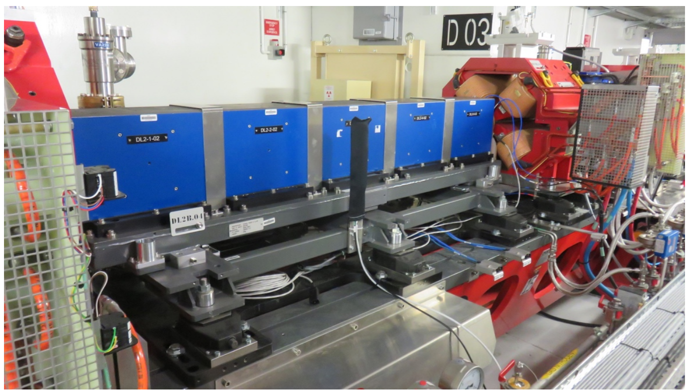
5th Workshop Energy for Sustainable Science at Research Infrastructures

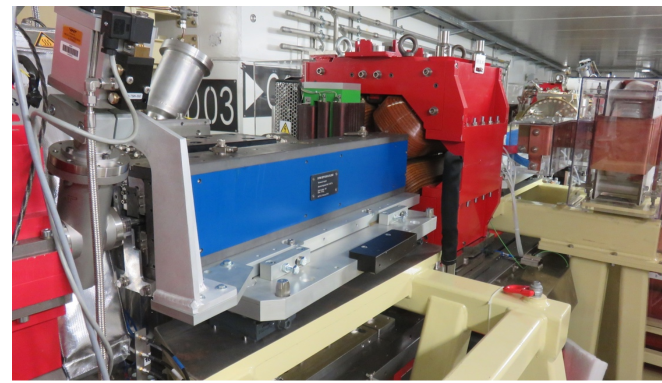
PSI, 28-29 November 2019

Permanent Accelerator Magnets for Light Sources

J.Chavanne

ESRF, Grenoble , France





ESRF | The European Synchrotron

OUTLINE

Storage ring based Light sources

- 3rd Generation Light Sources
  - Experience with permanent magnets
- 4th Generation Light sources
  - context
  - Potential for permanent accelerator magnets
- Example of ESRF upgrade: EBS
- Summary

3RD GENERATION LIGHT SOURCES


ESRF 6 GeV (France)

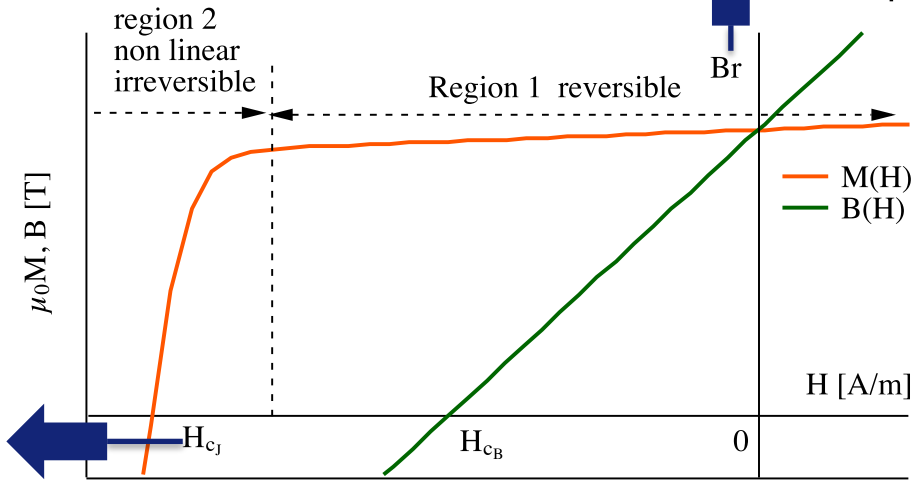

APS 7 GeV (USA)


SPRING8 8 GeV (Japan)

- **Fully dedicated to Insertion Devices**
  - Large development of **Insertion Device**, **permanent magnet technology**
  - Several **undulators** installed in straight sections (~5m)
- First high energy facilities in 1990-2000 (6-8 GeV), then many medium energy (~3GeV),
- Horizontal emittance of a few nm.rad, hard X-rays
- High brilliance **~ 10^{19}** ph/s/0.1%bw/mm^2/mrad^2 **limited by horizontal emittance of electron beam.**

PM MATERIALS

Field performance

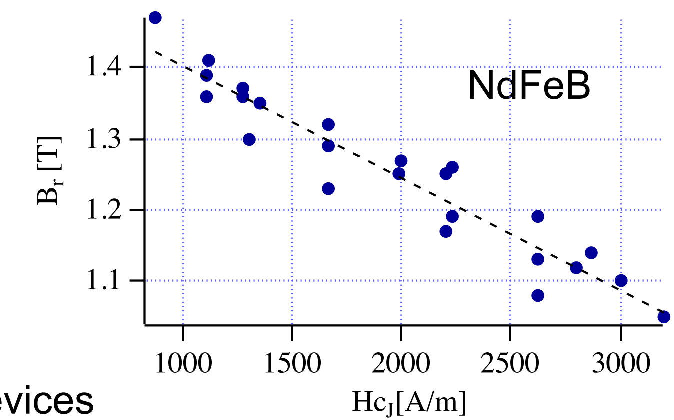


$$B(H)=\mu_o\,(H+M(H))$$

Stability

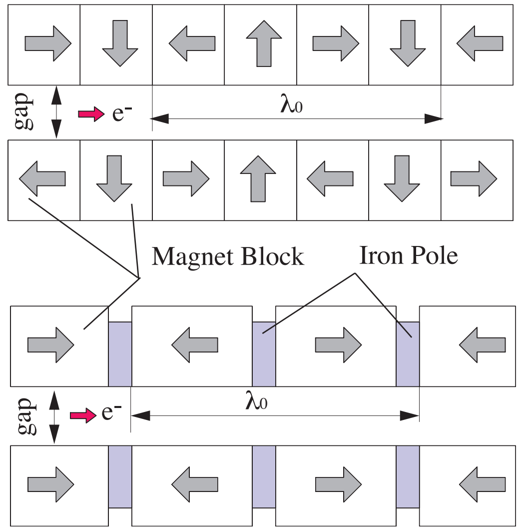
Material	Br [T]	Hc_j [A/m]
Sr Ferrite	0.2 - 0.42	150- 320
NdFeB	1.45 – 1.05	900- 3200
$SmCo_5$	0.8 - 0.9	2000
Sm_2Co_{17}	1.05 - 1.15	> 1500 - 1900

Highest temperature stability



Practical materials for accelerator PM devices

Periodic PM arrays for the production of high brilliance X-ray beams



$$B \approx \alpha B_r \exp(-\pi\, gap / \lambda_0)$$

Technology

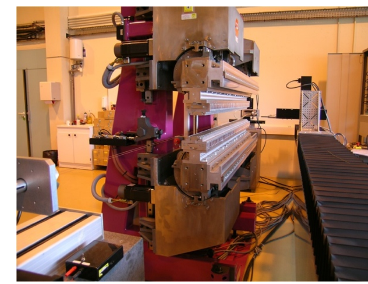
p.m material remanence

undulator period

Undulator peak field

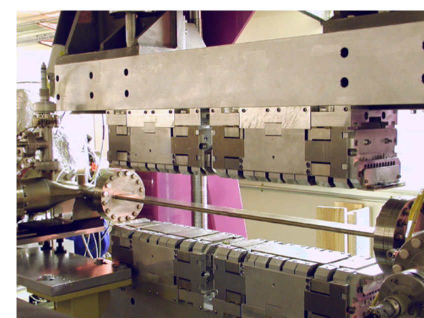
More than 95 % of IDs are PM based

- Field range: 0.1 to 3 T
- Period range : 10 mm to 300 mm
- Many ID types
  - Helical undulators
  - Revolver undulators
  - Wigglers
  - Etc ..



ESRF revolver undulator

PETRA III PM Helical undulator



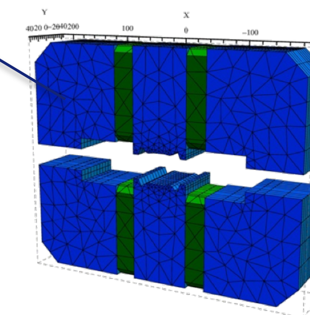
ESRF 3.1 T PM Wiggler

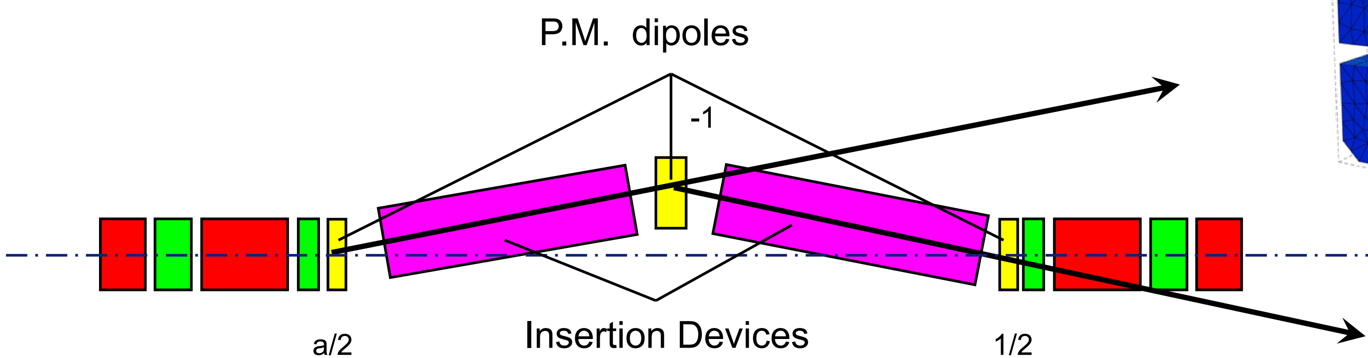
PM DEVICES FOR CANTED UNDULATORS

Short PM Dipoles for canted undulators

- Angular separation of undulator beam in same straight section
- 3 short compensated PM dipoles
- up to 5.5 mrad angle @ 6 GeV
- PM solution -> compactness
- Sm_2C0_{17} PM material
- 10 years stable operation @ ESRF

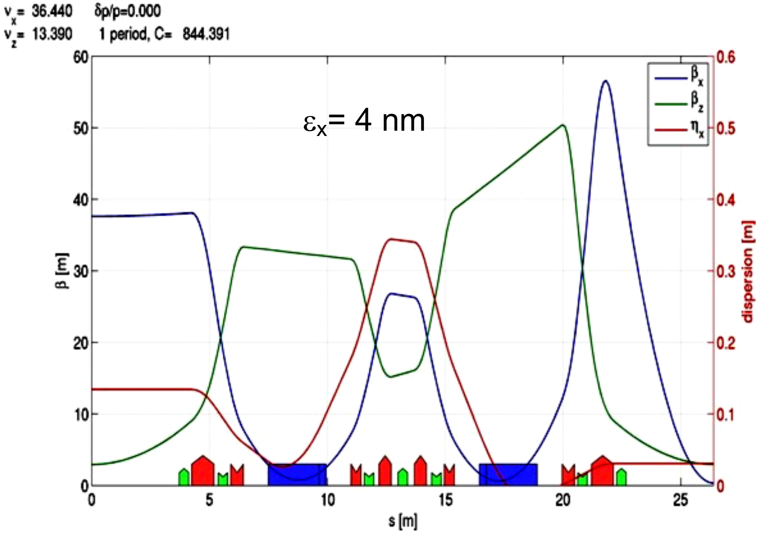
ESRF canting magnet (dipole field)





Schematic (not scaled)

4^{TH} GENERATION SR BASED LIGHT SOURCES: THE EVOLUTION TO MULTI-BEND LATTICE

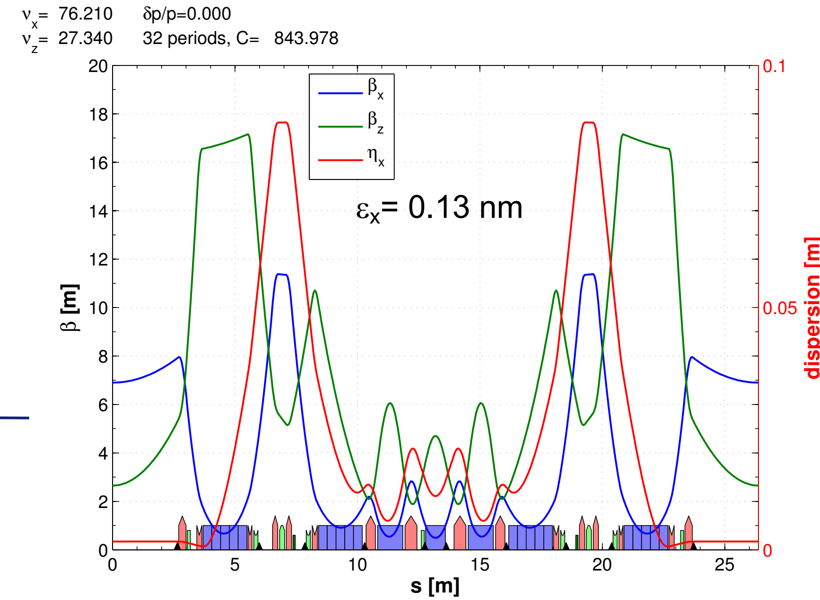


Double-Bend Achromat (DBA)

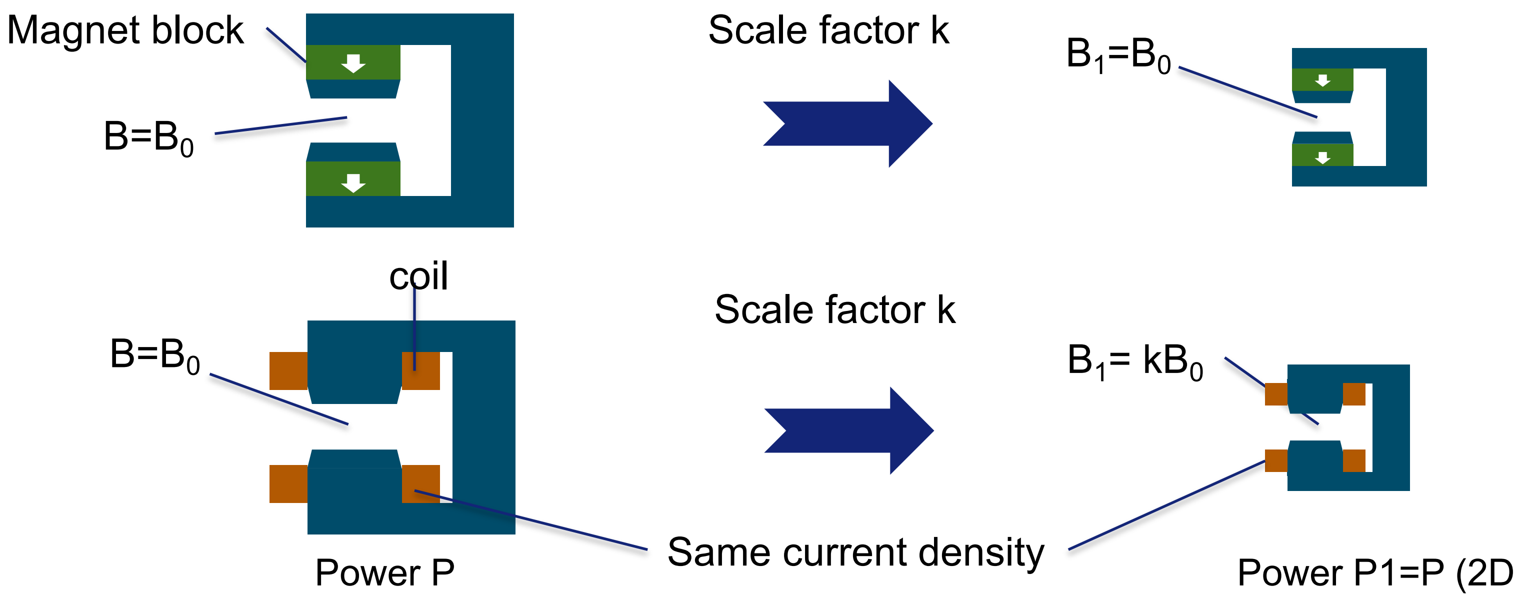
- Many 3rd gen. SR sources
- Local dispersion bump for chromaticity correction
- Large/moderate beta function

Multi-Bend Achromat (MBA) for lower emittance

- Hybrid Multi-bend (P. Raimondi)
- Dispersion bump for efficient chromaticity correction
  - “weak” sextupole B”< 0.5 kT/m
- Smaller beta functions
- Longer & weaker dipoles
- High gradient quadrupoles
- Higher number of magnets/cell: **compact magnet lattice**



GEOMETRICAL SCALING: SIMPLE CONSIDERATIONS



Small aperture magnets

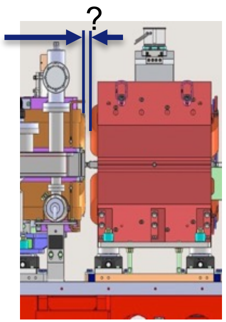
- Seems to favor permanent magnet technology

Resistive magnet: need to increase the total current for the same field after scaling

- Increase current density by 1/k factor -> $P1=P/k^2$ (2D)
- Increase copper cross section if possible

MAGNET DESIGN CONSIDERATIONS

space limitation	Wall plug power	Performance …. etc

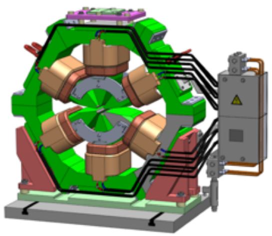


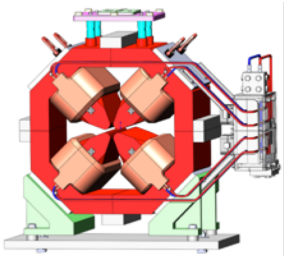
LONGITUDINAL SPACE !

Resistive magnets

Copper cross section adapted for reasonable current density

- ~ 3 A/ mm^2 @ nominal working point
- **Can only be adapted radially**
  - **~ similar or larger transverse size compared to magnets in 3GLS**



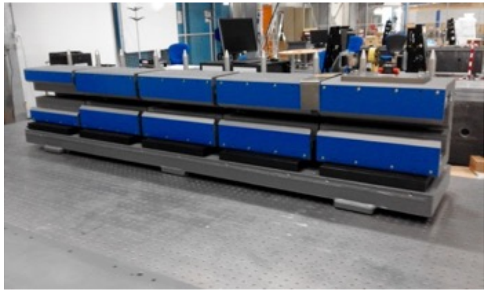


Permanent magnets

Primarily for fixed field magnets

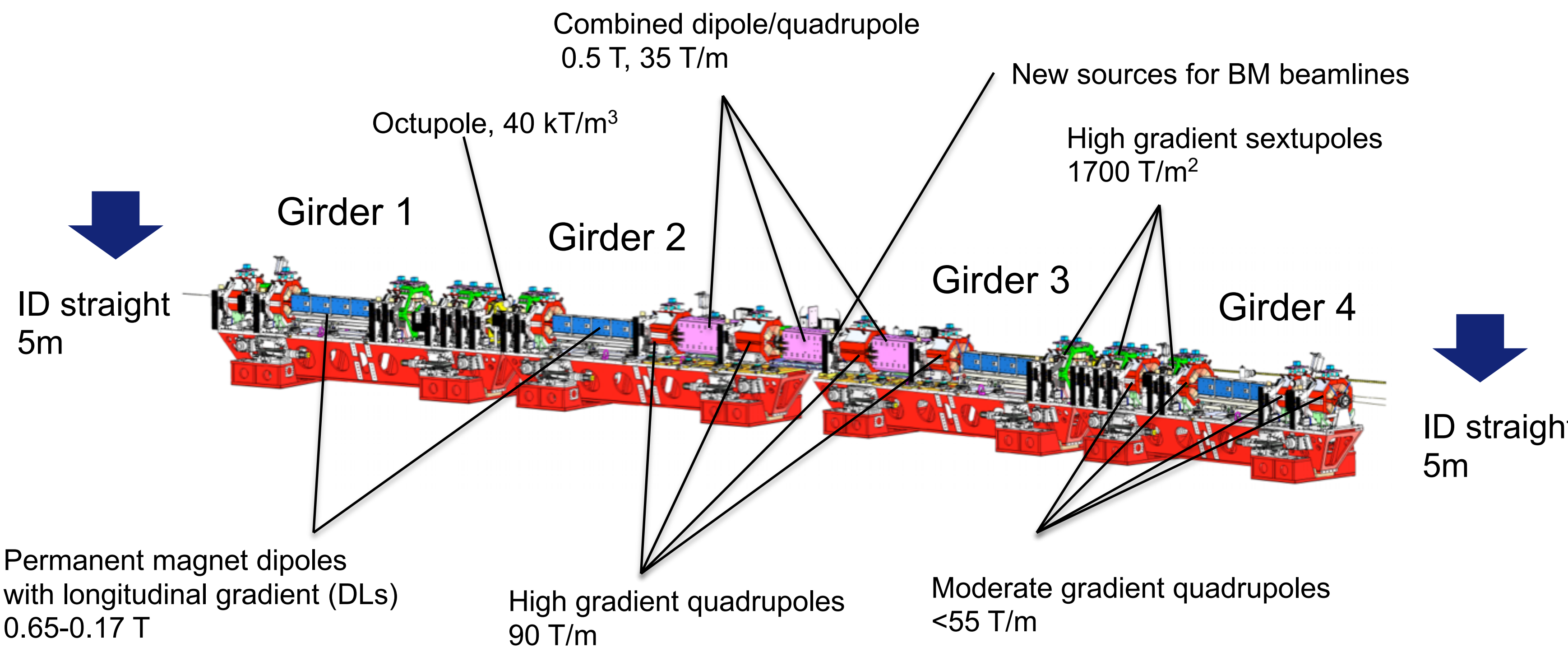
- **Dipoles**

Affordable technology and cost
Wall plug power=0



EBS SR MAGNET LATTICE

New magnet lattice to be installed in 2019, 128 girders, 4 girders/ cell:



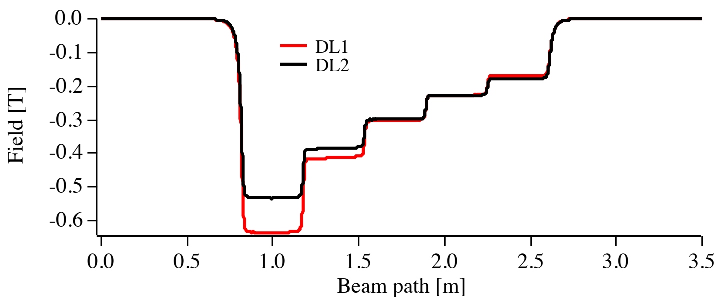
33 magnets/Cell ~ 1000 magnets to build

PERMANENT MAGNET DIPOLES

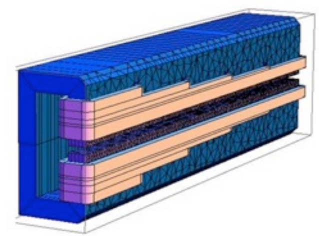
Dipoles with longitudinal gradient (DL)

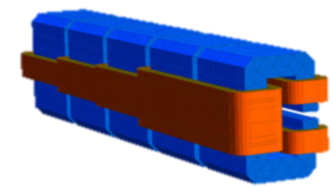
Non constant field along beam path

- Field matched to varying horizontal dispersion (emittance reduction)
  - Higher field at lower dispersion
  - Lower field at higher dispersion
- Practically done with field steps (5 in our case)

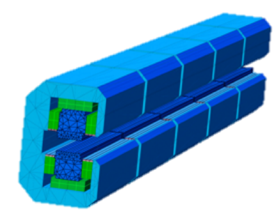


Early resistive designs





Permanent magnet design

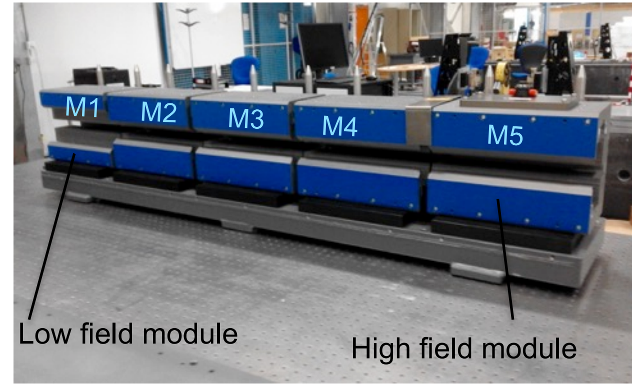


Permanent Magnet (PM) structure

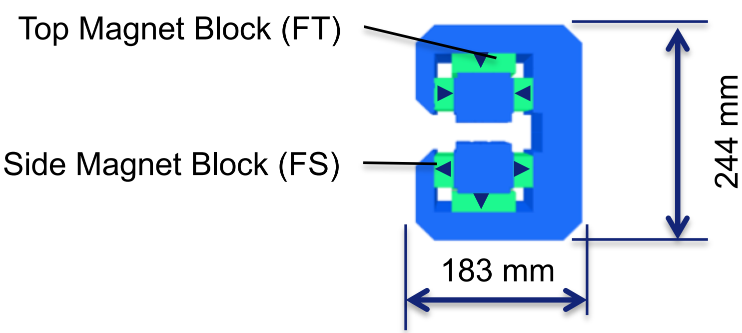
- Demonstrate feasibility of low cost PM Dipoles
  - Low procurement cost
  - Low running cost ~ 0
- Benefits from in-house experience on PM devices (Insertion-Devices)
- Well adapted to the segmentation approach
- compactness

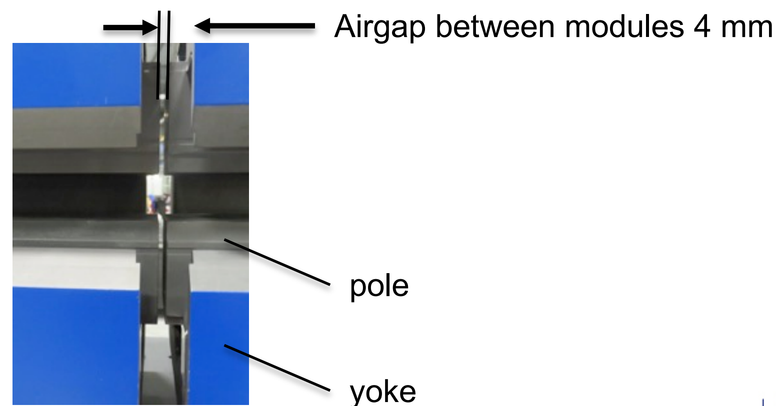
DL MAGNETIC STRUCTURE

Parameter	Value	Unit
Field	0.64 to 0.17 (DL1) 0.53 t0 0.17 (DL2)	T
Mech. length	1784	mm
Gap	25	mm
Deflection angle	31.7 (DL1), 29.4 (DL2)	mrad
Power	0	kW
PM weight/DL (Sm_2C01_7)	~ 45	kg
# of units	128+4	
GFR (HxV)	26x18	mm
$\Delta B/B$ in GFR	$<10^{-3}$	



- Module M2 to M5 geometrically identical but populated differently with magnet blocks
- Module M1 (low field) modified for integration of a photon beam absorber





DL IRON MATERIAL: PROCUREMENT, QUALITY CONTROL

Raw hot rolled material (low carbon steel)

Flame cutting + heat treatment

Semi finished product (iron blocks)

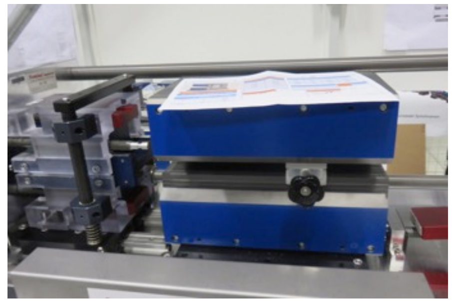
Delivery to sub-contractors for machining
Surface treatment
Assembly without PM
Painting

DL ASSEMBLY

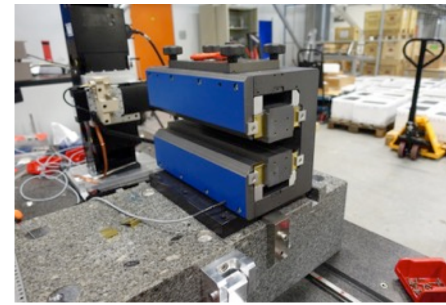
Magnet blocks (Sm_2C0_{17}, Magsound,)

Machined empty modules
AMF (UK), CECOM (It)

Magnet block insertion in modules
(dedicated tools)



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

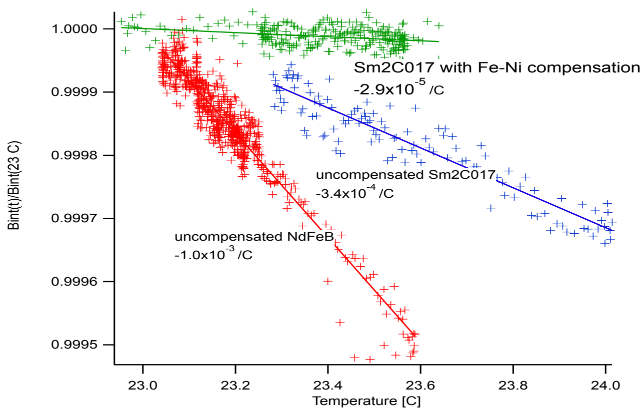


DL assembly

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

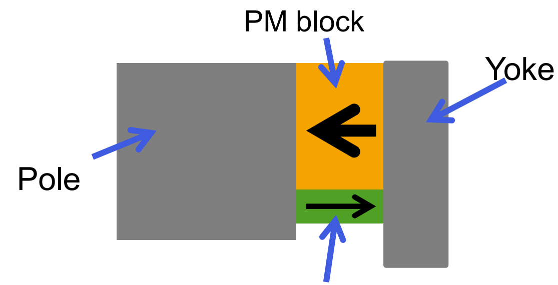
TEMPERATURE STABILITY

- Dominated by PM material temperature coefficient
- Can be compensated by passive FeNi shunts

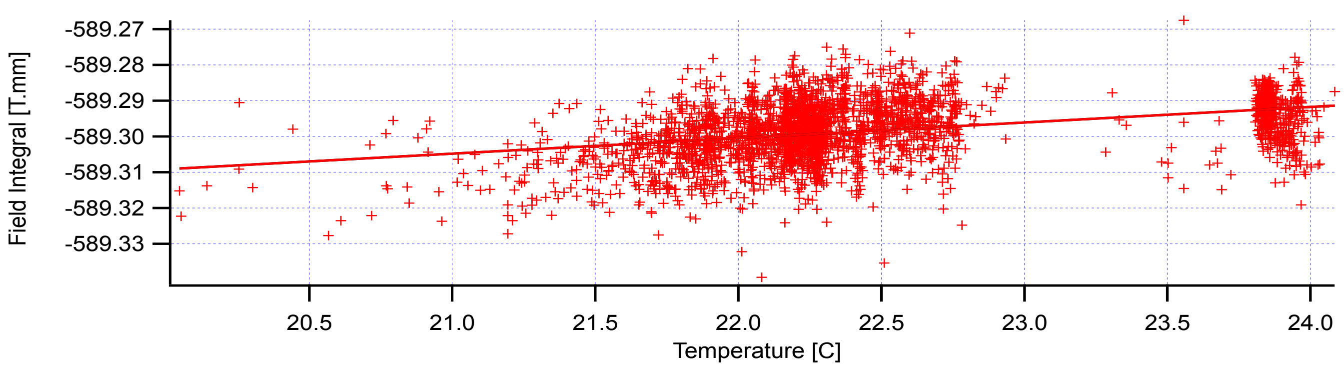


Field integral measurements on PM DL modules NdFeB, Sm_2C0_{17}

Material	C_T=dB/B/dT
Sm_2Co_{17}	– 3.3 10^{-4}
$Nd_2Fe_{14}B$	– 10^{-3}



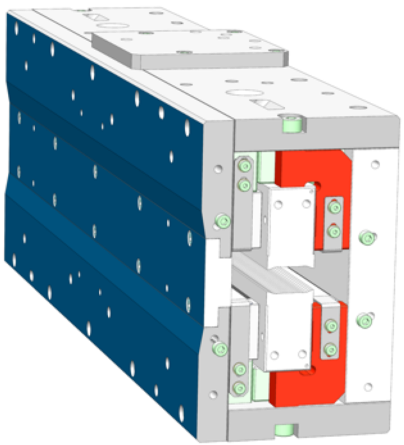
Special FeNi shunt , thickness 0.8 mm to 4.5 mm depending on module type (Thermoflux 55/100 G, curie temperature ~ 55 C, ~ -2%/C)

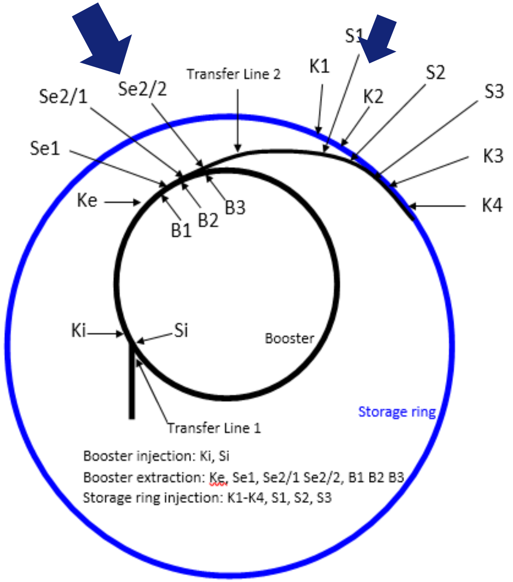


Test DL: DL2B_11_14
Measurements spread over 1 year:

Residual temperature coefficient ~ 10 ppm/C

PERMANENT MAGNET SEPTA: R&D TOPIC

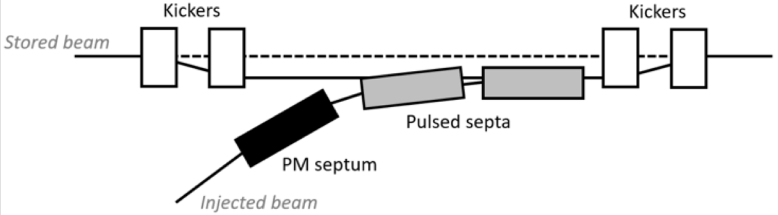




Main parameters

- 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 as DL magnets

Note: Se2/2 and S1 exist as electromagnetic versions + existing PS as fallback config



PERMANENT MAGNET DIPOLES FOR SYNCHROTRON LIGHT SOURCES

Green Field facilities:

- **SIRIUS** (3 GeV, 120 pm Brazil, under commissioning)

Sirius-Details of the New 3.2 T Permanent Magnet Superbend

James F. Citadini, Luana N. P. Vilela, R. Basílio, M. Potye
IEEE Transactions on Applied Superconductivity 2018

20 Super bend units

- **HEPS** (6 GeV, 38 pm, China, under construction)

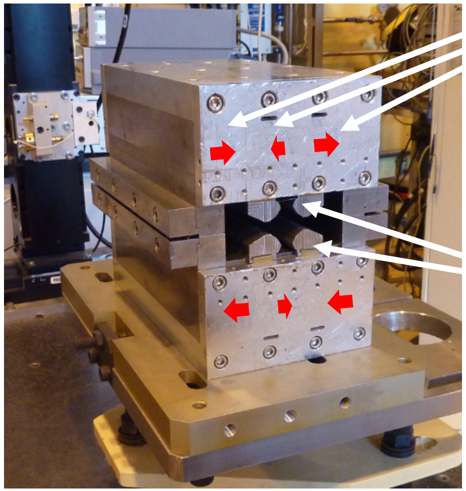
    - Use of LGBs (DLs) 5 dipoles/cell ,48 cells, 1 central LGB with enhanced field (BM source)

Upgrade projects: permanent magnet dipoles adopted or considered for

- SLS 2
- DIAMOND 2
- SOLEIL 2
- ALS
- …..

Clear evolution toward permanent magnet technology for dipoles in next generation light sources

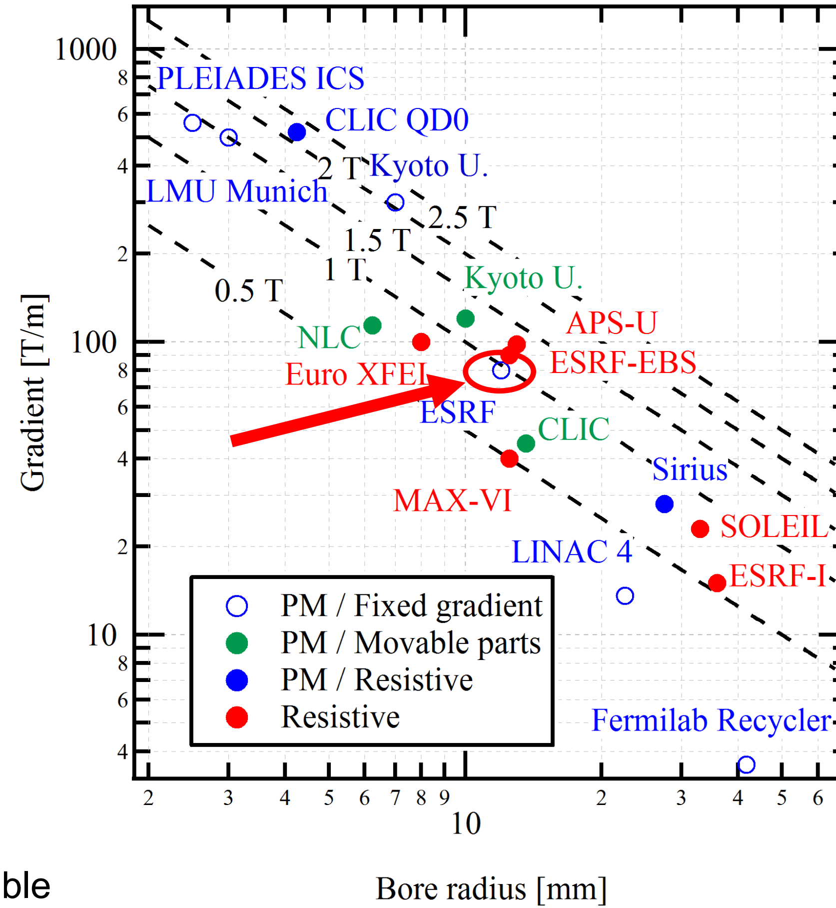
PERMANENT MAGNET QUADRUPOLES: STATE OF THE ART



(Courtesy P. N'gotta, G. Le Bec [N'gotta 15])

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

Possible gradient variation (additional coils) ± 3% feasible



PERMANENT MAGNET QUADRUPOLES

- not considered for ESRF EBS
  - R&D not compatible with timescale of the project
    - However devices with limited field variation seems feasible
      - Combined function dipole/quadrupole (DQs)
      - high gradient quadrupoles
  - Serial production methods for PM quadrupoles to be established

- Under consideration for different upgrade projects
  - SLS 2
  - SOLEIL 2

Very compact magnet lattice required for low emittance

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 , Power Supply Group

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

SUMMARY

Permanent magnet technology clearly coming in next generation light sources

- Comes from experience with permanent Insertion Devices in 3GLS
- Mainly for dipole magnets for the time being
- Next step is for quadrupole and combined function magnets
  - Limited field variation (few %)
  - …..
- Conventional resistive magnets can be optimized for lower power consumption

Potential important reduction in energy consumption for magnets in 4th GLS

ACKNOWLEDGMENTS

Insertion Device and magnet Group

P. Arnoux
I. Asparuhov (Thesis student)
C.Benabderrahmane
F. Bidault
B. Cottin
E. Fene
G. Giroud
G. Le Bec
M. Paulin
C.Penel
F. Revol
R. Versteegen

Accelerator and Source Division(ASD) colleagues

Instrumentation Services and Development Division (ISDD)

Technical Infrastructure Division (TID)

THANK YOU FOR YOUR ATTENTION