WP11.3 Update

WP11.3: Permanent Magnet Quadrupoles and Combined Function Magnets for Ultra-Low Emittance Storage Rings

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I.FAST Annual Meeting, CERN

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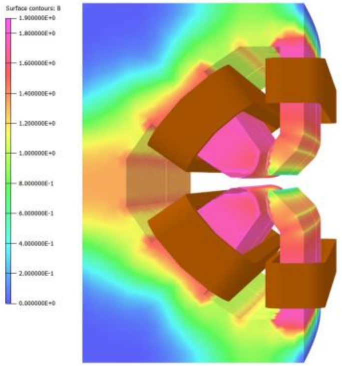
Task description

- *Task 11.3: Permanent Magnet Quadrupoles & Combined Function Magnets for Ultra Low-Emittance Rings*
  - Partners: UKRI – Diamond Light Source – Kyma
- This task addresses the need for reducing the electricity consumption and carbon footprint in future storage rings
- Two prototypes to be designed, assembled and tested: (**D11.3**)
  - PM-based strong focusing quadrupole magnet
  - PM-based combined function dipole-quadrupole (DQ) magnet
- Parameters similar to Diamond-II and other facilities
- Second-stage prototypes
  - Basic concept already tested
  - Examine requirements for cost-effective series production
- Adjustment using either coils or motors

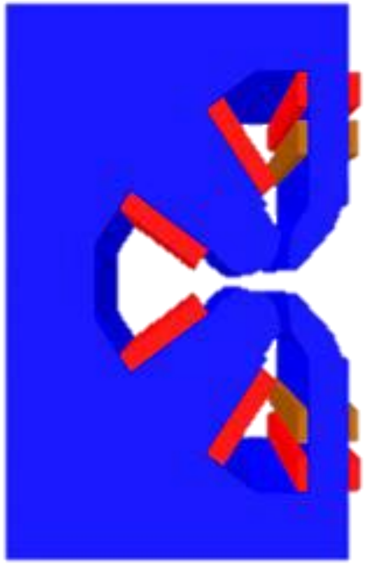
UKRI's ZEPTO tunable PM quadrupole



Diamond combined function DQ magnet

Diamond-II prototype

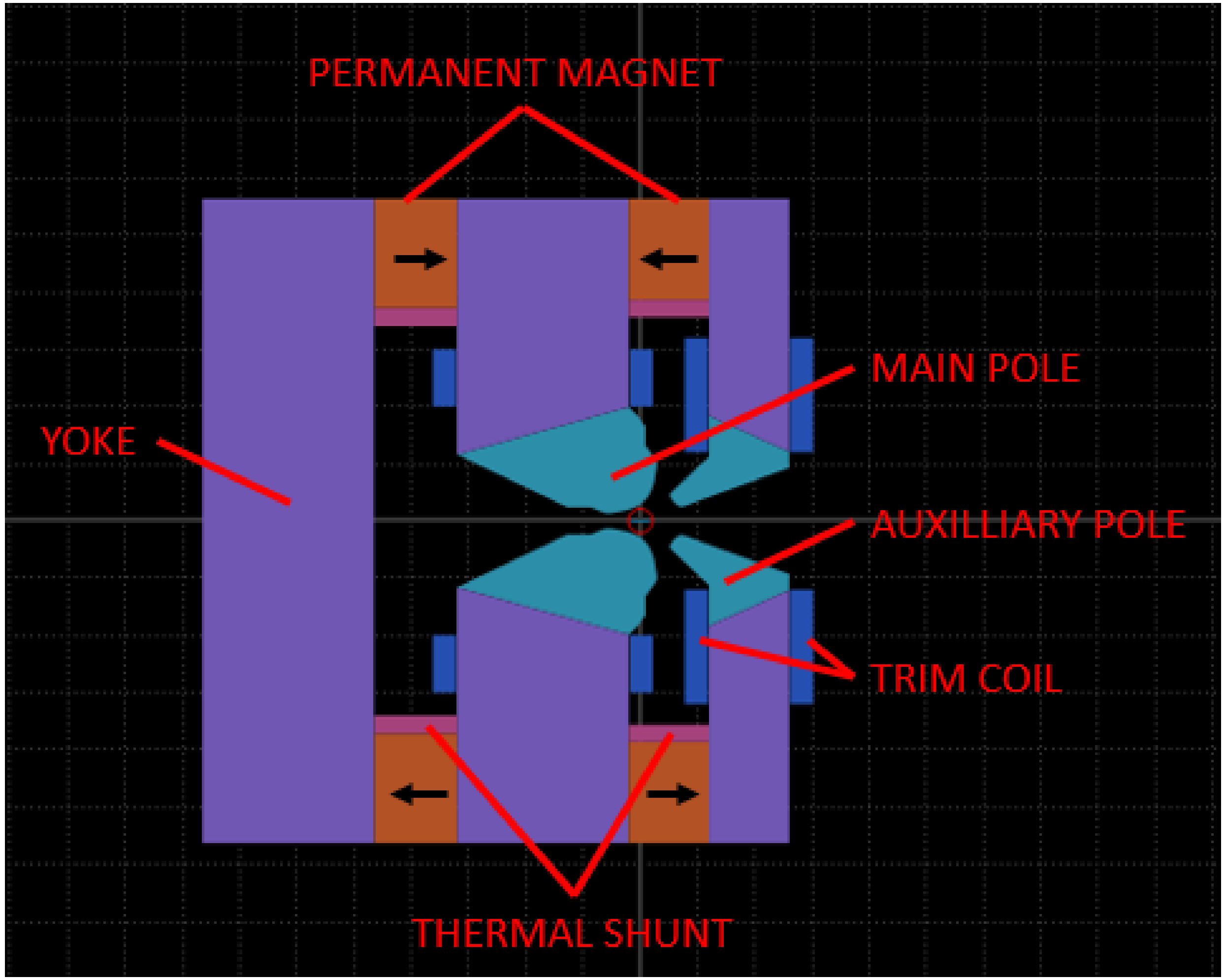
- Combined function dipole-quadrupole magnet
- Permanent magnet version
- Tunable over a small range using coils
- Single-sided:
  - Achieve high gradient
  - More efficient than offset quadrupole



Parameter	Value	Units
Central dipole field	0.695	T
Central gradient	32.4	T/m
Magnetic length	870	mm
Integrated dipole field	0.605	T.m
Integrated gradient	28.2	T
Bending radius	16.795	m
Good field region diameter	14	mm
Field quality *ΔB/B*	5×10^{-4}	
Gradient quality *ΔG/G*	1×10^{-3}	
Integrated multipoles	$< 10^{-3}$	
Dipole tuning range	±2.5%	
Gradient tuning range	±2.5%	
Aperture (main poles)	13	mm
Aperture (aux poles)	24	mm
Maximum yoke height	563.4	mm
Beam axis height above base of support	475	mm
Maximum yoke length	931	mm

2D Magnet Model

- Two large main poles
- Two smaller auxiliary poles
- PMs: NdFeB, grade 40EH
  - PMs far from beam, so low risk of radiation damage
  - High remanent field (1.32T at 20°C)
  - Reasonably high coercivity (2388 kA/m)
- Yoke and poles: XC06 low-carbon steel
  - Pole profile shaped to produce dipole and quad fields, and to maximise field quality
  - Poles to be curved to follow beam path
- Thermal shunts: Fe-Ni alloy
  - Negative temperature coefficient
  - Optimise thickness of shunts to flatten variation at operating temperature
- Trim coils
  - Independent variation of dipole and quadrupole fields
  - Tuning over a range of ±2.5% from nominal values
  - Aim to keep current density low and use air-cooled coils



3d model

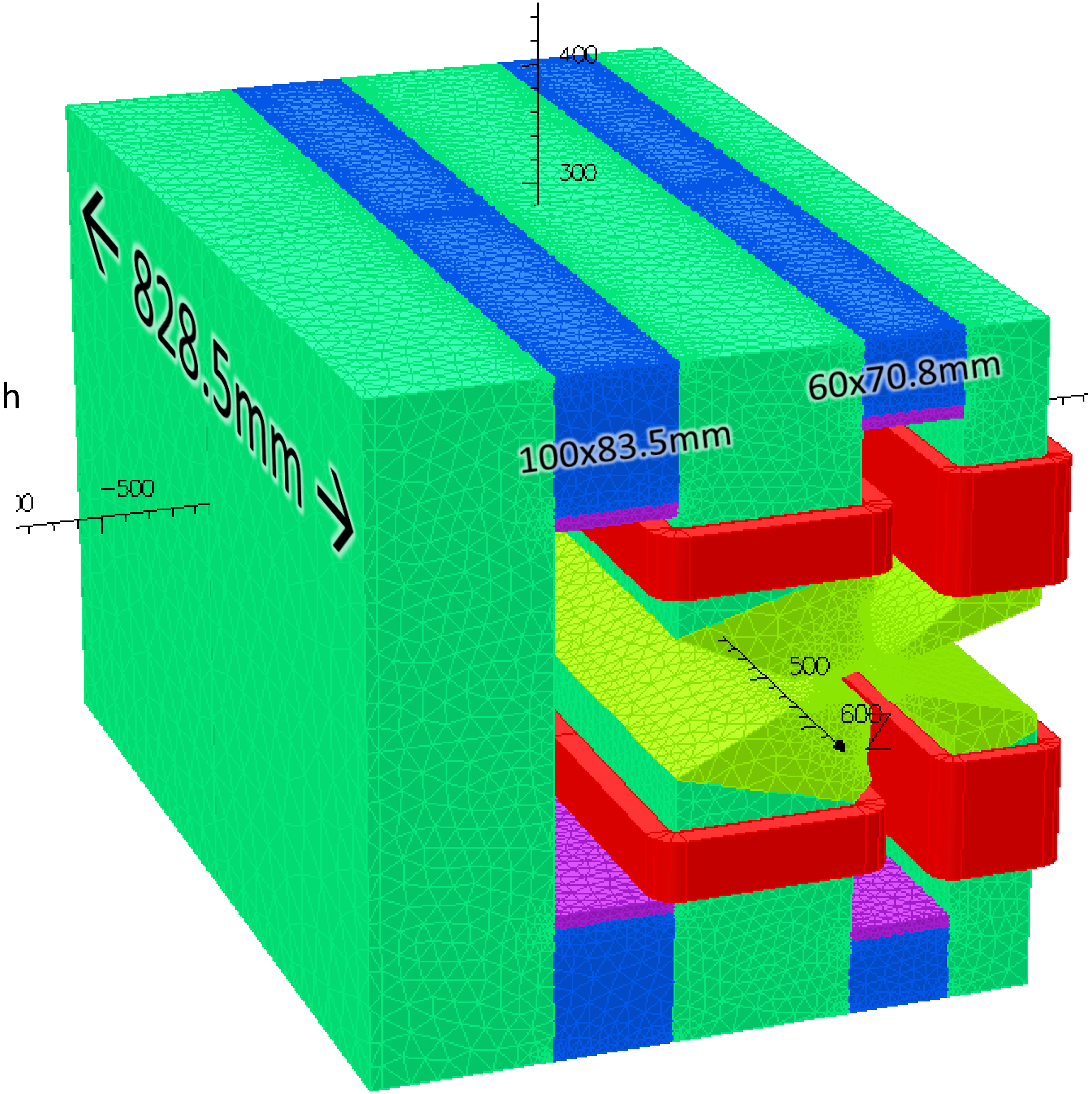
- 3D model with same pole tip profile as 2D model
- Total yoke length **828.5 mm**
- Pole tips are **curved** to give constant dipole along beam path

- Dipole Field: **0.695 T**
- Gradient: **32.4 T/m**

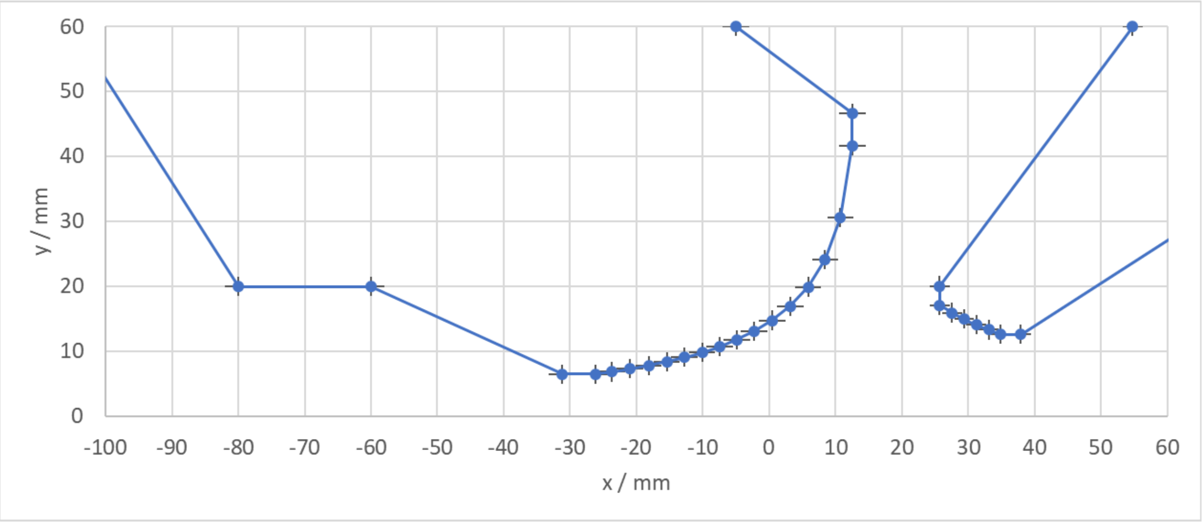
- Good field region: **±7 mm**
- ΔB/B within GFR: **7.5×10^{-6}**
- ΔG/G within GFR: **1.3×10^{-4}**

- FeNi shunt to reduce temperature variation
- Thickness: **11.3 mm** (main), **16.4 mm** (aux)
- Relative change with temperature
  - **-6e-6/°C** (field); **5e-5/°C** (gradient)

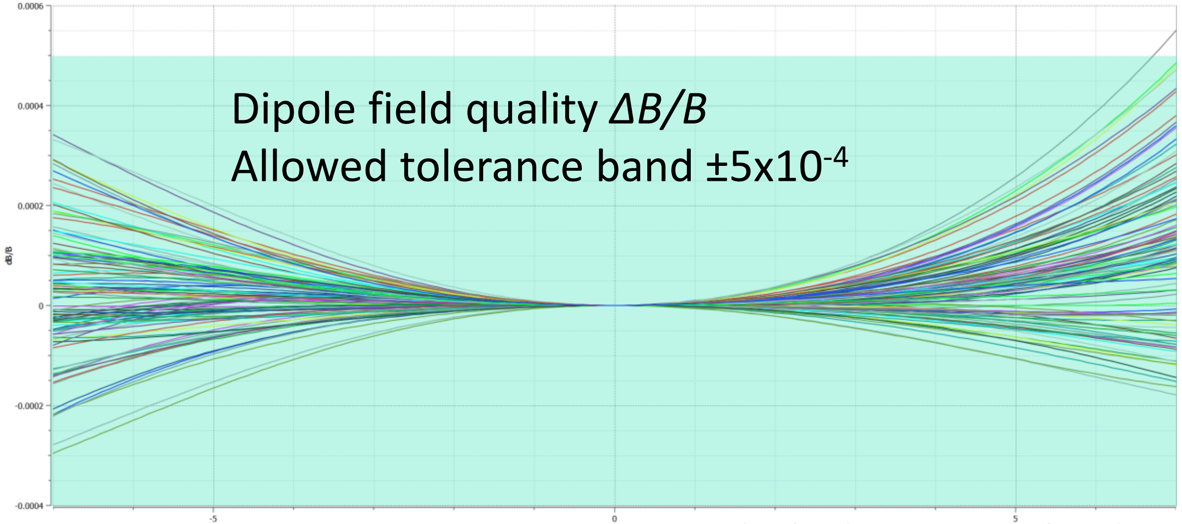
- Current densities of **±2 A/mm²** in the coils
  - **±6%** in field, **±8%** in gradient

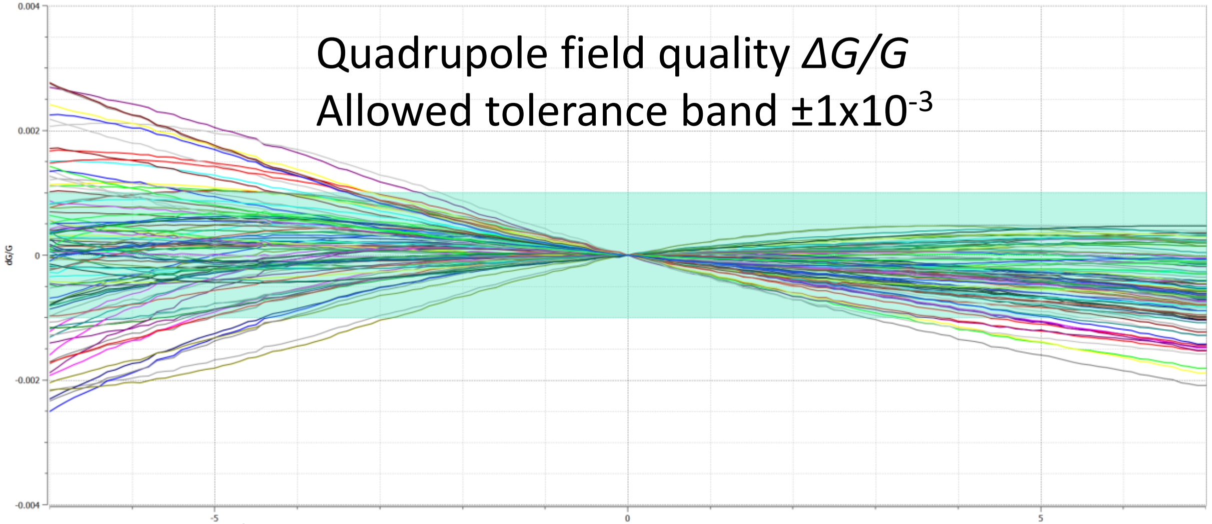


Tolerances

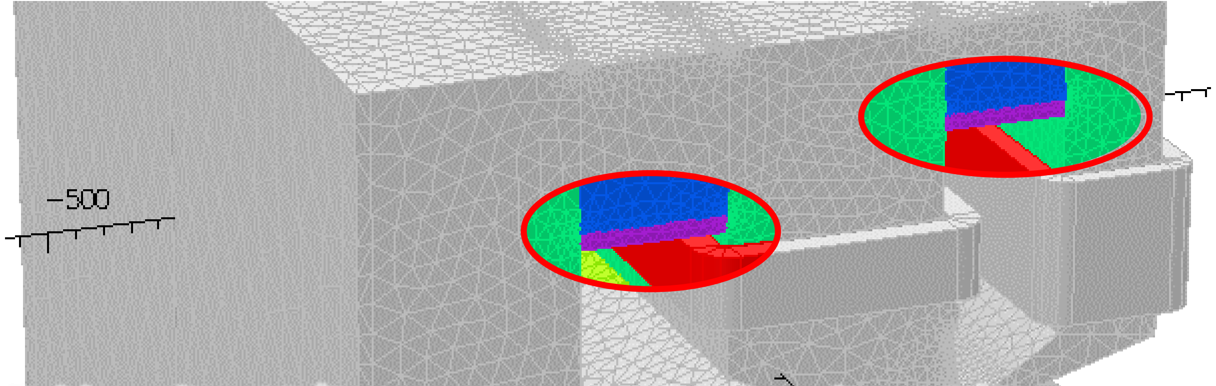


- Modelled pole tips with random movement of points up to ±20μm
- Some results are out of allowed tolerances
- Further work required


Dipole field quality *ΔB/B*
Allowed tolerance band $\pm 5\times10^{-4}$

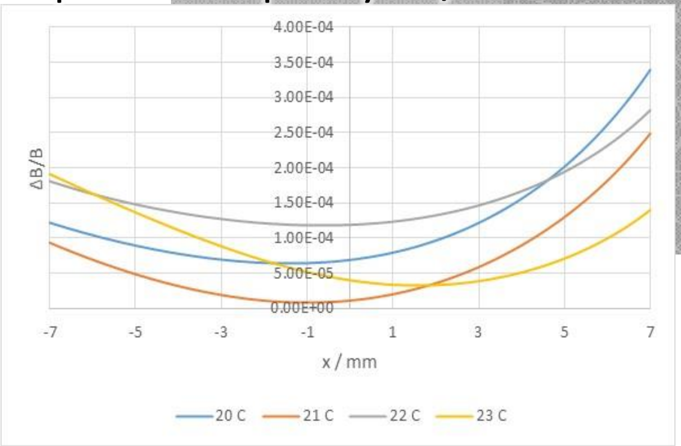

Quadrupole field quality *ΔG/G*
Allowed tolerance band $\pm 1\times10^{-3}$

Temperature stability

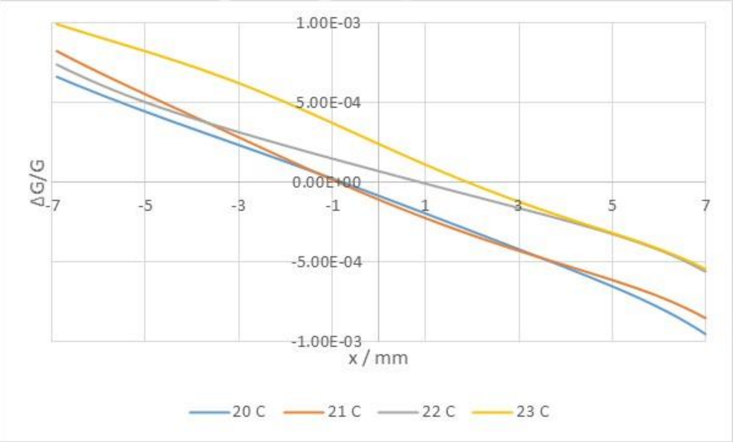


- FeNi shunts alongside the PMs act to stabilise the temperature variation
  - Temperature coefficient is opposite to that of the PMs
  - Optimised shunt gives a minimum variation around room temperature (20-23°C)
  - Vary shunt heights for the best field quality in this region
- Shunt thickness:
  - **11.3 mm** (main), **16.4 mm** (aux)
- Relative change with temperature
  - **1x10^{-4}/°C** (field); **5x10^{-4}/°C** (gradient)

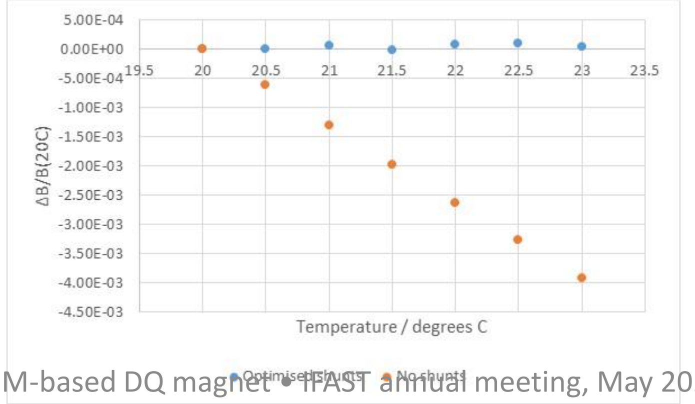
Dipole field quality *ΔB/B*



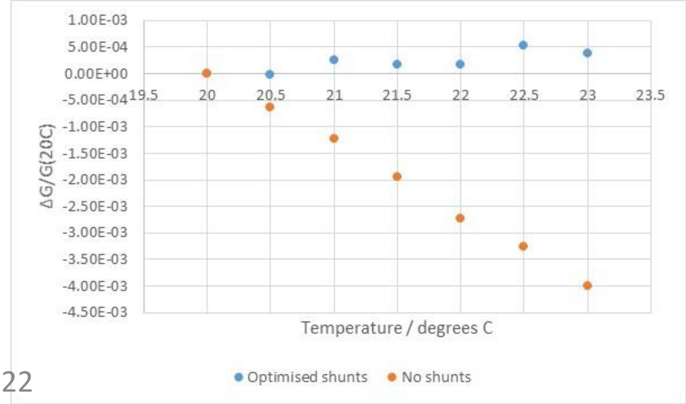
Gradient quality *ΔG/G*



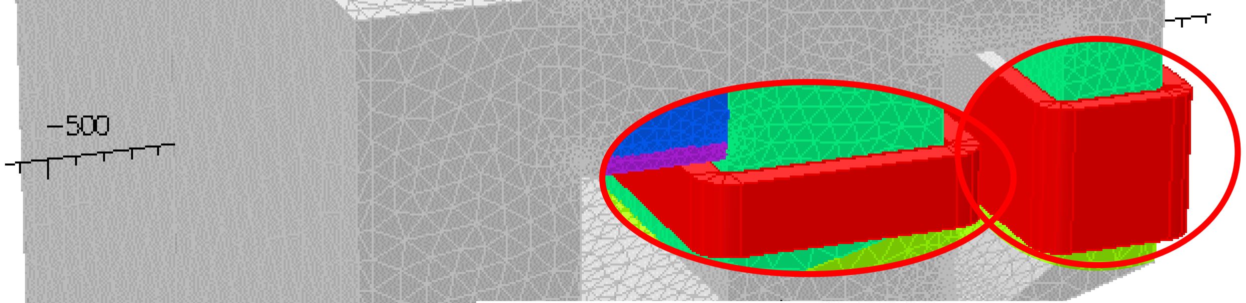
Dipole temperature variation



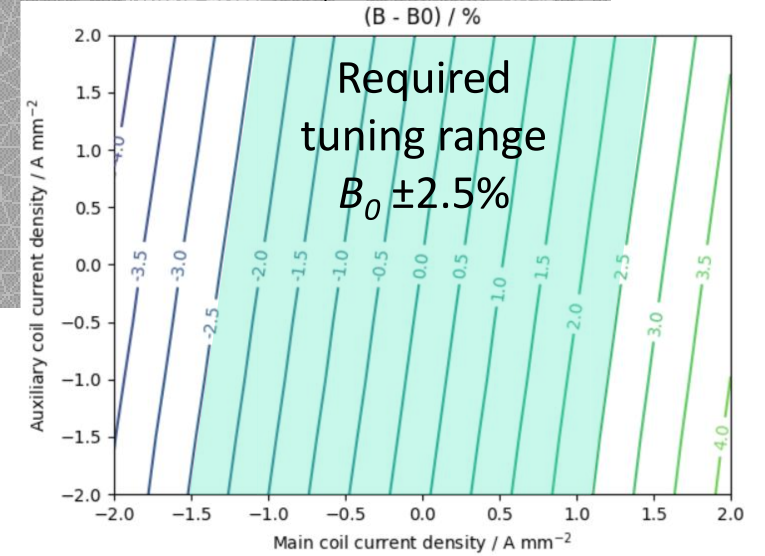
Gradient temperature variation

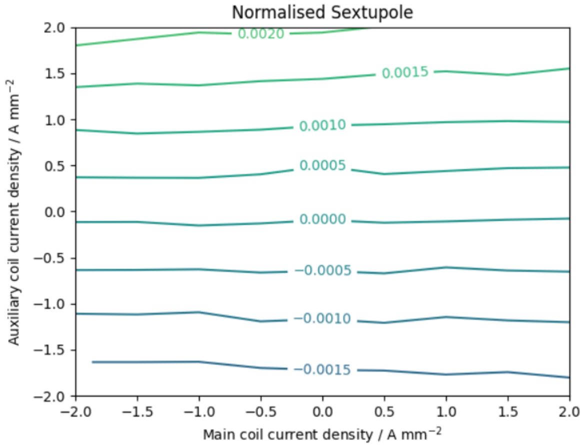


3D Central Field Tuning

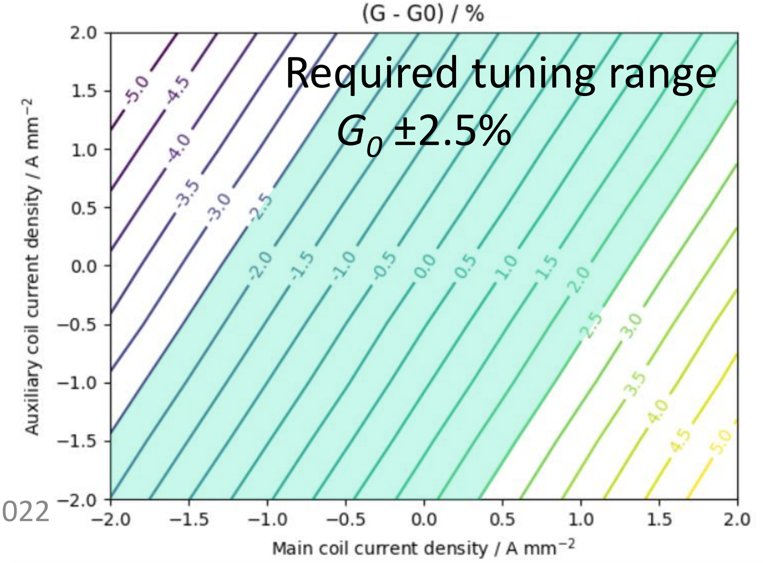


- Can expect similar coil current densities (~2 A/mm^2) for range of B ± 2.5% and G ± 2.5%
- Sextupole component mainly depends on current in aux coil
- Estimate power dissipation of ~200 W per coil at 2 A/mm^2, assuming copper coils


Required tuning range B_0 ±2.5%



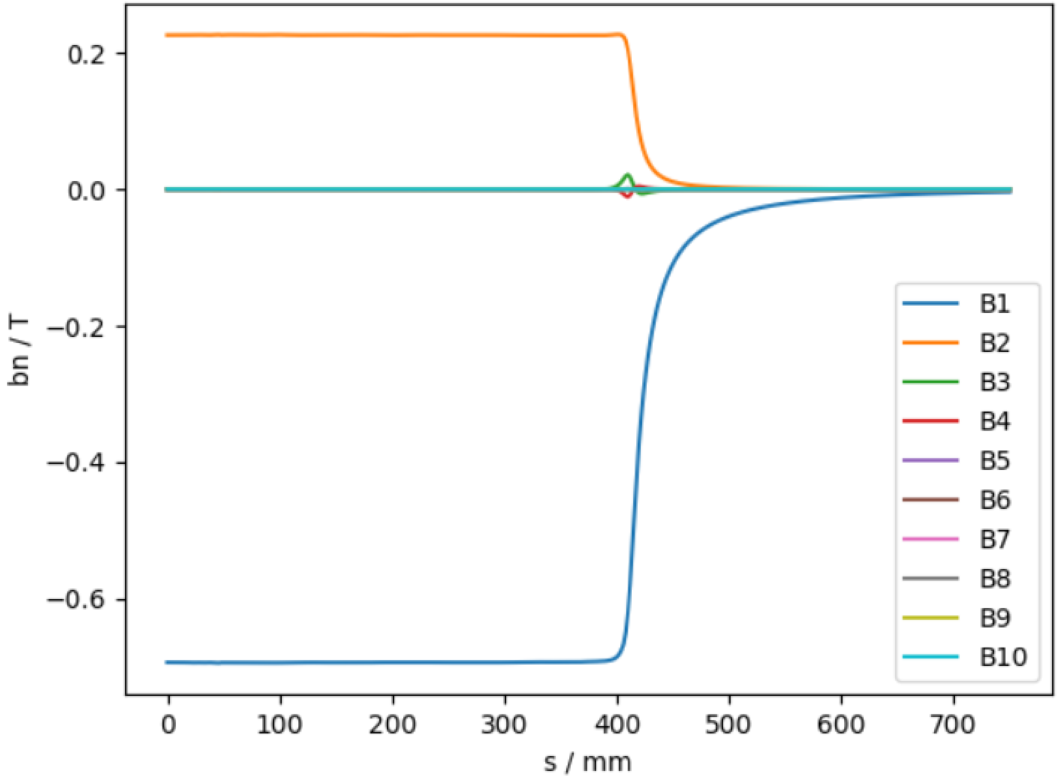
	Main coil	Aux coil	Units
Coil height	35	45	mm
Coil width	20	20	mm
Average turn length	1971	1851	mm
Packing factor	0.5	0.5	
Maximum current density	2	2	A/mm²
Maximum power dissipation	51.33	61.98	W


Required tuning range G_0 ±2.5%

3D Integrated Fields

- Model physical length 828.5 mm
- Physical length tuned to get target integrated dipole field
- Integrated gradient lower than target due to different effective lengths of dipole and gradient

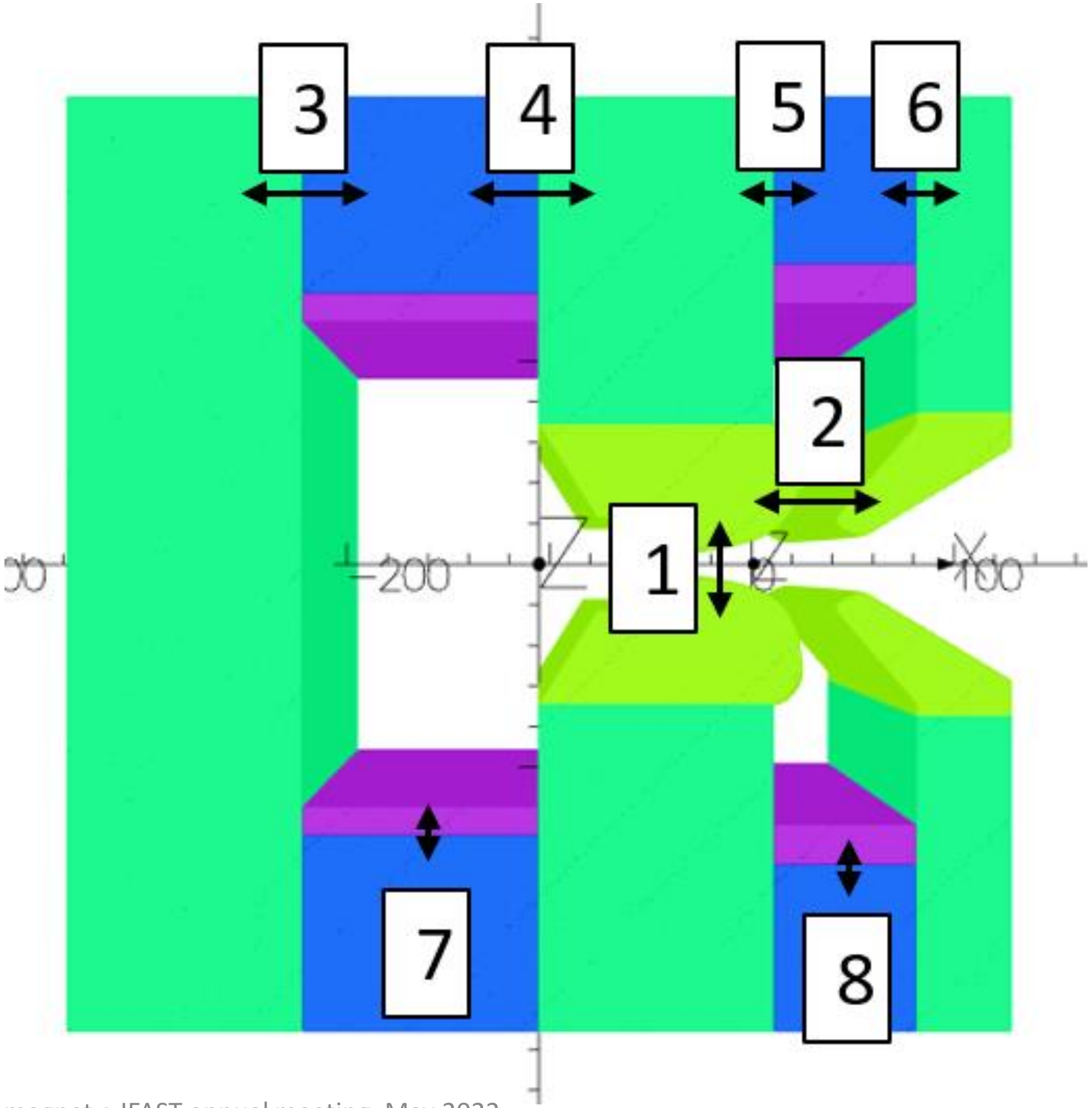
Component	Unit	Model Value	Nominal
∫ b1 ds	T.m	0.6047	0.6047
∫ b2 ds	T/m.m	27.3526	28.1857
∫ b3 ds	T/m^2.m	0.9956	0
∫ b4 ds	T/m^3.m	-1.036E2	0
∫ b5 ds	T/m^4.m	1.407E4	0



Magnetic Forces

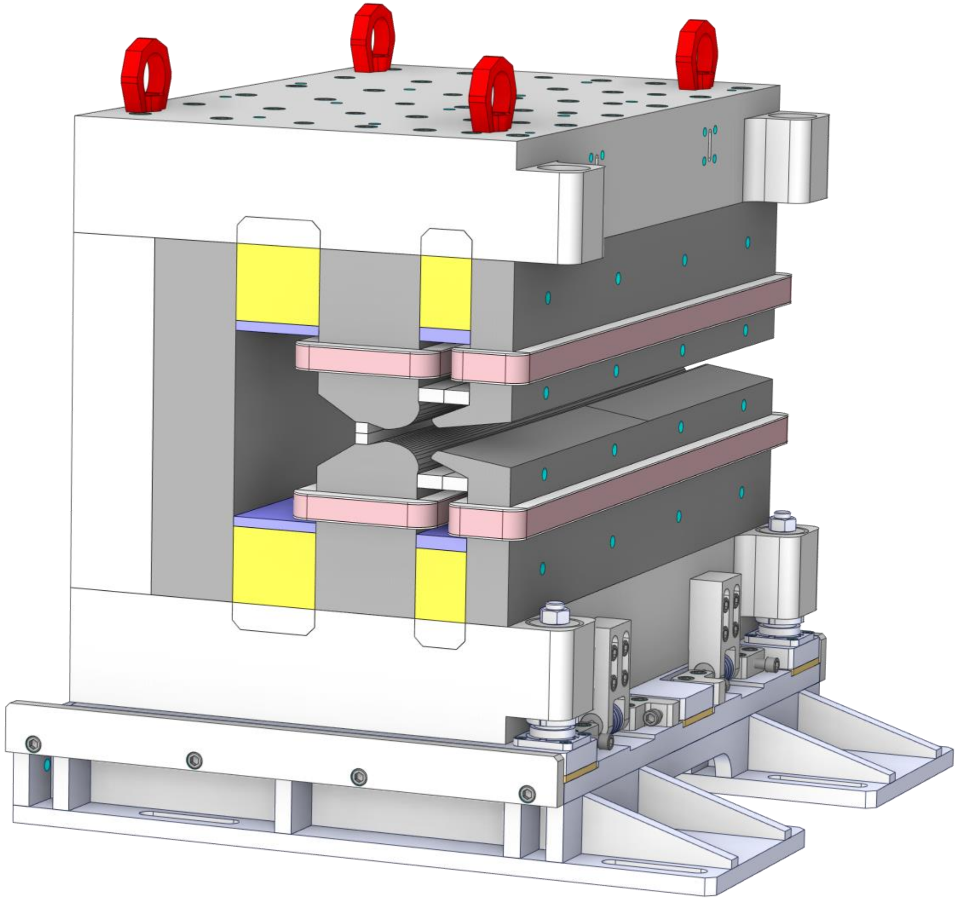
#	Description	Magnitude [kN]
1	↕ Main poles	30
2	Main ↔ aux poles	5
3	Main PM ↔ back yoke	41
4	Main pole ↔ main PM	40
5	Main pole ↔ aux PM	31
6	Aux pole ↔ aux PM	31
7	Main PM ↔ shunt	0.3
8	Aux PM ↔ shunt	0.7

- PMs are placed immediately next to magnetic steel pieces, giving rise to very large forces between them
- Great care must be taken during assembly to manage these forces
- Large forces also exist between the poles: need to ensure that they are held apart securely against them



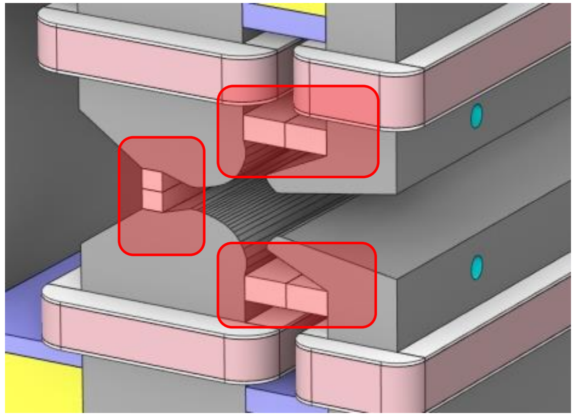
Mechanical Engineering Design

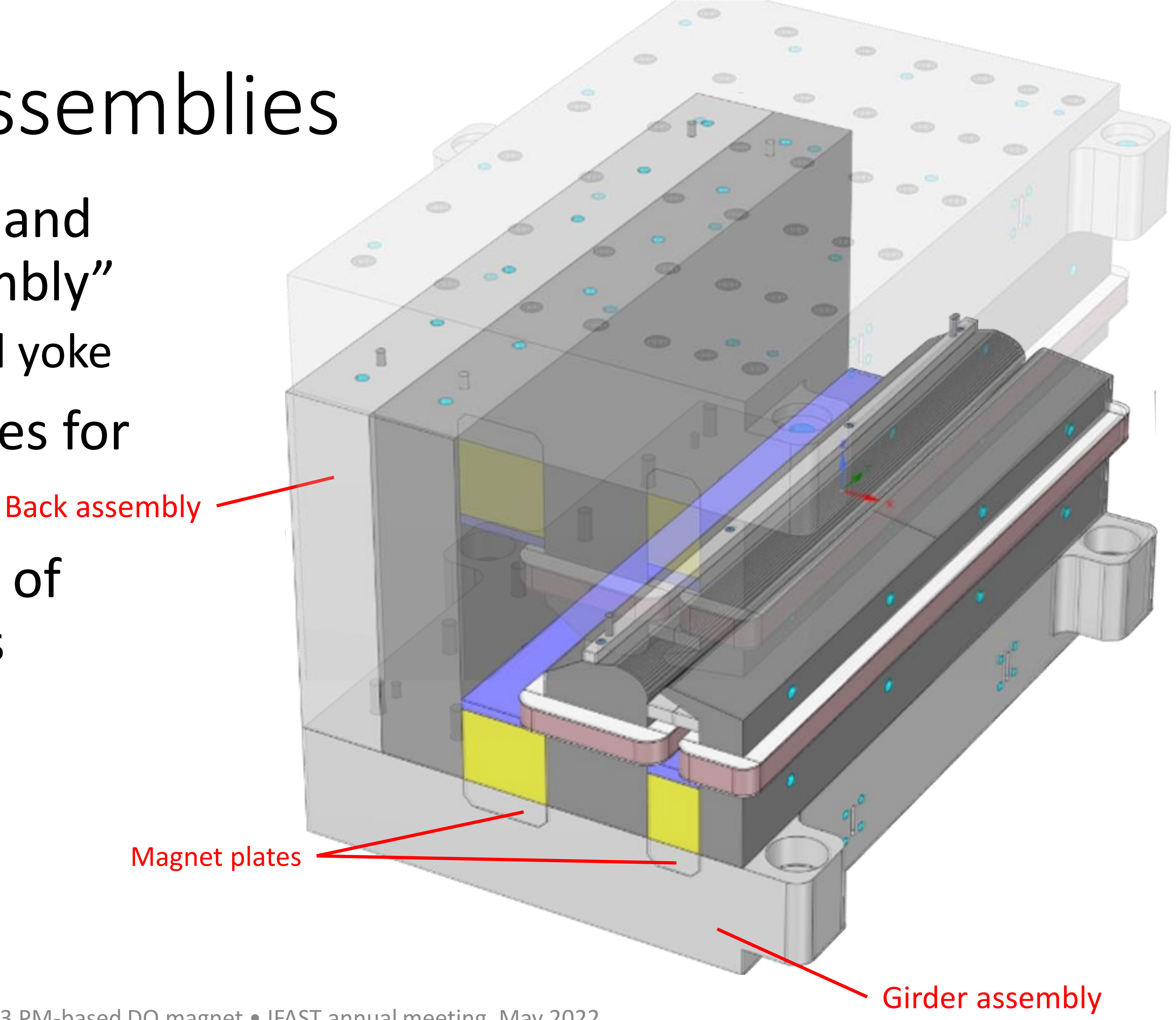
- Treated like an insertion device with an external C-shaped support structure
- Need to consider how the ferromagnetic parts are positioned precisely against magnetic forces
- The device will be placed on a girder and installed around an existing vacuum chamber
- Needs alignment features to allow adjustment in X, Y, Z, pitch, roll, yaw



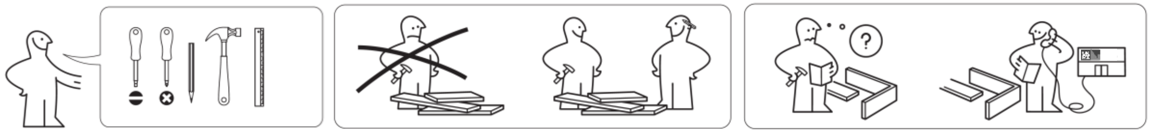
Subdivision into assemblies

- Two "girder assemblies" (top and bottom) and one "back assembly"
  - Back assembly: Al block + steel yoke
- PM blocks glued on to Al plates for assembly
- Spacers to control separation of poles against magnetic forces





Sub-assembly build



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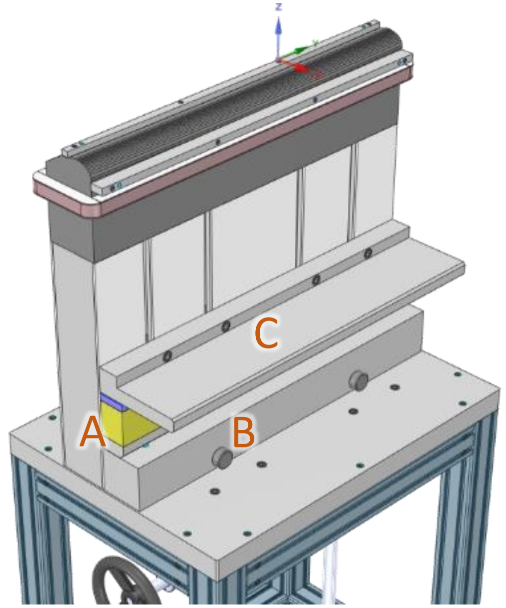

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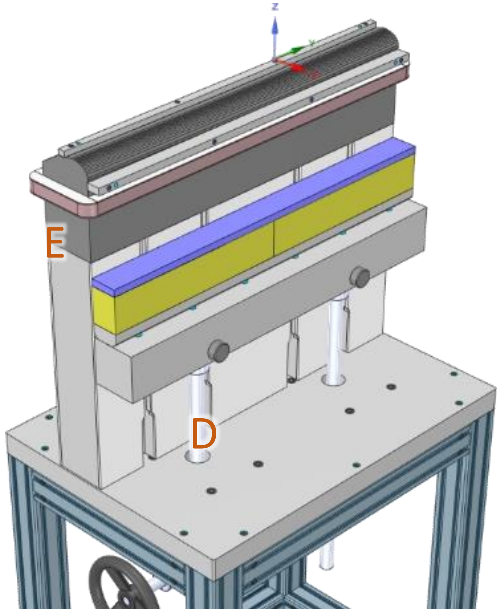

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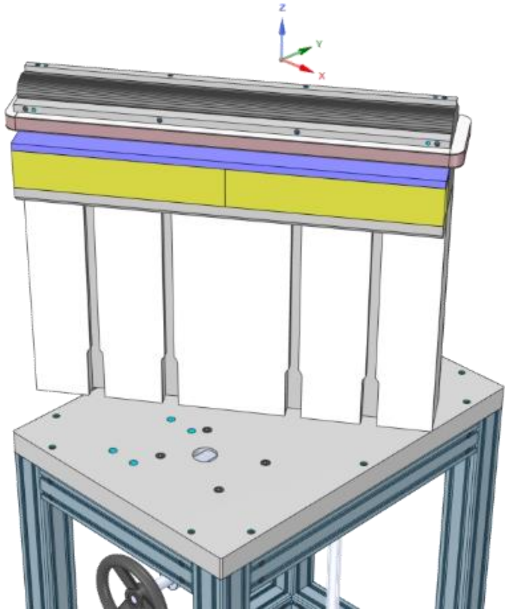

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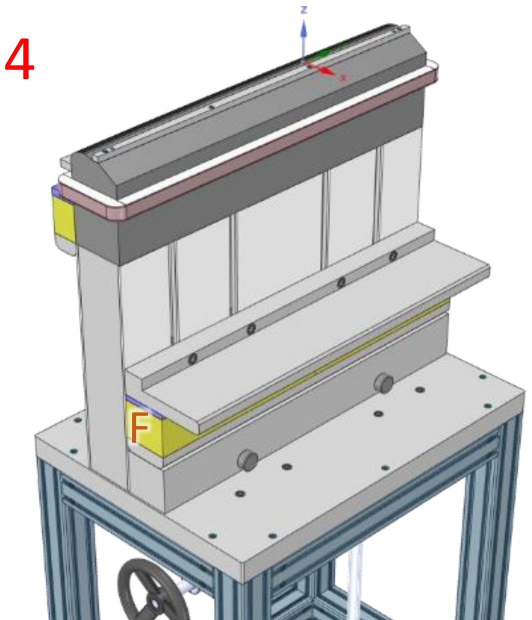

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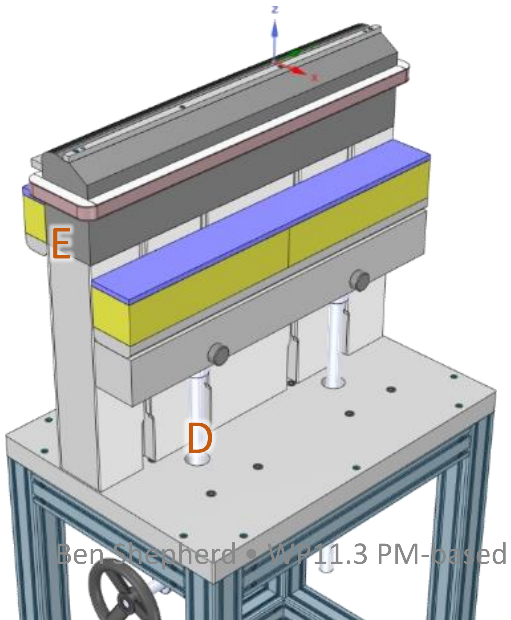

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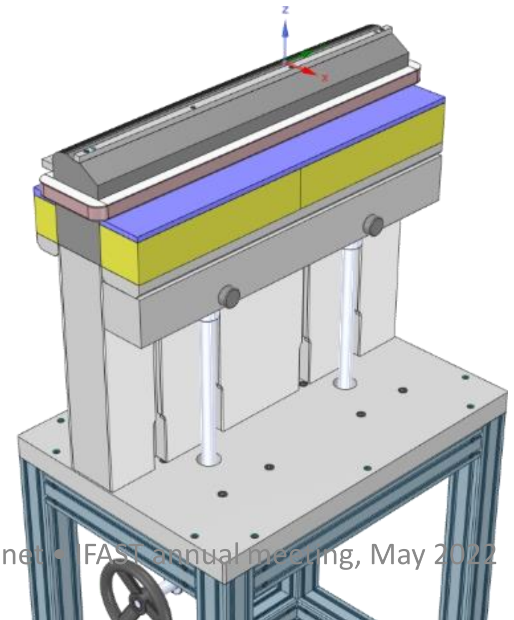
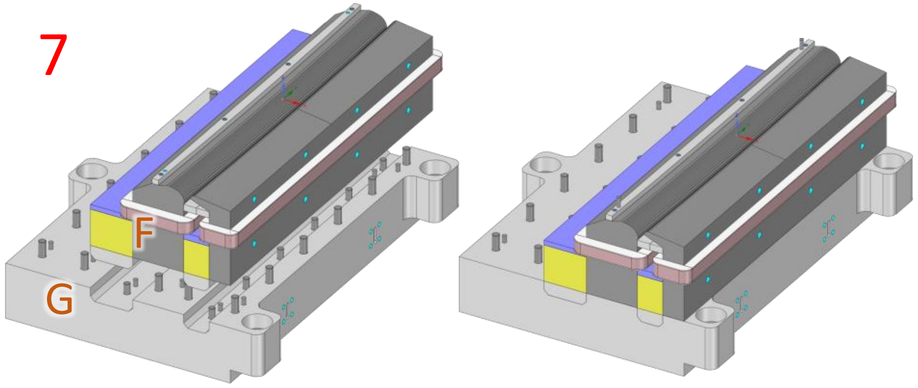


1. Attach **aux magnet A** to **slide bar B** under **protection separator C**
2. Attach **screw jack actuator D**, remove protection separator, slide aux magnet up to **centre pole E**
3. Remove slide bar and screw jack actuator, rotate assembly through 180°
4. Attach **main magnet F** to **slide bar B** under **protection separator C**
5. Attach **screw jack actuator D**, remove protection separator, slide main magnet up to **centre pole E**
6. Remove slide bar and screw jack actuator, remove sub-assembly from rig

Assembly sequence

7



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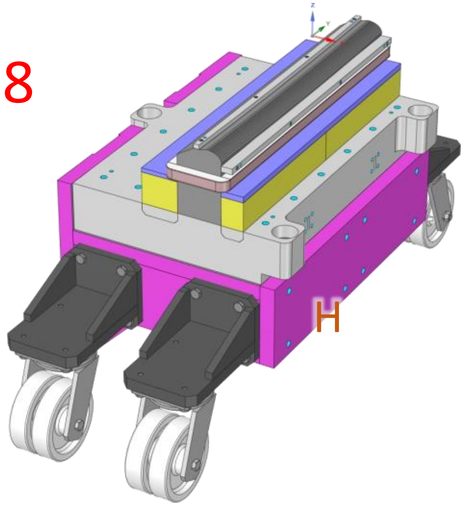

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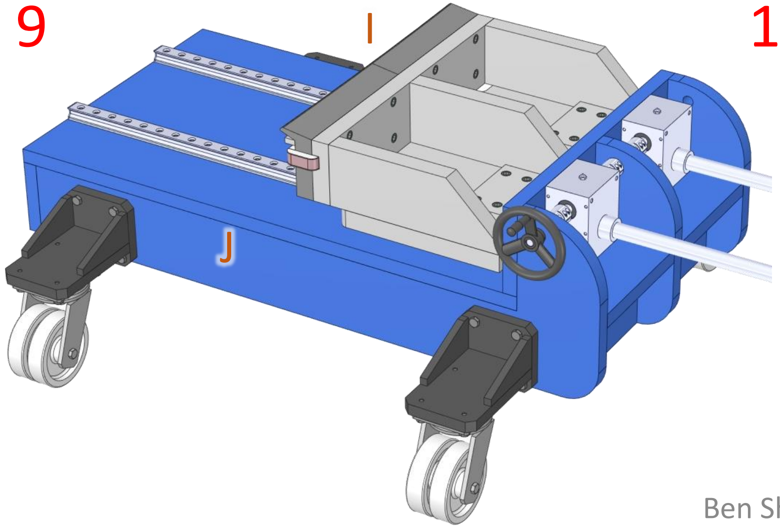

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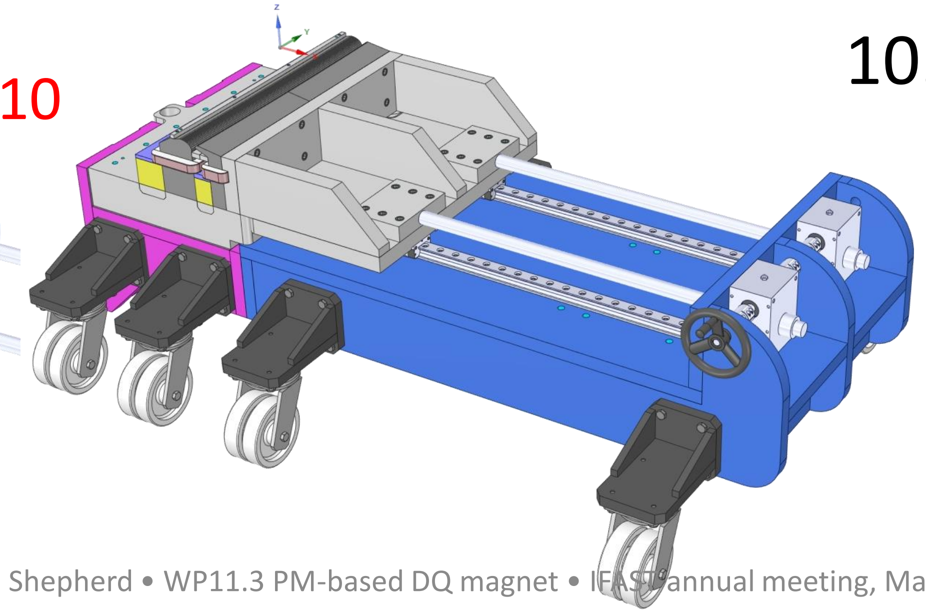
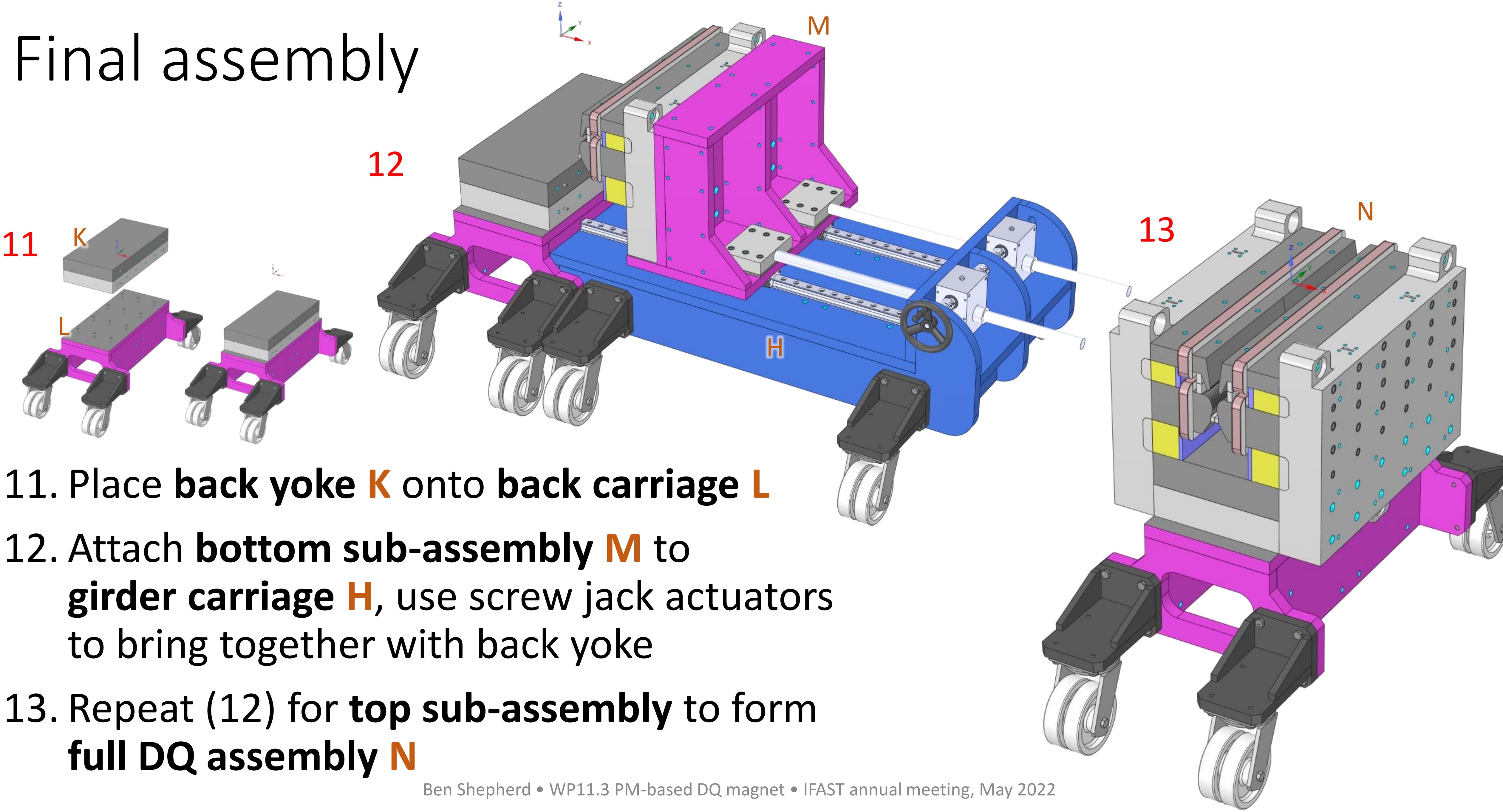


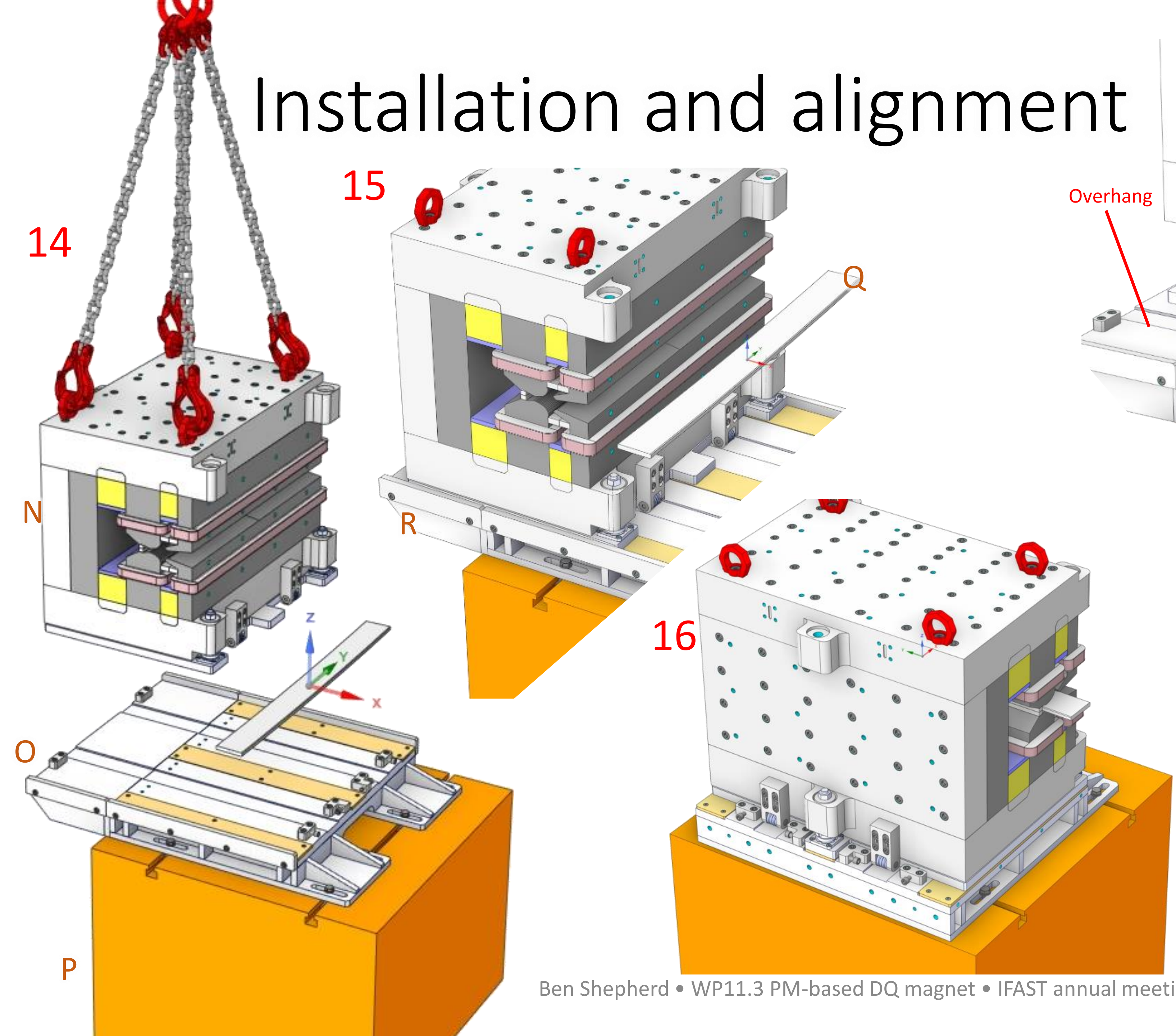
7. Lower **magnet sub-assembly F** onto **girder plate G**
8. Place partially-assembly girder onto **girder carriage H**
9. Attach **front pole I** onto **main assembly rig J**
10. Using screw jack actuators, slide front pole up to meet magnet sub-assembly

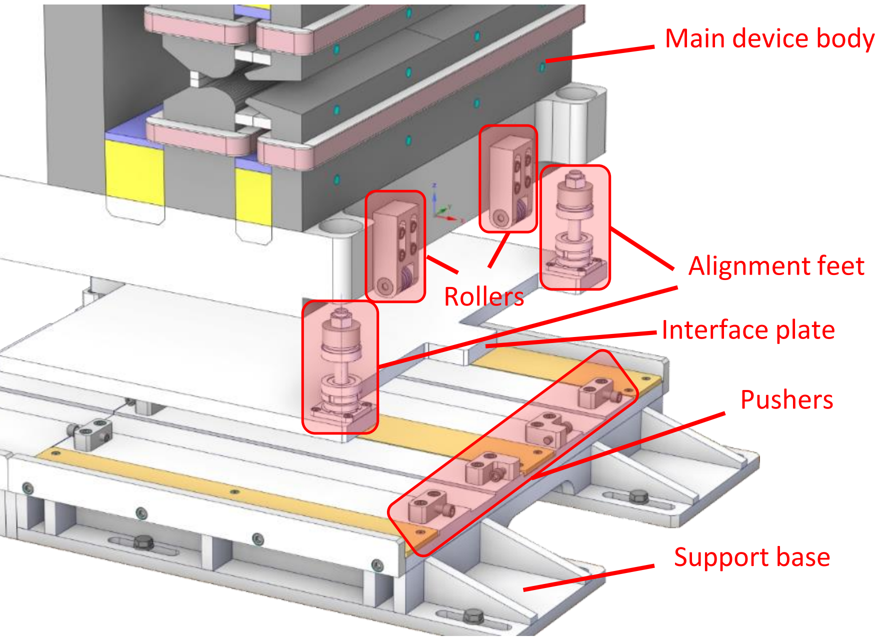
Final assembly



11. Place **back yoke K** onto **back carriage L**
12. Attach **bottom sub-assembly M** to **girder carriage H**, use screw jack actuators to bring together with back yoke
13. Repeat (12) for **top sub-assembly** to form **full DQ assembly N**

Installation and alignment





14. Install **support base O** onto **beam P**; lower **assembled DQ N** onto support base
15. Slide DQ across support base around **vacuum chamber Q**; remove **overhang R**
16. Perform fine alignment to vacuum chamber

WP11.3 Next Steps

- Magnet design
  - Refine tolerance studies
  - Try to make pole shape more robust against manufacture errors
  - Finalise coil design: decide on air- or water-cooled coils
- Mechanical design and assembly
  - Produce final detailed design
  - Procure PMs and other materials and tooling
  - FEM analysis
- Next prototype: PETRA-IV
  - Another DQ magnet, or a pure quadrupole
  - Parameters to be decided: strength, tuning range, field quality…

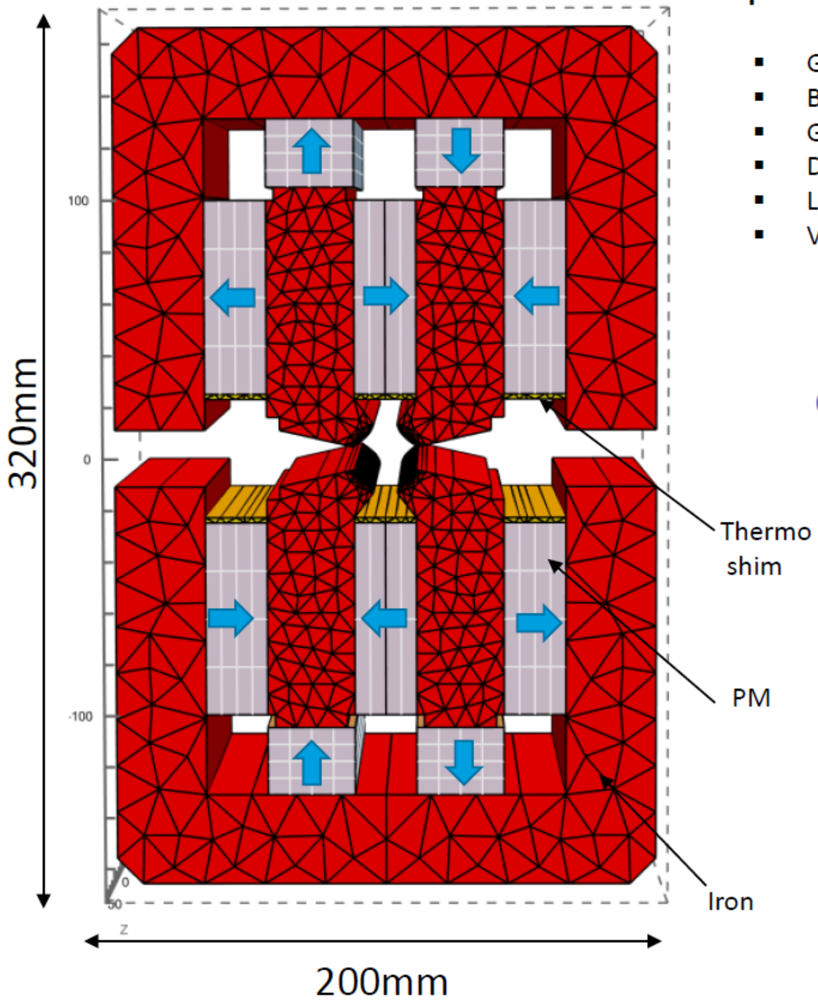
PETRA-IV PM Quadrupole proposal

Slide from R. Bartolini

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

PM-based Quadrupole – Preliminary Design

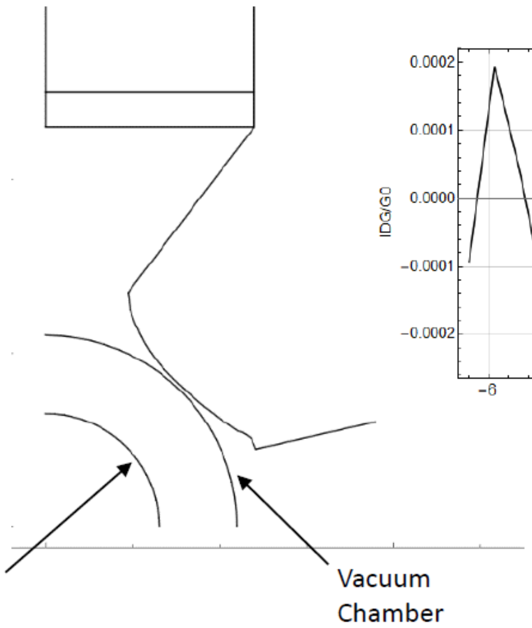
(Patrick N'Gotta, FS-US)

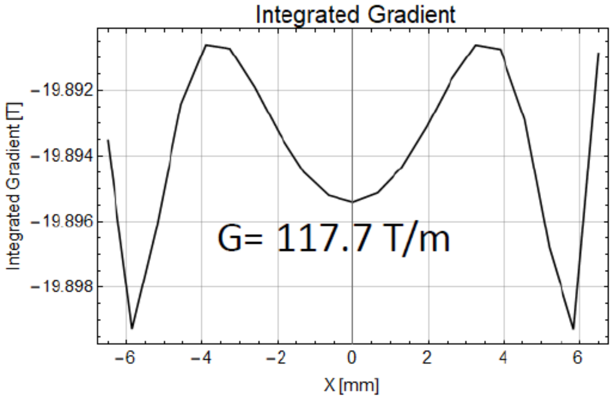


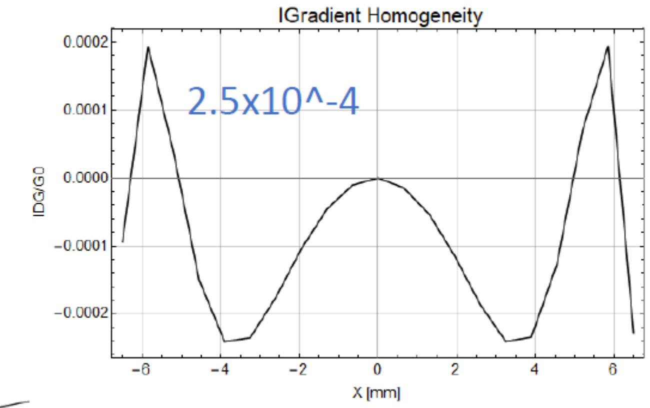
Specification for Petra IV PMQ

- 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

Optimized Pole shape







Harmonics

1	0	0.
2	-0.12932	1.
3	0	0.
4	0.0000531461	-0.000410966
5	0	0.
6	0.0000140801	-0.000108878
7	0	0.
8	-0.000151464	0.00117123
9	0	0.
10	0.0000890791	-0.000688826
11	0	0.
12	5.52245×10^{-6}	-0.0000427037
13	0	0.
14	-1.16126×10^{-6}	8.97975×10^{-6}
15	0	0.

Integrated Harmonics

Normalized Harmonics (Unit)

Principal concept: P.N'Gotta, PRAB 19 (2016) 052401

Conclusions

- Combined function DQ magnet with Diamond-II parameters
- Magnet design
  - PM-based; 0.7 T; 32 T/m; ±2.5% adjustability
  - Temperature compensating shims ensure high stability
- Concept mechanical design
  - Assembly, installation and alignment procedures
- Viable concept design that meets the spec
- On track to build first IFAST PM prototype
- Future work: decide on PM prototype to build for PETRA-IV

- Acknowledgements:
  - **Alex Hinton** (STFC), magnet design
  - **Tadej Milharcic** (Kyma), mechanical design