Hans-H. Braun on behalf of the SwissFEL team :: Paul Scherrer Institut

SwissFEL C-band Linac and S-band Linac for FERMI

FCC week'19

Brussels, 25th June 2019

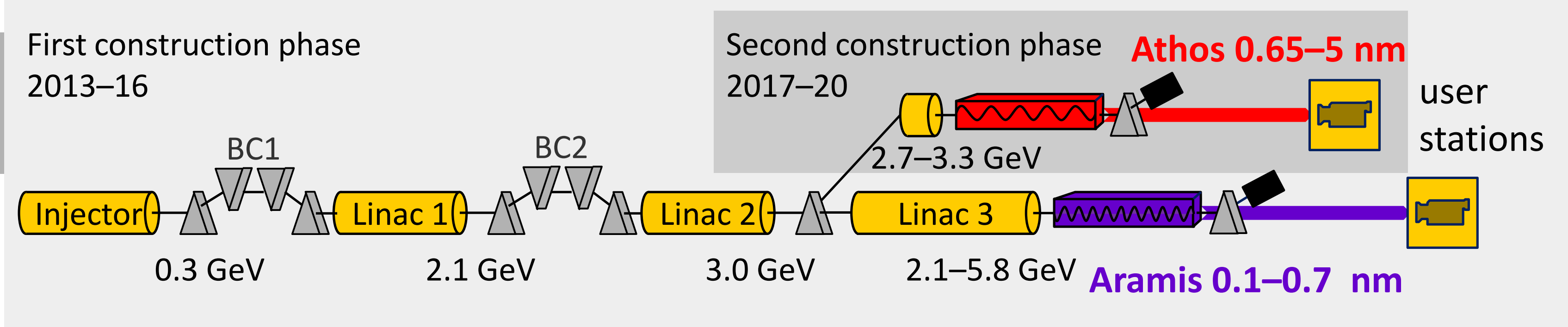
SwissFEL Overview (I)

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2018

Regular user operation since Jan. 2019

Main parameters:

Photon wavelength: 0.1–5 nm

Photon energy : 0.2–12 keV

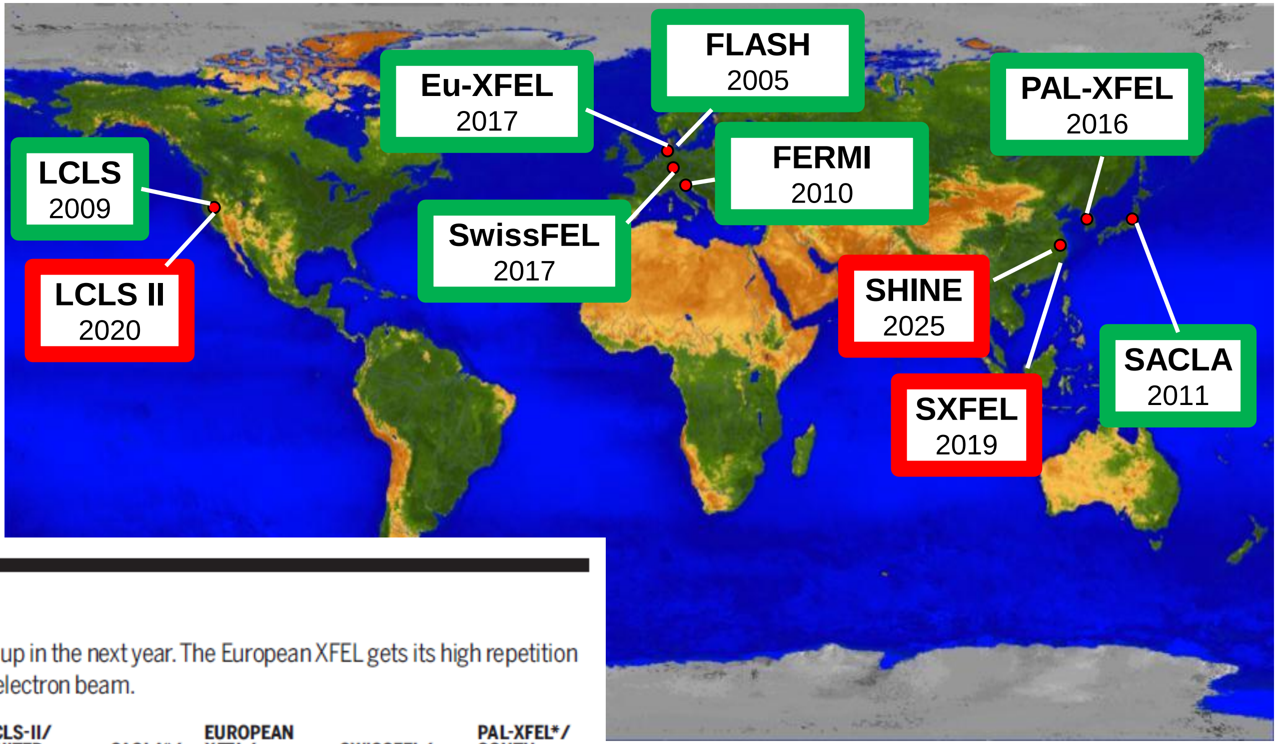
Pulse duration : 1–20 fs

Electron energy : up to 5.8 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

Short wavelength FEL user facilities



Going great guns

Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

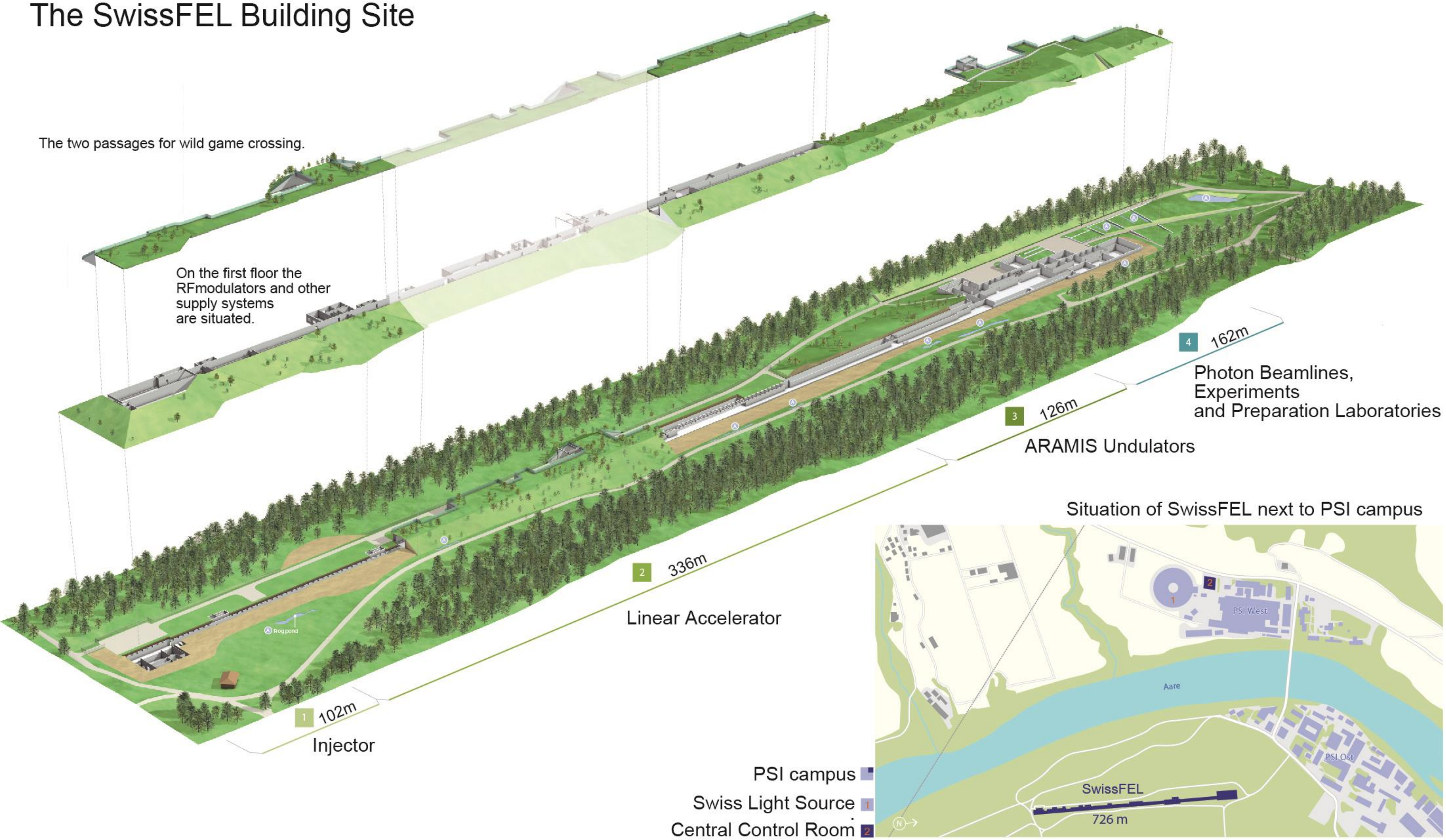
NAME/COUNTRY	LCLS/ UNITED STATES	LCLS-II/ UNITED STATES	SACLA*/ JAPAN	EUROPEAN XFEL/ GERMANY	SWISSFEL/ SWITZERLAND	PAL-XFEL*/ SOUTH KOREA
Date of first x-rays	2009	2020	2011	2017	2017	2016
Cost (in U.S. millions)	$415	$1000	$370	$1600	$280	$400
Number of instruments	7	9	8	6	3	4
Max. electron energy (GeV)	14.3	4.5	8.5	17.5	5.8	10
Min. pulse duration (femtoseconds)	15	15	10	5	2	30
Pulses per second	120	1,000,000	60	27,000	100	60

*SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser

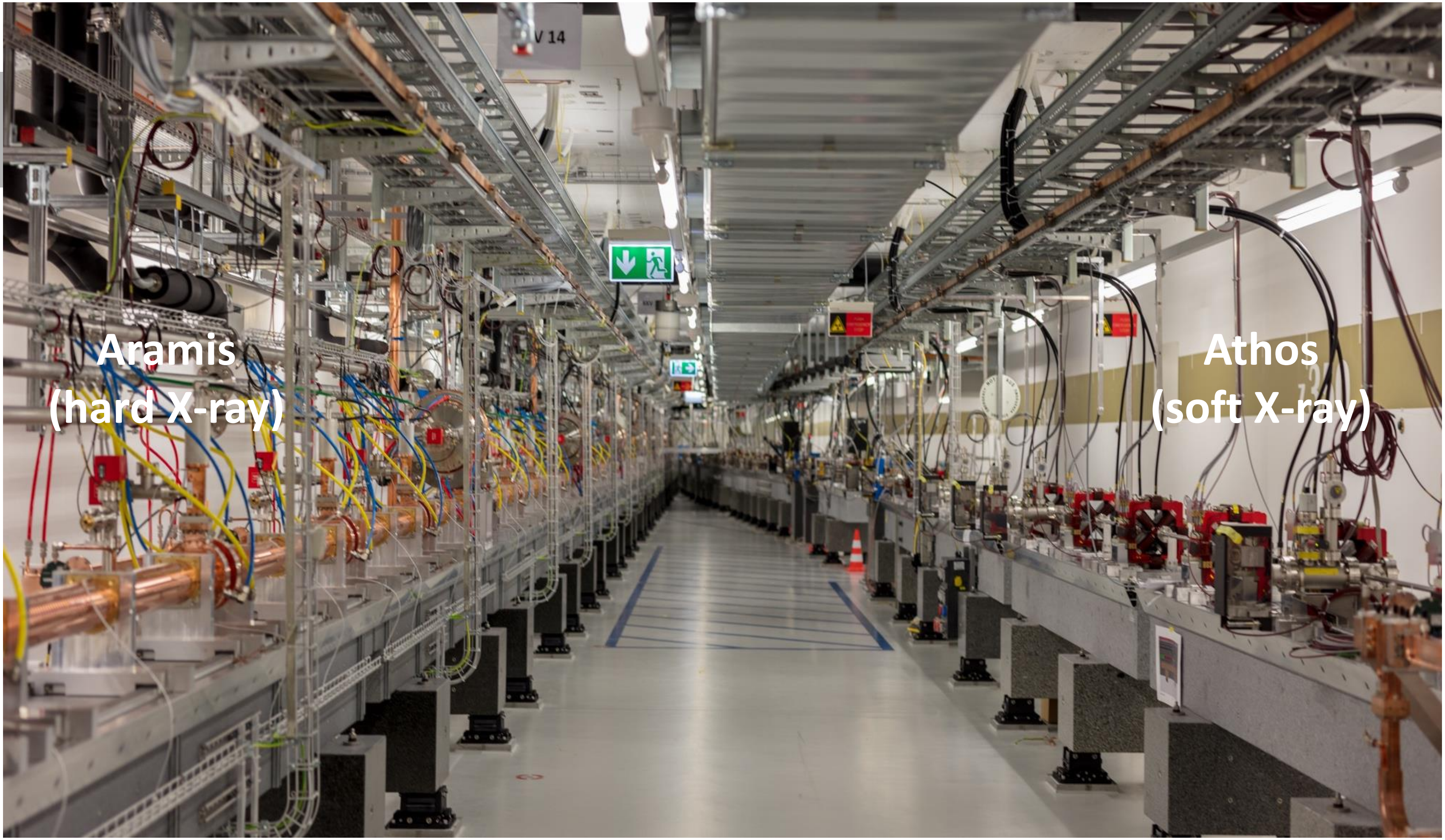
sciencemag.org SCIENCE

SwissFEL Building

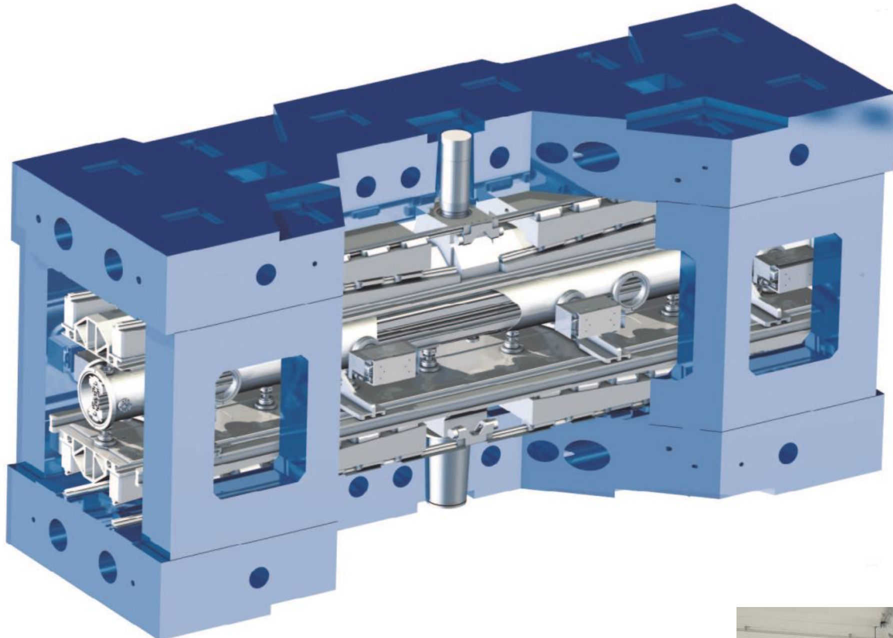
The SwissFEL Building Site



SwissFEL Overview (II): Aramis and Athos



SwissFEL overview (III): Aramis Undulator



- In-vacuum, variable-gap undulators
- **Undulator period 15 mm**
- Nominal gap 4.5 mm for K = 1.2. **minimum gap 3 mm** for K=1.8
- Array of 1060 permanent magnets (NdFeB with diffused Dy) per module
- 13 modules of 4 m length
  - Total length 65 m
  - Active length 52 m

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SwissFEL Overview (IV): Experimental Areas

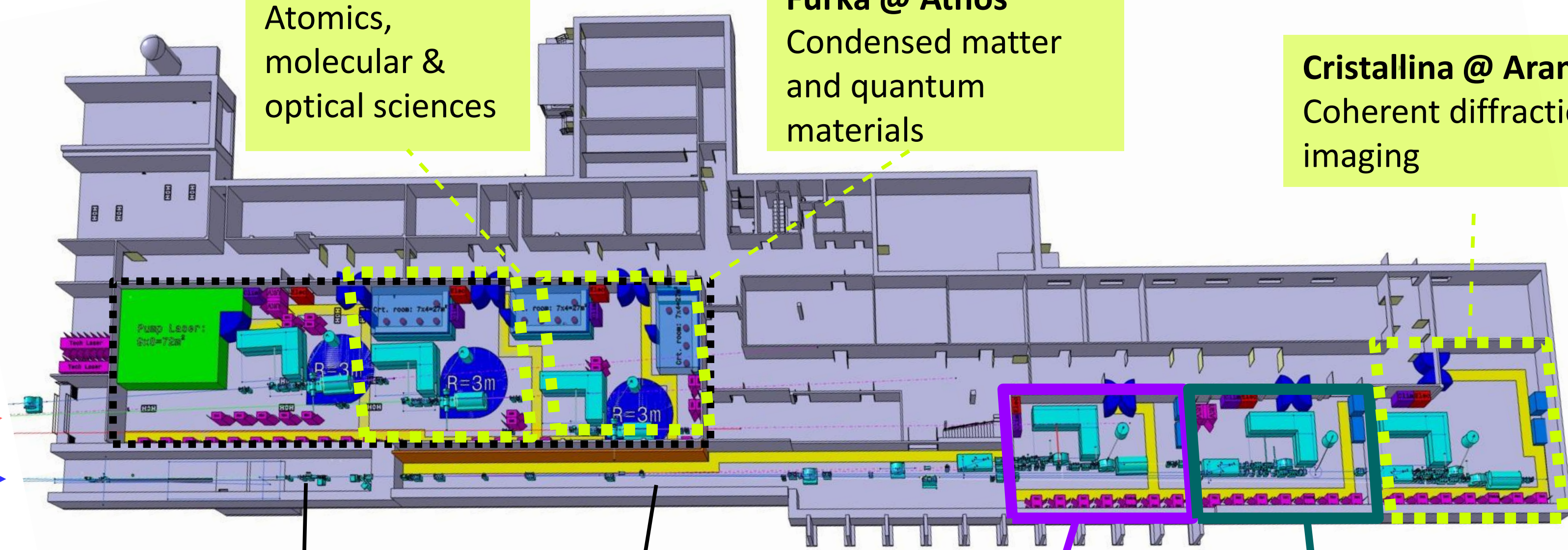
Majola @ Athos
Atomics, molecular & optical sciences

Furka @ Athos
Condensed matter and quantum materials

Cristallina @ Aramis
Coherent diffraction imaging

Athos FEL

Aramis FEL



Aramis front end

Aramis optical hutch

Alvra @ Aramis
- Multipurpose pump-probe
- Ultrafast biology and chemistry

Bernina @ Aramis
- Pump-probe crystallography
- Ultrafast dynamics in solid matter, strongly correlated systems
- Structural biology (MX – macromolecuar crystallography)

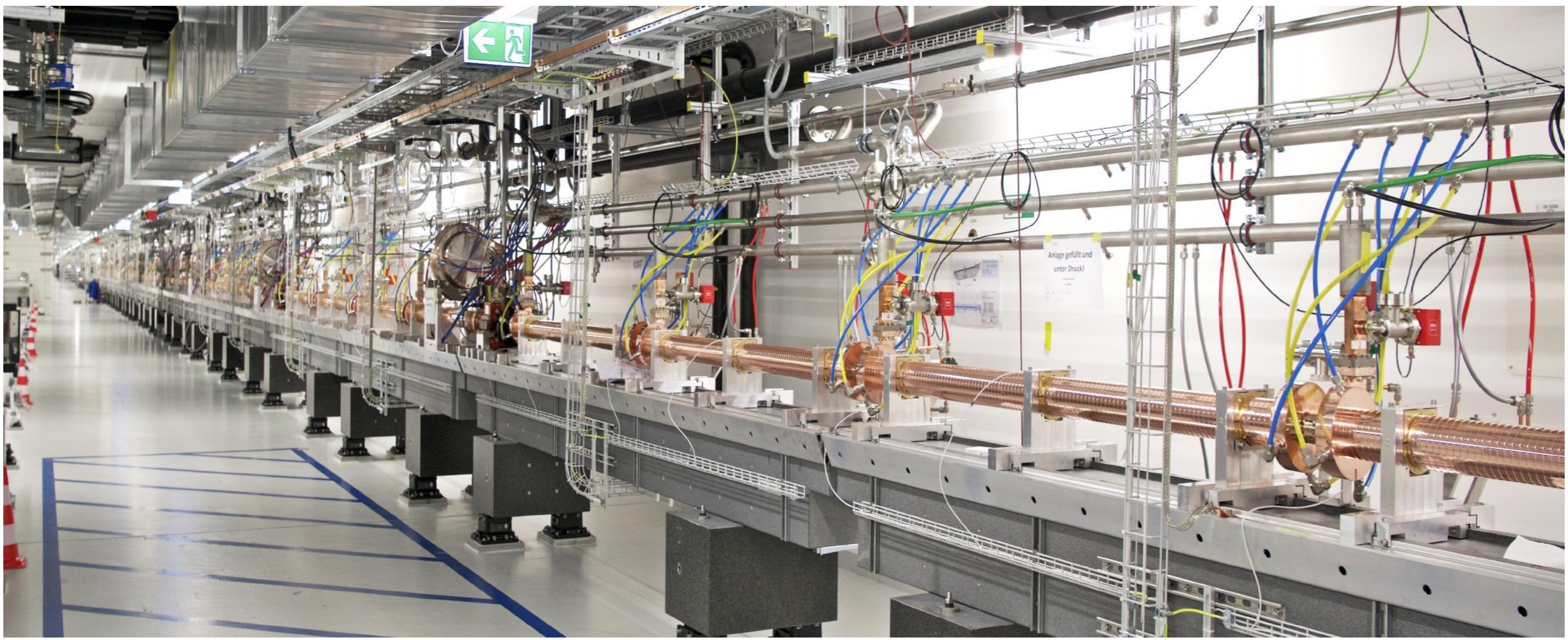
Alvra and Bernina
- Pilot user experiments in 2018
- Regular user operation since January 2019

Athos stations: first users in 2021

Cristallina @ Aramis: first users in 2022

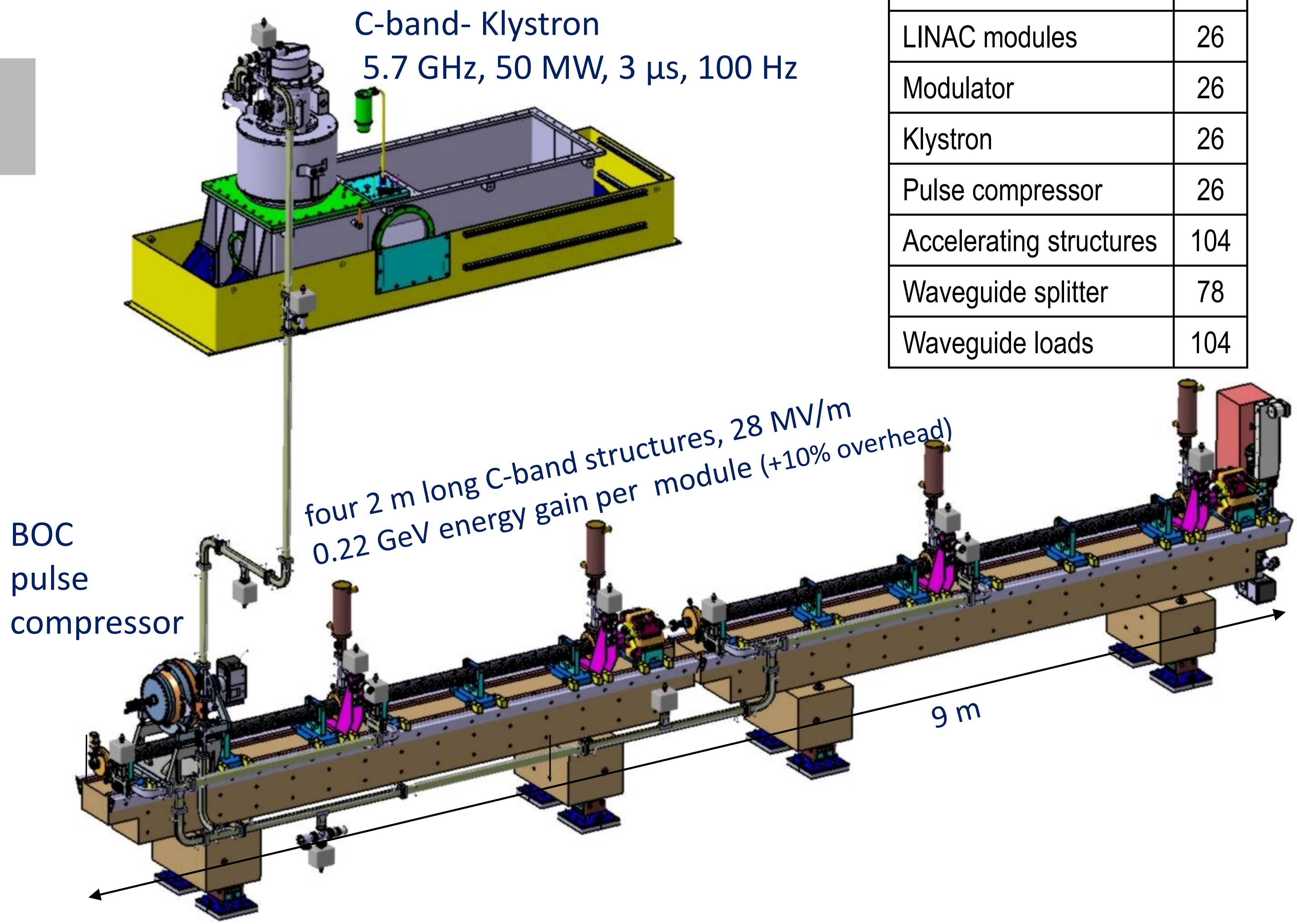
SwissFEL C-band Linac

- **26 modules of 4 x 2m structures**
- All modules running at 100 Hz
- Currently operating at a total energy of up to **6.0 GeV** with 25 modules
  (0.3 GeV from injector, one module as hot spare)



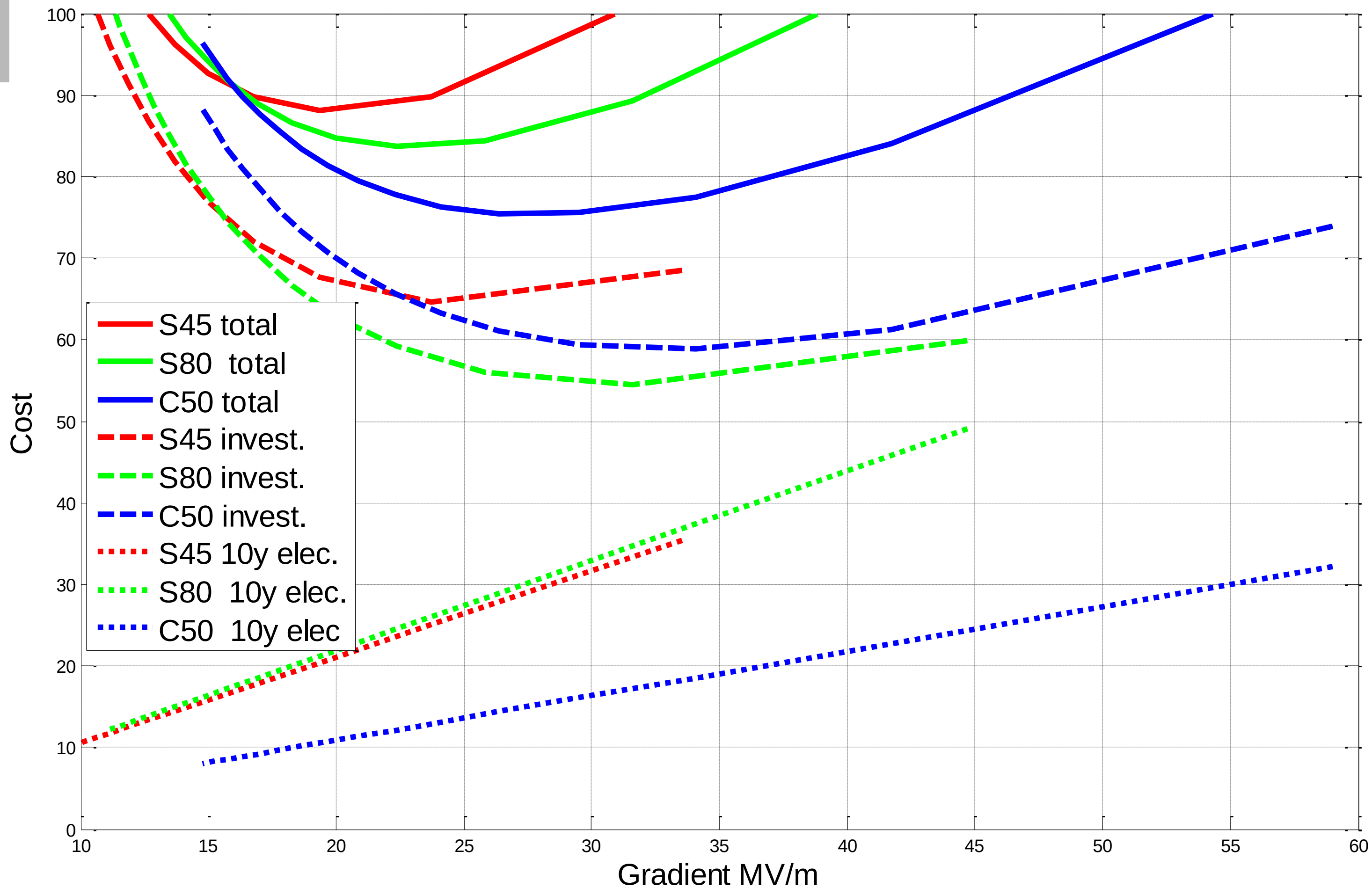
SwissFEL Main Linac building block

Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104



Linac cost optimization for SwissFEL

Cost vs. gradient for S-band with 45 MW klystron,
S-band with 80MW klystron
and C-band with 50 MW klystron



Advantage of C-band is in real-estate needs and electricity consumption

Production principles for SwissFEL Linac

Cups, couplers and pulse compressors produced with UP machining and metrology
→ on tune, no tuning provisions, no tuning procedures

Automated stacking procedure for optimum reproducibility

Vacuum brazing of full stack in one brazing step

No cleaning procedure after brazing but clean conditions throughout production, measurement and assembly

Structure acceptance tests:

- Network analyzer measurement with bead-pull
- Vacuum and water tightness

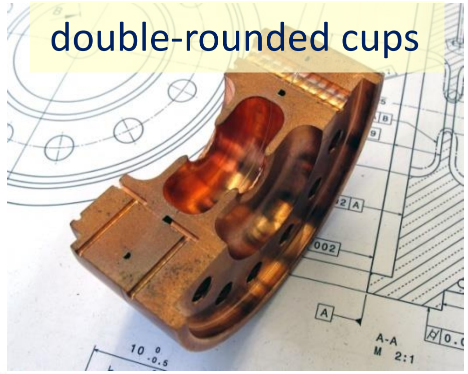
No vacuum bake-out
→ Avoids mechanical stress, misalignment and deformation of structures and waveguides.
Simplifies mechanical and vacuum design.
Reduces cost.

Linac module integrates waveguide distribution and RF pulse compressor
→ Pre-assembly in clean conditions outside tunnel, only beampipe and waveguide between girders need to be connected in tunnel.

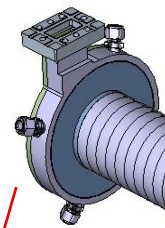
All RF power conditioning in final location. Reduces cost.

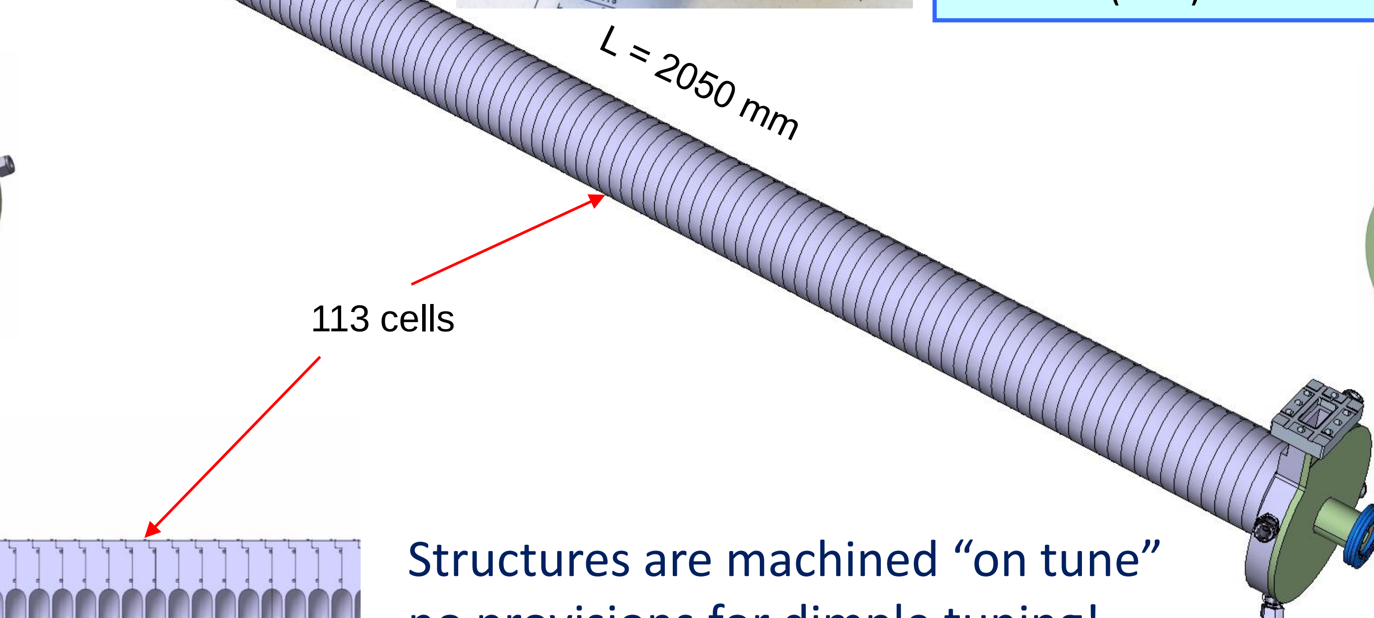
C-band structure

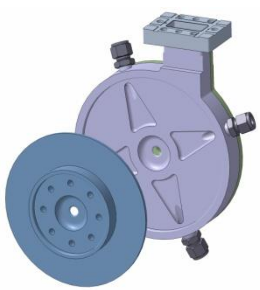
Specifications:	
Phase adv.	2π/3
Filling Time:	322 ns
vg/c:	3.10% - 1.19%
R/Q:	7.23 kΩ – 8.70 kΩ
Q:	10035 - 9950
Iris radius (20°C):	7.244 mm – 5.436 mm



J-Coupler input

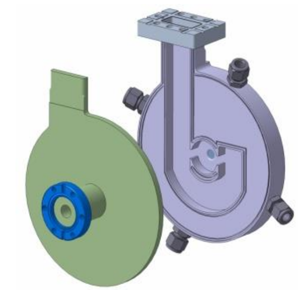


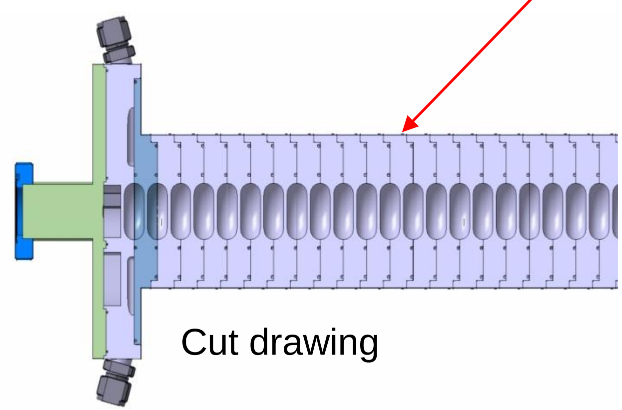




L = 2050 mm

113 cells





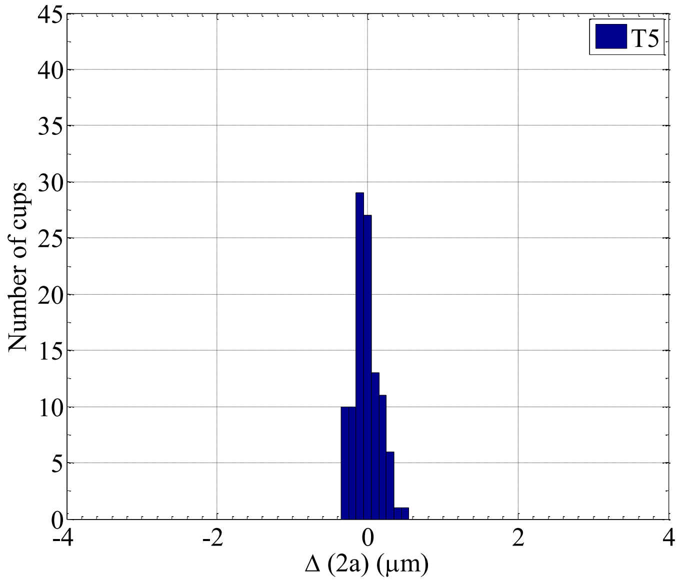
Cut drawing

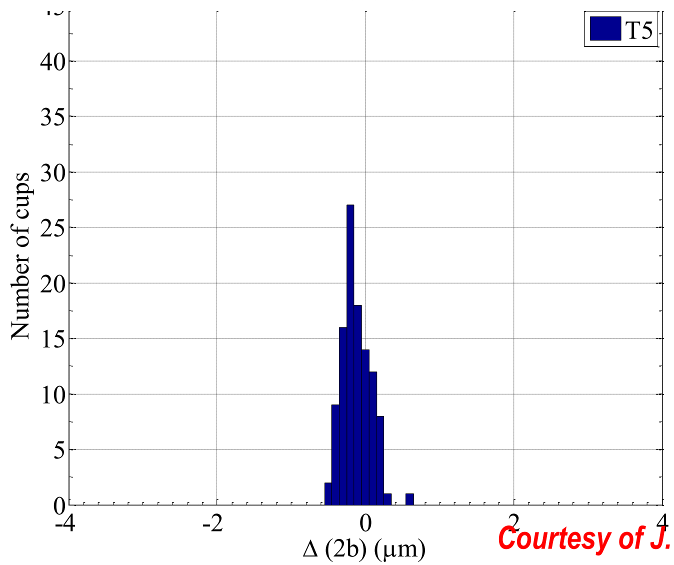
Structures are machined "on tune"
no provisions for dimple tuning!

J-Coupler output

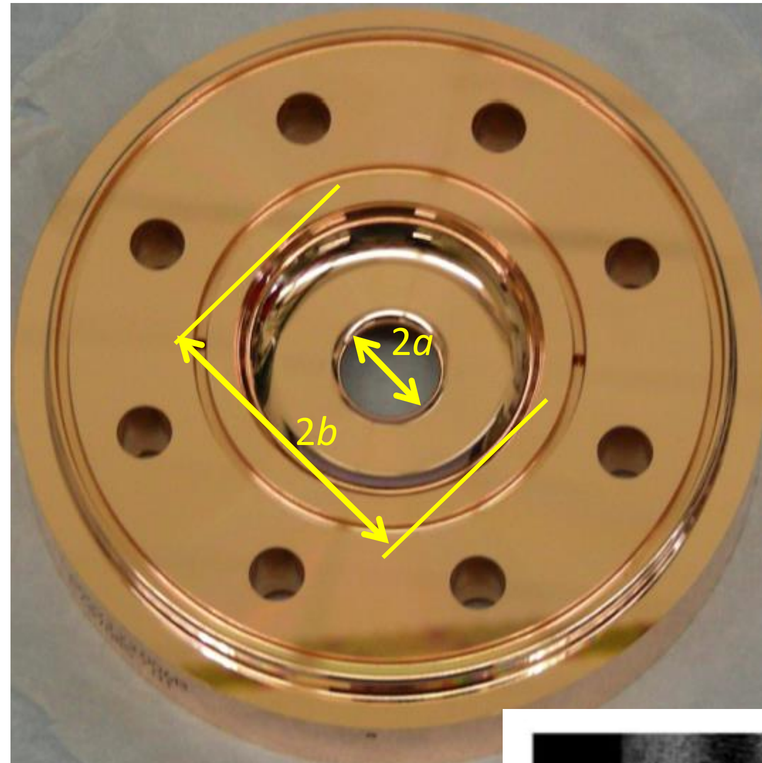
cooling

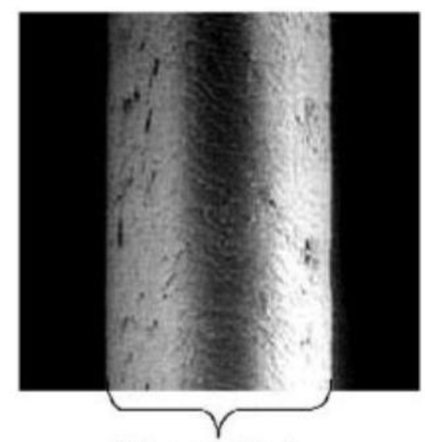
Achieved precision at VDL-ETG-Switzerland





Courtesy of J.Y. Raguin

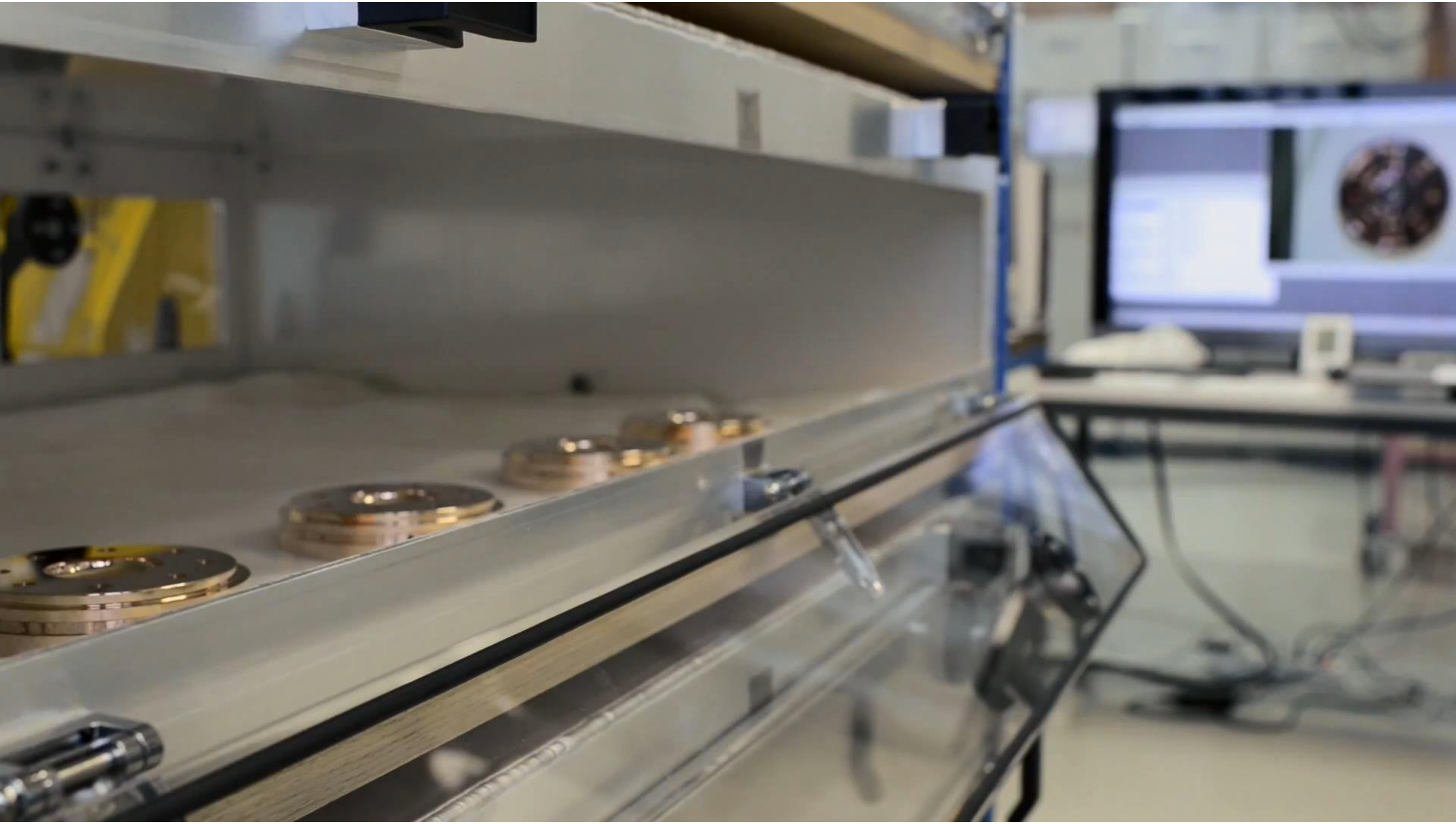




Human Hair
(60 μm diameter)

Typical examples of metrology on a structure: on top histogram iris diameter ,
on bottom histogram iris cell diameter

Stacking of C-band structure



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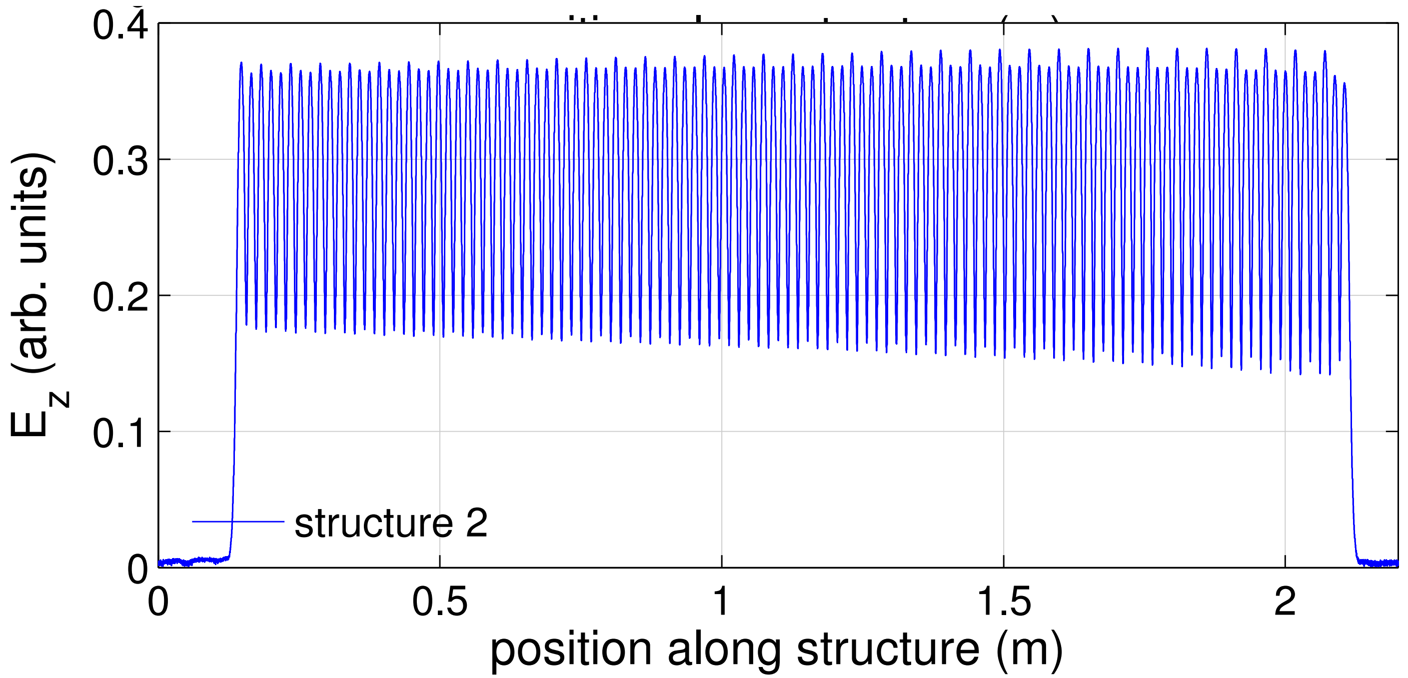
C-band structure after brazing

High temperature ≈ 900^0C
vacuum brazing with silver alloys

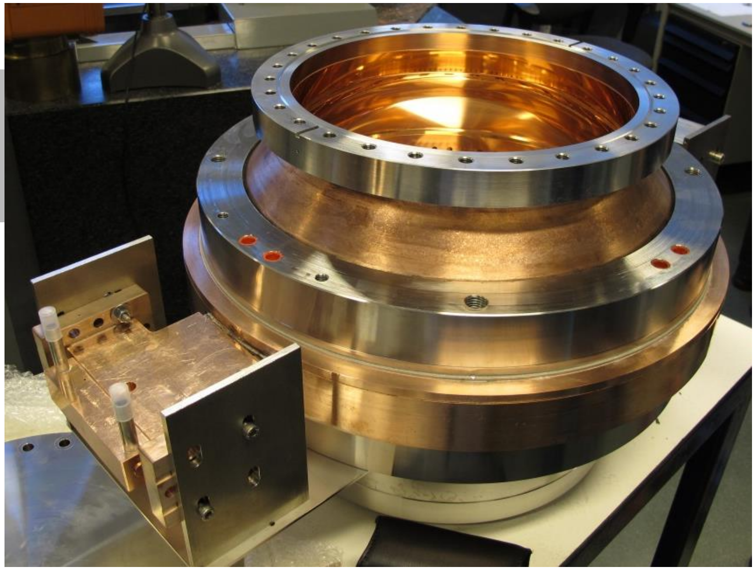
PINK vertical furnace
for structures with L ≤ 3m

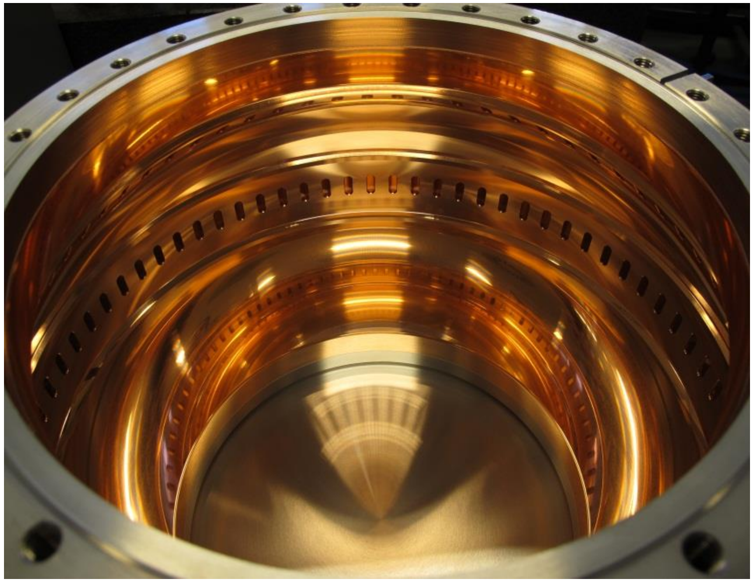
C-band structure: longitudinal field distribution from bead pull

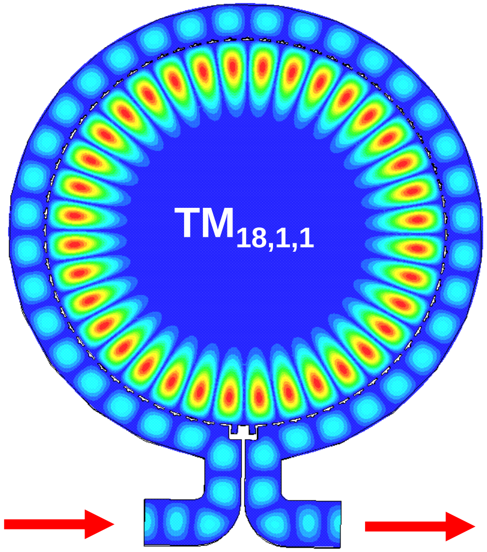


BOC Pulse compressor

whispering gallery mode







RF design:

- ✓ Single cavity
- ✓ Whispering gallery mode with analytical solution
- ✓ intrinsic high Q>200000

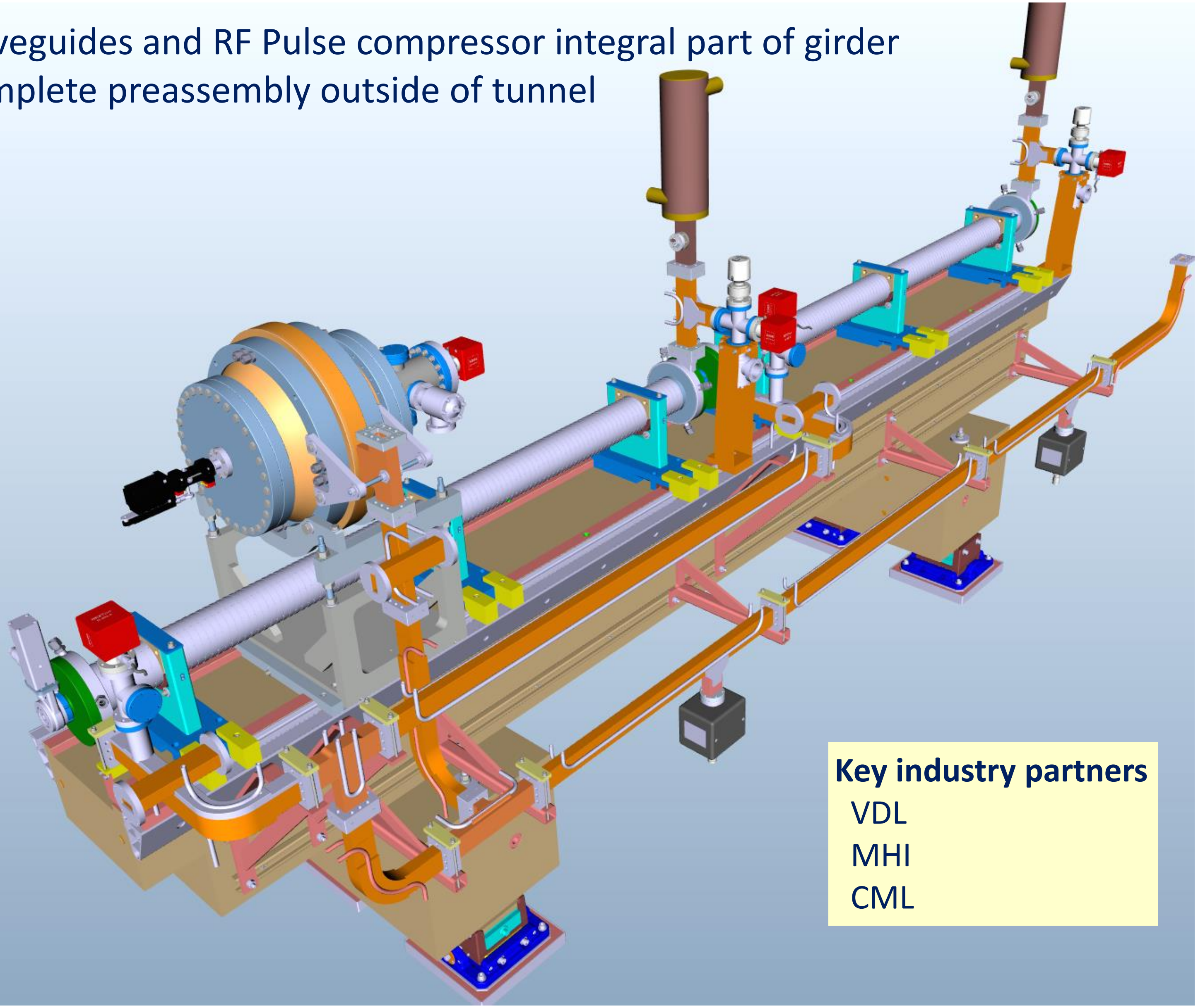
Mechanical design:

Simple and robust design:

- ✓ Inner body from a single piece
- ✓ Two brazing steps
- ✓ Machined on tune

Linac girder

Waveguides and RF Pulse compressor integral part of girder
⇨ complete preassembly outside of tunnel



Key industry partners
VDL
MHI
CML

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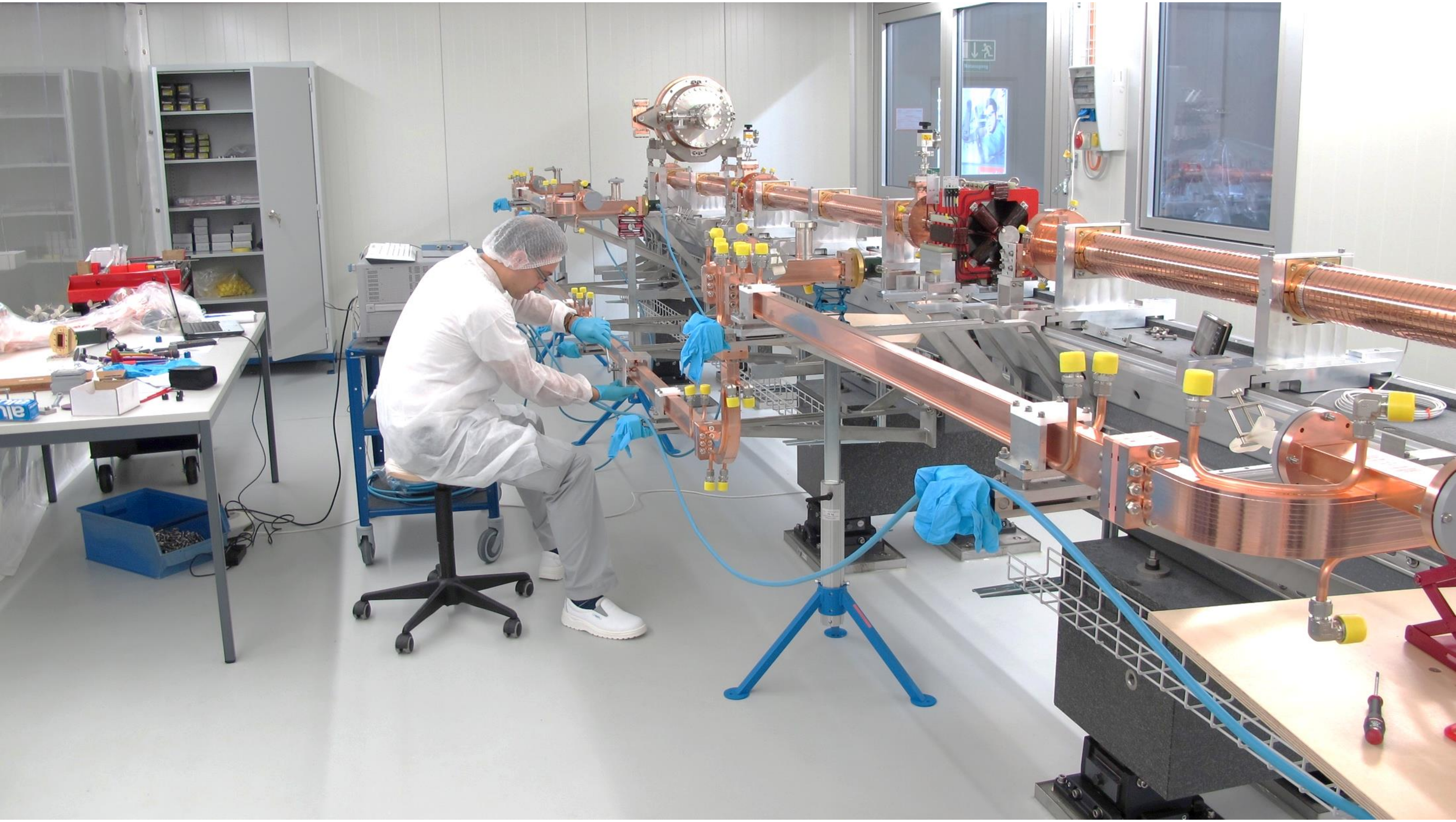
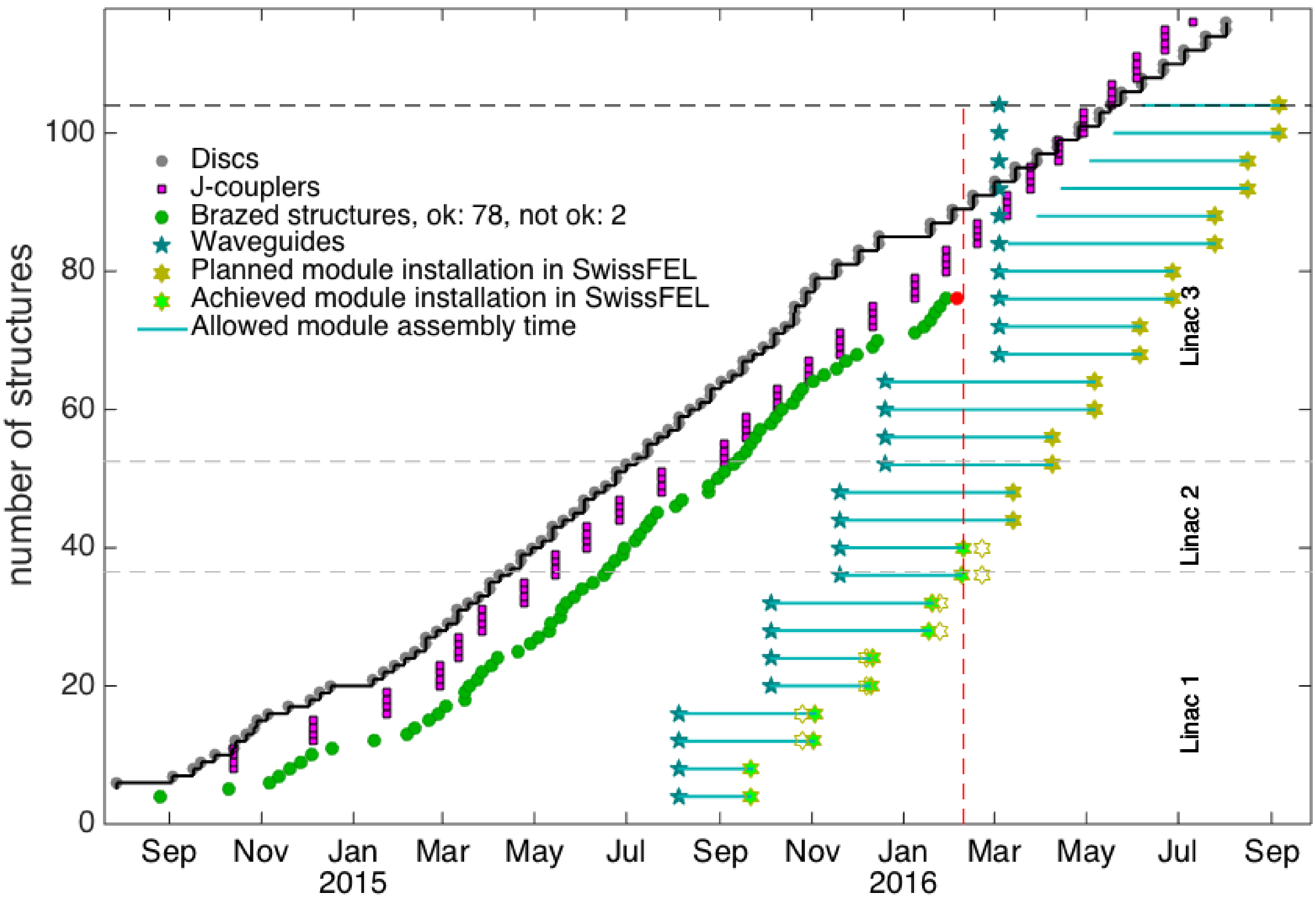
C-band module assembly



Installation and tuning of waveguides (waveguides delivered from MHI-MS)

Two year Linac production and assembly schedule



Results of C-band structure production

116 structures have been produced

104 structures are presently in operation

4 more Structures will be used in ATHOS FEL for fast energy scans

All structures passed low power acceptance test

So far no structure has failed during high power conditioning or operation

Structure straightness is excellent (≈ 10-20 µm)

Field flatness (measured with bead pull) is excellent

Normal operation is at 100 Hz, 28-32 MV/m (limited by RF power)

Typical RF power conditioning time of one module ≈ 1 month

Breakdown rates after conditioning are very low
One (first) structure was tested up 52 MV/m with $2\cdot10^{-6}$ breakdown rate
(one breakdown every 83 min)

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RF Structure activities with SwissFEL production protocol since completion of SwissFEL production

Activity	Collaboration	Goal
Two X-band (12GHz) structures for CLIC high gradient testing	PSI, CERN	Performance comparison of SwissFEL and CLIC production protocol
Five X-band deflecting structures	PSI, DESY, CERN	femtosecond scale beam diagnostic for FELs and novel accelerators
S-band short demonstrator and 3m S-Band structures	PSI, FERMI FEL at ELETTRA/ Trieste	Replacement of aging 6m BW structures with structures of ≥30MV/m at low BD-rate

Engineering | Lancaster University

Xbox-2: T24PSI N1/2

Courtesy of Lee Millar, CLIC week 2019

Overview:

- "Tuning free" technology.
- Manufactured by The Paul Scherrer Institute (PSI) using the same production line as SwissFEL.
- Allowed opportunity for a comparative study between the vacuum brazed technology applied by PSI to the diffusion bonding, which is presently used by CERN for CLIC structures.

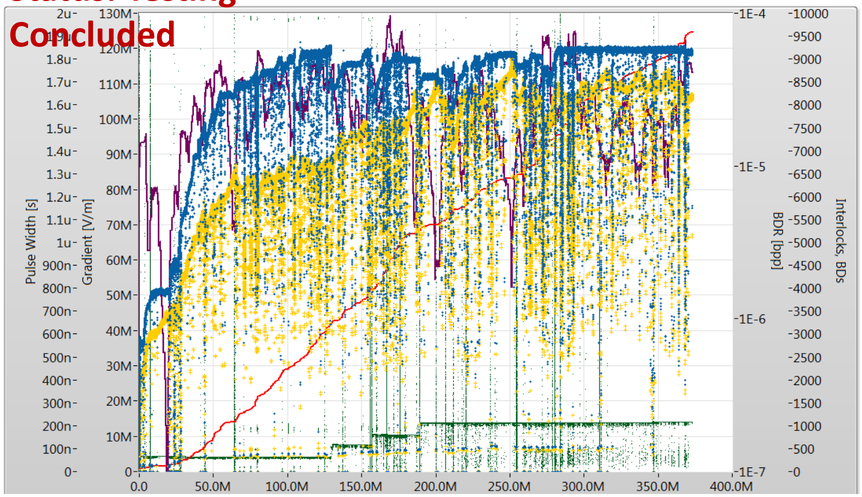
T24 PSI N1 (left):

- Reached 120MV/m at 200ns pulse length during testing.

T24 PSI N2 (right):

- Ran long term at different pulse length and gradients to investigate BDR dependencies (more on this later).
- Ran at 103MV/m for over 3 days uninterrupted without a BD

Status: Testing Concluded



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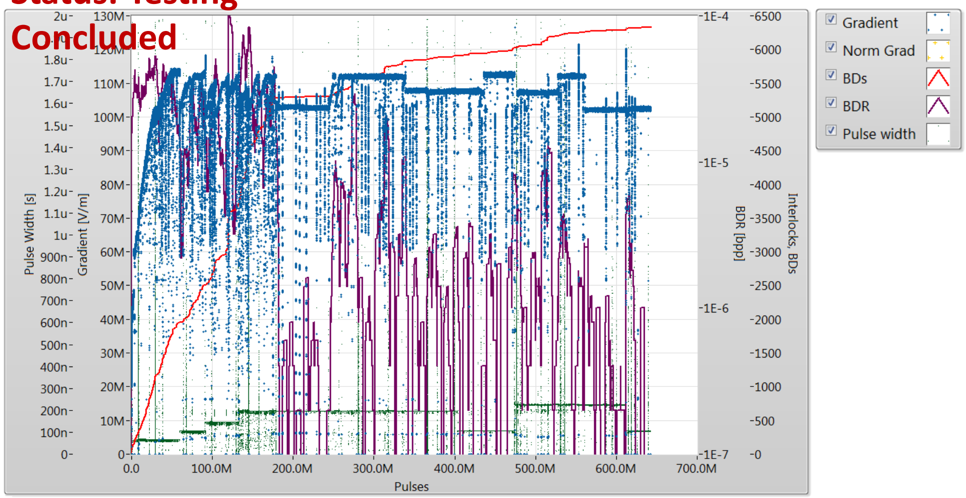
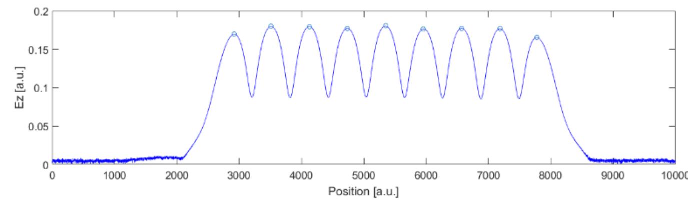


Figures: Conditioning curves for the PSI1 (left) and PSI2 (right) structures.

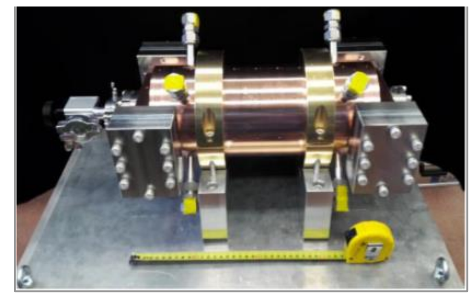
S-band project with ELETTRA for FERMI FEL

12/04/2017 **ELETTRA and PSI sign an agreement on a collaboration for the production and test of a short prototype**

13/03/2018 bead pulling on the test structure

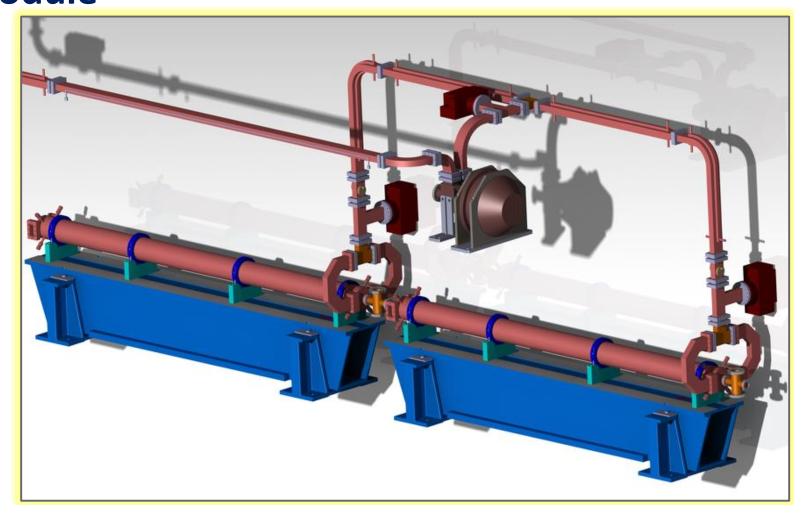


04/2018 installation of the test structure in the FERMI test stand and start of the power test



~4*10^{-8} BDR @ 35 MV/m

02/05/2019 **ELETTRA and PSI sign an agreement on a collaboration for the production of an full size S-band demonstrator module**
(2 structures, 3m length each)



28/05/2019 RF design ready (from Nuaman)

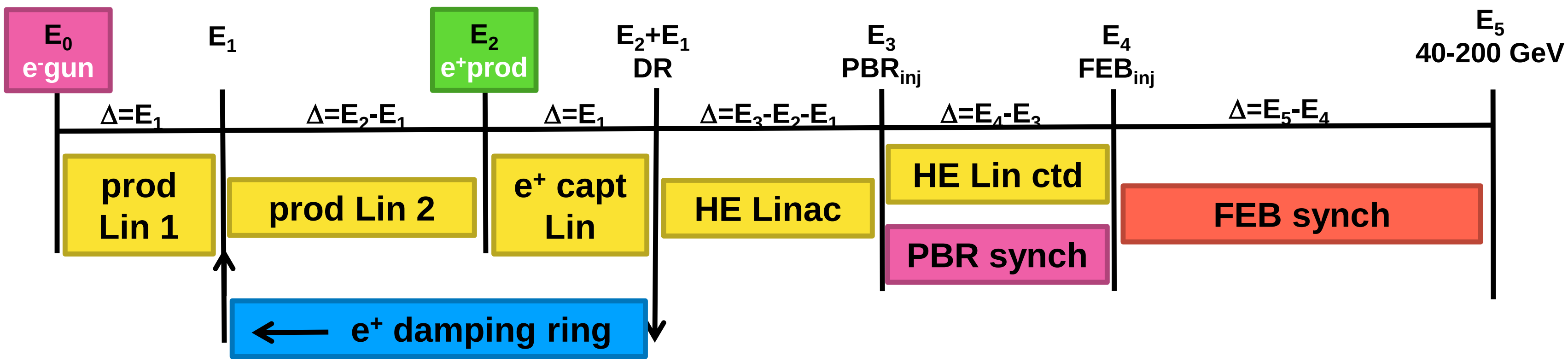
06/06/2019 Mechanical drawings ready

Today

Early 2020 Goal: S-band module ready

Relevance for FCC-ee ?

FCC-ee injector schematics



For e^+ production and capture 3 GHz S-band is well suited because of large acceptance and capability to handle high beam currents

For high energy linac 5.7 GHz C-band is more economic
in real estate requirements, investment and operation cost

The SwissFEL production protocol demonstrated to be very well adapted for C-band
The PSI – ELETTRA collaboration aims to demonstrate by 2020 that this is also true for S-band

FCC-ee injector, first look at Linac

FCC-ee Conceptual Design Report (V0.20, 8 November 2018)

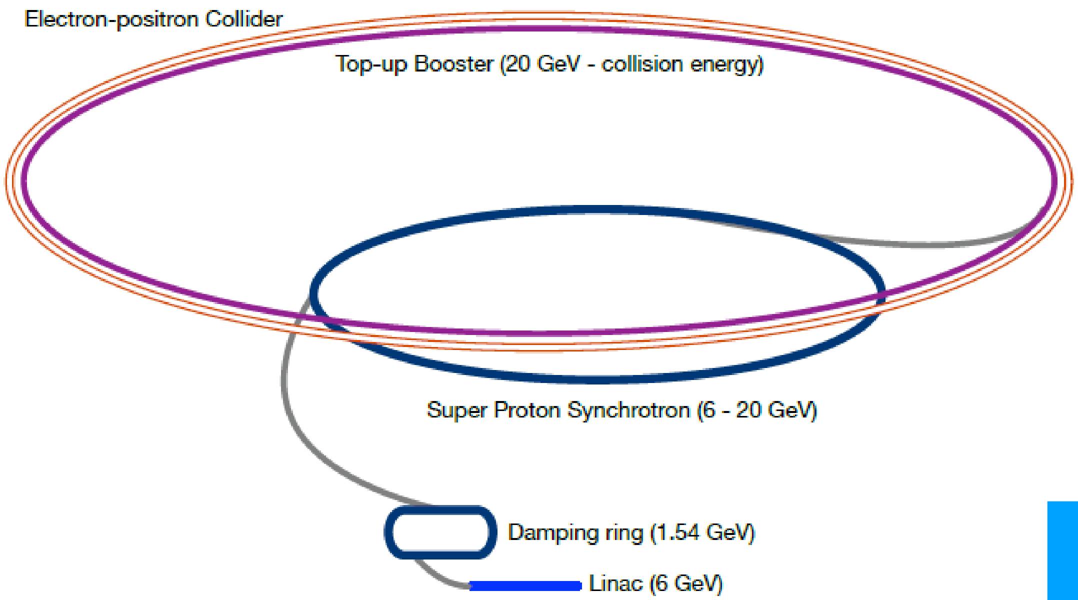
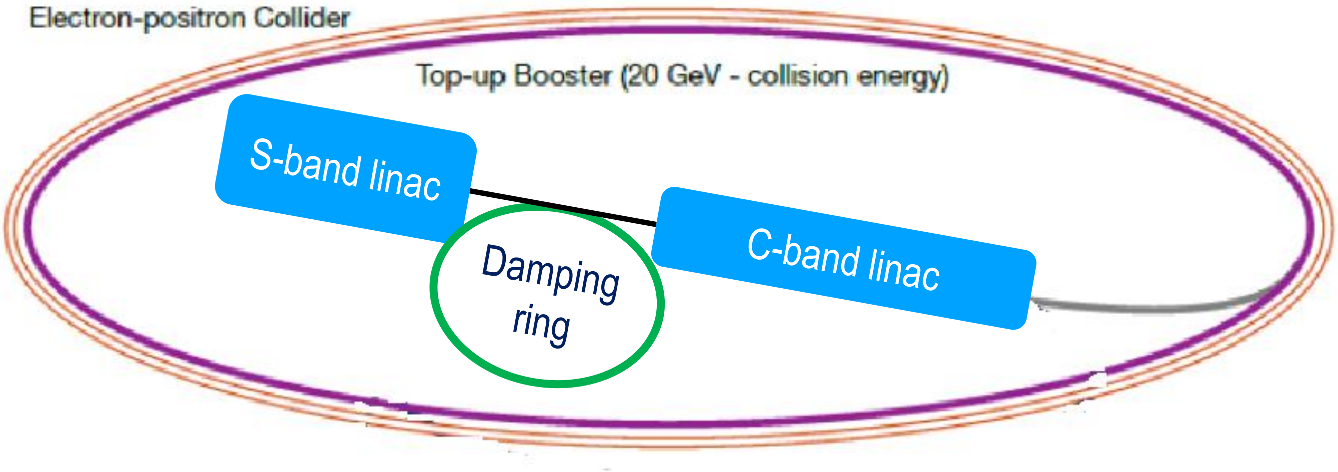


Figure 6.1: Schematic layout of the FCC-ee injector complex, with the SPS serving as PBR.

	S-band Linac	C-band Linac Opt. 1
Energy gain	2 GeV	4 GeV
Final energy	n.a.	6 GeV
Length	0.12 km	0.16 km
Gradient	20 MV/m	30 MV/m
Number RF stations	17	17
Cost incl. building	50 MCHF	50 MCHF

FCC-ee injector, second look at Linac



	S-band Linac	C-band Linac Opt. 2	C-band Linac Opt. 3
Energy gain	2 GeV	18 GeV	44 GeV
Final energy	n.a.	20 GeV	46 GeV
Length	0.12 km	0.7 km	1.7 km
Gradient	20 MV/m	30 MV/m	30 MV/m
Number RF stations	17	75	184
Cost incl. building	50 MCHF	230 MCHF	550 MCHF

Arguments for a 46 GeV injector linac for FCC_ee

The Z_0 mode is by far most demanding for top up injection.
Direct injection in the collider from the linac relaxes requirements for the booster synchrotron.

Polarised Electrons could be injected in main ring for precise energy calibration without waiting times for Sokolov Ternov and polarization wiggler (E. Gianfelice-Wendt talk this morning)

Linac could be operational well before FCC_ee main ring and booster
This would allow for a rich experimental program before FCC_ee completion for example on:

- Test and optimize injector operation of FCC_ee main ring
- Test and calibrate FCC_ee detectors with Z_0 at low luminosity in SLC like configuration
- Develop and test advanced positron production schemes based for example on
    - laser e^--beam interaction (expanding on SLAC E144)
    - Undulator produced photons beams (ILC approach)
- Beam driven plasma wakefield acceleration experiments
- Gamma radiation FEL
- …

Timeline for a 46 GeV injector linac for FCC_ee

<table>
<tr><th></th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th><th>2031</th><th>2032</th><th>2033</th><th>2034</th><th>2035</th><th>2036</th><th>2037</th><th>2038</th><th>2039</th><th>---</th><th>2054</th></tr>
<tr><td>FCC_ee storage rings and main booster</td><td colspan="11">FCC-ee accelerator R&D and technical design</td><td colspan="8">FCC-ee accelerator construction, installation, commissioning</td><td colspan="3" rowspan="3">Operation</td></tr>
<tr><td>FCC_ee detectors</td><td colspan="7">Detector R&D and concept development</td><td colspan="4">FCC-ee detector technical design, collaborations</td><td colspan="8">detector construction, installation, commissioning</td></tr>
<tr><td>FCC_ee detectors alternative scenario</td><td colspan="7">Detector R&D and concept development</td><td colspan="4">FCC-ee detector technical design, collaborations</td><td colspan="4">construction</td><td colspan="2">calibration on Z_0</td><td colspan="2">final installation</td></tr>
<tr><td rowspan="2">FCC_ee_linac</td><td colspan="4" rowspan="2">Project preparation</td><td colspan="4">Procurement and pre-assembly</td><td colspan="2" rowspan="2">Installation</td><td colspan="9" rowspan="2">Commissioning and experiments</td><td colspan="3" rowspan="2">Operation as FCC_ee injector</td></tr>
<tr><td colspan="4">Tunnel construction</td></tr>
</table>

Acknowledgments

Many thanks to

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Nuaman Shafqat (FERMI)
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Michael Benedikt (CERN)
Frank Zimmermann (CERN)

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