SwissFEL Undulators

Thomas Schmidt
PSI
on behalf of SwissFEL ID Project Team

LCLS II meeting


342.0 müM
325.0 müM

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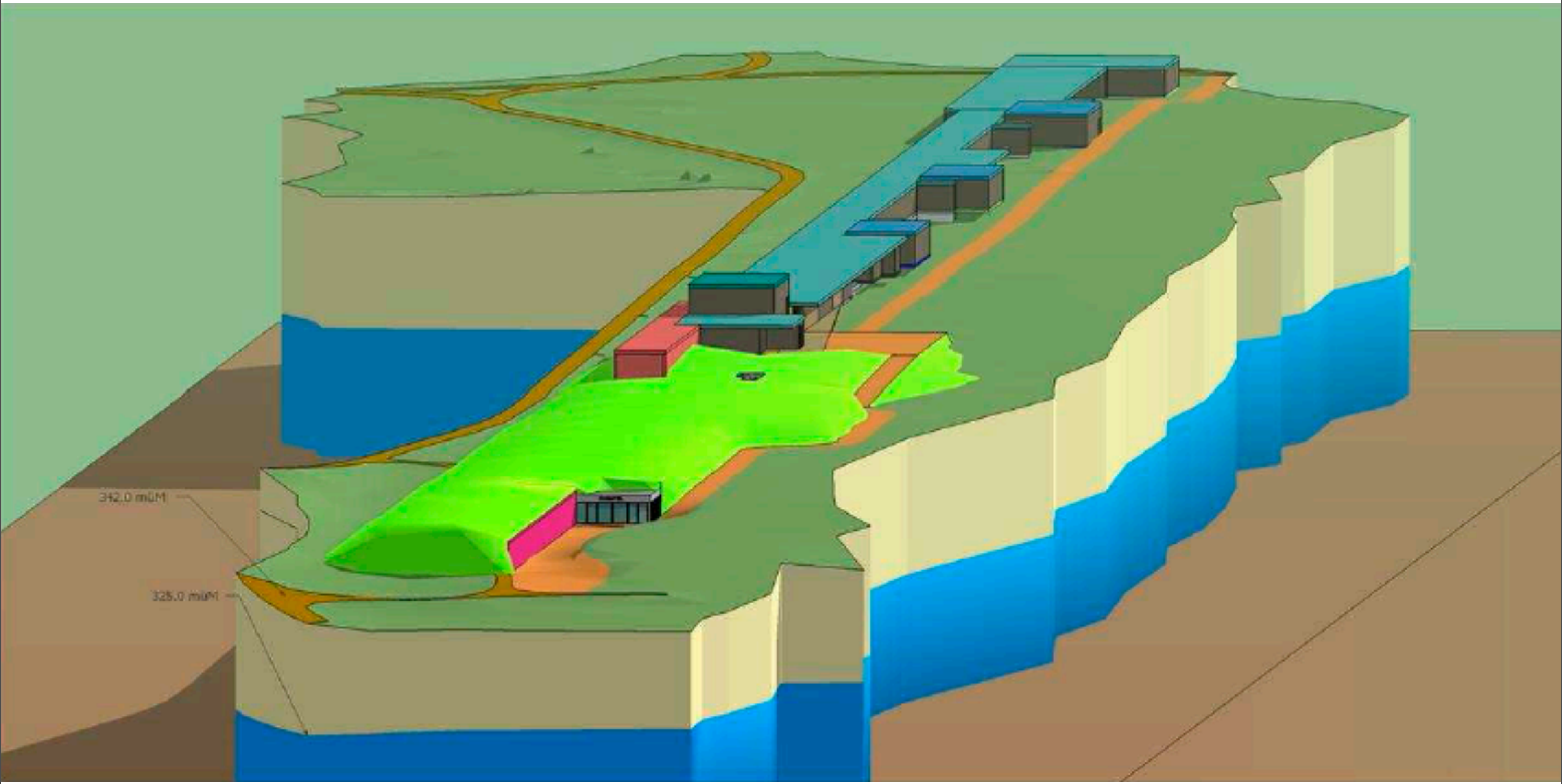
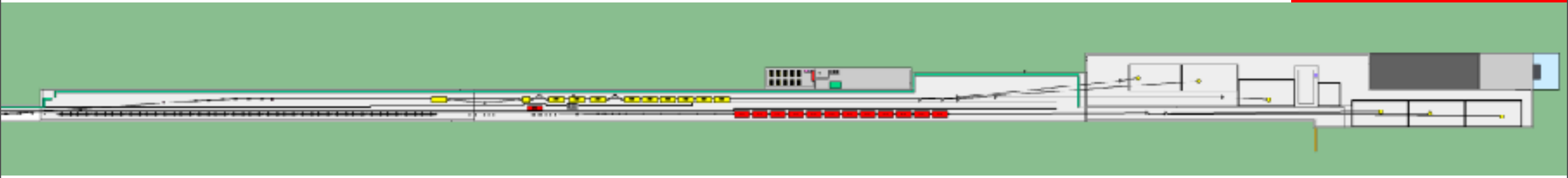
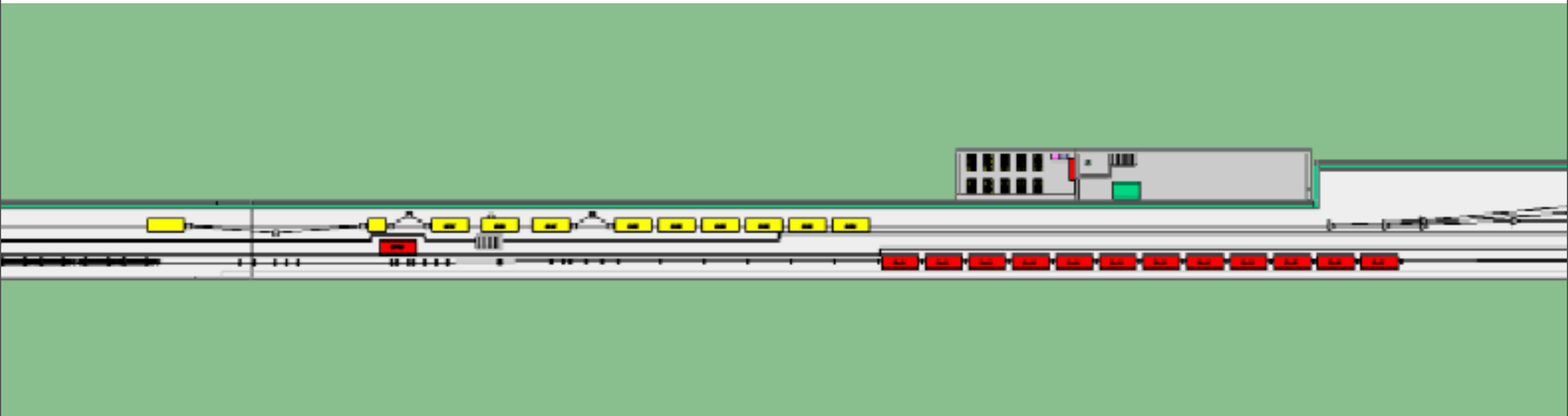
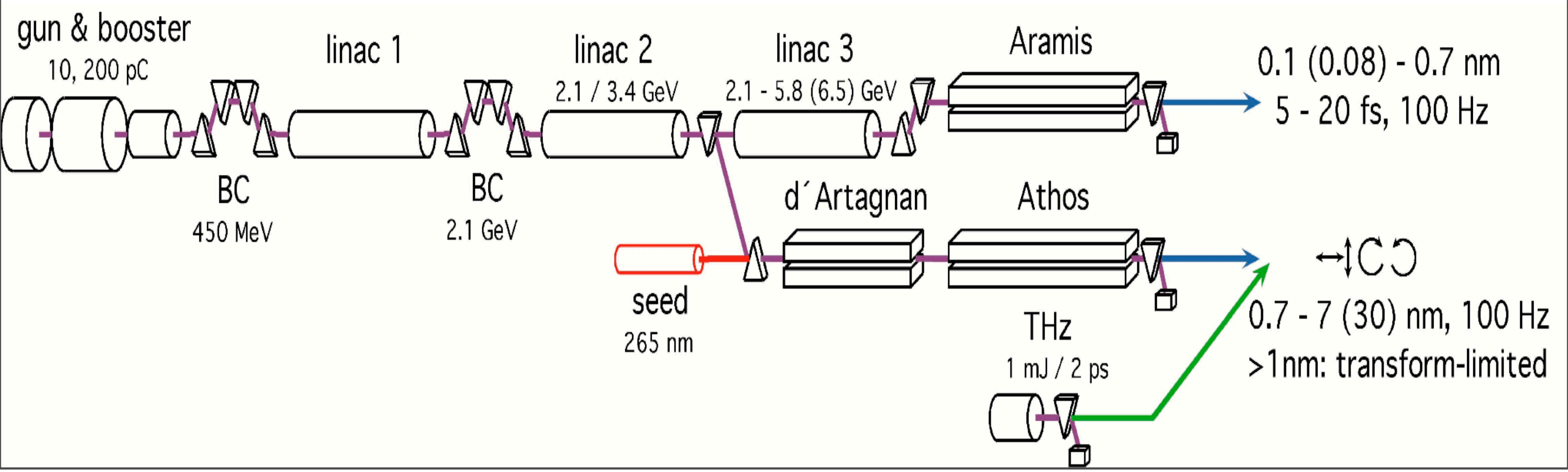
+ SwissFEL



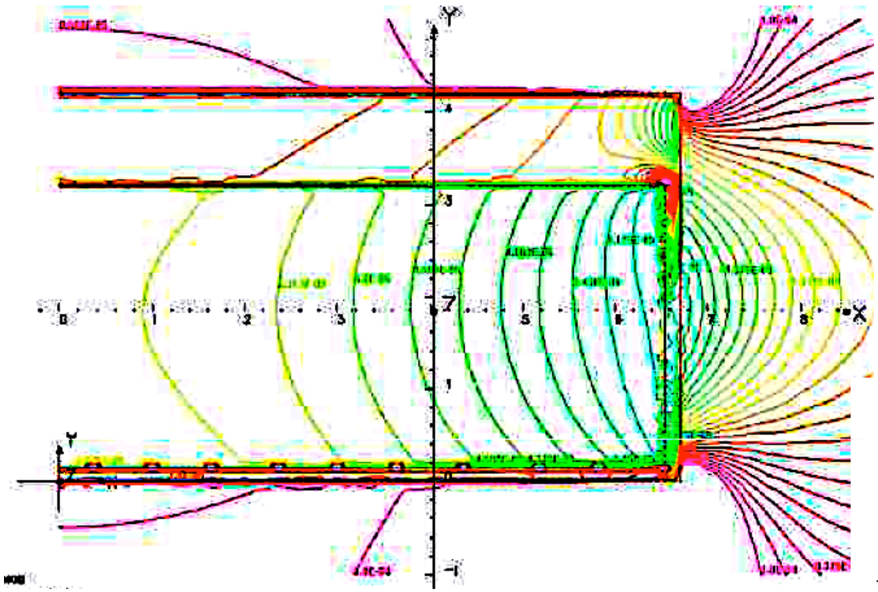


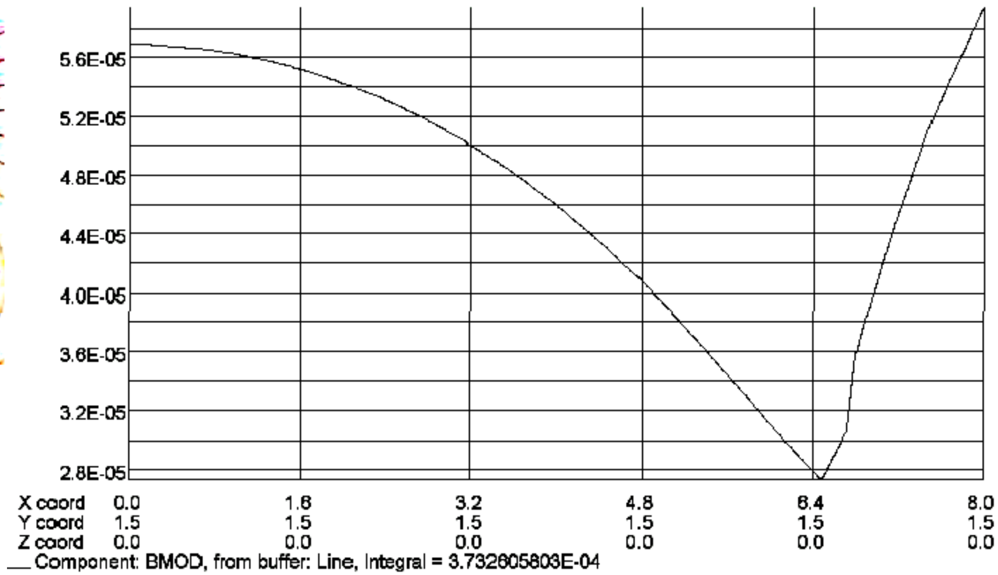



gun & booster
10, 200 pC
BC
450 MeV
linac 1
BC
2.1 GeV
linac 2
2.1 / 3.4 GeV
linac 3
2.1 - 5.8 (6.5) GeV
Aramis
0.1 (0.08) - 0.7 nm
5 - 20 fs, 100 Hz
seed
265 nm
d´Artagnan
Athos
THz
1 mJ / 2 ps
0.7 - 7 (30) nm, 100 Hz
>1nm: transform-limited

Shielding earth field in undulator tunnel

Opera 3D
by Marco Negrazus





attenuation factor
in undulator tunnel: 1.7 - 3
in linac tunnel: 5 - 8

Undulator Strategy for SLS

SPring-8

Hitachi
Danfysik
PSI

hard x-ray: (5 - 20 keV)

small period
small gap
in-vacuum undulators
high harmonics (13^{th})

ID	gap
U24	6 - 12 mm
U19	4.5 - 7 mm
U14	4 - 6 mm
	length: 2m

soft x-ray: (10 eV - 2 (8) keV)

BESSY

PSI

variable polarization
circular and inclined
electromagnetic
APPLE II
standard, fixed gap

ID	gap	
UE56	16 - 70 mm	
UE54	16 - 70 mm	(up to 28^{th}harm)
UE44	11.4 mm	
	length: 2 - 3.4m	

Undulator Strategy for SLS

hard x-ray: (5 - 20 keV)

SPring-8

small period
small gap
in-vacuum undulators
high harmonics (13^{th})

Hitachi
Danfysik
PSI

ID	gap
U24	6 - 12 mm
U19	4.5 - 7 mm
U14	4 - 6 mm
	length: 2m

soft x-ray: (10 eV - 2 (8) keV)

BESSY

variable polarization
circular and inclined
electromagnetic
APPLE II
standard, fixed gap

PSI

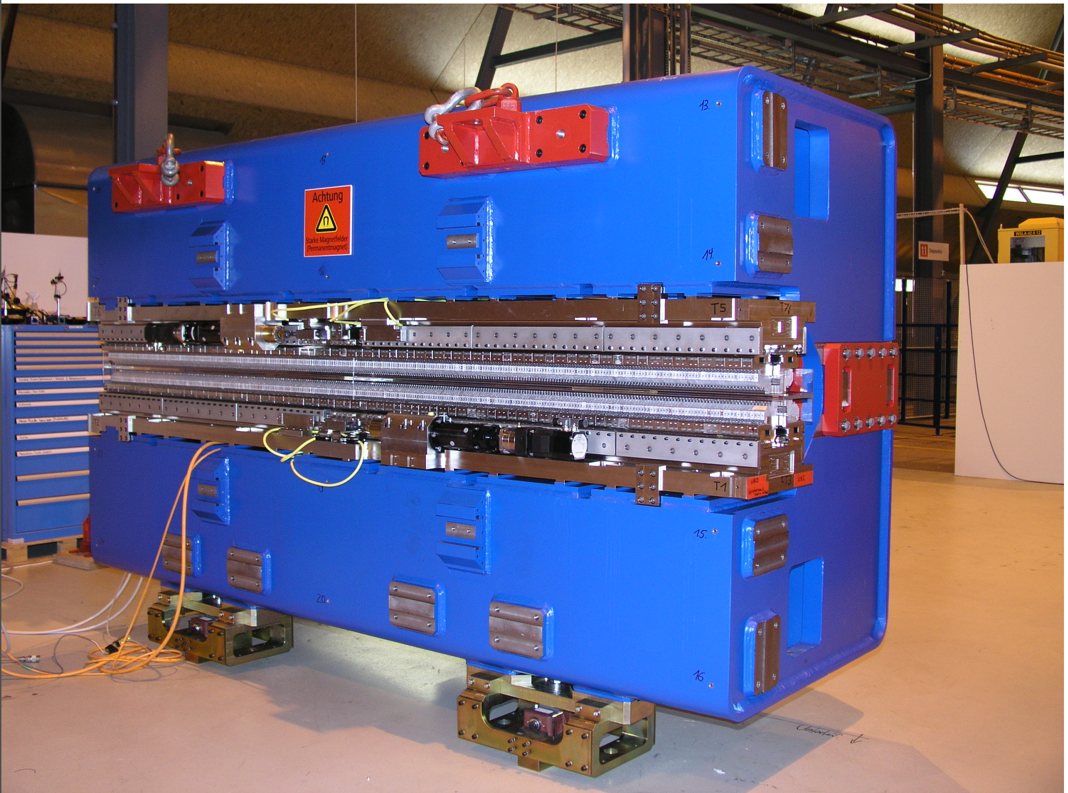
ID	gap	
UE56	16 - 70 mm	
UE54	16 - 70 mm	(up to 28^{th}harm)
UE44	11.4 mm	
	length: 2 - 3.4m	

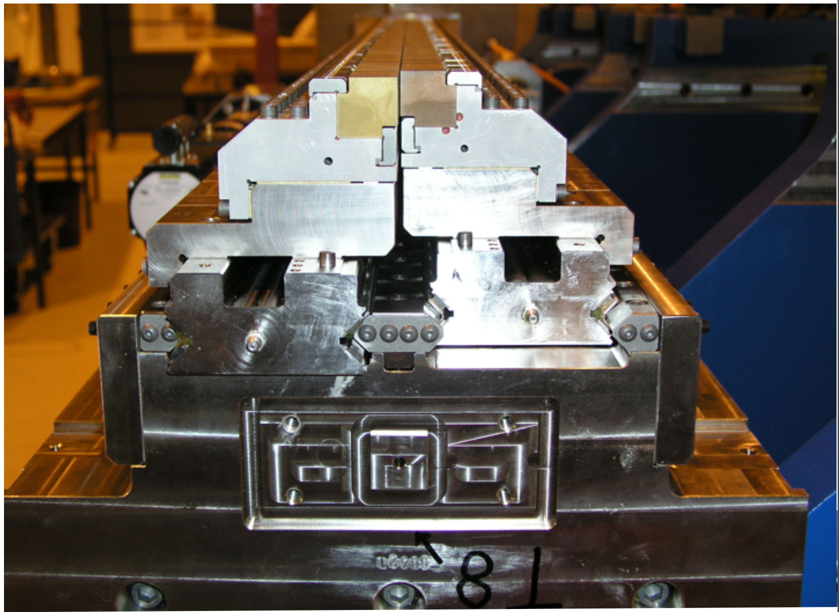
U15, gap > 4mm, length 4m

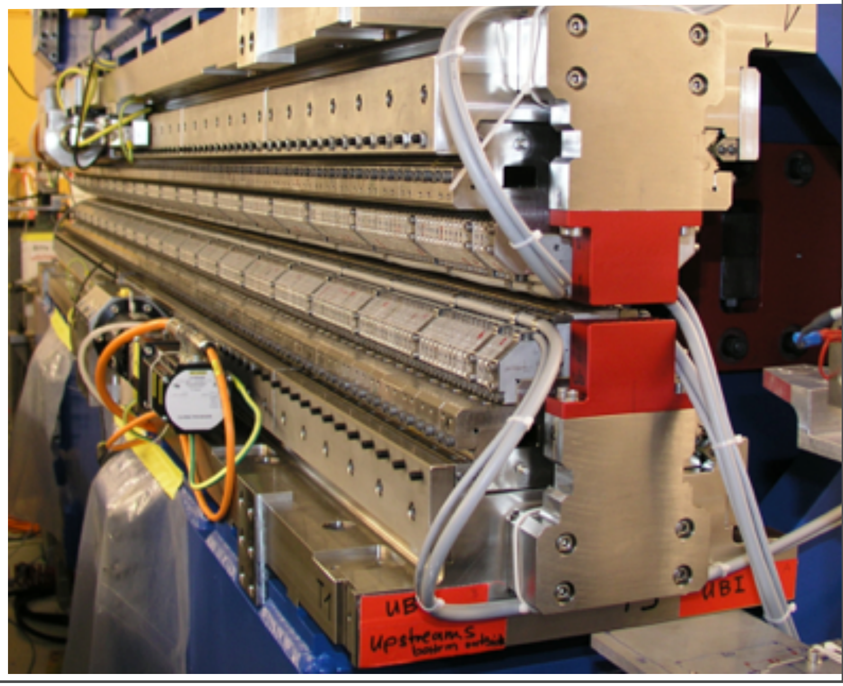
UE40, gap 6.5mm, length 4m

Undulator Strategy for SwissFEL

UE44 - fixed gap APPLE II*







*R. Carr, Adjustable phase undulator,
NIM A306, 391 (1991)

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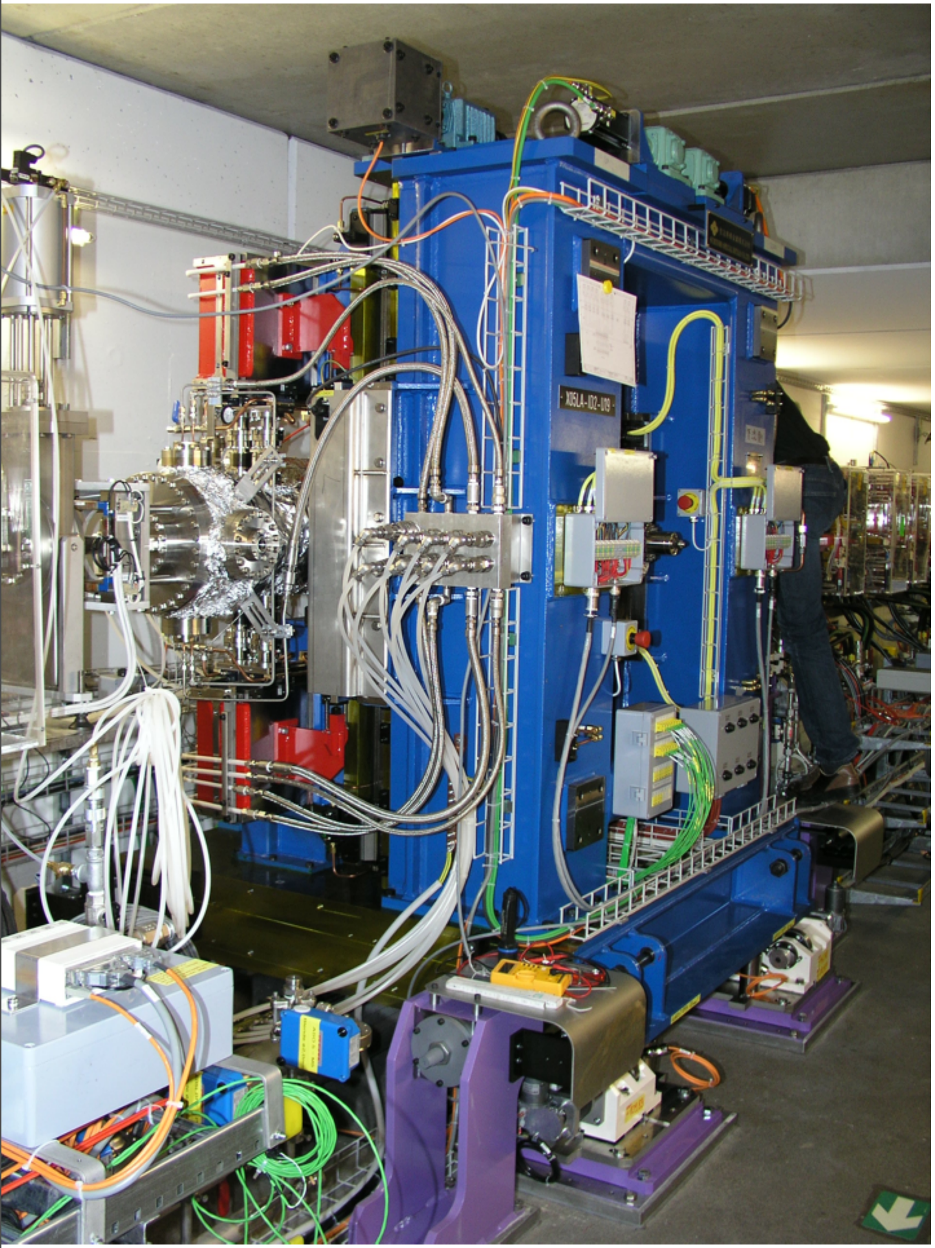
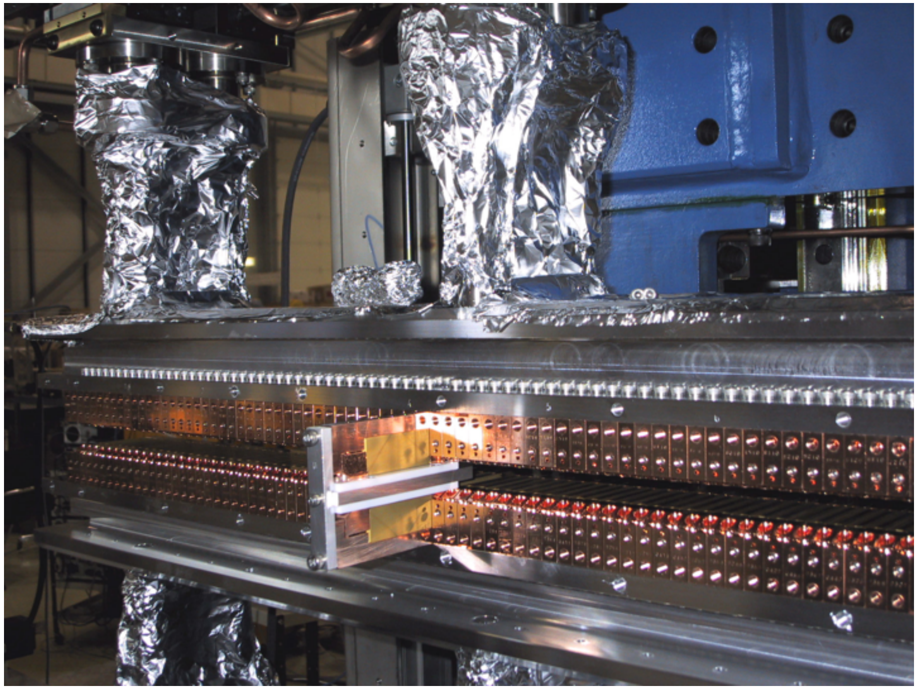
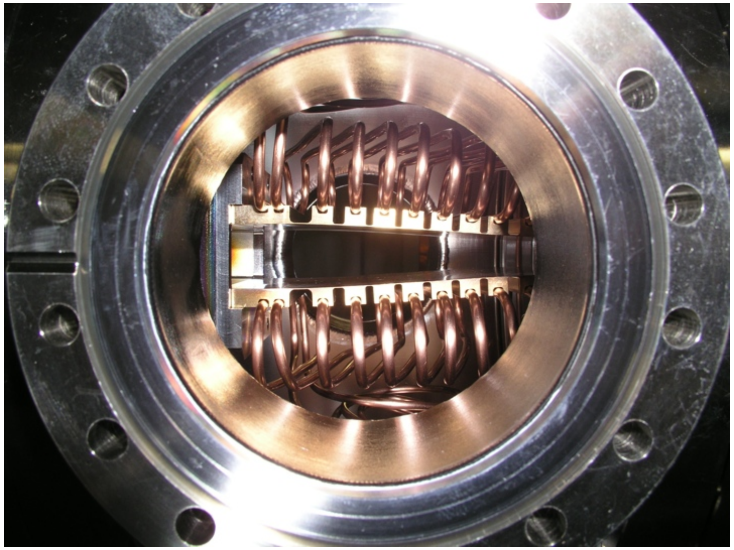
U19 - in vacuum Undulator







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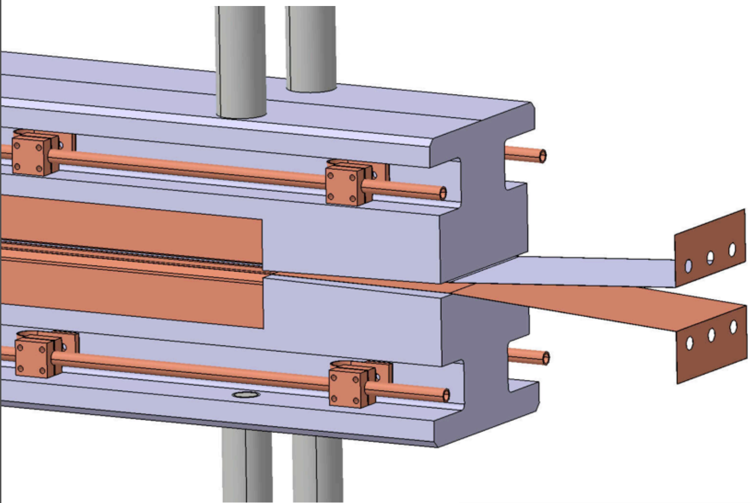
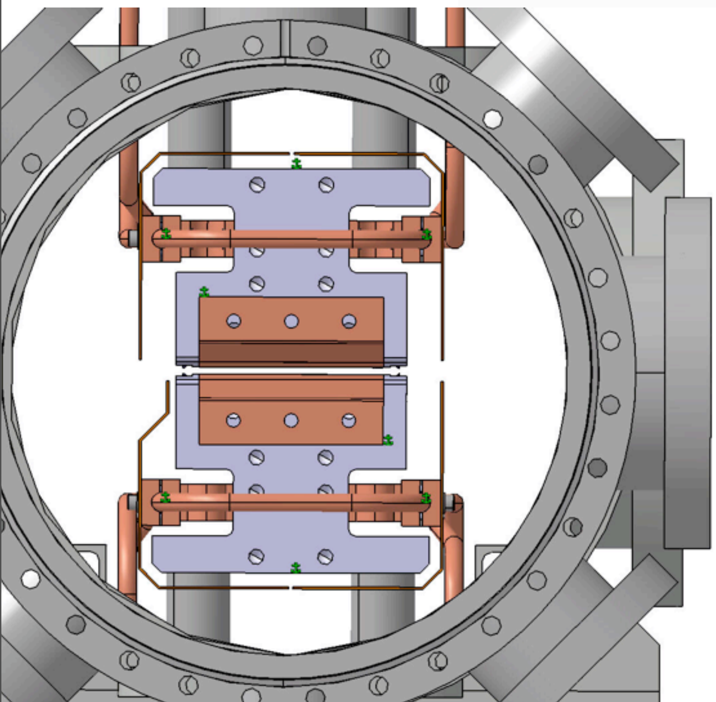
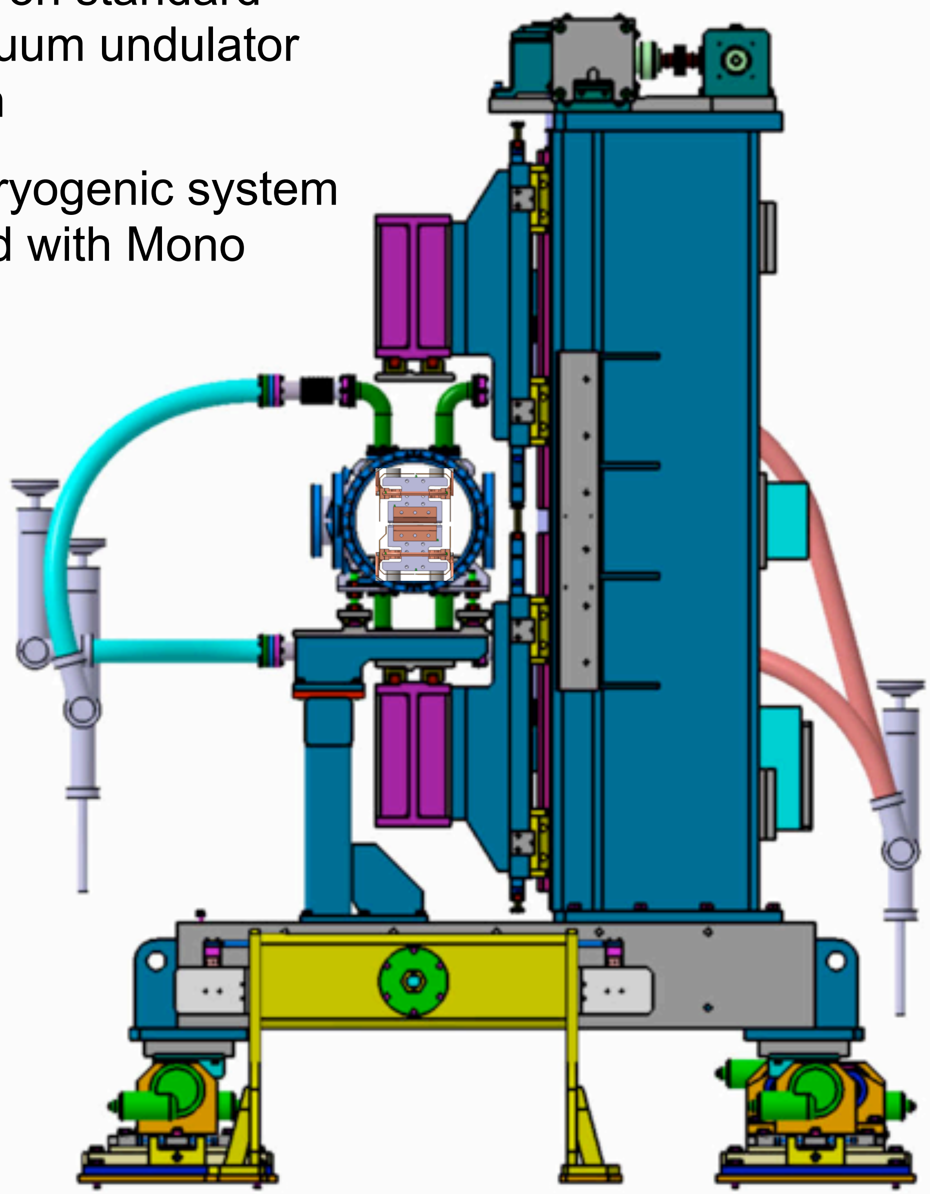
U14 - cryogenic Undulator



based on standard
in-vacuum undulator
design

LN2 cryogenic system
shared with Mono

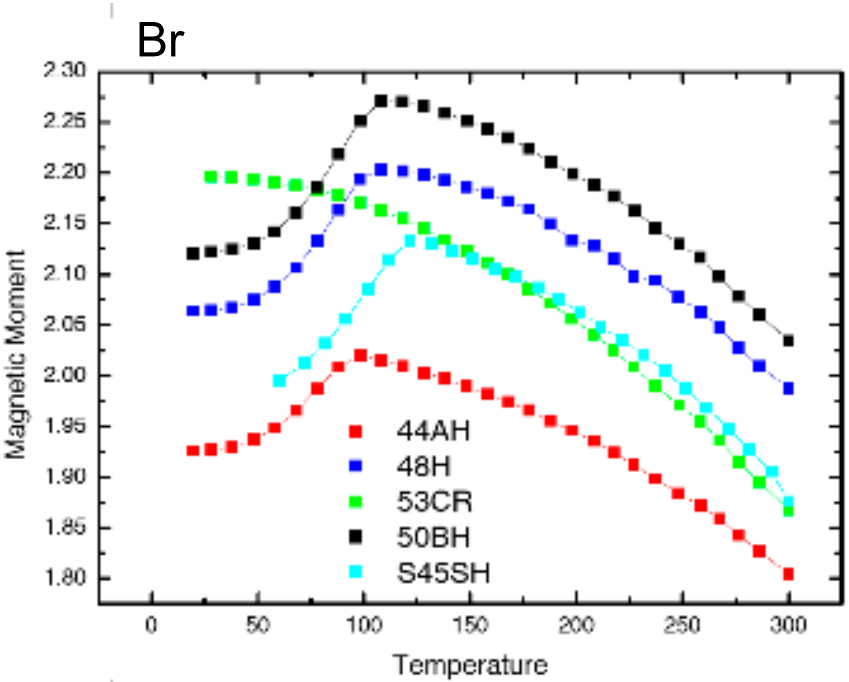


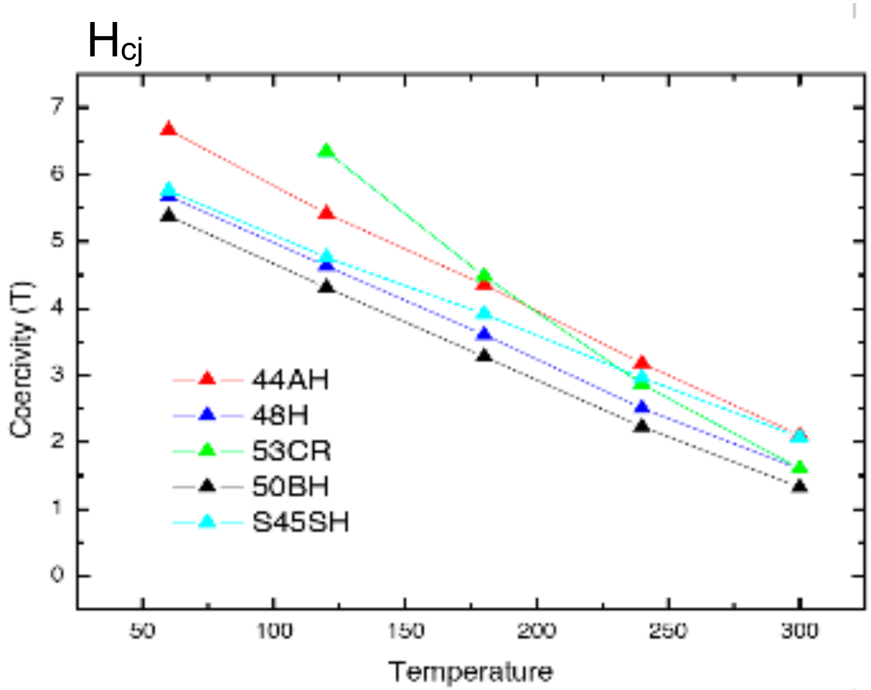


U14 - cryogenic Undulator

+ SwissFEL

use dBr/dT and dH_{cj}/dT





high field ➪ small period

high stability ➪ small gaps

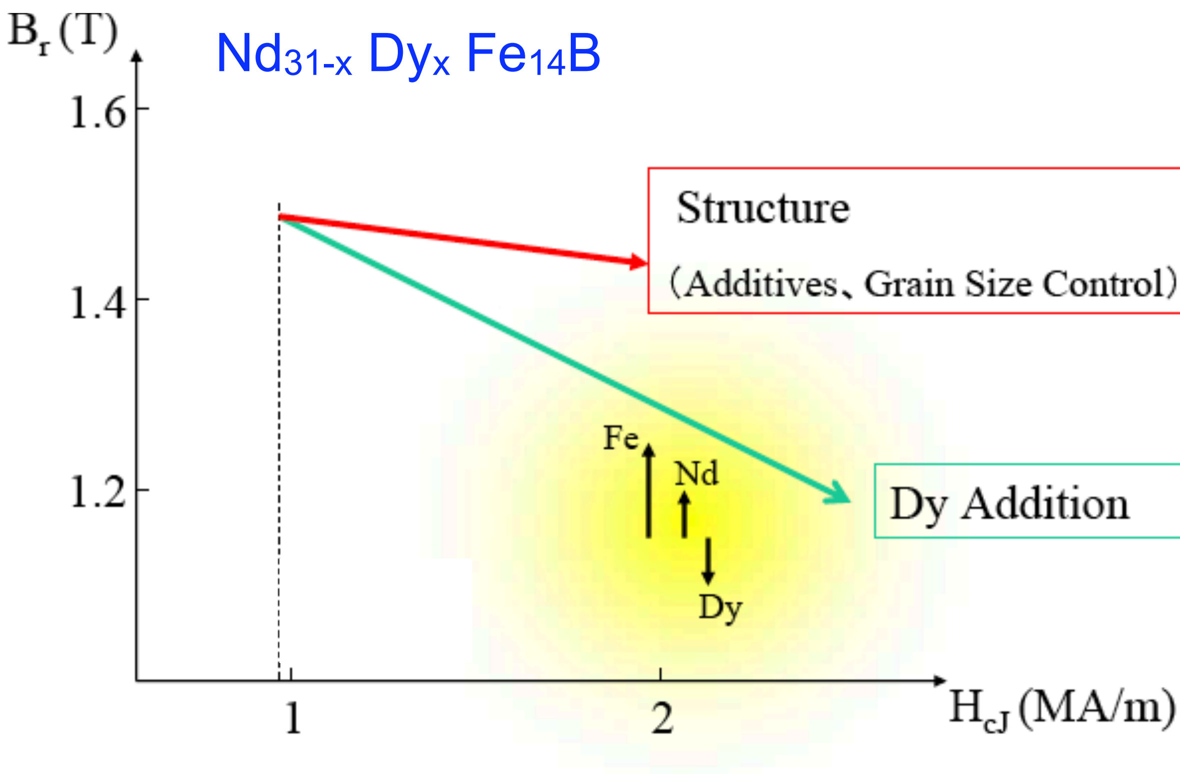
CPMU cryogenic permanent magnet undulator

SPring-8 Patent (2003)

2 Undulators (ESRF installed 2008, SPring-8 / PSI (magnetic meas.)

U19 - in vacuum Undulator

- stabilize magnets by replacement of Nd with Dy ($Dy_2Fe_{14}B$)
  increased stability but lower strength (U19: NdFeB ~ SmCo)

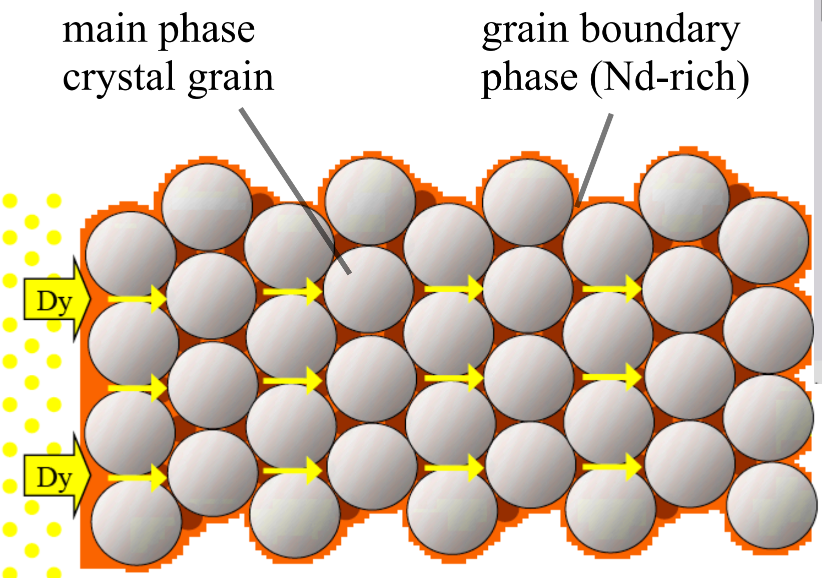


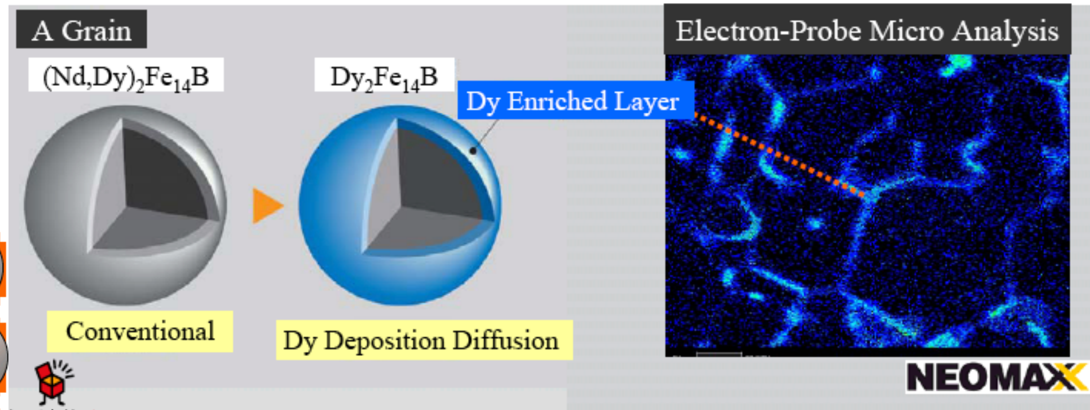
(courtesy of Hitachi Metals Ltd.)

New fabrication technique

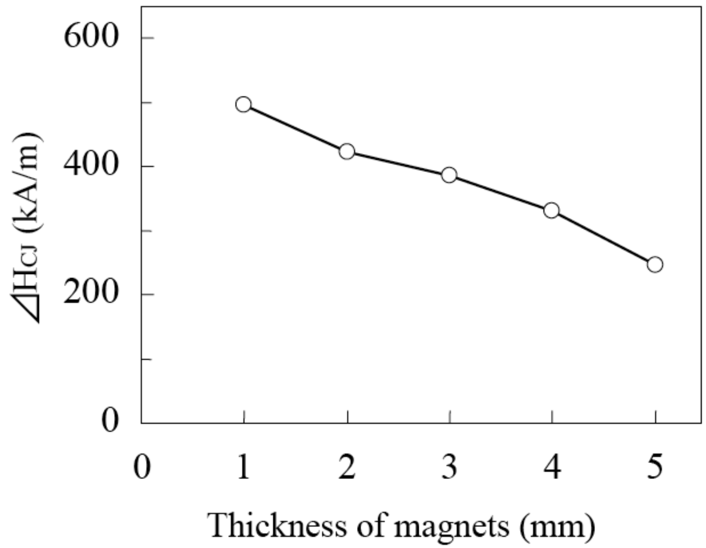
vapor diffusion of Dy into the machined magnet (Hitachi Metals Ldt.)

increase of stabilization without reduction of remanence



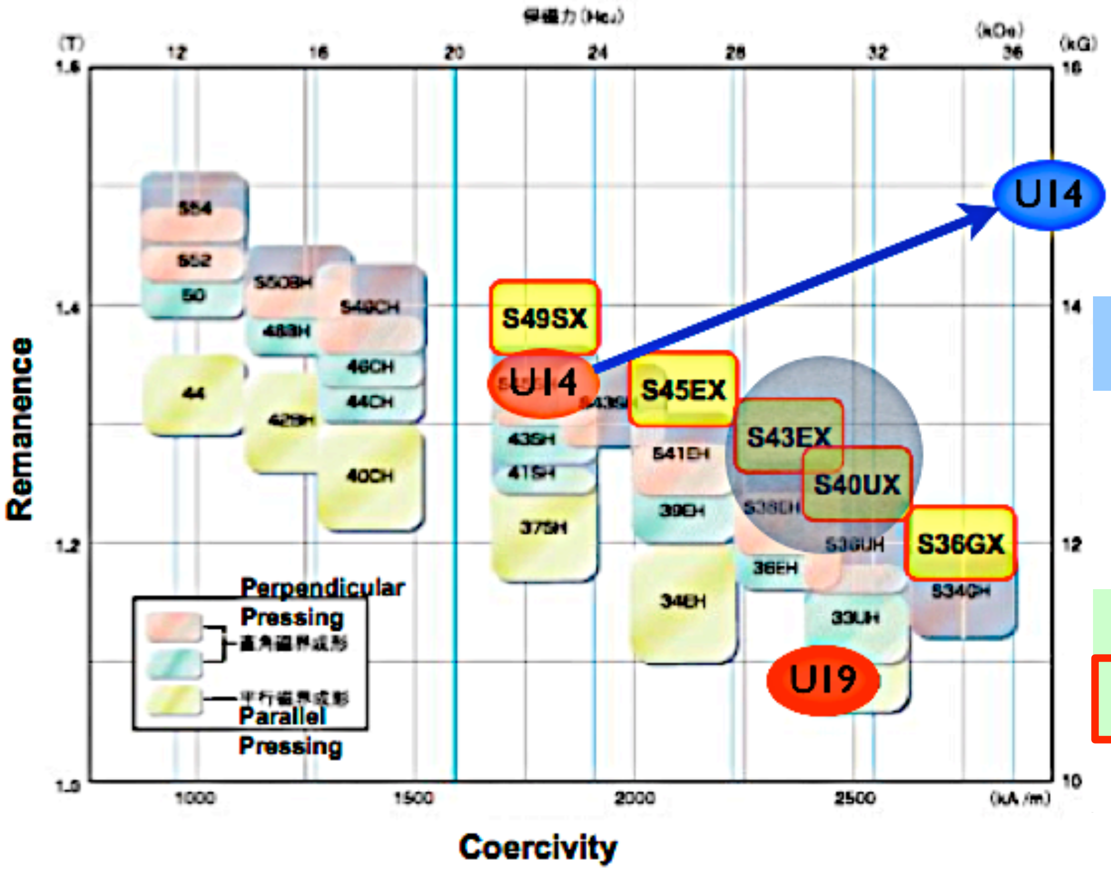


for thin magnets only
(U15 magnets: ~2.25mm)



(all figures courtesy:Hitachi Metals Ltd)

NdFeB grades



courtesy Hitachi Metals Ltd.

$Nd_2Fe_{14}Br$ + Diffused Dy

Material code	Br	Hc_J	Temp Coeff Br	Temp Coeff Hc_J
	[T]	[kA/m]	[%/°C]	[%/°C]
S49SX	1.36÷1.42	≥1671	-0.11	-0.55
S45EX	1.30÷1.36	≥1990	-0.10	-0.50
S43EX	1.26÷1.32	≥2228	-0.10	-0.48
S40UX	1.22÷1.28	≥2387	-0.10	-0.47
S36GX	1.17÷1.23	≥2626	-0.09	-0.44

NdFeB grade for SwissFEL U15

Hard x-ray Undulator U15

Type	Hybrid - In Vacuum				
# units	12				
Period	15				mm
# periods	266 (including ends)				
Magnetic length	3990				mm
K-values	1.8	1.4	1.2	1.0	-
GAP	3.2*	4.2	4.7	5.5	mm
Bz max	1.27	1	0.85	0.7	T
Br	1.25				T
Hc_J	>2400				kA/m
Magnet size	WxHxT=30x20x2.25				mm
Pole size	Wb/WtxHxT=20/15x16.5x3				mm
Max GAP	20.0				mm
ΔGAP	0.3				µm

*Minimum magnetic GAP (Vacuum GAP=3mm)

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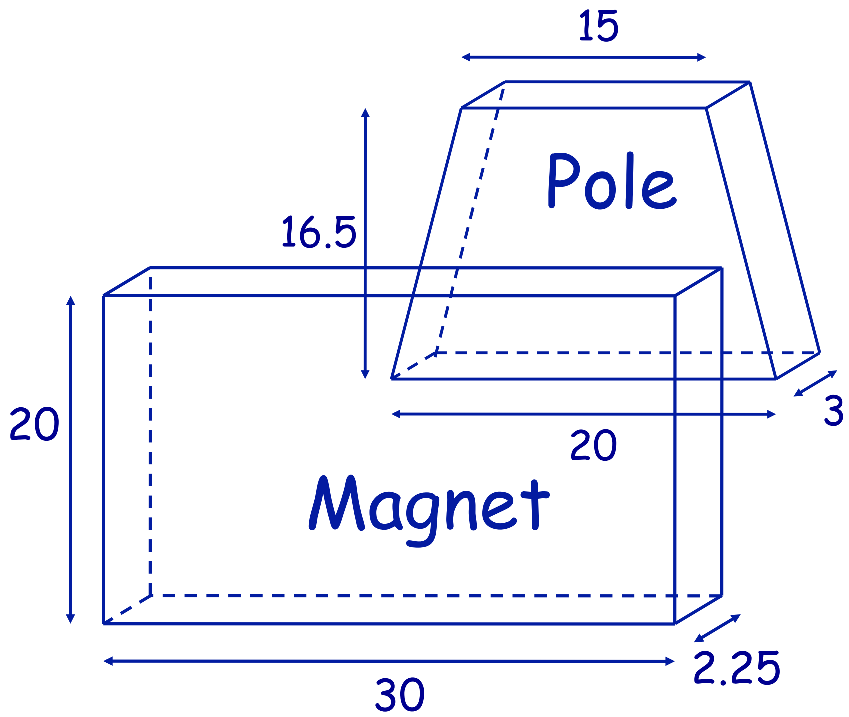
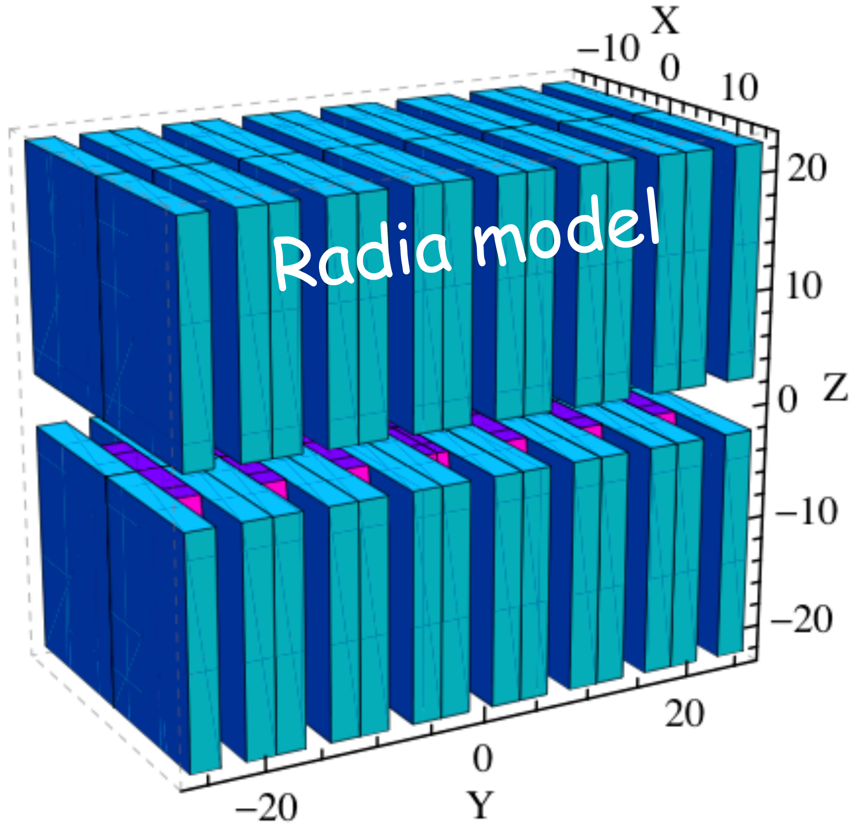
U15 magnetic optimization

- K-value (B)
- Good field region $\Delta B/B<10^{-4}$
- Magnetic forces
- Cost→material

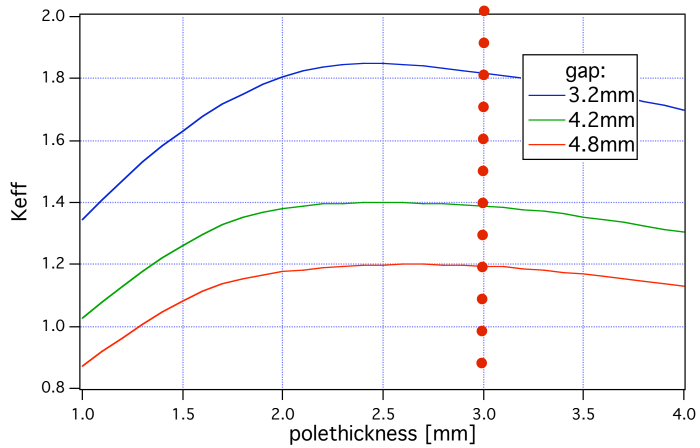


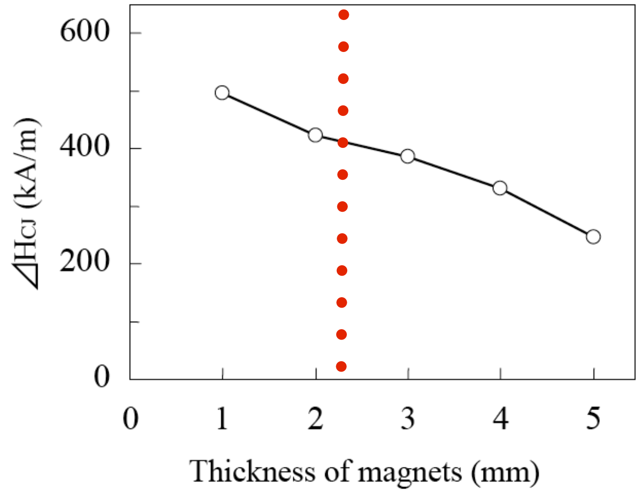


Magnet Design: Pole thickness

Polethickness: 3.0mm

Magnet: 4.5mm (2 x 2.25mm)



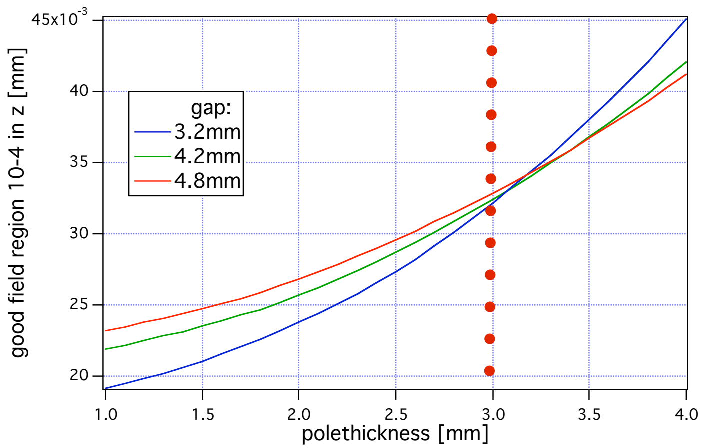


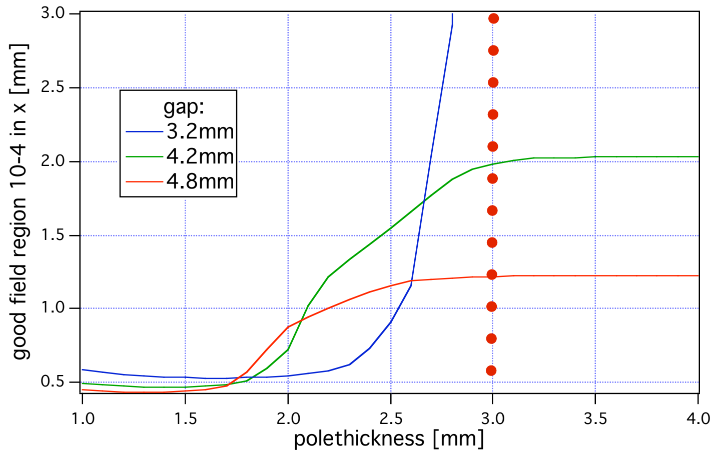
diffused Dy: increase in coercivity

courtesy

Hitachi Metals Ltd.

good field region:





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Magnet Design: pole tip variation

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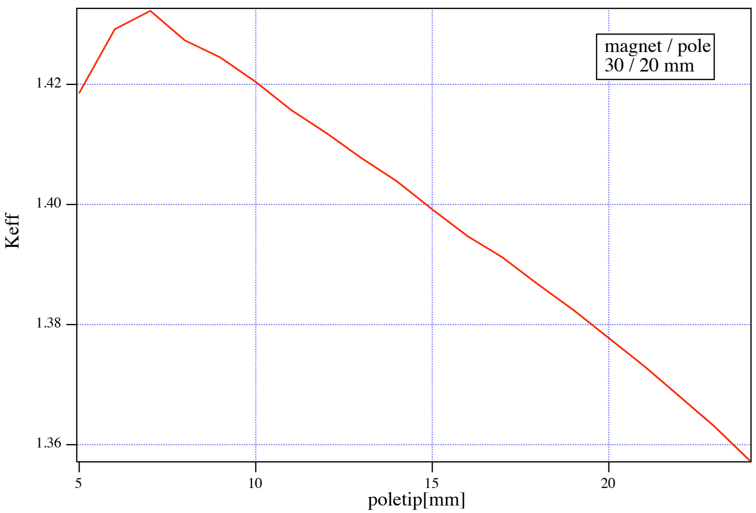
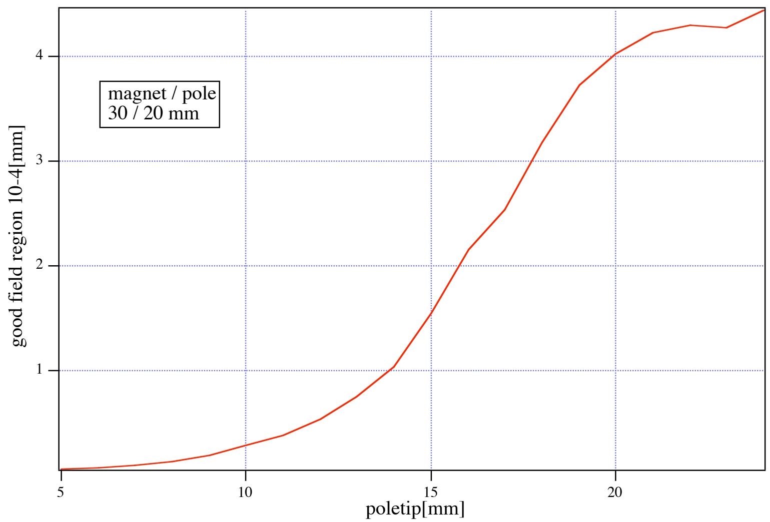
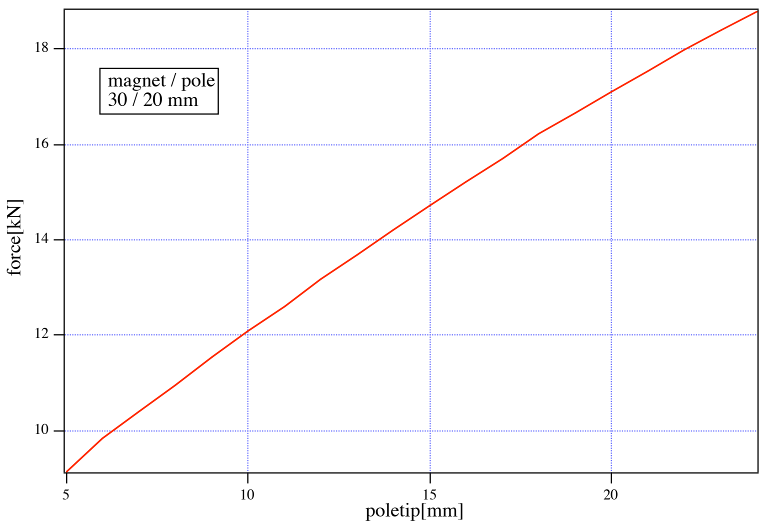
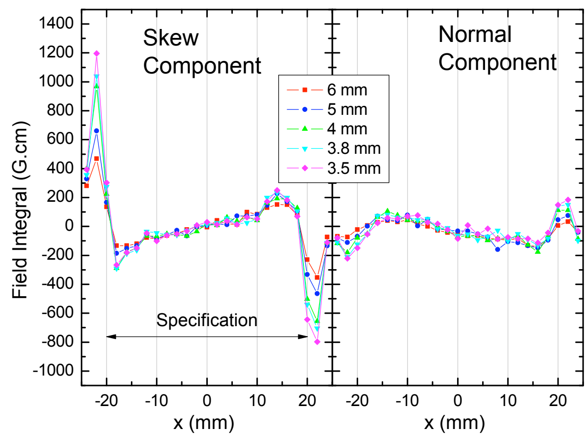






Minimum polewidth:
good field integral region for U14: ±18mm with pole width 42mm
critical to control magnetic field at the magnet/pole edges
➥ U15 with pole tip 15mm: field control ±5mm



SLS
CPMU14

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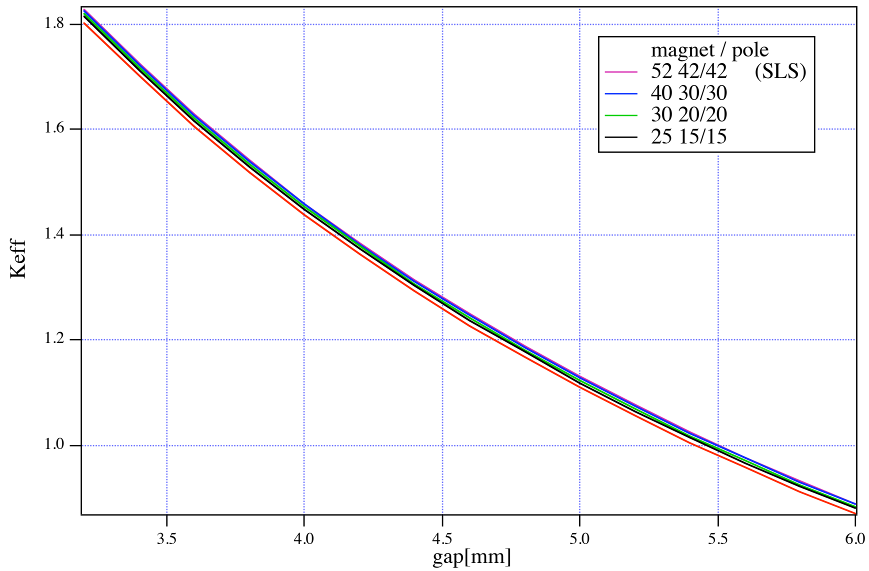
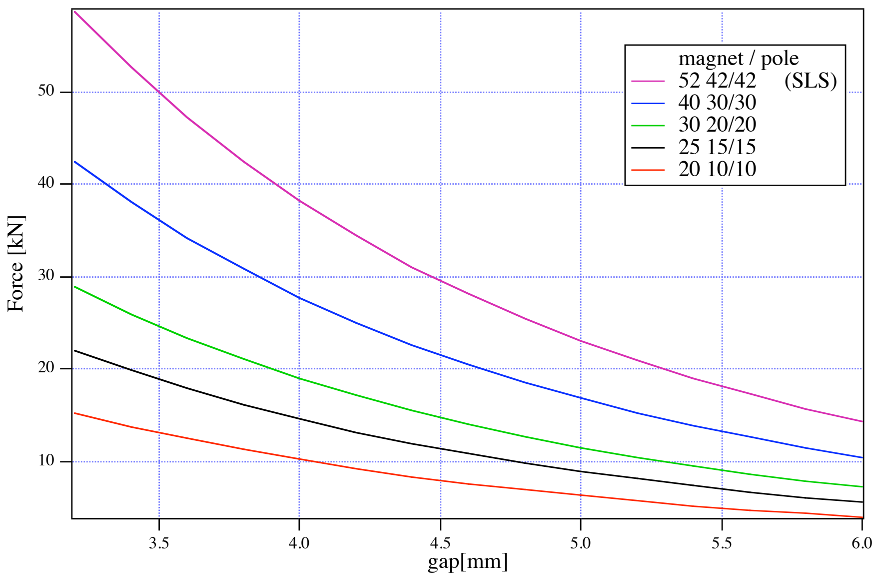
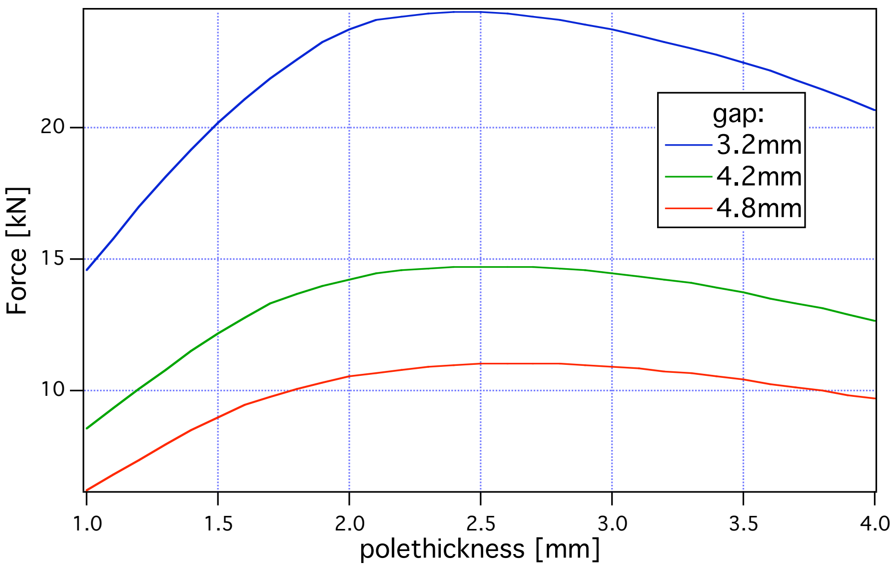
Magnetic Forces







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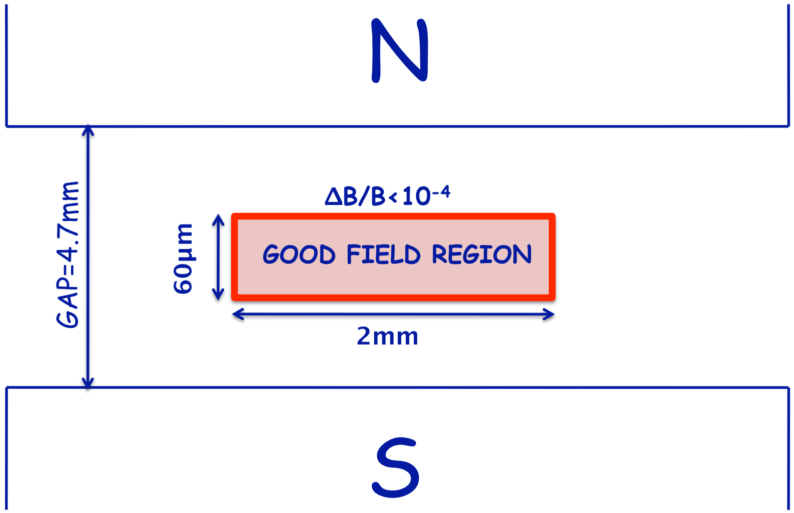
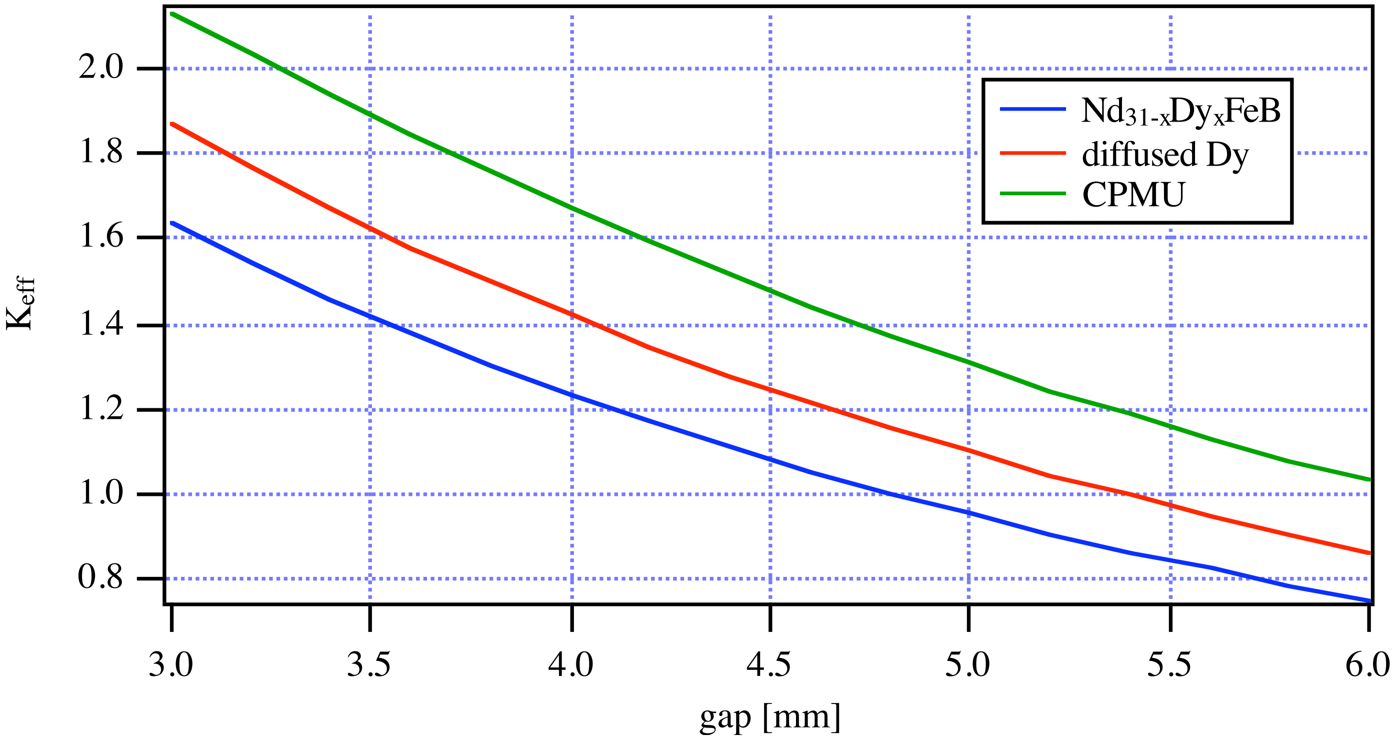

N
ΔB/B<10-4
GOOD FIELD REGION
GAP=4.7mm
60μm
2mm
S


Keff
gap [mm]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Nd31-xDyxFeB
diffused Dy
CPMU

Soft x-ray Undulator zoo (draft)

name	UE40	UE60	U60	U100	U110H	
period	40	60	60	100	110	mm
gap (magnetic)	6.5 (8) - 24	8 - 40	8 - 40	9 - 27	7 -	mm
K	3.5 - 0.9	5.2 - 0.9	5.2 - 0.9	15.2 - 4.8		
gap (vacuum)	5 x 10	6 x 12	6 x 12	8 x 16	6 x 12	mm
gap variation	32	32	32	32	32	mm
open gap / Kmin^2	38.5 / 0.3	40 / 0.86	40 / 0.9	41 / 2.5		
magnet size	20x20x10	20x20x10	40x20x10	40x25x40	30x30x25	mm^3
pole size	-	-	-	20x25x35	-	
remanence	1.08	1.08	1.08	1.25	1.25	T
Bz / Bx	0.94 / 0.81	0.8 / -	0.8 / -	1.63 / -	- / 1.41	T
Kz / Kx	3.5 / 3.0	3.2 / -	3.5	15.2 / -	- / 14.5	
type	APPLE II	APPLE II	PPM 4 x 1	Hybrid	APPLE II LV fixed	
units	6	2	1	2	1	
unit length	4	4	4	4	4	m
number of periods	98	64	64	38	35	

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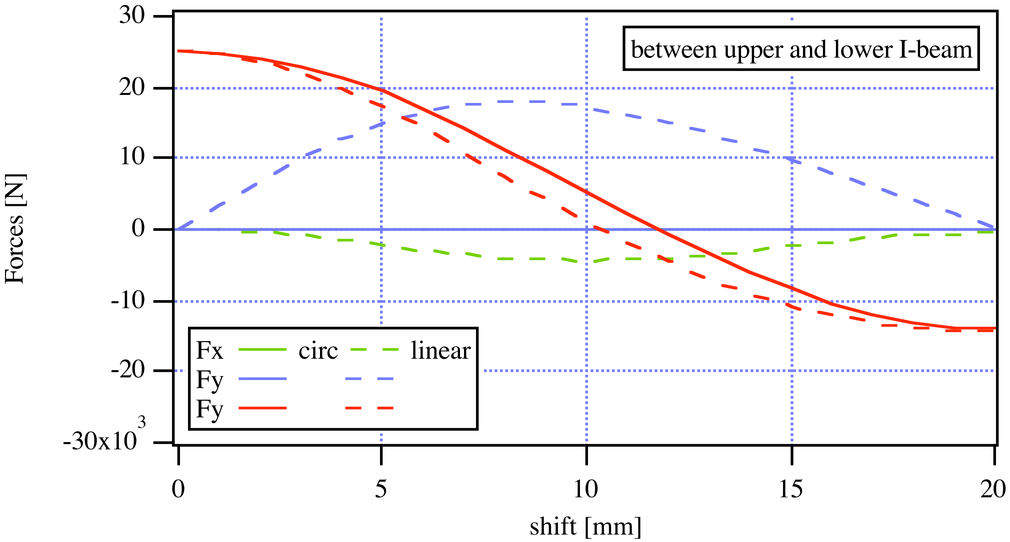
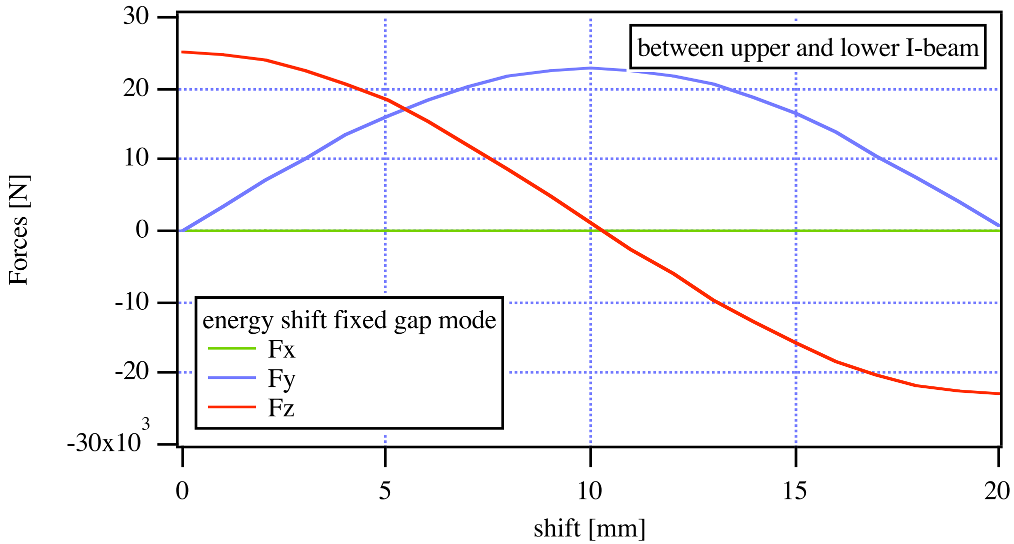
3D - Forces for APPLE II





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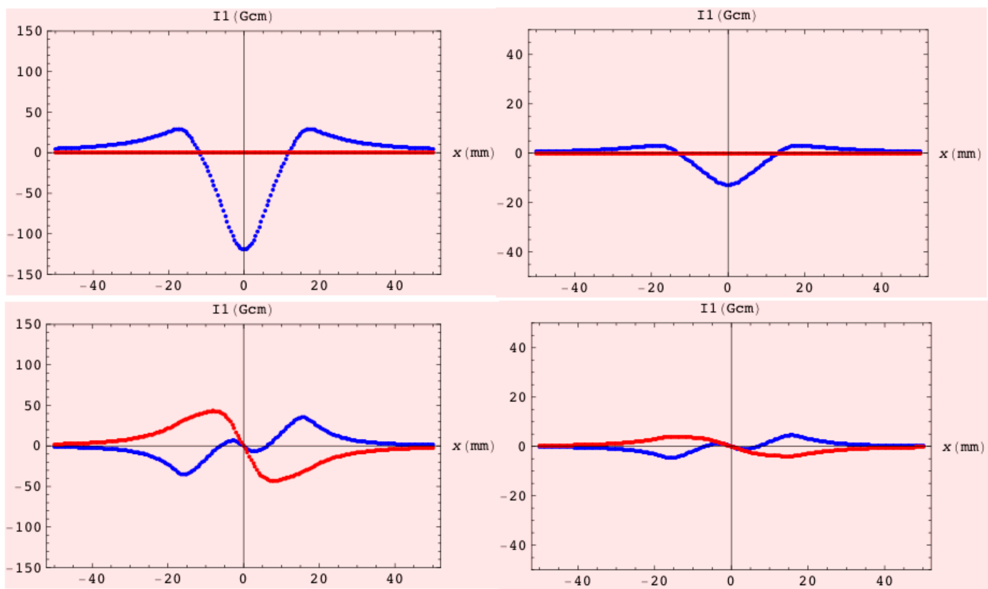
Magnets for UE40 / UE60

	Sm_2Co_{17}	NdFeB		
grade		standard Dy	diffused Dy	CPMU
radiaton hard	yes	yes		
Br [T]	1.1	1.08	1.25	1.5
dB/dT [%/K]	-0.035	-0.1	-0.1	flat top
permeability	1.01/1.04	1.06/1.15		
mech. prop.	brittle	good		
suitable for	UE40	UE40	U15	U15

Sm_2Co_{17} is an alternative

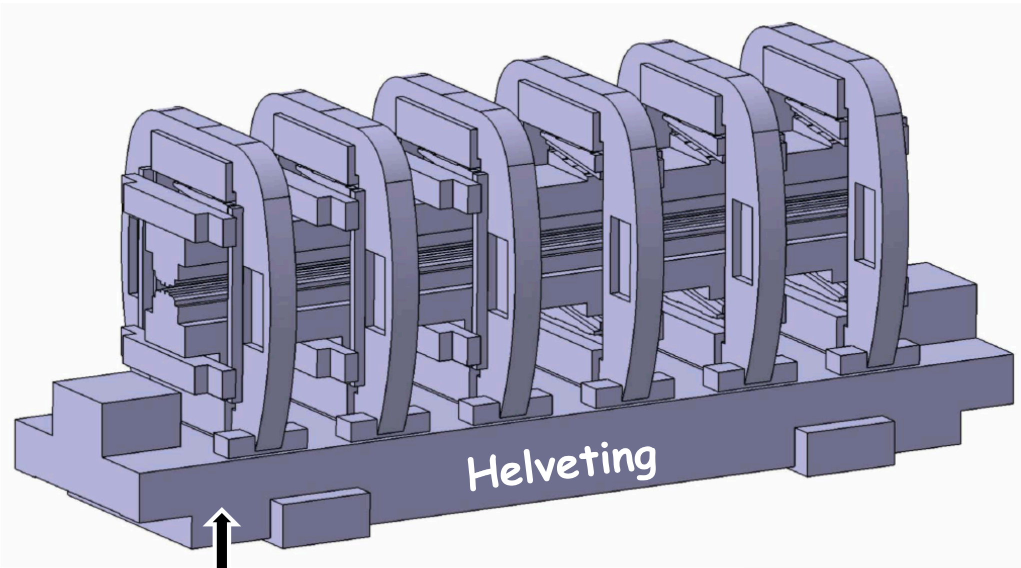
dB/dT
less nonlinearities

NdFeB Sm_2Co_{17}

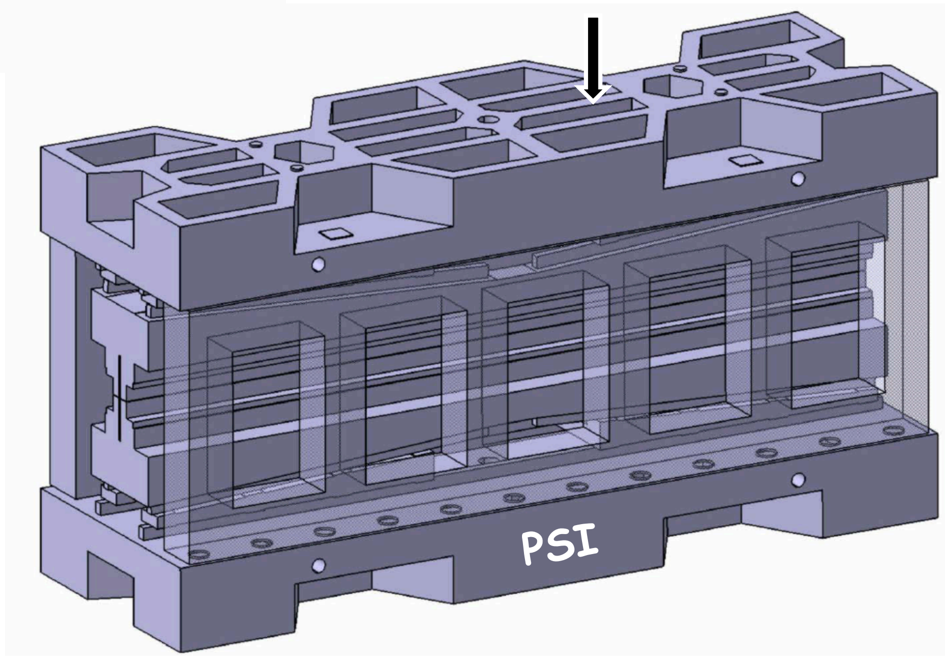


smaller permeability
causes lower shift dependent
field integral errors

Design Concepts

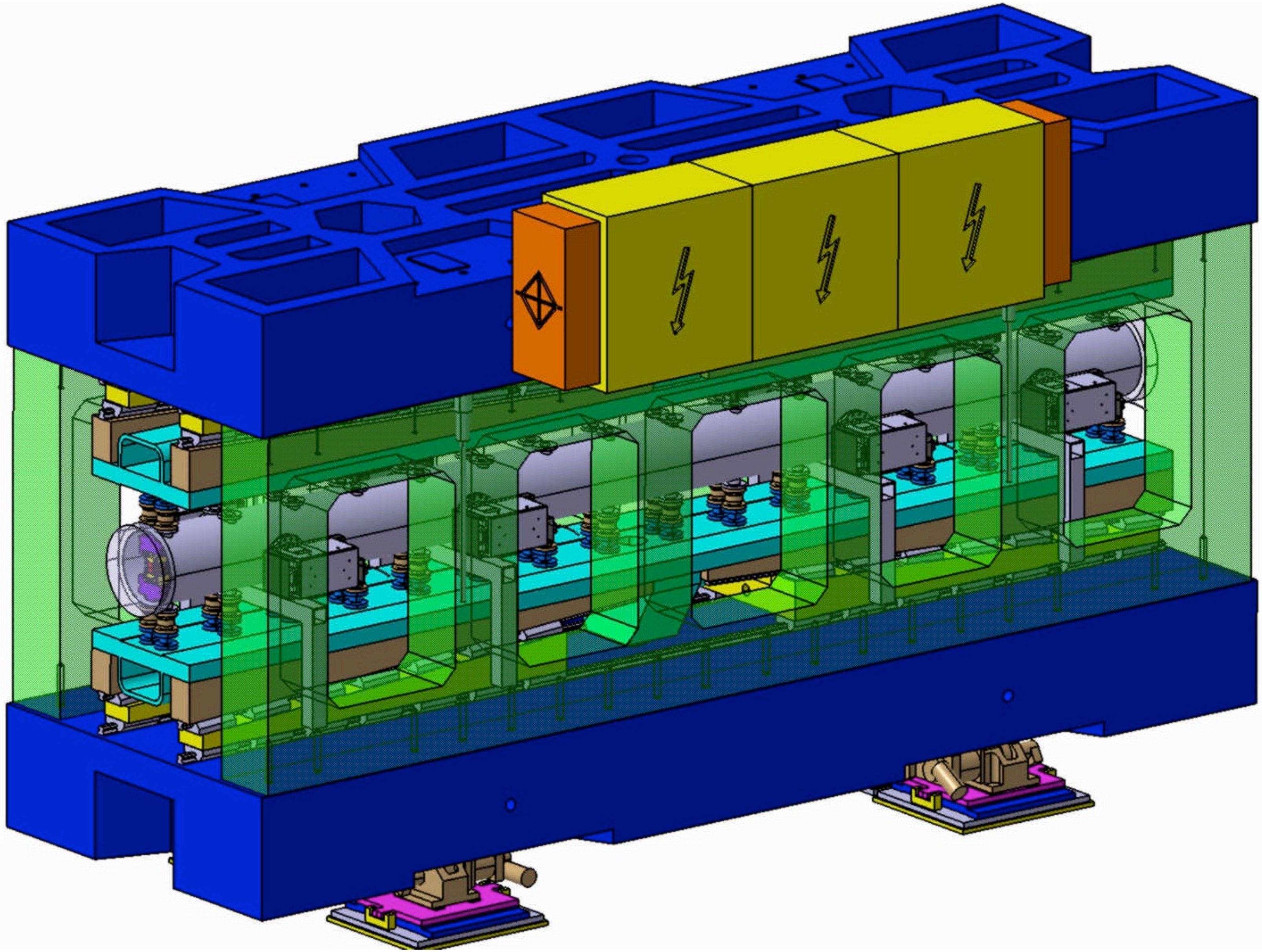


frame (base&sides) cast mineral
gap drive wedges with 4 motors
nearly full support of I-beam
gap change due to load: within 3μm (CATIA FEM single model only further studies required)
precise gap settings of 1G (0.3μm)



Base: cast mineral
Windows: cast iron
Gap drive: 12 motorized wedges
pro: active correction of the bendings due to complexity in drive system (number of motors / encoder units only the choice if active correction really needed
for use with APPLE II longitudinal reinforcement required (then similar to PSI)

Design status April 2010



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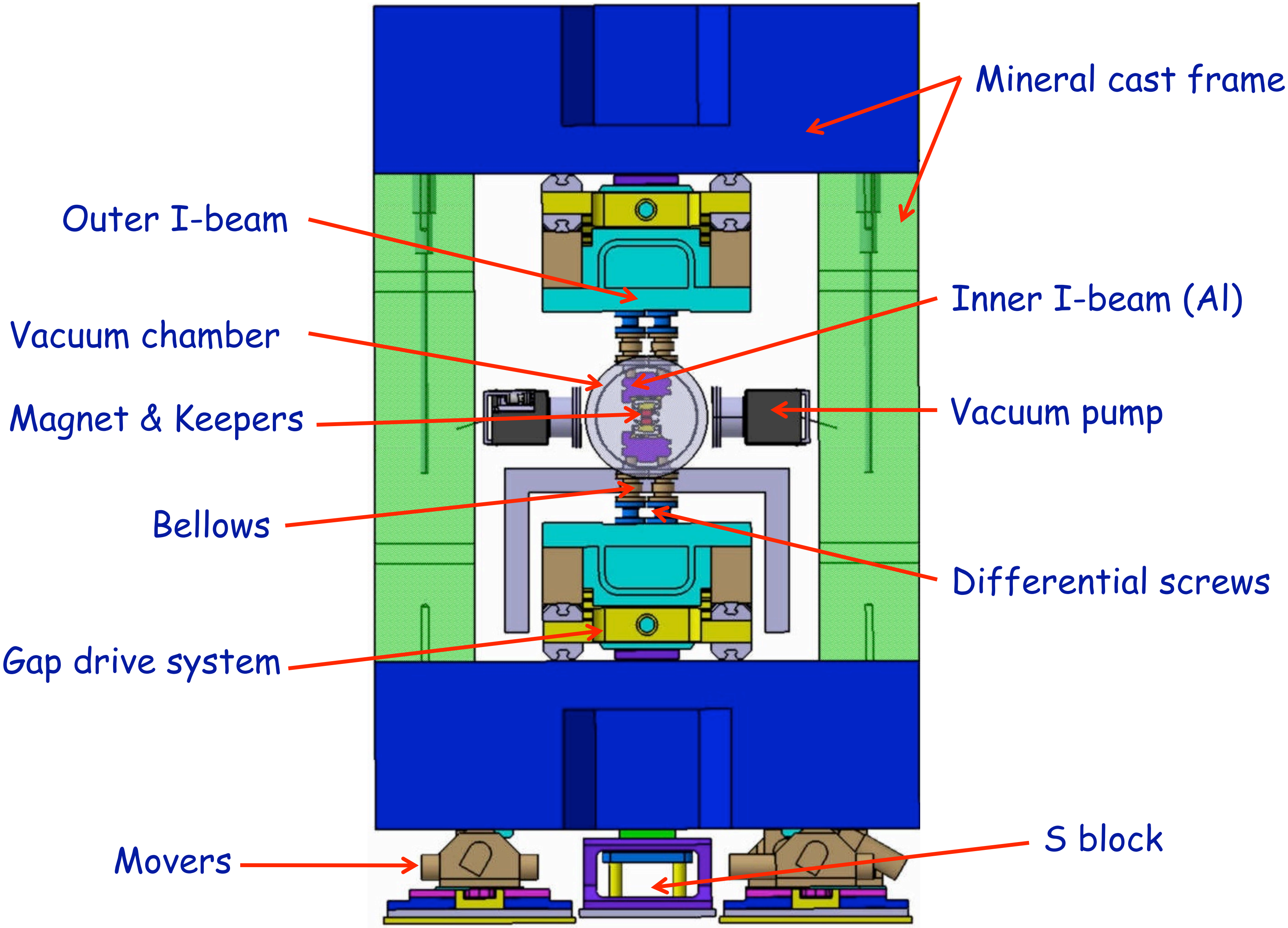
Mineral cast frame
Outer I-beam
Inner I-beam (Al)
Vacuum chamber
Magnet & Keepers
Vacuum pump
Bellows
Differential screws
Gap drive system
Movers
S block

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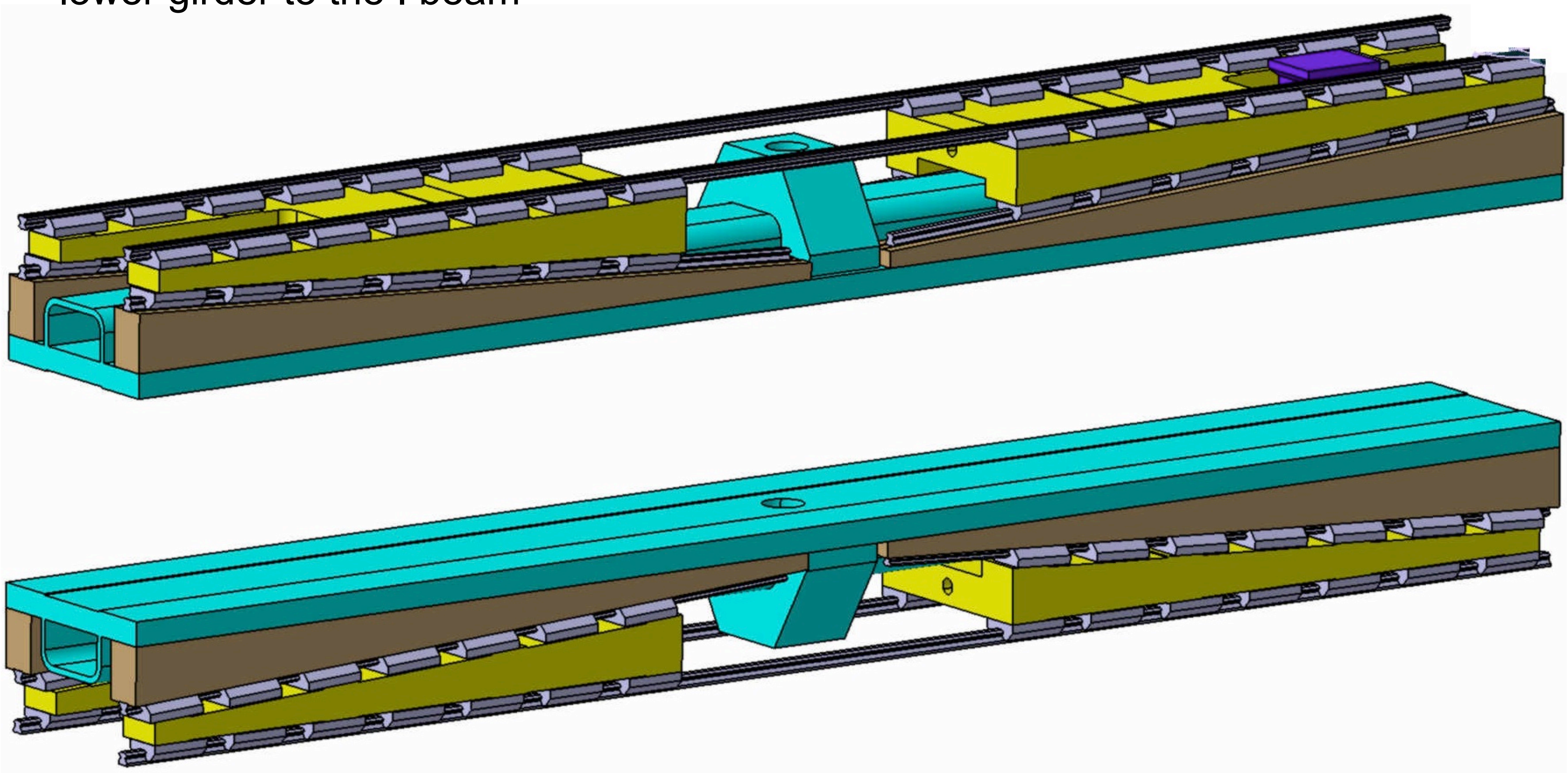
Gap drive based on wedges

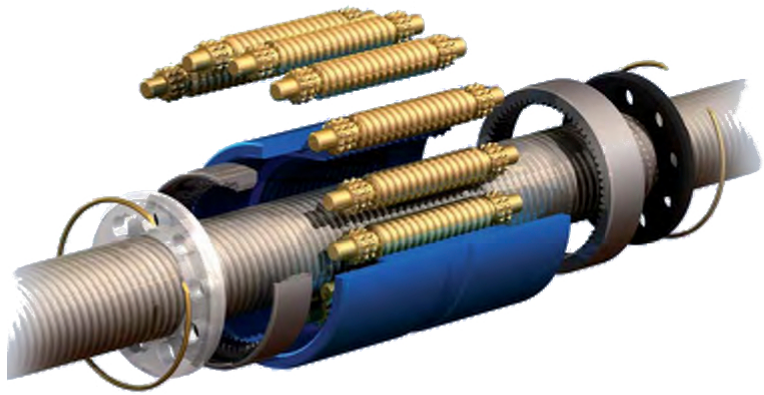
to transfer the stiffness of the lower girder to the I beam

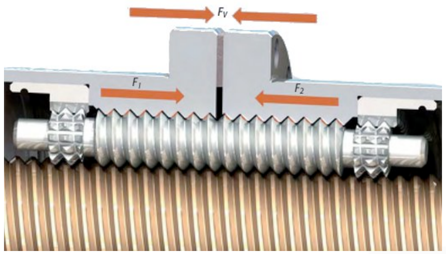


all wedges have to machined together!

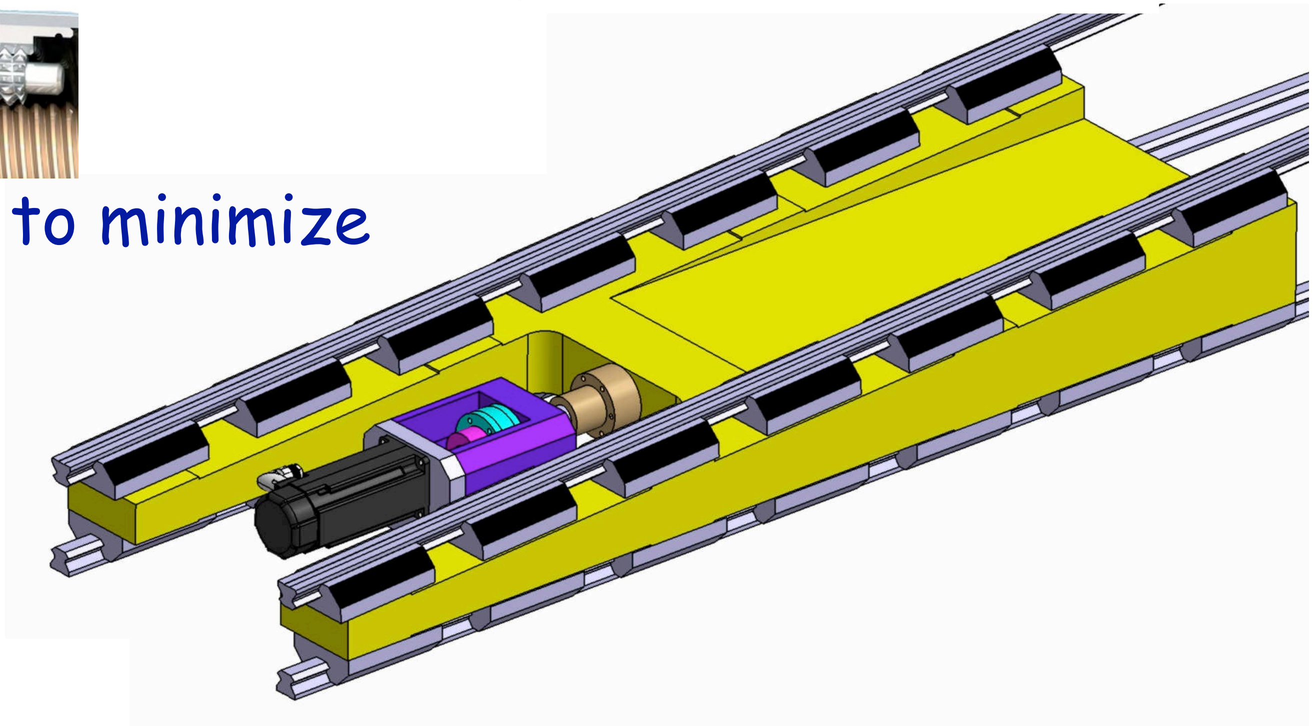
Motor and spindels

Satellite roller screws
1mm/turn →
no need for gearbox!

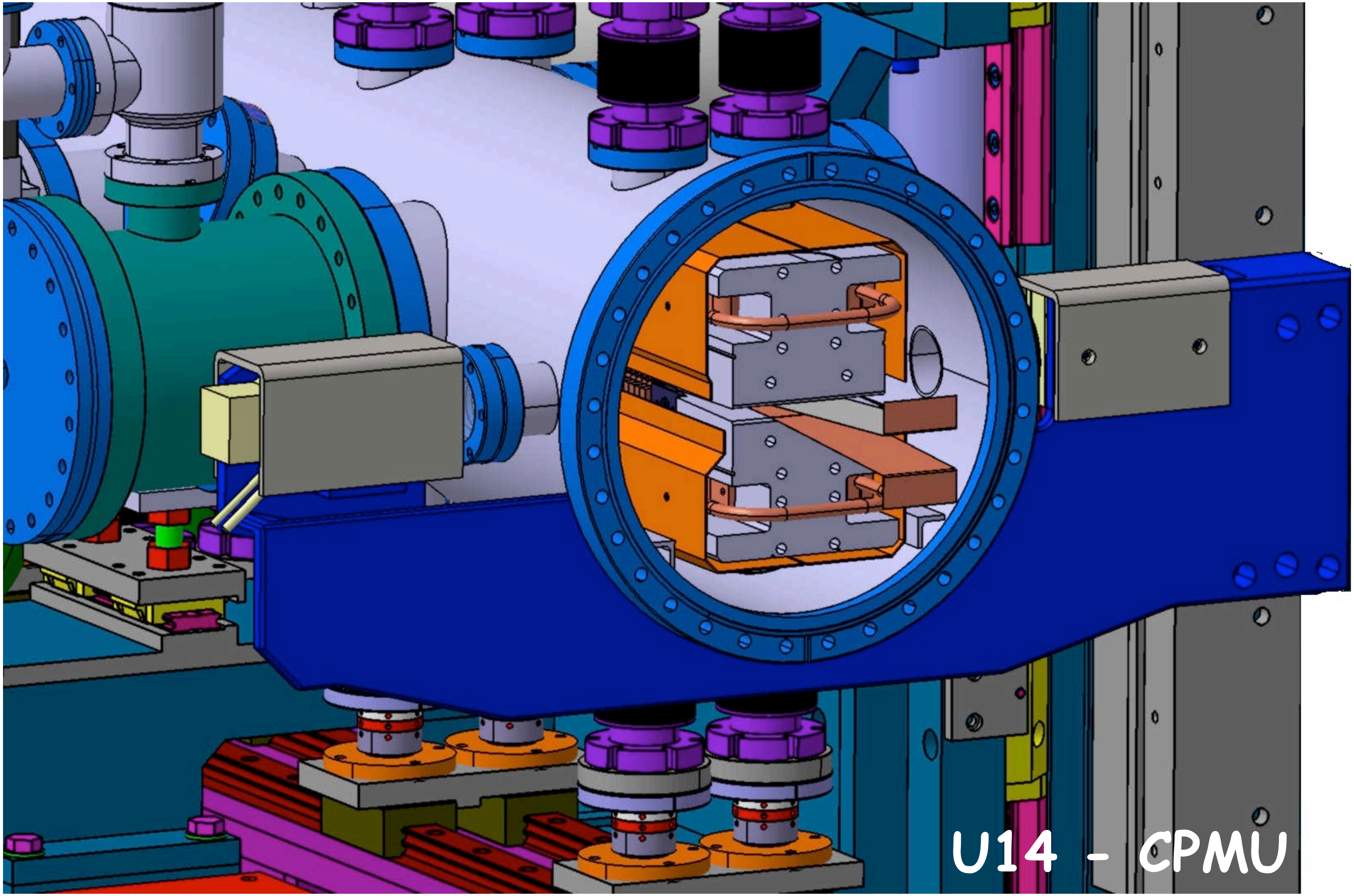




Pre loading to minimize backlash



Gap measurement (optical)



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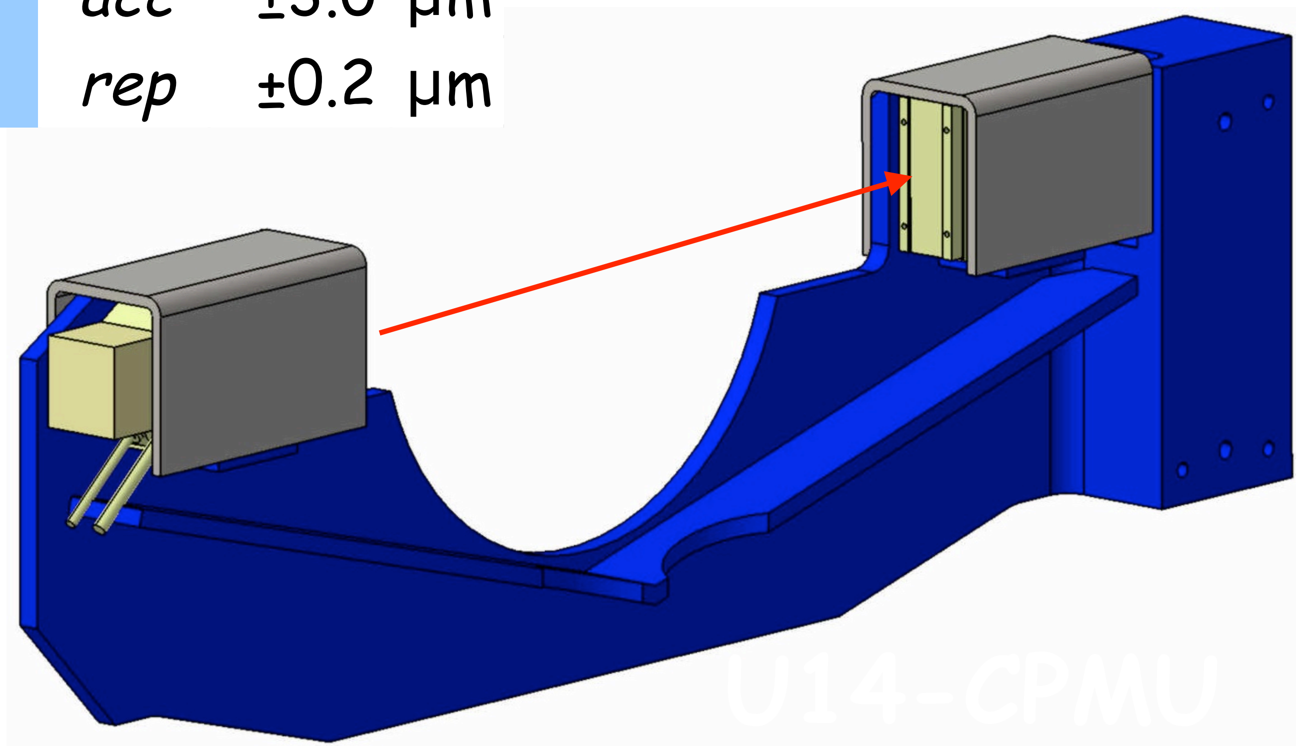
Gap measurement (optical)

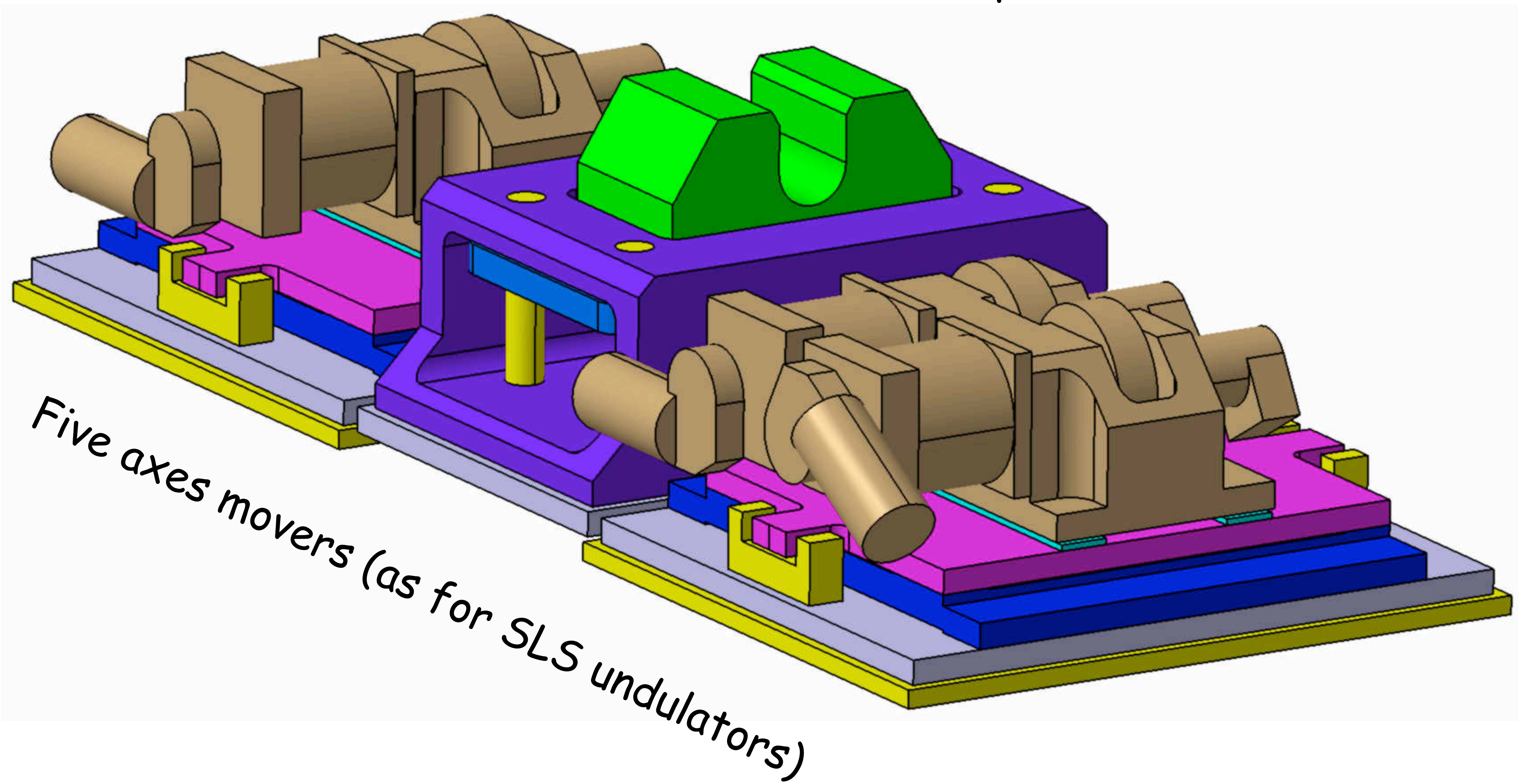
3 Models

"6mm"	*acc*	±0.5 µm
	rep	±0.06 µm
"30mm"	*acc*	±2.0 µm
	rep	±0.15 µm
"65mm"	*acc*	±3.0 µm
	rep	±0.2 µm



Cam-shaft mover (Stanford)

+ SwissFEL



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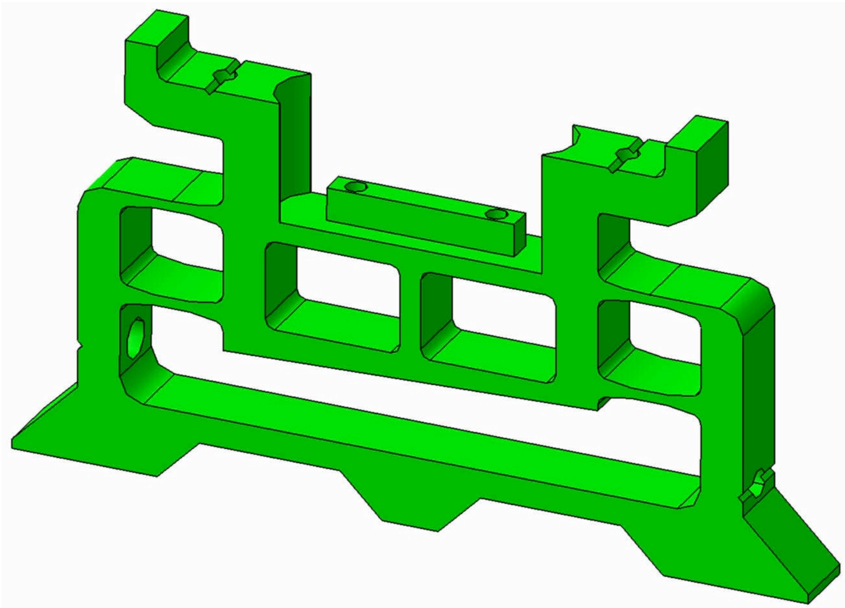
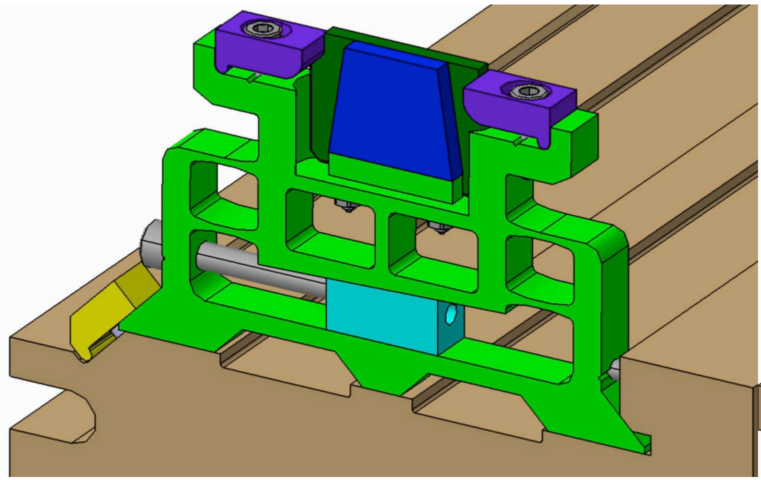
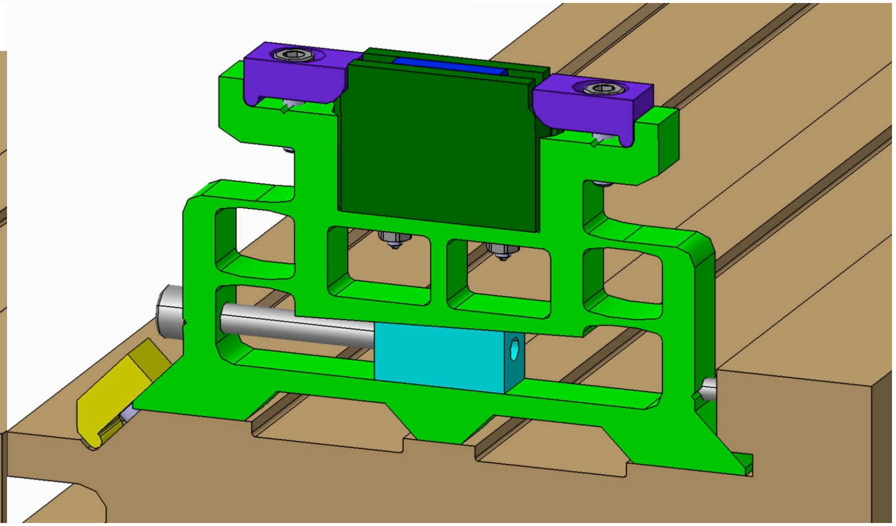
Adjustable Keeper

extruded Al







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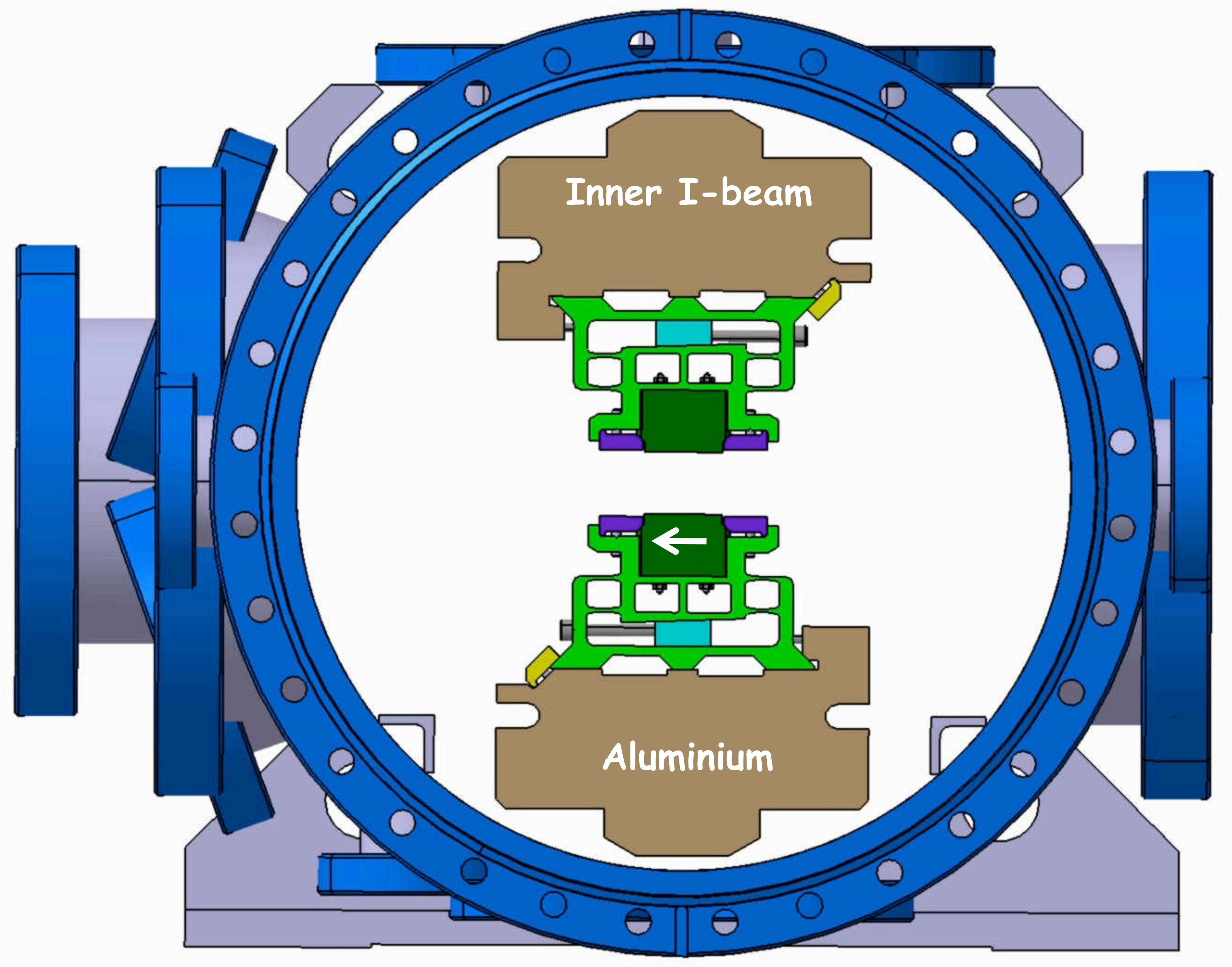
U15 vacuum vessel



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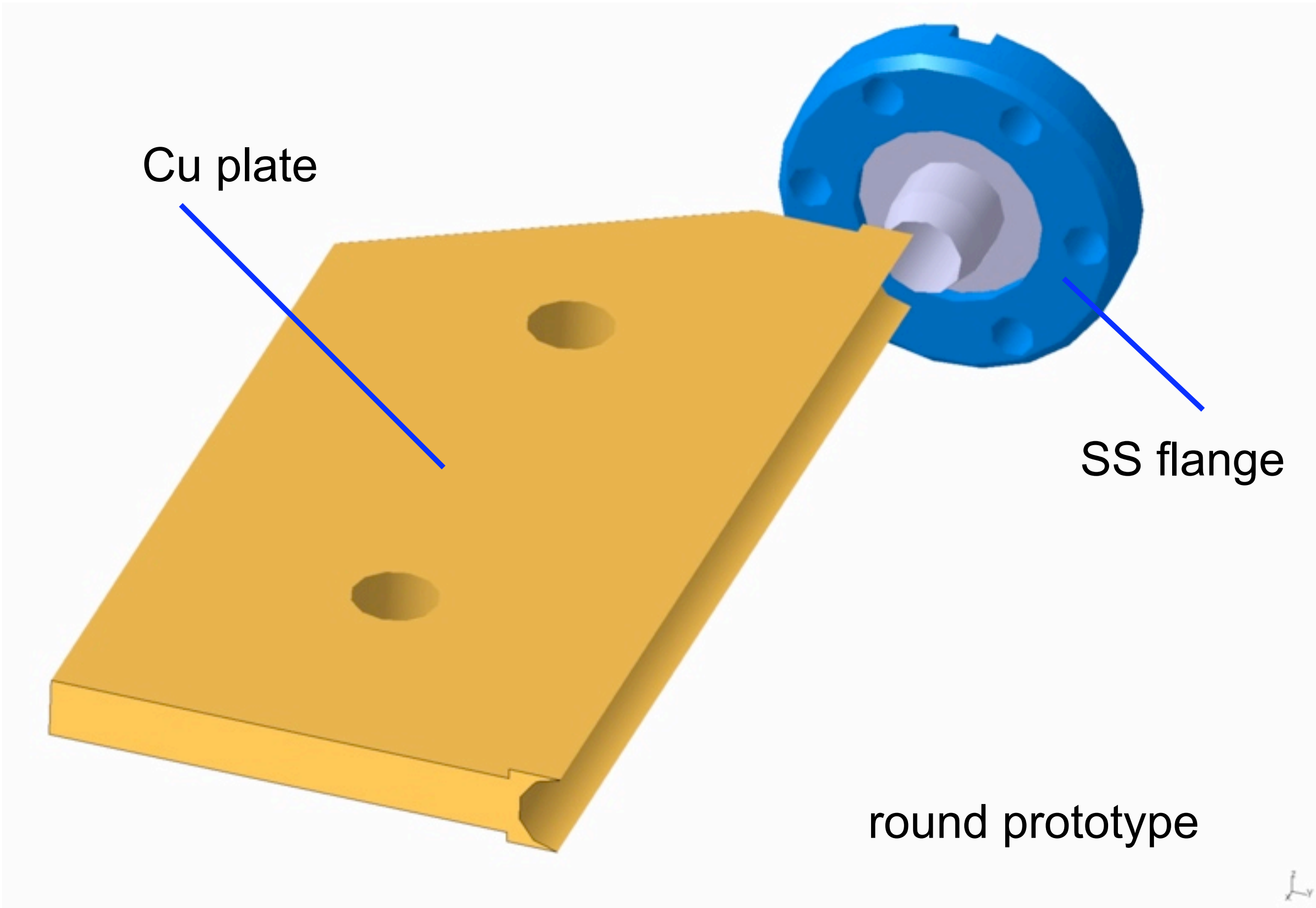
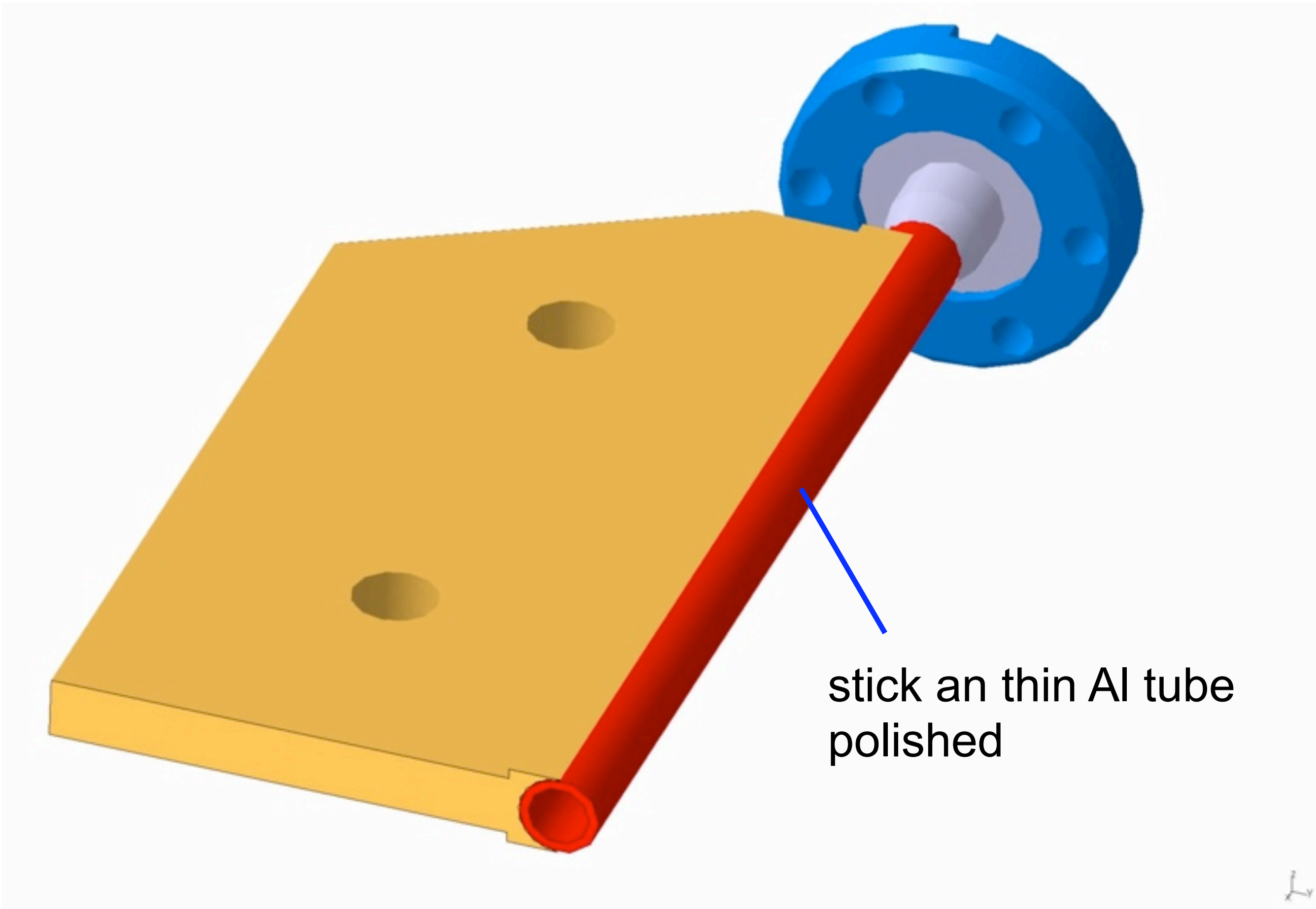
Vacuum chamber

new fabrication process for vacuum chamber (Lothar Schulz)

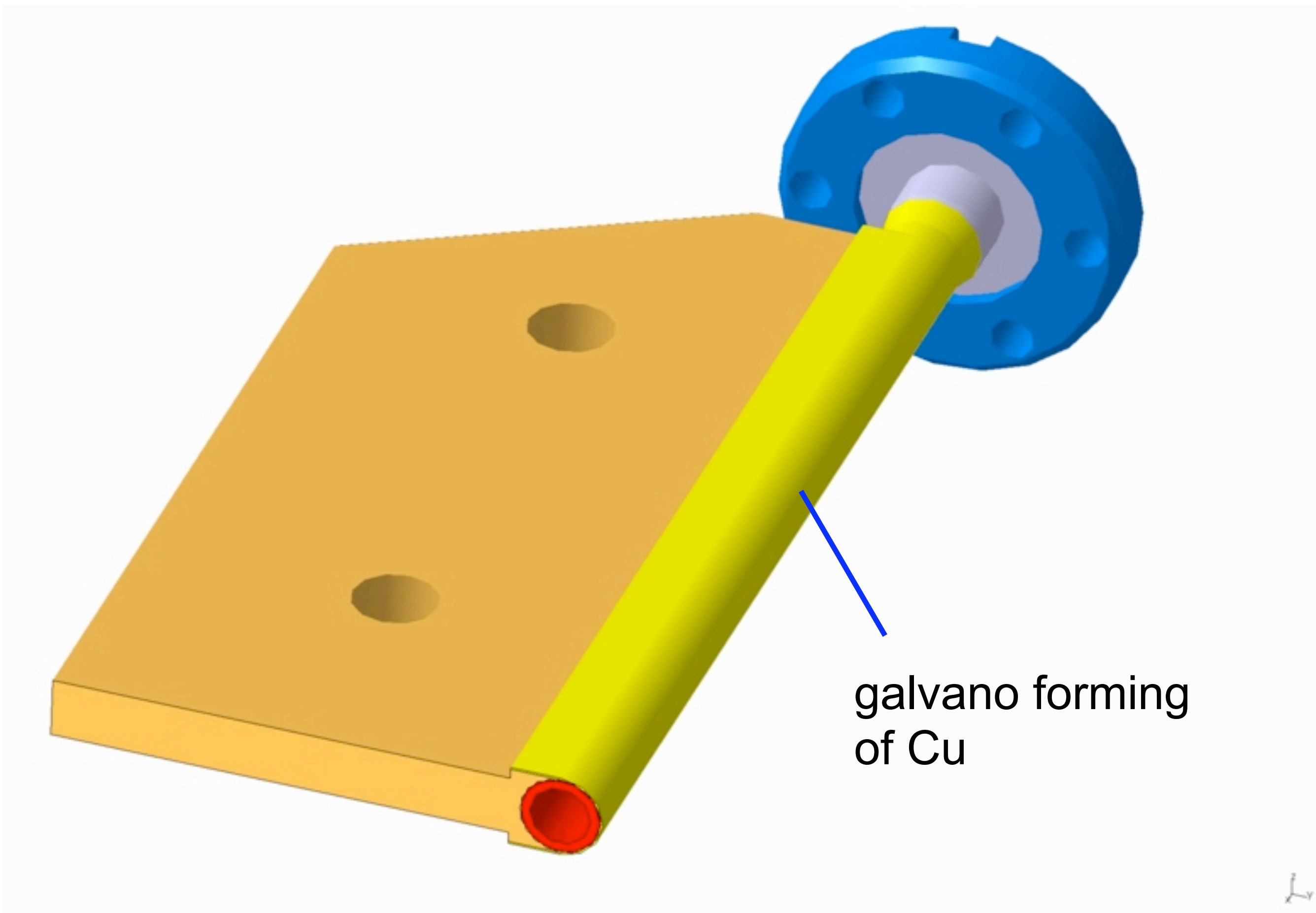


Vacuum chamber



stick an thin Al tube
polished

Vacuum chamber



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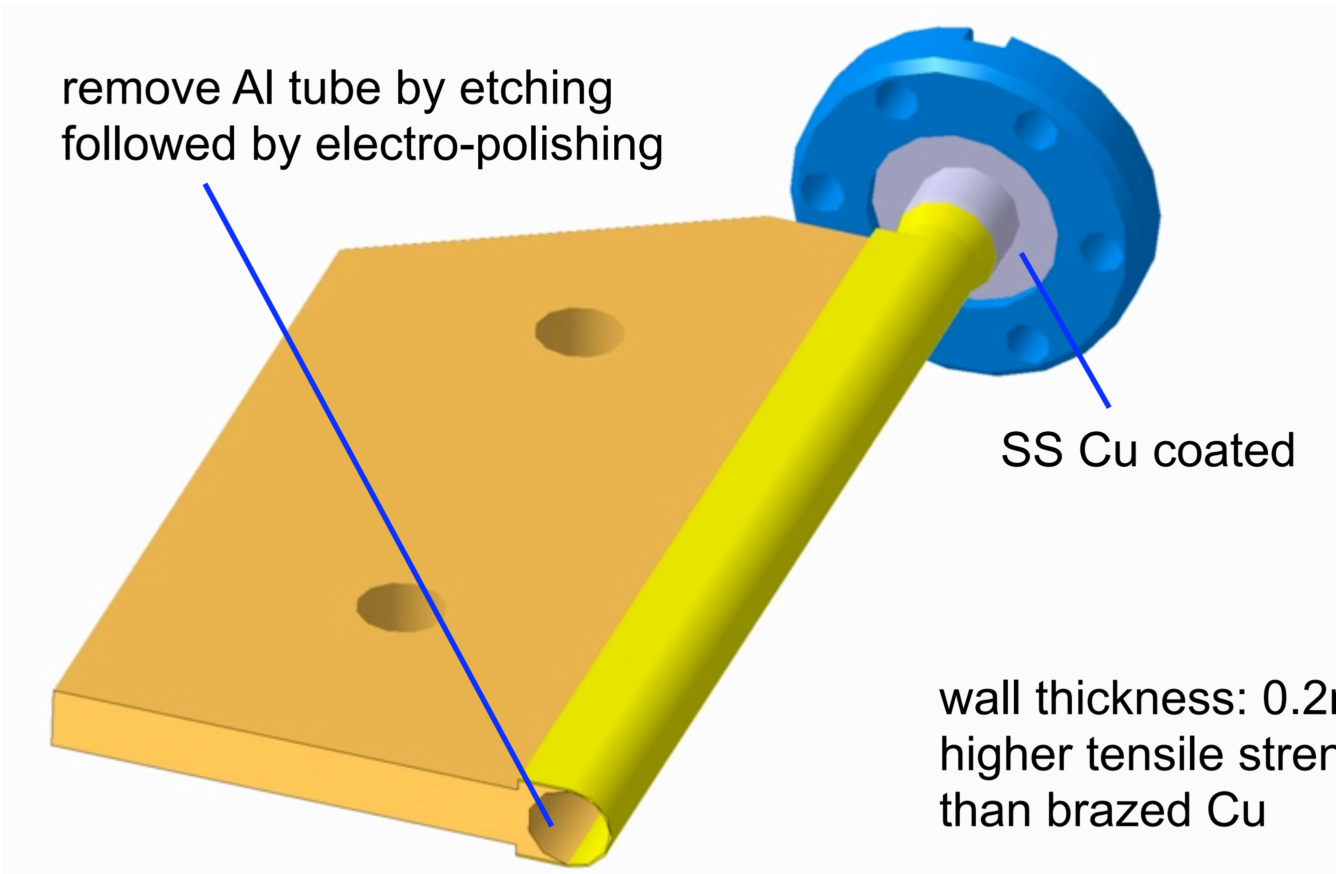
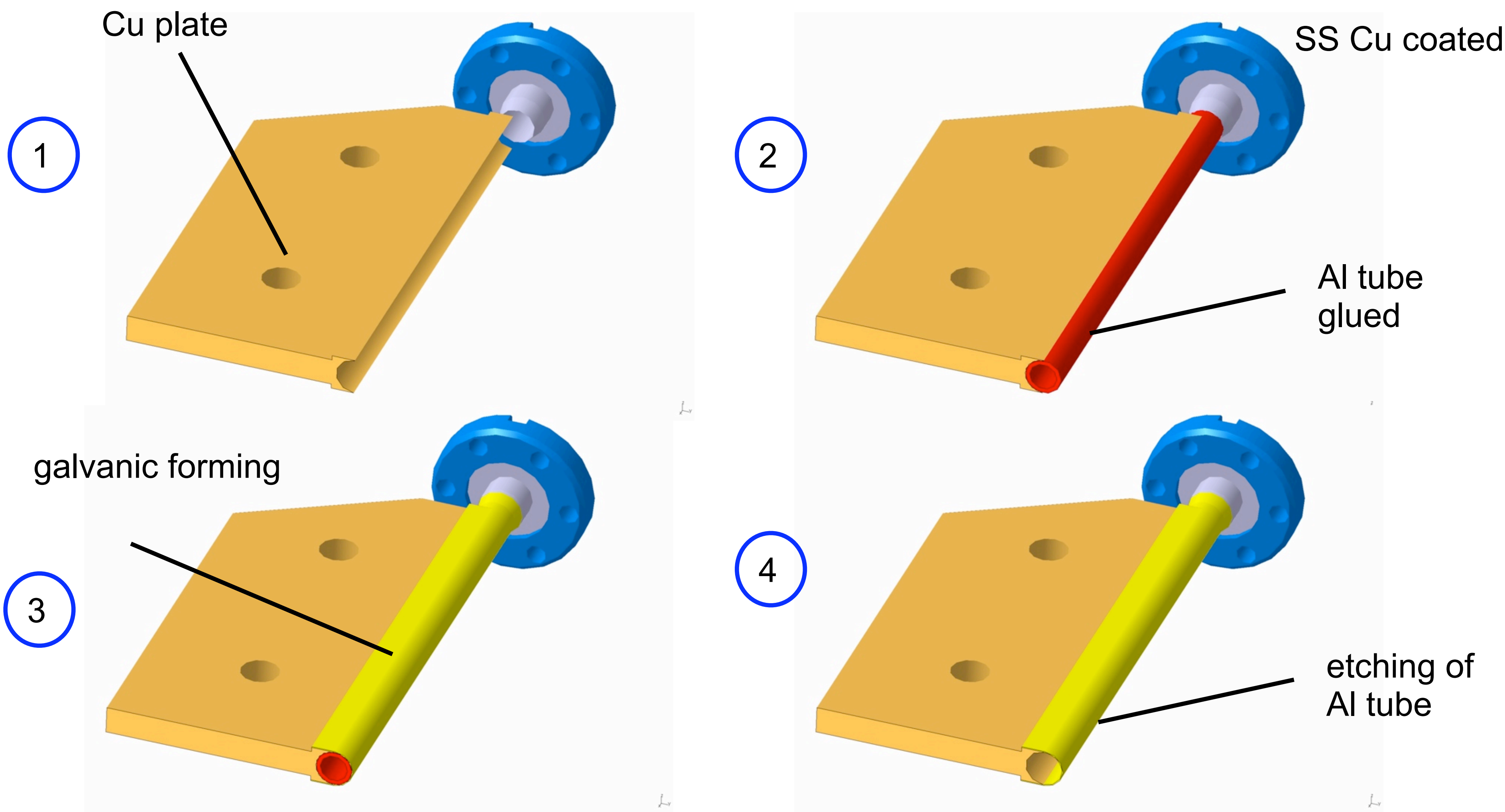
Vacuum chamber



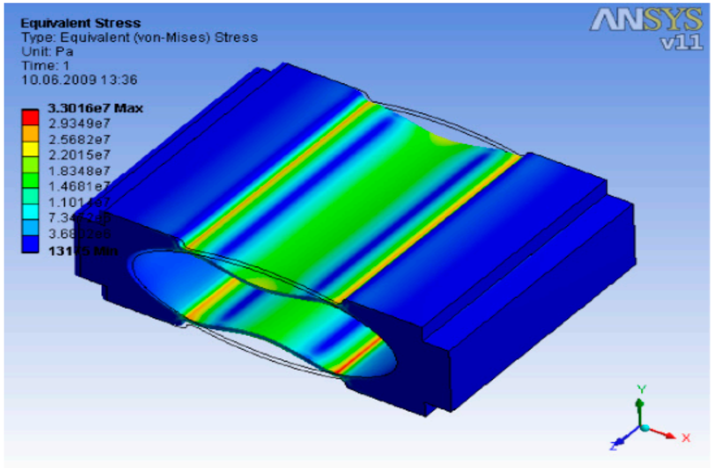
Lothar Schulz +
Galvano-T , Siegen, Germany,
www.galvano-t.de

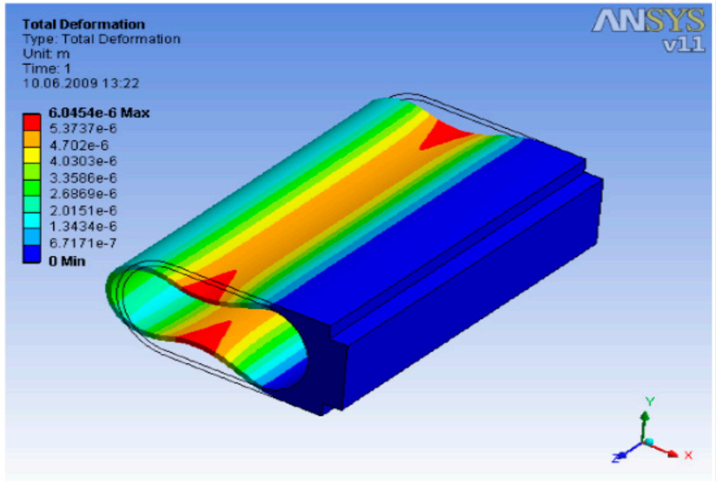
Vacuum chamber

Lothar Schulz +
Galvano-T, Siegen, Germany

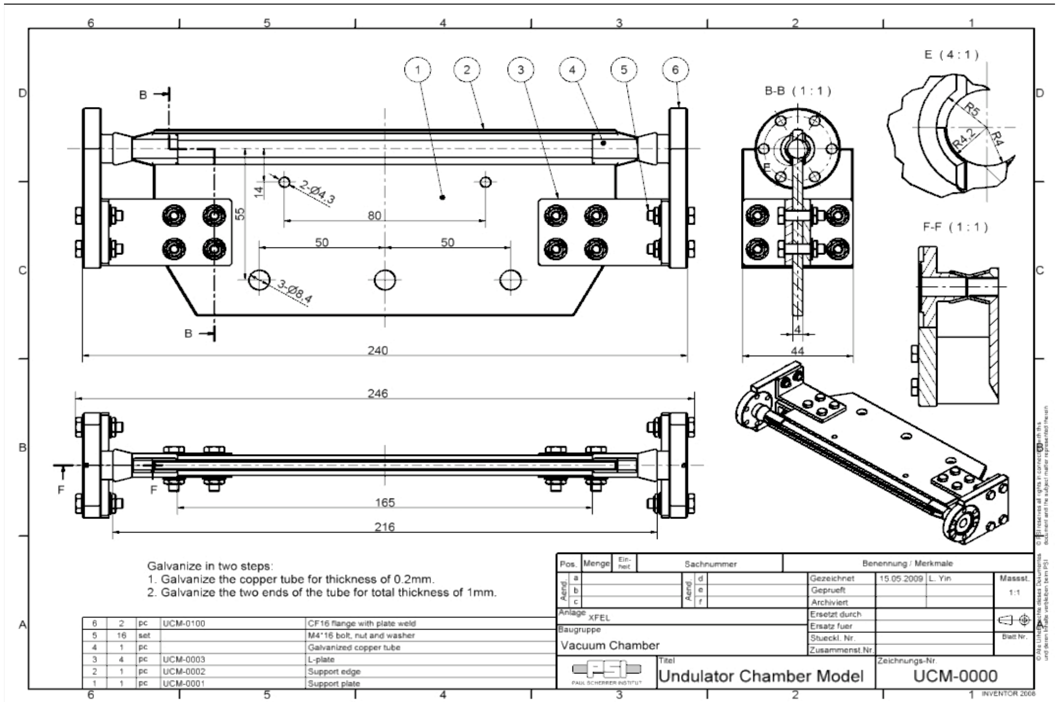


Vacuum chamber





stabilization for elliptical chambers



25cm long test chambers manufactured round tube 8mm tube

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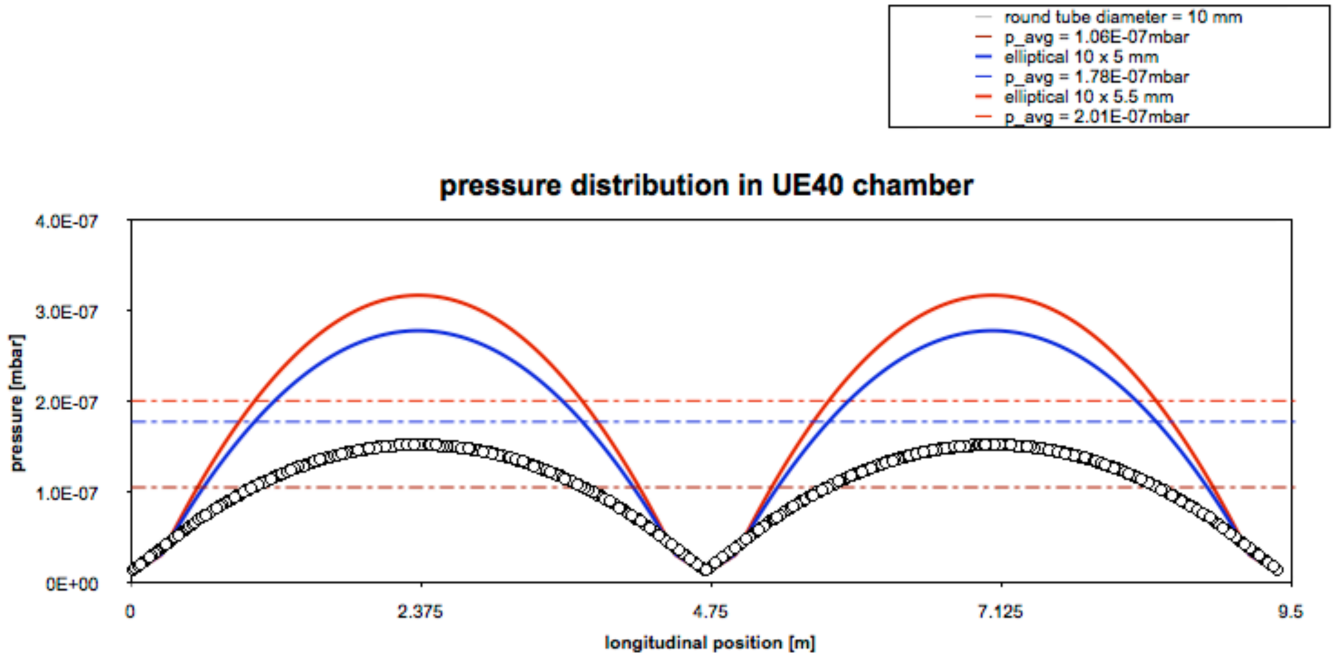
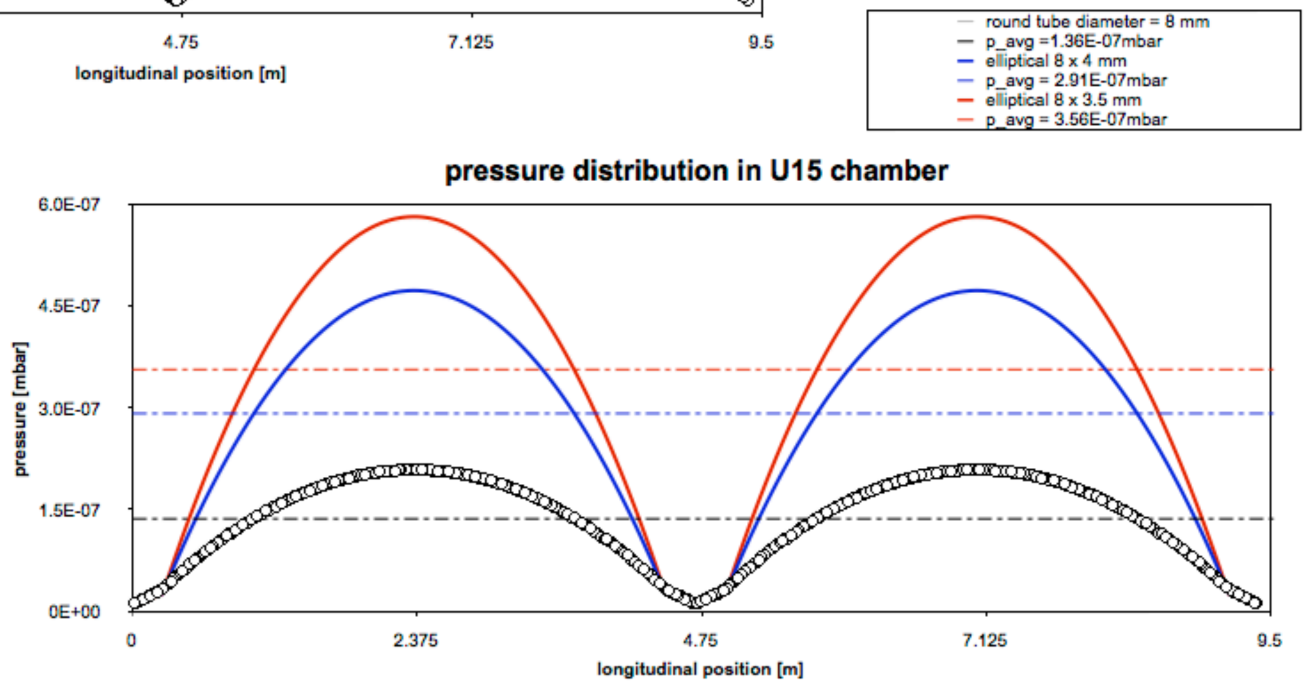
+ SwissFEL



$2\ 10^{-7}$ mbar



$3.5\ 10^{-7}$ mbar

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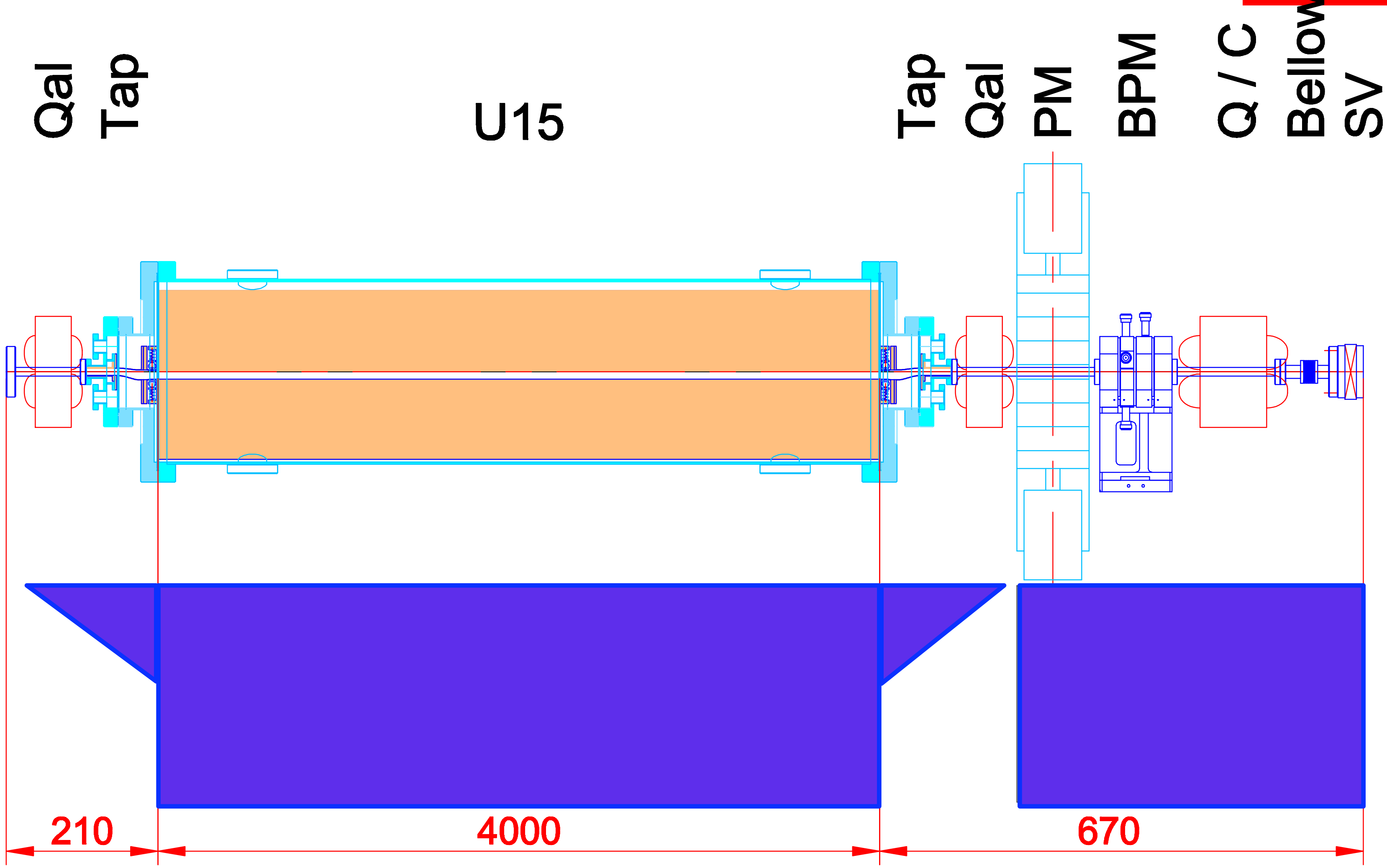

SwissFEL 6 GeV

U15 CELL Layout

Side View

19.04.2010

L. Schulz

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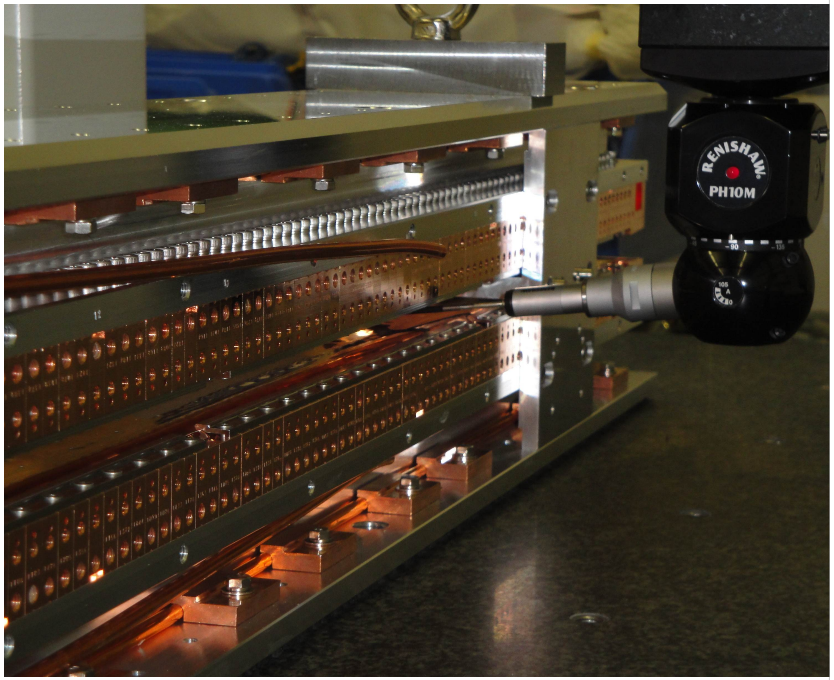
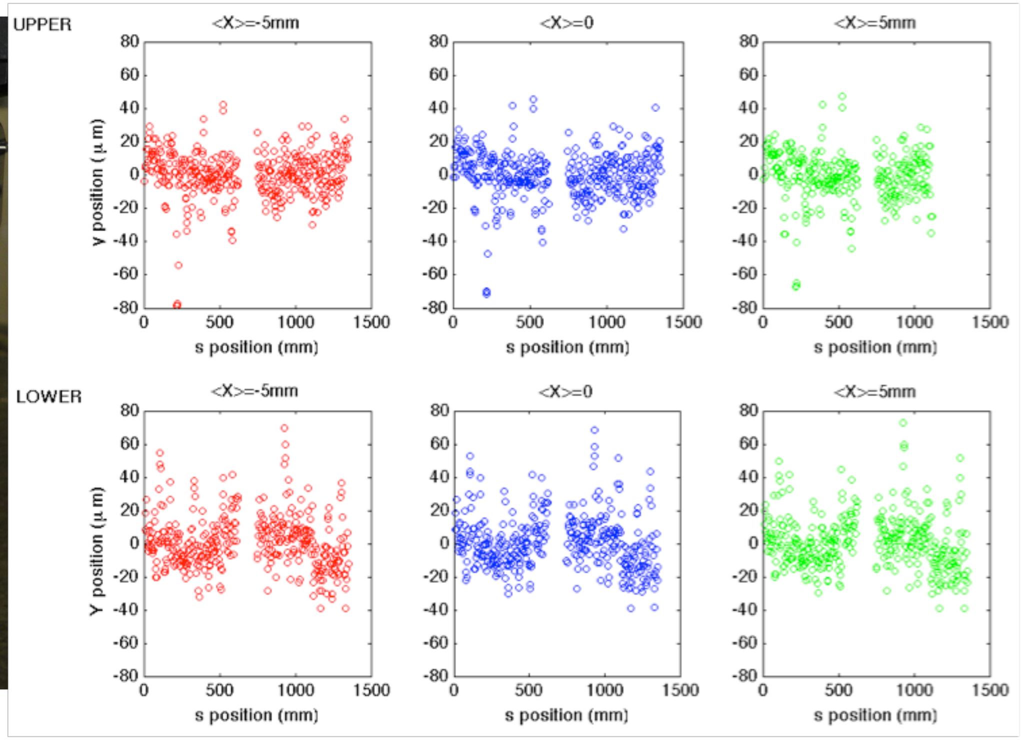
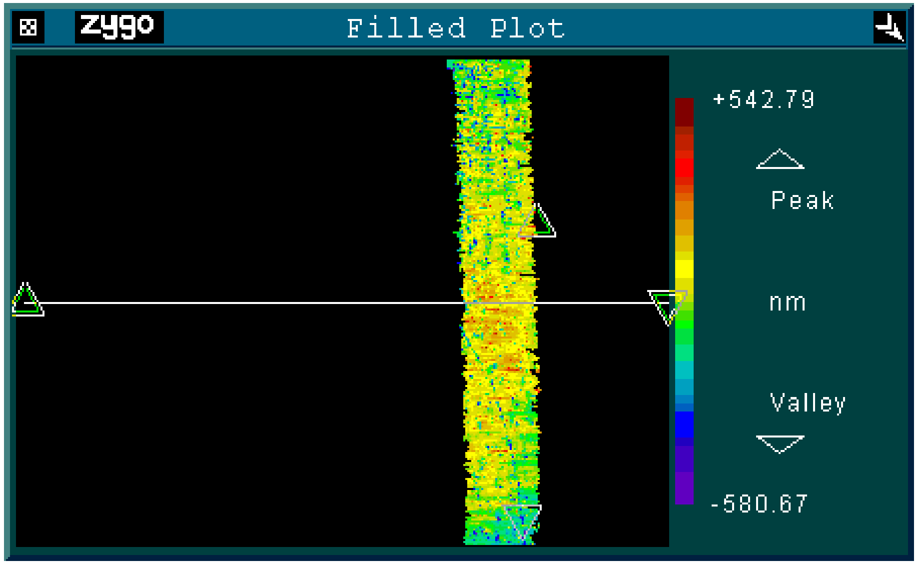


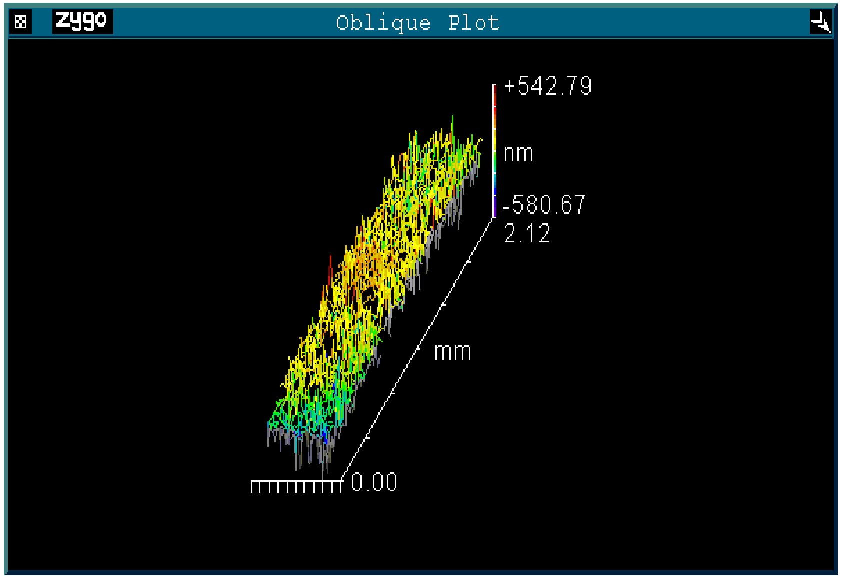


	<X>=-5mm	<X>=0	<X>=5mm	
UPPER	16.7	16.1	16.1	
	11.8	12.1	12.4	[µm]
LOWER	15.1	14.8	14.6	
	17.2	17.7	17.7	

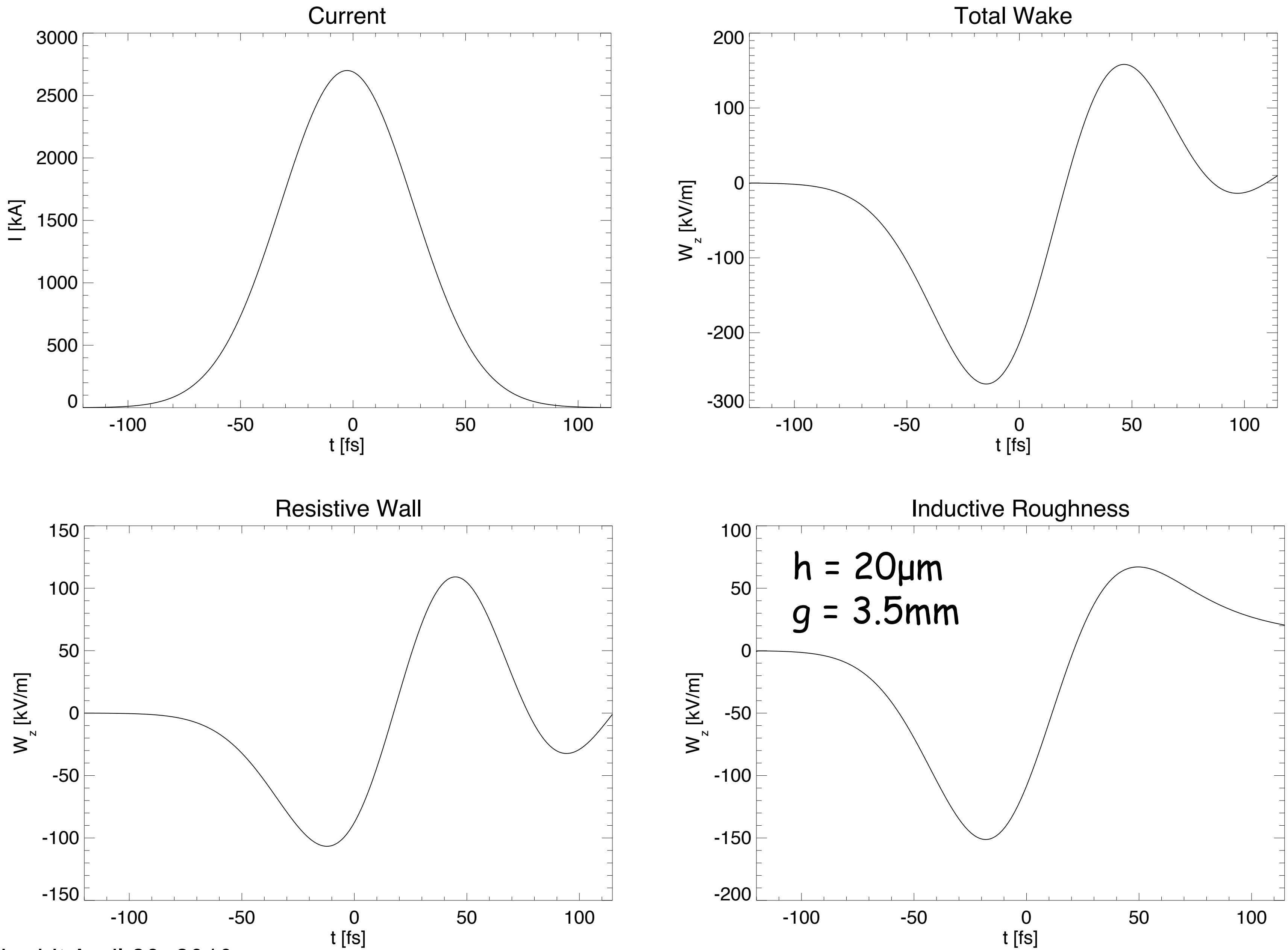
Surface Roughness of Cu-Ni foil

Number	RMS (nm)	PV* (nm)
1	119.55	1123.47
2	126.77	1521.51
3	102.95	1084.19
4	102.73	1083.45
∅	113.00	1203.15





Wake fields (Sven Reiche)



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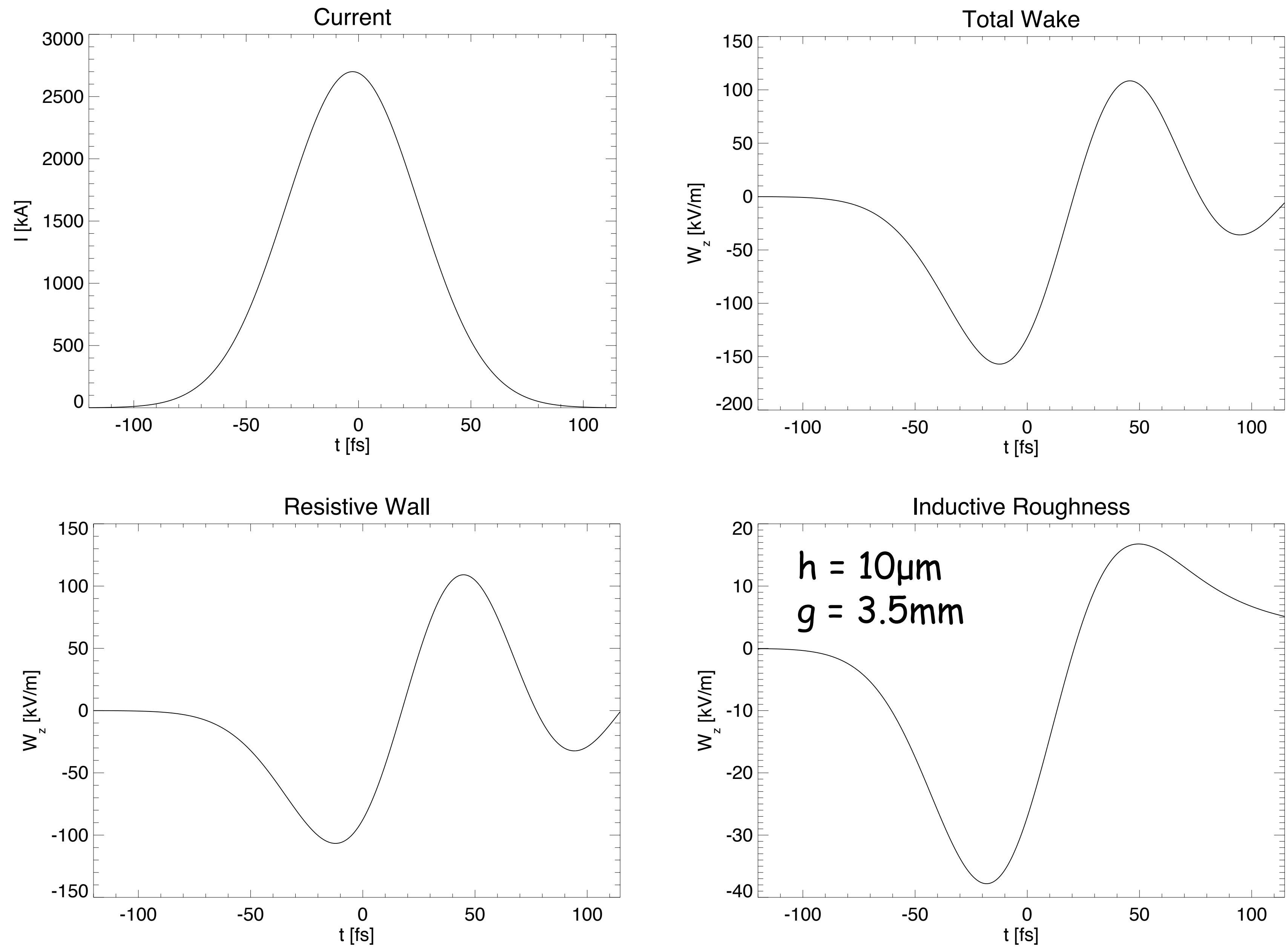
Wake fields II (Sven Reiche)



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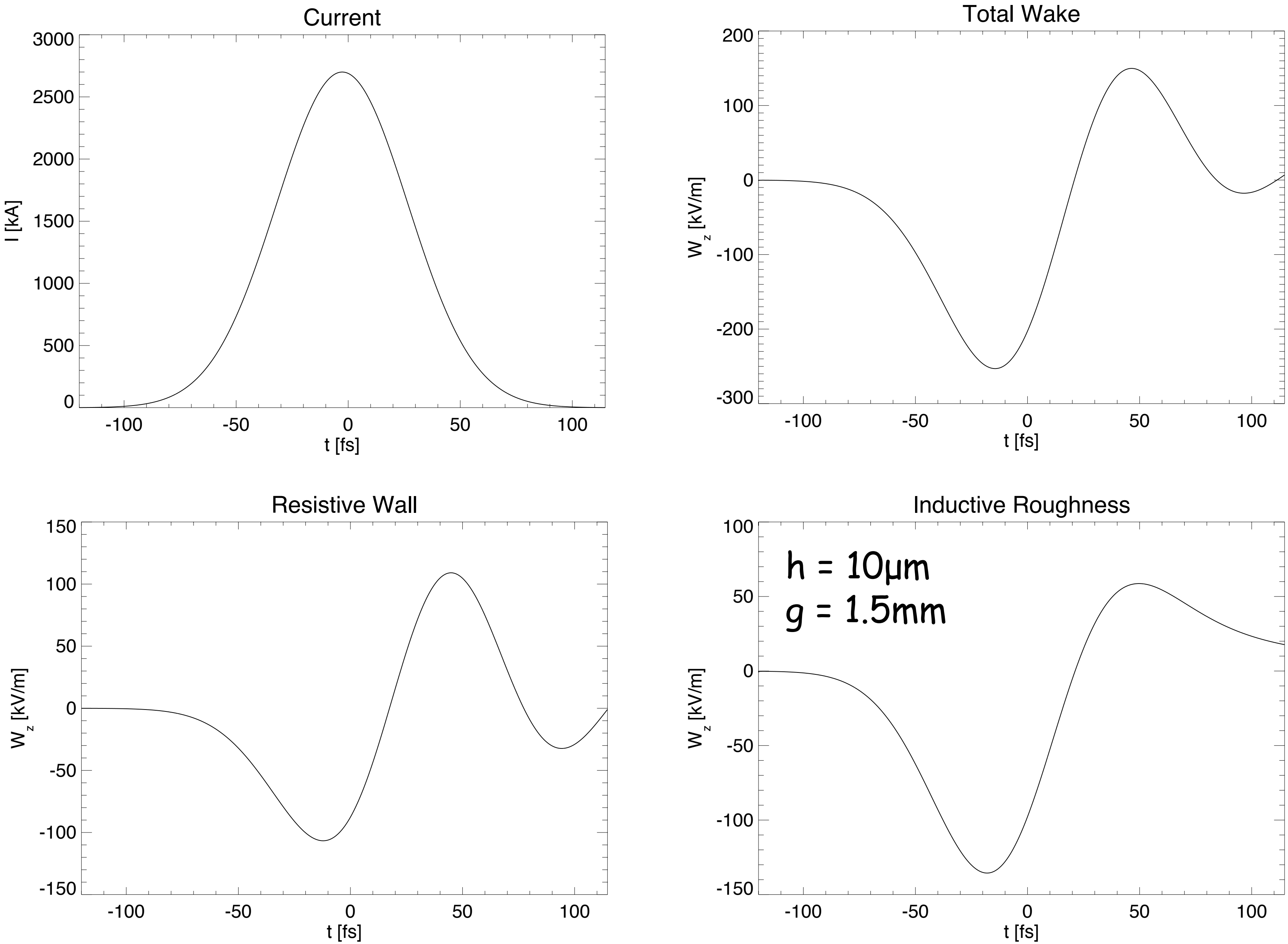
Wake fields III (Sven Reiche)

+ SwissFEL



	Conceptual Design & Review (CDR)	PSI
	Detail Design & Review (DDR)	PSI (Industry)
Public call for tender (WTO) for Prototype production		
Prototype	Manufacture	Industry
	Assembly	Industry/PSI
	Optimization	PSI
	Evaluation	PSI
Public call for tender (WTO) for Series production		
Series	Manufacture	Industry
	Assembly	Industry/PSI
	Optimization	PSI
	Evaluation	PSI
	Installation	PSI

- The Master Company is the selected bidder for manufacture of the undulators
- The Master Company is responsible for the procurements of all the components but "magnets"
- To guarantee the specifications PSI shall make guidelines to the Master Company for some sub-systems:
  - Frame
  - Vacuum system (vessel, pumps, valves, bellows, gauges, taper)
  - Electrical system (motor, encoder, breaks)
  - Alignment system (movers)
  - Controls
- The Master Company is responsible for the assembly of all the components but the vacuum chamber (PSI)

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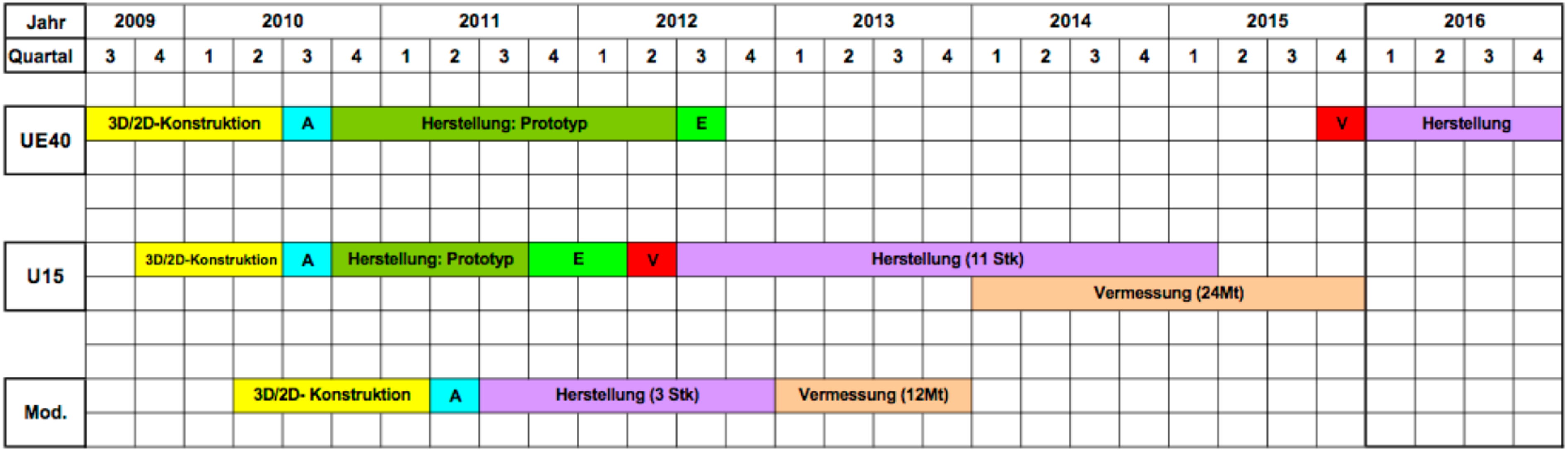
+ SwissFEL

Time schedule

A. Imhof; 2. November 2009



E= Evaluation = Finales Design-Review und magnetische Vermessung

A = Ausschreibung

V = Vergabe

	Von	Bis	Dauer [Monat]	Tätigkeit	Aufwand [MannMonat]	Personal
1	Juli 2009	Dez. 2009	6	3D-Konstruktionen	60	10
2	Jan. 2010	April 2010	4	2D-Zeichnungen	20	5
3	Mai 2010	Aug. 2010	4	Devisierung & Auftragsvergabe	15	3
4	Sept. 2010	Sept. 2011	12	Herstellung des Prototypen: Überwachung	20	2
5	Okt. 2011	Dez. 2012	3	Evaluation	3	1
6	Jan. 2013	Mai 2013	4	Vergabe der Serie	12	3
7	Juni 2013	Dez. 2014	19	Herstellung, Überwachung	38	2
8	Jan. 2015	Jan. 2016	12	Lieferung, Vermessung, Montage	60	5
			64		**228**	**3.5**

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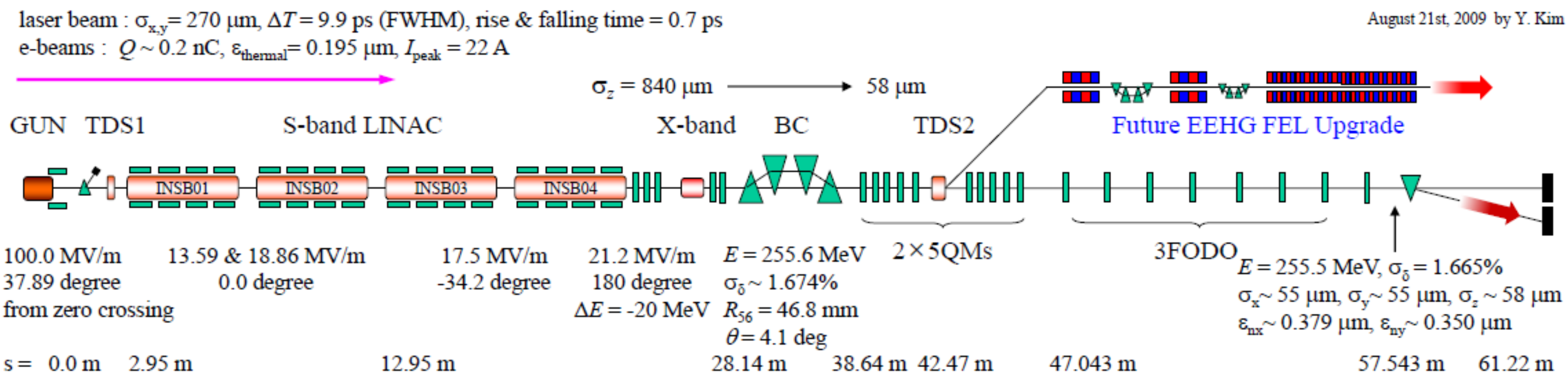
SwissFEL injector test facility



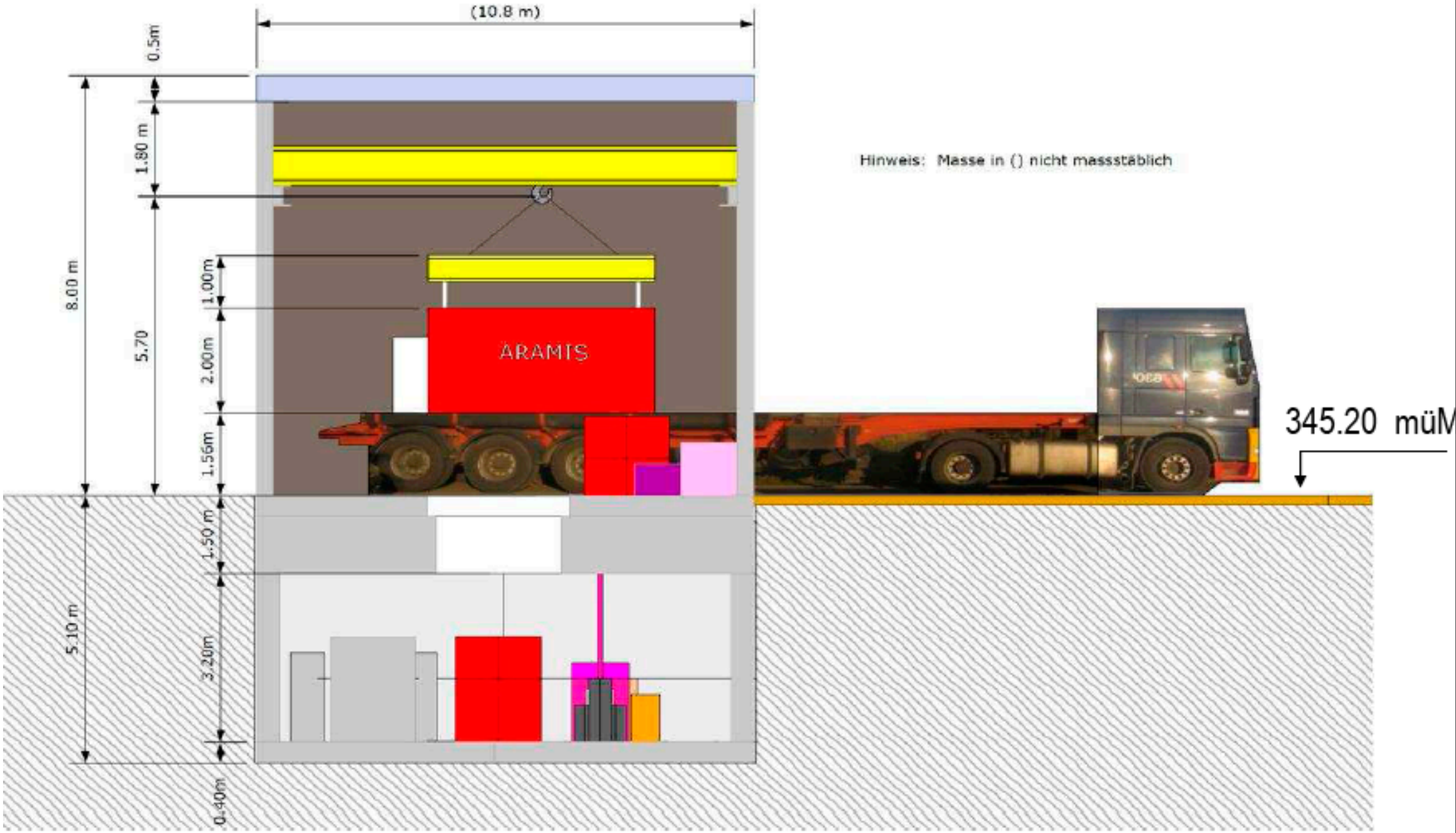
U15 full size prototype will be used for EEHG seeding

saturation expected with 50nm

UE40 small units for modulators

- We are at the end of the conceptual design:
  - All key components have been identified
  - and solutions have been produced → ongoing validation
- We should be ready for the first call for tender in September 2010
- Next step is to finalize the DDR, two options:
  - PSI alone
  - PSI + industries
- Still open the option of a U15 non in-vacuum for the series production: R&D ongoing on the U40 vacuum chamber…

Thanks for your support



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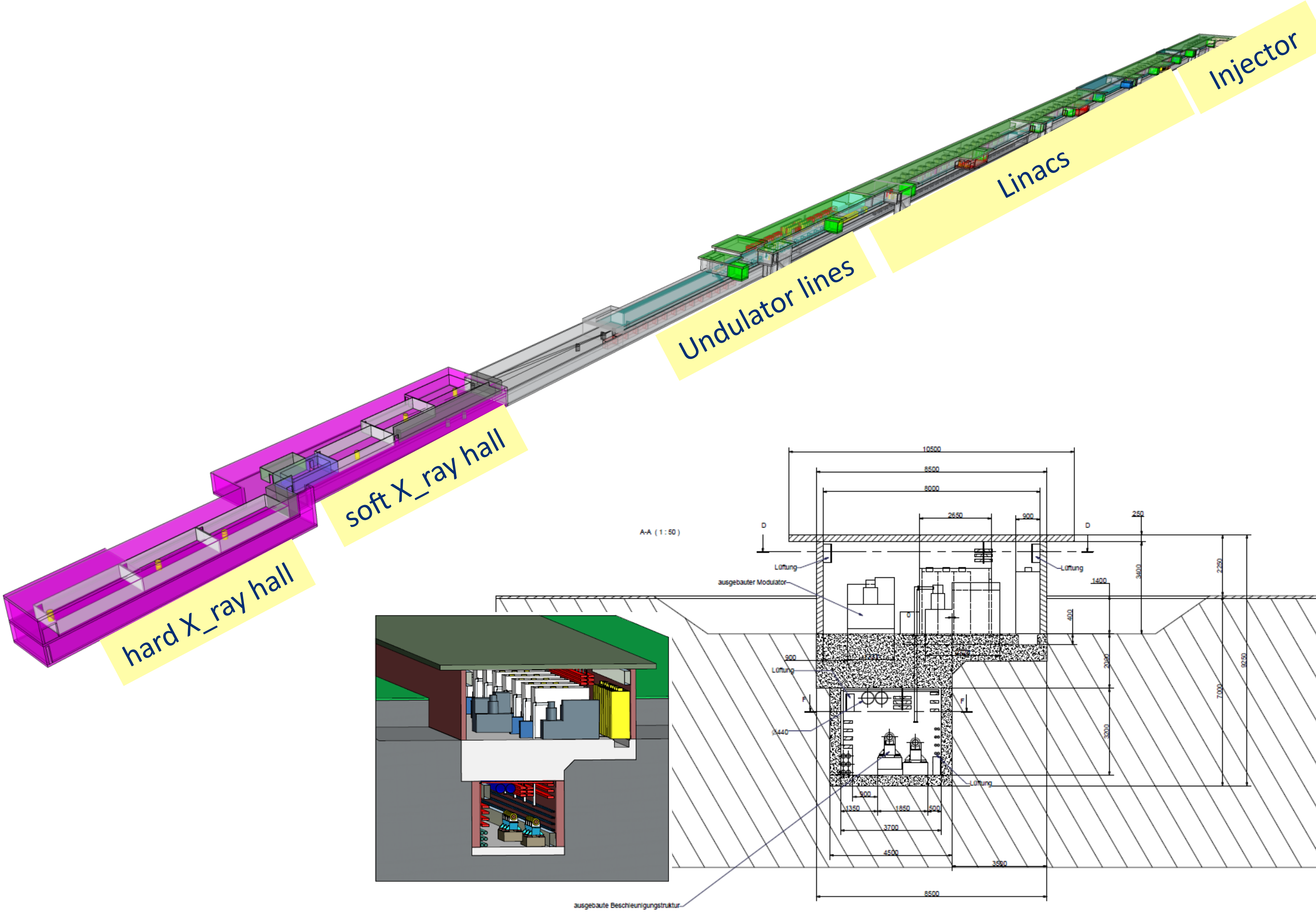

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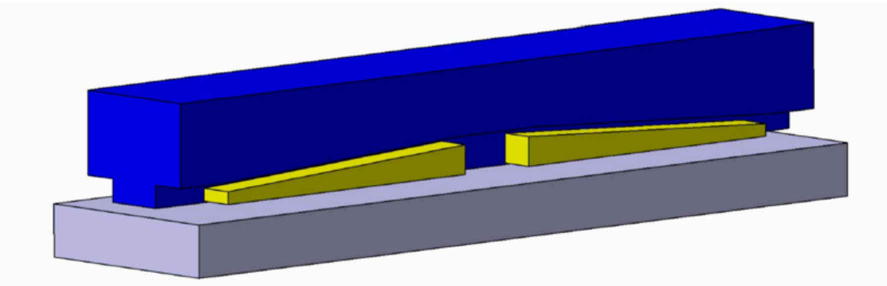
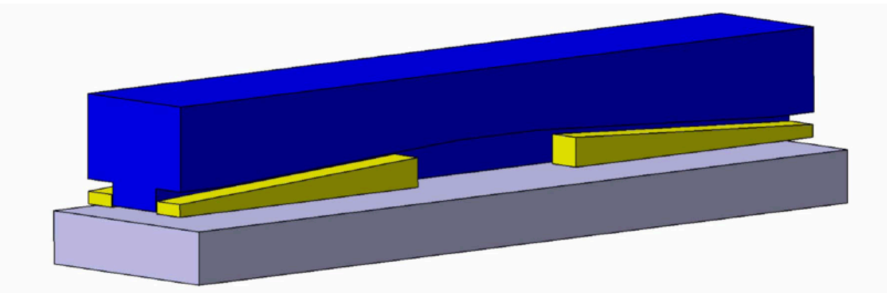
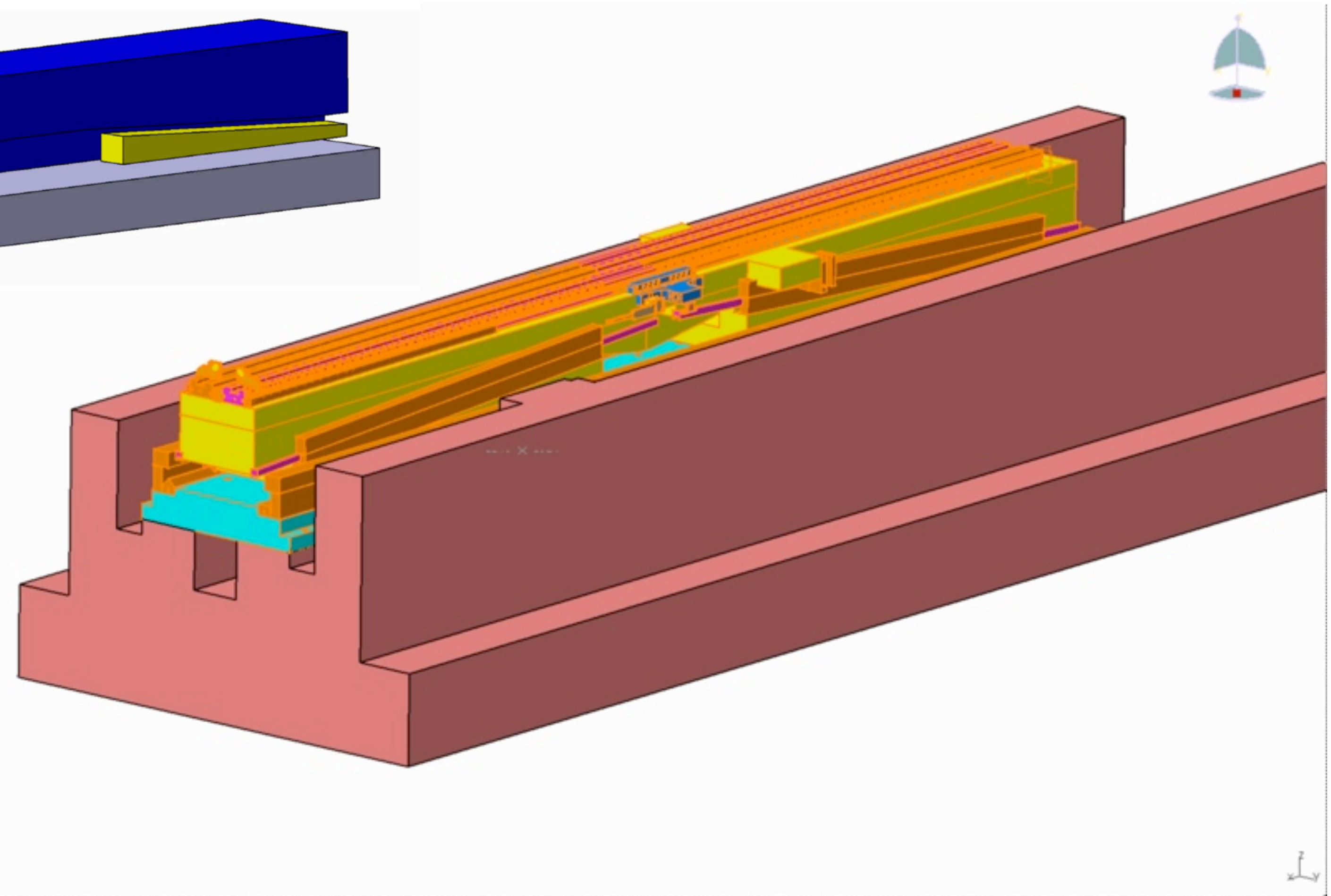
Wedge gap adjustment





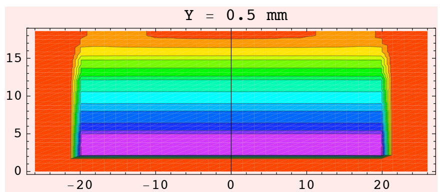
to transfer the stiffness of the lower girder to the I beam

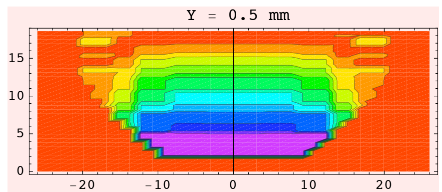


	NdFeB NMX 27VH	Sm_2Co_{17}	NdFeB diffused Dy	NdFeB CPMU
Radiation hard	☺	☺	☺	☺
dB/dT	-0.1 %/K	-0.035 %/K	-0.1 %/K	plateau
Permeability	1.06 / 1.15	1.01 / 1.04	1.06 / 1.15	1.06 / 1.15
mech. properties		more sensitive	improved	improved
Remanence B_r	1.08 T	1.1 T	> 1.25 T	1.5 T
suitable for	U40 / UE40	U40 / UE40	U15	U15

U15

use of Dy diffused NdFeB at RT and flux concentration on axis: Br ↑ F ↓





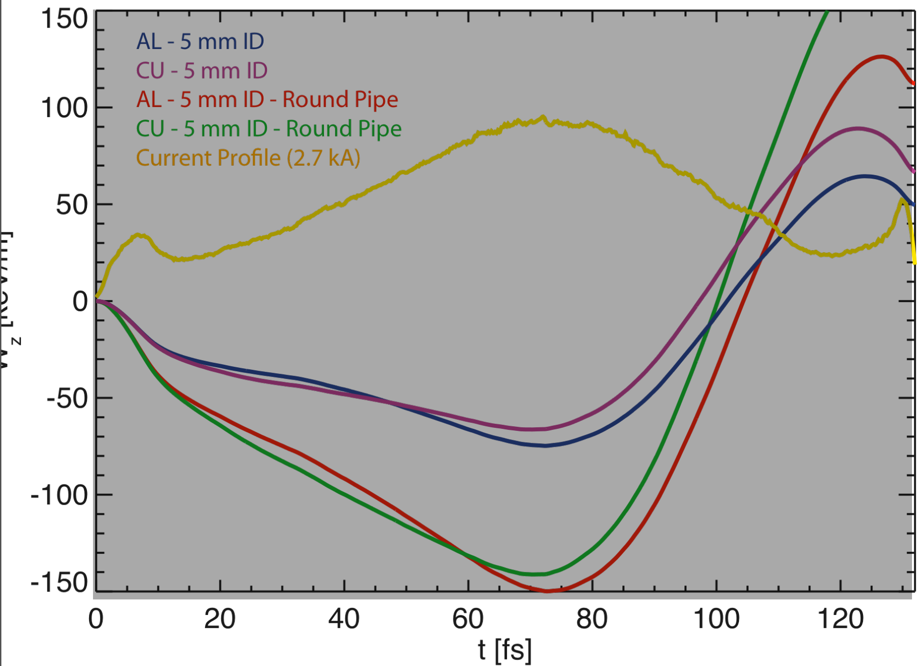
UE40

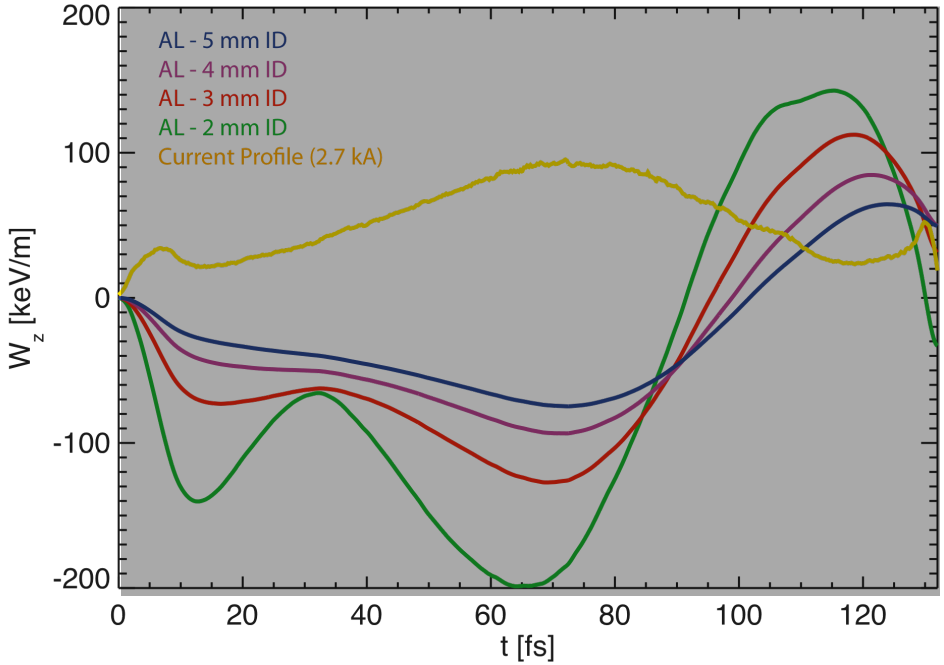
FEL operation allows for small gap 6.5mm magnetic 5mm vacuum gap

small magnet blocks 20 x 20 mm + low Br > NdFeB or Sm_2Co_{17}

Minimum Gap

Wakefield Effects (Stupakov-Bane Model)





UE40 - fixed vacuum chamber

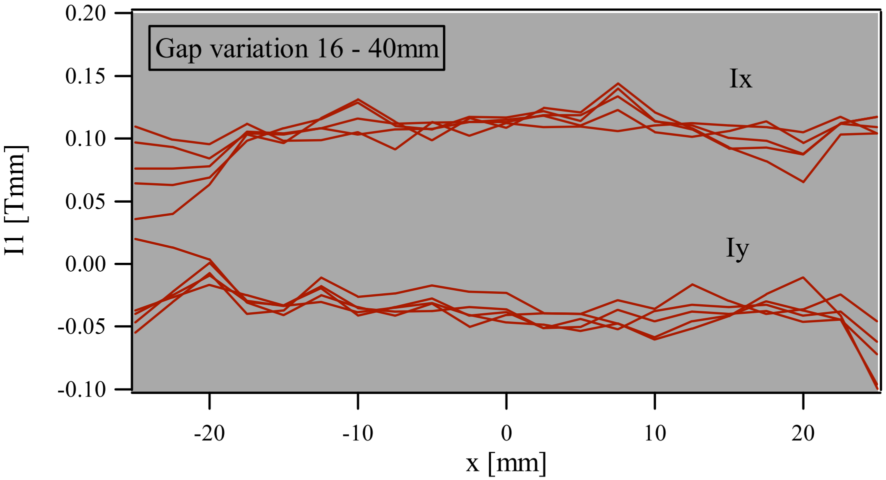
gap: 5mm elliptical
flattens current profile

U15 - in vacuum undulator

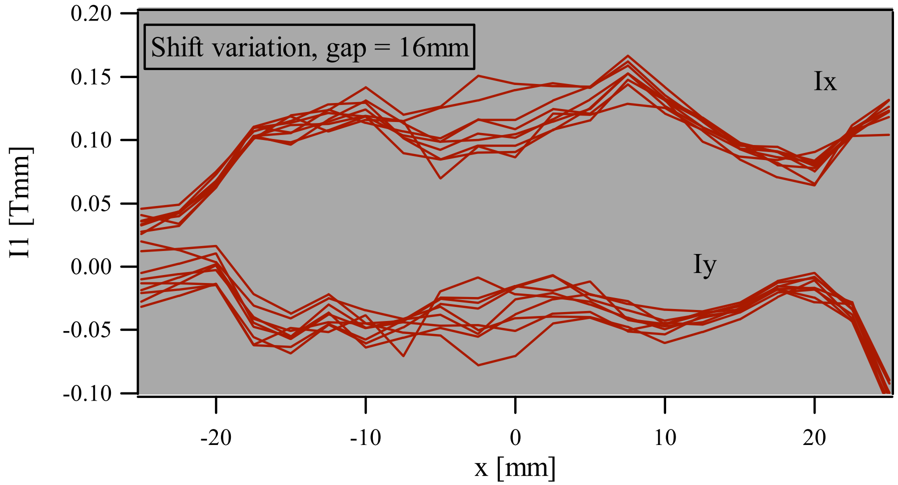
minimum gap: 4mm

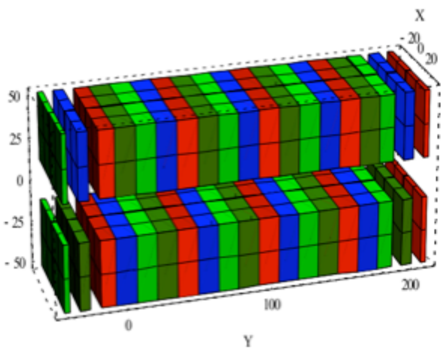
UE40: Shift dependent field integrals

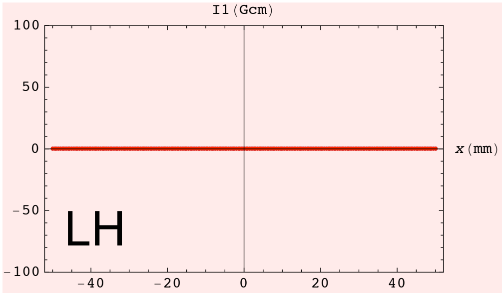
Field Integrals $\int B\, dy$

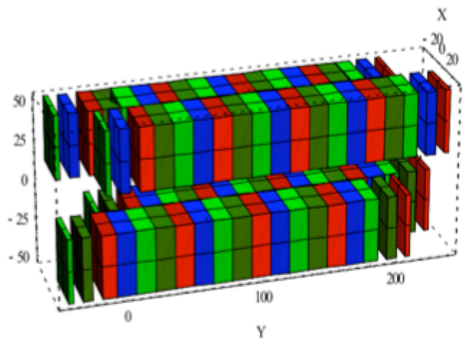


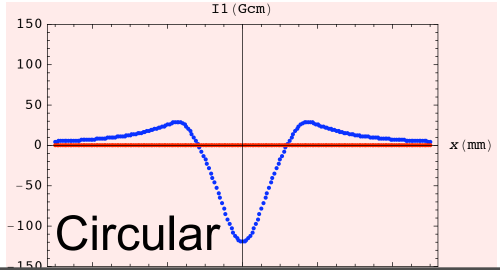
Systematic error due to μ - 1 effect
$\mu_\perp = 1.06$, $\mu_= = 1.15$ for NdFeB

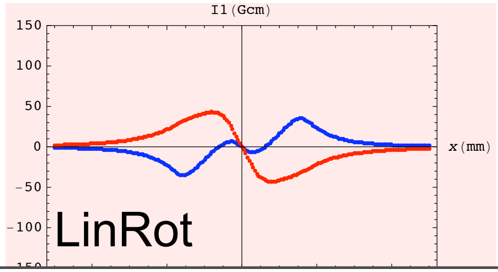












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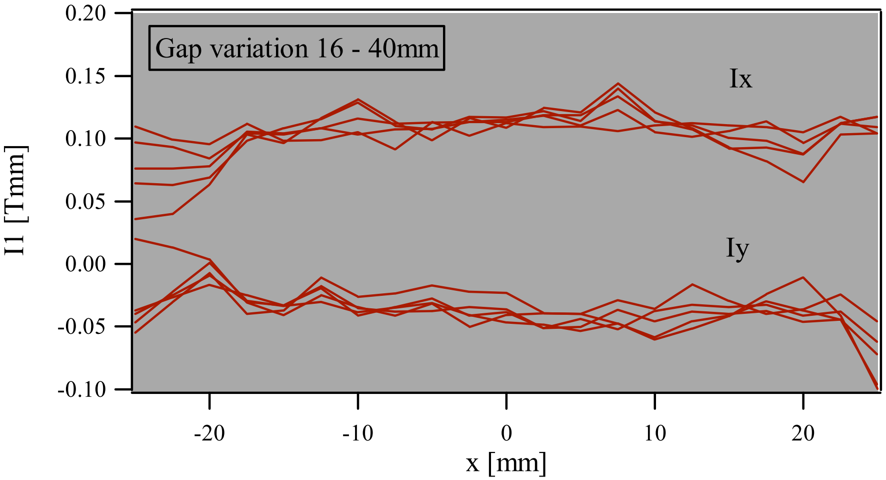
UE40: Shift dependent field integrals

Field Integrals $\int B\,dy$



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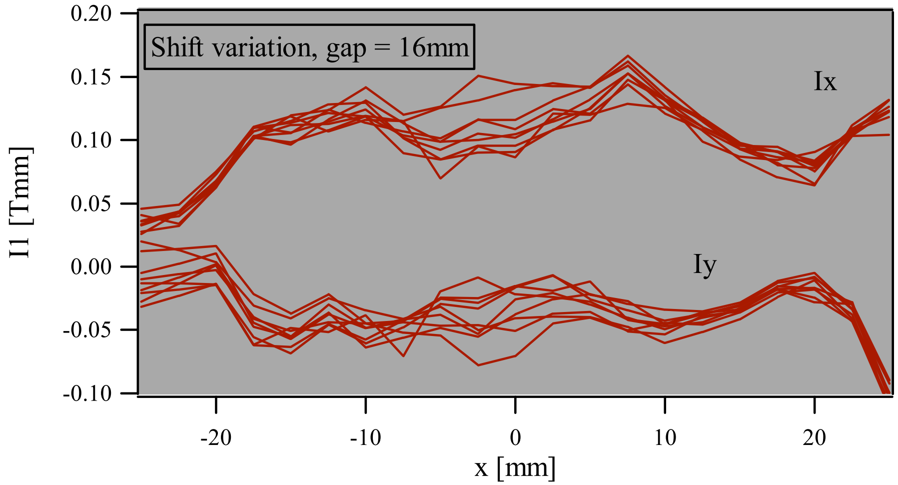
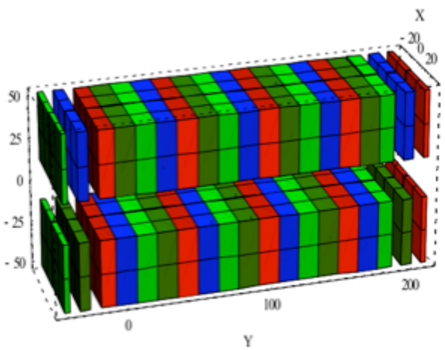
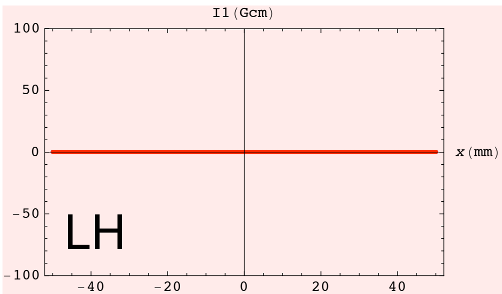
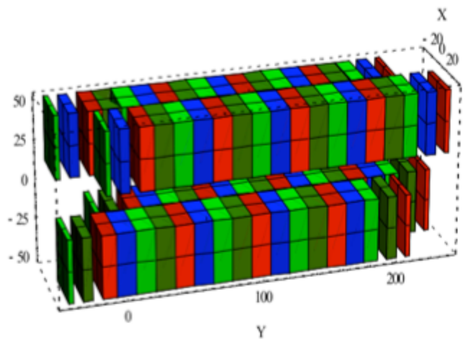
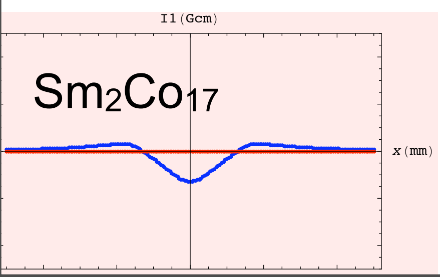
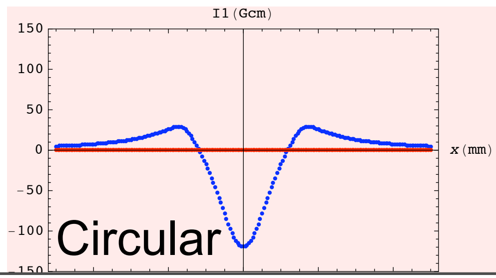


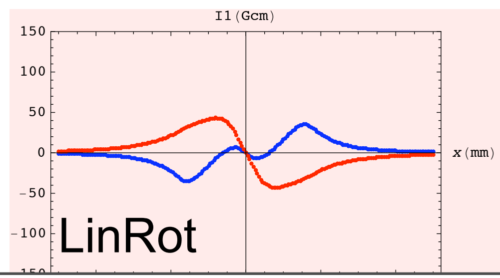


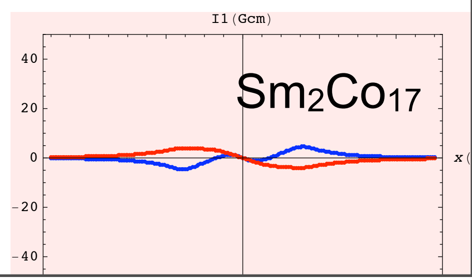




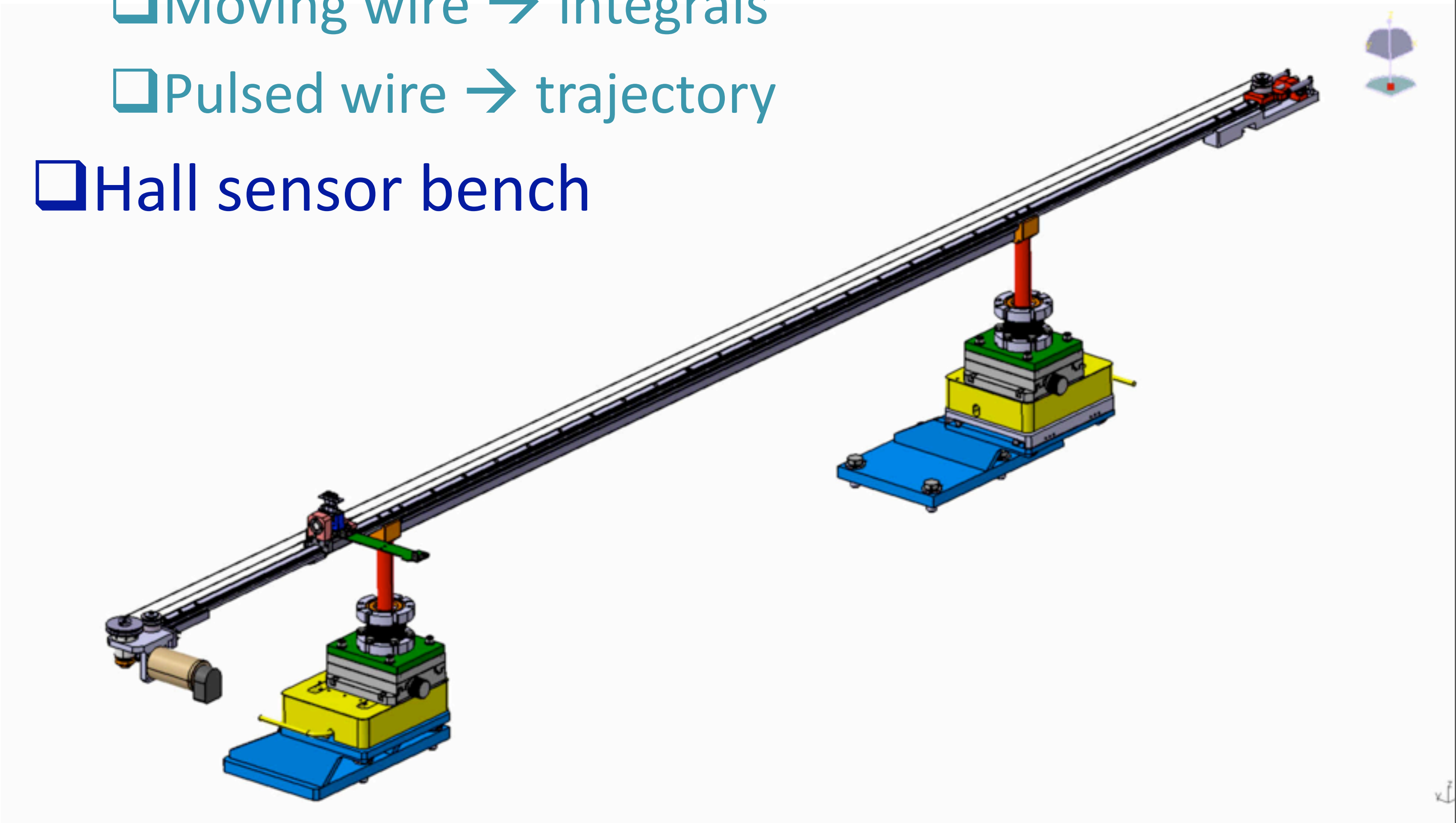


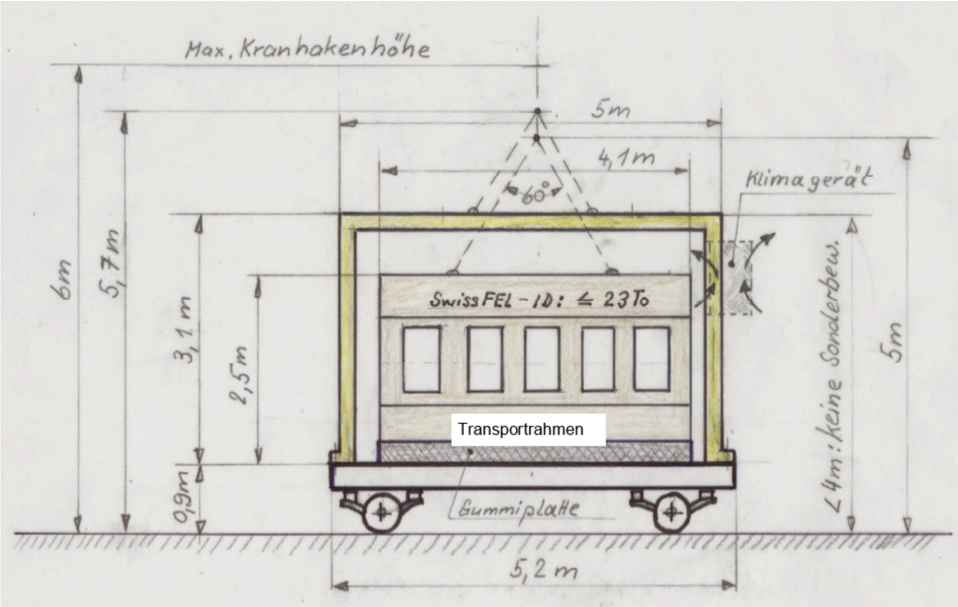




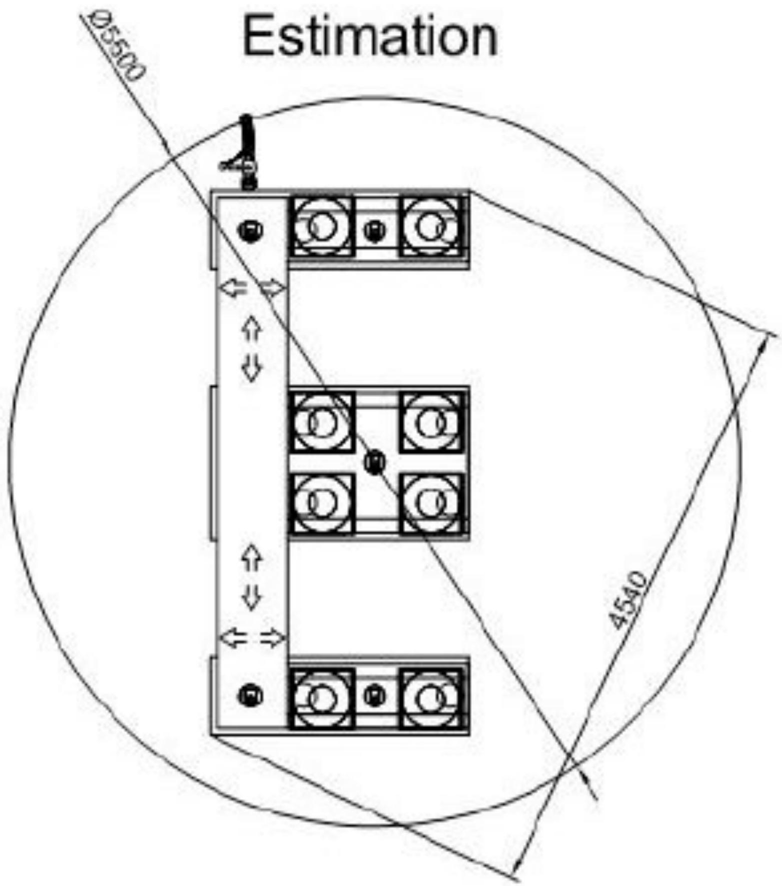


- Single stretch wire
  - Moving wire → integrals
  - Pulsed wire → trajectory
- Hall sensor bench





Transport in tunnel with motorized air cushion system



Transport from manufacturer to measurement Lab and from lab to PSI SwissFEL building in temperature controlled transport box on a rubber sheet