ALERT 2019 workshop

Advanced Low Emittance Rings Technology

Summary Session 6: Magnets

D. Einfeld

ALERT 2019 workshop

Advanced Low Emittance Rings Technology

Ben Shepherd (Daresbury):
 Development of Adjustable Permanent Magnet Quadrupoles

Les Dallin (CLS):
 Electromagnets with High Gradients for CLS 2.0

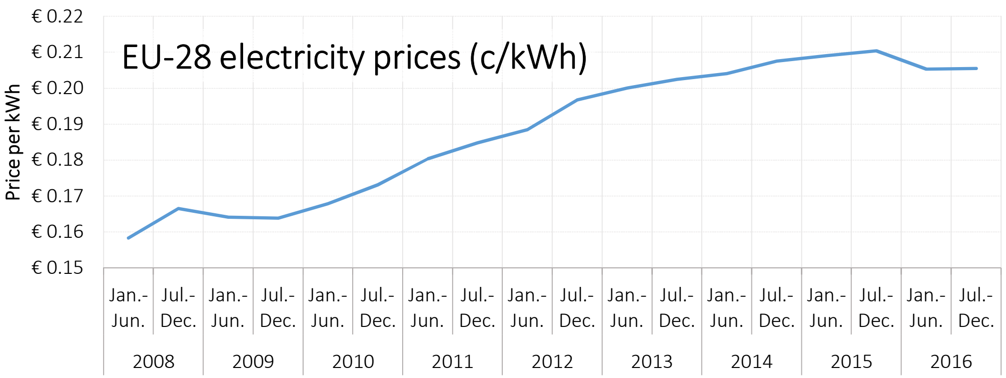
Abolfazl Shaveh (DLS):
 Magnet design for Diamond-II Upgrade

Ciro Calzolaio (PSI):
 Magnets for the SLS Upgrade

ALERT 2019 workshop

Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

Motivation for designing permanent magnet quadrupoles: electricity consumption and compactness



Permanent magnets already widely used in accelerators: mostly for **undulators** and **wigglers** in light sources

Best materials today:

- **$Nd_2Fe_{14}B$** for highest strength (B_r)
- **Sm_2Co_{17}** for highest stability (H_{cj})
- **$Pr_2Fe_{14}B$** at low temperature (77 K)

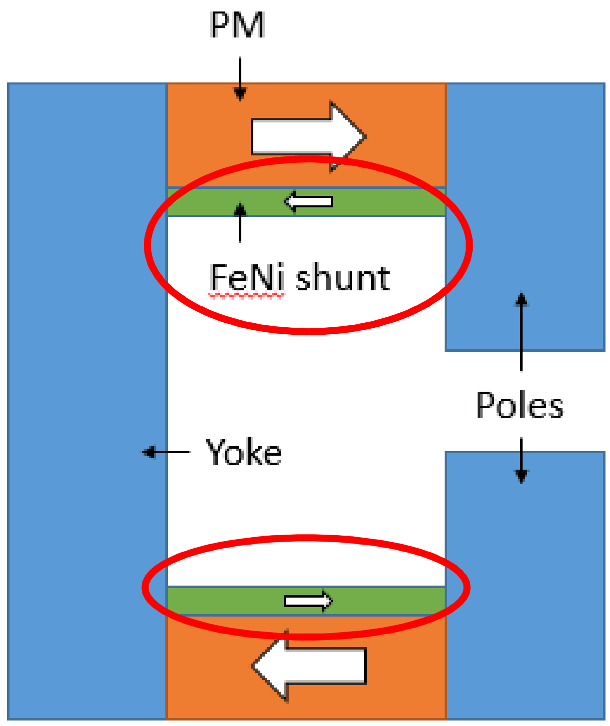
Advantages: No power, no water, compact, higher gradients

Disadvantages: Tuning difficult, PMs variable, temperature dependent, radiation damage.

Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

Permanent magnets have high temperature coefficients: NdFeB: **-0.1%/°C,** SmCo: **0.03%/°C**

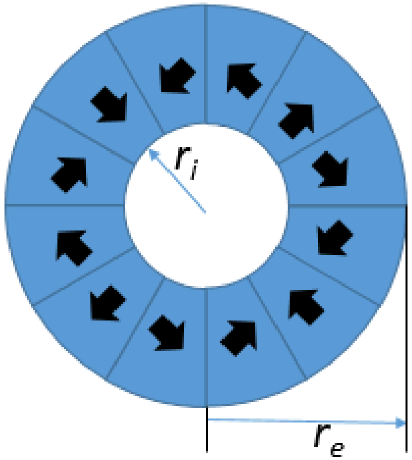
Possible to compensate using FeNi shunt:



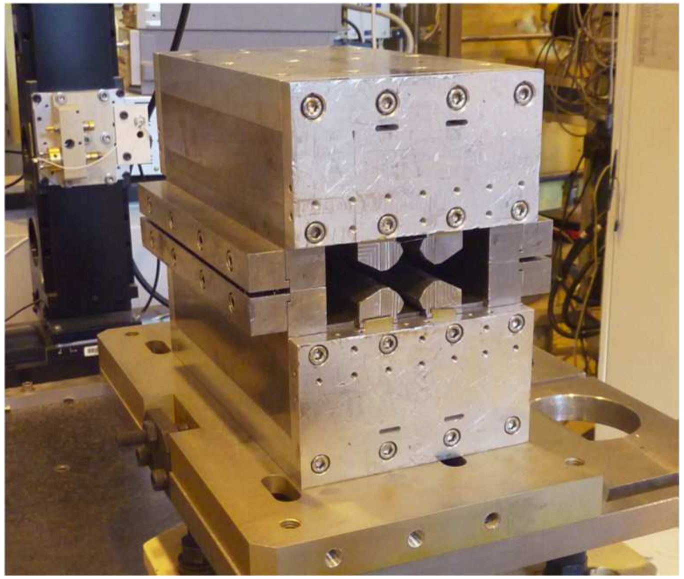
Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

Permanent Magnet Quadrupoles :

Halbach array:



For r_i = 10 mm, r_e = 20 mm, B_r = 1.38 T, M = 16 → G = 130 T/m

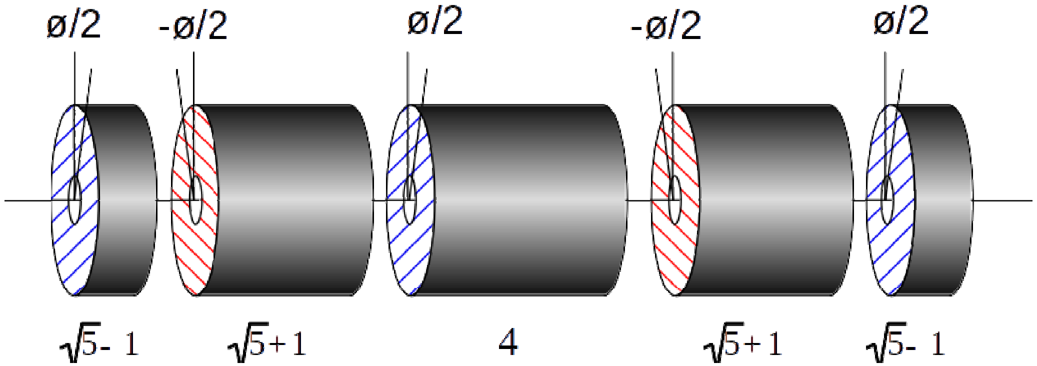


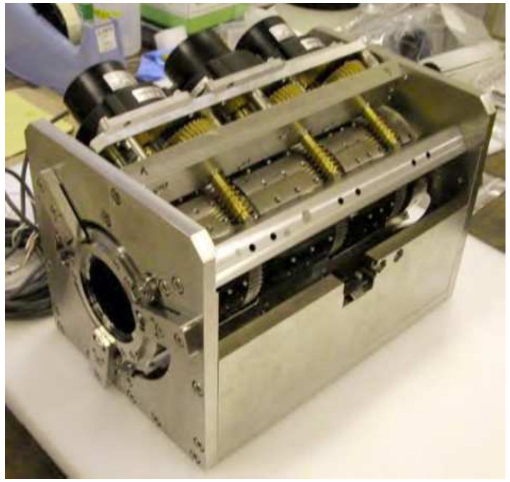
ESRF PM Quadrupole :

85 T/m gradient
226 mm length
12 mm bore radius

Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

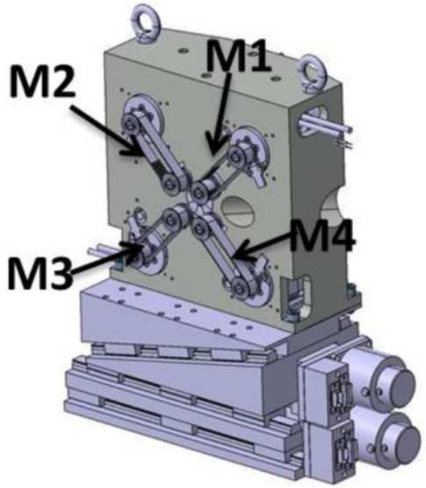
ILC adjustable PM quadrupole :

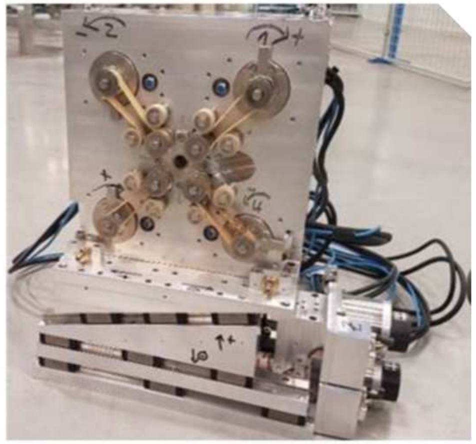




SOLEIL Adjustable Quadrupole: QUAPEVA

12 mm gap
100 mm length
110-210 T/m gradient



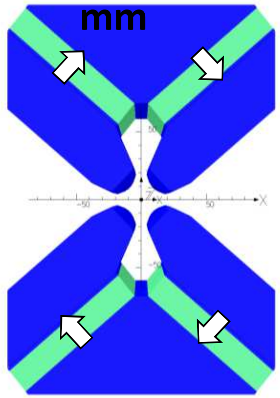


Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

ZEPTO Quadrupoles: High Strength

- Gradient **15-60 T/m**
- Pole gap **27.2 mm**
- Field quality **±0.1%** over **23 mm**
- Length **230 mm**

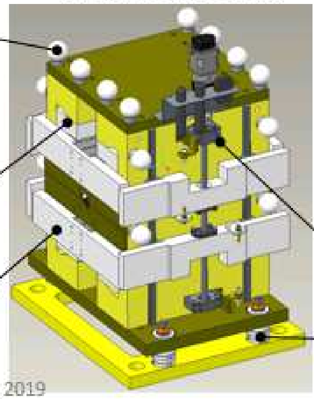
Stroke = **0 to 64 mm**



ZEPTO-DLS Project

- Quadrupole specifications
  - Max integrated gradient **7.6 T**
  - Min integrated gradient **0.2 T**
  - Aperture diameter **32 mm**
  - Field quality $\Delta G/G_0$ < **$5\text{x}10^{-3}$** at $r \leq$ 10 mm
  - **Splittable** to allow installation around vacuum chamber

CAD model of the design

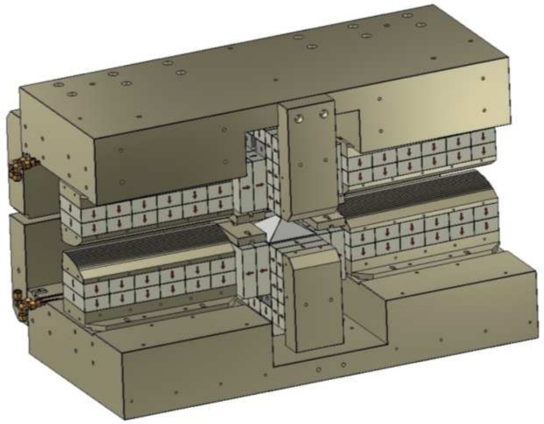


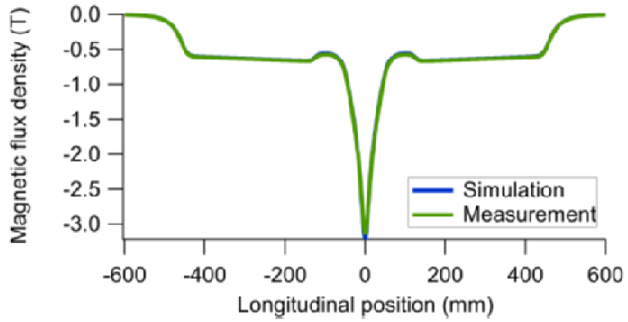
PM blocks
Sm_2Co_{17}, B_r 1.03 T
72x94x268 mm
90 mm movement

Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

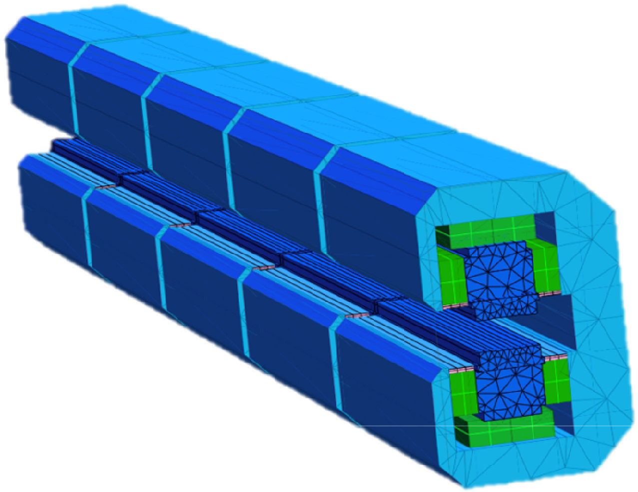
Permanent Magnet Dipoles :

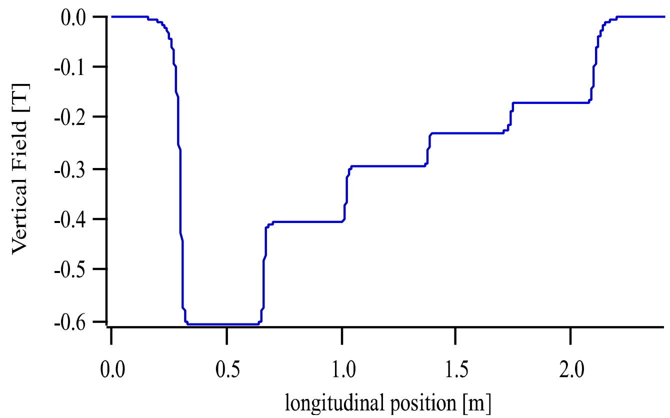
Sirius "Superbend" Dipole





ESRF Longitudinal Gradient Dipoles

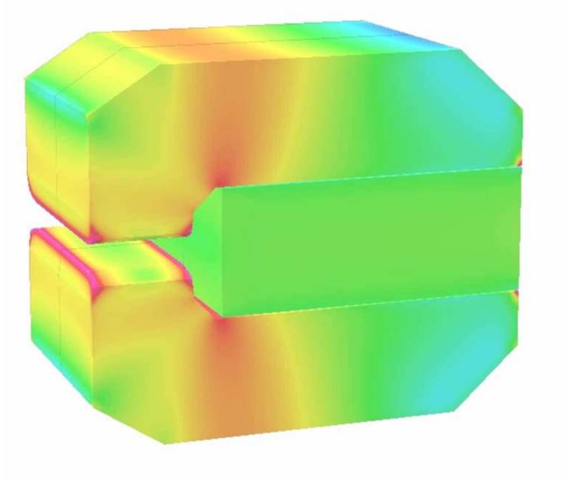


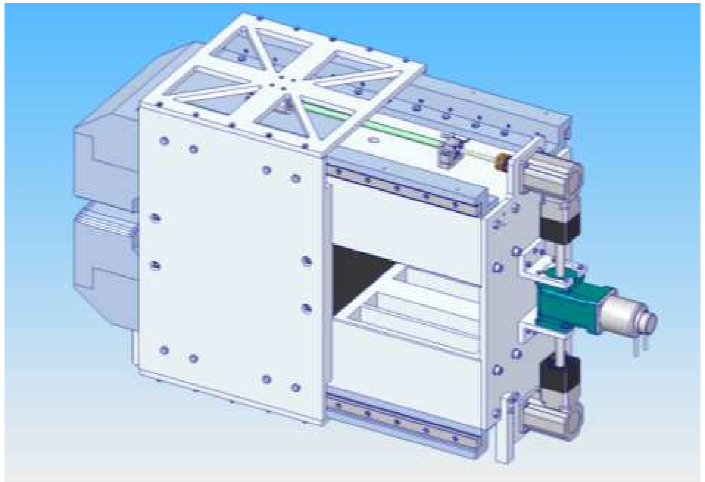


Vertical field vs. longitudinal position

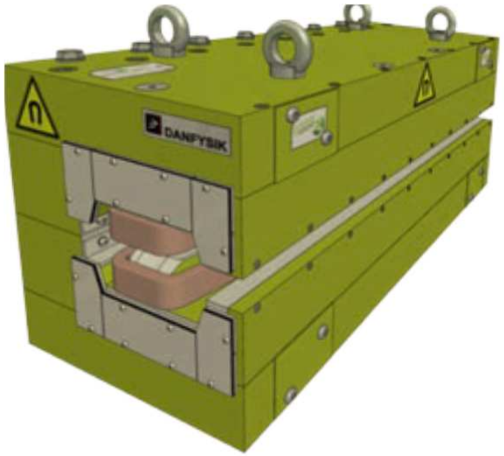
Ben Shepherd (Daresbury): Development of Adjustable Permanent Magnet Quadrupoles

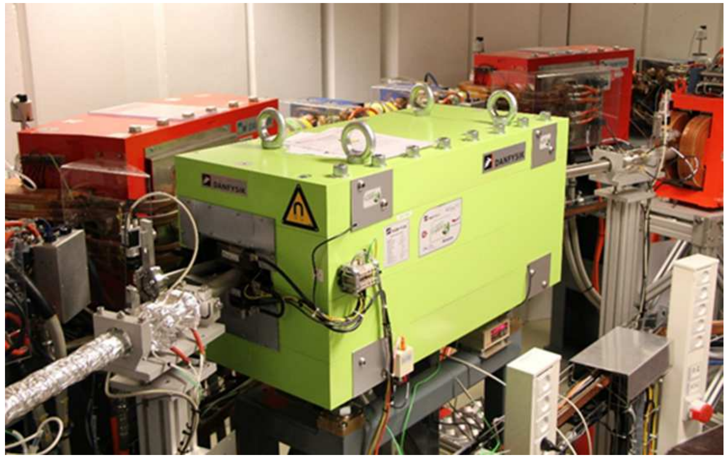
ZEPTO Dipole Design:





Danfysik Green Magnets:





Conclusions

Many accelerators are now using PM dipole and quadrupoles

Several advantages to using PMs:

- Compact
- Low power
- No vibration

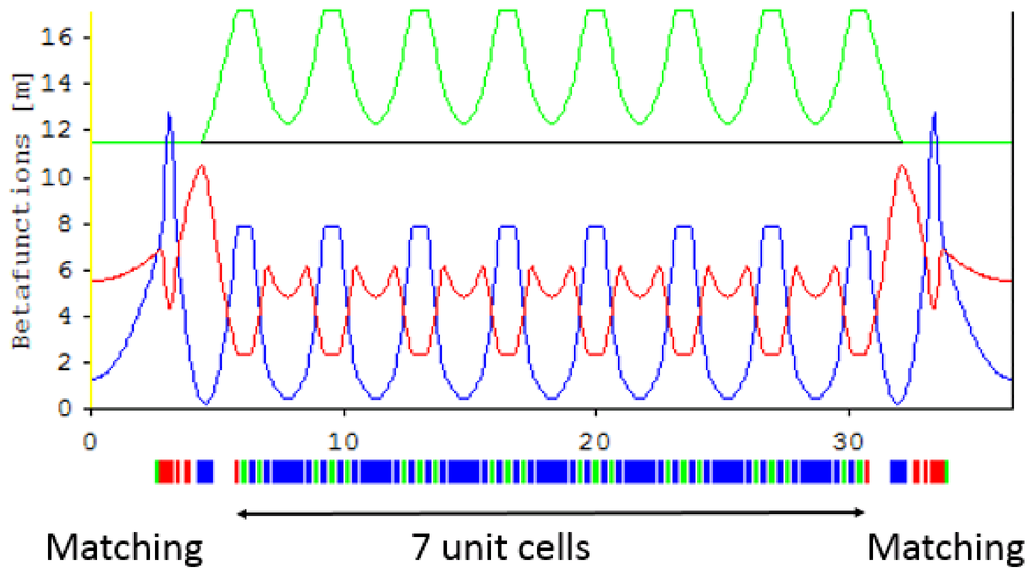
Disadvantages can be mitigated

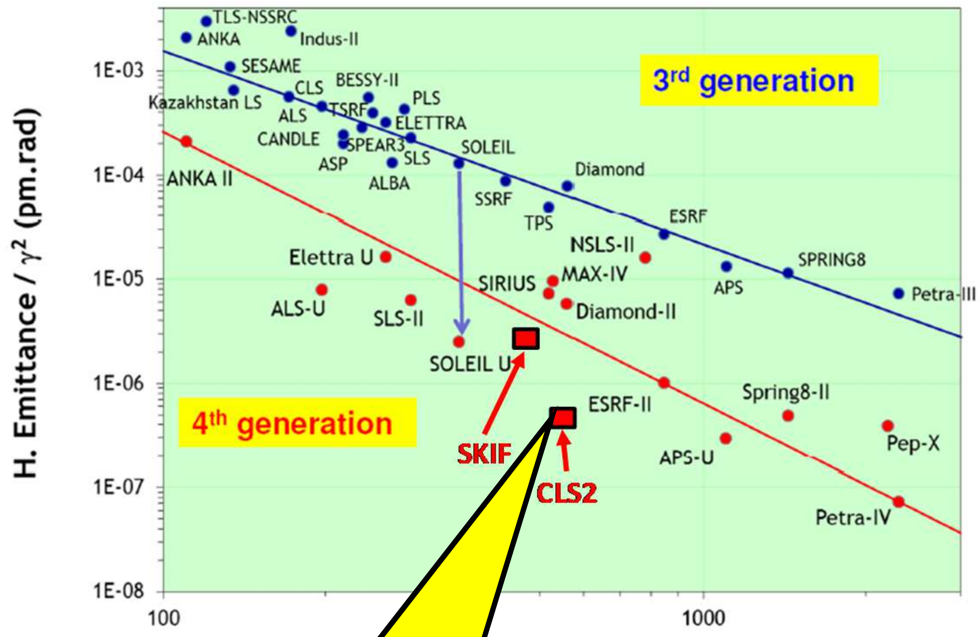
- Tuning
- Temperature variation
- Radiation effects

Variety of different tuning methods

Les Dallin (CLS): Electromagnets with High Gradients for CLS 2.0

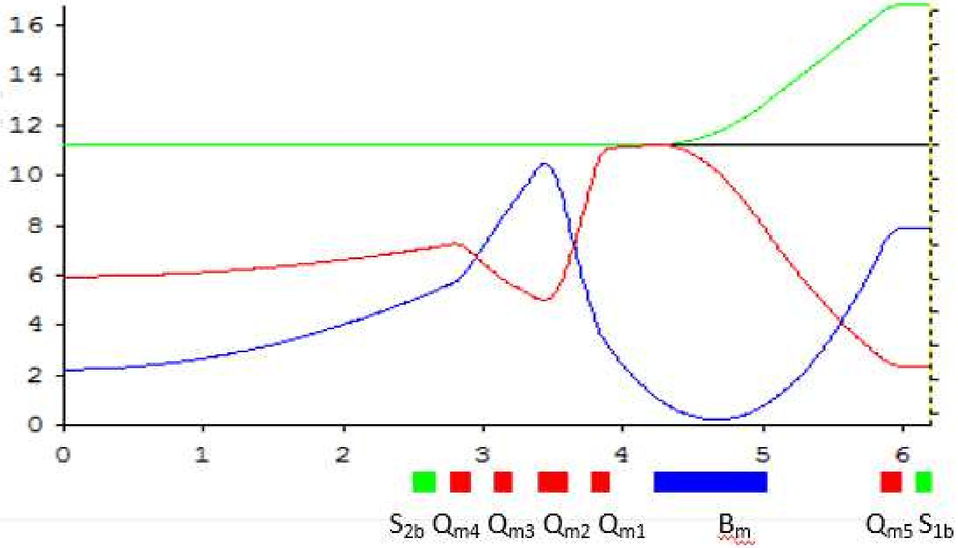
CLS 2 – 3 GeV Ultralow Emittance Light Source

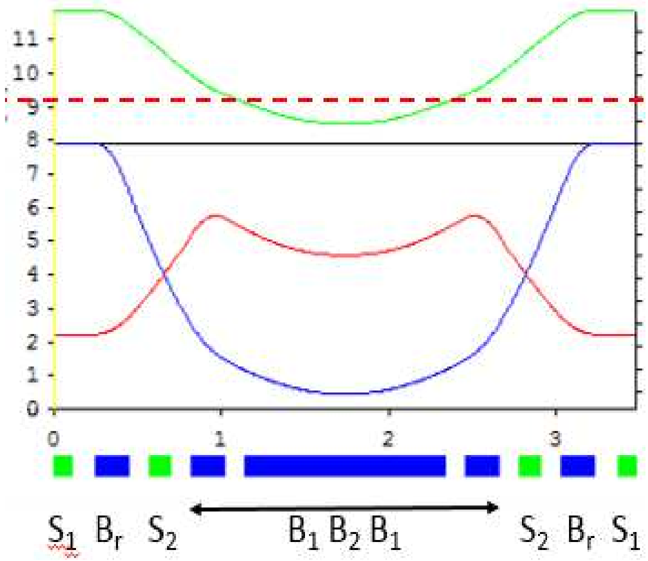




Congratulation reaching this number. This is a "World Record".

Magnets for CLS 2 (roughly the same specifications as for other 4th GLS)





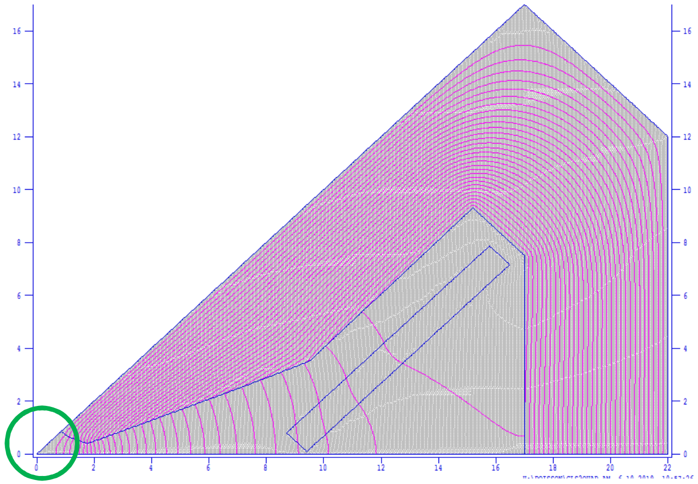
	qm1	qm2	qm3	qm4	qm5
Gradient [T/m]	-85.22	86.58	9.59	-35.33	66.16
current [Amp]	150	150	50	75	184

	S1*	S1b*	S2	S2b	
Gradient [T/m^2]	2103	1586	2126	0	
current [Amp]	60	60	60		

	BR	B1	B2	BM	
length [m]	.20	.20	1.2	0.8	
B [T]	-0.1745	0.1745	0.3944	0.3835	
B' [T/m]	48.5	48.5	4.21	-6.0	

Les Dallin (CLS): Electromagnets with High Gradients for CLS 2.0

Adjust Ø to evaluate various quadrupole magnets



Ø [mm]	B' [T/m] (90% eff.)
18	120
24	90
30	73

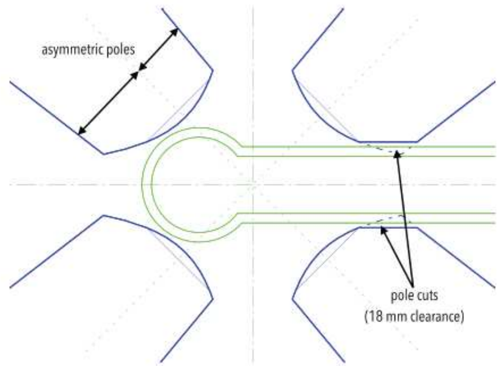
E.g.: Ø = 24 mm
Relative Multipoles
@ 10 mm

n	B_n/B_2
6	-9.8E-04
10	-8.6E-05
14	-1.8E-05
18	-2.7E-07
22	6.5E-06
26	1.3E-05

Aperture Ø = 18 mm; 24 mm; 30 mm

Getting the photon beam out: open-sided quadrupole Qm5 (Ø = 3.0 cm)

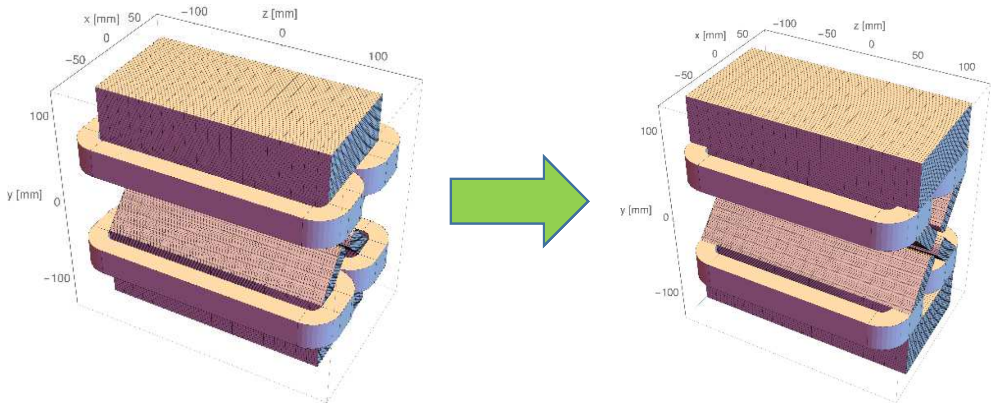
Getting the photon beam out: open-sided quadrupole Qm5



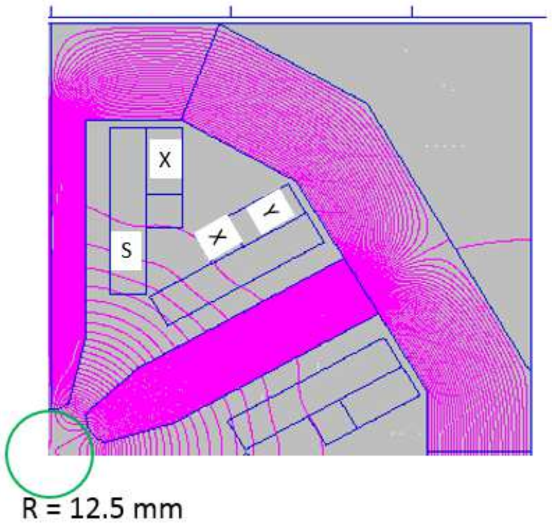
ALERT 2019 workshop

Les Dallin (CLS): Electromagnets with High Gradients for CLS 2.0

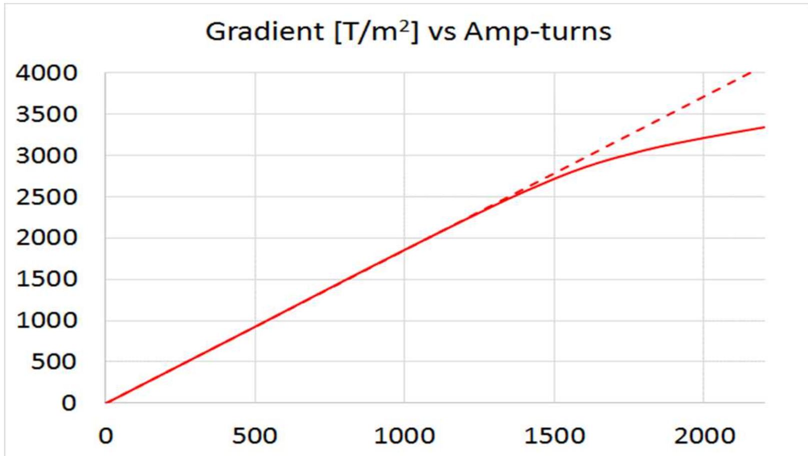
Reducing the Longitudinal Footprint



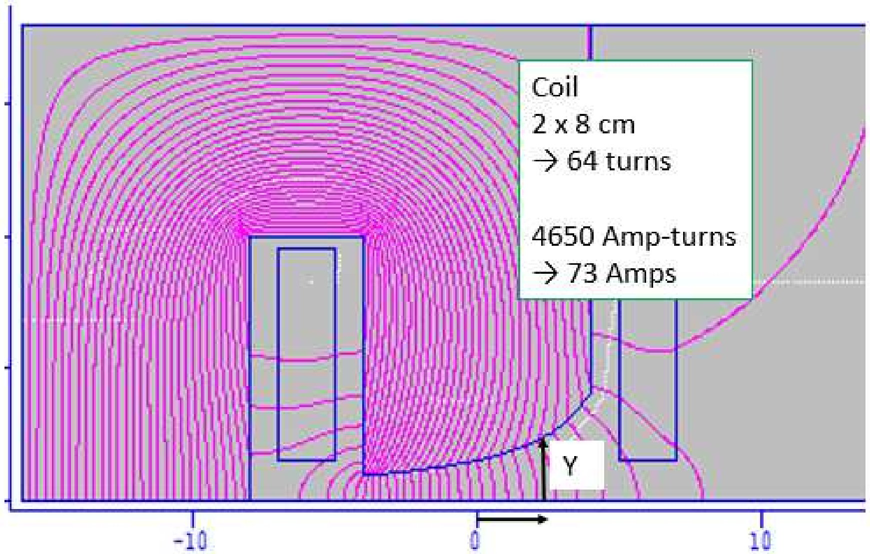
Sextupole Design



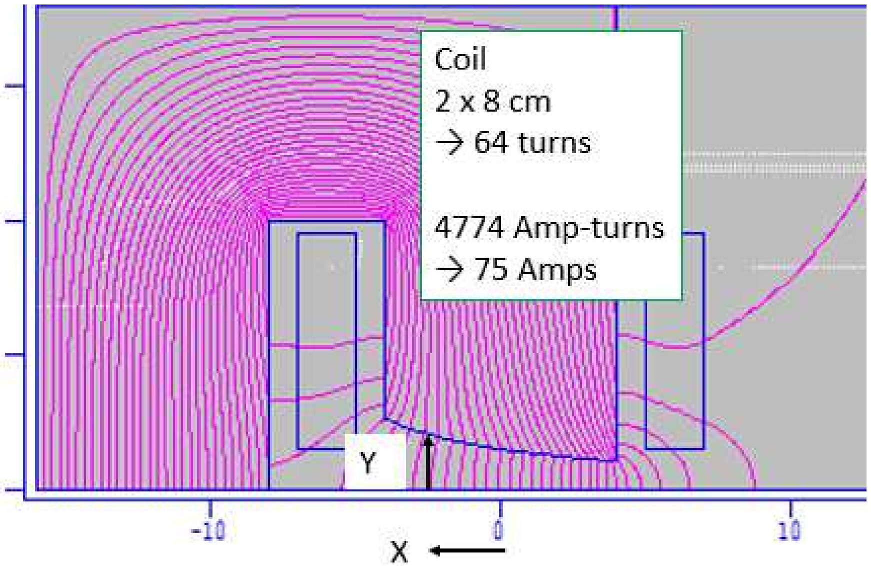
S1, S2, S1b and S2b magnets
- **12.5 mm aperture radius**
- **coils for X and Y correctors**



Bend Magnets : Use longitudinal gradient bends to reduce emittance



BM Design
half gap = 1.5 cm
B'_{final} = 6.01 T/m (< 0.2% off)



B2 (focussing bend)
half gap = 1.5 cm
B'_{final} = 4.23 T/m (< 0.5% off)

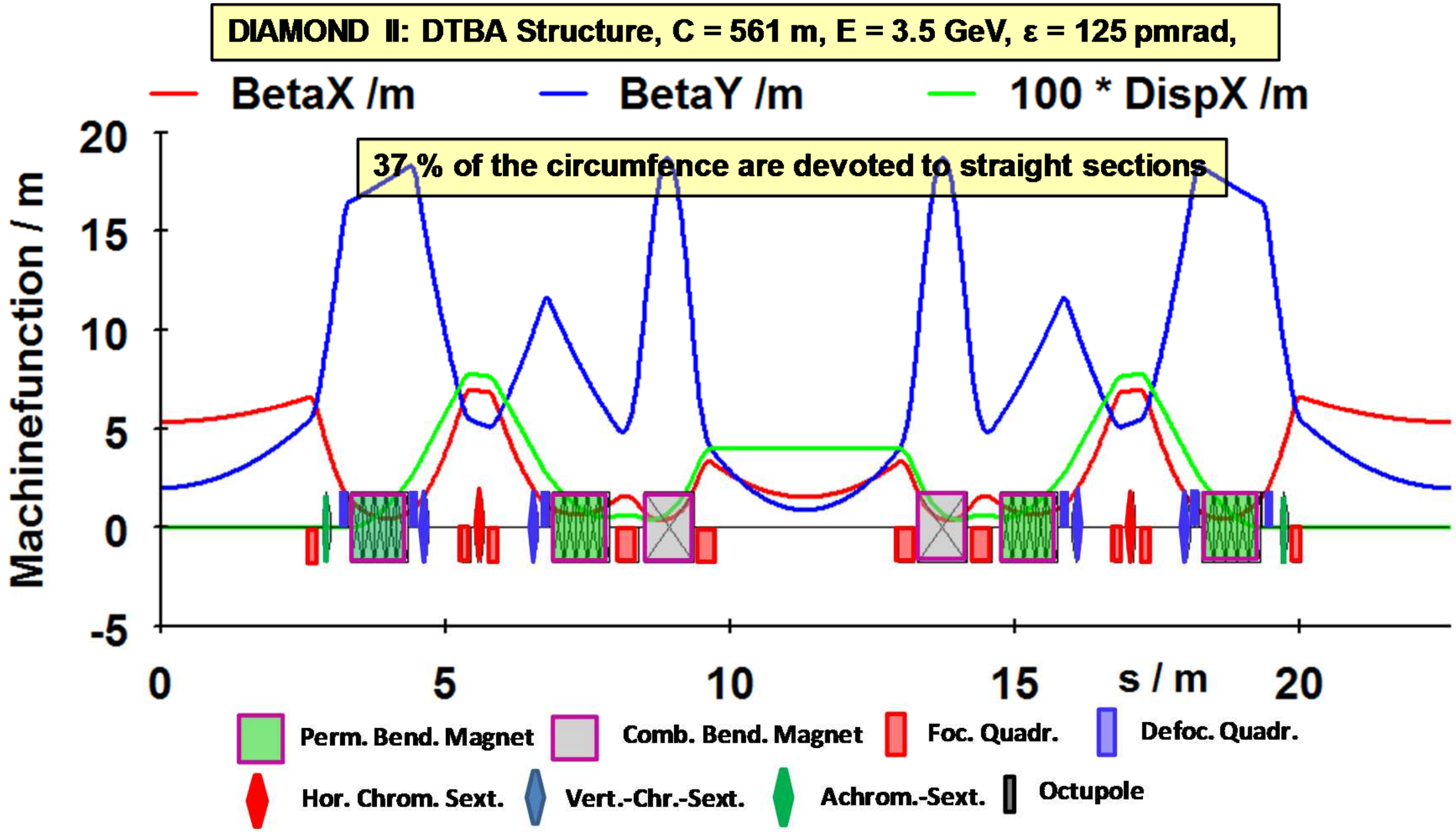
Les Dallin (CLS): Electromagnets with High Gradients for CLS 2.0

Preliminary designs for CLS 2 Magnets are in progress

- **high gradient electromagnets are used**
- **“simple” designs are used**
- **no special steel is required**

Ultralow Emittance is achieved: 25 pm-rad @ 3 GeV
(an aggressive optics design)

Abolfazl Shaveh (DLS): Magnet design for Diamond-II Upgrade



Specifications of the magnets (roughly the same as for ESRF-EBS)

Magnet	Length	Field	Maximum Strength			No. of magnets	Type
			G_0	S_0	O_0		
	[m]	[T]	[T/m]	[T/m^2]	[T/m^3]		
Longitudinal Gradient Dipoles (DL)	1	0.29 to 0.76	0	0	0	96	Permanent Magnet
Transverse Gradient Dipole (DQ)	0.87	0.7	-33	0	0	48	Electromagnet
Quadrupole Magnet (QM)	0.105 0.15 0.185 0.25 0.36	-	85	-	-	396	Electromagnet
Sextupole Magnets (SM)	0.1 0.14	-	-	3850	-	288	Electromagnet
Octupole Magnet (OM)	0.09	-	-	-	110300	48	Electromagnet
Corrector	0.08	Bx: 0.150 By: 0.150				12	Electromagnet

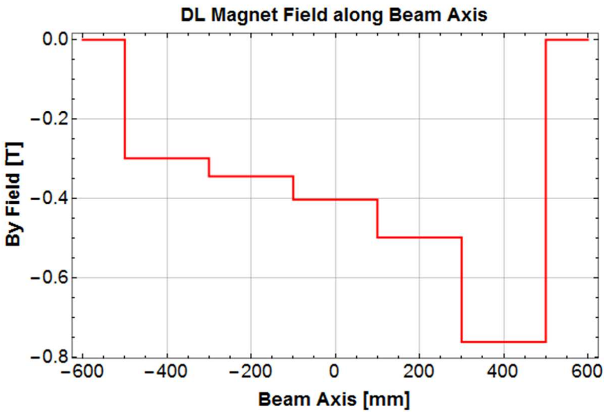
ALERT 2019 workshop

Abolfazl Shaveh (DLS): Magnet design for Diamond-II Upgrade

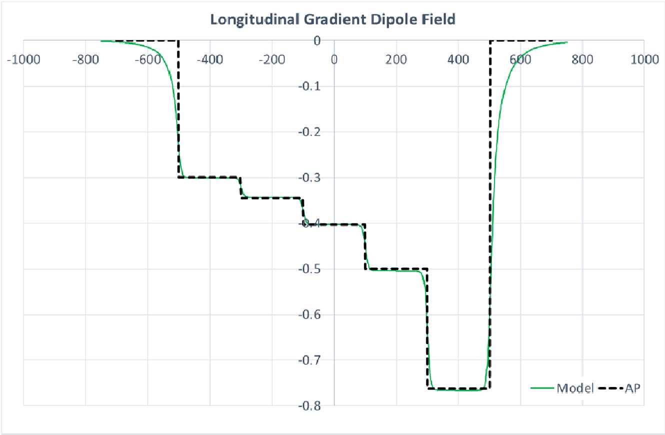
Longitudinal Gradient Dipole (DL) (like ESRF-EBS)

Current activities:

- **Studying the DL magnets' cross-talk to the neighbouring magnets (i. e. quadrupoles) and investigating how to compensate this effect**
- **Considering the other options for magnetic field tuning (i.e. trim coils or mechanically adjustable magnetic shunts)**
- **Performing the process design for DL magnets including fabrication, assembly, alignment and measurements (i.e. building an in-house prototype)**



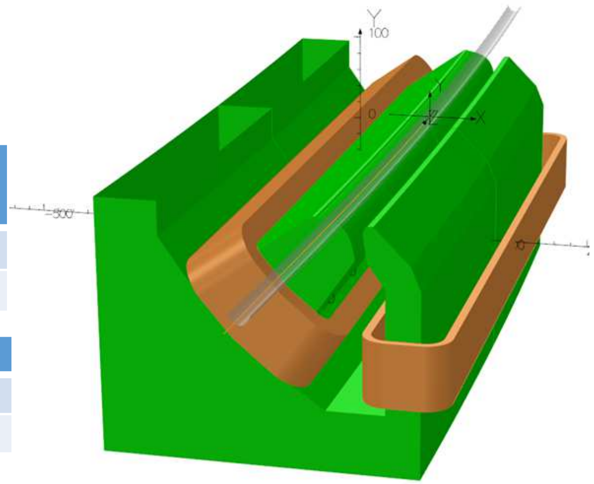
Parameter	Diamond-II	ESRF-EBS
Field [T]	0.3 – 0.76	0.17 – 0.55 (or 0.67)
Gap [mm]	26	25
Length [m]	0.980	1.85
Magnet Mass [kg]	270	400
PM Mass [kg]	43	45



Transverse Gradient Dipole (DQ)

Component	Centre Field $[T/m^{n-1}]$	Integrated Field $[T/m^{n-1}.m]$	L_{eff} [m]
Dipole (n=1)	-0.6936	-0.607	0.875
Quadrupole (n=2)	32.96	28.6	0.868

n	3	4	5	6
Central Multipoles [%]	0.04	0.03	0.02	0.00
Integrated Multipoles [%]	-0.04	0.08	0.02	0.00



First time introduced and used by ESRF

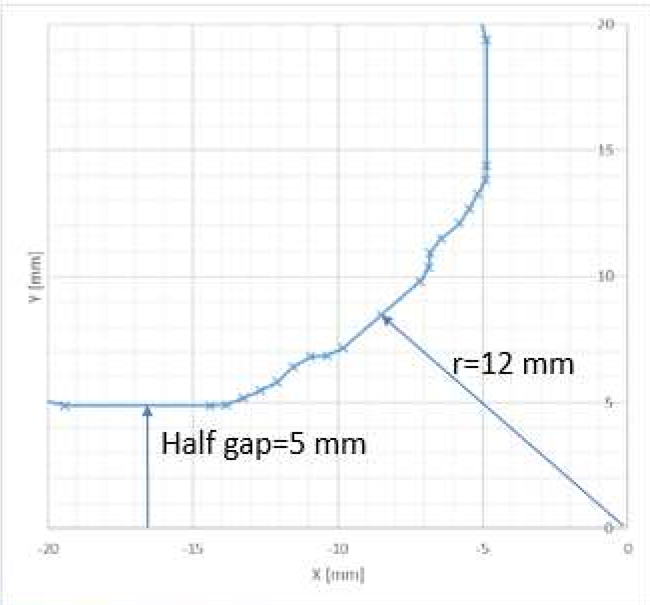
Current Activities:

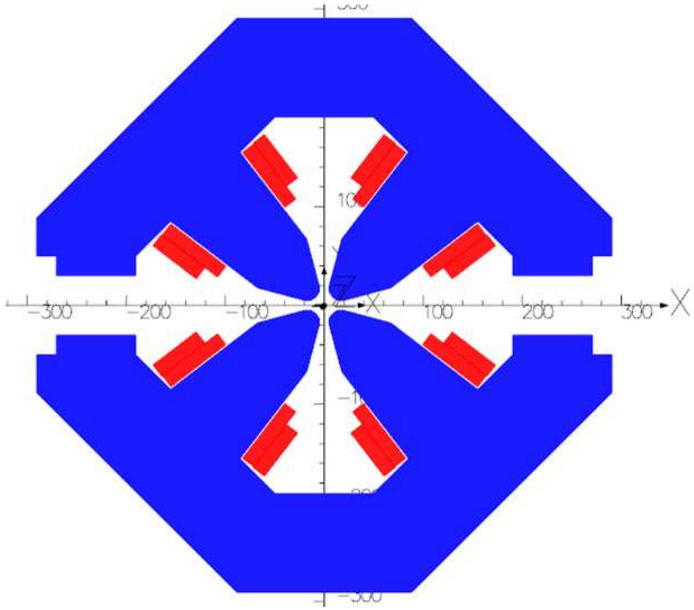
- Considering the possibility of using the existing Dipole Power Supply Circuit by designing a new coil assembly

High Gradient Quadrupole Magnet

Pole Profile Options (r=12 mm, pole-to-pole gap>10mm)

- Conventional hyperbolic profile with high permeable material for the pole tip
- Segmented pole profile with standard yoke

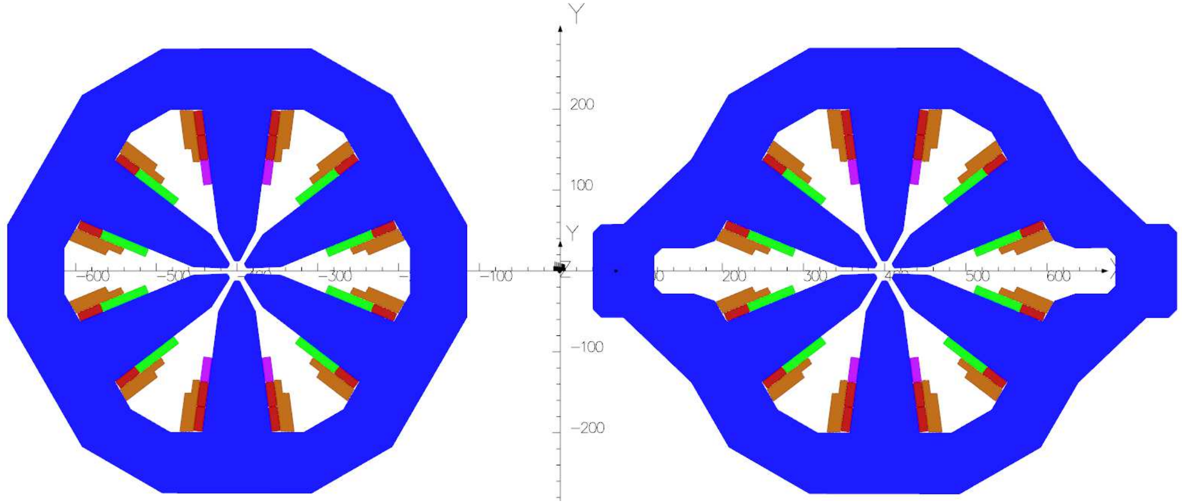




Current Activities:

- Design revision to remove end chamfers (simplifying the magnet manufacturing)
- Considering different aperture radii for accommodating vessels in Anti-Bend configuration (r=12, 12.75, 14.25 mm)

Sextupole Magnet



Field component and errors at 10 mm

Where: n=1, 2, 3, 4, … refer to Dipole, Quadrupole, Sextupole, Octupole…

n	9	15
Central Multipoles [%]	-0.74	-0.53
Integrated Multipoles [%]	-0.56	-0.63

	n	1	2	3	4	5	6	7	8	9	10	11
Bx	an/a1 [%]	100	-8.74	-0.02	5.21	-35.05	-0.01	4.1	-0.16	-0.02	-0.13	1.87
	ʃan.dz/ ʃa1.dz [%]	100	-7.58	-0.06	4.25	-28.74	0	3.07	-0.11	0.03	-0.13	1.52
By	bn/b1 [%]	100	0.82	-	0.47	34.96	-0.03	4.12	0	-1.9	-0.01	-1.85
	ʃbn.dz / ʃb1.dz [%]	100	0.79	-	0.43	28.69	-0.01	3.02	0.01	-1.87	-0.02	-1.53

Current Activities:

- Design revision to reduces variety of Sextupoles
- Further field optimisations

Abolfazl Shaveh (DLS): Magnet design for Diamond-II Upgrade

DL Magnets Manufacturing and Alignment

- **For Every Module:**

1. Assembling modules with sorted PM blocks and shunt pieces
2. Measuring the magnetic field integral profile along beam axis
3. Tuning the integral field to the nominal value (known from the model) by altering shunt pieces
4. Relating the beam axis to the outer fiducials using laser tracker or FARO arm

- **For DL assembly**

1. Aligning modules in the assembly and relating the assembly fiducials to the beam axis
2. Measuring the magnetic field integral for the DL assembly and performing extra tuning if necessary
3. Aligning the DL assembly on the girder using laser tracker

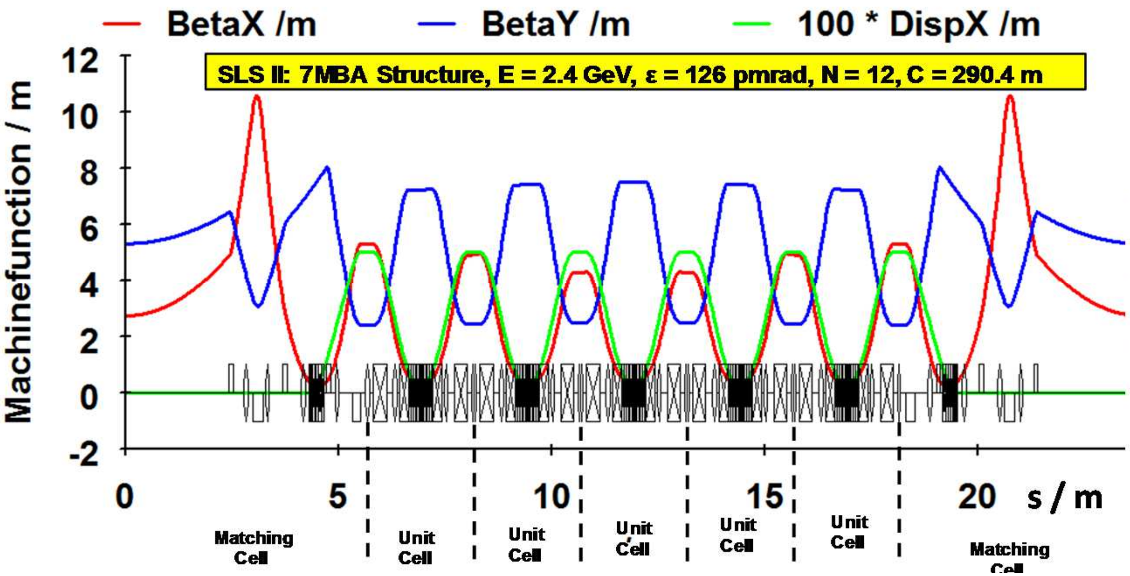
DQ Magnets Measurement and Alignment

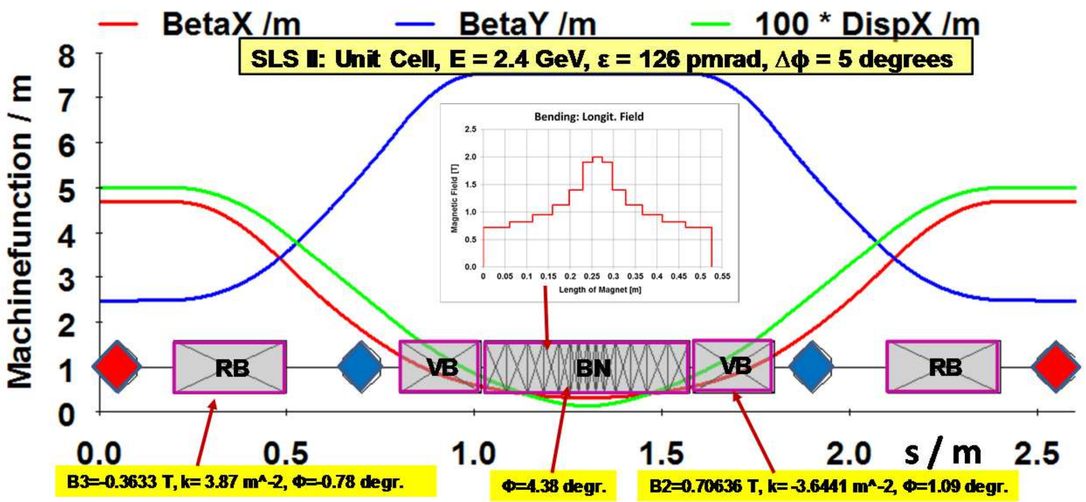
- Hall probe measurements (presumably at the manufacture site)
- Relating beam axis to the outer fiducials
- Aligning DQ on the girder using laser tracker

Multipoles Magnets

- Option 1: Postproduction measurements and shimming, then aligning mechanically
- Option 2: Aligning in-situ using stretch wire bench

Lattice of one cell and the unit cell





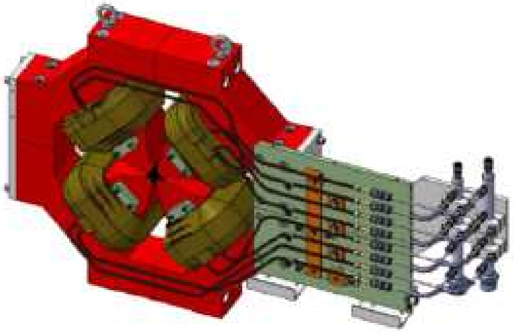
ALERT 2019 workshop

Ciro Calzolaio (PSI): Magnets for the SLS Upgrade

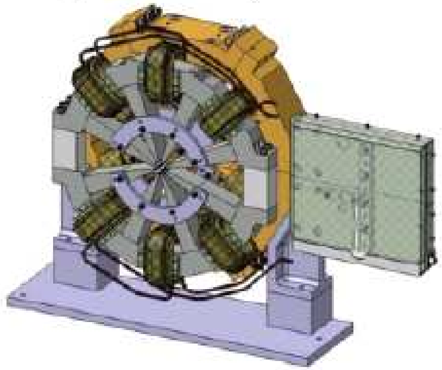
PAUL SCHERRER INSTITUT PSI

SLS upgrade: magnets zoo

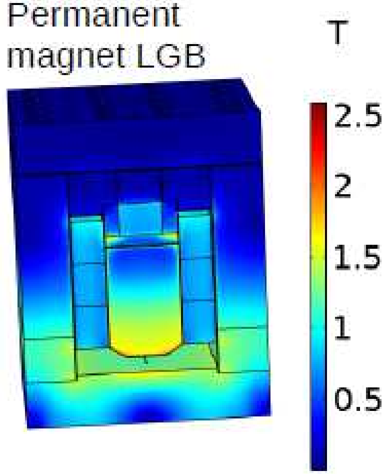
Quadrupole (78T/m, 66A)



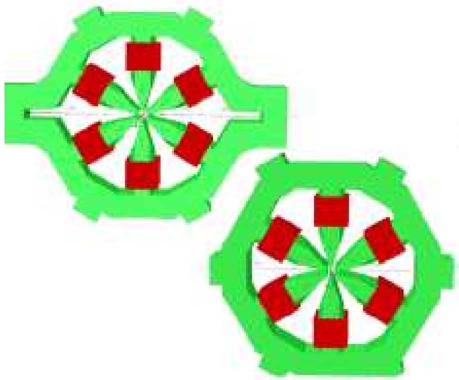
Sextupole-octupole (45000T/m³)



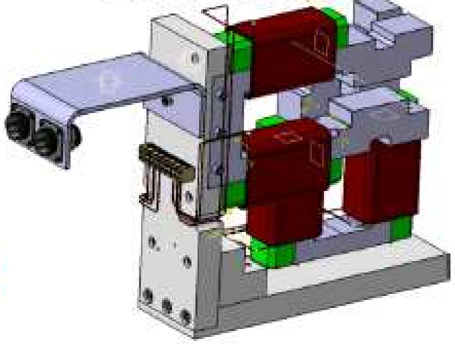
Permanent magnet LGB



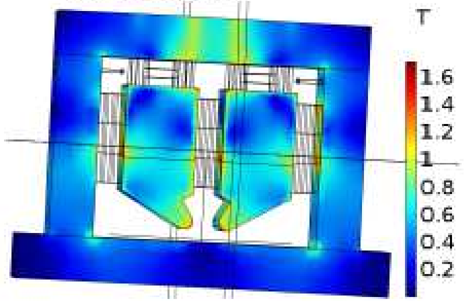
Sextupole (4000T/m², 45.8A)



Corrector magnet

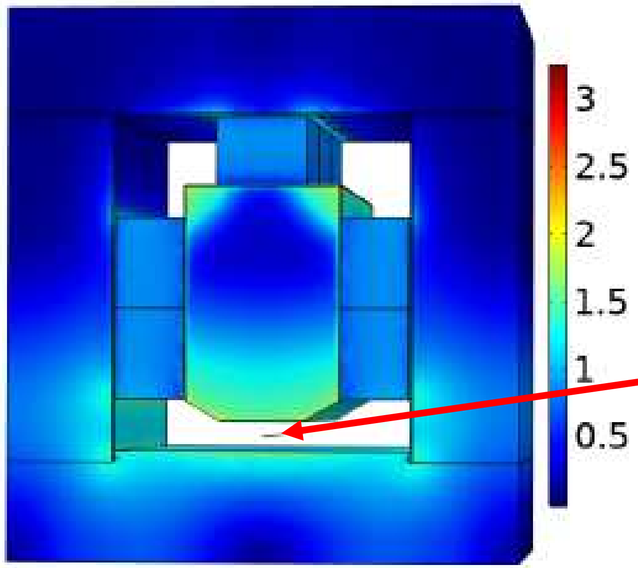


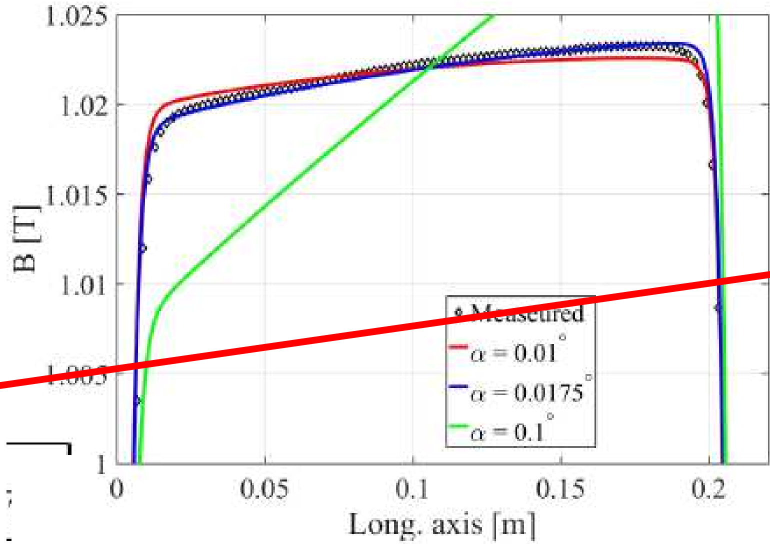
Permanent quadrupole



Ciro Calzolaio (PSI): Magnets for the SLS Upgrade

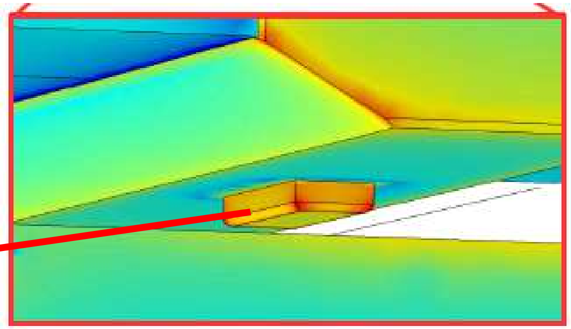
BN magnet, B-field profile

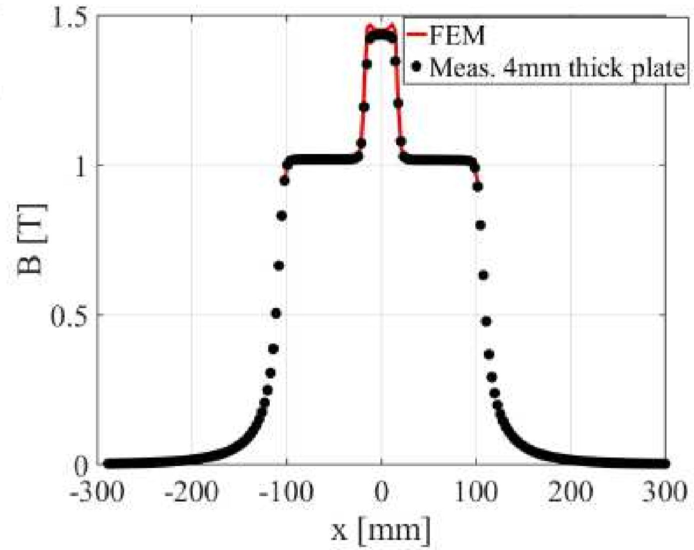




	Arnold
PM size [mm]:	30 x 40 x 70
μ_r	1.017
$B_r[T]$	1.25

BN magnet, B-field profile with peak





PAUL SCHERRER INSTITUT PSI

Specifications and consequences for the magnet design

Specifications

- Narrow B-field profile: FWHM < 75 mm;
- Peak field in the GFR>4T:
- $\int Bdl = 0.54Tm$ (as for the RT dipoles);
- Available longitudinal space: 415 mm;
- Vacuum chamber OD: 20 mm

Consequences

- $B_{conductor}/B_{GFR} > 1.3$
  - **4T peak → Nb-Ti (baseline)**
  - 6T peak → Nb_3Sn
  - >6T peak→ HTS
- Cooling system: conduction

Additional constraints (valid for all the magnets)

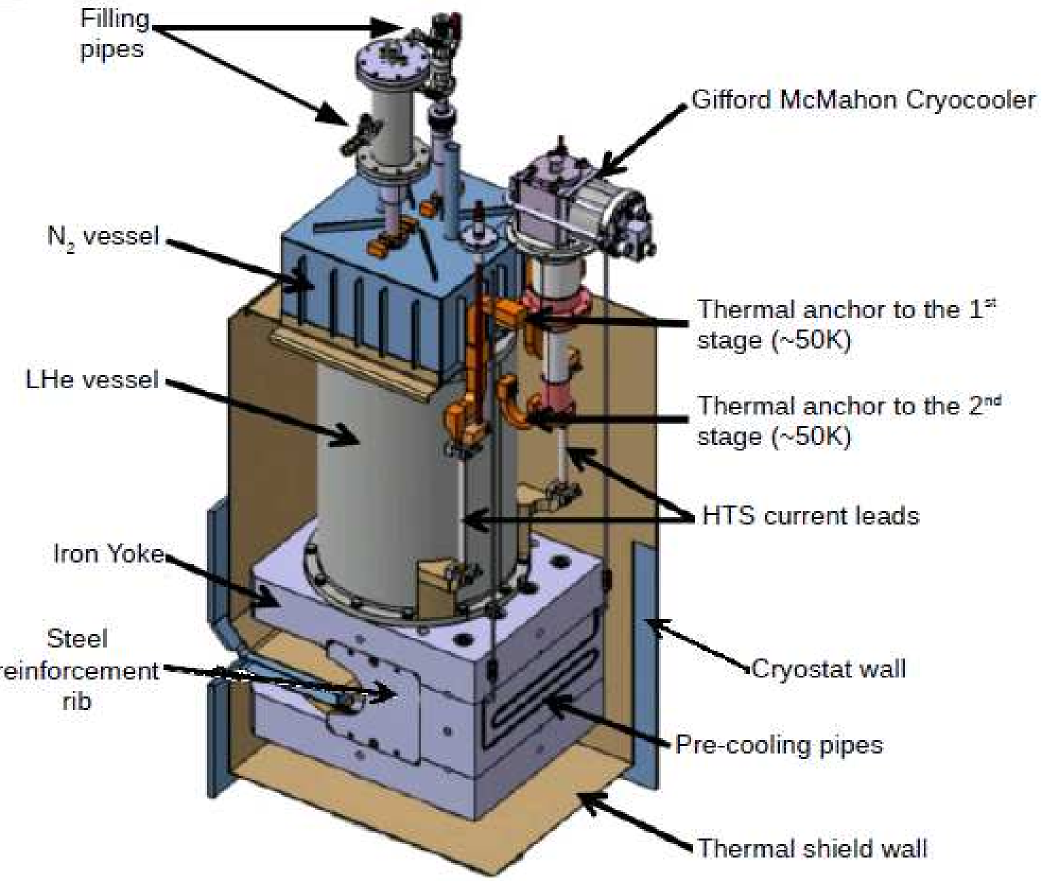
<u>Installation strategy in the tunnel</u> (possibility to mount/exchange the magnets keeping the vacuum chamber in place)
+
Necessity to evacuate the synchrotron radiation

- **C-shape magnet**
  - Lower mechanical rigidity;
  - Higher stray field.
- <u>Baseline</u>: open geometry without integrated vacuum chamber;
- Vacuum chamber integration under discussion.

Ciro Calzolaio (PSI): Magnets for the SLS Upgrade

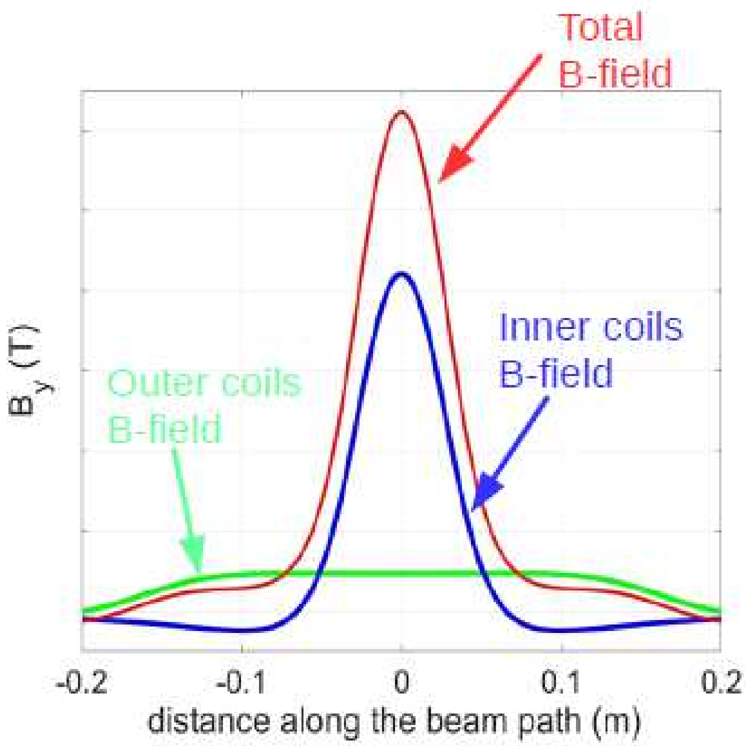
PAUL SCHERRER INSTITUT PSI

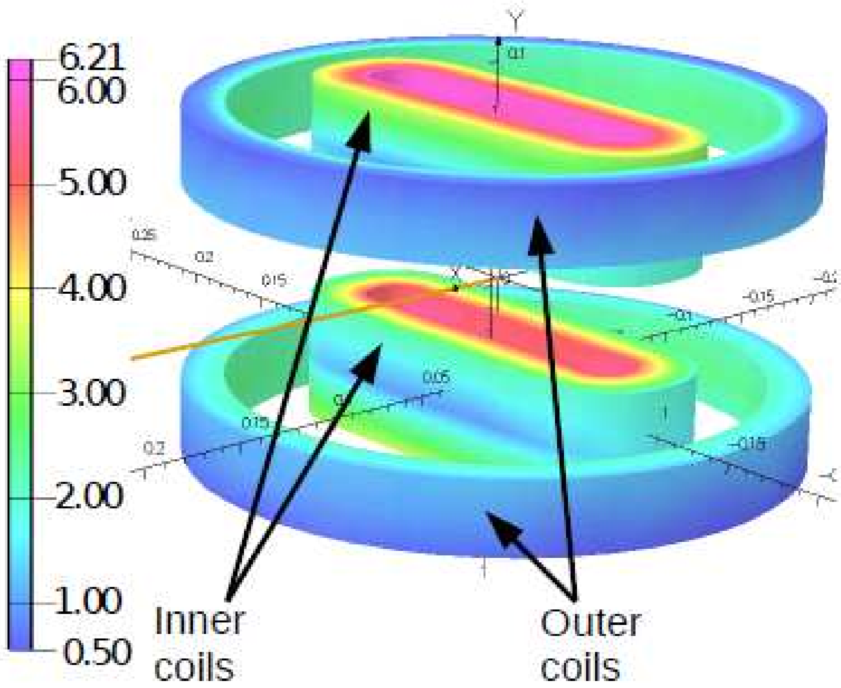
Superbend magnet main components



PAUL SCHERRER INSTITUT PSI

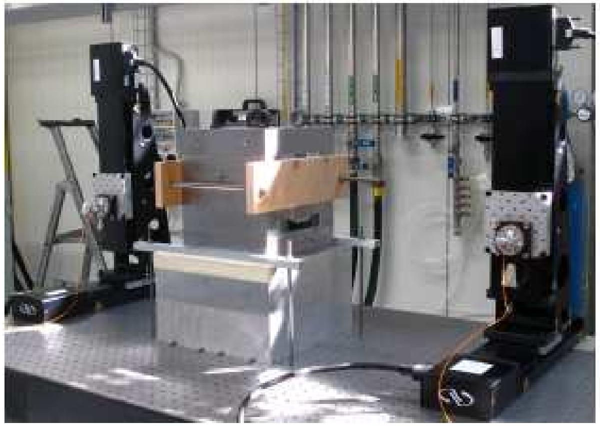
Magnetic design



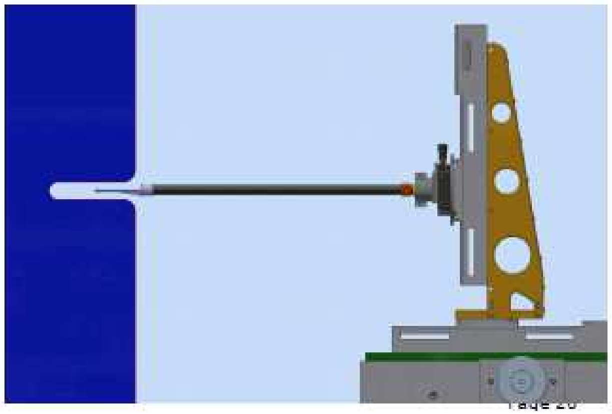


Magnetic measurements (1)

Moving wire: field integral



Compact Field mapper



PAUL SCHERRER INSTITUT PSI

Conclusions

For the SLS upgrade we need innovative magnet design:

- High field Permanent LGB magnet: energy consumption;
- RT combined function electro-magnet: space requirement;
- High field Superconducting LGBs: hard X-rays sources (up to 80 keV).

- The design and construction plans for the electromagnets is almost ready;
- The optimization and the prototyping of the permanent magnets is ongoing;
- The conceptual design (magnetic + thermal + mechanical + quench) for a 4T peak superbend is ready;
- The BN and the BS magnets will be interchangeable: same field integral and length.