The Challenges and Benefits of Increased Application of Permanent Magnets to Future Light Sources

FLS 2023

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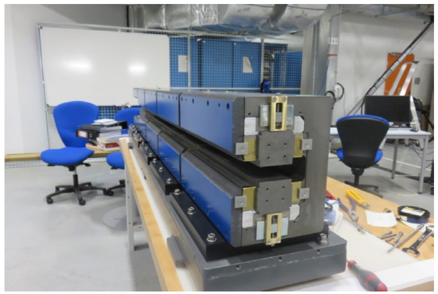
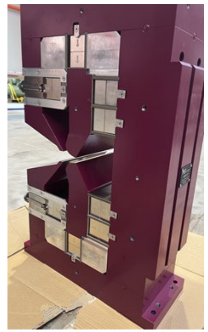


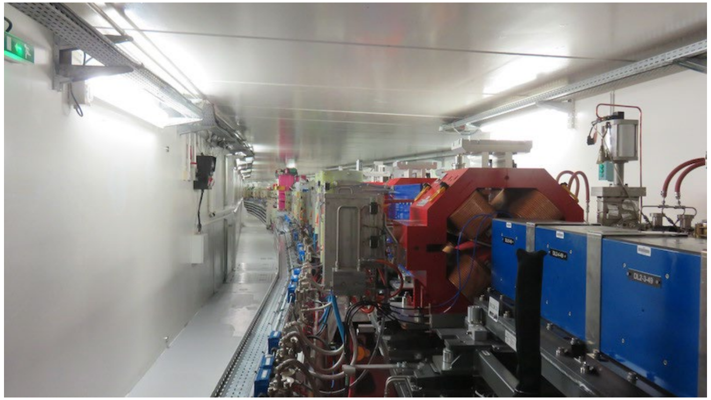
ESRF EBS Dipoles



SLS 2.0 Dipole-Quadrupole

Soleil II quadrupole

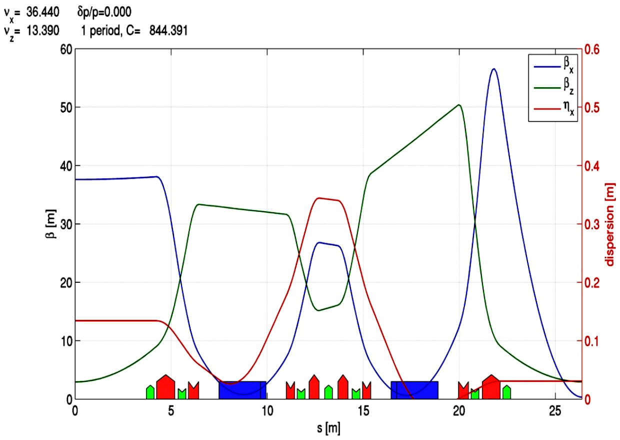
OUTLINE



- Context & motivation
- Permanent magnet materials
- Panorama of permanent magnet developments at some Light Sources
- Challenges with new MBA magnet lattices
- Summary

CONTEXT & MOTIVATIONS

Ingredient #1: Development of new low emittance magnet lattices

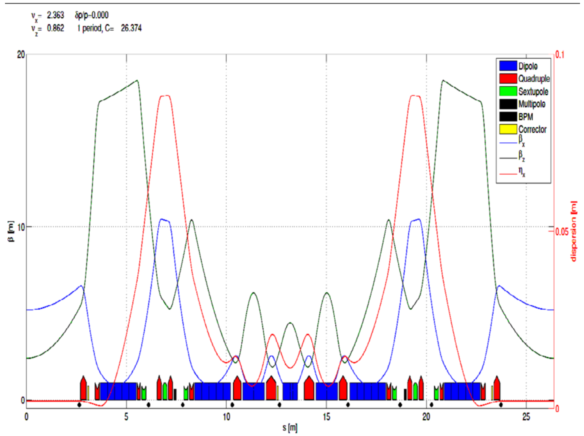


Double-Bend Achromat (DBA)

- Many 3rd gen. SR sources
- Local dispersion bump (originally closed) for chromaticity correction

Former ESRF (DBA) cell

- Ex = 4 nm•rad
- tunes (36.44,13.39)
- nat. chromaticity (-130, -58)



Proposed HMB cell (P.Raimondi)

- multi-bend for lower emittance
- Dispersion bump for efficient chromaticity
- Fewer sextupoles than in DBA
- Longer and weaker dipoles => less SR
- No need of "large" dispersion on the inner dipoles

ESRF EBS cell (7BA)

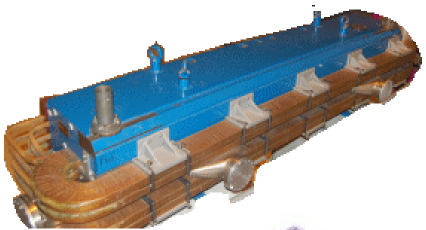
- Ex = 140 pm•rad
- tunes (76.21, 27.34)
- nat. chromaticity (-99, -82)
- In operation since 2020

Many upgrade or green field projects worldwide

CONTEXT & MOTIVATIONS (CONT'D)

Ingredient # 2: Electrical Energy

example: former ESRF dipole magnet



Power/ dipole: 10 kW
64+1 magnets
25 years operation

RUNNING COST !

former ESRF dipoles: 0.85 T

Procurement: 2.3 MEuros
Running cost: 6.8 MEuros over 25 Years
(costs updated to 2017)

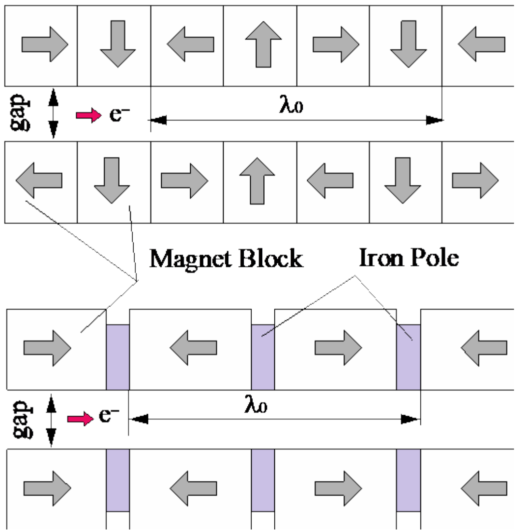
- Storage ring based Ligth Sources operate at fixed electron energy
- Increacing cost for electricity

→ develop alternative technology for constant (permanent) dipole magnets with lower running cost

CONTEXT & MOTIVATIONS (CONT'D)

Ingredient # 3:

Experience with permanent magnets (PMs) in 3rd Generation Light Sources: Insertion Devices

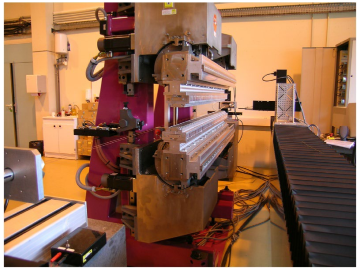


Pemanent magnet structures

Periodic transverse magnetic field along beam axis

More than 95 % of IDs are PM based

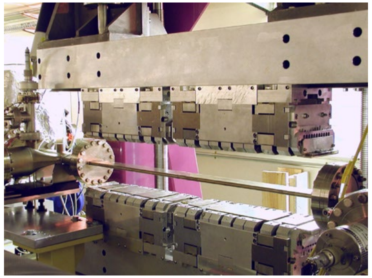
- 20-30 years experience in many labs
- Field range: 0.1 to 3 T
- Period range : 10 mm to 300 mm
- Many different concepts



Revolver undulator

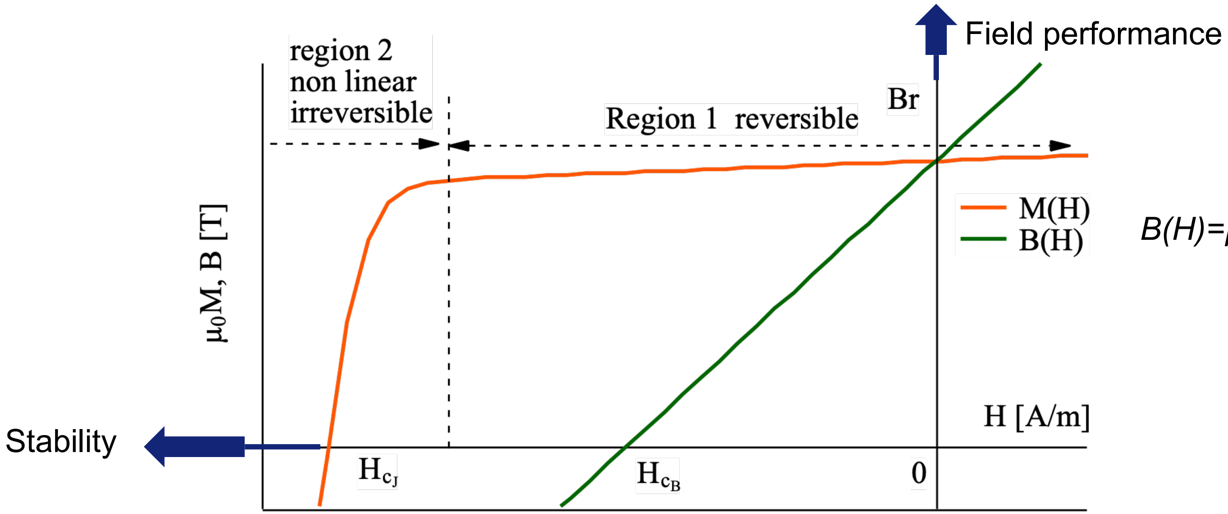
Petra III Helical Undulator

In-Vacuum Undulator



High Field Wiggler

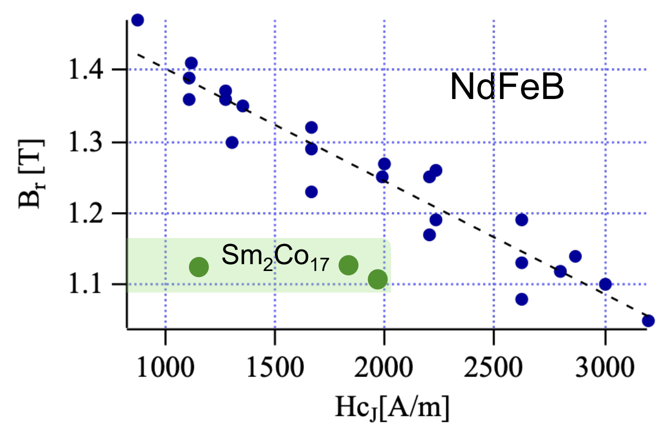
PERMANENT MAGNET MATERIAL



$B(H)=\mu_o\ (H+M(H))$

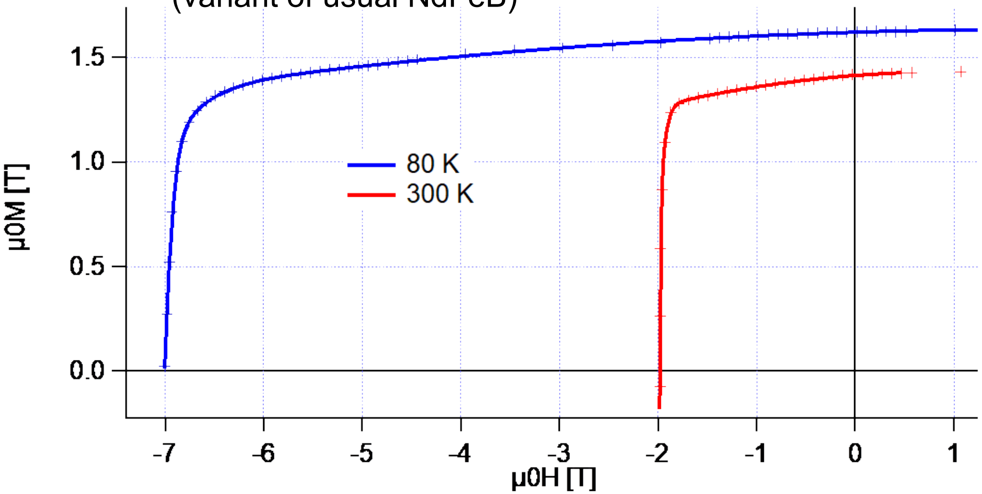
		Hc_j [A/m]
Sr Ferrite	0.2 - 0.42	150- 320
NdFeB	1.45 – 1.05	900- 3200
$SmCo_5$	0.8 - 0.9	2000
Sm_2Co_{17}	1.05 - 1.15	> 1100 - 2000

Practical materials for accelerator PM devices



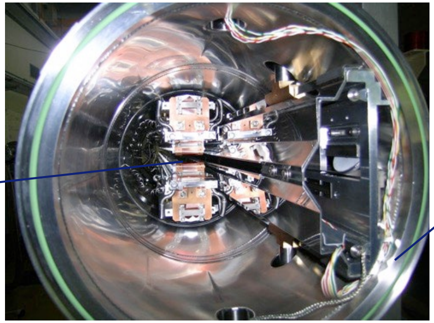
PM MATERIAL AT LOW TEMPERATURE

material $Nd_{0.2}Pr_{0.8}FeB$ with GBD
(variant of usual NdFeB)



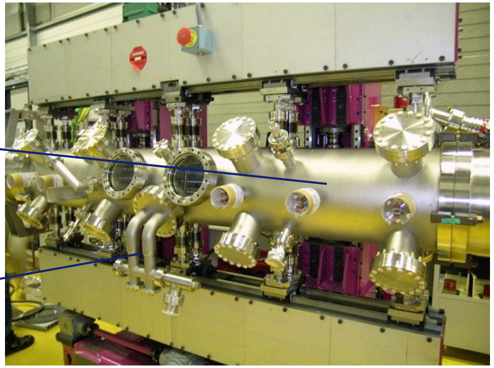
- PM materials develop interesting properties at low temperatures (Liquid nitrogen)
  - Very High coercivity (stability)
  - Higher remanence
- Used for the construction of Cryogenic Permanent Magnet Undulators (CPMUs)

magnets



Vacuum chamber
D=0.3 m, L=2 – 3 m

LN_2 Cooling
outlets



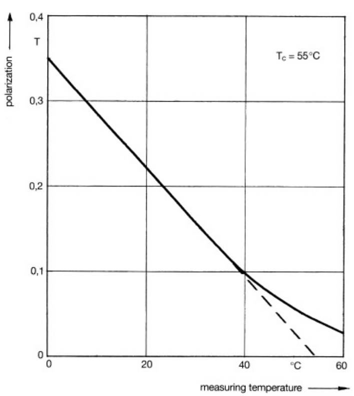
PM MATERIAL STABILITY VS TEMPERATURE

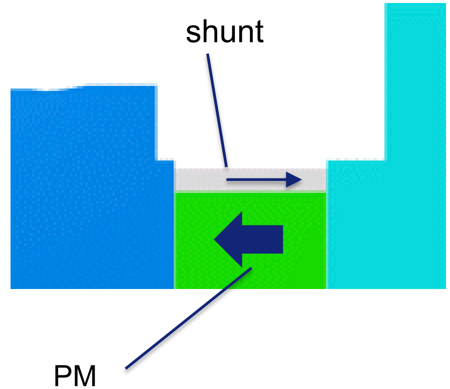
PM materials are sensitive to temperature variations

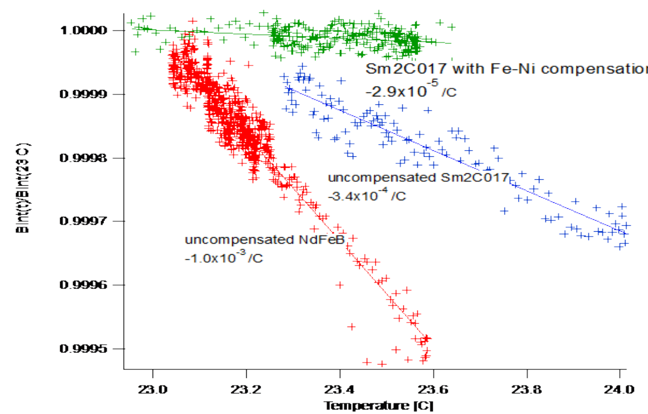
- Can be compensated if PM device has remote tuning capacity
- Can be compensated with a passive scheme
  - Fixed field devices
    - Use of a passive correction with special Fe-Ni alloys
    - Low curie temperature (40 ~ 100 deg C)
    - Flux shunt approach
    - dB/B < 10^{-5}/C after compensation

	cfBr[%/C]
Sr Ferrite	-0.2
NdFeB	-0.11
$SmCo_5$	-0.04
Sm_2Co_{17}	-0.035

Best material for
- Thermal stability
- Resistance to radiation induced demagnetization







TIME STABILITY

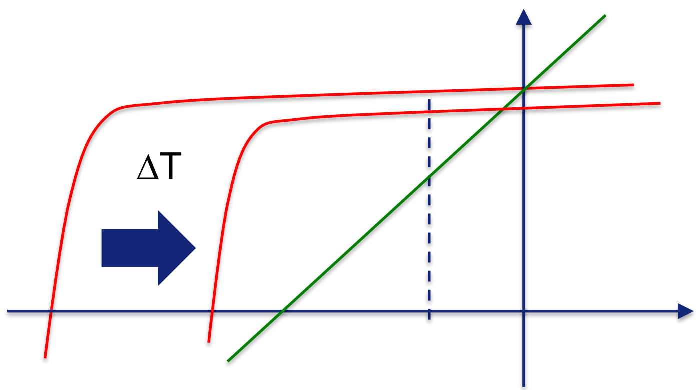
Permanent magnets : metastable energy state
Slow demagnetization vs time due to thermal activation

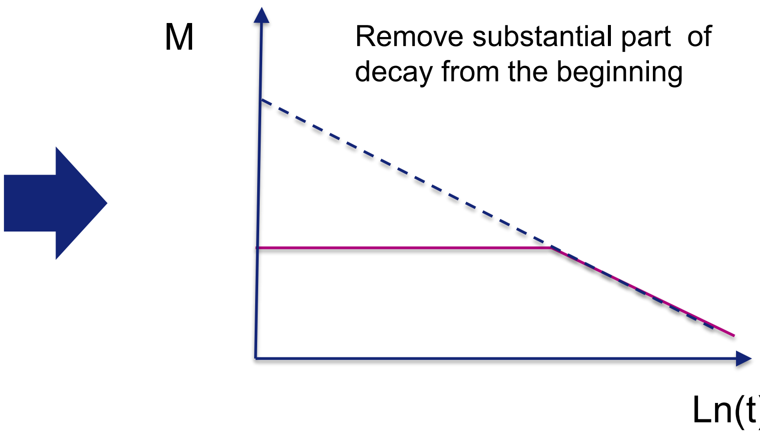
Magnetic viscosity

Constant temperature
Constant working point in PM

$$\frac{\Delta M}{M_0} = -\frac{s}{M_0}\ln(t/t_0) = -\lambda\ln(t/t_0) = \frac{\Delta B}{B_0}$$

Pre-stabilization with temperature: increase temporarily magnetic viscosity

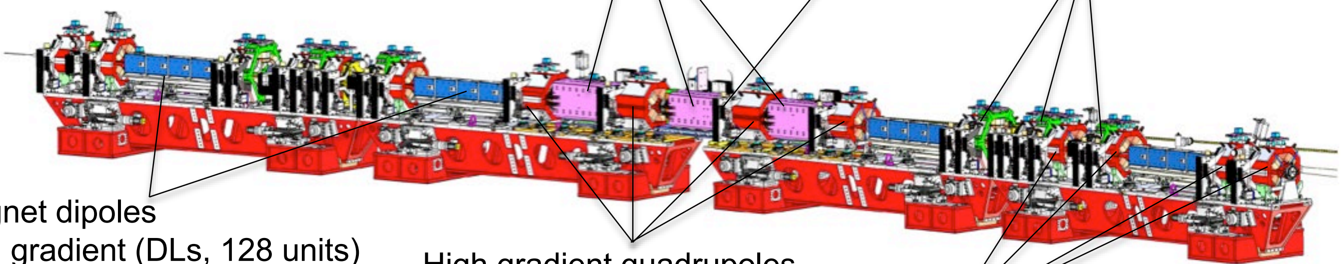


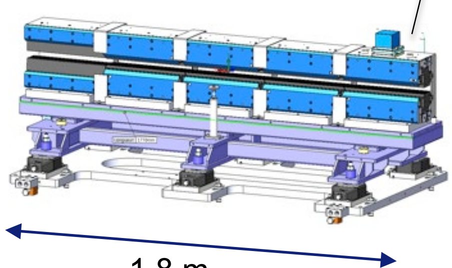


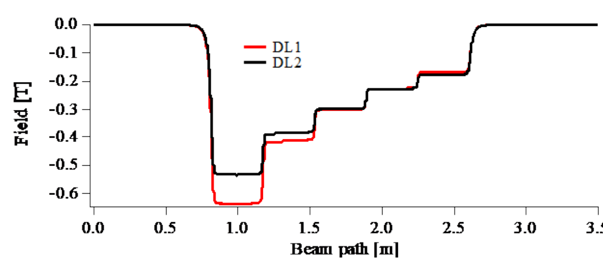
EBS LATTICE MAGNETS

Magnets in one cell (~26.3 m), 32 cells for the ESRF storage ring

- Compact magnet lattice
- 4 supporting girders/cell





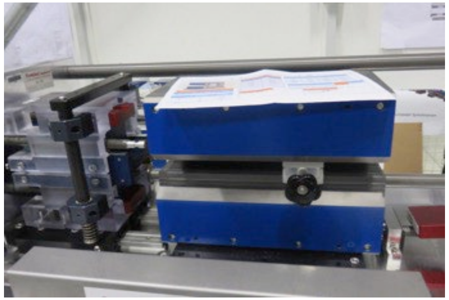


DLS ASSEMLBLY & MAGNETIC MEASURMENTS (INHOUSE)

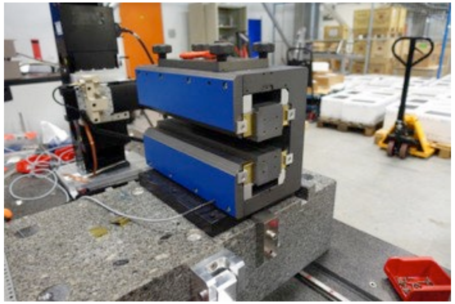
Magnet blocks (Sm_2C0_{17})

Machined empty modules

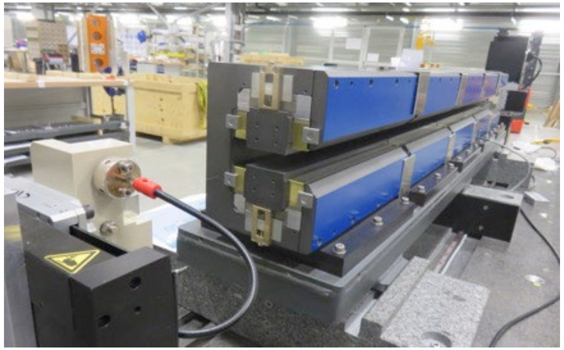
Magnet block insertion in modules (dedicated tools)



Magnetic measurement & field tuning for individual modules (stretched wire)



DL assembly



Magnetic measurements of full DL & final field tuning((stretched wire)

- 13 000 PM blocks
- 6 tons of PM material

MAGNETIC MEASUREMENTS & FIELD TUNING

For PM devices magnetic measurements are specifics:

- No remote field tuning
- Magnetic field (integrated) needs to be measured accurately

Passive field tuning relies on flux shunt methods

Needs larger field than nominal for the uncorrected PM structure

POWER AND ENERGY CONSUMPTION

ESRF figures

	ESRF 2018	EBS
Dipole magnets, Cabling and Power supply (DQ's for EBS)	720 kW	188 kW
Quadrupole, Sextupoles, Octupoles without correction	1625 kW	984 kW
Correctors and Steerers (average with aligned magnets)	10 kW	11 kW
Total	**2355 kW**	**1183 kW**
Energy for one year operation (7200 H: USM+MDT)	**16.9 GWh**	**8.5 GWh**

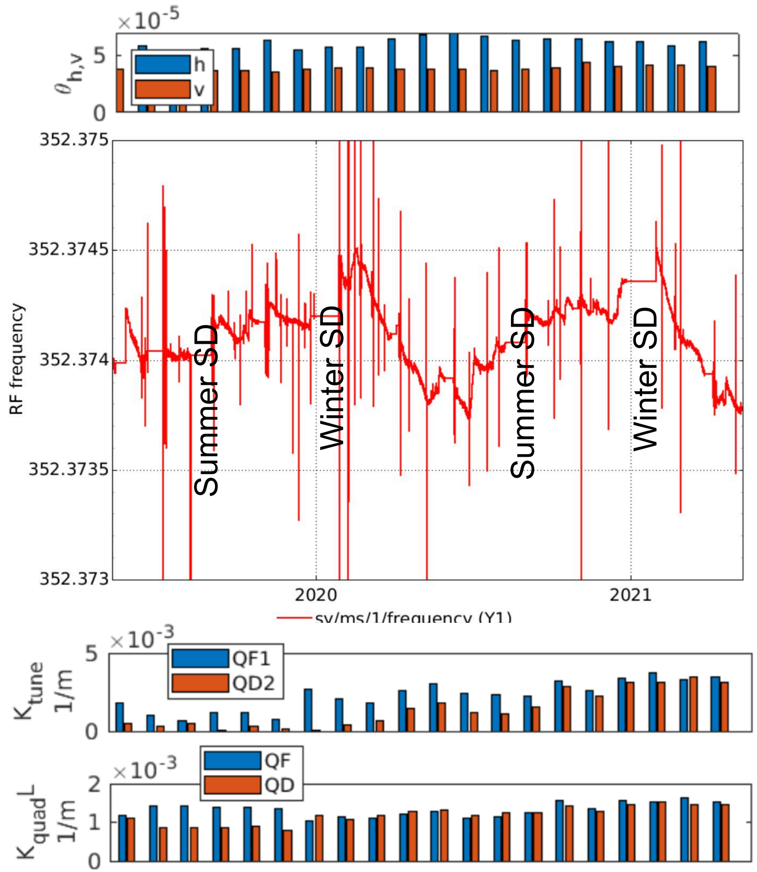
Courtesy of J.F Bouteille

PM dipoles + reduced current density in electromagnets

The Electrical power required for the EBS magnets is half that of the previous lattice

No maintenance /intervention on DLs since installation

PERMANENT DIPOLES DRIFTING AFTER 2 YEARS ? NO FROM A B.D. POINT OF VIEW



Horizontal steerers strengths not drifting, average is kept to zero to use RF frequency for SR length variations

RF frequency shift is following seasonal almost-reproducible variations.

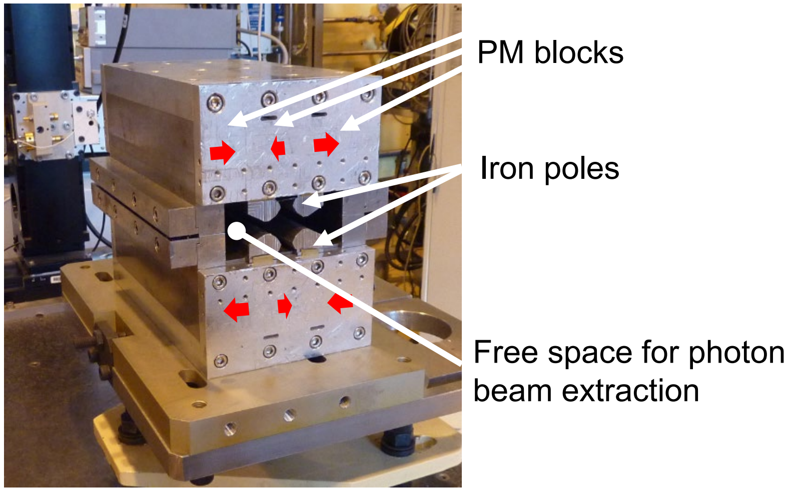
Imagine the SR as a VERY SLOW BOOSTER RAMPING DOWN in ENERGY. RF will not change. Beam ENERGY would reduce to adapt to the lower dipole fields in the SR.

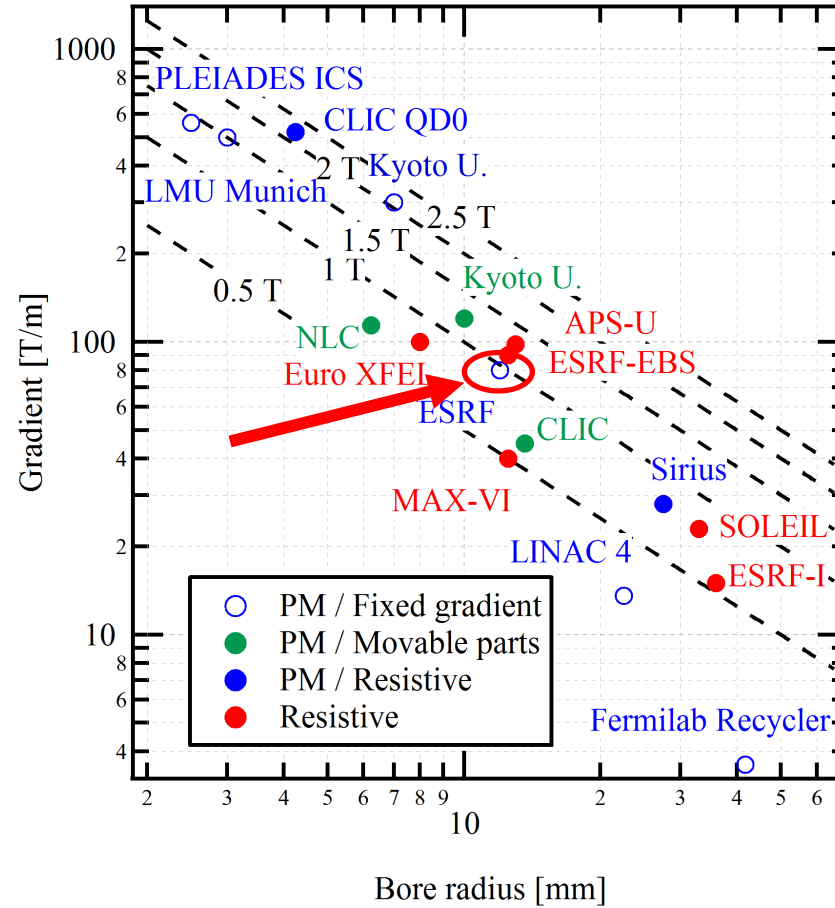
We may then look at the AVERAGE QUADRUPOLE correction

After 2 years of operation it is not possible to observe clearly any loss of field in the permanent dipoles.

Slide form S.Liuzzo: ESRF beam dynamics group)

PERMANENT MAGNET QUADRUPOLES





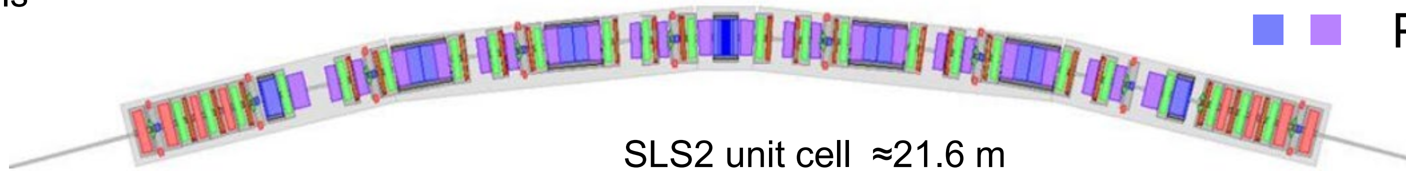
- ESRF Fixed gradient PMQ R&D
  - Iron dominated magnet
  - *Gradient 85 T/m, r_0=12 mm*
  - *$DG/G \leq 10^{-3}$ at $\pm r_0/2$*

Feasabilty of PMQ for SR Light sources

SLS 2.0 MAGNET LATTICE

E=2.7 Gev
12 7BA cells

New ring installation : October 23-December 24



PM devices

SLS2 unit cell ≈21.6 m

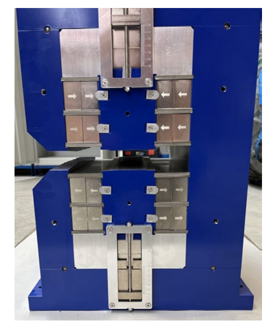
PM material: NdFeB

Magnet type	Field/gradient	technology
Dipoles	1.35 T	PM
Combined DQ	0.85 T - 40 T/m	PM
Reverse Bend	0.27 T – 80 T/m	PM
Quadrupoles	90 T/m	EM
Sextupoles	6000 T/m^2	EM
Octupoles	60000T/m^3	EM

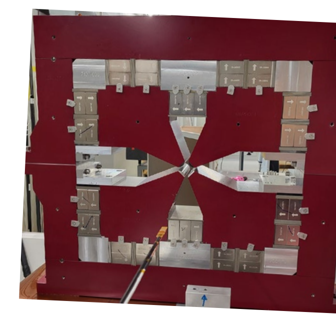
≈ 890 electromagnets
≈ 420 permanent magnets

- 34000 NdFeB magnet blocks

Combined Dipole/quadrupole



Dipole



Reverse bend
(shifted quadrupole)

Significant magnet crosstalk studies

Magnet bore. Diameter/gap ≈ 22 mm

Thanks to S. Sanfilipo, PSI

SOLEIL II

E=2.75 Gev
20 (7BA-4BA) cells

Project currently in TDR phase

≈ 820 electromagnets
≈ 470 permanent magnets

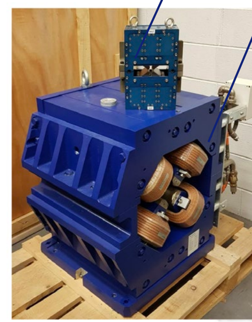
PM material: Sm_2CO_{17}

Magnet type	Field/gradient	technology
Combined DQ	0.6-1.2 T / 17-22 T/m	PM
Reverse Bend	0.27 T – 80 T/m	PM
Quadrupoles	0.1-0.22 T/ 80-120 T/m	PM
Sextupoles	8200 T/m^2	EM
Octupoles	100000/m^3	EM
N Quad corrector	≈ 1T integrated grad.	EM

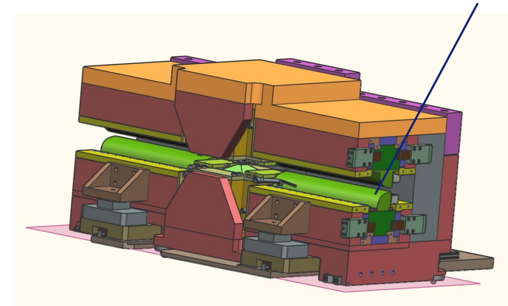
Magnet bore. Diameter/gap 16-23 mm

SOLEIL II PM quadrupole

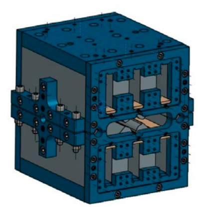
Present SOLEIL EM quadrupole



DQ gradient with tapered single pole



Long PM DQ quadrupole
Central BM field (1.2, 1.7, 3 T)



PM quadrupole
Reverse bend

Structure comparable to Sirius superbend (Brazil)

Thanks to F. Mareau, SOLEIL

PETRA IV PROJECT

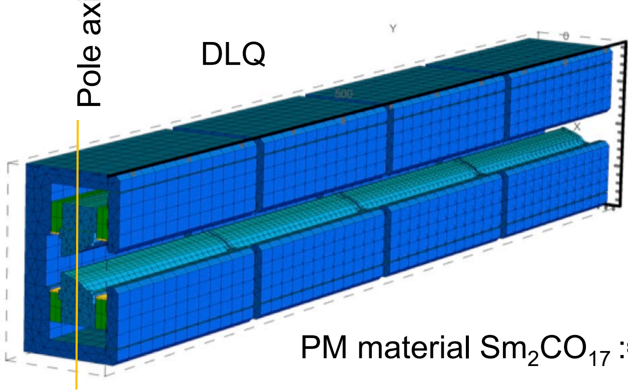
E=6 Gev
72 6BA cells

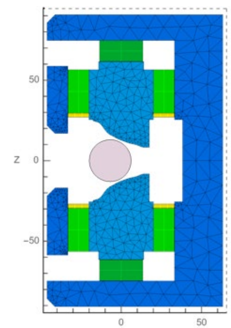
Project currently in TDR phase

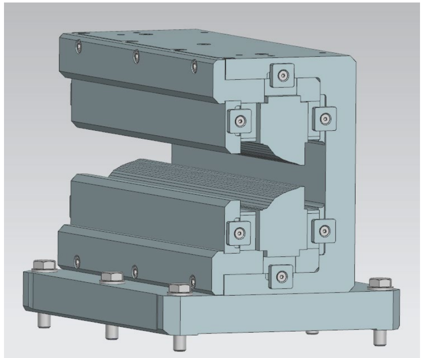
All PM dipoles ≈ Similar as EBS + transverse gradient (0.19-0.29 T, 6.6-11.3 T/m)
3 families

Pole axis

DLQ

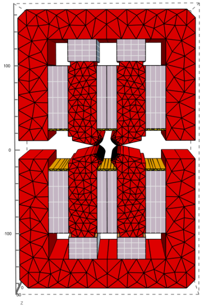






DLQ module

PM material Sm_2CO_{17} :≈ 45 000 PM blocks for 432 Dipoles



- Gradient: 120 T/m
- Bore Radius: 11 mm
- GFR: +-6.5 mm
- DG/G0: 5.10^-4
- Length: 0.169 m
- Vertical gap: 8.8mm

InnovEEA grant (KIT, DESY, GSI, HZB)
Design studies for PM-based
high-gradient quadrupoles

Thanks to M. Tischer , DESY

ELECTRICAL ENERGY

Energy [GWh] per year for the storage ring magnets

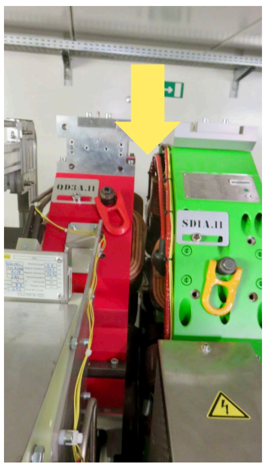
facility	Before Upgrade	After Upgrade	ratio
ESRF	16.9	8.5	0.5
SLS	6.4	2.6	0.4
SOLEIL	5.4	1.2	0.22

The reduction in electrical energy for the magnets is substantial

SOME ISSUES :MAGNETIC CROSSTALK

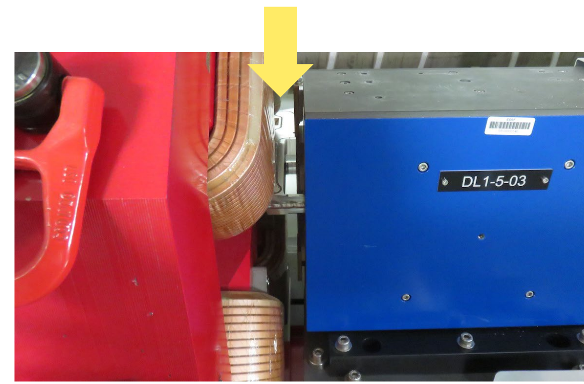
- **very compact new magnet lattices**
  - Reduced distances between successive magnets (4-15 cm yoke to yoke @ EBS)
  - Slightly modified field strength/quality in involved magnets
  - Common denominator for all projects

examples



quadrupole sextupole

DQ magnet quadrupole



quadrupole PM DL

MAGNETIC CROSSTALK (CONT'D)

- For EM magnets the field strength can be generally retuned

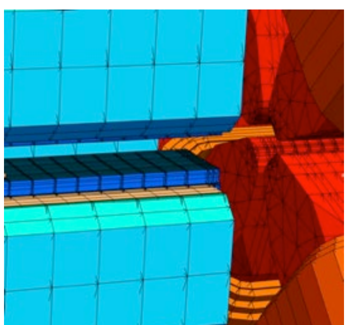
Challenge for PM devices

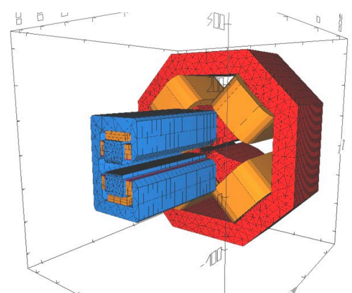
- Field strength & quality for standalone PM magnets must anticipate cross-talk effects
  - Time consuming 3D magnetic simulations
  - Dedicated magnetic measurements

Different possible approaches:

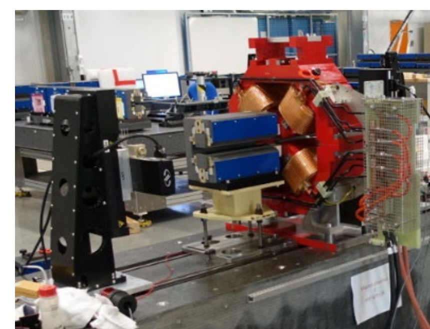
- Local change magnet to magnet distance
- Use of magnetic shield or modification of magnet yoke
- Refine the nominal PM magnet field strength
- ….

Magnetic simulations





Magnetic measurements

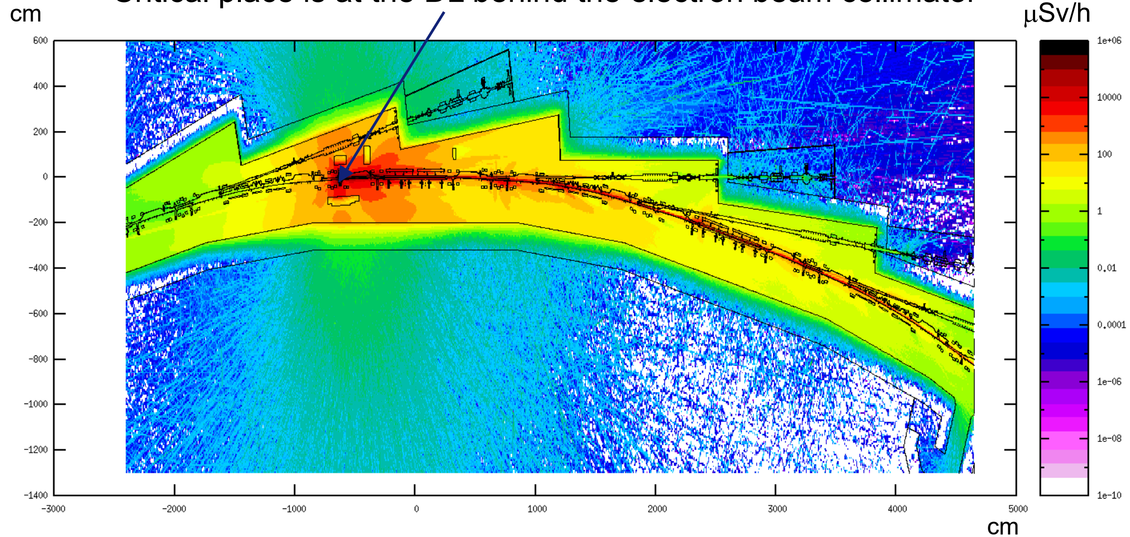


LONG TERM STABILITY

Main concern: radiation induced demagnetization in magnet blocks vs time

- Machine dependent
- Control of beam losses : use of (many) BL monitors
- Possible simulations (ex FLUKA)

Critical place is at the DL behind the electron beam collimator



FLUKA simulations

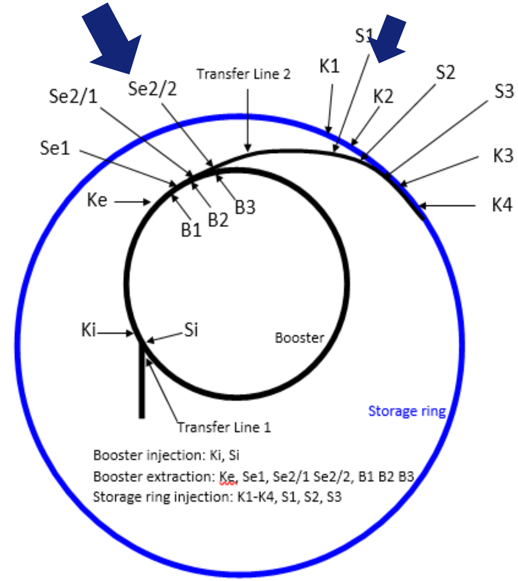
- Primarily done for safety requirements
- Input: electron losses due to Touschek effect
- Worse case:
  - 90 mA 16 bunchs
  - Estimated 1.8 H lifetime in EBS
- Evaluation of radiations in DL
- Photon neutron dose in permanent magnets

Neutron doses at PM blocks are found lower than in PM of In-Vacuum undulators at minimum gap (in operation since 15 years)

However this should be considered only as an indication …

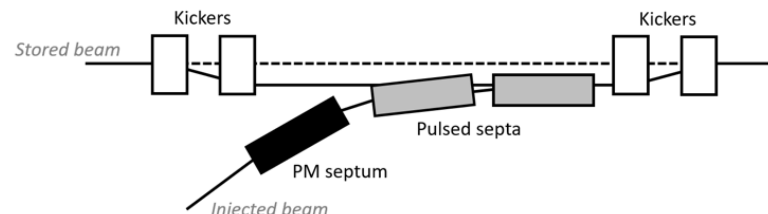
PERMANENT MAGNET SEPTA: R&D TOPIC

Survey of field stability vs time



Main parameters

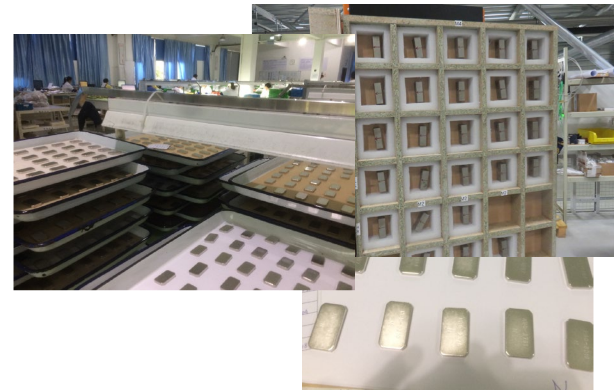
- Field: 1 T
- Lengths: 0.57 m (Se2/2) and 0.98 m (S1)
- Minimum gap: 13 mm
- Injected to stored beam distance in PM septum: 127 mm
- Same technology & PMs as DL magnets



- PM septa installed in in area with possible high beam losses (injection area)
- So far no visible change in PM septa strength since January 2020
- to be continued ….

PM RECYCLING

New magnet blocks before assembly



Increasing use of PM material in accelerators

- Recycling the PM material becomes an obvious question but with specificities for accelerators

- needs to be carefully checked for non activation
  - temporary storage
  - dedicated measurement system & validated procedure to be done inhouse before release (rules defined with ASN)

- Presently preparing transfer of old PM material used for undulators to a local company (MagREEsource)

Robotized measurements done for the old SR components

SUMMARY

The application of permanent magnet in the accelerators of light sources has developed rapidly during the last 10 years

- **Complicated compact PM structures can be built , technology reaching progressively maturity**
  - Segmented dipoles with longitudinal gradient
  - Combined function magnets (DQ)
  - High gradient quadrupole magnets
  - Important progresses in magnetic cross-talk control with PM devices thank to performing simulation tools
  - Dedicated magnetic measurements & field tuning methods
  - Potential of permanent magnets at cryogenic temperature to be evaluated (80 K)

- **Substantial reduction of electrical energy consumption**

- **Long term stability to be surveyed**

- **PM life cycle management**

THANK YOU FOR YOUR ATTENTION