CCT FF quad design status

MDI workshop

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30/1/2018

Introduction

- I will attempt a summary of the work done during the last couple of years culminating with the publication in MT25 (paper and poster) on:

Wed-Af-Po3.01

A Method for Greatly Reduced Edge Effects and Crosstalk in CCT Magnets

M. Koratzinos, ETH Zurich, G. Kirby, J. Van Nugteren, CERN, E. R. Bielert, Univ. Illinois at Urbana

***Abstract*— Iron-free CCT magnet design offers many advantages, one being the excellent field quality and the absence of multipole components. However, edge effects are present, although they tend to integrate out over the length of the magnet. Many modern accelerator applications, however, require that these magnets are placed in an area of rapidly varying optics parameters, so magnets with greatly reduced edge effects have an advantage. We have designed such a magnet (a quadrupole) by adding multipole components of the opposite sign to the edge distortions of the magnet. A possible application could be the final focus magnets of the FCC-ee, where beam sizes at the entry and exit point of the magnets vary by large factors. We have then used this technique to effectively eliminate cross talk between adjacent final focus quadrupoles for the incoming and outgoing beams.**

***Index Terms*— CCT, correction, edge effects, magnet, multipole**

I. Introduction

CANTED- cosine-theta (CCT) magnets have been around since the seventies [1], however only recently have they

In the general case of a coil that produces an arbitrary selection of multipole fields, the centre-line defining the shape of the groove (and the position of the centre of the powered cable) for one of the two coils of the CCT is described by the equation

$$x = R\cos\theta\,;$$

$$y = R\sin\theta\,;$$

$$z = \sum_{n_B}\left[\frac{R\sin(n_B\theta)}{n_B\tan\alpha_{n_B}} + \frac{\omega\theta}{2\pi}\right] + \sum_{n_A}\left[\frac{R\cos(n_A\theta)}{n_A\tan\alpha_{n_A}} + \frac{\omega\theta}{2\pi}\right] \quad (1)$$

Where R is the radius of the coil, A and B are the skew and normal components of the field, n_A and n_B are the skew and normal multipoles ($n_B = 1$ is the dipole component, $n_B = 2$ the quadrupole component, etc., same with $n_A = 1$: skew dipole component, etc.). The angles α_{n_A}, which could be a function of z, are the angles of the groove (or wire) with respect to

Why the CCT approach?

- FF quads are separated by 66mm at the tip closer to the IP
- Beam pipe is 30mm diameter, so inner bore cannot be smaller than 40mm
- For a 100T/m gradient, field at 20mm radius from the centre of the beam pipe will be 2T – the maximum field will be more than 3T
- Relying on (a very thin sheet of) iron to shield the magnets from cross talk at such fields would not work. This means that a design relying on iron would need to limit the field gradient (to perhaps 60T/m??
- ➔ iron-free approach seems the only way forward

Why the CCT approach? (II)

- Field quality needed is a very stringent factor! (my first attempt with a residual crosstalk field of <1 unit for all multipoles resulted in using 30% of our emittance budget! - subsequent work reduced the multipole components to below 0.1 unit, and this was acceptable)
- With the CCT approach, one can design a magnet with a multipole mix that changes every ~1 cm! (this is necessary as the two FF quads sit at an angle)

Dimensions, specs

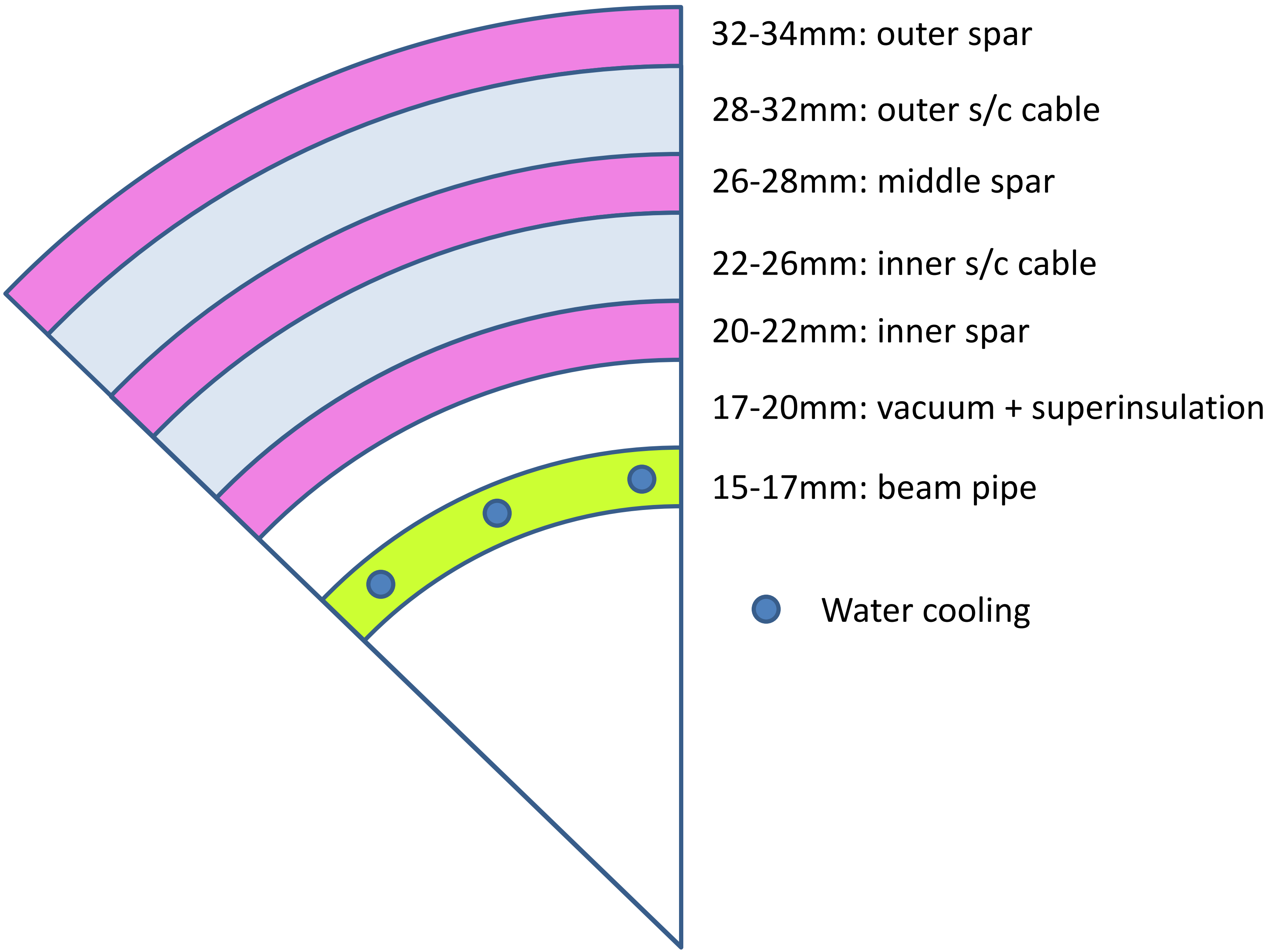
- The quads (QC1L1, QC2L2, QC2L3) follow the specs provided by Katsunobu
- I provide the multipole files at the correct magnetic lengths and approximate strengths separately for each magnet
- Katsunobu can change the strengths (linearly, as there is no iron) and combine magnets (again linearly, as there is no iron)

	L (m)	B’ @ tt (T/m)	B’ @ Z (T/m)
QC1L1	1.2	-94.4	-96.3
QC1L2	1	-92.6	+50.3
QC1L3	1	-96.7	+9.8
QC2L1	1.25	+45.8	+6.7
QC2L2	1.25	+74.0	+3.2

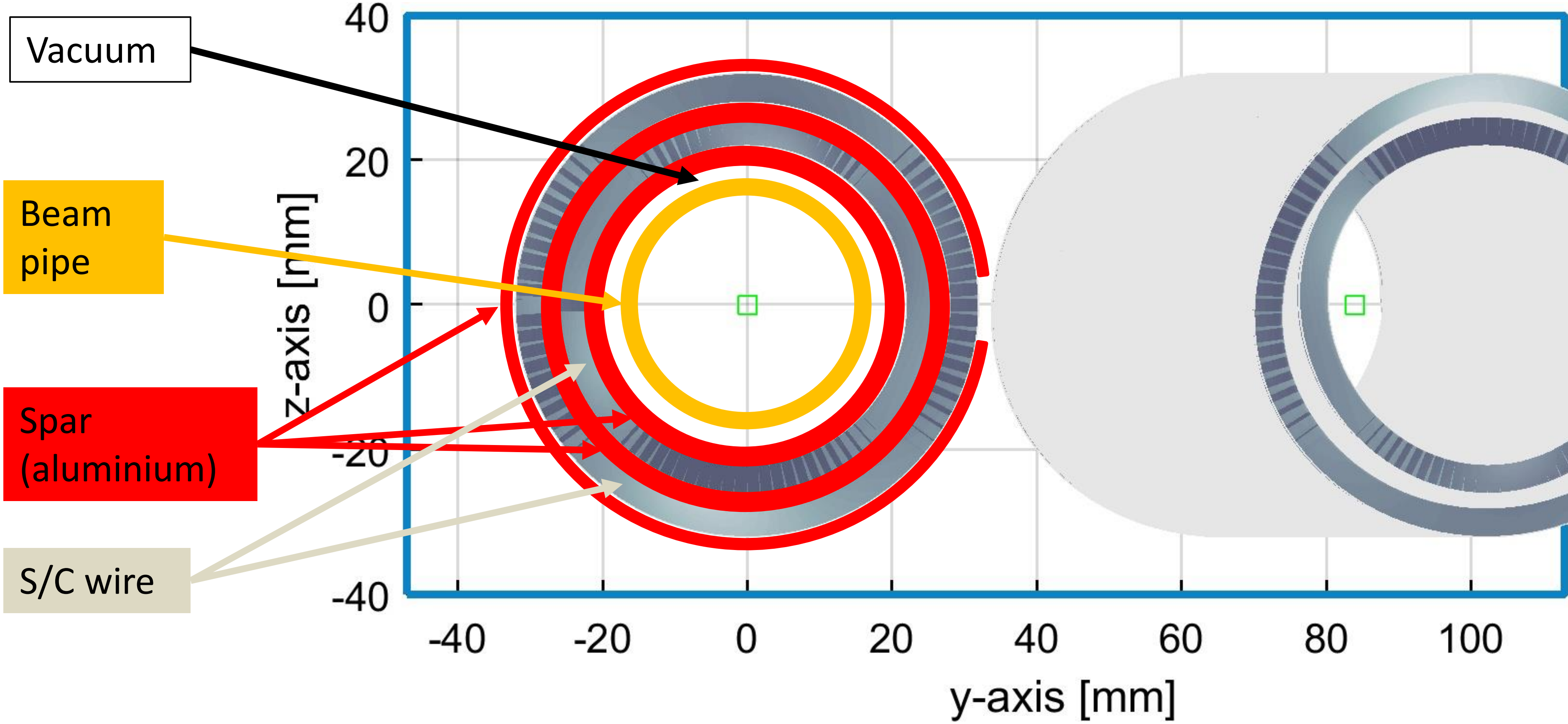
Transverse dimensions

- Beam pipe is 30 mm diameter
- In the FF quads the first winding starts at 42mm
- The inner substrate starts at 40mm
- We are investigating if all the cooling needed can fit between 30 and 40mm.
- In this design there is a 2mm gap between the two FF quads at 2.2m
- The cable used has a cross section of $2\times4=8mm^2$. The critical current through this cross section permits gradients in excess of 150T/m. If we do not need this capability, we can reduce the size of the cable to 2×3mm. In this way we can reduce the overall radius of each quad by 2 mm (or increase the gap between them by 4mm)

Dimensions - radius



Transverse dimensions



Heat load and cooling needs

According to E. Belli:

- For the most difficult case, QC1L1
- e-cloud: for SEY=1.1 ~20W/m, for SEY=1.2 ~200W/m
- resistive wall: for copper, ~100W/m
- direct SR heating: zero (I assume that masks will take all direct SR)

From the above, the heat load appears to be O(100)W/m

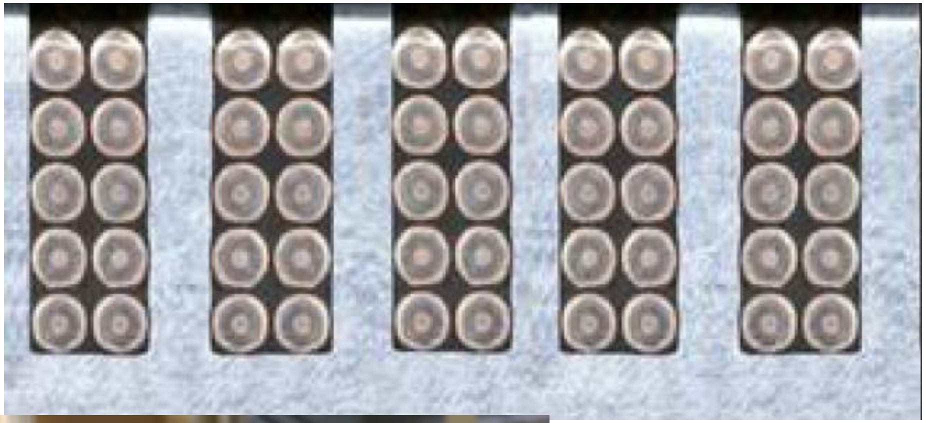
The cable

- The groove for the cable is 2 × 4 mm (8mm^2 cross section).
- The critical current if one uses 8 windings of standard LHC NbTi strand is more than 7120 A at 3 T (with a lot of space to spare).
- This corresponds to more than 150T/m. If needed, a quad with 200 T/m can be manufactured

Type	#Fil	Cu:SC	Diameter (mm)		Critical Currents (Amps @ 4.2K) at Fields (Tesla, T)				Fil Dia (µm)
			Bare	Insulated	3T	5T	7T	9T	
56S53	56	00.9:1	0.30	0.330	125	100	55	20	30
			0.40	0.430	270	190	120	45	39
			0.50	0.540	470	330	205	70	48
			0.60	0.643	620	440	270	100	58
			0.70	0.753	850	600	370	135	68
			0.85	0.896		790	490	175	83
54S43	54	1.3	0.30	0.330	100	80	45	16	25
			0.40	0.430	215	150	90	30	35
			0.50	0.540	300	215	135	50	45
			0.60	0.643	500	350	210	65	55
			0.70	0.753	710	435	280	90	60
			0.85	0.896	890	640	400	135	75
			0.95	1.000		780	480	165	85
			1.04	1.094		880	550	200	90
			1.25	1.300		750	240		110

The cable

I am using the same cable and winding scheme as the D2 corrector HiLumi magnet, currently being prototyped.

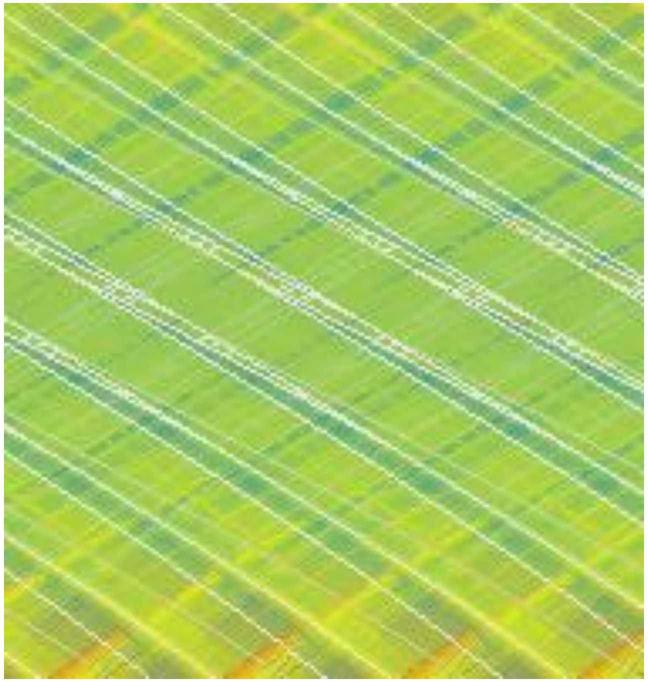


D2: 5X2 individual insulated strands
This magnet: 4X2 individual strands

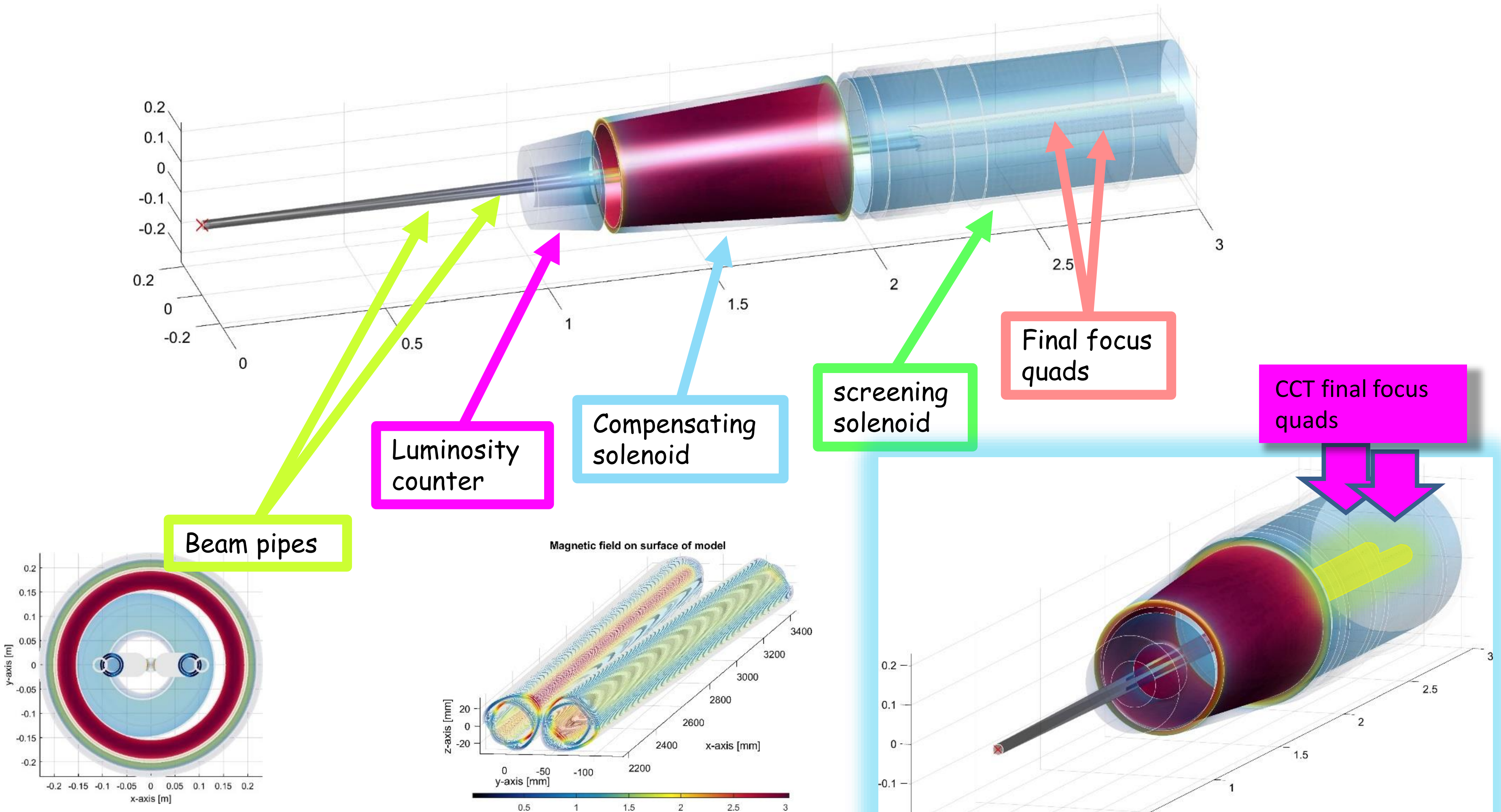
Wiring tool in action

Packing

- The pitch between grooves is 5mm and the width of the groove is 2mm. The angle is 60 degrees.
- So the space between grooves is between 1 and 3 mm (5mm-2mm/cos(60)=1mm (min) and 5mm-2mm=3mm (max))

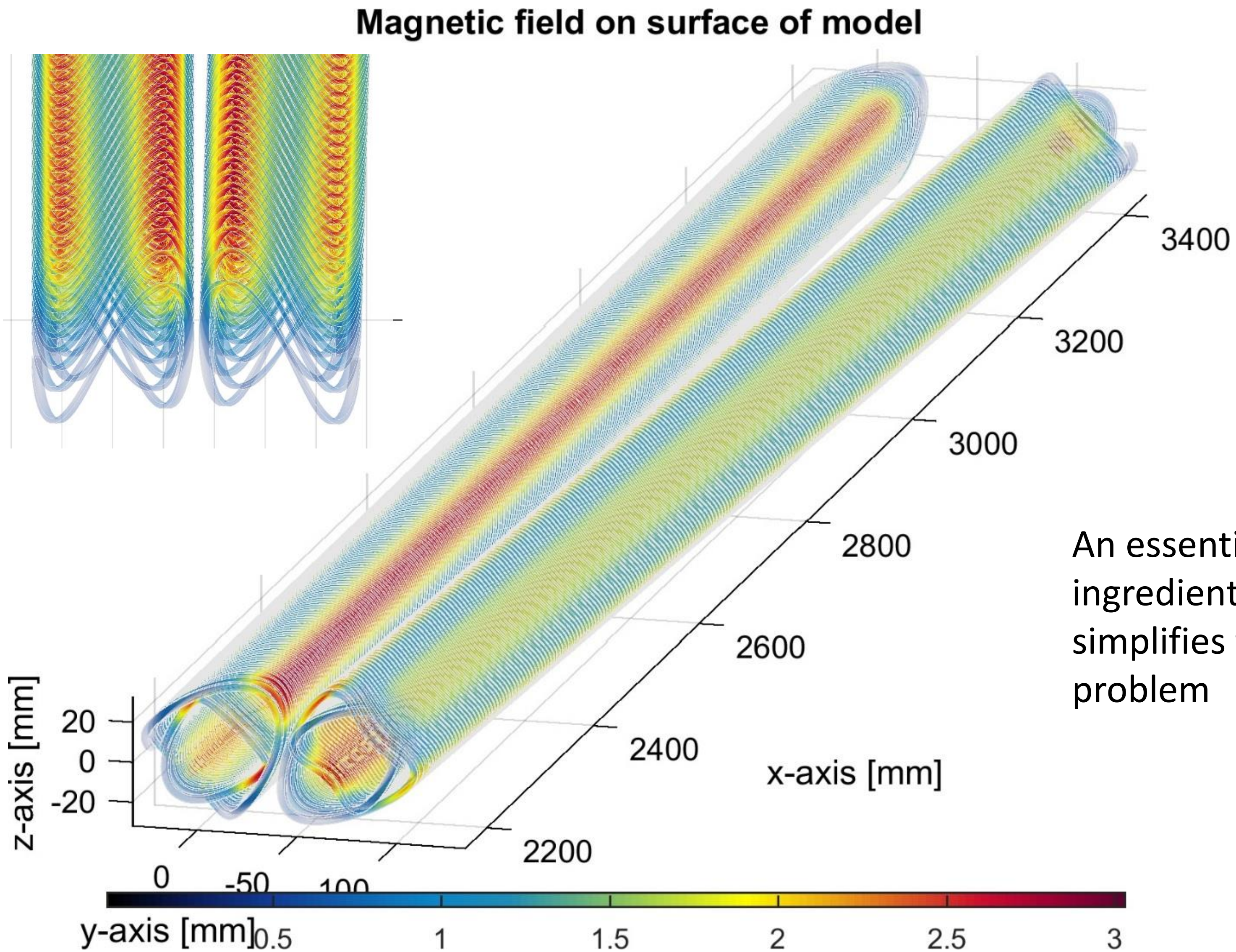


The IR



X-Y view –looking towards the IP

The mirror arrangement

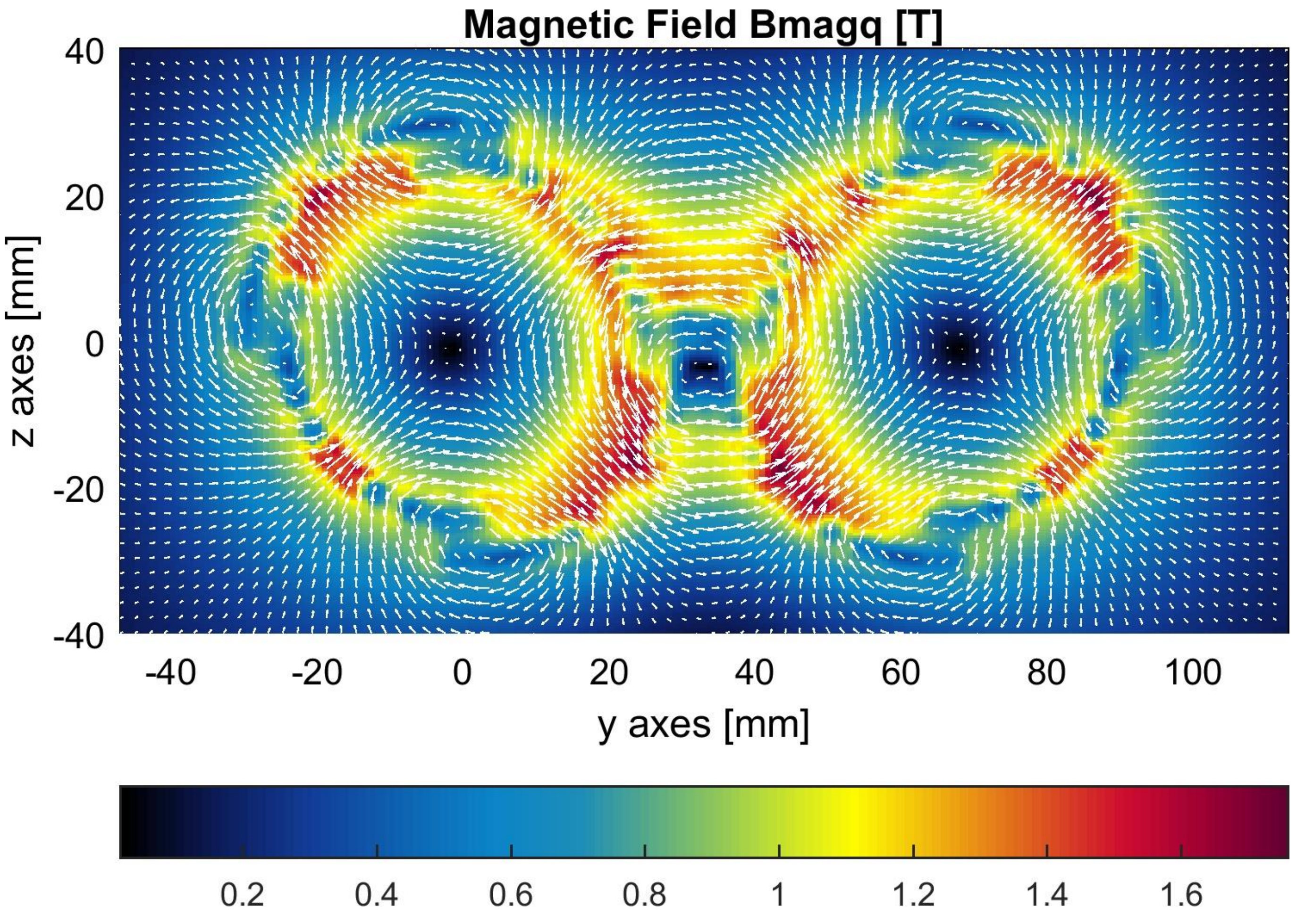


An essential ingredient that simplifies the problem

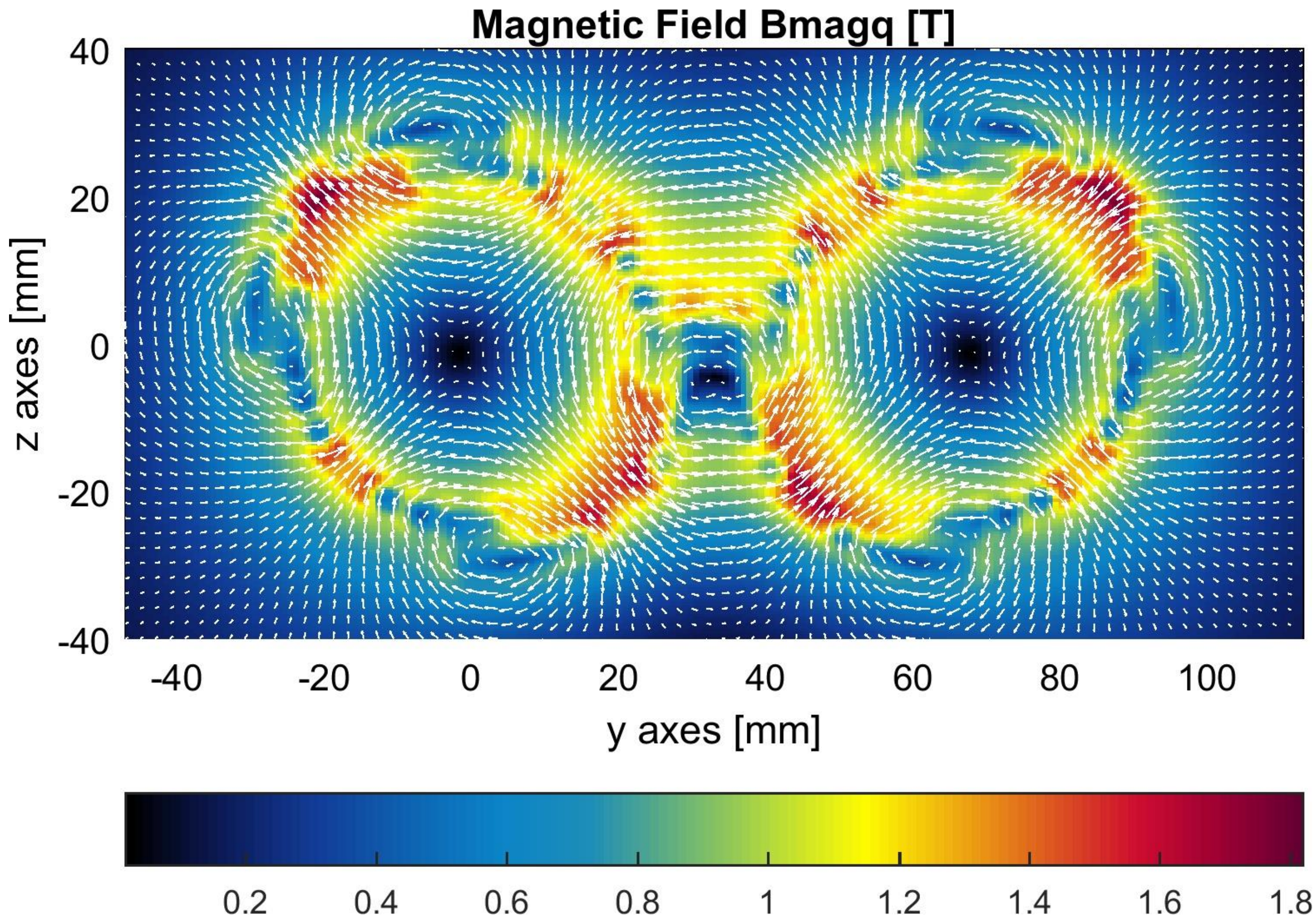
Corrections

- Crosstalk is corrected along the entire length of the quad
- The design of the twin aperture quad is done so that the two adjacent quads have a mirror-symmetric design – this simplifies the process a lot, as there is a single correction file applicable to both quads
- Edges are corrected locally on both sides of the quad.
- The last two windings of the coil have a much larger pitch, 15mm and the two adjacent ones 7mm.
- I have concentrated on QC1L1, for QC1L2 and QC1L3 only edge correction was performed (they are far away from each other, so iron could be an option)

Field map at 2200 mm, no correction



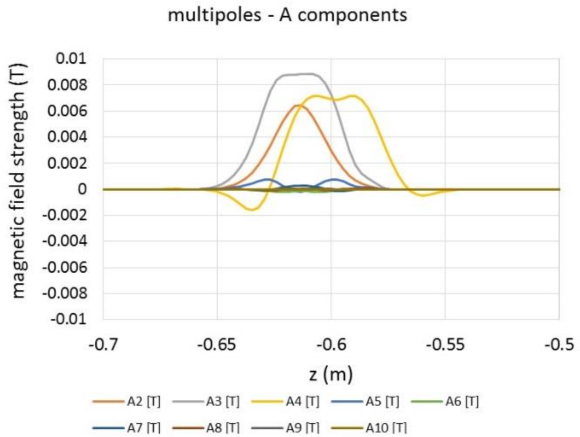
Field map at 2200 mm, with correction

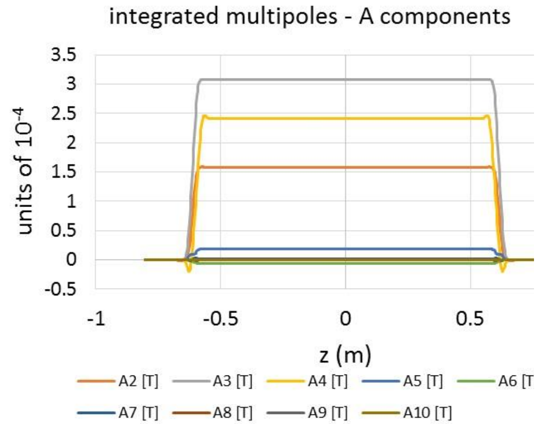


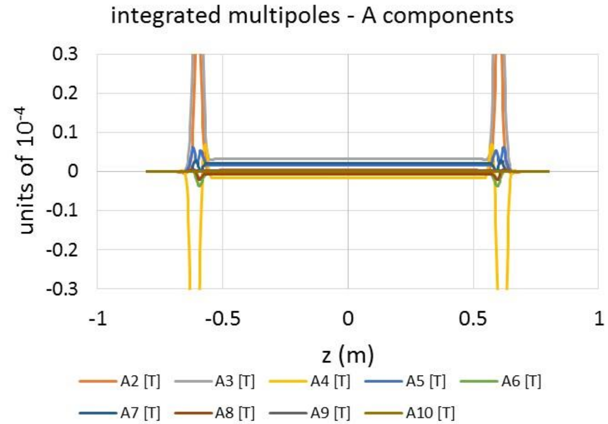
QC1L1 single coil edge correction

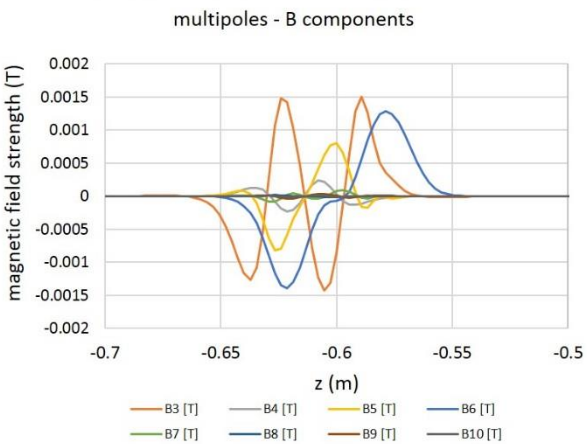
- Integrated multipoles before (centre) and after correction (right)

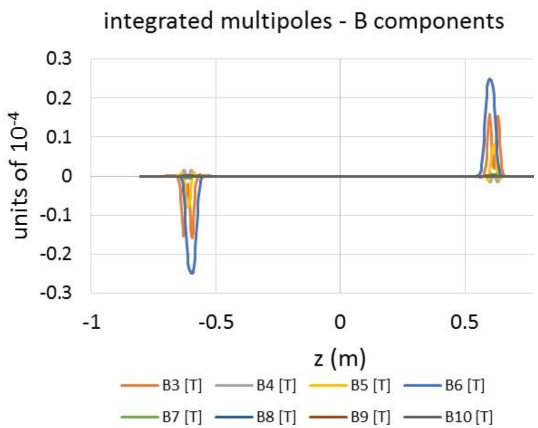
Before correction | Before correction | After correction

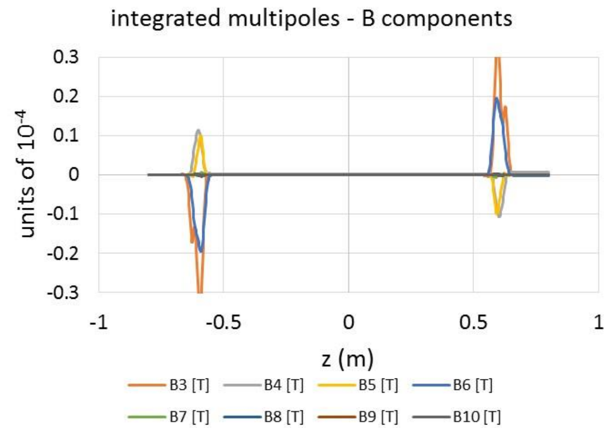






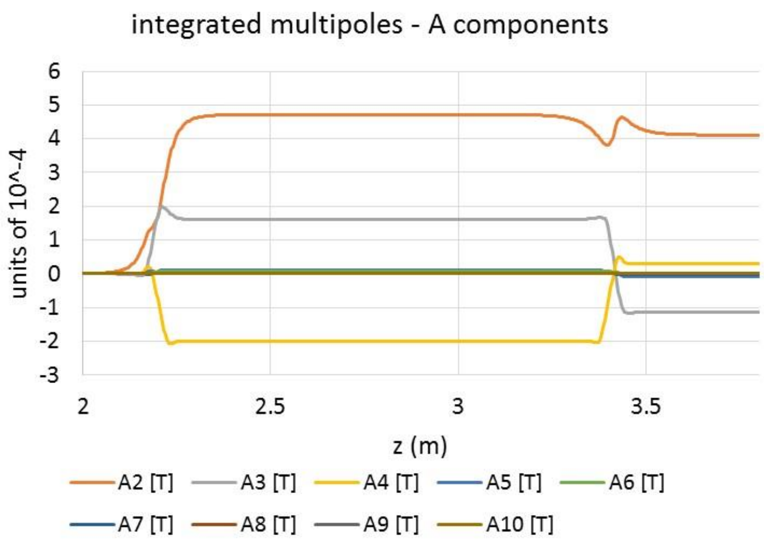


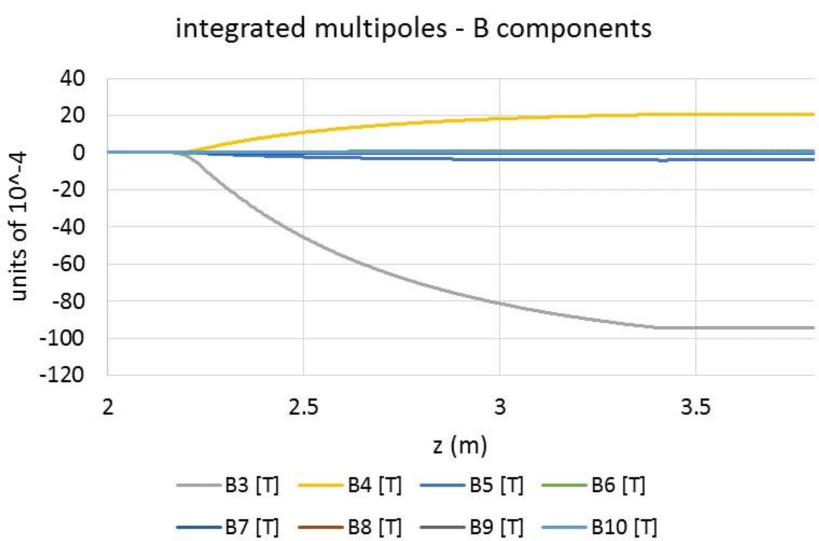




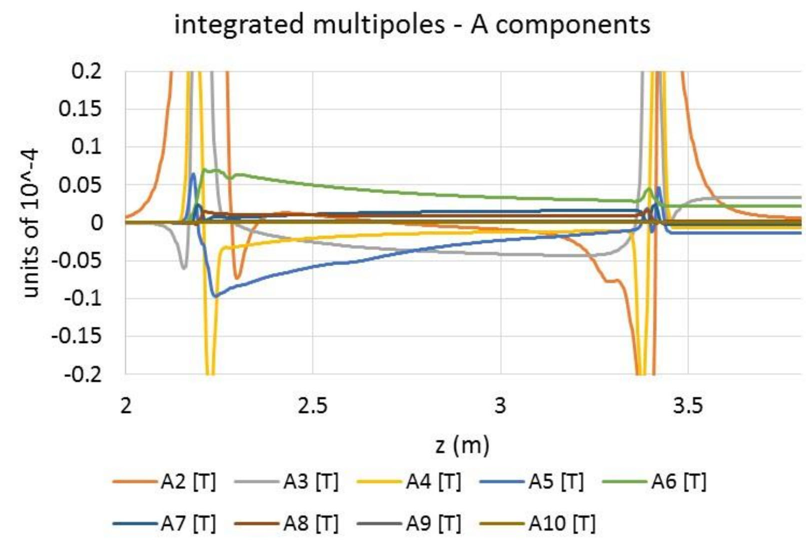
QC1L1 double coil crosstalk correction

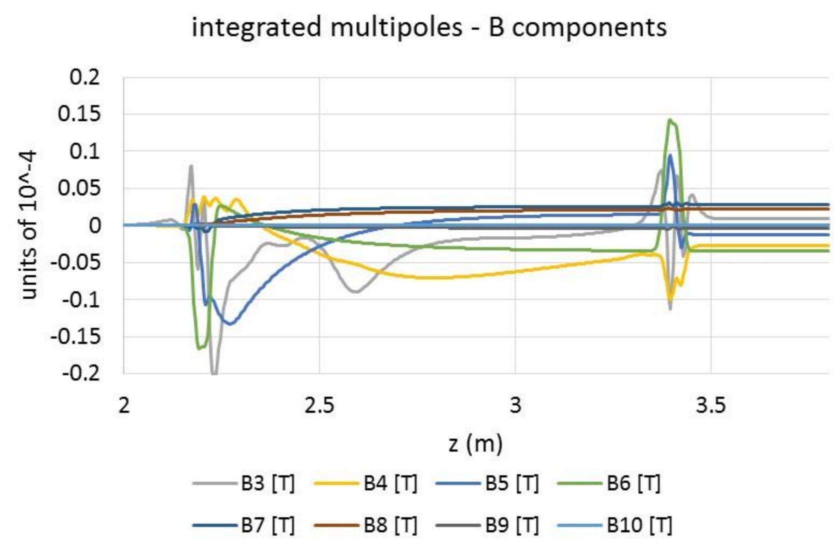
before





after





Magnitude of correction

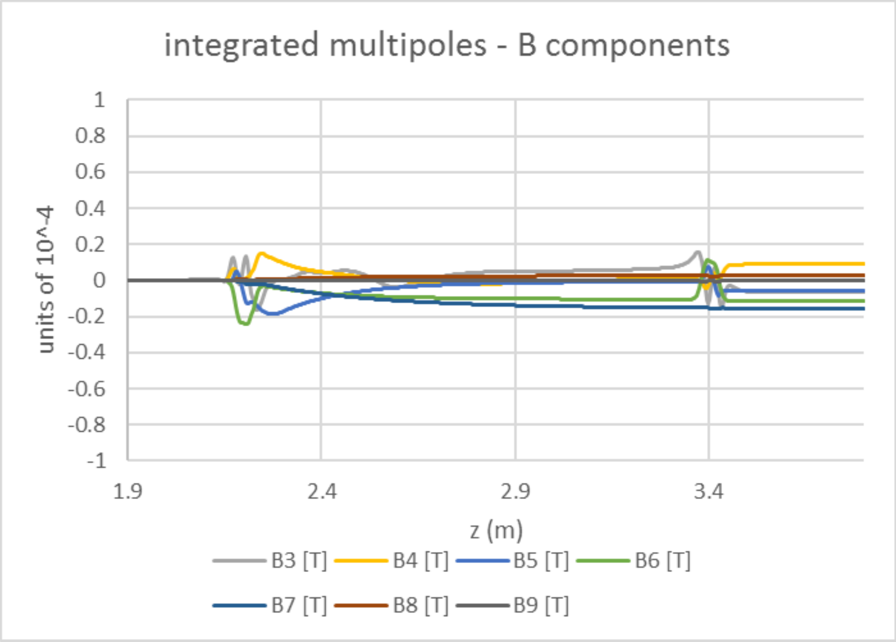
TABLE 2
SIZE OF CROSSTALK CORRECTION (IN DEGREES) ALONG THE LENGTH OF THE QUADRUPOLE. THE EDGES HAVE BEEN EXCLUDED FROM THIS TABLE. B2, THE MAIN COMPONENT, IS ALSO GIVEN FOR REFERENCE

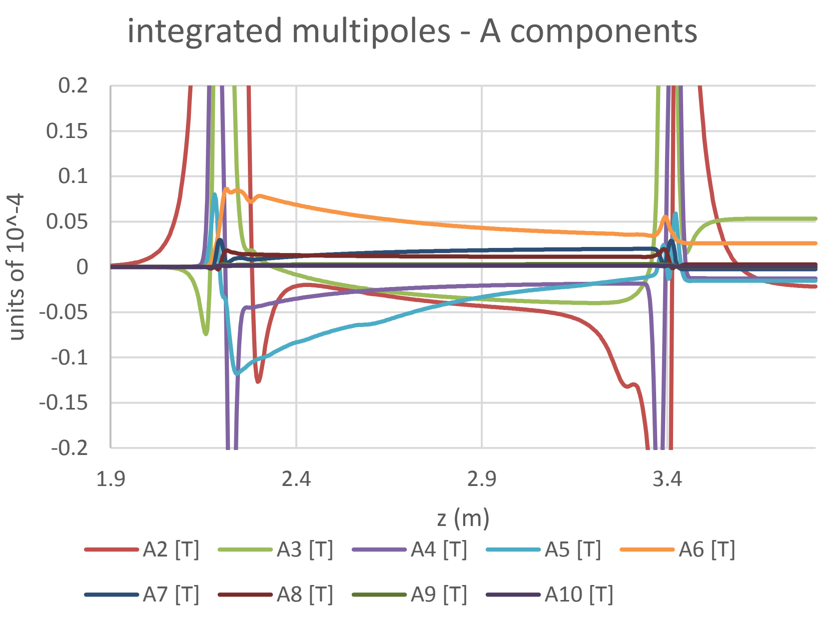
	A2	**A3**	**A4**	**A5**	**A6**	**B2**	**B3**	**B4**	**B5**	**B6**
α **max**	0	0	0	0	0	60	5.1	-4.0	2.0	-1.4
α **min**	0	0	0	0	0	60	0.8	-0.3	0.1	-0.0

Internal misalignment study

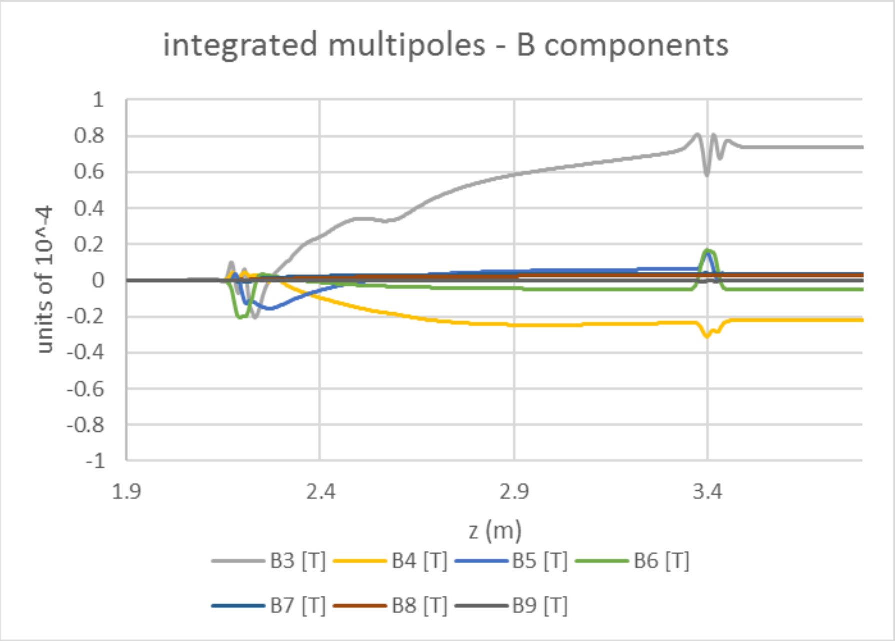
- I looked at the effect of misalignment to understand the mechanical tolerances we would need to follow during construction.
- QC1L1: has two objects of ~1m long, separated by ~10cm. A mechanical alignment of ~20um should be possible.
- To be able to see the effect clearly, I have introduced a misalignment of 100um both in x (globally, no tilt) and by 100um in y (ditto) in one of the two adjacent quads.

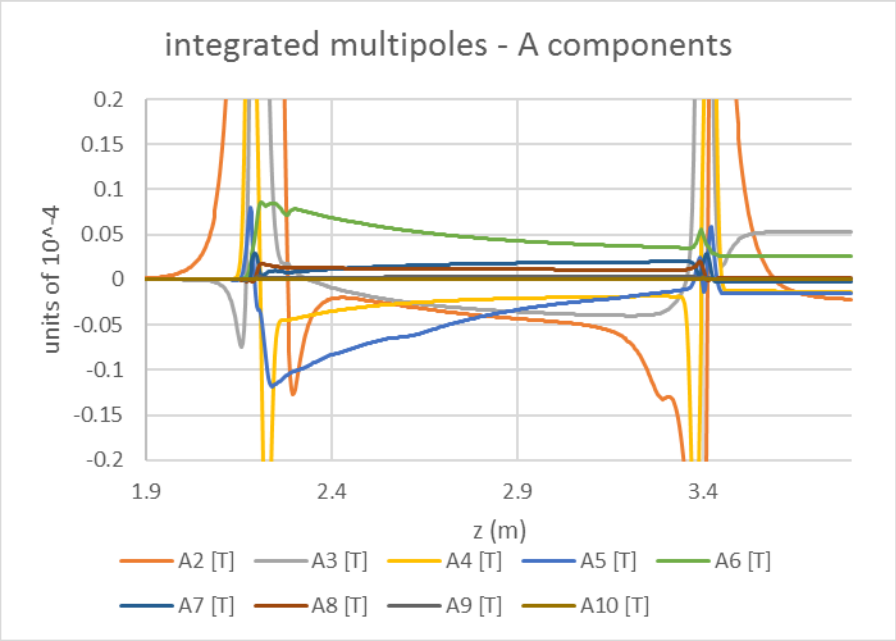
Perfect alignment



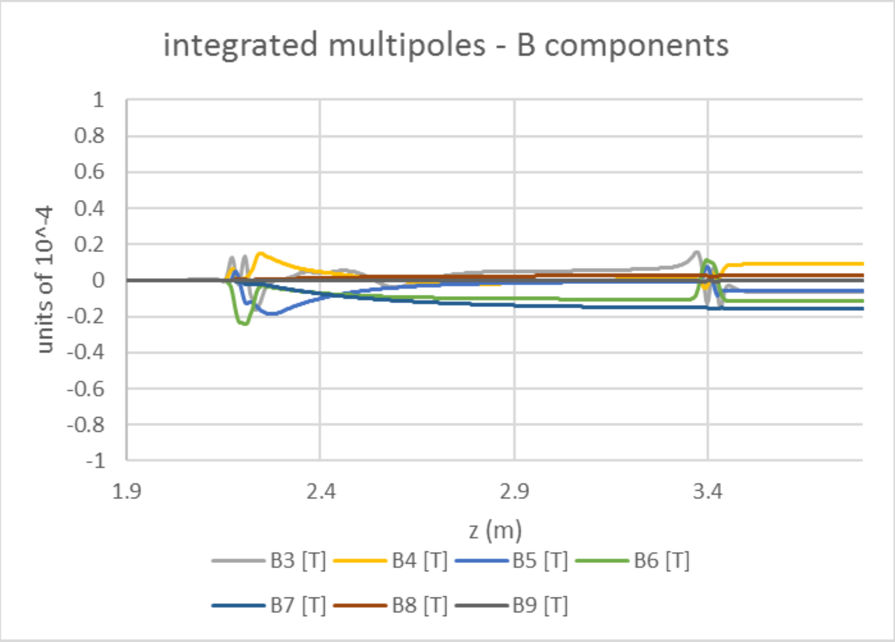


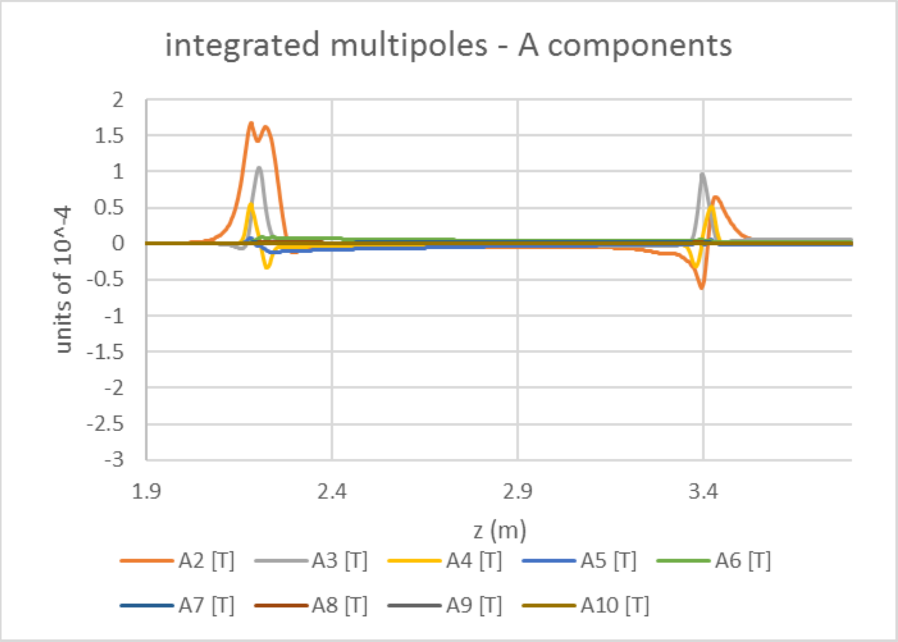
100um displacement in x



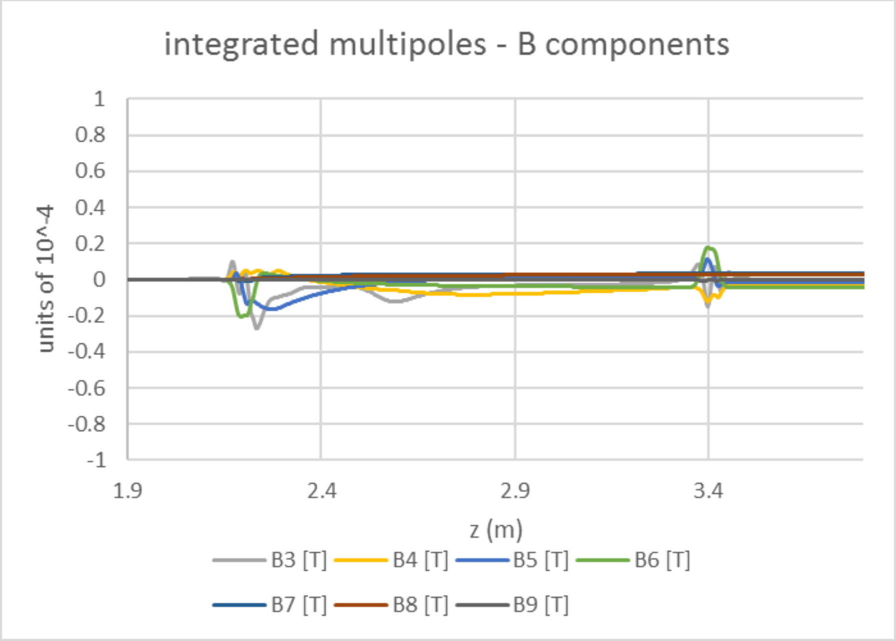


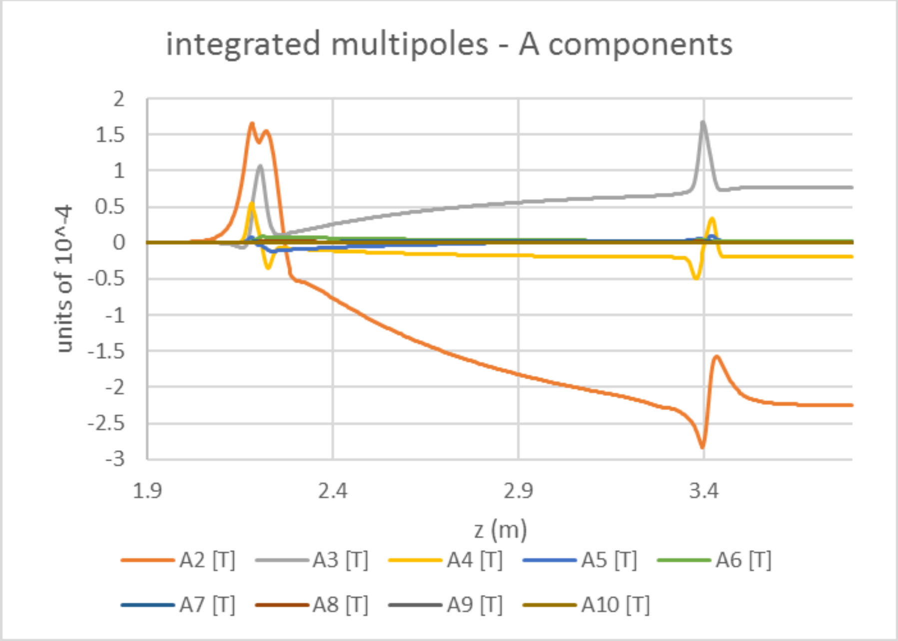
Perfect alignment





100um displacement in y





Summary of internal misalignment study

- Multipoles affected are B3 (for misalignment in x) and A2 and A3 (for misalignment in y)
- Any combination of misalignments is simply a superposition (linear system due to the absence of iron)
- To stay with multipole components less than one unit, alignment must be better than 30um

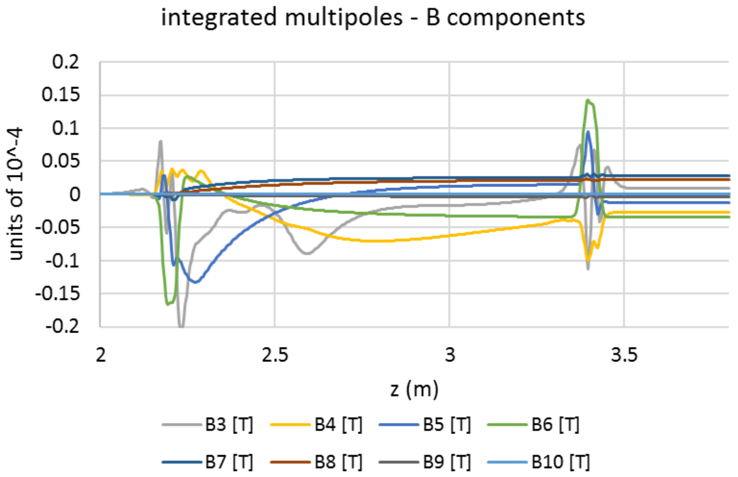
Beam-detector misalignment

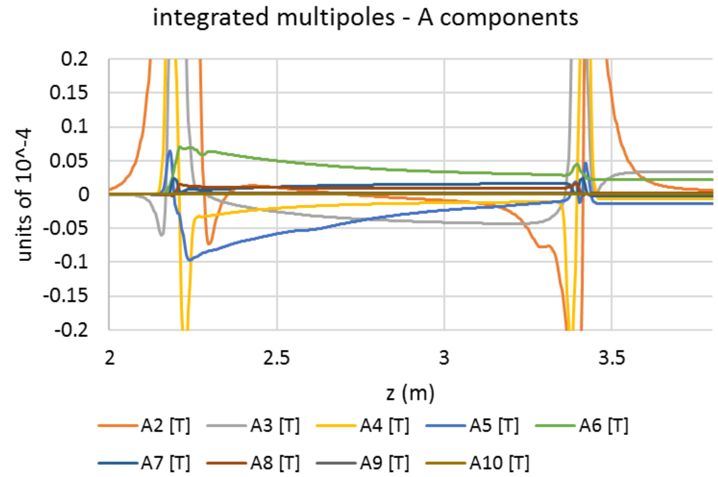
- The questions I will try and answer today have to do with the following:
  - What happens if the beam enters QC1L1 with an offset or at an angle?
  - Is there a significant B3 component that necessitates the use of a dedicated corrector?
  - Is there space to fit the necessary correctors close to QC1l1?

Beam offsets analysis

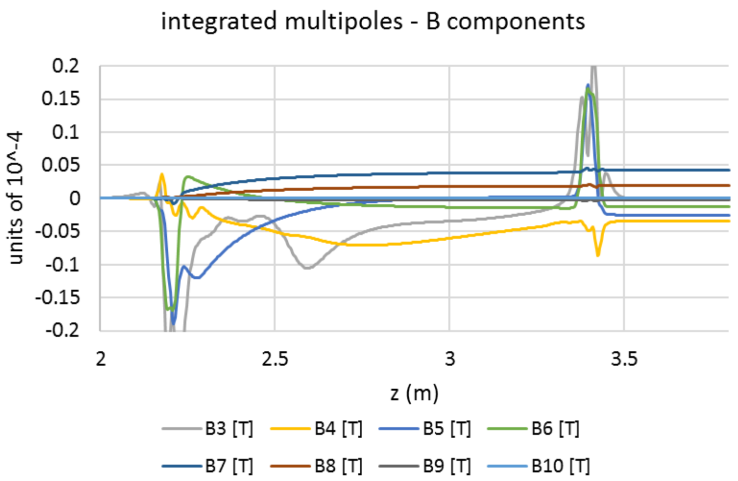
1. Move the beam 1mm in x
2. Move the beam 1mm in y
3. Tilt the beam 1mrad

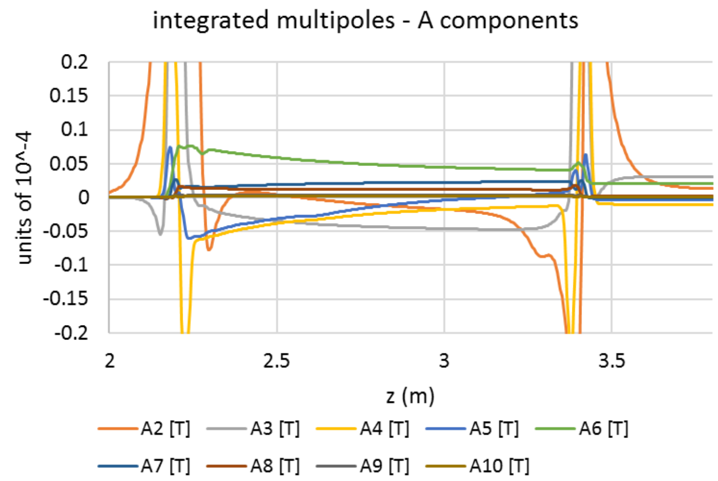
Perfect alignment





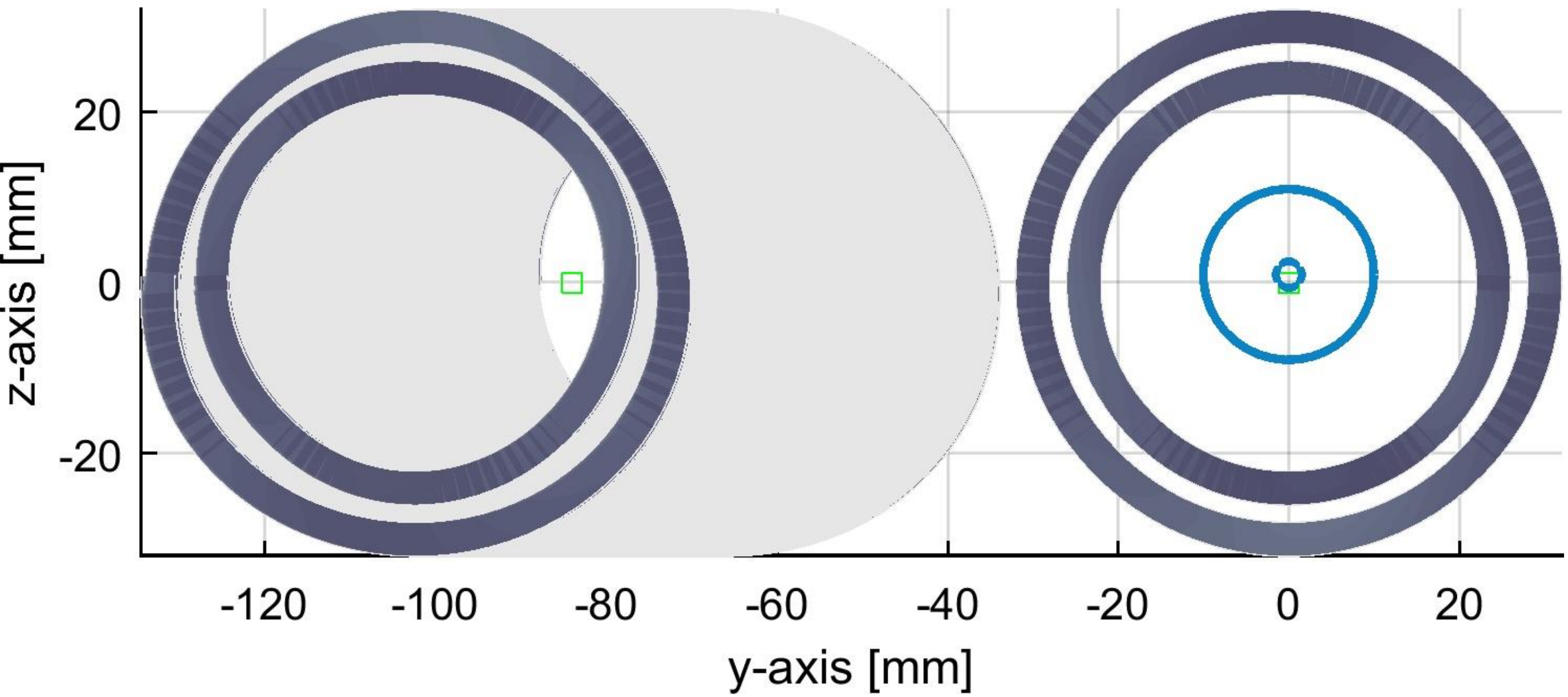
Beam offset by 1mm in x



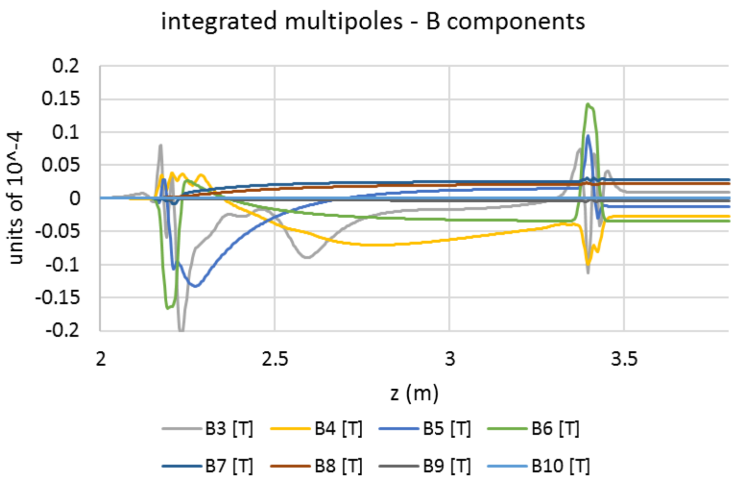


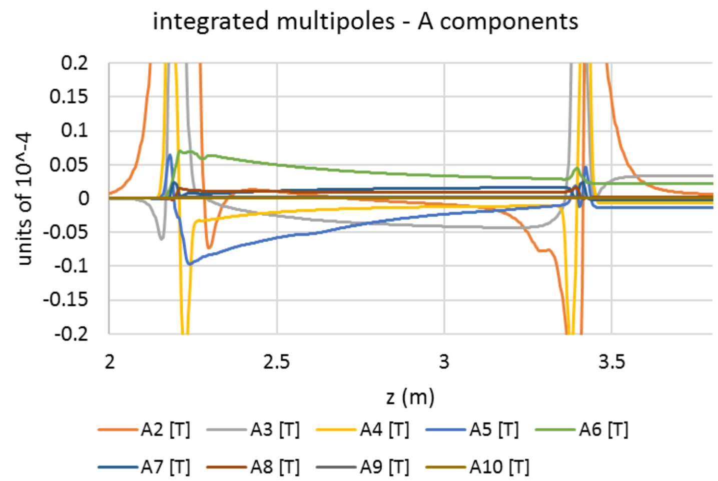
➔ Effect is negligible

Beam offset by 1mm in y

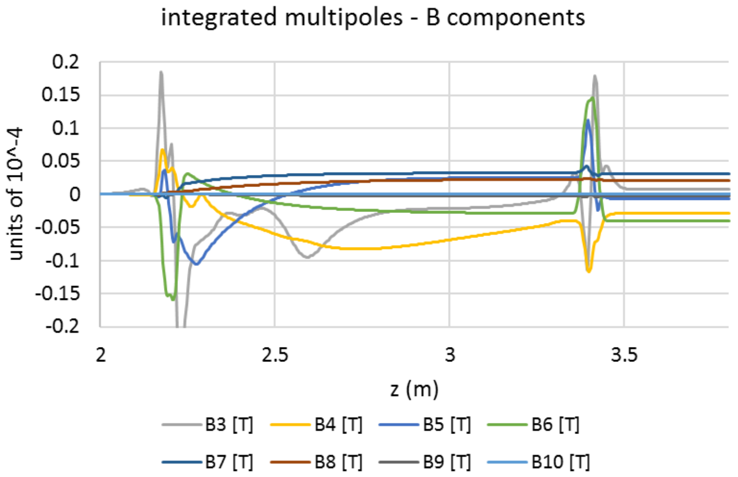


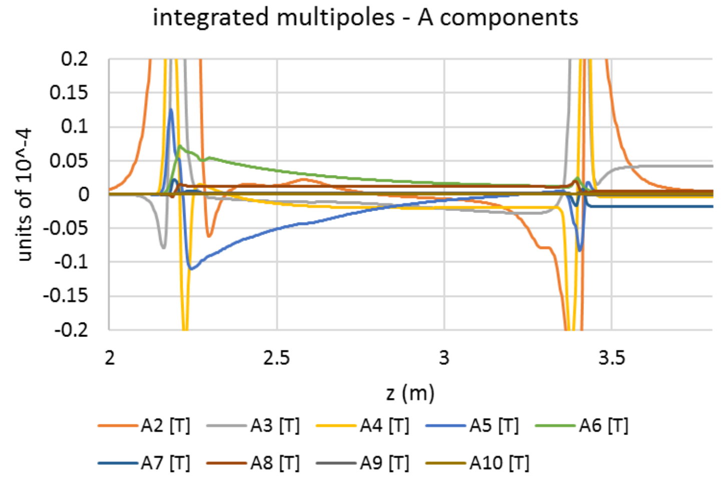
Perfect alignment





Beam offset by 1mm in y

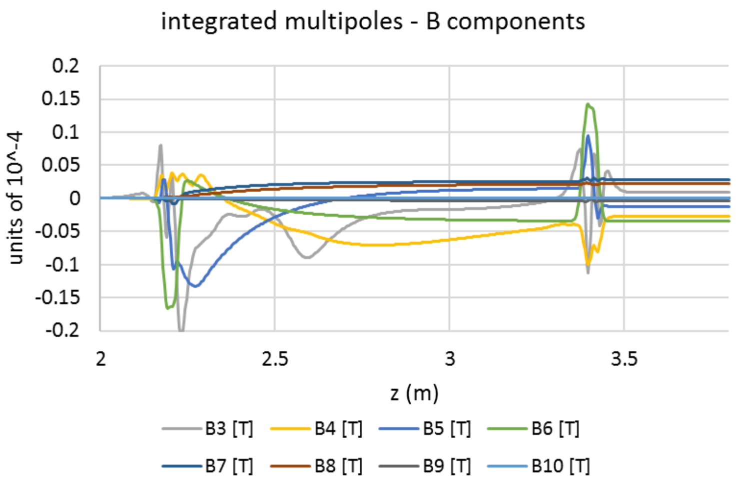


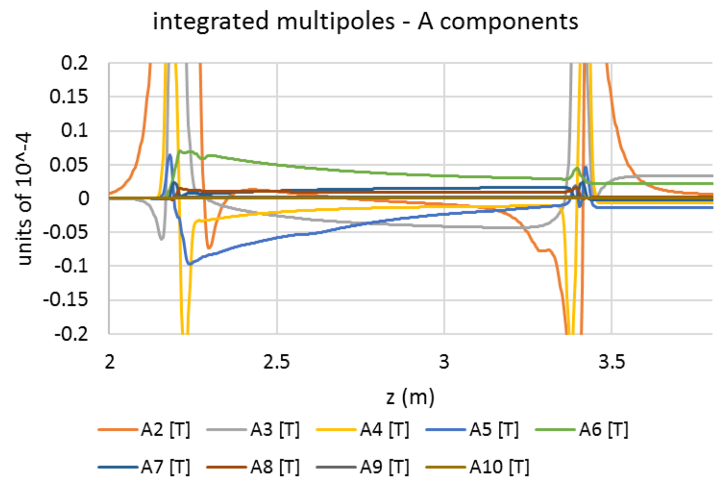


Beam tilt

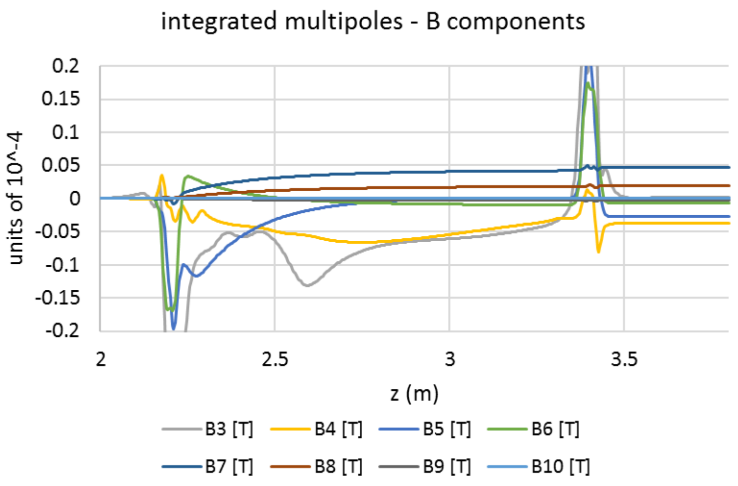
- Beam tilt by 0.5mrad in x
- Beam tilt by 0.5mrad in y

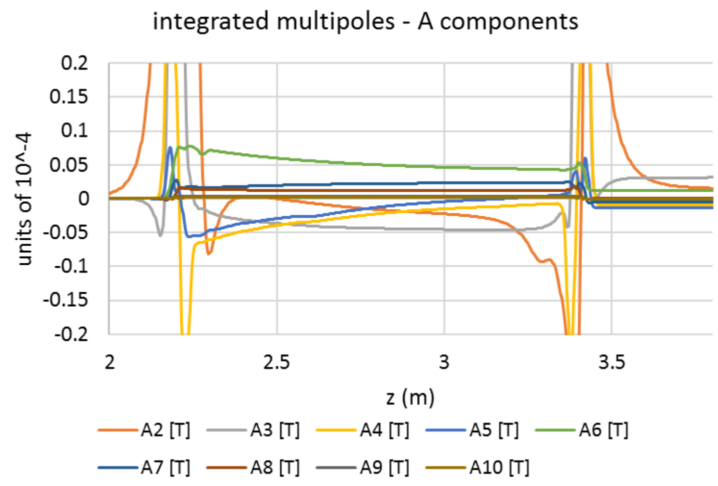
Perfect alignment



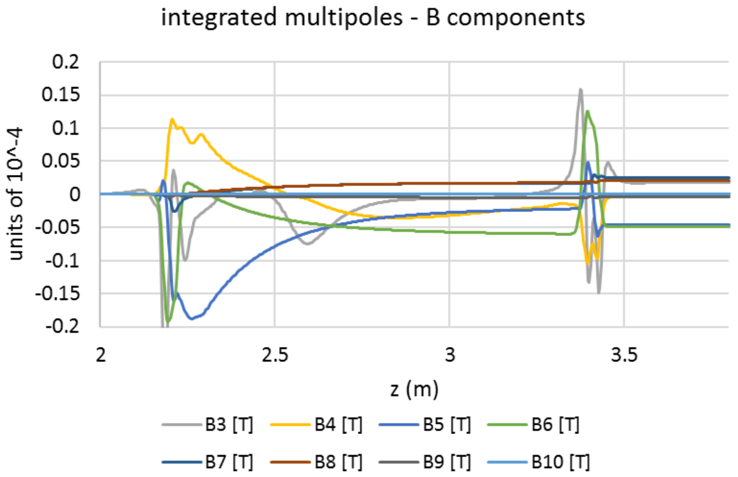


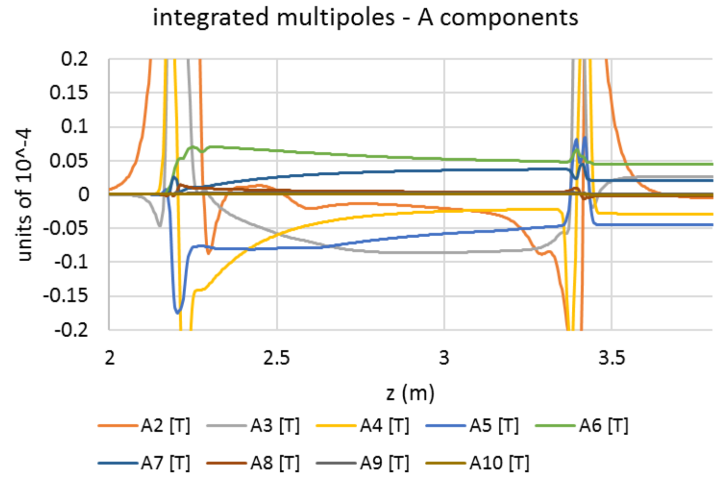
beam tilt of 0.5mrad in x





beam tilt of 0.5mrad in y





beam tilt of 0.5mrad in y

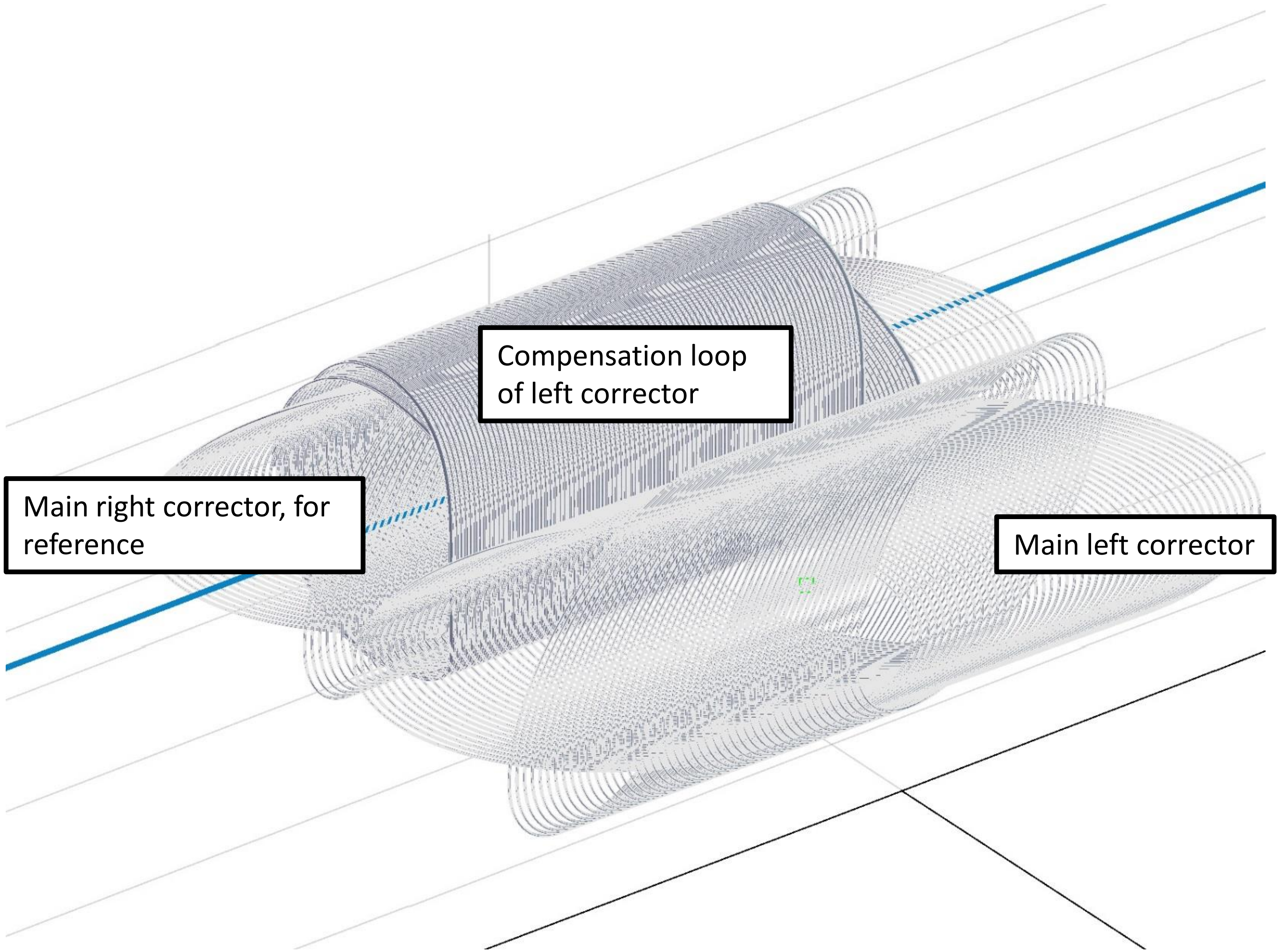
Conclusions on misalignment

- Internal misalignment should be better than 30um.
- Beam/detector misalignment of around 1mm has a negligible effect on field quality, due to the excellent field quality of the CCT design
- Ditto for 0.5mrad tilt
- The values of 1mm and 0.5mrad come from optics (Katsunobu) as expected typical values

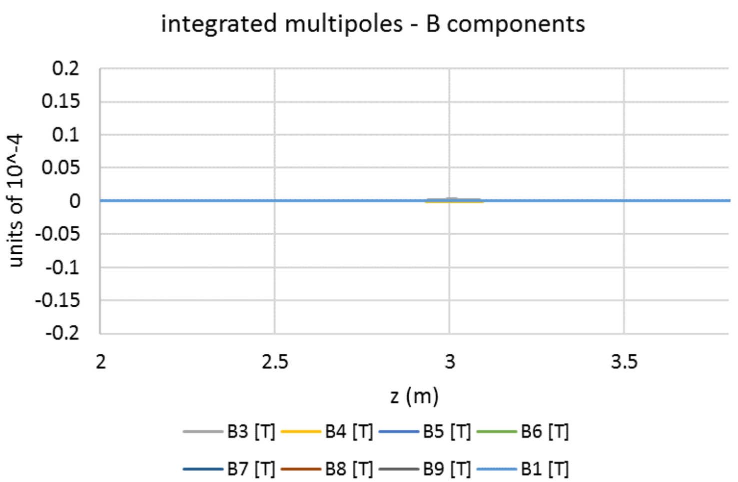
Embedded correctors

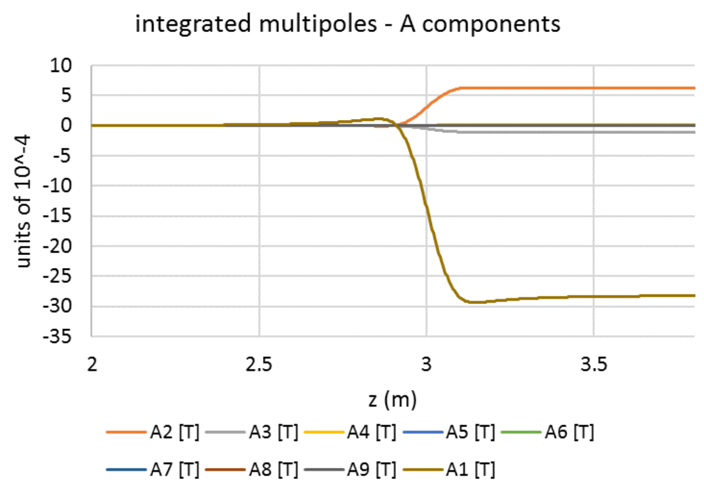
- The design can have embedded correctors (x and y dipole correctors, skew quadrupole correctors, etc.)
- Each corrector is very thin and comprises four extra rings that go in the outside of the main quadrupole
- For excellent performance, each corrector has its compensating coil on the other aperture (powered in series)

Example of dipole corrector

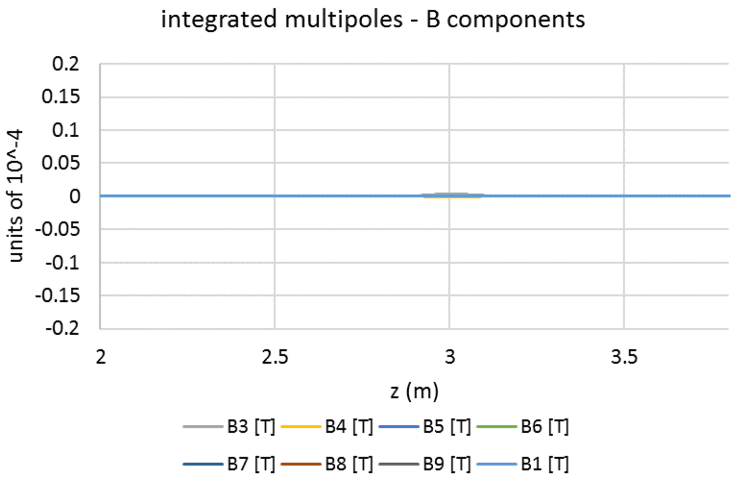


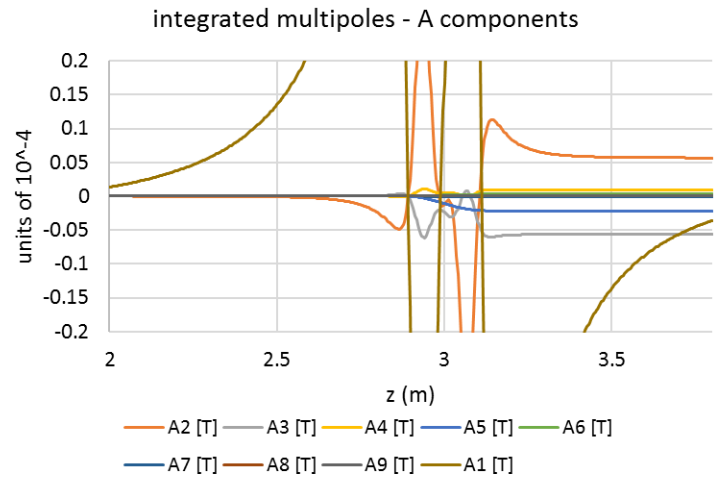
No compensation. Left x corrector ON (200A), effect on right beam pipe



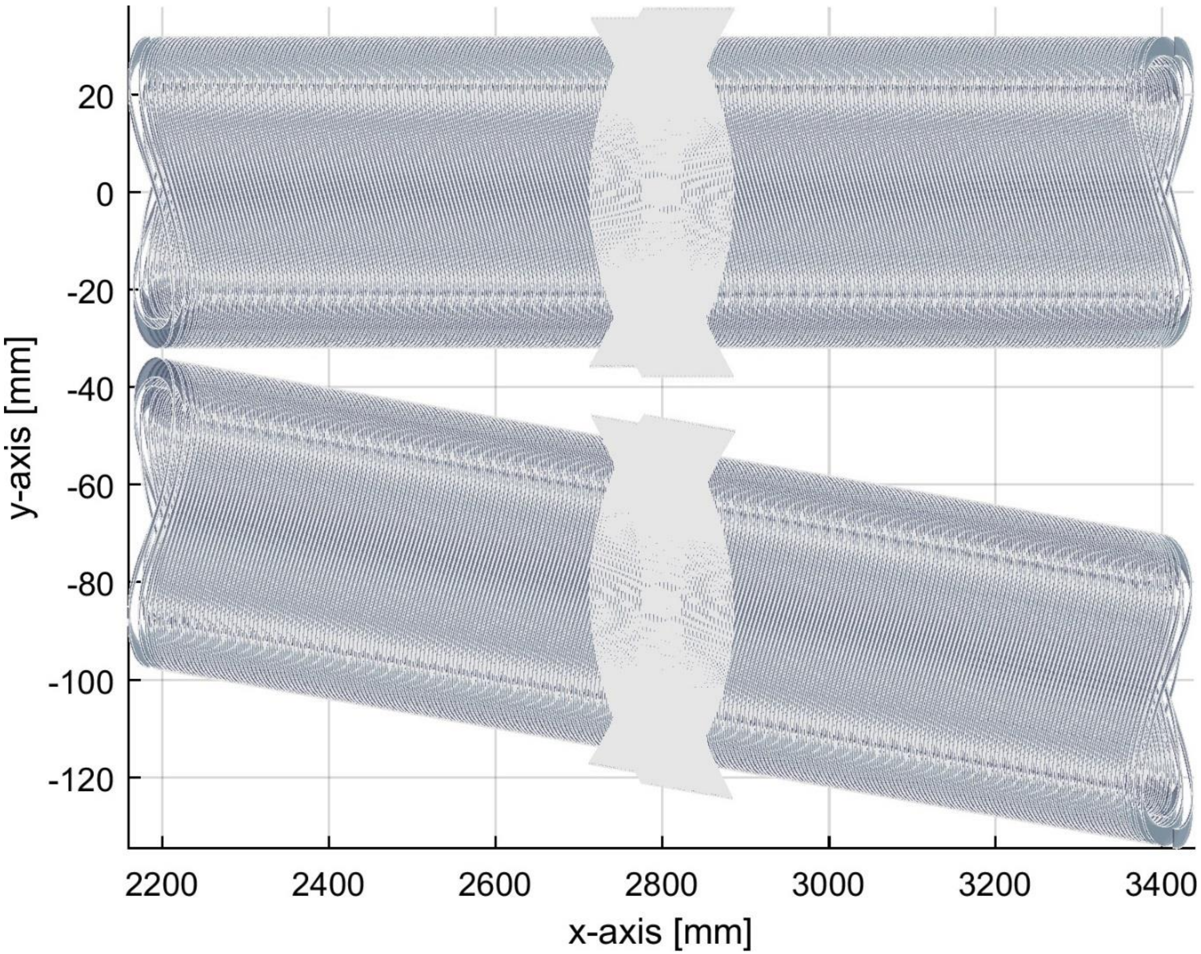


WITH compensation. Left x corrector ON (200A), effect on right beam pipe



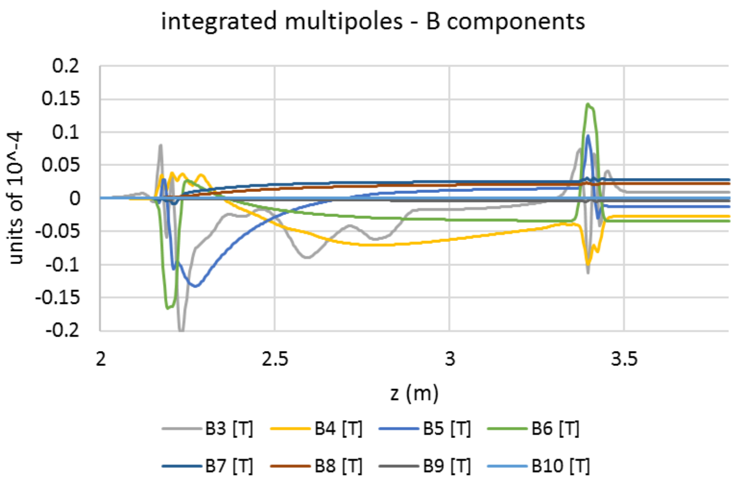


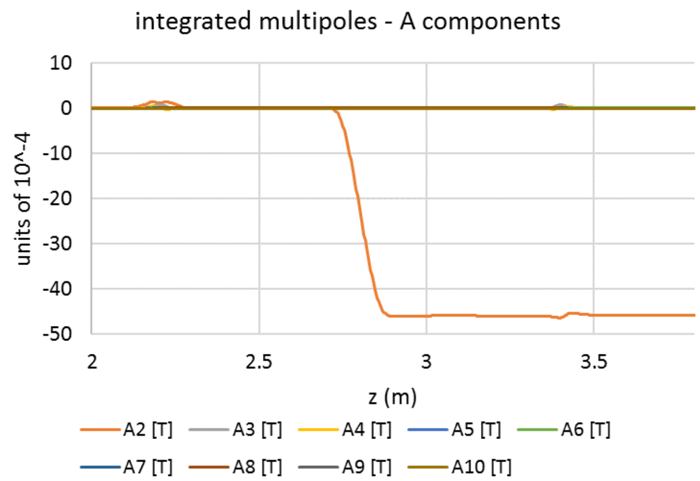
Study of skew quadrupole corrector



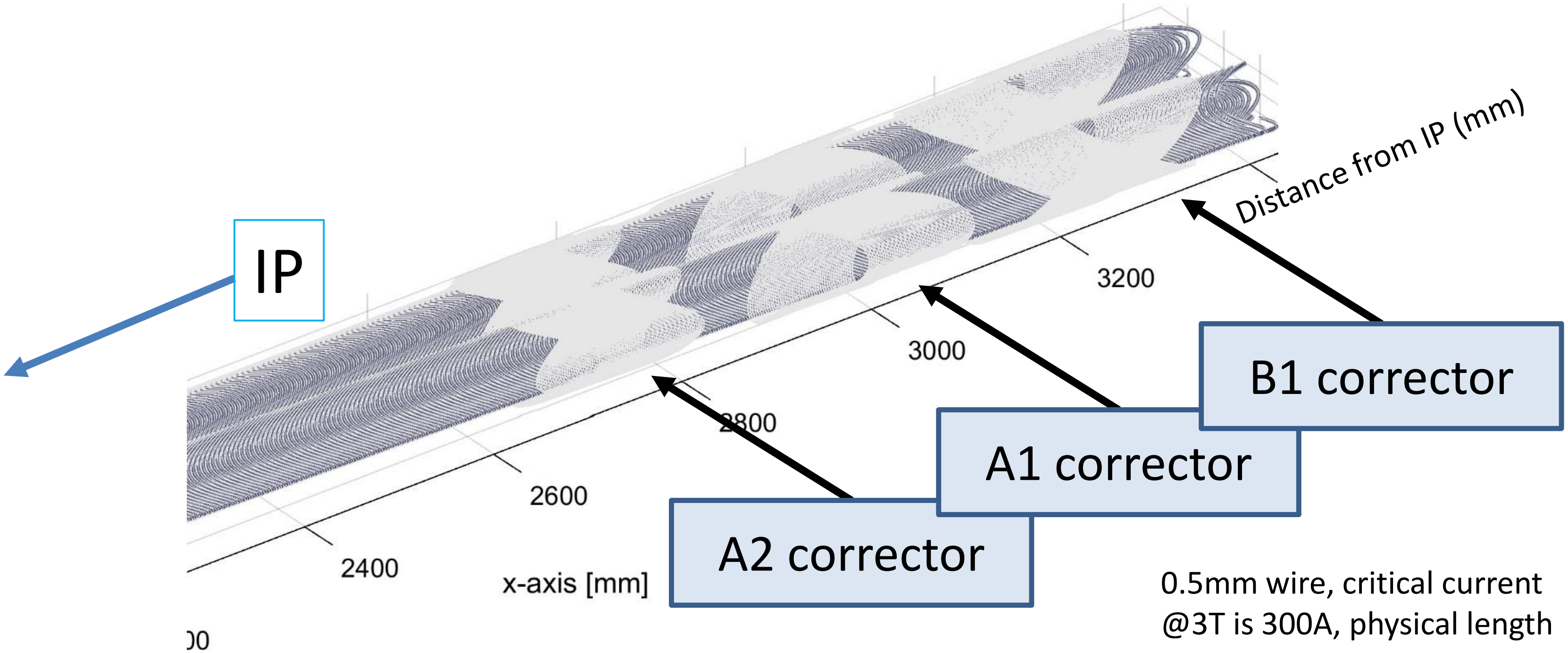
- Physical length ~20cm,
- 0.5mm cable,
- 200A (critical current for this cable @3T is 300A)
- gives ~40 units of correction

Corrector ON





All QC1L1 correctors – A1, B1 and A2



0.5mm wire, critical current @3T is 300A, physical length ~20cm

There is enough space for even five correctors, with no loss of packing factor

Effect of correctors

- Three correctors installed with single wire, 0.5mm, about 20cm long, current 200A (critical current @3K is 300A).
- Strength of correctors:
  - A1 25mT.m (210 units)
  - B1 17mT.m (145 units)
  - A2 35 units

Conclusions on correctrors

- No need for a dedicated B3 corrector, at least not due to field quality at the vicinity of the IP
- The design can incorporate A1, B1, A2 correctors superimposed on QC1L1 with room to spare.
- The design is very compact

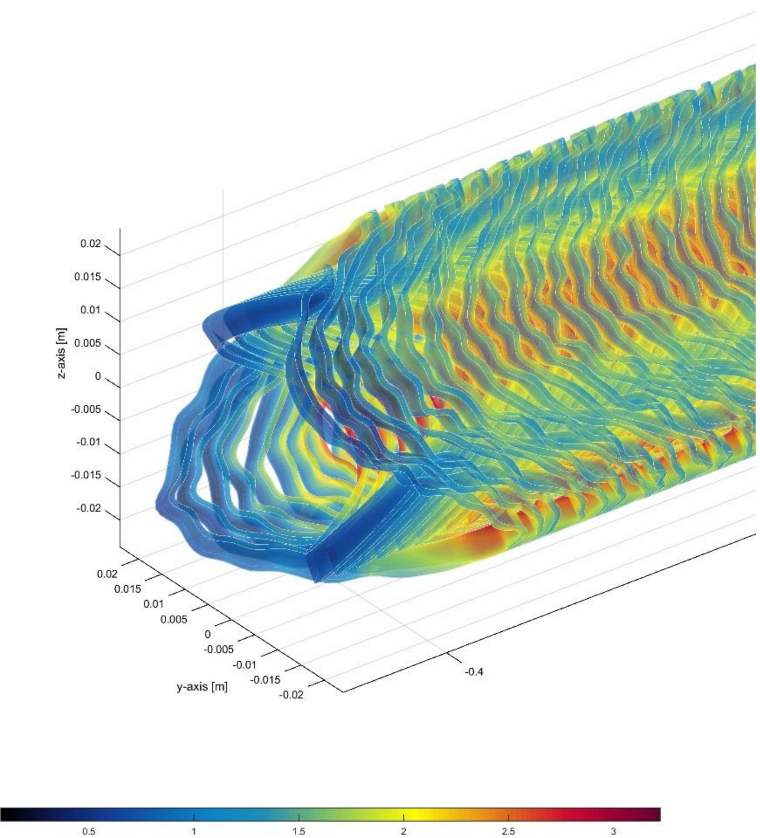
Next steps

- Finish the alignment error study - introduce imperfections in the design and test their effect on multipole components (this was done two years ago, will be repeated)
- Build a prototype!

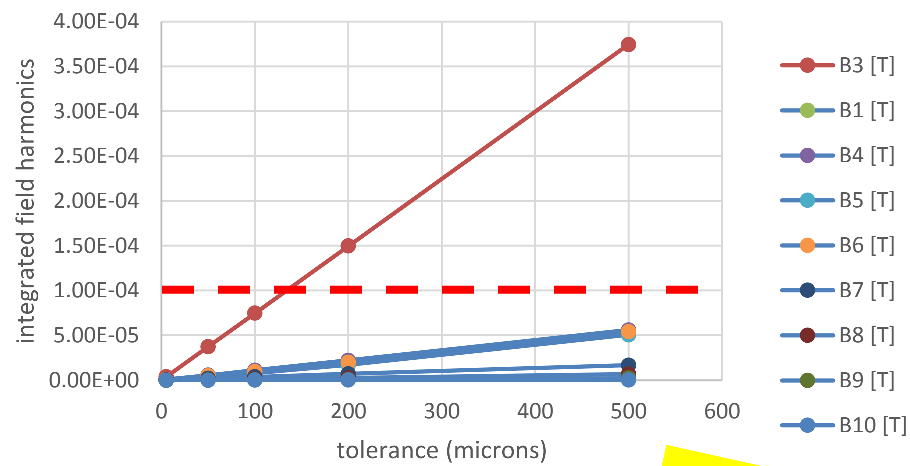
Imperfect coil study – old analysis

- This analysis still to be done – first results show that winding errors need to be larger than 100 µm to have an effect (16cm long quad)

exaggerated winding errors

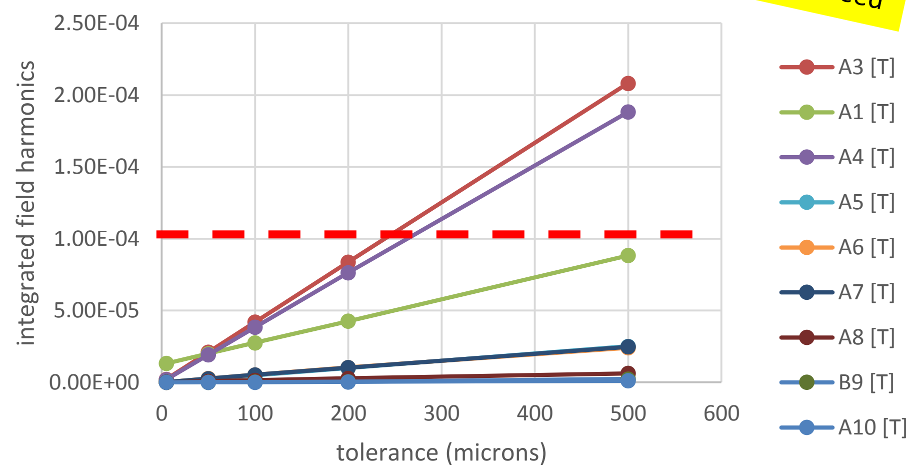


B components



only a single seed

A components



Winding errors – old analysis

Using a 16cm-long quadrupole

- Going through (only) 10 seeds and with a winding error in r of 200μm and a winding error in z of 200 μm (10 points per turn), the maximum field errors were as follows:

B1 [T]	B2 [T]	B3 [T]	B4 [T]	B5 [T]	B6 [T]	B7 [T]	B8 [T]	B9 [T]	B10 [T]
1.75E-04	---	1.11E-04	5.83E-05	1.90E-05	1.69E-05	1.14E-05	3.02E-06	1.66E-07	3.80E-07
A1 [T]	A2 [T]	A3 [T]	A4 [T]	A5 [T]	A6 [T]	A7 [T]	A8 [T]	A9 [T]	A10 [T]
1.10E-03	1.22E-04	5.84E-04	9.39E-05	7.13E-05	1.42E-05	1.78E-05	2.98E-06	3.84E-06	2.22E-07

Components B1, B3, A1, A2, A3 are above our limit of 1E-4 but real quad is 10 to 20 times bigger – errors will average out. But I need a bigger computer for this work

Thank you