Development of APPLE-III Undulators for FLASH

An Afterburner for FLASH2

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on behalf of DESY’s Insertion Device (FS-US) and Mech. Design Group (ZM1)

FEL2022 Conference, Trieste, 25.08.2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

New Scientific Demands for Free Electron Lasers

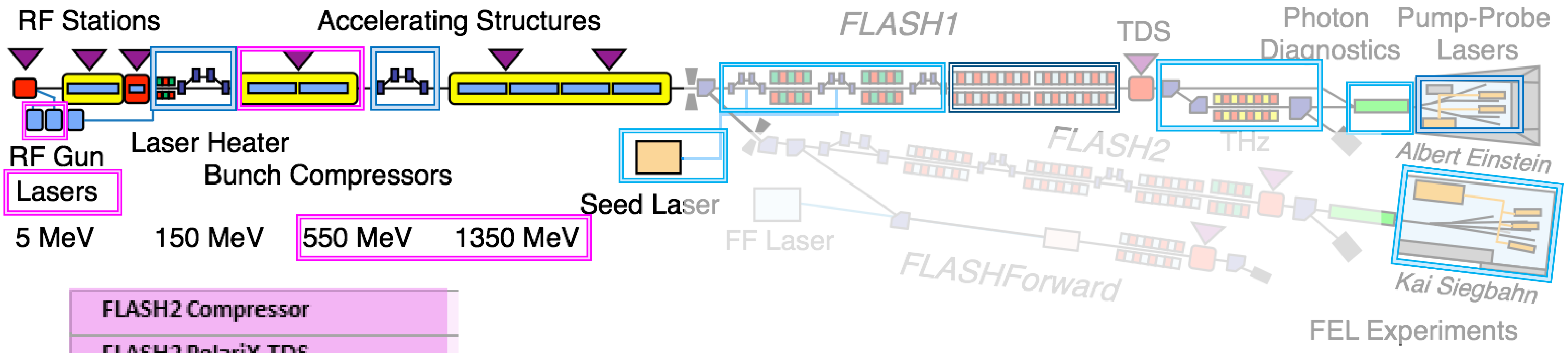
and their realization within the FLASH2020+ project (TUP51)

User's „dream machine“	Scientific purpose	FLASH2020+ plans	FEL line	@ FEL2022
Extended wavelength range	Reach O and N K-edges and 3d metal L-edges	Increase accelerator energy, use advanced undulator schemes	FLASH1 and FLASH2	MOP37
Variable polarization	Circular dichroism for magnetism and chirality	Flexible APPLE-III undulators and afterburner	FLASH1 and FLASH2	THBI1
Flexible pump-probe schemes	Resonant excitations	Flexible schemes with optical laser and FEL options for multi-colour pump-probe experiments	FLASH1 and FLASH2	FRAO4
Fourier-limited pulses	Stable, small bandwidth spectroscopy and coherence applications	Laser-manipulation of electron bunches at 1MHz: **Seeding**	FLASH1	TUP42
Ultrashort pulses at 1fs and shorter	Ultimate temporal resolution, highest power	New undulator combinations (currently not funded)	FLASH2	MOP39
CW operations (100kHz)	Low hit rate experiments	*Postponed as long-term goal (2030+)*		

Courtesy L.Schaper

FLASH2020+

Current Shutdown ...and Seeding Upgrade in 2024/25



FLASH2 Compressor
FLASH2 PolariX TDS
Linac Energy Upgrade
New Injector Laser
FLASH2 Afterburner
New FL1&FL2 Pump-&Probe-Lasers
New BC1 and LH
New BC2
New Beamline FL23

Seeded FLASH1
THz Source
New Beamline FL11
New Photon Diagnostics FLASH1
New Undulator Schemes FLASH2
New Lasing Concept FLASH2

***Combination of HGHG and EEHG*:**

Fully coherent pulses with
variable wavelength (60 – 4 nm)
tens of fs duration and
1MHz repetition rate.

Variable polarization: ***Apple III radiators***

Courtesy L.Schaper

Topics

APPLE-III Afterburner for FLASH2 ↘

full scale prototype for FLASH1 Seeding IDs

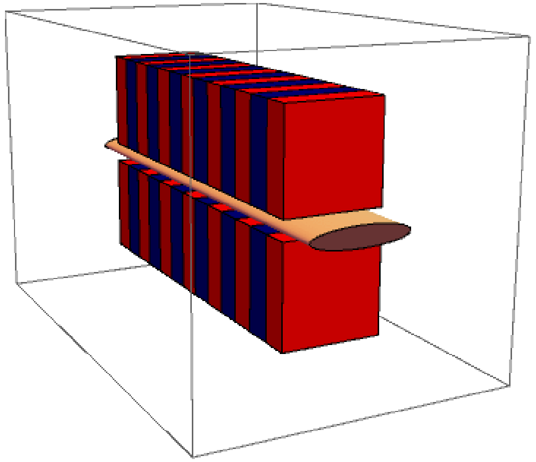
- Introduction
- Specifications
- Concept & Prototype
- Magnet Design
- Mechanical Design
- Magnetic Measurements

CoWorkers

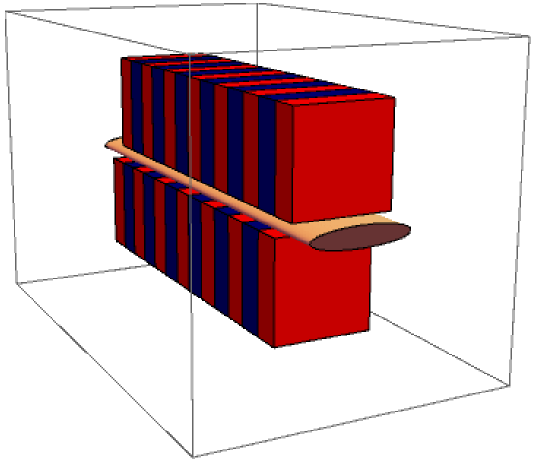
Major Contributions by

- Undulator Group FS-US
  - Jacques Abenhaim
  - Philip Eckoldt
  - Kathrin Götze
  - Paul Neumann
  - Patrick N'Gotta
  - Andreas Schöps
  - Sayali Telawane
  - Pavel Vagin
  - Thorsten Vielitz
- Mechanical Design Department (ZM1)
  - Hilmar Bienert
  - Hakan Bolat
  - Daniel Meissner
  - Torsten Ramm
  - Peter Talkovski
- Production Planning (ZM2)
  - Björn Hager
  - Matthias Schacht
  - Martin Steudel
  - Florian Andersen (ZMQS)
- Photon Science Machine Shop (FS-BT)
  - Markus Kowalski and colleagues
- FLASH Team (L.Schaper, E. Ferrari et al.)
- Valuable input by J.Bahrdt (HZB) and T.Schmidt (PSI)

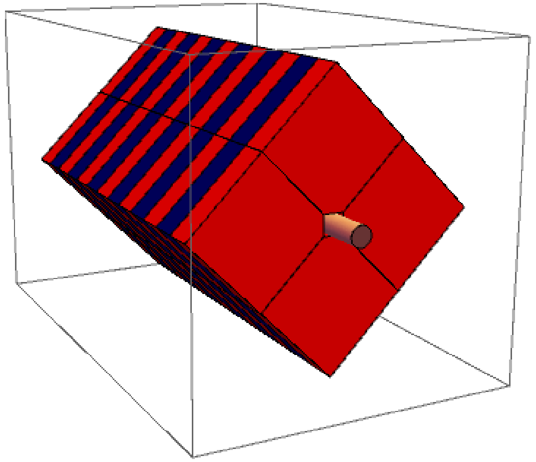
Permanent Magnet Undulators



Variable gap

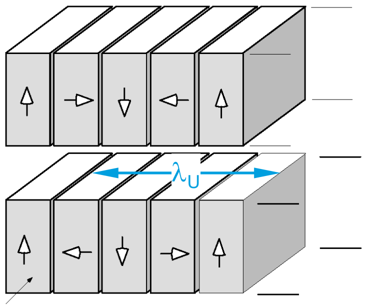


Adjustable phase

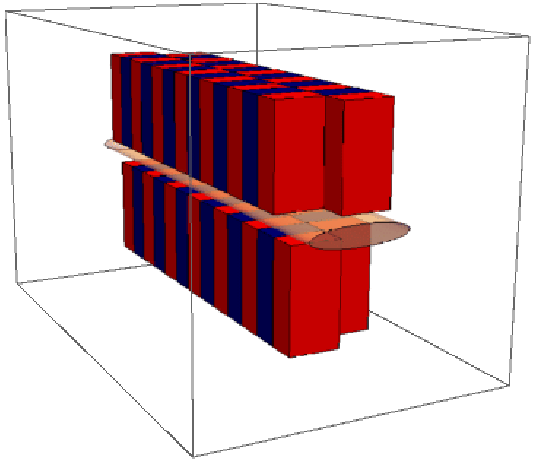


DELTA

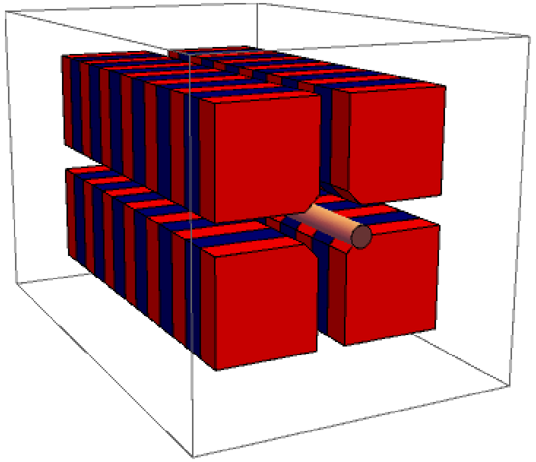
Period length λ_U



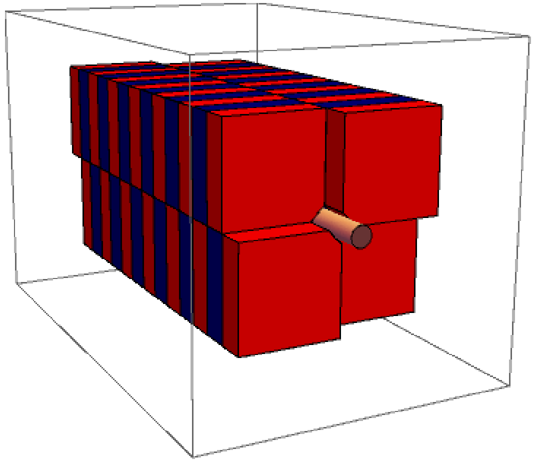
17.5mm for APPLE-III afterburner @FLASH2



APPLE-II

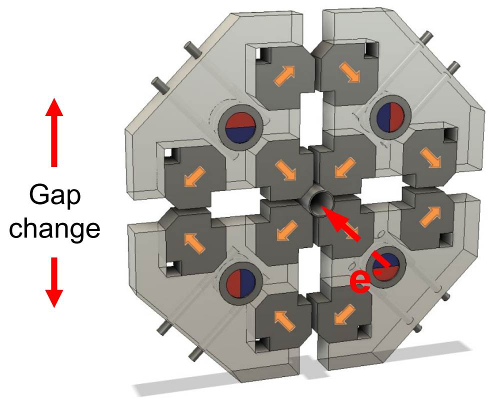


APPLE-X



APPLE-III

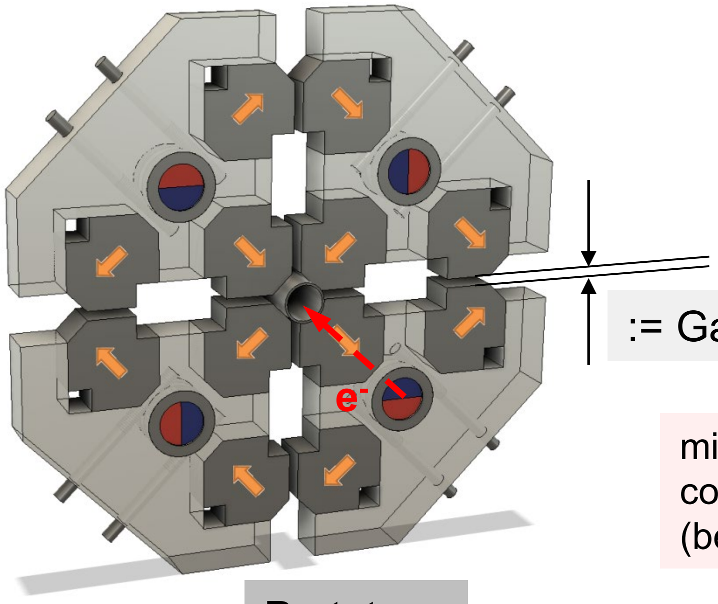
J. Bahrdt et al., *Proc. FEL Conference 2004, 610*
Proc. SRI Conference 2003, AIP CP 705, 215 (2004)



APPLE-III

APPLE III – Concept and Overview

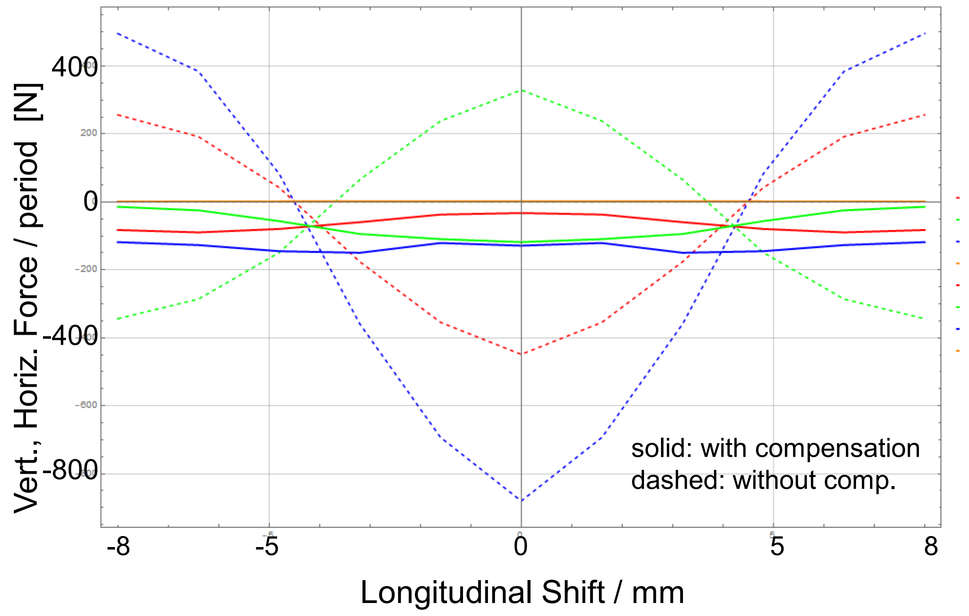
for FLASH2 Afterburner and FL2020+ Seeding IDs



Prototype

20x20mm2 NdFeB magnets with cutouts and clipped edge

min. diagonal magnet distance: 8.0mm corresponds to Gap=1.0mm (beam pipe: d_{outer}=7mm, $\varnothing_{inner}$=6mm)



Force Compensation Concept (Apple2):
BESSY, SRI2018, AIP Conf. Proc. 2054, 030031 (2019)

Features:

- APPLE III provides highest field
- Force reduction up to factor of 8
- Half period → Full period keepers
- Correction magnet → replaced by virtual shimming of keepers

Most prominent change from prototype towards final structure

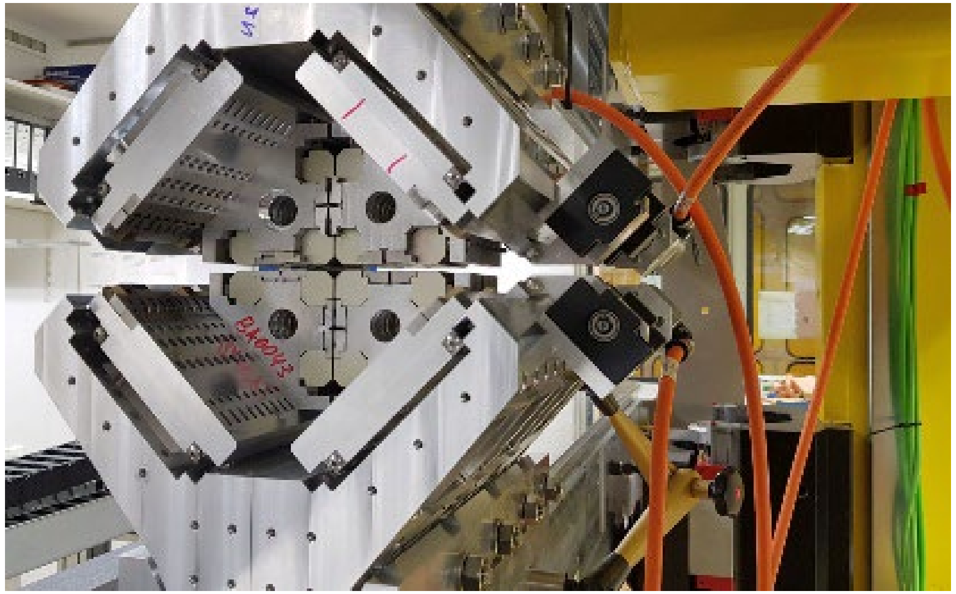
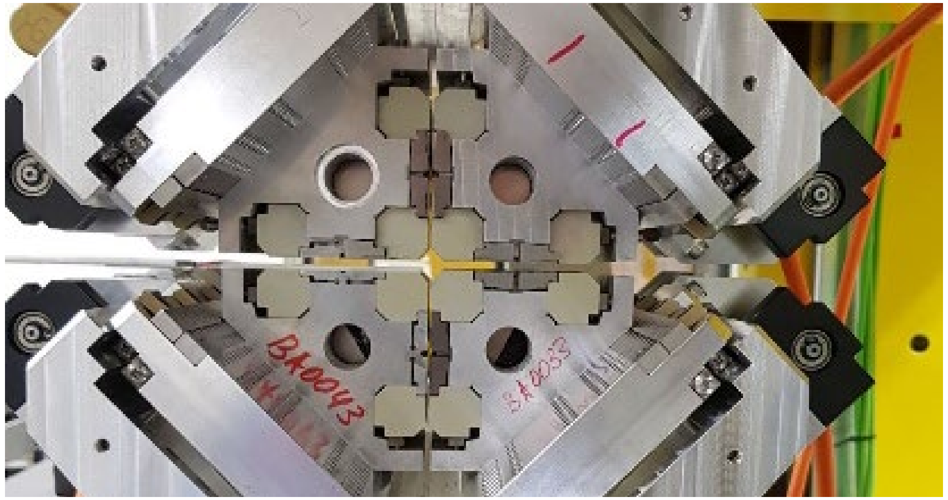
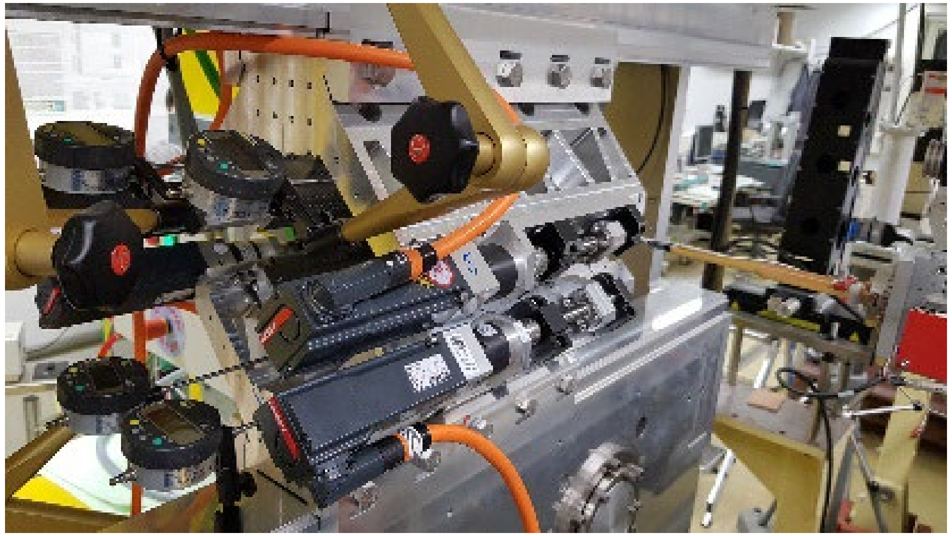
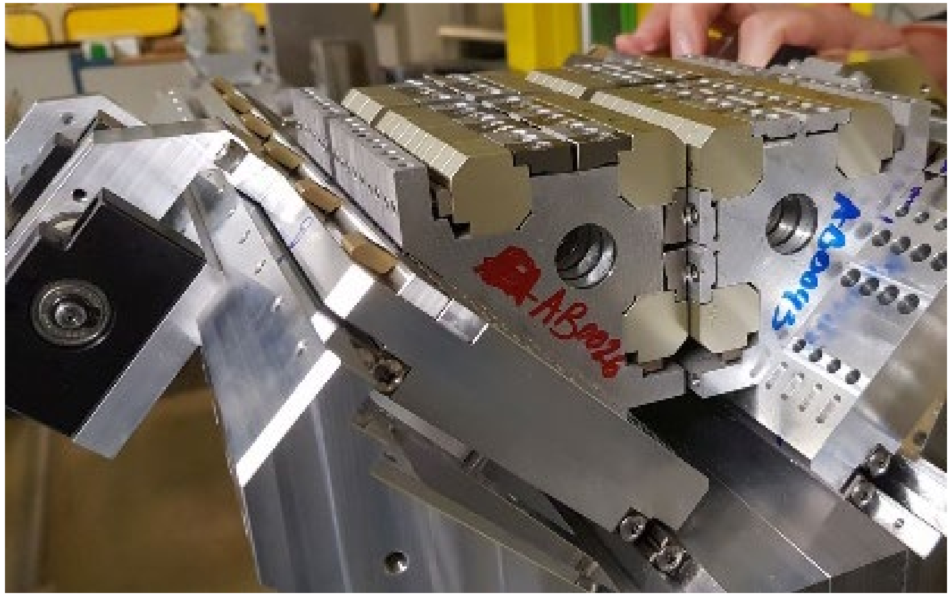
$$K = K_{lin} = K_{circ} = \frac{e}{m_0 c} \lambda_U B_{eff}$$

$$\lambda_R = \frac{\lambda_U}{2\gamma^2}\left(\frac{K^2}{2} + 1\right)$$

APPLE-III Prototype Test Structure

per = 16mm

N~16

APPLE III Afterburner (FLASH2) – Parameter Range

Wavelength specification

- 1.39 – 1.77 nm (890 – 700 eV)
- Linear and circular polarization

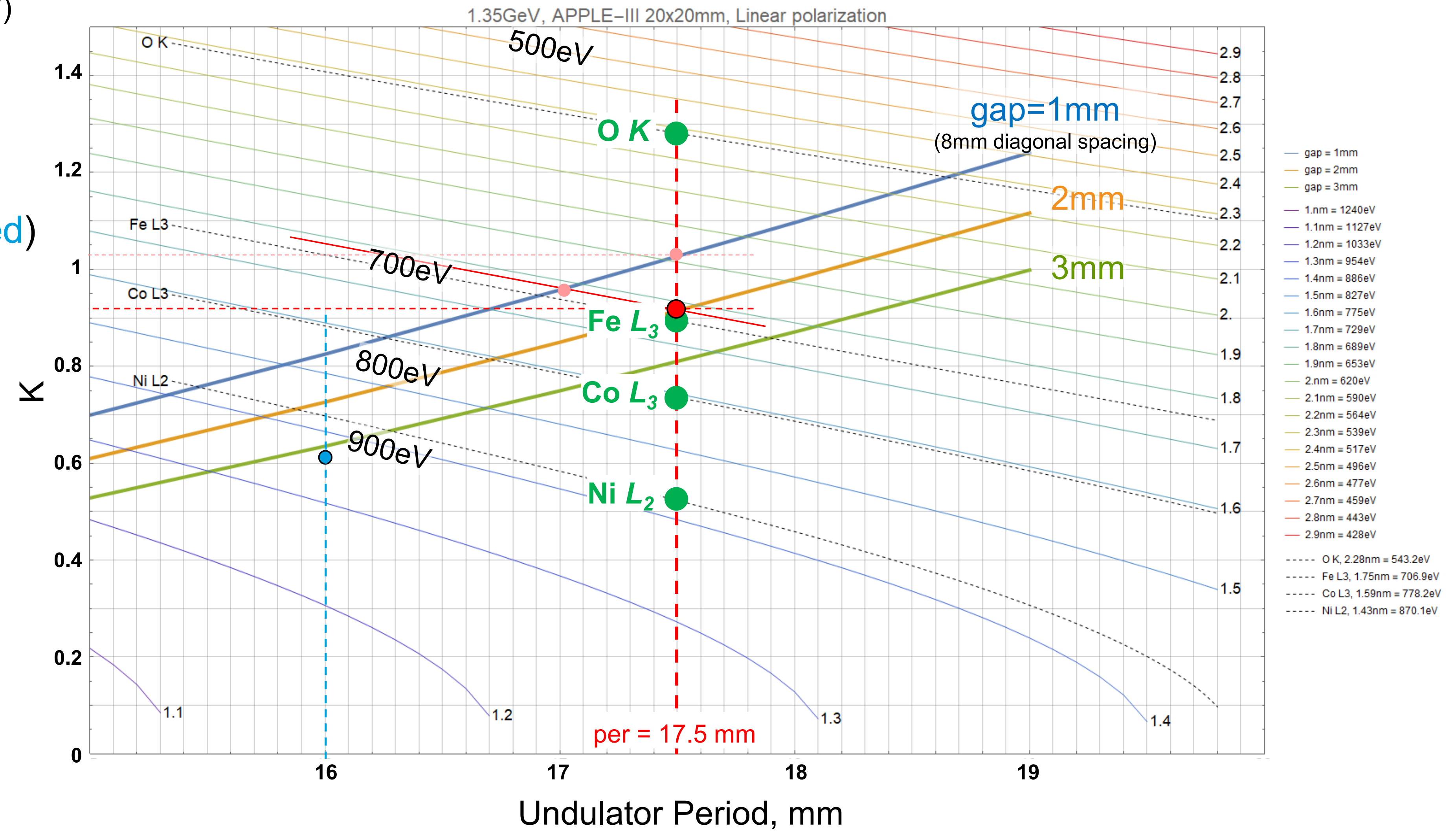
Period length selection

prototype results (measured)

- per=16mm, gap=3.2mm
- K=0.61

final specification

- per=17.5mm, gap=1.0mm
- K=0.92
- includes K~0.1 margin for compensation of errors
- B=0.56T
- Phase error < 10° rms
- L=2.5m



APPLE-III Transverse Field Dependence

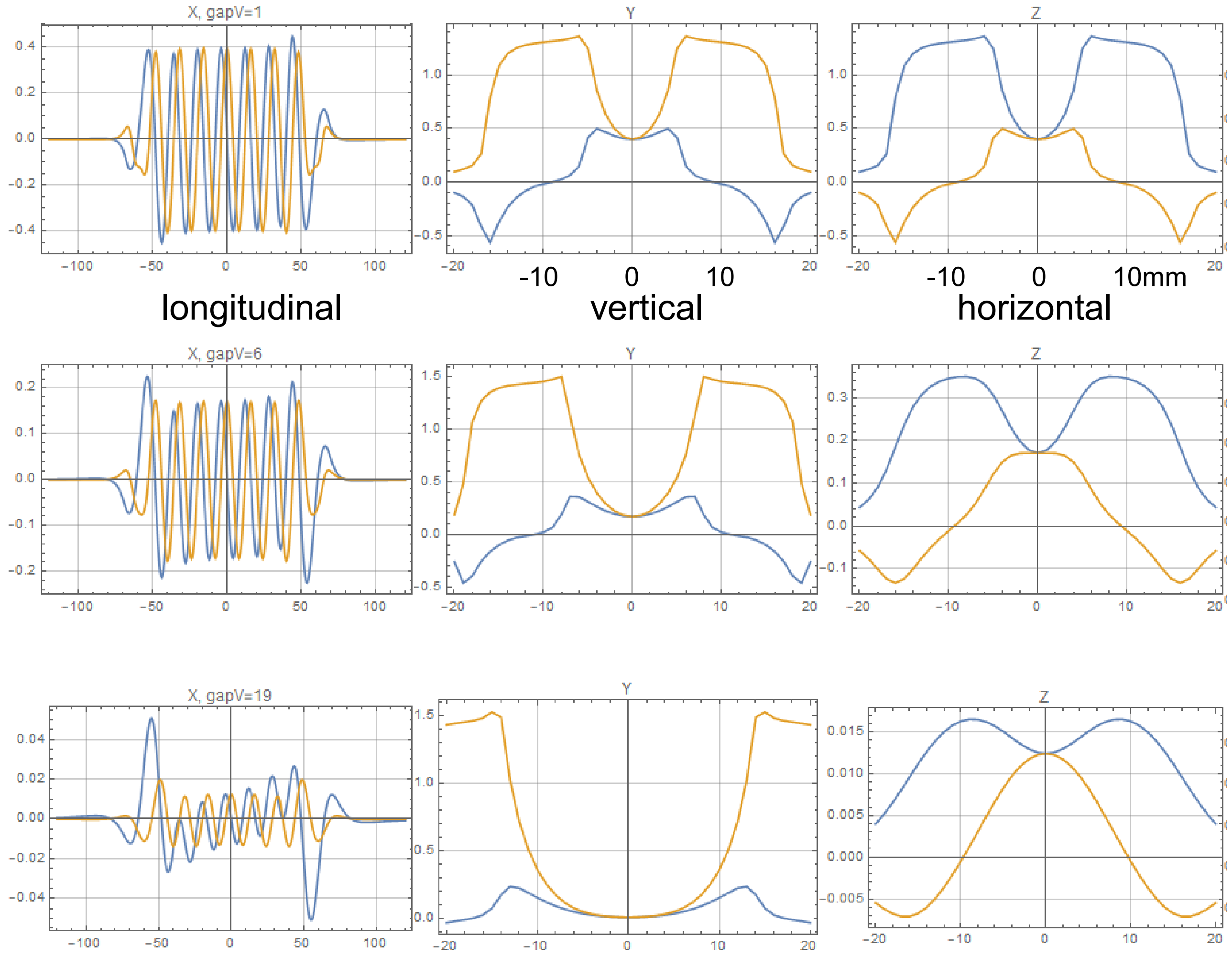
Circular mode

By – vertical
Bz - horizontal

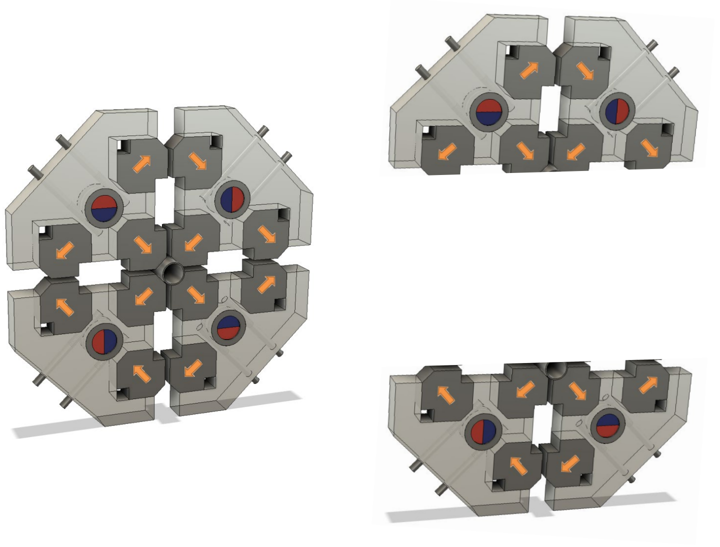
gap=1

gap=6

gap=19



- Symmetric configuration at minimum gap
- Focusing effect of vertical field
  - for all gaps
- De-/Focusing of horizontal field
  - depending on gap

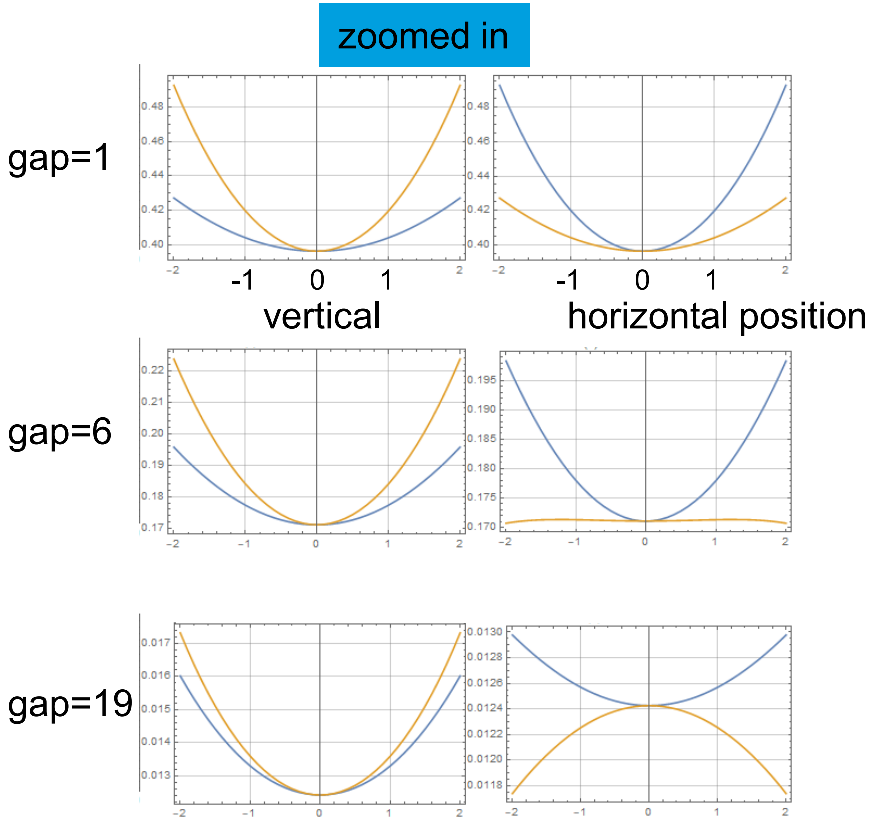


APPLE-III Transverse Field Dependence

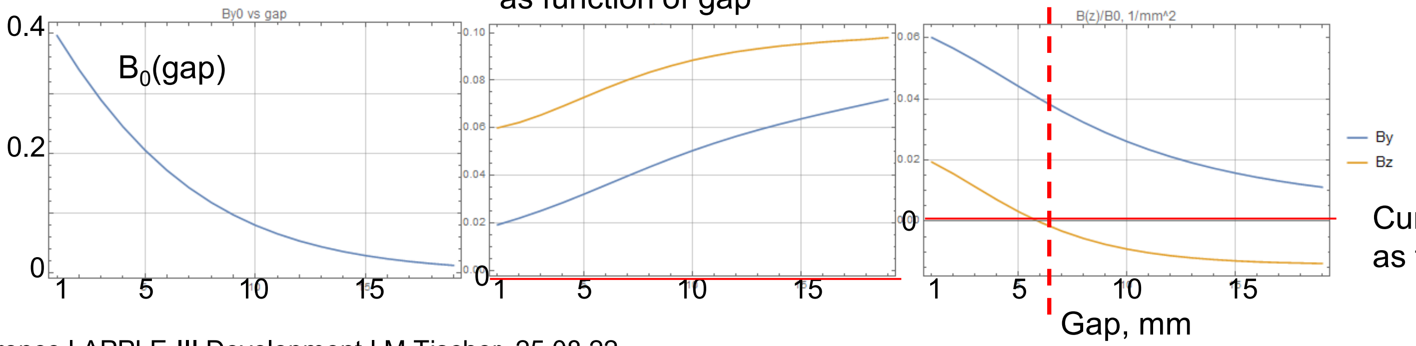
Circular mode

By – vertical
Bz - horizontal

- Symmetric configuration at minimum gap
- Focusing effect of vertical field
  - for all gaps
- De-/Focusing of horizontal field
  - depending on gap
  - ~”friendly” within the useful gap range



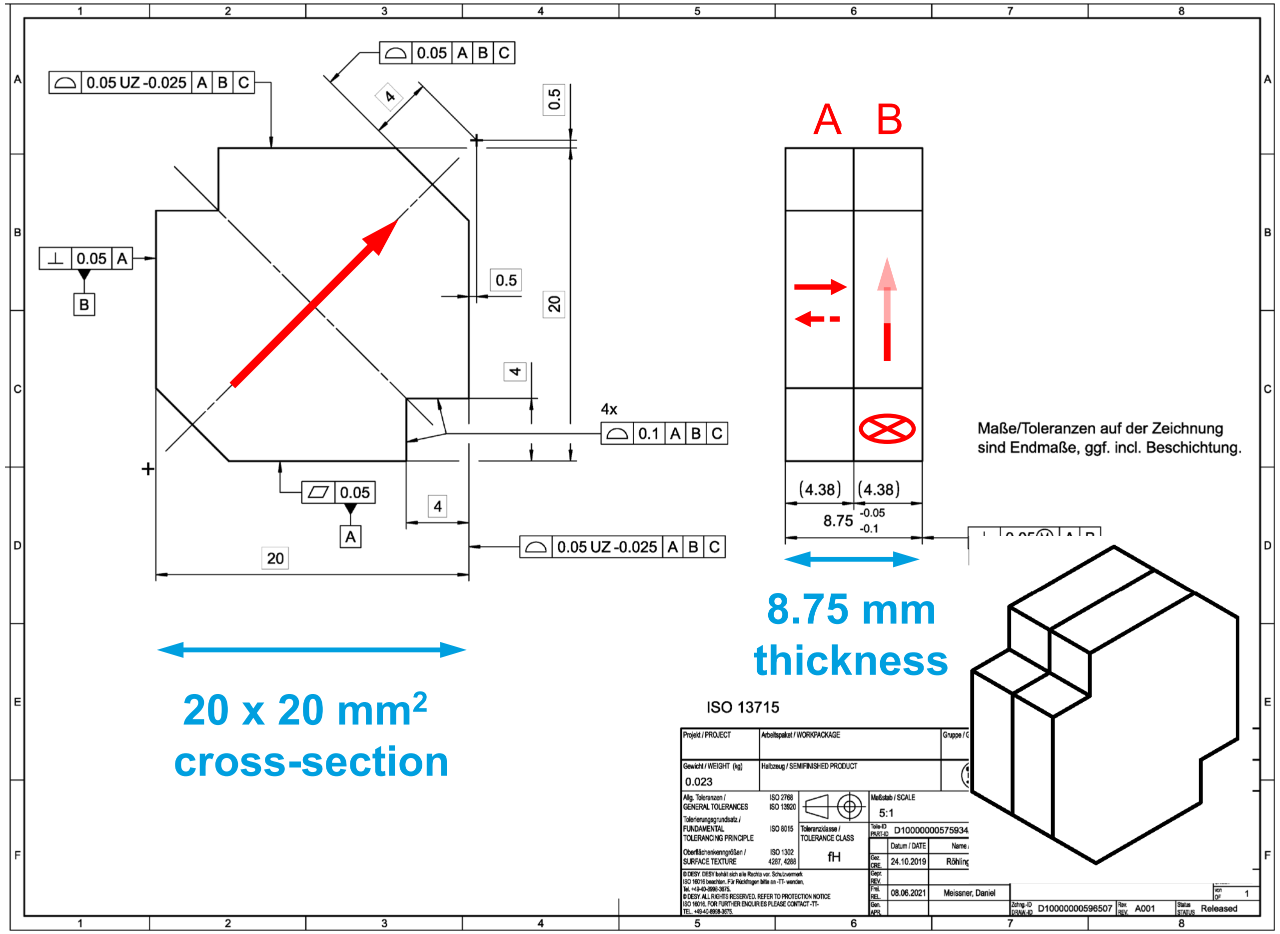
Curvature ($\sim y^2$) vertical as function of gap



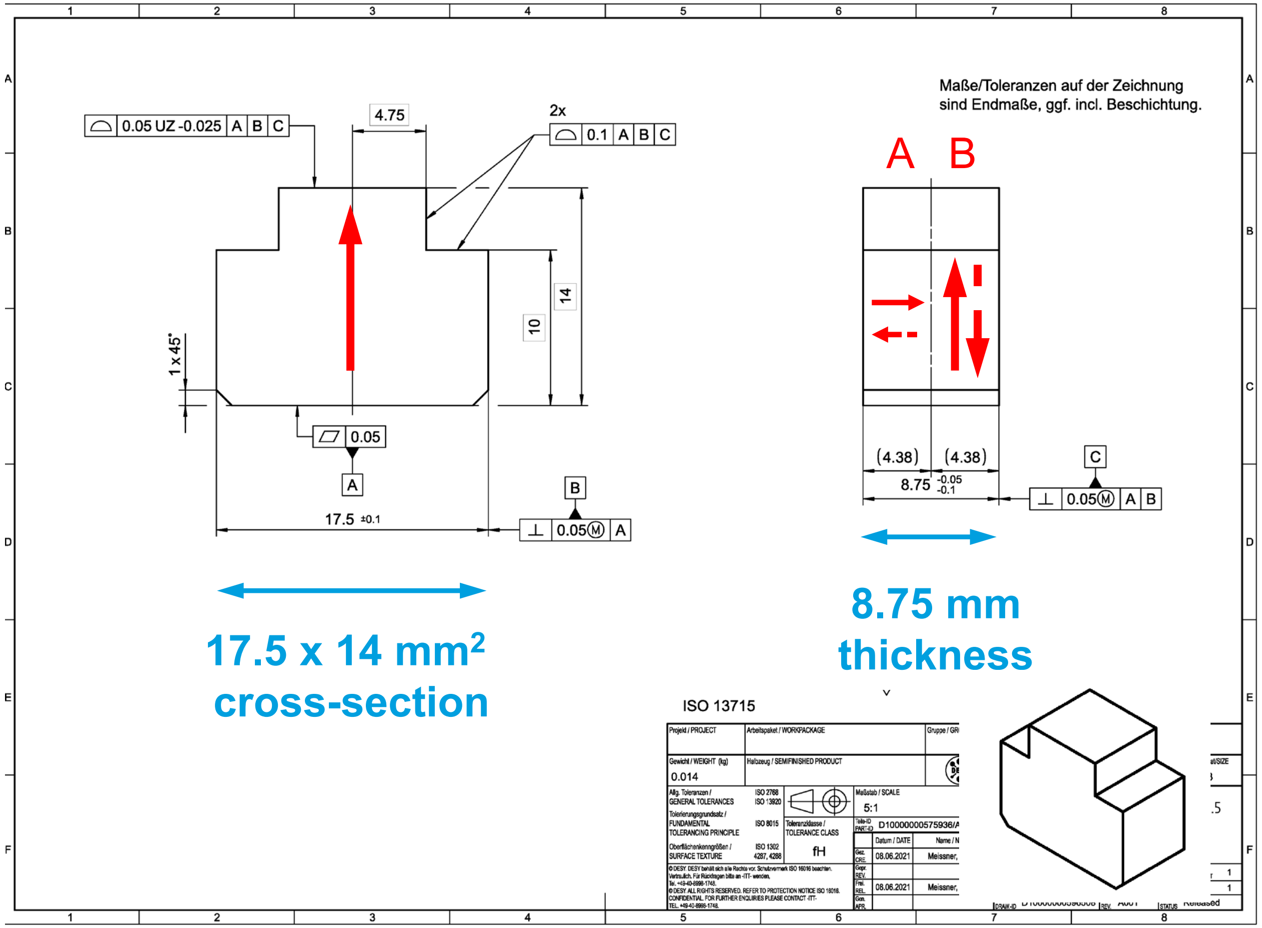
Curvature ($\sim z^2$) horizontal as function of gap

Magnet – Mechanical Dimensions

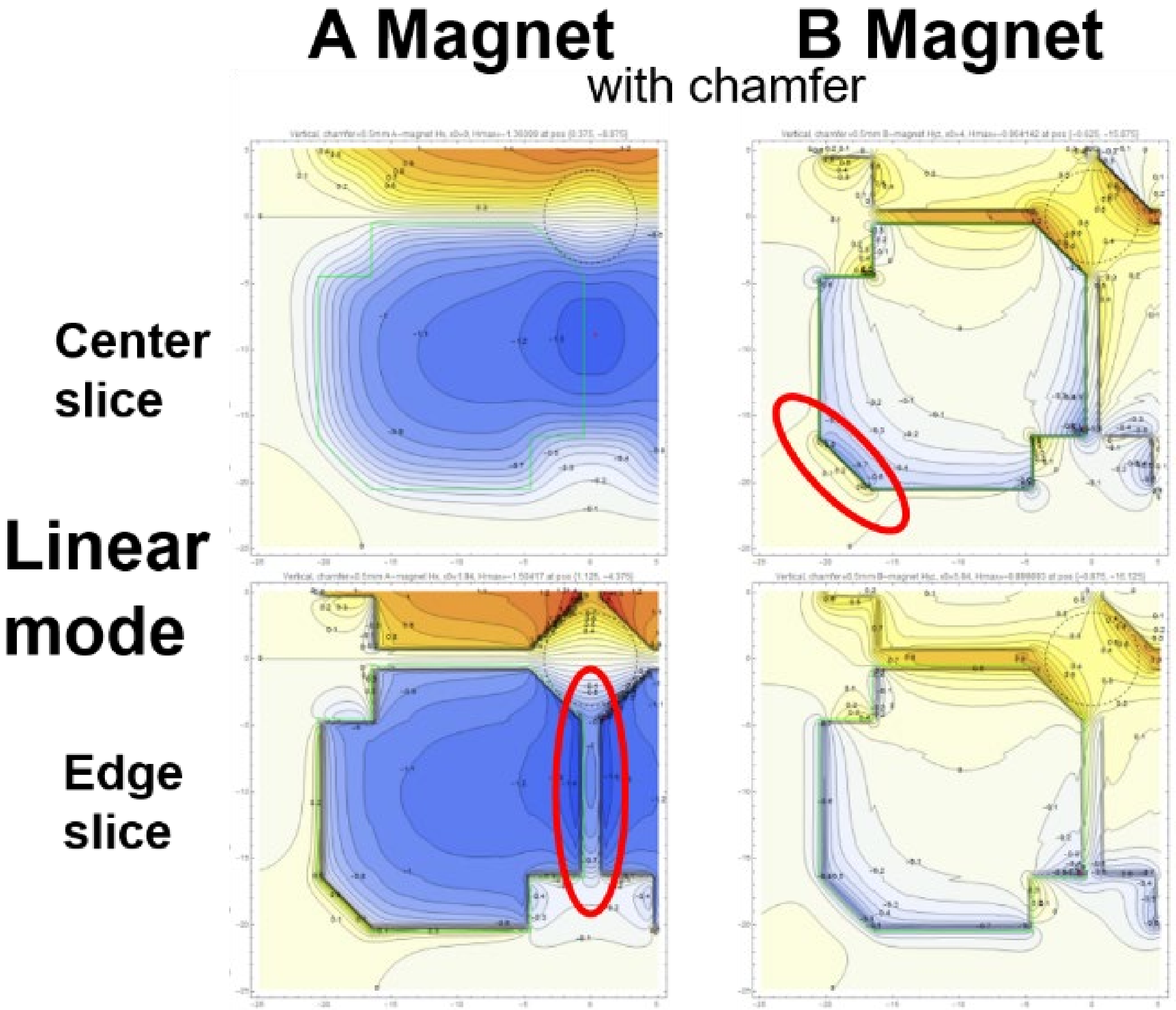
Main Magnet Pair



Force Compensation Magnet Pair



Demagnetizing Fields

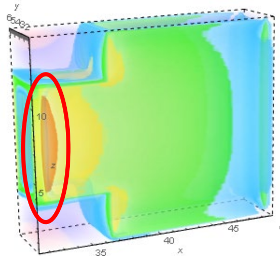


- Maximum demagnetizing fields in between rows for A and on opposite edge for B magnet
- Higher demagnetizing fields for A magnets: 18kOe, B magnets: 15kOe → different grades for A and B
- Highest demagetizing fields for force compensation A magnet, ~20kOe

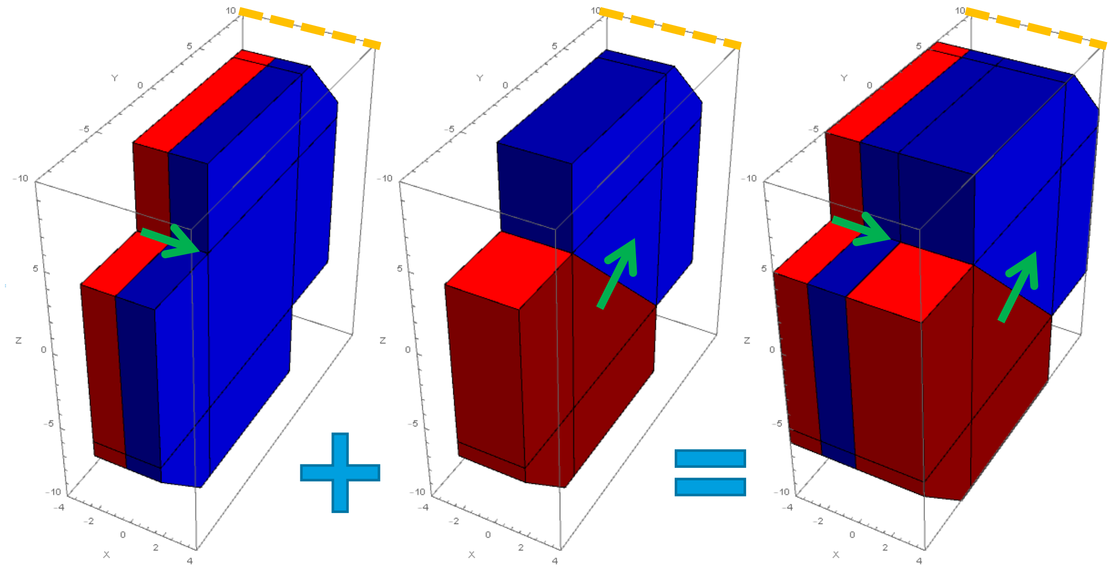
Magnet Specification (NdFeB)

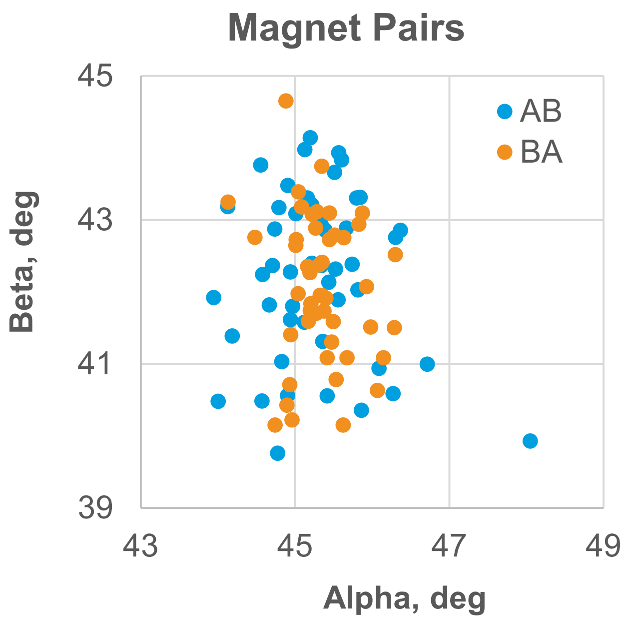
	A	B	Comp.Magn.
min. Br	1.32 T	1.36 T	1.26 T
min. Hcj	21 kOe *	18 kOe *	26 kOe

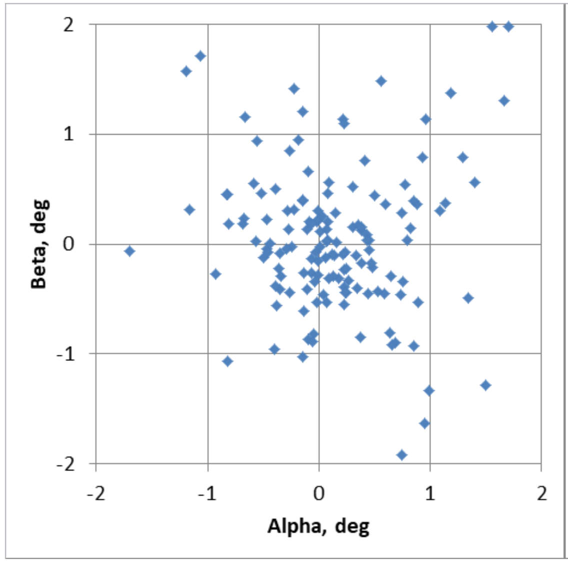
* before GBD-treatment (+5kOe)

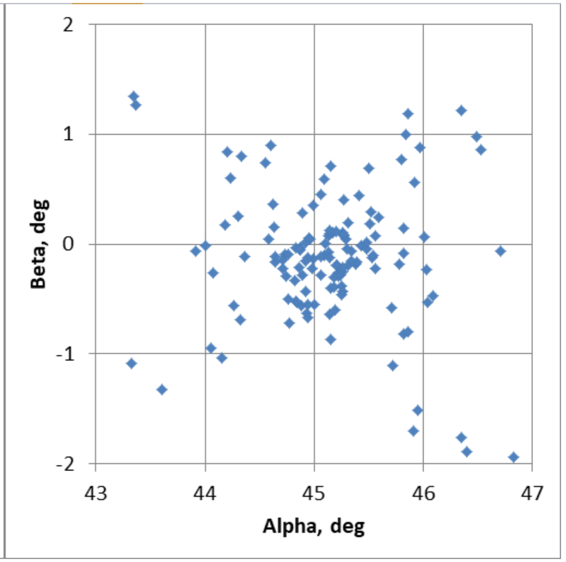


Combined (glued) Single Magnets



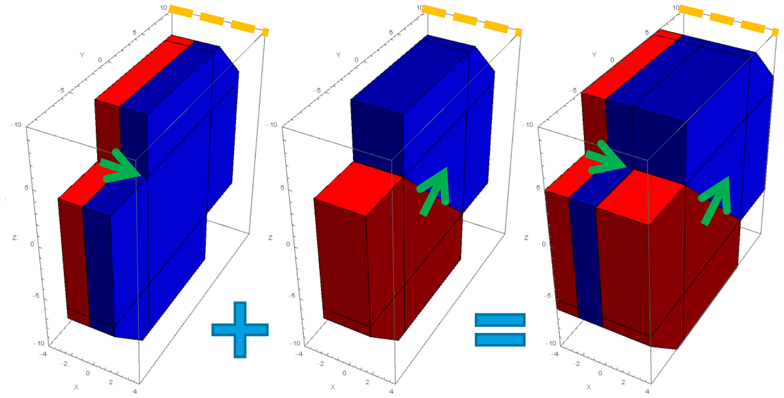






- Magnet sorting of single magnets (only for prototype)
- Magnetic errors of single magnets are similar to usual magnets ~0.7° rms, despite of smaller magnets and 45° magnetization direction
- Angular error after gluing slightly increased to 1.2° rms, absolute values of magnetization angle cannot be interpreted directly

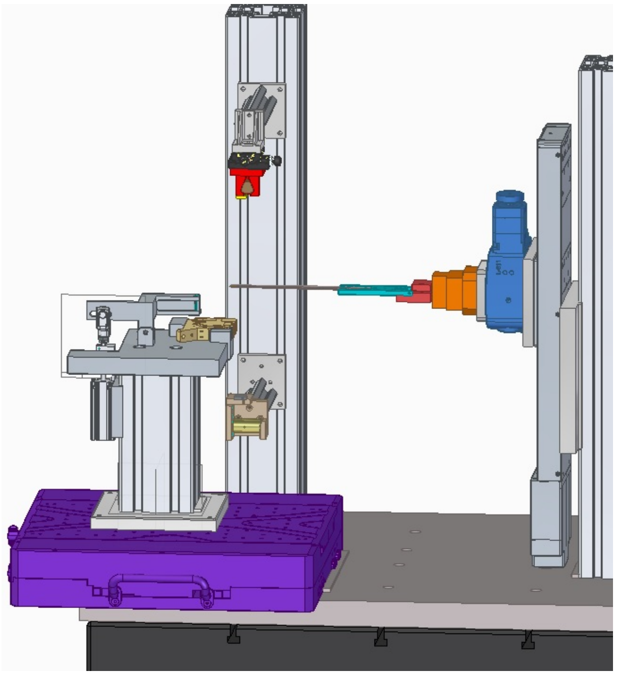
Magnet – Manufacturing & Characterization



Fabrication of magnet pairs (specification to vendors)

- Production of both, single A and B magnets from die-pressed TP-material
- Magnet errors: 1% Mr scatter and 1.5° angular errors
- GBD treatment for all single magnets
- Gluing of single magnets to AB-pairs in *fully randomized* configurations
- Coating of magnet pairs

Magnetic measurements



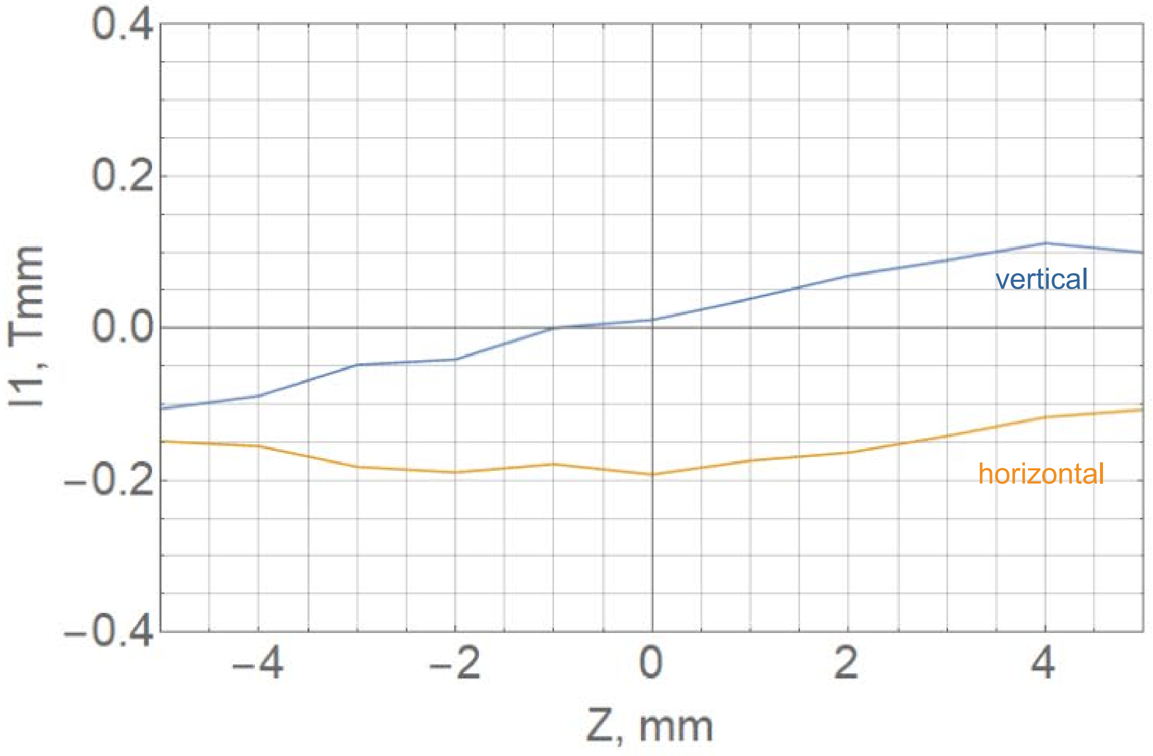
- Helmholtz coil measurements of completed AB- and BA-magnet pairs
- Hall mapper ("camera") measurements of magnets (possibly)
- Short stretched wire stand for assembled magnet keepers
  - direct measurement of field integral errors on-axis
  - additionally Hall probe for field amplitude/phase error

Magnet structure assembly

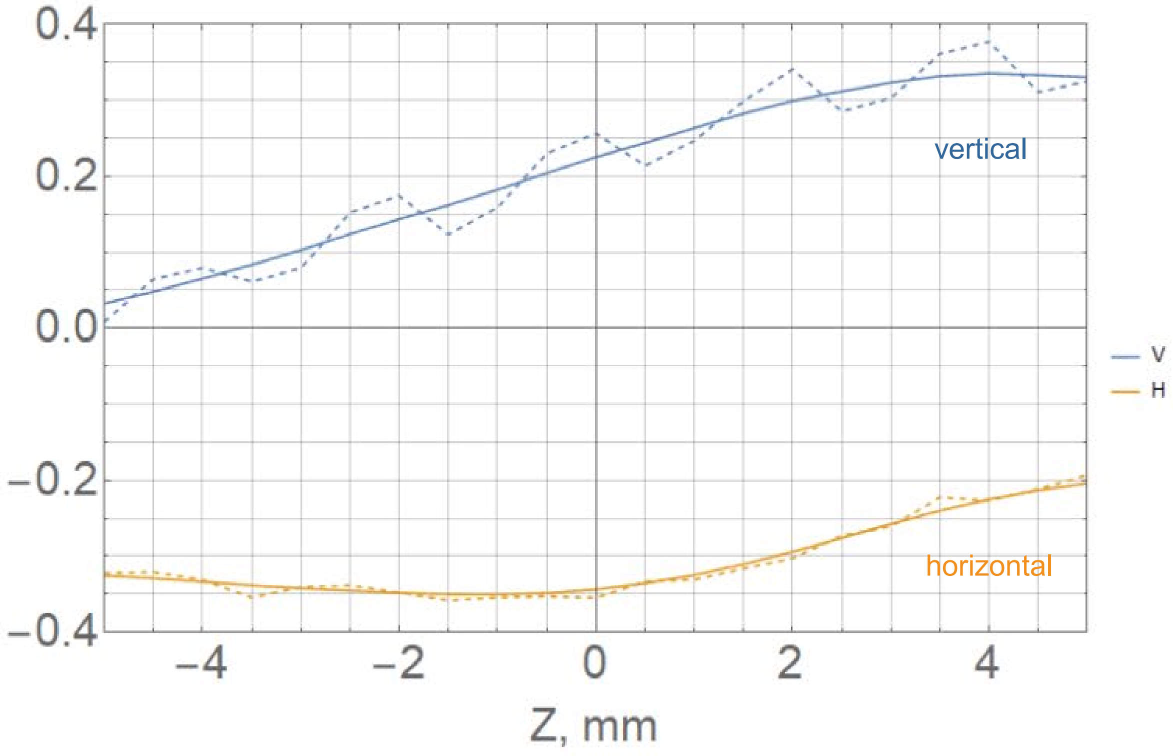
- Sorting of keepers based on Helmholtz, SW and Hall probe data
- Magnetic measurement and pre-shimming of upper and lower girders separately

Test Sorting of Short Prototype Structure

Assembled structure (16 periods) measured with Hall probe bench + earth field



Prediction from individual magnet measurements with stretched wire (background earth field subtracted)



Reasonably good agreement except for some global offset due to an imperfect consideration of the ambient field contribution

APPLE-III Field Error Correction

Decomposition of field errors

Two measurements with different shift of one axis.

M1 = B1(x) + B2(x) + B3(x) + B4(x)
M2 = B1(x + shift) + B2(x) + B3(x) + B4(x)

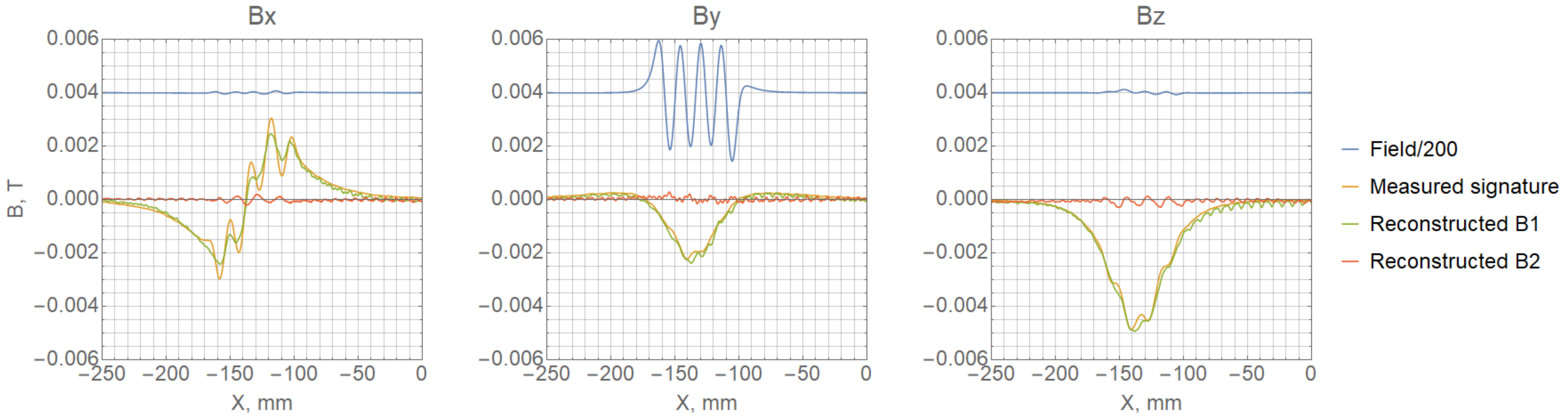
Difference of two measurements eliminates B234

D = M2 - M1 = B1(x+shift) – B1(x)

Looks like derivative: (f(x+dx) – f(x)) / dx, with dx = shift

"integrated" back as: **B1[i] = B1[i-shift] + D[i]**

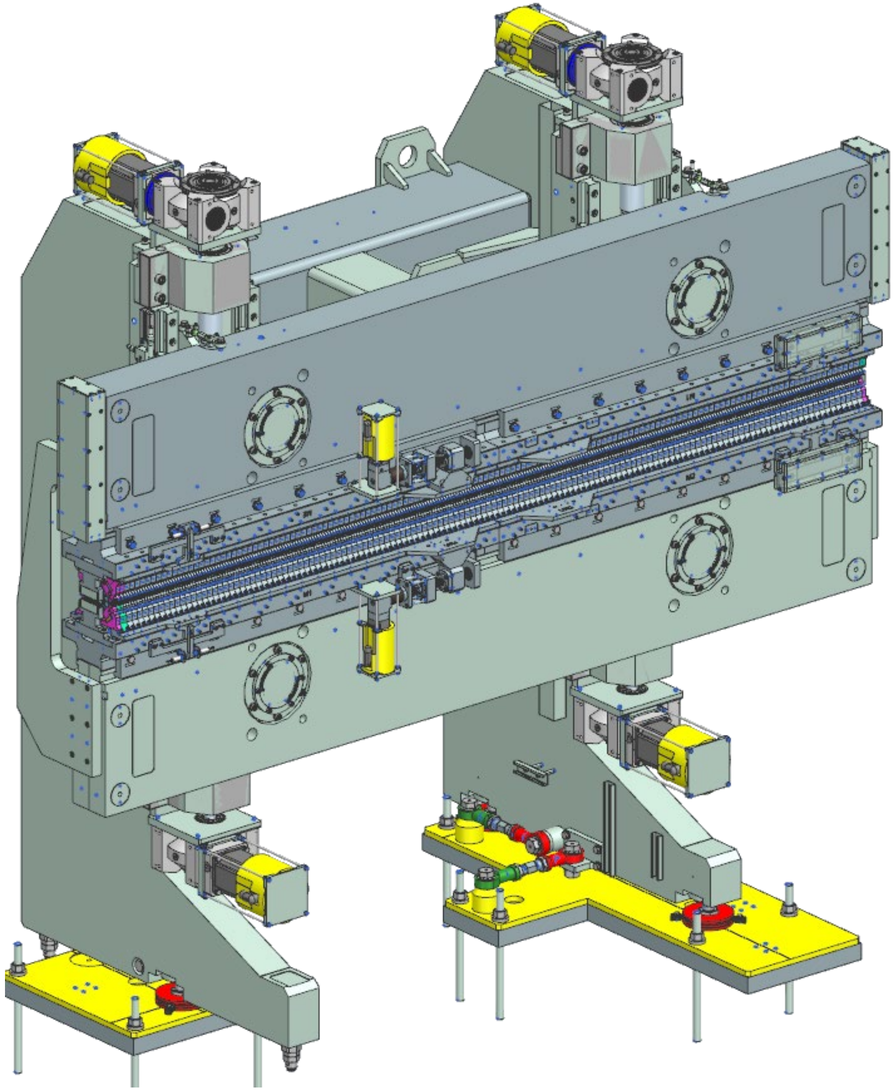
Test: Field error introduced in row B1



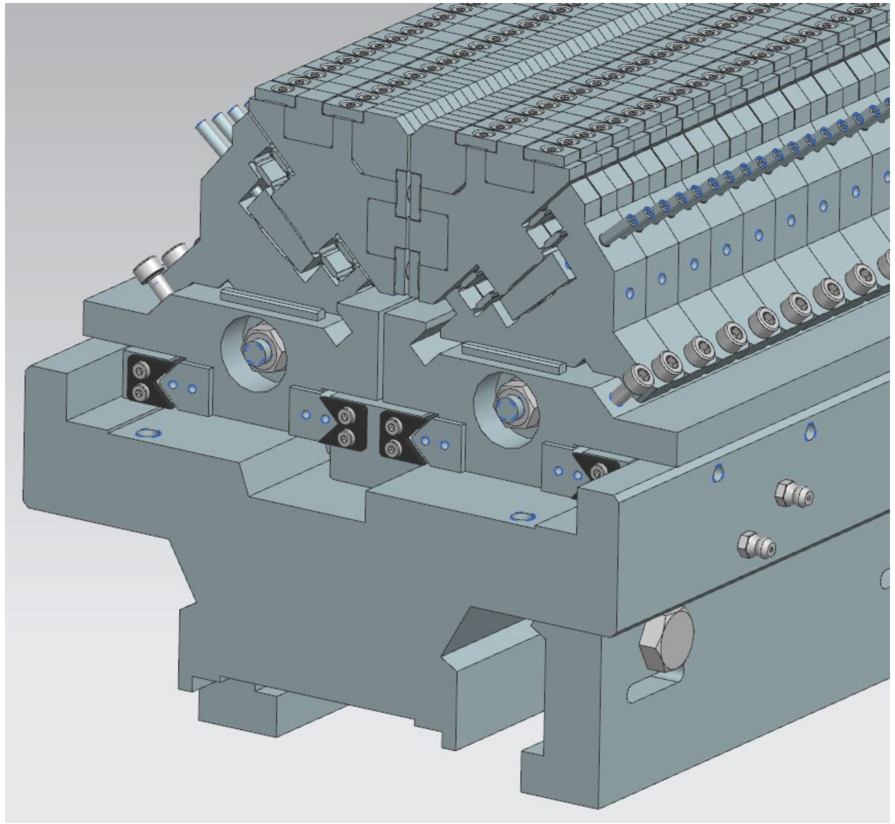
Mechanical Design Overview

APPLE-III

- Undulator Frame
  - Magnet Girder
  - Gap Drive



- Magnet Structure
  - Main Girder
  - Subgirder
  - Keepers
  - Shift Drive System
  - Shift Position Encoder

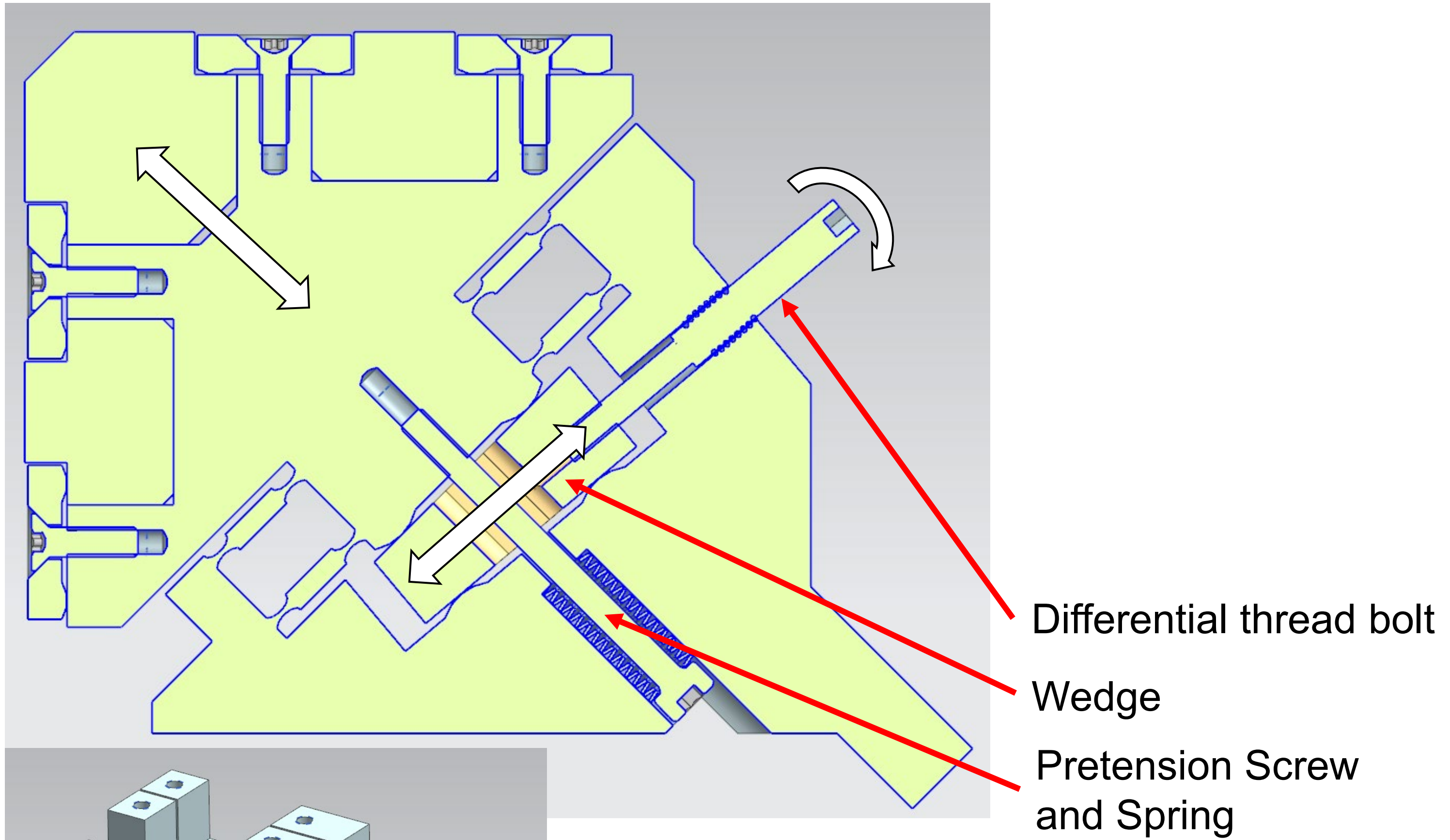


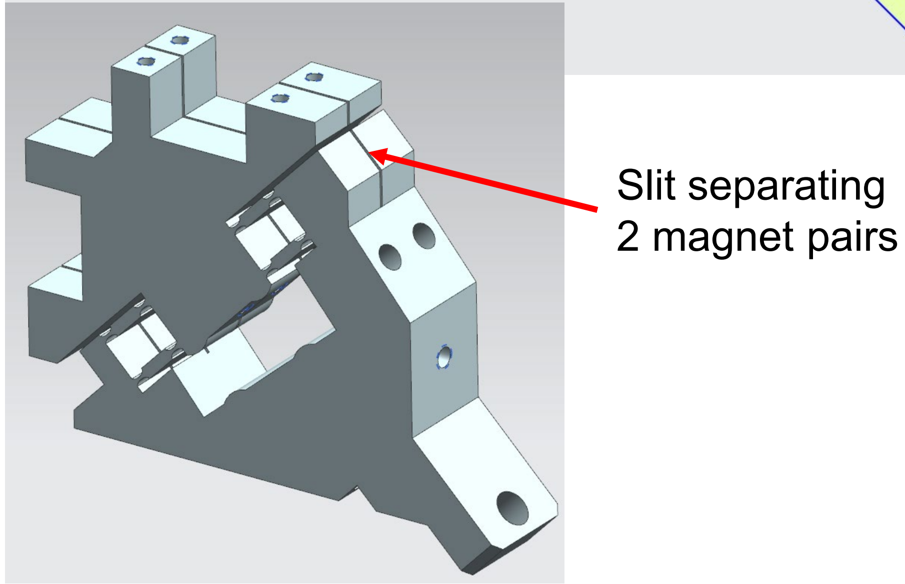
Keeper Design

General Design and Flexure Hinges

- Main magnets can be adjusted perpendicularly to the beam
- 4 bar linkage as parallel guide mechanism
- Individual adjustment of both magnets on one keeper
- Adjustment range +/- 0.2mm

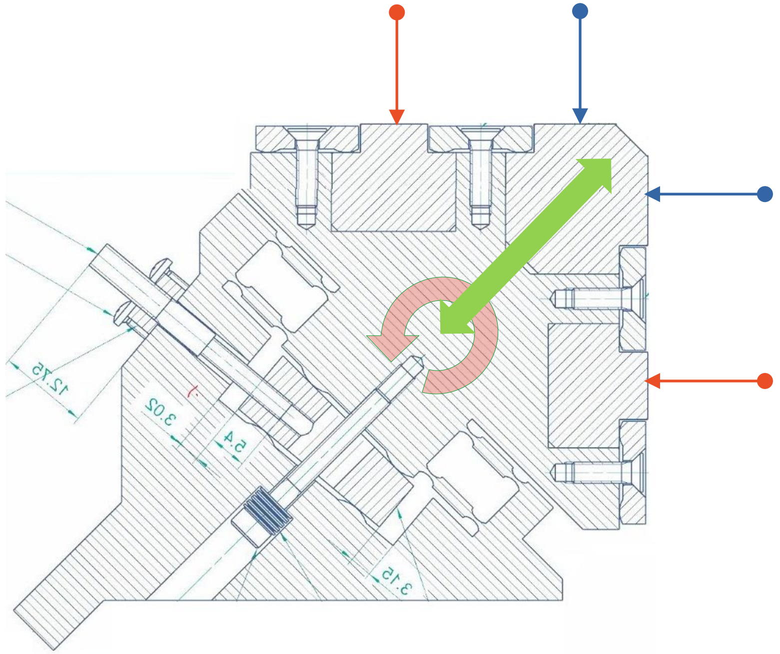
- Mechanics:
  - Differential thread bolt (P1=0.7 and P2=0.5)
  - Wedge angle 5°
  - Theoretical resolution:
    0.2mm x tan 5° = 0.017 mm/rev



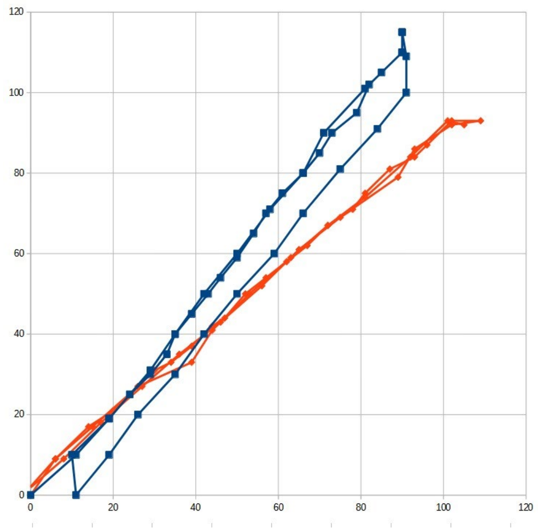


Weak Link Tuning Mechanism

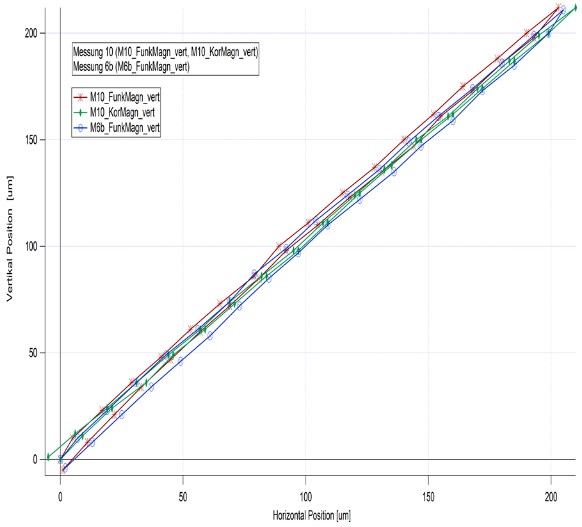
Accuracy and Reproducibility Problems



Initial behaviour

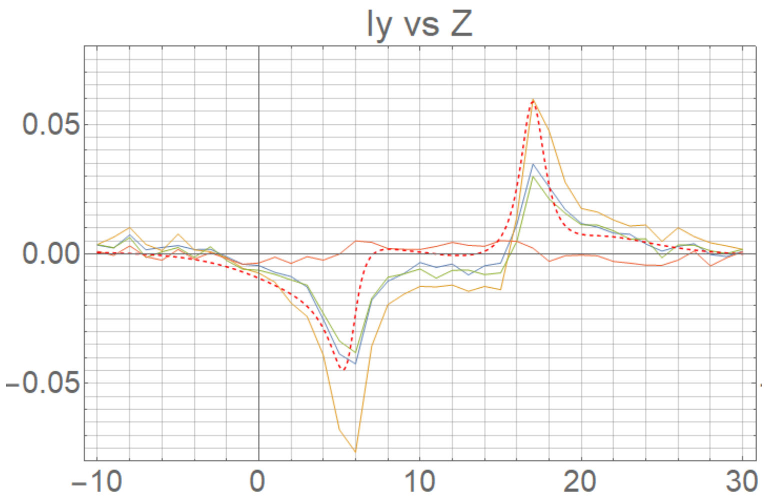


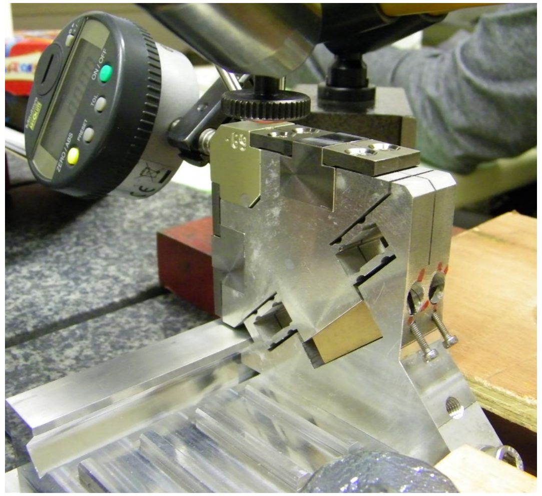
Improved springs



Non diagonal movement of main magnet caused by additional ~1mrad rotation

Confirmed by magnetic measurements (fitting magnet position & rotation in Radia to match magnetic measurements)

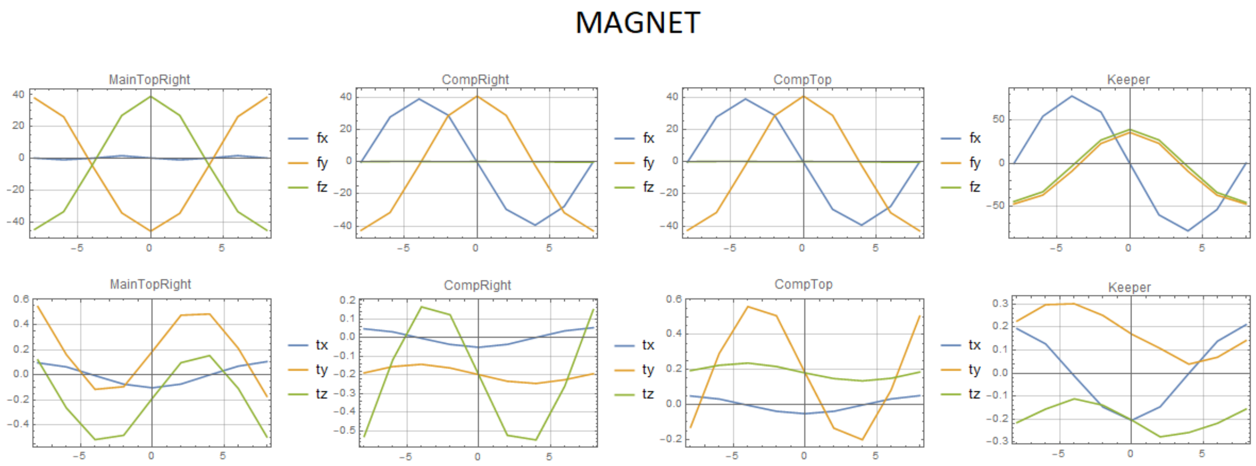


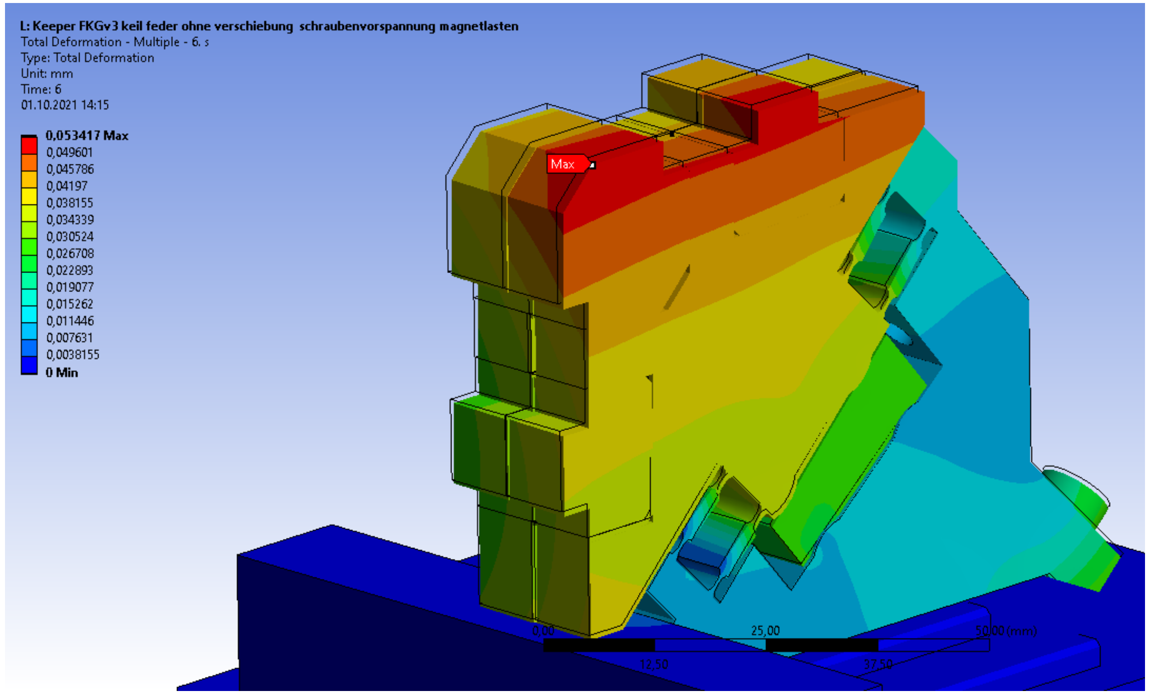


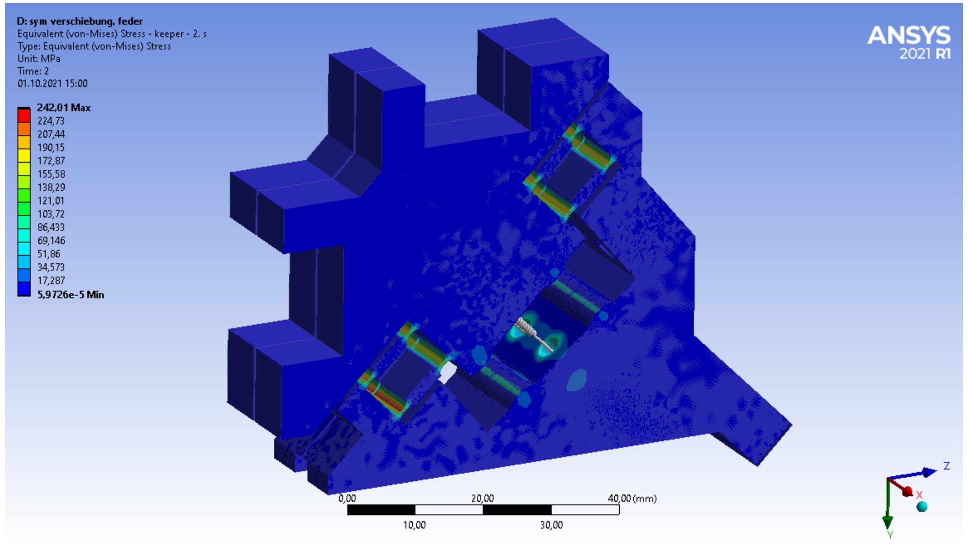
Keeper Design

Magnetic Forces on Keepers and Deformation

- Force Compensation reduces overall net forces on rows and quadrants of keepers
- Moments stay relatively high
- All forces and moments vary with shift
  - Direction rotates around with shift
  - Magnitude stays nearly constant

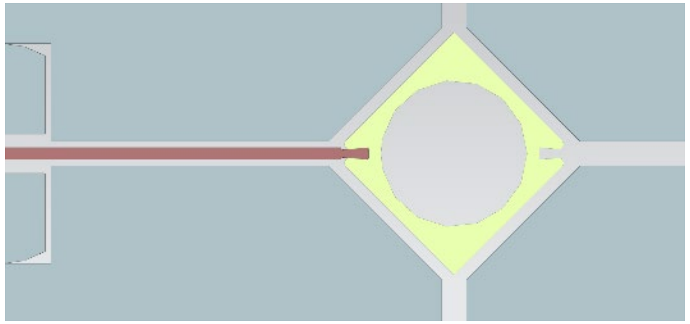






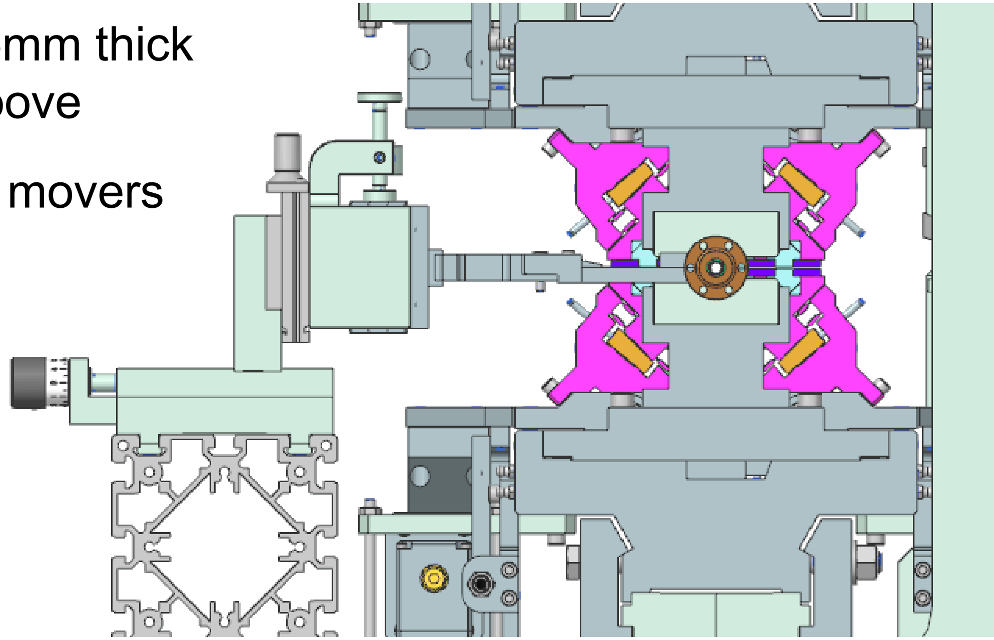
Vacuum Chamber and Support

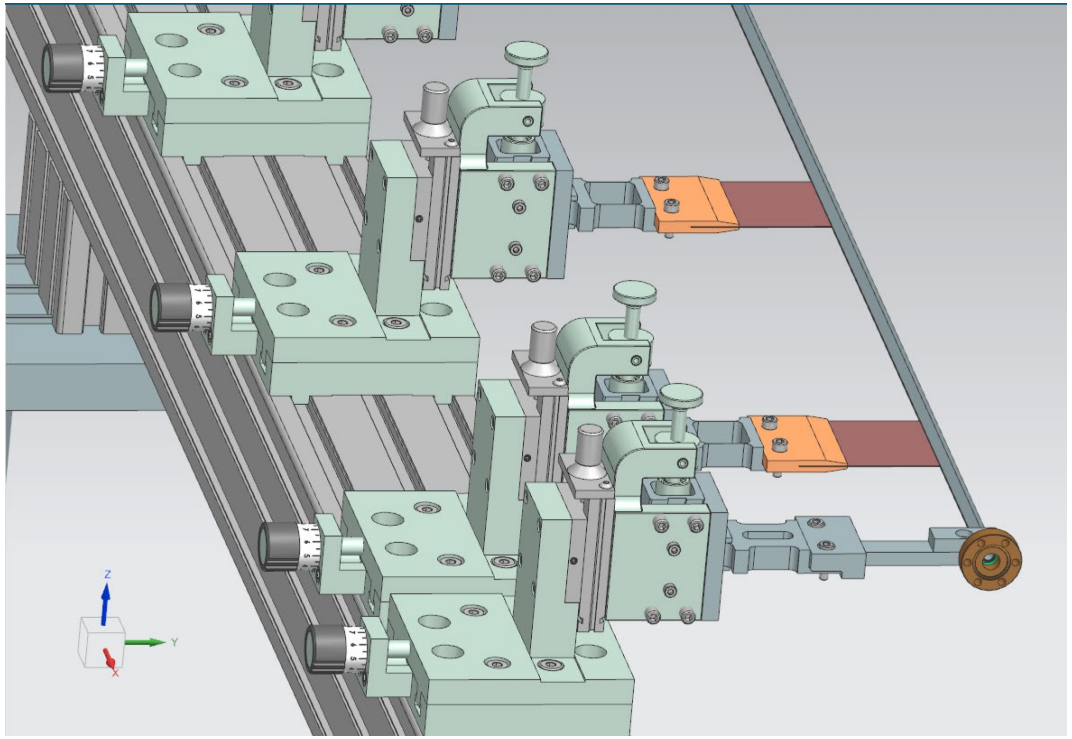
- Extruded aluminum chamber
- 7x7mm^2 cross-section
- Dm 6mm inner bore
- Length ~2.5m



Courtesy A. de Zubiaurre Wagner, S. Lederer

- Support by 0.5mm thick blades in a groove
- Adjustment by movers





Present Status & Schedule (Afterburner @FLASH2)

- Support mechanics available
- All long lead items in production
- Keeper and magnets expected to come in fall
- Shift rails and sub-girder until end of the year

- Keeper assembly
- Keeper measurements
- Mounting
- Magnetic tuning
- Installation at FLASH2 in 2nd half of 2023

Thank you