Permanent Magnet Dipoles for the ESRF Upgrade

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OUTLINE

- Context & motivation
- Design
- Construction
- Magnetic measurements
- Temperature stability
- Summary

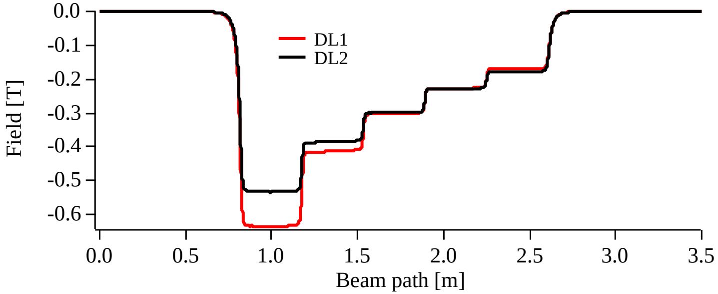
ESRF | The European Synchrotron

PERMANENT MAGNET DIPOLES

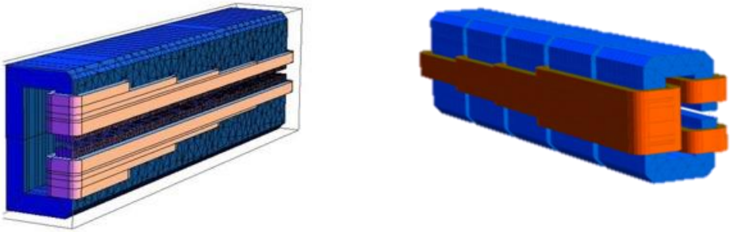
Dipoles with longitudinal gradient (DL)

Non constant field along beam path

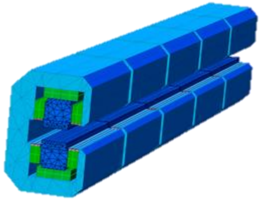
- Field matched to varying horizontal dispersion (emittance reduction)
  - Higher field at lower dispersion
  - Lower field at higher dispersion
- Practically done with field steps (5 in our case)



Early resistive designs



Permanent magnet design

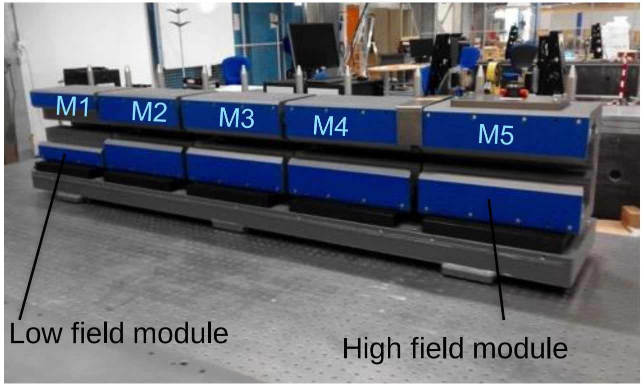


Permanent Magnet (PM) structure

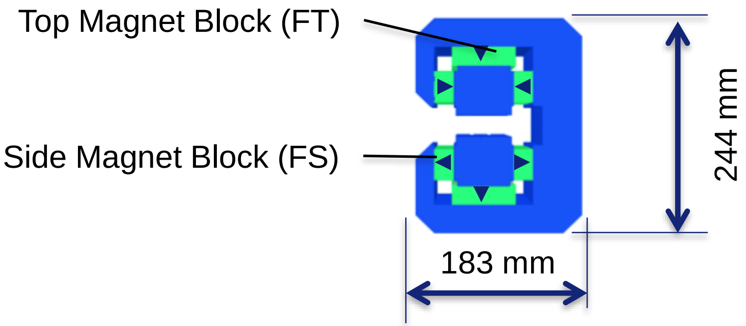
- Demonstrate feasibility of low cost PM Dipoles
  - Low procurement cost
  - Low running cost ~ 0
- Benefits from in-house experience on PM devices (Insertion-Devices)
- Well adapted to the segmentation approach
- compactness

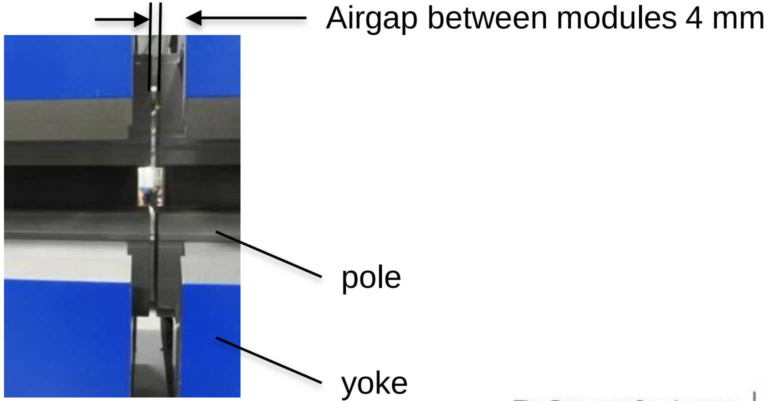
DL MAGNETIC STRUCTURE

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	~ 45	kg
# of units	128+4	
GFR (HxV)	26x18	mm
$\Delta B/B$ in GFR	$<10^{-3}$	

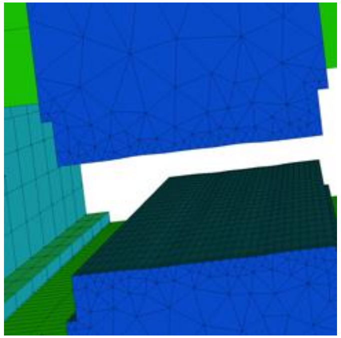


- Module M2 to M5 geometrically identical but populated differently with magnet blocks
- Module M1 (low field) modified for integration of a photon beam absorber

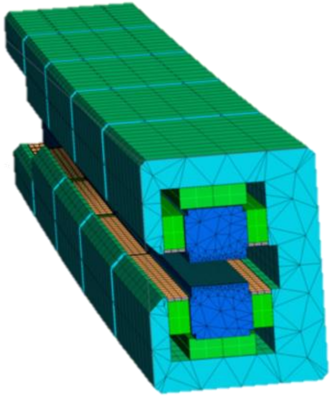




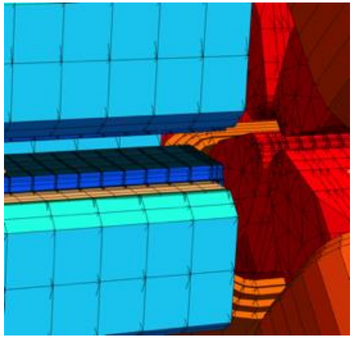
DL MAGNETIC DESIGN



Pole shape optimization



3D magnetic model (RADIA)



Magnetic cross-talk with neighboring magnets

Beam dynamic model

- Field representation
- Magnetic length
- Multipoles
- ..etc

Magnetic optimization

- Magnetic interaction between modules (gap between modules)
- Modules place on curved beam path
- Magnetic crosstalk with neighboring magnet
- Field tuning scheme (flux shunts)
- passive thermal compensation (Fe-Ni shunts)

… etc

Simulation of magnetic measurements
(Stretched moving wire)

- individual modules
- full magnet assembly
- Field integrals

PERMANENT MAGNET MATERIAL

PM material: Sm_2C0_{17} XGS30H (Magsound, China, http://www.magsound.com)

Magsound
SANHUAN MAGSOUND

Recent progress in Sm_2Co_{17} materials @ Magsound

Material	Grade	Energy Product(BH)max		Residual Induction Br		Coercive Force HcB		Intrinsic Coercive Force Hcj		Density D	Rev.Tenp Coeff α(Br)	Curie Temp TC	Max Working Temp Tw
		KJ/m^3	MGsOe	T	KGs	KA/m	KOe	KA/m	KOe	g/cm^3	%/℃	℃	℃
	XGS30M	223-247	28-31	1.08-1.12	10.8-11.2	318-804	4.0-10.1	398-1194	5.0-15.0	8.4	-0.03	≥850	350
	XGS30	223-247	28-31	1.08-1.12	10.8-11.2	700-828	8.8-10.4	1194-1990	15.0-25.0				
	XGS30H	223-247	28-31	1.08-1.12	10.8-11.2	700-828	8.8-10.4	≥1990	≥25.0				
	XGS32M	231-255	29-32	1.10-1.15	11.0-11.5	318-804	4.0-10.1	398-1194	5.0-15.0				
	XGS32	231-255	29-32	1.10-1.15	11.0-11.5	755-850	9.5-10.7	1194-1990	15.0-25.0				
	XGS32H	231-255	29-32	1.10-1.15	11.0-11.5	755-858	9.5-10.8	≥1990	≥25.0				
New grades	XGS33M	238-255	29.9-32	1.12-1.17	11.2-11.7	318-836	4.0-10.5	398-1194	5.0-15.0				
	XGS33	238-255	29.9-32	1.12-1.17	11.2-11.7	820-860	10.3-10.8	1194-1990	15.0-25.0				
	XGS33H	238-255	29.9-32	1.12-1.17	11.2-11.7	843-868	10.6-10.9	≥1990	≥25.0				

15000 magnet blocks ordered (~13000 effectively used)

- 6 tons of material
- 2 main types of PM blocks + 1 for field adjustment (¼ block)
- Two batches: delivery September 2016 & December 2016
- Thermal stabilization @ 120 C

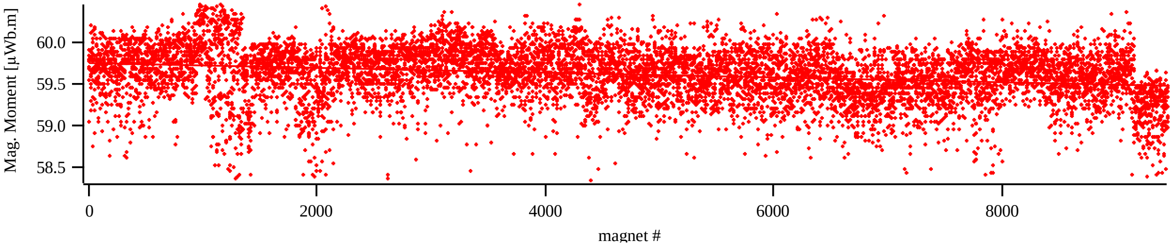
Sm_2C0_{17}

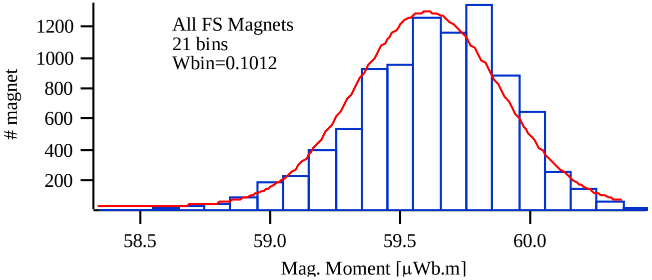
- Low temperature coefficients
- High radiation hardness

  Resistance to radiation induced demagnetization

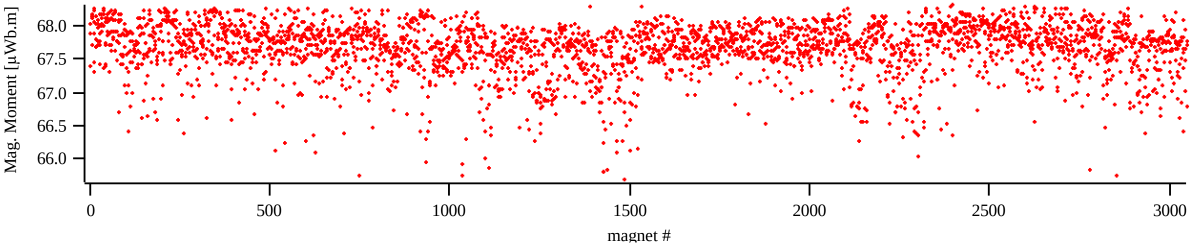
MAGNET BLOCKS DATA

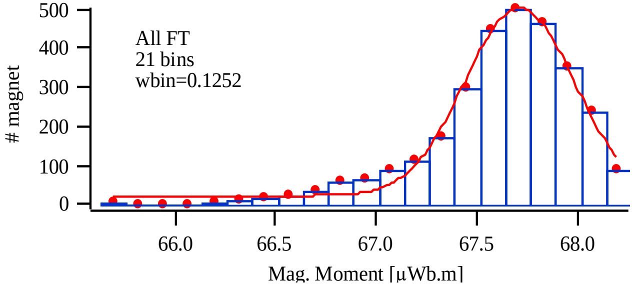
Measured magnetic moments





Magnet type FS: (max-min)/avg=3.5 %, stdev/avg=0.52 %





Magnet type FT: (max-min)/avg=3.9 %, stdev/avg=0.57 %

Use of magnet sorting

DL IRON MATERIAL: CONTROL OF STEEL QUALITY

Raw hot rolled material (low carbon steel)

Flame cutting + heat treatment

Semi finished product (iron blocks)

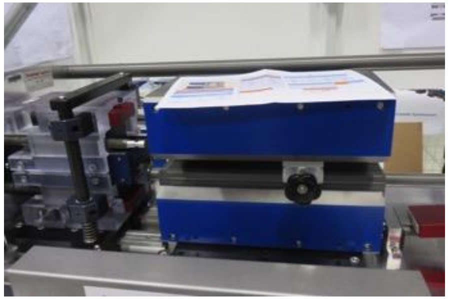
Delivery to sub-contractors for machining
Surface treatment
Assembly without PM
Painting

DL ASSEMBLY: DONE IN-HOUSE

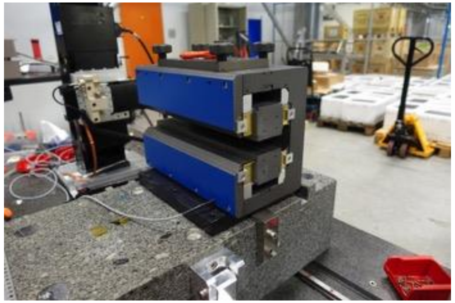
Magnet blocks (Magsound,)

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

Magnet block insertion in modules
(dedicated tools)



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

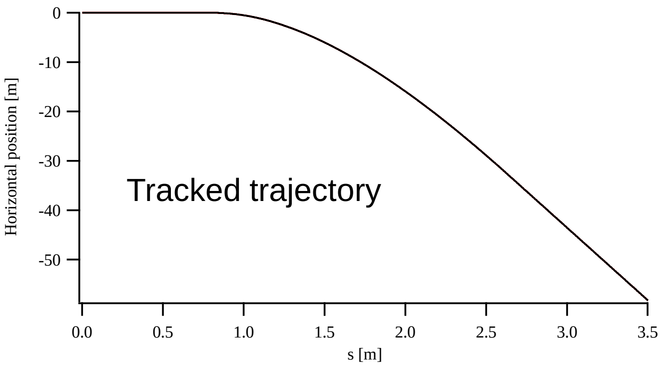


DL assembly

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

DL FOR LATTICE DESCRIPTION

Example DL2 model with 5 (field, magnetic length)



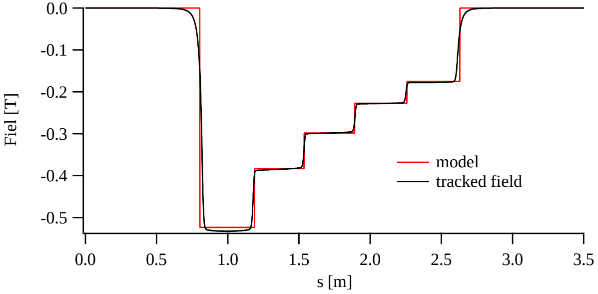
Find $B_i, L_i (i = 1{,}5)$

with

$$\sum_{i=1}^{5} B_i L_i = nominal\ integral$$

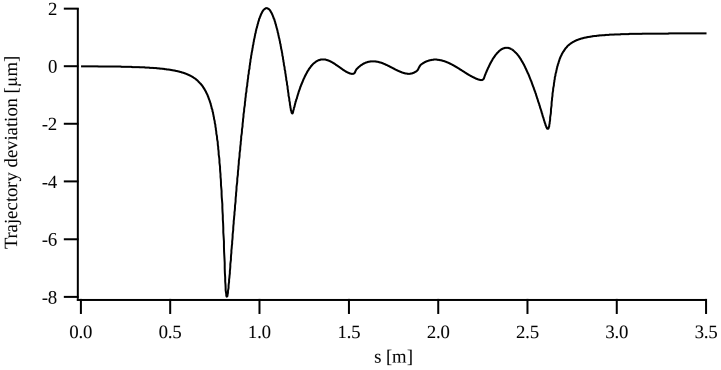
and

$$Min\ (|modelled\ trajectory - tracked\ trajectory|)$$



DL2

B [T]	L[m]
-0.5232	0.383
-0.3831	0.348
-0.2979	0.356
-0.2273	0.365
-0.1751	0.371



MODULAR CONCEPT

5 independent modules/ DL

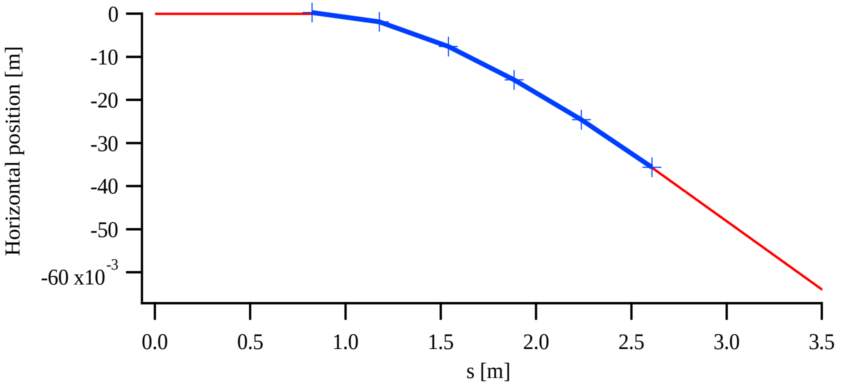
A module can be removed/installed from/in the assembly

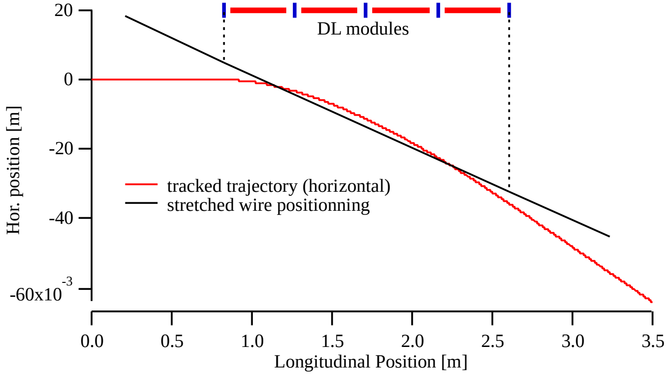
Possible implementation of quadrupole function in one or two modules

- Same yoke
- Modified pole & magnet block distribution
- Future development

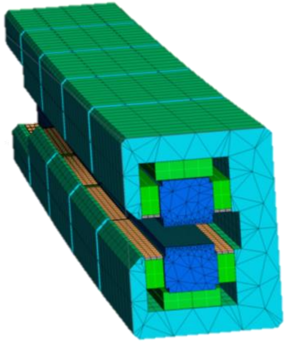
ANTICIPATION OF MAGNETIC MEASUREMENTS WITH 3D MODEL

Stretched wire positioned according to the best line fit of tracked trajectory between end pole faces of DL





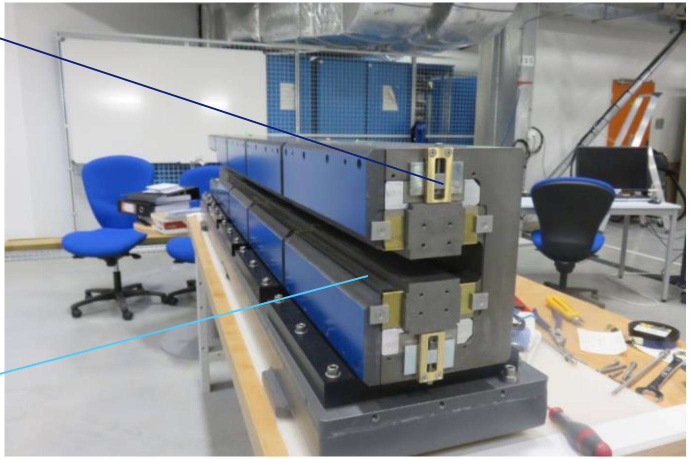
Module axis placed on trajectory (5 straight segments)



~ curved magnet

INDIVIDUAL MODULES

- Field tuning of each module
  - Limited tuning of the full assembly
  - Needs knowledge of the “ideal” integral for each module
  - Tuning done with Fe-Si shims (flux shunt)



Needs to anticipate the magnetic crosstalk between modules to achieve targeted DL integral:

$$\left| I_{sum} = \sum_{k=1}^{5} I_k \right| > |I_{DL}|$$

Integral of individual module

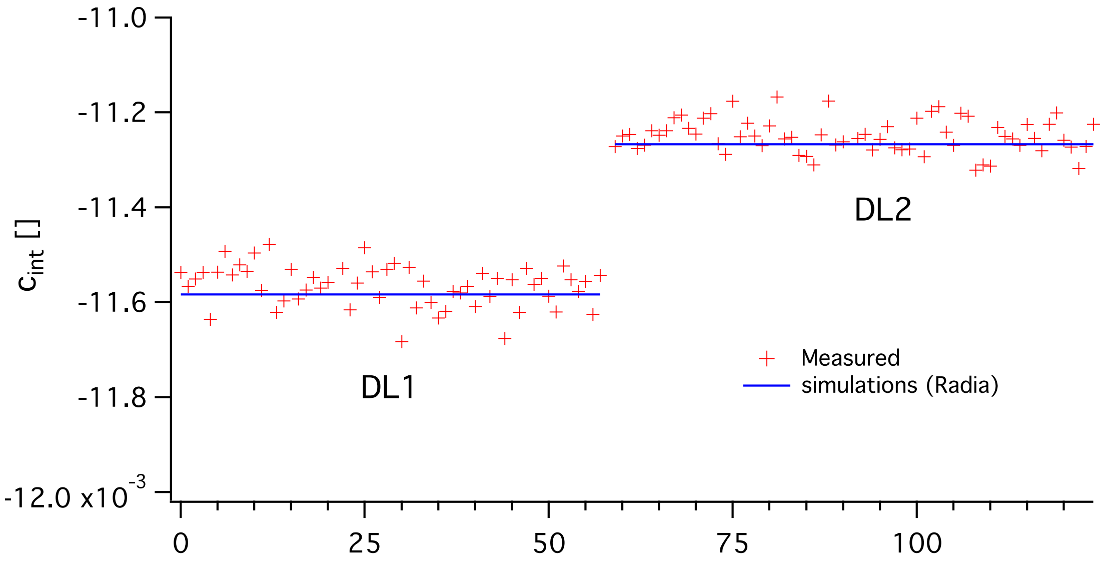
Integral of full assembly

Simulation results

$$c_{int} = \frac{I_{sum} - I_{DL}}{I_{DL}} = \begin{cases} -1.13\ \%\ for\ DL2 \\ -1.16\ \%\ for\ DL1 \end{cases}$$

MAGNETIC CROSSTALK BETWEEN MODULES

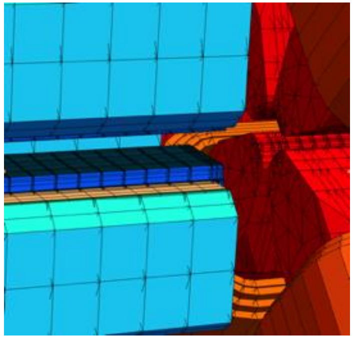
Magnetic measurements of individual modules and assembly give access to c_{int}



$$c_{int} = \frac{I_{sum} - I_{DL}}{I_{DL}}$$

The measured values for c_{int} agree very well with simulations

MAGNETIC CROSSTALK WITH NEIGHBORING QUADRUPOLES

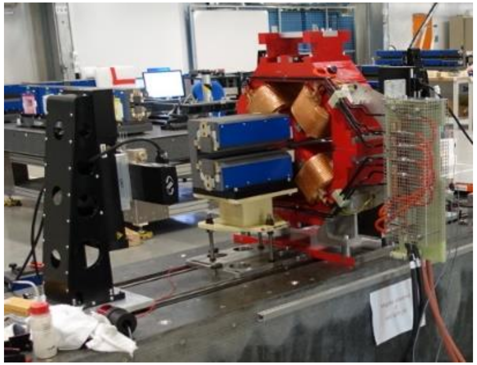


distance iron to iron quadrupole DL

- 47 mm for DL1 (both sides)
- 47 mm & 150 mm for DL2

Magnetic simulation :

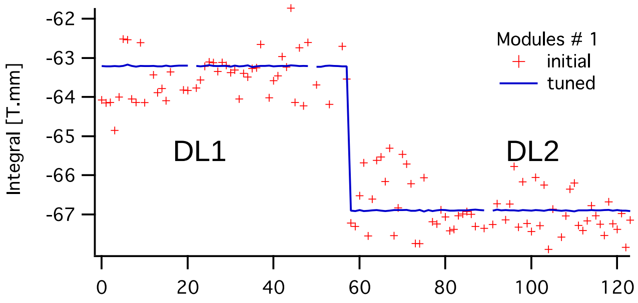
- 0.46 % reduction in deflection angle for DL1
- 0.15 % for DL2
- Confirmed with measurements

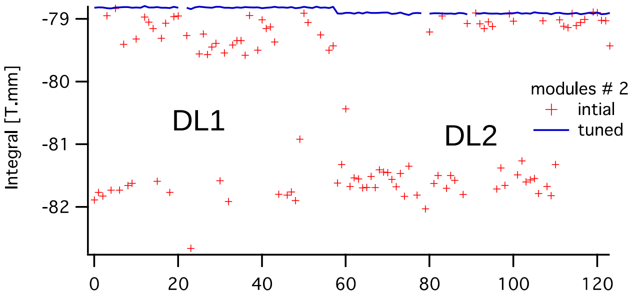


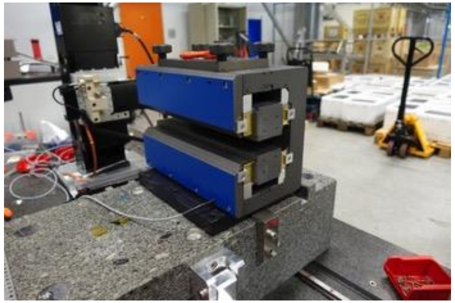
End module strength increased by 0.96 % for DL1

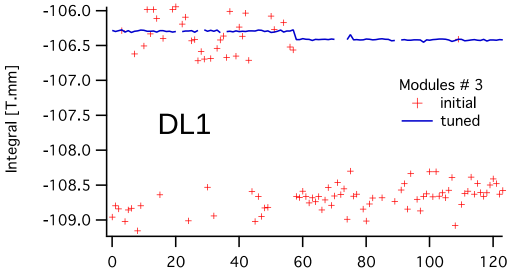
End module strength increased by 0.96 % & 0.13% for DL2

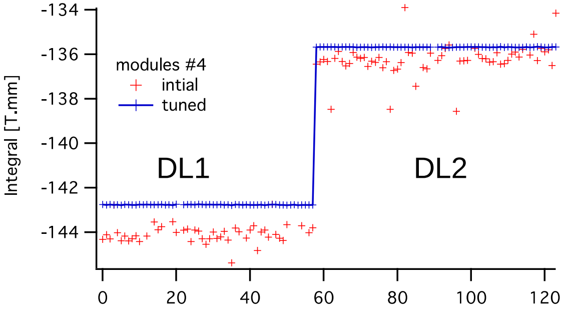
MEASUREMENT AND TUNING OF INDIVIDUAL MODULES

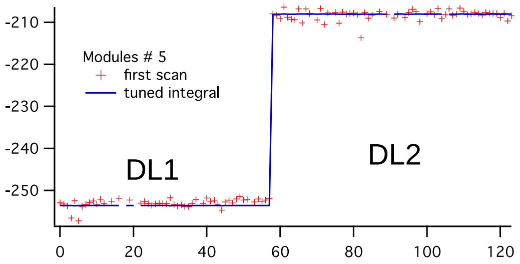








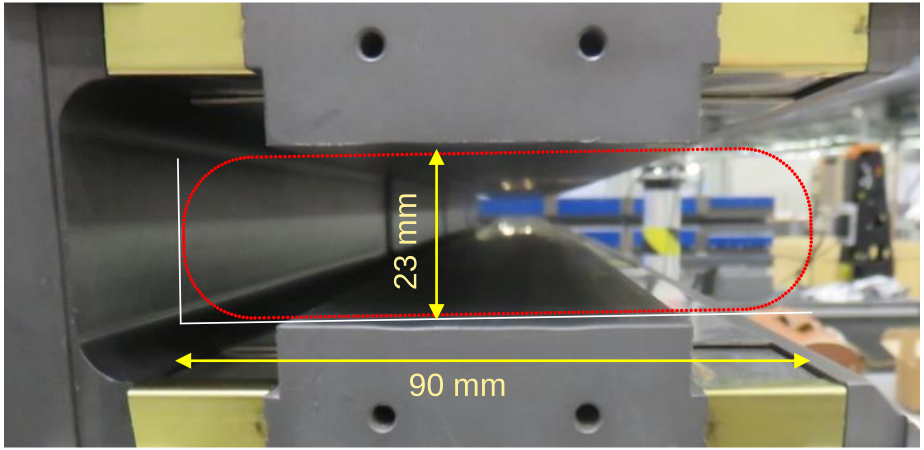




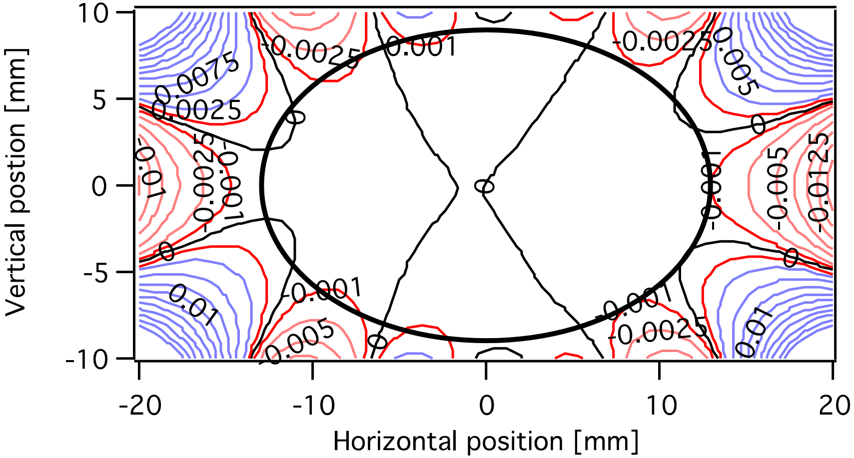
In total 132 x 5 modules assembled and tuned

DL MAGNETIC MEASUREMENTS

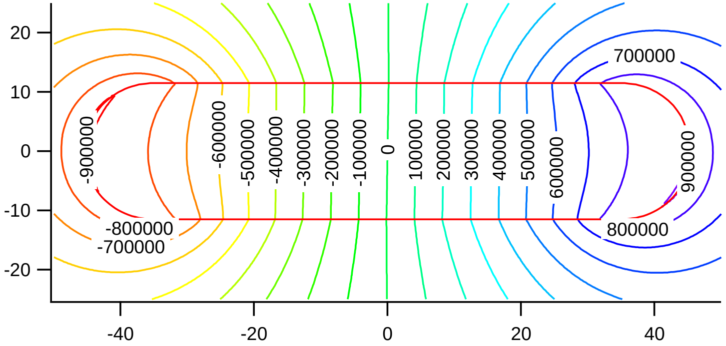
DLs



DB/B



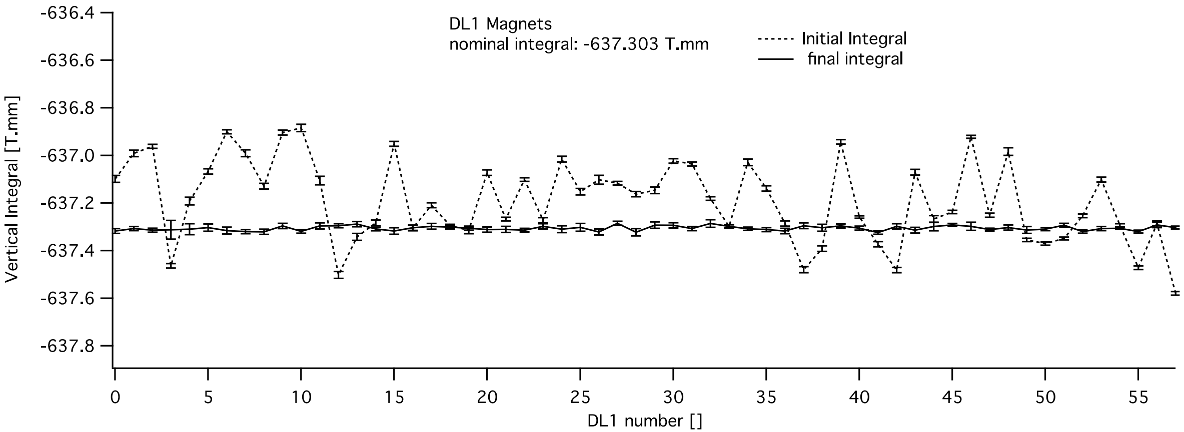
Field integral homogeneity in GFR

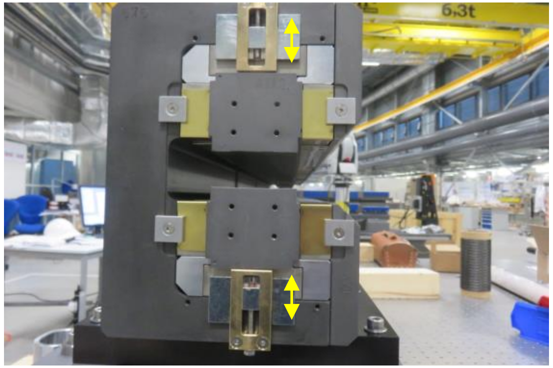


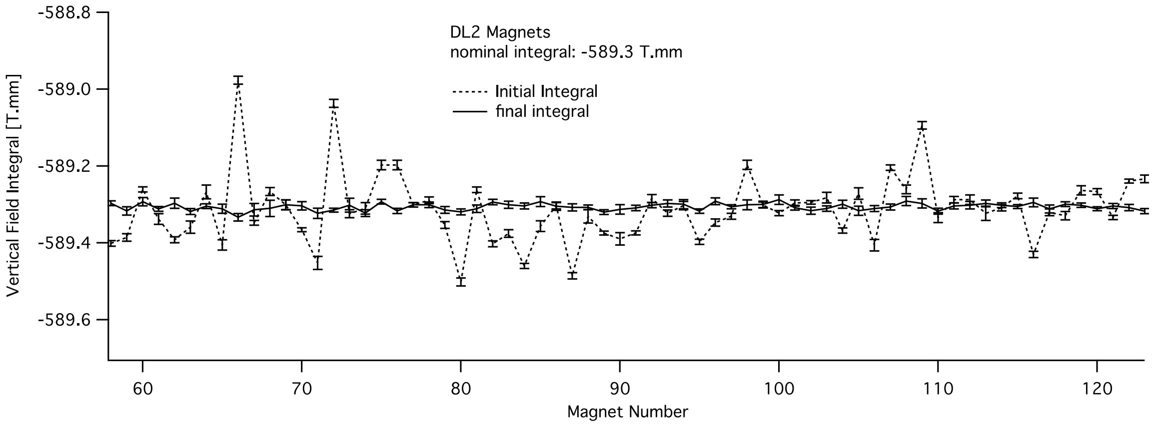
- 332 segments
- pole gap 24.5 mm
- Segment length 0.62 mm

DL FIELD INTEGRAL AT CENTER

DL field tuning using movable shunts



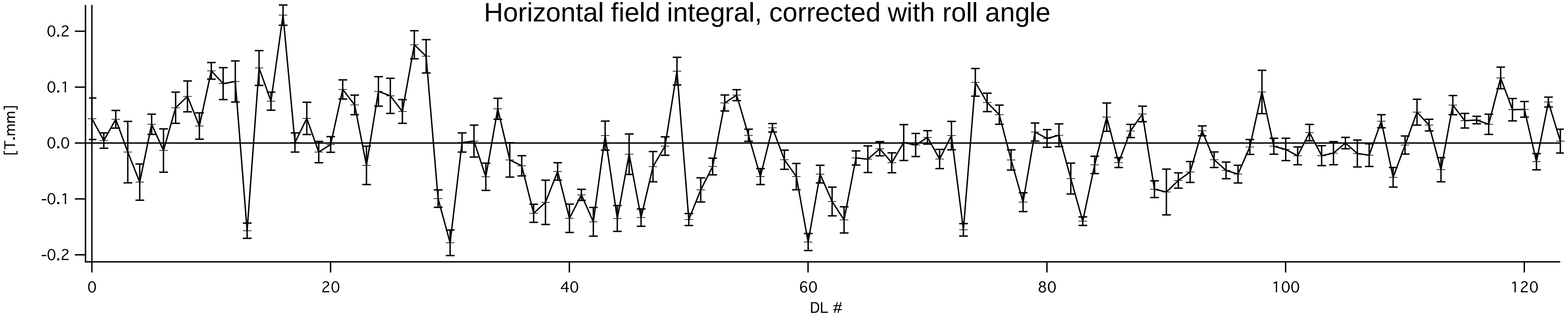




Measurement repeatability

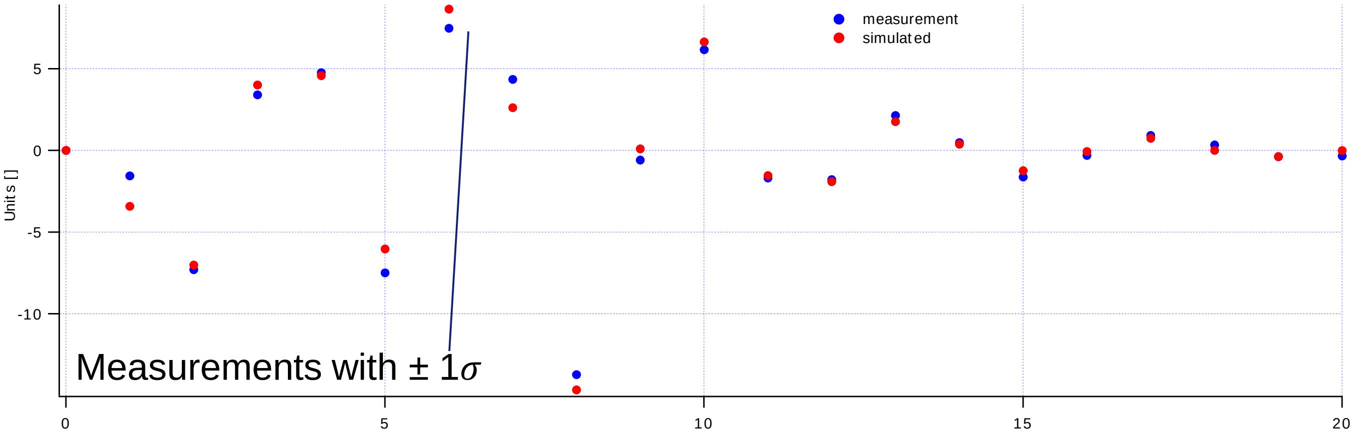
$$1\sigma/\mathrm{B} \approx 2.510^{-5}$$

FIELD INTEGRAL & HARMONIC ANALYSIS (STRAIGHT INTEGRALS)


Horizontal field integral, corrected with roll angle

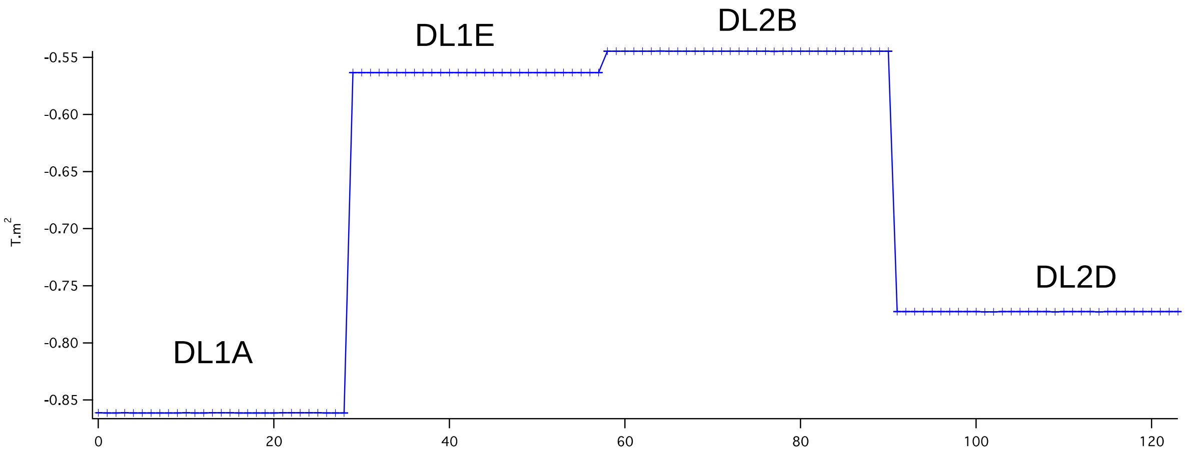
Harmonic analysis

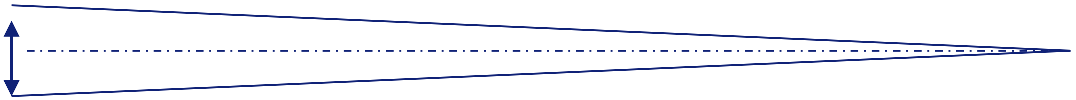
Simulation using RADIA model



Measurements with ± 1σ

2ND INTEGRAL



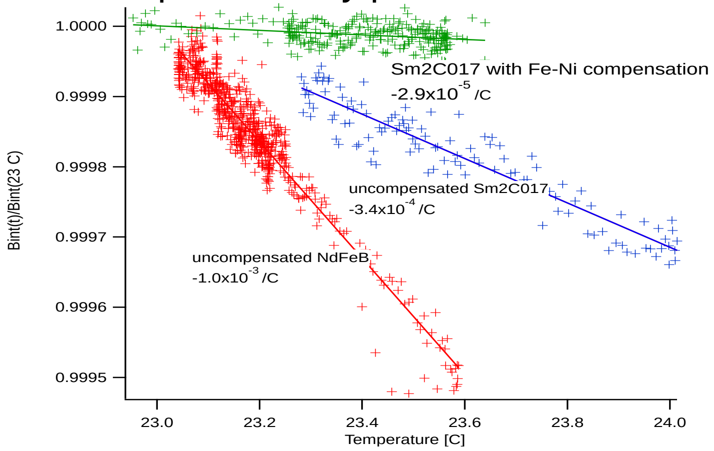


Second integral tuned with movable end shims.

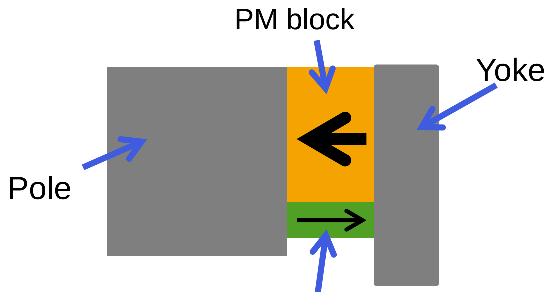
TEMPERATURE STABILITY

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

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



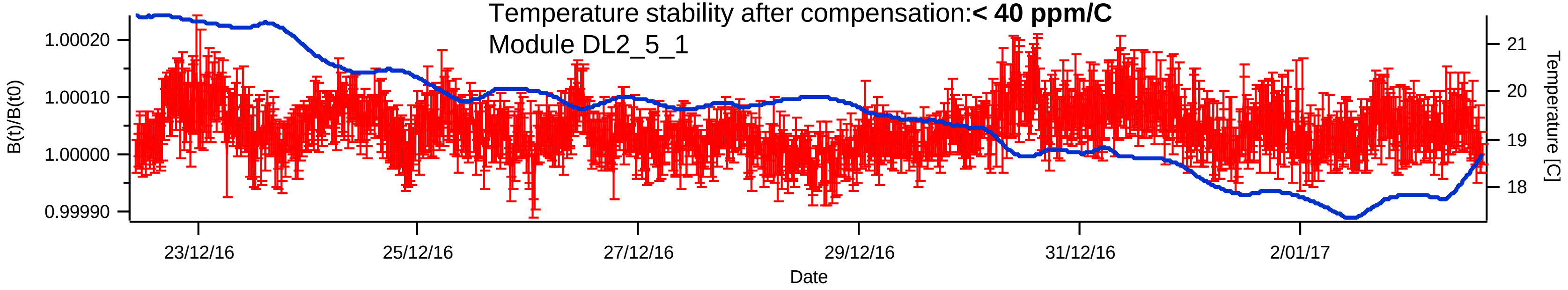
Field integral measurements on PM DL modules NdFeB, Sm_2C0_{17}



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)

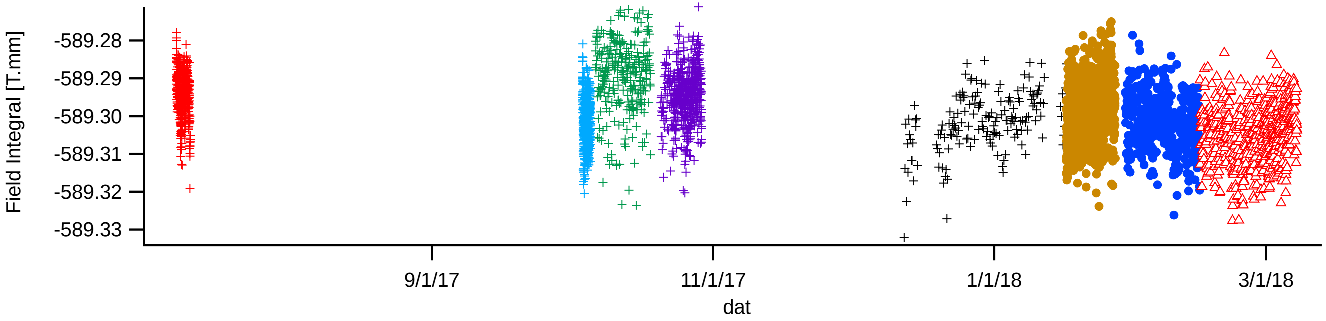
Temperature stability after compensation:**< 40 ppm/C**

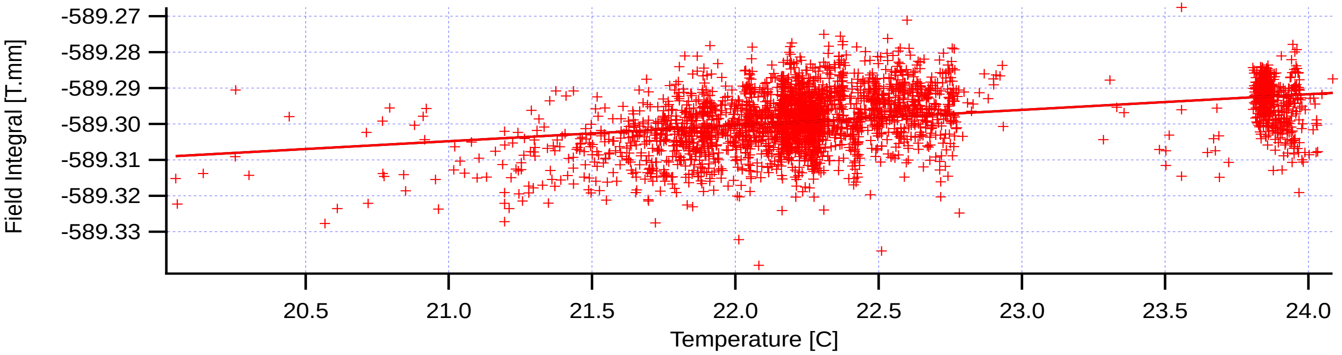
Module DL2_5_1



TEMPERATURE STABILITY

Measurement of integral & temperature vs time





Residual slope ~ 10 ppm/C

Magnet: DL2B_11_14

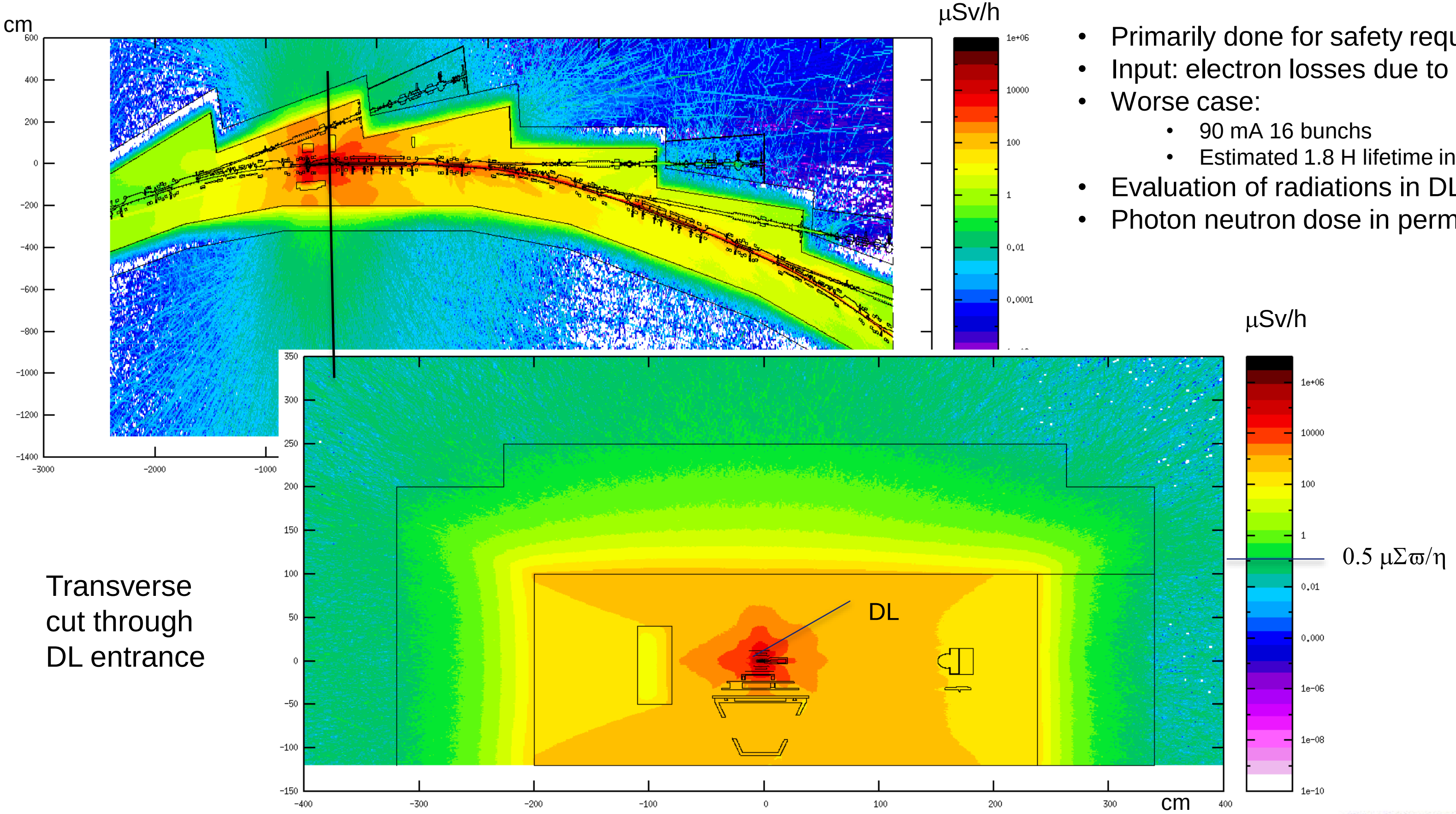
RADIATIONS IN PERMANENT MAGNETS

ESRF storage ring: 6 GeV,

Critical place is at the DL behind the electron beam collimator

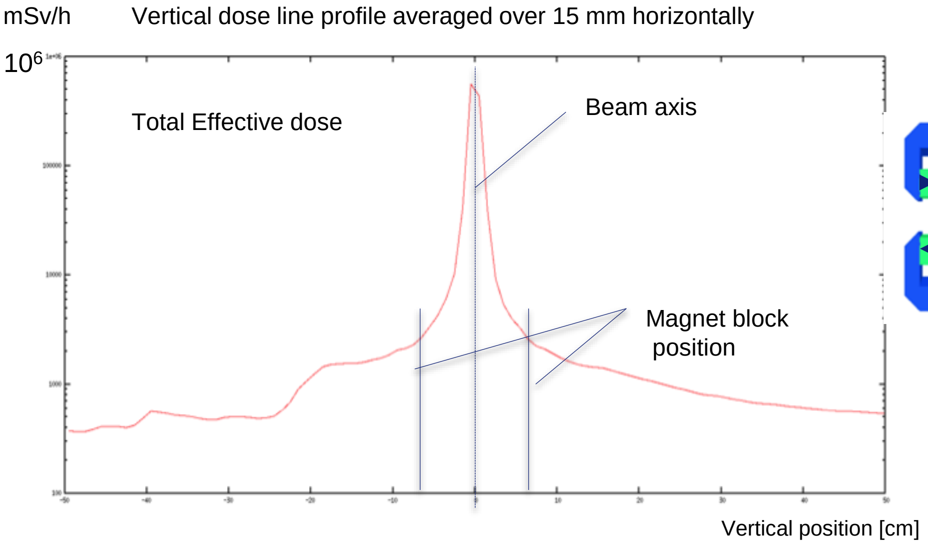
FLUKA simulations

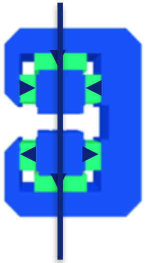
- Primarily done for safety requirements
- Input: electron losses due to Touschek effect
- Worse case:
  - 90 mA 16 bunchs
  - Estimated 1.8 H lifetime in EBS
- Evaluation of radiations in DL
- Photon neutron dose in permanent magnets

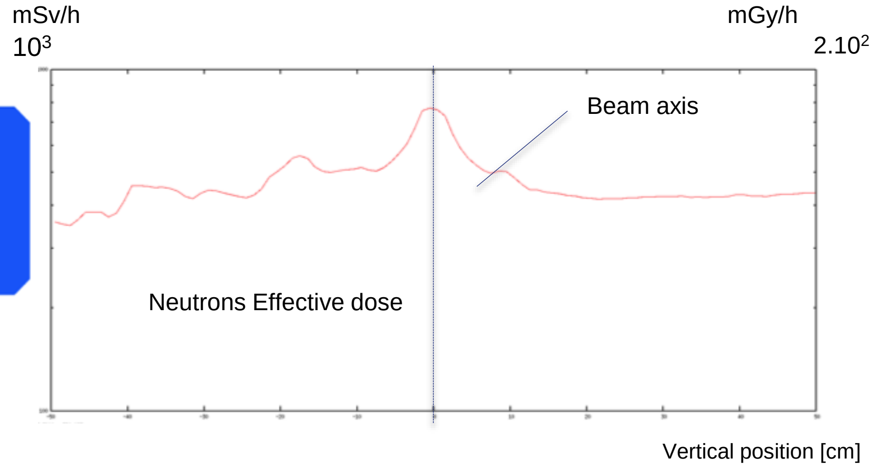


Transverse cut through DL entrance

RADIATIONS IN PERMANENT MAGNETS (CONT'D)







In present storage ring Sm_2C0_{17} permanent magnets used in low gap undulators: In-Vacuum undulators

- Magnetic gap 6 mm
- Neutron doses at PM blocks are ~ 1 Gy/h derived from beam loss measurements
- No visible demagnetization of permanent magnet material after 15 years of operation (< 0.2 %)

Magnetic stability vs radiations should be enough for 20-25 years operation

STATUS & SUMMARY

Status

- Production completed before mid October 2017
- Installed in the ring tunnel

Summary

- Methods and technics for a large scale production of PM dipoles have been developed
- Simple magnetic structures, no electrical power
- Segmented (modules) approach for DLs has interesting flexibility
- Sm_2Co_{17} material is the most suitable to ensure long term magnetic stability
- Magnetic measurements with stretched moving wire very efficient and reliable