PROSPECTS FOR THE USE OF PERMANENT MAGNETS IN FUTURE ACCELERATOR FACILITIES

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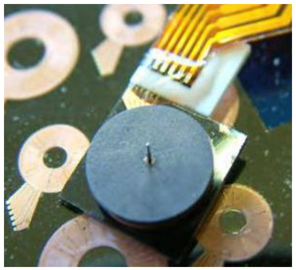
Grenoble, France

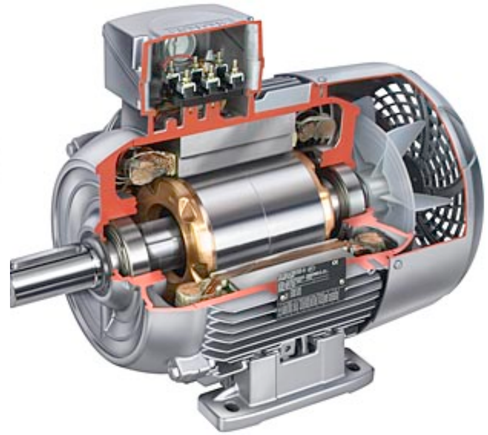
CONTENT

- Generalities
- Permanent magnets (PM) in accelerators
  - Operated PM devices
  - R&D
- PM stability
- Summary

SCALE FACTORS

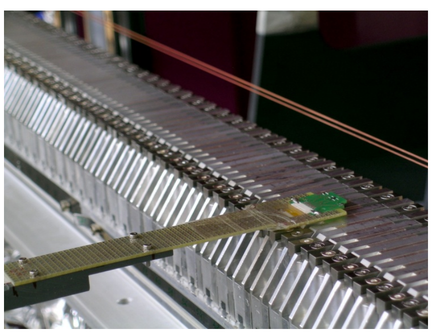
PM: Permanent Magnet

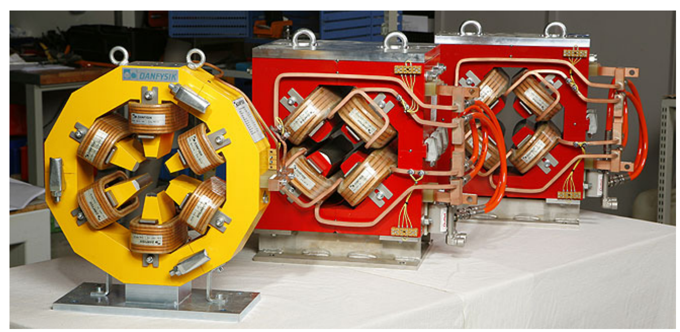




PM micro-motor   PM DC motor   Asynchronous motor   Power plant generator

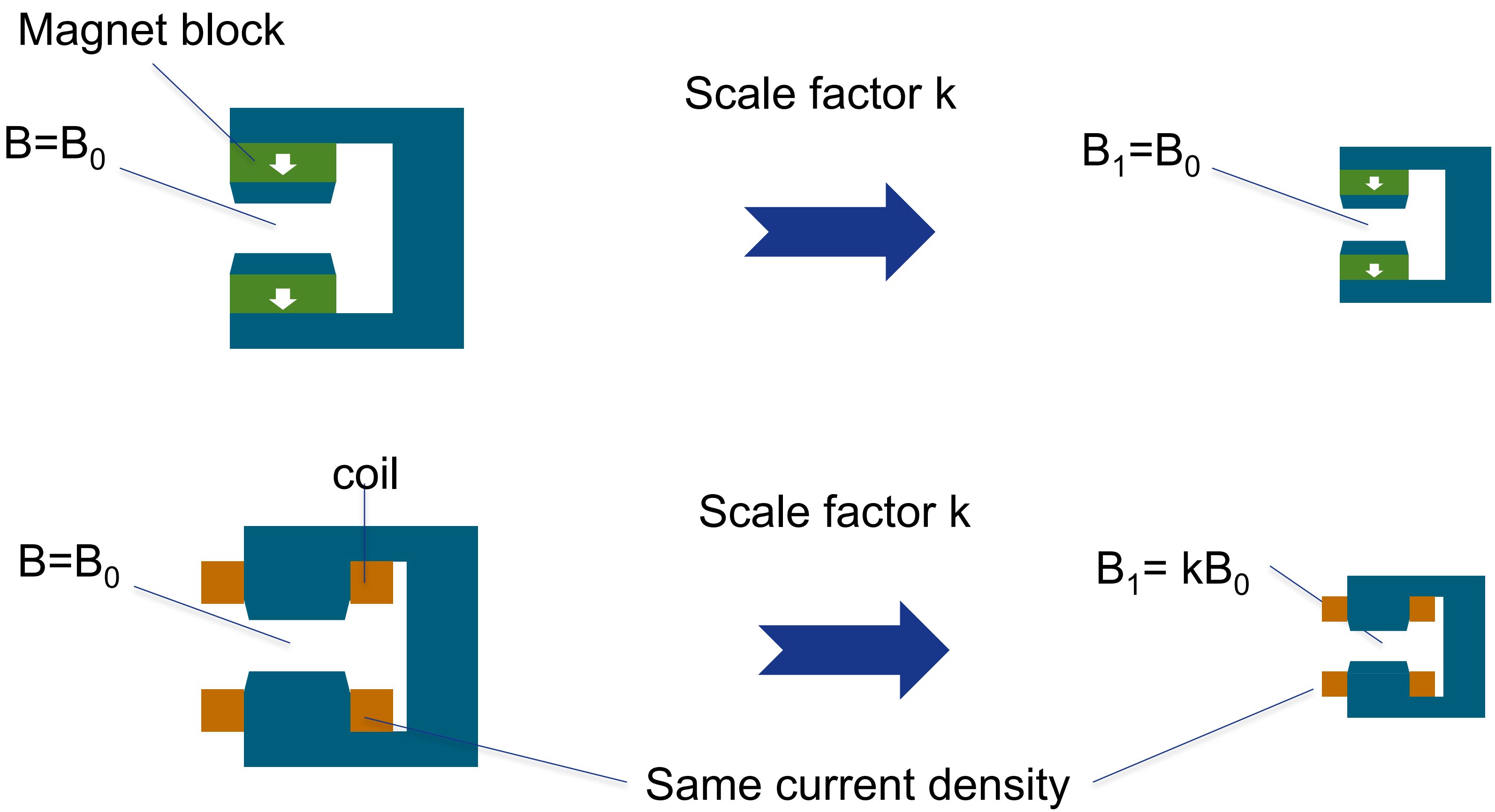
mm → **m**





Short period undulator   Lattice magnets

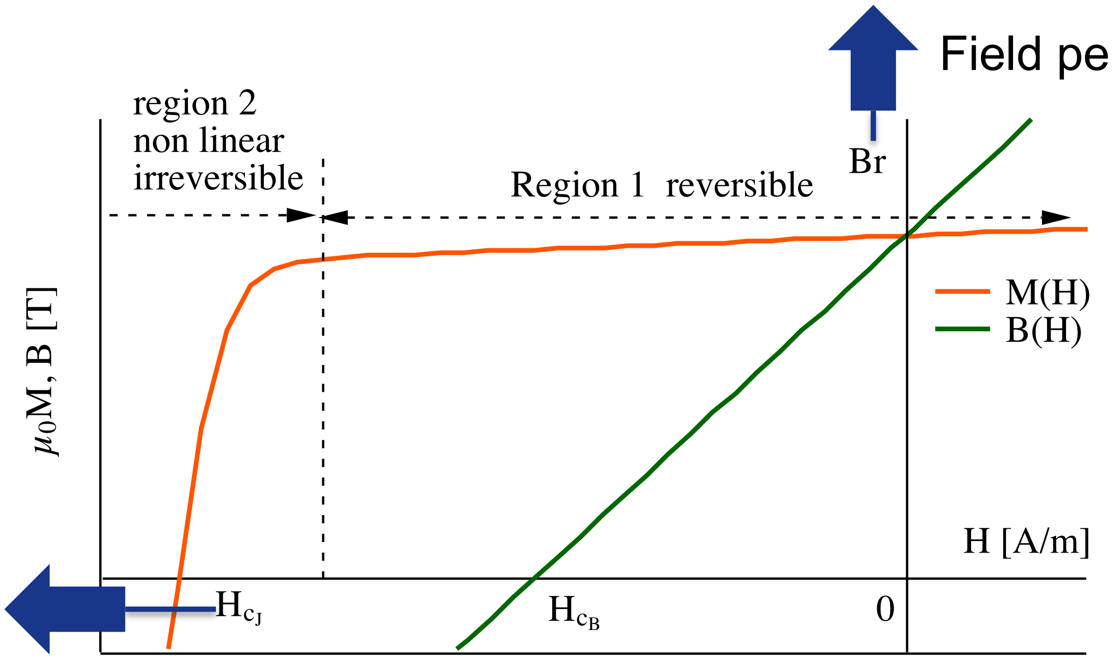
GEOMETRICAL SCALING



Small aperture magnets

- Compact PM devices
- Resistive devices less compact due to limitation in current density

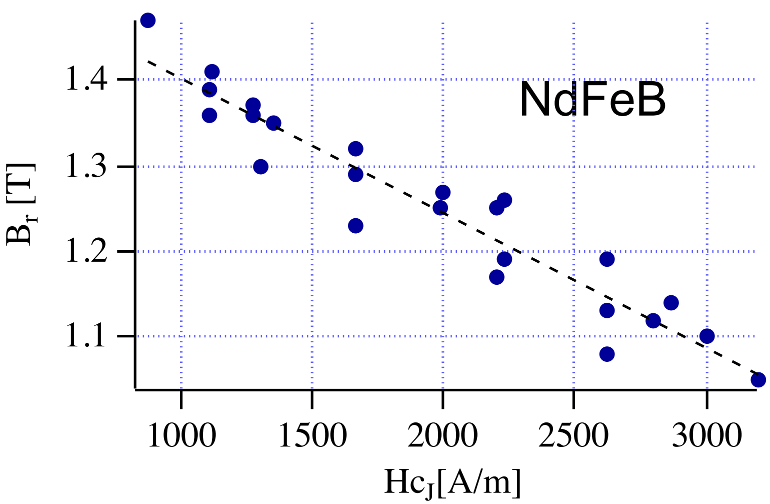
Field performance



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

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



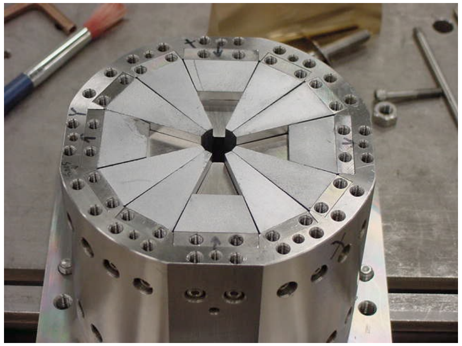
Practical materials for accelerator PM devices

PM IN ACCELERATORS

ESRF IDs

Insertion Devices

“Superstrong PMQ”, Takanori Mihara,



PM Mutlipoles for final focus in colliders

Present

PM in accelerators

Lattice magnets

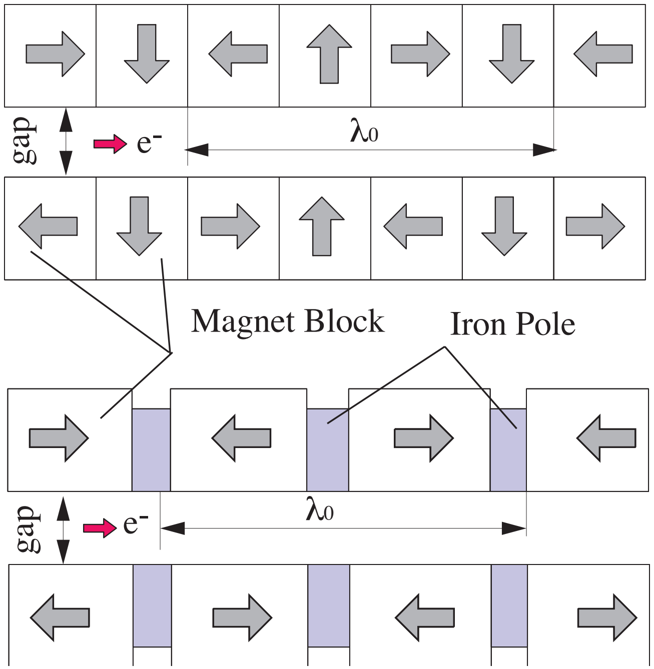
Fermilab recycler

Future

Linear colliders

DLSRs

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



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

Technology

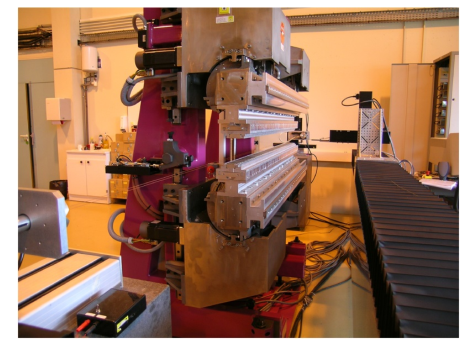
p.m material remanence

undulator period

Undulator peak field

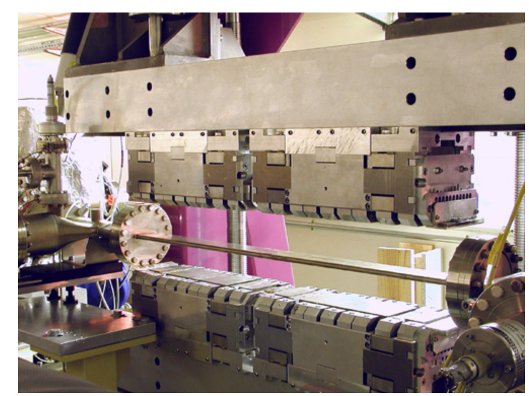
More than 95 % of IDs are PM based

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



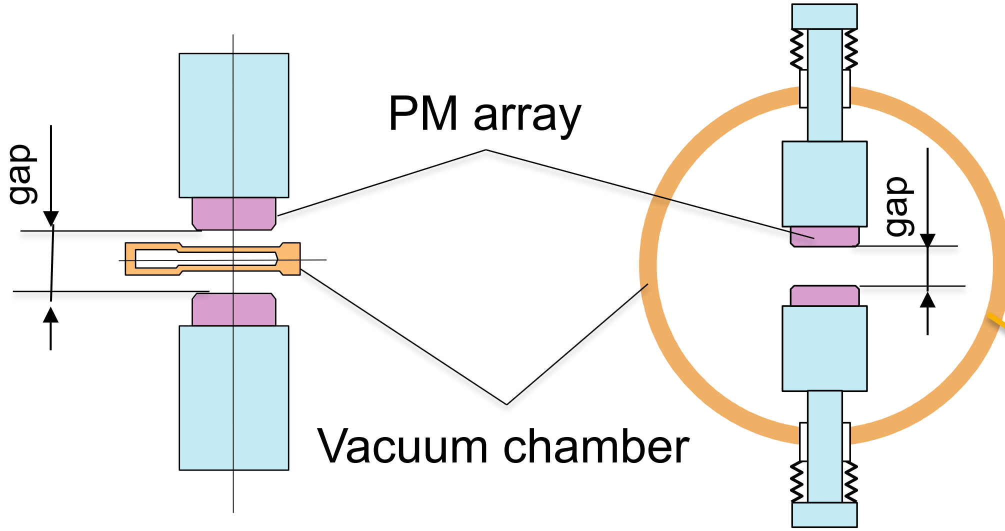
ESRF revolver undulator

PETRA III PM Helical undulator



ESRF 3.1 T PM Wiggler

IN-VACUUM UNDULATORS: SMALLER GAP, SMALLER PERIOD



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

Min. gap ~ 10 mm

Period: 32~ 70 mm

Min. gap ~ 4 mm

Period: 14~ 28 mm

Permanent magnets can be UHV compatible

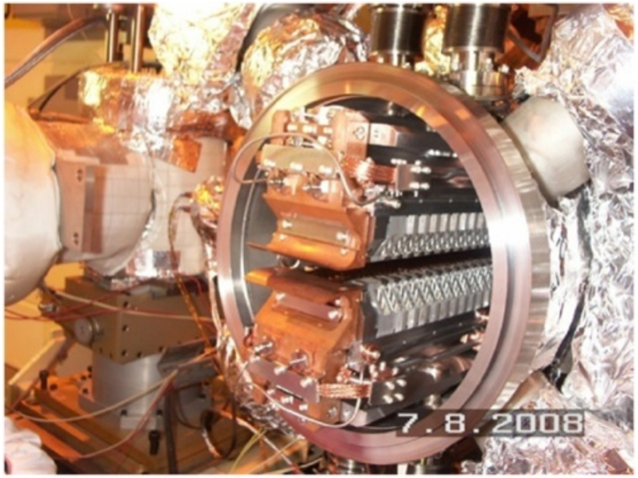
- Needs coating: Nickel, Al IVD, TiN.
- Typical residual pressure ~ 10^{-9} mbar in operation
- PM materials: NdFeB, Sm_2Co_{17}

Important international development of IVUs following success at SPRING 8
Minimum gap limited by effect on beam (beam losses)

CRYOGENIC PM UNDULATORS (CPMUS)

CPMU= IVU+ cryogenic cooling of PM arrays (*)

- Higher performance PM materials
- Higher stability
- Better vacuum
- NdFeB or PrFeB
- Liquid nitrogen or cryocooler
- Several devices in operation in different 3GLS

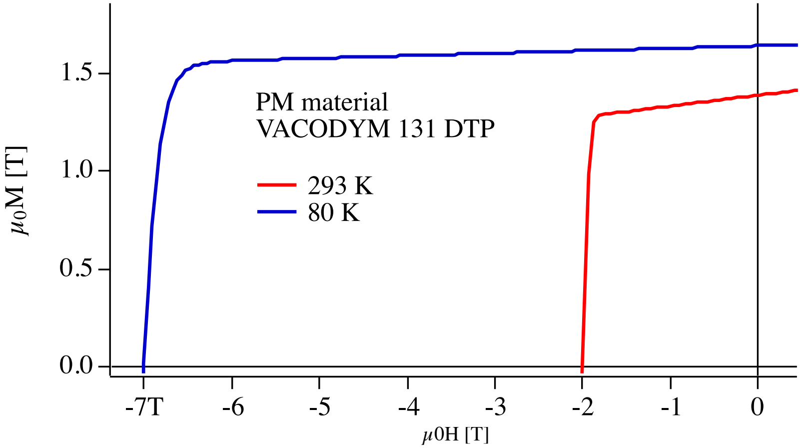


3rd CPMU under construction @ ESRF

PM material: Vacodym 131 DTP (PrFeB)

Br =1.62 T,| $\mu_0 Hc_J$|~ 7 T @ 80 K

Min. gap=4 mm
period 14.5 mm
B_{max}=1.26 T

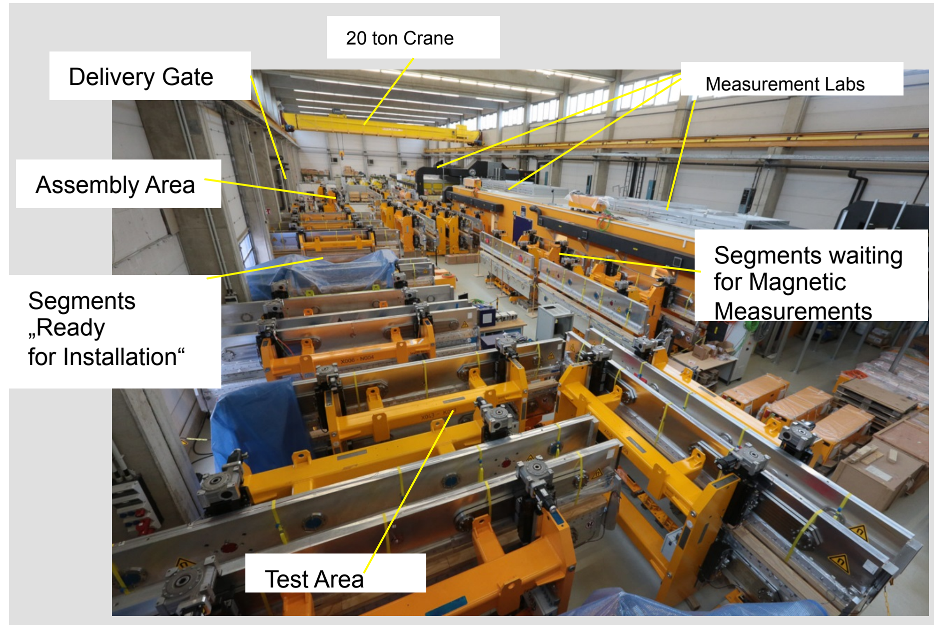


(*) SPRING 8 proposal : Phys. Rev. ST AB,Vol. **7**, 050702 (2004)

Example of large scale undulator production

J. Pflueger, XFEL

Undulator Assembly in DESY Hall 36



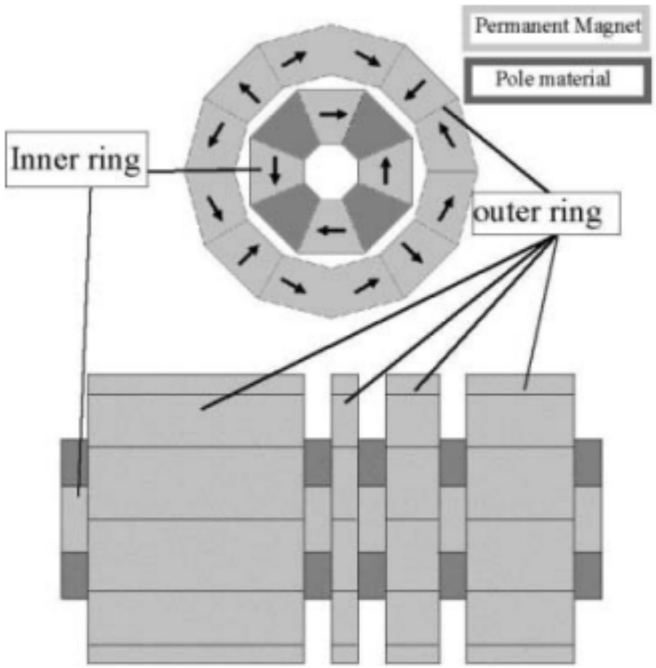
J. Pflueger, XFEL

Three undulator lines

Parameter	Sase1/2	Sase 3
Period [mm]	40	68
# of 5 m segments	35*2	21
Total undulator length [m]	175 *2	105

- 455 m of undulators
- 17 tons of NdFeB PM

Development of compact and tunable small aperture magnets



Y. Iwashita, EPAC 2006

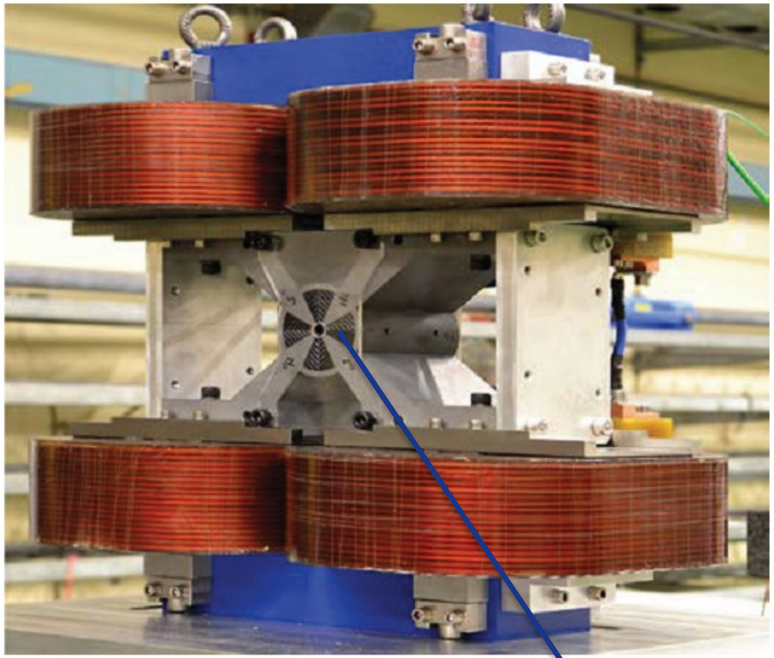
ILC final focusing

PM

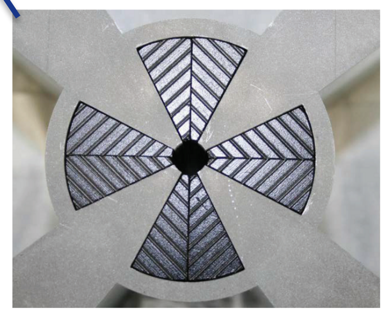
Gradient 120 T/m

Aperture 20 mm

Tuning by 7 T/m steps



M. Modena, IPAC12



CLIC QD0 final focusing

Iron dominated, Coils + PM

Gradient 525 T/m

Aperture 8.25 mm

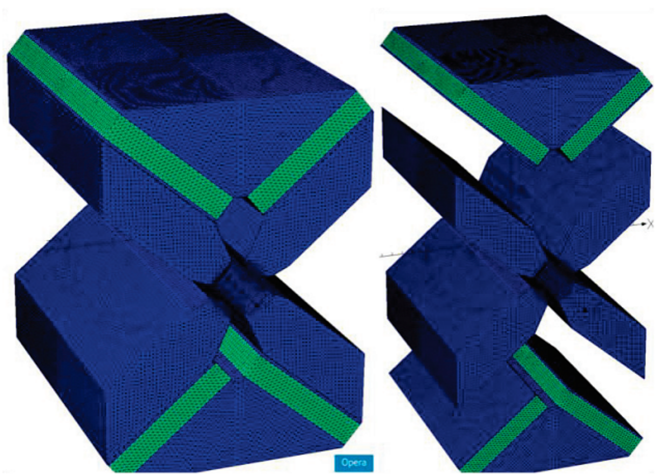
Tuning range 80 %

PM QUADRUPOLES FOR THE CLIC DRIVE BEAM

Specific requirement @ CLIC : low power to air

PM quadrupoles type 1

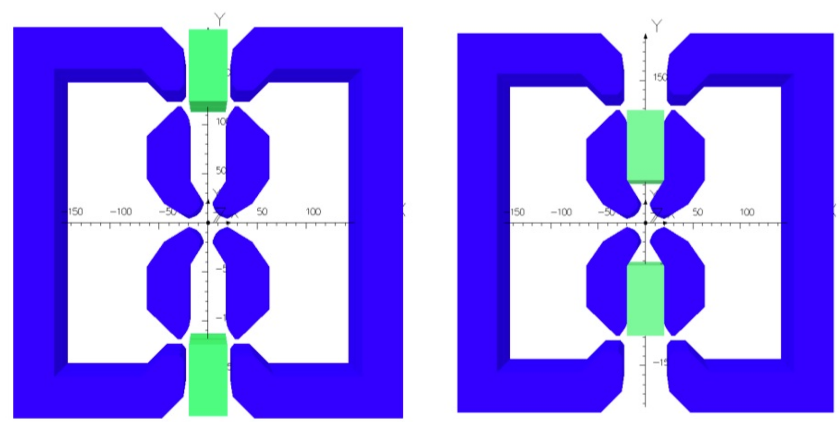
Iron dominated, PM
Gradient 60.4 - 15 T/m
Aperture 27.2 mm
Tuning range 75%



B.Shepherd, Daresbury, IPAC 2012

PM quadrupoles type 2

Iron dominated, PM
Gradient 43.4 - 3.5 T/m
Aperture 27.6 mm
Tuning range 80%

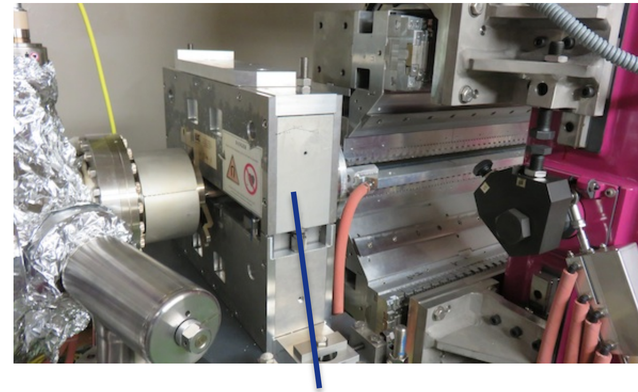


B.. Shepherd, CLIC workshop 2014

42 000 units needed

Canted undulators in 3GLS

- Angular separation of undulator beam in same straight section
- 3 small compensated PM dipoles
- up to 5.5 mrad angle @ 6 GeV
- PM solution -> compactness



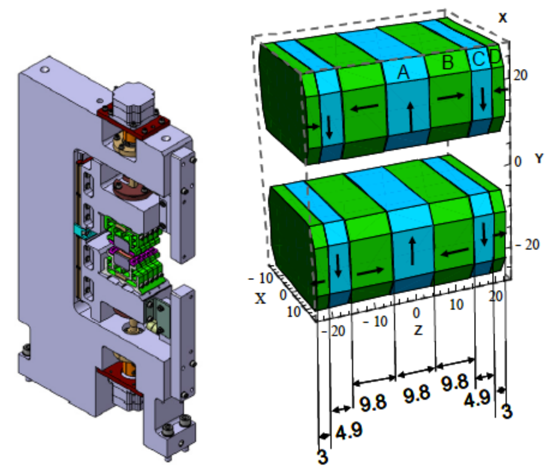
ESRF canting magnet

- **Phase shifters for FELs**
  - Compactness
  - Remote gap control

XFEL

I. Moya ,Linac 2012

SWISSFEL



R. Ganter, FEL2012

FERMILAB RECYCLER: PM AS LATTICE MAGNETS

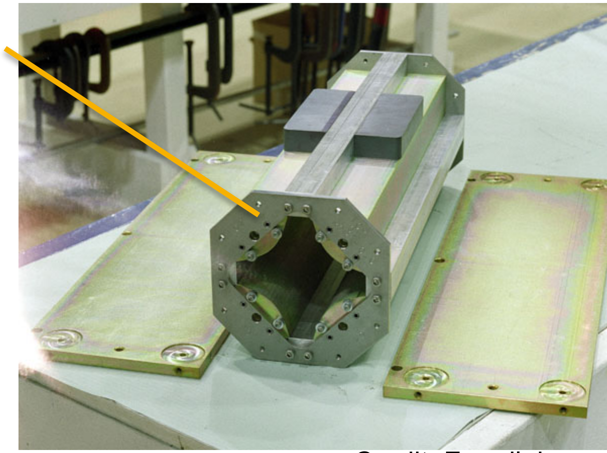
Recycler

Main injector

Credit: Fermilab

Strontium ferrite block

quadrupole



Credit: Fermilab

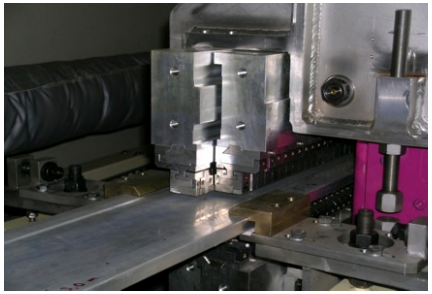
Combined Dipole quadrupole

- Circumference : 3.3 km
- ~480 magnets
- PM material: Strontium ferrite
- Fixed low field magnets
- Passive temperature compensation
- More than 10 years operation

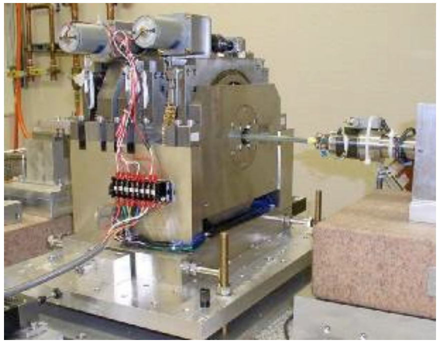
FIELD VARIATION WITH PM DEVICES

1- moving part(s) of PM structure

- Can be 100 % field variation (IDs)
- Magnetic forces/torques can be significant
- Need stiff guiding assembly
- PMQ magnetic axis stability versus field strength can be an issue
- Reliability of motion control (encoders)
- Cost of mechanical structure



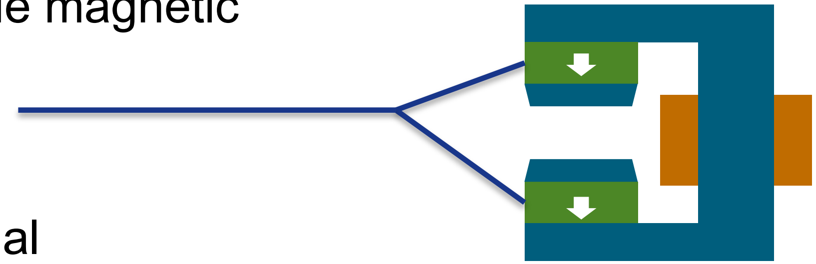
ESRF ID



Adjustable PMQ, Y.Iwashita, Tokyo U.

2- Mixed PMs and coils

- Reduced coil efficiency with PM inside magnetic circuit
  - PM block = air gap for coil
- Field variation: few percent of nominal



DIFFRACTION LIMITED STORAGE RINGS (DLSR)

Several facilities with upgrade projects

Electron beam emittance
1 – 4 nm.rad

3GLS

ESRF
APS
SPRING8

DBA lattices

New magnets

New lattice: 7BA

Electron beam emittance
0.08 ~ 0.15 nmrad

DLSR

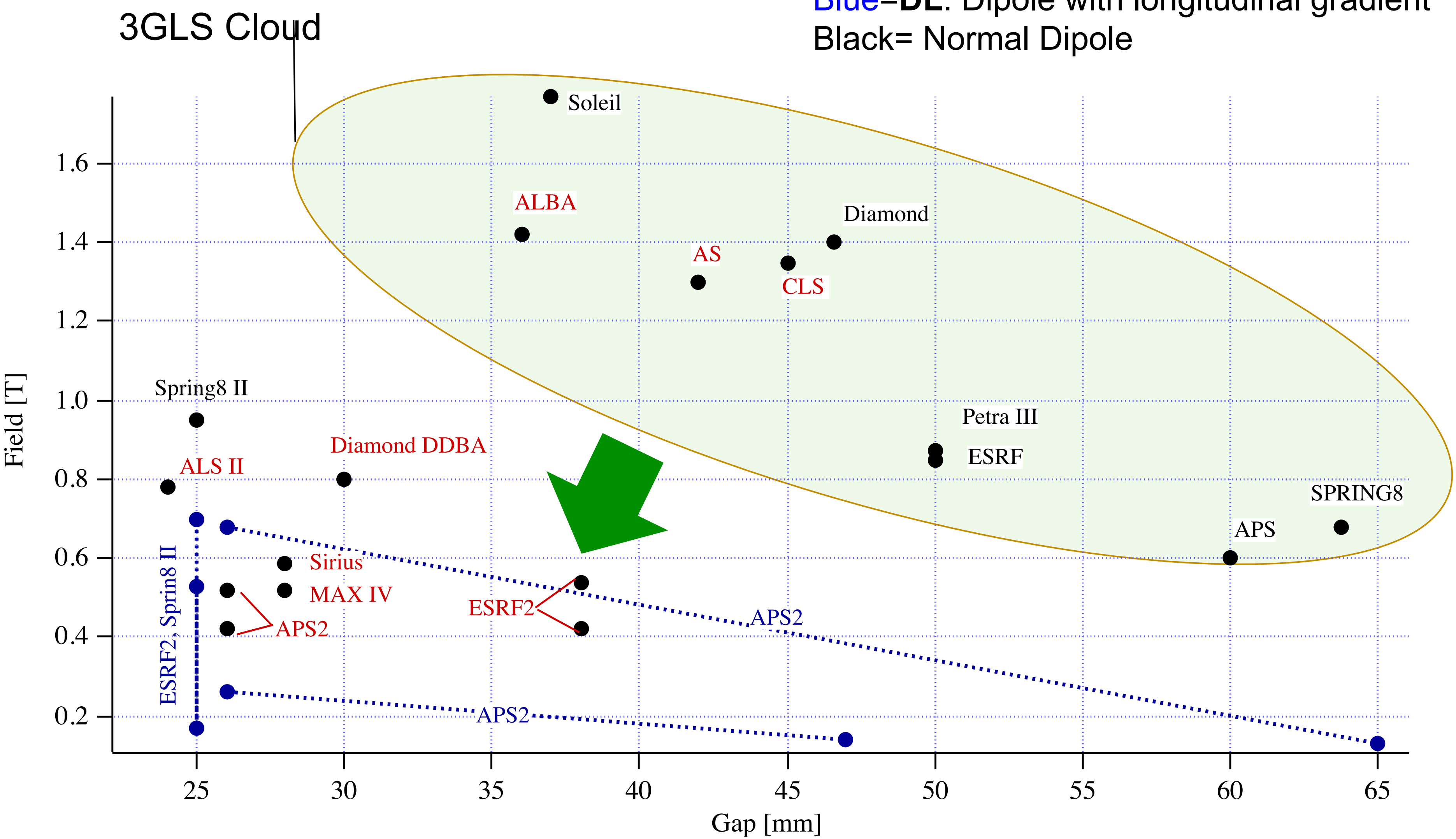
Two green-field facilities under construction
Electron beam emittance
0.25 - 0.28 nm.rad

MAX IV

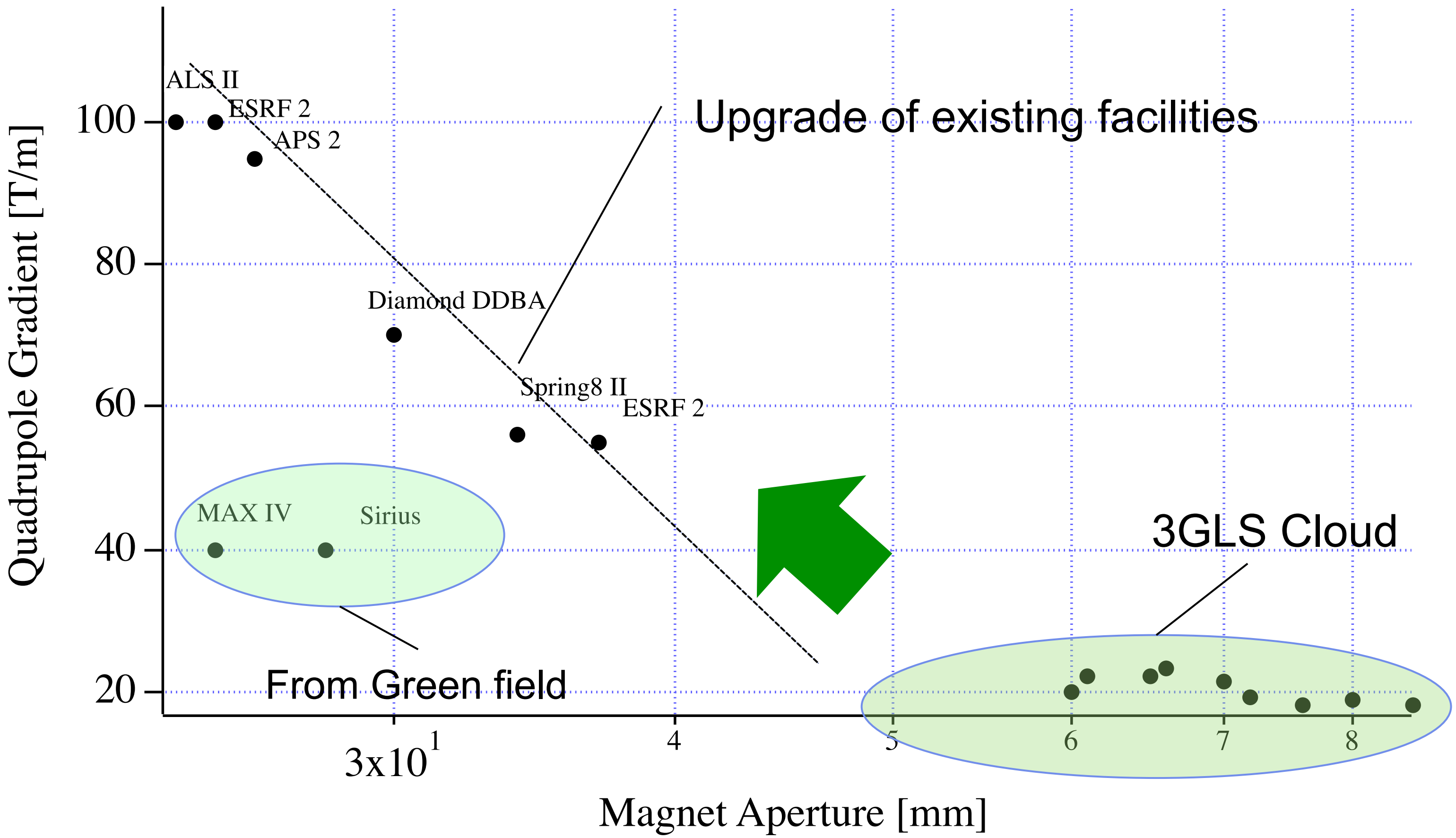
Sirius, brazil

BENDING MAGNETS IN DLSR

Red=**DQ**: Combined dipole quadrupole
Blue=**DL**: Dipole with longitudinal gradient
Black= Normal Dipole



QUADRUPOLE MAGNETS IN DLSRS

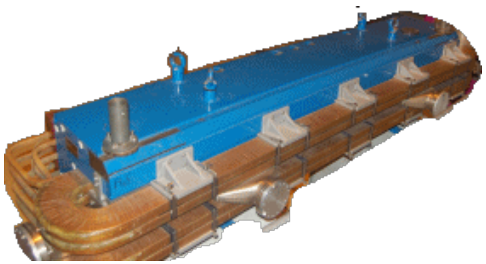


Quadrupole gradient primarily increased with reduction of aperture
Mostly demanding for upgrade projects (has to cope with existing cell length)

FIXED FIELD MAGNETS: BENDING MAGNETS

Example of ESRF dipole magnets in present lattice

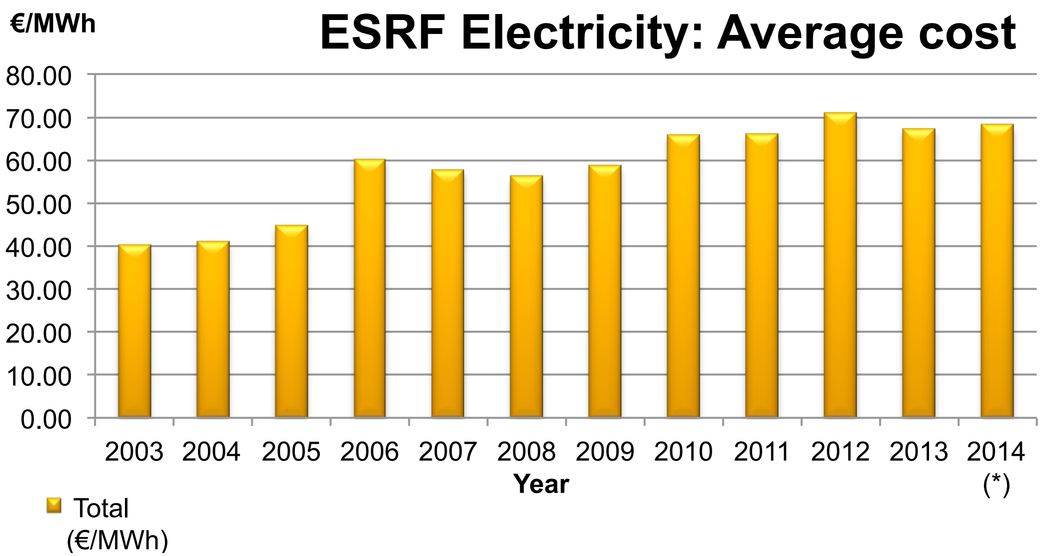
0.85 T BM



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

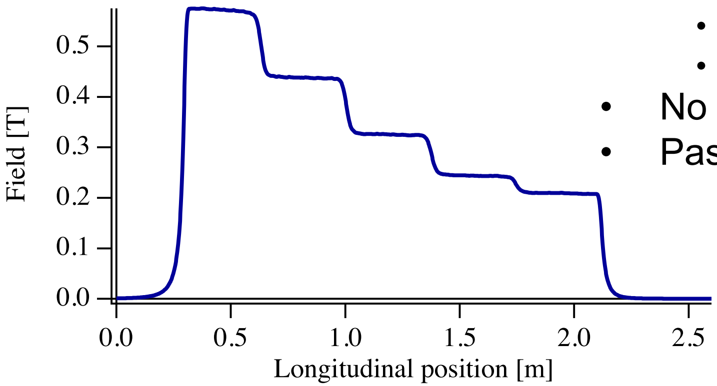
Procurement: 2.3 MEuros
Running cost: 6.3 MEuros

(Updated costs to present)

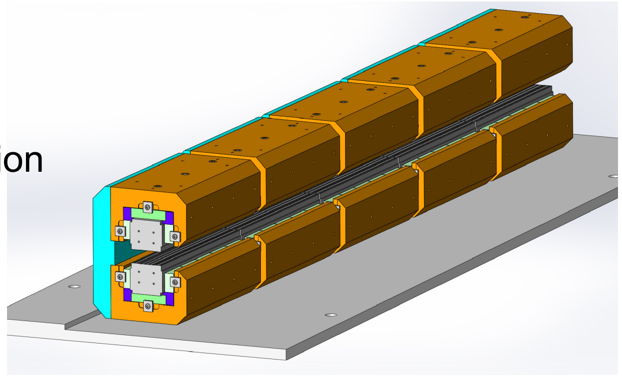


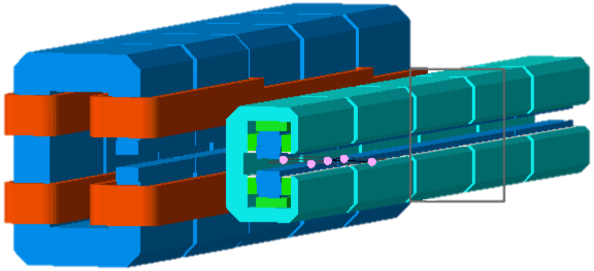
ESRF II: running cost over 15 years has to be evaluated

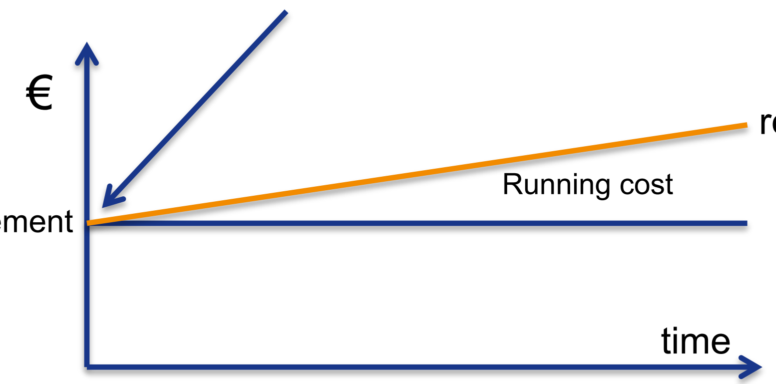
ESRF NEW LATTICE :PM DIPOLE WITH LONGITUDINAL GRADIENT (DL)



- PM material
  - Sm_2Co_{17}
  - Strontium Ferrite
- No remote field tuning
- Passive temperature compensation







- Sirius has PM super bent

	resistive	PM
Length[m]	1.785	1.785
Weight [kg]	1200	380
Power [kw]	1.3	0
# units	128	128

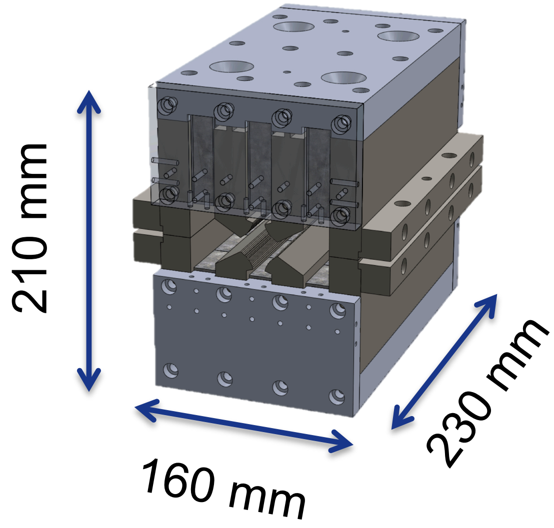
HIGH GRADIENT PM QUADRUPOLE: R&D @ ESRF

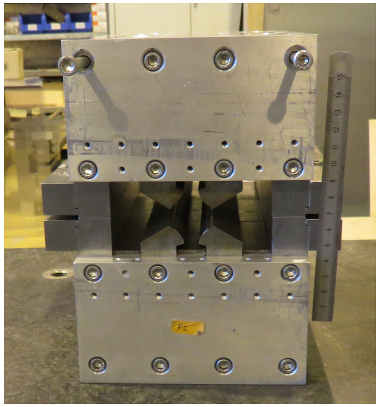
Quadrupoles with limited field variation (± 2 %)

- Design of resistive version completed

First PM prototype as R&D subject

- simple hybrid structure with rectangular magnets
- Aperture radius 12 mm
- Dedicated pole shape
- Gradient ~ 85 T/m
- length 230 mm
- 30 kg
- no field variation for this version





Under assembly
To be measured
& tuned

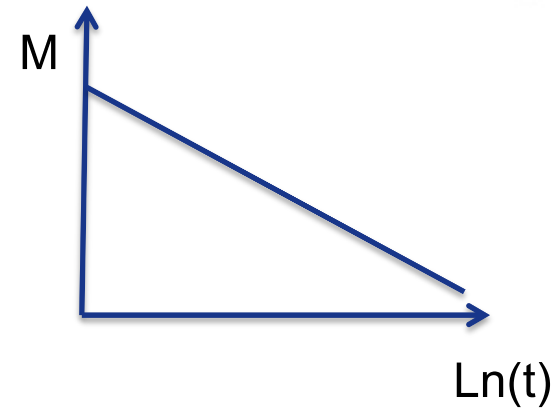
MAGNETIC STABILITY: TIME STABILITY

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

Magnetic viscosity

Constant temperature
Constant working point in PM

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



Logarithm decay observed on all PM materials

Magnet tests at Fermilab: Material Sr Ferrite

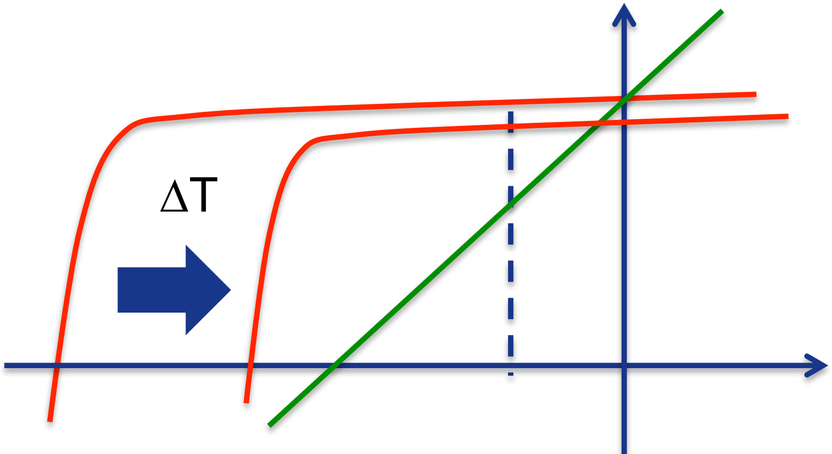
$$\frac{\Delta B}{B_0} \approx -1.0e^{-4}\ln(t/t_0)$$

Magnetic viscosity for NdFeb & Sm_2Co_{17} can be significantly smaller

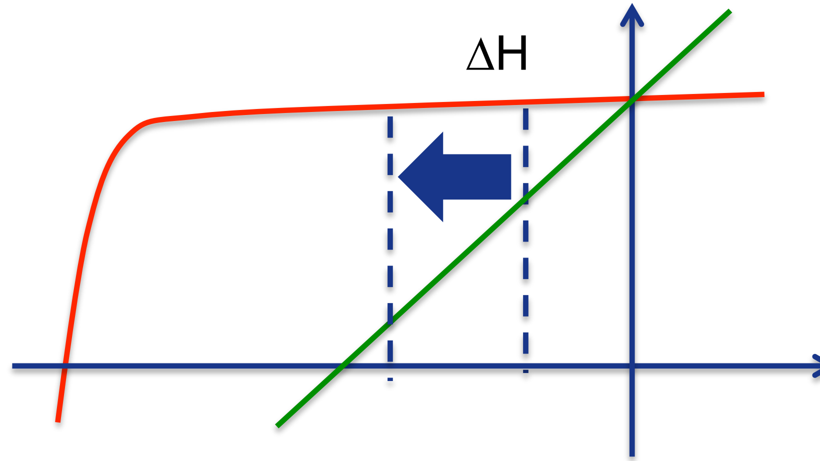
Number of days since magnetization	field Loss [%]
10 days	0.023
1 year	0.059
10 years	0.082
100 years	0.105

TIME STABILITY (CONT.)

Pre-stabilization: increase temporarily magnetic viscosity

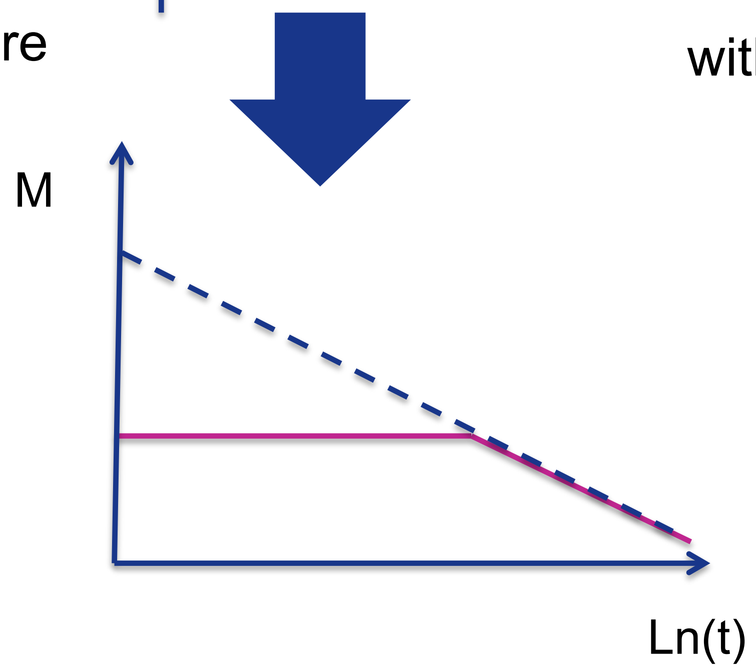


with temperature



with field

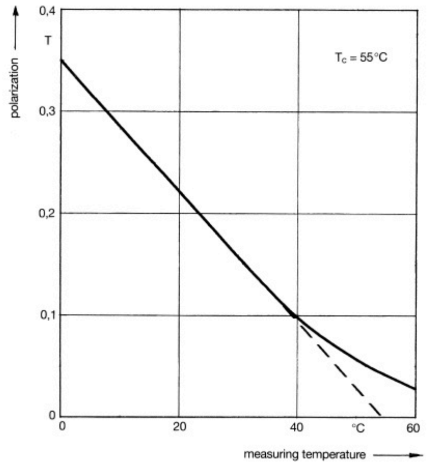
Remove substantial part of decay from the beginning

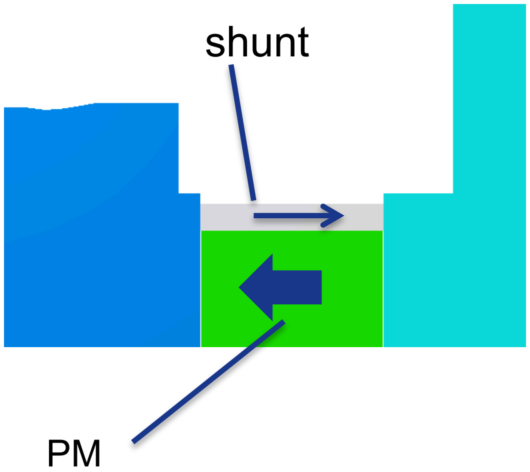


PM materials are sensitive to temperature variations

Material	cfBr [%/C]
Sr Ferrite	-0.2
NdFeB	-0.1
$SmCo_5$	-0.04
Sm_2Co_{17}	-0.03

- Can be compensated if PM device has remote tuning capacity
  - **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





RADIATION DAMAGES

- **Undulators damaged by radiation in several facilities**
  - ESRF, APS, PETRA III
  - important studies done at SPRING8 (T. Bizen) and Cornell (A.B. Temnykh)
- **Effect similar to that of a thermal partial demagnetization**
  - Magnetization recovered after re-magnetization
  - Concept of thermal spikes in magnet material, likely due to high energy photoneutrons

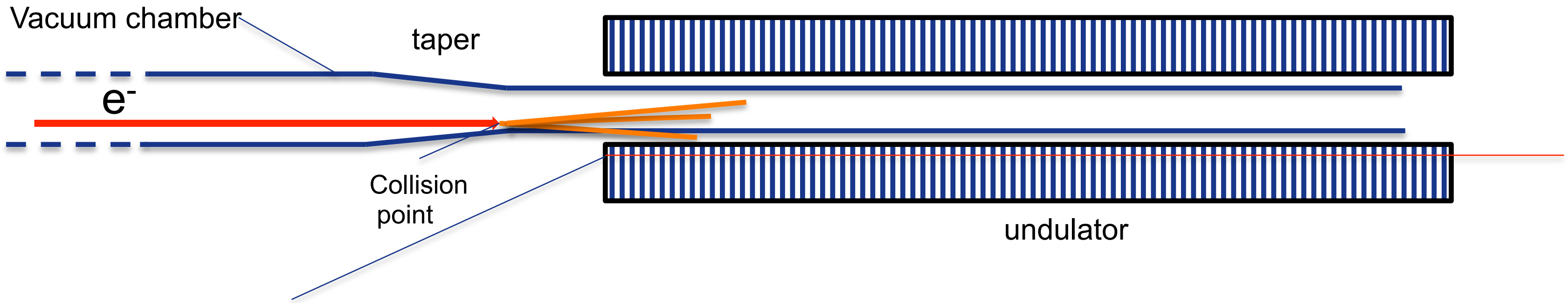
Sm2Co17/NdFeB materials in IDs

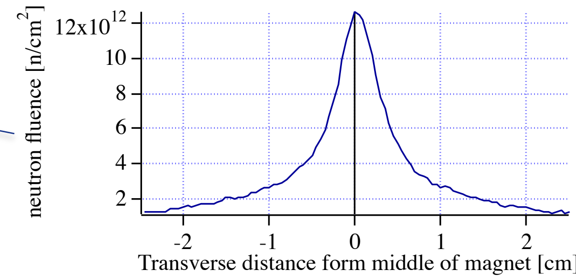
- Sm_2C0_{17} has the highest resistance to radiation induced demagnetization
- Thermally stabilized high coercivity (~ 2800 kA/m) NdFeB can be similar to Sm_2C0_{17}
- Similar observation with “cryocooled” NdFeB (CPMUs)
- High dependence on the working points (H,M) in magnet

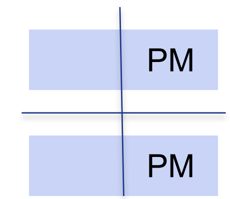
Process defined by coercivity of the PM material Hc_J and related temperature coefficient

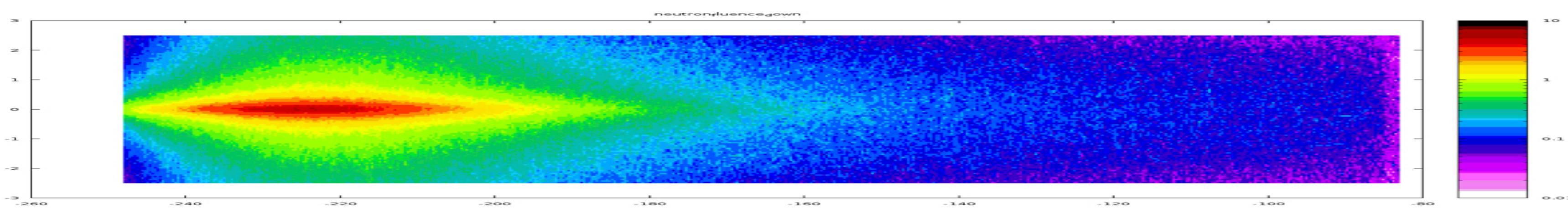
RADIATION DAMAGES (CONT.): IMPORTANCE OF 3D SIMULATION

Example: undulator closed on narrow chamber









Assume 4.0 e12 electrons lost on taper ~ 1 year operation

Software simulations with FLUKA (http://www.fluka.org/)

SUMMARY/CONCLUSION

Use of PM devices in present accelerators

- Specialized devices
    - Compact: IDs, PMQs
    - No other simple alternative
    - Energy saving not the primary target
- Low cost full PM based ring @ Fermilab

Use of PM devices in future accelerators

- Specialized devices as now
- Energy saving will become an important issue
    - Colliders
        - PM quadrupoles for low heat to air
        - High gradient PMQ with field variation at IP
    - DLSRs
        - PM technology still in direct competition with resistive technology
        - Seems advantageous for fixed field devices (BMs)
        - Possibly interesting for quadrupoles with limited field variation

SUMMARY/CONCLUSION (CONT.)

Stability of PM devices in accelerators

- **Time stability**
  - Very small decay vs time
  - Can be mitigated with pre-aging methods

- **Temperature stability**
  - Effect needs to be compensated
  - Active Field variation
  - Passive method

- **Radiation damages**
  - Significant progress in understanding various mechanisms
  - Further studies probably needed
  - central role of coercivity
  - Availability of accurate simulation tools

Thank you