Synchrotron Light Sources

based on Storage Rings

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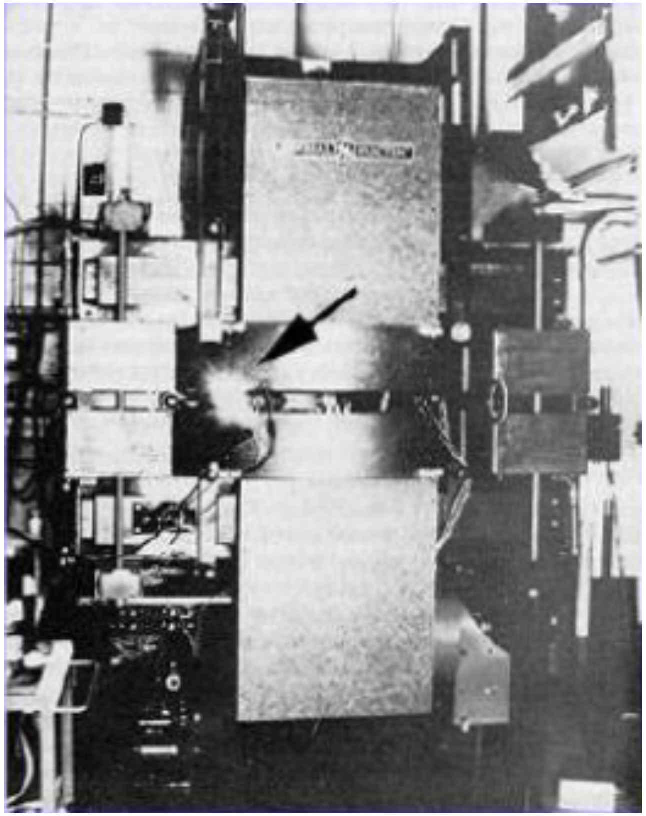
LNLS – Brazilian Synchrotron Light Laboratory

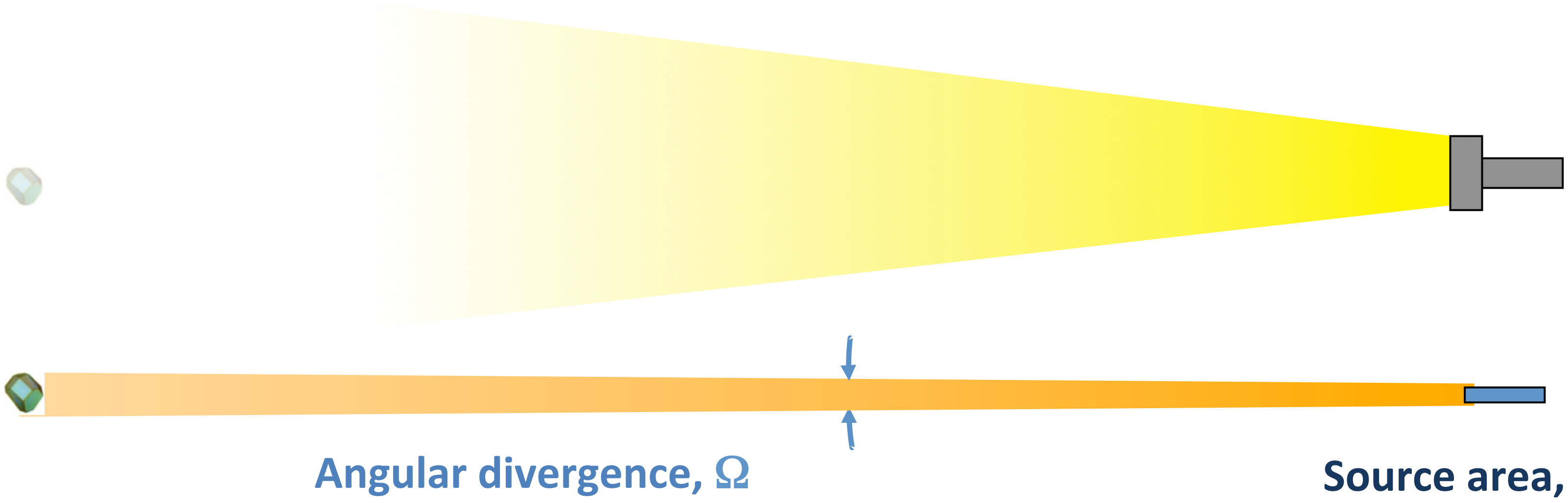
Synchrotron Radiation – Short introduction

- Accelerator-based synchrotron radiation was first observed at General Electric Research Laboratory in USA in 1947 in a type of accelerator known as synchrotron. The visible radiation was generated by electrons that were deflected by a magnetic field in a circular trajectory. Since then, the radiation generated in these machines is called synchrotron radiation.
- We now use the name synchrotron radiation (light) to describe radiation that is emitted from charged particles traveling at relativistic speeds when they change direction, regardless of the accelerating mechanism and shape of the trajectory.
- In a synchrotron, the particles are constantly changing energy, and this is not very attractive for a light source. The advent of storage rings, where the particles have fixed energy, provides a far more attractive source.
- Although synchrotron radiation can cover the entire electromagnetic spectrum, we are interested in radiation in the UV, soft and hard-X ray regimes.



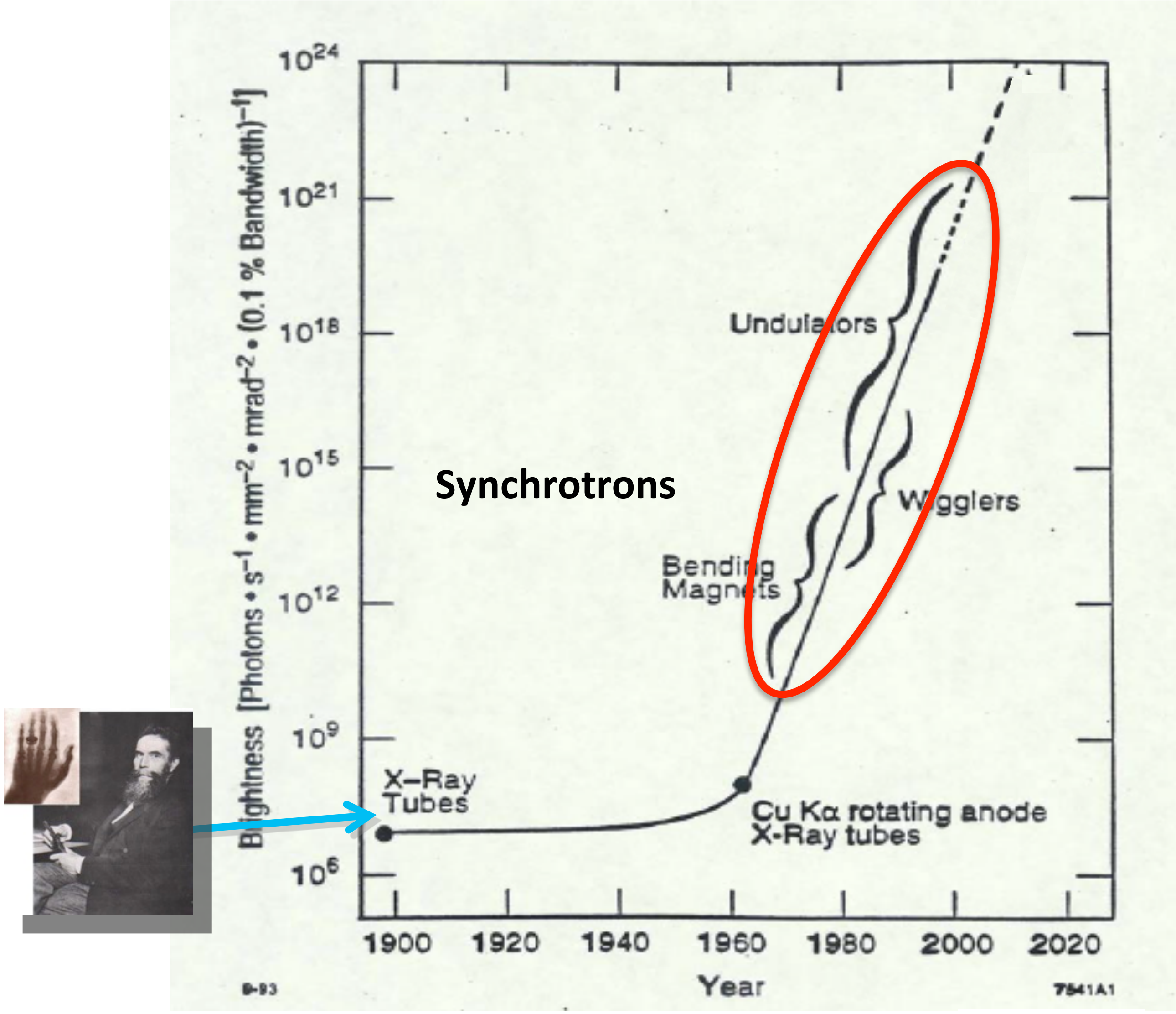
A “good” source of light – high brightness

- Intense, high flux (photons/s).
- Small and collimated.



$$\boxed{Brightness = \frac{Flux}{S \times \Omega}}$$

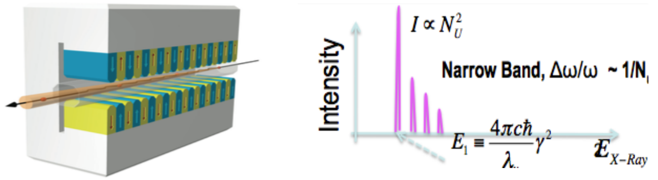
Historical evolution of X-ray brightness



Herman Winick March 26, 2007

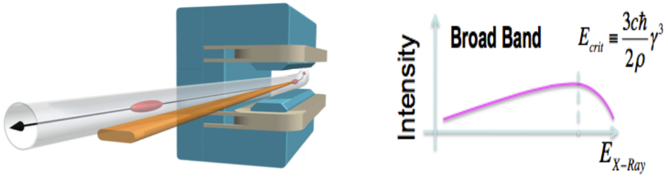
4th Generation Light Source
X-FELs, ERLs, …

4th Generation SR
approaching diffraction-limit with undulators



3rd Generation SR
optimized for brightness, wigglers and undulators

2nd Generation SR
dedicated sources, bending magnets



1st Generation SR
parasitic operation, bending magnets

Storage Ring Light Source – Physics & Engineering in action

Nature of the problem

To provide stability conditions for a ultra-relativistic beam of electrons to be stored for a long period radiating synchrotron light.

To produce an ultra-relativistic electron beam

Injector

- Electron gun
- Linear accelerator
- Synchrotron booster

To store the electron beam for many hours

Storage ring

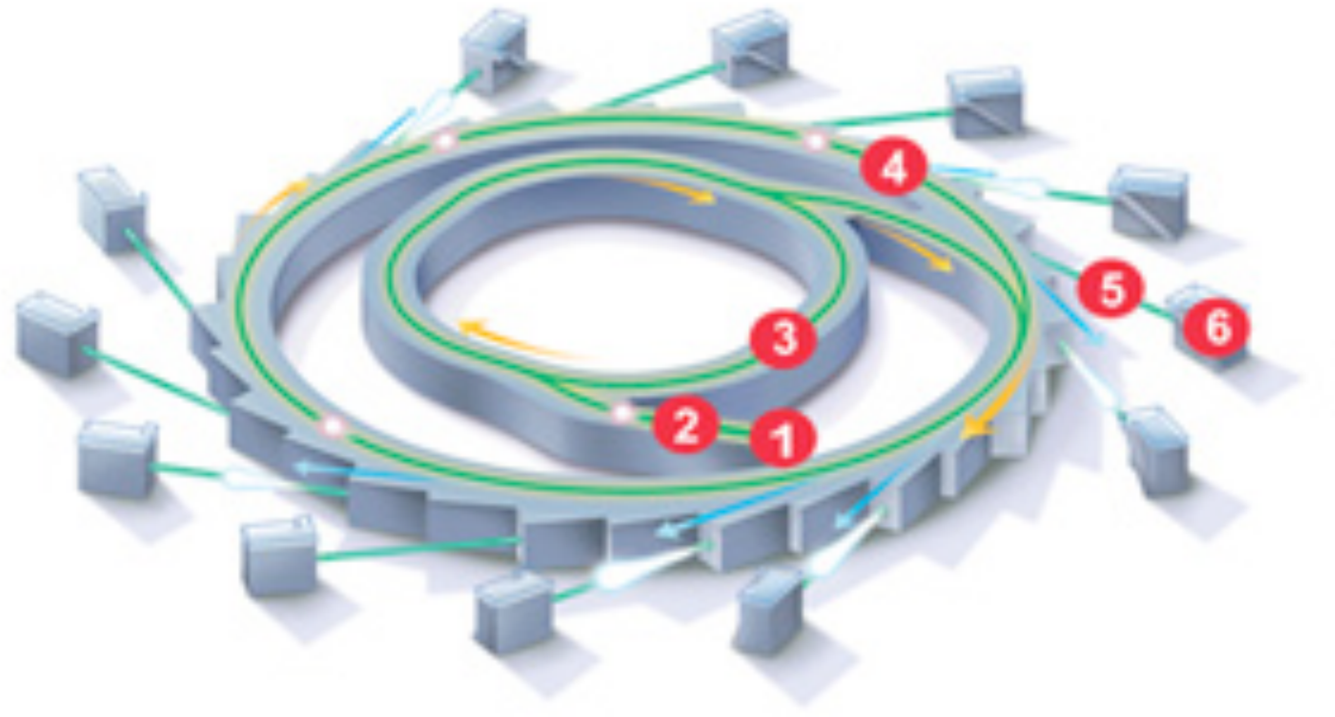
- Magnetic lattice to guide and focus the beam
- Ultra-high vacuum
- RF system
- Beam position stabilization system
- Controls system

To deliver the radiation to the experiments

Beamlines

- Optical elements
- Sample environment
- Detectors
- Data acquisition and control

A Synchrotron Light Source based on Storage Ring

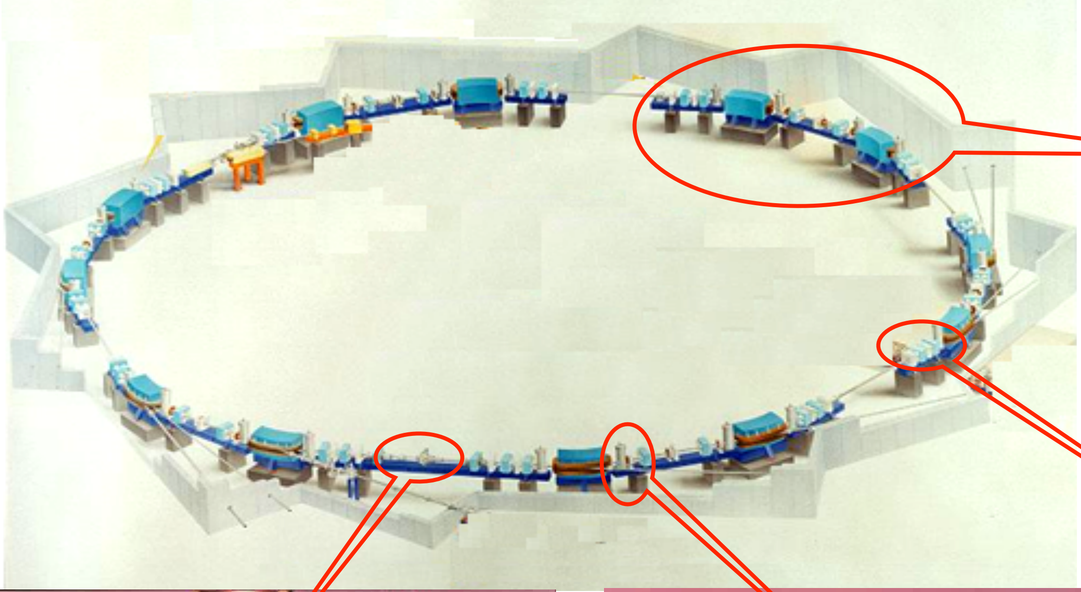


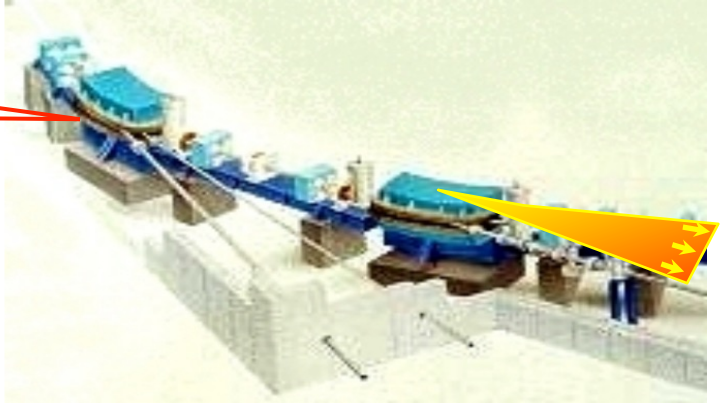
① Electron gun
② Linear Accelerator – Linac
③ Booster synchrotron
④ Storage ring
⑤ Beamlines
⑥ Experiment stations

- Many experimental stations can operate simultaneously with high average power and high repetition rate (100-500 MHz).

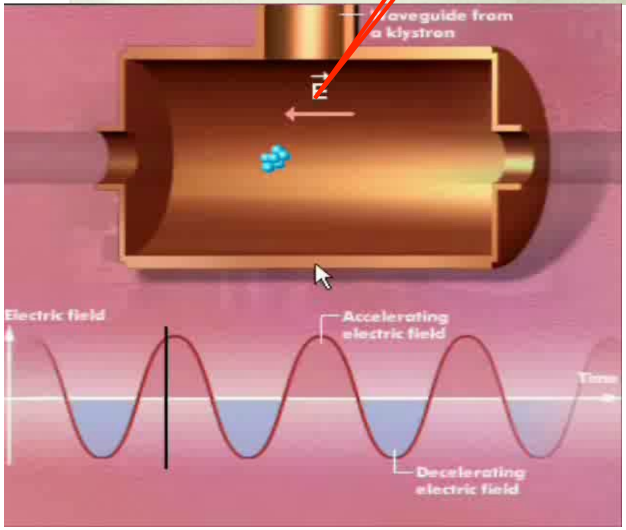
Some Storage Rings Worldwide

The electron storage ring

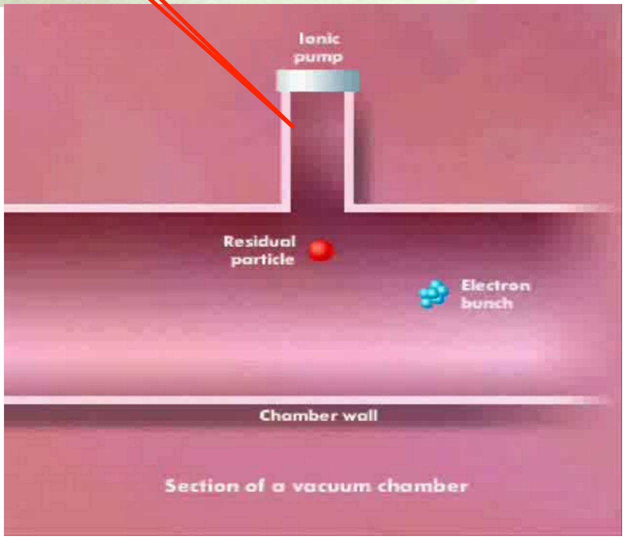




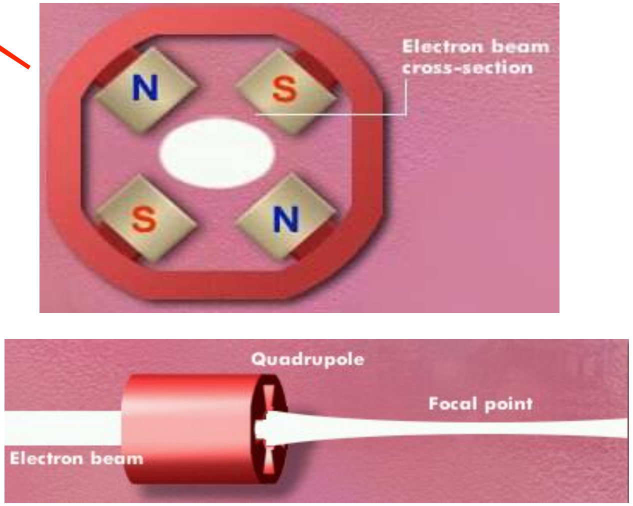
bending magnets



RF cavities



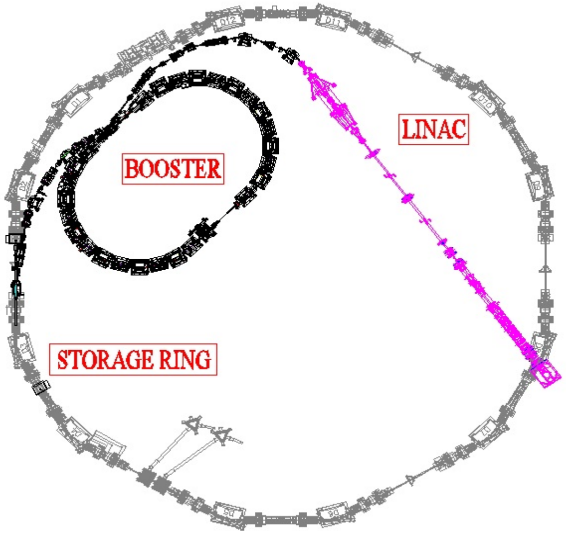
vacuum chambers

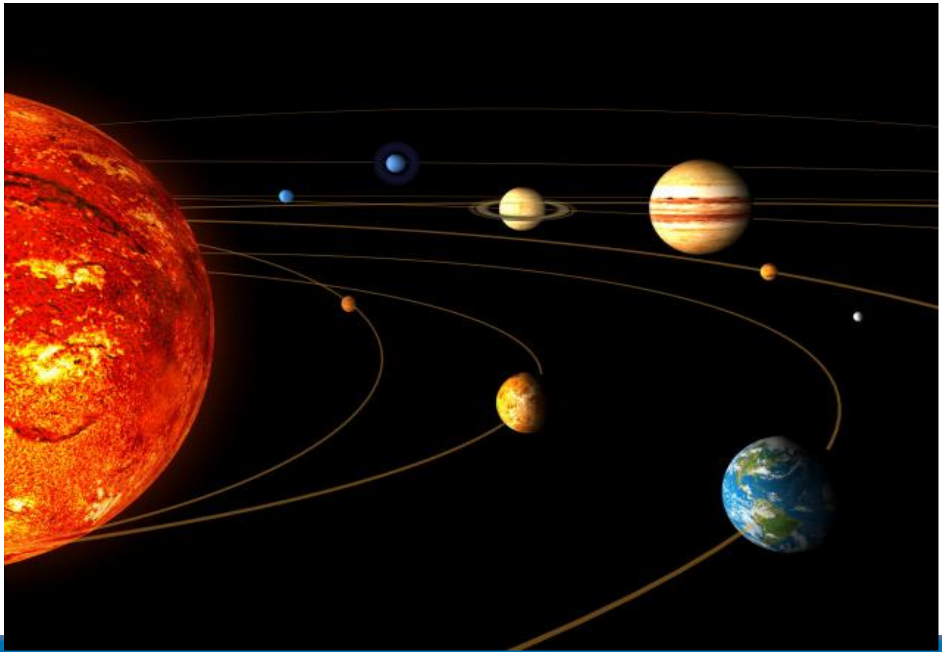


quadrupoles

The challenge of the long term stability

- An the present LNLS storage ring, electrons make 3.2 million turns per second.
- Long-term stability means to provide conditions for stable motion of the electrons for about 10 hours.

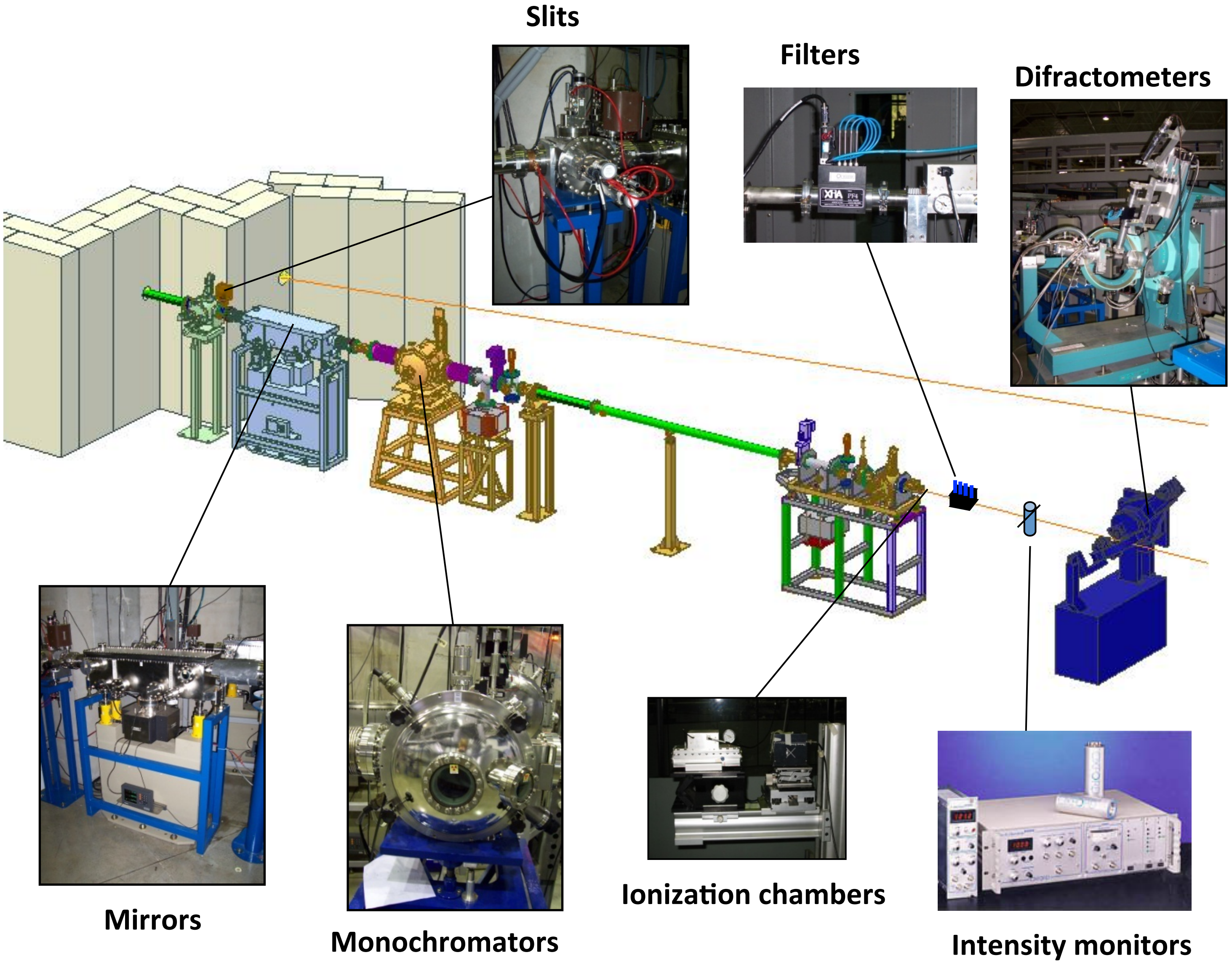




The equivalent time for stability analysis of the movement of the Earth around the Sun would be 115 billion years.

The beamlines

- **Optical elements** – slits, filters, monocromators, mirrors, polarizers
- **Sample** – difractometer, temperature, pressure, magnetic fields
- **Detectors** – gas chambers, CCD cameras, image plates
- **Data acquisition and control**

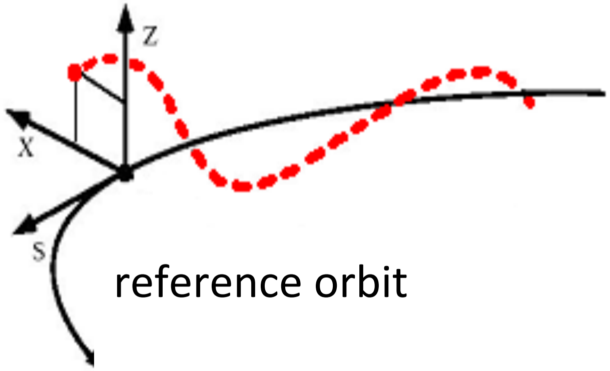


Transverse motion – a quick overview

Electrons are held in a storage ring by magnetic fields disposed along an ideal orbit.

bent by dipoles, focused by quadrupoles, chromatically corrected by sextupoles

Stable electrons oscillate around a closed reference orbit ⟹ betatron oscillations



reference orbit

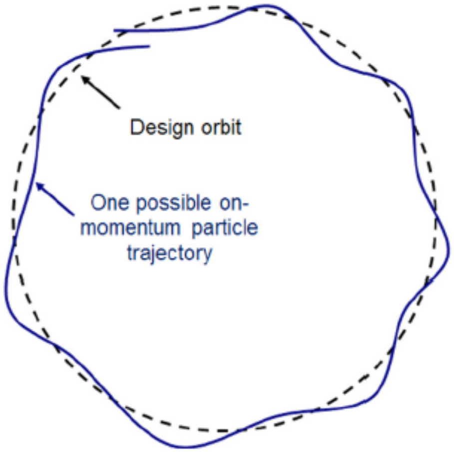
$$x = \boxed{x_\epsilon} + \boxed{x_\beta}$$

off-energy orbit

betatron displacement

BETATRON TUNE

$$\nu = \oint \frac{ds}{\beta(s)}$$



envelope

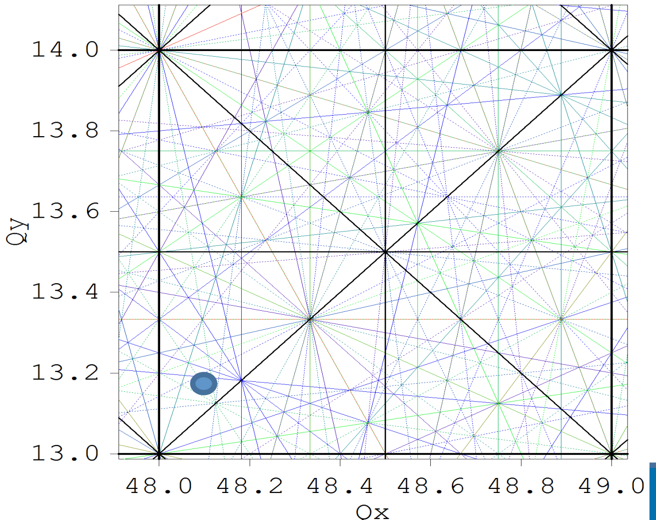
$$x_\beta(s) = \boxed{\sqrt{\epsilon\beta(s)}}\, cos(\phi(s) - \phi_0)$$

$$\phi(s) = 2\pi \int_0^s \frac{ds}{\beta(s)}$$

$$x'_\beta(s) = -\sqrt{\frac{\epsilon}{\beta(s)}}\,[\alpha(s)cos(\phi(s) - \phi_0) + sin(\phi(s) - \phi_0)]$$

The closed reference orbit depends on the energy

⟹ dispersion function
$$x_e(s) = \eta(s)\frac{\epsilon}{E_0}$$



Transverse motion – a quick overview

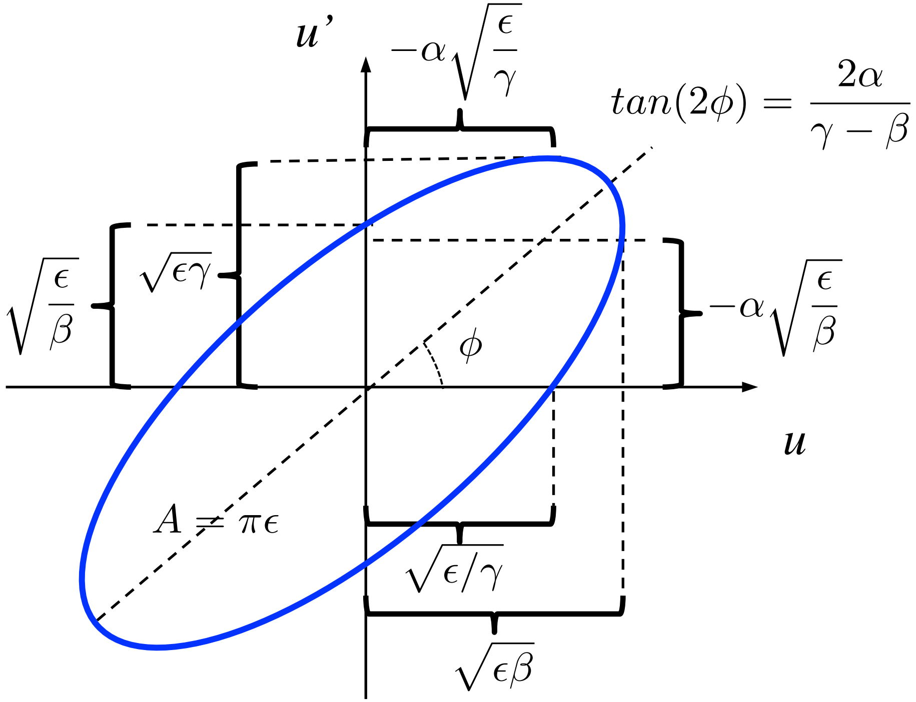
Twiss parameters

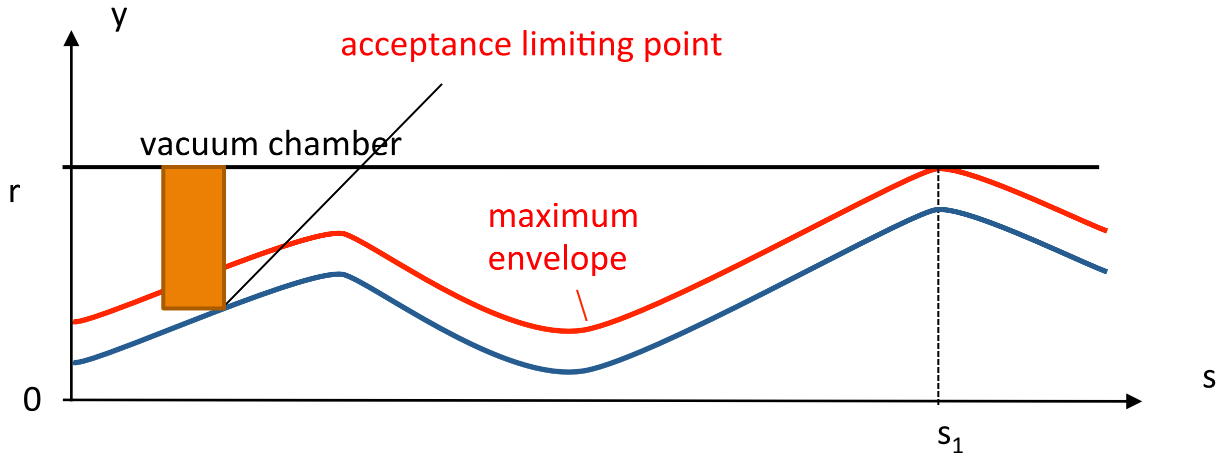
$$\beta, \quad \alpha = -\frac{1}{2}\beta', \quad \gamma = \frac{1+\alpha^2}{\beta}$$

$$u = x, y$$

$$\gamma u^2 + 2\alpha u u' + \beta u'^2 = \epsilon$$

$$E(s) = \sqrt{\epsilon\beta} = trajectory\ envelope$$



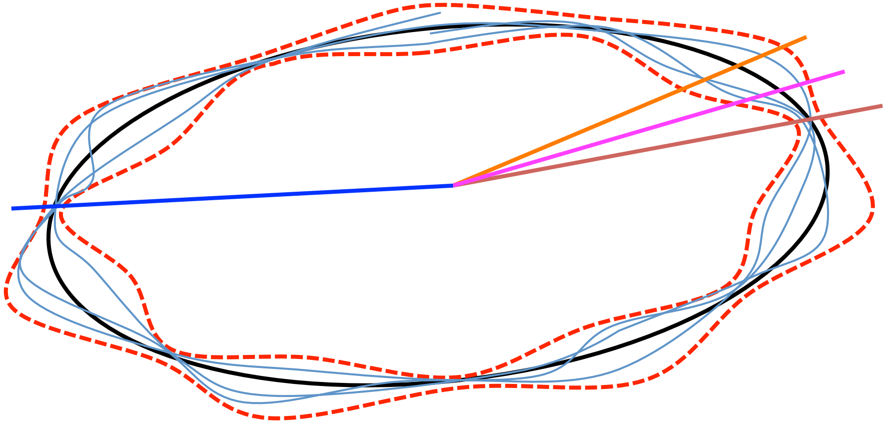


Acceptance

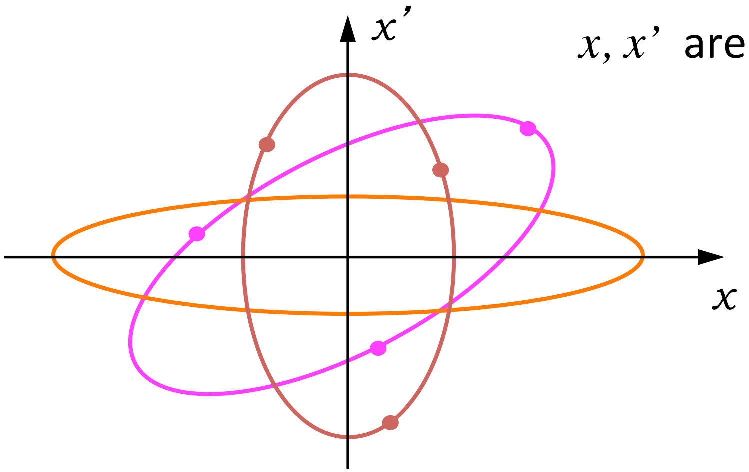
$$A = r^2/\beta(s_1)$$

$$\boxed{A = [r(s)^2/\beta(s)]_{min}}$$

Electron beam emittance and brightness

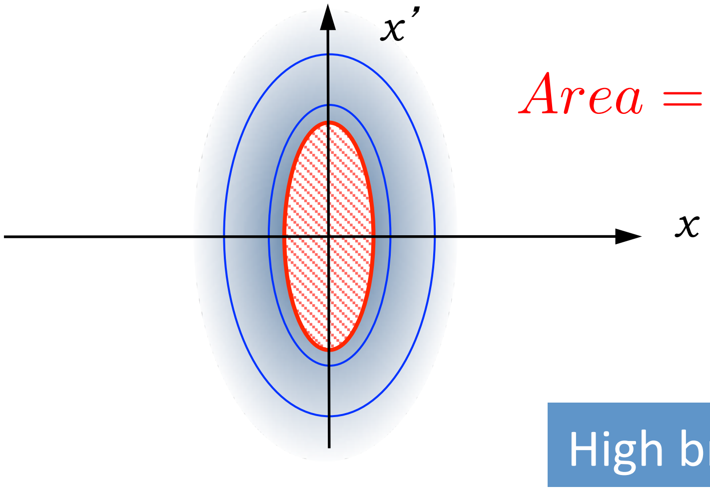


Phase space for a single particle



x, x' are conjugate variables

Phase space for a beam of particles



$$Area = \pi\sigma_x\sigma_{x'} = \pi\epsilon$$

emittance

$$\sigma_x = \sqrt{\beta_x\epsilon_x}$$

$$\sigma'_x = \sqrt{\gamma_x\epsilon_x}$$

$$Brightness = \frac{\dot{N}_{photons}/(d\omega/\omega)}{4\pi^2\underbrace{\sigma_x\sigma_{x'}\sigma_y\sigma_{y'}}_{\epsilon_x\epsilon_y}}$$

High brightness = small beam emittance

Difraction Limited Light Sources

- A point source electron gives a finite photon spot size due to diffraction.

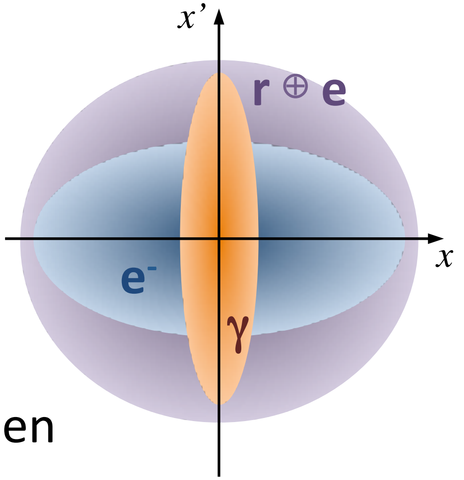
diffraction limited photon
phase-space area

$$\epsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$ for Gaussian beam

$$\epsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{2\pi}$$ for undulator beam

- Transverse emittance of X-ray beam is a convolution of photon emittance and electron beam emittance, $\epsilon_u = \epsilon_{x,y}$.

$$\epsilon_{beam}(\lambda) = \epsilon_r \oplus \epsilon_u = \sqrt{(\sigma_r^2(\lambda) + \sigma_u^2)}\ \sqrt{(\sigma'^2_r(\lambda) + \sigma'^2_u)}$$



- The synchrotron light from undulator is **Diffraction Limited** when

$$\epsilon_{x,y} \leq \epsilon_r(\lambda) = \frac{\lambda}{2\pi}\ (or \frac{\lambda}{4\pi})$$

Diffraction limit for 10 keV
$\varepsilon_{x,y}$ ≈ 20 (or 10) pm.rad

Difraction Limited Light Sources

- For undulator of length L

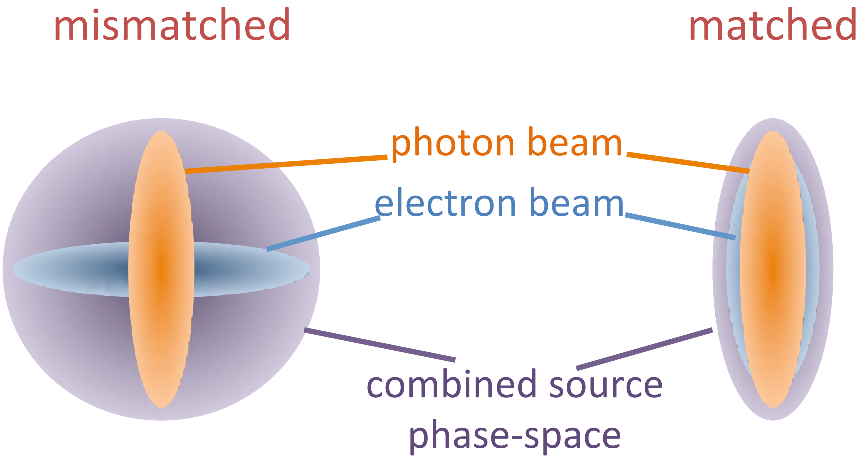
$$\sigma_r(\lambda) \approx \frac{\sqrt{2\lambda L}}{2\pi} \qquad \sigma'_r(\lambda) \approx \sqrt{\frac{\lambda}{2L}}$$

- For the electron beam

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\ \beta_{x,y}} \qquad \sigma'_{x,y} = \sqrt{\epsilon_{x,y}/\beta_{x,y}}$$

- It is important to match the phase-space ellipse orientations to gain maximum photon beam brightness!

$$\frac{\sigma_r(\lambda)}{\sigma\prime_r(\lambda)} = \frac{\sigma_{x,y}}{\sigma\prime_{x,y}} \Rightarrow \boxed{\beta_{x,y}^{opt} = \frac{L}{\pi}}$$



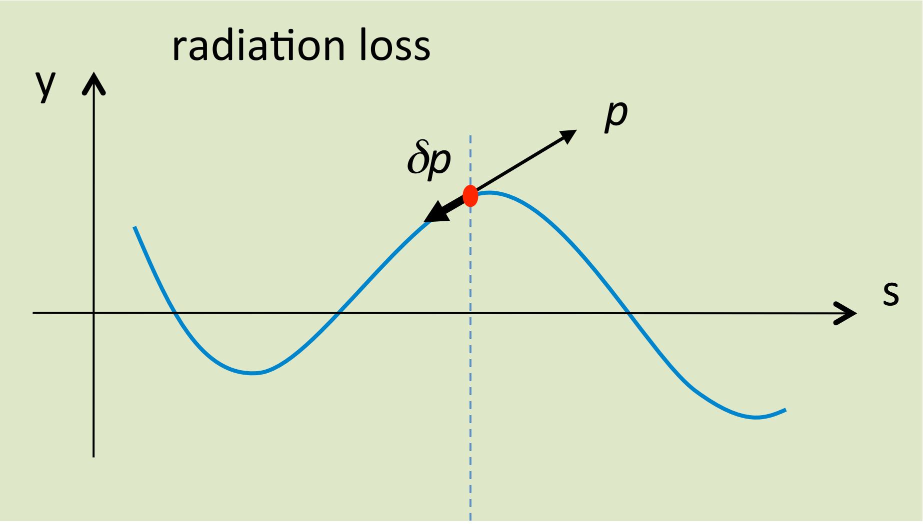
Electron Beam Equilibrium Emittance

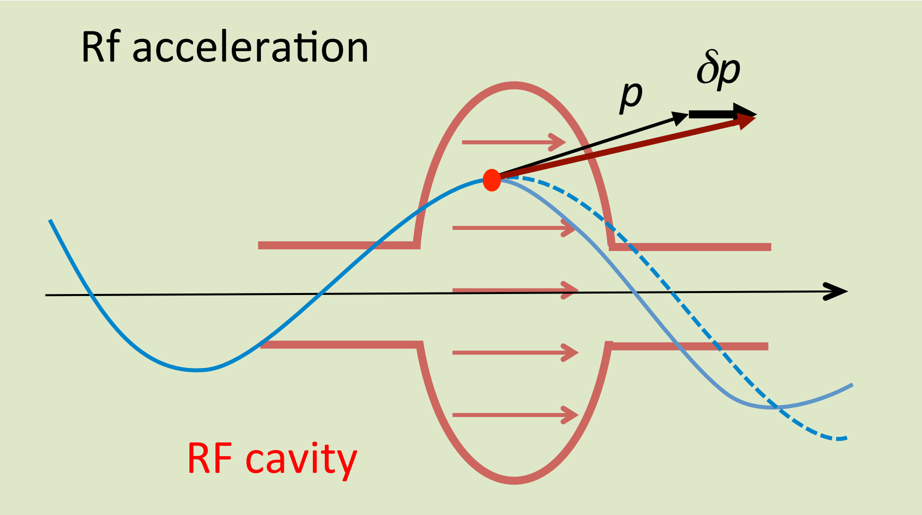
The equilibrium electron beam emittance is a balance between **quantum excitation** from discrete photon emission and **radiation damping** of betatron motion.

Radiation damping

Let's look first at the vertical betatron oscillations. The momentum loss δp from synchrotron radiation is along the direction of the electron momentum p. There is no change in the displacement or the slope of the trajectory.

The RF accelerating force is, on average, parallel to the desing orbit, so momentum is restored only to the longitudinal motion. The slope of the trajectory decreases and the betatron oscillations are damped.





Electron Beam Equilibrium Emittance

Quantum excitation

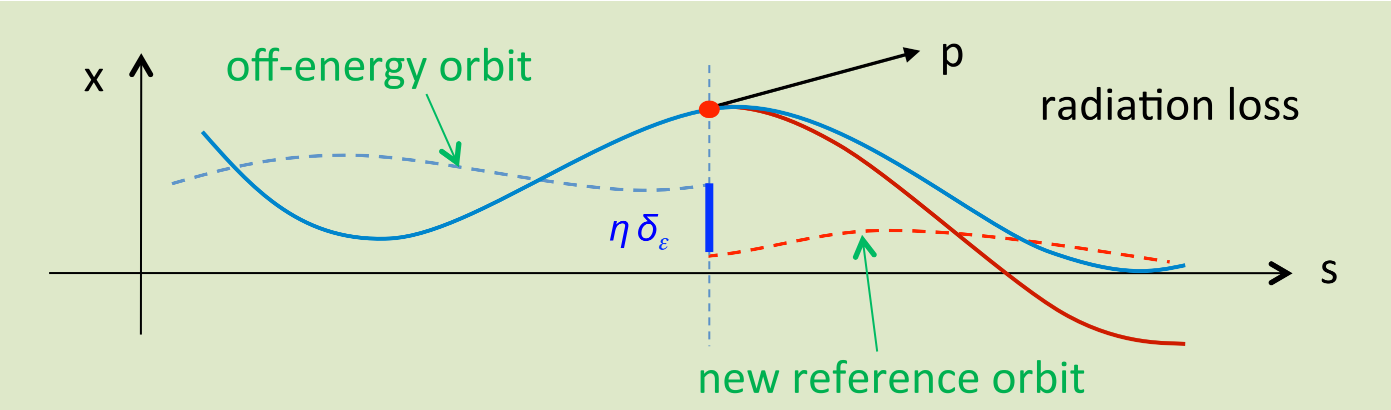
Now let’s turn to the radiation effects on the horizontal betatron oscillations. A new element arises, as compared to the vertical case because the horizontal position is composed of 2 parts:

$$x = \underbrace{x_\epsilon}_{\text{off-energy orbit}} + \underbrace{x_\beta}_{\text{betatron displacement}}$$

When a photon is emitted there is a sudden change in the energy of the electron but the electron position x in space is not changed. When the energy of an electron changes by δ_ϵ in a region with dispersion η, the off-energy orbit change by $\delta x_\epsilon = \eta\delta_\epsilon$. So there must be a compensation change in x_β such that

$$\delta x = \delta x_\beta + \delta x_\varepsilon = 0 \quad \Rightarrow \quad \delta x_\beta = -\delta x_\epsilon = -\eta\delta_e$$

The electron starts oscillating with respect to a new reference orbit.



Electron Beam Equilibrium Emittance

- In the horizontal plane there is the same damping contribution from RF acceleration as in the vertical plane and equilibrium emittance ε_x is determined by the balance between radiation damping and quantum excitation.

- In the vertical plane, if the design orbit lies strictly in the plane of the orbit, with no vertical deflections, there are no first-order effects from quantum excitation. However, perturbations from construction imperfections in a real ring introduces coupling between horizontal and vertical oscillations producing vertical emittance. The coupling is described by the coupling coefficient κ and can be controlled by skew quadrupoles.

$$\kappa = \frac{\epsilon_y}{\epsilon_x}$$

$$\epsilon_x = \frac{1}{1+\kappa}\epsilon_0 \qquad \epsilon_y = \frac{\kappa}{1+\kappa}\epsilon_0$$

$$\epsilon_x + \epsilon_y = \epsilon_0$$

natural emittance

Horizontal Emittance and Machine Lattice

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint \mathcal{H}(s)/\rho(s)^3 ds}{\oint 1/\rho(s)^2 ds}$$

$\gamma = E/E_0$

emittance

$C_q = 3.84 \times 10^{-13} m$

damping partition number

curvature radius

dispersion's betatron amplitude

$$\mathcal{H} = \frac{\eta^2 + (\alpha\eta + \beta\eta')^2}{\beta}$$

η: dispersion function

β, α: Twiss functions

- Emittance depends on the optics at places where the orbit has a finite curvature:
  - Dipoles for the bare machine (without Insertion Devices)

- For constant ρ lattice

$$\boxed{\epsilon = C_q \frac{F\gamma^2\theta^3}{J_x}}$$

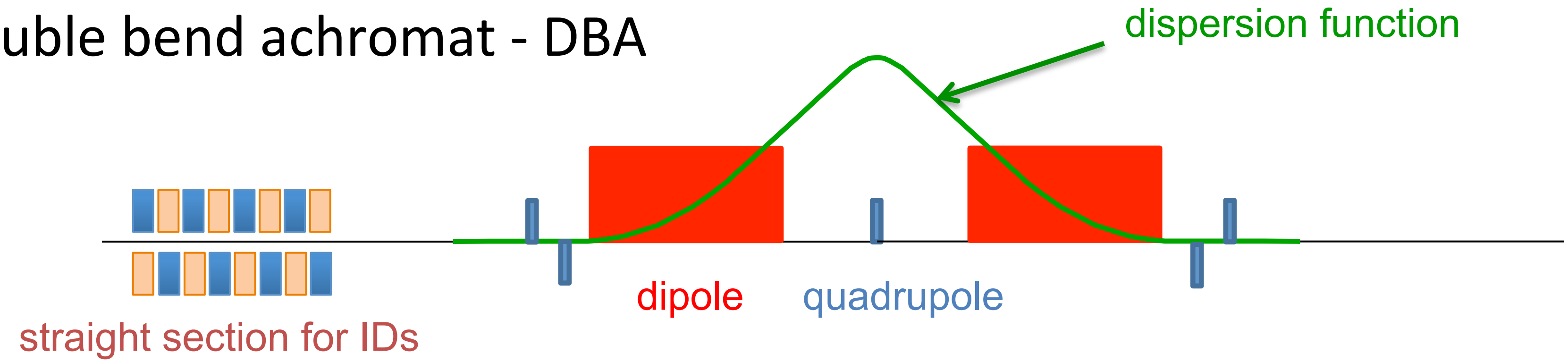
deflection per dipole

Theoretical minimum

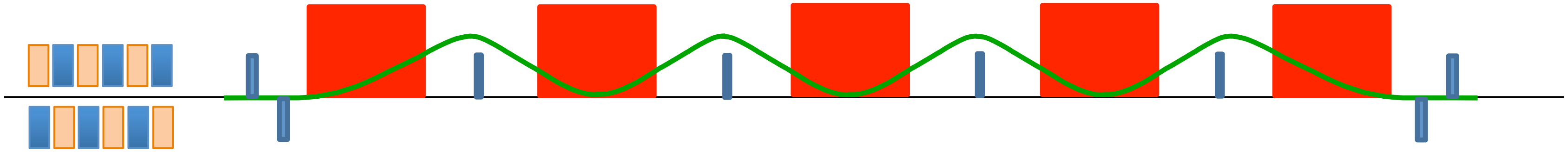
$$F_{min,achrom} = \frac{1}{4\sqrt{15}} \qquad F_{min} = \frac{1}{12\sqrt{15}}$$

Horizontal Emittance and Machine Lattice – MBA

Double bend achromat - DBA

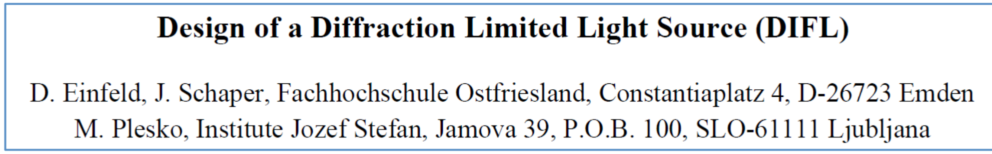


Multiple bend achromat – MBA
many small deflection dipoles!

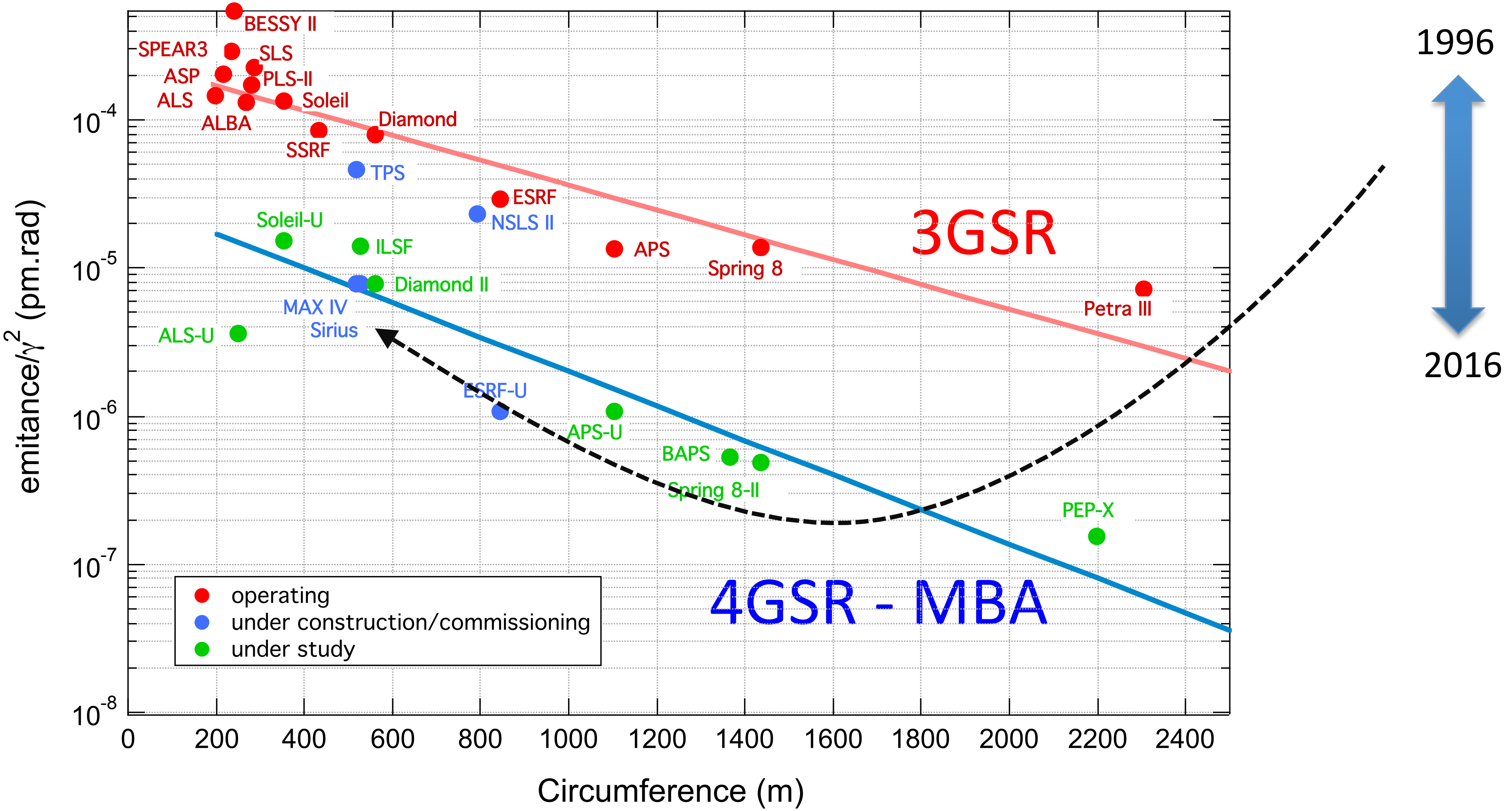


4th Generation Storage Rings (4GSR) are based on MBA lattices
5BA, 7BA, 9BA

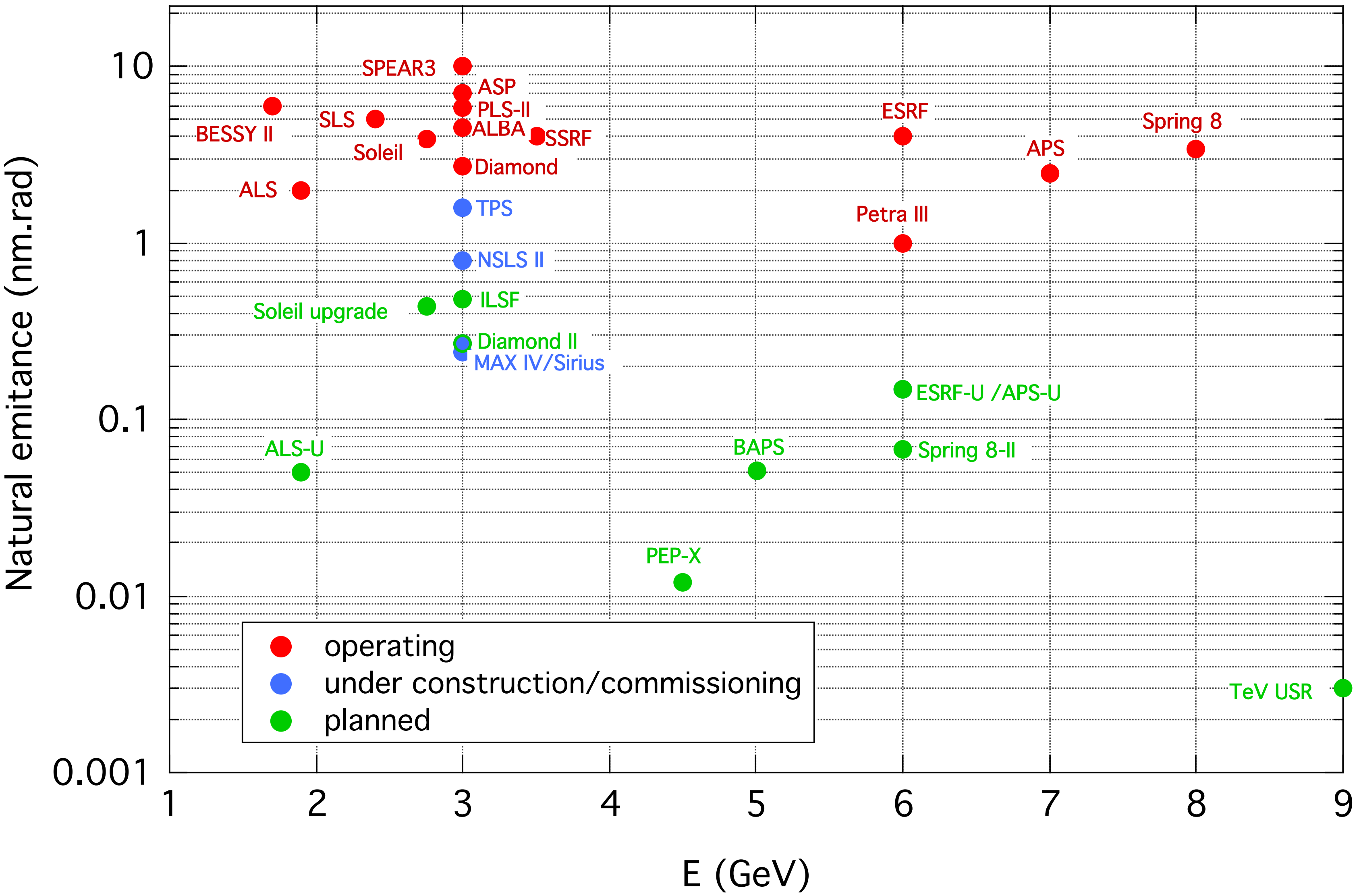
The Storage Ring Generational Change


Design of a Diffraction Limited Light Source (DIFL)

D. Einfeld, J. Schaper, Fachhochschule Ostfriesland, Constantiaplatz 4, D-26723 Emden
M. Plesko, Institute Jozef Stefan, Jamova 39, P.O.B. 100, SLO-61111 Ljubljana



Emittance vs energy



New storage rings and some upgrade plans

Name	Energy [GeV]	Circumf. [m]	Emittance* [pm]	Lattice	Status
Petra-III	6.0	2304	4400 → 1000		operating
NSLS-II	3.0	792	2100 → 550	30-DBA	operating
TPS	3.0	518	1600	24-DBA	operating
MAX-IV	3.0	528	330 → 200	20-7BA	commissioning
Sirius	3.0	518	250 → 150	20-5BA	construction
ESRF U	6.0	844	147	32-7BA	started
APS U	6.0	1104	65	40-7BA	study
Spring8-II	6.0	1436	68	48-5BA	study
ALS U	2.0	200	100	12-9BA	study
Diamond U	3.0	562	275	24-DDBA	started

* (bare lattice) → (with IDs/damping wigglers)

What we can do better (besides increasing M)

- Increase damping partition number J_x by adding transverse field gradient in dipoles.

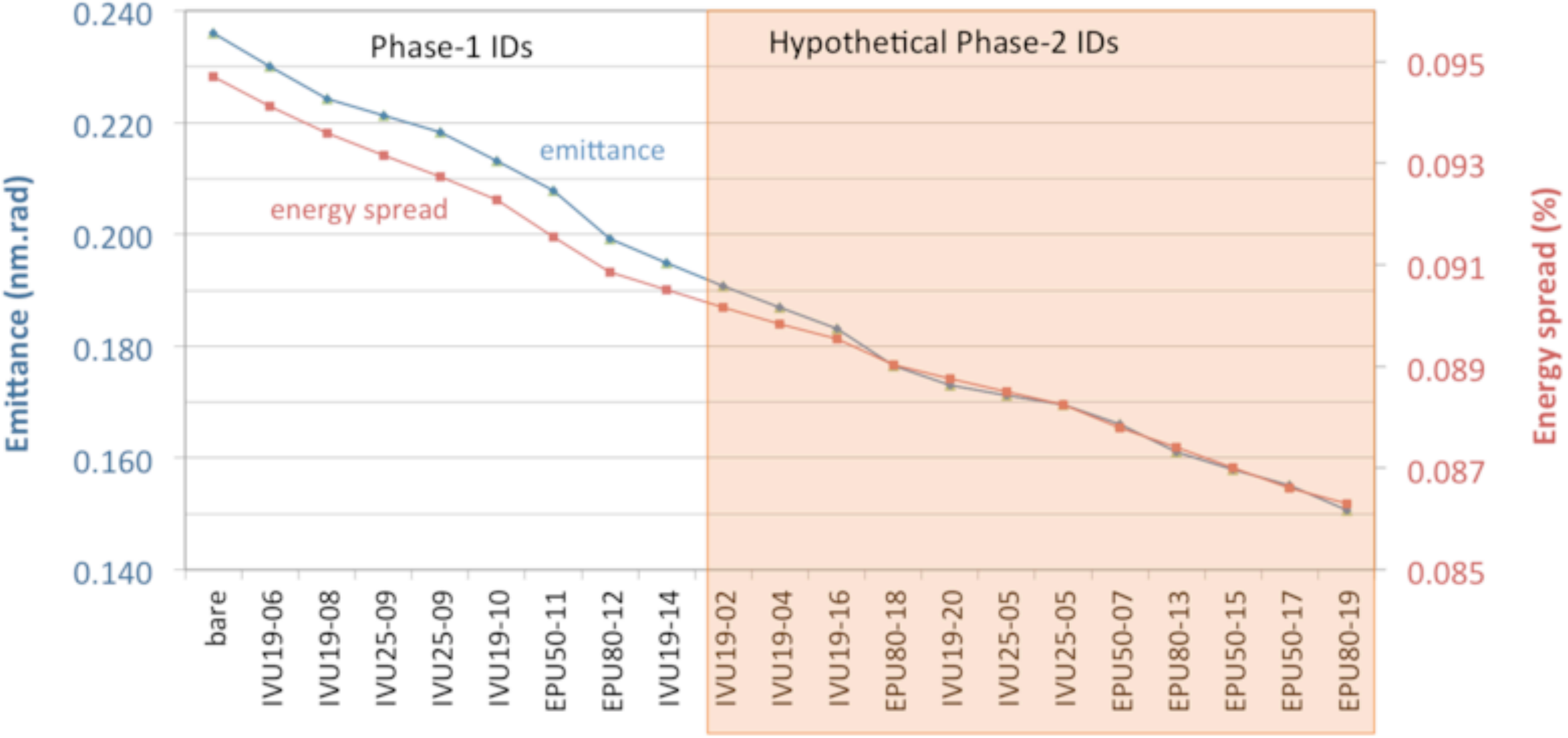
$$J_x = 1 - \frac{\oint (1-2n)\eta |h(s)^3| ds}{\oint h(s)^2 ds}$$

- Longitudinal dipole gradient

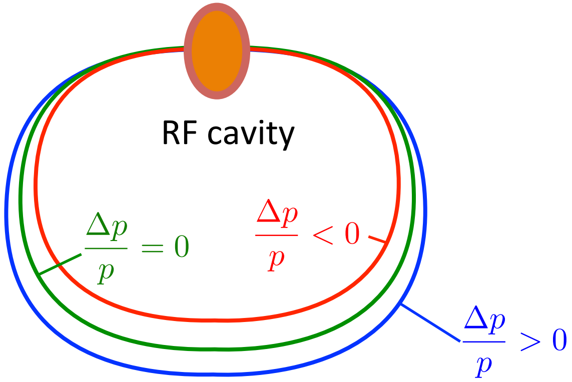
$$\epsilon_x \propto \oint \mathcal{H}(s)\; h(s)^3 ds$$

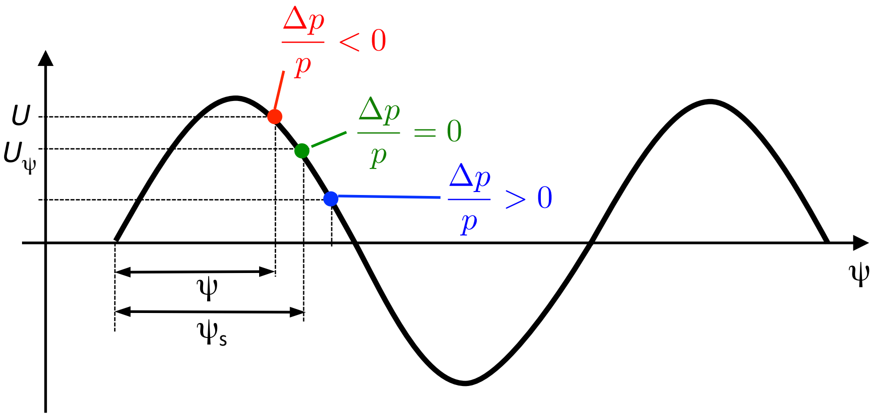
  - Curvature function $h(s) = 1/\rho(s)$
  - To keep product small: compensate variation in $\mathcal{H}(s)$ with variation in $h(s)$
  - Radiate more (high curvature) where $\mathcal{H}(s)$ is small.
- Achromatic cells and low field dipoles to enhance emittance reduction with Insertion Devices.
- Different dipole lengths, shorter dipoles at cell ends, where $\eta = \eta' = 0$.
- Damping wigglers (NSLS-II, Petra-III).
- Anti-bends (SLS).

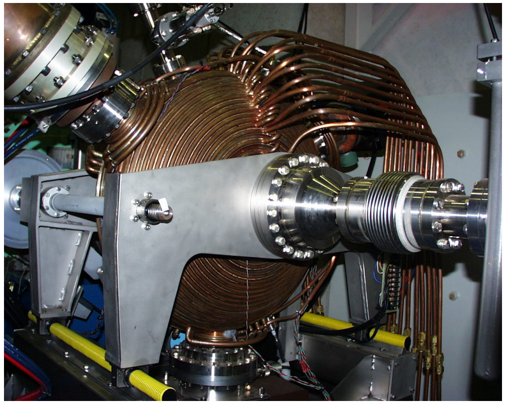
Effect of insertion devices on Sirius emittance



The longitudinal plane – phase stability







476 MHz RF cavity at LNLS

- Particles circulating in a ring gain energy from RF cavity (microwave fields).
- Particles travel at constant speed $v \approx c$, but path length along orbit can vary.
- Every time the particle with nominal energy travels through the cavity we want $U_{RF} = U_{radiated}$. ⇒ synchronicity condition for the synchronous particle.
- To meet this condition, *Circumference = h λ_{RF}*, *h* is an integer called the harmonic number.
- For particles with different energy: Principle of Phase Focusing [Veksler (1945), McMillan (1946)]

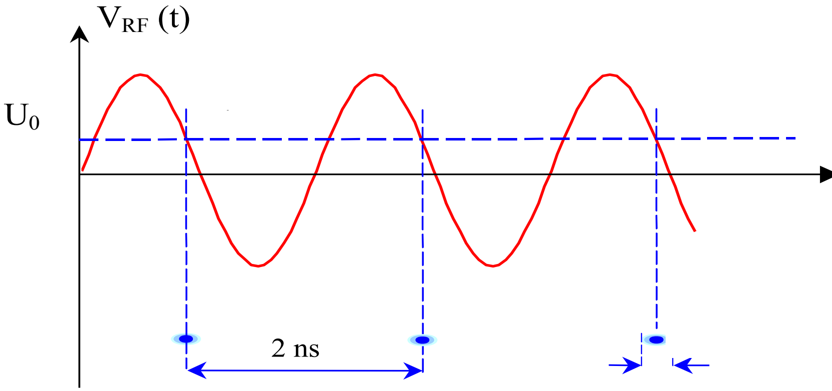
Synchronous particle	ψ_s	
$\Delta p/p<0$ arrive earlier	$\psi < \psi_s$	(gain more from RF)
$\Delta p/p>0$ arrive later	$\psi > \psi_s$	(gain less from RF)

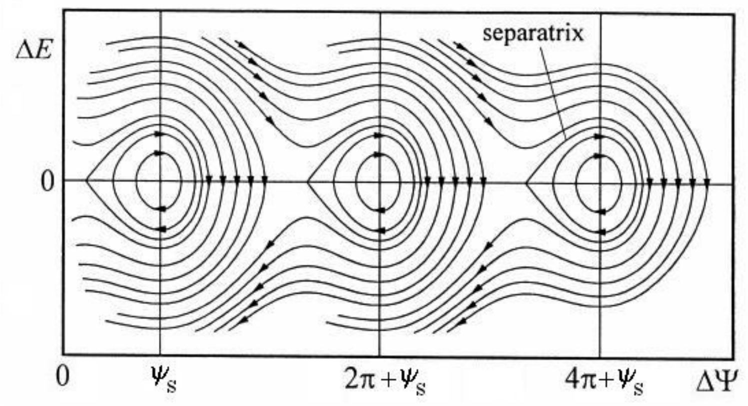
- Electrons are bunched around synchronous particle and perform synchrotron oscillations. The restoring force is given by the slope of the RF voltage.

Figura: Klaus Wille, The Physics of Particle Accelerators, Oxford 2000

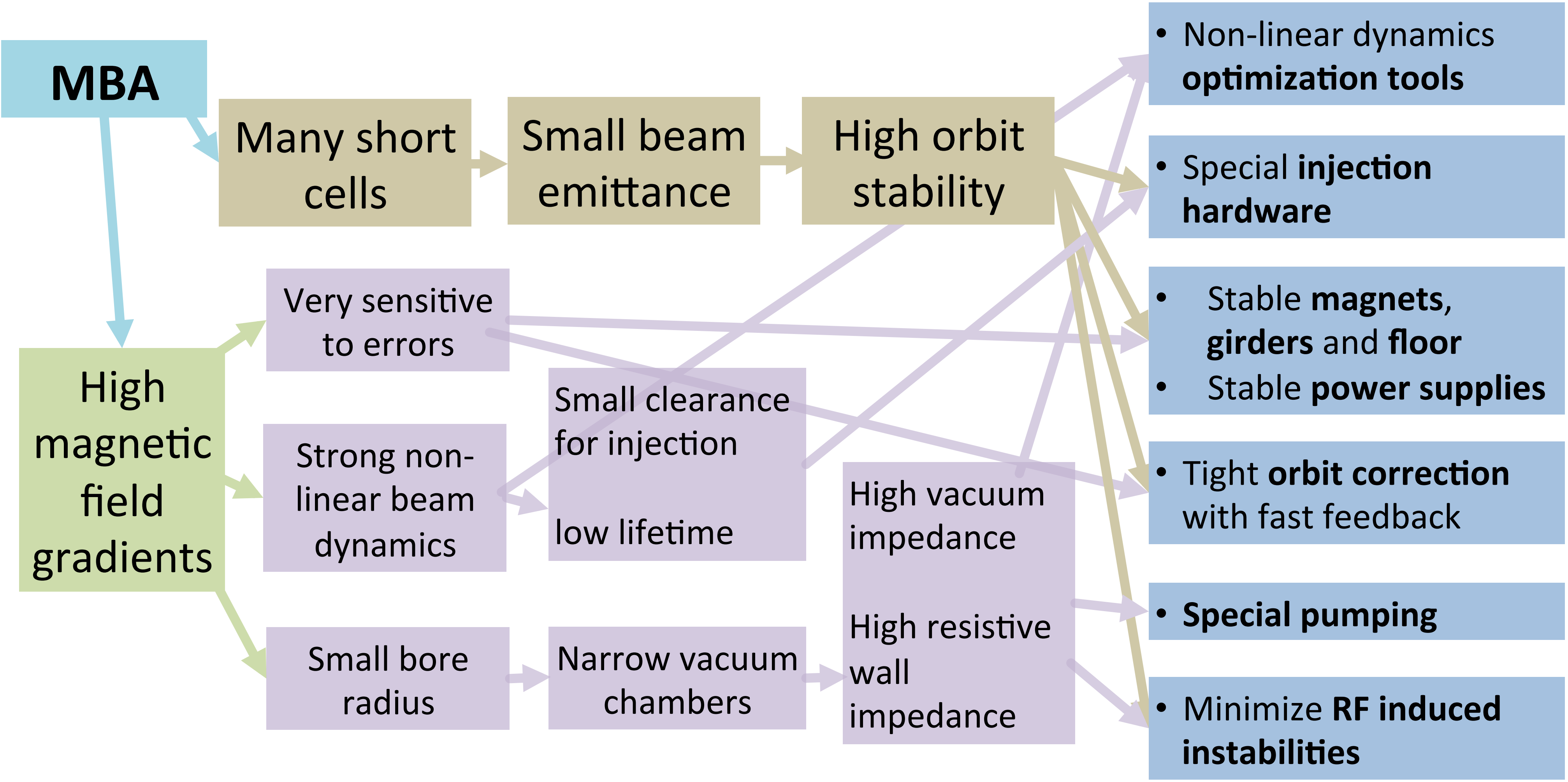
The longitudinal plane – phase stability

- Storage rings have many rf-buckets that can be filled with particles (or not).
- Different filling patterns can be provided, for example, all bunches filled, single-bunch, few-bunches, hybrid with a bunch in the middle of a gap and all other bunches filled.
- The current per bunch will depend on the filling pattern and can be limited by beam instability issues.
- The bunch length is also an important parameter. It determines the light pulse length and is directly related to the electron density in the bunch.
- The electron density affects the beam lifetime and IBS.
- The bunch length also determines the frequencies generated by the beam. Sort bunches can generate very high frequencies.
- It is generally necessary to lengthen the bunch in low emittance machines by means of Higher Harmonic Cavities, e.g., 3rd HC.





The Multi Bend Achromat Challenges



MBA

Many short cells

Small beam emittance

High orbit stability

High magnetic field gradients

Very sensitive to errors

Strong non-linear beam dynamics

Small clearance for injection

low lifetime

Small bore radius

Narrow vacuum chambers

High vacuum impedance

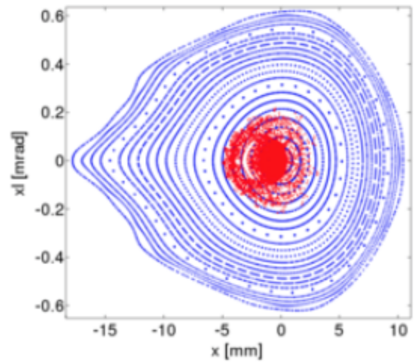
High resistive wall impedance

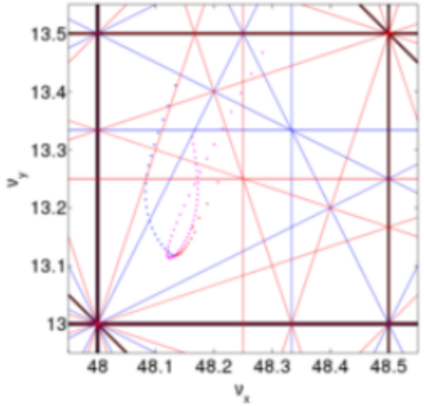
- Non-linear dynamics **optimization tools**
- Special **injection hardware**
- Stable **magnets**, **girders** and **floor**
- Stable **power supplies**
- Tight **orbit correction** with fast feedback
- **Special pumping**
- Minimize **RF induced instabilities**

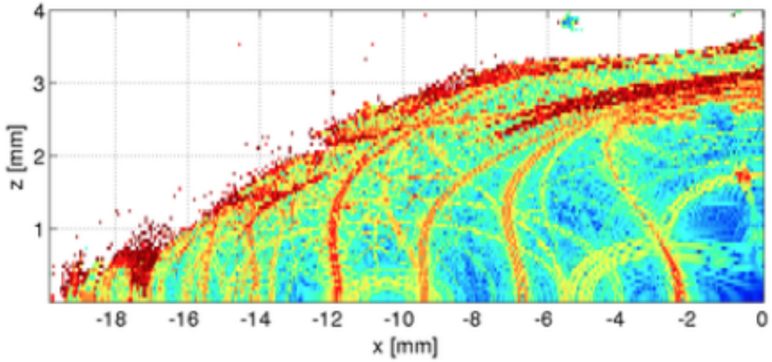
Recent advances in accelerator technology are helping to overcome the challenges, but many issues are still open and still need R&D.

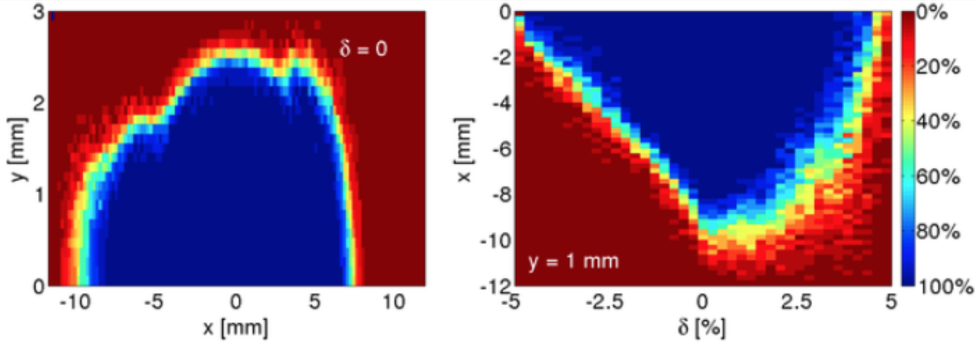
Beam dynamics optimization

- Software tools available for optimization
  - MAD8, MAD-X
  - OPA
  - Accelerator Toolbox
  - Elegant
  - Tracy
  - …
- Simulation and optimization methods
  - Symplectic tracking
  - Frequency map analysis
  - MOGA: multi-objective genetic algorithm
  - Trial & error (based on experience)
  - …



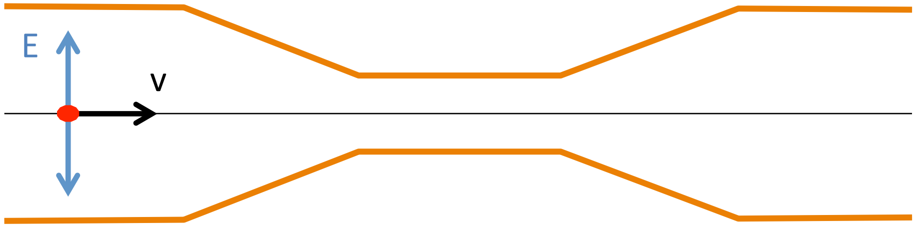


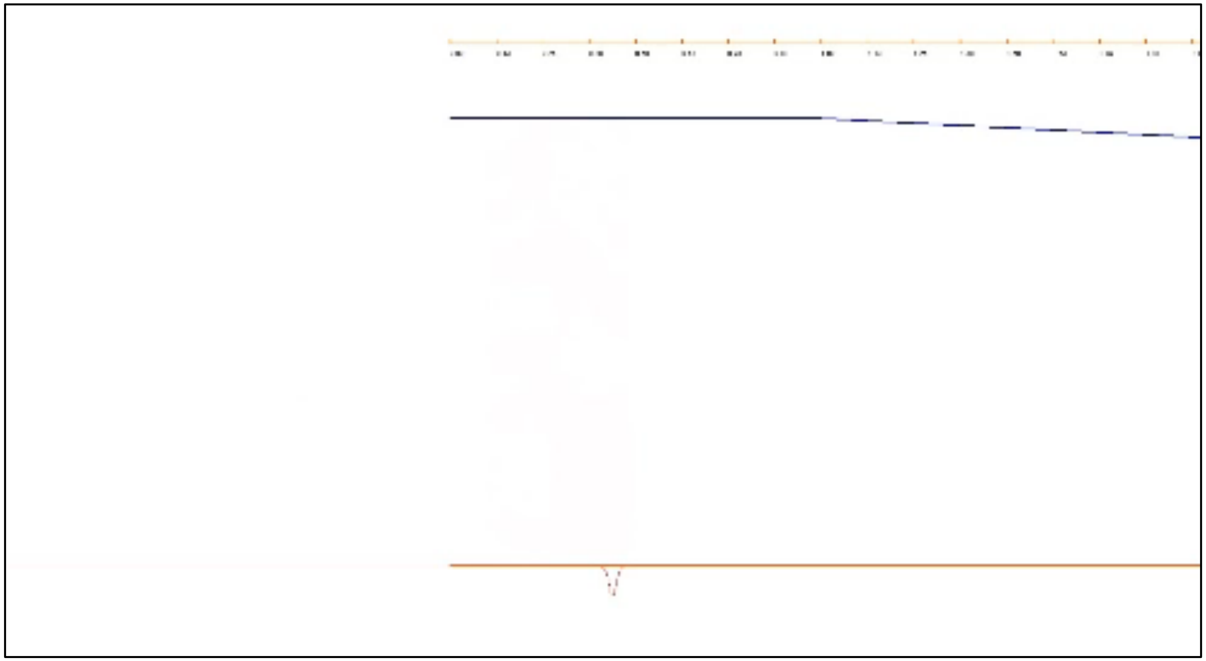




Impedance and collective instabilities example

- Electromagnetic simulation showing the longitudinal electric field of an electron bunch going through a taper section with ECHOz2.





Courtesy Fernando Sá, LNLS

Beam stability challenge

- Example: beam size for Sirius

ε_x = 0.15 nm.rad (with Phase 2 IDs) coupling = 1%

rms beam size (μm)			
	High β SS	Low β SS	superbend
Horizontal	52	15	7.3
Vertical	3	1.5	2.8

Stability Goal

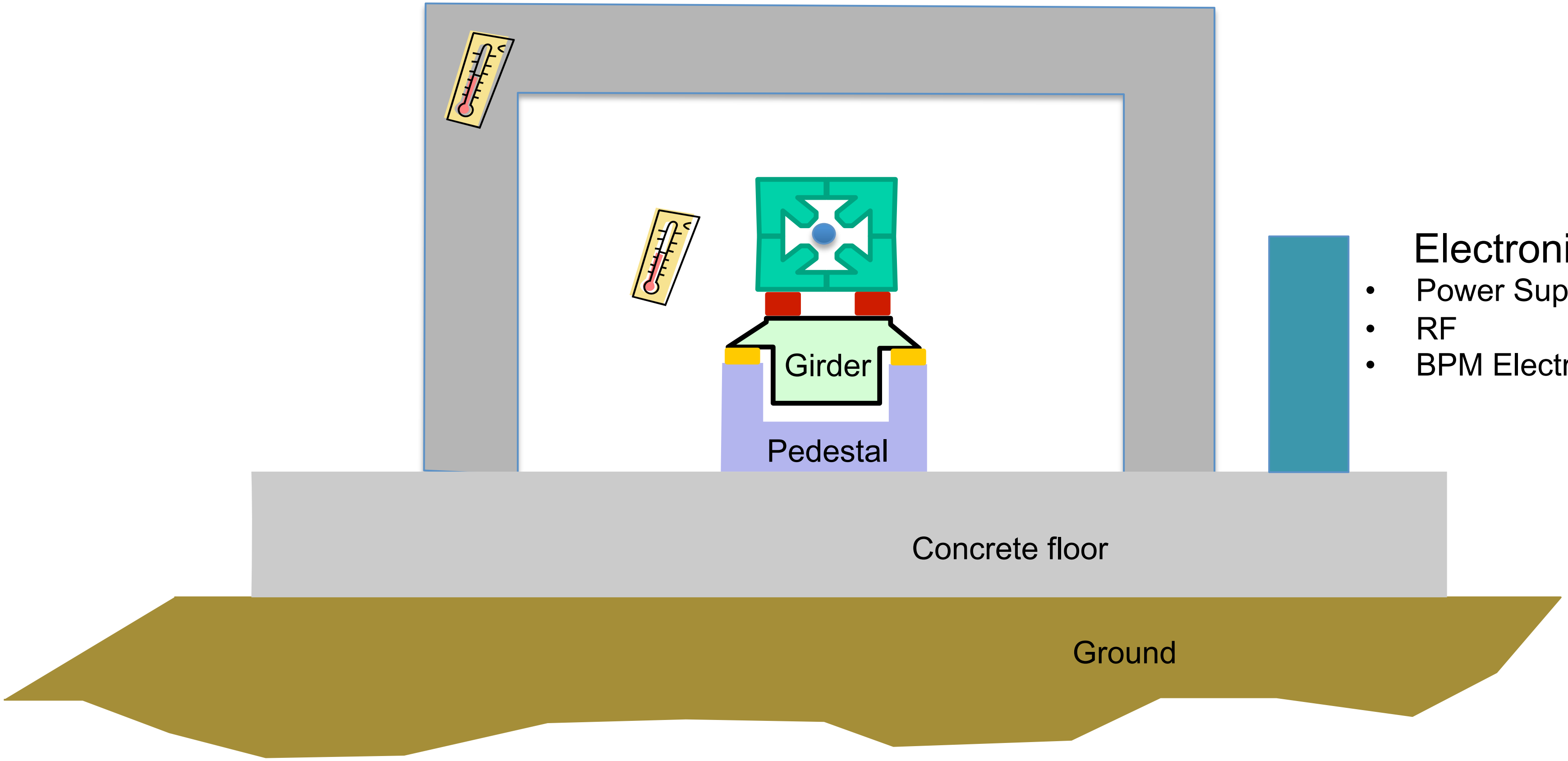
Beam motion $\lesssim$ **5%** of beam size at source points.

$\Delta x \lesssim 0.4\ \mu\text{m}$ $\Delta y \lesssim 0.1\ \mu\text{m}$

Beam stability challenge

Sources of beam motion	**Measures that can be taken**
Long term stability (months) - Ground motion, seasonal effects, etc	- Care with building foundations, floor
Medium term stability (hours) - - Tunnel and hall temperature variations, movement of the vacuum chambers (especially in decaying current mode)	Reference BPMs to beamlines - SR tunnel temperature stabilization - Experimental hall temperature stabilization - Top-up, care with BPM support
Short term stability (min to ms) - - Mechanical vibrations (cranes, compressors, traffic), ID changes, booster operation	Reference e^- beam to BPMs - Slow orbit feedback - Fast orbit feedback - feedforward
Very short term stability - High frequency ground/mechanical vibrations, power supply ripple, transient during top-up injection	- Feedback is not effective, source of perturbation must be limited

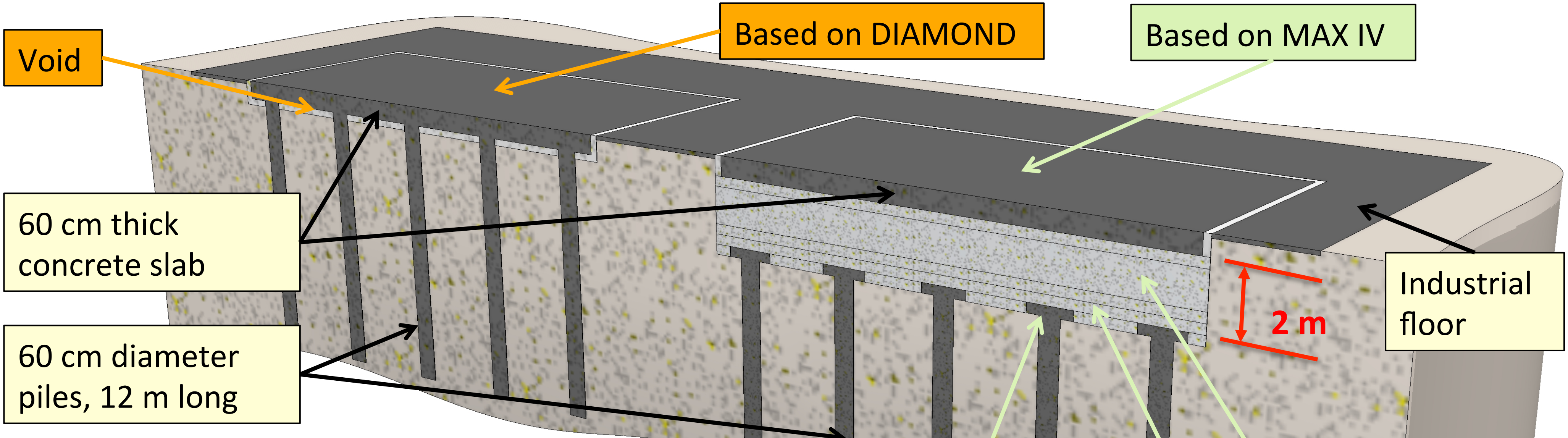
It's all about stability !



Electronics

- Power Supplies
- RF
- BPM Electronics

Prototype Slabs for Sirius (13.5m x 6.5m each)



Void

Based on DIAMOND

Based on MAX IV

60 cm thick concrete slab

60 cm diameter piles, 12 m long

2 m

Industrial floor

Soil-cement

Geogrid layer

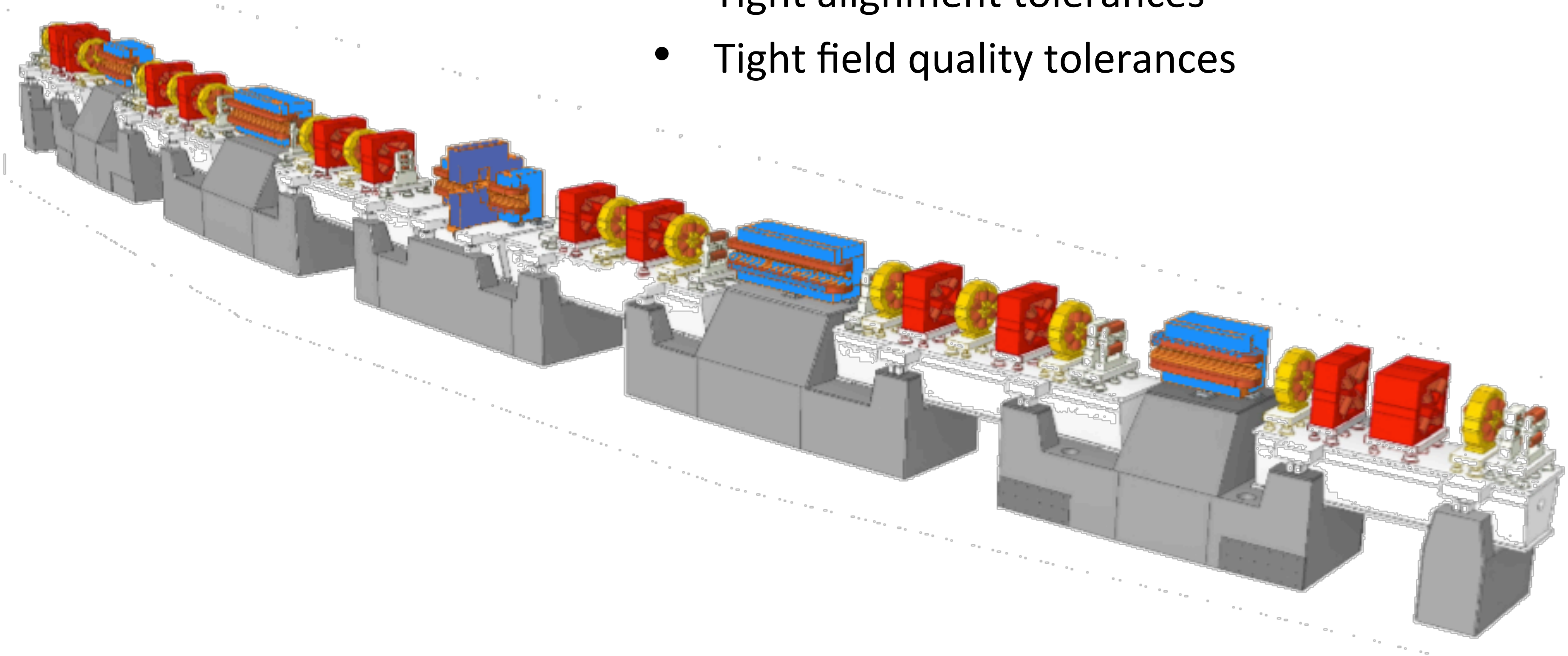
1.5m x 1.5m pile head

Chosen after analysis of different labs: *Petra III, ESRF extension, Alba, NSLS II…*

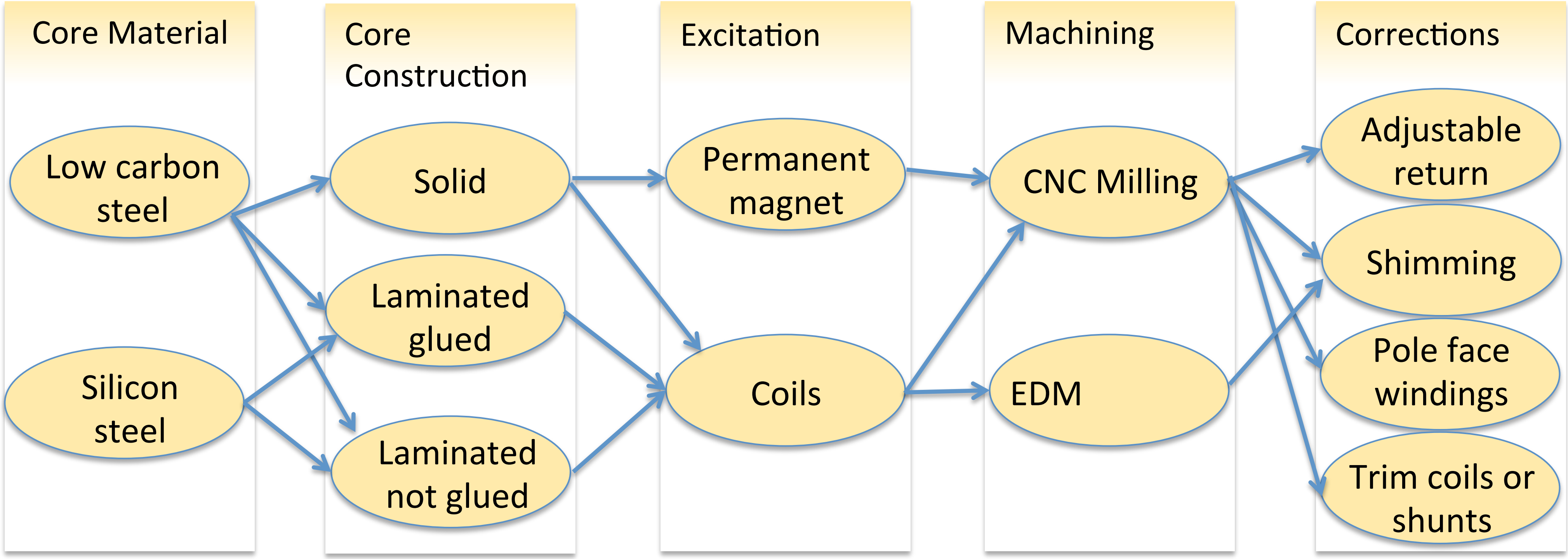
and important talks with: *Nick Simos, Markus Schloesser, Lluis Miralles, Yves Dabin, Jim Kay, Brian Jensen…*

Subsystem example: magnets

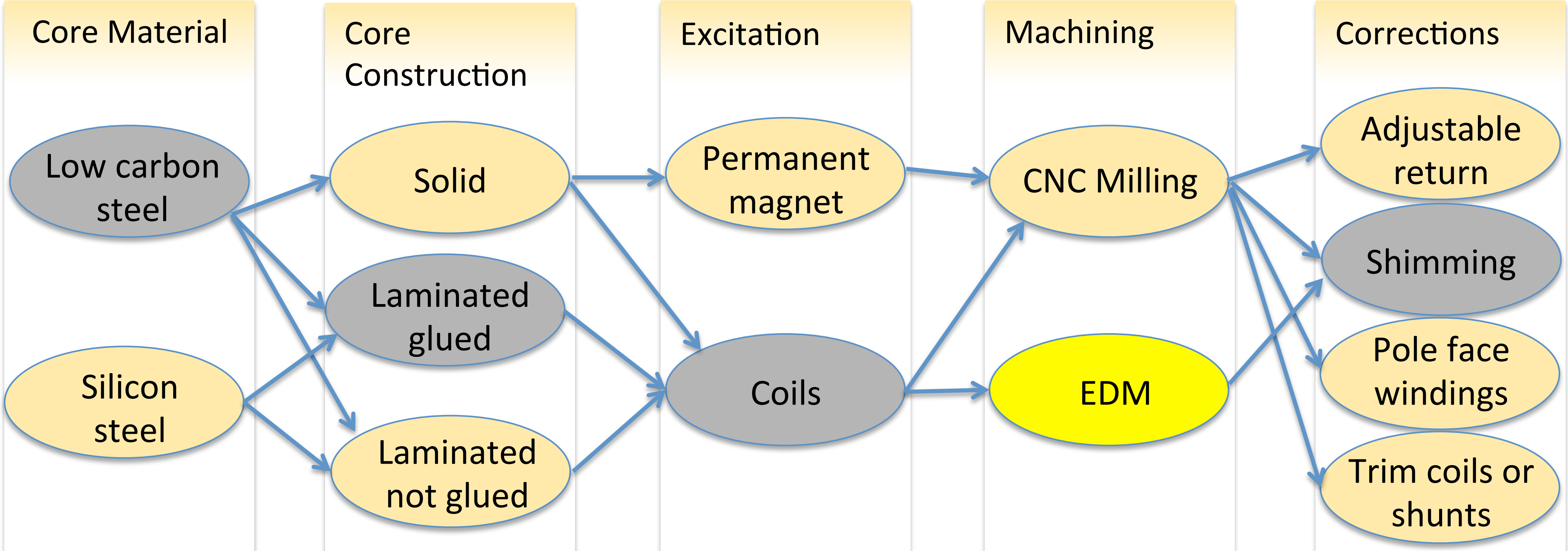
- Very compact magnet lattice
- Strong focusing magnets
- Small bore radius
- Tight alignment tolerances
- Tight field quality tolerances



Magnet design and manufacturing



Magnet design and manufacturing



Core Material
- Low carbon steel
- Silicon steel

Core Construction
- Solid
- Laminated glued
- Laminated not glued

Excitation
- Permanent magnet
- Coils

Machining
- CNC Milling
- EDM

Corrections
- Adjustable return
- Shimming
- Pole face windings
- Trim coils or shunts

- NSLS-II Sextupole
- ALS Sextupole

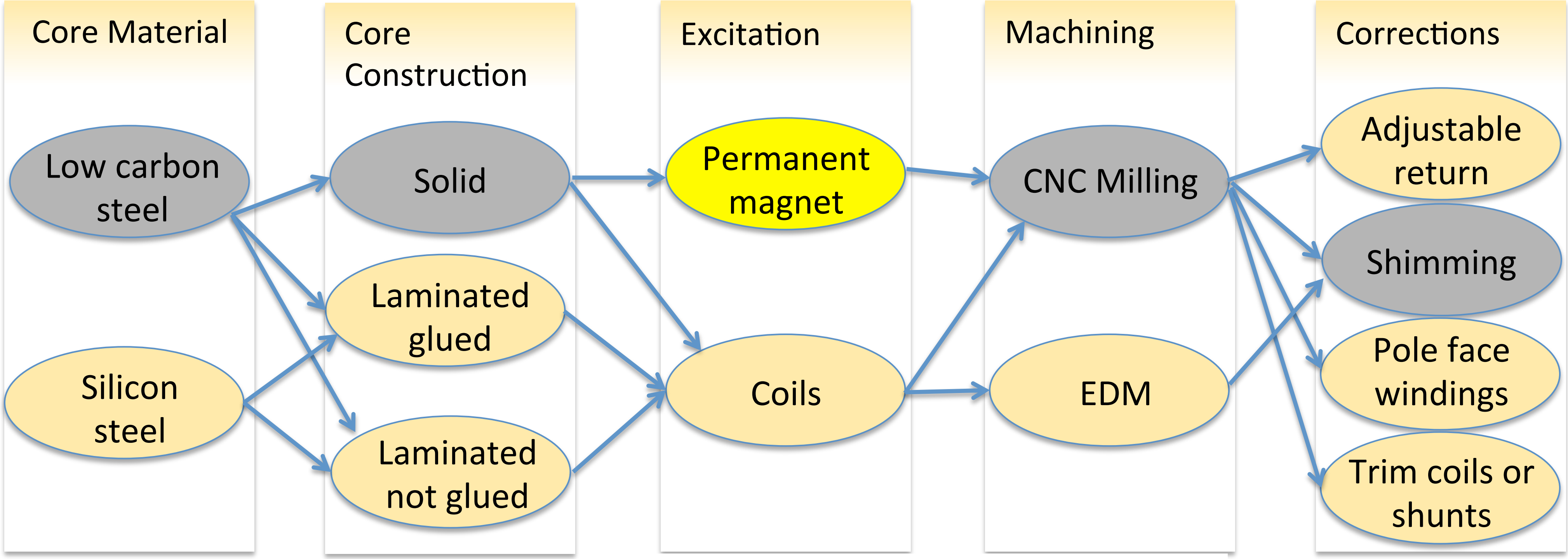
- Reduces stacked errors
- High precision

- Time consuming (20 h)

ALS (SINAP)

NSLS-II (IHEP)

Magnet design and manufacturing



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Machining
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Corrections
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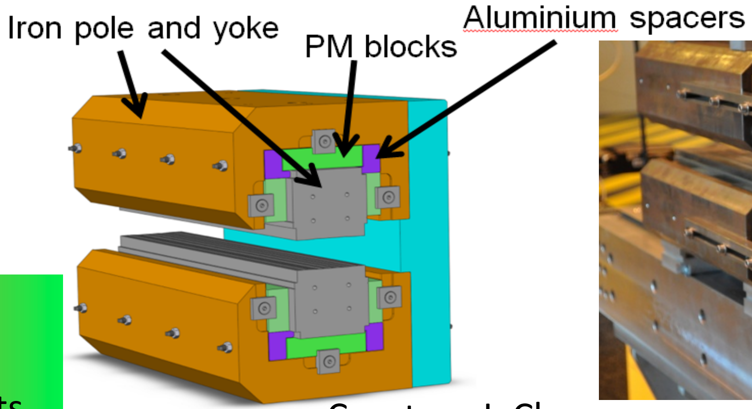
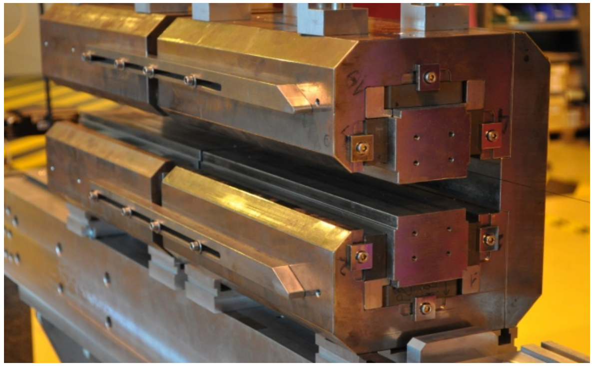
- Shimming
- Pole face windings
- Trim coils or shunts

- SIRIUS 3.2 T superbend
- ESRF II
- SPRING-8 II

- No ripple
- No electricity bill
- No water vibration

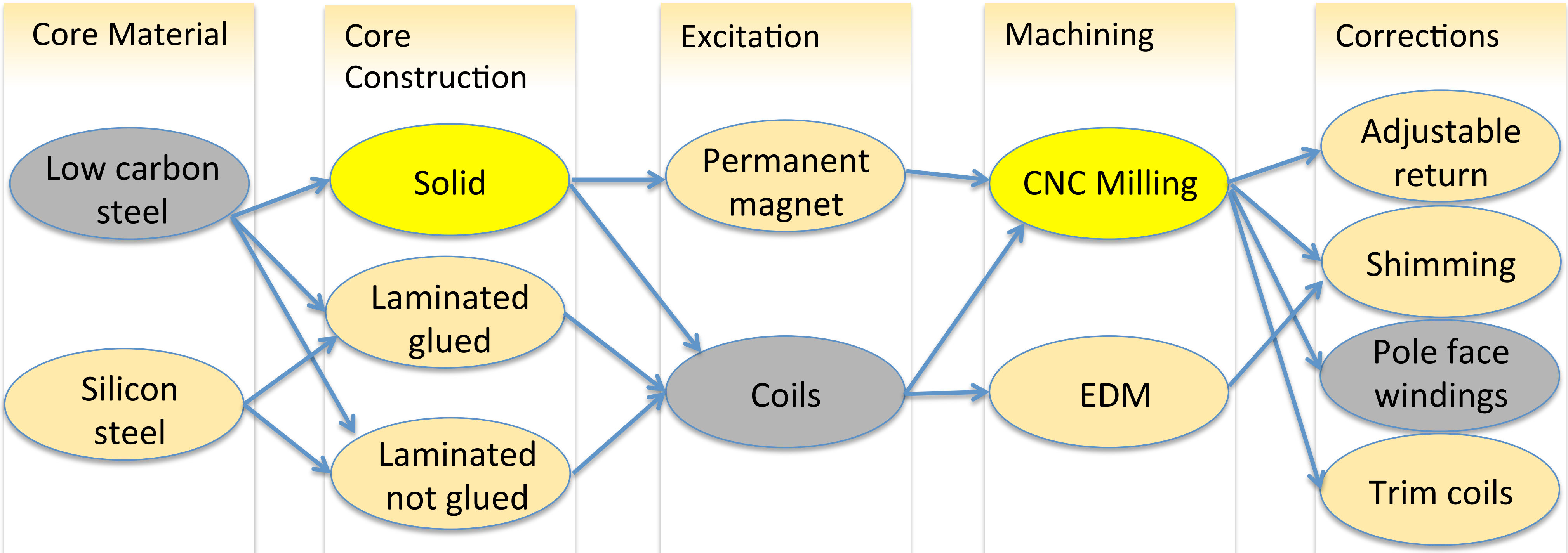
- Fine tuning
- Radiation damage
- Temperature effects





Courtesy J. Chavanne

Magnet design and manufacturing



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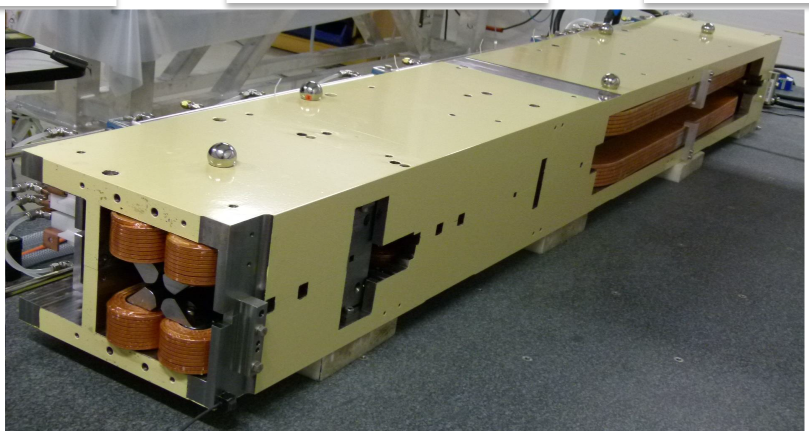
Machining
- CNC Milling
- EDM

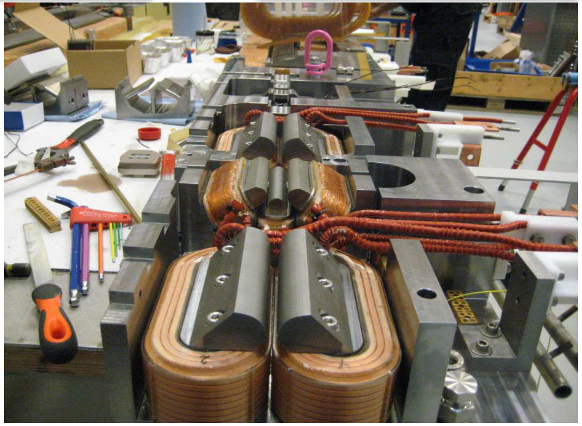
Corrections
- Adjustable return
- Shimming
- Pole face windings
- Trim coils

- MAX-IV

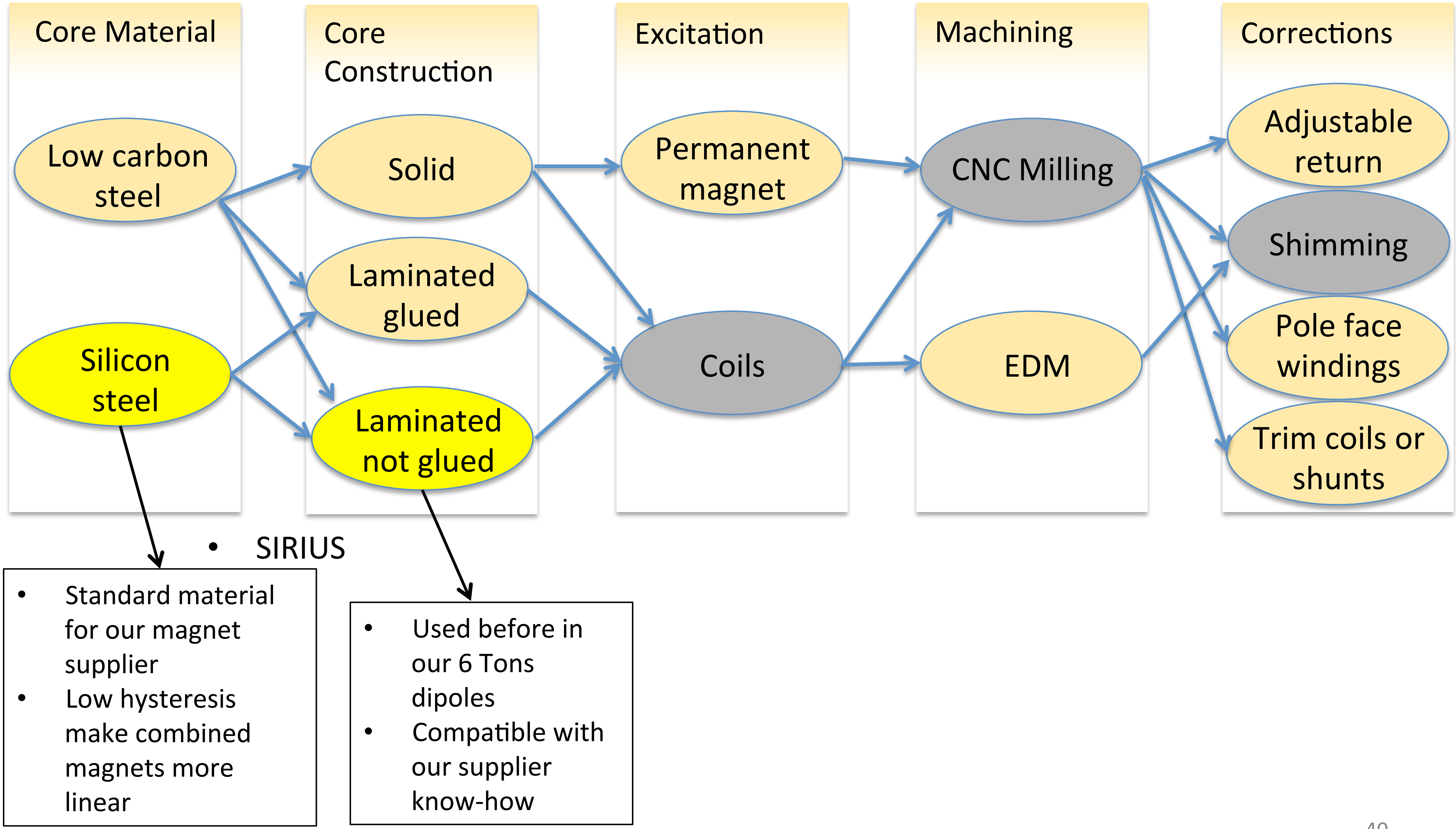
- No alignment
- High rigidity

- Need of high quality and homogeneous steel
- Hard to measure





Sirius storage ring magnet design and manufacturing



Core Material

Low carbon steel

Silicon steel

Core Construction

Solid

Laminated glued

Laminated not glued

Excitation

Permanent magnet

Coils

Machining

CNC Milling

EDM

Corrections

Adjustable return

Shimming

Pole face windings

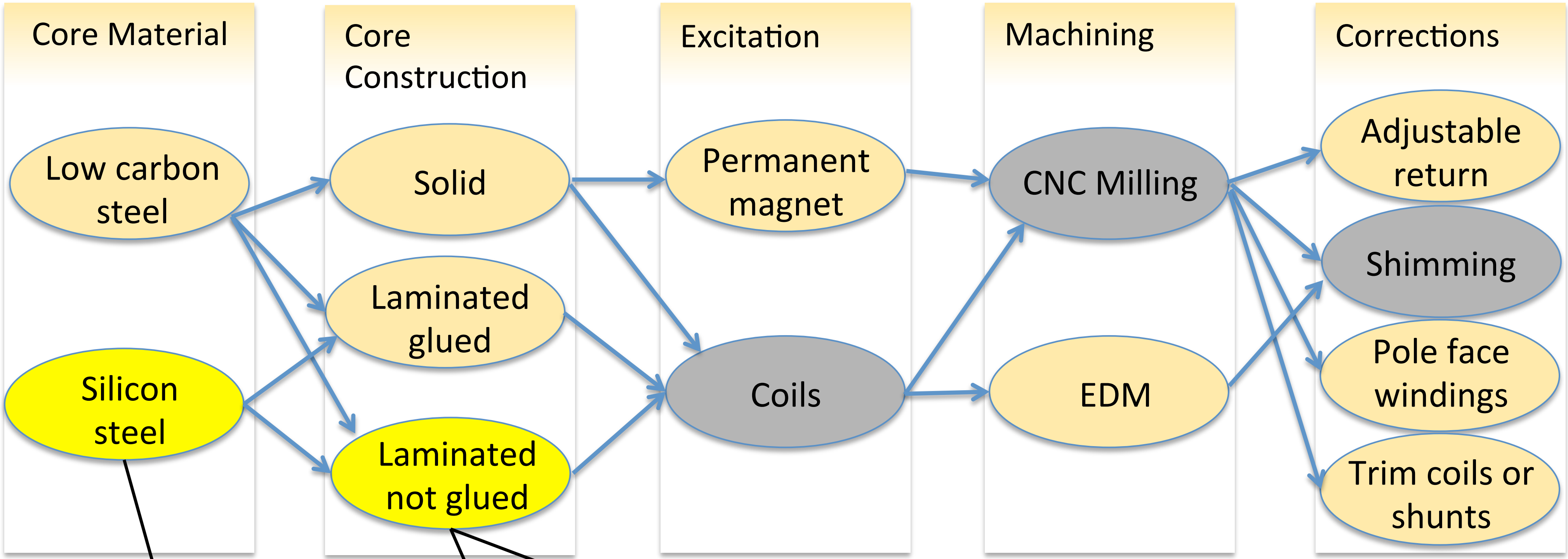
Trim coils or shunts

- SIRIUS

- Standard material for our magnet supplier
- Low hysteresis make combined magnets more linear

- Used before in our 6 Tons dipoles
- Compatible with our supplier know-how

Sirius storage ring magnet design and manufacturing



Core Material

Low carbon steel

Silicon steel

Core Construction

Solid

Laminated glued

Laminated not glued

Excitation

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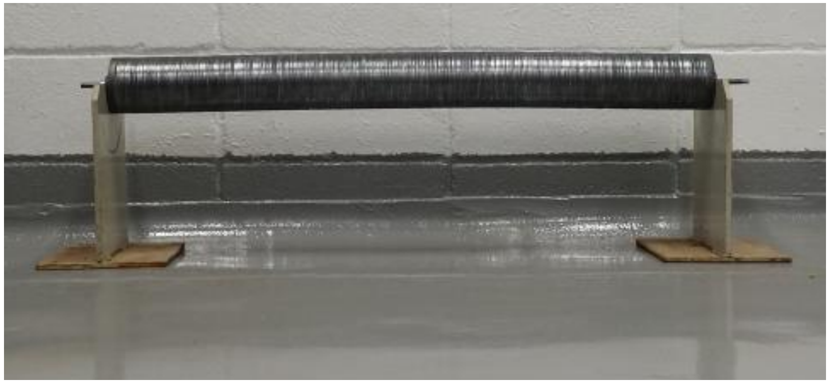
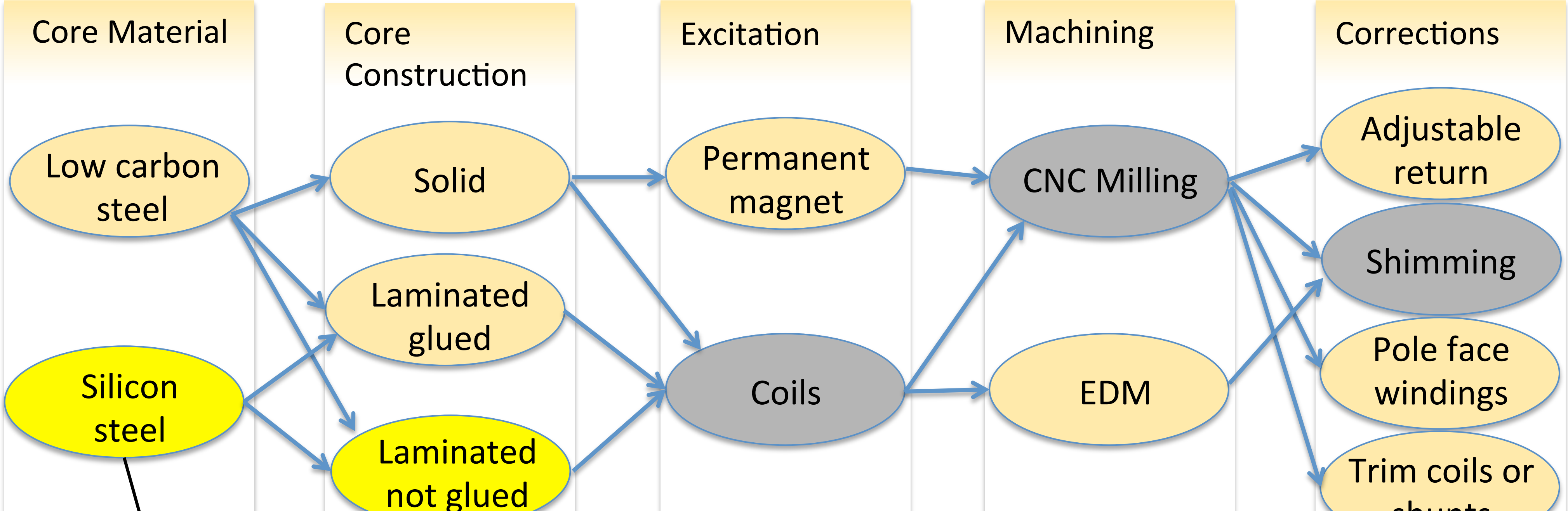


Sirius storage ring magnet design and manufacturing



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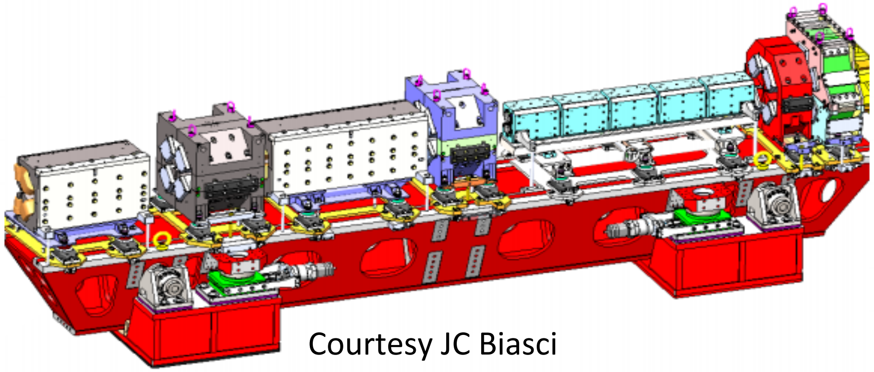
If you can not convince them using just mathematics...

Magnet + Girder options

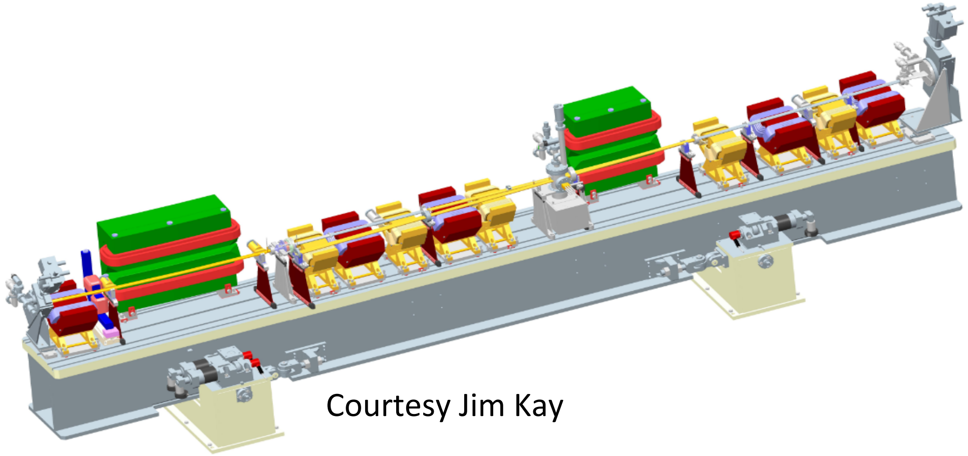


Courtesy JC Biasci

Adjustable magnets

ESRF II, NSLS II...

- *High precision machined magnets*
- *Rigid girder and pedestal*

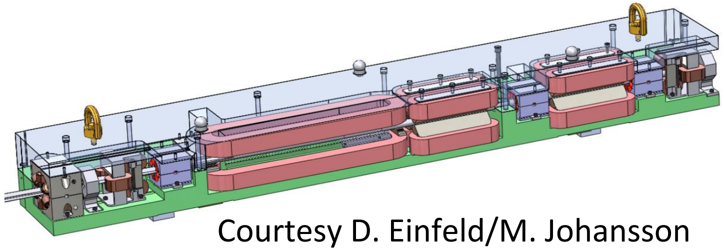


Courtesy Jim Kay

Shimmed (or glued) magnets

DIAMOND II, SLS, TPS, PETRA III…

- *High precision machined magnets*
- *Rigid girder and pedestal*
- *High precision girder*

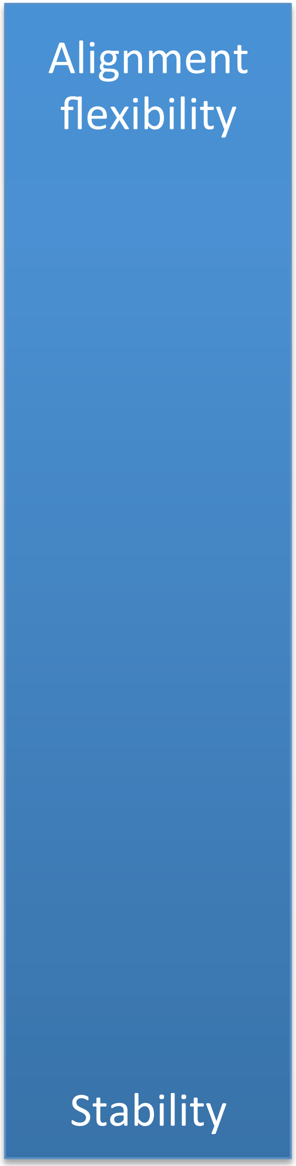


Courtesy D. Einfeld/M. Johansson

Magnet block

MAX IV…

- *High precision machined magnets*
- *Rigid block and pedestal*
- *High precision block*

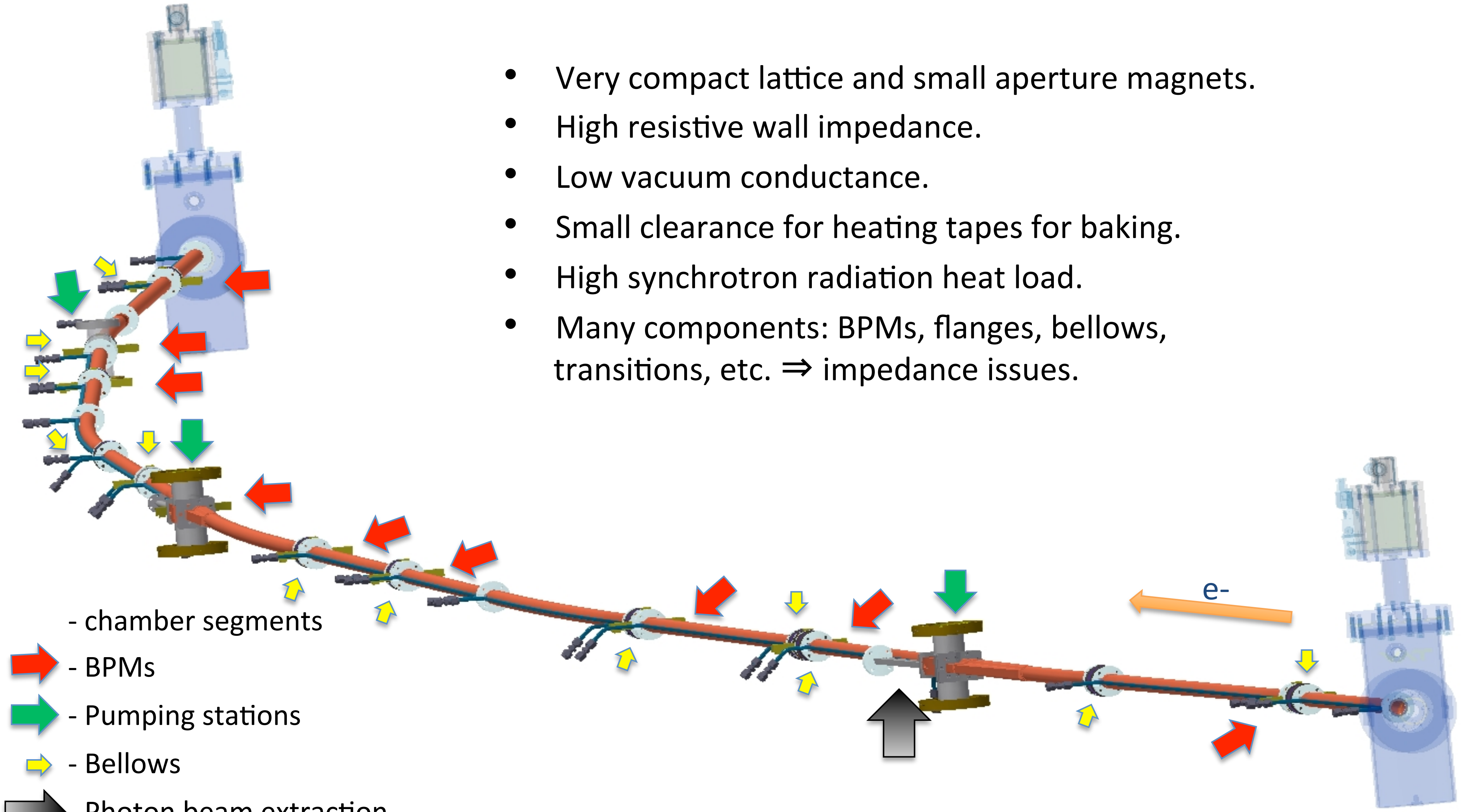


Alignment flexibility

Stability

Subsystem example: vacuum

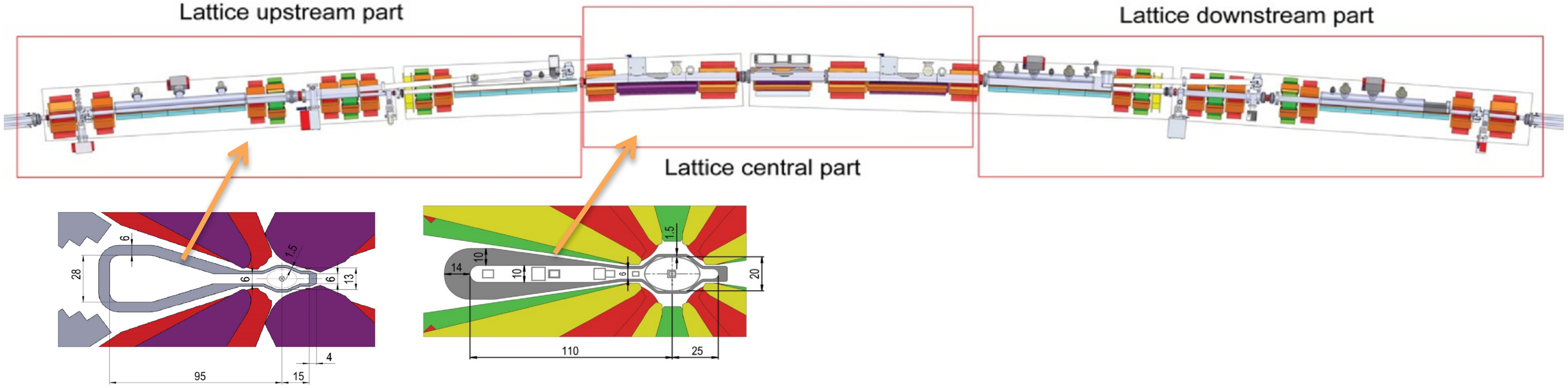
- Very compact lattice and small aperture magnets.
- High resistive wall impedance.
- Low vacuum conductance.
- Small clearance for heating tapes for baking.
- High synchrotron radiation heat load.
- Many components: BPMs, flanges, bellows, transitions, etc. ⇒ impedance issues.



- chamber segments
➡ - BPMs
➡ - Pumping stations
➡ - Bellows
➡ - Photon beam extraction

Discrete pumping strategy (ESRF II, SPRING8 II, DIAMOND II)

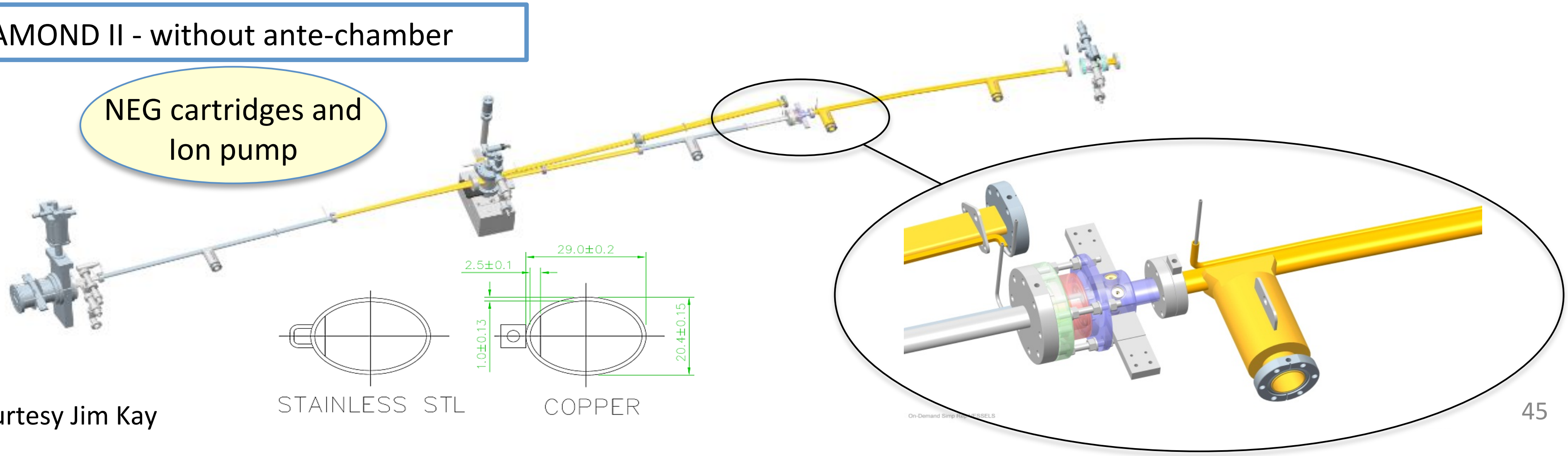
ESRF II - with ante-chamber



Courtesy JC Biasci

DIAMOND II - without ante-chamber

NEG cartridges and Ion pump



Courtesy Jim Kay

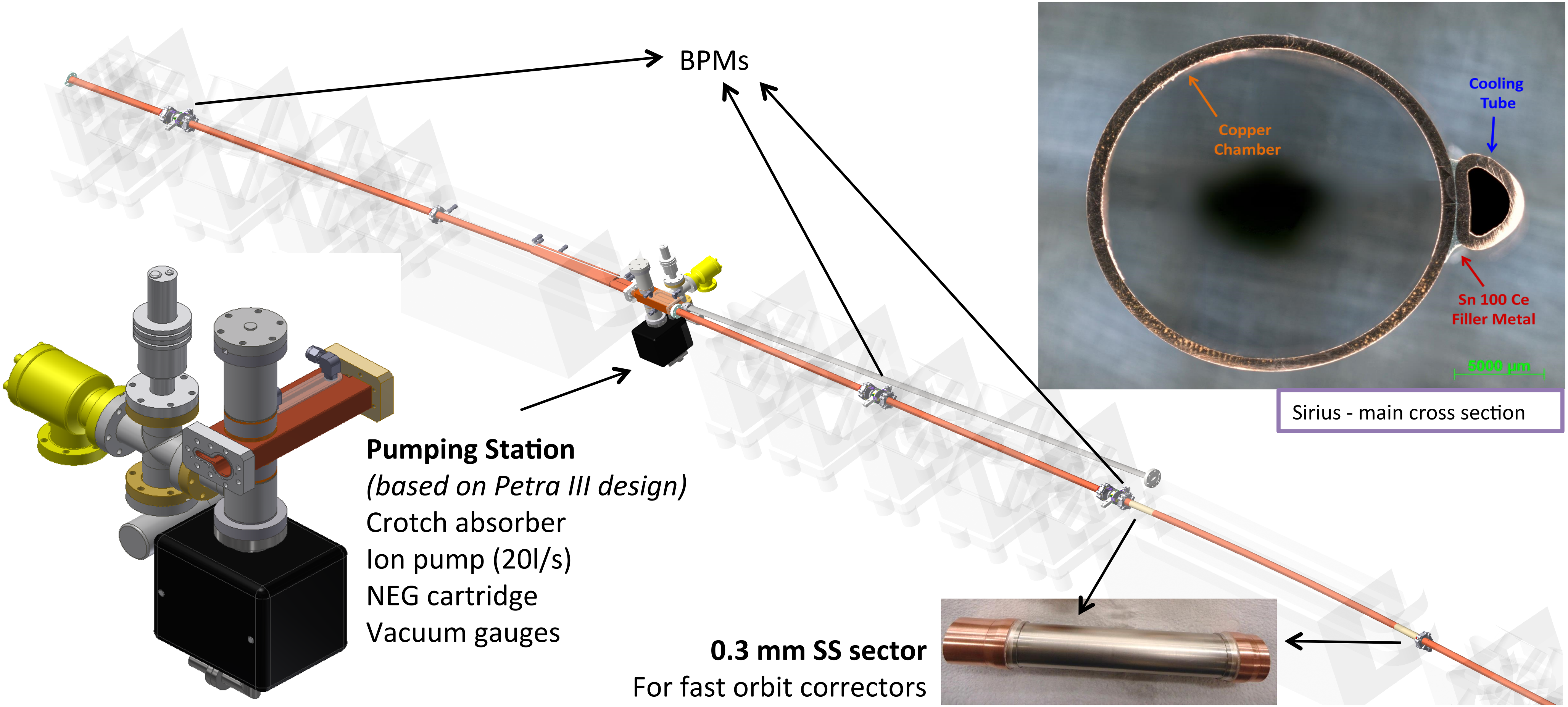
Distributed pumping strategy with NEG coating (MAX IV, SIRIUS)

Pros (full NEG coated strategy)**:**

- Simple chamber's design
- More compact -> space saving
- Low PSD yield -> Fast vacuum conditioning

Cons (full NEG coated strategy)**:**

- Limited number of activations (10 …?...30)
- High temperature bake-out for NEG activation
- Many bellows to accommodate chamber's expansion during bake-out



BPMs

Pumping Station

(based on Petra III design)

Crotch absorber

Ion pump (20l/s)

NEG cartridge

Vacuum gauges

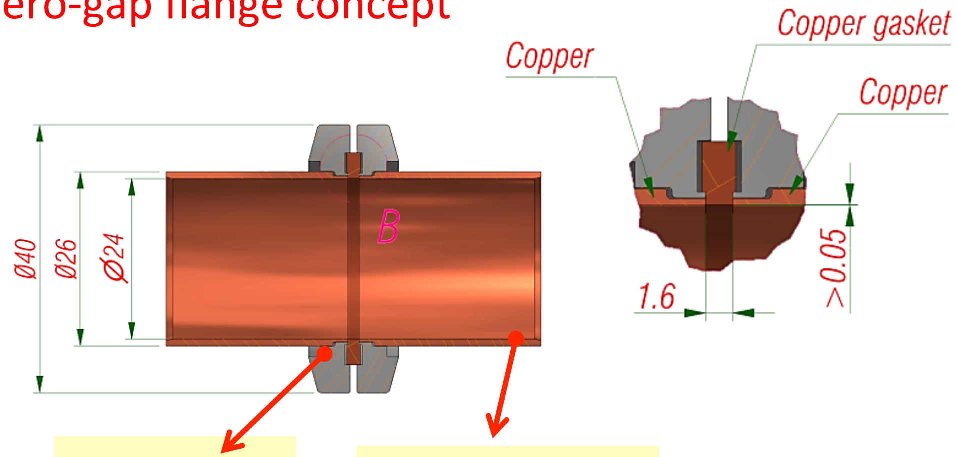
Sirius - main cross section

0.3 mm SS sector

For fast orbit correctors

Some vacuum component design for Sirius

zero-gap flange concept

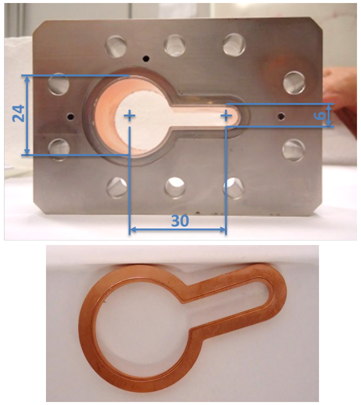


Brazed joint

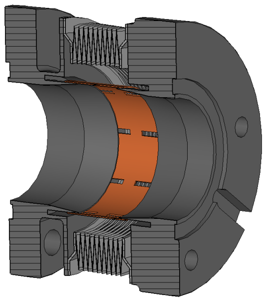
to be TIG welded

NEG coating R&D – dipole chamber

Keyhole design

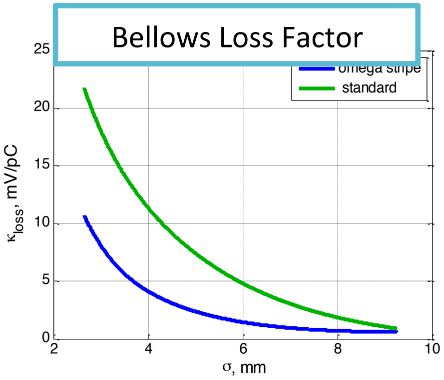


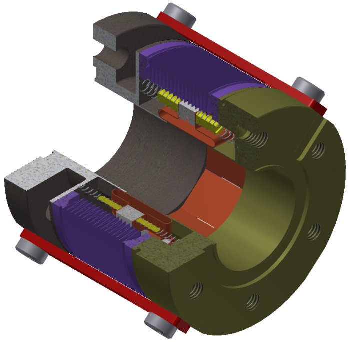
low loss-factor bellows



standard

Bellows Loss Factor





omega stripe under study

- The Synchrotron Radiation Light Source community is going through a very exciting time, with hundreds of new developments under way both in the machine and scientific applications sides. Many new machines and machine upgrades are expected for next years.

- This is still an open community and international cooperation is one of the most important sources for learning and advancing in this area.

Muchas Gracias!