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Terry Garvey - Paul Scherrer Institut

Les activités accélérateur a l'Institut Paul Scherrer

Journées Accélérateurs de la SFP, Roscoff, octobre 2017

Presentation outline

Panorama of accelerators on-site.

- Currently operating machines and future up-grades
  - HIPA, SLS → SLS-2 (2021-24), COMET
- Accelerator(s) under construction - I will describe mainly the radio-frequency linac
  - SwissFEL
    - ARAMIS (hard X-ray line of SwissFEL) 2013 – 2016 → 17
    - ATHOS (soft X-ray line of SwissFEL) 2017 - 2020
- R&D projects
  - X-band structures, solid state amplifiers, compact synchrotrons, THz acceleration, superconducting magnets.

Accelerators at PSI

- 590 MeV Proton cyclotron – HIPA
  - neutron spallation source, thermal and ultra-cold neutrons
  - particle physics program UCN, MEG
  - high flux muon beams - µSR
- 2.4 GeV, 400 mA electron storage ring: Swiss Light Source (SLS)
  - for synchrotron radiation
- 250 MeV super conducting proton cyclotron – COMET
  - for proton therapy.
- 5.8 GeV electron linac - under construction for SwissFEL

Particle beams available at PSI
protons (health),
photons, neutrons and muons (research)

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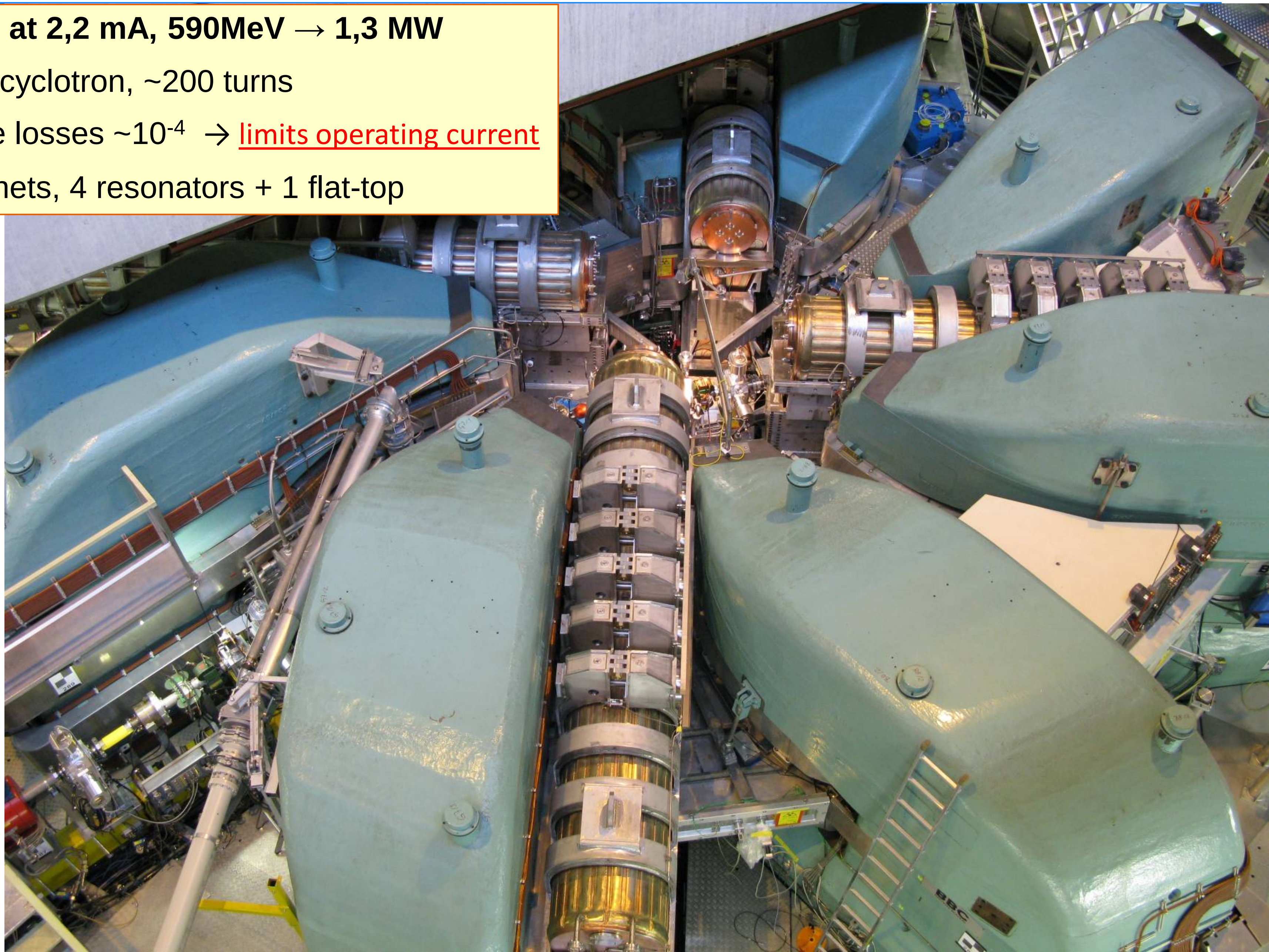
The Ring Cyclotron (HIPA)

Operated at 2,2 mA, 590MeV → 1,3 MW

➔ sector cyclotron, ~200 turns

➔ relative losses ~10^{-4} → limits operating current

➔ 8 magnets, 4 resonators + 1 flat-top



HIPA Pre-Accelerators: Cockroft-Walton and Injector II cyclotron

Cockroft Walton

➔ current ~ 12mA in cw operation

➔ Energy 870 keV

Injector II

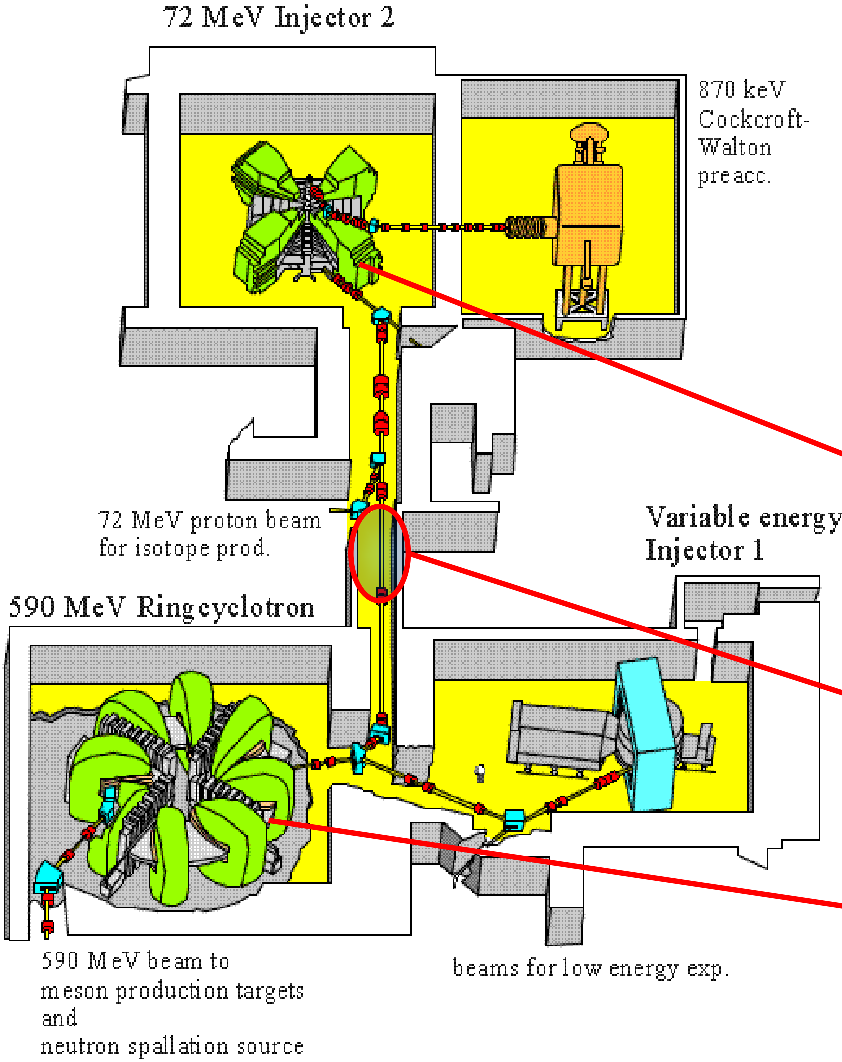
➔ current <2.6mA; Energy 72MeV

➔ sector cyclotron

➔ 2 resonators, 2 flat-top cavities

➔ upgrade: 2 new resonators to replace flat-top cavities.

- An upgrade program is in progress for the facility, aiming for **3mA, 1.8MW**
- the major upgrade path foresees increased turn separation by **higher energy gain per turn (new resonators)**, thus **reducing losses** at extraction; in addition: new harmonic buncher system for the Ring Cyclotron ($10xf_0$)



New RF-Components

Injector II

New 50 MHz Resonators 2&4

72 MeV Line

500 MHz Buncher (Super-Buncher)

Ring

New 50 MHz Cu-Cavities

(ev. new flat-top system)

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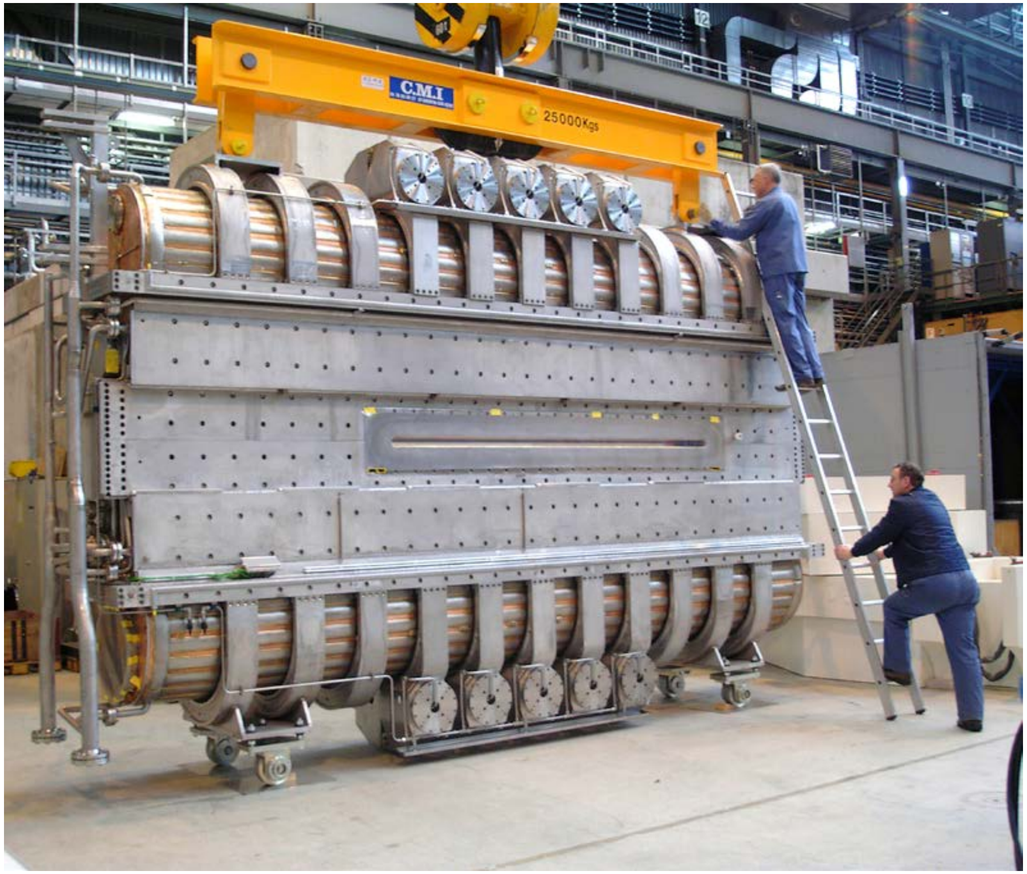
New 50 MHz Ring Cyclotron Cavity

All installed



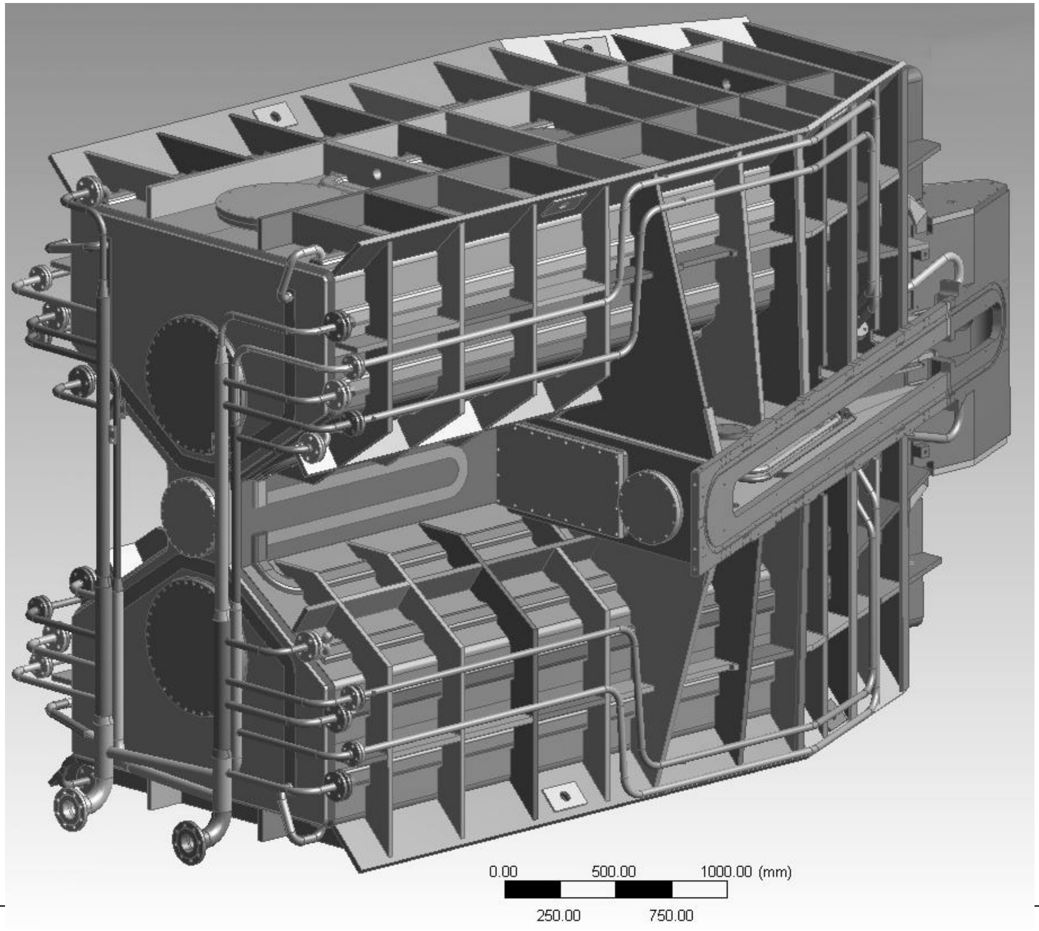
Specification

Resonance frequency:	50.6328 MHz
Accelerating voltage:	1.4 MV
Dissipated power:	500 kW
Tuning range:	540 kHz
Cavity wall:	Cu-OFHC
Support structure:	316LN
Vacuum pressure:	1e-6 mbar
Cooling water flow:	34 m3/h
Dimension:	5.6x3.9x0.95 m
Weight:	25'000 kg

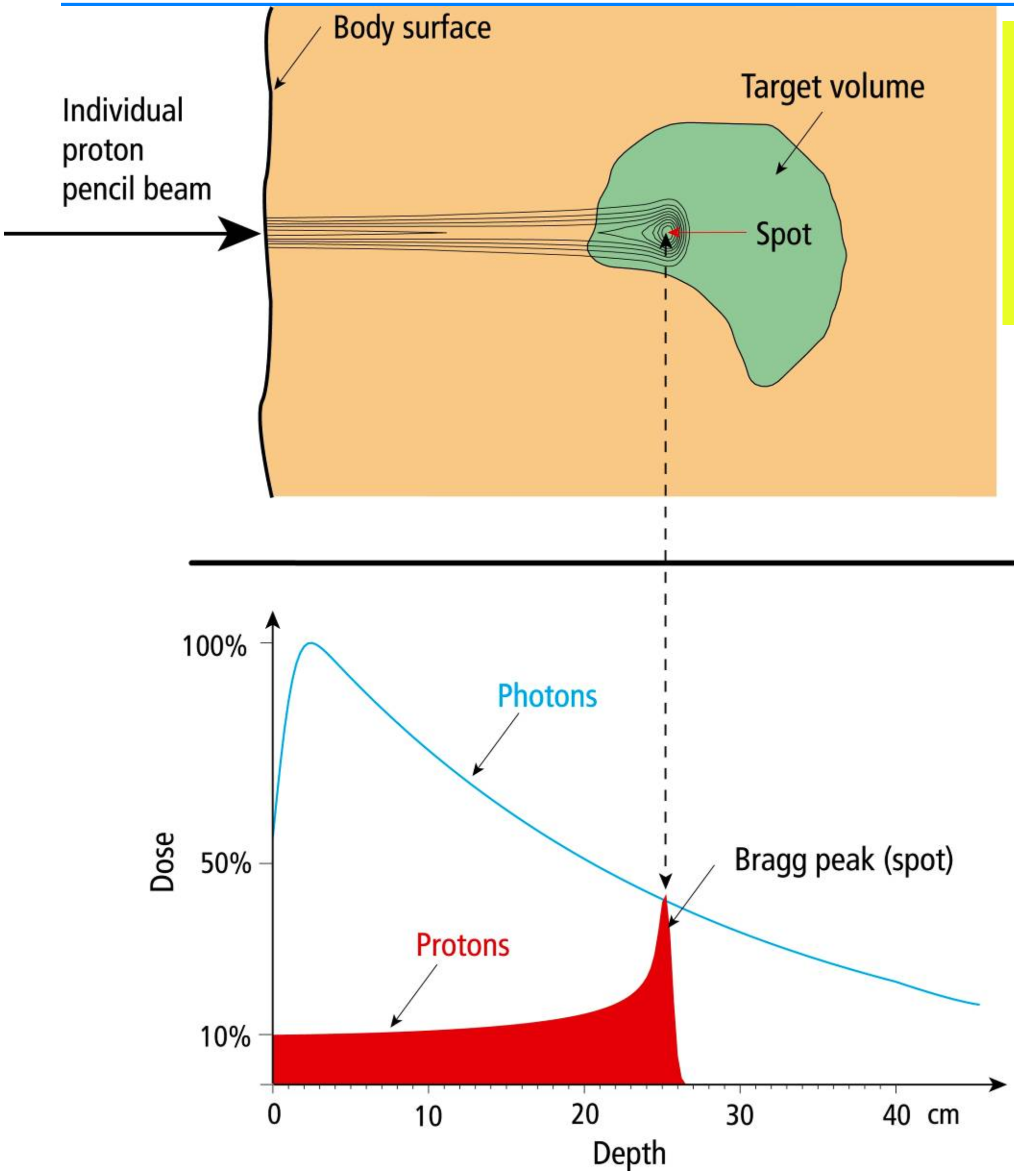
Two new 50 MHz Resonators for Injector II

Made in France!

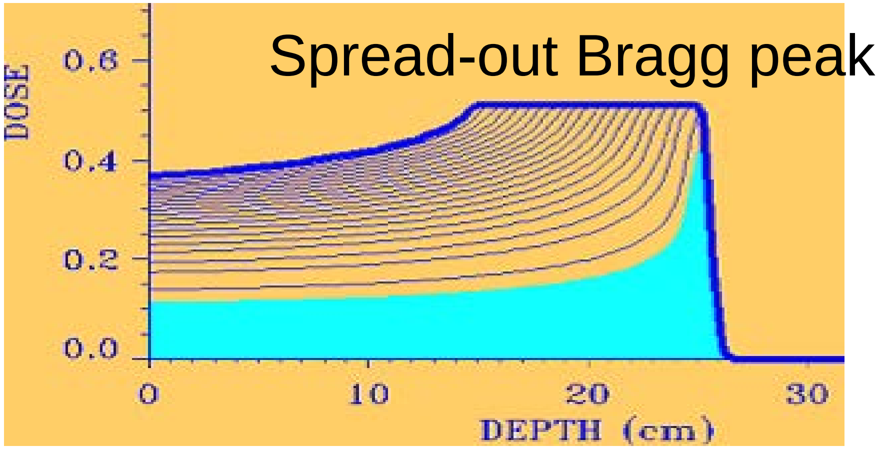
Installation 2018



Protons for radiotherapy



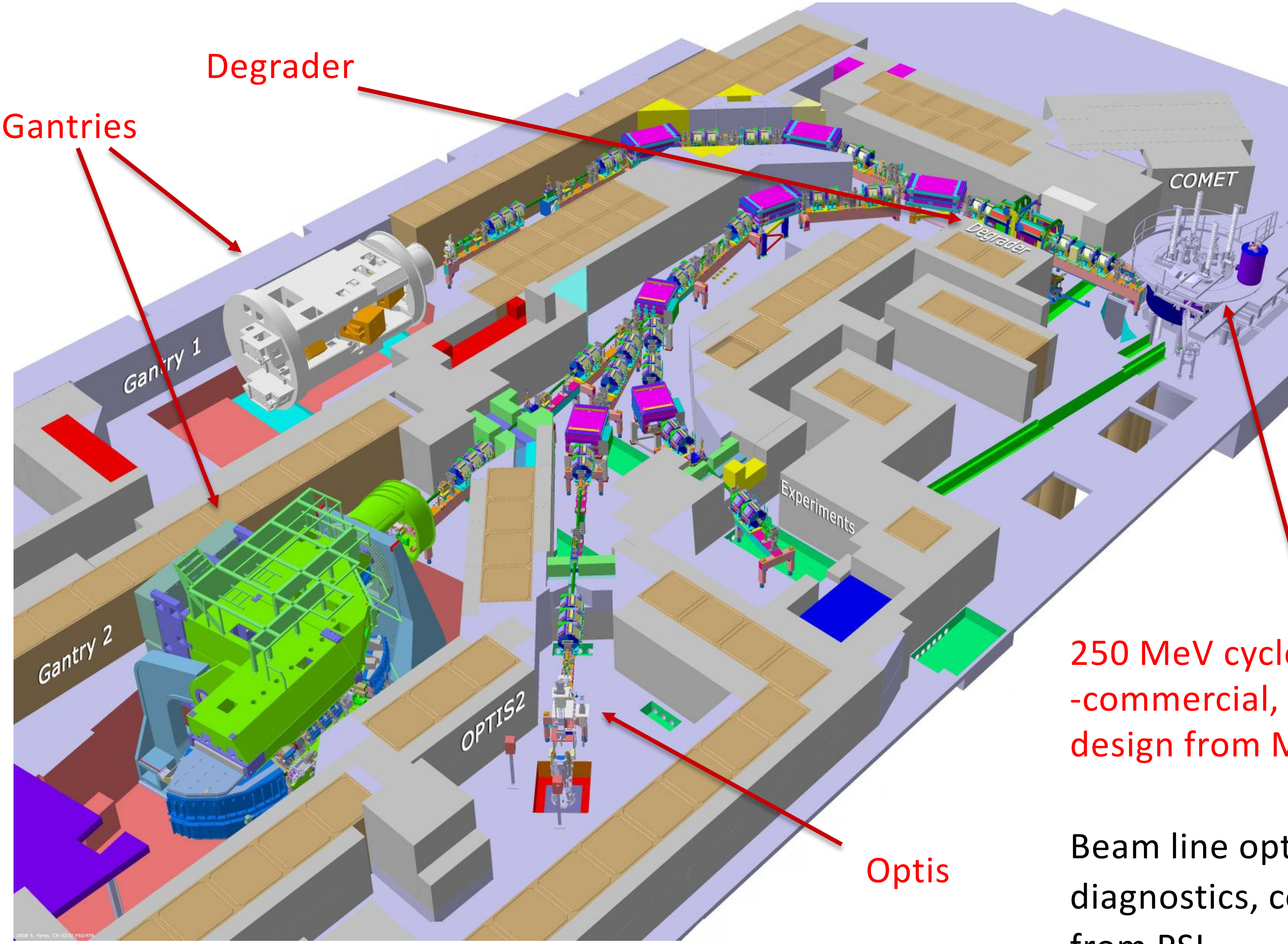
Radiation dose should be delivered to tumour while sparing the healthy cells that surround the tumour. The existence of the Bragg "peak" makes protons an attractive choice for therapy.



Layout of dedicated proton therapy facility.

Degrader

Gantries



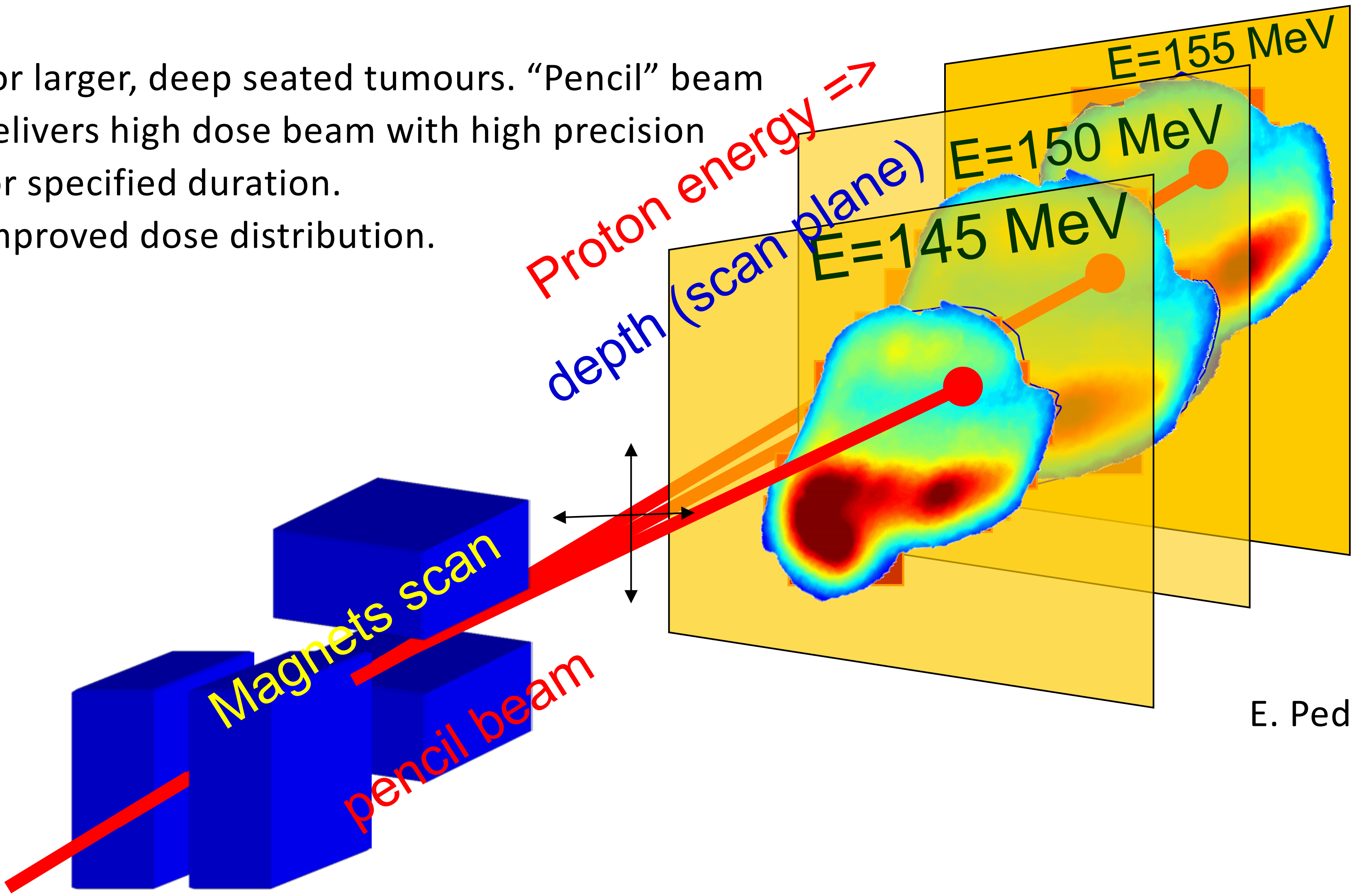
250 MeV cyclotron -commercial, after a design from Michigan

Optis

Beam line optics, diagnostics, controls from PSI.

3D Pencil beam: spot scanning

For larger, deep seated tumours. “Pencil” beam delivers high dose beam with high precision for specified duration.
Improved dose distribution.



E. Pedroni

Gantry – 2 – large rotating beam-line

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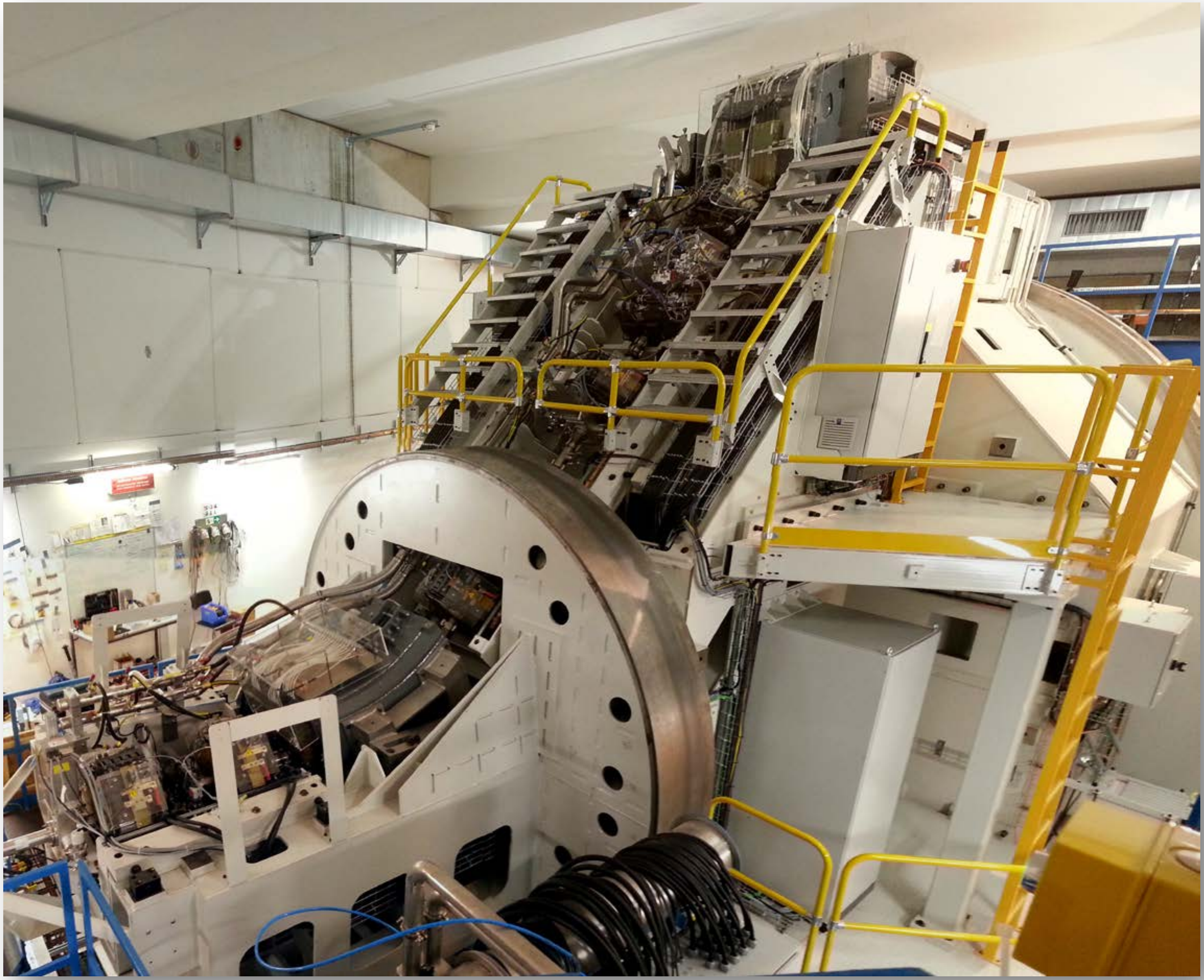
Gantry 3 installation at PSI (financed by Canton)

State of the art - large, heavy, costly



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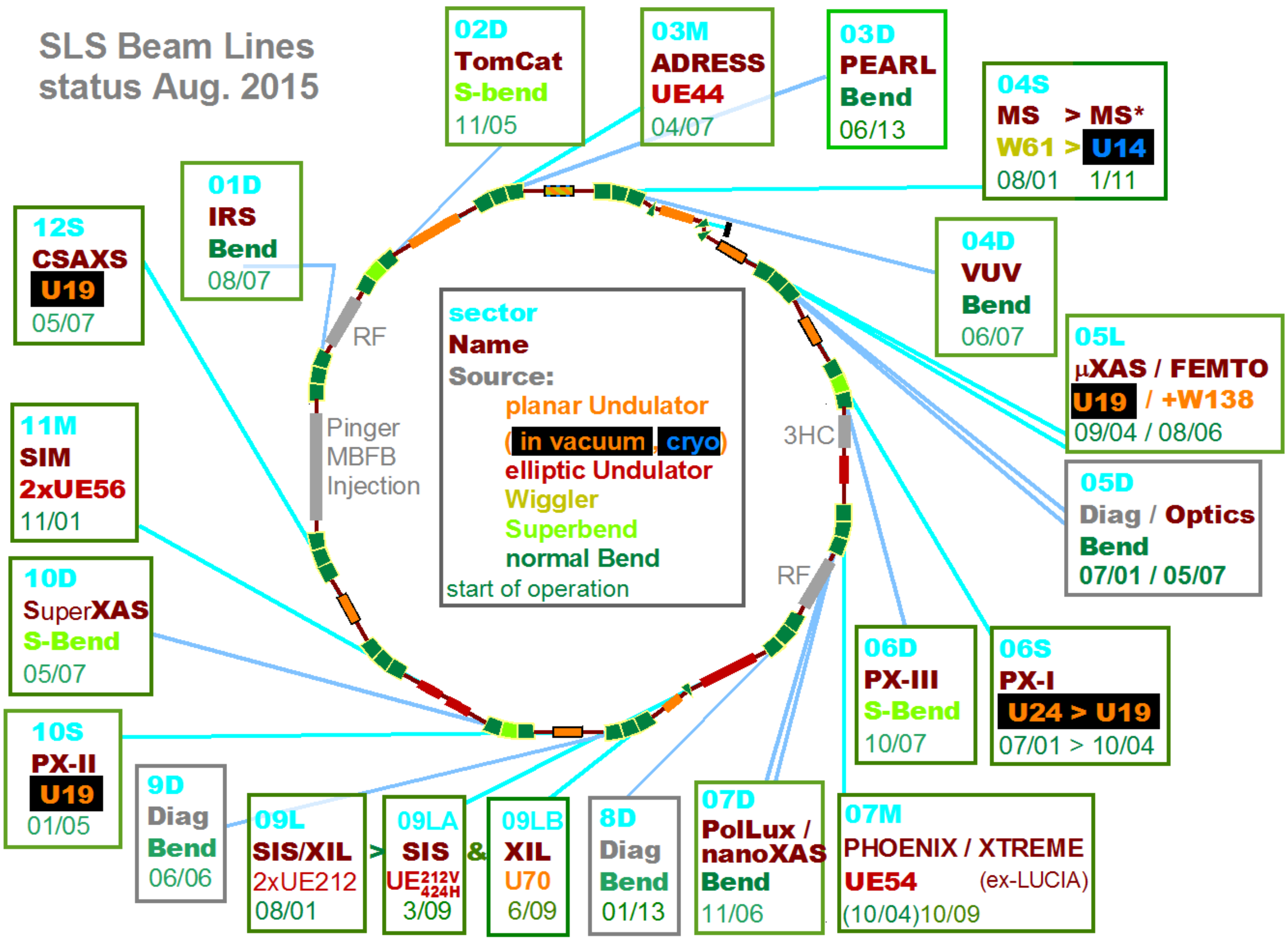
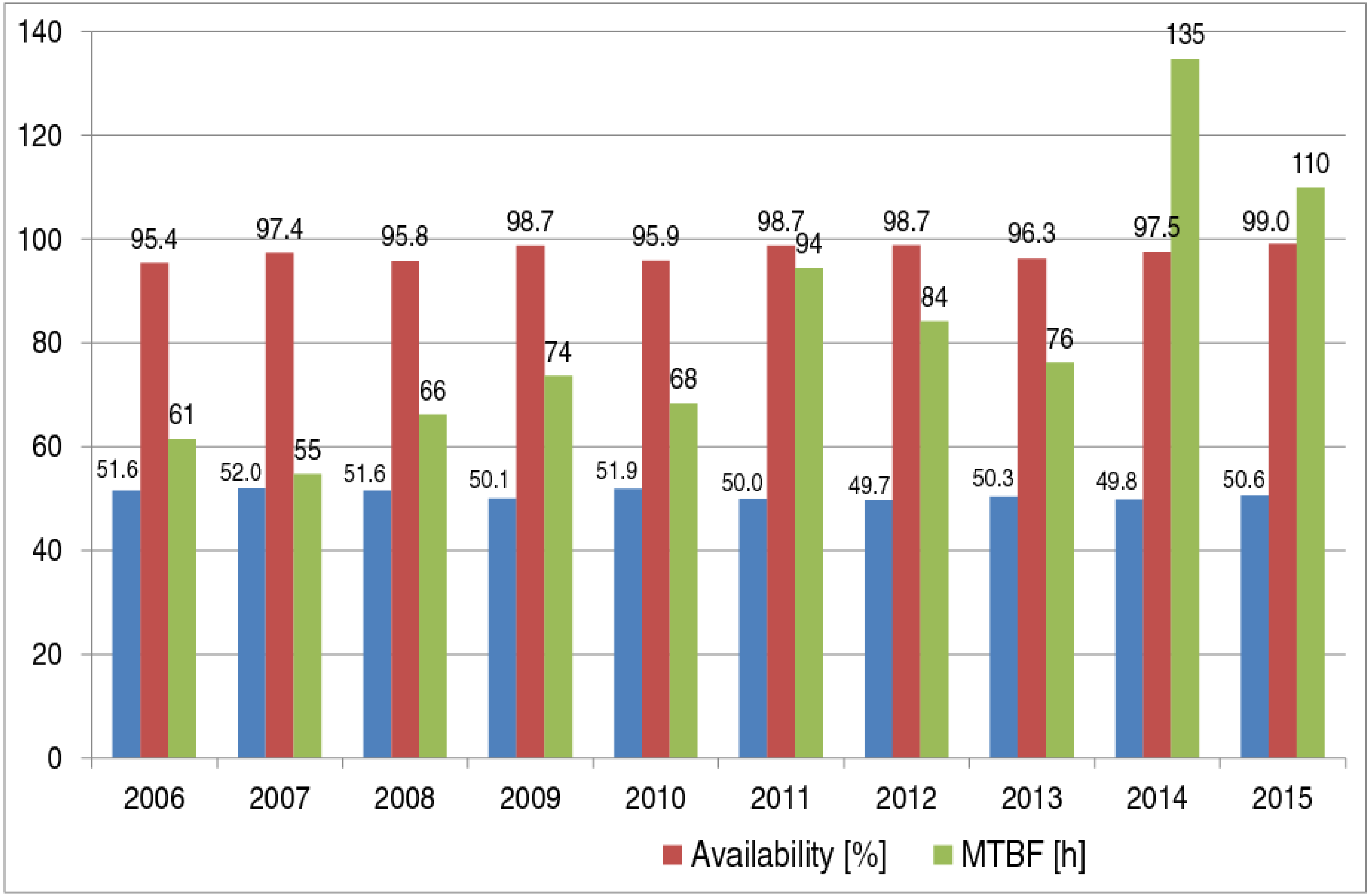
Schematic of the SLS and its beamlines. 3rd generation synchrotron radiation source.



SLS operational reliability



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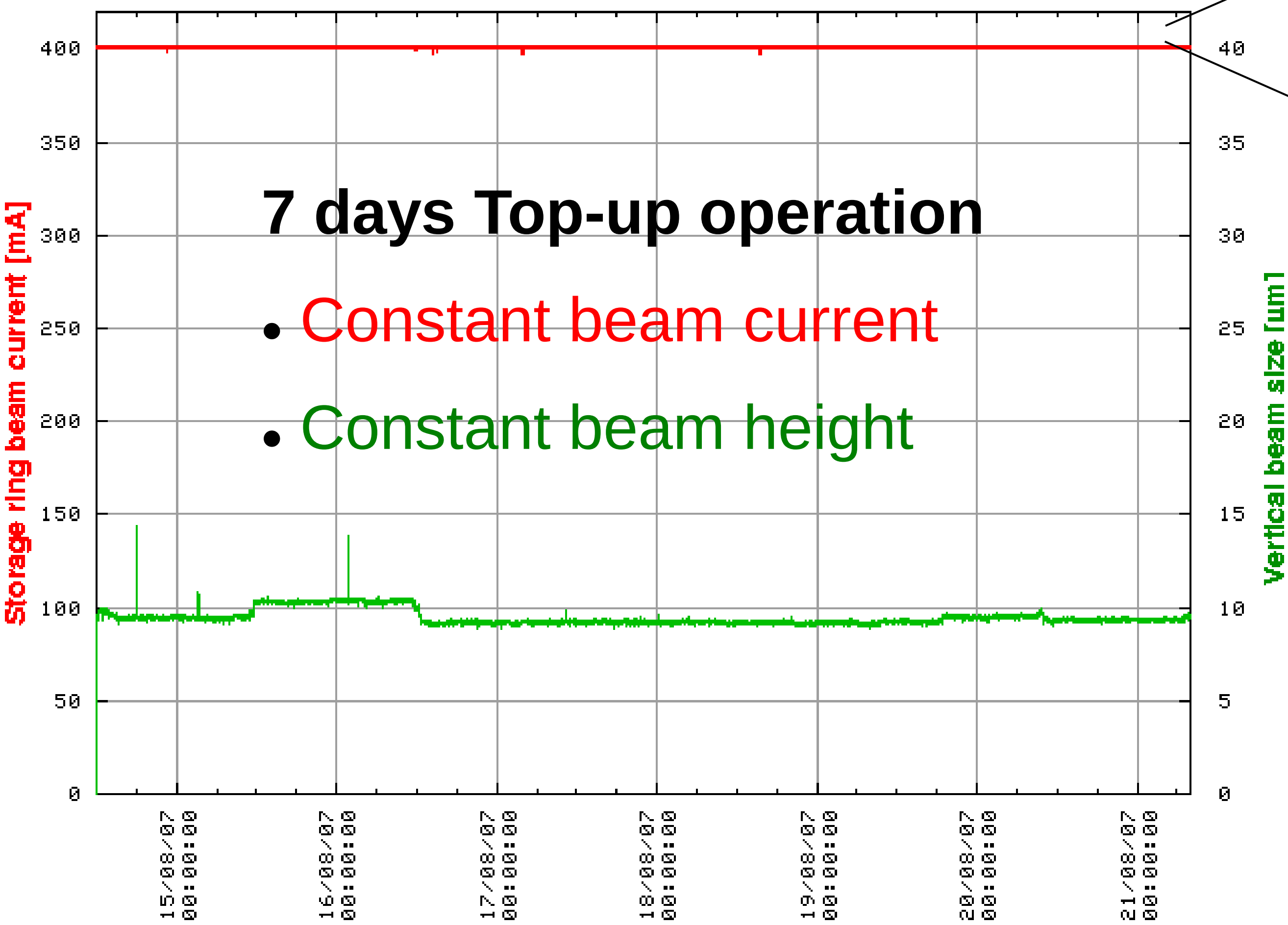
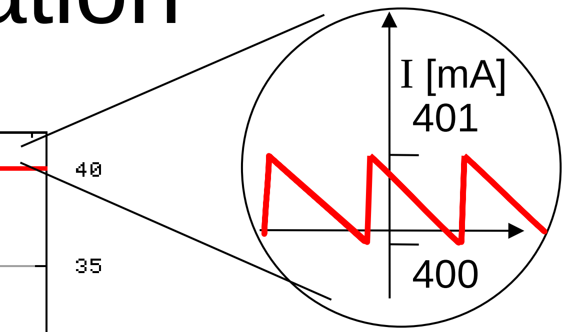
The SLS provides beams of extremely high stability in intensity and position thanks to precision BPMs and digital FOFB.

SLS top-up operation



7 days Top-up operation

- Constant beam current
- Constant beam height



Lifetime ~8 h for:

- 400 mA
- Coupling 0.13 %
- ε_y= 7 pmrad

→ inject ~1mA every 100sec

SLS-2 Lattice parameters (A. Streun)

Name	SLS*)	SLS-2#)
Emittance at 2.4 GeV [pm]	**5069**	**102 → 126**♦)
Lattice type	TBA	**7**BA
Circumference [m]	288.0	290.4
Total *absolute* bending angle	360°	561.6°
Working point $Q_{x/y}$	20.43 / 8.22	39.2 / 15.30
Natural chromaticities $C_{x/y}$	–67.0 / –19.8	–95.0 / –35.2
Horizontal damping Partition J_x	1.00	1.71
Momentum compaction factor $[10^{-4}]$	6.56	–1.33
Radiated Power [kW] 1)	208	222
rms energy spread $[10^{-3}]$	0.86	1.03 → 1.07♦)
damping times x/y/E [ms]	8.9 / 8.9 / 4.4	4.9 / 8.4 / 6.5

1) assuming 400 mA stored current, bare lattice without IDs

*) SLS lattice before FEMTO installation (<2005)

#) SLS-2 with 3 superbends

♦) including intra-beam scattering for 1 mA bunch current (400 mA in 400 of 484 buckets; 500 MHz),
10 pm vertical emittance, 1.4 MV RF voltage,
3rd harmonic cavity for 2.2×bunch length.

Motivation for SwissFEL at PSI

Strong scientific case advanced by research community: desire to have high spatial (~ Ångstrom) and temporal (~ femtosecond) resolution →SASE FEL.

SwissFEL built as a national facility in a “small” country. Cost must fit within a limited financial enevelope.

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \quad \Rightarrow \quad \gamma = \sqrt{\frac{\lambda_U}{2\lambda}\left(1+\frac{K^2}{2}\right)} \propto € \qquad Cost \propto \gamma$$

The linac is a cost driver, cost scales roughly linear with electron beam energy γ

Laser wavelength λ is given as specification

$$\varepsilon_N \approx \gamma \frac{\lambda}{4\pi}$$

$\Rightarrow$Period length λ_U and K ($\propto B\,\lambda_U$) have to be kept small

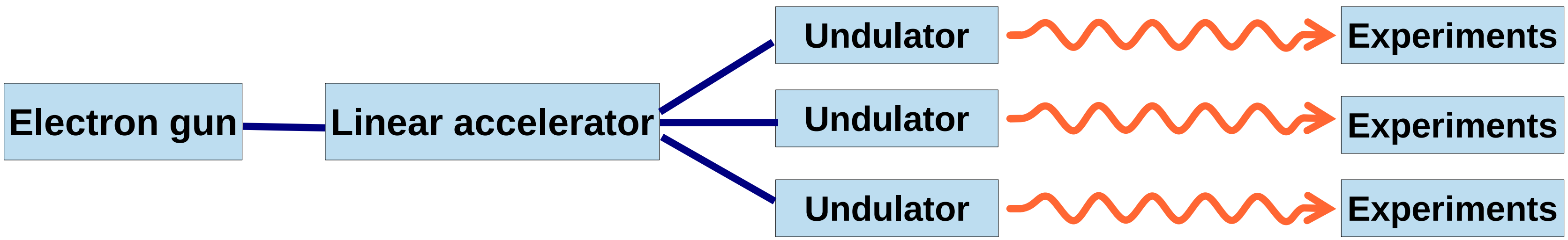
Wish to use lowest electron beam energy compatible with one Ångstrom operation !

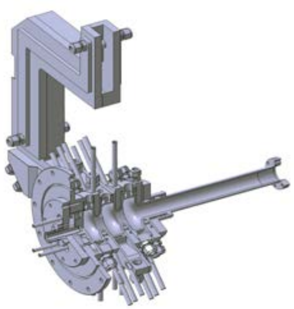
Site constraints: Power consumption ≤ 5 MW

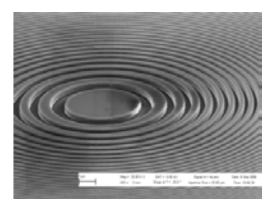
Facility length ≤ 900 m.

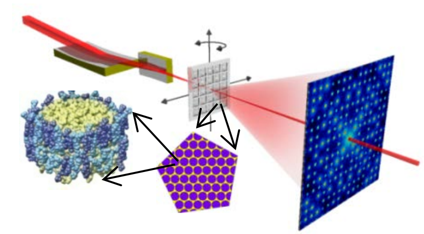
Ingredients of an X-ray FEL

Generation of high-brightness electron beam	Electron beam acceleration	X-ray generation with FEL process (SASE)	X-ray transport and focussing









Maximize e^- beam brilliance

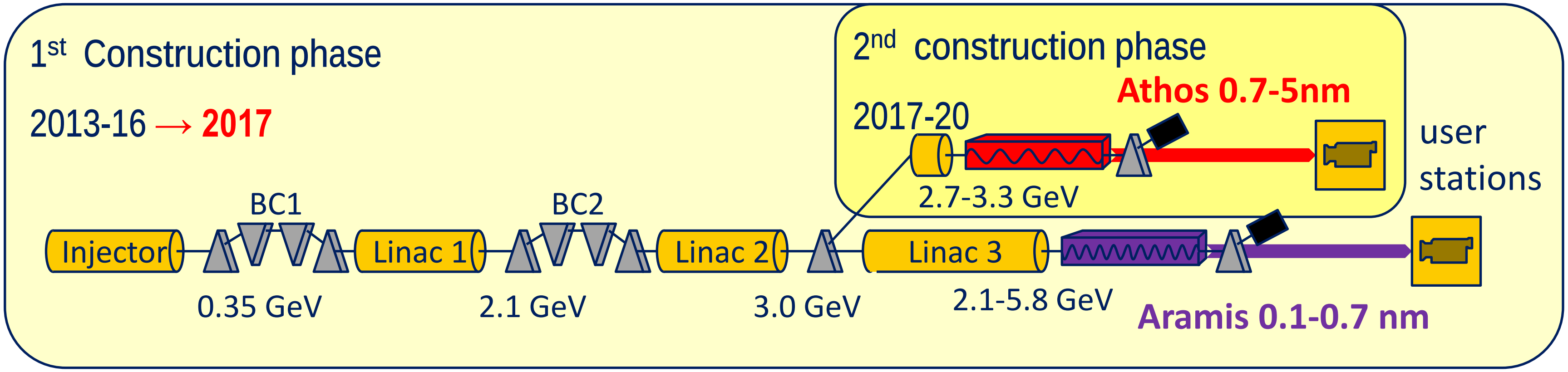
$$B_n = \frac{2}{\pi^2}\frac{I_{Peak}}{\varepsilon_n^2}$$

Minimize € / GeV

Minimize period length λ_u

High quality X-ray optics in presence of high power density

SwissFEL



Aramis

- Hard X-ray FEL, λ=0.1-0.7 nm
- Linear polarization, variable gap, in-vacuum Undulators
- First users 2018

Athos

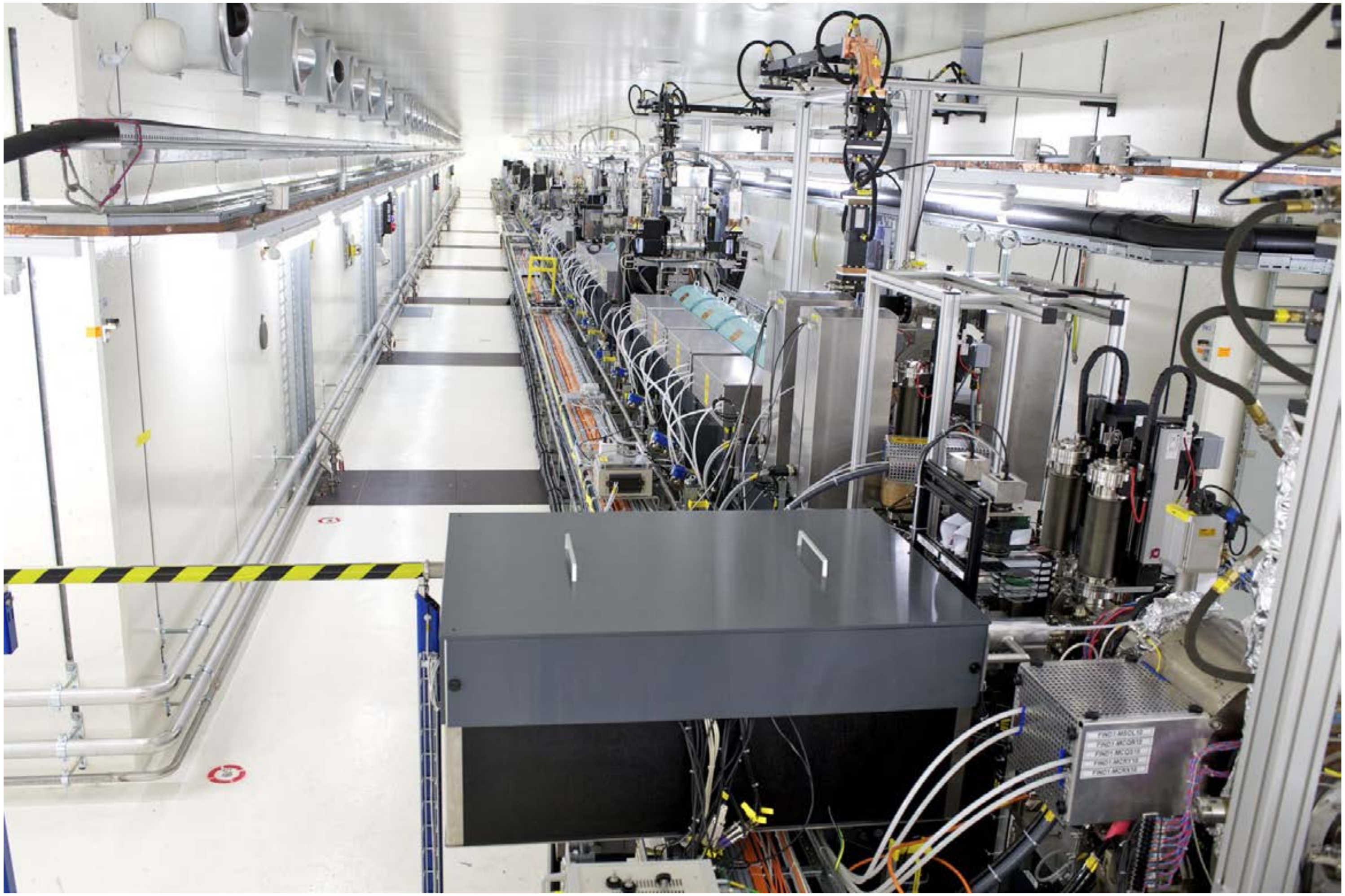
- Soft X-ray FEL, λ=0.65-5.0 nm
- Variable polarization, Apple-X undulators
- First users 2021

Main parameters

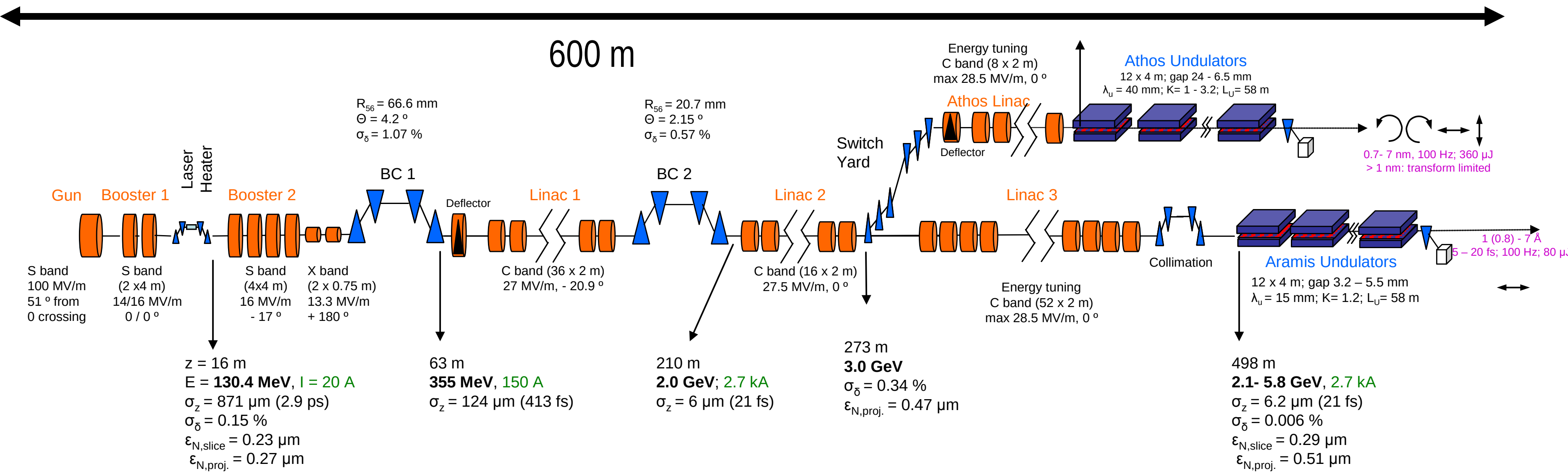
Wavelength from	1 Å - 50 Å
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

View looking downstream of SwissFEL injector 2010-14

Built to measure / confirm required beam parameters – slice emittance, energy spread, bunch length compression, learn to control RF amplitude and phase stabilty, develop diagnostics and synchronisation.

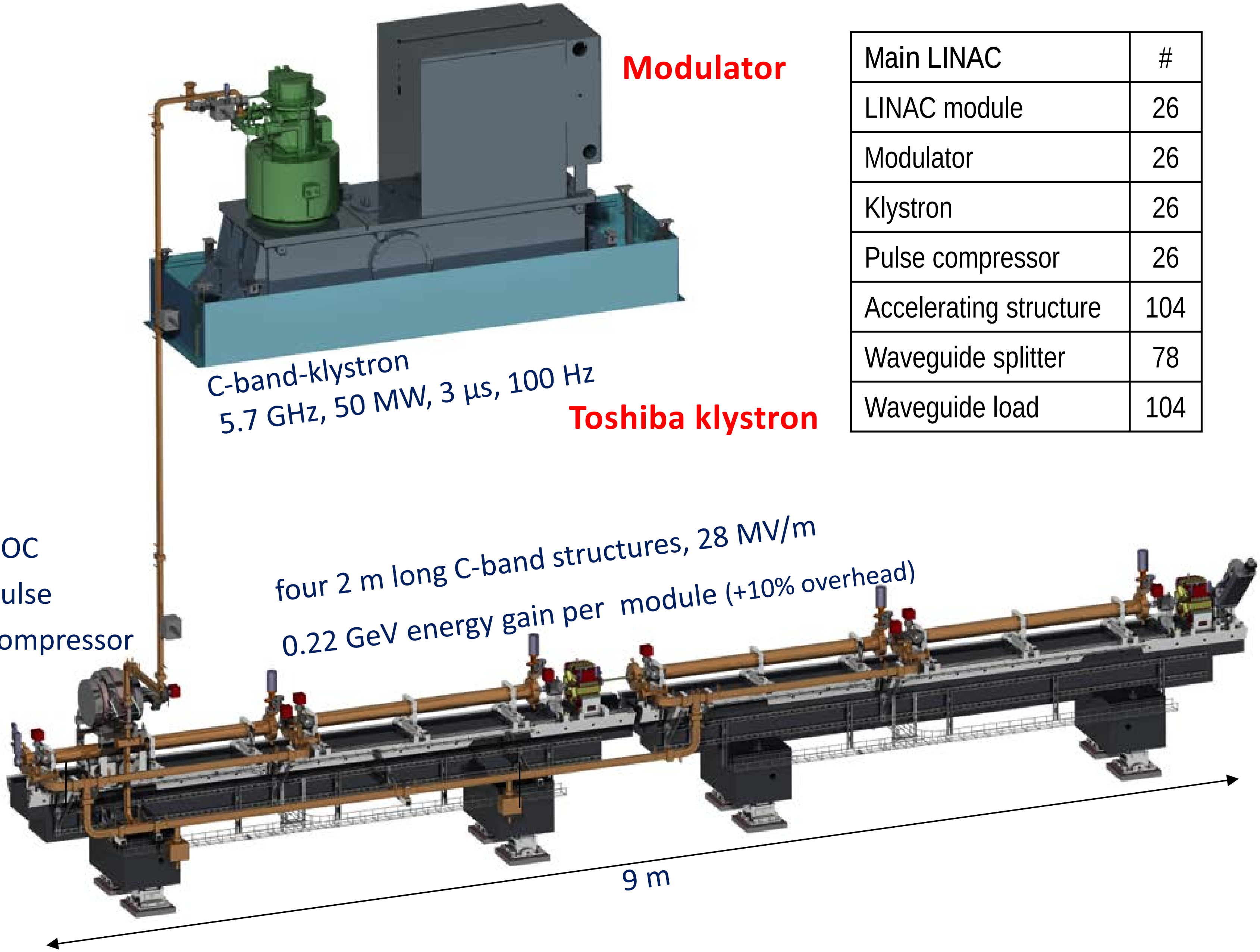


Layout of SwissFEL



- **Technology choice:**
  - **RF photo-electron gun (2.5 cell), S-band**
  - **2 Stage compression at highest energy possible to minimize RF phase and amplitude tolerances**
  - **C-band linac (fewer RF stations, linac length and less mains power than S-band)**
  - **X-band for linearizing phase space before BC 1**
  - **2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz**

The SwissFEL linac module

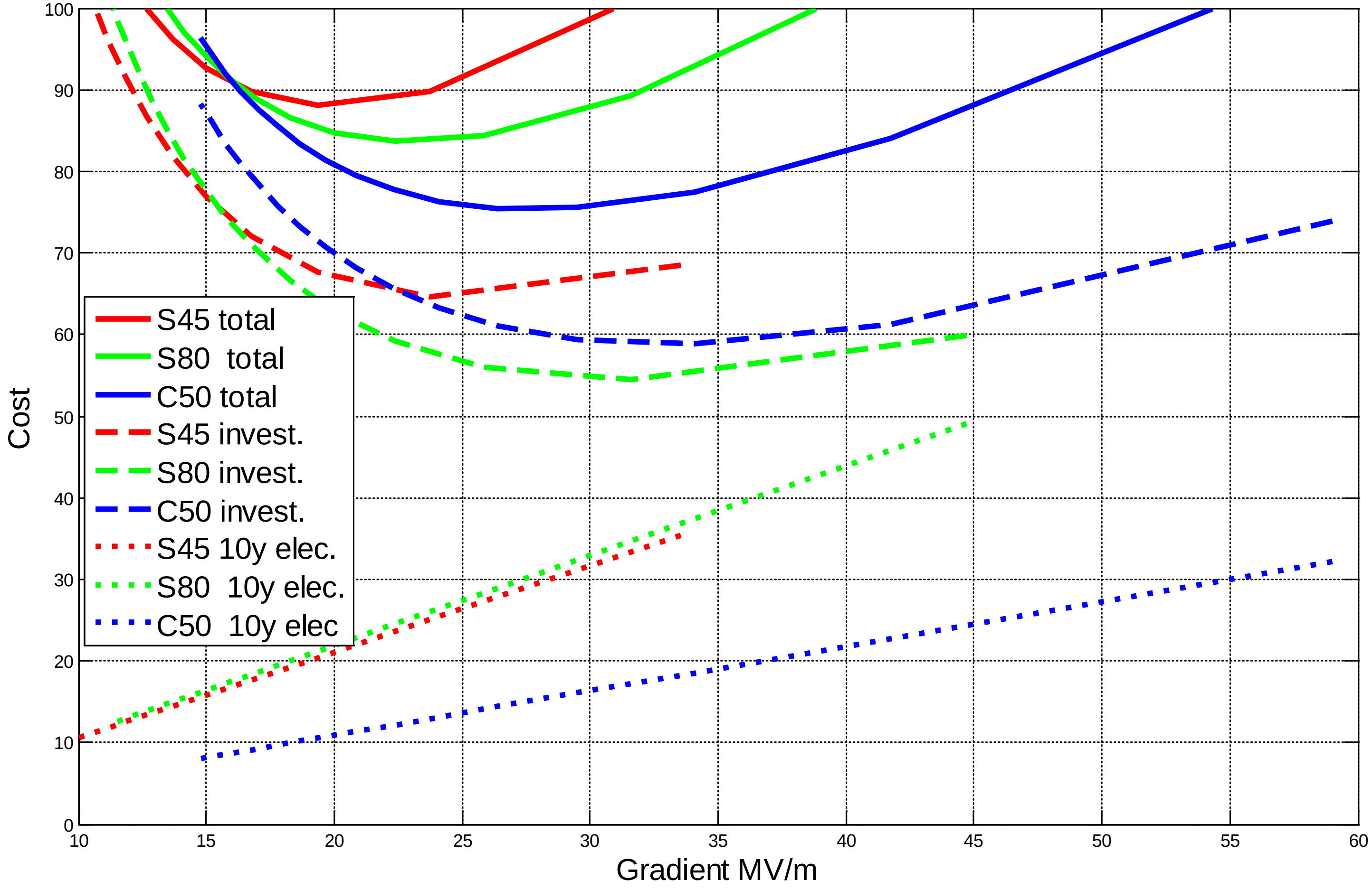


Main LINAC	#
LINAC module	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structure	104
Waveguide splitter	78
Waveguide load	104

Why C-band? Choice of RF structure frequency

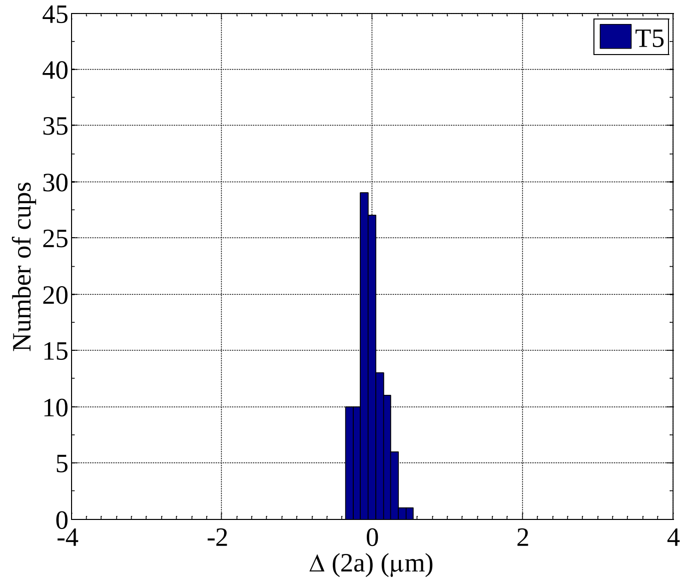
- Linac cost as a function of frequency

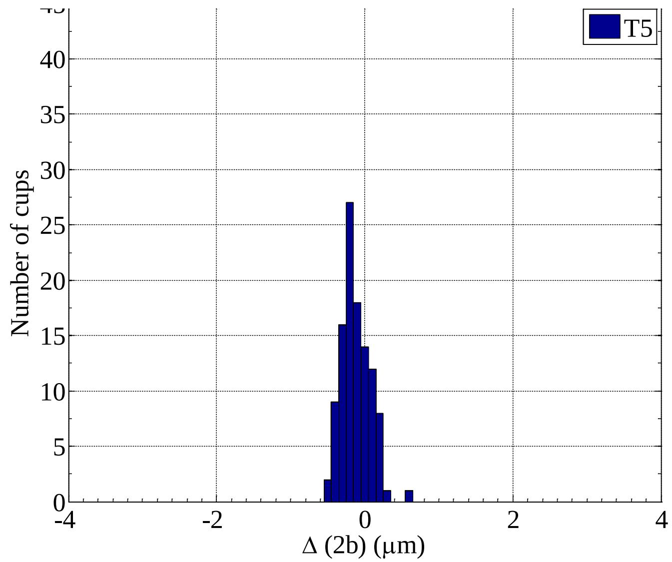
S-band with 45 MW klystron, S-band with 80 MW klystron, C-band with 50 MW klystron

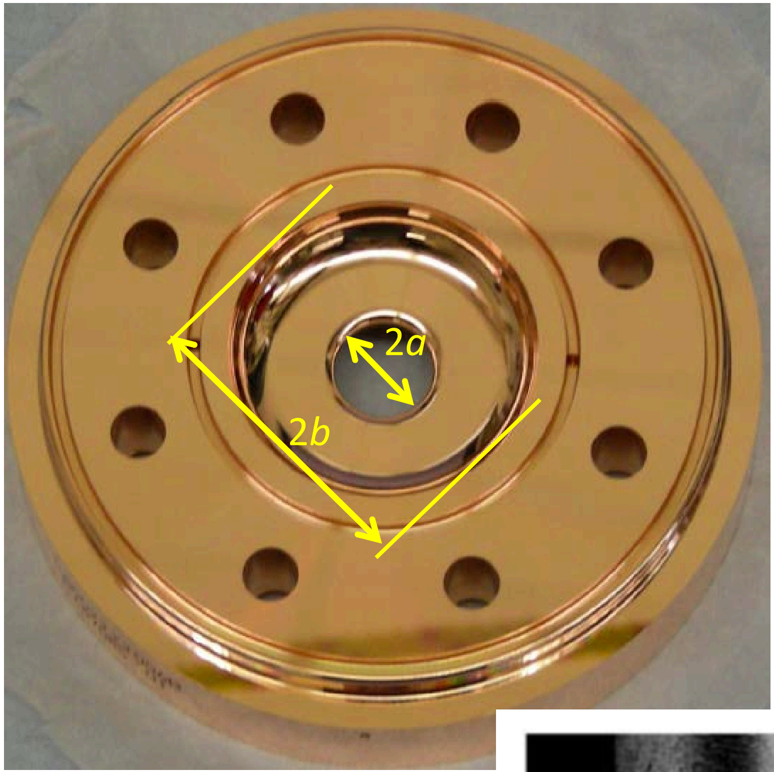


Advantage of C-band is in real-estate needs and electricity consumption

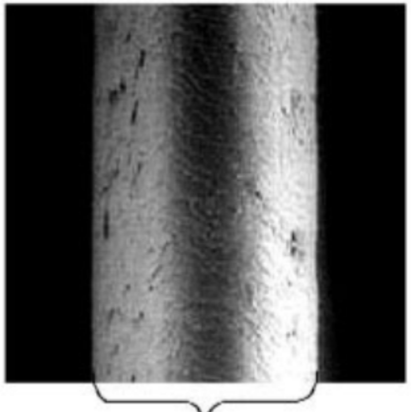
Precision manufacturing of copper disks in Trübbach







Courtesy of J.Y. Raguin



Typical examples of metrology on a structure:

Top: histogram iris diameter; Bottom: histogram iris cell diameter

C-band structures

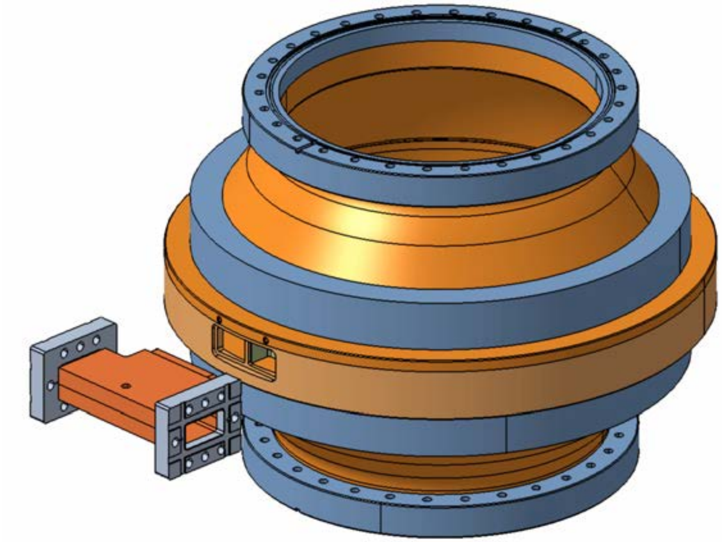
- Structures are machined “on tune”, no provisions for dimple tuning!
- Cup manufacturing with micron precision at VDL ETG Switzerland
- Coupler manufacturing at VDL ETG
- Stacked by robot at PSI
- Vacuum-brazed at PSI
- Production rate: 1-2 / week
- Production finished August 2016

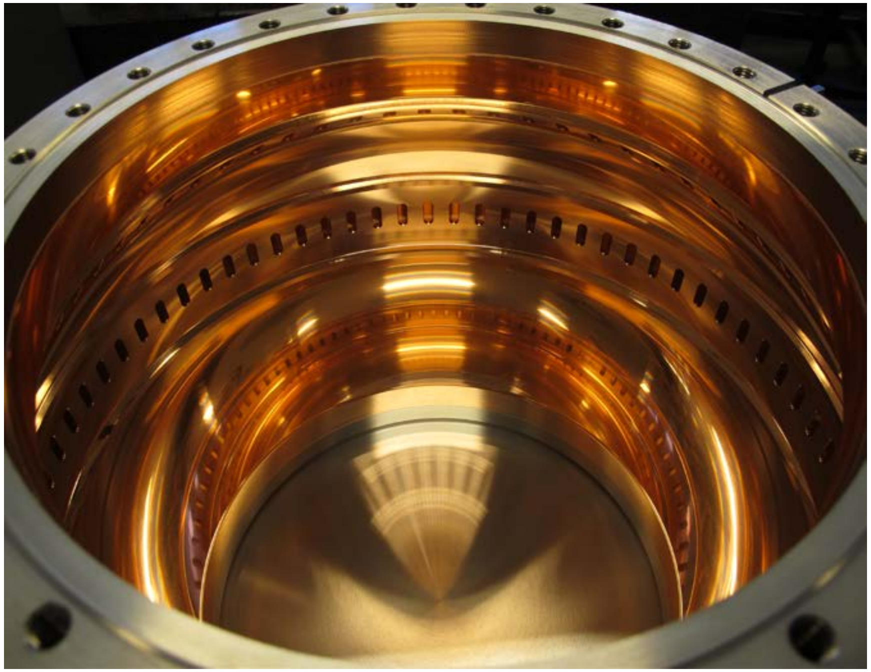
- **High power results for first structure:**
  - → Conditioned to 52 MV/m
  - → Break-down rate at 52 MV/m ≈ 2×10^{-6}
  - → At nominal 28MV/m, break-down rate negligible (well below the specified threshold of 10^{-8})

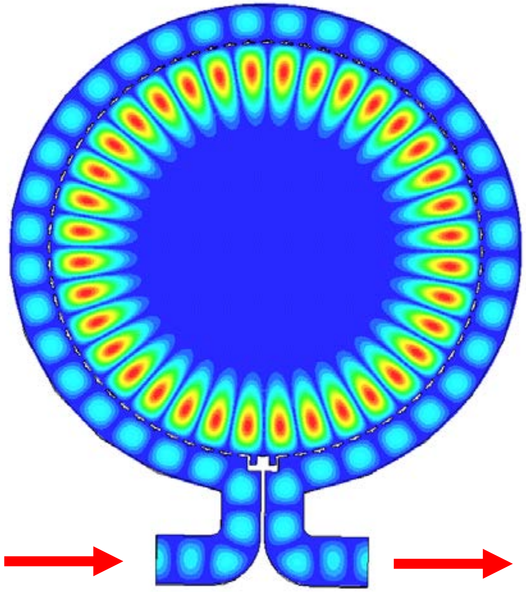
The C-band accelerating structures installed in the tunnel

- last girder installed 13.09.16 (RF design by J.Y. Raguin)

BOC (barrel open cavity) design







Solid-state modulators for C-band linac

- ✓ Two prototypes were tested at PSI for evaluation of the series.
- ✓ **50 MW / 3µs RF, 370kV / 344A / <20 ppm voltage stability pulse to pulse @ 100 Hz**

AMPEGON

Type-µ modulator prot. for PSI C-band

- 13 modulators (Linac 1, Linac 2)

ScandiNova

K2-3 proto. for PSI C-band

- 13 modulators (Linac 3)

- ✓ Progressive increase of beam energy to final energy of 5.8 GeV
- ✓ First Pilot Experiments by End 2017 (requested 3 GeV beam)

PSI developed RF Gun (has features of LCLS and LAL/CERN PHIN gun)

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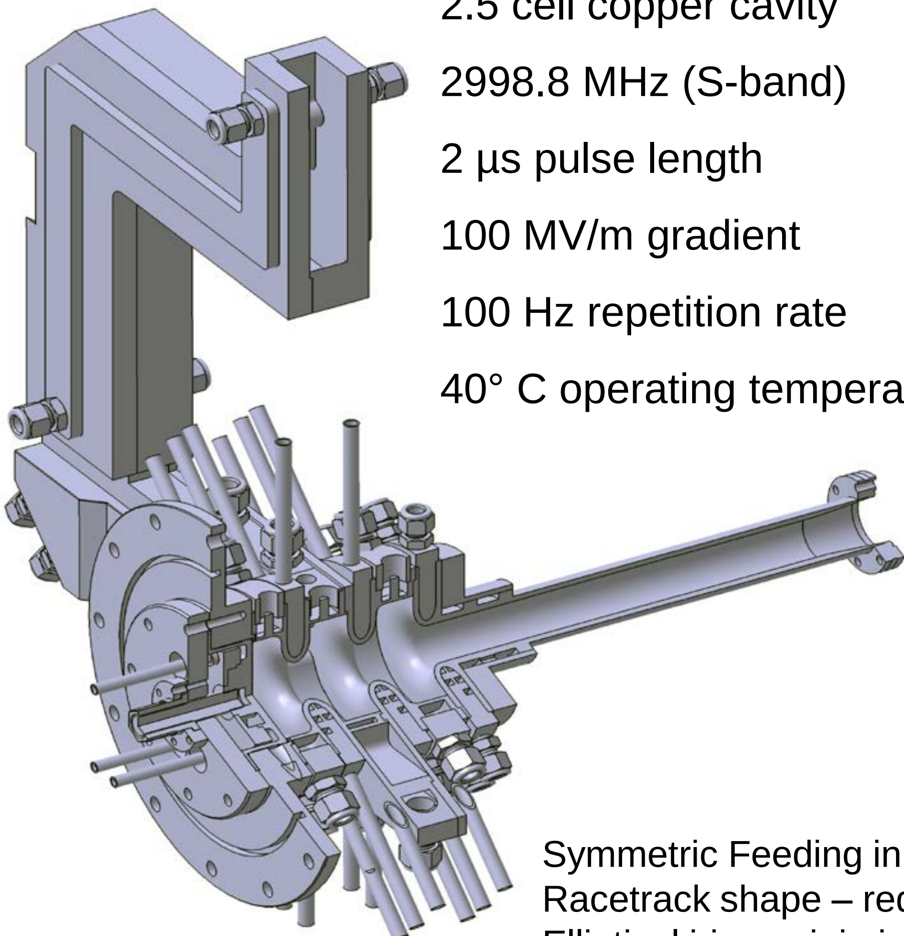


2.5 cell copper cavity

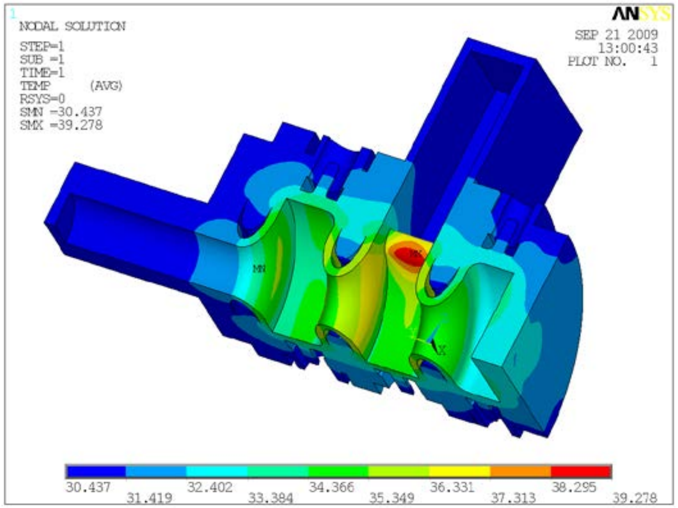
2998.8 MHz (S-band)

2 µs pulse length

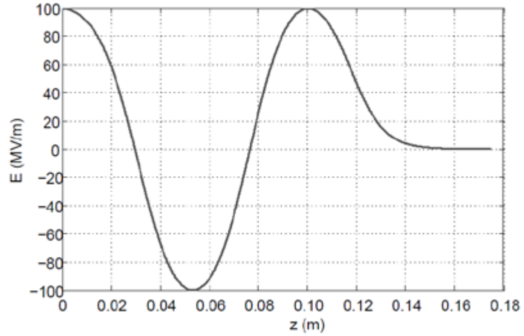
100 MV/m gradient

100 Hz repetition rate

40° C operating temperature



Thermal analysis of cavity.



On-axis E-field

Symmetric Feeding in Central Cell
Racetrack shape – reduce quad components
Elliptical iris – minimize surface fields

Large iris thickness – mode separation > 15 MHz

Longitudinal space requirements

Active length S-band acceleration	24 m
Active length C-band acceleration	208 m
ARAMIS string of undulators	60 m
Other beam line elements	273 m
Photon beam transport	100 m
Experiment halls	50 m

Total facility length **715 m**

⇒ ***No strong motivation for very high gradients***

⇒ ***C-band instead of S-band is motivated by power consumption and number of RF stations !***

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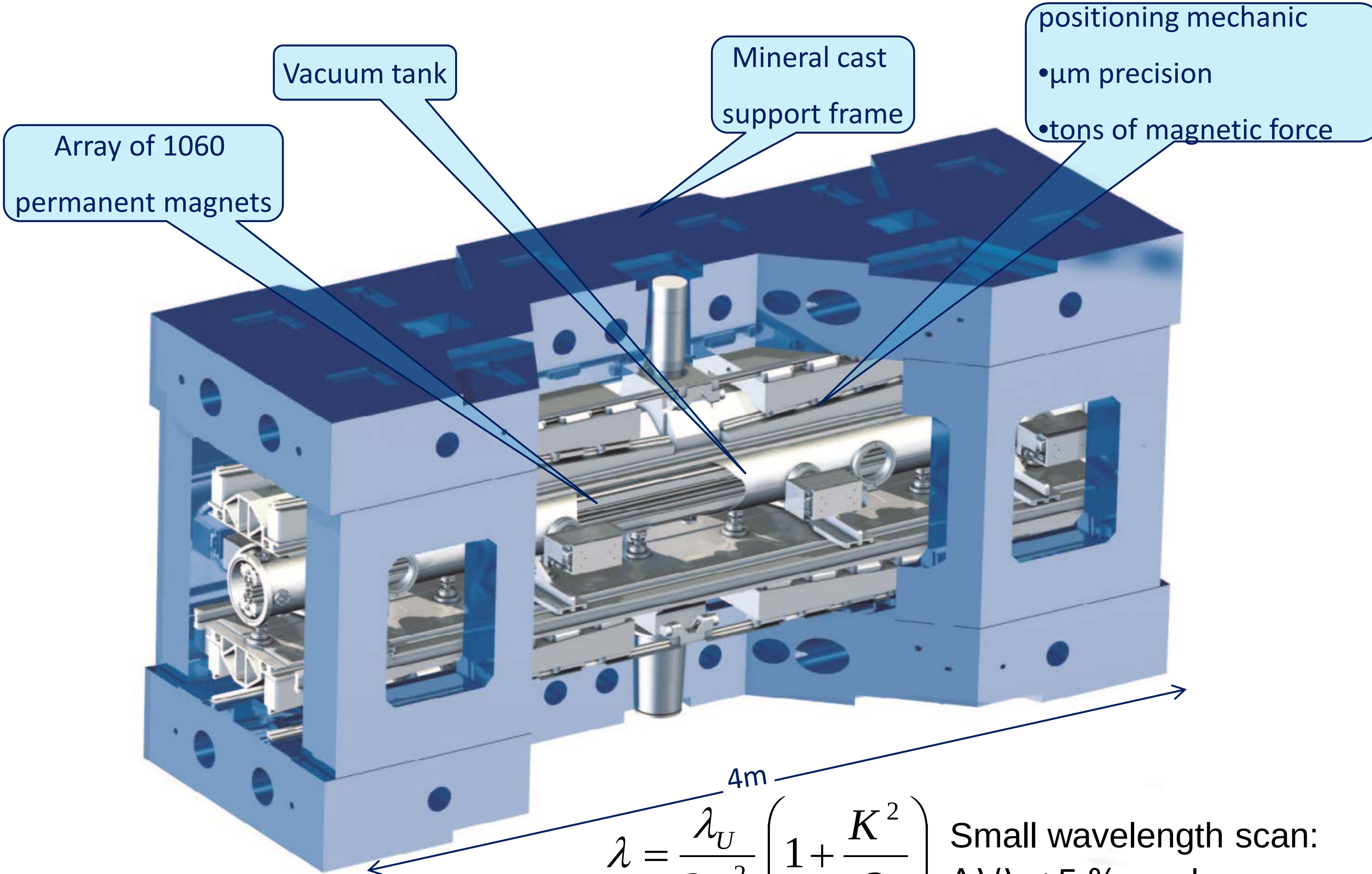
The SwissFEL building in the Würenlingen forest

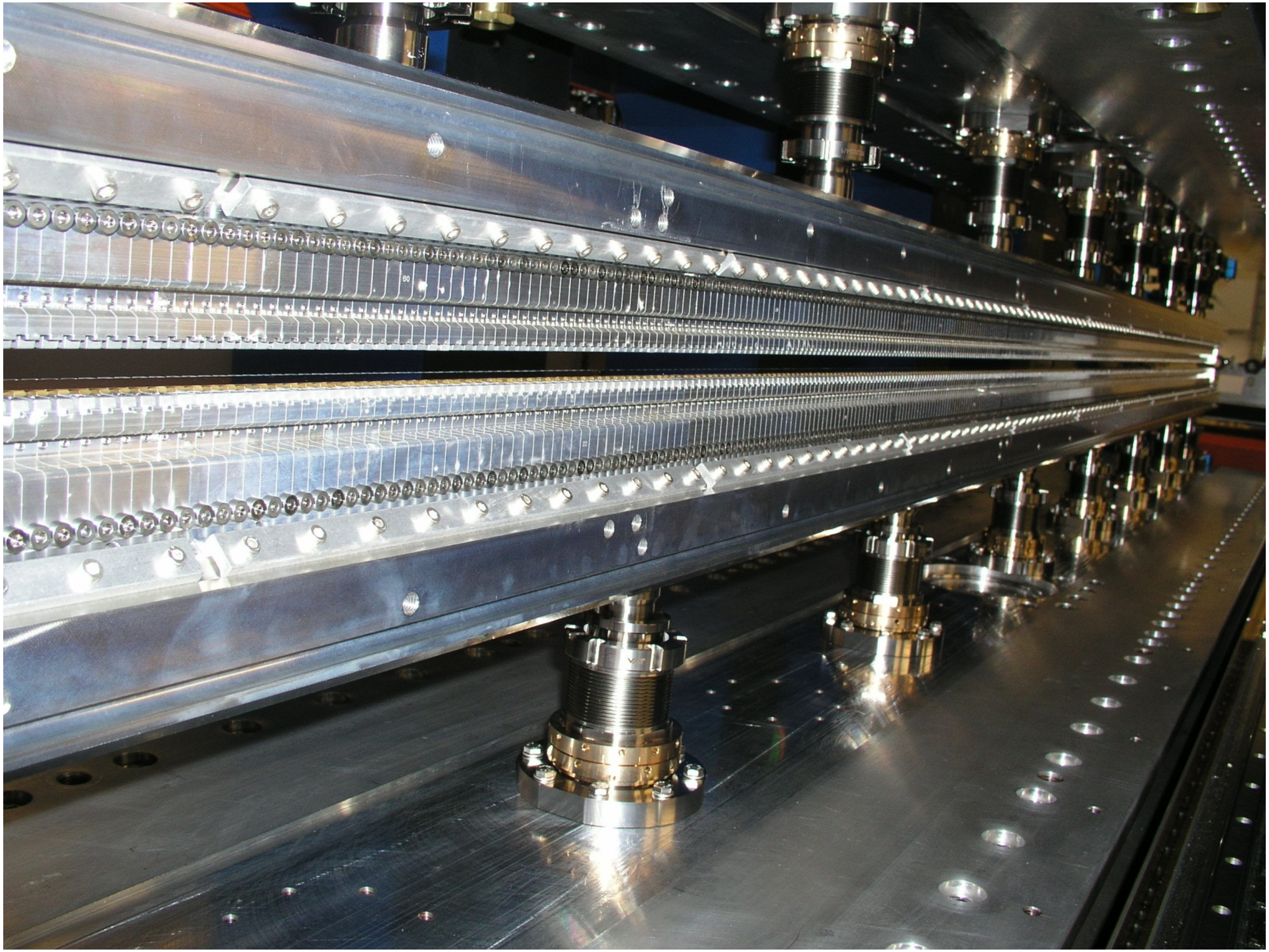
U15 Undulator for ARAMIS beamline



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

Small wavelength scan:
$\Delta\lambda/\lambda < 5\ \%$ → change gap.

Magnet Array for U15 Undulator (outside of its vacuum chamber)



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Beamline complete from Photo-injector to beam dump October 7th 2016.

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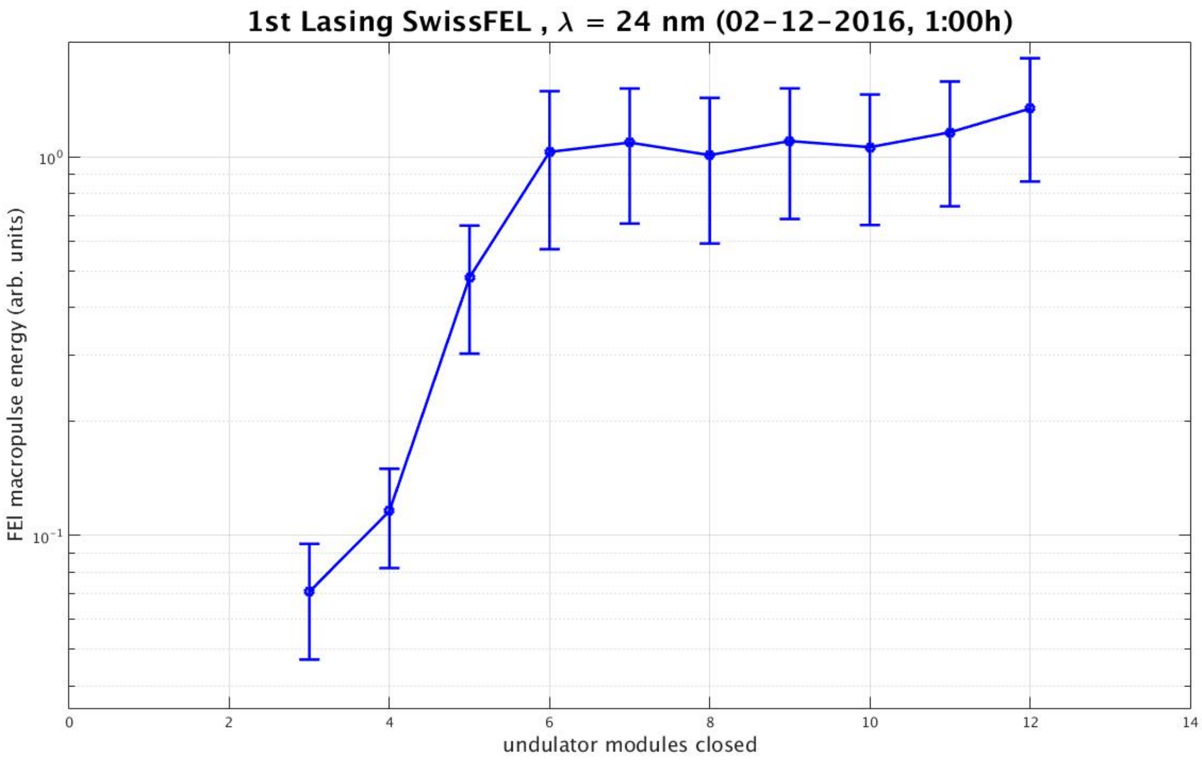
First lasing at moderate wavelength on 2.12.2016



Obtained with only 345 MeV beam energy, signal measured with Si-Diode
(half the injector RF + 1 main linac C-band RF station)
Mainly a systems test!

5.12.2016 SwissFEL Inauguration

On December 5th 2016, PSI held an inauguration ceremony for its new l arge-scale research facility SwissFEL, with Johann N. Schneider-Ammann, President of the Swiss Confederation, in attendance.

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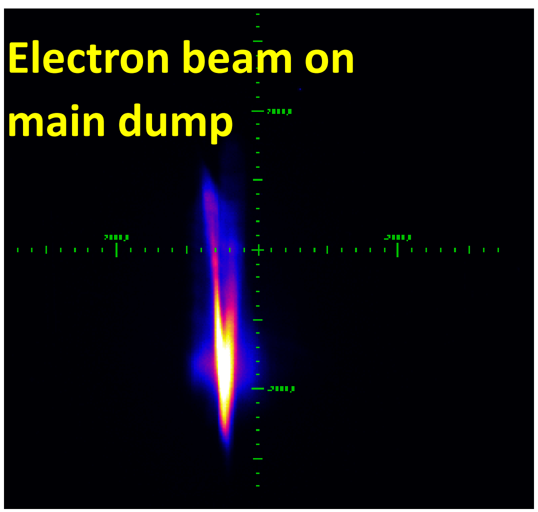
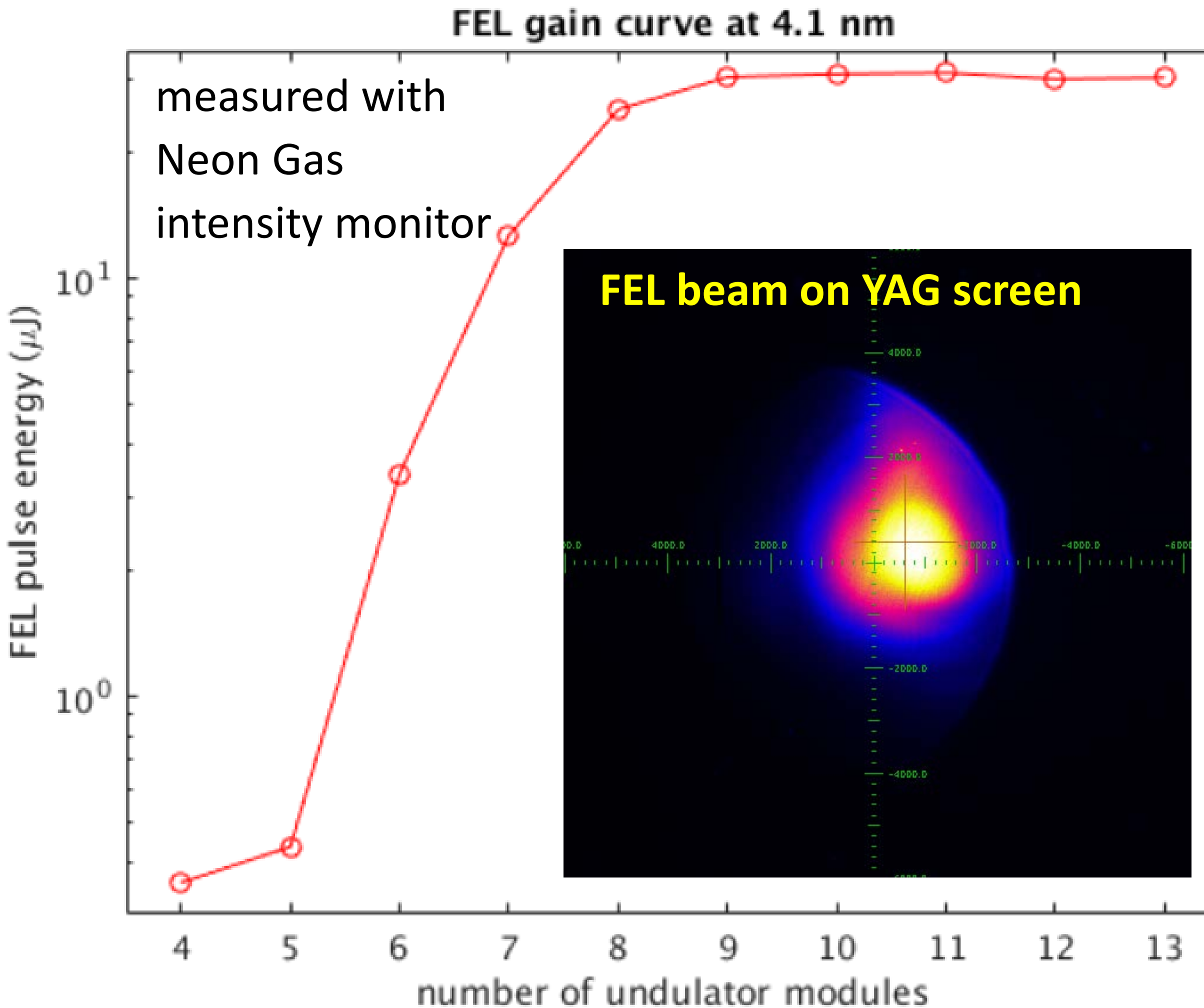
Commissioning progress May 15, 2017

First Lasing in nominal SwissFEL wavelength range (0.1-5.0 nm)!

Currently lasing at 1.3 nm !

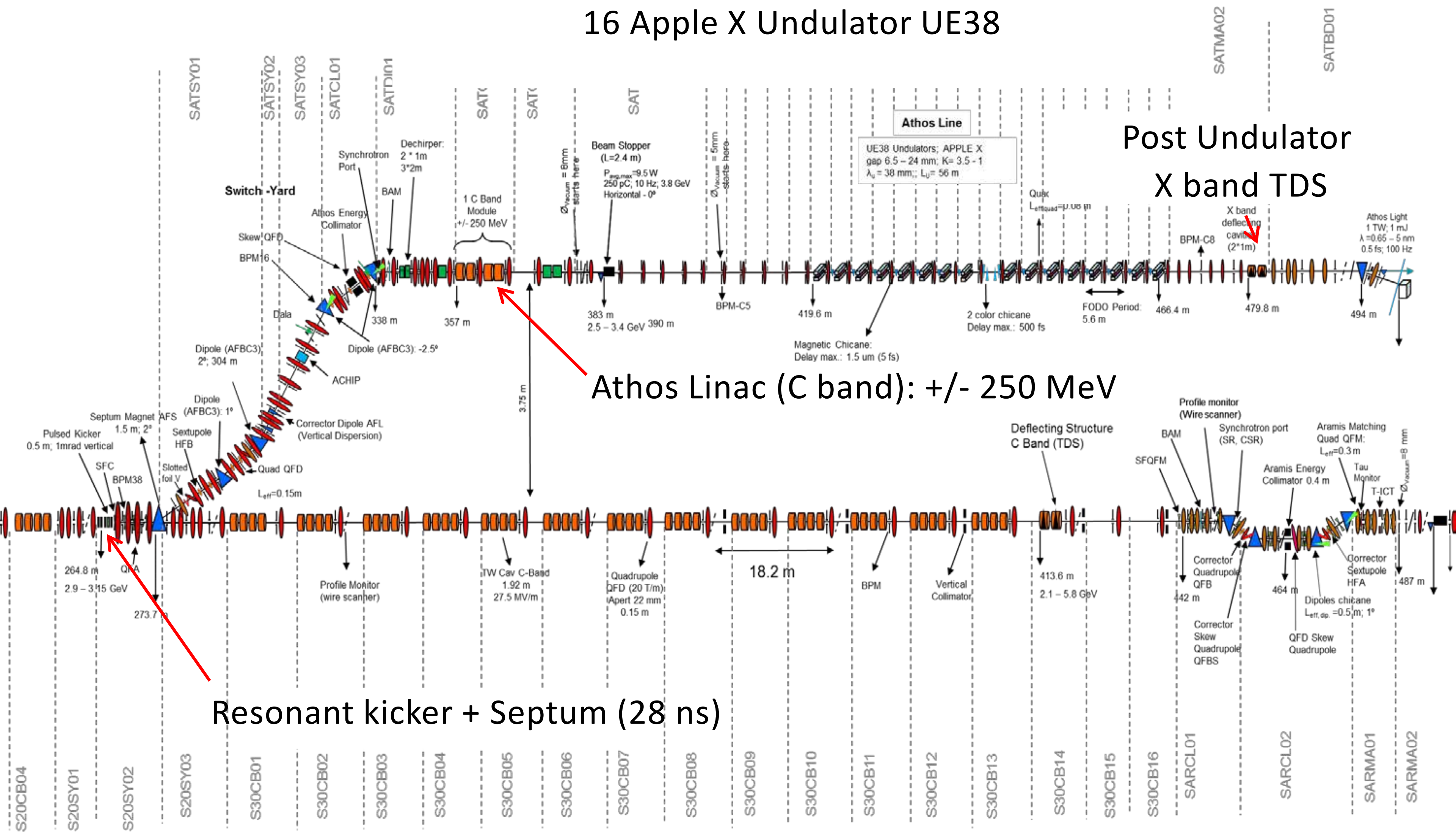
E_{e^-}	0.91	GeV
q_B	145	pC
σ_t (rms)	≈0.4	ps
K	1.2	
λ_{FEL}	4.1	nm
W_{FEL}	≈30	µJ





Athos Layout

16 Apple X Undulator UE38

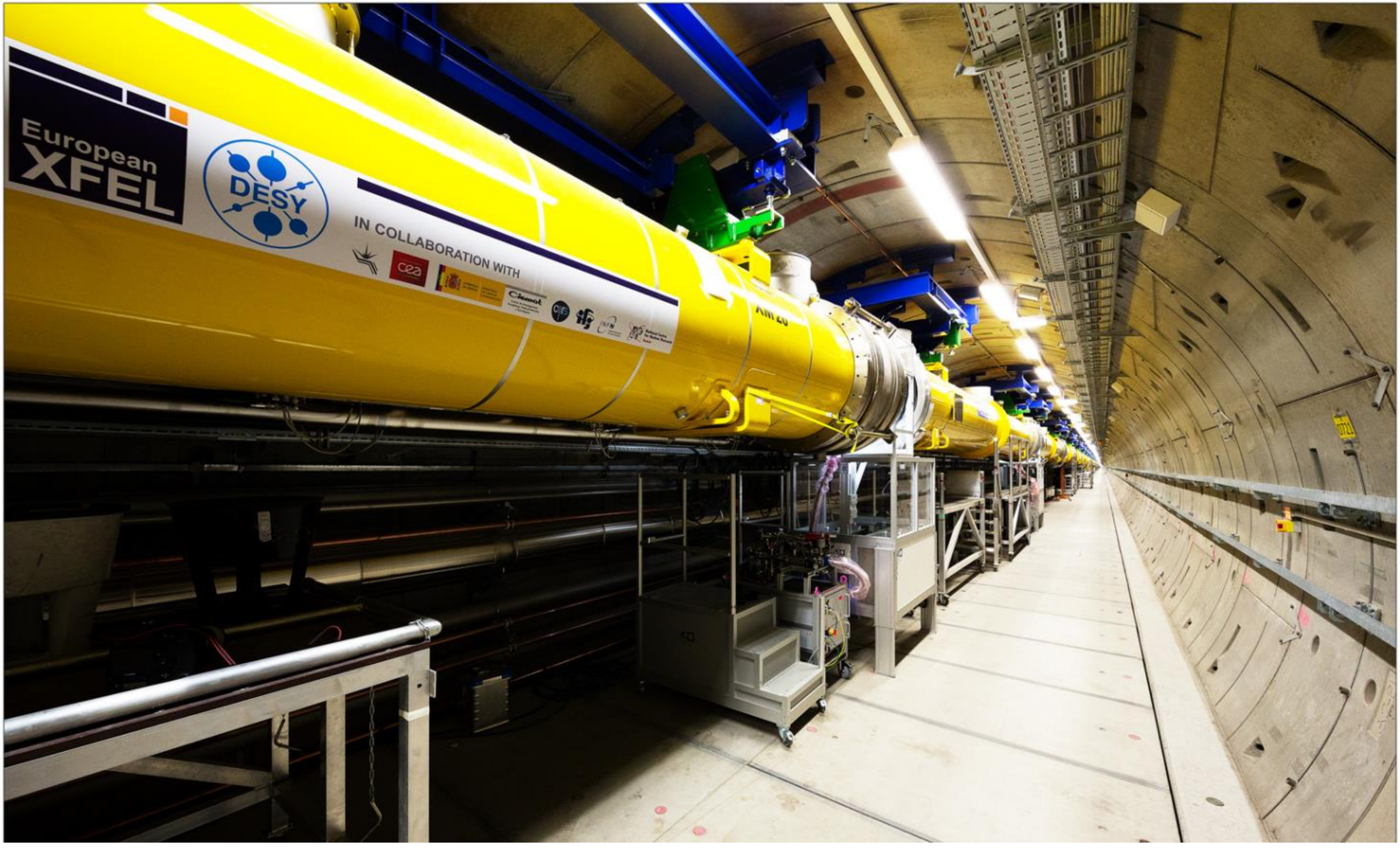


Post Undulator X band TDS

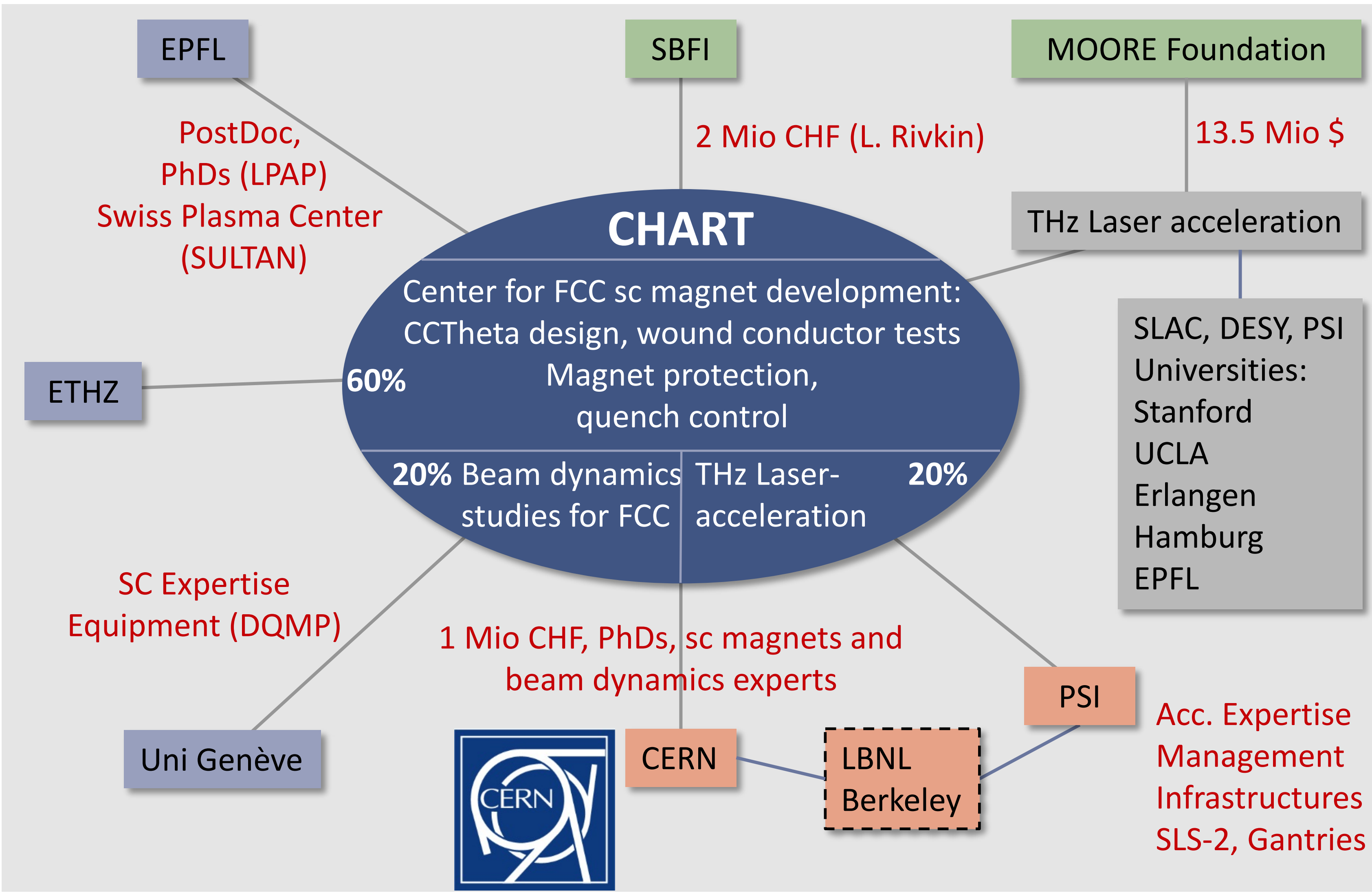
Athos Linac (C band): +/- 250 MeV

Resonant kicker + Septum (28 ns)

European X-FEL - Mise en service 2017.
Swiss "in-kind"contribution carried out by PSI
- BPM and IB transverse feedback electronics



Swiss Center for **A**ccelerator **R**esearch and **T**echnology (CHART)

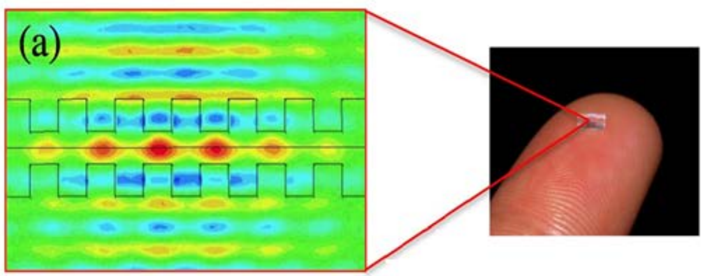


Accelerator on a Chip International Program (ACHIP)

13,5 M$ grant award

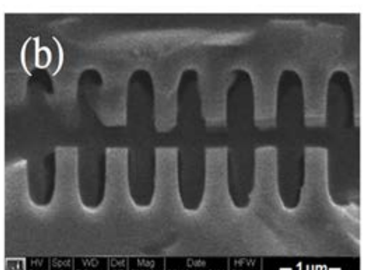
Grant holders - R. Ischebeck, L. Rivkin

Laser irradiation



Aim to demonstrate acceleration in a dielectric structure powered by THz radiation.

But also THz «streaking»! – Measurement of attosecond bunches.



Experiments taking place on SwissFEL linac

Tests on injector - measure wakes, damage thresholds

Full tests on ATHOS beam line ~ 2019.

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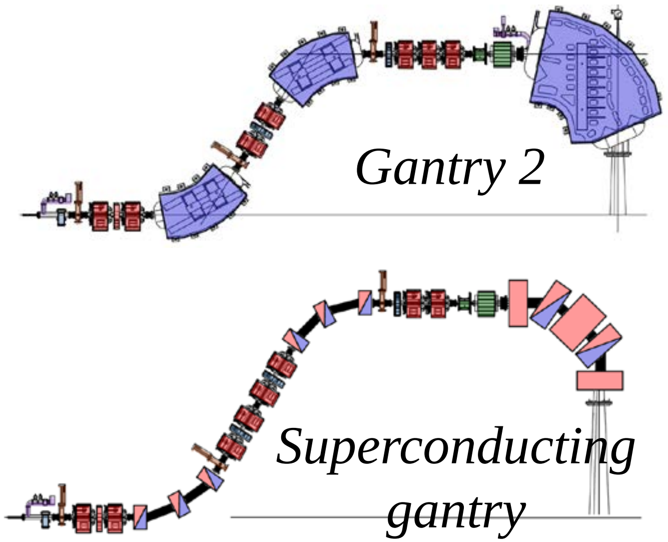
R&D on superconducting gantry designs for particle therapy

- Design study of: **Gantry** with **Superconducting magnets**



- **EXPECTED IMPROVEMENTS:**

⇒ **NOT much smaller, but:**

⇒ **Weight: 200 tons → 50 tons → Cost !**

⇒ **Field size: 12 x 20 cm^2 → 20 x 20 cm^2**

⇒ **Energy acceptance 1.5% → 20 %**

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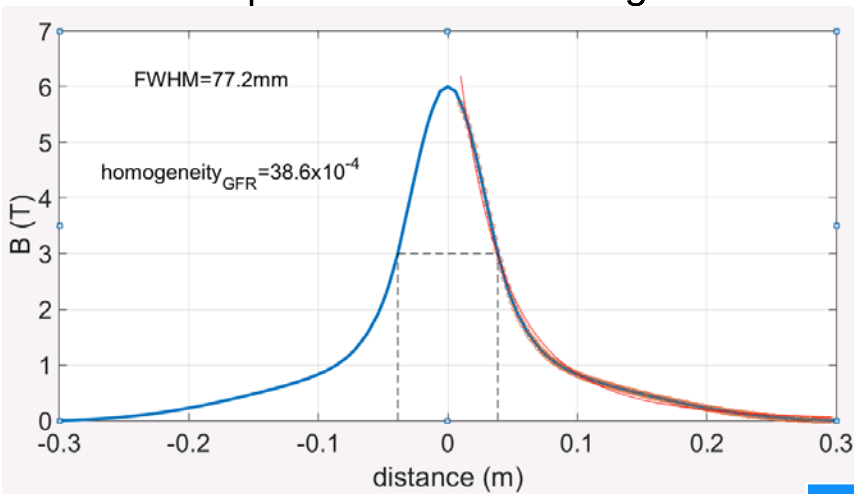
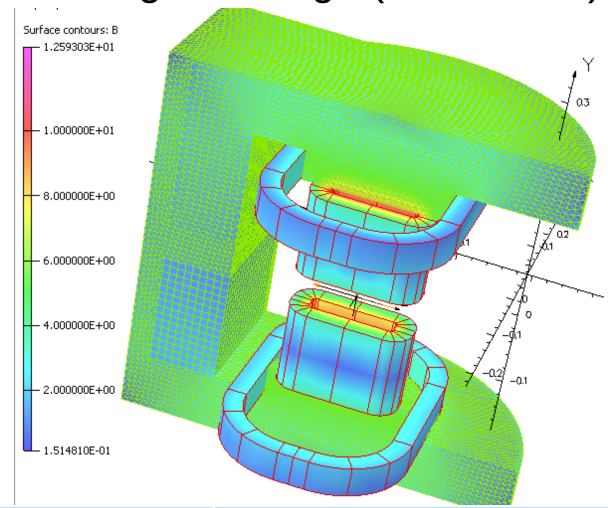
6 T- Superbend for the SLS 2.0- Design

Field profile-from the design



Magnet design (OPERA3D)



Specification	value
B_{peak}	≥ 5.0 T
FWHM	≤ 65 mm
GFR	6_H x 8_V mm^2
ΔB/B	≈$2x10^{-4}$

Magnet parameters	value
Aperture	57 mm
B_{peak}	6 T
Tot. Magnetic energy	105 kJ
I_{op} Tot inner coils	1.12 MA
I_{op} Tot outer coils	0.23 MA
Cooling	Indirect (conduction)
T_{op}	4.5 K
Superconducting wires	Nb_3Sn

Wakefield measurements at FACET (SLAC)

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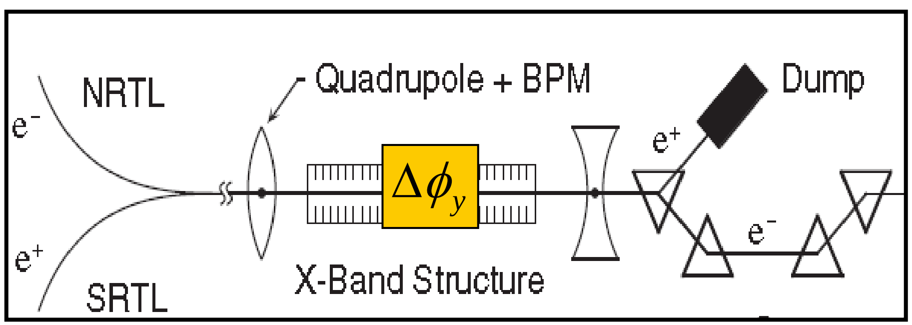
- Aim: Measure the wake-fields using positron (drive) and electron (witness) bunches.
- Wake-fields are excited by **driving positron bunch** passing through the structure with an offset from the linac axis.
- The **electron witness bunch** gets a kick from the excited wake-fields.
- The **transverse wakefield** can be calculated from the measurements of the deflection angle of the witness bunch with respect to a reference trajectory.

Experimental confirmation od damping would be desirable (before building 30 km of them!)

$$\Delta\phi_y = \frac{q_w Q_d L e^{-\left(\frac{\omega\sigma_d}{2c}\right)^2} e^{-\left(\frac{\omega\sigma_w}{2c}\right)^2}}{E_w} \cdot W_\perp(t)\Delta y_d$$



PHYSICAL REVIEW ACCELERATORS AND BEAMS **19**, 011001 (2016)

Beam-based measurements of long-range transverse wakefields in the Compact Linear Collider main-linac accelerating structure

Hao Zha,[1] Andrea Latina,[1] Alexej Grudiev,[1] Giovanni De Michele,[1,2,3] Anastasiya Solodko,[1] Walter Wuensch,[1] Daniel Schulte,[1] Erik Adli,[4,5] Nate Lipkowitz,[4] and Gerald S. Yocky[4]

[1]*CERN, European Organization for Nuclear Research, 1211 Geneva, Switzerland*
[2]*PSI, Paul Scherrer Institut, 5232 Villigen, Switzerland*
[3]*EPFL, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*
[4]*SLAC National Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*
[5]*Department of Physics, University of Oslo, 0316 Oslo, Norway*

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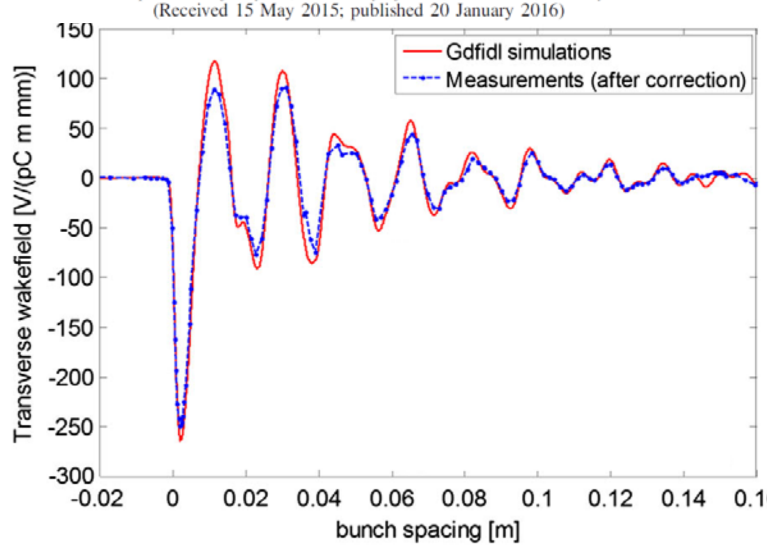
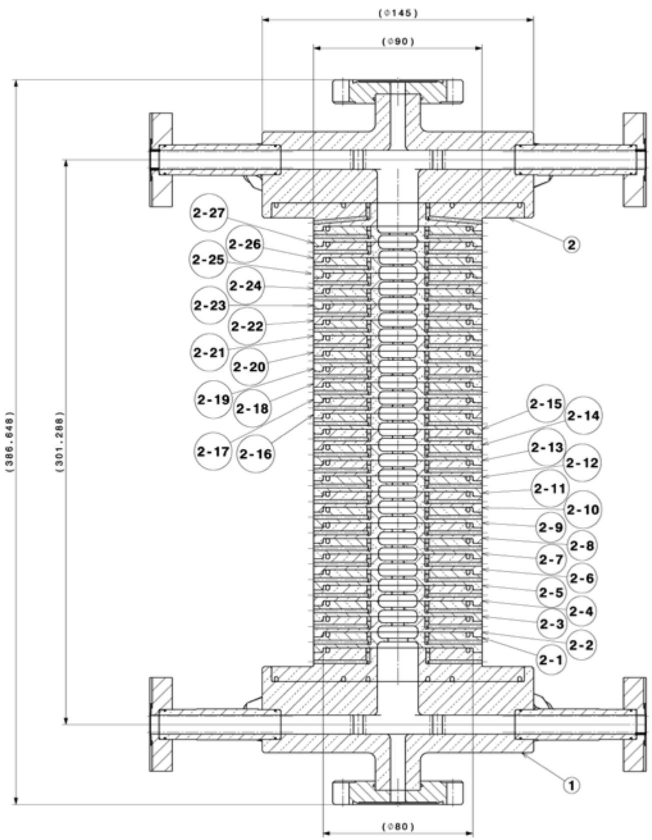


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

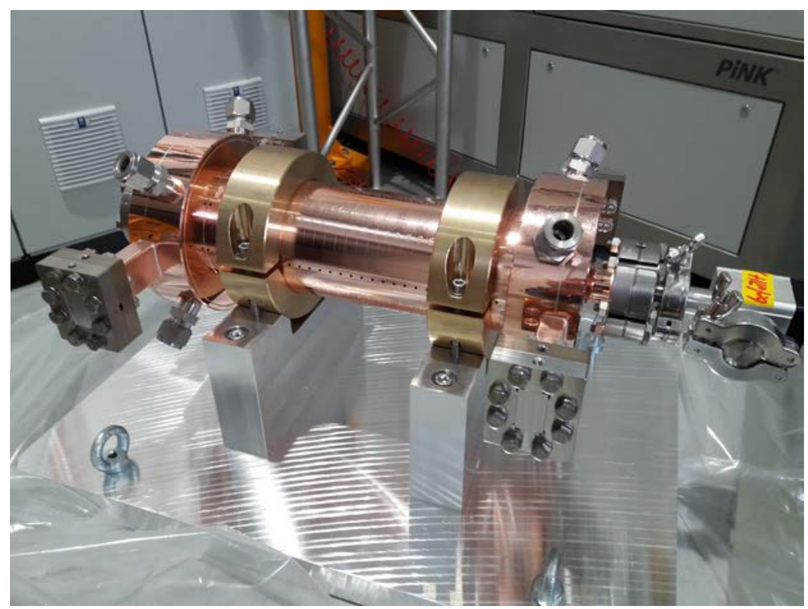
CERN-PSI X-band accelerating structures

SNF Grant – Rivkin, Garvey

27 cells + input couplers ($2\pi/3$)



- Tolerances on the drawing is $\pm 2\ \mu m$ (iris aperture and cell diameter (R_a = 25 nm).
- Parts are all fabricated (by VDL)
- Assembling and brazing at PSI
- 2 structures:
  - ✓ first one under high-power test at CERN
  - ✓ second one is brazed and vacuum tight and ready for bead-pull measurements at CERN.

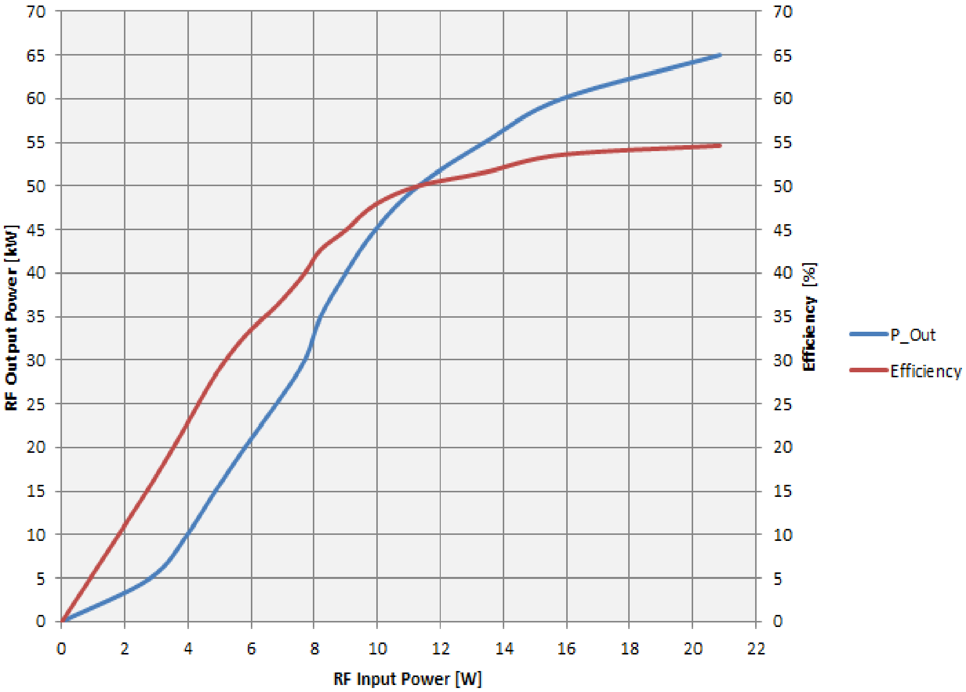


500 MHz Solid State Amplifier

CTI grant – Garvey, Gaspar

Technology pioneered by SOLEIL

•Technology Transfer PSI -> Industry
•New generation of solid state amplifier to replace SLS booster klystrons (eventually SR klystrons)

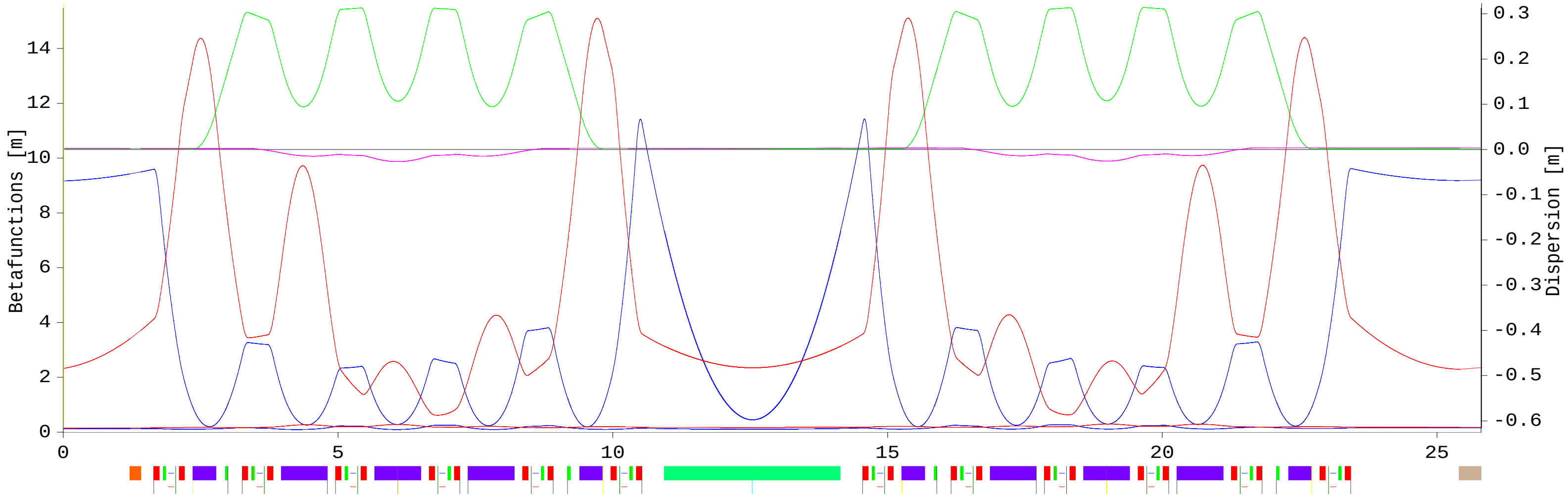


Compact Source for Actinic Mask Inspection - Motivation for this study

CTI grant – Garvey, Wrulich

- There is a general consensus within the semiconductor community that EUVL will be the next-generation HVM technique for producing smaller and faster integrated circuits.
- Advances in multi-layer Mo-Si mirrors with high reflectivity (~ 70%) and large bandwidth (~2%) will make 13.5 nm the wavelength of choice.
- The development of metrology methods at EUV wavelengths for mask inspection will be indispensable for the success of EUVL.
  - A mask inspection tool (RESCAN) is currently being developed on an SLS beam-line (Y. Ekinci et. al.) with the support of private industry.
- However, the development of such an inspection tool only makes sense if a source of EUV radiation, having the required properties, can be built and operated in an industrial environment at an acceptable cost.
- We propose here a **compact** (~ 5 m x 12m) synchrotron radiation source for this purpose.

Linear optics design (A. Streun)

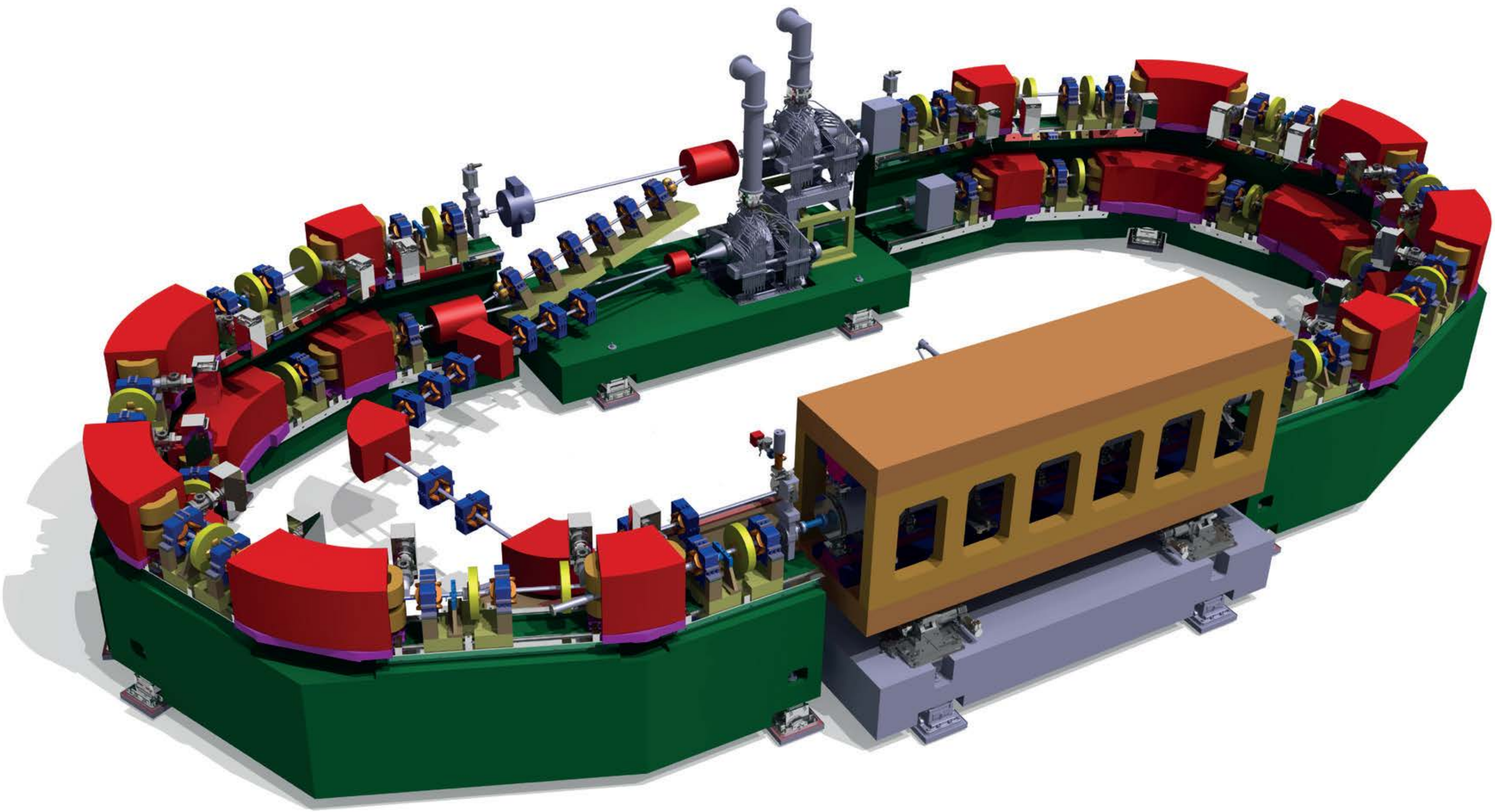


Storage ring optical functions (β_x , β_y , D_x, D_y)

Lattice features

- Strong horizontal focussing: strong quads → small magnet bore; strong sextupoles to correct chromaticity.
- Weak dispersion (MBA) ensures adequate momentum acceptance despite small aperture → needed to reduce particle loss to Touscheck scattering.
- Skew-quad windings in sextupole to generate some vertical emittance → reduce Touscheck scattering.
- Small β_x at center of undulator → minimise source-point size → brightness.
- β_y reduced at undulator extremities to reduce particle losses (small vertical gap).
- Magnetic elements would be installed / aligned on girders. Simulations show orbit correction due to misalignments (100 µm, 100 µrad) easily corrected with 1 mrad correction coils.

Does it all fit? - COSAMI 3-D integration



- Collaborations between PSI and France:
  - In accelerators, simply not enough.

    Co-operation with SOLEIL (solid state amps, femto-slicing, simulation tools).

    Collaboration with CEA/Saclay for the SLS 3rd harmonic SC cavity

    Activities in H2020 «network»program ARIES – high efficiency klystrons

    Participation in common collaborations, CLIC/CTF3, E-XFEL

However; Strong potential for collaboration between ESRF-EBS and SLS-2.

To conclude: I hope to have shown that there is a strong and vibrant accelerator program in place at PSI, particularly in operation and construction. Hopefully increased basic R&D will be stronger also in future.

Many thanks to the «bureau»for the opportunity to make this presentation.

And many thanks for your attention.