

PAUL SCHERRER INSTITUT



Romain Ganter on behalf of HERO Team

Status HERO / EEHG Project

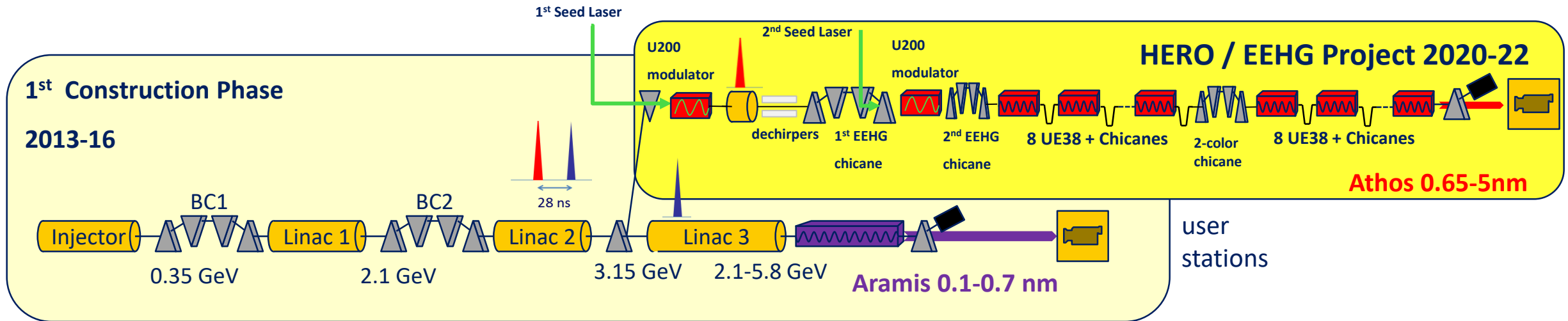
SwissFEL Performance Workshop – January 2022

Outline:

- Goals
- Status 1st Phase: HERO
- Status 2nd Phase : EEHG
- Timeplan first tests HERO

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ERC Grant - HERO: Hidden, Entangled and Resonating Orders

First Phase: 1st slicing in Summer 2022

=> increase temporal coherence

=> generation of train of mode-locked attosecond pulses

Second Phase: 1st Echo Enabled Harmonic Generation in Spring 2023

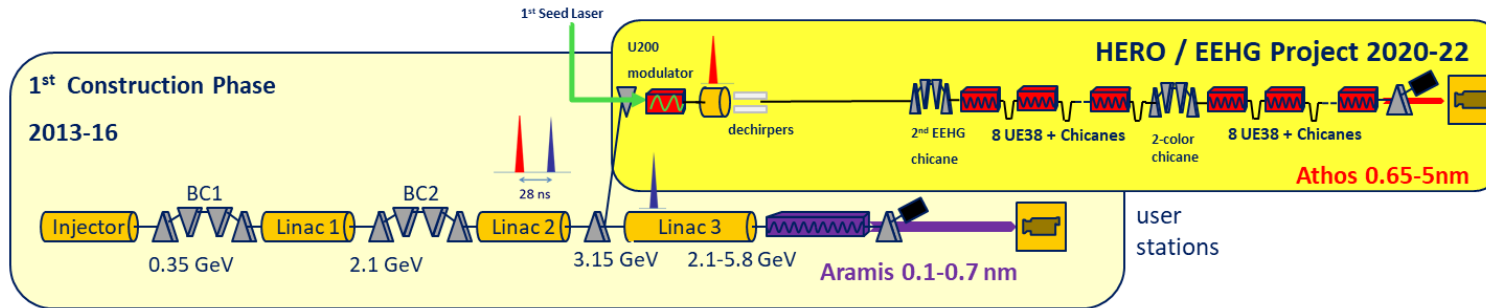
=> higher spectral brightness

=> X ray pulses synchronized with external source

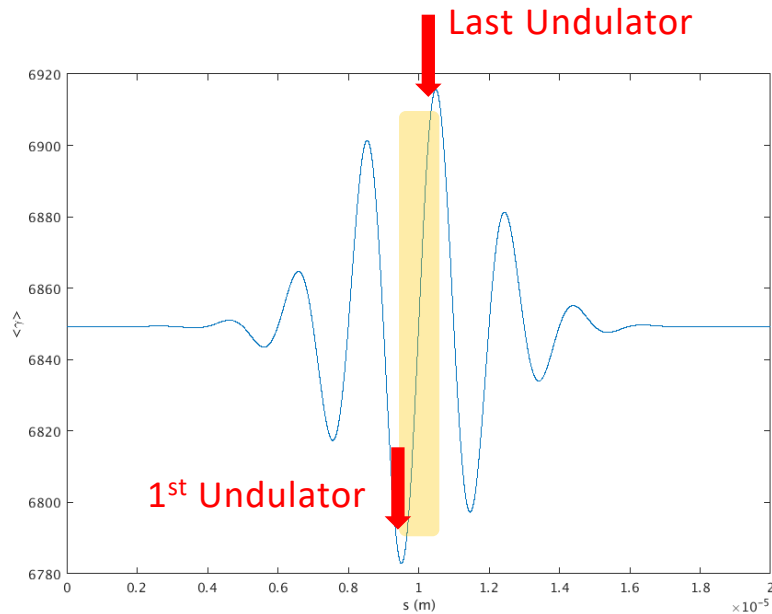
Goal:

Fully coherent x-ray laser

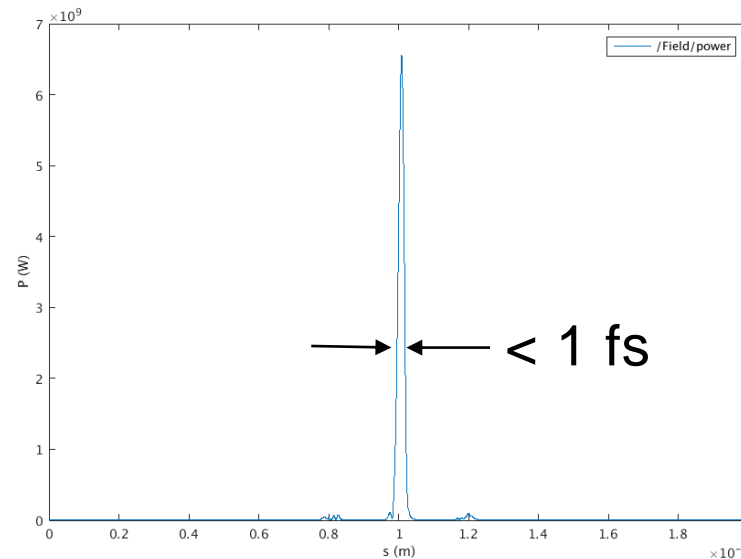
Slicing predicted performance



ESASE (Enhanced SASE):
Induced energy modulation
=> density modulation
=> Train of short pulses (*)



Bunch Energy modulation at Undulator entrance

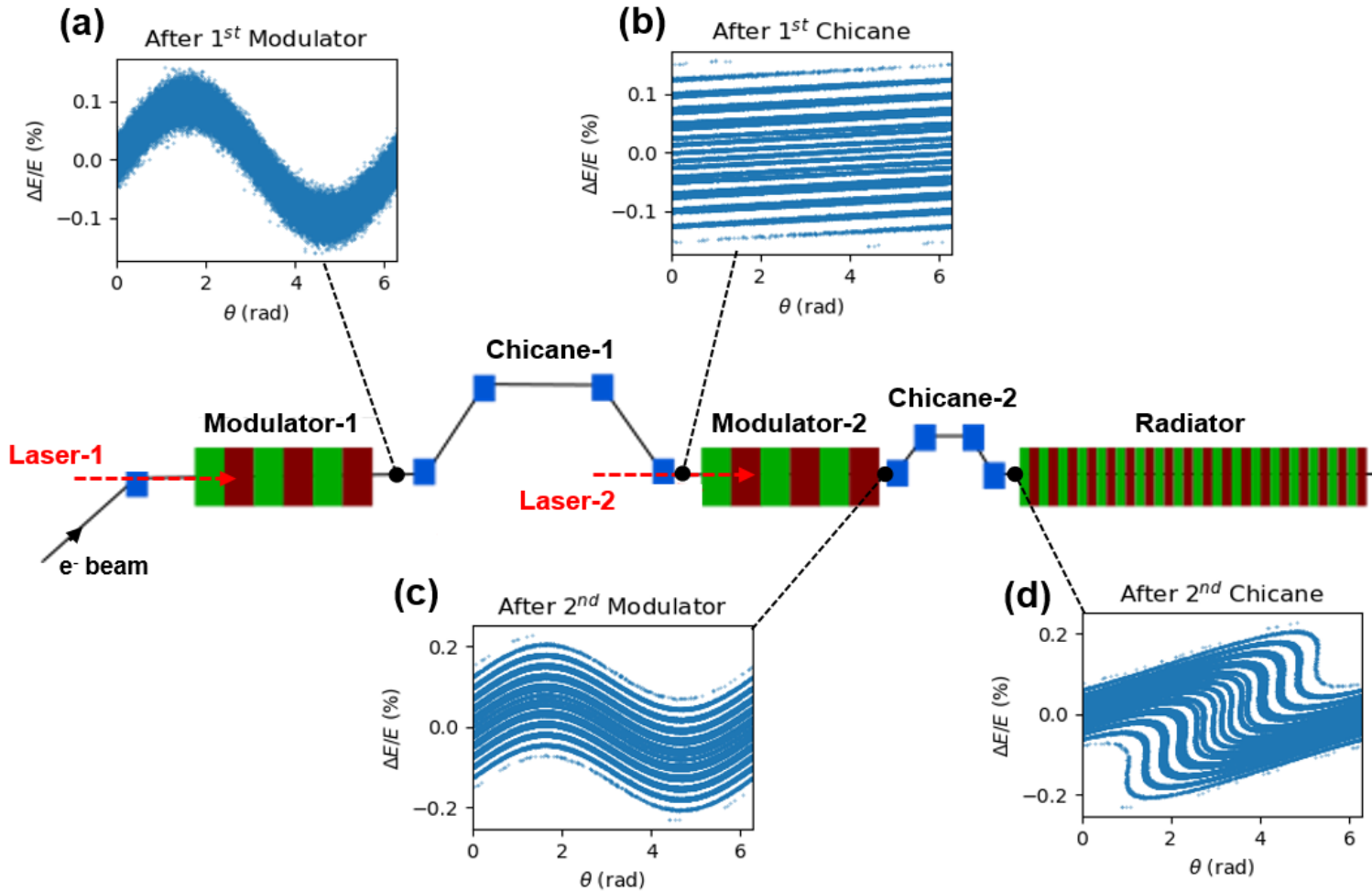


Undulator positive **tapering** synchronized with FEL pulse **slippage** over Energy **Chirp**

- Single pulse or pulse train:
- 1uJ / pulse
 - < 1 fs / pulse
 - 0.1-0.4 % BW rms

(*) A. A. Zholents, *Physical Review Special Topics-Accelerators and Beams*, vol. 8, no. 4

EEHG Principle

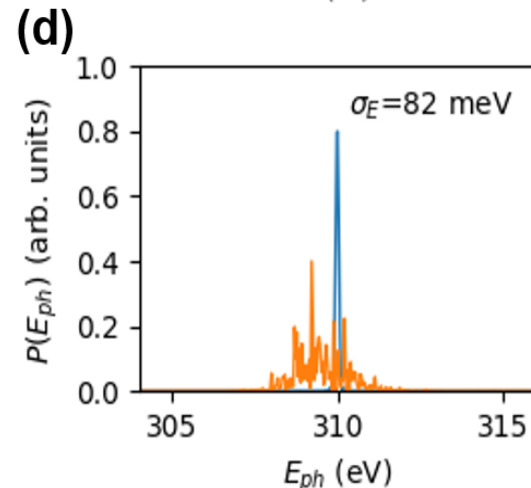
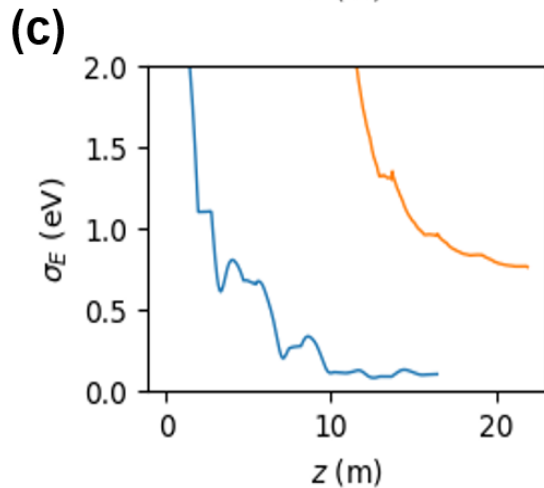
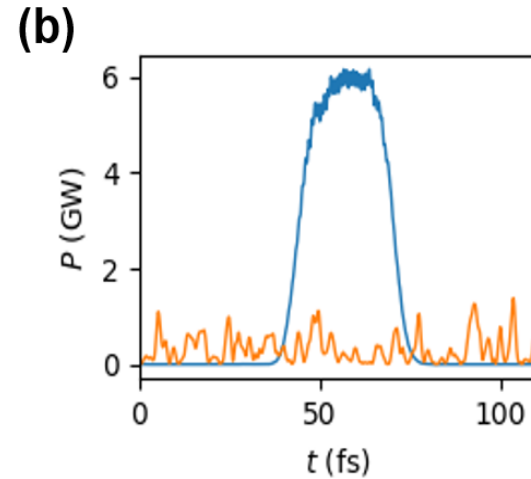
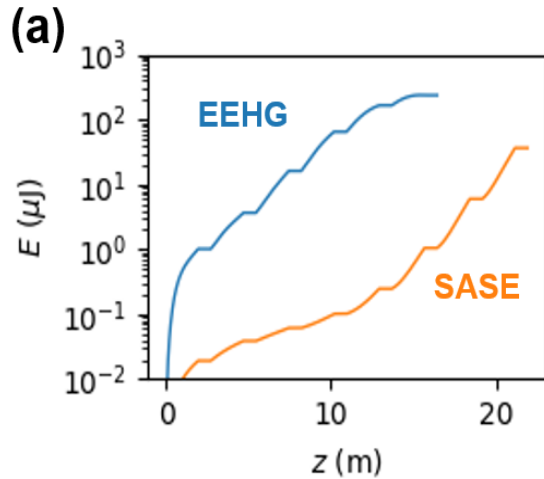


- (a) Energy modulation imprinted on bunch by 1st laser (λ)
- (b) Dispersive chicane converts energy modulation in fine striated energy bands (non linear)
- (c) 2nd Laser (λ) energy modulation
- (d) Another dispersive section to convert fine energy band in fine density modulation (λ/h high harmonic)

Radiator is then tuned on the periodicity of this fine modulation !

=> Radiation at high harmonic of seed laser wavelength with its coherence properties

Example of the water window wavelength : 4 nm (66th harmonic of a 264 nm seed laser)



Single narrow spectral line: 80 meV rms
Peak power > 5 GW (100 μJ pulse energy)
Pulse duration of ≈ 20 fs FWHM.

EEHG Simulation parameters:

$R_{56}^{(1)} = 10 \text{ mm}; R_{56}^{(2)} = 152 \mu\text{m}$

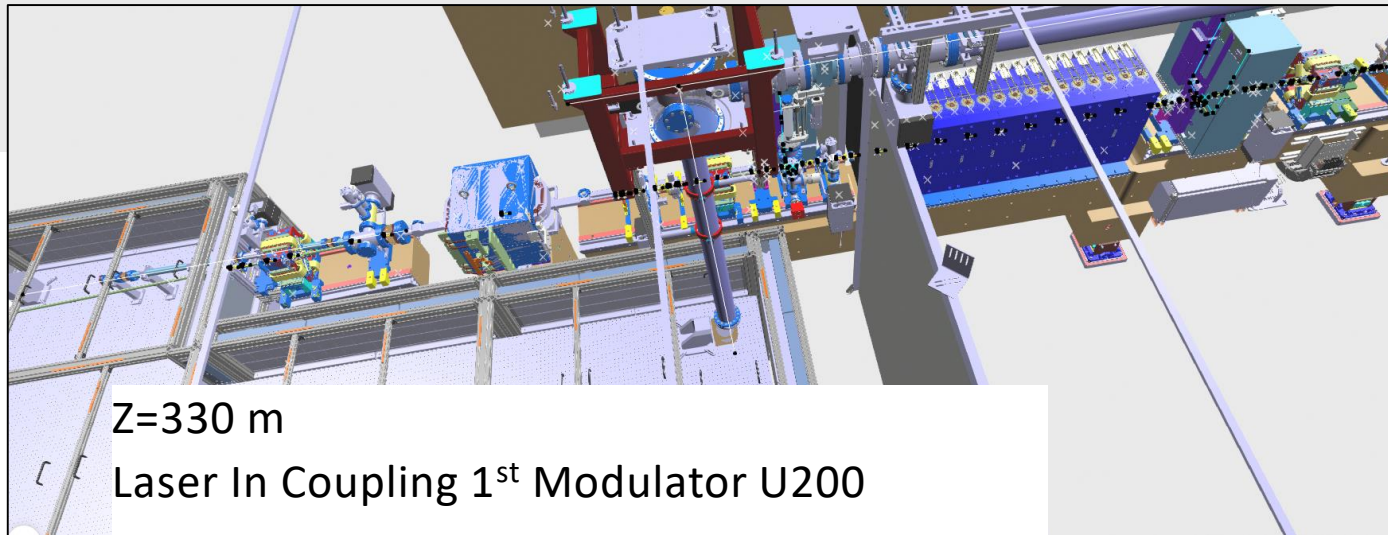
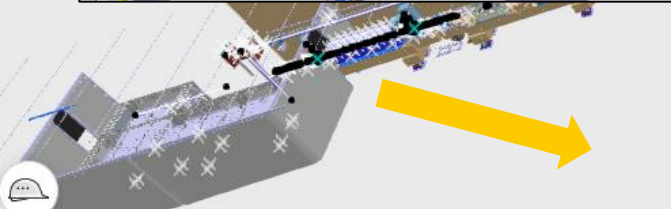
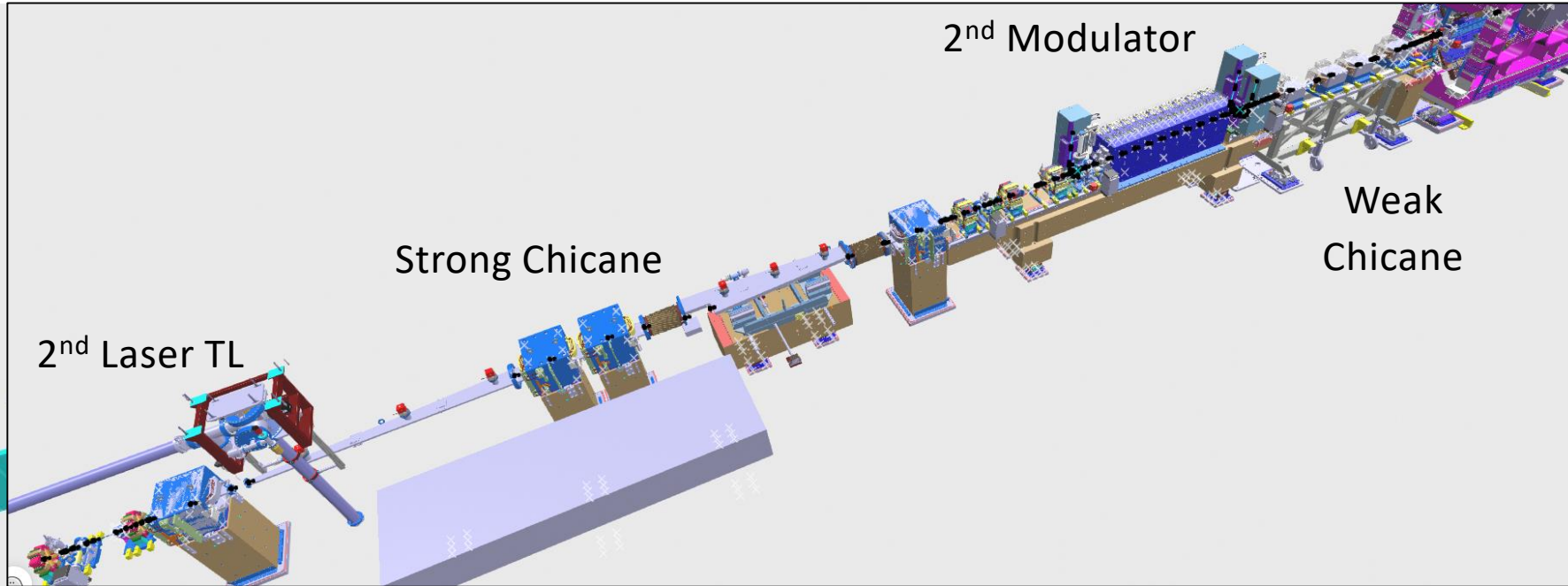
$I_{\text{Laser1}} = 100 \mu\text{J}; I_{\text{Laser2}} = 10 \mu\text{J}$ for a 25 fs rms pulse
beam waist $w_0 = 300 \mu\text{m}$.



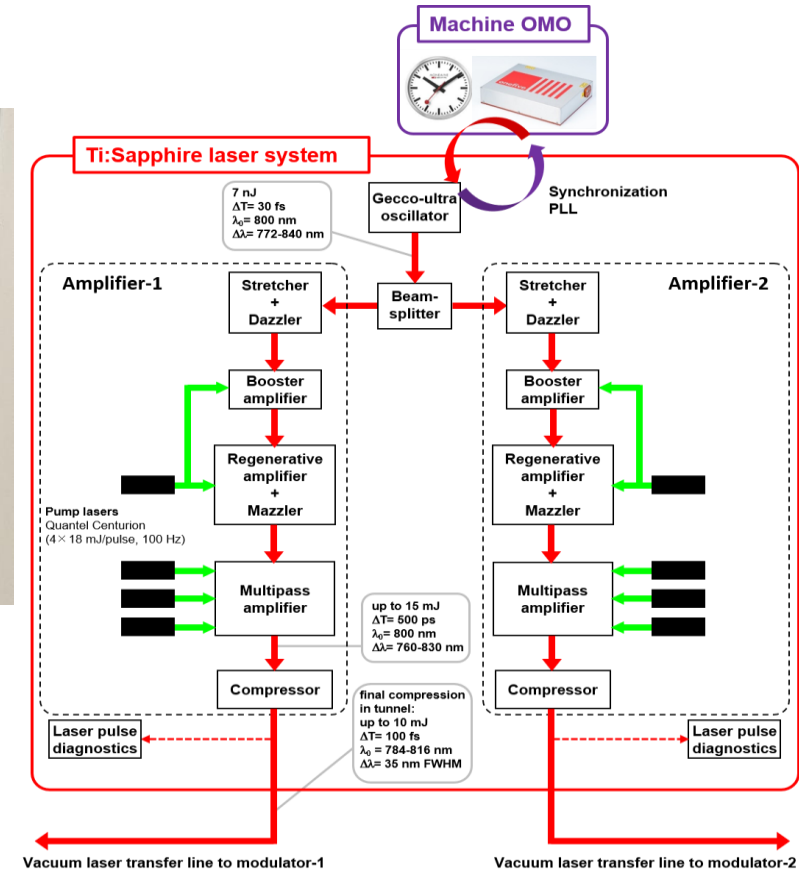
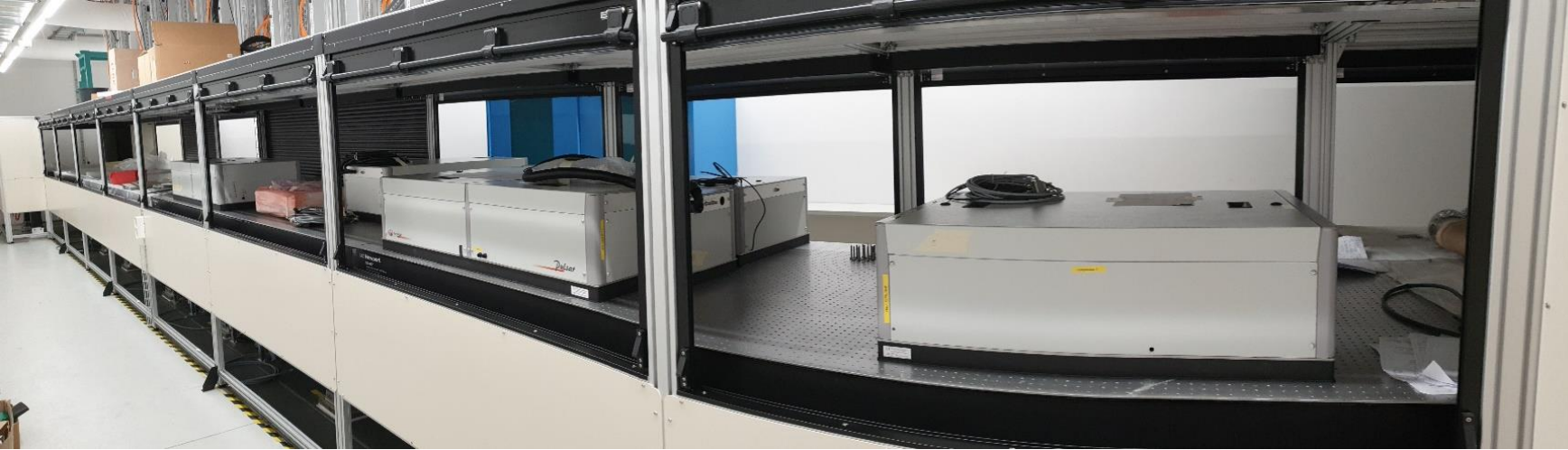
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EEHG Layout



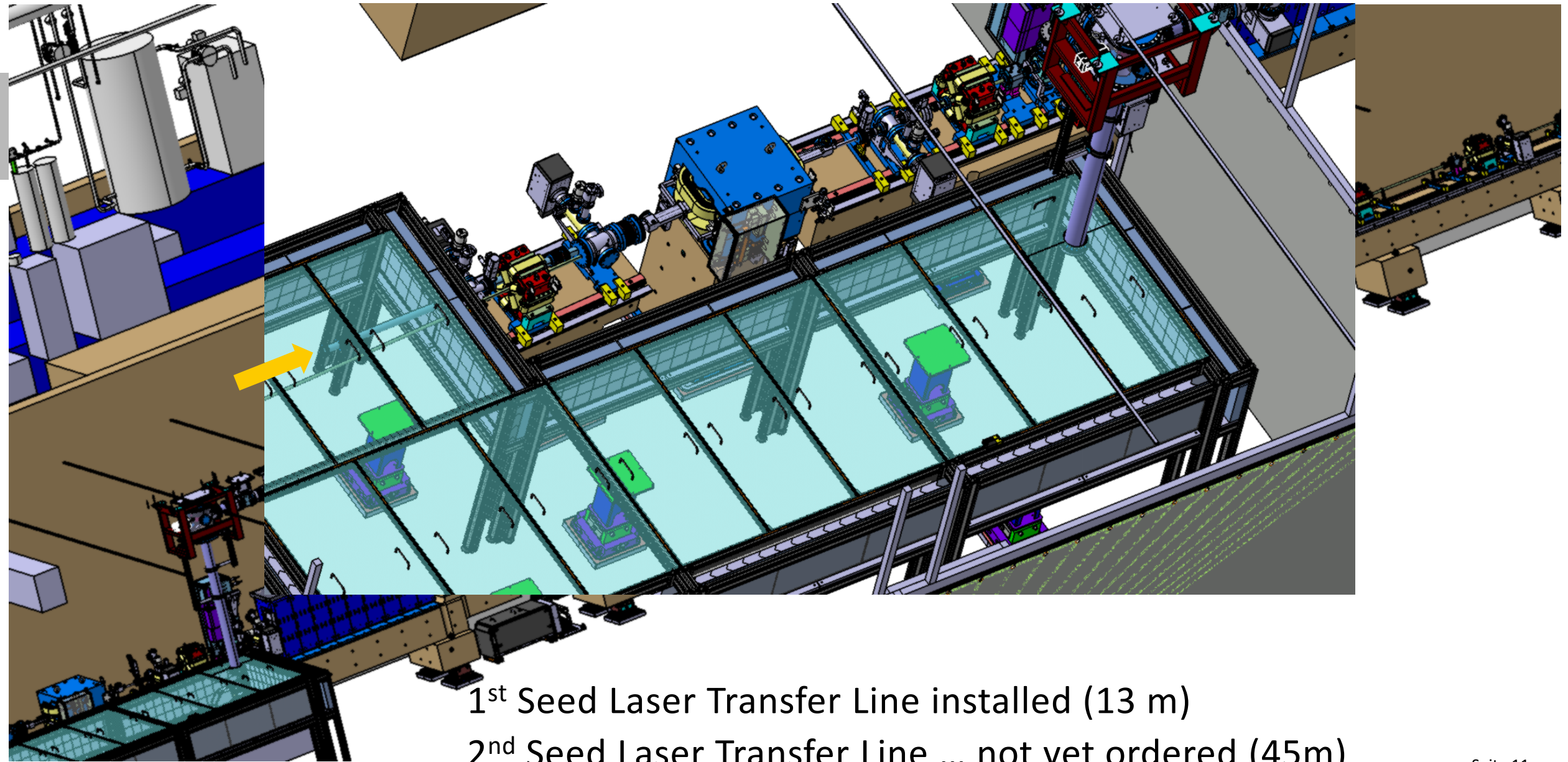
Seed Laser status



Laser installed and in Operation:
12 mJ / 25 -100 fs FWHM at 800 nm
Tunability 794 - 816nm ... on going

Courtesy of A. Trisorio

Laser Transfer Line EEHG



1st Seed Laser Transfer Line installed (13 m)

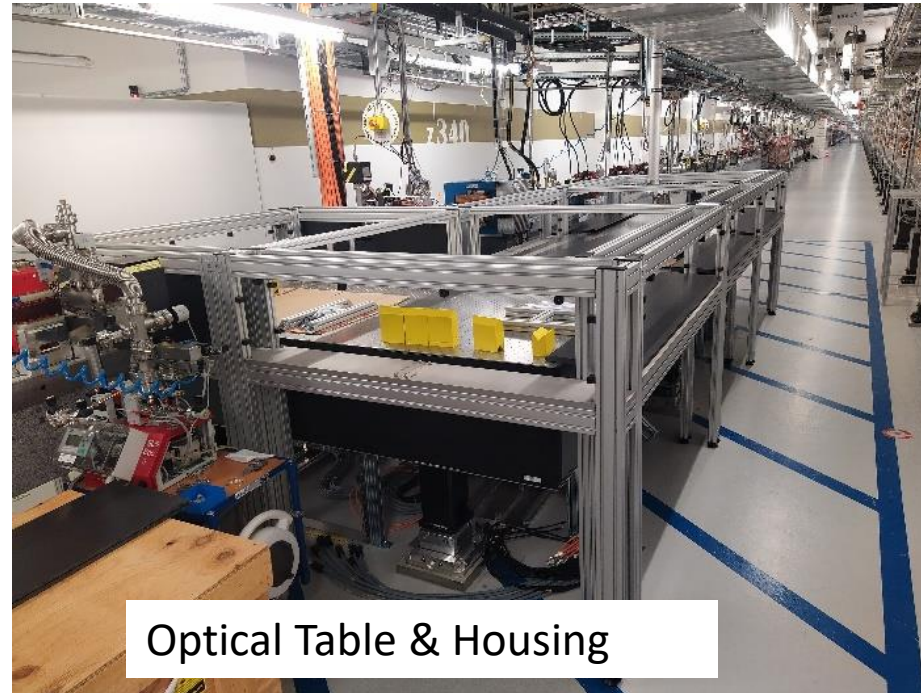
2nd Seed Laser Transfer Line ... not yet ordered (45m)

Laser Transfer Line: 1st In Coupling

Transfer line mounted

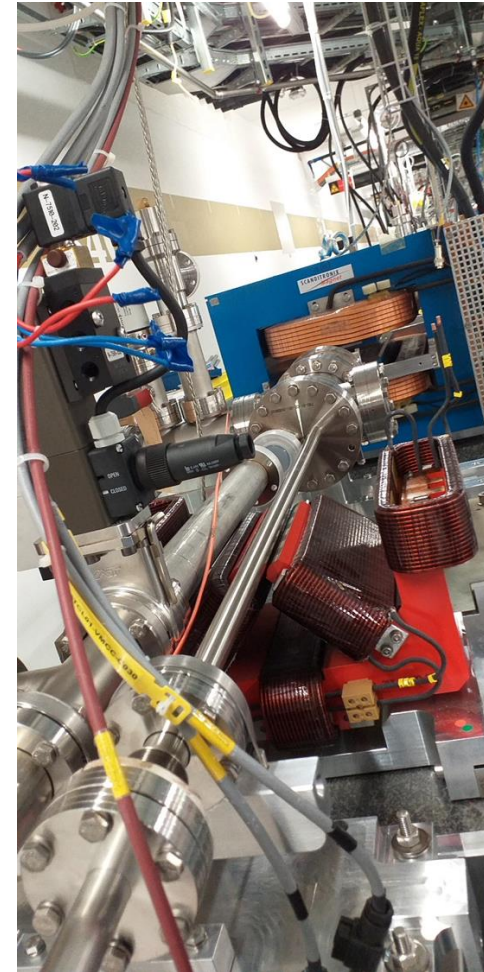


First Laser transport in tunnel February 23rd



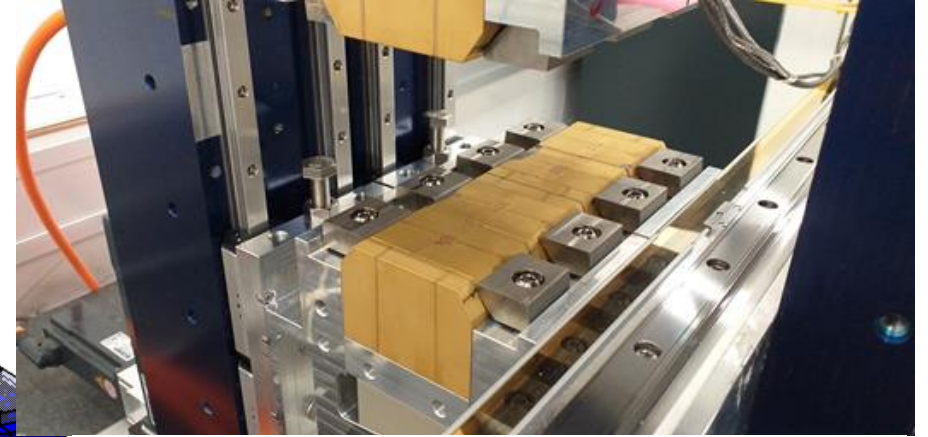
Optical Table & Housing

Laser incoupling viewport

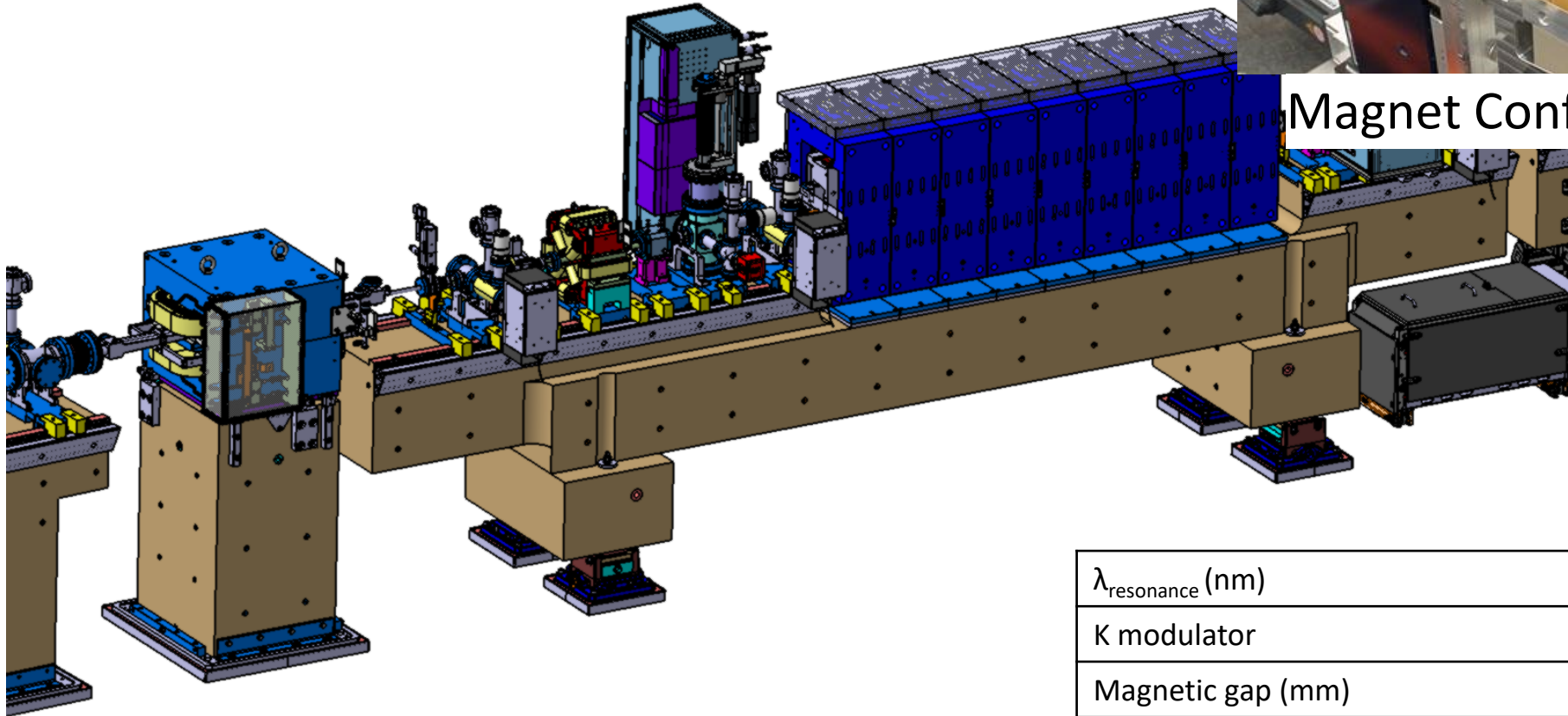


Modulator U200

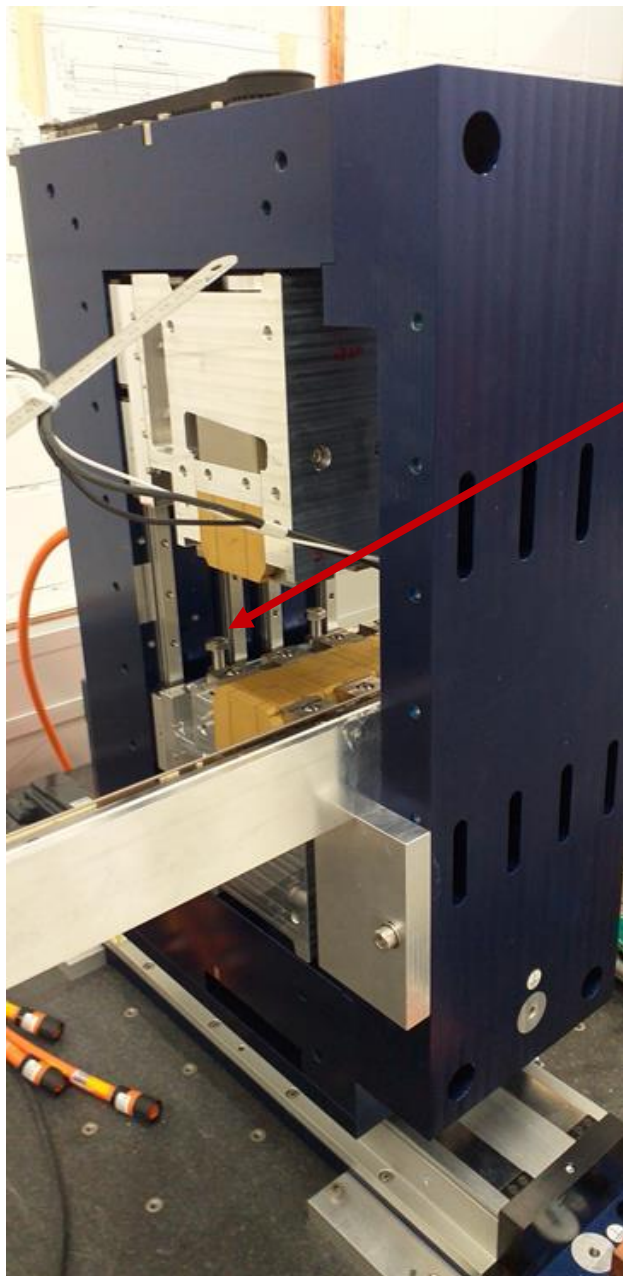
- Stacking of 9 CHIC chicanes (NdFeB)
- 36 motors for undulator shimming



Magnet Configuration: ++ / --



$\lambda_{\text{resonance}}$ (nm)	1500	800
K modulator	32.1	23.4
Magnetic gap (mm)	10.2	15.2
Vacuum inner dimension (mm)	8*16	8*16

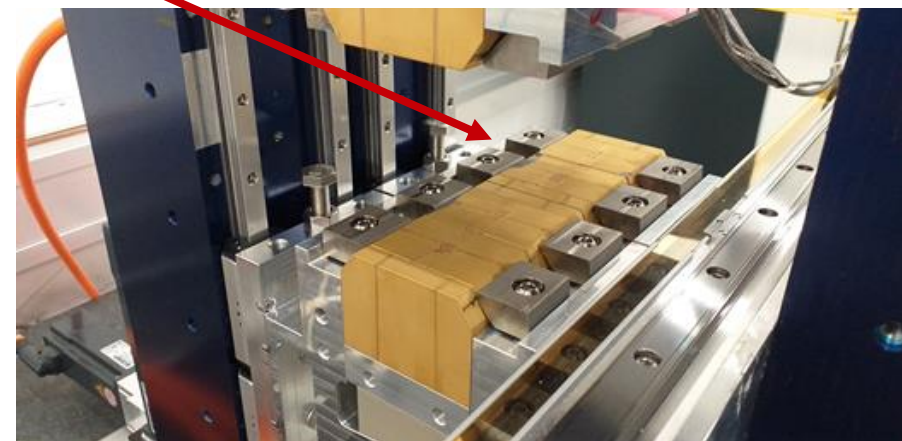
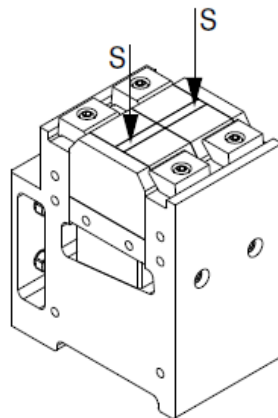


Issue: magnet to magnet parallelism (repulsion forces)

New: 4 guiding rails (to better hold magnets):
=> situation improved but not perfect

=> Blocks will be glued together 2 by 2 !

=> U200 Delayed !



Magnet Configuration: ++ / --

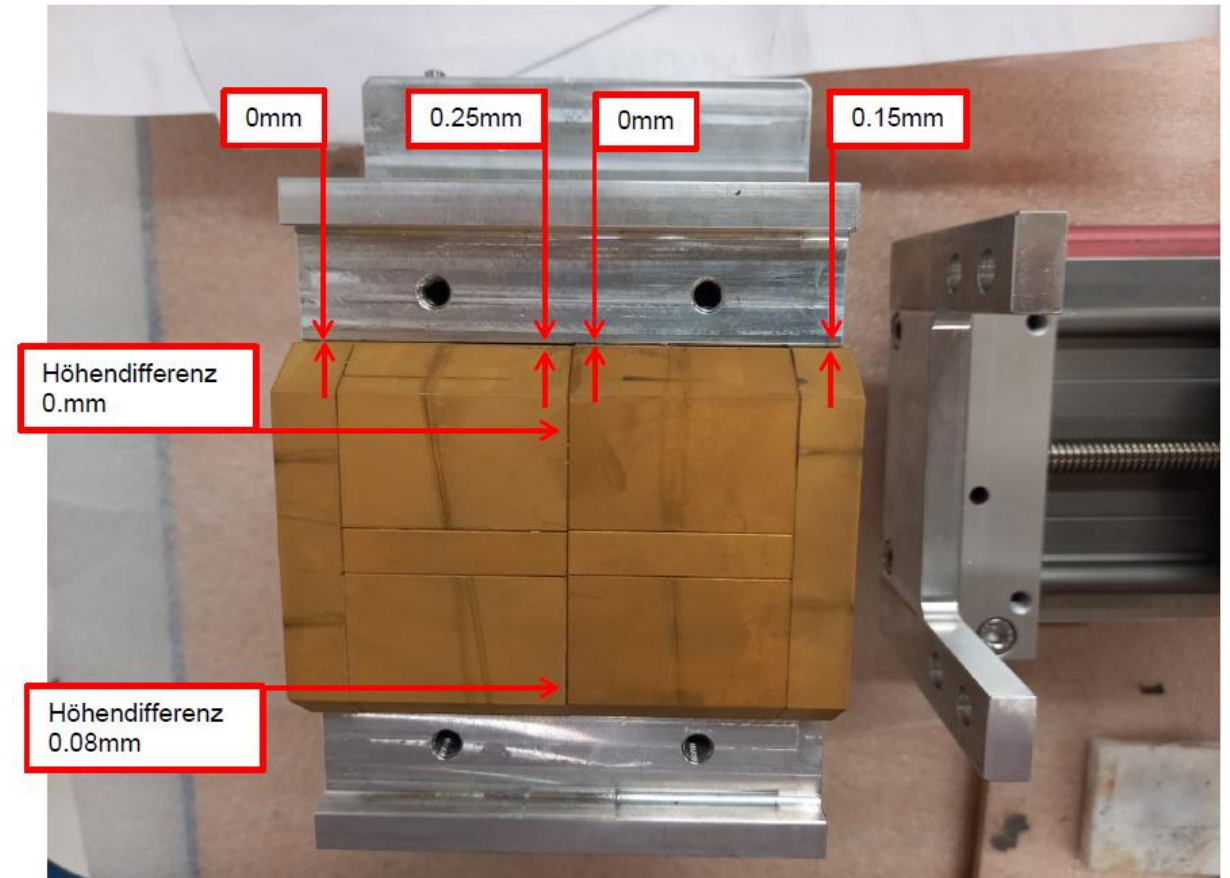
Gluing Procedure for Modulator 1 Magnets

- **Delivery of glued Magnet to PSI: All blocks at PSI !**
- Workshop closed due to covid on 1st week of Jan !
- Assembly of CHIC chicanes started this week !
- **U200 assembly on girder: End of Feb. 2022**

U200 is Critical Path of HERO Project !



Assembly Modulator HERO PSI
2. Satz



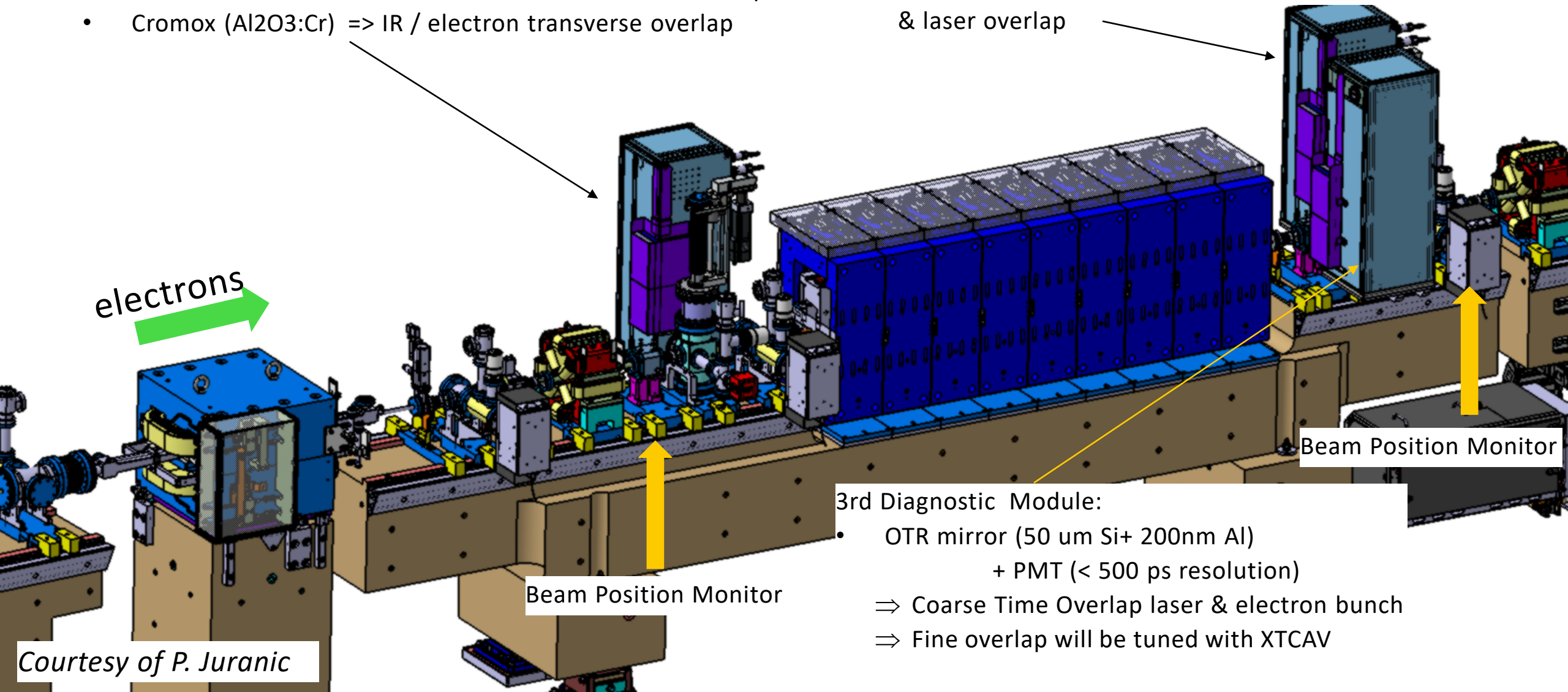
Diagnostic electron / laser overlap

1st Diagnostic Module:

- YAG screen + camera => UV / electron transverse overlap
- Cromox (Al₂O₃:Cr) => IR / electron transverse overlap

2nd Diagnostic Module:

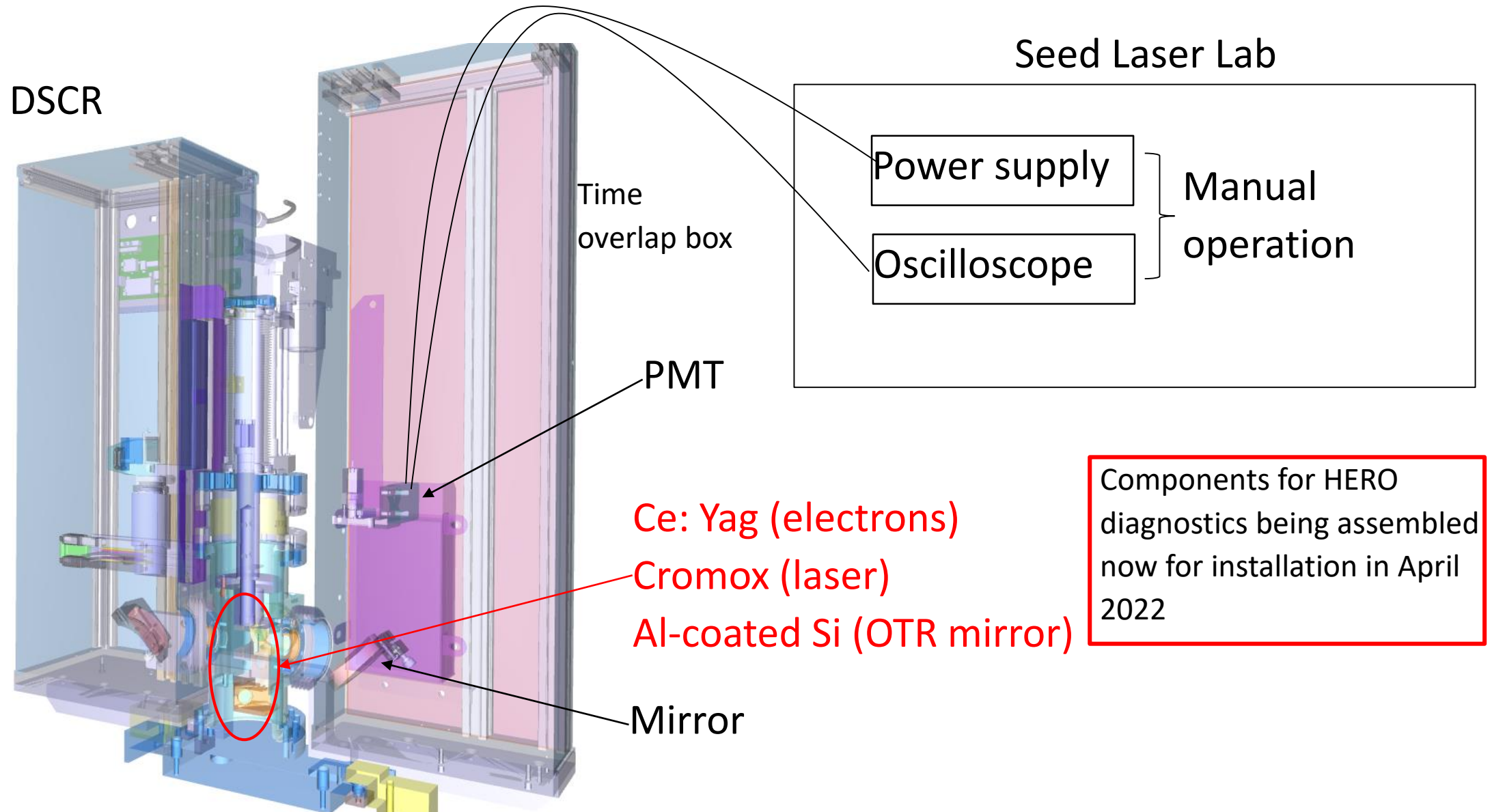
- YAG screen + camera => UV/ e- beam overlap
- Cromox (Al₂O₃:Cr) with aperture => pointing feedback & laser overlap



3rd Diagnostic Module:

- OTR mirror (50 um Si+ 200nm Al)
+ PMT (< 500 ps resolution)
=> Coarse Time Overlap laser & electron bunch
=> Fine overlap will be tuned with XTCMV

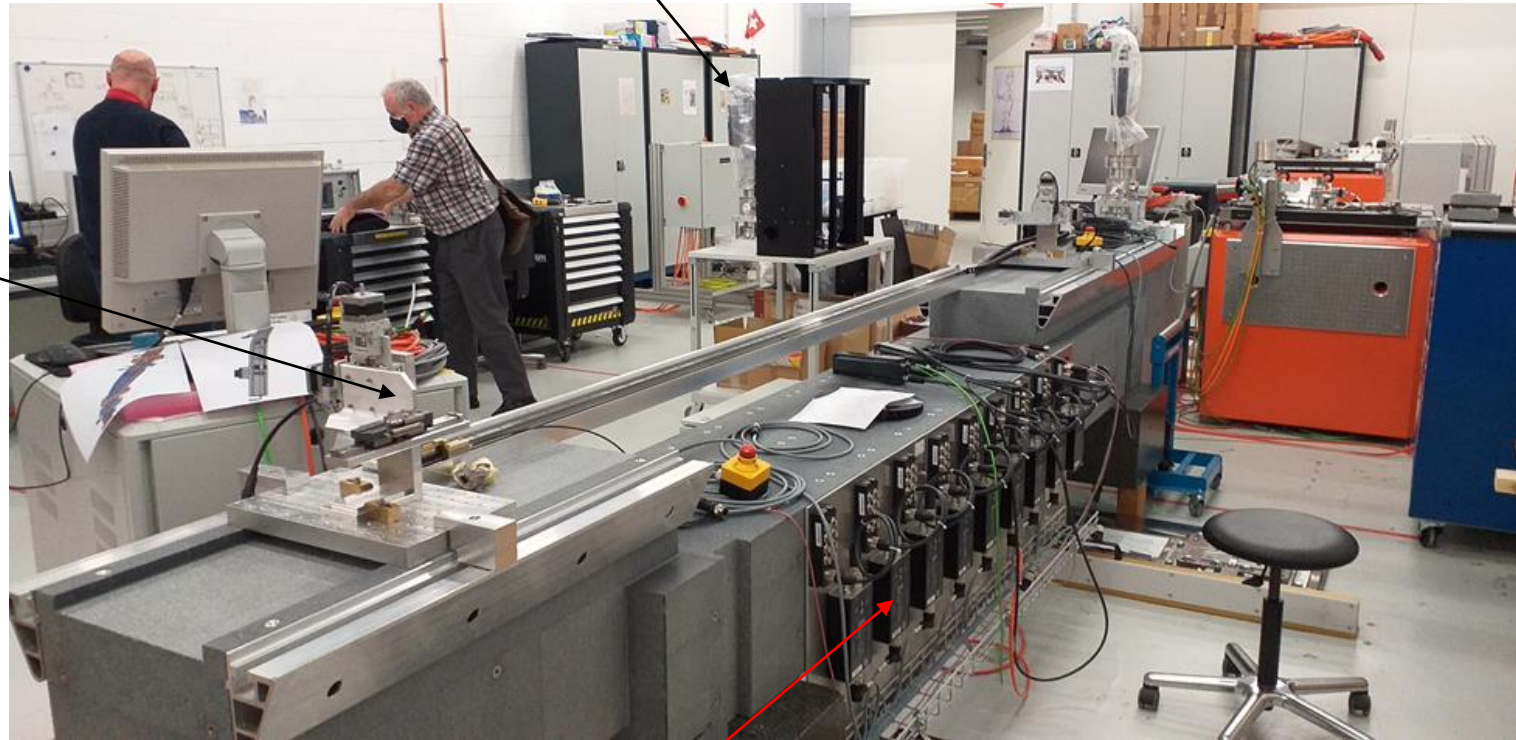
HERO timing and visualization instruments



U200 Girders Preparation

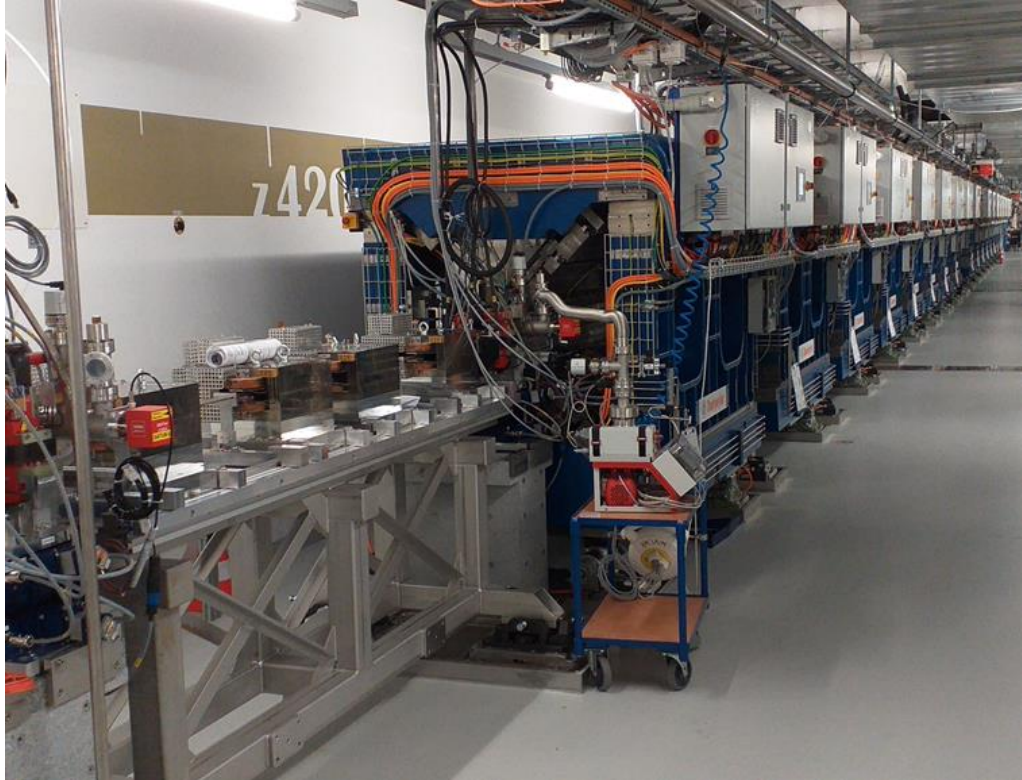
- Diagnostic screen under assembly (all components here)

Hall Probe system for U200 shimming

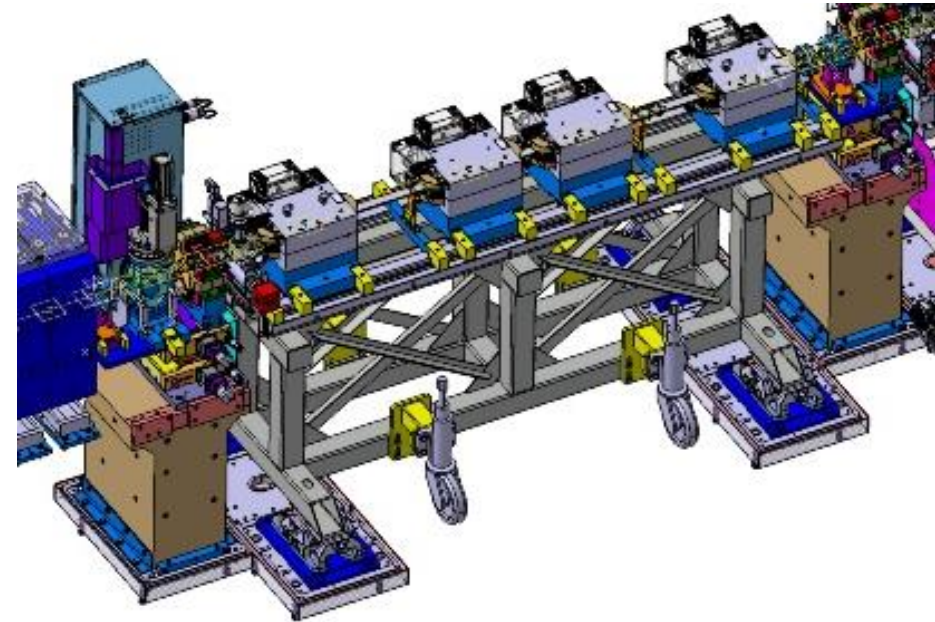


BPM, Quads, BAM ready for pre-assembly !

U200 motor control (40 motors): new Beckhoff driving cards installed and under test with dummy motors

2nd magnetic chicane Chicane**Status**

Installed in front of Radiator and Commissioned !

**Specifications:**

Nominal Compression: $R_{56}^{(2)} = 150 \text{ um}$

HERO - AFSS 4 Dipoles Chicane - SATUN05	Max.
Deflecting angle	1.55 deg (27 mrad)
Transverse offset at central dipole	18.4 mm
R_{56}	849 um
Delay in fs	1.41 ps at 3.15 GeV
AFSS Magnet Length	311 mm
AFSS Integrated field (T.m)	0.00191 T.m/A
Chicane Total length	2.12m
Maximum Current PS	150 A

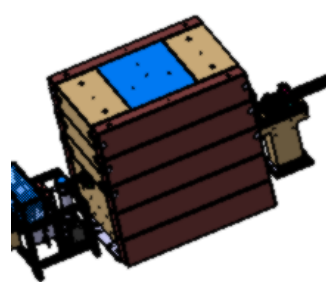
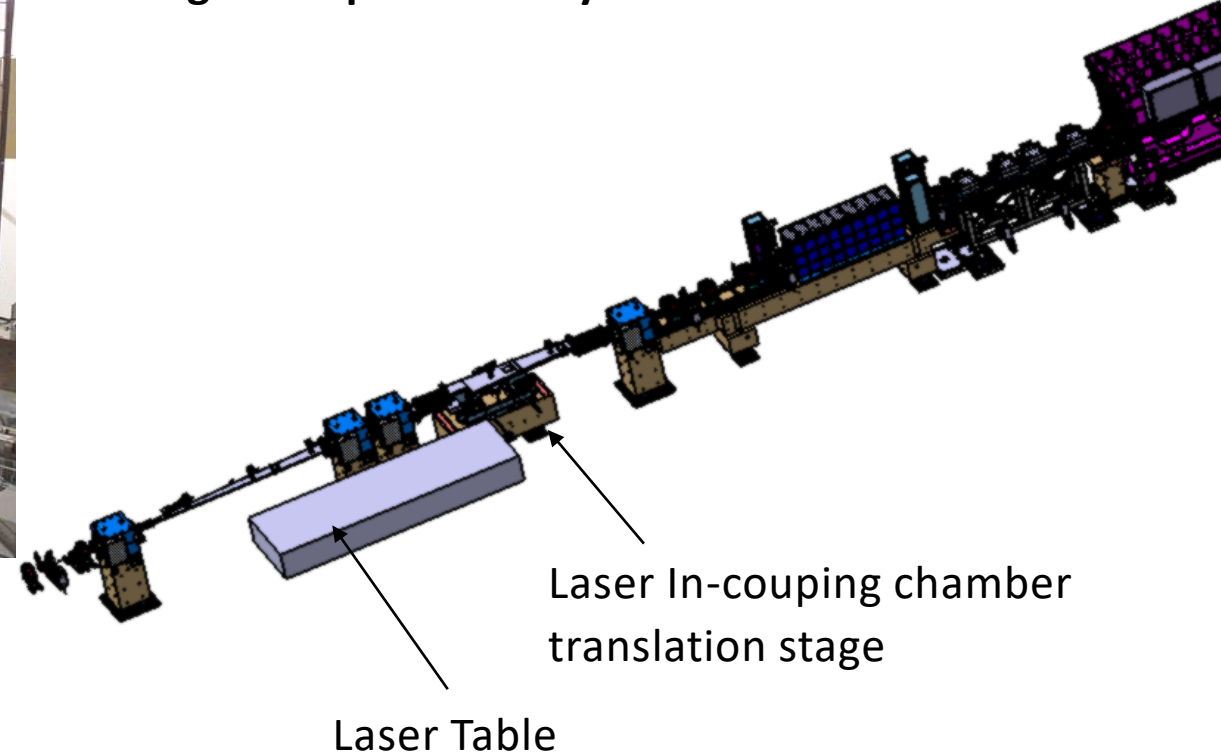


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Strong chicane and 2nd U200 modulator

All ground plates ready for Installation

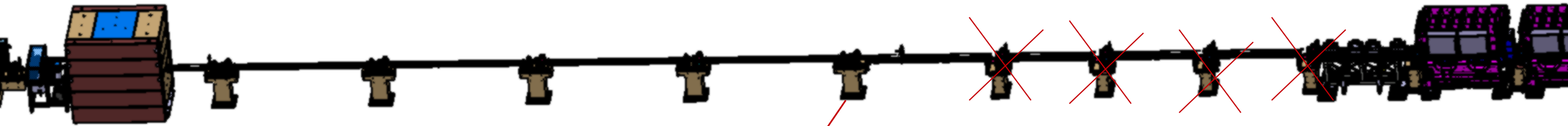


Large Chicane Hardware:

- Granite blocks at PSI
- Dipole Magnets at PSI and measured
- Vacuum chamber offers requested

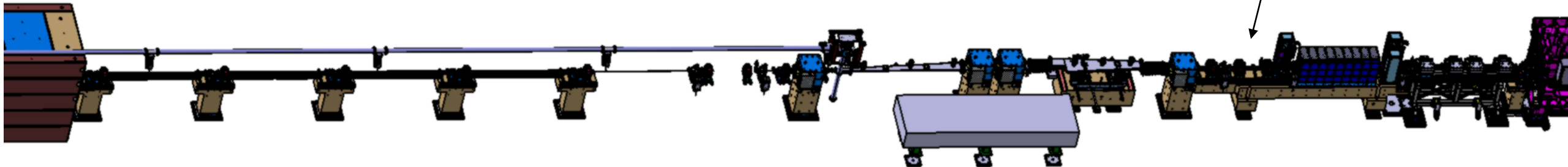
EEHG Chicane Installation (August or December 2022)

Now



Major modification of the line !

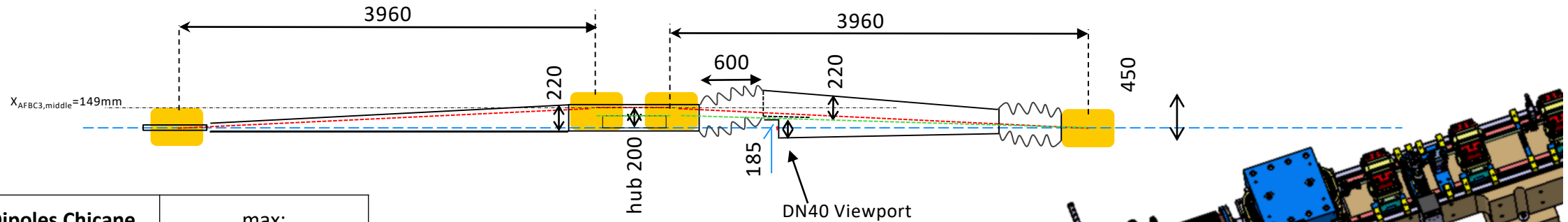
With EEHG



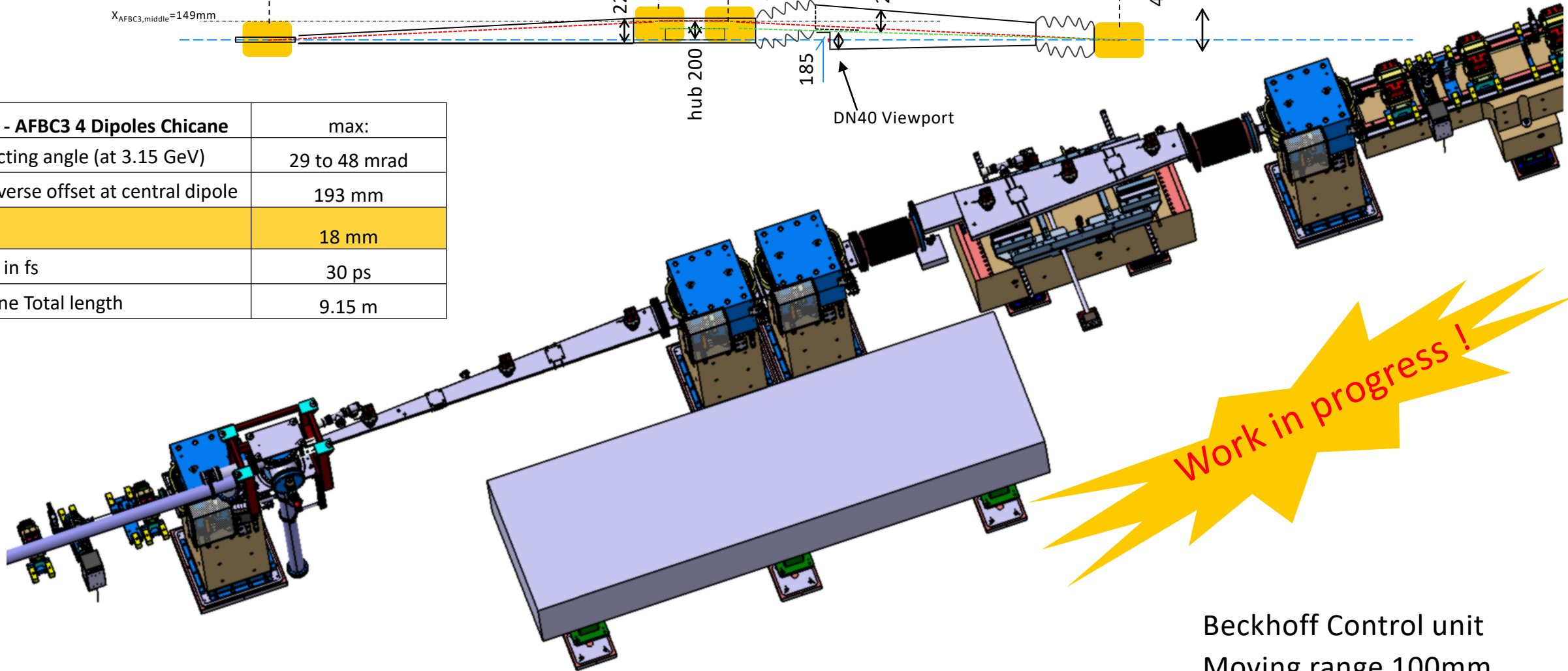
EEHG U200: August 22

Strong chicane and In Coupling (August 22 or Dec. 22) !

EEHG 1st Magnetic Chicane



EEHG - AFBC3 4 Dipoles Chicane	max:
Deflecting angle (at 3.15 GeV)	29 to 48 mrad
Transverse offset at central dipole	193 mm
$R_{56}^{(1)}$	18 mm
Delay in fs	30 ps
Chicane Total length	9.15 m



Work in progress!

Beckhoff Control unit
Moving range 100mm



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HERO - EEHG Status Installation



2nd magnetic chicane
(installed)

1st magnetic chicane:
~~SD April 22~~ -> August 22

Seed laser room (Nov 21)

U200 2nd Modulator
~~Shutdown August 2022~~

2nd Laser Transfer Line (EEHG)
~~Shutdown August 2022~~ Dec. 22

1st Laser Transfer Line
Shutdown August 2021 -> ~~Nov. 21~~ -> Jan 22 & Feb 22

U200 1st Modulator:
Shutdown April 22

HERO – EEHG Milestones

HERO Installation Milestones		2020				2021				2022				2023			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MS1	Official Project Start	◆ 01.01.20															
MS2	Air conditioning installation completed			15.11.2020 ◆													
MS3	Laser Table installed (room & tunnel)				◆ 06.01.2021												
MS4	Chicane SATUN05 installed in Tunnel					◆ 15.04.2021											
MS5	Laser Room Completed (ready for laser installation)					◆ 30.08.2021	◆ 30.10.2021										
MS6	U200 Modulator assembled and characterized						◆ 01.10.2021			◆ 01.02.2022							
MS7	U200 Modulator girder installation (with diagnostic)							◆ 21.11.2021		◆ 30.04.2022							
MS8	Laser Transfer Line HERO Installed							◆ 21.11.2021		◆ 15.01.2022							
MS9	Laser Installation in Seed Laser Room completed							◆ 31.12.2021		◆ 31.03.2022							
MS10	Laser aligned in transfer line + optical setup in tunnel									◆ 30.04.2022							
MS11	First Slicing - End of HERO phase of Project										◆ 21.06.2022						
MS12	Installation Second Laser Transfer Line											◆ 30.08.2022					
MS13	EEHG laser system installed in the lab											◆ 30.08.2022					
MS14	Installation second U200 Modulator SATUN04											◆ 30.08.2022					
MS15	Laser aligned in 2nd transfer line + optical setup in tunnel												◆ 15.11.2022				
MS16	Installation 2nd EEHG chicane												◆ 15.11.2022				
MS17	First slicing in 2nd EEHG Modulator												◆ 01.12.2022				
MS18	First EEHG Pulses with one laser													◆ 01.04.2023			

DUO Calendar

← Calendar of ATHOS from January to June 2022 →



Installation U200
Laser alignment
X band deflector (Polarix)

HERO Commissioning May – June 2022:

- Hardware commissioning with beam
 - U200
 - Diagnostics
- 1st laser / beam overlap (Polarix)

If Photon Beam Stopper OPEN
=> Athos End Stations must be in LASER MODE !

Shift types

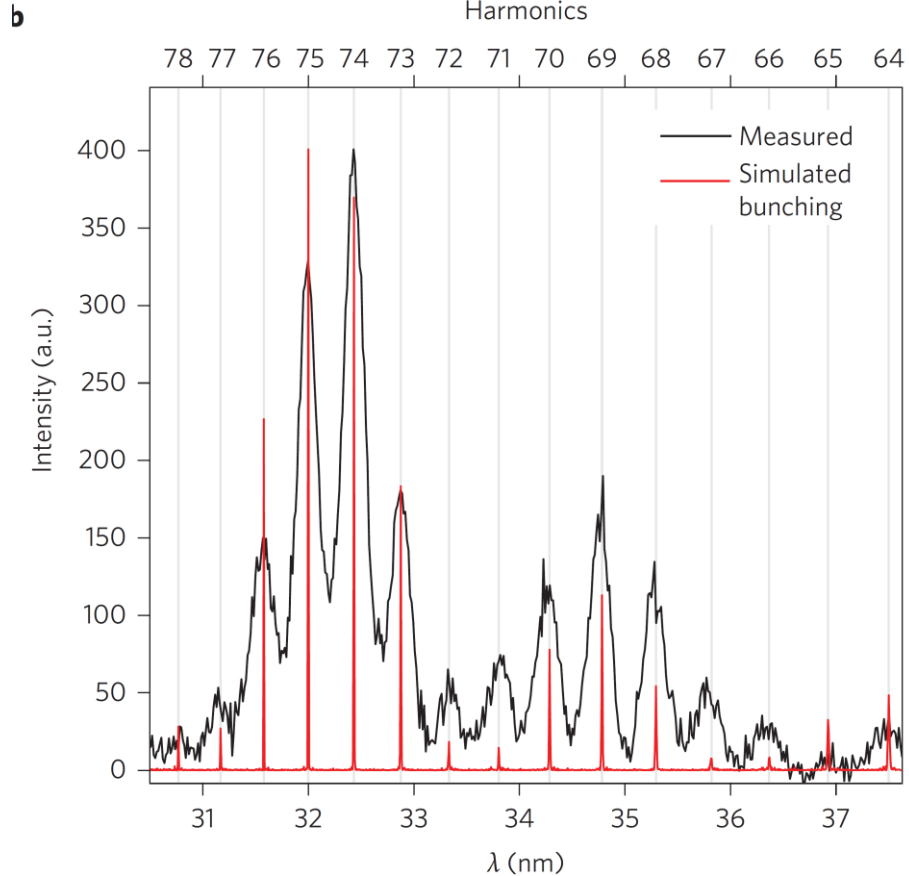
- Machine start-up / FEL set-up
- Beamline development
- Machine development
- Scheduled

- HERO is an EEHG scheme to be implemented in SwissFEL Athos
 - Goals:
 - shorter gain length (higher peak currents)
 - shorter pulses (slicing effect of seed laser)
 - more longitudinal coherence (seed laser periodicity)
 - higher spectral brightness (smaller energy spread of lasing electrons)
 - more stability (synchronization with seed laser)
 - First Step: Slicing and compression planned for Summer 2022
 - EEHG first tests planned for Summer 2023
 - Budget of EEHG: 4.8 MCHF (3.9 MCHF already invested)



- End

EEHG Sources / Experiments example

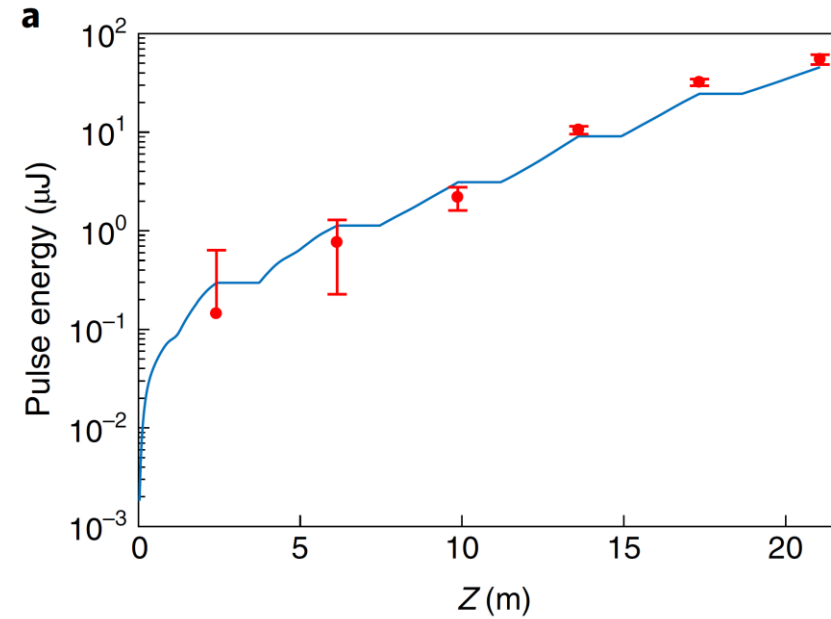


2400 nm -> 32 nm

Hemsing et. al. in NATURE PHOTONICS | VOL 10 | AUGUST 2016 512 |



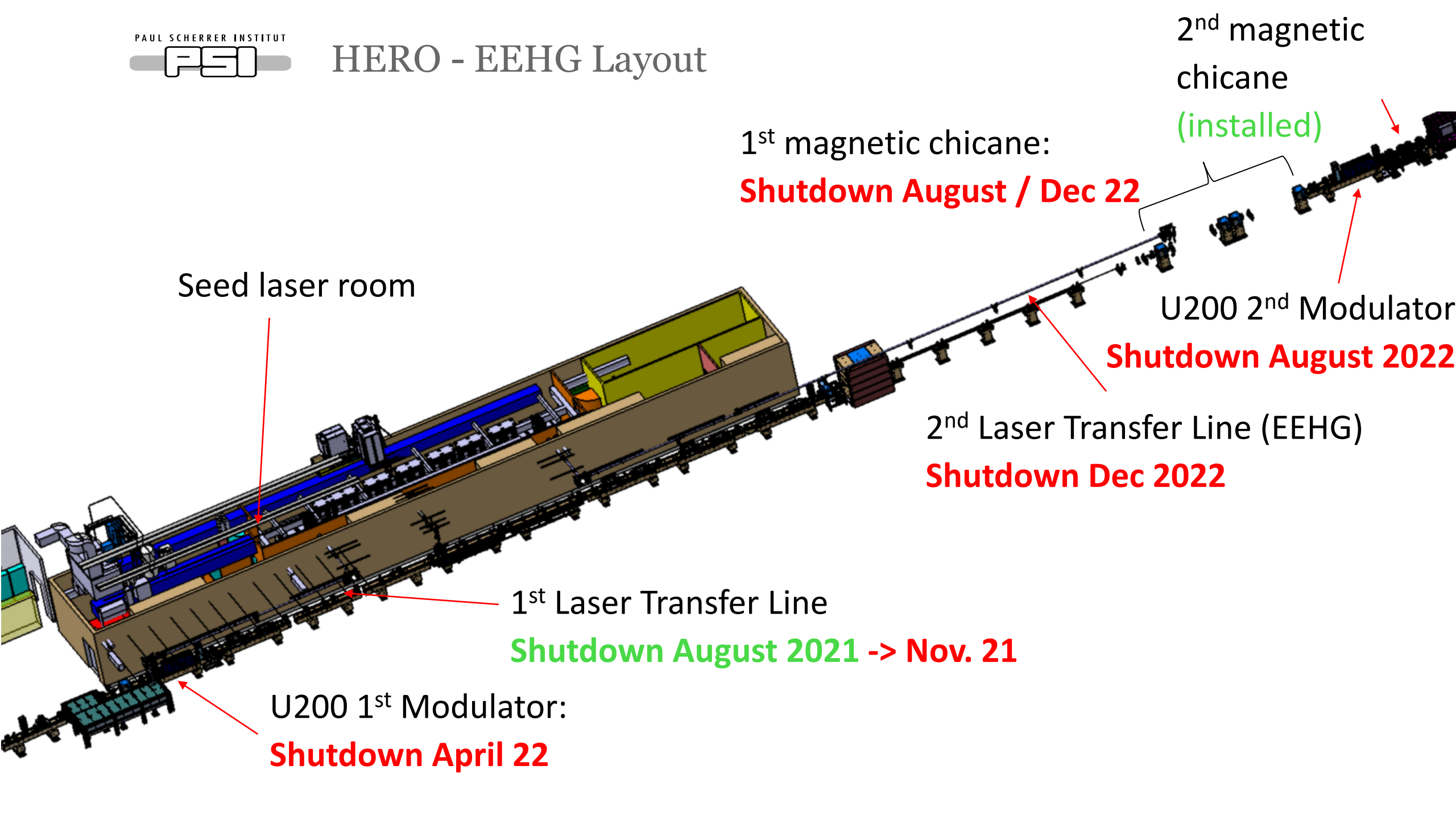
Promising technique towards fully coherent soft x-ray laser with increased spectral brightness and shot to shot spectral stability



264 nm -> 5.9 nm with FEL amplification

Ribič et. al. in Nature Photonics | VOL 13 | AUGUST 2019 | 555–561 |

HERO - EEHG Layout



Seed laser room

1st magnetic chicane:

Shutdown August / Dec 22

2nd magnetic chicane
(installed)

U200 2nd Modulator
Shutdown August 2022

2nd Laser Transfer Line (EEHG)

Shutdown Dec 2022

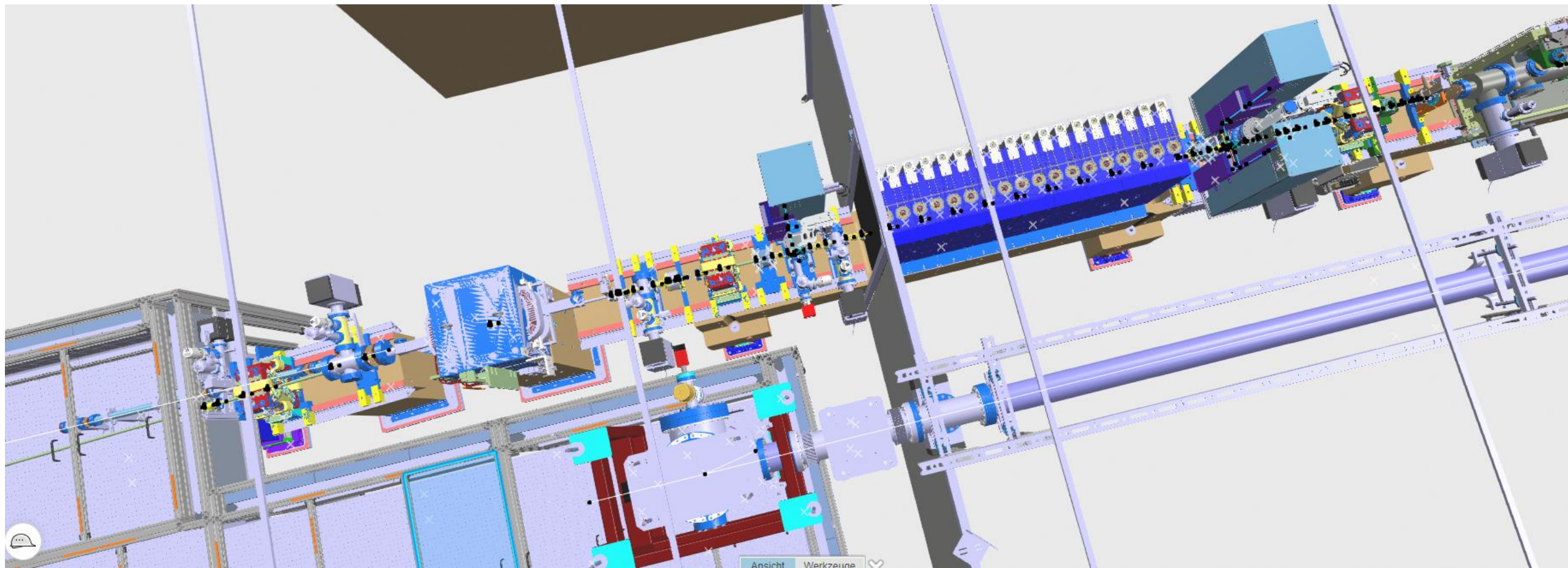
1st Laser Transfer Line

Shutdown August 2021 -> Nov. 21

U200 1st Modulator:

Shutdown April 22

- Outline:
 - Shutdowns
 - Seed laser and Laser Transfer Line (Alexandre)
 - U200
 - EEHG Chicane



Parameter Table

Parameter Table HERO & EEHG			
	Operating Value	Maximum Value	Comment
Electron Bunch Parameters			
Bunch Energy in GeV	2.9 -3.15 (1st modulator)	2.9 - 3.4	Athos linac is downstream first U200
Bunch duration in U200 HERO	50 fs rms		
Bunch duration in U200 EEHG	50 - 100 fs rms		
Bunch diameter in first U200	beta = 30m; 50 um rms		
Bunch diameter in second U200	beta = 15 m; 25 um rms		
Repetition rate	100 Hz	100 Hz	
Energy Spread (with Chirp) at first modulator U200	0.6 % rms		
Energy Spread (without Chirp) at second modulator U200	0.03 - 0.6%		
HERO - AFSS 4 Dipoles Chicane - SATUN05			
	Operating range	Max.	
Deflecting angle	0 - 1.55 deg.	1.55 deg (27 mrad)	
Transverse offset at central dipole		18.4 mm	
R ₅₆		849 um	
Delay in fs		1.41 ps at 3.15 GeV	
AFSS Magnet Length		311 mm	
AFSS Integrated field (T.m)		0.00191 T.m/A	BL=2865320.0 G.mm at 150 A
Chicane Total length		2.12m	
Maximum Current PS		150 A	
U200 Modulator			
Number of CHIC frames	1 - 8.5 full period	8.5	
Period Length	200 - 600 mm		
Vacuum Chamber Inner dimension - ovale (width *height)		16mm*8mm	outer height 9mm (8.5)
Vacuum Chamber Outer dimension - ovale (width *height)		17.2 mm * 9.2 mm	tolerance +/- 0.2
Modulator length (magnetic length)	1800 mm		
Minimum Gap between magnets	9.8 - 20 mm	9.8 mm	straightness; shimming
Magnet Block Br (NdFeB)	1.206 T	N/A	
Number of period	8 +2*0.5	N/A	
Magnet Block Length	50 mm	N/A	
K max	37 (gap = 10.2)		
resonant wavelength 1	800nm at K=24.7 and 3.15 GeV	N/A	795nm +/- 16nm
resonant wavelength 2	400nm	N/A	2nd harmonic
resonant wavelength 3rd harmonic	265 nm		also 266 nm with 795 nm
Phase synchronisation of 1st and 3rd harmonic	yes		phase slippage control
earth magnetic field correction	yes		
EEHG - AFBC3 4 Dipoles Chicane			
	min:	max:	
Deflecting angle	1.67	2.79 deg (48 mrad)	3.15 GeV
Transverse offset at central dipole	115 mm	193 mm	
R ₅₆	6.4 mm	18 mm	
Delay in fs	10.7 ps	30 ps	
AFBC3 Magnet Length	529.2mm	529.2mm	
AFBC3 Integrated field (T.m)	0.51267 T.m at 150A	0.51267 T.m at 150A	measured
Chicane Total length	9.15 m	9.15 m	

Laser Parameters for HERO at 800 nm / 266 nm			
Pulse duration	variable and <100 fs rms	min. 25 fs rms at 800nm	the pulse may be frequency chirped; min. pulse duration not cleared yet
Nominal wavelength	800nm / 266 nm		mix of both wavelength possible
Wavelength tunability around nominal wavelength	± 16nm / ±5.3 nm		
Maximum peak power on target	21.3 GW		0.5 mJ – 100 fs rms pulse at 266nm; 5 mJ at 800nm
Energy stability	<2% rms		Over 1000 shots
Repetition rate	1-100Hz		Match Rep. rate machine
Electron beam size on target	50 µm rms		
Laser beam radius on target	>350 µm rms		450 um if Rl=80cm
Rayleigh length	~50 cm		80 cm would be better
Relative temporal jitter electron-laser at laser output	<50 fs rms		Over 100 shots (CW link)
Relative temporal drift electron-laser on target	Stabilized as best as possible		Required laser arrival time monitor and active feedback
Polarisation	Linear, in plane of the modulator		
Remote controlled param.	Pulse energy, nominal wavelength, alignment on target		
Laser Parameters for EHHG at 266 nm			
Pulse duration	variable and <100 fs rms	min. 25 fs rms	pulse should be stretched from 50 to 100 fs rms (laser is chirped)
Nominal wavelength	266 nm		
Wavelength tunability around nominal wavelength	±5.3 nm		
Maximum peak power on target	21.3 GW		0.5 mJ – 100 fs rms pulse at 266nm
Energy stability	<2% rms		Over 1000 shots
Repetition rate	1-100Hz		Match Rep. rate machine
Electron beam size on target	50 µm rms		
Laser beam radius on target	450 µm rms		450 um if Rl=80cm
Rayleigh length	~50 cm		80 cm would be better
Relative temporal jitter electron-laser at laser output	<50 fs rms		Over 100 shots (CW link)
Relative temporal drift electron-laser on target	Stabilized as best as possible		Required laser arrival time monitor and active feedback
Polarisation	Linear, in plane of the modulator		
Remote controlled param.	Pulse energy, nominal wavelength, alignment on target		
Options	2 pulses		with fixed delay
Options	2 pulses		phaselocked; variable intensity

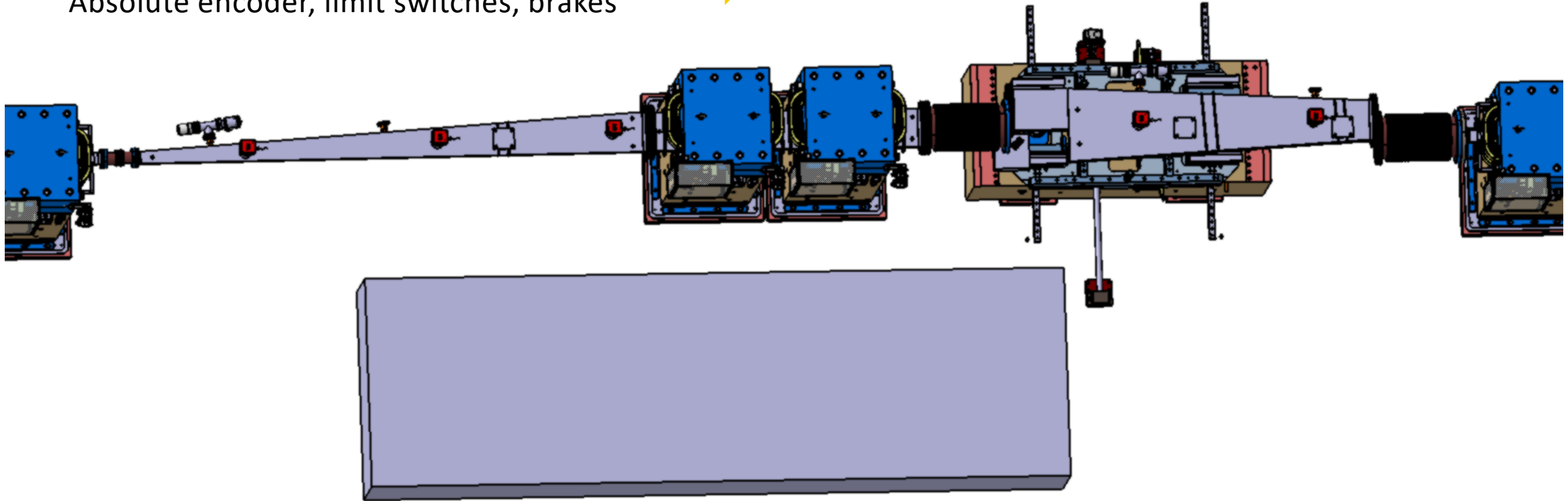
Motion Specification for EEHG Chicane

2 phase stepper motors

Absolute encoder, limit switches, brakes



Beckhoff Control unit (M. Bruegger)



- Moving range: 100 mm (translation in X)
- Two operating positions: IN or OUT
- Position IN should be precise (100nm reproducibility) because it moves a mirror to couple a laser beam into the Athos axis.
- Speed: > 1mm/s
- Frequency of motion: one motion per day in average

- **Outline:**
 - Shutdowns
 - Seed laser
 - **U200**
 - EEHG Chicane



- Outline:
 - Shutdowns
 - Seed laser
 - U200
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Detailed timeplan

Mitte Dezember	Erste Laser Licht im Seed Laser Labor	Laser Group	
December 2021 - Dez 22	Maschinenbau Sicherheit Analyse fur EEHG motorisierte Schickane	R. Ganter / E. Zehnder / W. Rendler	
Jan-22	Lieferung geklebte Hitachi Magnets (U200#1) im Keeper	T. Schmidt; Arnold Magnetic	4 Block / Rahme (32 Bloecke) eventuell Teil Lieferung
31/12/2021	Milestone: Laser Installation in Seed Laser Room completed	Laser Group	
23.12.2021-12.01.2022	Aufbau Boden Platten fur EEHG Laser Tisch & EEHG Schickane Mover; Platten: Bohren und giessen	Hallendienst + Vermessung	Bodenplatteam PSI; + Hilfswerkzeug; Bohrplan?
23.12.2021-12.01.2022	Fertig Aufbau Laser Transfer Linie an die Decke im Tunnel (pumpen ...)	Hallendienst + Vakuum	Neue Zeichnungen .Koordinaten und Montage Plan
23.12.2021-12.01.2022	Installation housing and shielding HERO Tunnel Laser Table	Laser Group +Hallendienst	soll koordiniert werden mit Vakuum Laser Einkoepplun
12.01/2021	Milestone: Laser Transfer Line HERO Installed	Laser Group + Vacuum + Hallendienst	
01/02/2022	Milestone: U200 Modulator assembled and magnetically characterized	ID Group	
bis Ende Januar	Vormontage Diagnostic Komponenten + Mirror test im Undulator Labor (HERO + EEHG)	P. Juranic / M. Baldinger / B. Rippstein	Zutritt an Labor - Unten Staub Geschuetzt
Ende Januar bis Maerz	Bestellung Langlaefer (Granit, Fuhrungen, ...) fur EEHG motorizierte Supporte	G. Kotrle / AVOR	
bis Ende April	Camera Server Software for seed laser room	S. Foeira	Verkabelung???
bis Ende April	Installation Controls HW (VME, Wago, Motor Control M force Motor, Timing Patchen; Network Patching) for Laser Components in L3.140	K. Bitterli, T. Celcer, E. Divall	Kurt wird es im sept / okt installieren ; Network Switch
23/24 Feb. Shutdown	HERO Laser Transfer Line: Laser alignment justierung vom Spiegel mit gespeertes Tunnel; Pumpdown Laser Pipe	Laser Group, Vacuum	Tunnel Gesperrt fur andere Gruppe
bis Ende Februar	Montage 9 CHIC Rahmen mit geklebte Magnete im OTLA	AIK / S. Danner	Arnold wird erste Lieferung Anfang Januar machen => P
bis Ende Februar	Bestellung second Laser Transfer Line (EEHG)	G. Kotrle / P. Klopfer/ AVOR	
Anfang Maerz	Montage 9 CHIC Schickanen auf Girder + Beckhoff Kontroll	S. Danner + Vermessung + Elektriker ? (D. Knill)	Guenter Kolb fur Mobilev ?
bis Ende Maerz 2022	Shimming (Motor) & Magnetische Measurements of U200 (4 weeks)	M. Calvi / ID group	U200 will be measured with all CHIC assembled (not inc
21 Maerz	Vormontage U200 Girder Diagnostic Komponenten auf dem Girder im Undulator Labor + Quad + Vacuum	Diagnostic; Andreas; Karsten; Vacuum	Laser diode fur Vorjustierung
Maerz 2022	Delivery of Hitachi Magnet EEHG for second U200 Modulator	S. Danner	Rahmen fur zweite Modulator
Maerz - Juni 22	PSYL_L fur Labor Seed Laser Raum firma PILS (Installation und Test)	Alexandre; ASI;H.-J. Oehler; E. Huessler	Elektroschema ist bereit, HW muss bestellt werden
Maerz - Juni 22	Test Laser Room Safety - Interlocks - Laser Warnung Lamp	Alexandre; ASI; S. Mueller; E. Huessler	braucht detail Diskussion; Technische Spezifikation ??
??	PSYS_L fur Tunnel (Vorrang, Photon Shutter)		
August- Maerz	Konstruktion EEHG 4 Dipolen Schickanen Motorisierte System	P. Klopfer / S. Pfinninger / G. Kotrle	Mechanische bewegbar Vakuum Kammer basiert auf B
Ende Maerz	Transport U200 Girder ohne Vibration mit Anhaenger	Transport Dienst	
April	Montage 9 CHIC Rahmen mit geklebte Magnete im OTLA fur second EEHG girder	AIK / S. Danner	
04.04 bis 27.04 Shutdown	Montage Kufwasser Leitung EEHG Schickane und Anschliess von Speisegeraet	Wasser Group	
04.04 bis 27.04 Shutdown	Abbau SATDI01 Girder und Aufbau U200 girder im Tunnel	Vacuum Gruppe + Lars Binder+ Vermessung	ICT muss von alte zu neue Girder im Tunnel waehrend S
04.04 bis 27.04 Shutdown	HERO Laser Transfer Line: justierung innerhalb U200	Laser Gruppe	Tunnel muss auf Laser Modus sein und auch Maloja und
30/04/2022	Milestone: Laser aligned in transfer line + optical setup in tunnel	Laser Group	
30/04/2022	Milestone: HERO U200 Modulator girder installation (with diagnostic)	Diagnostic + Vacuum Group	
May 2022 -	Vormontage 2nd Girder Modulator U200 (EEHG) in Undulator Labor + Montage Schickanen auf Girder + Beckhoff Kontroll	S. Danner + Vermessung + Elektriker ? (D. Knill)	
Juni 2022 .	Shimming (Motor) & Magnetische Measurements of U200 (4 weeks)	M. Calvi / ID group	U200 will be measured with all CHIC assembled (not inc
Sommer 2022	Vormontage Motorisierte Support System EEHG	AIK - OTLA Werkstatt	Einheit ist aehnlich wie BC1 support
Sommer 2022	Vormontage AFBC3 Granit Block EEHG und motorisierte System		
21/06/2022	Milestone: First Slicing - End of HERO phase of Project	Beam Dynamics, Laser	Important milestone for the European Grant of th
	Apero		