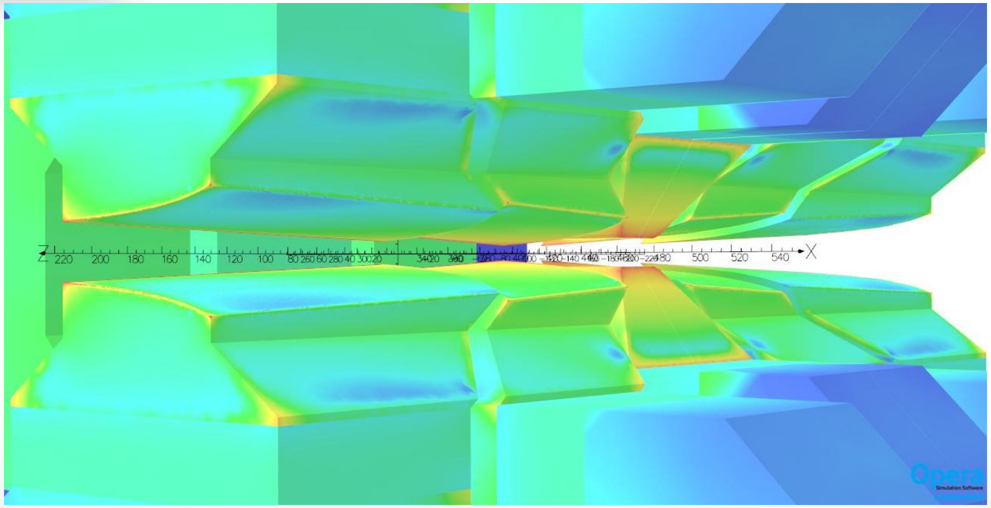
Design of a Dipole with Longitudinally Variable Field using Permanent Magnets for CLIC DRs



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Introduction

- CLIC: electron positron linear accelerator collider. Particle physics research in the multi-TeV energy scale

- Two beams of 3 TeV. Expected luminosity of $2\times10^{+34}$. Inversely proportional to the transverse beam emittance

- Damping rings (DRs) **to reduce the emittance** of the injector chain incoming beams. Lattice: theoretical minimum emittance (TME) cell and simple FODO lattice filled with high field superconducting damping wigglers

- The **horizontal emittance** is further reduced below the TME limit for a given magnetic structure by considering **dipole magnets with longitudinal variable bending field**. **Trapezium field profile dipoles are preferred** in the CLIC DR lattice

Technical specifications

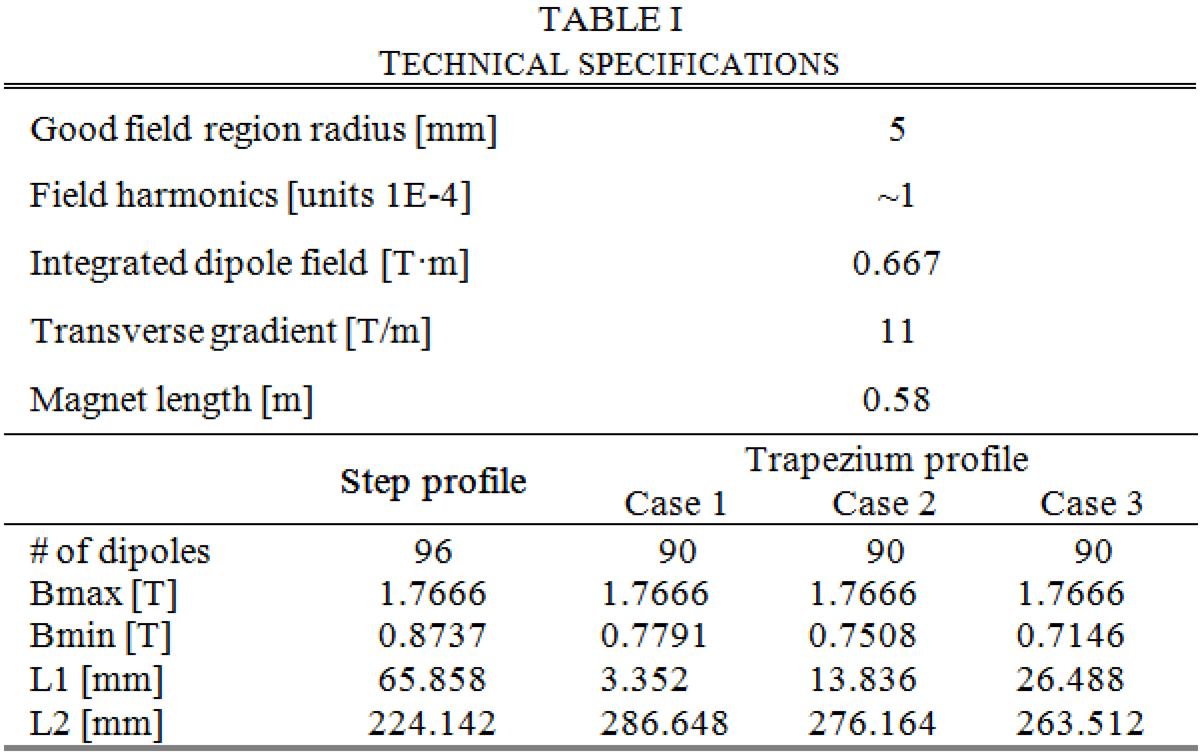
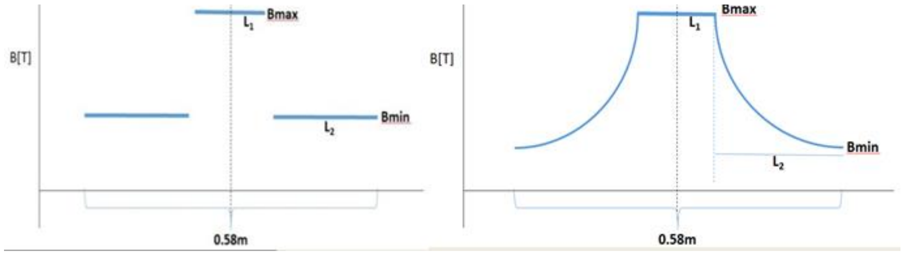


TABLE I
TECHNICAL SPECIFICATIONS

Good field region radius [mm]	5
Field harmonics [units 1E-4]	~1
Integrated dipole field [T·m]	0.667
Transverse gradient [T/m]	11
Magnet length [m]	0.58

	Step profile	Trapezium profile		
		Case 1	Case 2	Case 3
# of dipoles	96	90	90	90
Bmax [T]	1.7666	1.7666	1.7666	1.7666
Bmin [T]	0.8737	0.7791	0.7508	0.7146
L1 [mm]	65.858	3.352	13.836	26.488
L2 [mm]	224.142	286.648	276.164	263.512



Preliminary design

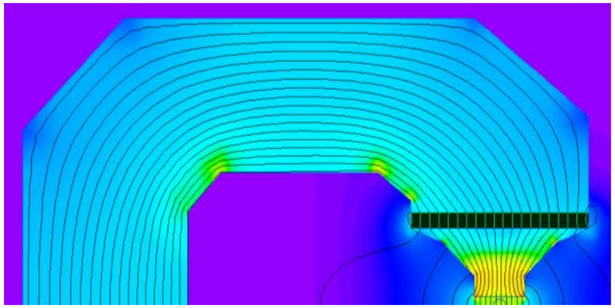
- C-shaped magnets: efficient use of space
- Gap is pointing outwards to ease synchrotron radiation evacuation
- Yoke made of pure iron (Armco). Average field below 1T
- **High saturation** in the high field region pole => Fe-Co (Vacoflux) preferred

- Straight magnet: higher quality machining, eases assembly
- Sagitta: 5mm. GFR centered with the pole and 2 additional regions with the same radius and displaced ± 2.5mm

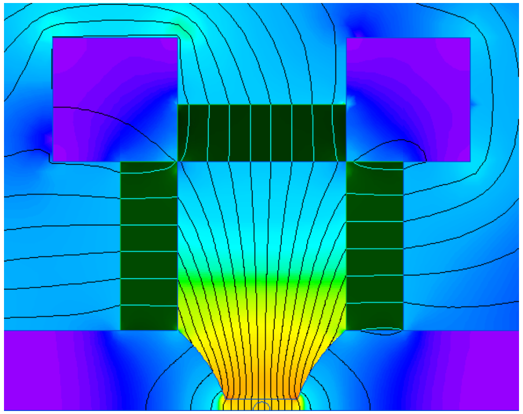
- Fixed field provided with **permanent magnets**
- Max Temp variation ±0.1ºC => **No specific temperature** compensation
- Taking into account radiation tolerance, volume and weight, maximum remanent magnetization, cost,…:
  - **SmCo** in the low field region
  - **NdFeB** in the high field region

Magnetic design: 2D

- ☐ Poles cross section is smaller in the tip than in the base: flux concentration, higher field peak in the gap
- ☐ Combined function magnet (dipolar and quadrupolar fields): hyperbolic profile in the pole tips
- ☐ 2D simulations in Quickfield



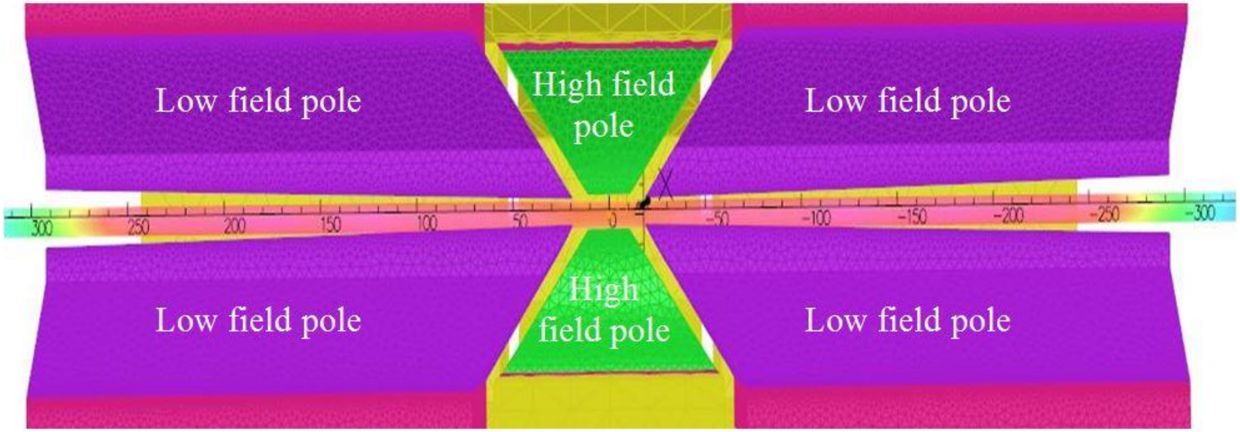
- ☐ Low field region: SmCo blocks in a flat configuration over the pole



- ☐ High field region: NdFeB in three blocks working in parallel to preserve the pole dimensions within reasonable limits. Highly saturated: much more difficult to reach the desired specifications

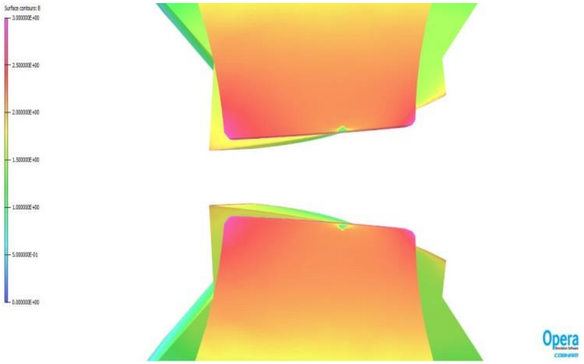
Magnetic design: 3D

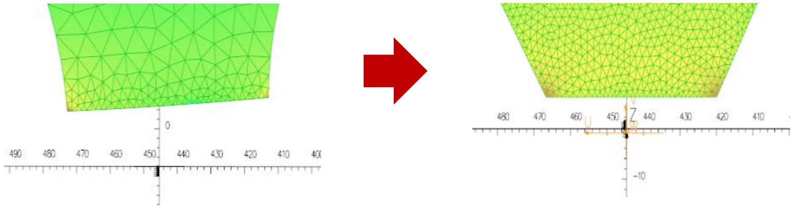
- Short magnet length (0.58 m) makes **2D simulations diverge from 3D**, particularly in the high field section, where the pole tip is approximately 7 mm wide
- Result comparison/validation: **Ansys Maxwell, ROXIE, COMSOL and Opera**
- **Crosstalk** between high and low field regions. To minimize it, the low field region pole tip has been extruded and the high field region pole tip chamfered
- Step profile: easily obtained
- Trapezium profile: tough challenges. Achieved introducing a **variable gap** along Z axis



Magnetic design: 3D

- ☐ High field region: **flat profile** due to the high iron saturation





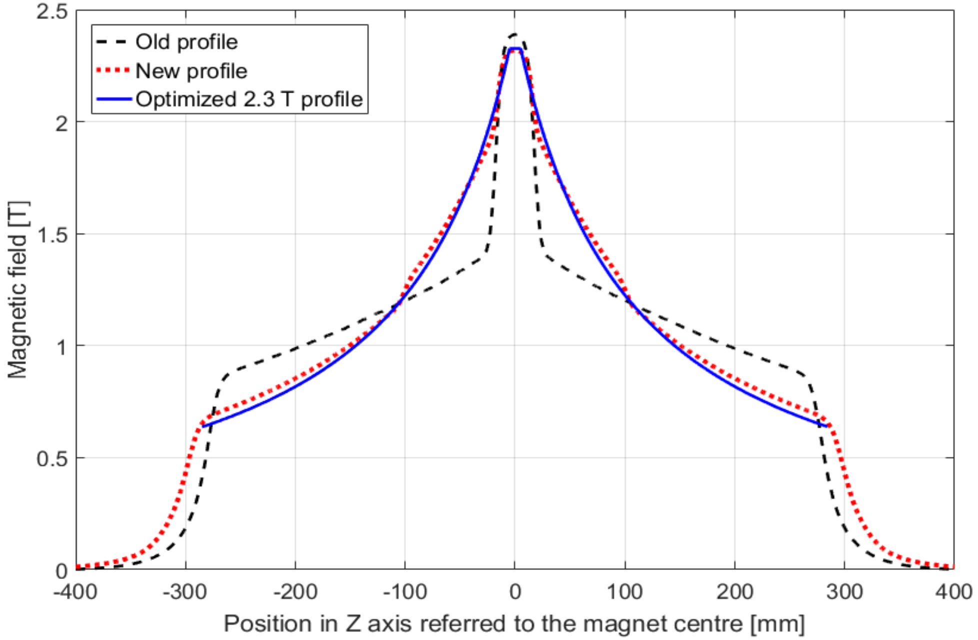
- ☐ Low field region gap: **not constant.** Different hyperbolas for each different gap height

- ☐ By contrast, to be mechanized with EDM, the pole tips must be **ruled surfaces**

- ☐ On account on these restraints: “**averaged hyperbola**”. Very good results in the simulations

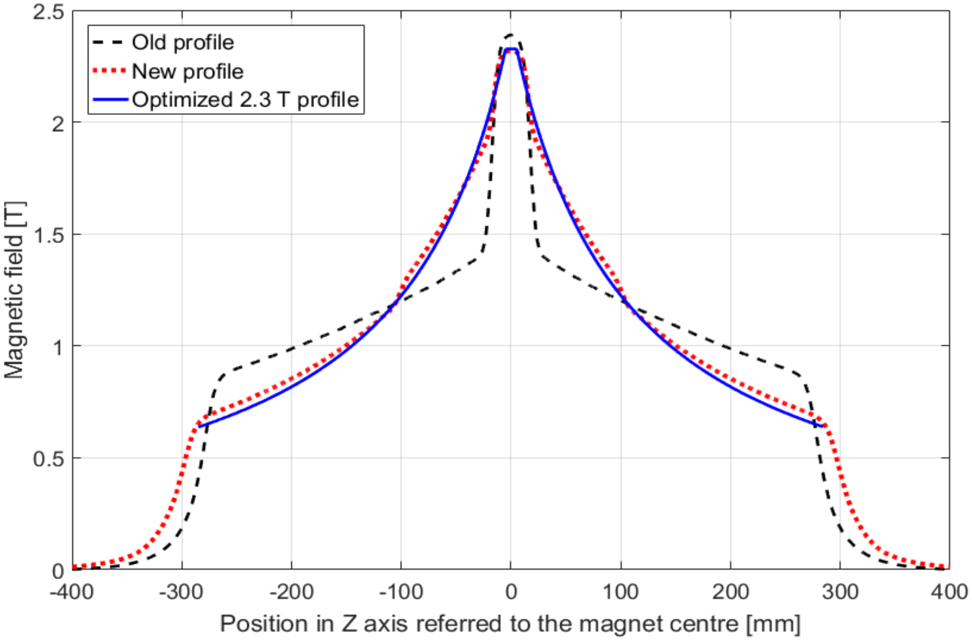
Upgrade to 2.3 T

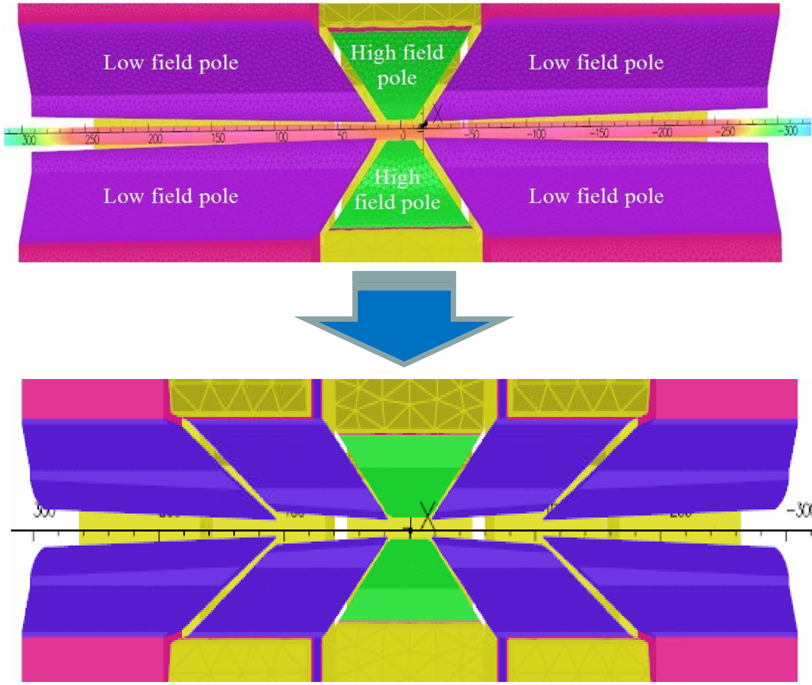
- ☐ Magnet originally limited to 1.77 T peak field as a reasonable value for a non-superconducting magnet
- ☐ 3D simulations: peak could be increased above 2 T, increasing emittance reduction factor while keeping the field quality
- ☐ A new 2.3 T optimized trapezium profile is finally proposed



Upgrade to 2.3 T

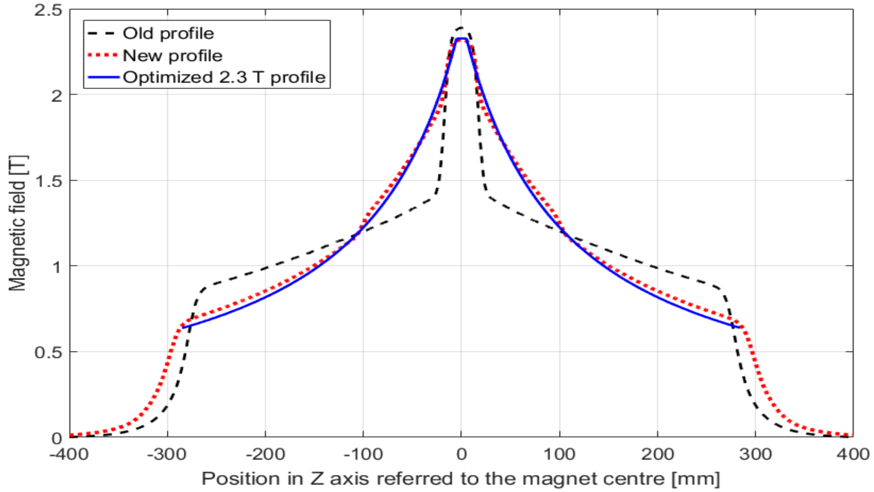
- ☐ At this point the magnet **is close to meet** the desired specifications.
- ☐ The obtained decay –“Old profile”- at both sides of the peak does not match the ideal one (hyperbolic)
- ☐ Impossible to get closer to the ideal decay –“Optimized 2.3 T profile”: a **new lay**out is introduced
- ☐ To follow the ideal hyperbolic decay, the **low field region is split** in two parts: **low and mid field region**





Upgrade to 2.3 T

- ❑ **Three** differentiated sections: **low, mid and high field**. This allows a higher F_{TME} 7, higher than the one originally proposed
- ❑ New hyperbolic profiles in the low and medium field regions, while the high field one maintains the flat pole tip
- ❑ Same configuration for the high and medium field regions PM: three NdFeB blocks working in parallel
- ❑ Low field region maintains the SmCO in one flat block over the pole
- ❑ With this upgrade the **maximum field** is increased up to 2.3 T and at the same time the field decay matches more precisely the ideal hyperbolic desired profile. Multipole values within the limits.



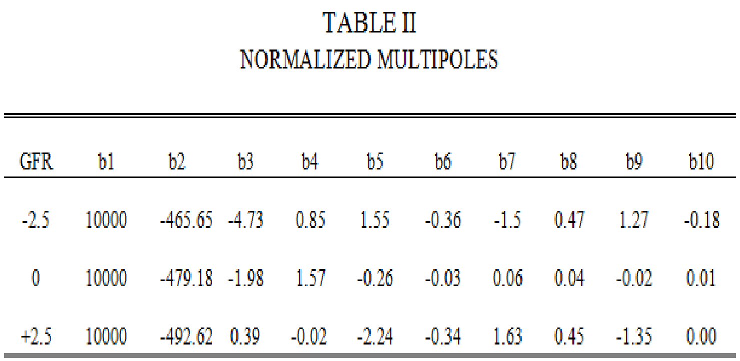


TABLE II

NORMALIZED MULTIPOLES

GFR	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10
-2.5	10000	-465.65	-4.73	0.85	1.55	-0.36	-1.5	0.47	1.27	-0.18
0	10000	-479.18	-1.98	1.57	-0.26	-0.03	0.06	0.04	-0.02	0.01
+2.5	10000	-492.62	0.39	-0.02	-2.24	-0.34	1.63	0.45	-1.35	0.00

Field trimming

- ☐ Two main possibilities to study the feasibility of varying the magnetic field ±5% :

  - Active: adding coils and their corresponding power supply

Pros:	Cons:
– Fast field trimming	– Higher cost
– Can be adjusted during operation	– More complex design

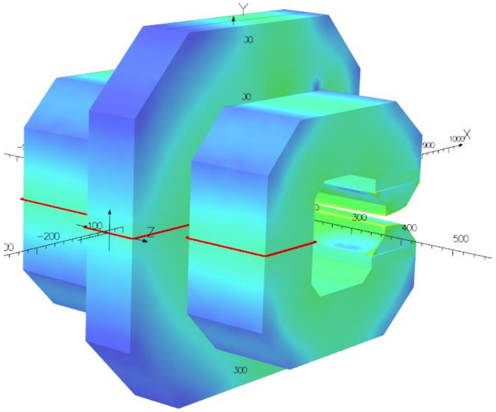
  - Passive: splitting the yoke in two parts and therefore making it possible to adjust the magnetic circuit reluctance

Pros:	Cons:
– Less expensive	– In principle the field cannot be adjusted during operation
– Simpler design	

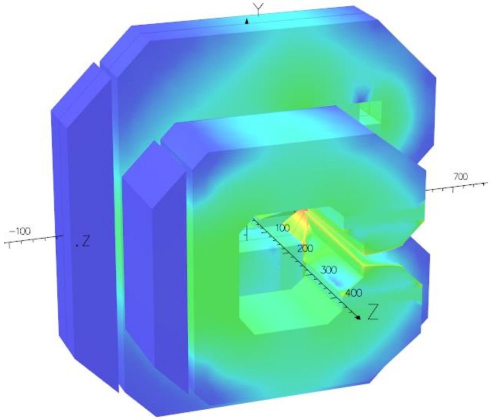
Field trimming

- ☐ Simulations

  - ➢ Active: due to the high iron saturation, the coils should be too large and water cooled. This approach gets away from the main ideas behind using permanent magnets: compactness and no need of power supply



  - ➢ Passive: feasible according to simulations. This is the preferred solution and it will be probably implemented with actuators to allow remote trimming.



Conclusions

- PM based design. High requested peak field implies dealing with iron saturation. Partially overcome using **Fe-Co** and **suppressing the hyperbolic profile** in the most saturated section.

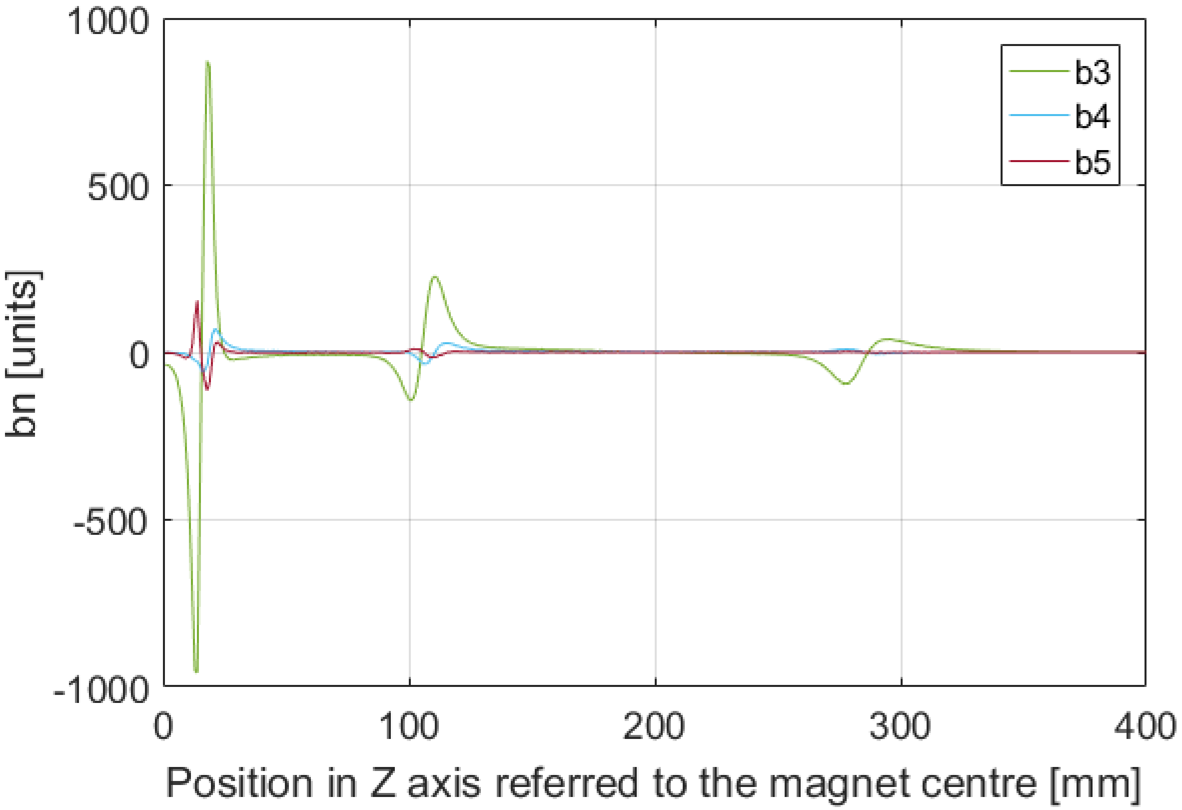
- Important challenge: **longitudinal gradient with trapezoidal decay**. Solved splitting the magnet in **three differentiated field regions** combined with an innovative **variable gap** solution

- The mentioned solutions finally lead to a validated proposal that **meets – and even exceeds** in terms of beam emittance reduction- the specifications. This achievement is due to the trapezoidal field profile, which has been implemented **for first time in an accelerator magn**et

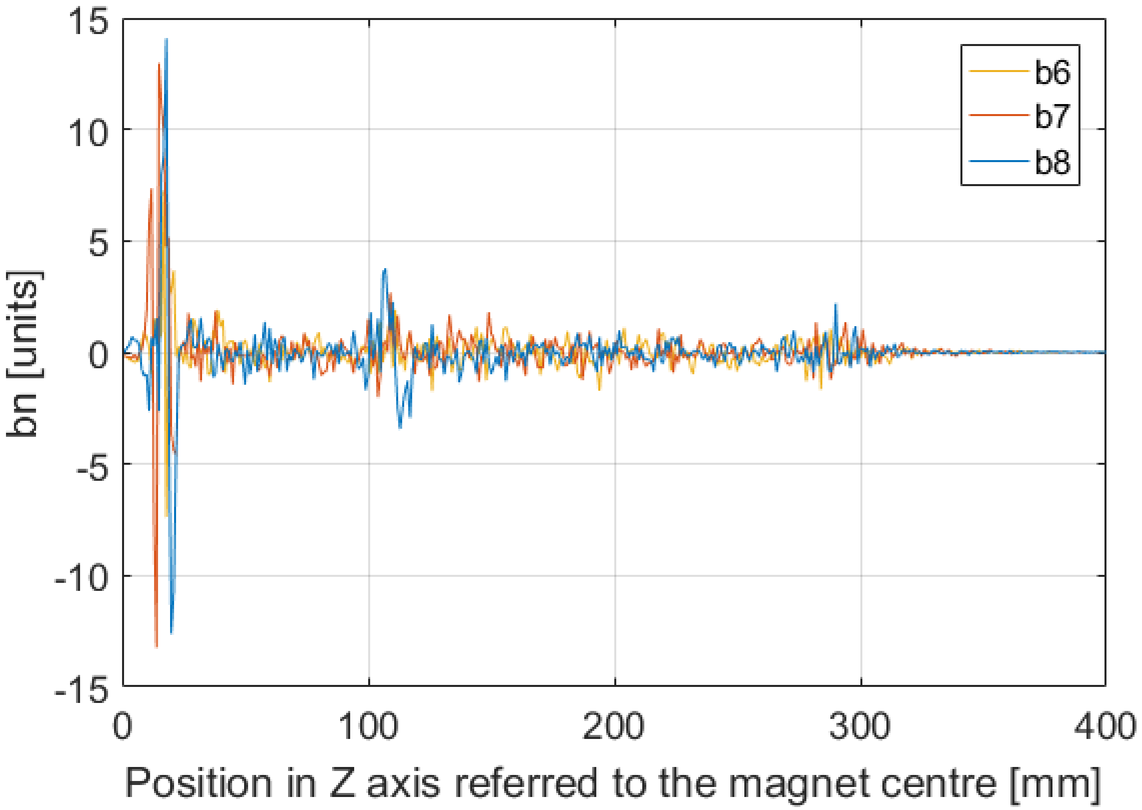
- The probable need of a **field trim** is also evaluated and implemented creating a **variable reluctance return path** for the magnetic flux using movable parts

Thank you for your attention!

Multipoles


1000
500
0
-500
-1000
bn [units]
0
100
200
300
400
Position in Z axis referred to the magnet centre [mm]
b3
b4
b5

Multipoles


15
10
5
0
-5
-10
-15
bn [units]
0
100
200
300
400
Position in Z axis referred to the magnet centre [mm]
b6
b7
b8