In-Vacuum Undulator IVU21 at PETRA

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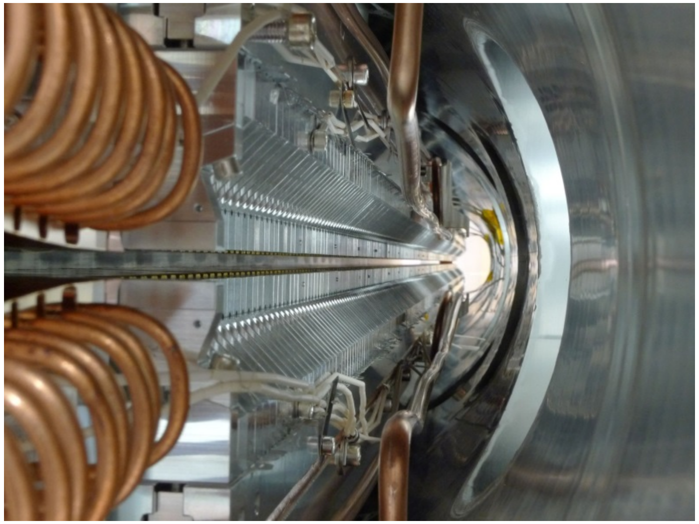
– on behalf of the Insertion Device Group FS-US –

Beschleuniger-Betriebsseminar 2018

19.02.2018

Undulator – In-Vacuum Undulator



Outline

> Intoduction

- Spectral specification

> Design & Fabrication

- Magnet structure
- Mechanical design
- Vacuum layout
- Controls
- Power dissipation & cooling

> Installation & Bakeout

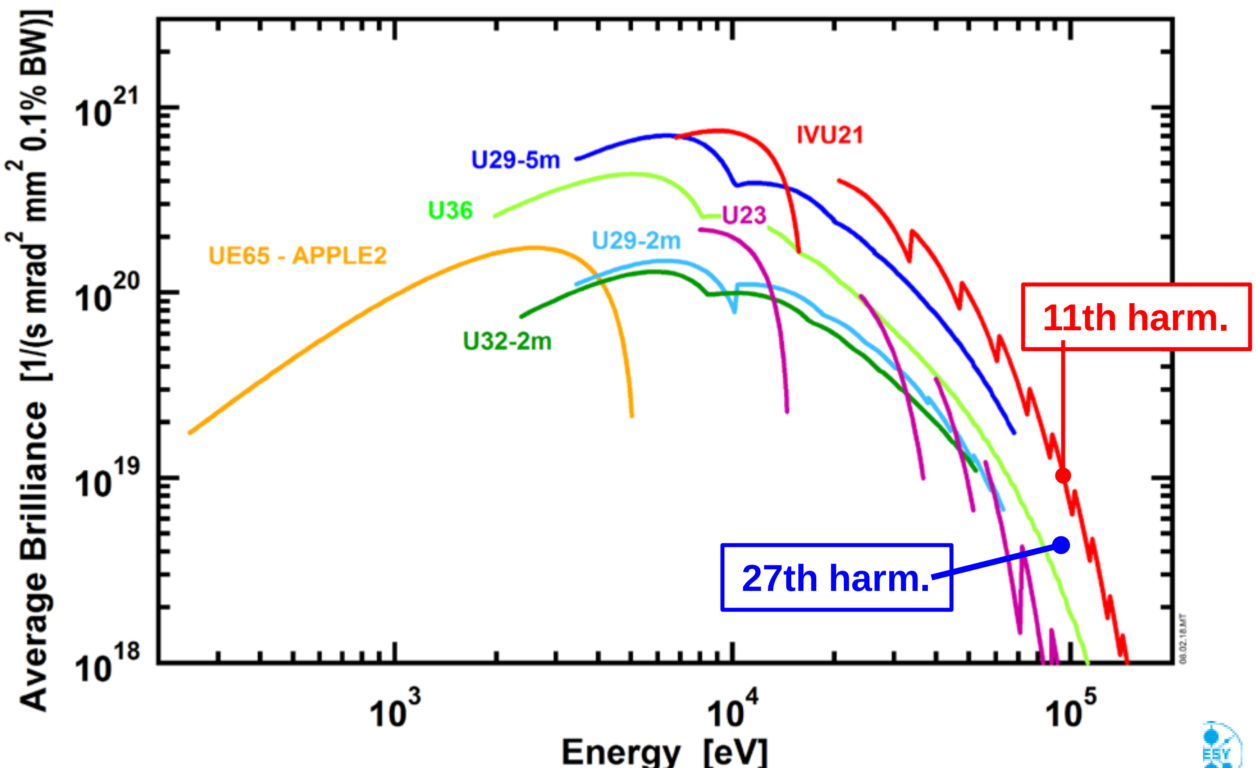
> Magnetic Measurements, Field Errors

Wozu einen In-Vacuum Undulator bei PETRA ?

- Material science Beamlines arbeiten bei hohen Photonenenergien ~80…150keV
- In-vacuum Undulatoren
  - kleineres magnetisches Gap bei gleicher vertikaler Apertur (beam stay-clear)
  - typisch: kurze Periodenlängen

Specification:
Gap = 7.0 mm
λ_U = 21.2 mm
L = 4 m
B_0 = 0.76 T
K = 1.49
E_1 = 7.8 keV
$dP/d\Omega$ = 0.20 W/µrad^2
P_{tot} = 5.2 kW

Continuously tunable above 50keV



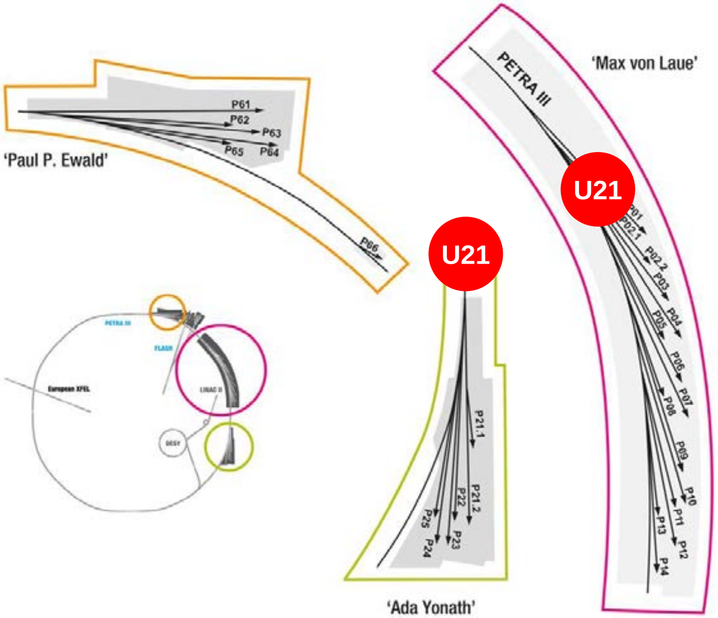
Overview

> PU07: HZ-Geesthacht & DESY FS

- High-energy X-ray materials science (HEMS)

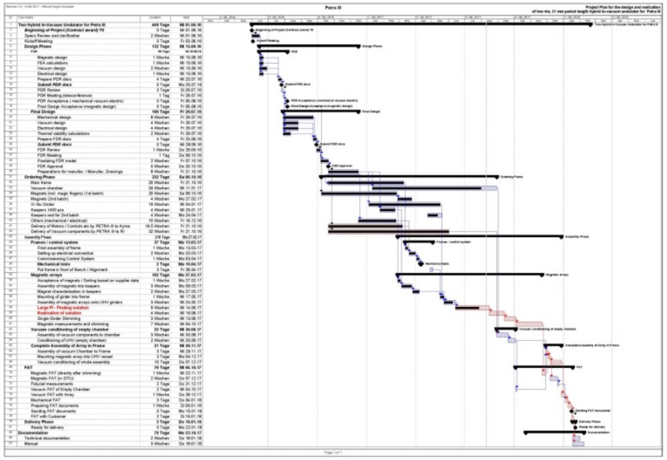
> PU21: Swedish Beamline

- Swedish Materials Science Beamline (SMS)



> Project Timeline

- 1st CFT 2012
- 2nd CFT 2015
- Project start 05/2016, delivery time 16 months (1st IVU)
- Delivery in 01/2018 (1st)



> Other involved groups

- Design Phase: FS-PE, MVS, MPY, MEA, ZM1 …
- Contruction: FS-US (AS,PV,MT), ZM1
  MVS (R. Böspflug, …), MPY (JK)

Magnetic Design

> Hybrid design

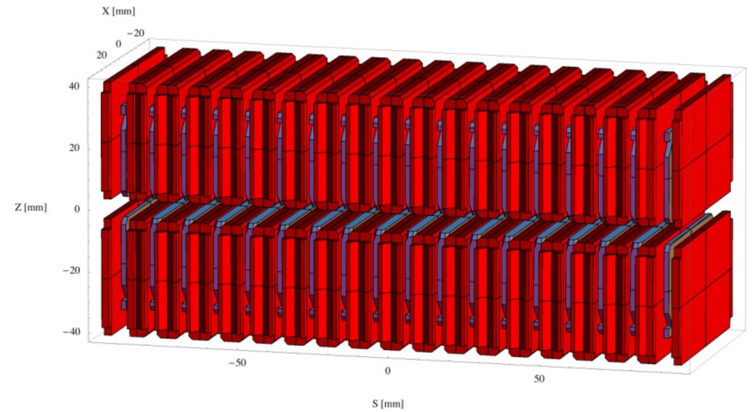
- NdFeB magnets, Permendur poles
- optimization of bulk and end modules, μ=μ(H)

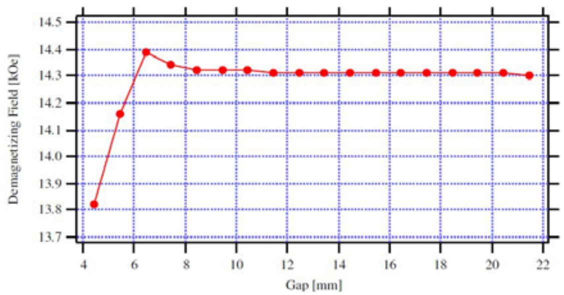
> Demagnetizing fields

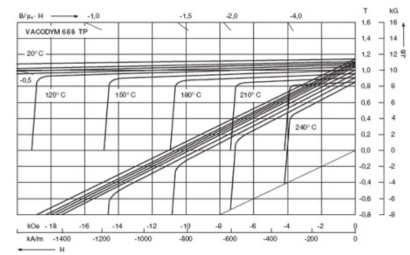
- temperature dependence of remanence B_r and coercive field H_{cj}
- magnet grade with diffusion enhanced H_{cj}
- coating: TiN ~5µm

> Keeper design

- vacuum and bakeout compatibility
- tuning concept

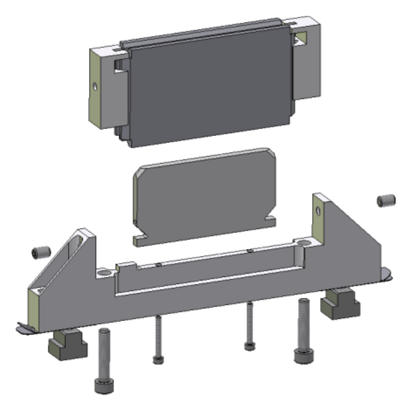


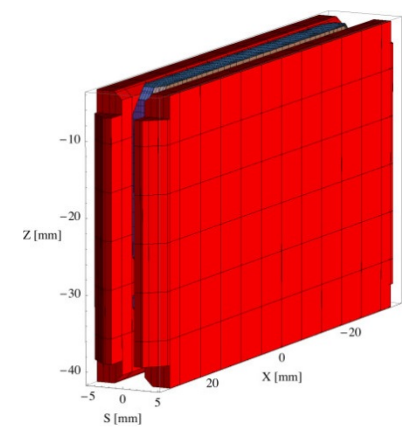




Magnetic properties of 38UH6+Tb

Typical B_r (T) at 20°C	1.24
Minimum B_r (T) at 20°C	1.22
Minimum H_{cj} (kA/m) at 20°C	3100
Minimum H_{cj} (kOe) at 20°C	39.0
Temp. Coef. B_r (%/°C)	-0.095
Temp. Coef. H_{cj} (%/°C)	-0.50
Typical B_r (T) at 120°C	1.12
Minimum H_{cj} (kA/m) at 120°C	1550
Minimum H_{cj} (kOe) at 120°C	19.5
Recoil permeability	1.05

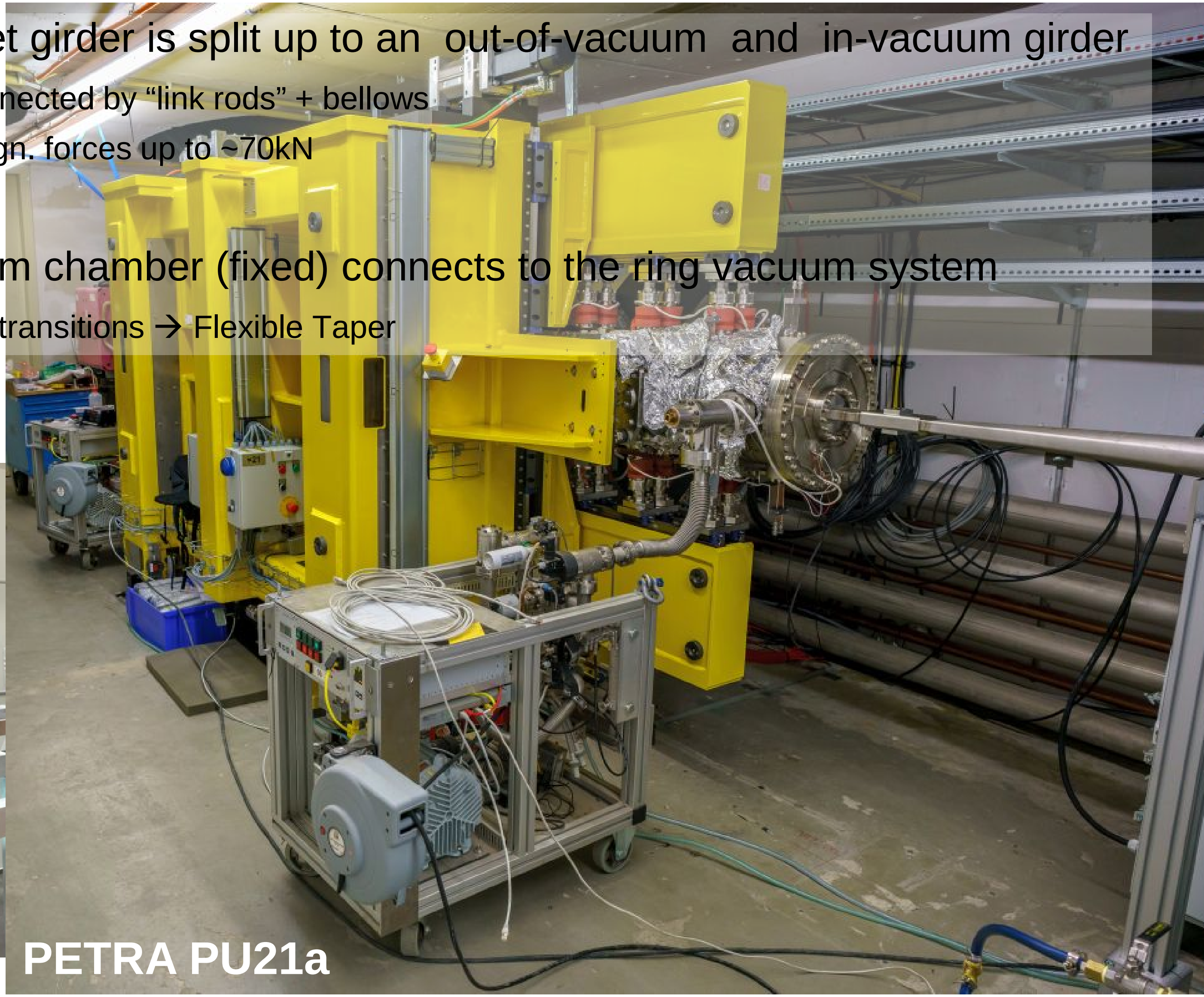


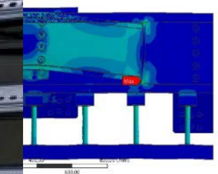


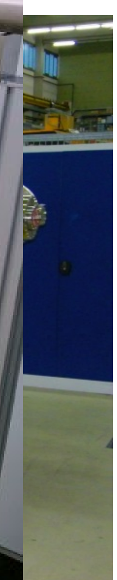
Mechanical Design

> Magnet girder is split up to an out-of-vacuum and in-vacuum girder
  - connected by "link rods" + bellows
  - magn. forces up to ~70kN

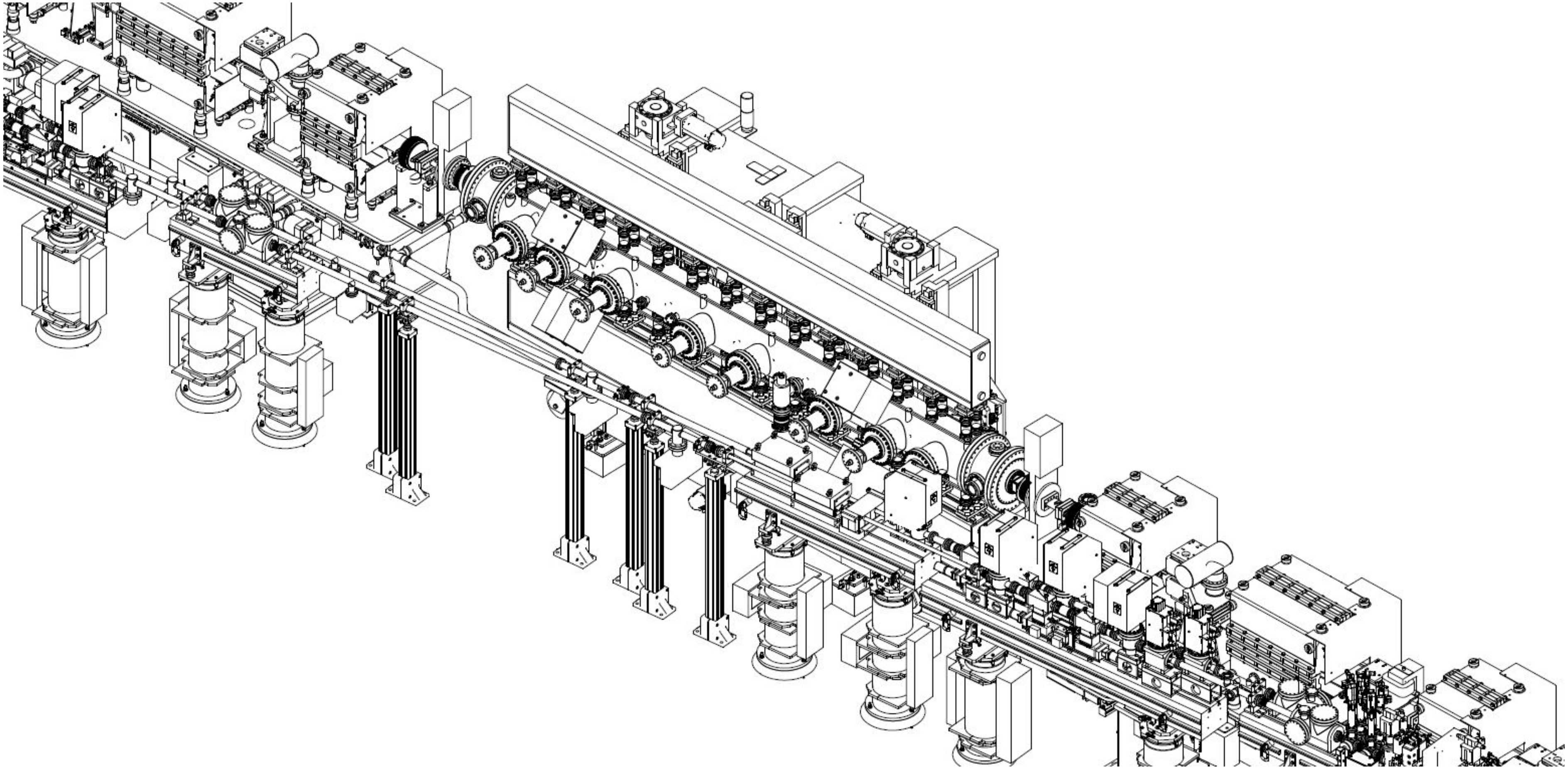
> Vacuum chamber (fixed) connects to the ring vacuum system
  - RF transitions → Flexible Taper







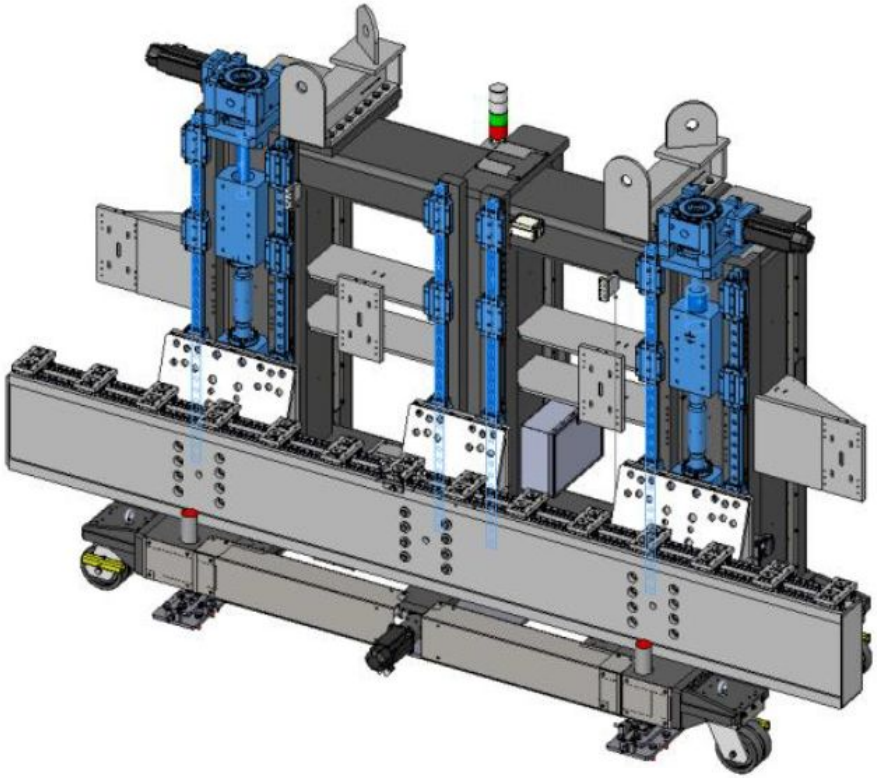
Mechanical Design – Installation at PETRA PU07

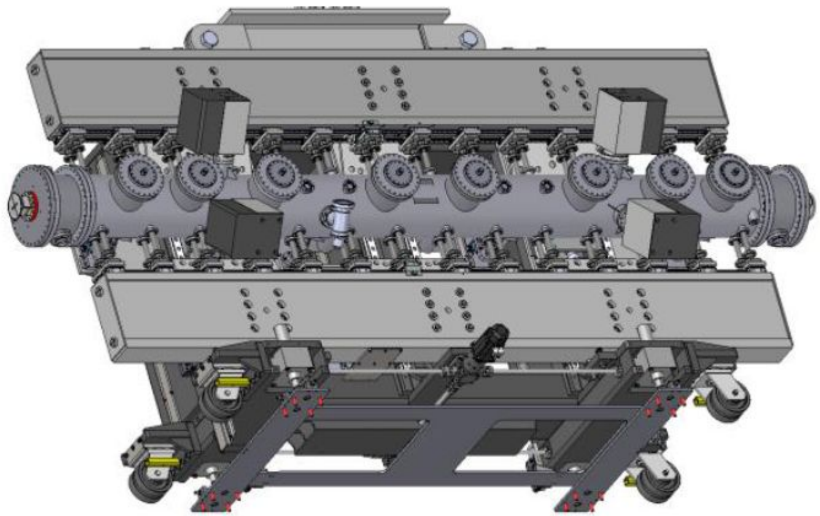


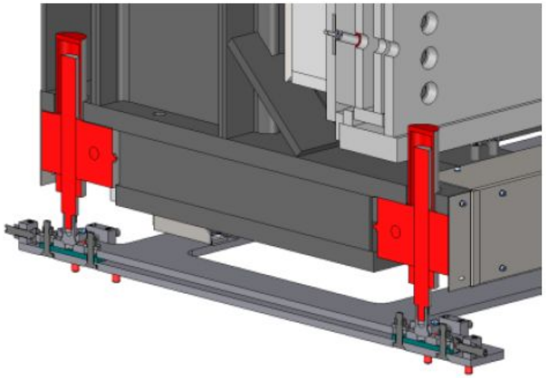
Mechanical Design

> 3-fold support and guiding of the girders
  - 2 axes drive
  - taper capability
  - thermal issues
  - bakeout capability

> Lift table for vertical fine adjustment



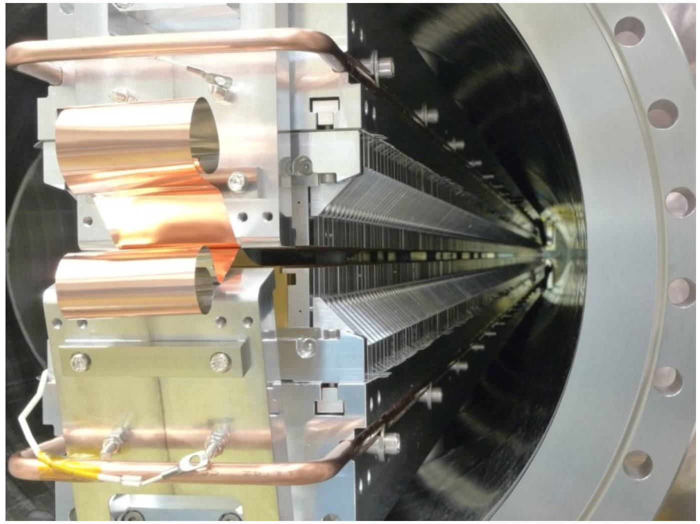




Mechanical Design – In Vacuum Parts

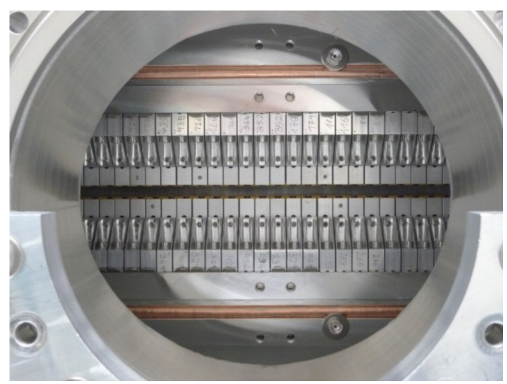
Issues:

- …
- UHV compatible
- Bakeout

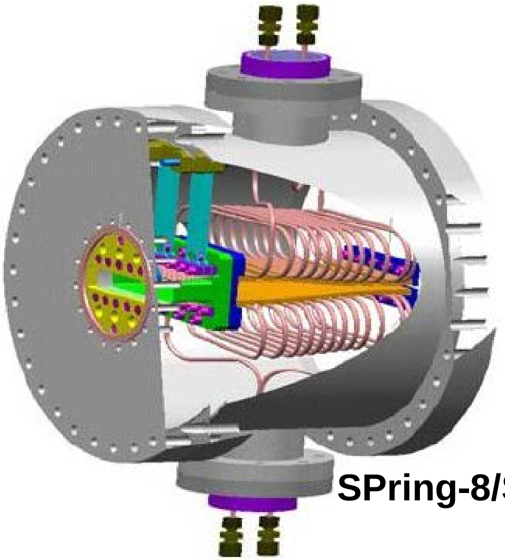


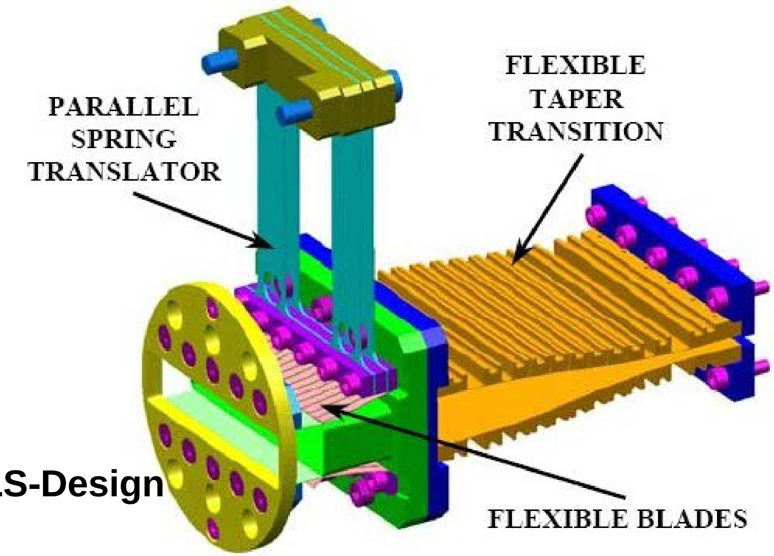
- Thermal expansion

Material	Expansion coefficient	Thermal expansion over 4m length
Al girder	2.3 e-5 / K	9.2 mm (at 120°C)
Cu (foil) Ni	1.6 e-5 / K 1.3 e-5 / K	6.4 mm (at 120°C) 5.2 mm
Stainless	1.6 e-5 / K	11.5 mm (at 200°C)

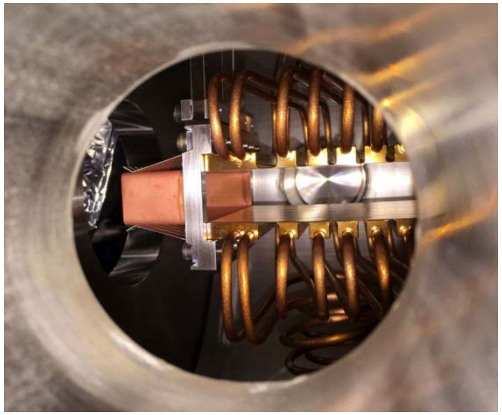


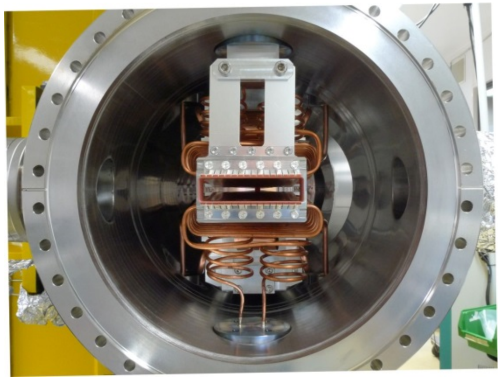
Mechanical Design – Flexible & Fixed Tapers





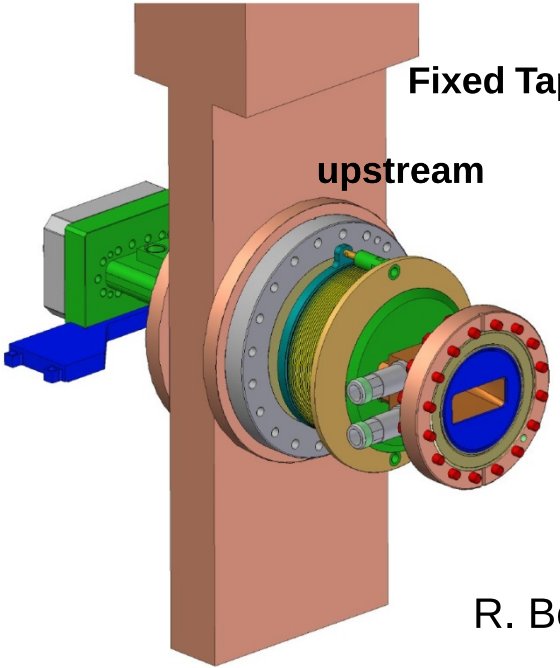
SPring-8/SLS-Design



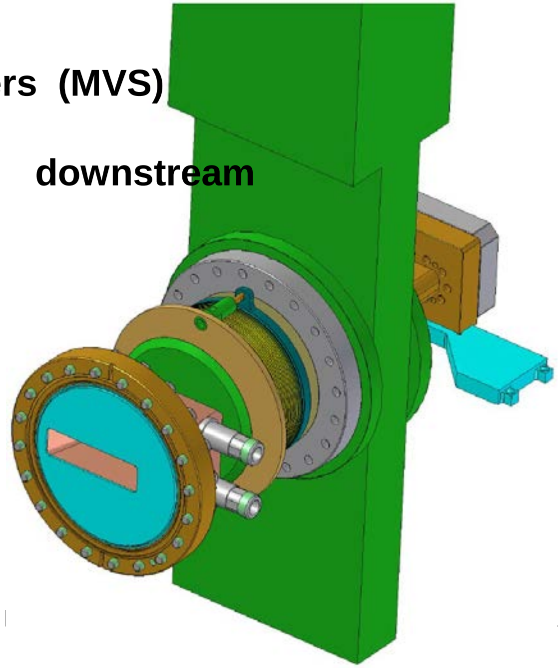


Fixed Taper Chambers (MVS)

upstream

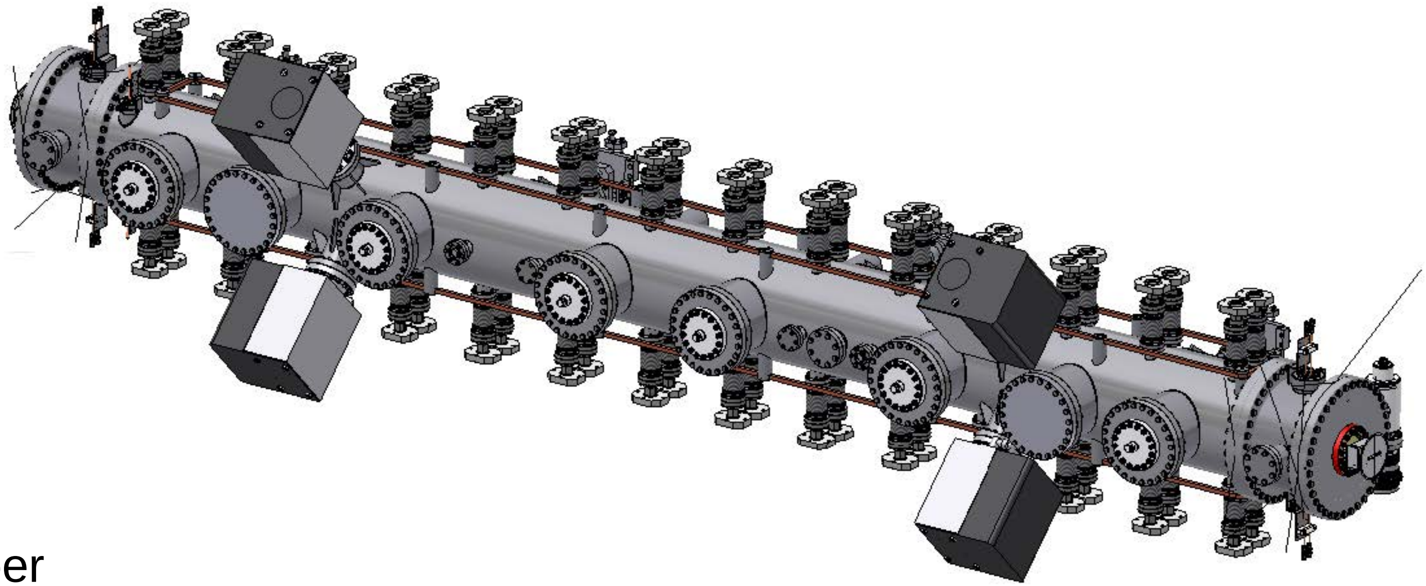


downstream

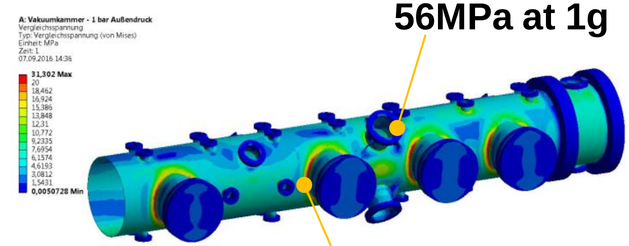


R. Böspflug

Vacuum Design



- Chamber
  ∅ = 300mm, L = 4m, 3mm thickness,
  material is 316L
- Flanges made from 316LN
- CF350 flanges towards the Flex.Taper chambers
- 4 support points to the mechanical frame



RP_{02}~215…175MPa (200°C)

- 14 link rod pairs at top and bottom, ports for pump, feedthroughs, gauges etc.

Vacuum Design – Pressure Calculations

> Total area ~ **37m²**

- vac.chamber $5m^2$
- tot. magn.structure $24m^2$

> Pumping Power

- **4 x 150 l/s**
  Ion Getter Noble Diode
- **6 x 2000 l/s**
  NEG pump

> Final pressure

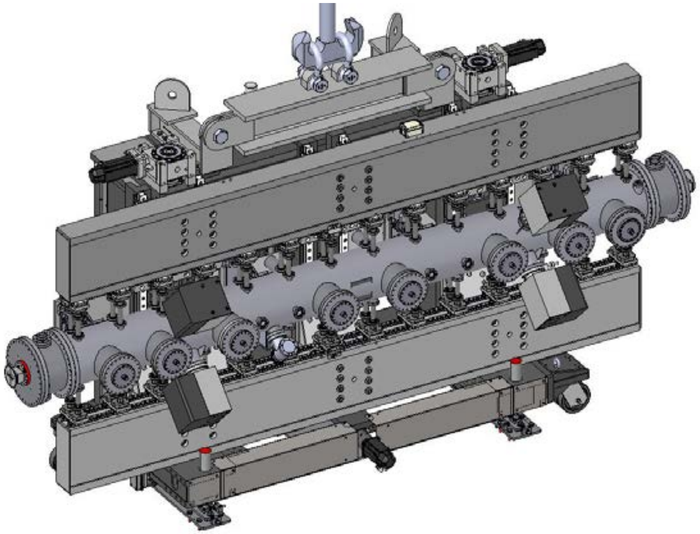
- ~1e-10 mbar (on paper)

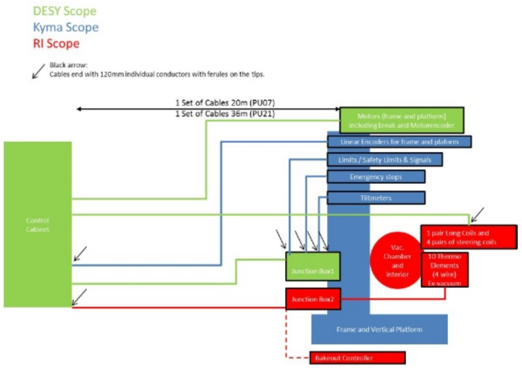
	A–D	E	F	G	H	I	J	K
1	Vacuum System Layout - Final Pressure Calculation for PETRA III IVU 4m (25.07.2016_SSZ_RI)							
2	**Outgassing Calculation**							
3	Surface	Comment	Surface per Part	Amount	Overall Surface	Material	Outgassing from Ref.	Gasload
4			[m^2]		[m^2]		[mbar · l/ (cm² · sec)]	[mbar*l/sec)
5	**Vakuumchamber SUM of all below from CAD**		5	**1**	**5**	316LN	5.33E-12	2.67E-0
6	Main Chamber	300mm Diam * 4m			0	316LN	5.33E-12	
7	End Caps	300mm Diam			0	316LN	5.33E-12	
8	Flanges				0	316LN	5.33E-12	
9	Bellows	59 - 39 mm Bellow from Datasheet	0.00196	56	0.10976	304	5.33E-12	5.85E-0
10	Link Rods	50mm diam * 0.2m	0.031415927	56	1.759291886	316LN	5.33E-12	9.38E-0
11	**IV Girder**	from CAD	1.84	**2**	**3.68**	Aluminium	5.30E-14	1.95E-0
12	Copper Tubes	8mm Tube, 20 m	0.502654825	2	1.005309649	Cu	1.46E-12	1.47E-0
13	**Keeper**	0.12*0.04*0.02	0.016	**740**	**11.84**	Alumnium	5.30E-14	6.28E-0
14	**Magnete**	38mmx 70mm x 4mm	0.006184	**1480**	**9.15232**	TiN	8.53E-13	7.81E-0
15	**Polstücke**	58mm*30mm*3.5mm	0.004096	**740**	**3.03104**	TiN	8.53E-13	2.59E-0
16	Taper							
17	CuBe Sheets		0.08	4	0.32	CuBe	1.46E-12	4.67E-0
18	Cu-Tube	8mm Rohr 3m	0.075398224	4	0.301592895	CuBe	1.46E-12	4.40E-0
19	Cu Foil	60mm breit 4m lang	0.48	2	0.96	Cu	1.46E-12	1.40E-0
20	Kapton Litz	100m for PT and Coil	6.28319E-06	100	0.000628319	Kapton	5.00E-11	3.14E-1
21								
22	Leckrate des Systems	<=2*10^-10						2.00E-1
23								
24							**Ges. Gasload**	**5.17E-0**
25	**Pumpspeed**							
26		**Comment**	**Number Pumps**	**Speed / Pump**	**Effektive Pumpspeed**	**Sum**		
27			**[#]**	**[l/sec]**	**[l/sec]**	**[l/sec]**		
28	Ionpump 300 L	-10% durch noble diode	4	135	121.5	486		
29	Getter Pumpen CapaciTORR	1000l/sec for CO	8	1000	600	4800		
30								
31					**Pumpenleistung**	**5286**		
32								
33	**Final Pressure**							
34	Assumption, Baleout of magentic structure @ 120°C, supported by Hot water circulation system. 150°C at Vacuum chamber							
35								
36								
37		**Achievable final pressure**	**9.78E-11**	**mbar**				

Controls

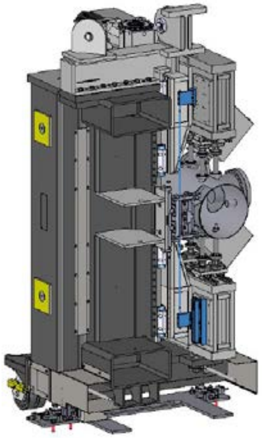
- 2-axes drive with left/right spindles
- 1-axis lift table

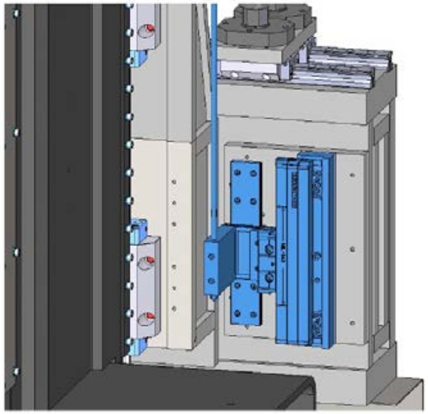
- servo motors
- rotary encoders on motors axis
- linear encoders for all axes





- software limits
- 2 layers of limit switches
- hard stop limits
- tilt sensors





- Readout of all temperatures
- 4+3 power supplies for air coils + ambient field coils
- Communication to Beamline, BKR, and MPS

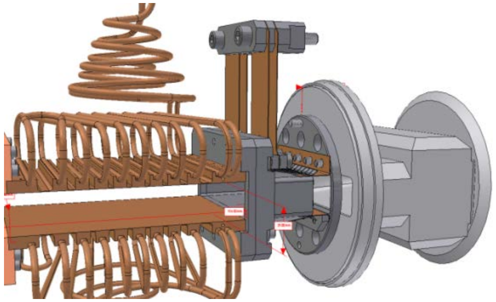
Power Dissipation

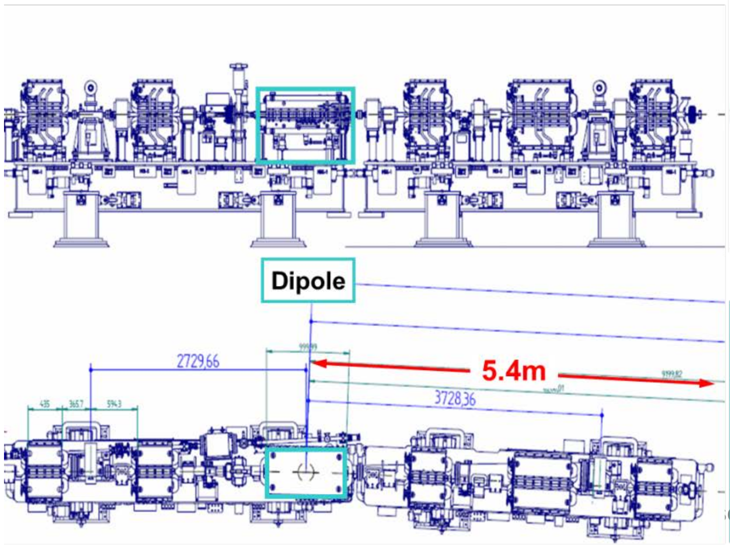
> Minimum gap and all aperture transitions (FixedTaper → Flex.Taper → Magnet structure) cause a small impedance growth of the machine: ~negligible

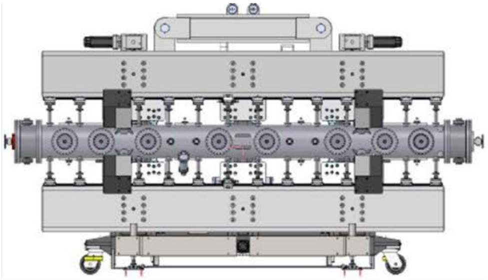
> Cooling issue due to power deposition onto magnet structure and flexible tapers

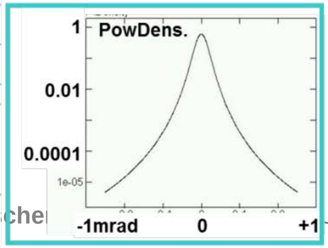
> Different mechanisms:

- Resistive wall effects
- Geometric wake field effects
- Synchrotron radiation from the dipole magnet upstream of the IVU









Power Dissipation (1) – Resistive Wake Field Effects

- Analytical approach for a round beam pipe:
  S.Krinsky (NSLS-1993, BNL-48792) or R.Wanzenberg/A.Piwinski (DESY-HERA-92-11)

- Dissipated Power $$P \approx \overset{\text{Number of bunches}}{M} \left(\overset{\text{Single bunch current}}{\frac{I_{av}}{M}}\right)^2 \underbrace{\left(\frac{\ell}{2\pi a}\right)}_{\text{Aperture}} \overset{\text{resistivity } \rho \,/\, \text{skin depth } \delta}{\Re_o} \left(\frac{R}{\sigma_s}\right)^{3/2}$$

- $\frac{1}{a} \rightarrow \frac{1}{l} \int \frac{1}{a(l)}\, dl$

- Beam current: 200 mA
- Number of bunches: 80
- Single bunch current: 2.5 mA
- Bunch length: 12 mm
- Magnetic gap: 5 mm
- Magnetic length: 4 m

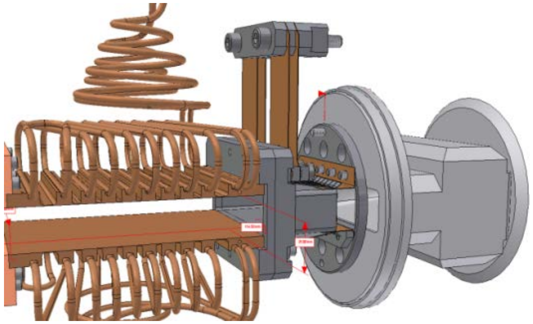
Dissipated Power / W	Magnet Structure	Flexible Taper
Plate	10	2
Round pipe (1)	**39**	6
Round pipe (2)	123	20

> Magnet Structure

- 100µm thin Cu/Ni foil
- consider 80 W (includes safety factor 2)

> Flexible Taper

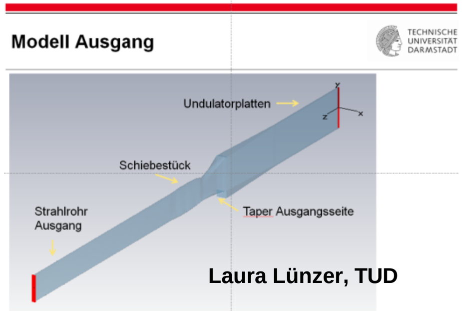
- CuBe blades
- consider 5 W ~ close to negligible

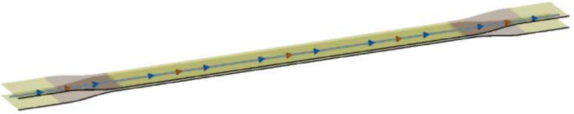


Power Dissipation (2) – Geometric Wake Field Effects

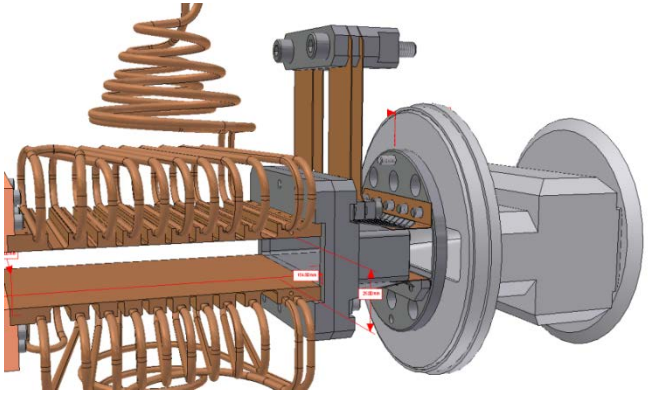
> Flexible Taper

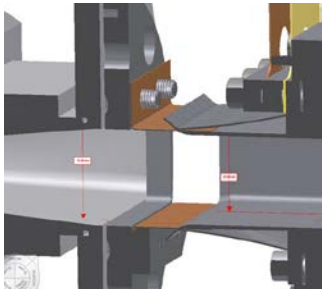
- collaboration R.Wanzenberg – TU Darmstadt
- expected dissipated power: 20…30 W
- considered for cooling layout: 60 W
- some other labs: no or no more cooling

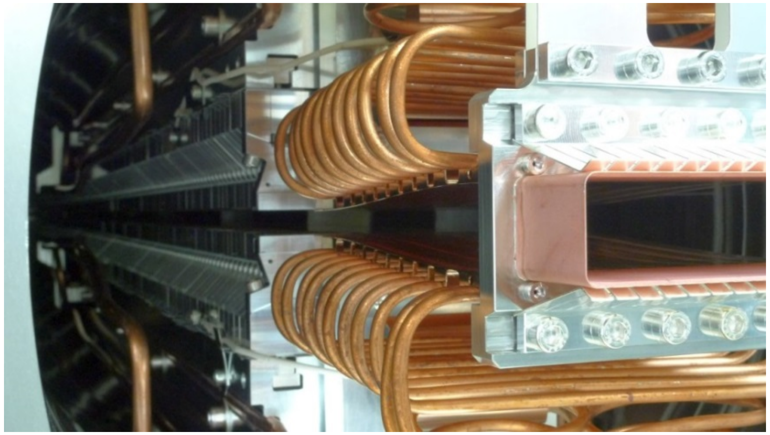




$$P_{tot} = N\, f_0\ q^2\, kloss \qquad k_{loss} = \int_{-\infty}^{+\infty} ds\ \lambda(s)\ W(s)$$





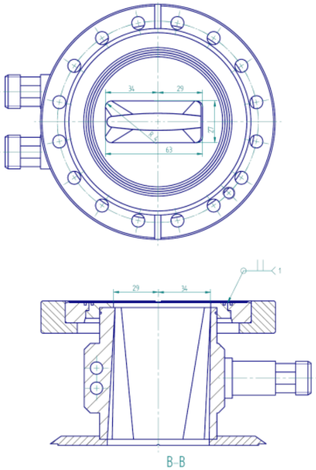


Power Dissipation (3) – Synchrotron Radiation Effects

> Synchrotron radiation from the upstream dipole magnet may hit the IVU

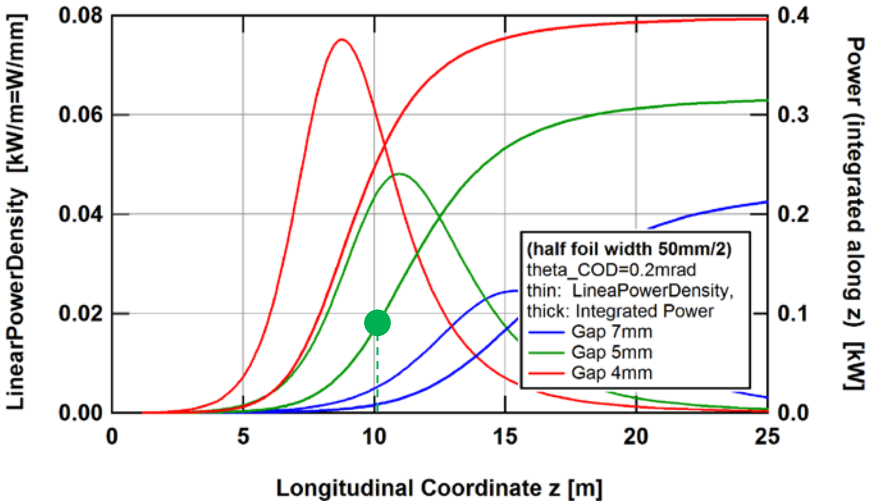
> Magnet Structure

- no problem for golden orbit: 1W (gap=7mm) … 3W (gap=5)
  on top/bottom part of Flex.Taper at exit side



- vertically mis-steered beam ~ 0.2mrad in upstream dipole

Dissipated Power / W	Up-stream	Center	Down-stream
Gap = 7mm	0.4	2	9
Gap = 5mm	3	24	89



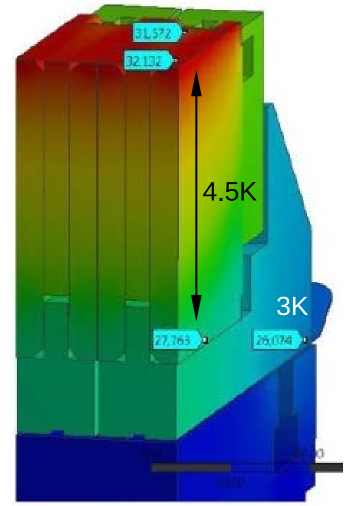
> Flexible Taper

- considered incident SR-power up to ~90 W

Water Cooling

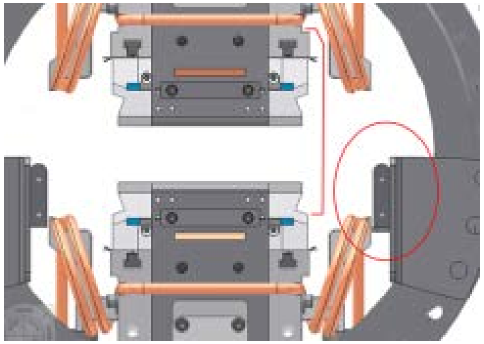
> Dedicated FEM calculations to study heat flow

- 7.5°C temperature raise at magnet surface (at pessimistic 0.1W/mm) due to poor heat conductivity of magnets and shim as a bottleneck
- CuNi foil is cooled indirectly
  contact area and heat transition coeff. are a big unknown

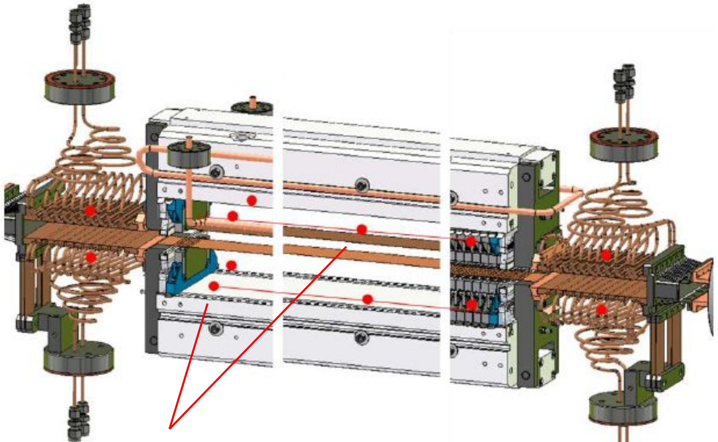


> 6 water circuits: 2x2 for flexible taper, 2 for magnet structure

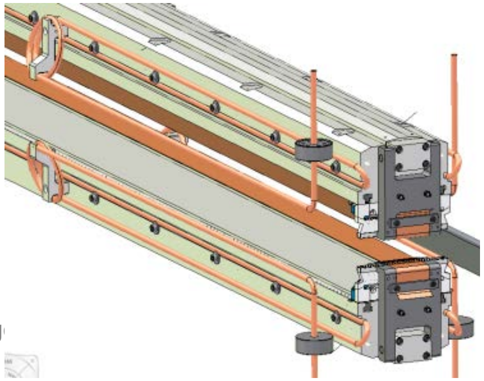
- pipes are moving gently with gap
- all operated in series
- stand-alone water chiller: "Proficool Primus", Natl.Lab,
  400W, +/-0.1K, ~0.8 l/min



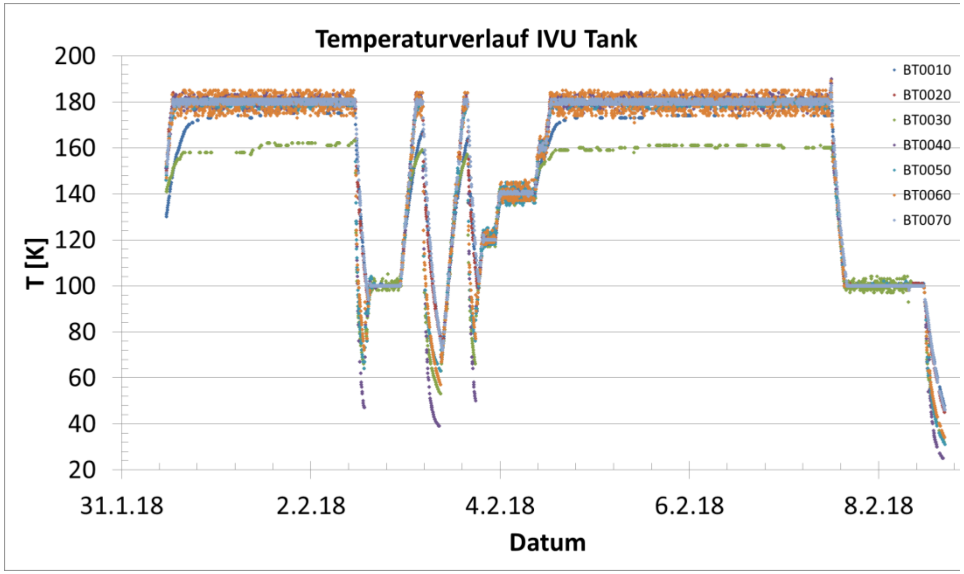
> Temperature sensors



12 Pt100 temperature sensors

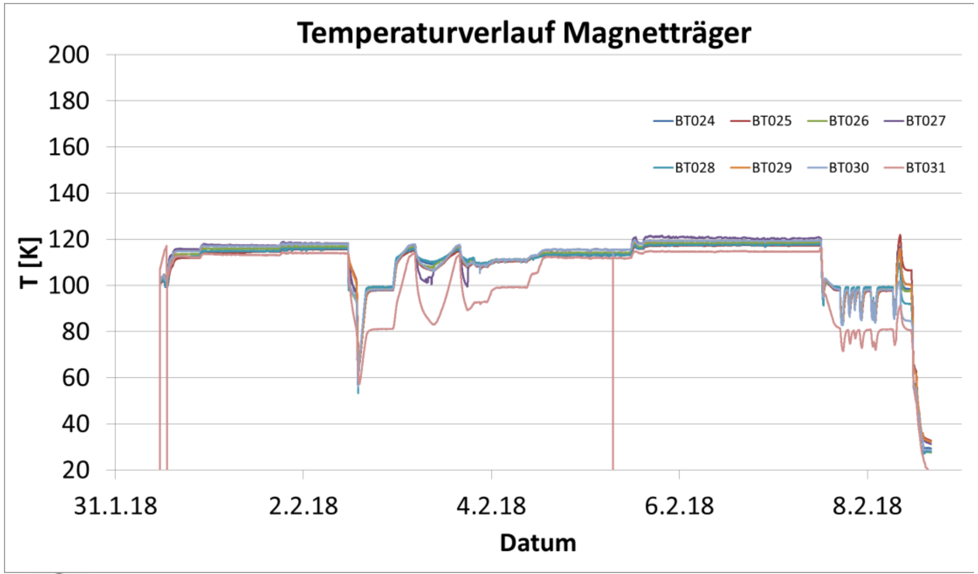


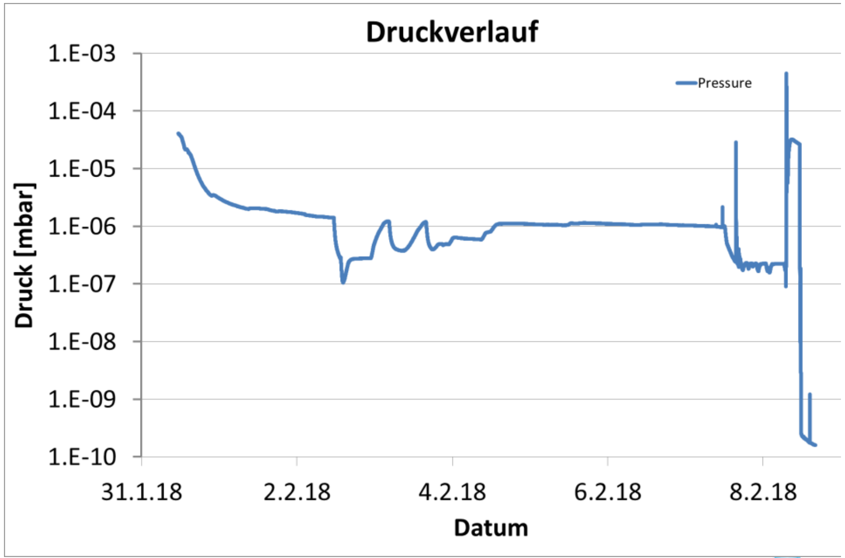
Bakeout



> Chamber, link rods, tapers: 180°C
> Magnet structure, IV-girders: 120°C

> Bakeout after installation
- ~7 days
- several hickups
- pressure 48h after bakeout: ok
- hydrocarbons: close to spec.

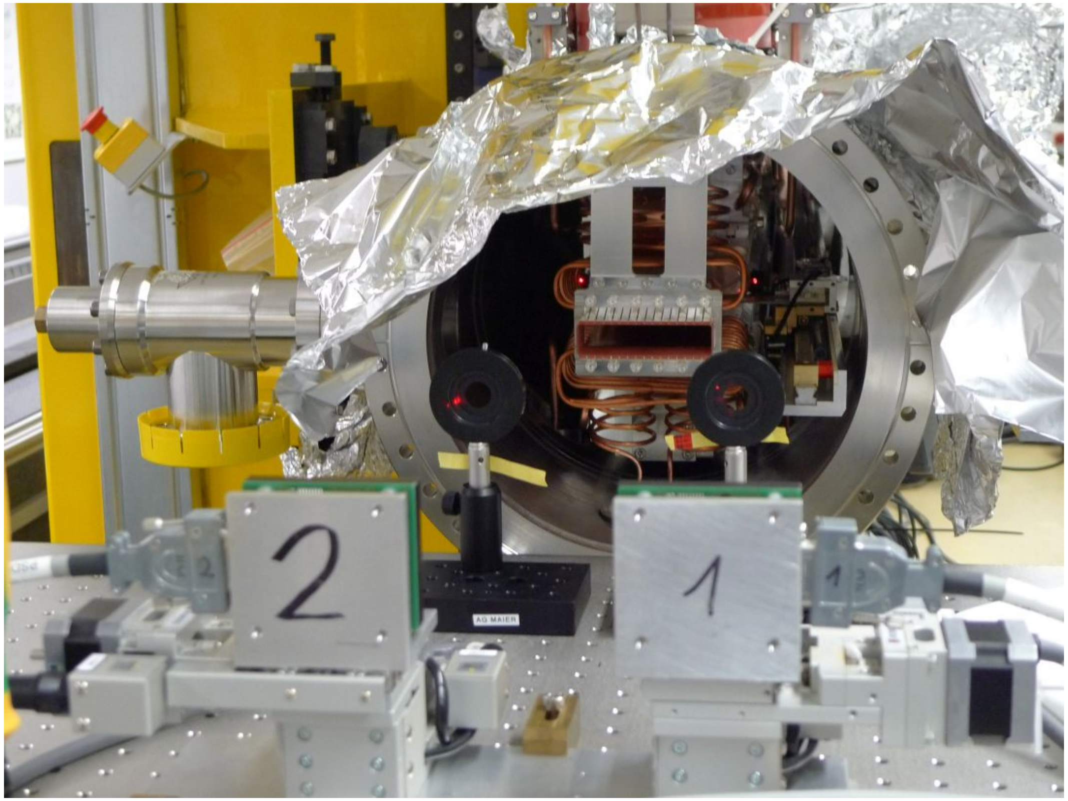


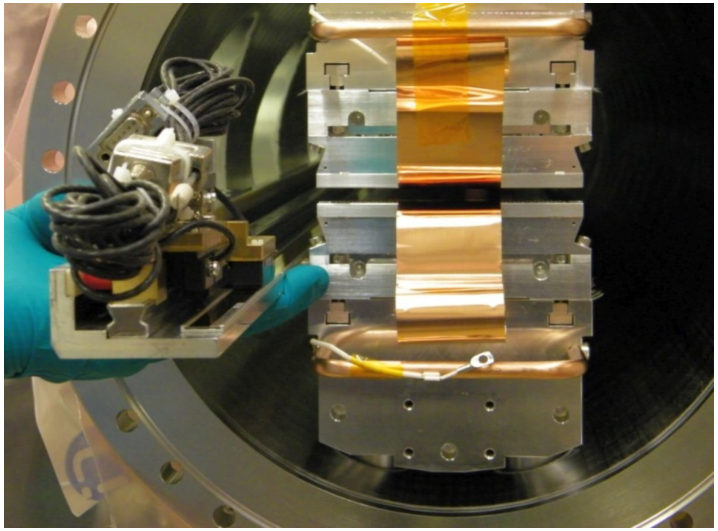


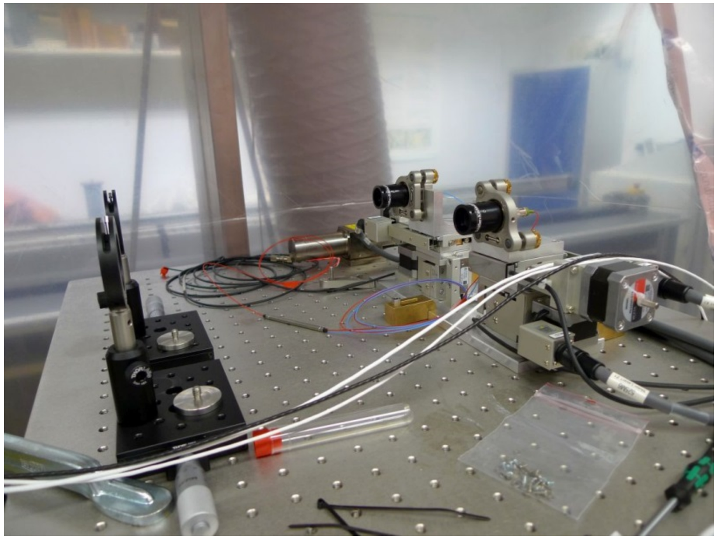
R. Böspflug

In-situ Magnetic Measurement Bench

SLS-Design

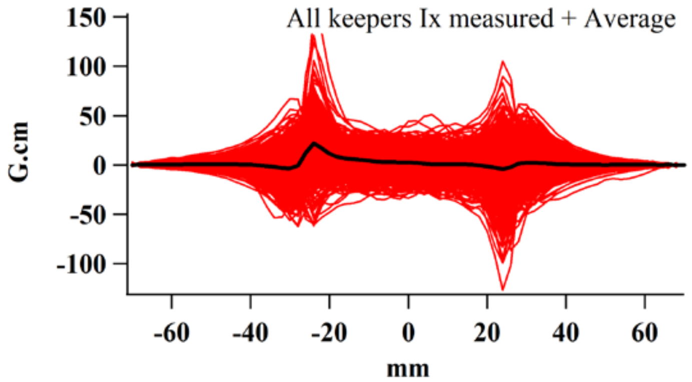


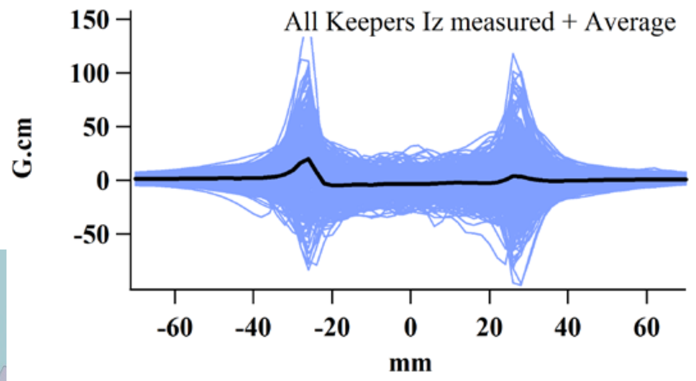


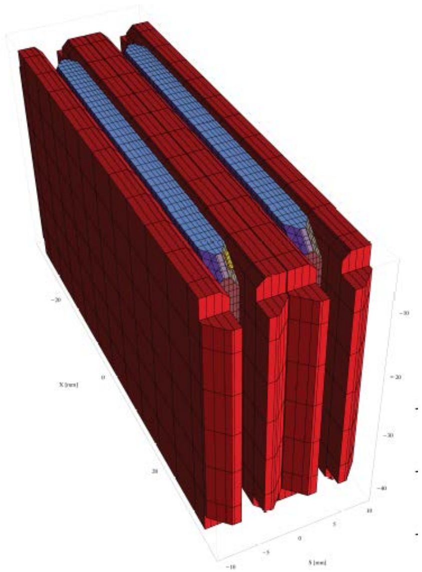


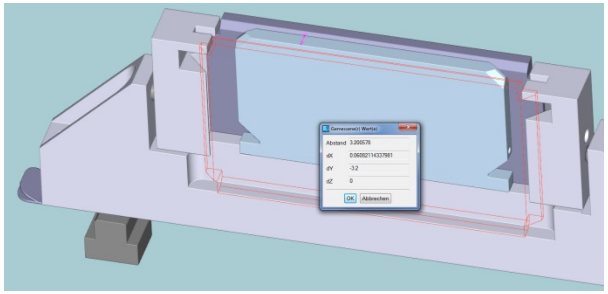
Magnet Keepers & Modules

- Systematic magnetic errors found in all magnet modules
  - large field integral values at the transverse module edges, both in Ix and Iz
  - Ix error cannot be cured!
  - origin not yet understood
  - small errors in the pole chamfers ?
  - error is not distributed randomly after assembly
  - also small mounting errors



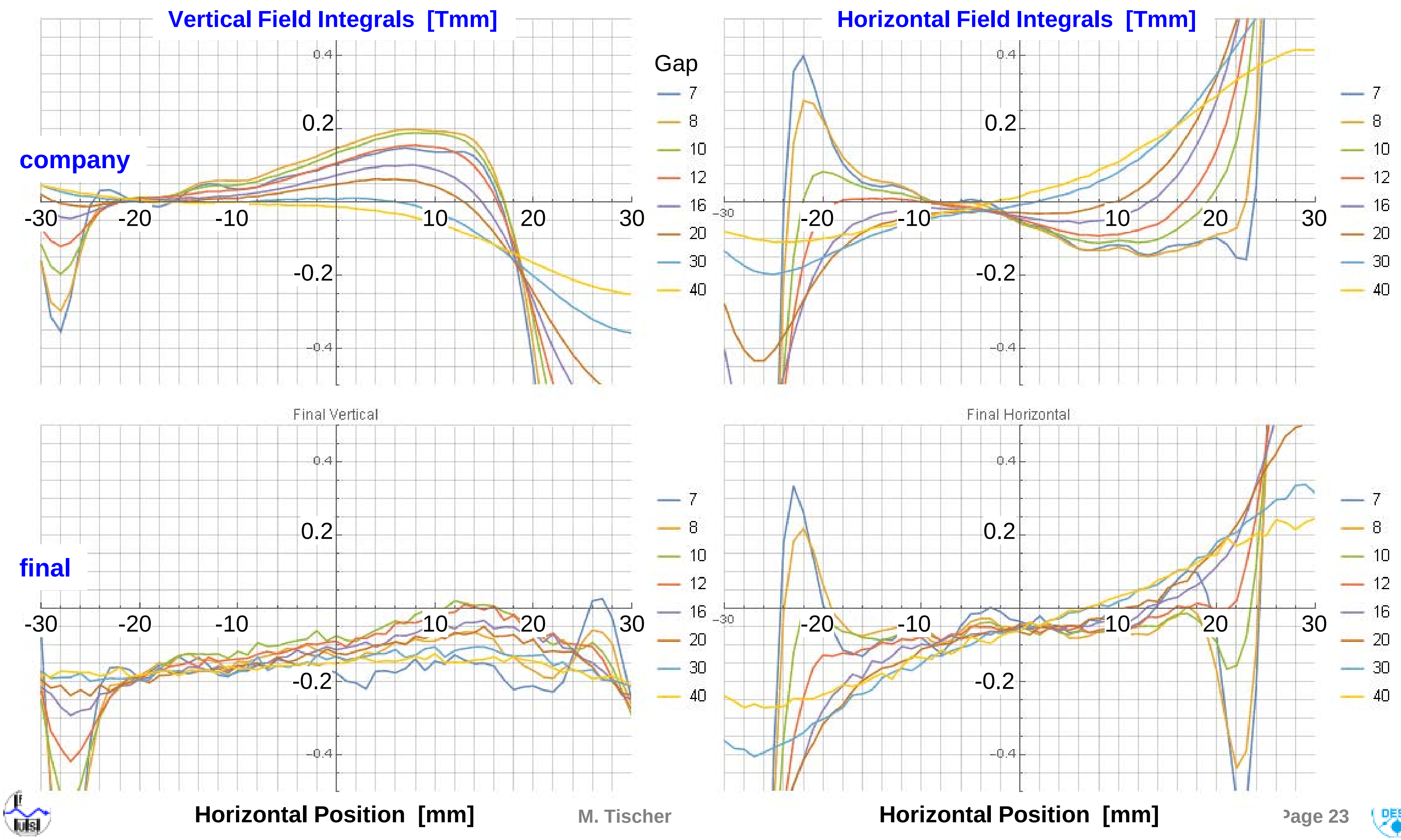




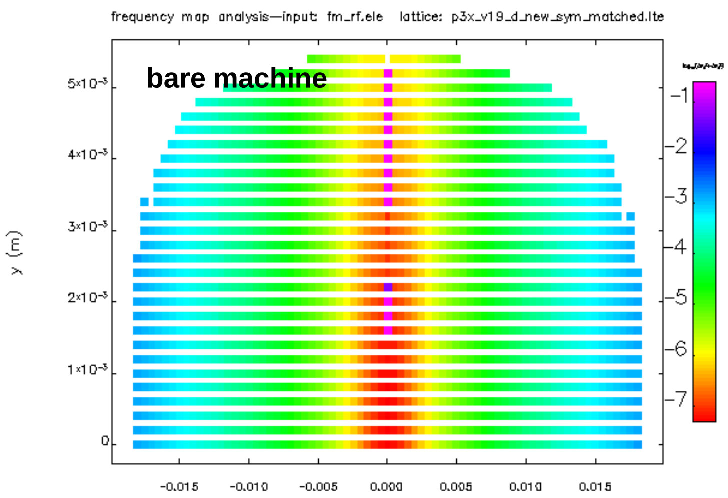


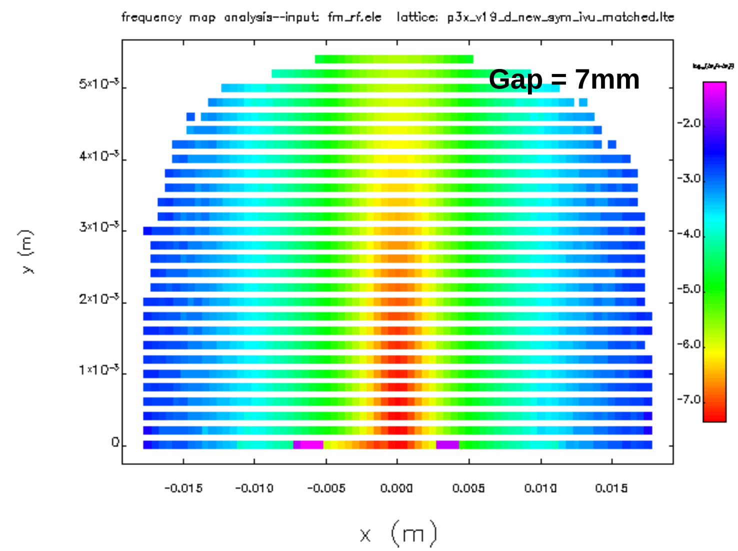
Magnetic Measurements (1)

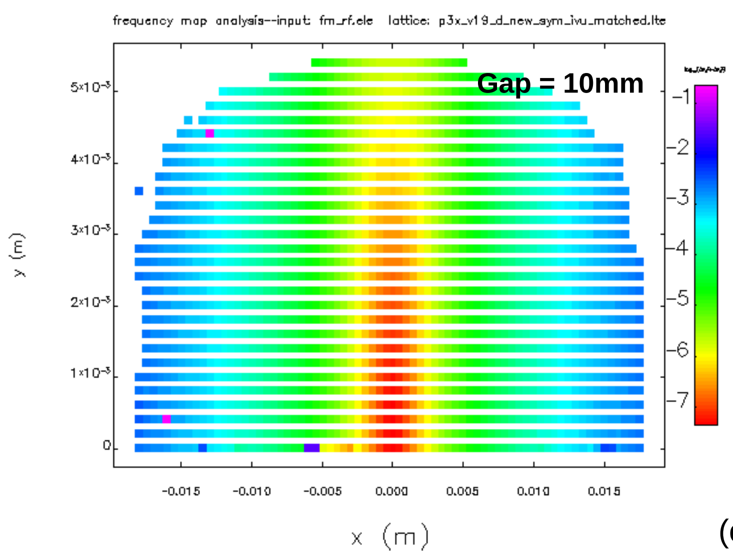
- Multipole errors: result at company significantly improved at DESY
- partial transfer of vertical to horizontal errors → less impact on injection



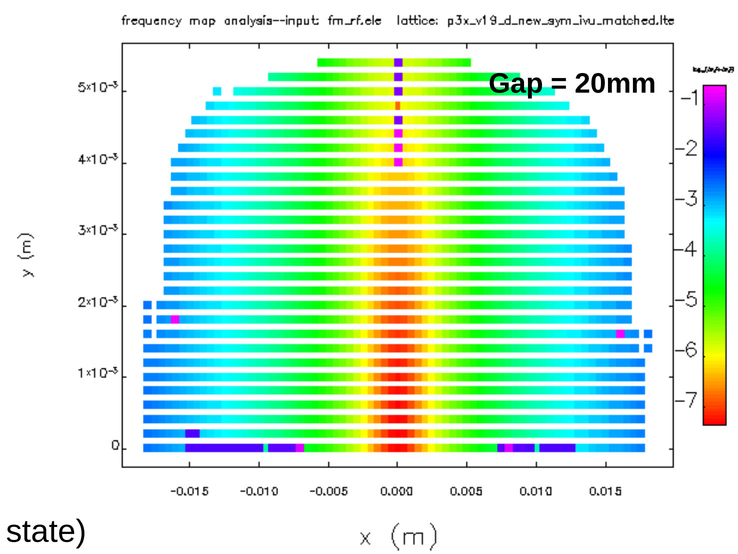
IVU-Multipole Errors – Effects on Dynamic Aperture







(close to present state)

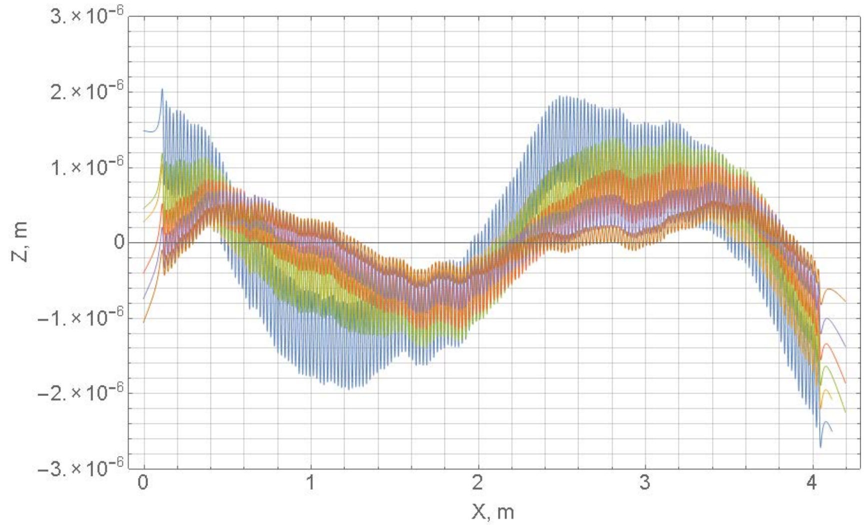


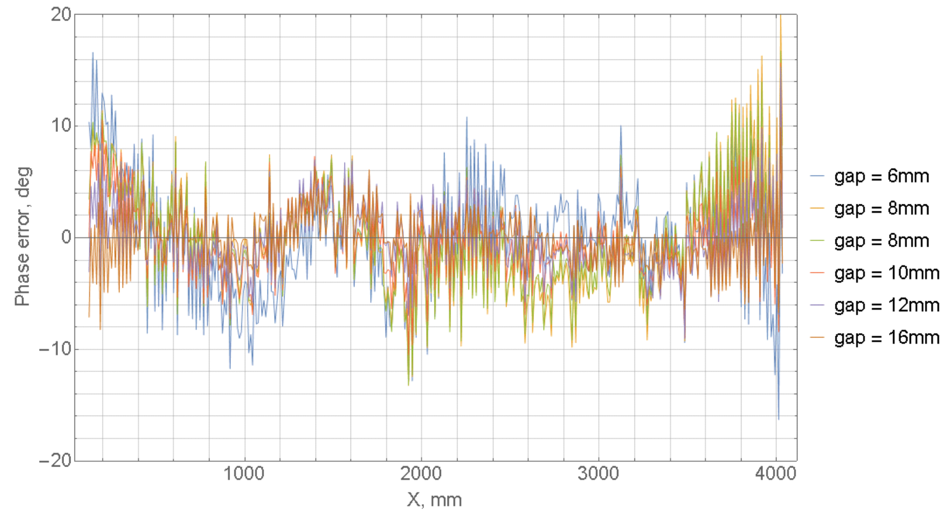
courtesy of Joachim Keil

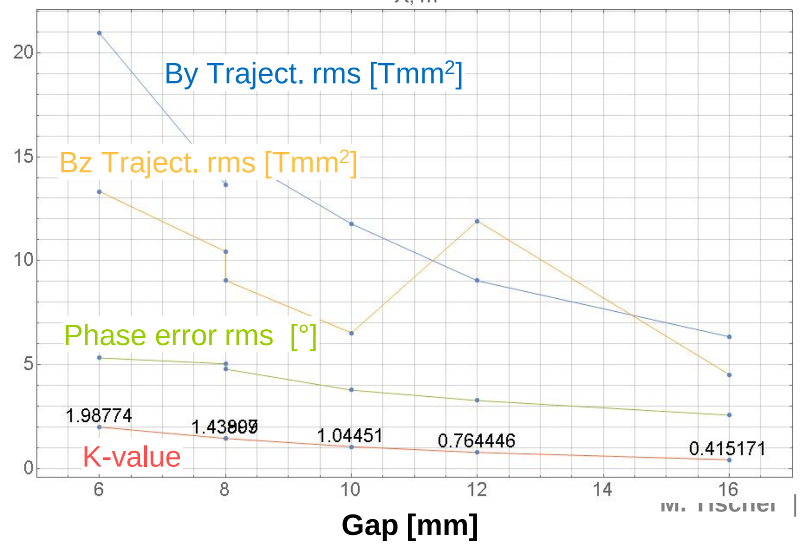
Magnetic Measurements (2)

> half-way reasonable results (but not yet in specs)

- kinks in the trajectory (due to shielding/amplification effects of fields frozen in the support structure)
- phase error too large for small gaps







> 2 pairs of additional kicker coils installed

- will improve the trajectory straightness
- will also reduce the phase error

> Thanks!