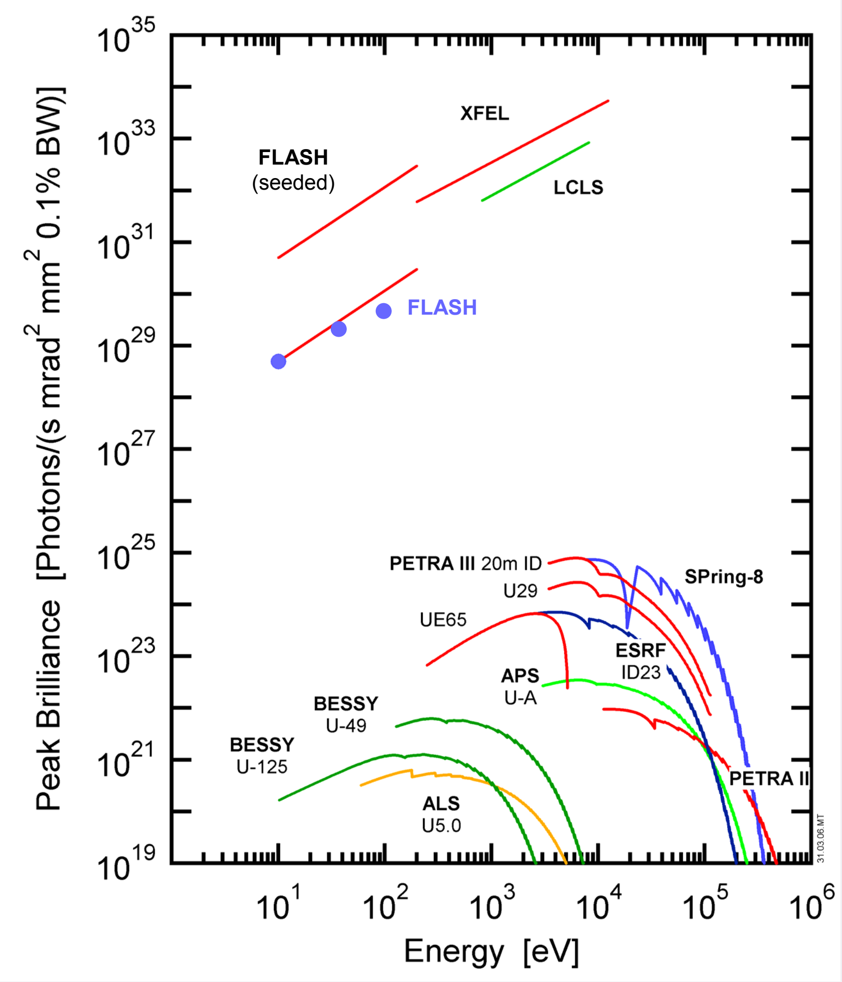
The European XFEL Project

Overall Design and Accelerator Technology
FLASH (VUV-FEL) Operation

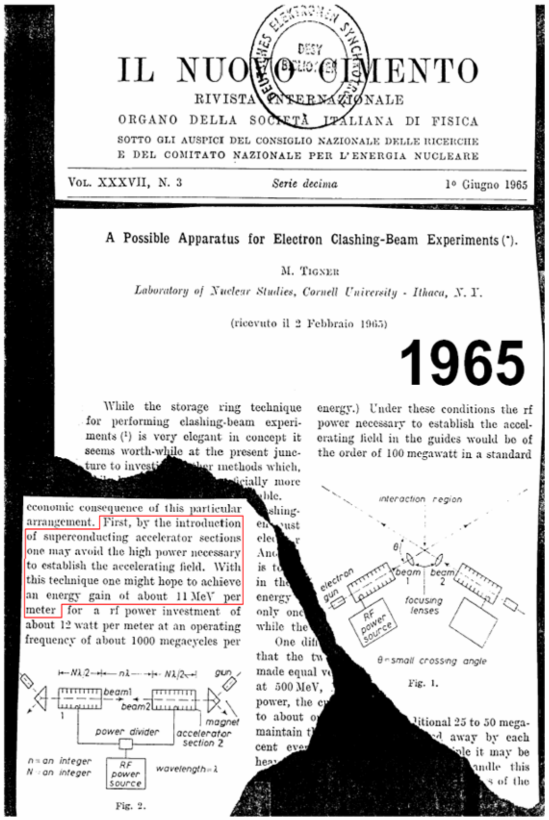
Hans Weise / DESY

Laser Light in the VUV and X-ray Wavelength Regime

- Based on the TESLA Technology and based on the VUV-FEL (FLASH)
- Proposal Oct. 2002 – X-ray FEL user facility with 20 GeV supercon-ducting linear accelerator in TESLA technology
- Approval by German government Feb. 2003 as European Project
- Commitment for 50% of funding + expected max.10% by Hamburg & Schleswig-Holstein, at least 40% European & international partners



TESLA Technology: An Old Idea as Basis for the XFEL



IL NUOVO CIMENTO
RIVISTA INTERNAZIONALE
ORGANO DELLA SOCIETÀ ITALIANA DI FISICA
SOTTO GLI AUSPICI DEL CONSIGLIO NAZIONALE DELLE RICERCHE
E DEL COMITATO NAZIONALE PER L'ENERGIA NUCLEARE

Vol. XXXVII, N. 3 — *Serie decima* — 1° Giugno 1965

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

1965

While the storage ring technique for performing clashing-beam experiments (1) is very elegant in concept it seems worth-while at the present juncture to investi… …er methods which, … …ficially more …able.

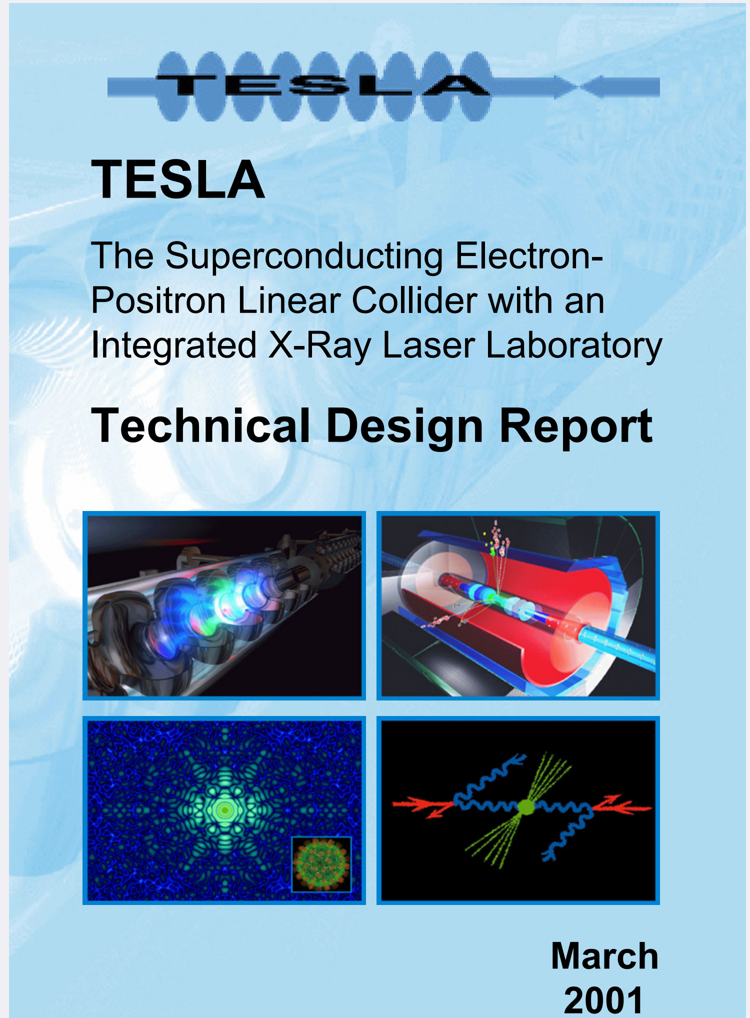
economic consequence of this particular arrangement. First, by the introduction of superconducting accelerator sections one may avoid the high power necessary to establish the accelerating field. With this technique one might hope to achieve an energy gain of about 11 MeV per meter for a rf power investment of about 12 watt per meter at an operating frequency of about 1000 megacycles per

energy.) Under these conditions the rf power necessary to establish the accelerating field in the guides would be of the order of 100 megawatt in a standard

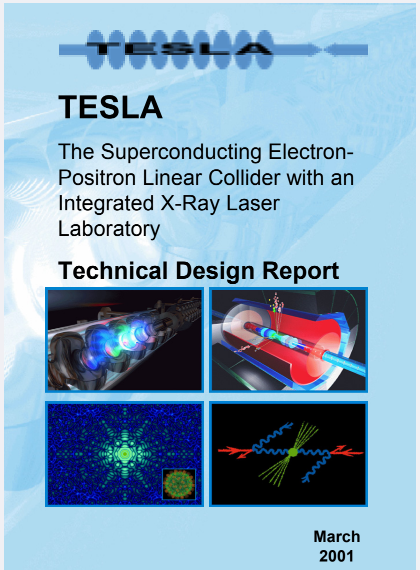
Fig. 1.

Fig. 2.

M. Tigner, A Possible Apparatus for
Electron Clashing-Beam Experiments
Il Nuovo Cimento Vol. XXXVII, No.3 (1965)



The XFEL Technical Design Report



03/2001	**XFEL as part of the TESLA LC**
10/2002	**Separation of the XFEL**
2005	**Detailed XFEL acc.layout**
2006	**Final TDR incl. detailed technical layout and experiments**

ILC TDR coming up soon (?!)

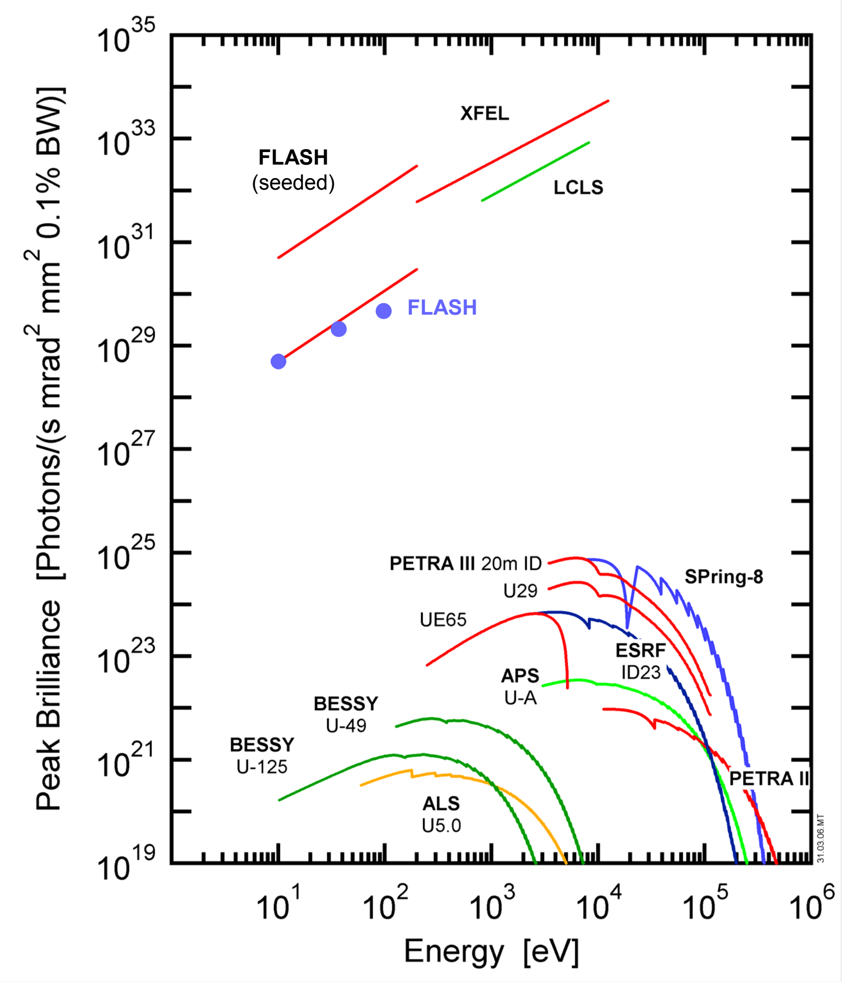
Laser Light in the VUV and X-ray Wavelength Regime

X-ray FEL radiation (0.2 - 14.4 keV)

- ultrashort pulse duration <100 fs (rms)
- extreme pulse intensities 10^{12}-10^{14} ph
- coherent radiation x10^{9}
- average brilliance x10^{4}

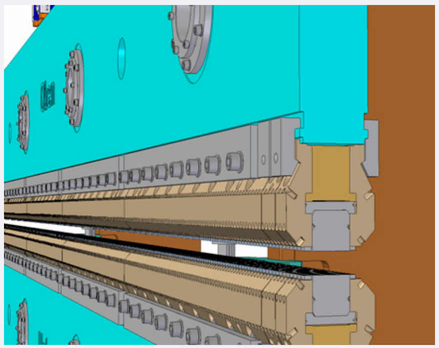
Spontaneous radiation (20-200 keV)

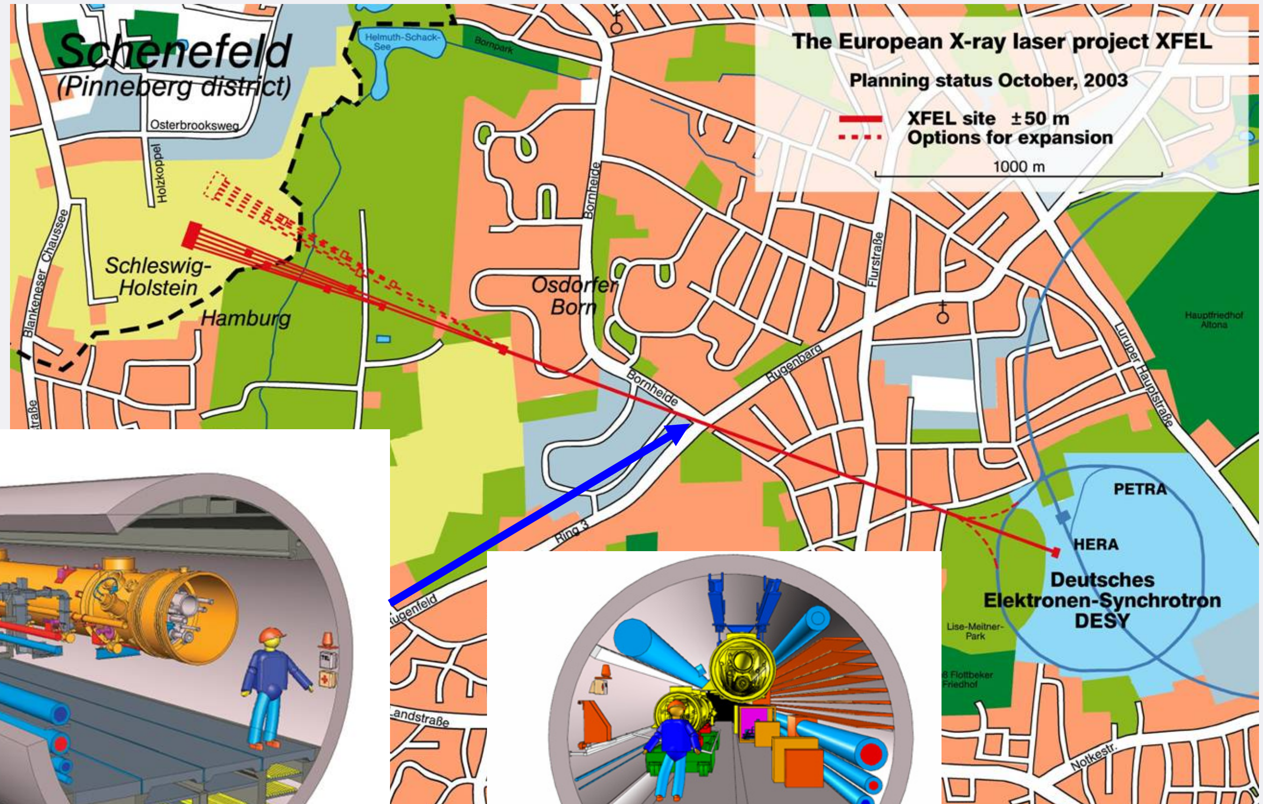
- ultrashort pulse duration <100 fs (rms)
- high brilliance

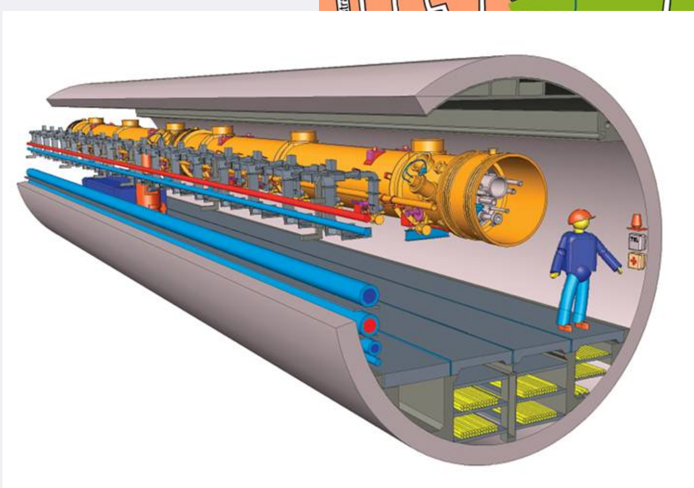


Overall Layout and Site

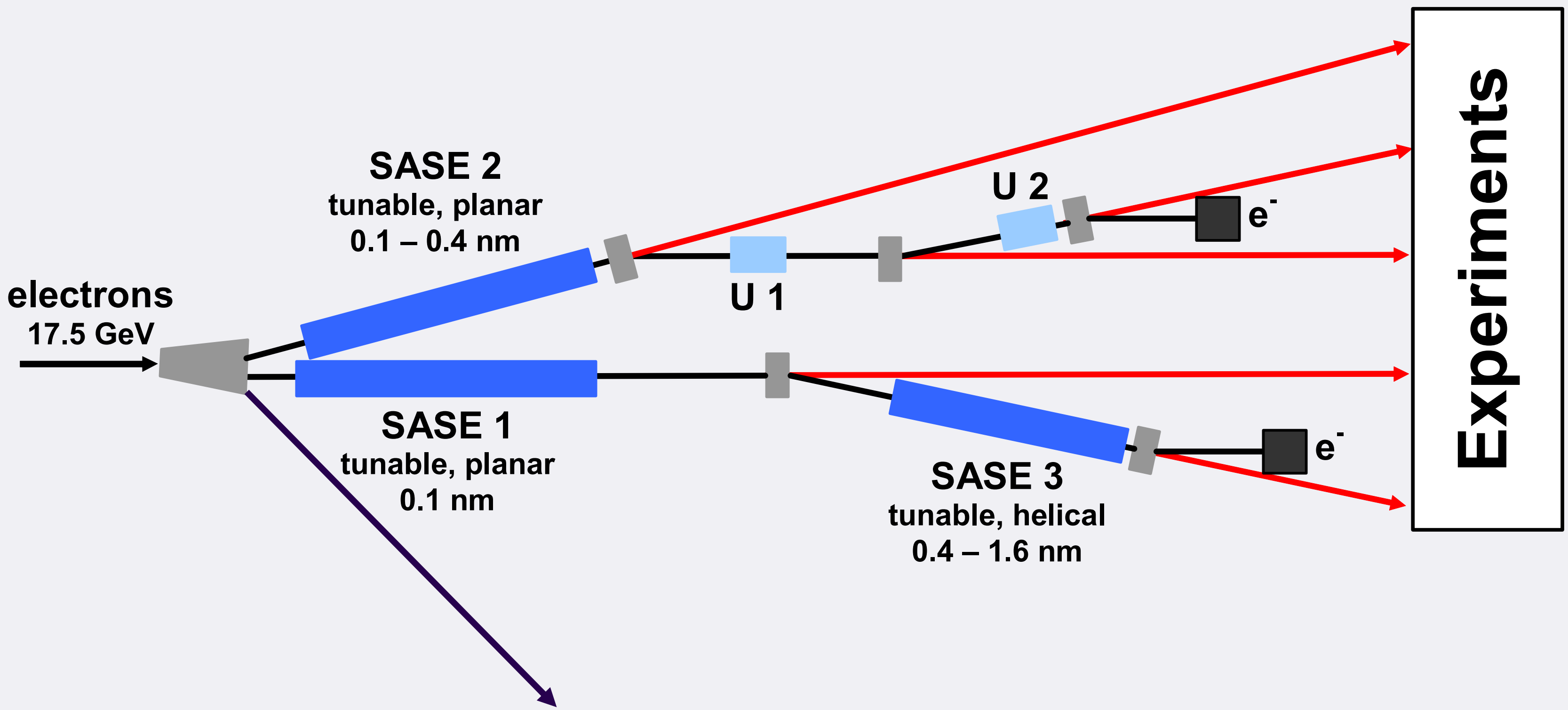
3.4km







Photon Beam Lines

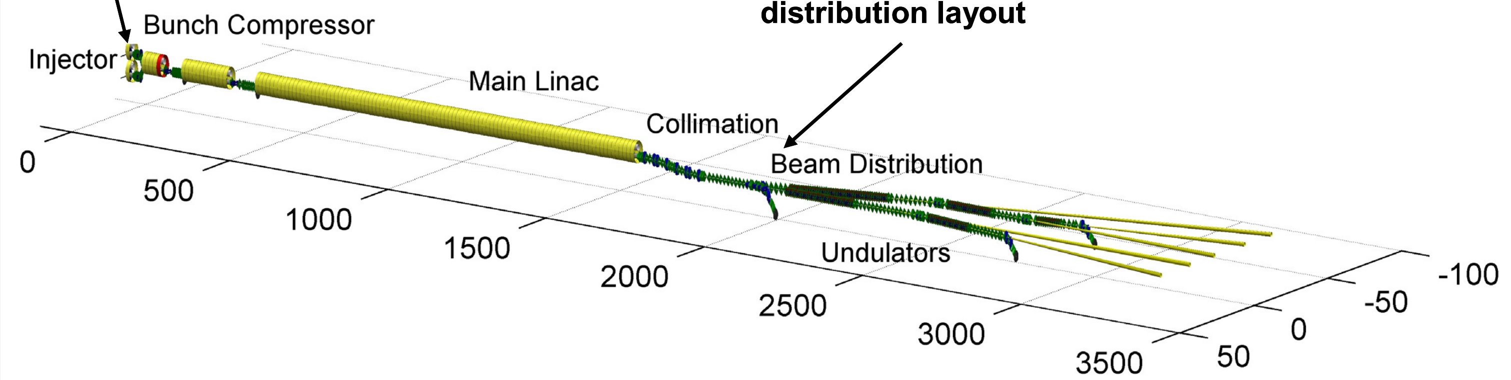


Possible extension by 5 more beam lines and 10 experimental stations

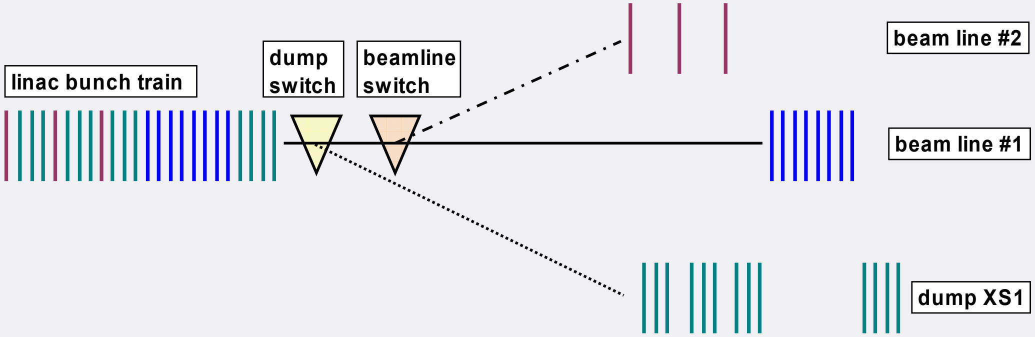
Accelerator Layout and Parameters

One injector initially installed

Connection to 2nd stage upgrade included in beam distribution layout



Different beam time structure to different experiments – concept using kicker devices permits large flexibility without having to change the (preferably homogenous) bunch train structure in the linac

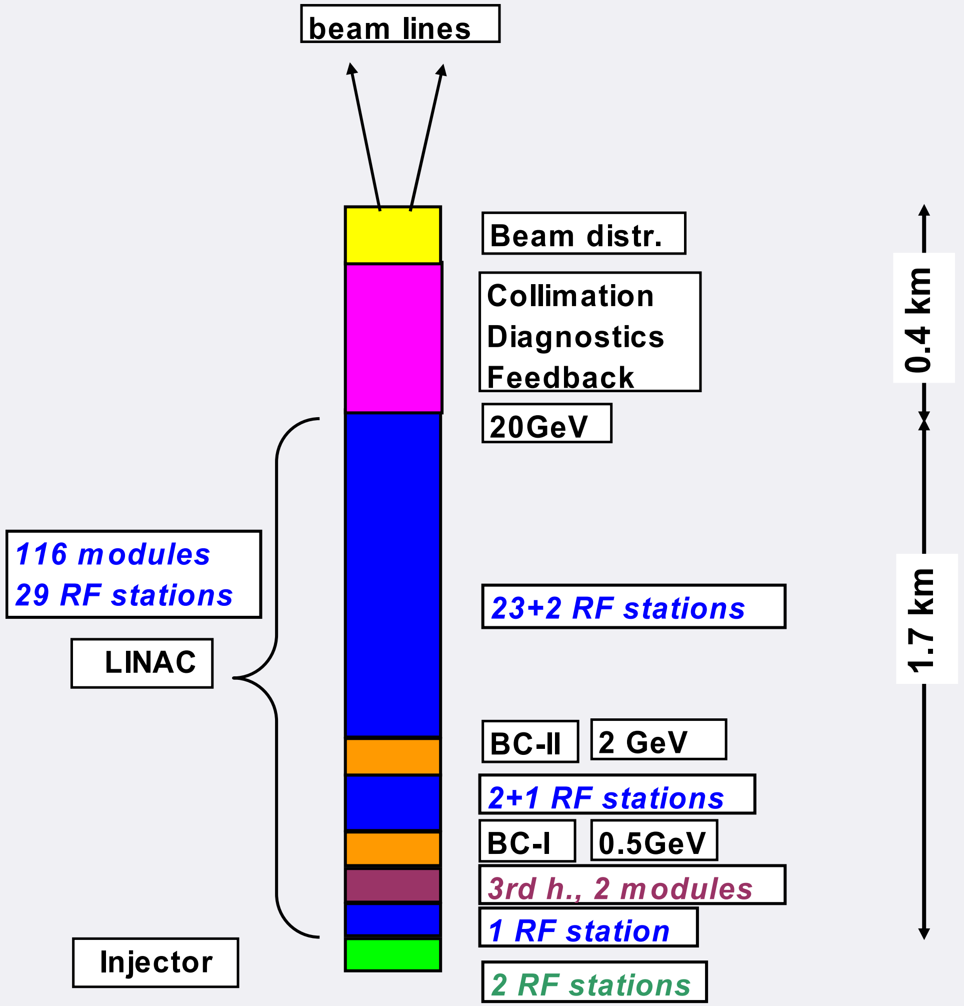


XFEL Accelerator Layout Supports Availability

2 – 20 GeV
- (23 + 2) x 4 = 100 acc.modules
- 800 cavities at 21.7 MV/m or
- 736 cavities at 23.6 MV/m
- (23 + 2) RF stations inside tunnel

500 – 2000 MeV
- 12 acc.modules
- 96 cavities at 15.1 MV/m or
- 64 cavities at 22.6 MV/m
- (2 + 1) RF stations inside tunnel

100 – 500 MeV
- 4 acc.mod.
- 32 cavities at 12.5 MV/m
- RF station outside tunnel



XFEL Accelerator Specs. (as Reference)

Energy for 0.1nm wavelength *(max. design energy)*	17.5 GeV *(20 GeV)*
# of installed accelerator modules	116
# of cavities	928
Acc. Gradient (104 active modules) at 20 GeV	23.6 MV/m
# of installed RF stations	29
Klystron peak power (26 active stations)	5.2 MW
Loaded quality factor Q_{ext}	$4.6 \cdot 10^6$
RF pulse length	1.4 ms
Beam pulse length	0.65ms
Repetition rate	10 Hz
Max. average Beam power	600 kW
Unloaded cavity quality factor Q_0	10^{10}
2K cryogenic load (including transfer line losses)	1.7 kW
Max. # of bunches per pulse *(at 20 GeV)*	3,250 *(3,000)* [1)]
Min. bunch spacing	200 ns
Bunch charge	1 nC
Bunch peak current	5 kA
Emittance (slice) at undulator	1.4 mm*mrad
Energy spread (slice) at undulator	1 MeV

1) The limitation to 3,000 bunches at 20 GeV beam energy is related to a maximum load of 300 kW on each of the beam dumps in the initially installed two electron beam lines.

Operational Flexibility & Upgrade Options

Energy variation:

change acc gradient only in main linac (keep low energy section up to 2nd BC unchanged)

post-linac beam lines are designed for ±1.5% dynamic acceptance → wavelength scan within a pulse train possible

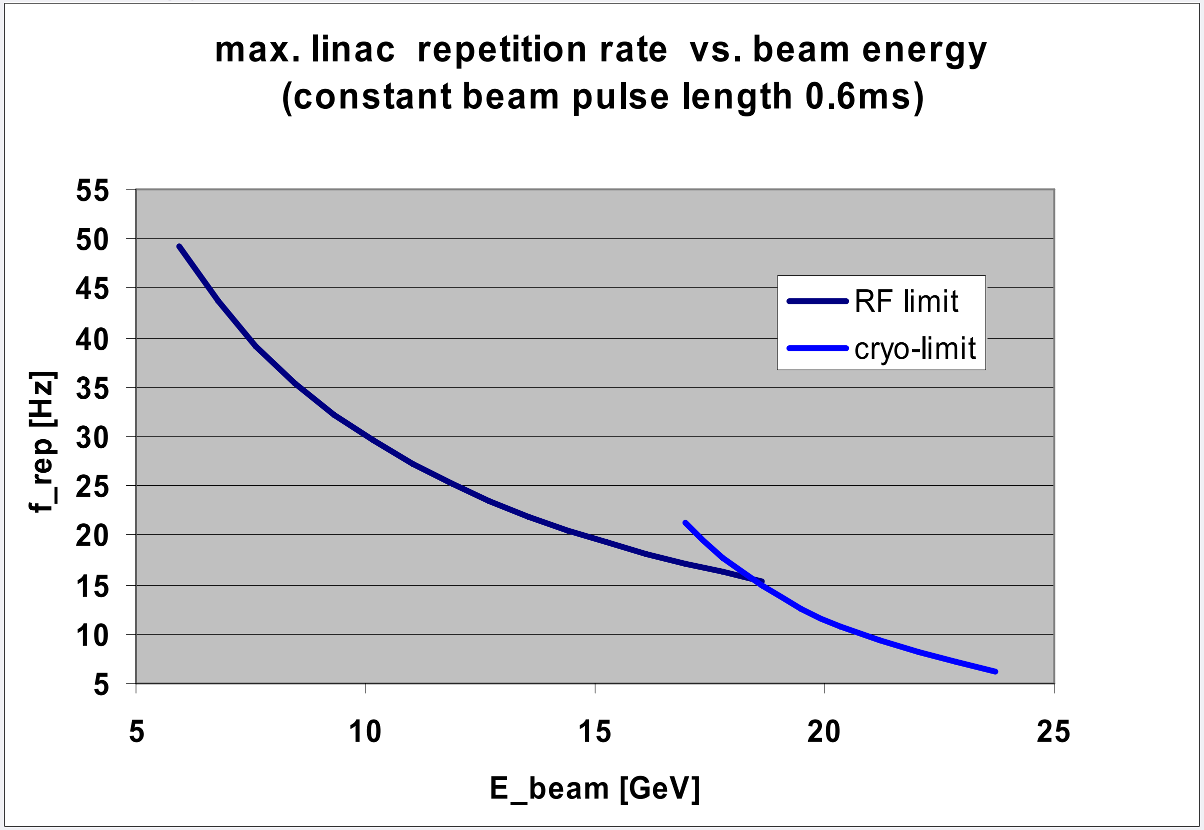
Expect performance of electropolished s.c. cavities better than baseline design specs → potential for higher energy/shorter wavelength:

RF and cryogenic systems can support linac operation up to ~ 24GeV (28MV/m), post-linac beam lines laid out for up to 25GeV

Operational Flexibility & Upgrade Options

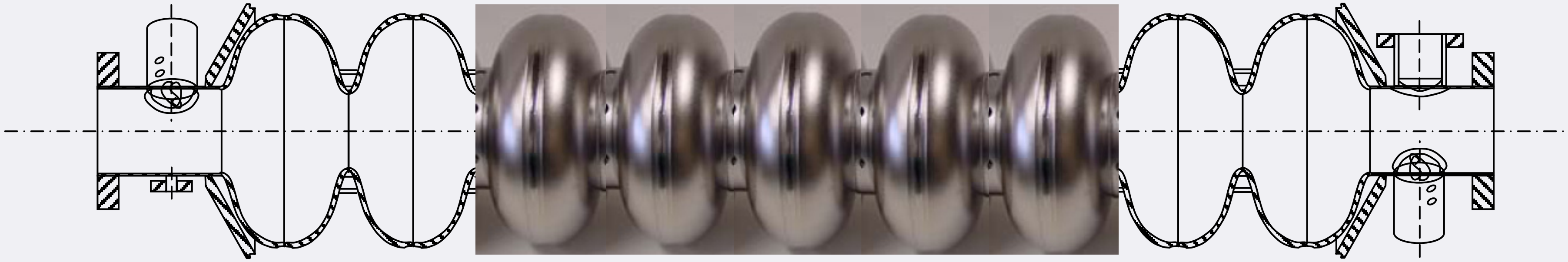
The overhead designed into tech sub-systems also permits higher duty cycle/rep rate of the linac (***if*** injector can support that) – depending on beam energy:

Assumption: RF and cryogenic systems operated at 80% of design limit



XFEL s.c. Cavities

cavity material		RRR 300 niobium
type of accelerating structure		standing wave
accelerating mode		TM010, π-mode
fundamental frequency	f_{RF} [MHz]	1,300
active length	L [m]	1.038
nominal gradient	E_{acc} [MV/m]	23.6
quality factor	Q_0	$>10^{10}$
cell-to-cell coupling	K_{cc} [%]	1.87
iris diameter	[mm]	70



RRR 300 niobium

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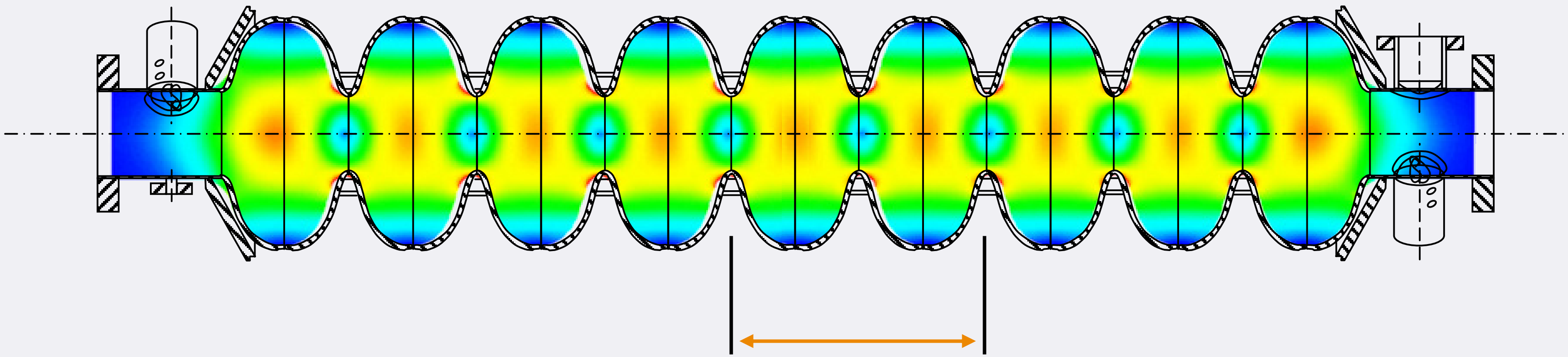

λ ≈ 23 cm ↷ 1.3 GHz

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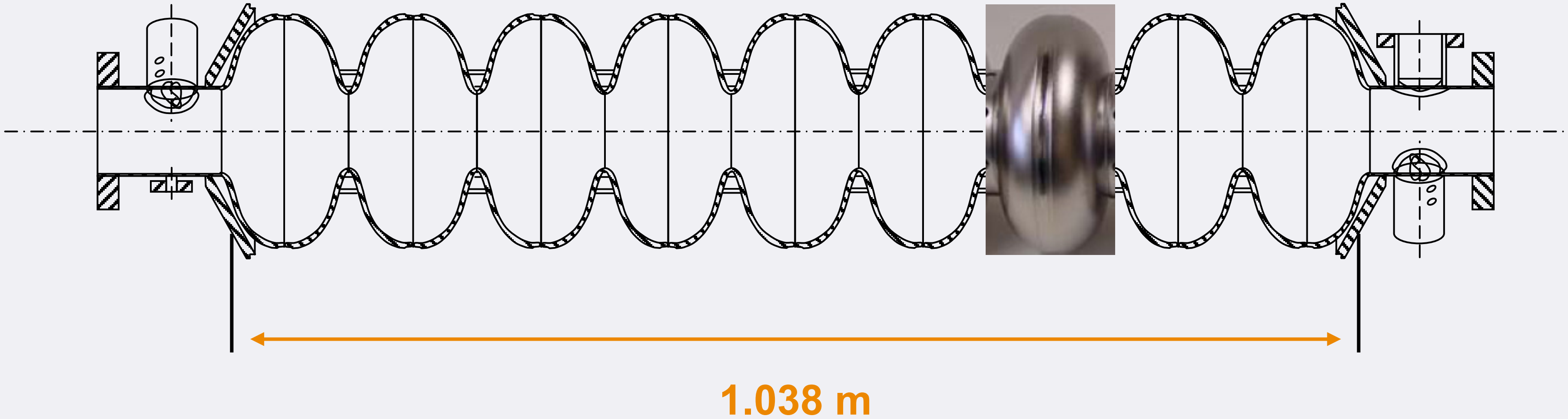

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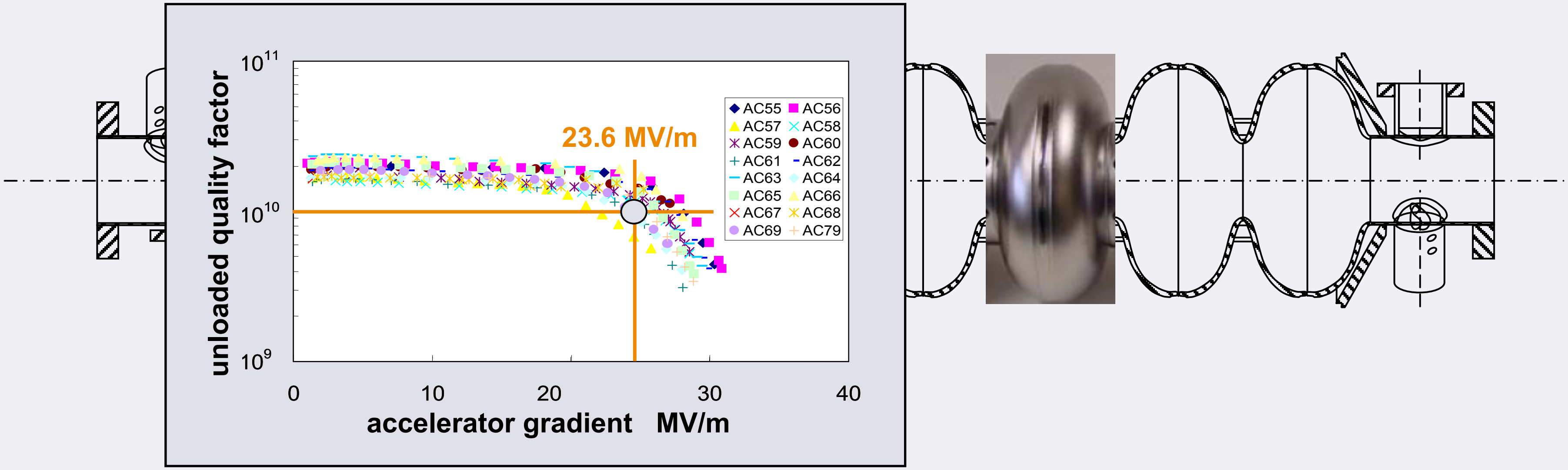

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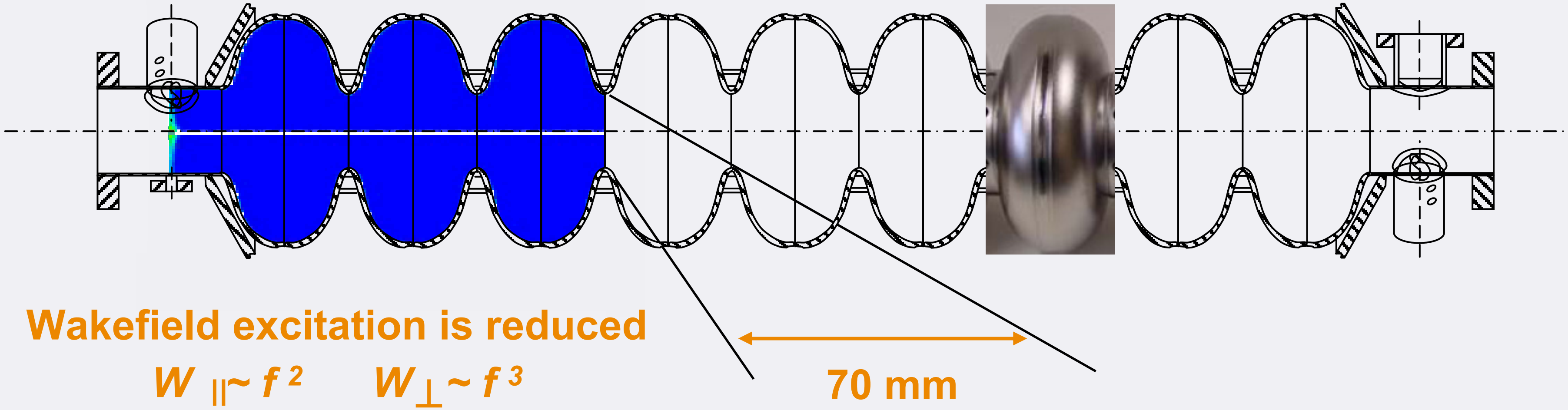
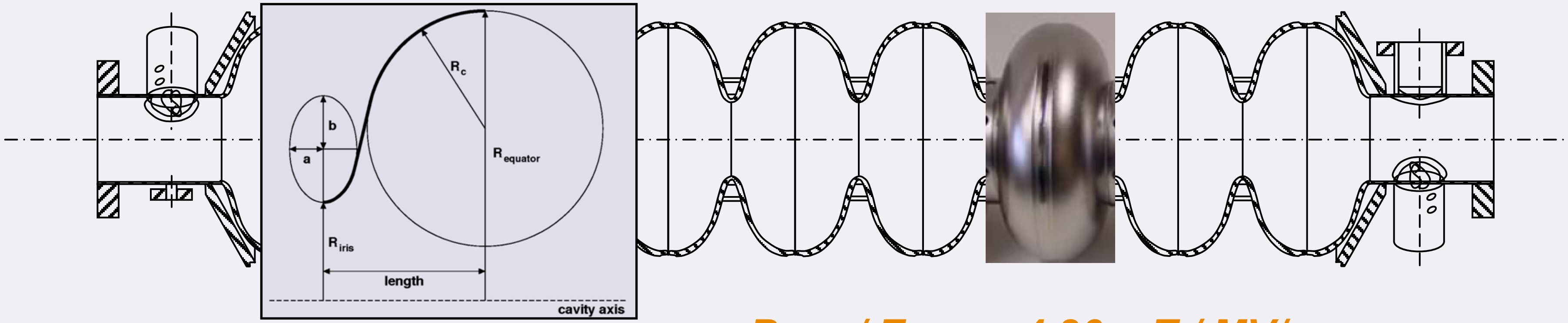


Wakefield excitation is reduced

$W_{||} \sim f^2$ $W_{\perp} \sim f^3$

XFEL s.c. Cavities

R/Q	[Ω]	1,036
E_{peak} / E_{acc}		2.0
B_{peak} / E_{acc}	[mT / MV/m]	4.26
Tuning range	[kHz]	± 300
$\Delta f / \Delta L$	[kHz / mm]	315
Lorentz force detuning constant	K_{Lor} [Hz / (MV/m)^2]	1
Q_{ext} of input coupler		4.6×10^6
cavity bandwidth f / Q_{ext}	[Hz] FWHM	283
fill time	[ms]	780
number of HOM couplers		2



optimized cavity shape

B_{peak} / E_{acc} = 4.26 mT / MV/m

↷ B_{peak} < 200 mT (B_c @ 2K)

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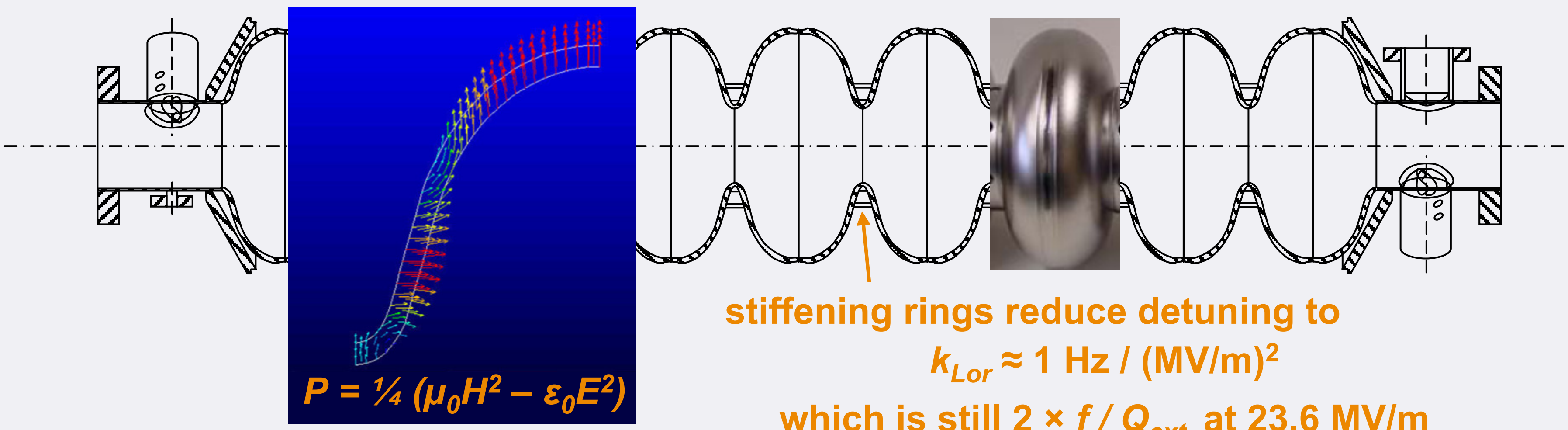

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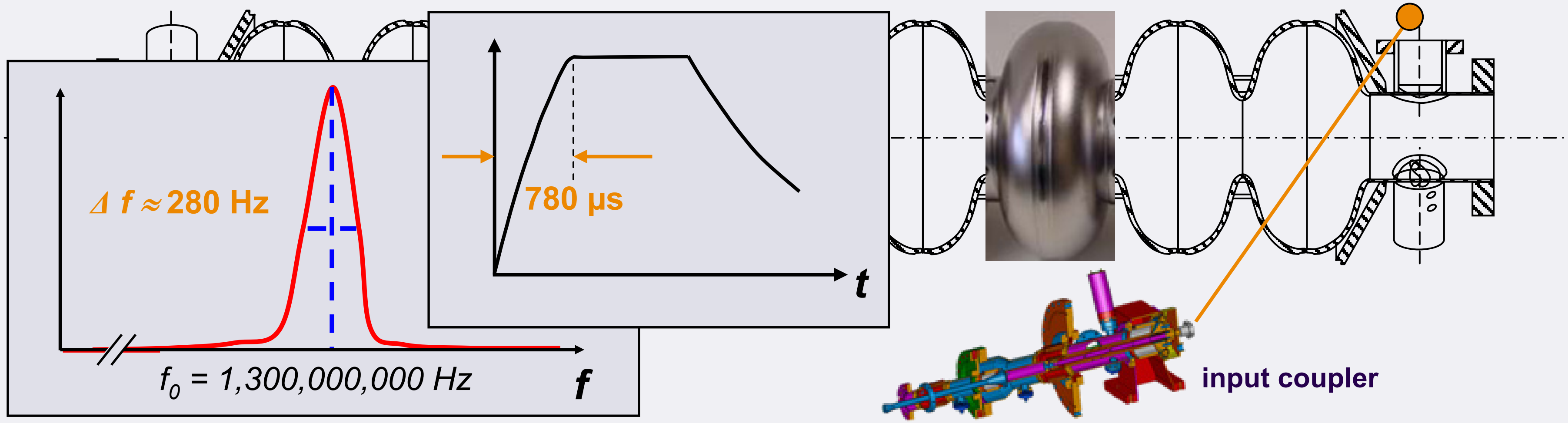

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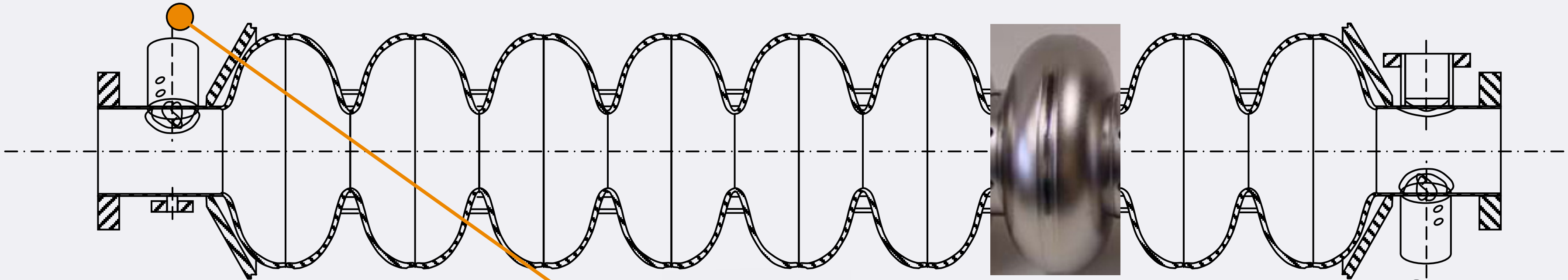
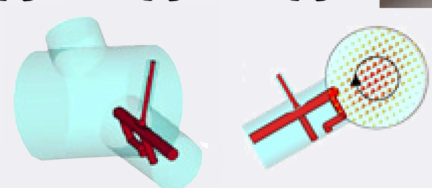
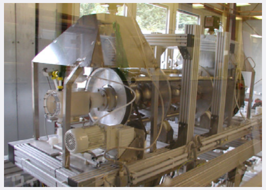


Higher Order Mode excitation has to be avoided.



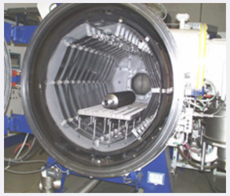
Cavity Prep. (XFEL Industrial Production)



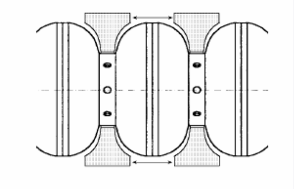
EP 150 µm (inside)

4 bar rinse

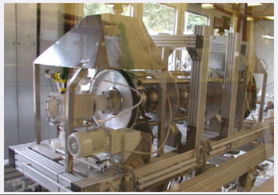
BCP 20 µm (outside)



UHV 800°C annealing

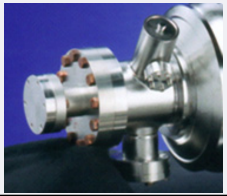


freq./ field flatness tuning

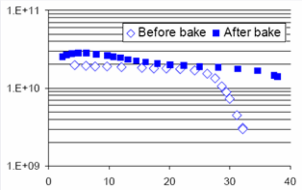


EP 30 µm (inside)

100 bar HPR



inst. pick-up / HOM

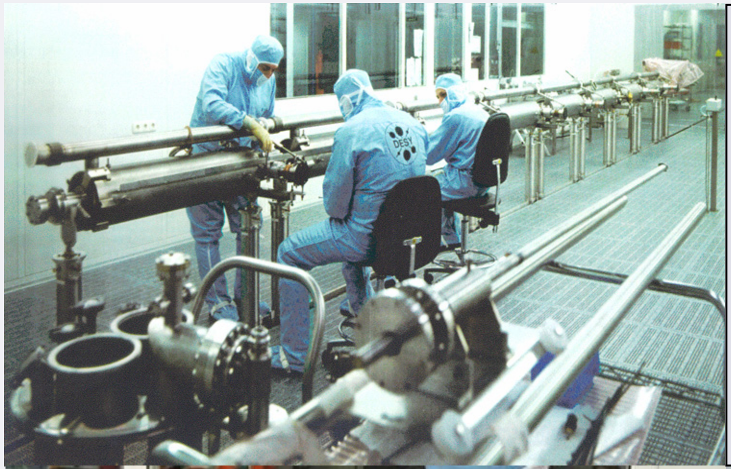


UHV 120°C baking

100 bar HPR (6 ×)

1. electro-chemical removal of a thick niobium layer (so-called damage layer) of about 150 µm from the inner surface
2. a rinse with particle free / ultra-pure water to remove residues form the electro-chemical treatment
3. outside etching of the cavities of about 20 µm
4. ultrahigh vacuum annealing at 800°C
5. tuning of the cavity frequency and field profile
6. removal of a thin and final layer of about 30 µm
7. rinsing with particle free / ultra pure water at high pressure (100 bar) to remove surface contaminants
8. assembly of auxiliaries (pick-up probe and HOM pick-up)
9. baking at 120°C in ultra high vacuum
10. additional six times rinse with high pressure ultra-pure water (100 bar)

Cavity String Assembly

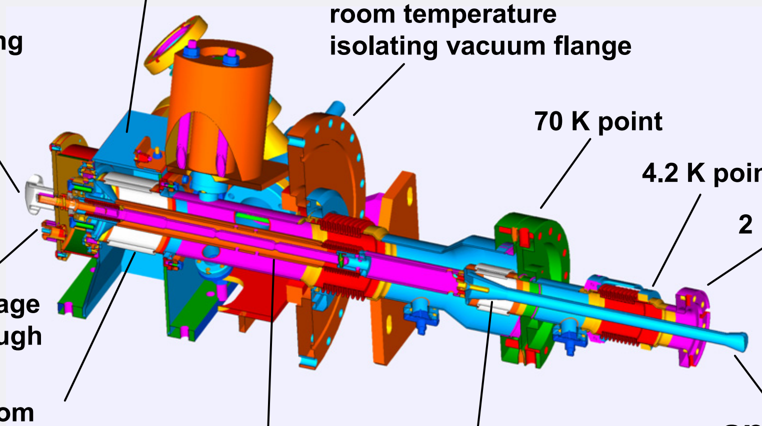


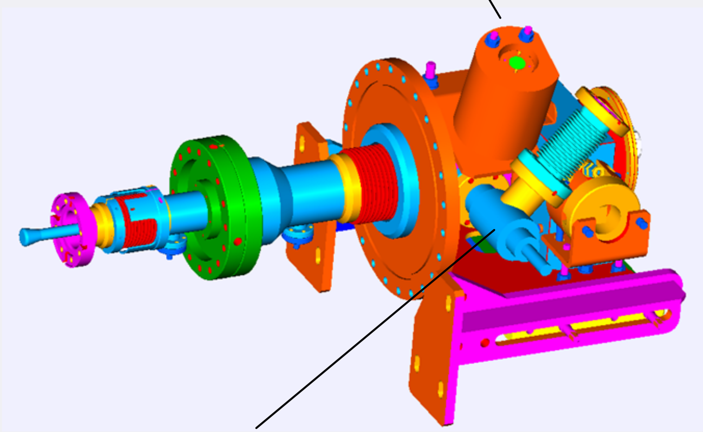
The assembly of an 8 cavity string

- is a standard procedure
- is done by technicians from the TESLA Technology Collaboration
- is well documented using the cavity database as well as an Engineering Data Management System
- was the basis for two industrial studies.

The transfer of this well known and complete procedure to industry has started.

Auxiliaries – Main Power Coupler





At 20 GeV design energy 120 kW are required for the 650 µs long beam pulse; with 10 Hz rep rate and 720 µs filling time the average power amounts to 1.6 kW.

Q_{ext} can be varied in the range of $10^6 - 10^7$. At 23.6 MV/m the optimum Q_{ext} is 4.6×10^6.

Couplers were tested to transmit 1.5 MW of peak RF power in traveling wave mode and 600 kW / 5 Hz in standing wave mode. In a 35 MV/m cavity test, one coupler was operated 2,400 hours at 2.5 kW average RF power.

The two window solution protects the cavity vacuum. Multipacting is suppressed by the coaxial line's design and additional bias voltage (up to 5 kV)

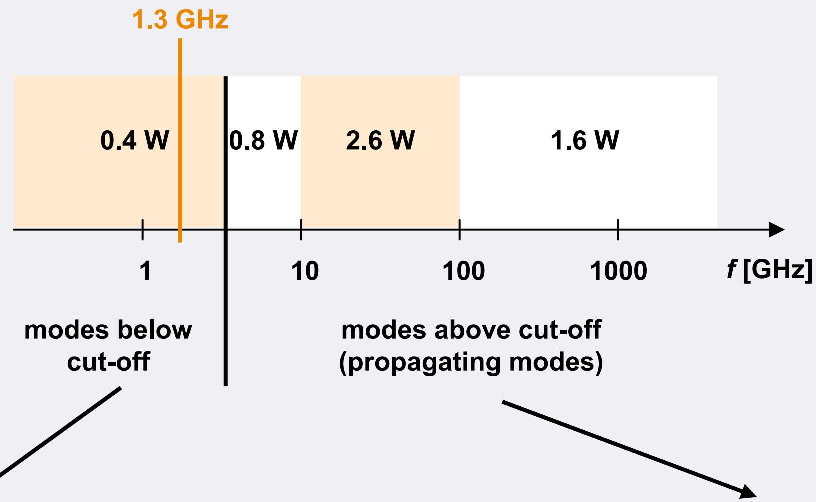
Industrial studies for 1,000 couplers are done at LAL Orsay. Recently the production of 30 couplers was supervised and the conditioning done at Orsay with great success.

Damping of Higher Order Modes (HOMs)

The spectrum of the electron bunch (σ_z = 25 µm) reaches high frequencies up to 5 THz.

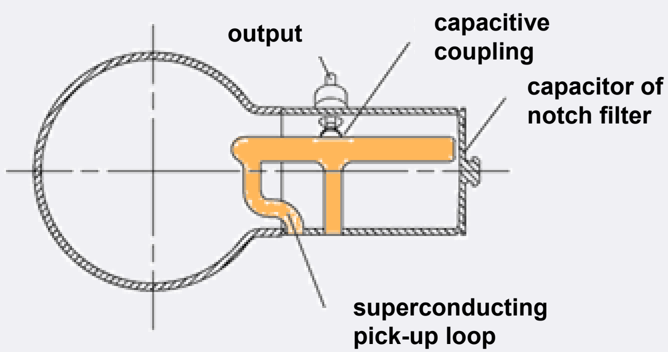
The standard accelerator module has an integrated loss factor of 135 V/pC.

The total power deposited by the nominal beam is 5.4 W per module.

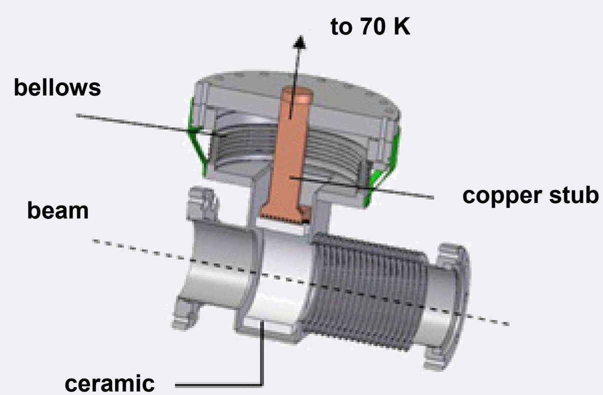


The design of the HOM coupler and the beam pipe absorber take into account a possible XFEL upgrade (more bunches / CW mode).

The HOM coupler was tested in CW mode. The absorber is specified for 100 W.

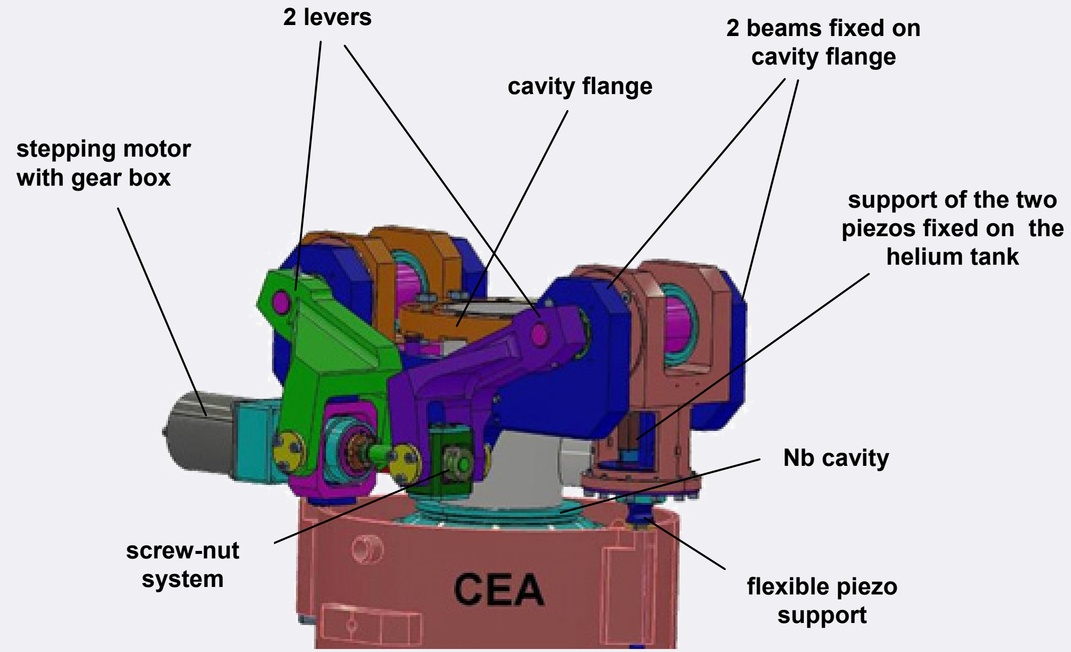


HOM coupler

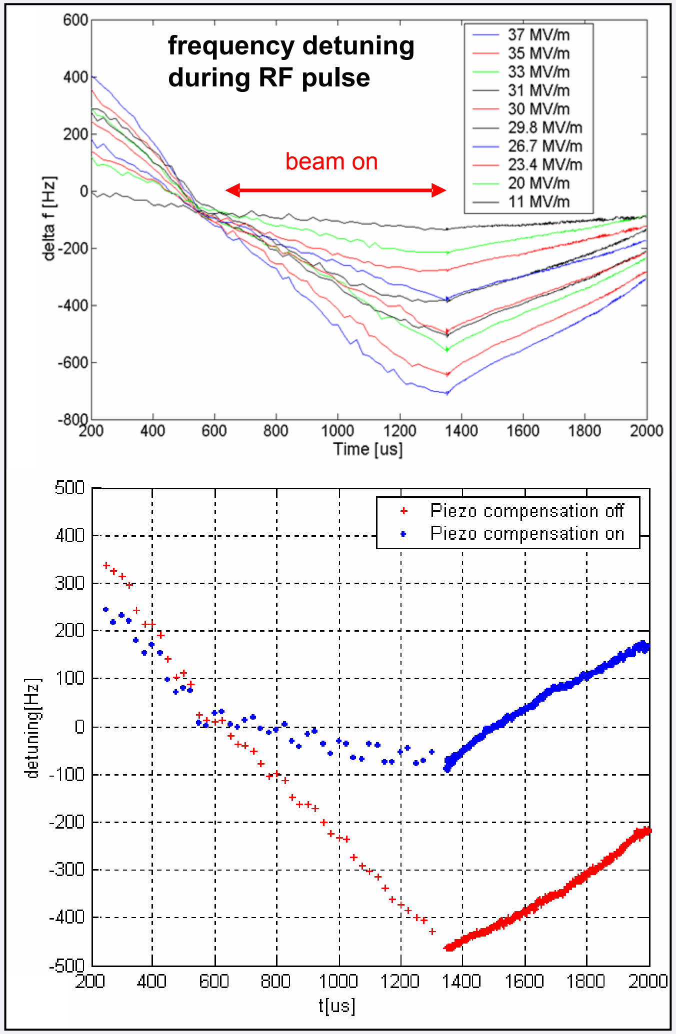


beam pipe absorber

Slow and Fast Tuner



The helium vessel acts as the mechanical reference (the titanium bellows is not shown)



The **slow tuner** compensates for drifts; 400 kHz range , 1 Hz resolution

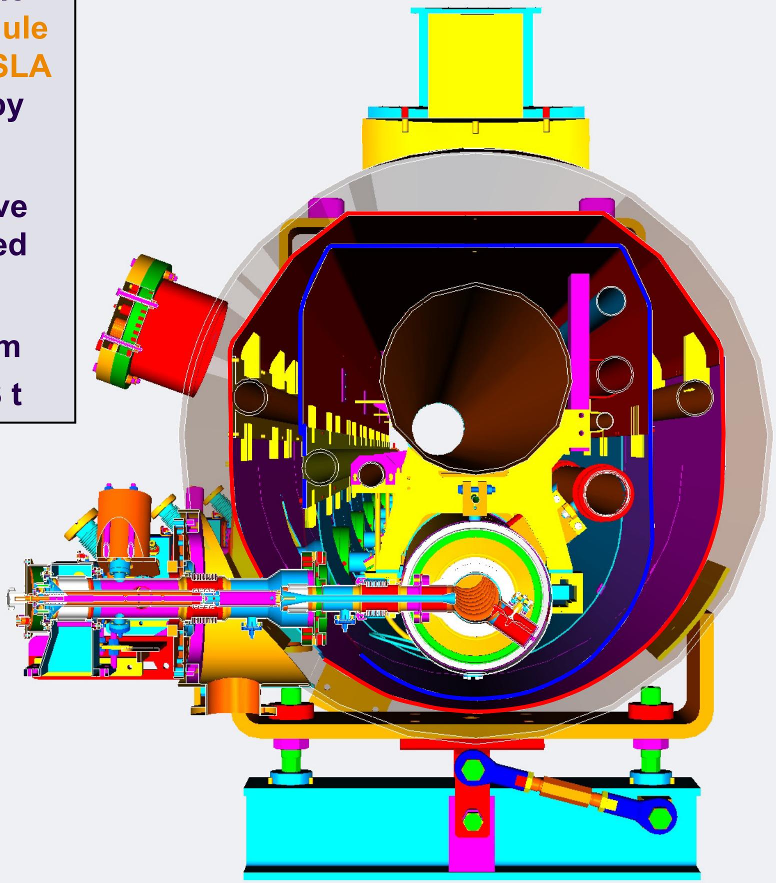
The **fast tuner** compensates the Lorentz-Force detuning during the RF pulse. It is based and piezo crystals.

Accelerator Module (Cryomodule)

The XFEL accelerator module is based on the 3rd cryomodule generation tested at the TESLA Test Facility and designed by INFN.

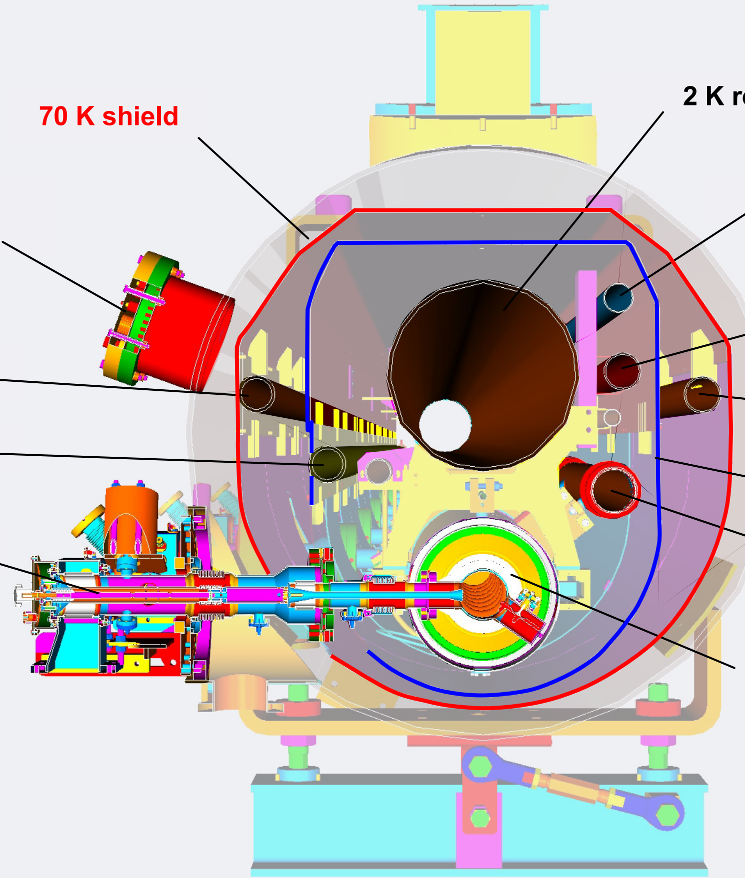
Already 10 cryomodules have been built and commissioned for the TTF Linac.

Length	12.2 m
Total weight	7.8 t

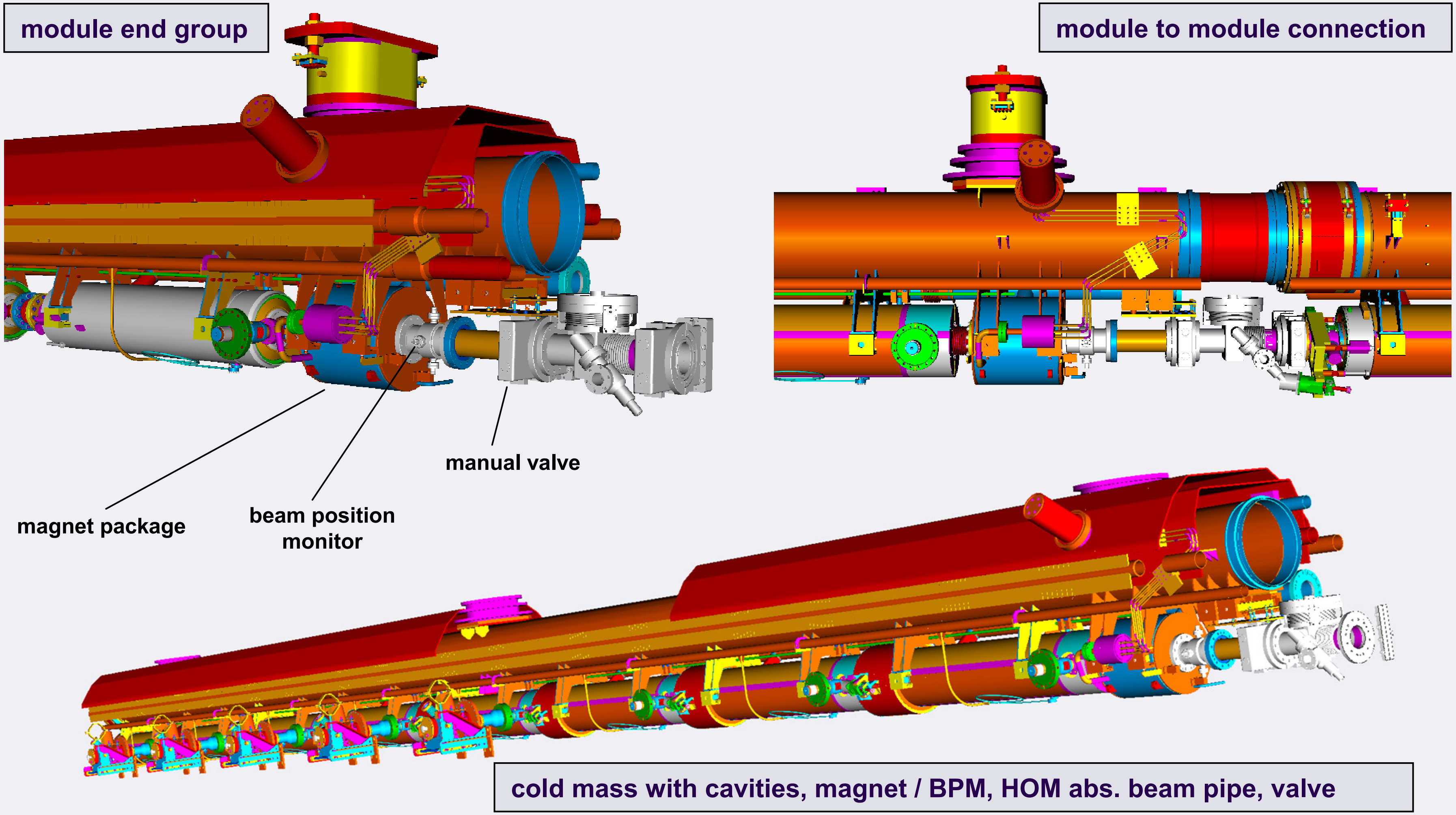


- 38” carbon steel vessel
- 300 mm He gas return pipe acting as support structure
- 8 accelerating cavities
- cavity to cavity spacing exactly one RF wavelength
- inter-module cavity to cavity spacing a multiple of one RF wavelength
- one beam position monitor / magnet unit
- manually operated valves to terminate the beam tube at both ends
- longitudinal cavity position independent from the contraction / elongation of the HeGRP during cool-down / warm-up procedure

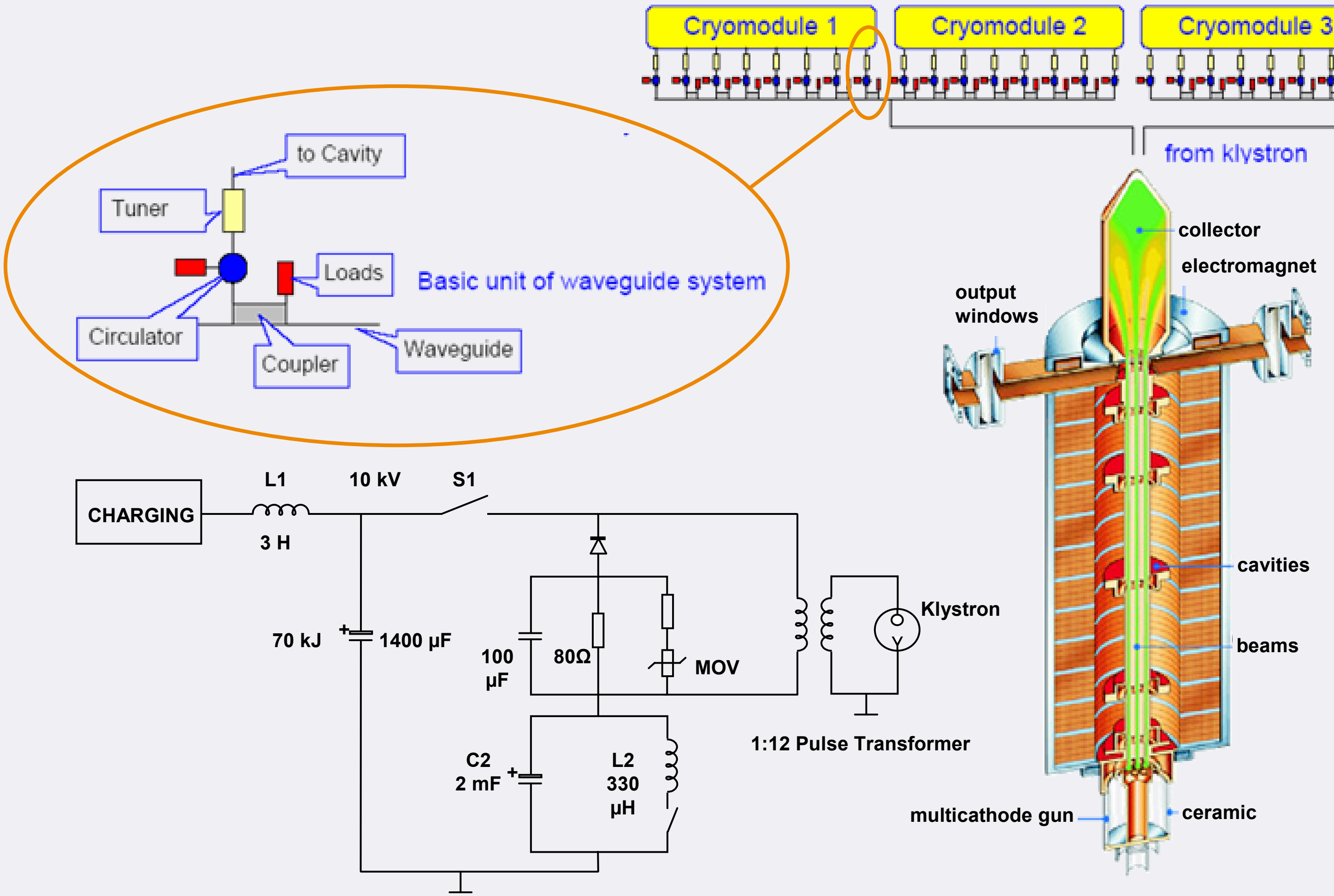
Accelerator Module (Cryomodule)



Accelerator Module (Cryomodule)



High Power RF System (Overview)



31 RF stations provide **10 MW peak** and **150 kW average**.

3.9 MW are required at nominal beam parameters and 20 GeV.

Incl. waveguide losses (6%) and regulation reserve (15%) **5.2 MW**.

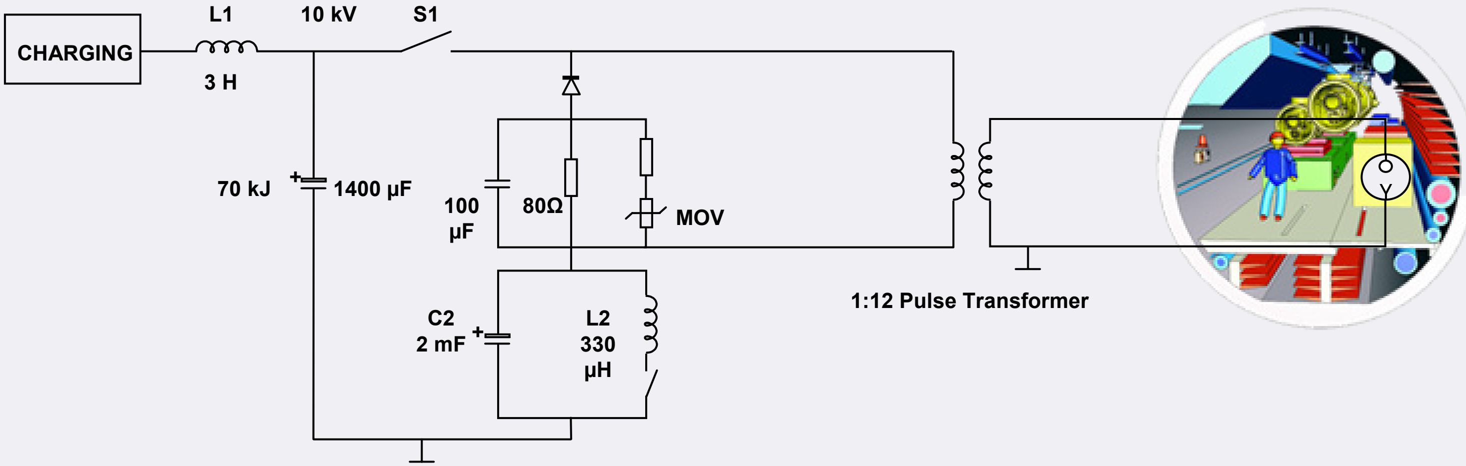
High Power RF System

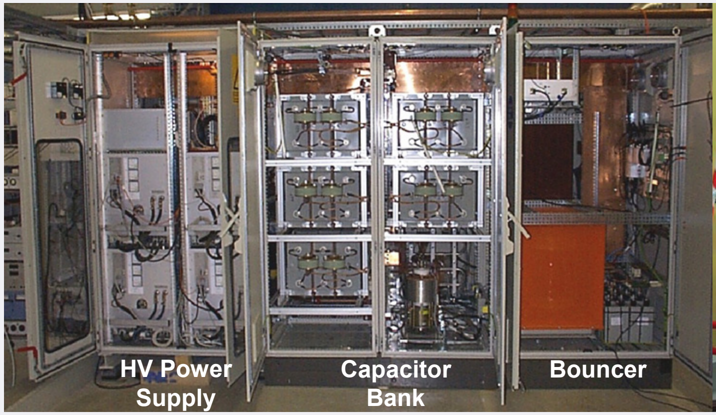
XFEL multibeam klystron development (much valued by ILC R&D experts)

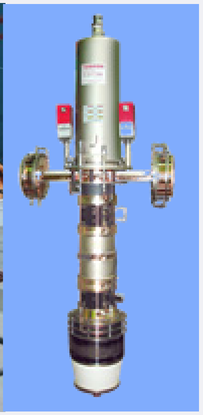
Encouraging results:

Just recently, the Toshiba tube was operated **continuously for more than 24 hours above 10 MW.**

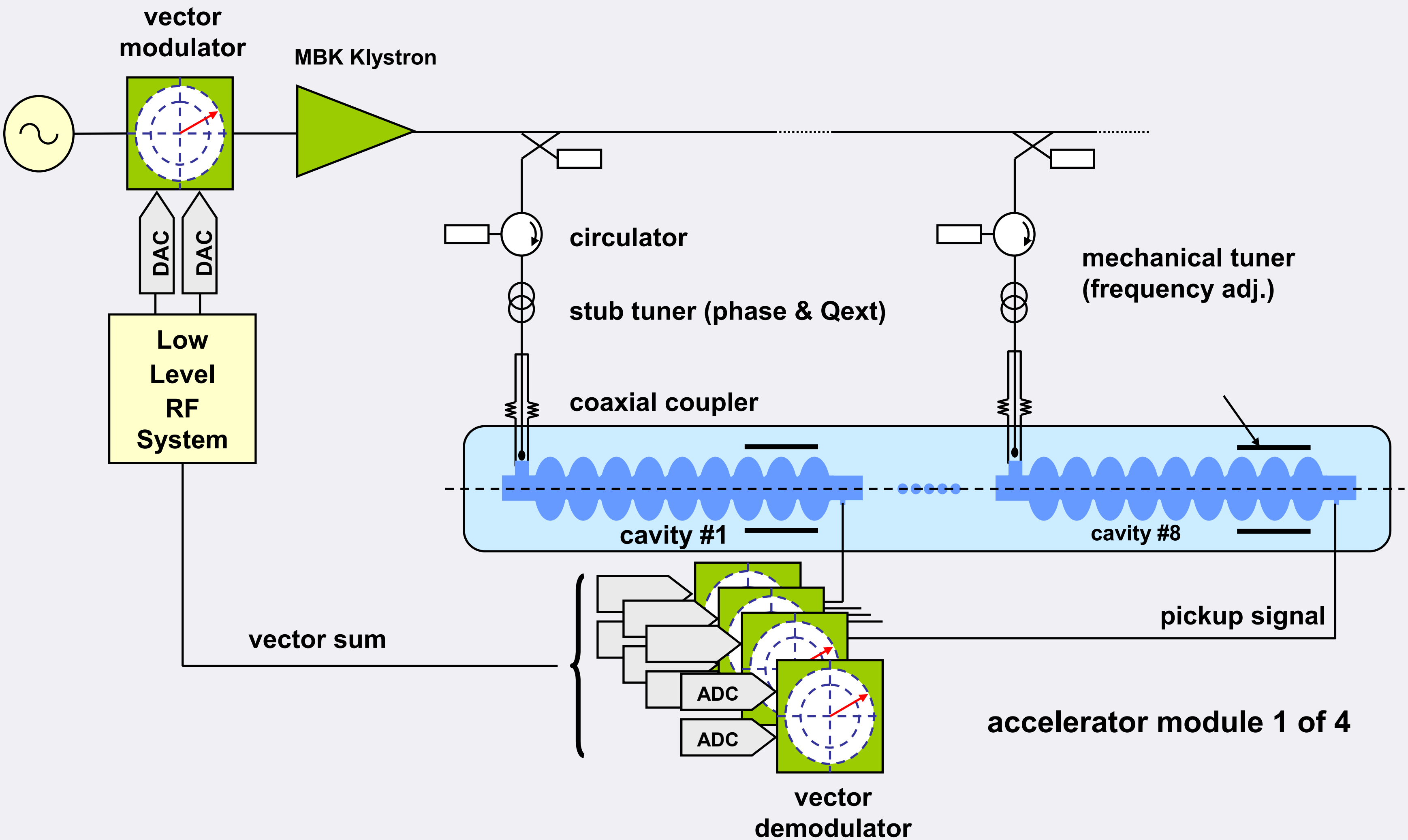
High Power RF System
(Modulator, Pulse Cable, Pulse Transformer)







Low Level RF Control



Low Level RF Control

Amplitude and Phase Stability

Design parameter are based on

- **bunch-to-bunch energy spread**
- **pulse-to-pulse energy spread**
- **bunch compression in the injector**
- **arrival time of the beam at the undulator**

The injector RF system needs 0.01% amplitude and 0.01 deg phase stability!!!

(stability of photon intensity)

TEST at FLASH (VUV-FEL)

Operational Requirements

Beside field stabilization, the RF system must provide

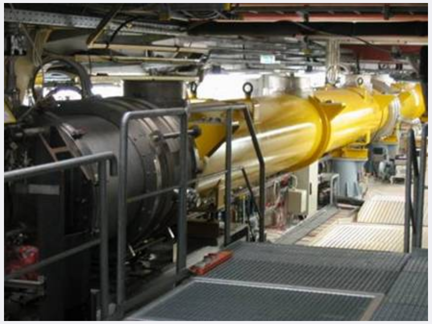
- **diagnostics for the calibration of gradient and beam phase**
- **measurement of the loop phase**
- **measurement of the cavity detuning**
- **control of the cavity frequency tuners (use fast tuner to correct Lorentz Force detuning)**
- **exception handling capability to avoid beam loss and to allow for maximum operable gradient**

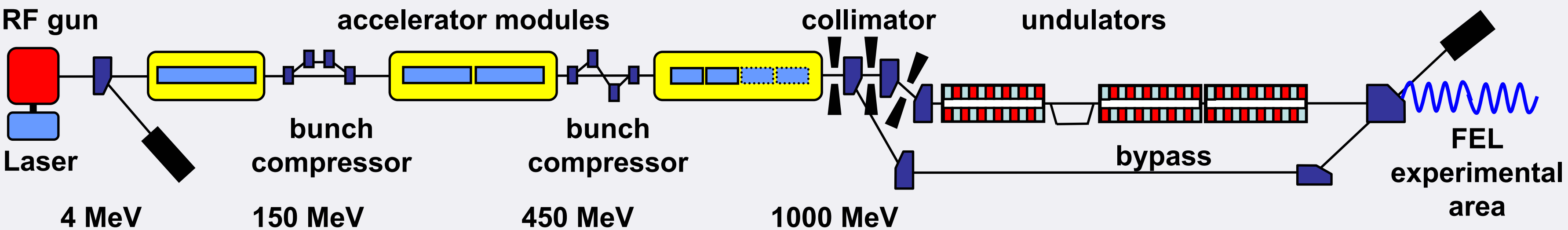
  e.g. cavity quench detection

  ‘communicate’ with spare RF stations

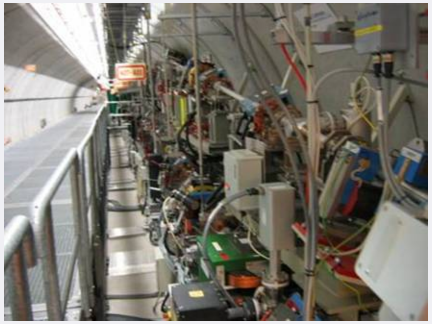
- **correct RF system parameters (feed forward tables) according to variable beam loading**

FLASH (VUV-FEL) Facility

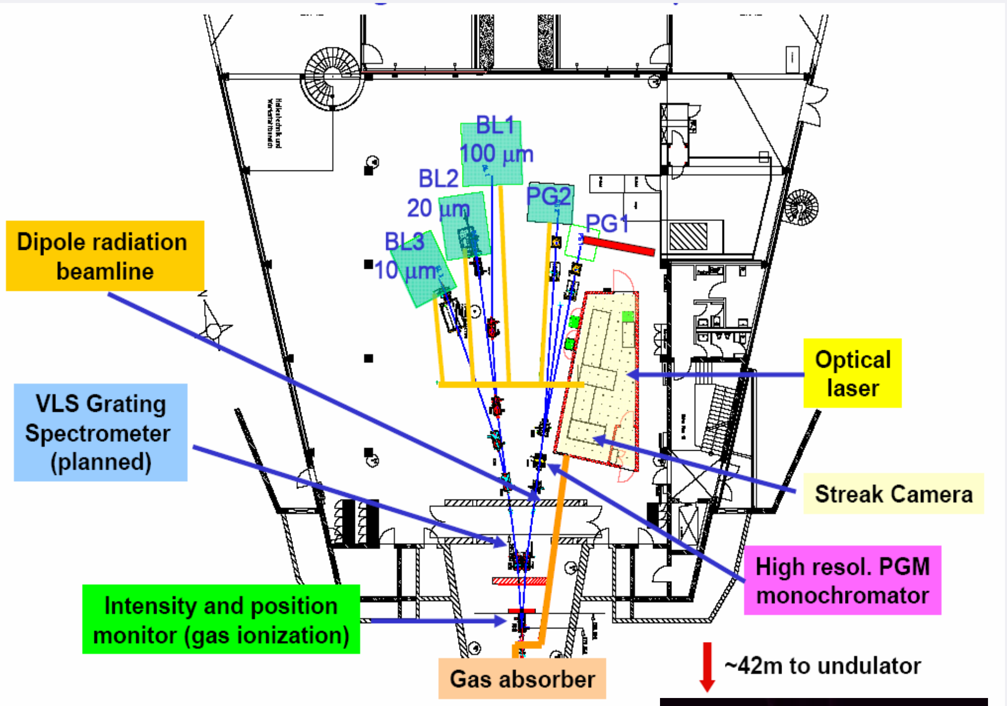


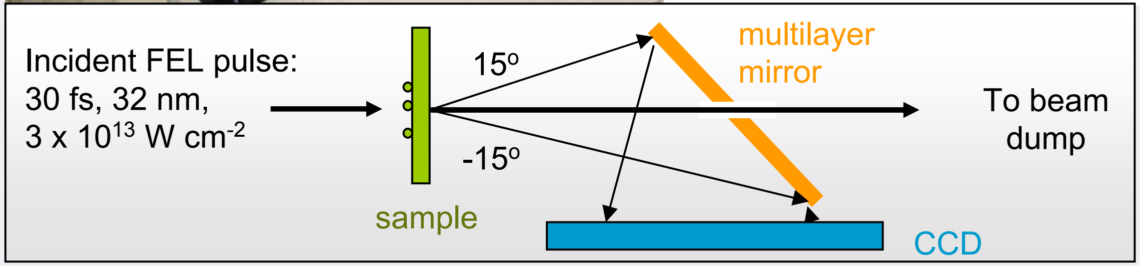


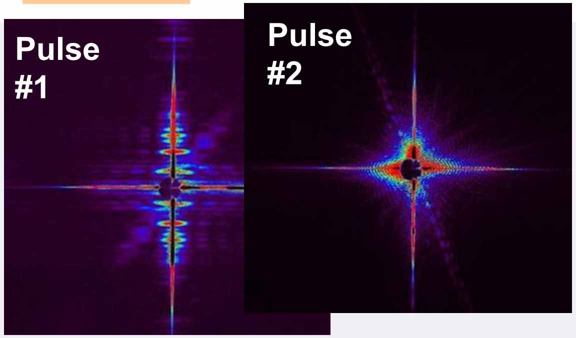



250 m

Many Happy Users at FLASH are Using the Photons





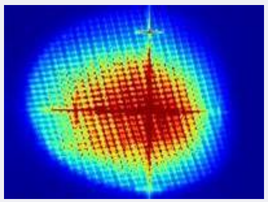


First demonstration of ultra fast coherent X-ray diffraction (Janosz Hajdu, Henry Chapman et al.)

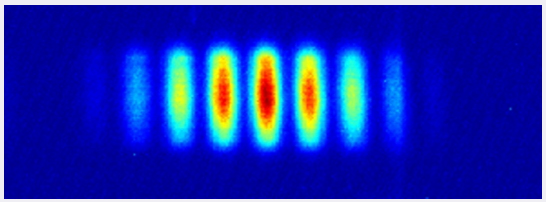
The FLASH Photon Beam

e.g. 25.5 nm wavelength

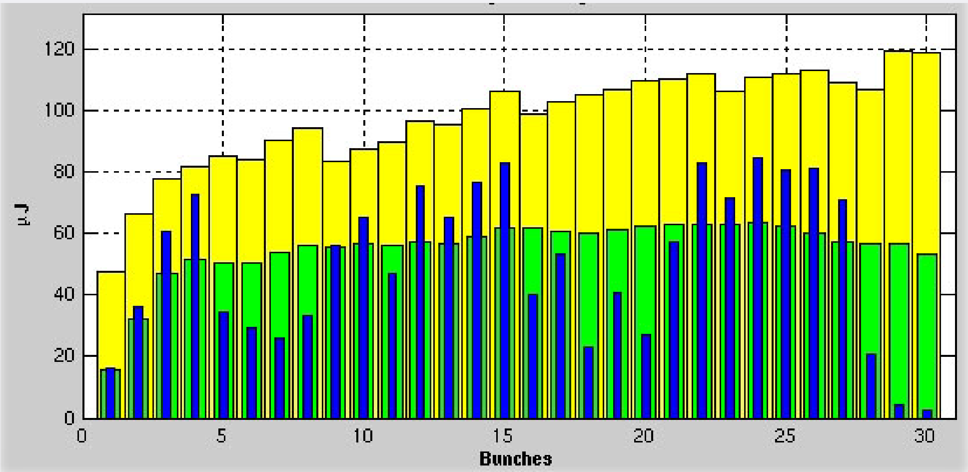
spot size



double slit diffraction pattern



3 mm spot size (FWHM) @ 18.5 m distance
angular divergence 160 μrad
→ high degree of coherence

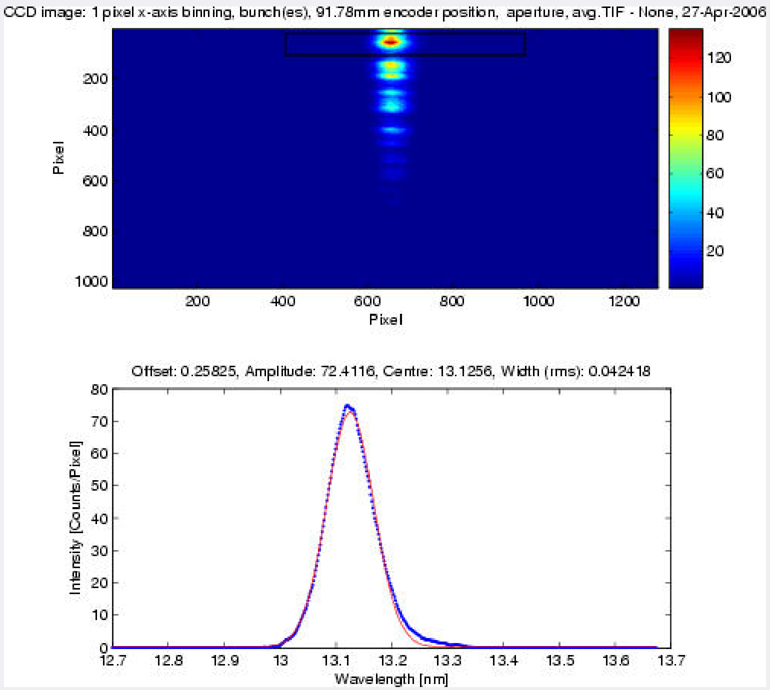


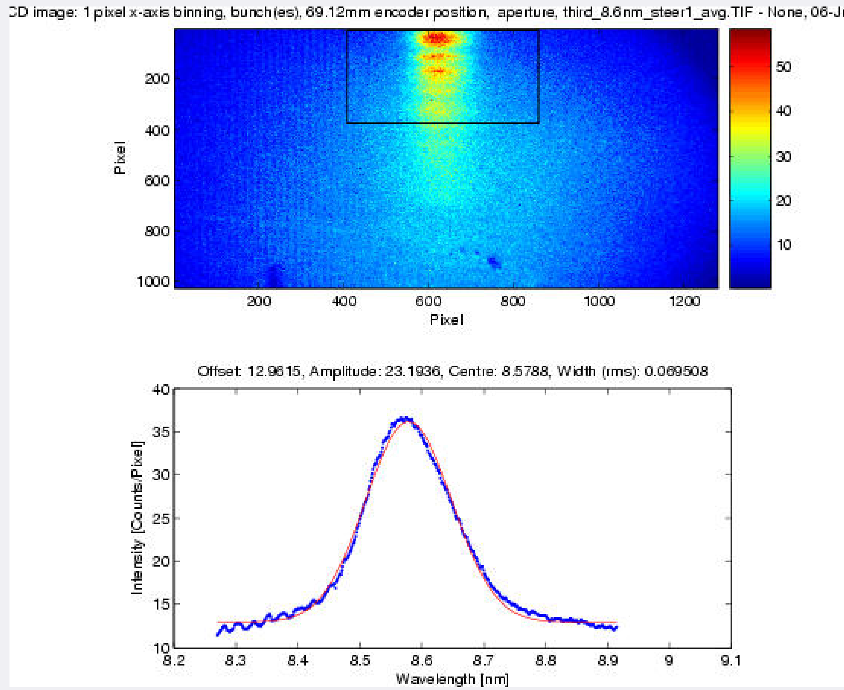
Wavelength (fundamental)	**48 – 13**	**nm**	**(tunable!!!)**
FEL third harmonic	**8.5**	**nm**	
Average energy per pulse	up to 65	μJ	
Maximum energy per pulse	120	μJ	
Radiation pulse duration	20 – 50	fs	
Peak power (calc. from average)	>1	GW	
Spectral width (FWHM)	**0.5 – 1**	**%**	
Angular divergence (FWHM)	160	μrad	
Peak brilliance (calc. from max)	**≈ 5×10^{29}**	ph/s/mrad^2/mm^2/(0.1% bw)	

Multibunch SASE signal (μJ) recorded with MCP Detector

max
average
single

FLASH Wavelength Records

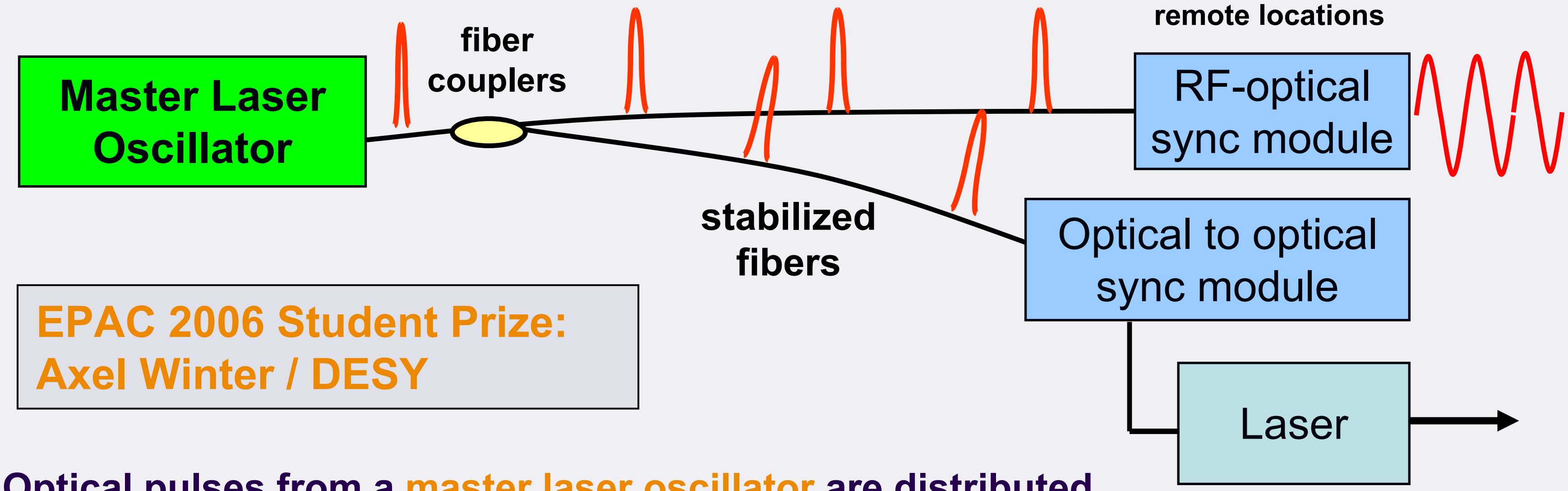




fundamental at λ=13.1 nm

3rd harmonic at λ=8.6 nm

Optical Synchronization System



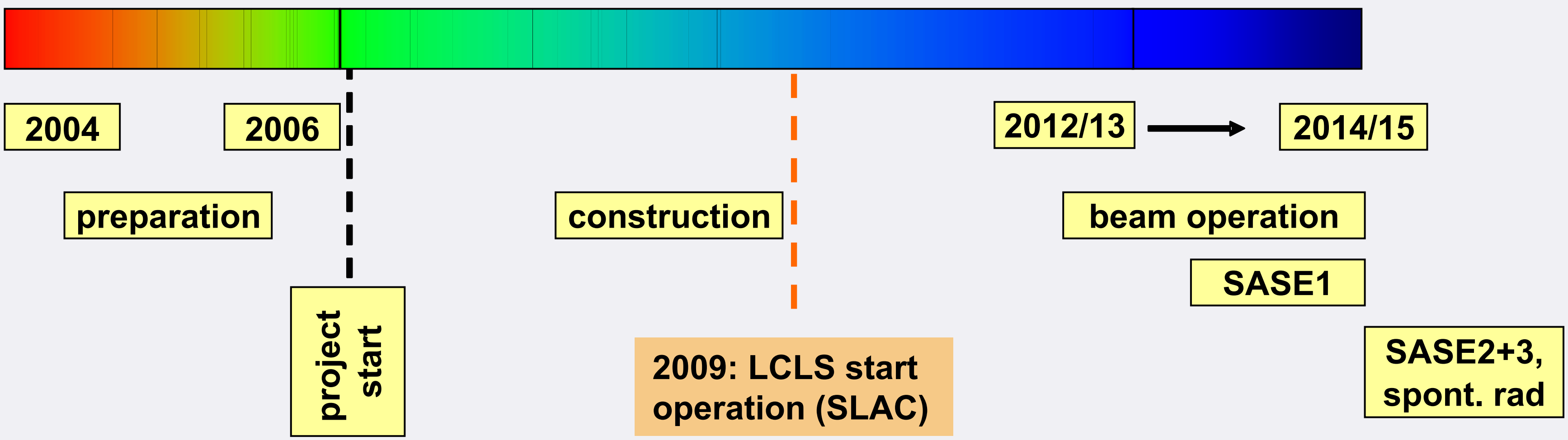
EPAC 2006 Student Prize:
Axel Winter / DESY

Optical pulses from a master laser oscillator are distributed via length-stabilized fiber links to locations in the machine

- 10 femtosecond drift-free stability between different locations
- RF can be extracted with few femtosecond jitter and probe laser systems can be optically synchronized with sub-fs jitter
- novel beam diagnostics possible using the optical pulse train directly
  - arrival time monitors with sub-100 fs precision
  - µm-precision beam position monitors

First Photons in the XFEL Experimental Hall in 2013

XFEL Time Schedule



- Time schedule assumes final project approval & funding at European level in 2006
- Site approval ("PFV") and preparations for placing orders for civil construction will happen before official project start

industrialization of all Linac sub-systems

production

commissioning

acceptance test and installation

input for ILC

2010: Results from major ILC R&D projects and conversion to pre-construction phase