Low emittance ring magnets

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Outline

- Reminder
- Low emittance rings
  - Damping rings
  - Synchrotron light sources
- Magnets for low emittance rings
- Longitudinal variable dipole field for CLIC damping ring
- Conclusions

References

PAPERS

[1] "Magnets for Low-Emittance Storage Rings: an Overview", P. Schnizer and J. Bengtsson, IEEE Trans. Appl. Supercond. Vol. 32, No. 6, Sept. 2022

[2] "4th generation light sources", H. Winick, PAC 97

[3] "Emittance reduction with variable bending magnet strengths: Analytical optics considerations and application to the Compact Linear Collider damping ring design", S. Papadopoulou, F. Antoniou, and Y. Papaphilippou, Phys. Rev. Accel. Beams 22, 091601, 2019

[4] "Longitudinally Variable Field Dipole Design Using Permanent Magnets For CLIC Damping Rings", IEEE Trans. On Appl. Superconductivity, 10.1109/TASC.2018.2795551

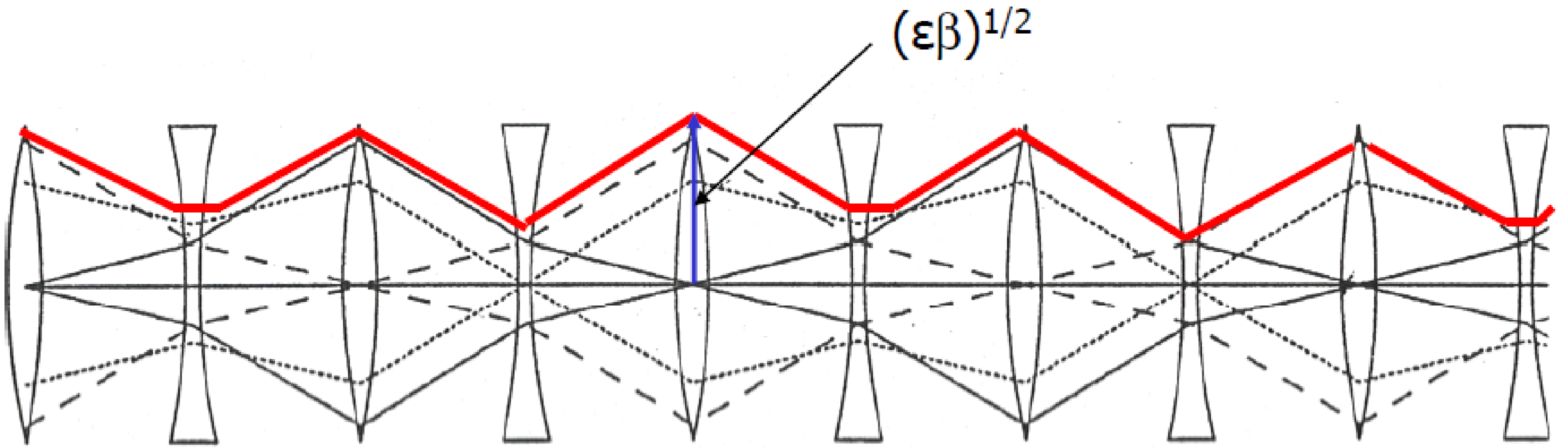
WORKSHOPS

[5] 3rd Workshop on Low Emittance Lattice Design - LEL 2022, https://indico.cells.es/event/1072

[6] Low Emittance Rings – Permanent Magnets, 2023, https://indico.cells.es/event/1072

Special thanks to M. Domínguez (CIEMAT), Y. Papaphilippou (CERN)

Reminder: The beta function β(s)



The β-function is the envelope around all the trajectories of the particles circulating in the machine.

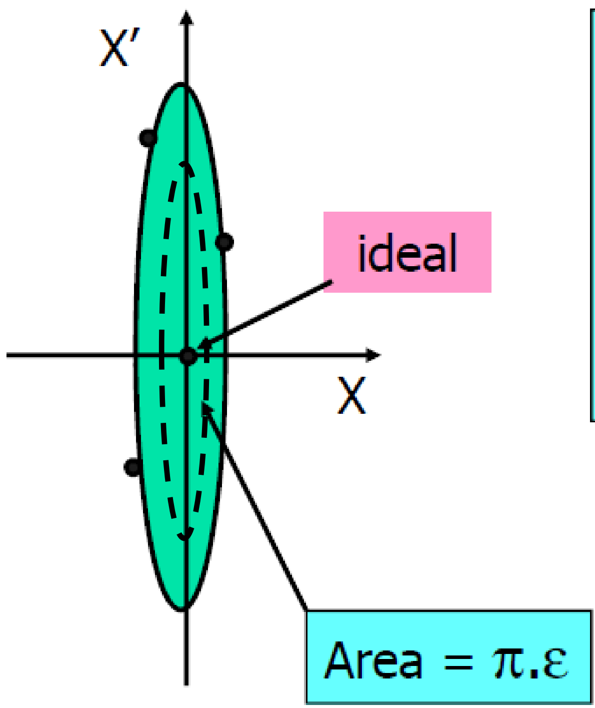
The β-function has a minimum at the QD and a maximum at the QF, ensuring the net focusing effect of the lattice.

It is a periodic function (repetition of cells). The oscillations of the particles are called betatron motion or **betatron oscillations**.

CAS Frascati 2008 Accelerators for Newcomers D. Brandt

Reminder: beam emittance ε

- Select the particle in the beam with the largest betatron motion and plot its position vs. its phase (x vs. x') at some location in the machine for many turns.



- ε Is the emittance of the beam [π mm mrad]
- ε is a property of the beam (quality)
- Measure of how much particle depart from ideal trajectory.
- β is a property of the machine (quadrupoles).

Beam size [m]

$$\sigma(s) = (\varepsilon.\beta(s))^{1/2}$$

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Reminder: synchrotron radiation

- Charged particles bent in a magnetic field emit synchrotron radiation!

Energy loss:

$eU_0 = A \, . \, \gamma^4/\rho$

with $\gamma = E/E_0 = m/m_0$ and m_0 is the rest mass

m_0 proton = 0.938 GeV/c^2

m_0 electron = 0.511 MeV/c^2

$(m_{o\text{-}p}/m_{o\text{-}e})^4 = (1836)^4 \cong 10^{13}$

Collider	B (T)	E/beam (GeV)	γ	eU_0 (GeV)
LEP ($e^+ e^-$)	0.12	100	196000	2.92
LHC (p-p)	8.3	7000	7500	0.00001

CAS Bruges 16-25 June 2009 Beam Dynamics D. Brandt 20

Radiation loss per turn is proportionally inverse to the fourth power of the particle rest mass

Reminder: brilliance or special brightness

BRILLIANCE – SPATIAL RESOLUTION – TRANSVERSE COHERENCE

- **Brilliance** is usually defined as:

$$B_n(\lambda) = \frac{F_n(\lambda)}{(2\pi)^2 (\Sigma_x \Sigma_z)(\Sigma'_x \Sigma'_z)}$$

(Gaussian approximation)

In photons/s/mm^2/mrad^2/0.1%b.w

Brilliance is the metric of a source that determines the achievable spectral, spatial, and temporal resolution.

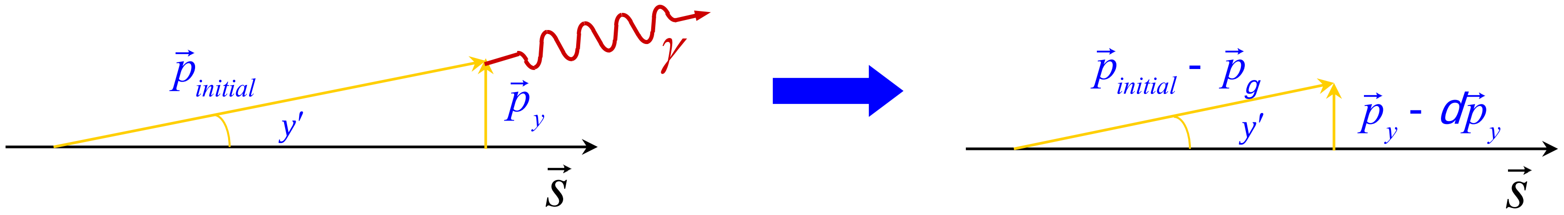
$F_n(\lambda)$ = total photon flux $\quad \Sigma_{x,z} = \sqrt{\sigma_r^2 + \sigma_{x,z}^2(e-)} \quad \Sigma'_{x,z} = \sqrt{\sigma'^2_r + \sigma'^2_{x,z}(e-)}$

- *It measures the concentration of emitted photons in the phase space*
- *It determines how good is the spatial resolution and time scale that we have available for the user's experiments in a ligth source*

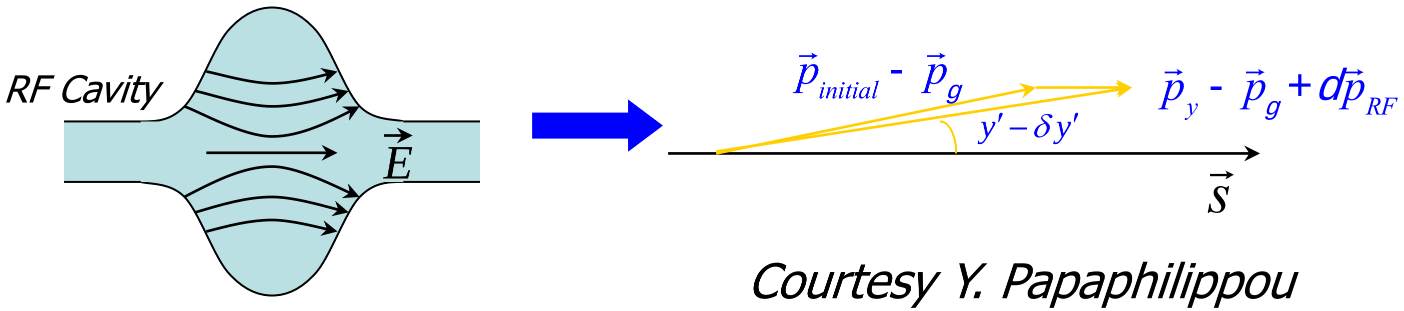
Courtesy A. Nadji

Reminder: radiation damping

- Radiation damping is the reduction in emittance due to the emission of photons as synchrotron radiation
- Synchrotron radiation is emitted in the direction of motion of electron, whose momentum is reduced but the angle remains the same



- The key for betatron damping is the energy recovery by the RF cavities, as only the longitudinal momentum is restored



Courtesy Y. Papaphilippou

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  - Damping rings
  - Synchrotron light sources
- Magnets for low emittance rings
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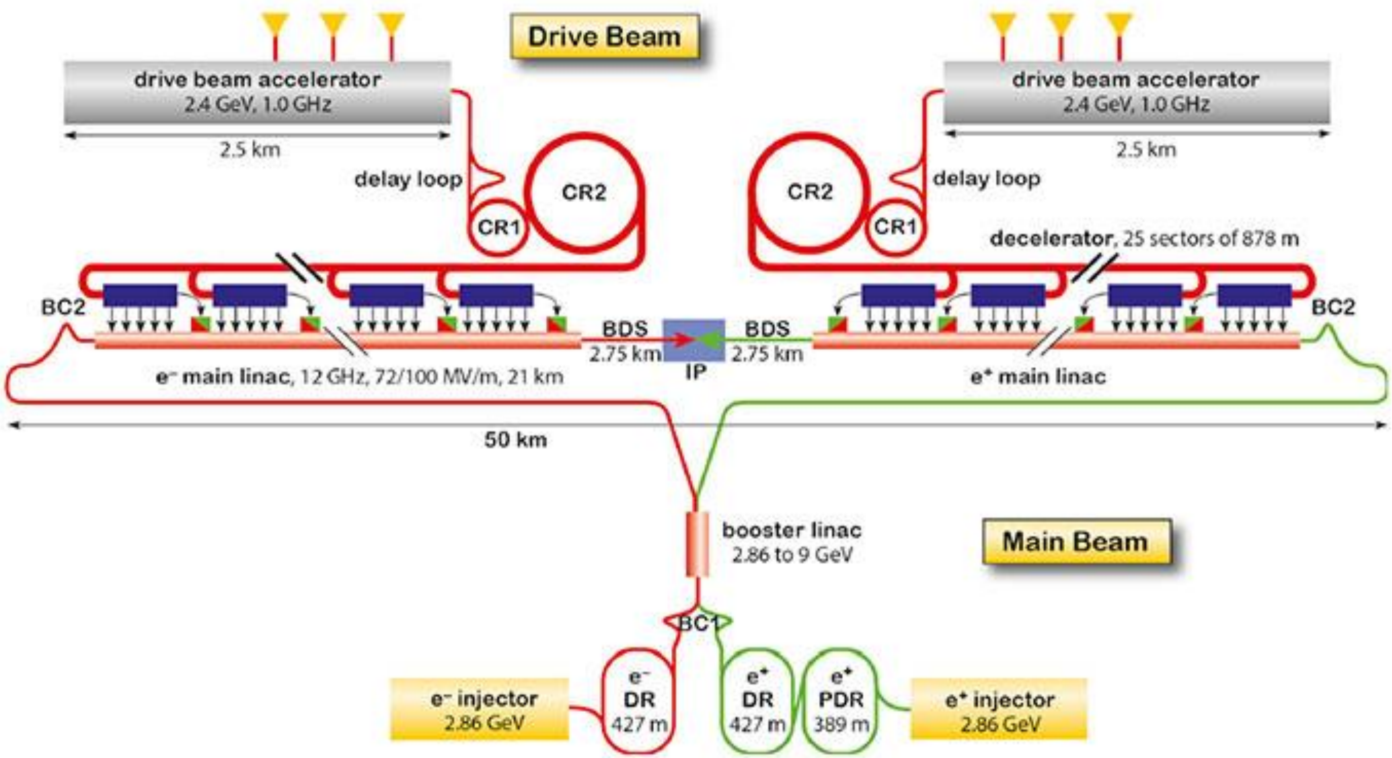
Low emittance rings

- There are two main types of facilities:
  - **Damping rings**:
    - Used in linear colliders to quickly reduce the emittance of the electron and positron beams at an early stage of the acceleration (CLIC, ILC).
    - Storage rings optimized for a fast damping time and a low emittance.
    - Interested in good longitudinal compaction of beams.
  - **Synchrotron light sources**:
    - Very stable beams with small emittance to produce brilliant synchrotron light.
    - Storage ring optimized to produce synchrotron radiation for users (experiments).
    - Interested in long lifetime of beam: optimized beam injection.
- The optics of future large e+/e- circular colliders is quite similar.

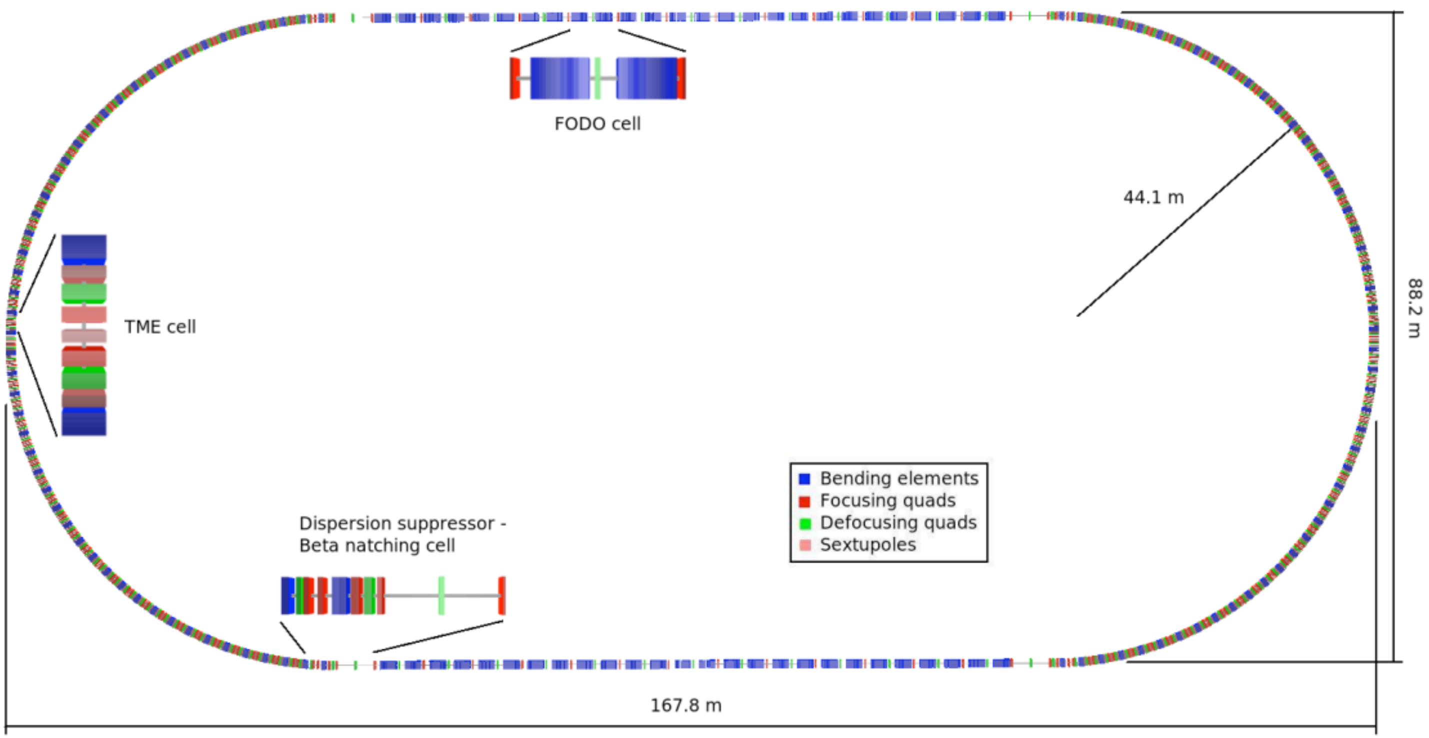
Damping rings: CLIC (I)

- Long chain of accelerators to prepare the beam for final acceleration in the main linac.



Damping rings: CLIC (II)

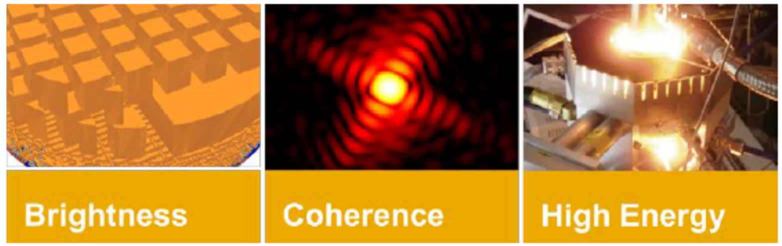
- Theoretical minimum emittance (TME) cells in the arcs and FODO cells with wigglers in the straight sections to reduce the emittance.
- Absorbers for synchrotron radiation.



Synchrotron light sources: new science (I)

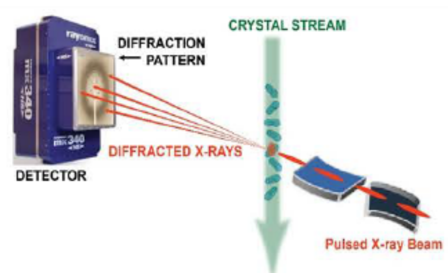
- In recent years, emergence of a whole new (4th generation) class of storage ring based light sources: Diffraction Limited Storage Rings (DLSR).
- Breakthroughs can be expected in high-resolution imaging, microscopy and spectroscopy. Allows science which is not possible or not even thinkable, today.
- Both the time range and the spatial length that can be explored are improved by orders of magnitude.
- The aim of 4th generation light sources is to achieve X-ray wavelengths, close to Free Electron Lasers range of operation.

Synchrotron light sources: new science (II)



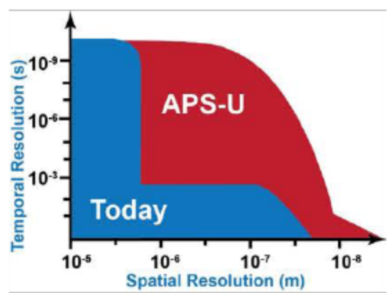
Small-Beam Scattering & Spectroscopy

- Nanometer imaging with chemical and structural contrast; few-atom sensitivity
- Room-temperature, serial, single-pulse pink beam macromolecular crystallography



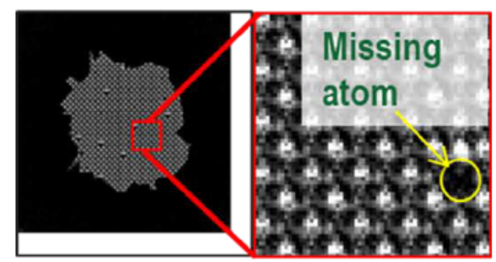
Resolution with Speed

- Mapping all of the critical atoms in a cubic millimeter
- Detecting and following rare events
- Multiscale imaging: enormous fields of view with high resolution



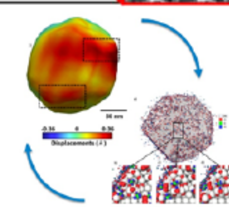
Coherent Scattering & Imaging

- Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
- XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,



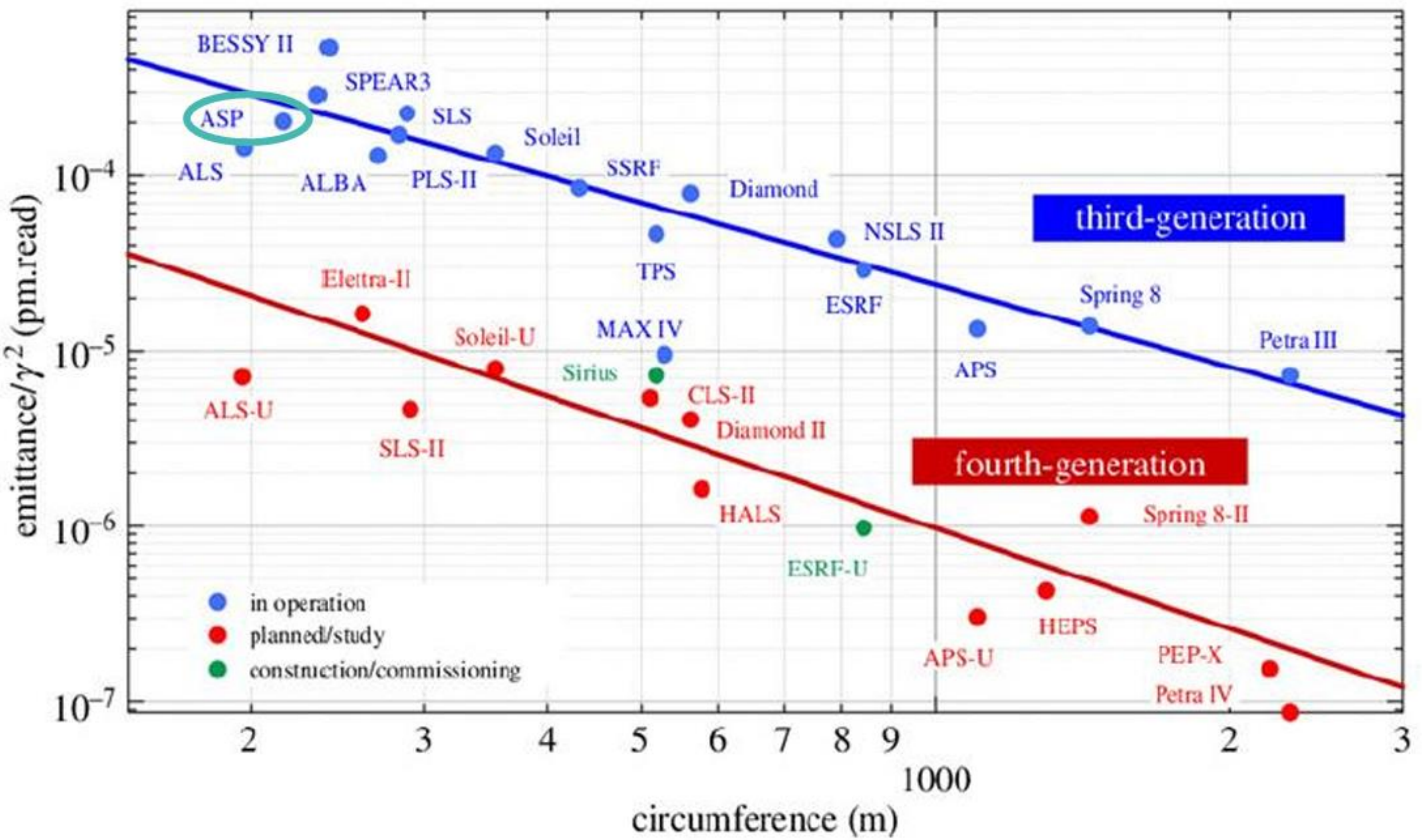
Exploit high performance computing, artificial intelligence

Automatic control of experiments, high volume data acquisition, analysis and reconstruction



Courtesy R. Hettel

Synchrotron light sources: trends



Courtesy R. Walker

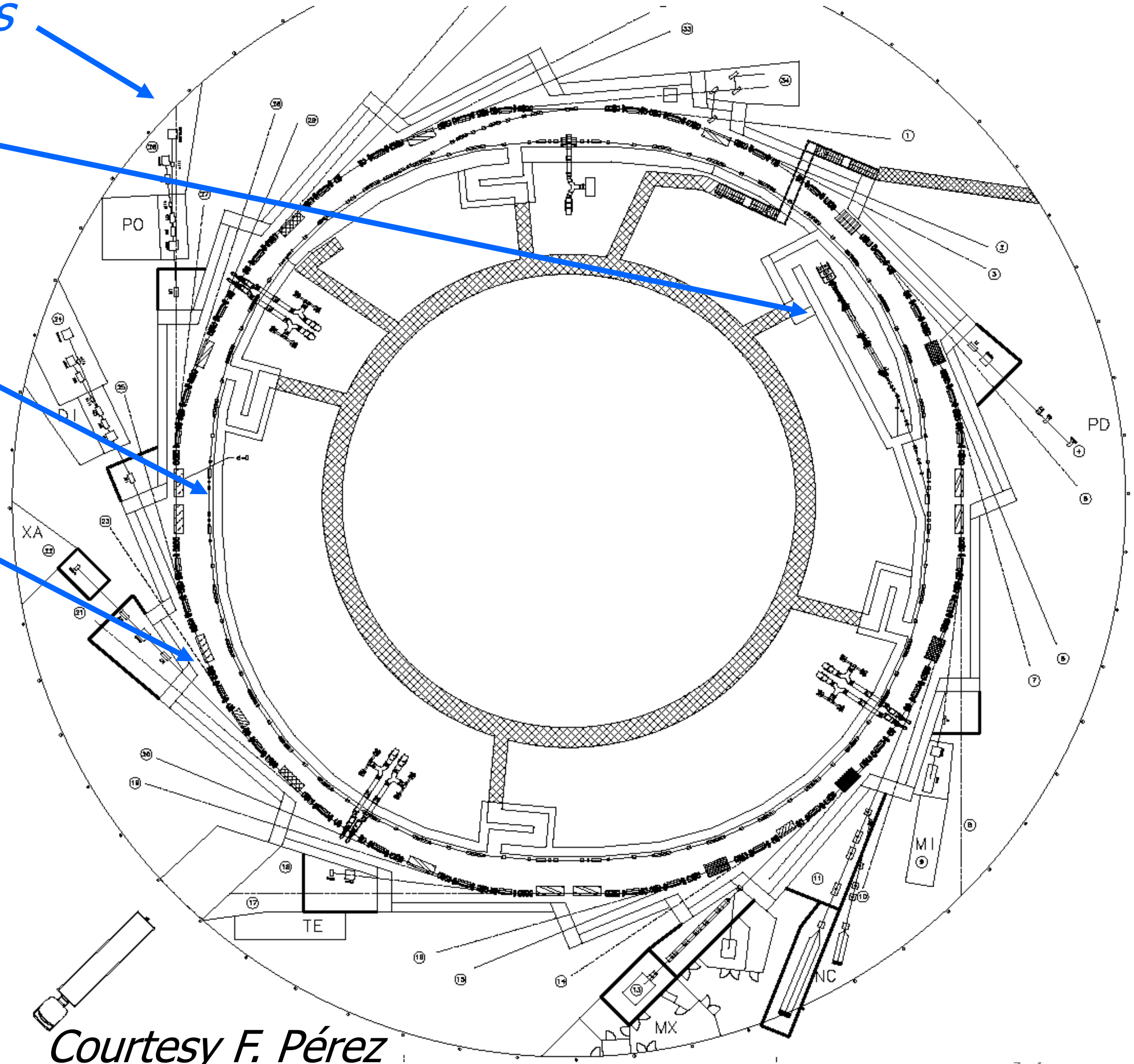
Synchrotron light source: ALBA (I)

Experimental lines

LINAC
100 Mev

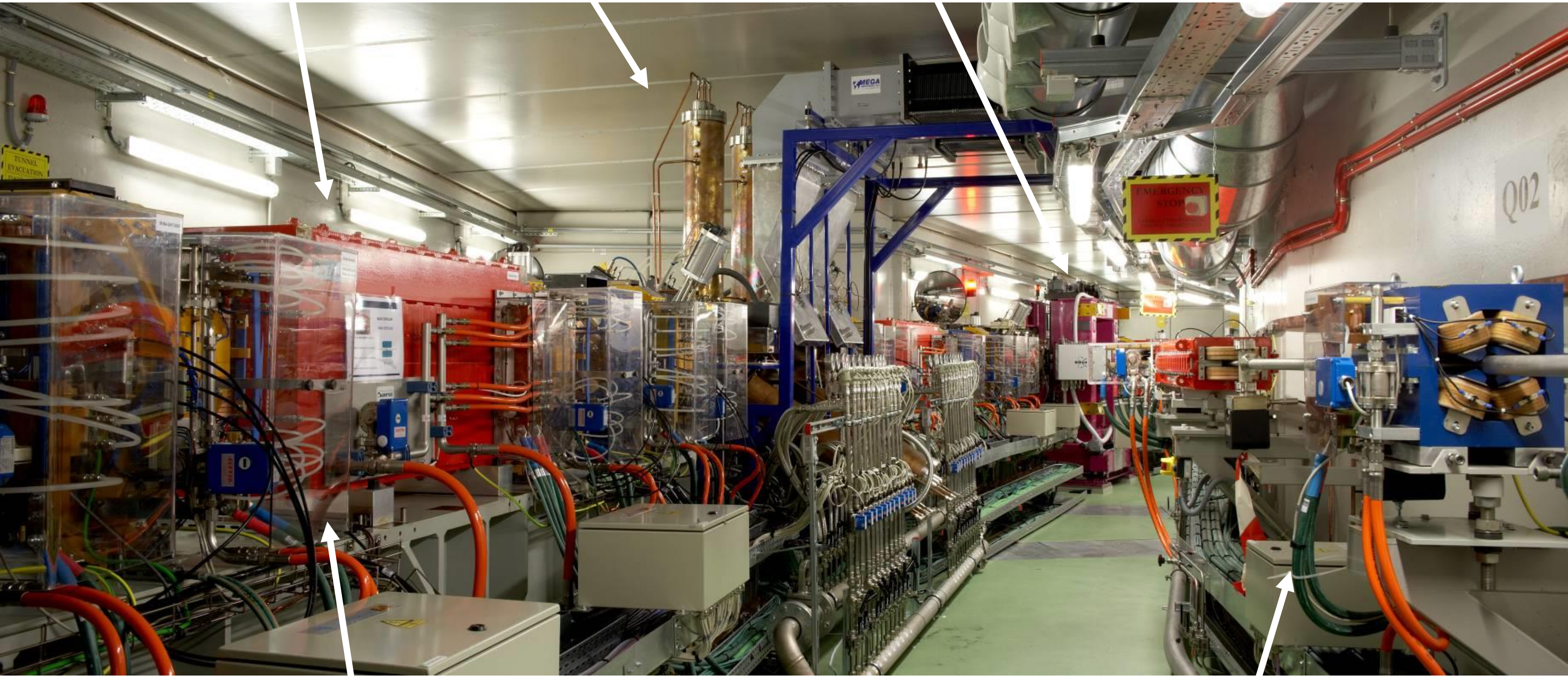
BOOSTER
100 MeV – 3 GeV

STORAGE RING
3 GeV



Courtesy F. Pérez

Synchrotron light sources: ALBA (II)



Courtesy F. Pérez

4th gen. light sources: MBA lattice

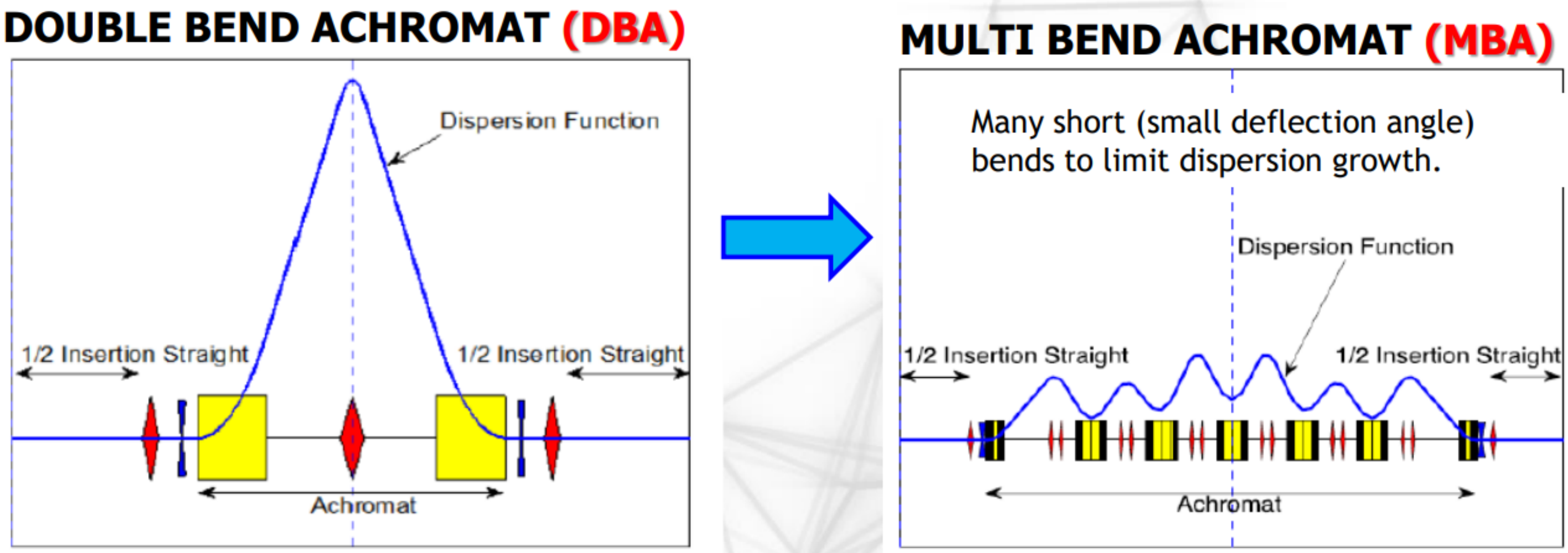
- Multi-Bend Achromat Cell: any short dipoles help to reduce the dispersion growth, that is, the horizontal emittance.

$$\varepsilon_x \approx F(lattice)\frac{E^2}{M^3}$$

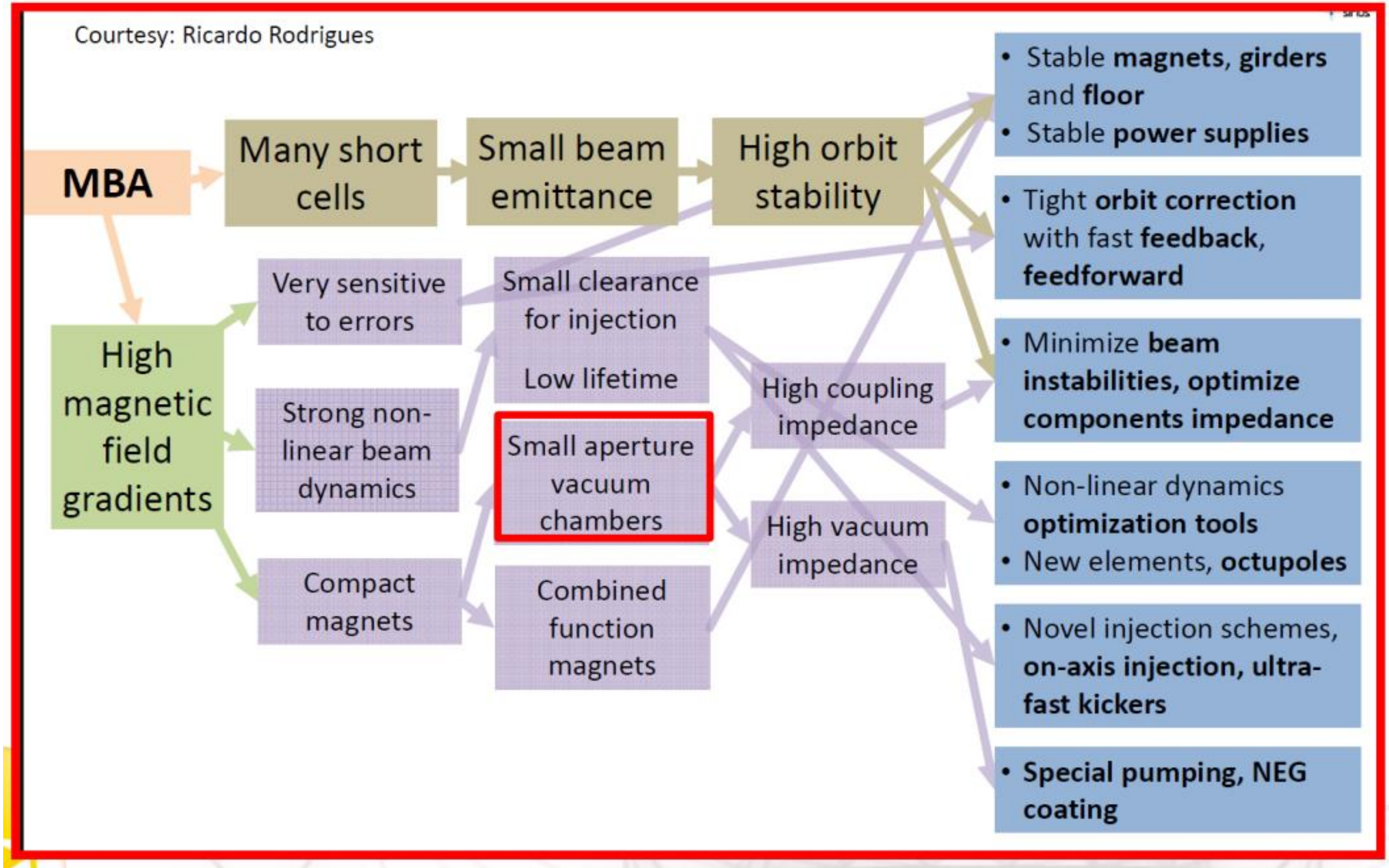
E= Electron Energy
M = Number of identical Bending Magnets

Exploit 1/M³ dependence

Courtesy A. Nadji



4th gen. light sources: challenges



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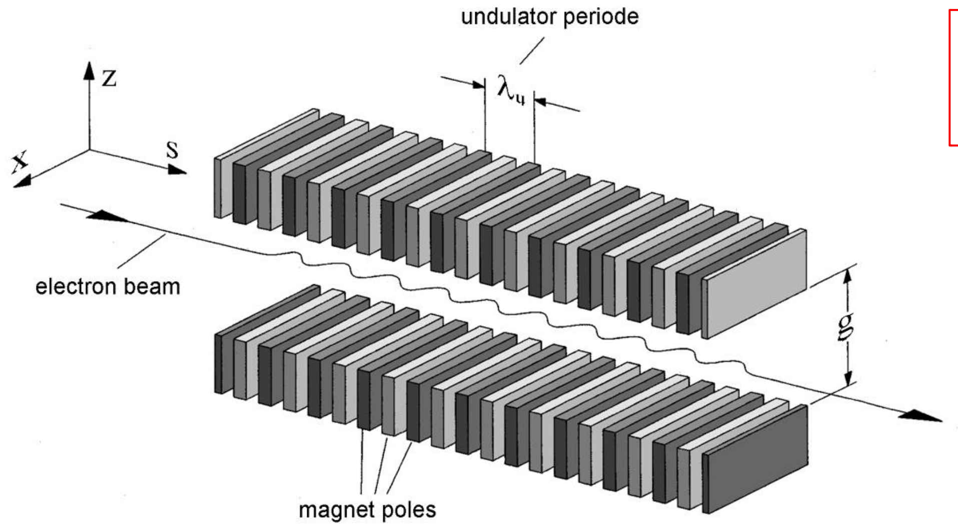
Magnets for low emittance rings

- Open aperture: dipoles and insertion devices should allow the exit of the synchrotron radiation outwards. All magnets should be installed around the vacuum chamber.
- Aperture dimensions: horizontal dimension of vacuum chamber is wider than vertical.
- Field strength: very demanding specifications for dipoles, quadrupoles and sextupoles.
- Field quality: very good field quality (few units).
- Combined function magnets: dipole + quadrupole.
- Dipoles with longitudinally variable fields.
- Cross-talk: magnets are very close.
- Tolerances: very demanding ~20-40 microns
  - Individually: because of the required field quality.
  - Facility: alignment and stability (vibrations).

Insertion devices

- In the first synchrotron light sources, the light was emitted only by dipoles.
- Then, insertion devices were developed to increase the brilliance: wigglers and undulators.
- The mechanical configuration is very similar, based on alternating vertical fields:
  - The wiggler has a broad emission spectrum.
  - The undulator has a narrow radiation bandwidth: there is a constructive resonance.



More info in the dedicated lecture

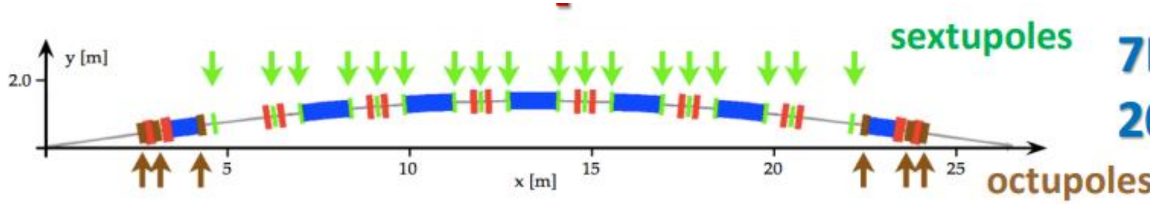
Courtesy K. Wille

Permanent magnets

More info in the dedicated lecture

- First used in insertion devices: short periods of alternating fields (Halbach array).
- Very active research in this field: new facilities make an intense use of these magnets.
- Advantages:
  - No energy consumption, no cooling.
  - More compact.
  - High fields (2 T dipoles, 100 T/m quads).
- Disadvantages:
  - Temperature dependence (solved with NiFe).
  - Radiation resistance (SmCo is better).
  - More complicated regulation.

Max IV: first 4th gen light source

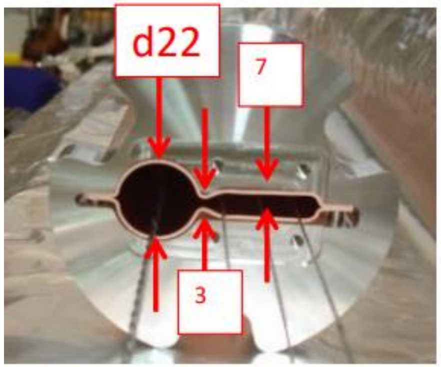


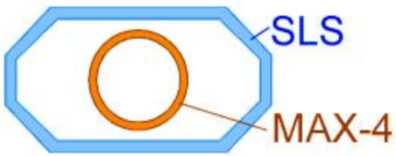
7BA

20 Cells

E = 3 GeV
C = 528 m
ε = 330 pm.rad

– **NEG coating :** Non-Evaporable Getter (~1 μm Ti-Zr-V layer).
The entire circumference of the MAXIV ring is NEG coated.





Beam pipe cross section:
$65 \times 32\ mm^2 \rightarrow \varnothing\ 22\ mm$

3 × smaller beam pipe

Vacuum chambers with very small openings become possible.

– **Low frequency RF (100 MHz):**

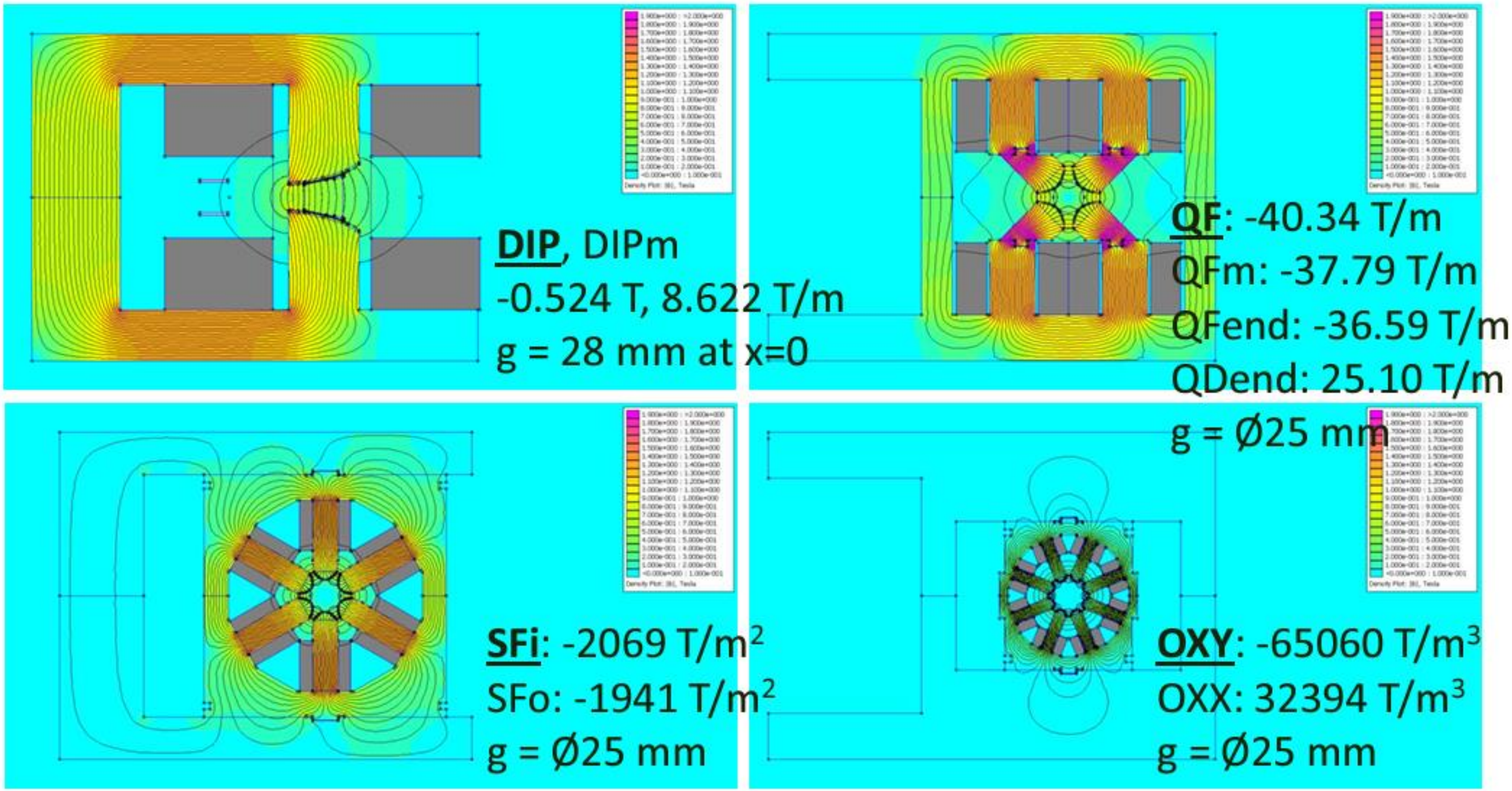
– **Integrated magnets for compactness:**

Machined out of solid iron block (~3.4 m)
Quadrupole :
ϕ = 25 mm
and G_{max} = **40 T/m.**

- Alignment based on mechanical tolerances (Reduced tolerances to 20 micron level).
- Good vibrational stability.

Courtesy A. Nadji

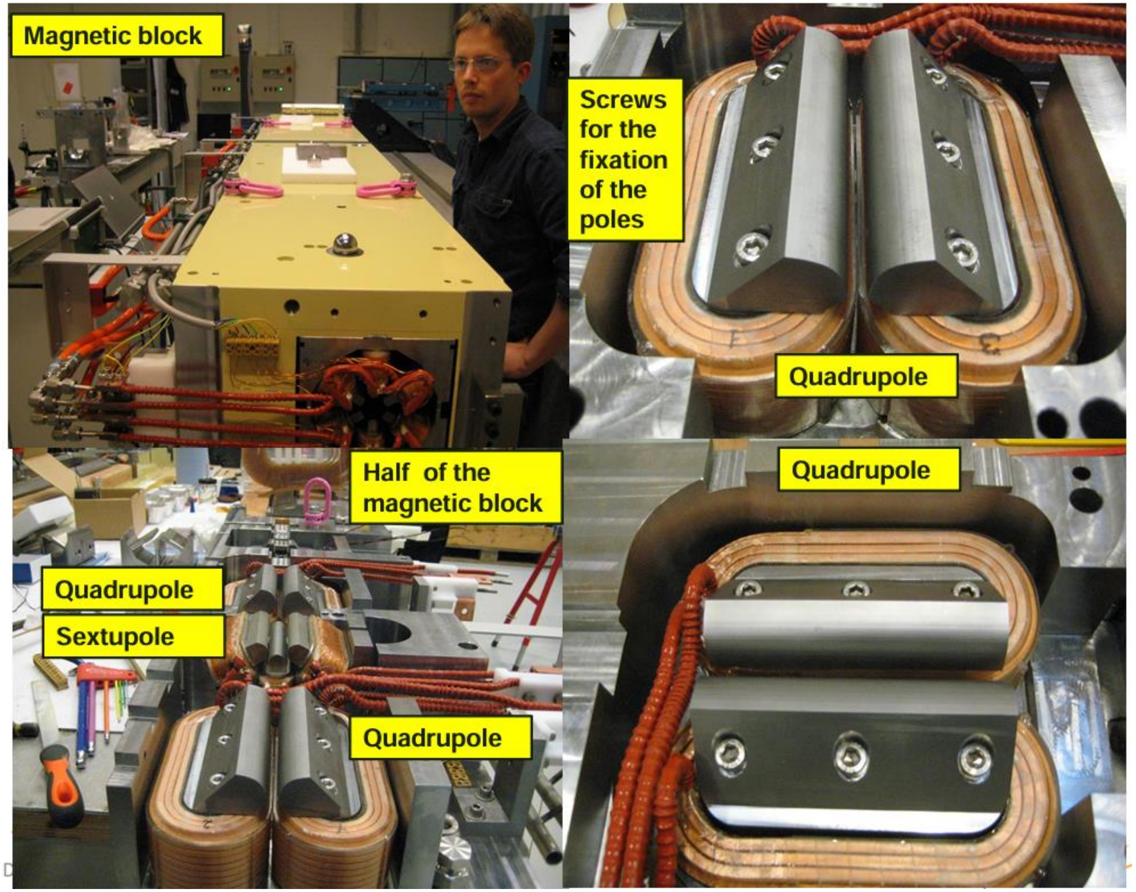
MAX IV: common iron yoke (I)



- 2D simulations using FEMM. 3D simulations with RADIA.
- No simulation of cross-talk.

Courtesy M. Johansson

MAX IV: common iron yoke (II)

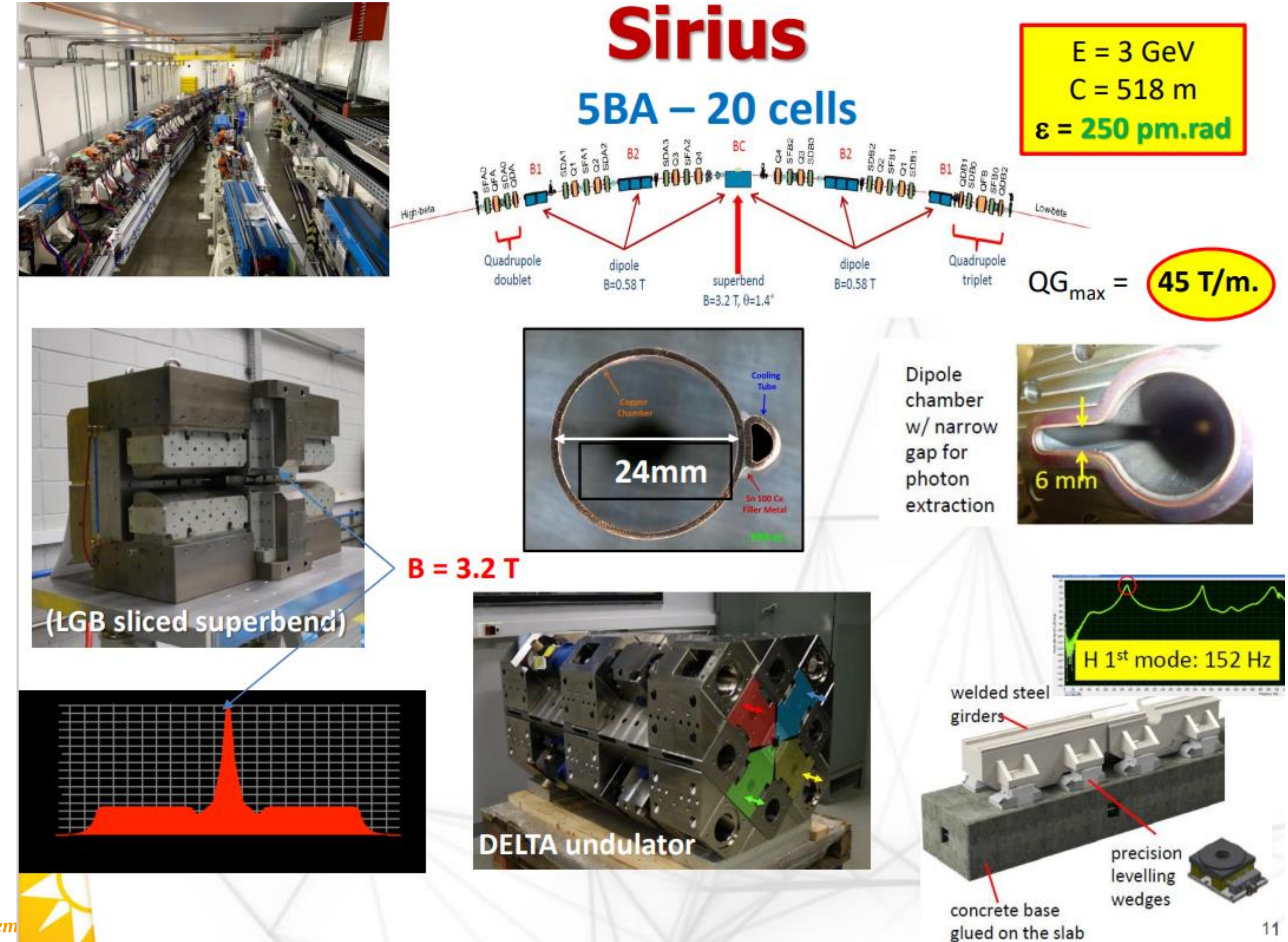


- Complicate assembly.
- No need for alignment of individual magnets: 20-40 micron requirement.

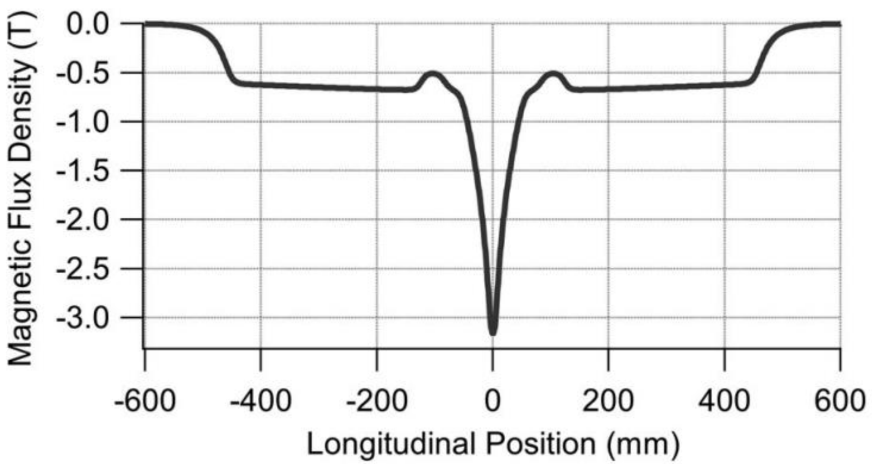
Courtesy M. Johansson

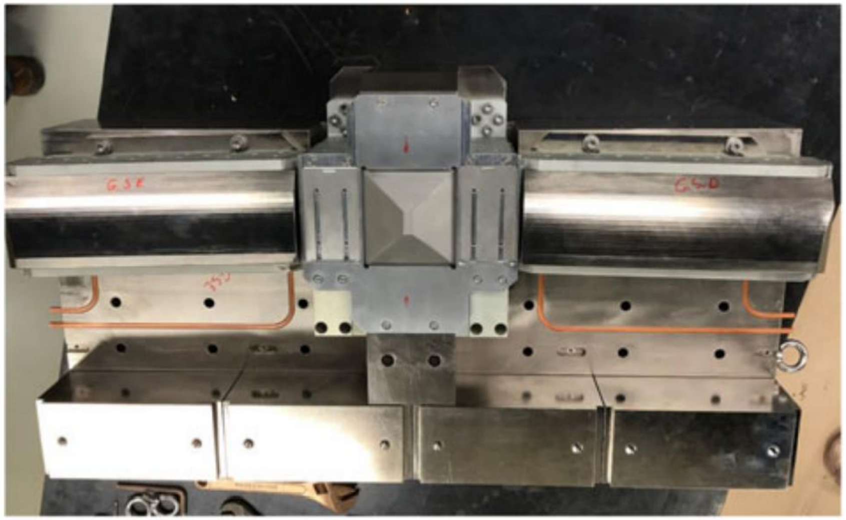
Sirius

Courtesy A. Nadji



Superbend: SIRIUS





- 3 T field bump!!
- The magnetic modules are temperature stabilized with cooling circuits.
- Assembly with external support structure.

Courtesy J. Citadini

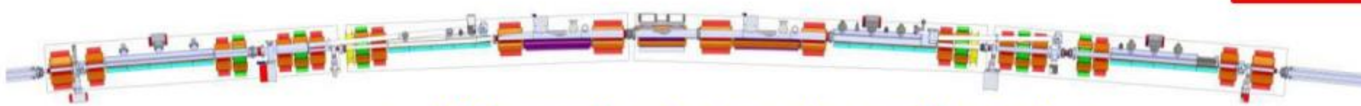
ESRF

Courtesy A. Nadji

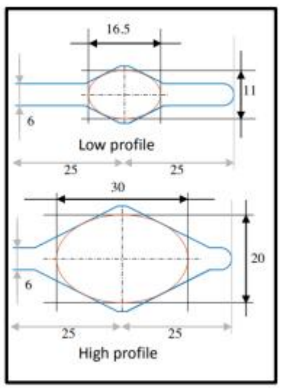
ESRF-EBS upgrade

7BA - 32 cells

E = 6 GeV
C = 844 m
ε = 140 pm.rad



- High gradient magnets small aperture
- Strong gradient dipoles
- Longitudinal gradient dipoles

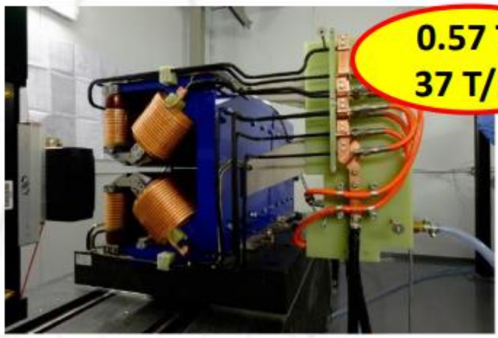


High gradient quadrupole

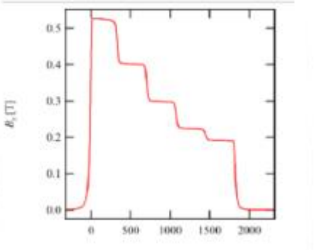
90 T/m

Dipole-quadrupole

0.57 T; 37 T/m

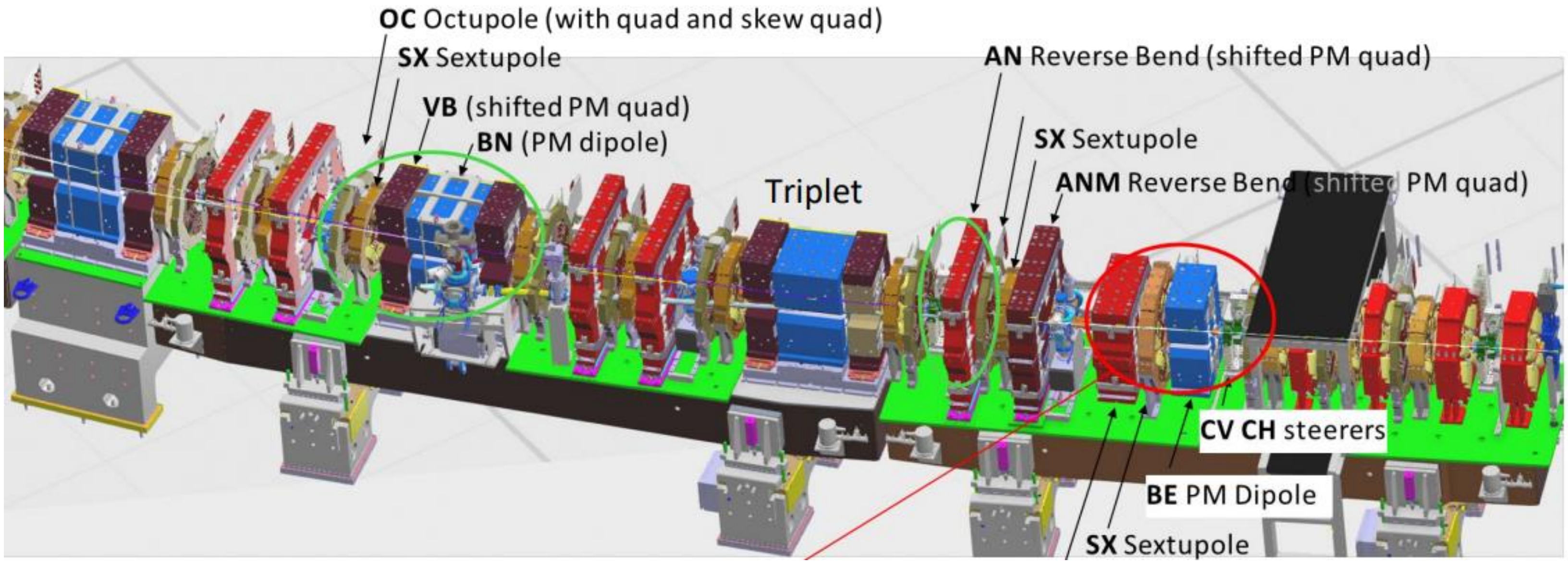


Longitudinal gradient permanent magnet dipoles



SLS

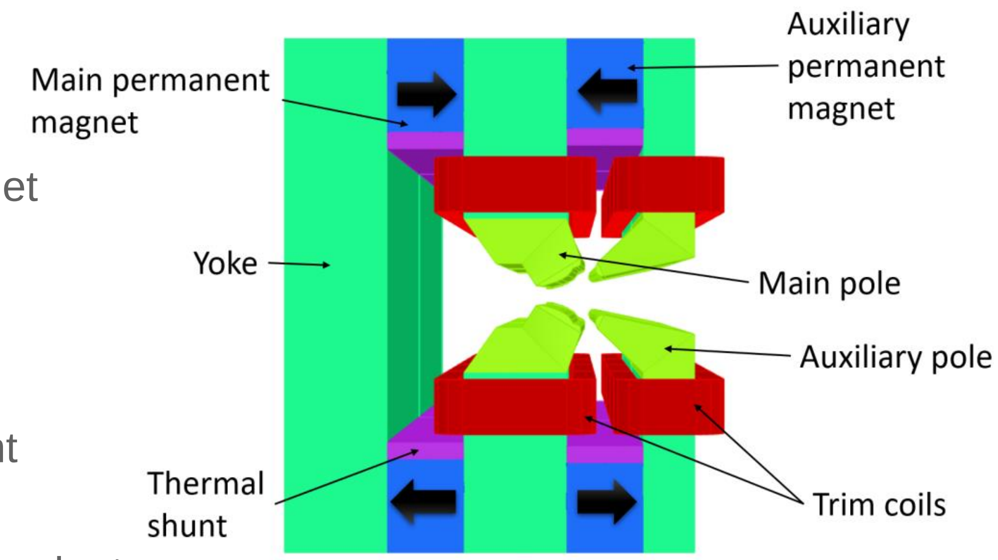
Courtesy C. Calzolaio

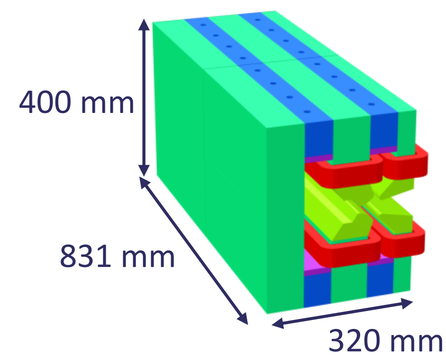


Diamond

Design Overview

- Hybrid Electromagnet-Permanent Magnet Tuneable Optics (HEPTO).
- Dipole = 0.7 T, Gradient = 33 T/m.
- Effective length = 0.870 m.
- Main source of field = NdFeB permanent magnet blocks
- Dipole and gradient fields require independent tuning of ±2.5% for commissioning purposes.
- Field tuning achieved by air-cooled trim coils.
- Yoke and poles made from XC06 low-carbon steel.

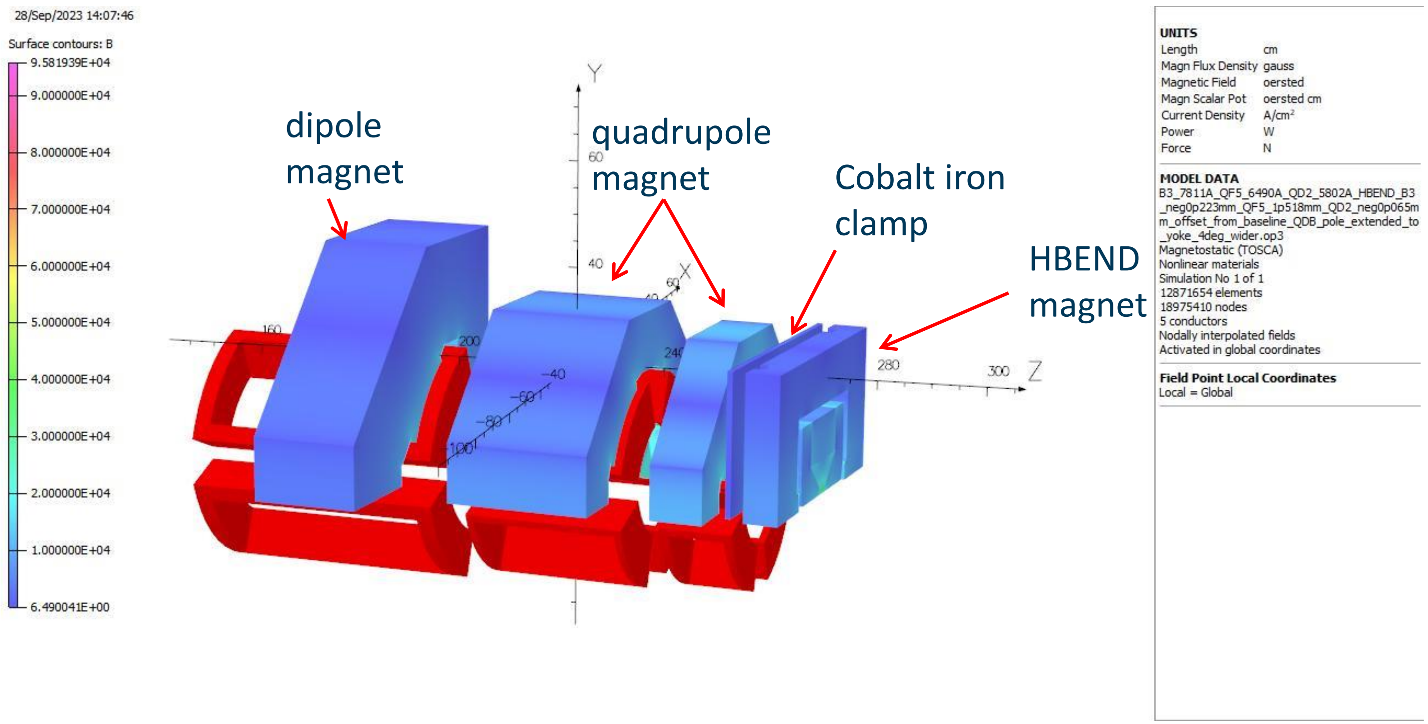




Alex Hinton ● Permanent Magnet Workshop 3

Courtesy A. Hinton

ALS-U: cross-talk



- To reduce the calculation time, mid-plane symmetry is used and symmetric boundary condition is used for both ends.
- Cobalt iron is used for field clamp to minimize magnetic cross talk between neighboring magnets.

Courtesy J. Young

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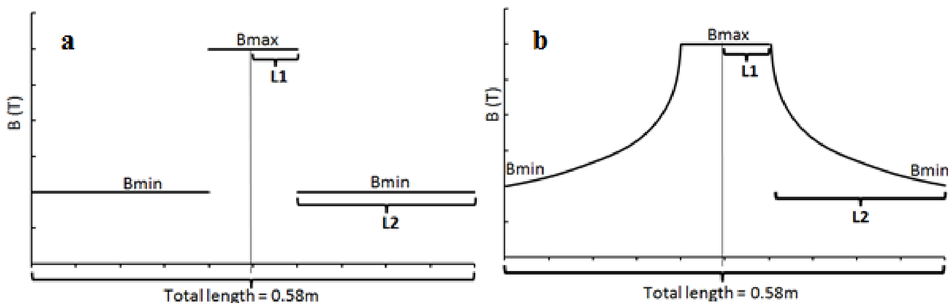
Technical specifications: CLIC damping ring

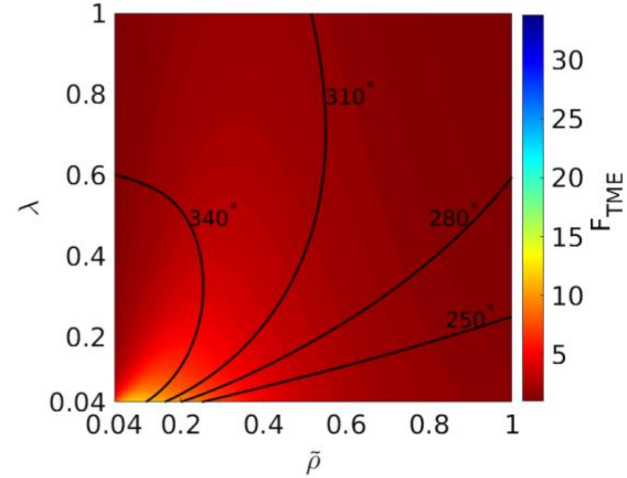
TABLE I
TECHNICAL SPECIFICATIONS

Good field region radius [mm]	5
Field harmonics [units 1E-4]	~1
Transverse gradient [T/m]	11
Magnet length [m]	0.58
Aperture diameter [mm]	13

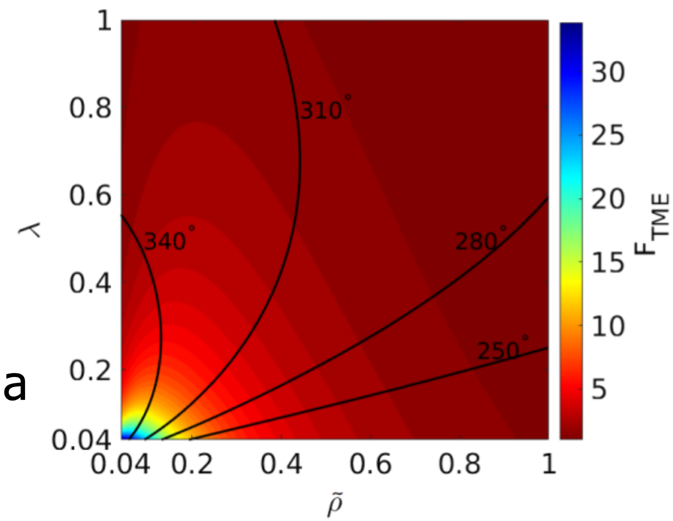
	Step profile	Trapezium profile		
		Case 1	Case 2	Case 3
# of dipoles	96	90	90	90
Dip. field [T·m]	0.625	0.667	0.667	0.667
Bmax [T]	1.7666	1.7666	1.7666	1.7666
Bmin [T]	0.8737	0.7791	0.7508	0.7146
L1 [mm]	65.858	3.352	13.836	26.488
L2 [mm]	224.142	286.648	276.164	263.512



Step profile



Trapezoidal profile



- A step field profile (FTME=4) or, even better, a trapezoidal one (up to 7), decreases the emittance beyond TME limit.

Magnetic calculations: 2-D

- 2D analytical calculations: magnetic circuit
  - Ideal poles: curves of constant scalar potential

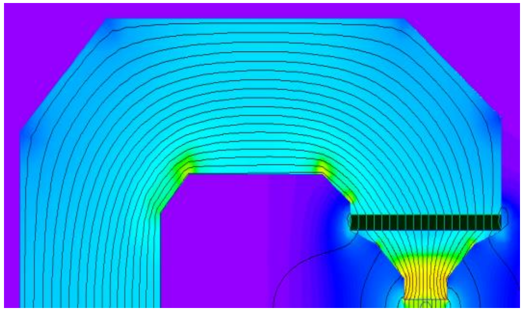
Remember Attilio and Stephan's lectures

dipole

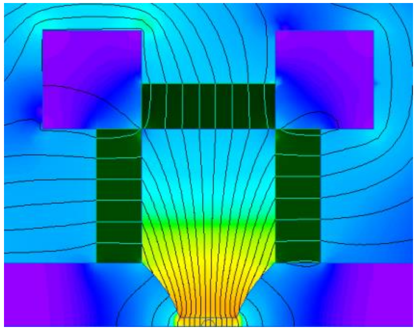
$\rho \sin(\theta) = \pm h/2$ $\quad$ $y = \pm h/2$ $\quad$ straight line

quadrupole

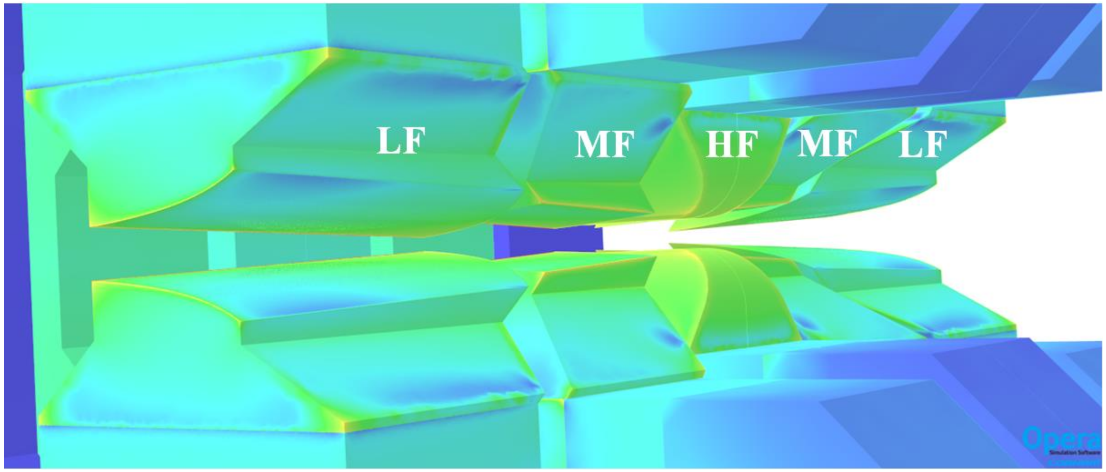
$\rho^2 \sin(2\theta) = \pm r^2$ $\quad$ $2xy = \pm r^2$ $\quad$ hyperbola



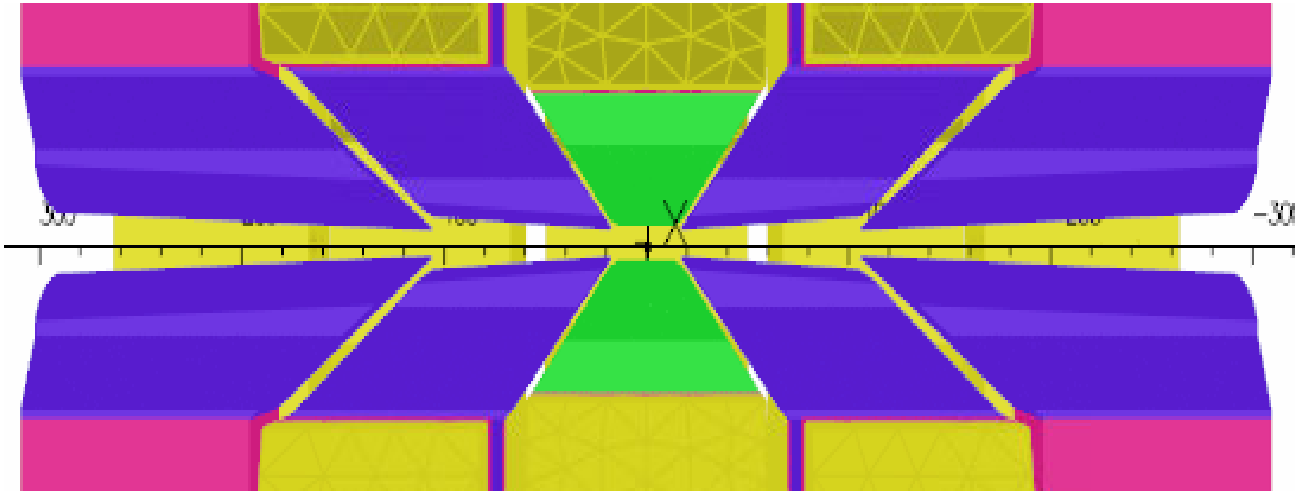
- 2D simulations in Quickfield
- Initially: two regions
  - Low field region: SmCo blocks in a flat configuration over the pole
  - High field region: NdFeB in three blocks working in parallel. Highly saturated



Magnetic simulations: 3-D



Significant cross-talk: 3-D simulations are necessary



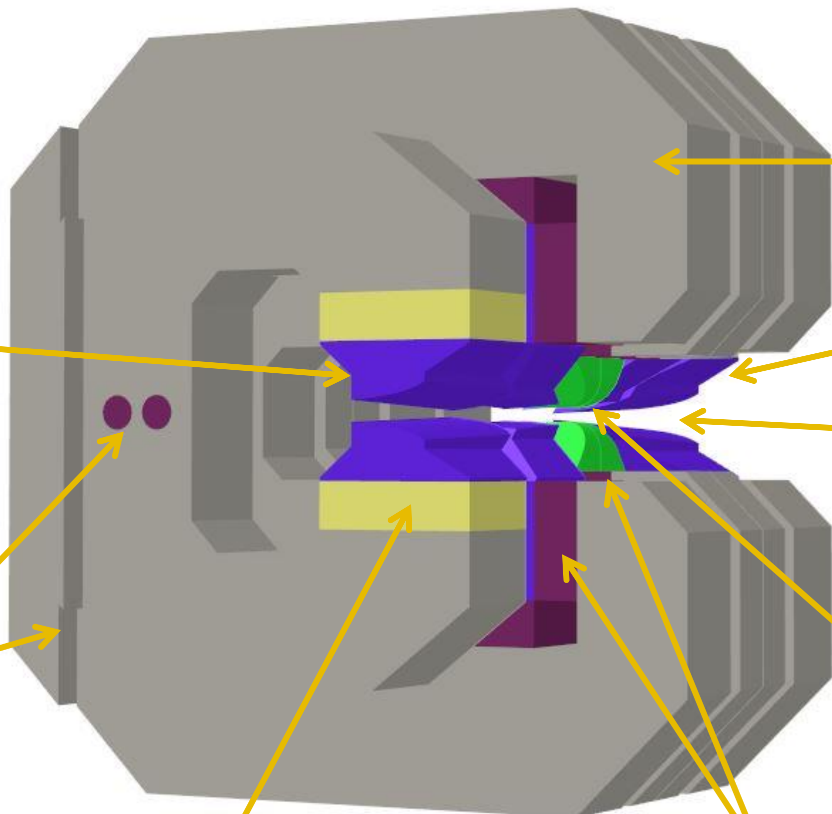
Engineering design

CLIC DRs Main Bending Magnet (Prototype)

Combined Function:
Longitudinal gradient with trapezoidal shape (2.3 T Peak)
Transverse gradient 11 Tm

Dimensions:
0.65 x 0.68 x 0.56 m

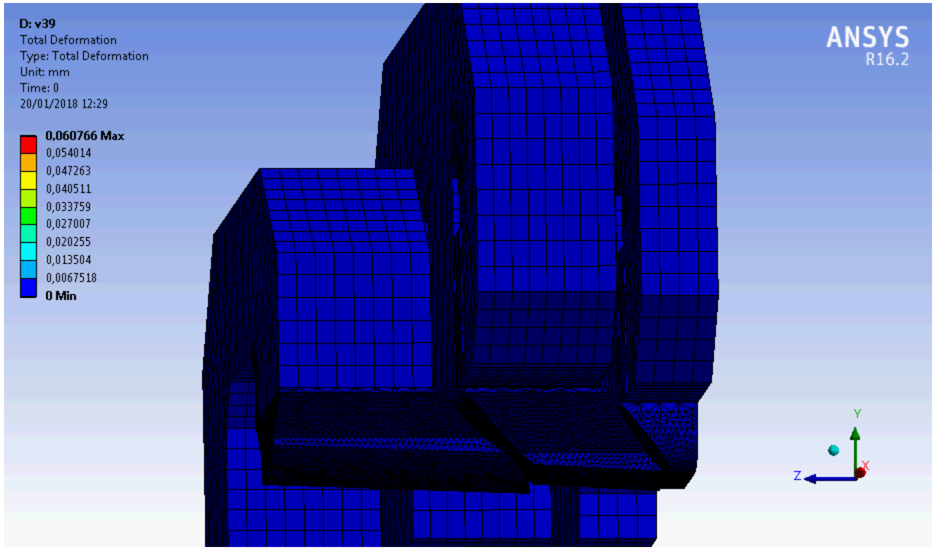
Weight: 1.2 T



Mechanical calculations

- Forces (analytically calculated with VW method):

	LF	MF	HF
Y axis	5272 N	5957 N	5425 N
Z axis	1047 N	1210 N	0 N (symmetry)



- Maximum Stress: 69 Mpa

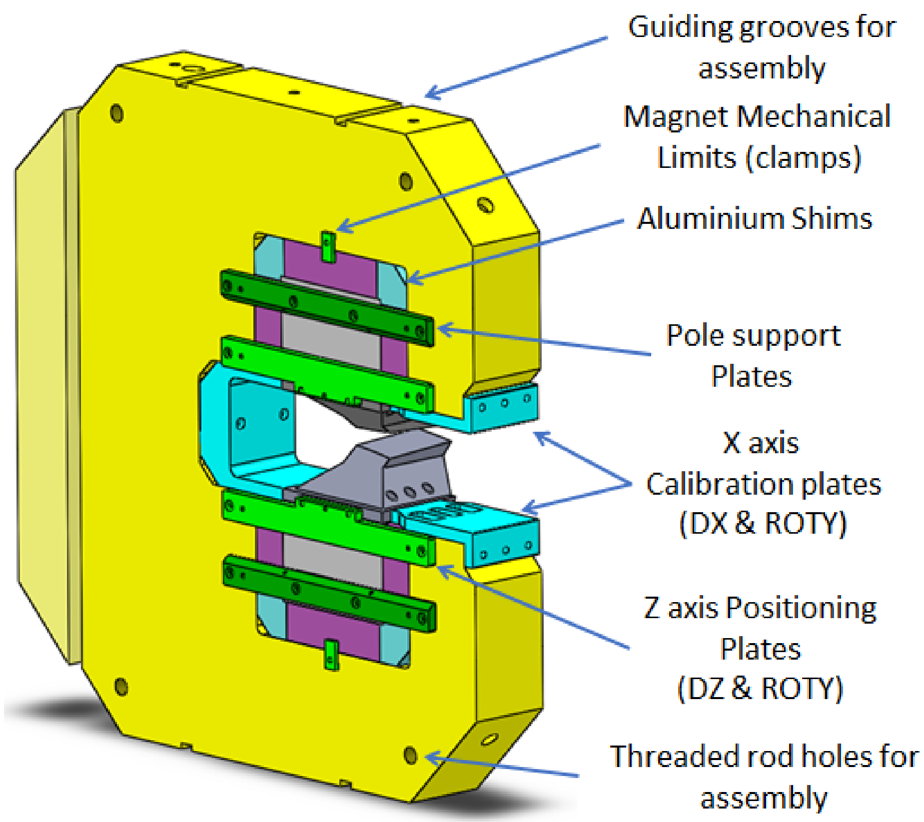
- Max. Deformations:
  - Y axis: 0.06 mm
  - Z axis: 0,009 mm

	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10
Base	10000	-567.9	5.5	2.1	-0.1	-0.1	-0.0	0.0	-0.0	0.0
Def	10000	-567.7	5.6	2.0	-0.2	-0.2	-0.1	0.0	-0.0	0.0

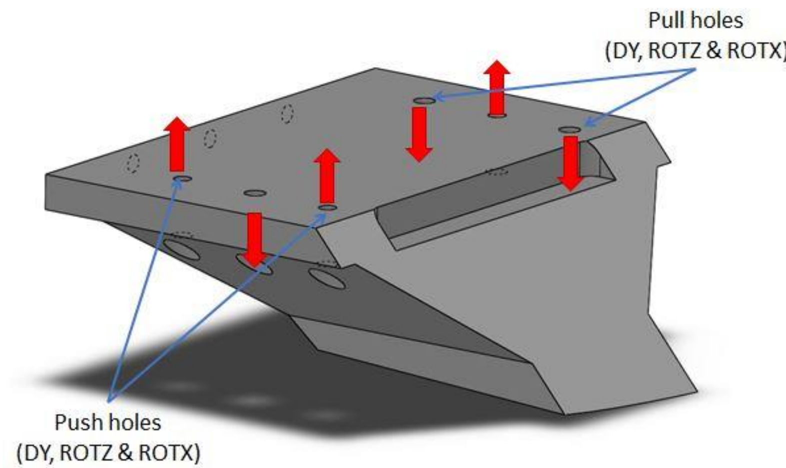
- Including these deformations in the Opera model, the multipole values are still kept within specifications.

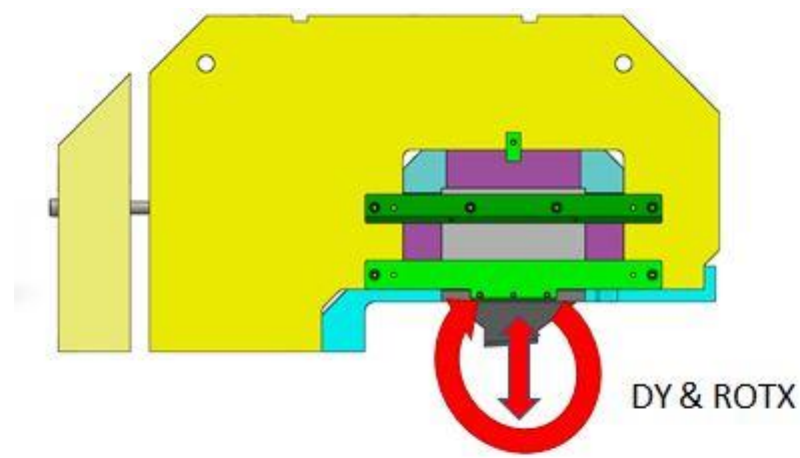
Mechanical design

- MF Module:

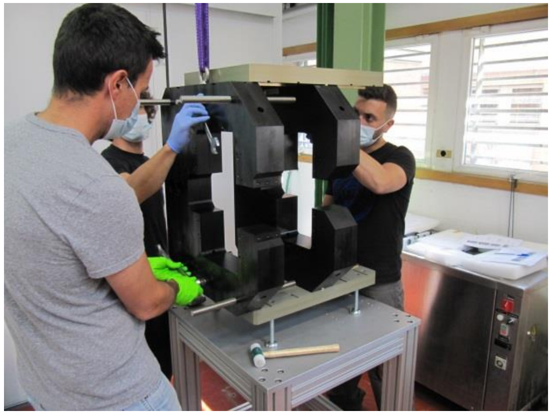


- Pole adjustments in X, Y and Z



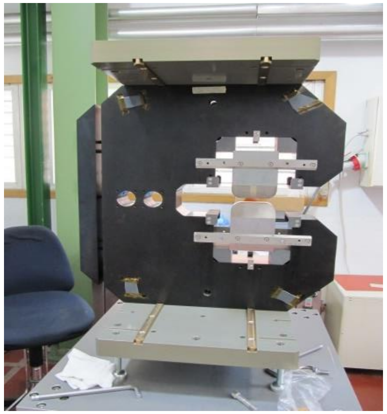


Preliminary assembly w/o magnets

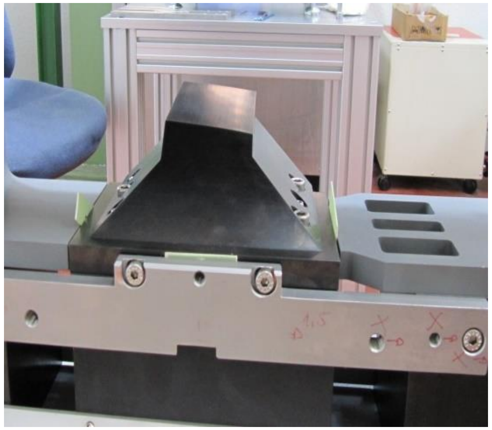


The modules' approach method was tested

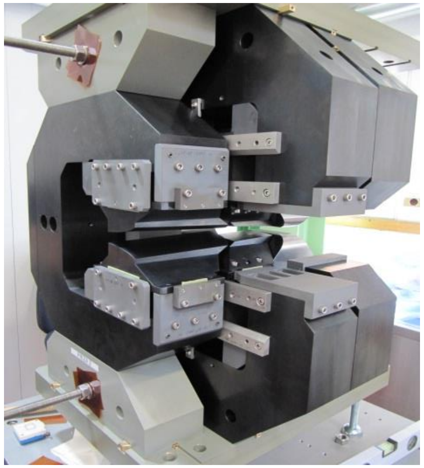
Each module was mounted separately, with all the parts except the PM



Then introduced following the bronze guides fixed to the plates

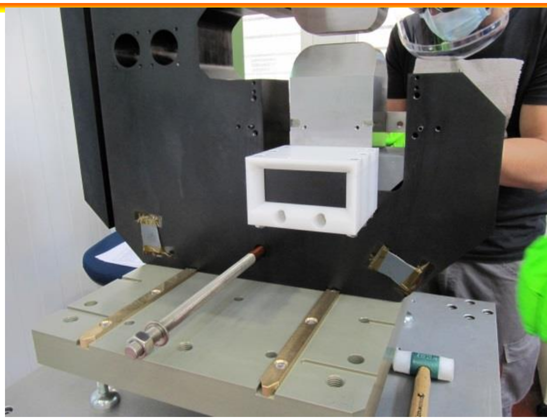


All the poles were fixed in their nominal position using gauges

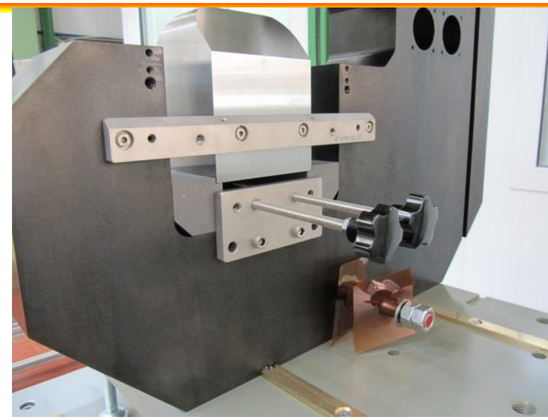


No major issues were found during this part of the process

Final assembly



The PM blocks were introduced using a POM box attached to the yoke



The insertion was controlled using these rods and plates…

…that have to be redesigned due to the huge forces involved

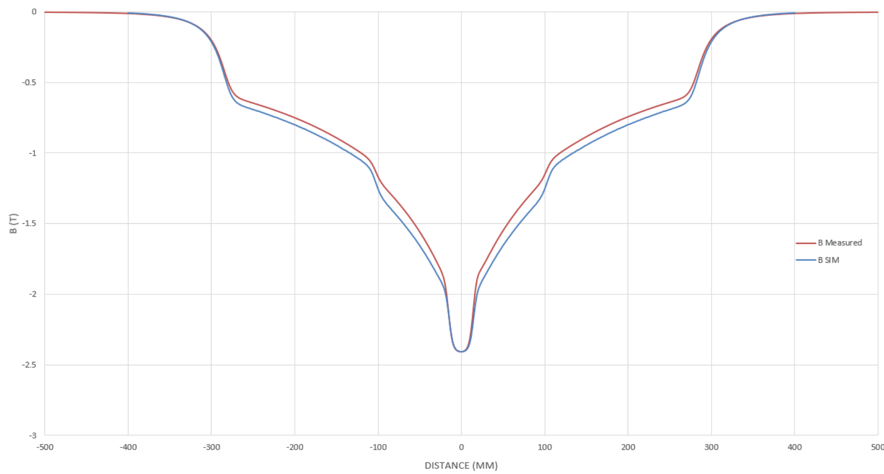
Magnetic measurements were done manually after each PM was inserted.

Module assembly

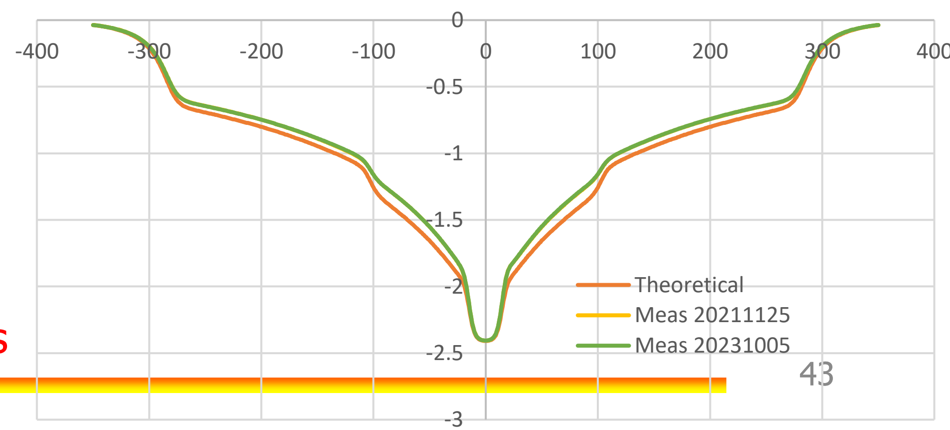
Magnet is finished

Magnetic measurements

- Proof of concept: First accelerator magnet with longitudinal trapezoidal gradient!
  Key factor in terms of beam emittance reduction

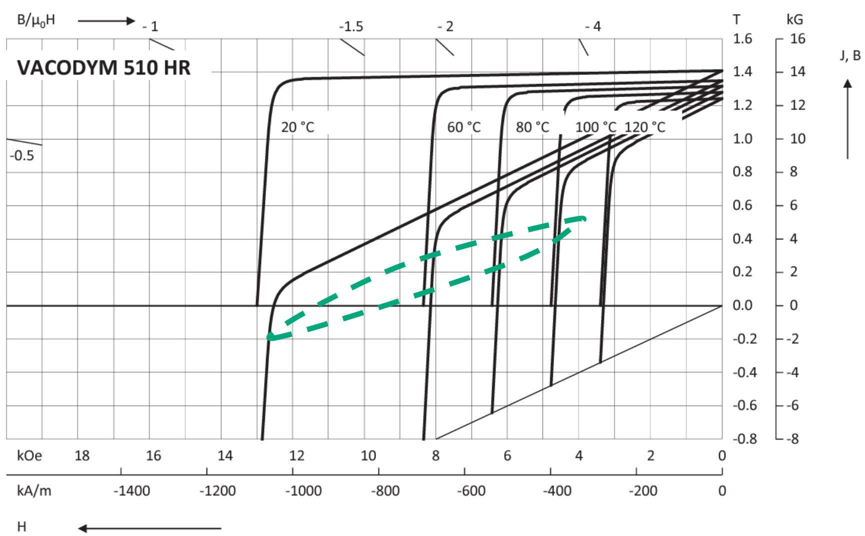


- Magnetic measurements in ALBA.
- Very good field quality achieved
- Quadrupolar component achieved
- Trapezoidal longitudinal field achieved…
  …With an issue: up to 5% difference in low and medium modules
- Design modification: missing anneal in the LF and MF poles (Armco)
- Two new annealed LF poles
- Test bench results did not change!
- Ongoing simulations on the assembly process



Magnetic materials

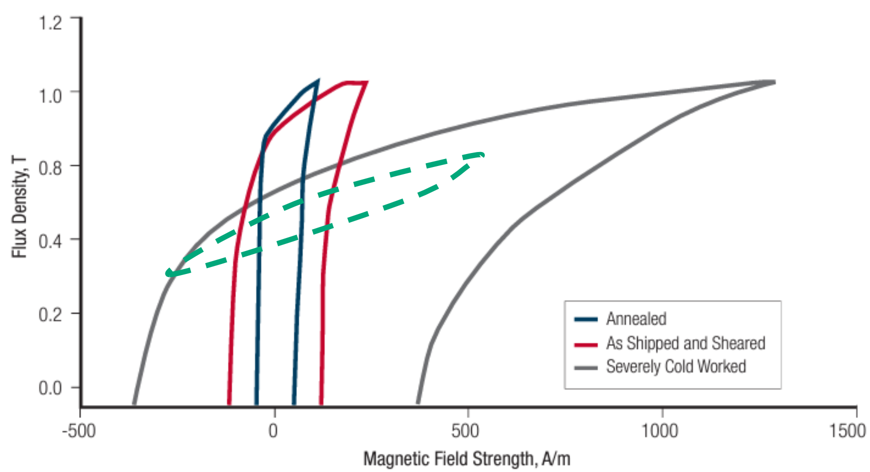
- We are checking possible demagnetization or hysteresis effects.



VAC data sheet

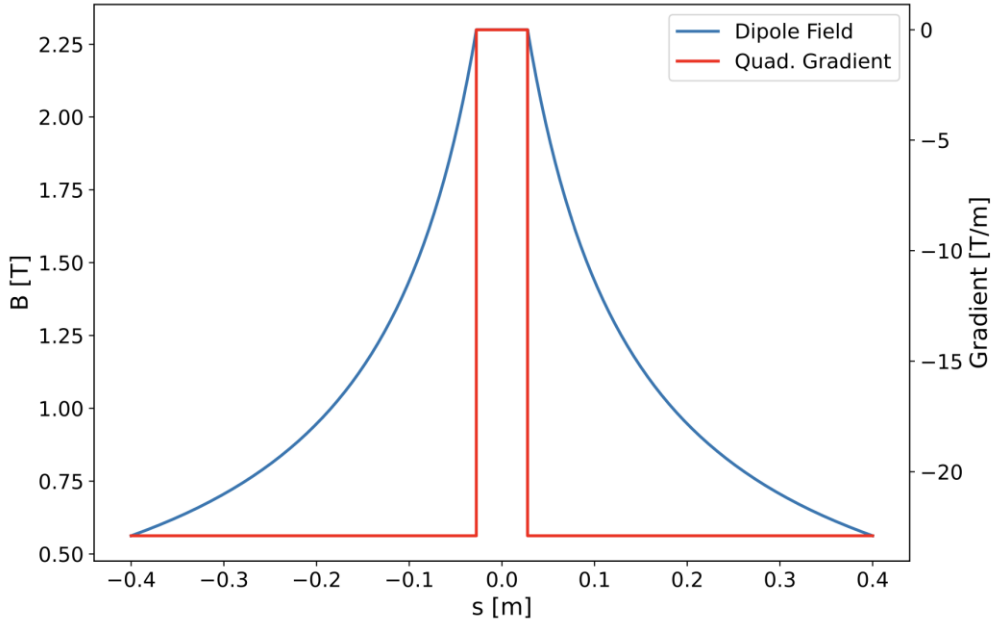
Next CAS on materials!

AK Steel data sheet



VAriable Dipole for the Elettra Ring - VADER

- ***Good field region:*** *+/- 6-8 mm*
- ***Gap:*** *17 mm*
- ***Quadrupolar gradient:*** *23 T/m*



Courtesy A. Poyet

Conclusions

- Low emittance rings include the damping rings for linear colliders and the fourth generation light sources.
- Main properties of the magnets for these facilities:
  - Very good field quality, high field strength
  - Narrow tolerances for alignment
  - Combined function magnets
- Permanent magnets take increasing importance
- We have reviewed an example of the development of a permanent magnet with variable longitudinal field: new trend for further reduction of emittance.
- Magnets are not the only limiting factor: vacuum, collective effects, dynamic aperture, injection…

Thank you for your attention!