High-Precision Magnetic Field Measurement and Mapping of the LEReC 180˚ Bending Magnet Using Very Low Field NMR Probe [140-400 Gauss]

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IMMW21
International Magnetic Measurement Workshop
24th – 28th June 2019

ESRF
The European Synchrotron

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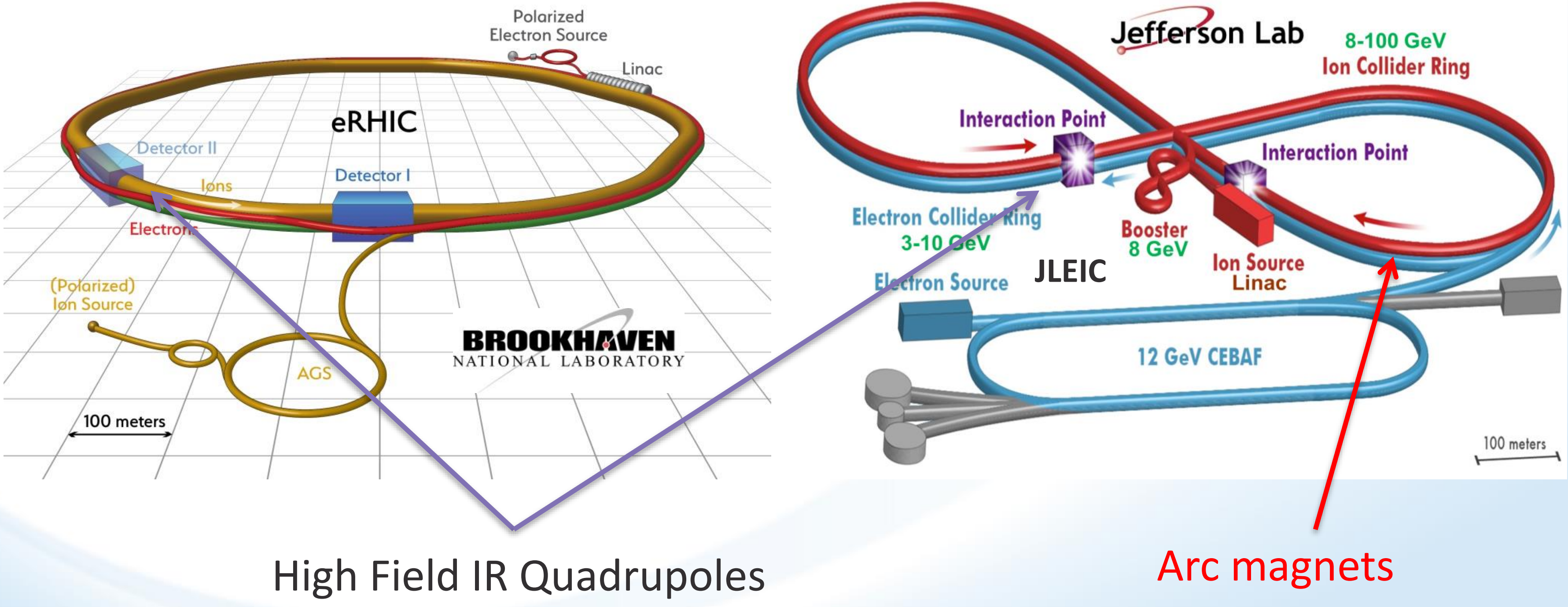
U.S. DEPARTMENT OF ENERGY

Outlines

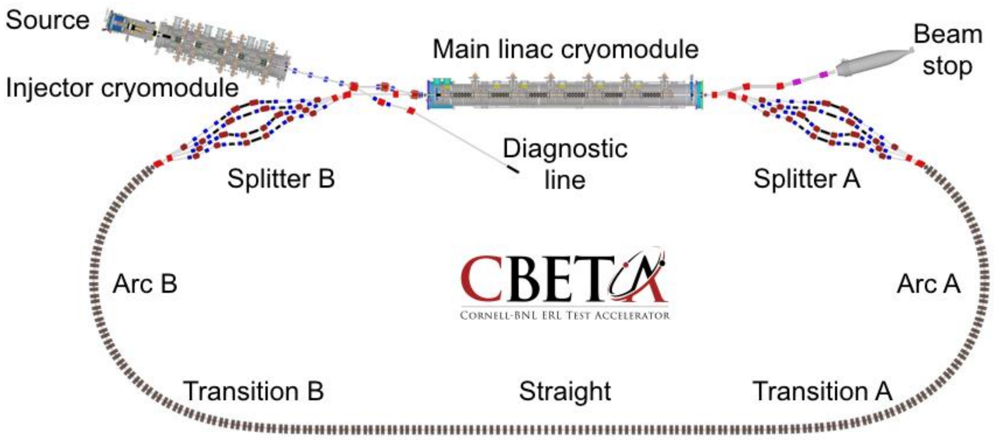
- Introduction: Measurement specs
- Preps:
  - Hysteresis loop
  - Plan
  - Repeatability test at center points
  - Measurement along center-center lines
  - Single radius at various currents
- Measurement at 5 heights and 5 radii
  - Three currents
  - Compared with simulated results
- Summary

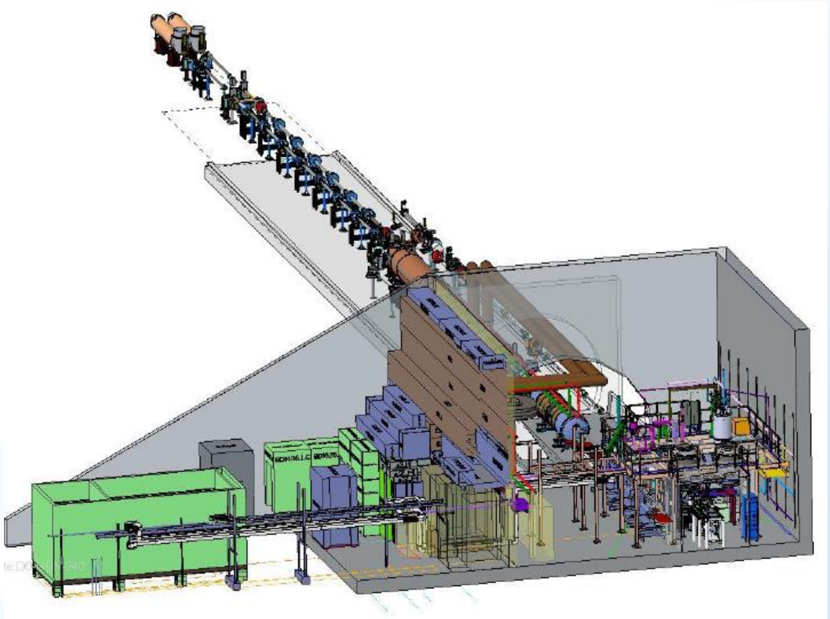
Electron Ion Collider



Multiple strategic R&D projects for eRHIC at BNL

The first ever electron cooling based on the RF acceleration of electron beams was experimentally demonstrated on April 5, 2019 at Low Energy RHIC Electron Cooler (LEReC) at BNL.



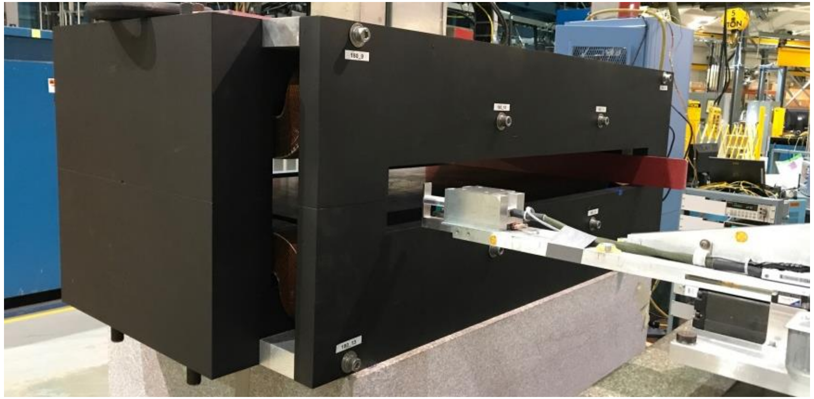


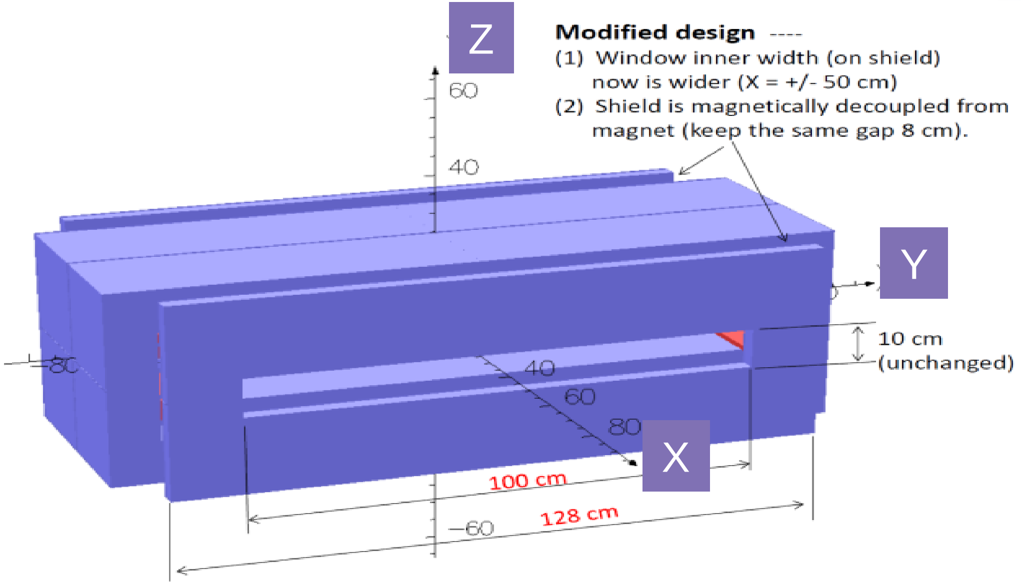
The Cornell-BNL Test accelerator has achieved Energy Recovery for the fist time on June 24th, 2019

Introduction

- The first critical step in obtaining successful 3D non-magnetized cooling of the Au ion bunches in the RHIC cooling section was matching the electron beam energy with a relative error less than 5e-4 to the ion beam energy.
- Since electron beam kinetic energy is just 1.6 MeV, measuring the absolute e-beam energy with required accuracy and eventually achieving the electron-ion energy matching was a nontrivial task.
- One of the key components is the 180 degree bend dipole which steers the electron beams from the “Yellow” to the “Blue” RHIC rings.
- **Precise knowledge of the magnetic field is critical and 10^{-4} accuracy in the integral field is required**.

Magnet overview, requirement, coordinate system

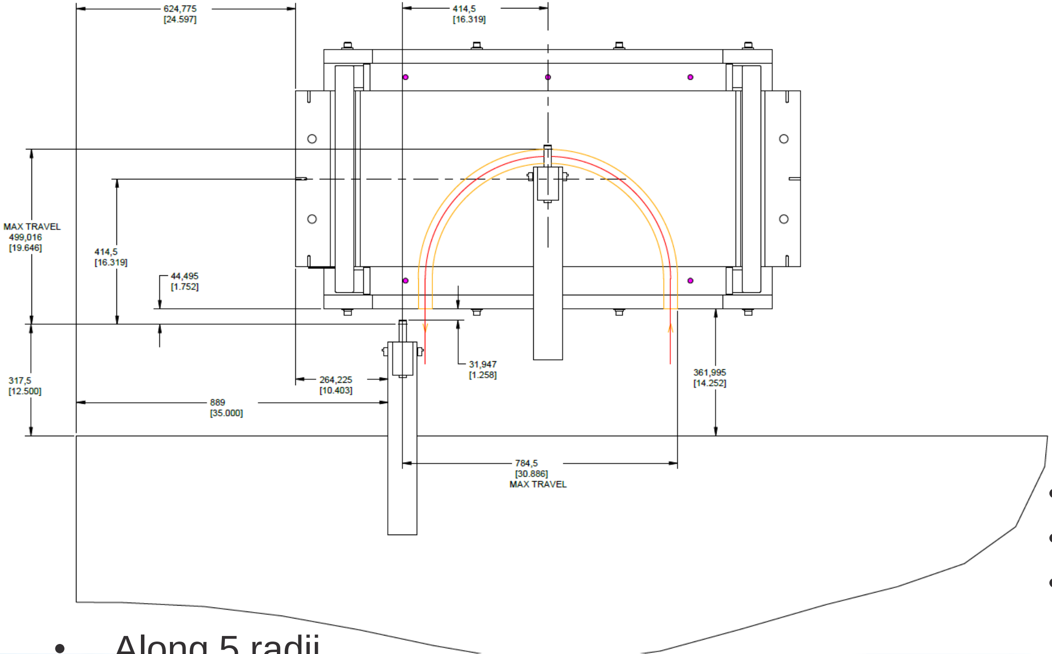




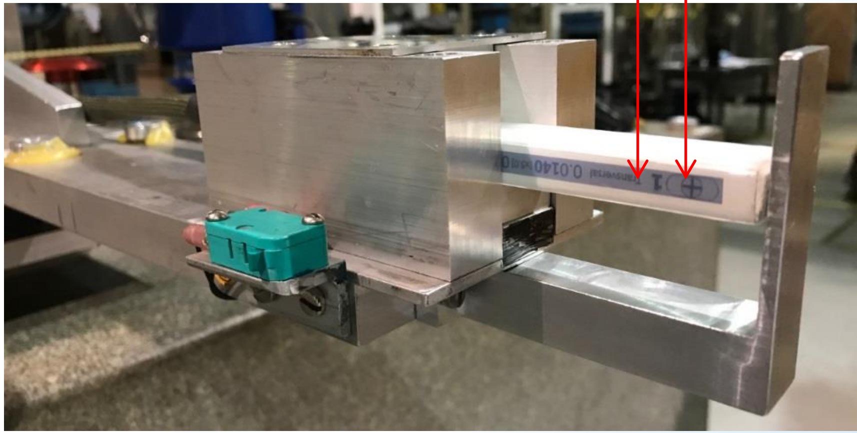
Field Strength Range	180 – 325 gauss
Measurement resolution	< 0.01 % (18.0 milligauss)
Absolute Accuracy	50 milligauss
Signal to noise ratio	< 20milligauss @ 180 gauss with a ~0.1 Hz measurement rate
Remotely located electronics	100 m ± 20%

Coordinate system for magnetic measurement and scanning

Measurement Plan, Hall/NMR Probe w Fixture



Hall NMR



- About 15 mm apart
- NMR height can be adjusted 10 mm/step
- Field at 5 heights to be measured, Z=0 mm, ±10 mm, ± 20mm,

- Along 5 radii
- Nominal R = 350 mm, R = 350 mm ±10mm, R = 350 ±20mm

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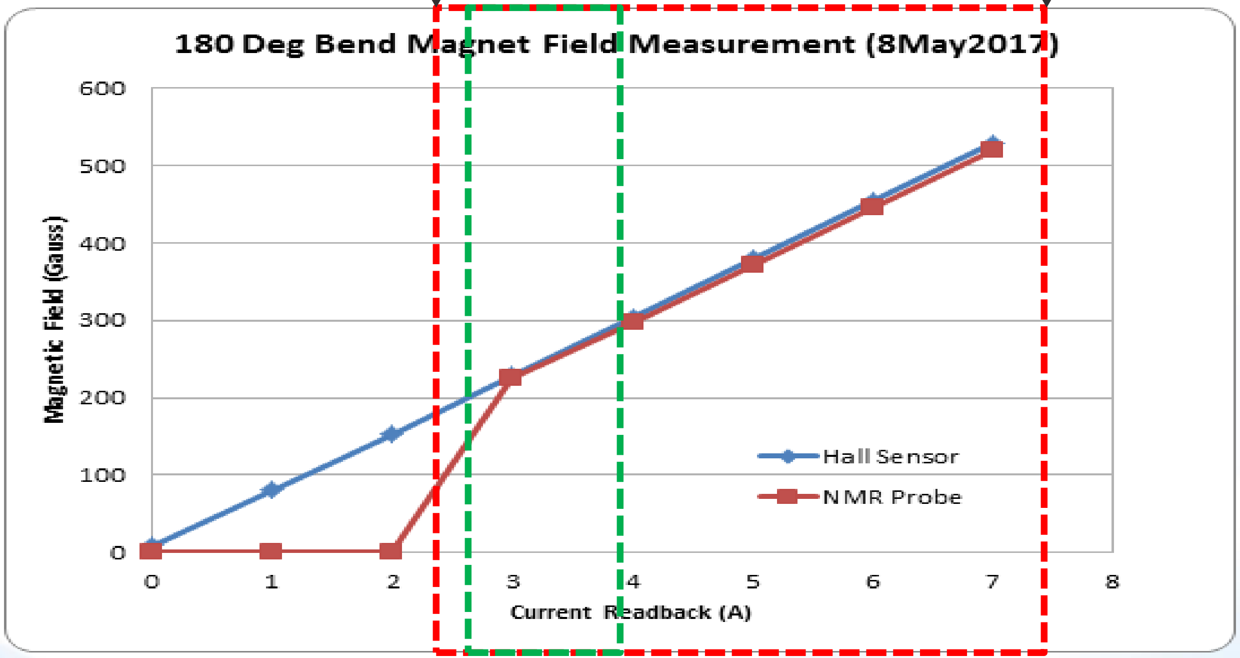
NMR probe test, low field – homogeneous field

2.25A, 146 Gauss

7.5 A, 561 Gauss



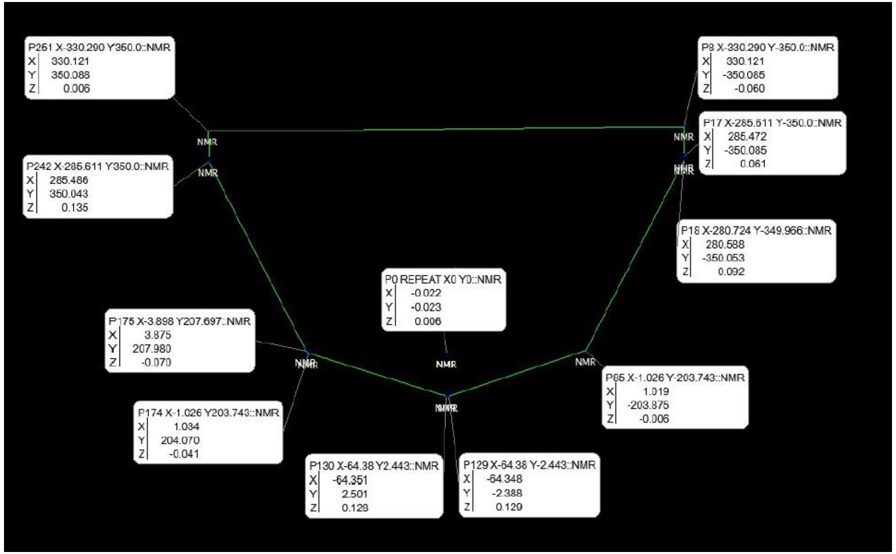
Measurements should be done at the field of
By=140 Gauss to **300 Gauss** (2.6 MeV operation).

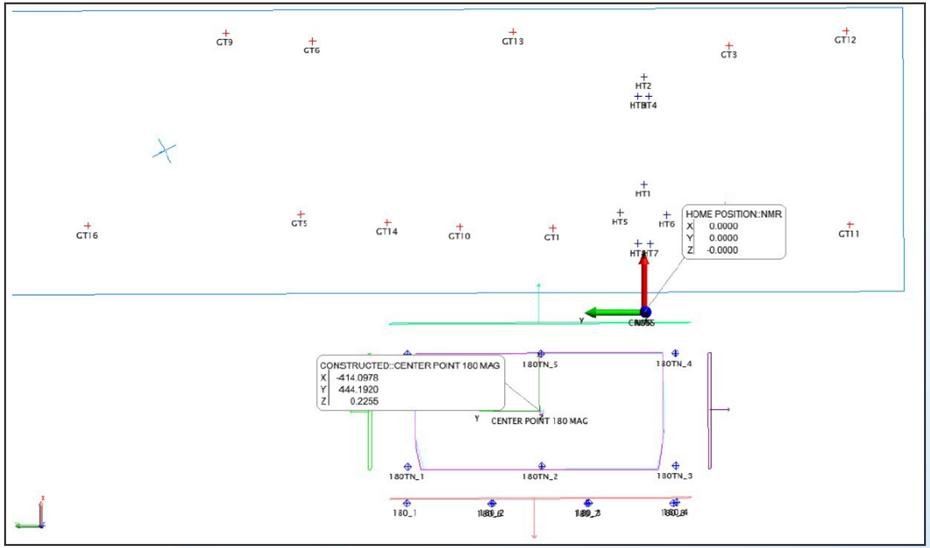
Challenges in the NMR locking and timing

- NMR Locking at low field is considerably challenging
  - Solutions, turn off the motor when starting to achieve NMR locking
- Motion drive:
  - X-axis direction is screw driven, and the Y-axis direction is belt drive though with linear encoder
  - Wait for ~10 seconds in total to achieve short-time equilibrium (ideally would maybe 20 seconds)
  - Even 10 seconds, overall each NMR runs takes 8-9 hours.

Survey

Point Group 180 DIPOLE REF (copy)::CONSTRUCTED			
Point Name	X (mm)	Y (mm)	Z (mm)
CENTER POINT 180 MAG	-414.0978	444.1920	0.2255

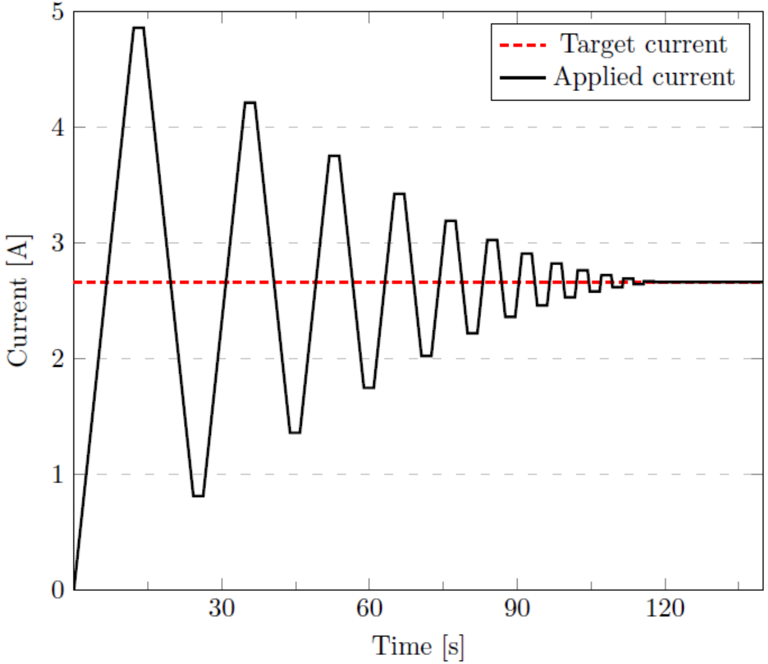


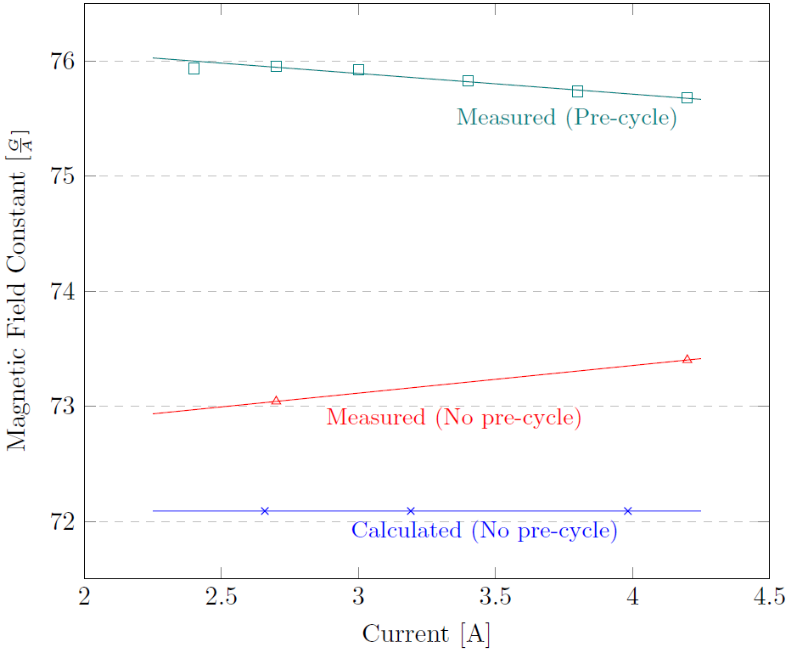


In-plane Z flatness <0.135 mm

Distance between NMR home and magnet center is
ΔX = -414.098 mm, ΔY = -444.192 mm

Hysteresis loop optimization – python program



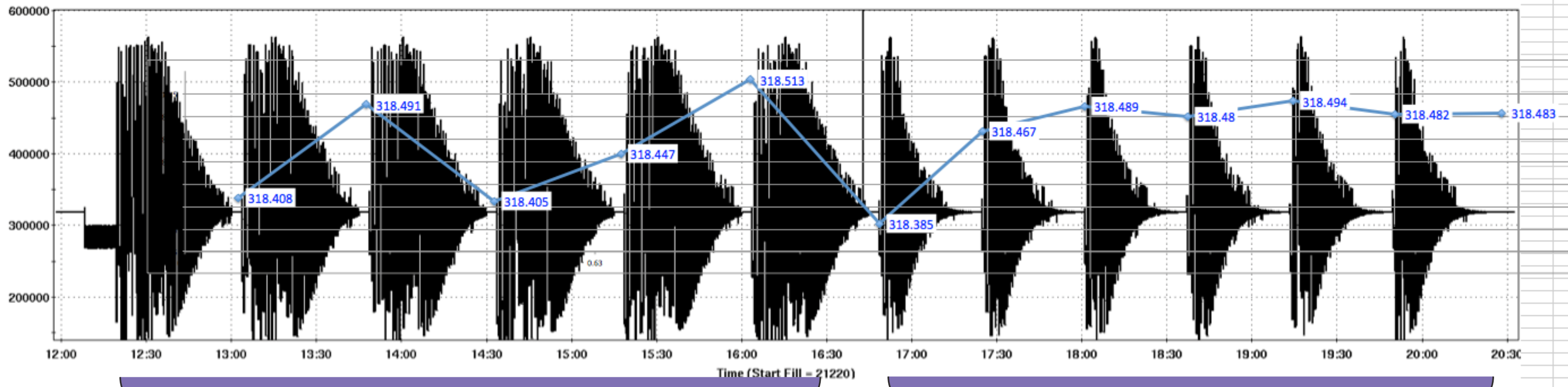


$$i_n = I\left(1 - (-1)^n[e^{-cn} - k]\right), n = 1, \ldots M,$$

$$t_n = \frac{|i_n - i_{n-1}|}{dI/dt}, n = 1, \ldots M,$$

With pre-cycle, repeatable

Repeatability test



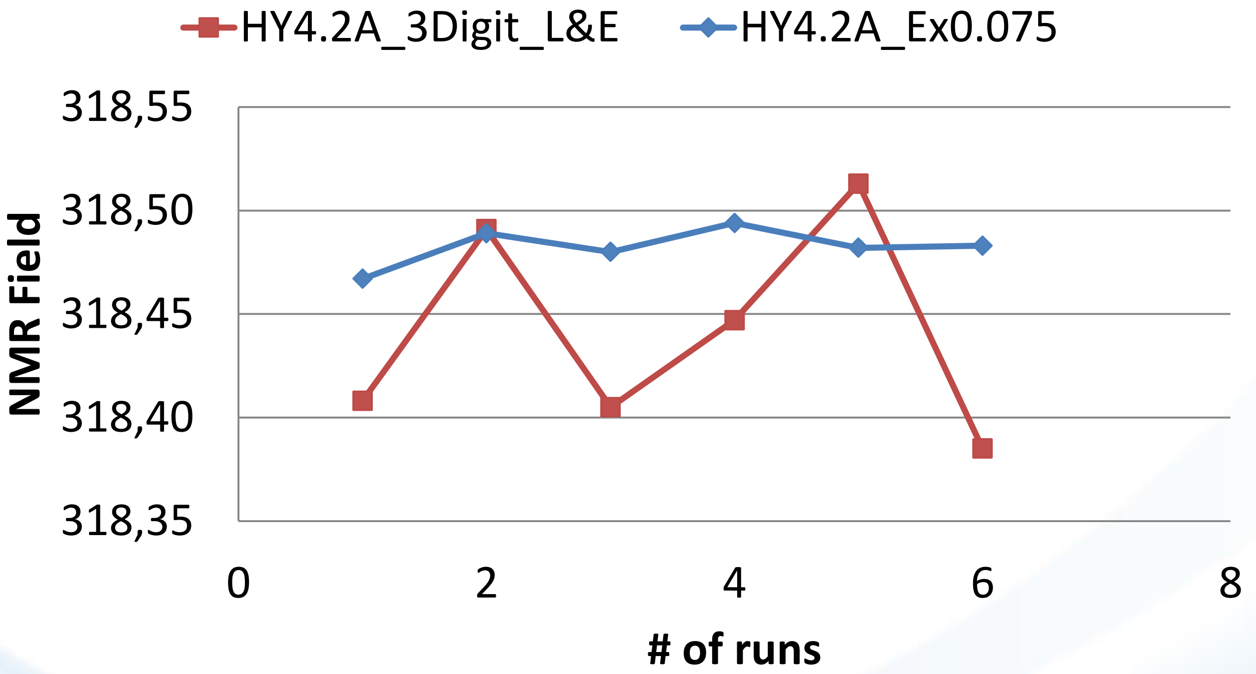
Hybrid_4.2A

1)	13:01:55	318.408
2)	13:46:54	318.491
3)	14:31:48	318.405
4)	15:16:11	318.447
5)	16:01:45	318.513
6)	16:46:58	318.385

Exponential Ex0.075

1)	17:23:03	318.467
2)	17:58:58	318.489
3)	18:35:12	318.480
4)	19:12:10	318.494
5)	19:48:08	318.482
6)	20:25:29	318.483

Exponential demagnetization is better
All the data taken in the following w Exp0.075

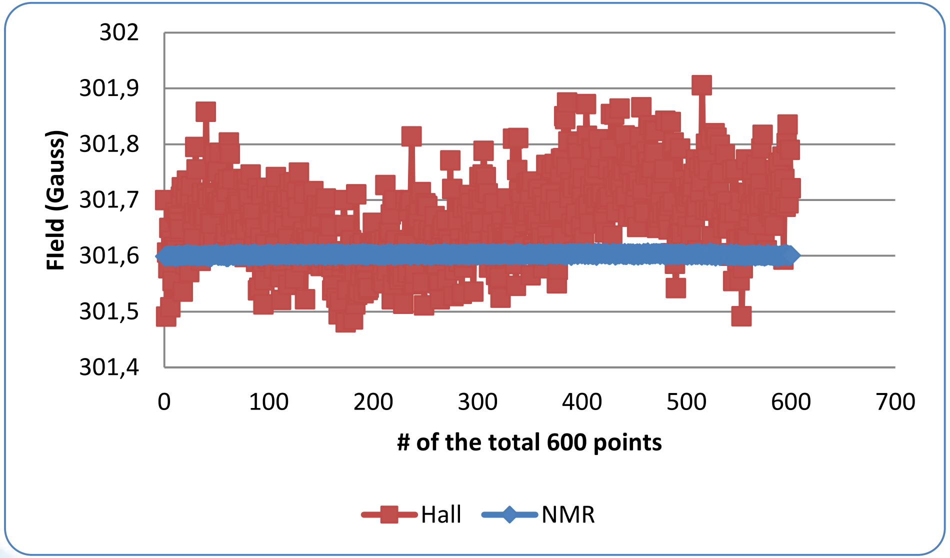


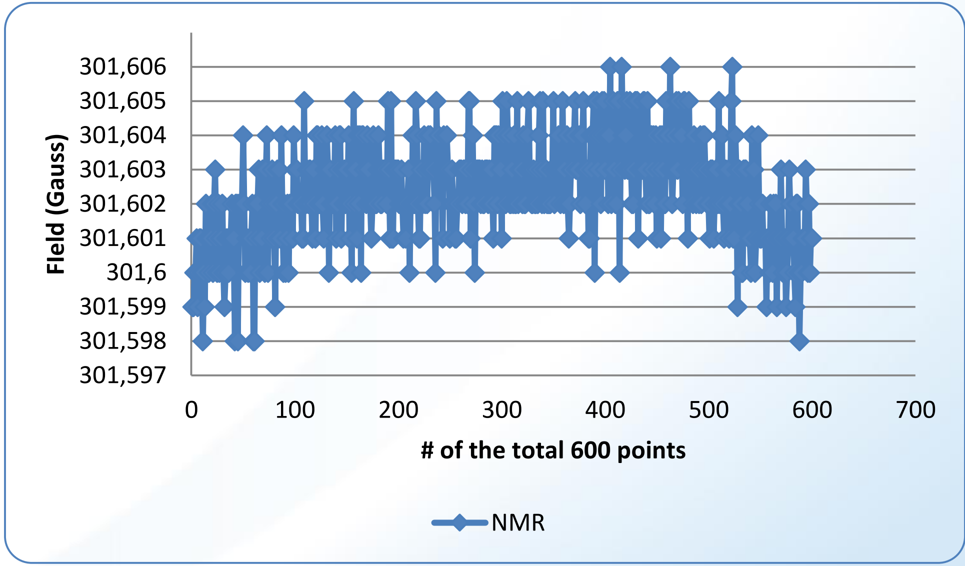
max ΔB of 27 milligauss.

max ΔB of 128 milligauss.

Precision Check at Magnet Center Point

NMR and Hall Repeatability Test at Magnet Center (0,0), at 301 Gauss with current 3.98A and over 12 hours

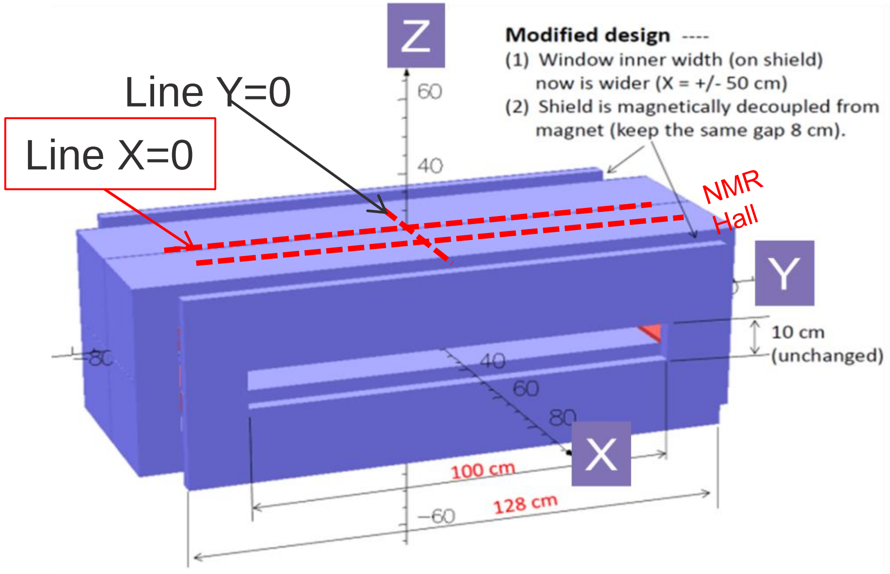


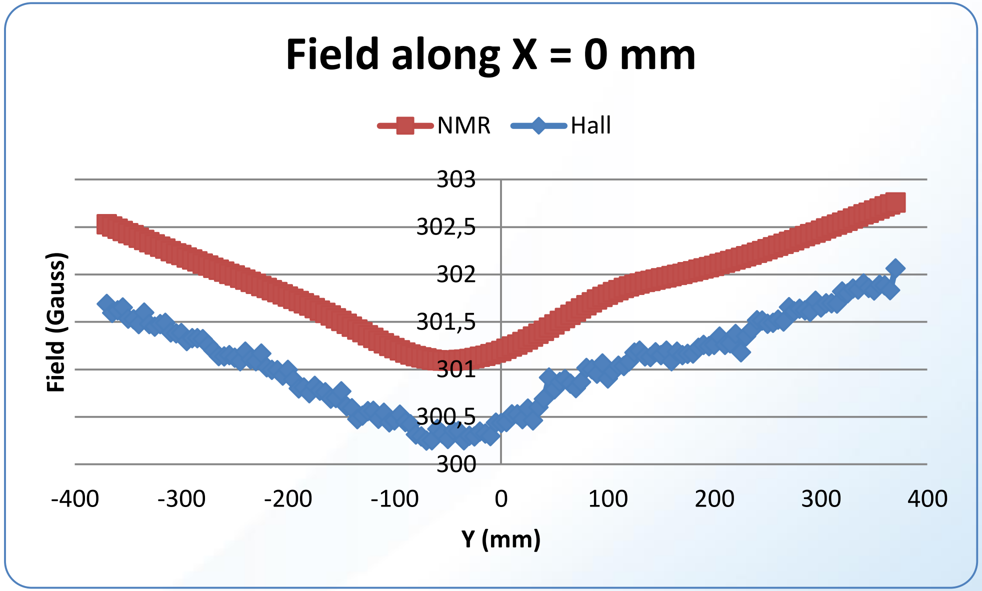


Hall precision, < 0.4 Gauss

NMR precision, 0.06 Gauss

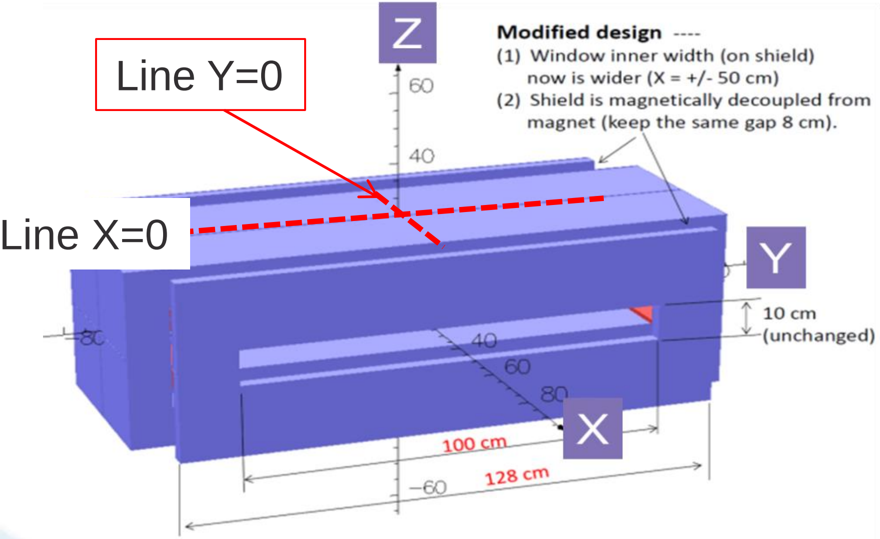
Field on magnet center lines, (0,Y,0)

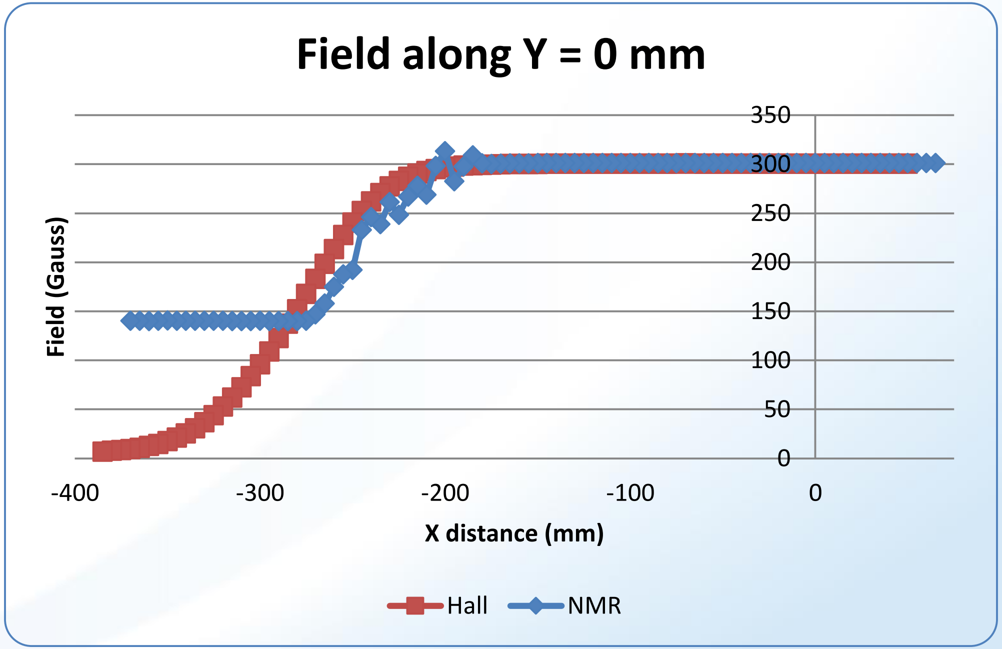




Hall can be corrected by NMR – design principle, Origin = center

Field on magnet center lines, (X, 0, 0)

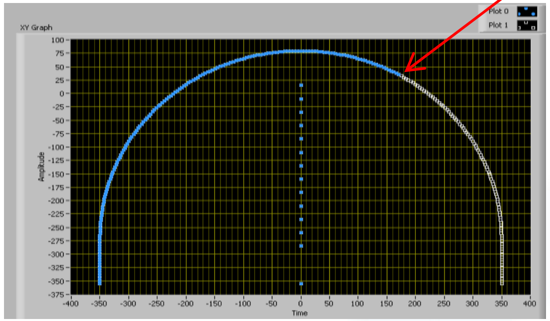




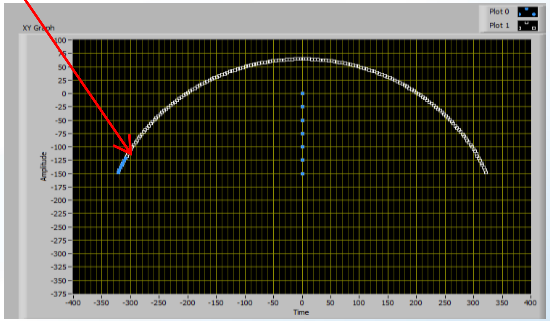
Measurement plan

- Part A – multiple points of currents/fields, ZHeight = 0mm, Radius 350 mm, 274 points – Hall and NMR (uniform field)
  - 2.4 A
  - 2.7 A
  - 3.0 A
  - 3.4 A
  - 3.8 A
  - 4.2 A

Real-time Probe Location



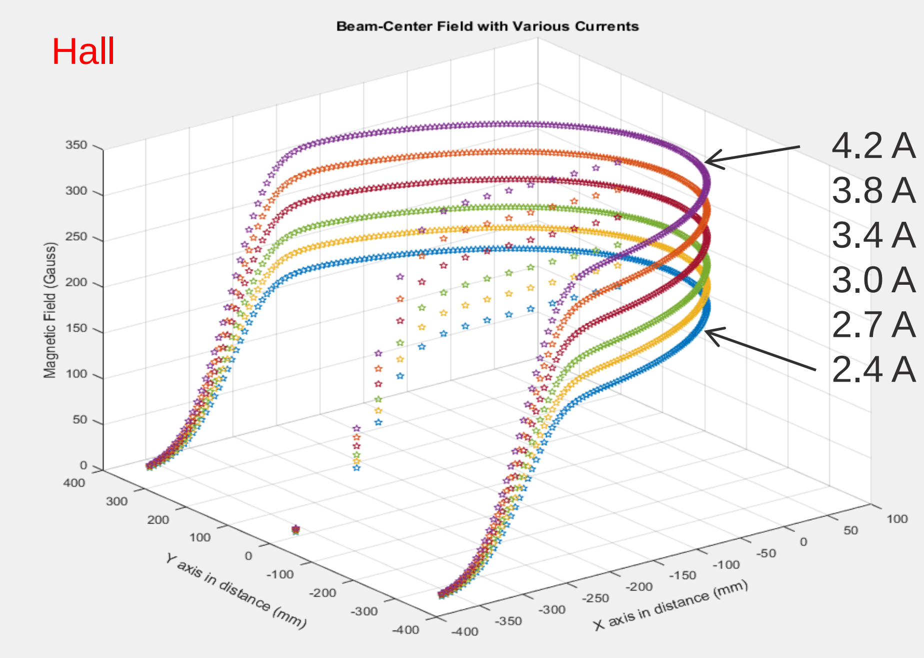
Hall

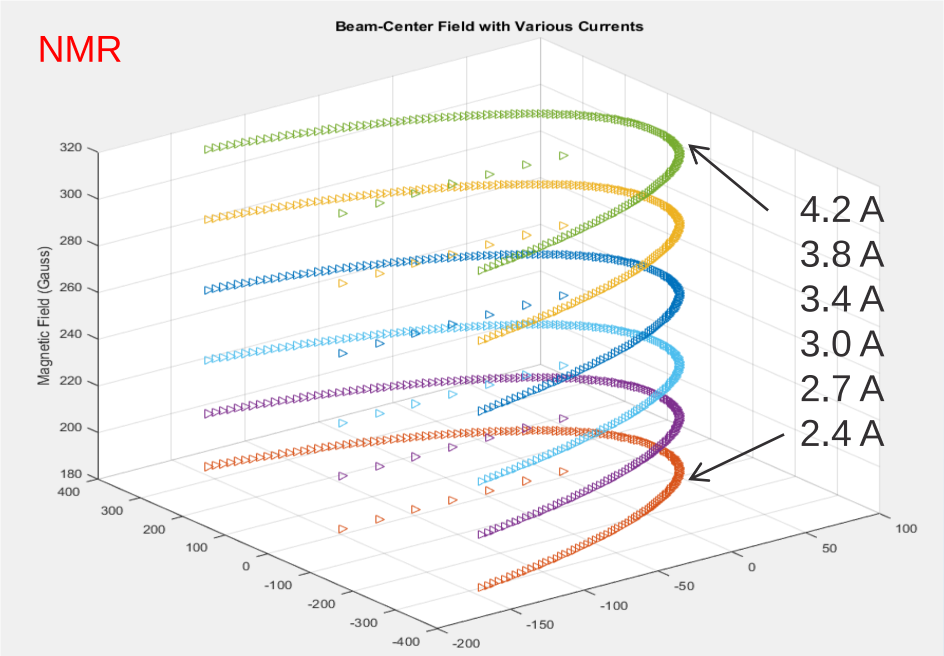


NMR

White – data planned,
Blue – data taken

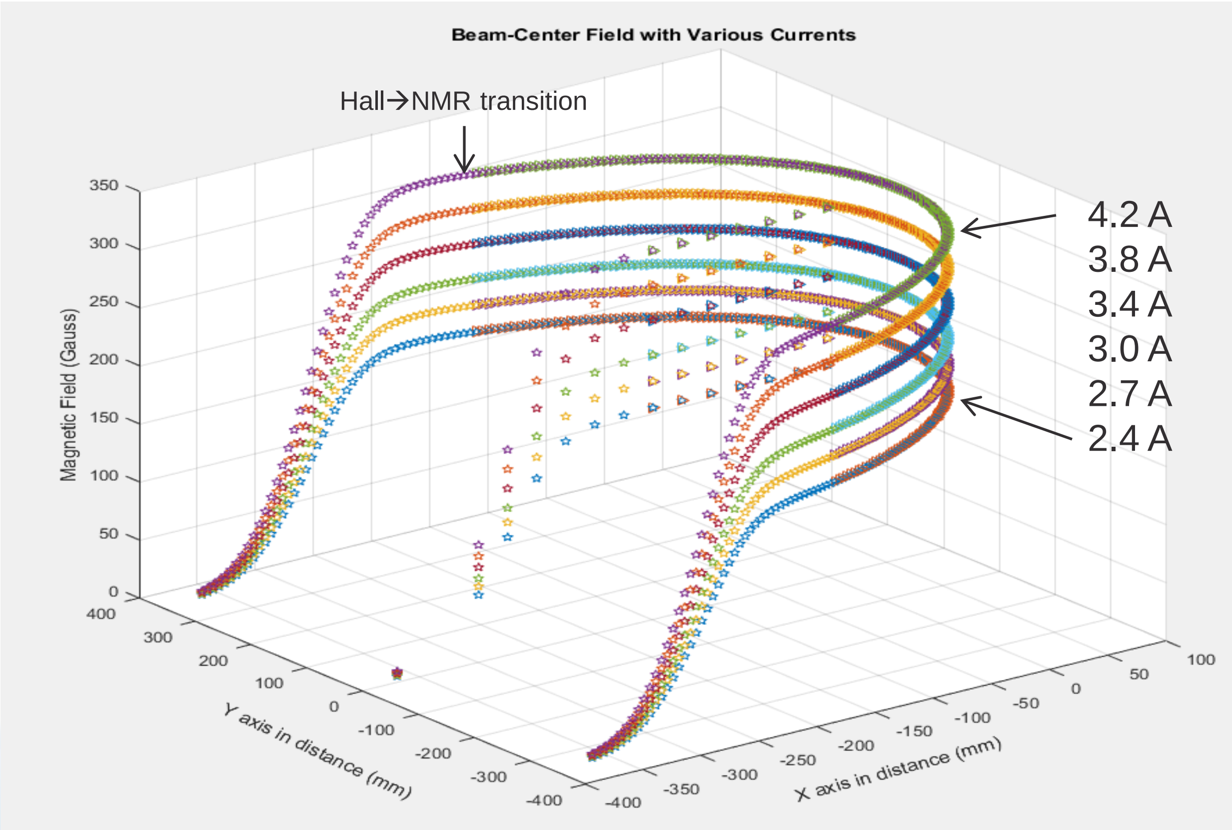
Along beam trajectory – Z center





- Both NMR and Hall Center points along X axis are corrected for reference/validation/correction
- They are aligned based on 15 mm offset

Measured NMR (full field) + Hall (lower field)

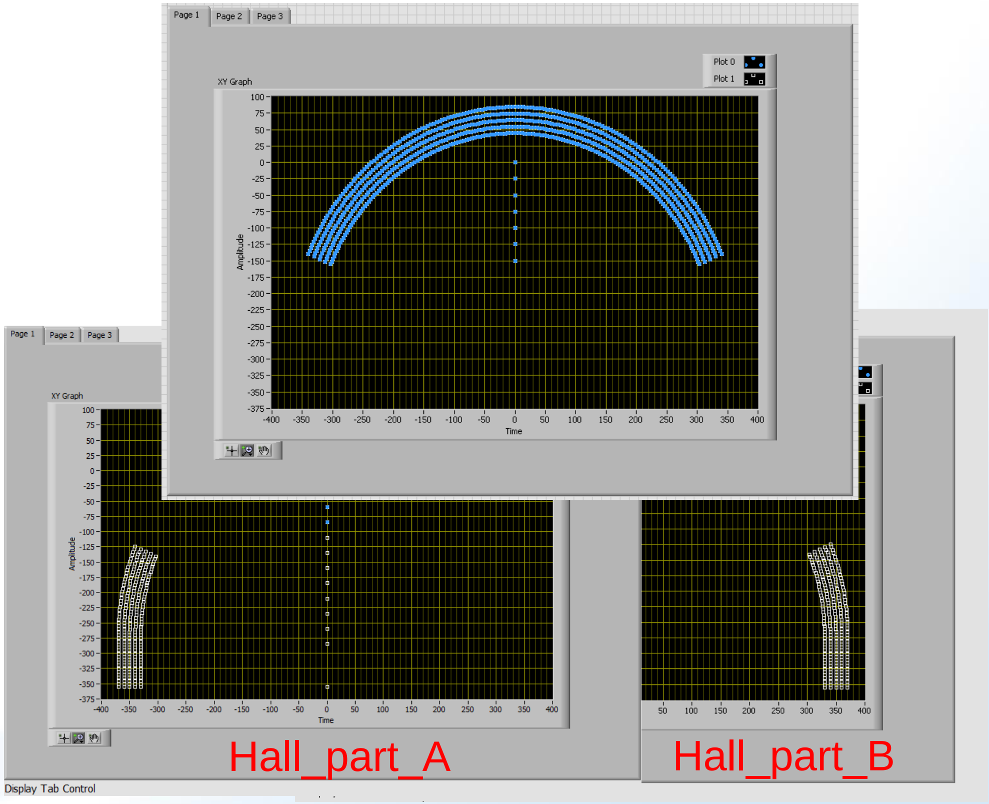


Scanning the Z = 0 mm, R = 350 mm trajectory using deferent operational currents.

Field Mapping Plan and Procedure

- All
  - Field of I=2.6586A
    - Z=0 mm,
    - Z=+10mm
    - Z=+20 mm,
    - Z=-10mm
    - Z=-20mm
  - Field of I=3.1911A
    - Z=0 mm,
    - Z=+10mm
    - Z=+20 mm,
    - Z=-10mm
    - Z=-20mm
  - Field of I=3.9833A
    - Z=0 mm,
    - Z=+20 mm,
    - Z=-20mm

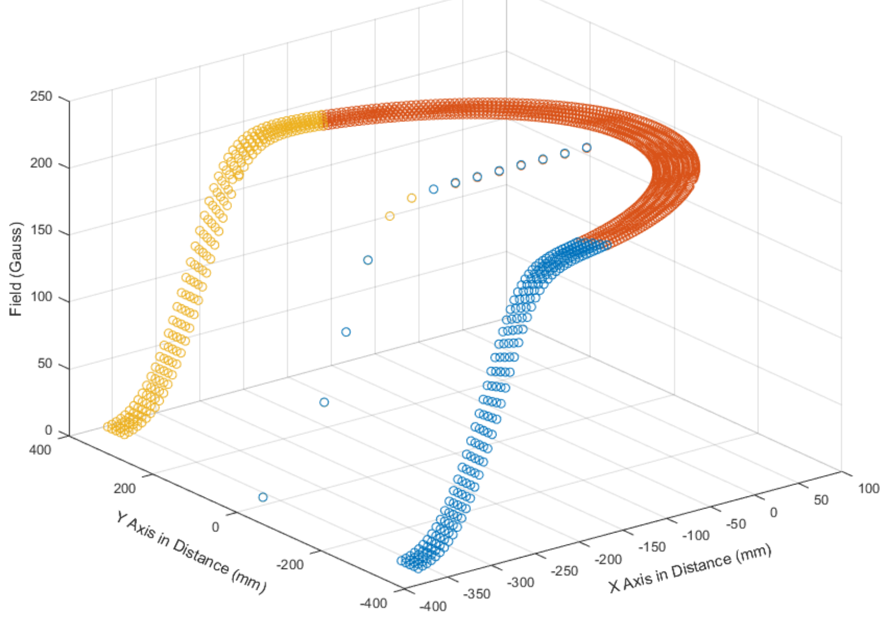
NMR



In-plane (same height) Results and Analysis

- A typical field scan with 5+1 different radii
  - Start with R 350 mm
  - R 330mm
  - R 340mm
  - R 350mm
  - R 360mm
  - R 370mm

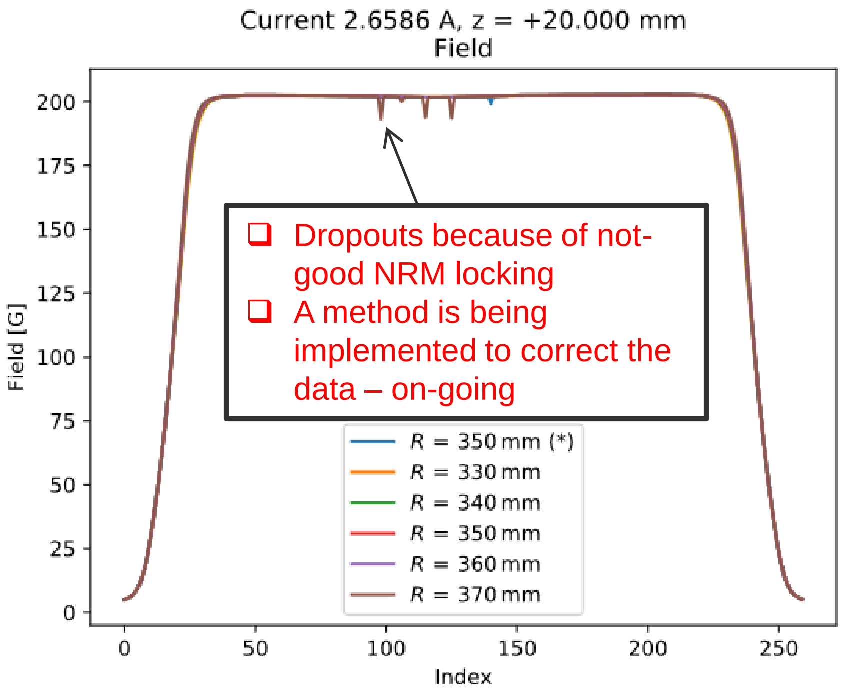
From inside to outside

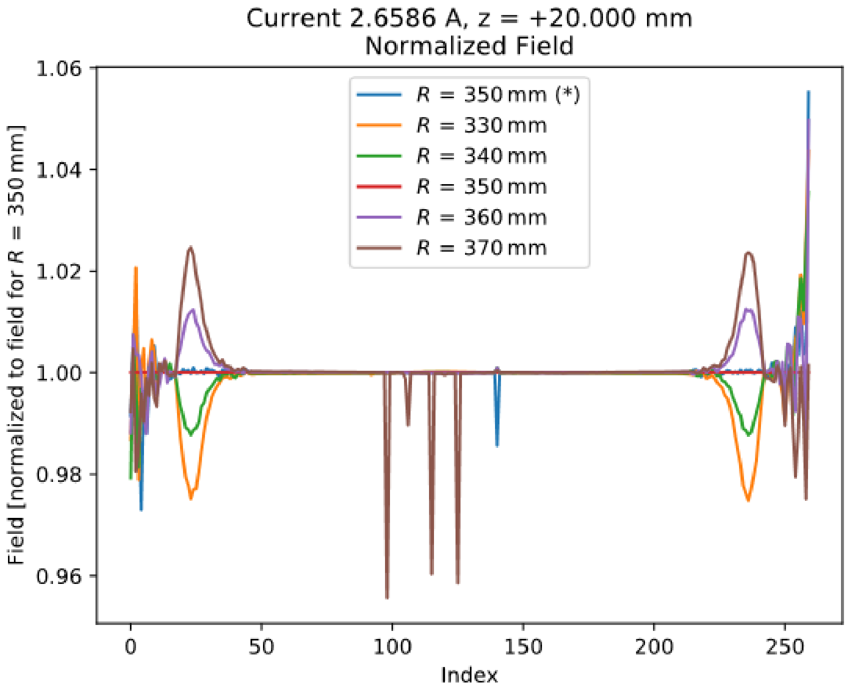


CURRENT OF 2.6586A

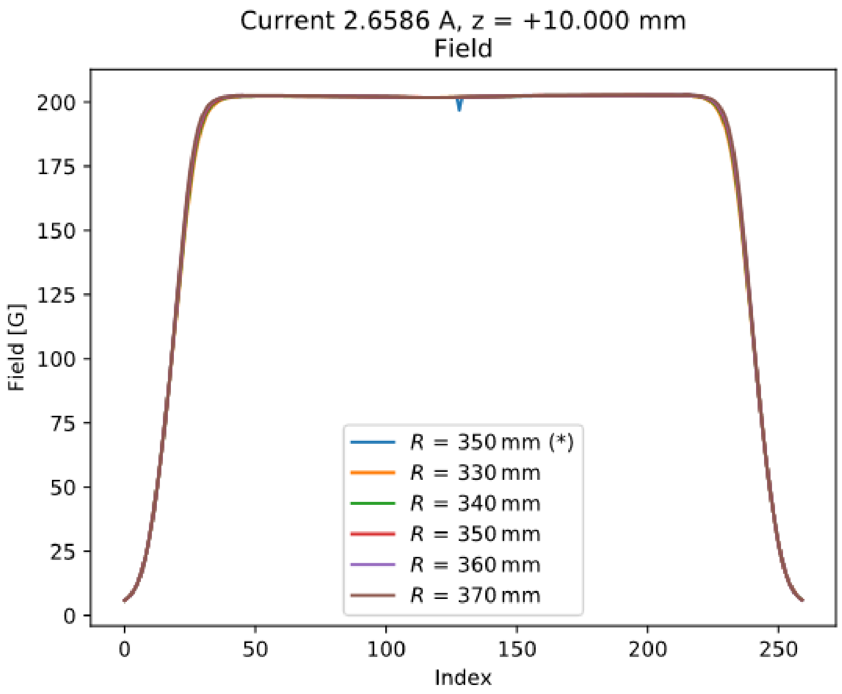
- Results
- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)

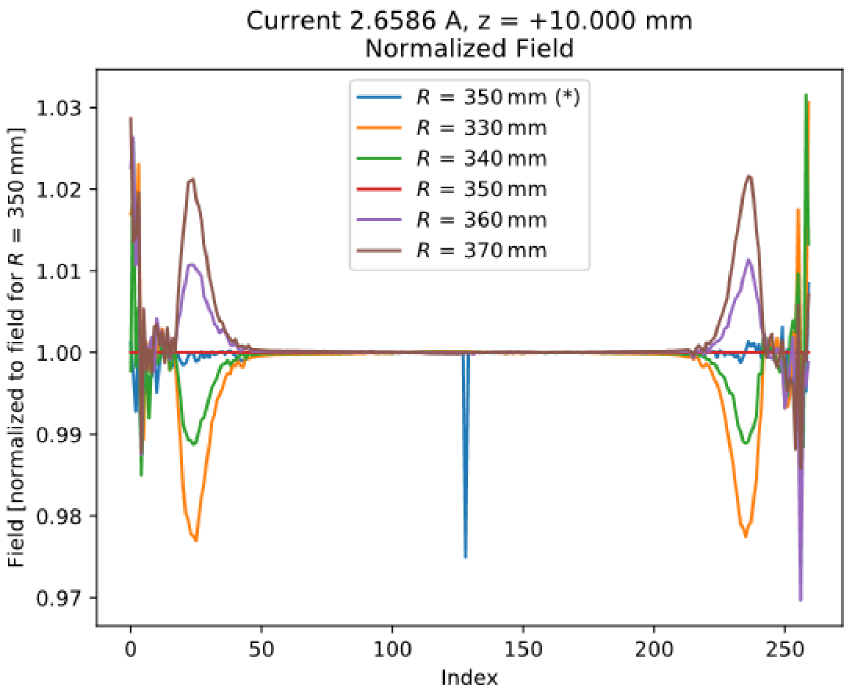
Field of I=2.6586A and z=+20mm
In-plane horizontal comparison



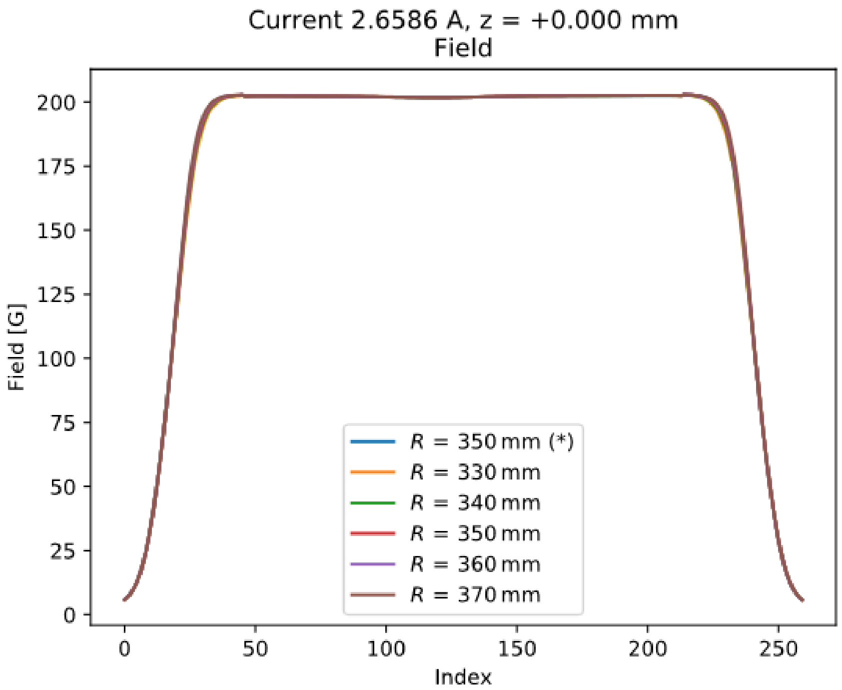


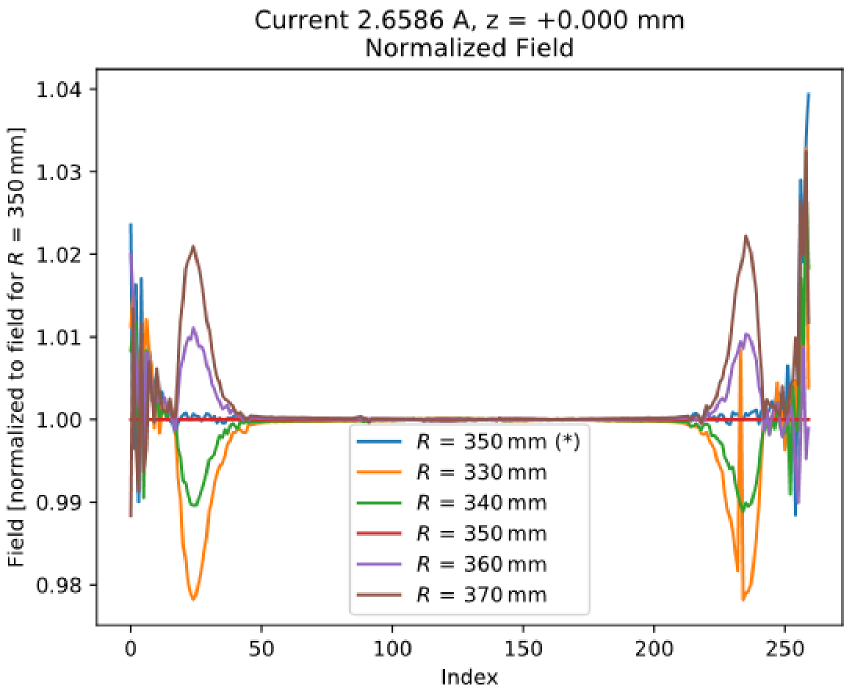
Field of I=2.6586A and z=+10mm
In-plane horizontal comparison



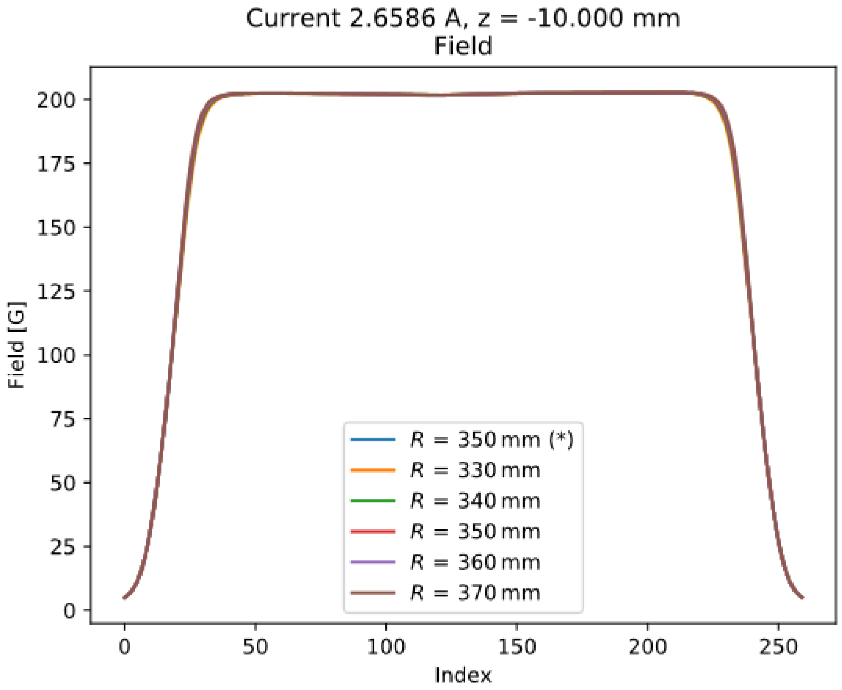


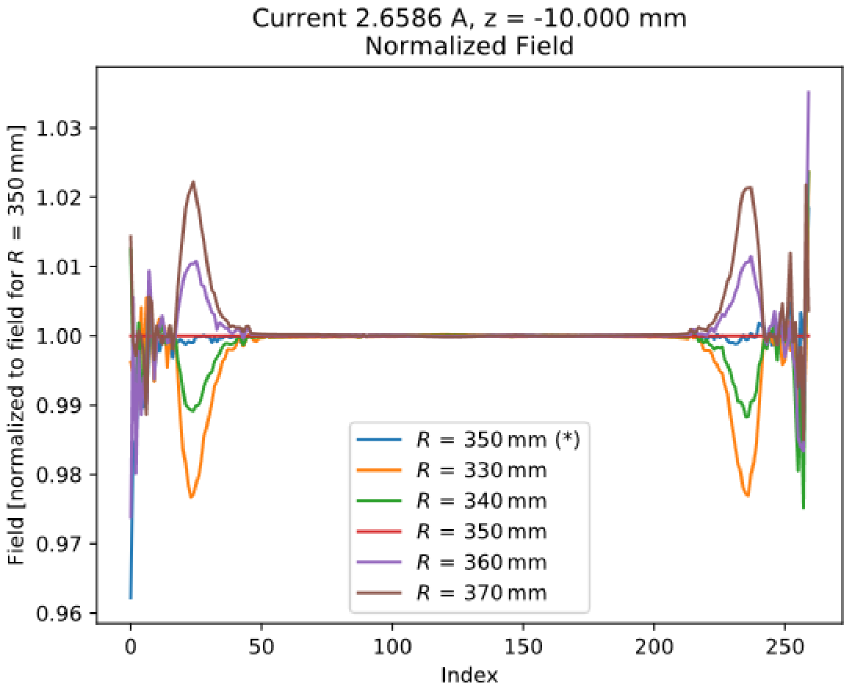
Field of I=2.6586A and z=+00mm
In-plane horizontal comparison



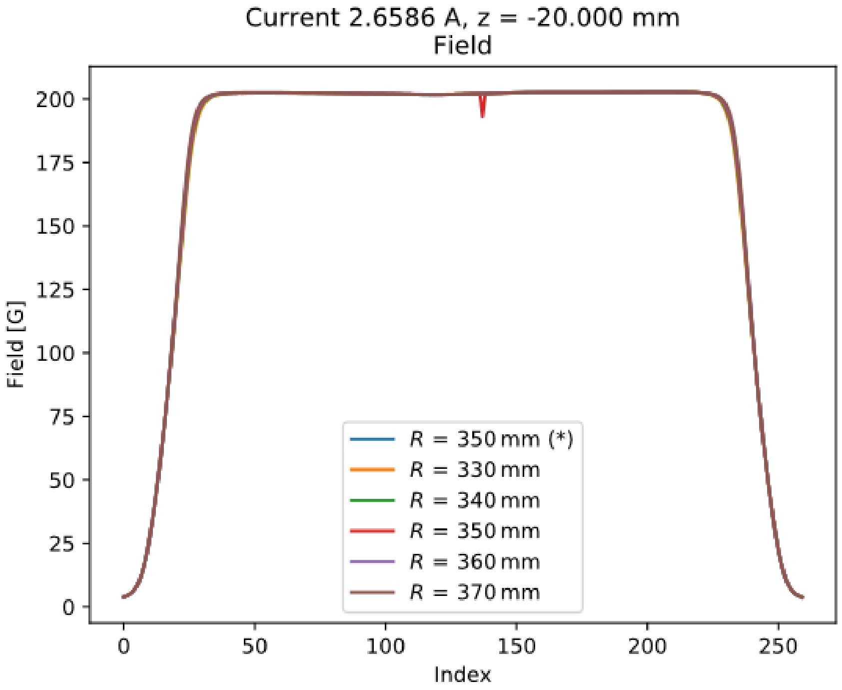


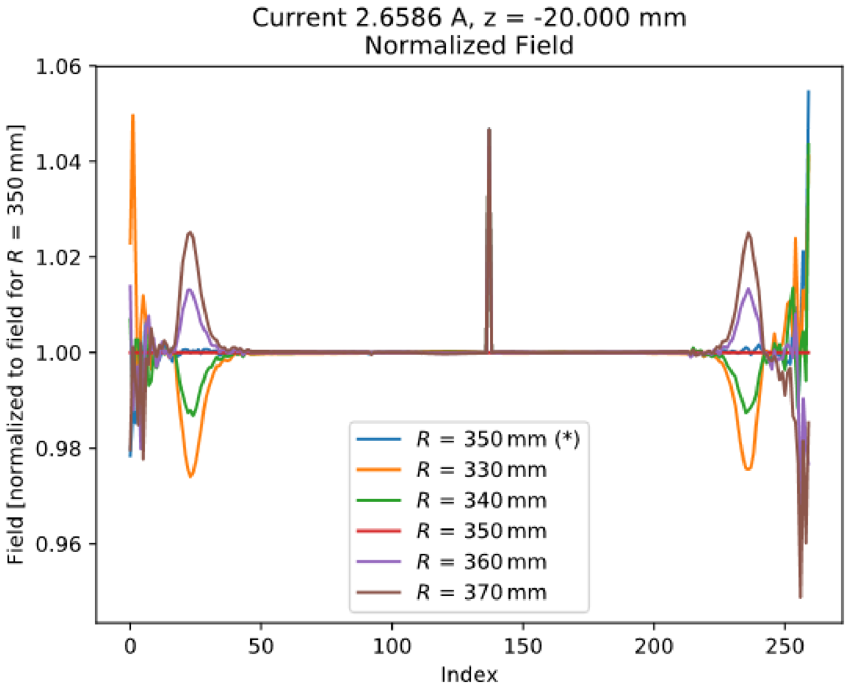
Field of I=2.6586A and z=-10mm
In-plane horizontal comparison



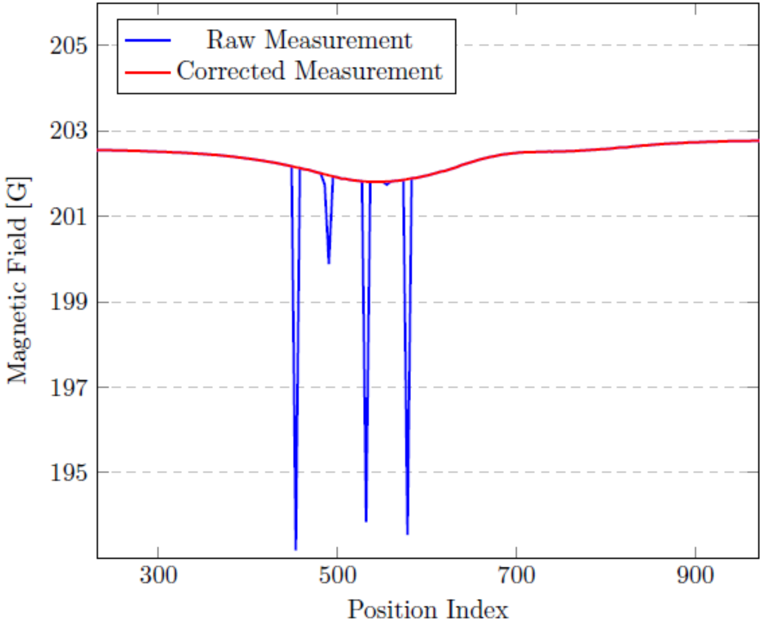


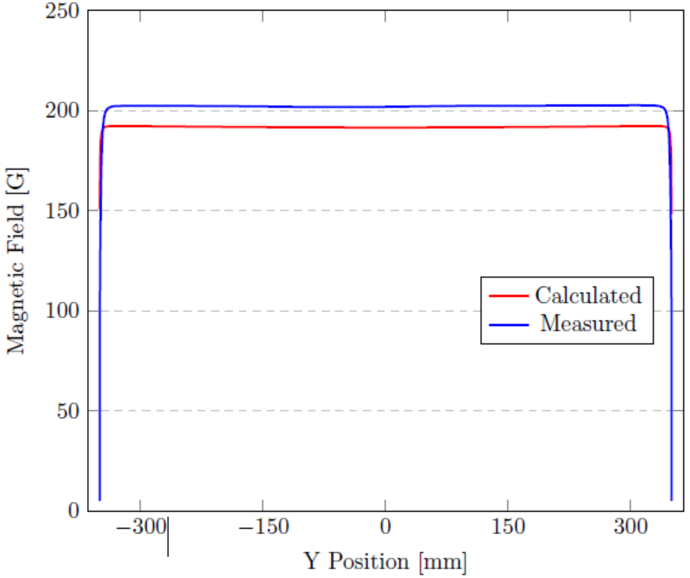
Field of I=2.6586A and z=-20mm
In-plane horizontal comparison





Data smoothing: correct drop-outs





[I, Z, R] = [2.6586 A, 20 mm, 370 mm]

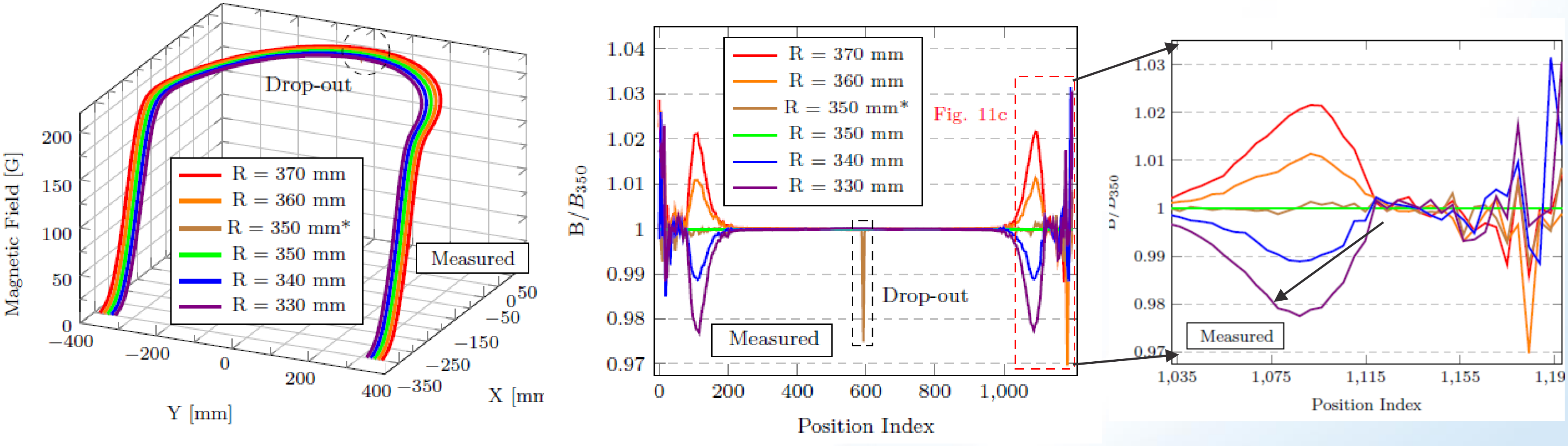
- Slight difference in quantity between simulated and measured data.
- Qualitative info helps data smoothing.
- Measured data → Beam operation

ANALYSIS AND DISCUSSIONS

I=2.6586A

Measured Results

Comparison plots of the measured magnetic fields for all radii, at a fixed Z = 10 mm elevation, with I = 2.6586 A. The radius of 350 mm was measured twice.



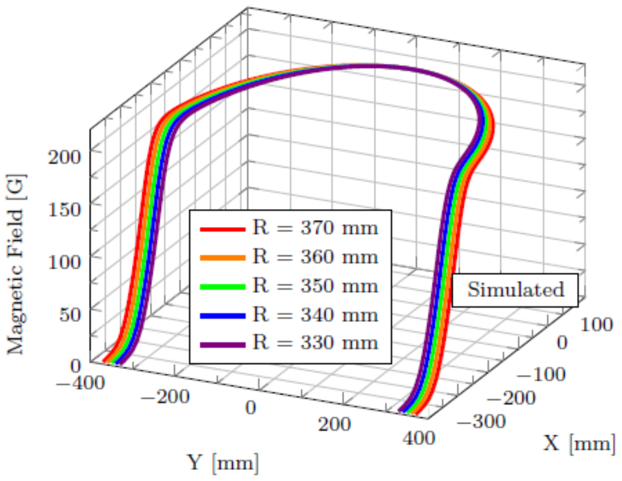
In plane full view

normalized

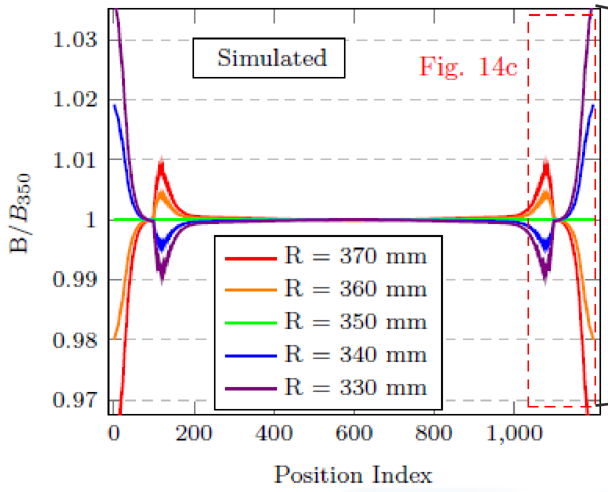
Zoom-in

Simulated data

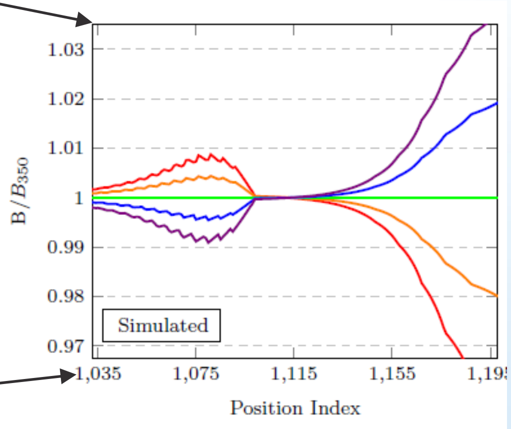
Comparison plots of the simulated magnetic fields for all radii, at a xed Z = 10 mm elevation, with I = 2.6586 A.



In plane full view



normalized



Zoom-in

Good agreement between measured and simulated

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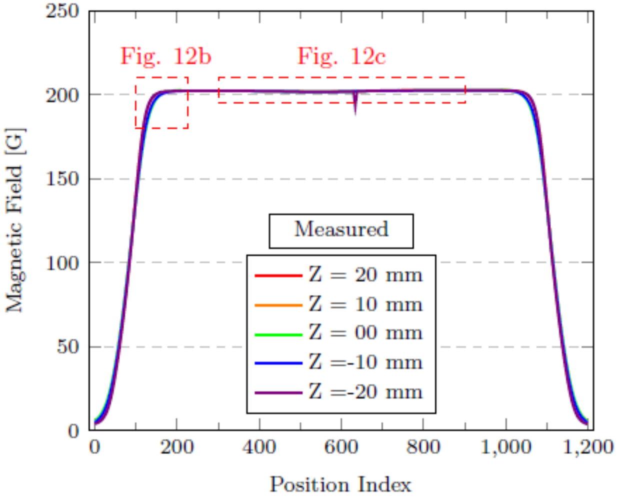
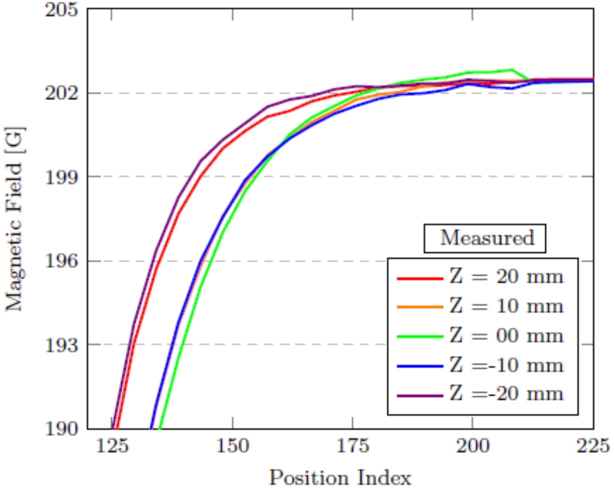
Measured Results

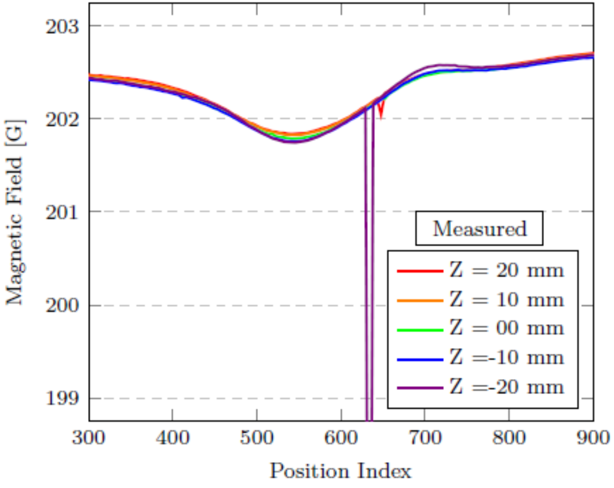
Same radius R = 350 mm,
Same current I = 2.6586 A,
Vertical comparison

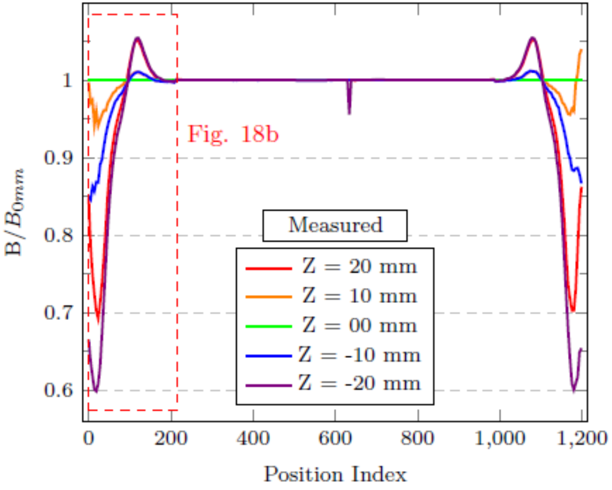




Asymmetry observed in measured data

But field at magnet edge, low field strength, less contribution to the field integral.



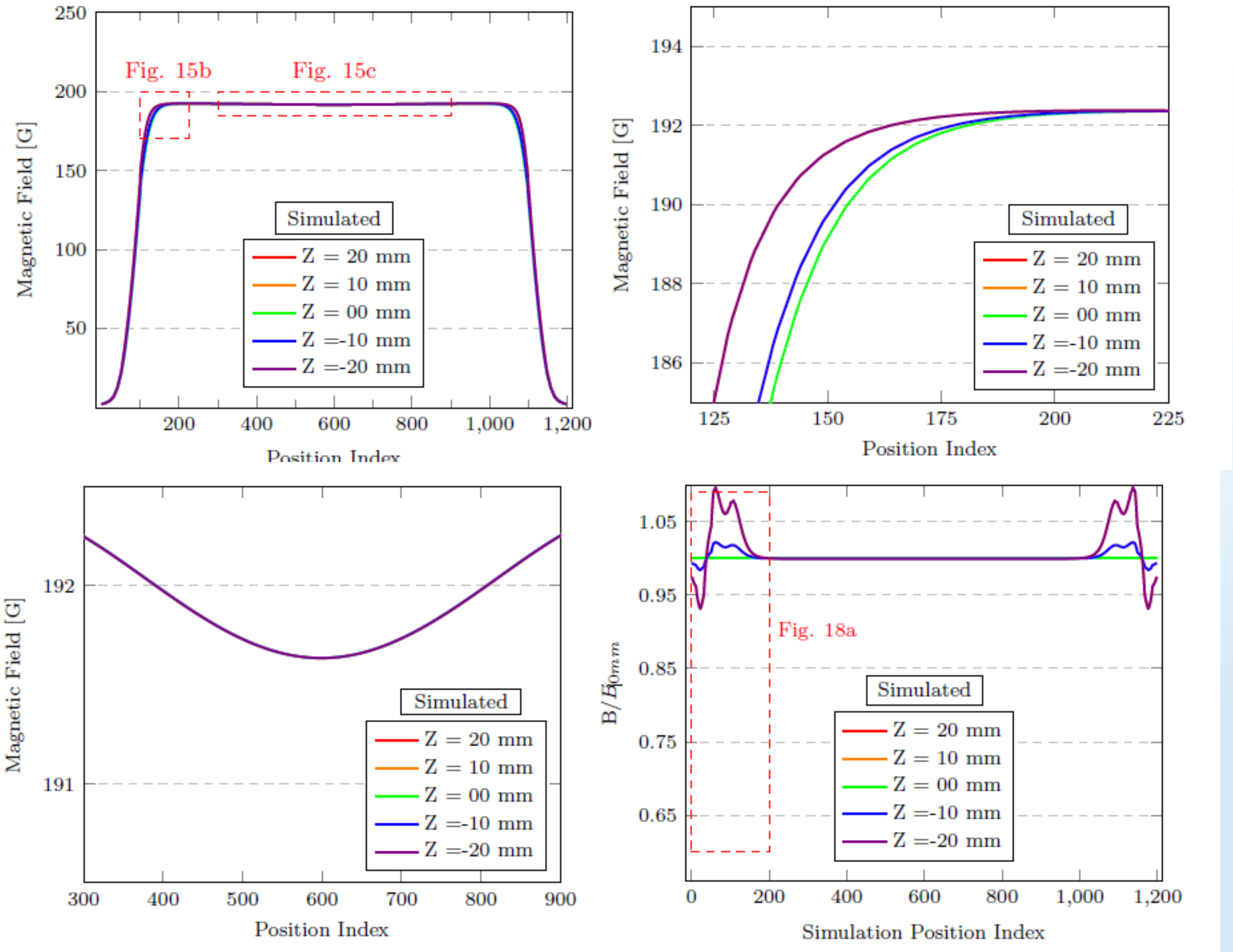


Simulated data

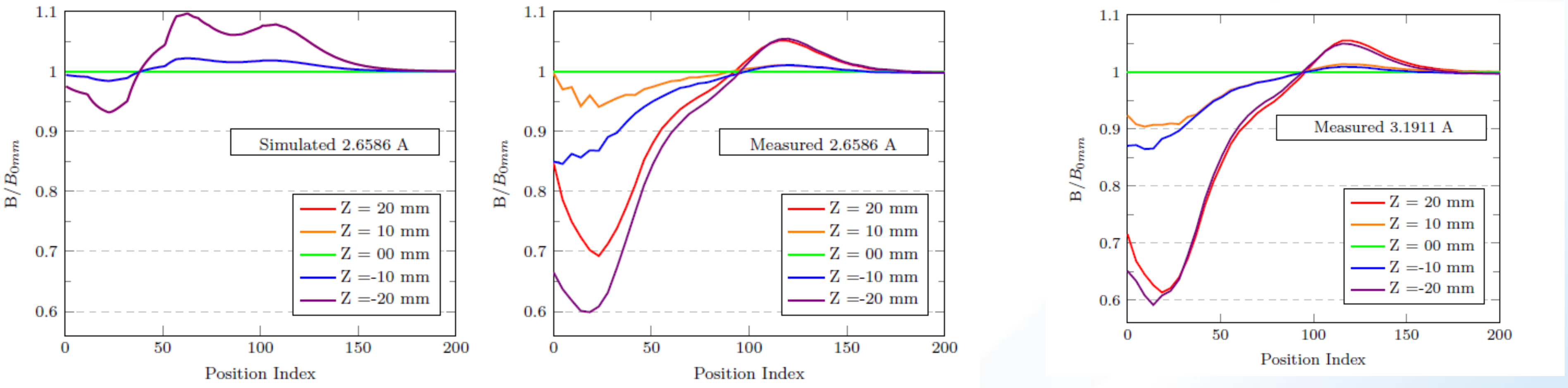
Same radius R = 350 mm,
Same current I = 2.6586 A,
Vertical comparison

Asymmetry observed in measured data

But field at magnet edge, low field strength, less contribution to the field integral.

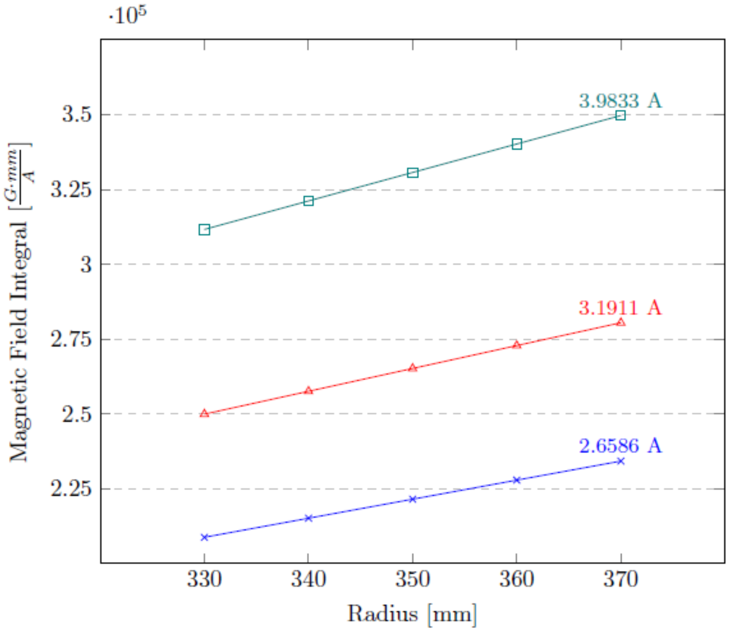


Closer look at asymmetry



- More variations in measured vs simulated,
- But field at magnet edge, lower field strength, less contribution to the field integral.
- Symmetry has been improved with higher current

Field integral – measured data



Current	Elevation*	Radius 330 mm	340 mm	350 mm	360 mm	370 mm
2.6586 A	20 mm	208794.0127	215158.6214	221516.0992	227890.3956	234247.7224
	10 mm	208726.6595	215109.5603	221479.2296	227855.1657	234227.0699
	0 mm	206290.5098	215065.6187	221431.4392	227801.0622	234196.1919
	-10 mm	208495.1037	214866.0687	221244.5334	227606.5791	233991.8624
	-20 mm	208559.2216	214918.1966	221278.1539	227625.8195	233996.4407
3.1911 A	20 mm	249937.4935	257569.7252	265196.9944	272842.2223	280469.8375
	10 mm	249981.8288	257626.0727	265264.7388	272902.0625	280551.6631
	0 mm	250060.6357	257692.7363	265332.0833	272989.4684	280617.4032
	-10 mm	250111.6537	257741.3119	265376.0085	273006.5926	280635.2356
	-20 mm	250172.6636	257805.8321	265440.5032	273068.4137	280702.6773
3.9833 A	20 mm	311638.4268	321158.9187	330674.3802	340185.3529	349700.8613
	0 mm	311519.1884	321031.7337	330544.5886	340062.9249	349586.4819
	-20 mm	311376.8089	320893.1379	330406.0179	339924.7336	349439.0384

Field integral calculated with corrected measured data for five radii, but same elevation of Z = 20 mm

Field integral information for the 180 deg dipole magnet for three deferent currents, at five radii, at deferent elevations.
Units: [Gmm]

Summary

- Have completed the mapping of 180 degree dipole for LEReC project.
  - Successfully applied high precision – low field NMR probe, combined with Hall probe.
  - Measured data provide very accurate picture, which is supported by its general agreement with computational predictions.
- Performed detailed analysis and comparison at various radius and height,
  - Slight asymmetry observed at magnet edges due to lower field strength, but small field strength → less contribution to the field integral.
- Field and integral information shared with physicist, and findings from these measurements can be directly used to support beam operation.

Thank you for your attentions

Backup slides

CURRENT OF 3.1911A

- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)

Better symmetry

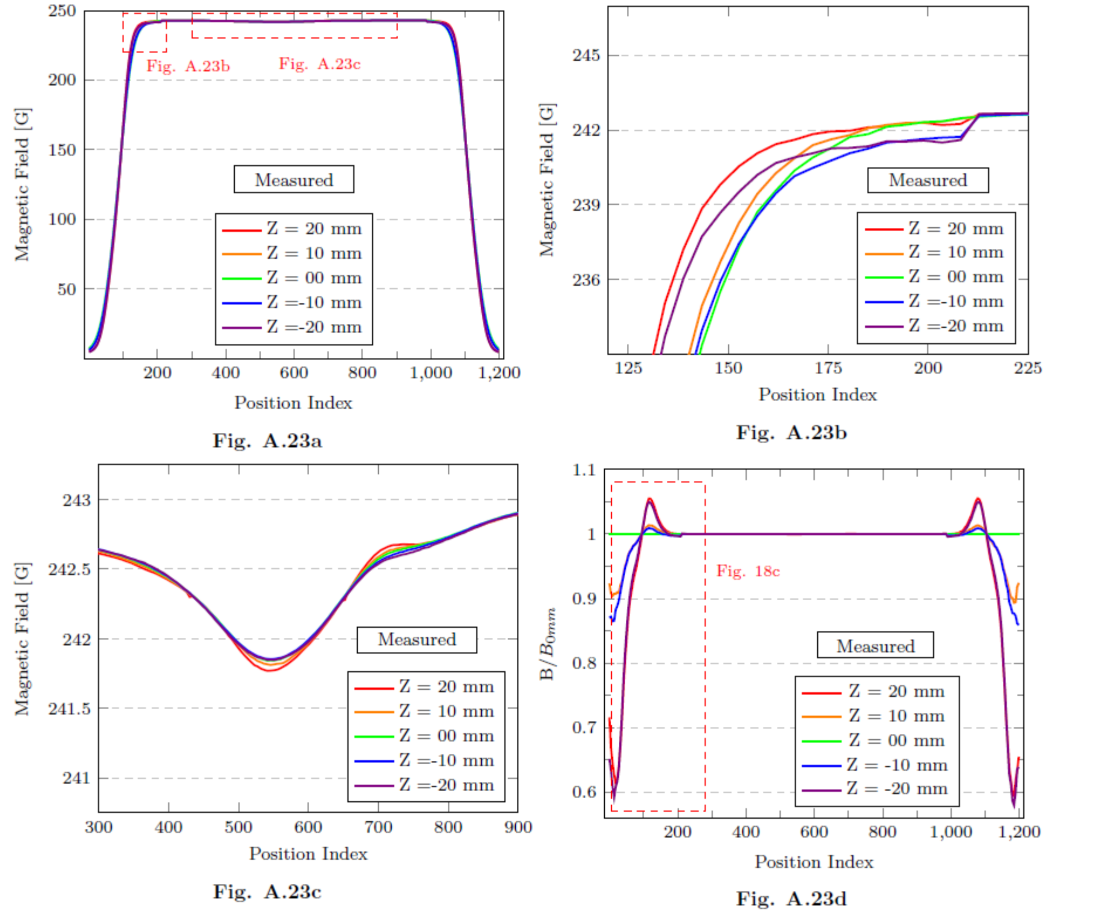


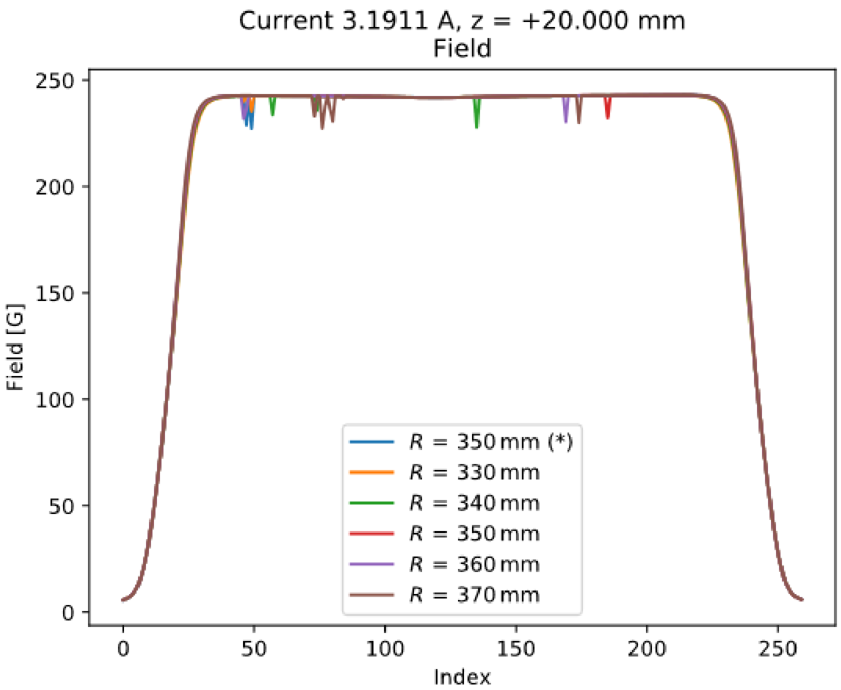
Fig. A.23a

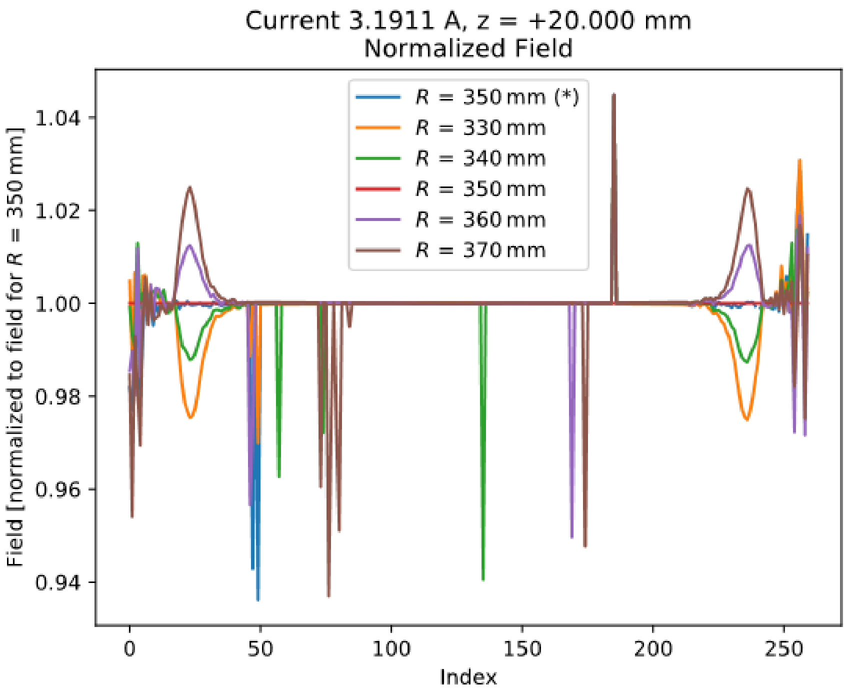
Fig. A.23b

Fig. A.23c

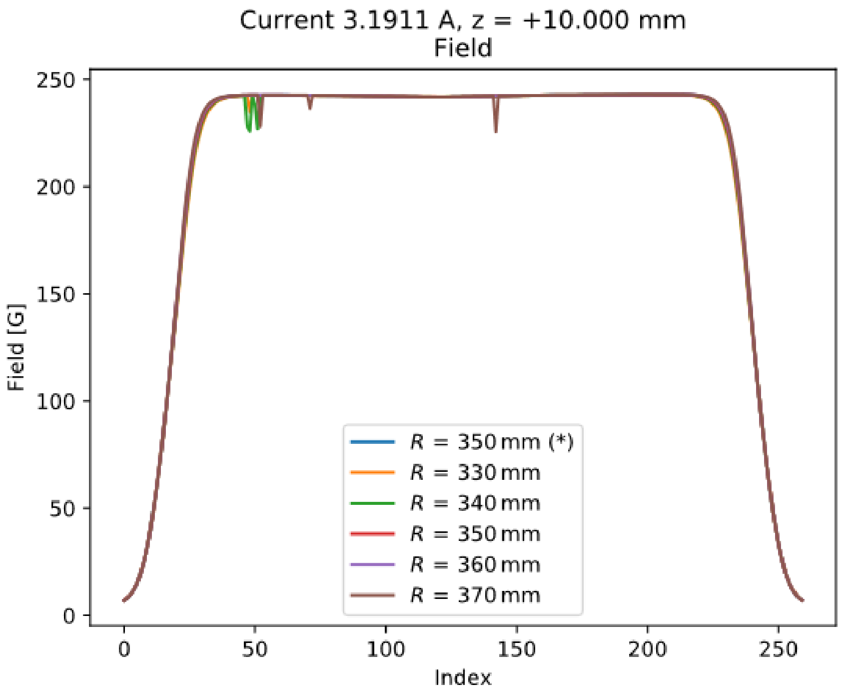
Fig. A.23d

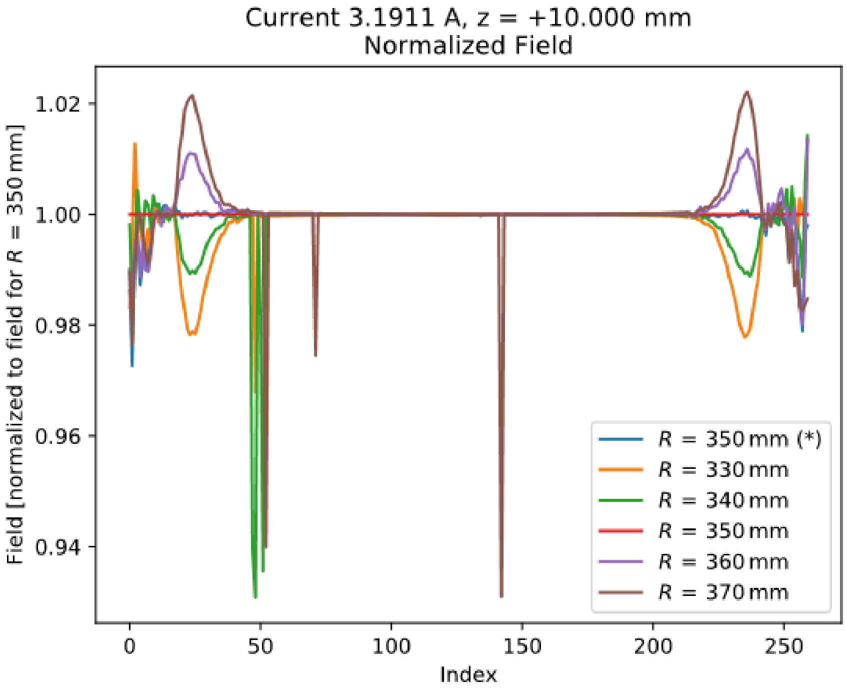
Field of I=3.1911A and z=+20mm In-plane horizontal comparison



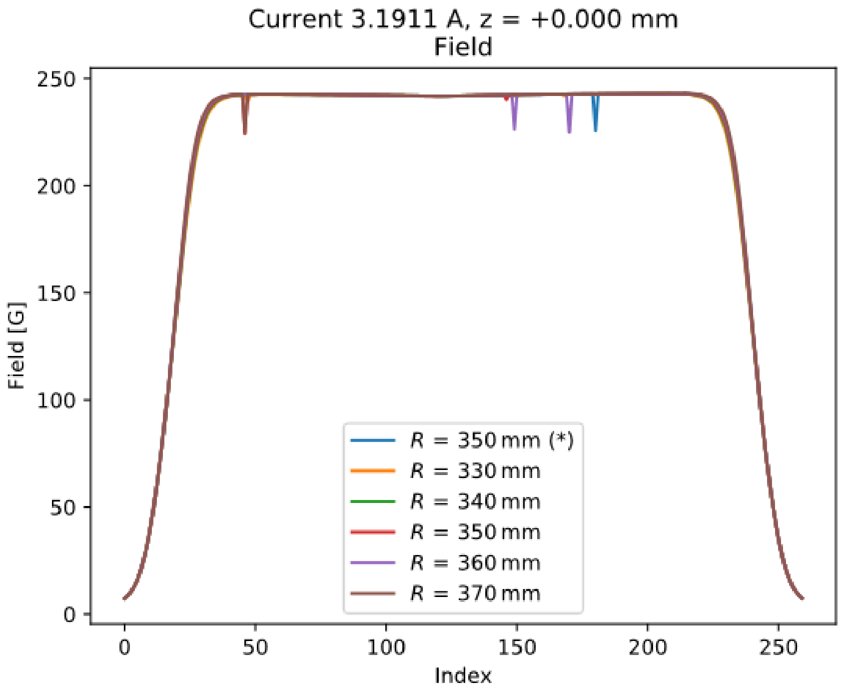


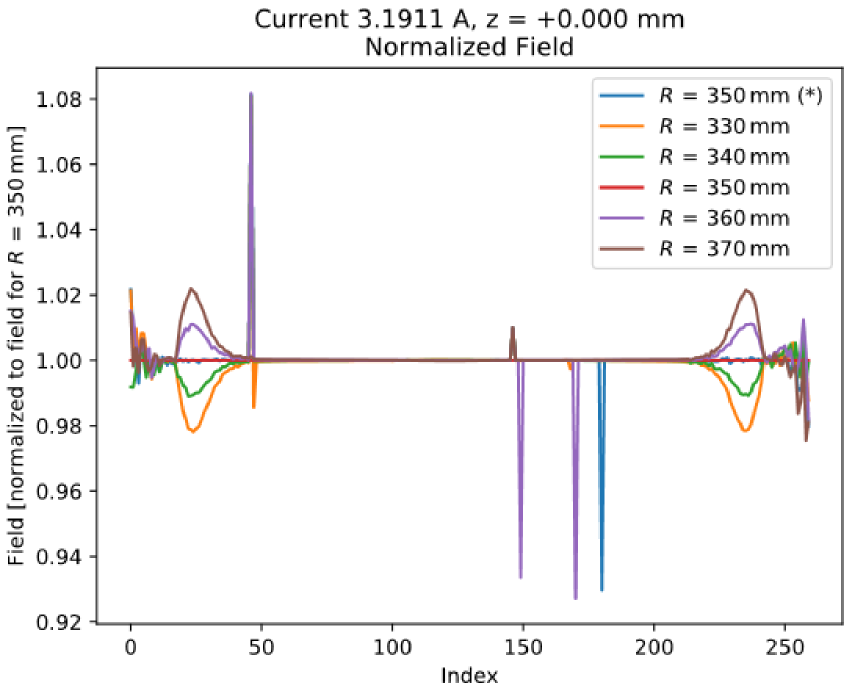
Field of I=3.1911A and z=+10mm In-plane horizontal comparison



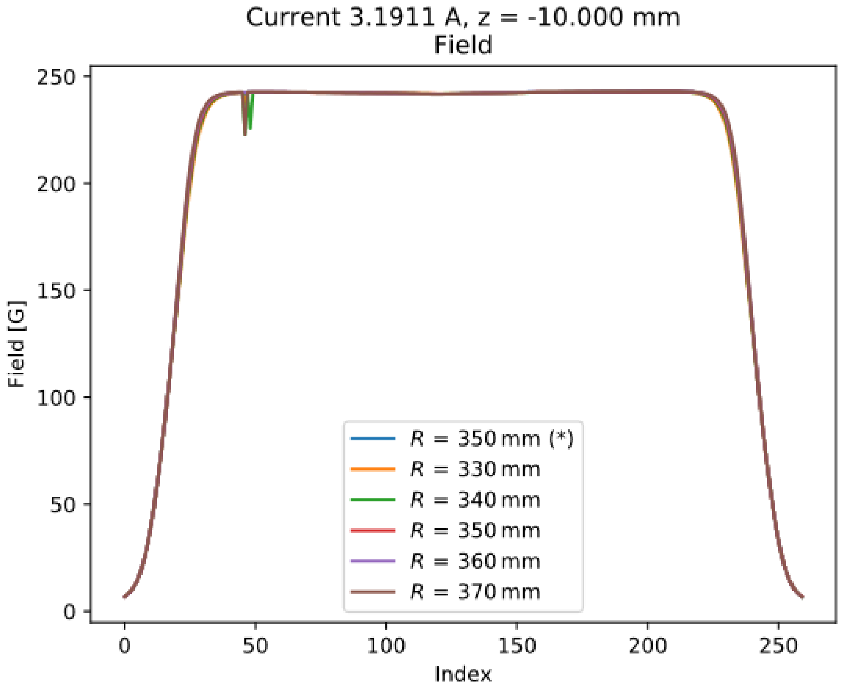


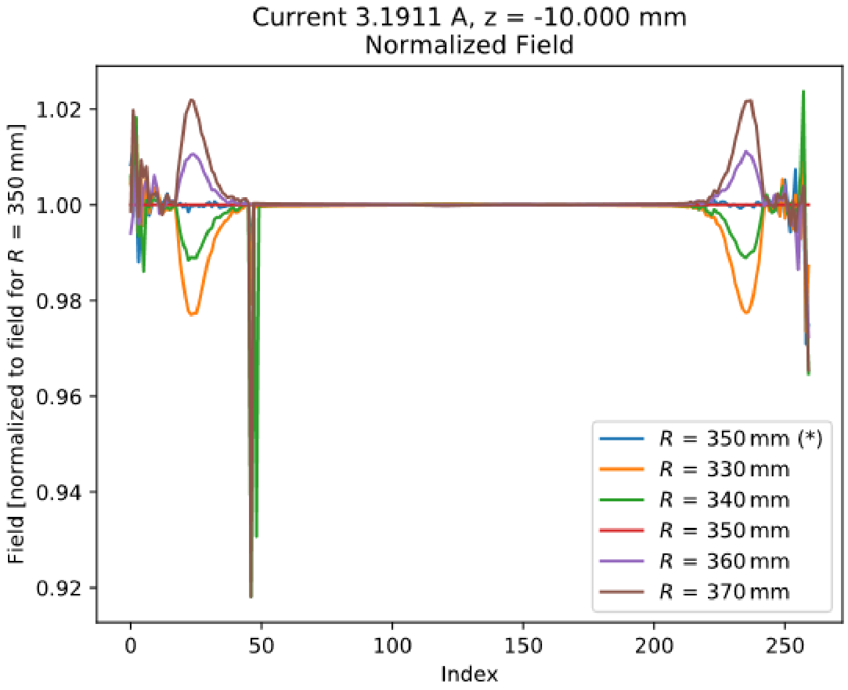
Field of I=3.1911A and z=+00mm In-plane horizontal comparison



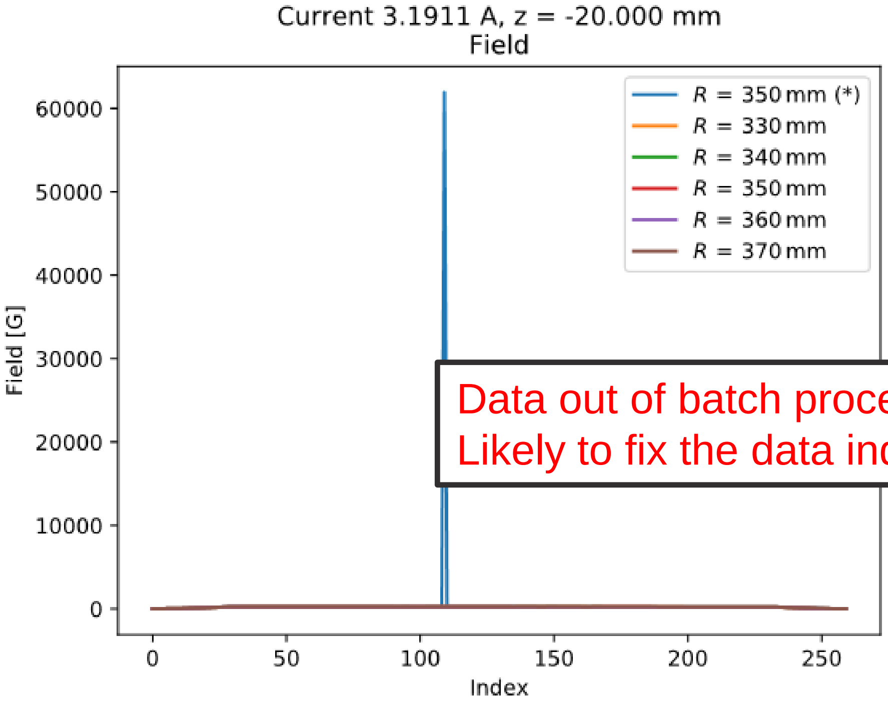


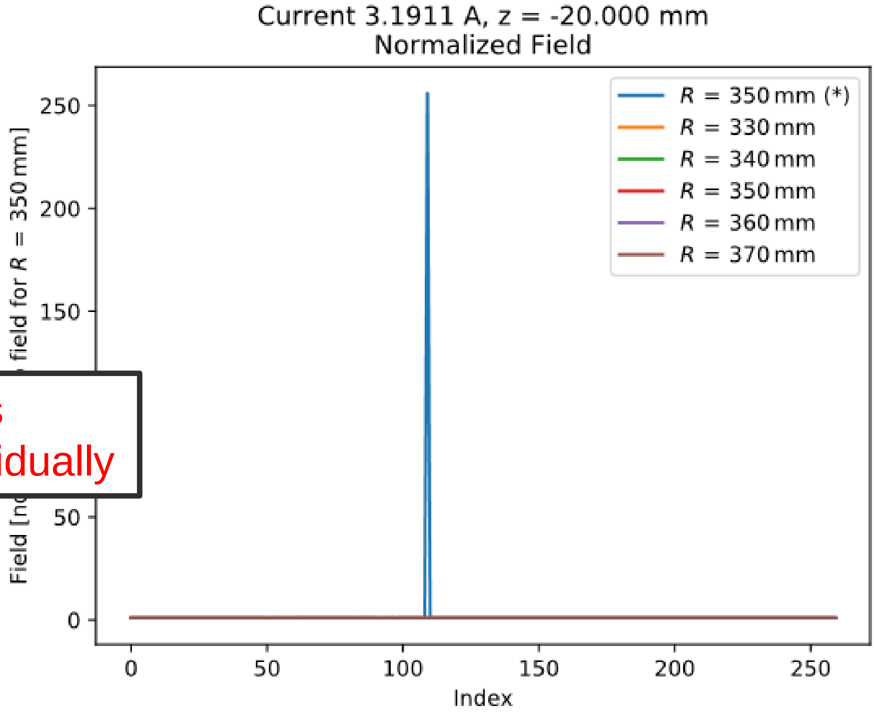
Field of I=3.1911A and z=-10mm In-plane horizontal comparison





Field of I=3.1911A and z=-20mm
In-plane horizontal comparison



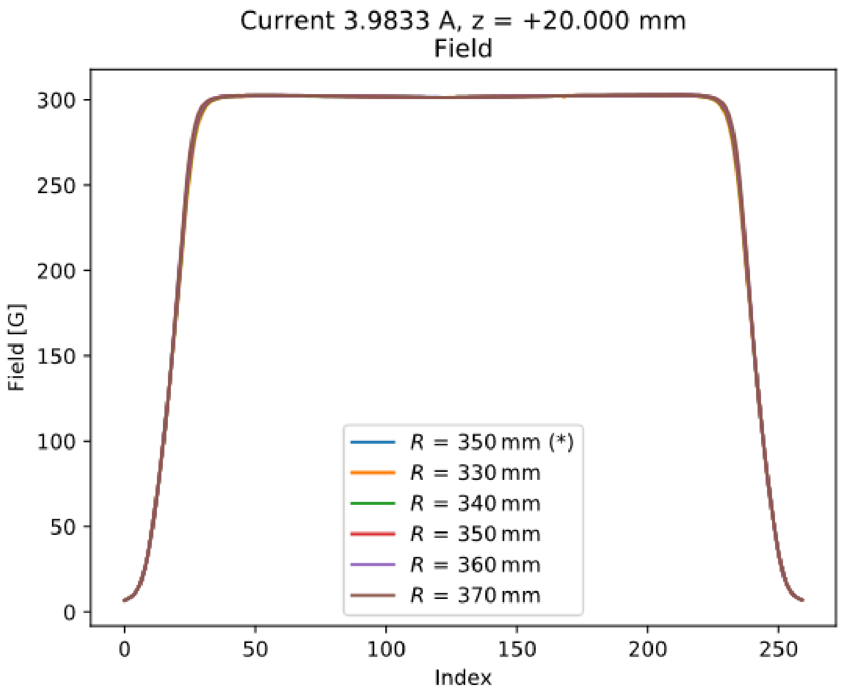


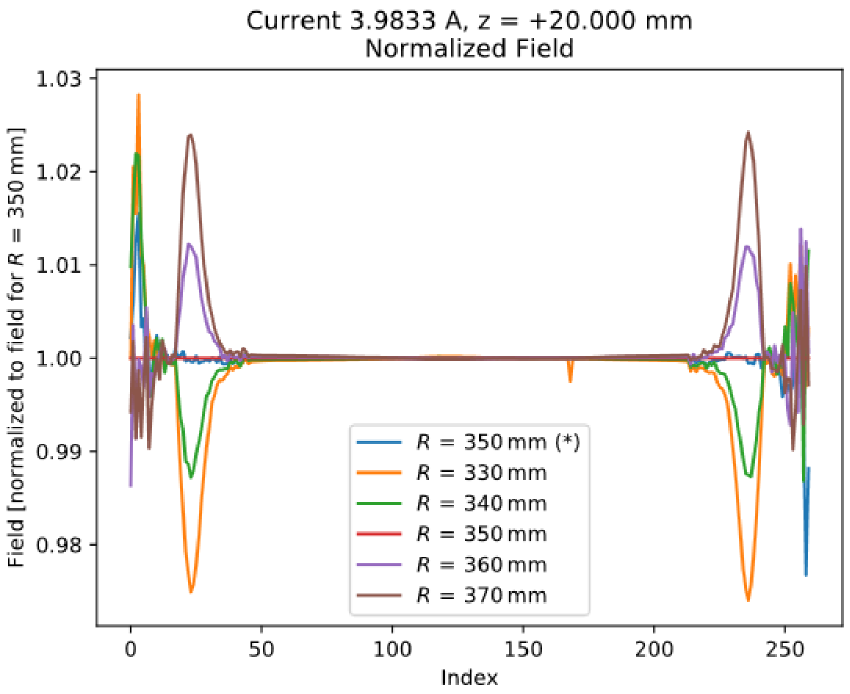
Data out of batch process
Likely to fix the data individually

CURRENT OF 3.9833A

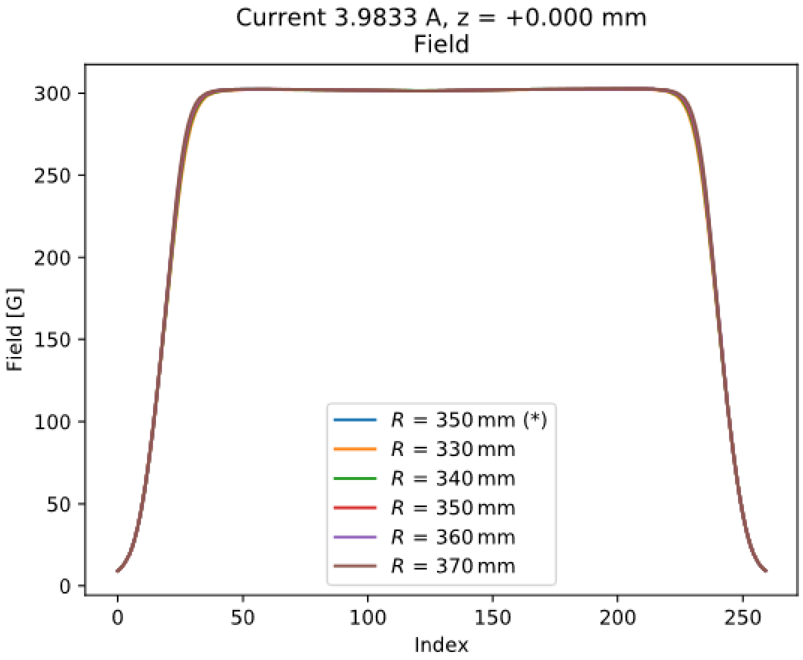
- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)

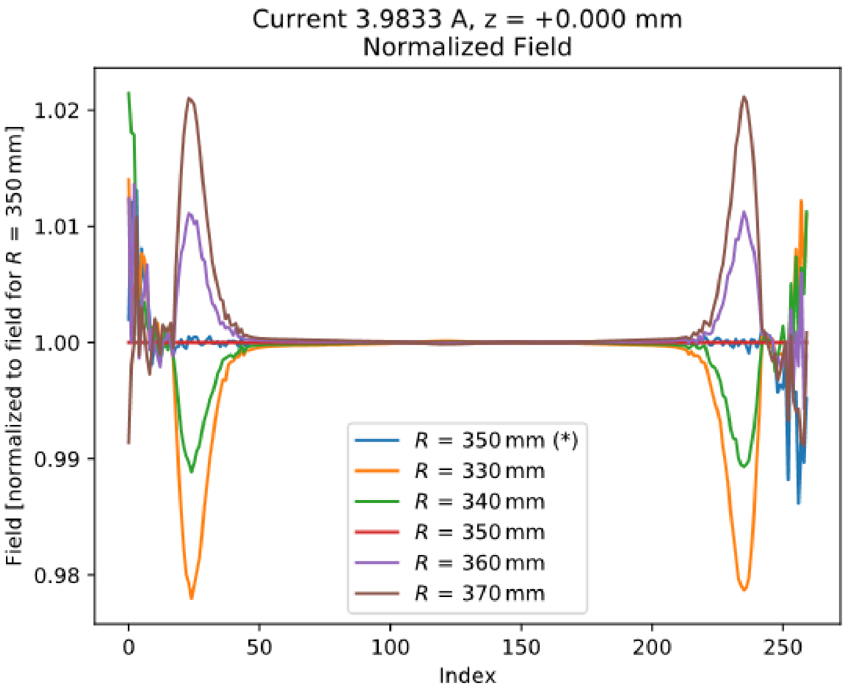
Field of I=3.9833A and z=+20mm In-plane horizontal comparison



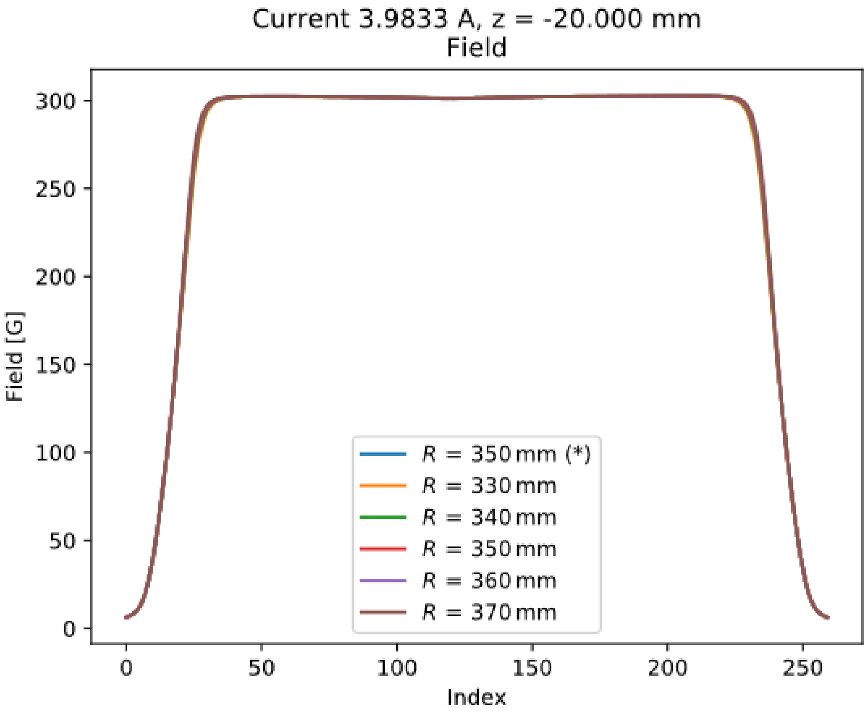


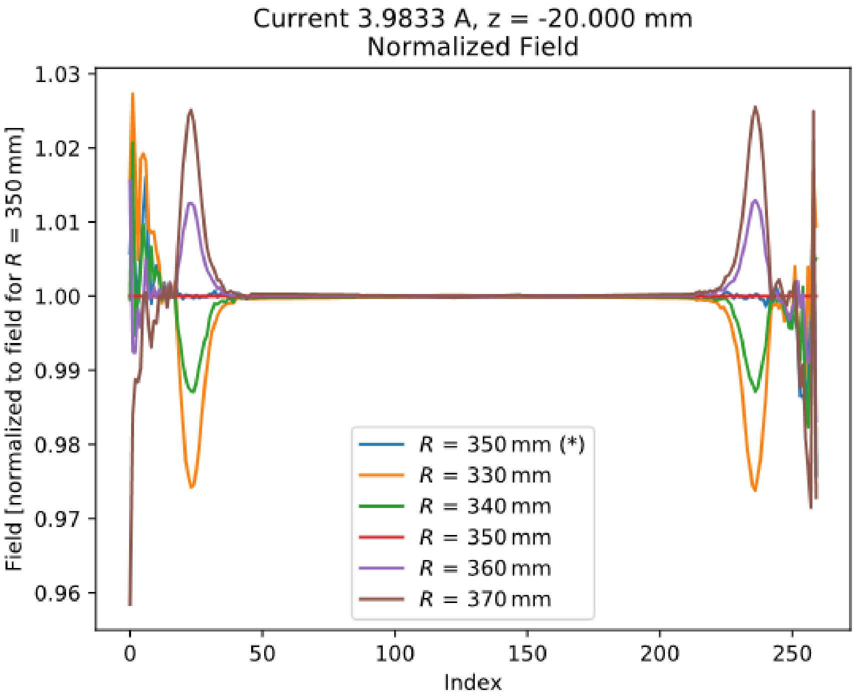
Field of I=3.9833A and z=+00mm In-plane horizontal comparison



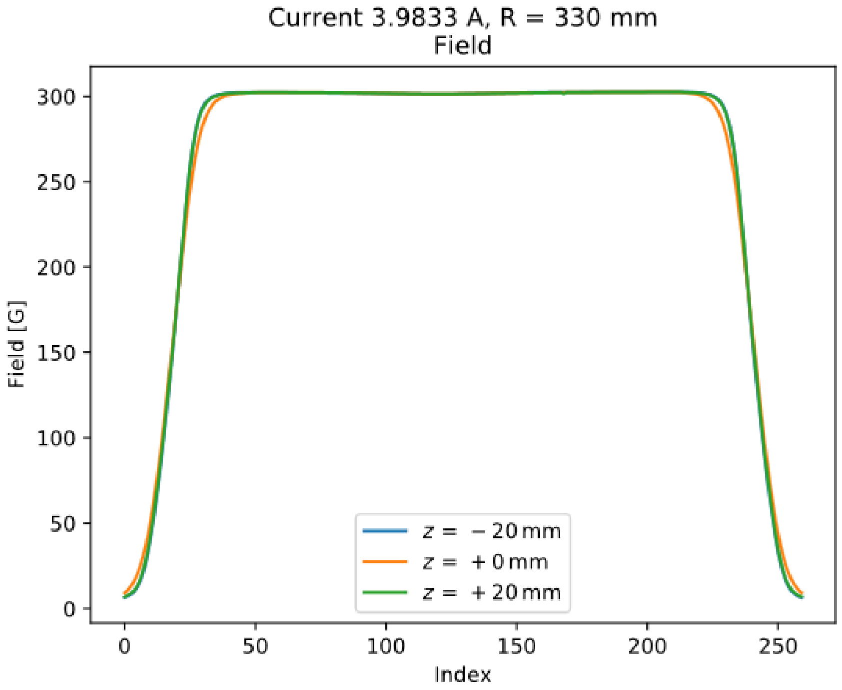


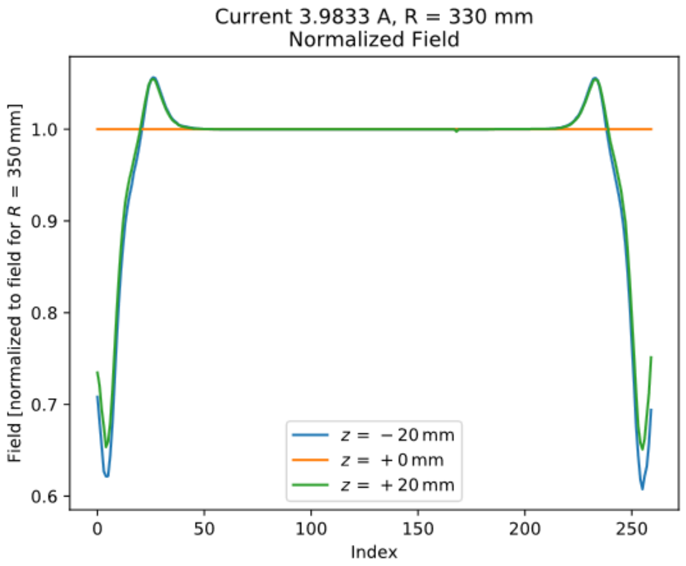
Field of I=3.9833A and z=-20mm In-plane horizontal comparison



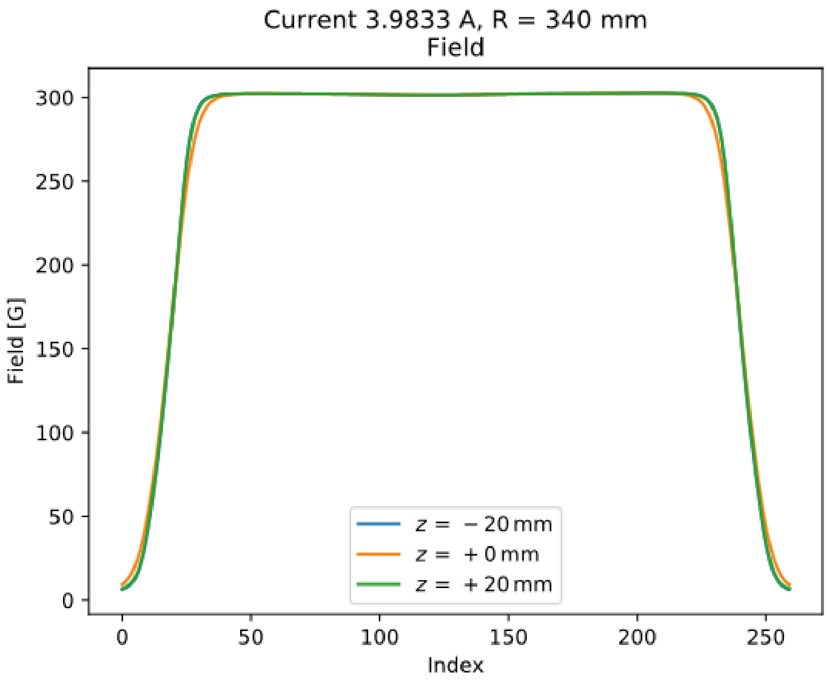


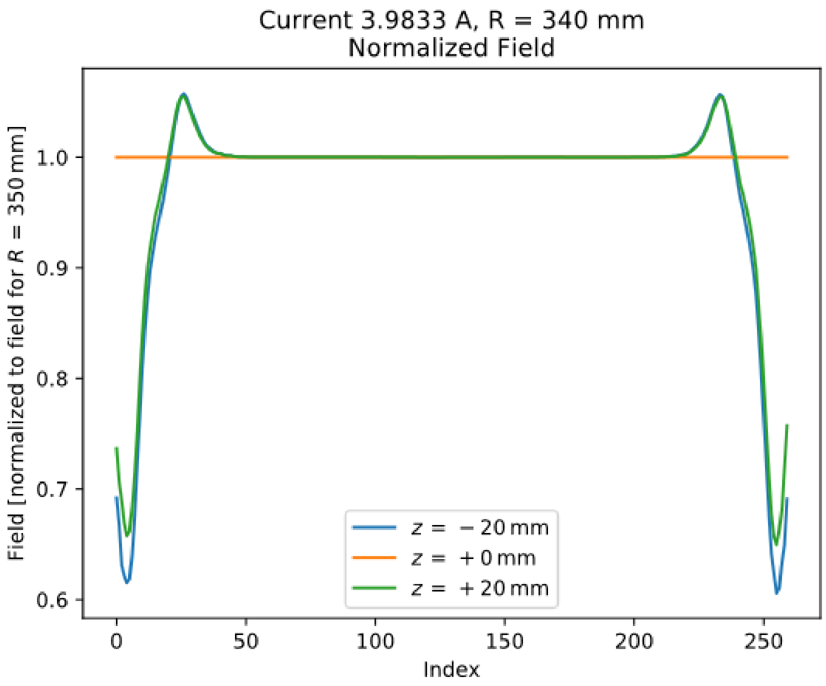
Field of I=3.9833A and R=330mm Vertical comparison



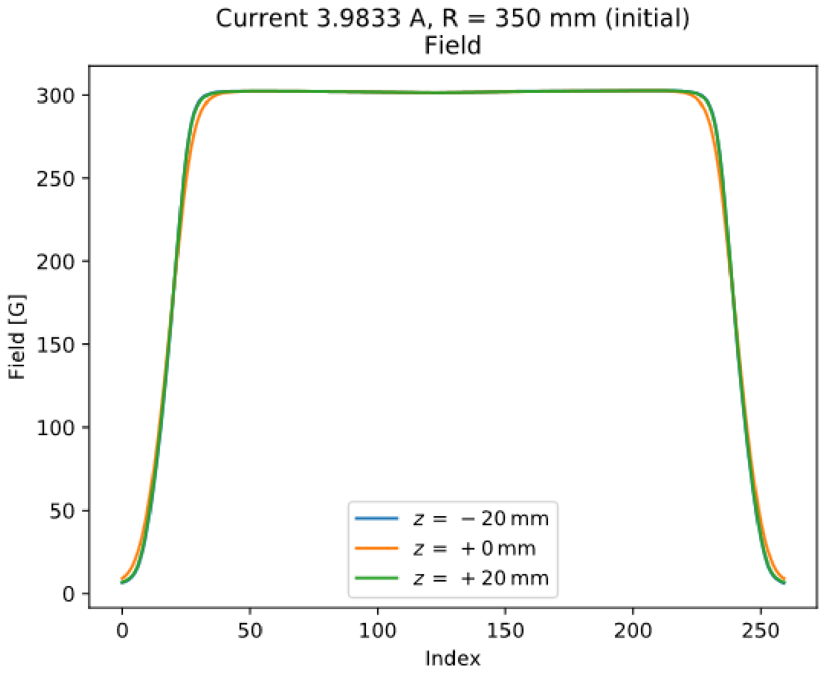


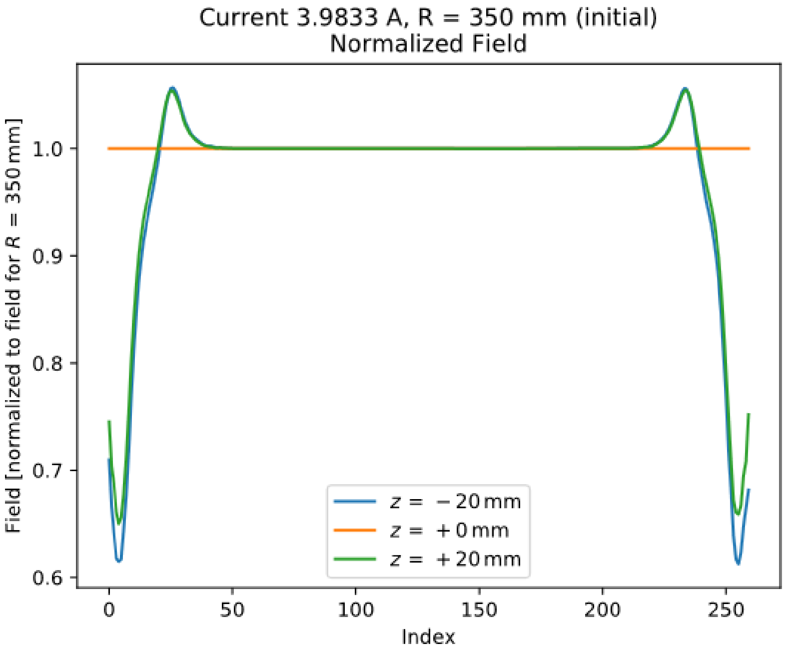
Field of I=3.9833A and R=340mm Vertical comparison



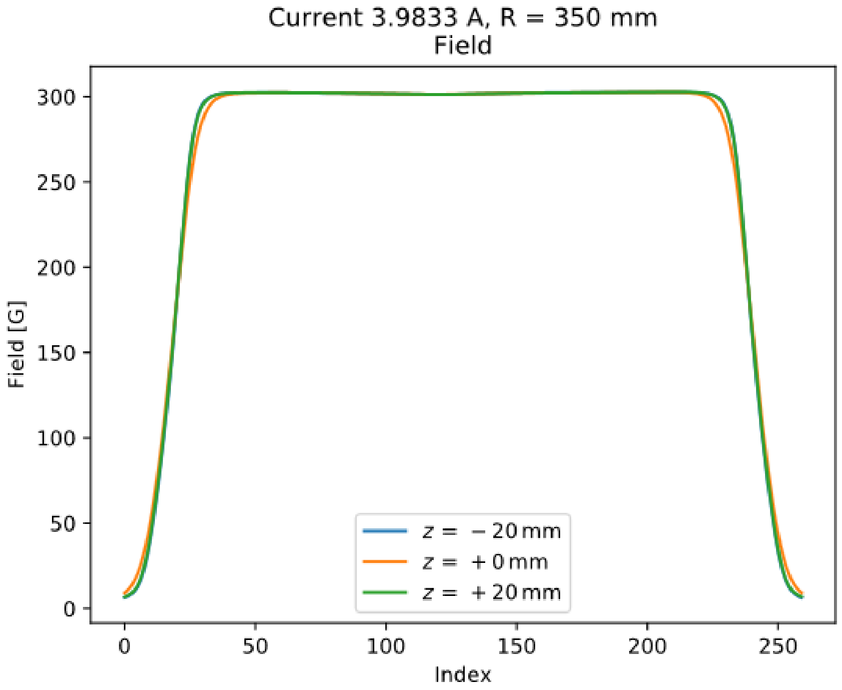


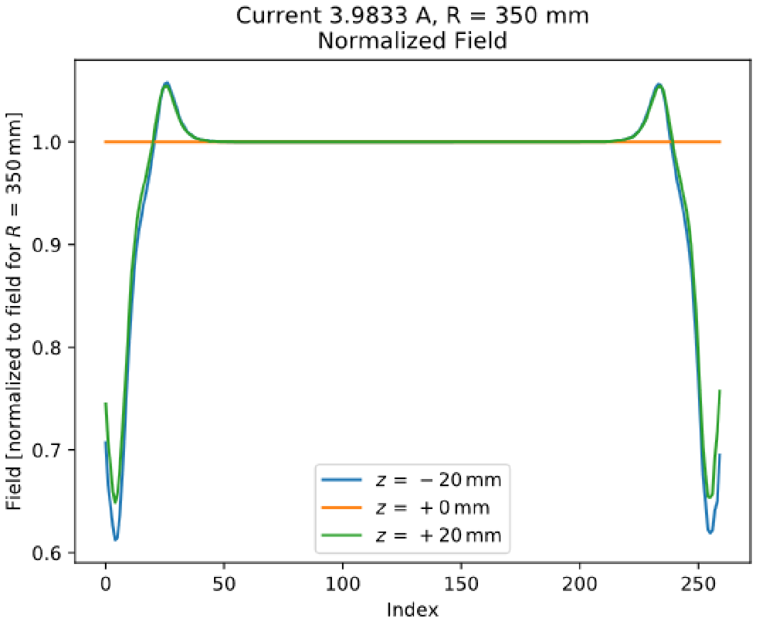
Field of I=3.9833A and R=350mm_Init Vertical comparison



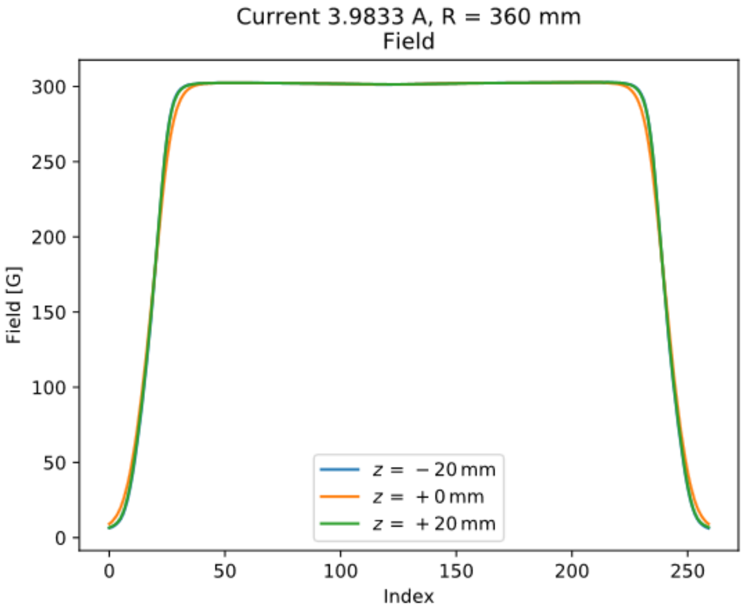


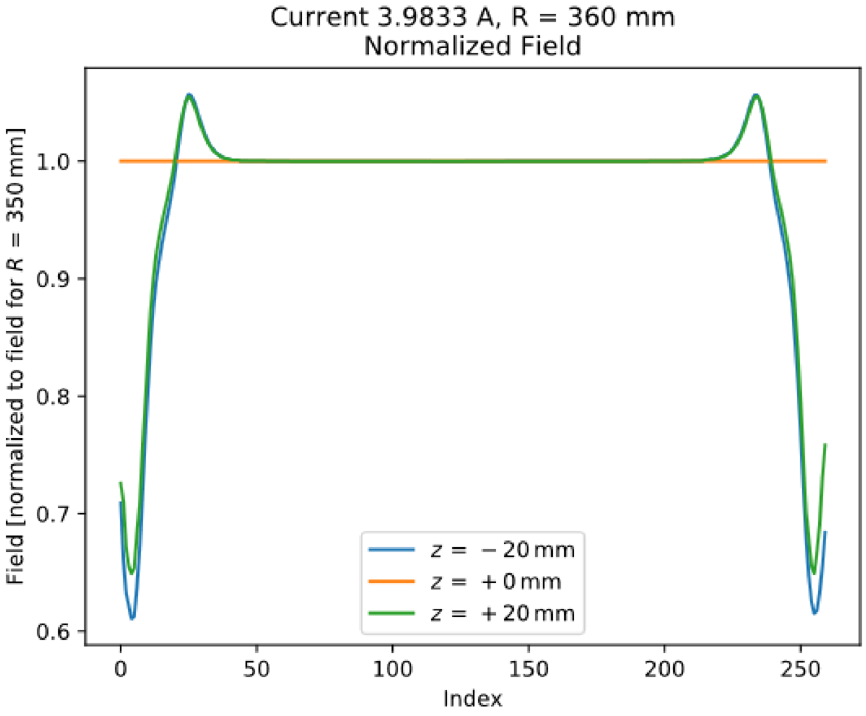
Field of I=3.9833A and R=350mm Vertical comparison



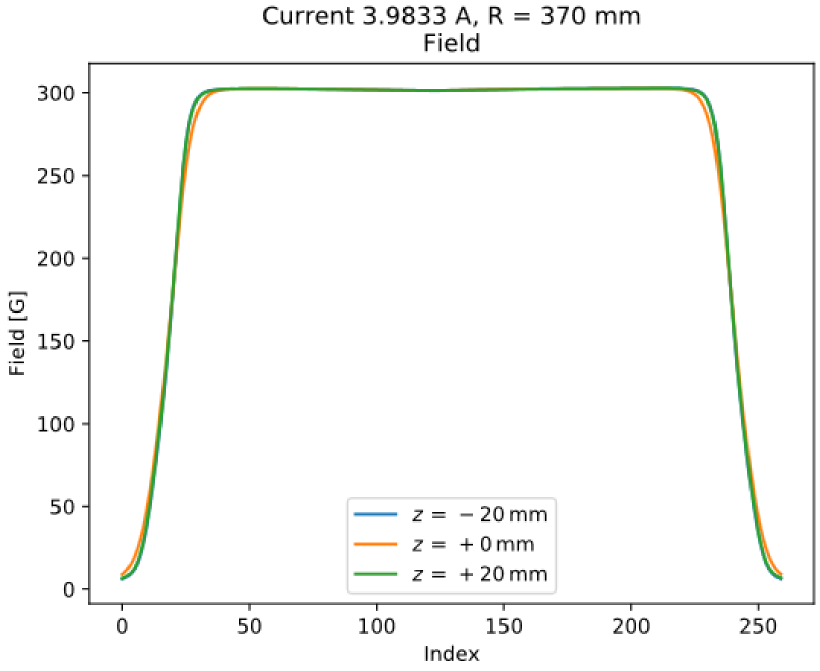


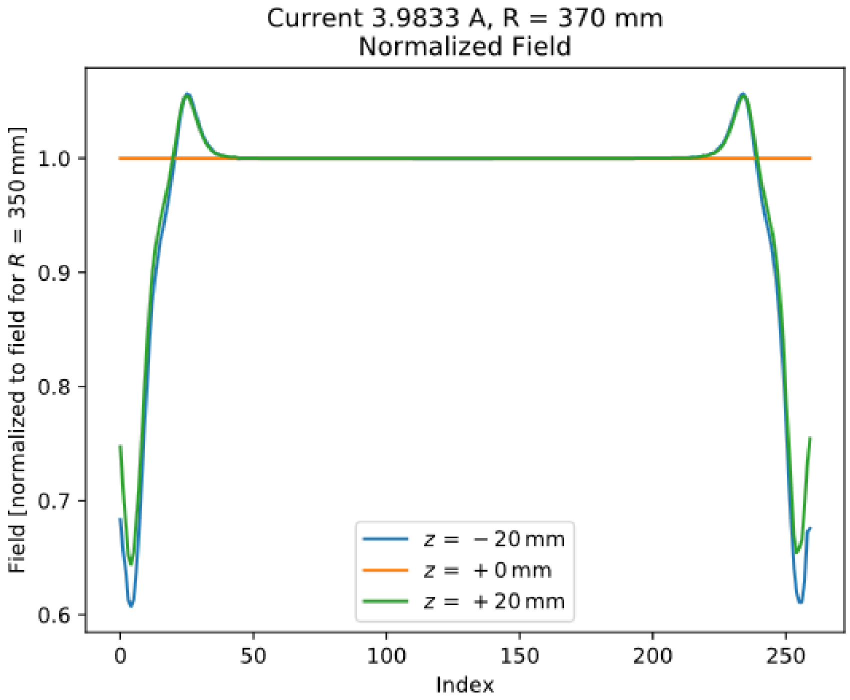
Field of I=3.9833A and R=360mm Vertical comparison





Field of I=3.9833A and R=370mm Vertical comparison





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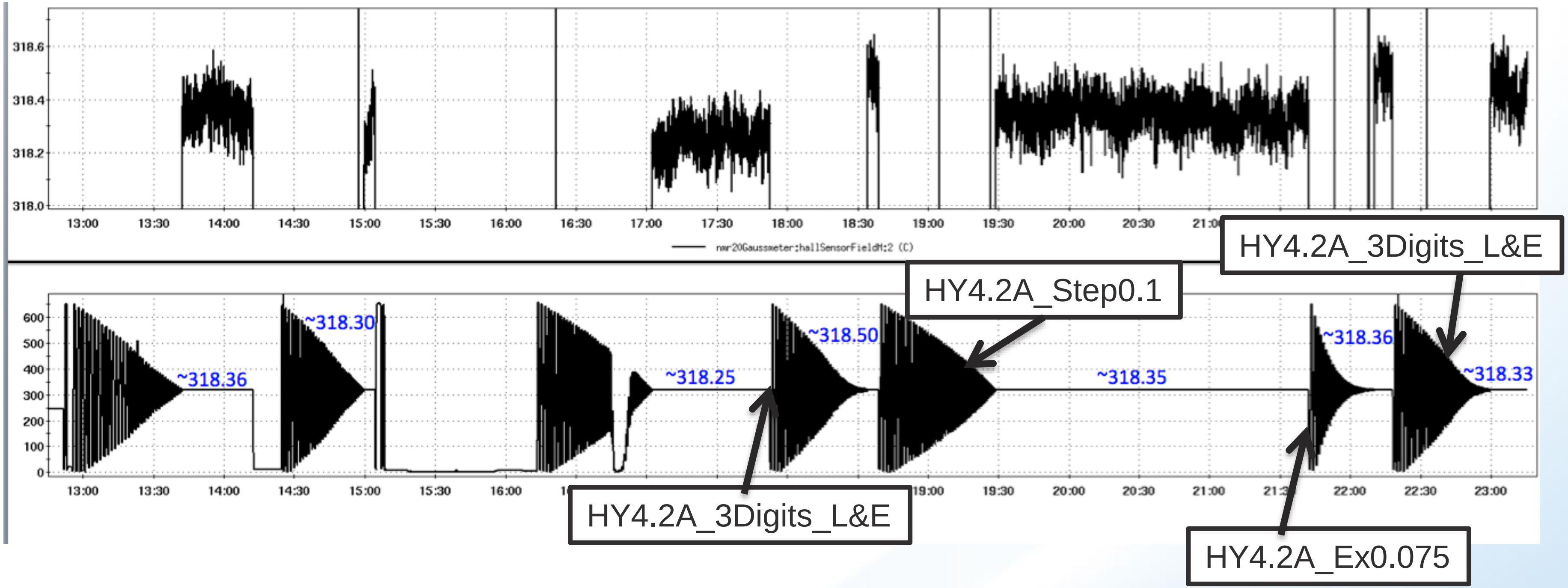
A FEW MORE THINGS

Hysteresis Loop



	HY4.2A_3Digits_L&E	HY4.2A_Step0.1	HY4.2A_Ex0.075	HY4.2A_3Digits_L&E
Hall	318.5	318.4	318.5	318.5
NMR	318.486	318.302	318.430	318.394