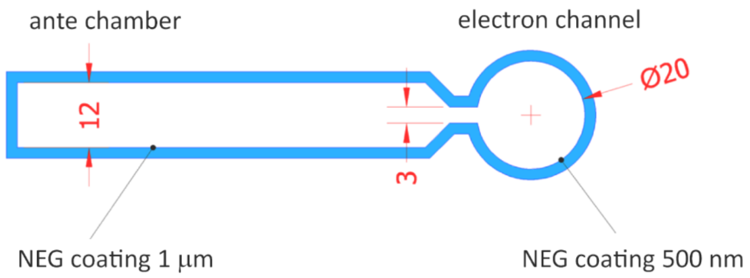
- 4th Generation rings have much smaller ‘dynamic aperture’ and require different injection methods.
  - On axis injection usually needed
  - They also require a higher quality beam going in -> linac injector

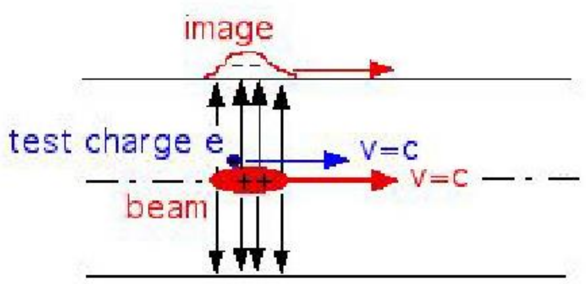




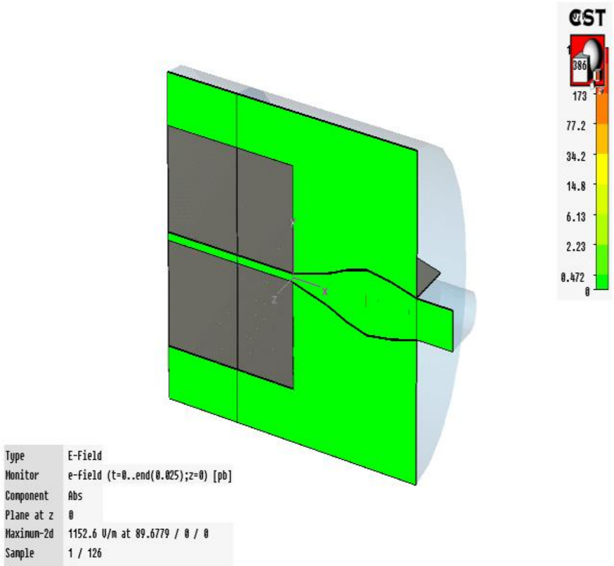
Vacuum chamber and Impedance

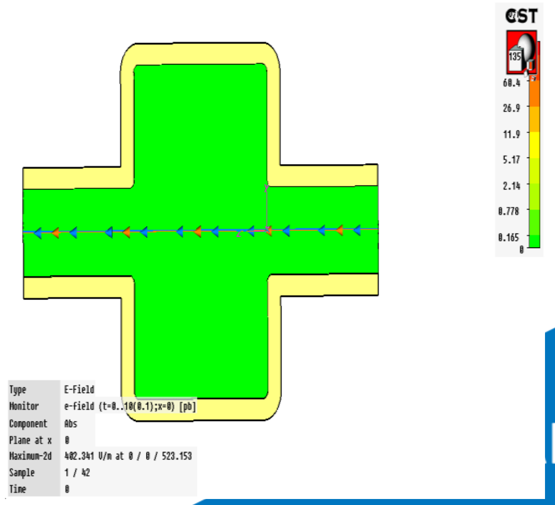
- Vacuum Chamber is much smaller
  - 32x70mm -> 20x20mm
  - Issues for vacuum pumping
  - NEG coating needed
- Impedance and beam stability





$$\frac{Z_{x/y}(y)}{n} = \frac{Z_0 L(1-i)\delta}{2\pi b^3} F_{1x/y}\left(\frac{a}{b}\right)$$





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Wrap Up

- High brightness is the key parameter for future light source and is generated by having emittance beams.
- 4th Generation lights sources are optimised to reach the diffraction limit of brightness.
- They are also challenging to design and build as they are much less forgiving.
- Other types of light sources are beginning to ‘disrupt’ the scene, but there will always be a place for storage ring based light sources.