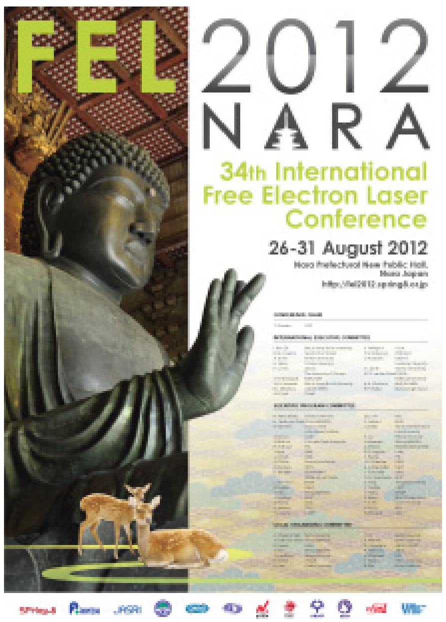
European XFEL Working Point Optimization and Status

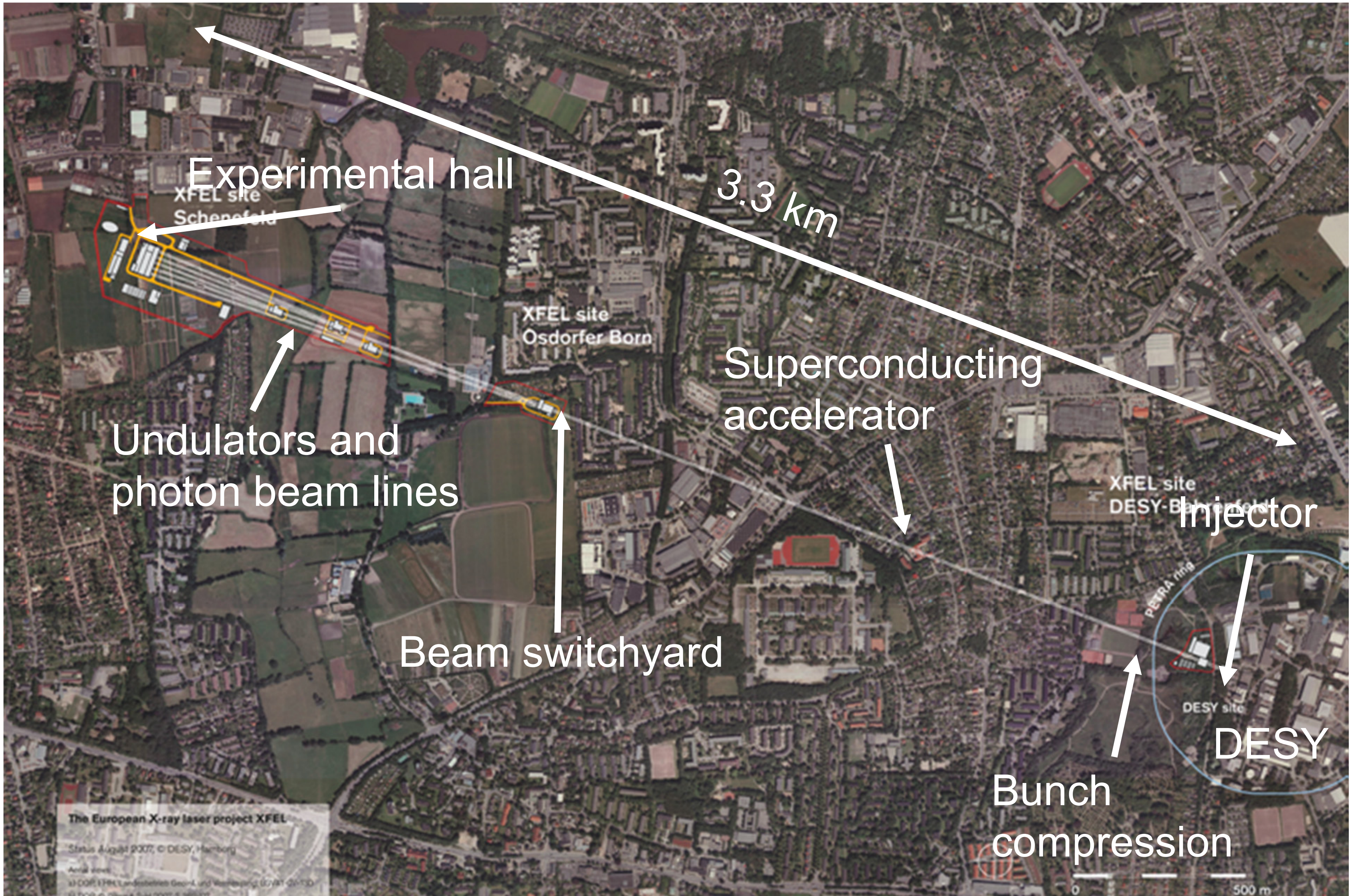


W. Decking, T. Limberg (DESY)
for the European XFEL Team

DESY

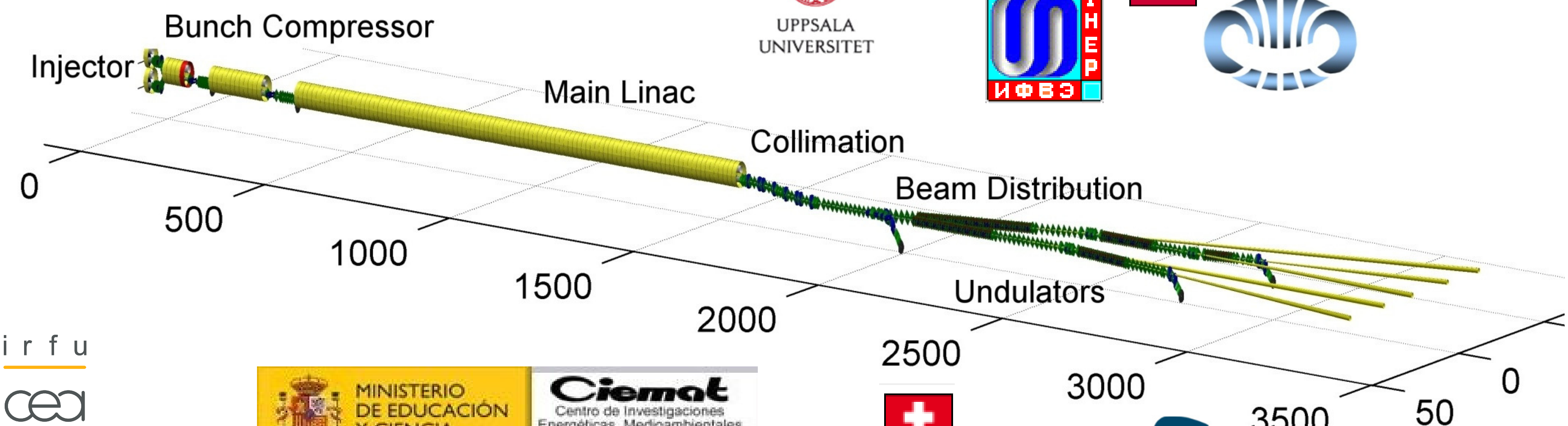
HELMHOLTZ ASSOCIATION

European XFEL in Hamburg



Accelerator Consortium

DESY
HELMHOLTZ ASSOCIATION
Stockholm University
UPPSALA UNIVERSITET



ИФВЭ IHEP

irfu
cea
saclay
cnrs
dépasser les frontières
In2p3

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Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
UNIVERSIDAD POLITECNICA MADRID

PAUL SCHERRER INSTITUT
PSI

Wrocław University of Technology

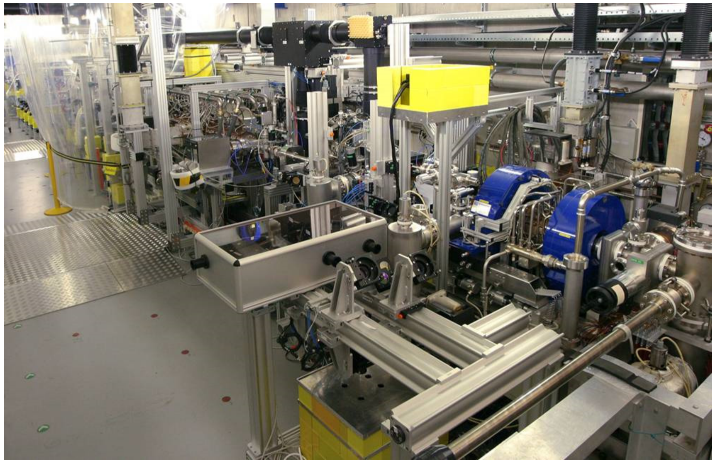
INFN
Istituto Nazionale di Fisica Nucleare
UNIVERSITAS STUDIORUM MEDIOLANENSIS

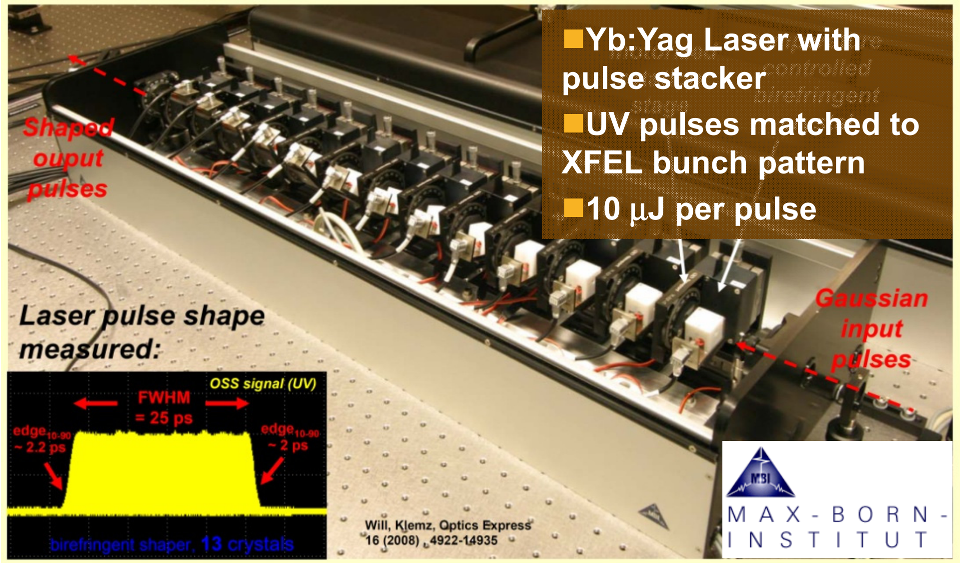
NARODOWE CENTRUM BADAŃ JĄDROWYCH
Świerk

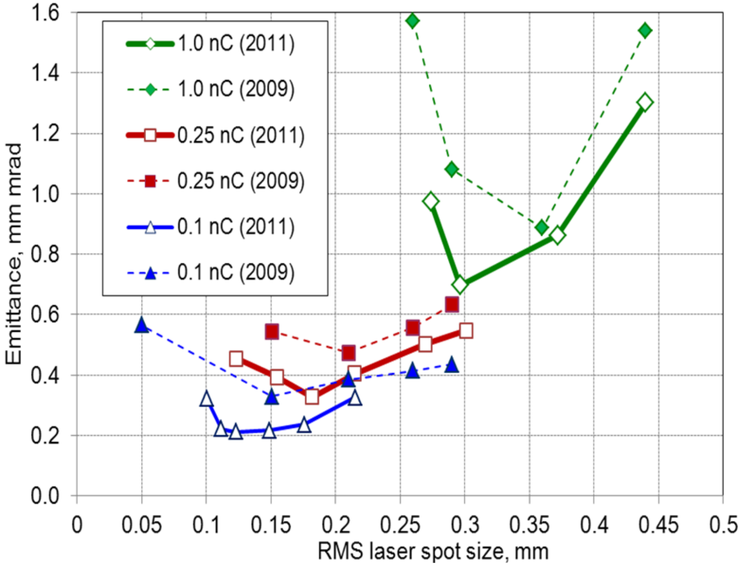
Institute of High Energy Physics
Chinese Academy of Sciences

Injector

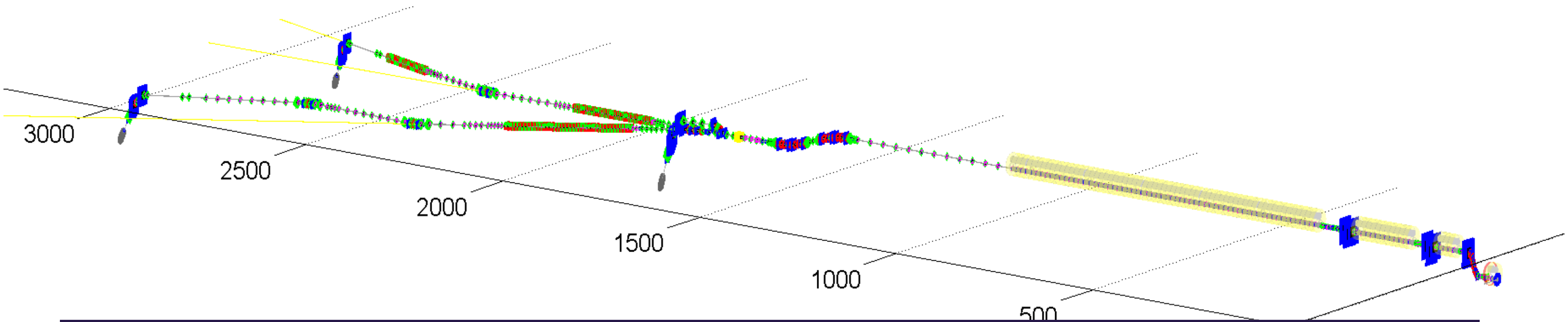
- Normal conducting photo-cathode gun
- CsTe-Cathode, 60 MV/m gradient
- Peak power ~ 6 MW, Average ~ 100 kW
  (2700 bunches with 10 Hz)
- In operation at FLASH and PITZ
- New best values for emittance achieved 2011
- Ongoing R&D on the drive laser to enhance flexibility and stability
- 'Laser Bouncer' in developement





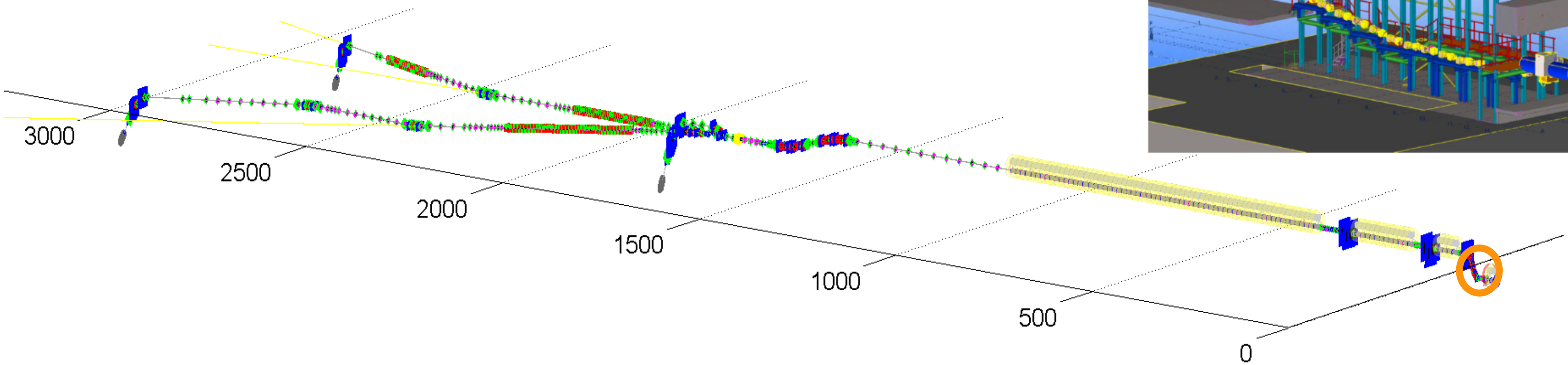


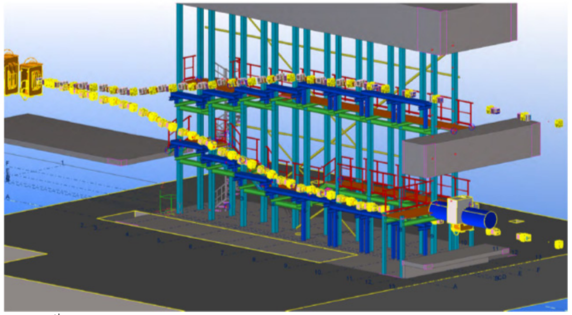
XFEL – New Parameter Set

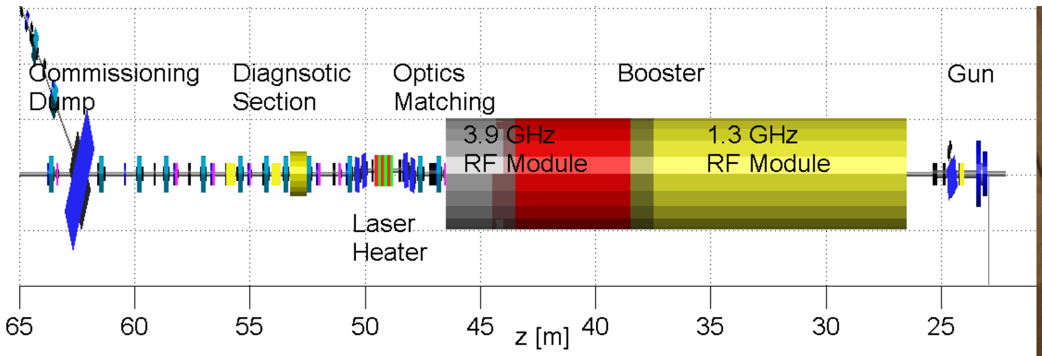


	Baseline	New Parameter Set
Electron Energy	17.5 GeV	10.5/14/17.5 GeV
Bunch charge	1 nC	0.02 - 1 nC
Peak current	5 kA	5 kA
Slice emittance	< 1.4 mm mrad	0.4 - 1.0 mm mrad
Slice energy spread	1.5 MeV	4 - 2 MeV
Shortest SASE wavelength	0.1 nm	0.05 nm
Pulse repetition rate	10 Hz	10 Hz
Bunches per pulse	3000	2700

Injector





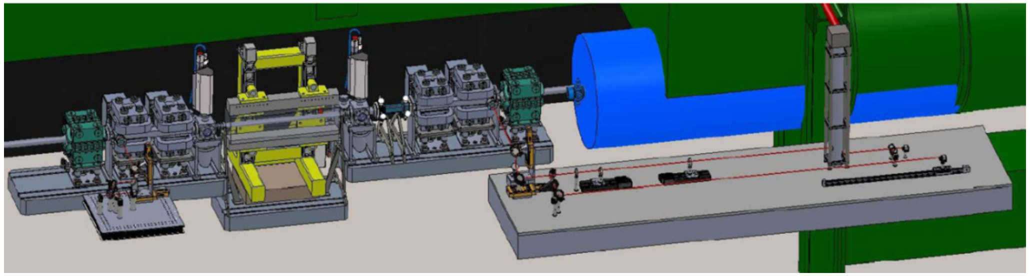


Injector schematic layout

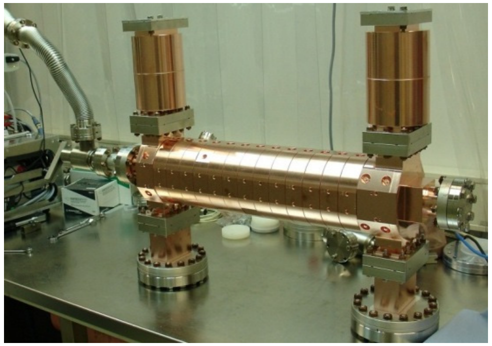
Level 7 of injector building

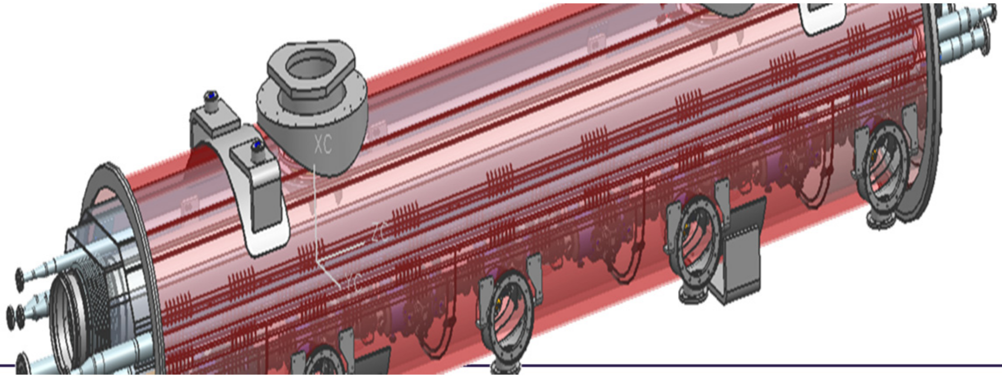
Injector

- Laser heater mechanical design matured, first components tendered



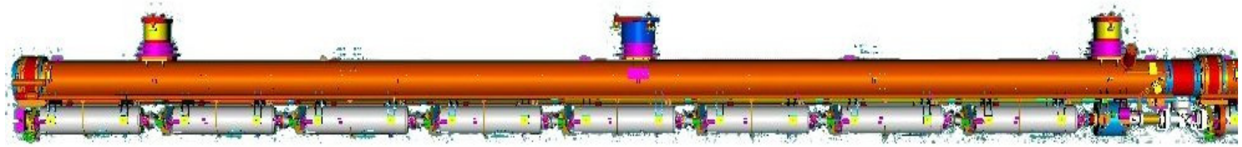
- Low remanence focusing quadrupoles produced
- Prototype of transverse deflecting structure produced, to be installed at PITZ
- 3.9 GHz accelerator module (for bunch length control), design finished, prototype cavities in test





17.5 GeV Linac

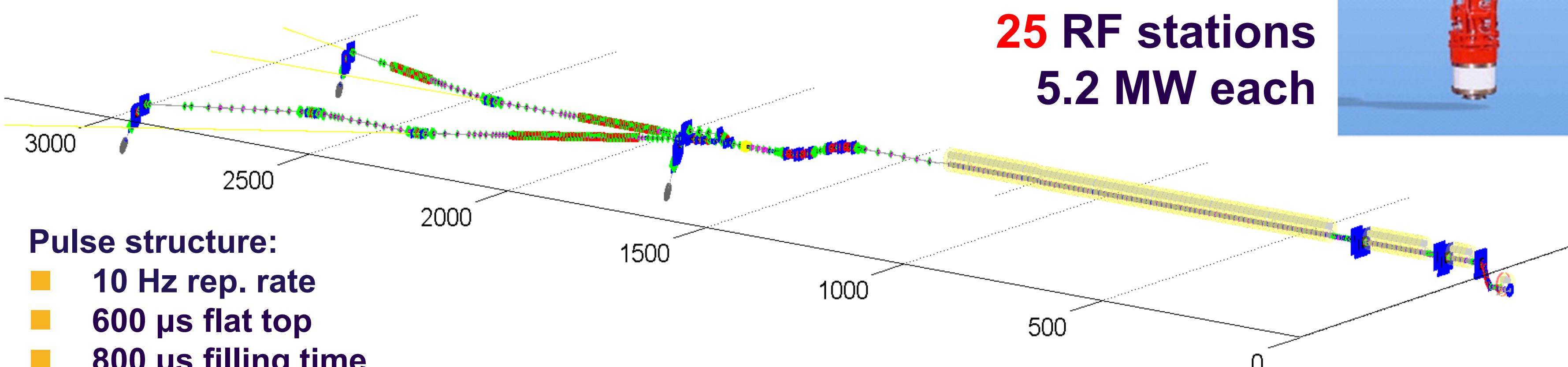
100 accelerator modules



800 accelerating cavities

1.3 GHz / 23.6 MV/m

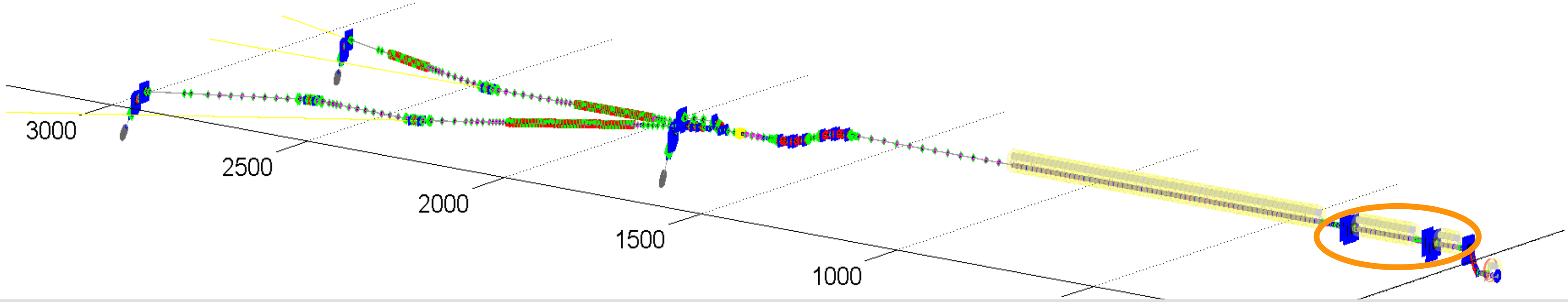
25 RF stations
5.2 MW each



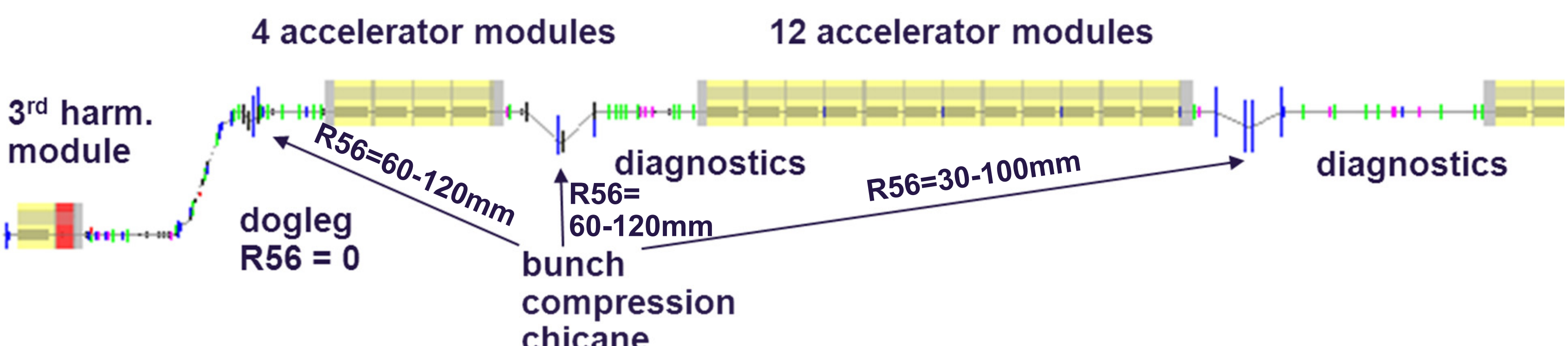
Pulse structure:

- **10 Hz rep. rate**
- **600 µs flat top**
- **800 µs filling time**

Bunch Compression



3 stage bunch compression for wide range of compression scenarios and minimized sensitivities to RF-regulation imperfections and electron beam driven instabilities



σ_σ = 2 mm
I_{peak} = 50 A
σ_E = 0 %
E = 130 MeV

→

σ_σ = 1 mm
I_{peak} = 100 A
σ_E = 1.5 %
E = 130 MeV

→

σ_σ = 0.1 mm
I_{peak} = 1 kA
σ_E = 1 %
E = 500 MeV

→

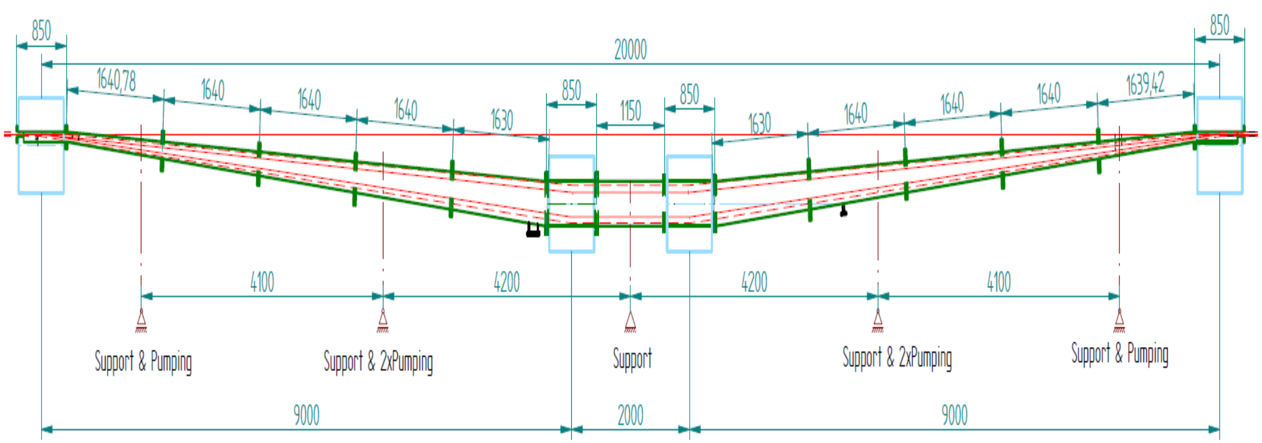
σ_σ = 0.02 mm
I_{peak} = 5 kA
σ_E = 0.3 %
E = 2000 MeV

→

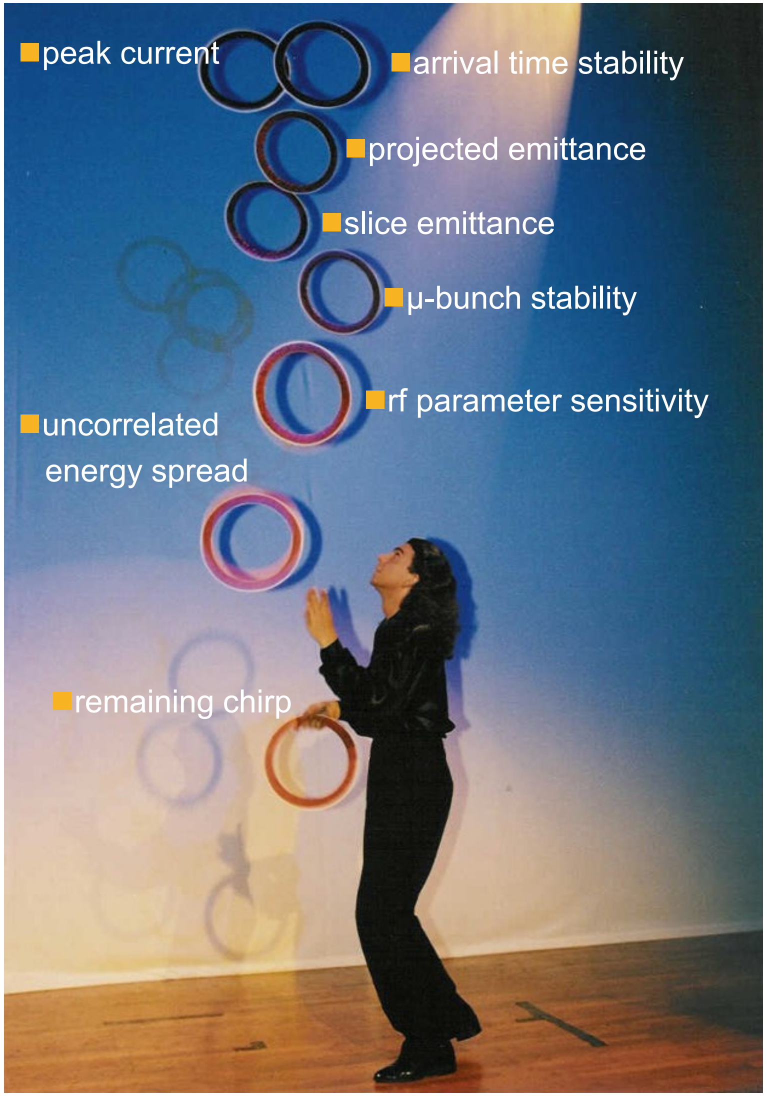
Bunch Compression Chicanes

- Fixed wide vacuum chamber for variable R56
  - No moving vacuum parts in the vicinity of superconducting structure
  - No wake from bellows
  - Fast changes of R56 via beam energy

- First dipole magnets for the chicane produced
  - Challenging field quality requirements will be achieved by individual pole shimming



Calculation of BC Working Points: Criteria and Constraints



Calculation of BC Working Points

- total compression to stage n: $C_n(s) = \left(\frac{d}{ds} S_n(s) \right)^{-1}$

  With: s = initial long. Position and
  s_n = long. position after stage n

- two stage compression:

$$\begin{pmatrix} E_0 \\ E_1 \\ C_0 \\ C_1 \\ C_1' \\ C_1'' \end{pmatrix} = f\left(A_0, \varphi_0, A_0^{(h)}, \varphi_0^{(h)}, A_1, \varphi_1 \,\middle|\, \psi_0, \psi_1 \right)$$

- BC energies: E_0, E_1
- compression factors: C_0, C_1
- higher derivatives: C_1', C_1''

working point parameters (y)

LINAC parameters (x): amplitudes and phases

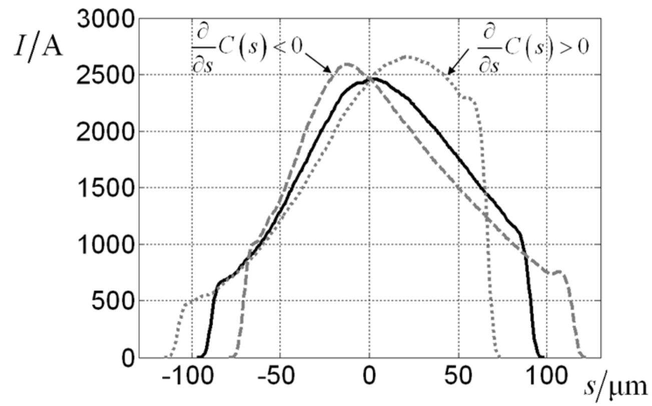
compressor parameters (p): magnet strengths or R_{56}

$$\mathbf{y} = f(\mathbf{x}, \mathbf{p})$$

For a simplified model, inverse function can be calculated: $\mathbf{x} = g(\mathbf{y}, \mathbf{p})$

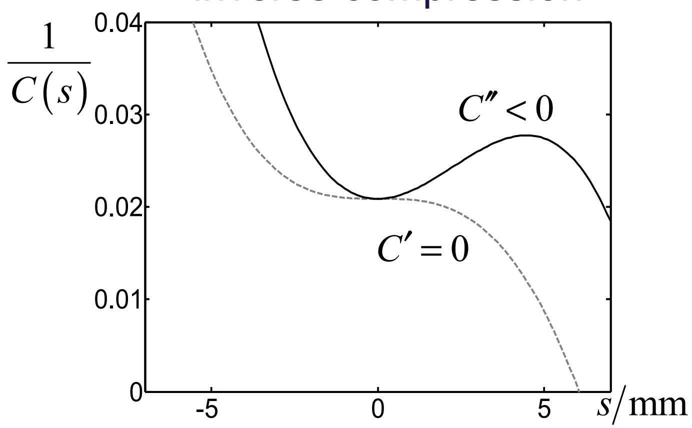
Longitudinal Bunch Profile Parameterization

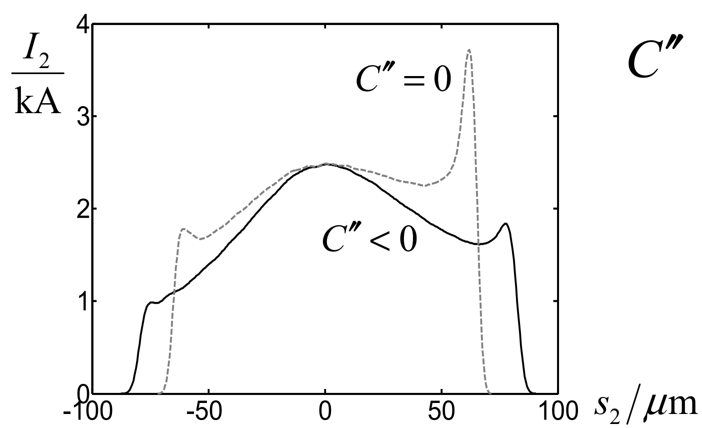
higher derivatives of total compression are used to specify bunch shape



C' bunch center and symmetry

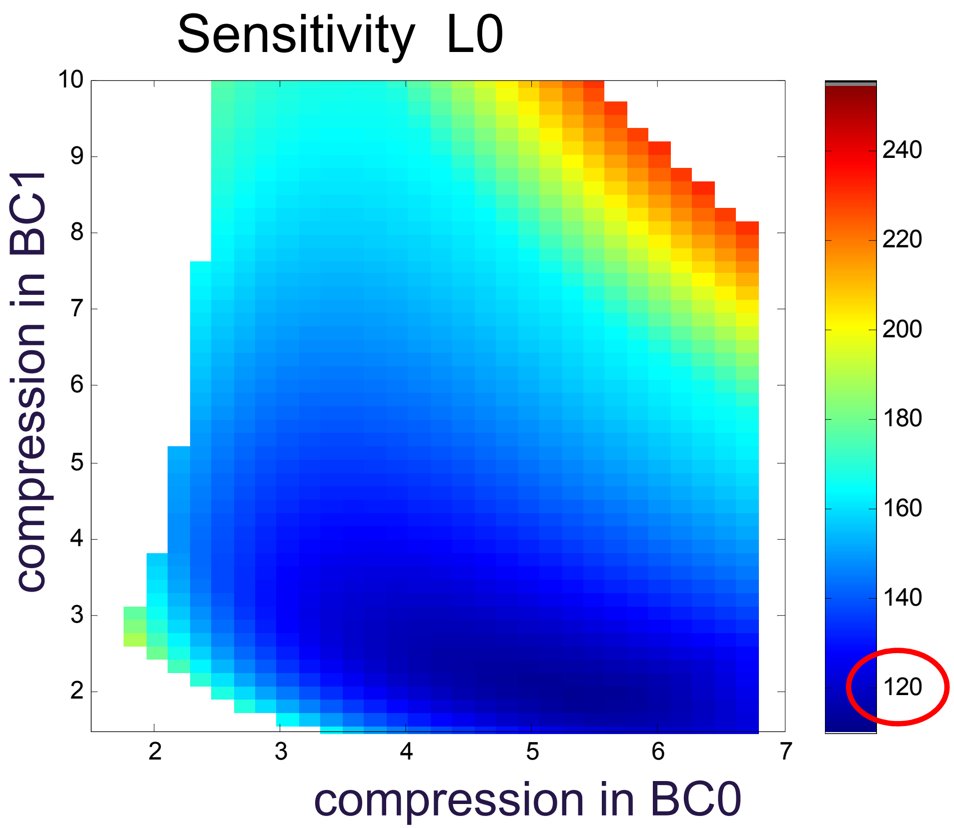
inverse compression

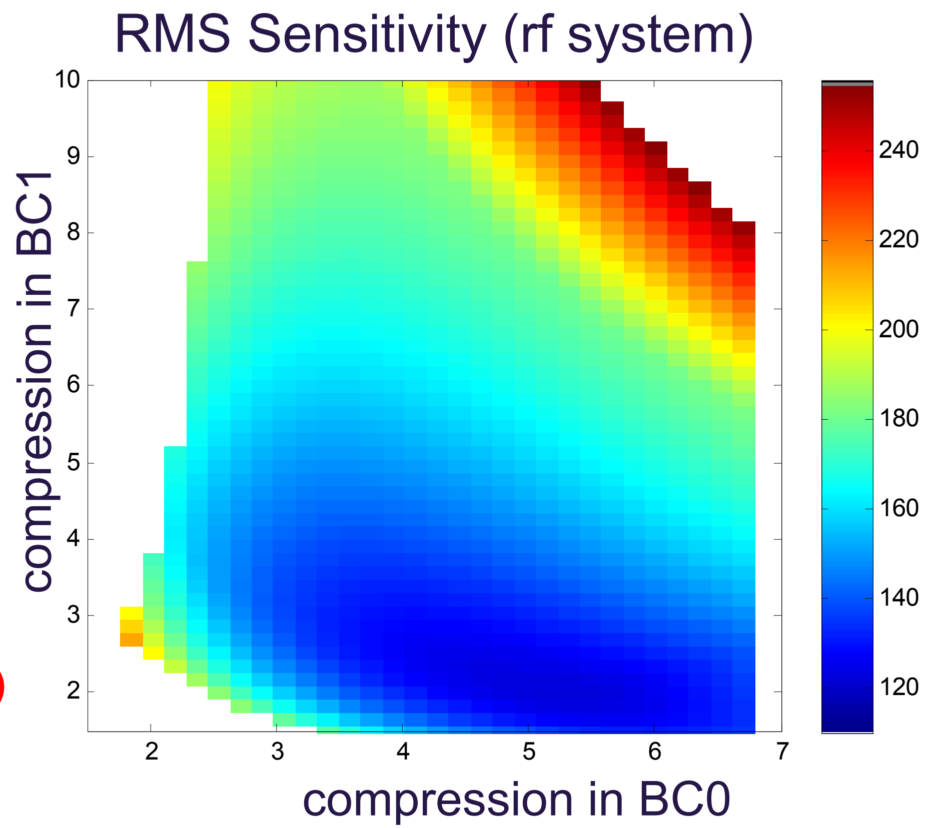




C'' bunch tails

Example: XFEL – BC working point vs. rf Sensitivity





$$S_0 = 120 \qquad \left|\frac{\Delta C}{C}\right| < 0.1 \;\rightarrow \left|\frac{\Delta A_0}{A_0}\right| < \frac{0.1}{120} \approx 0.00083$$

Micro-Bunching Instability Gain Curves

integral equation method:

Heifets,Stupakov: PhysRev ST, 064401 2002
Huang, Kim: PhysRev ST, 074401 2002

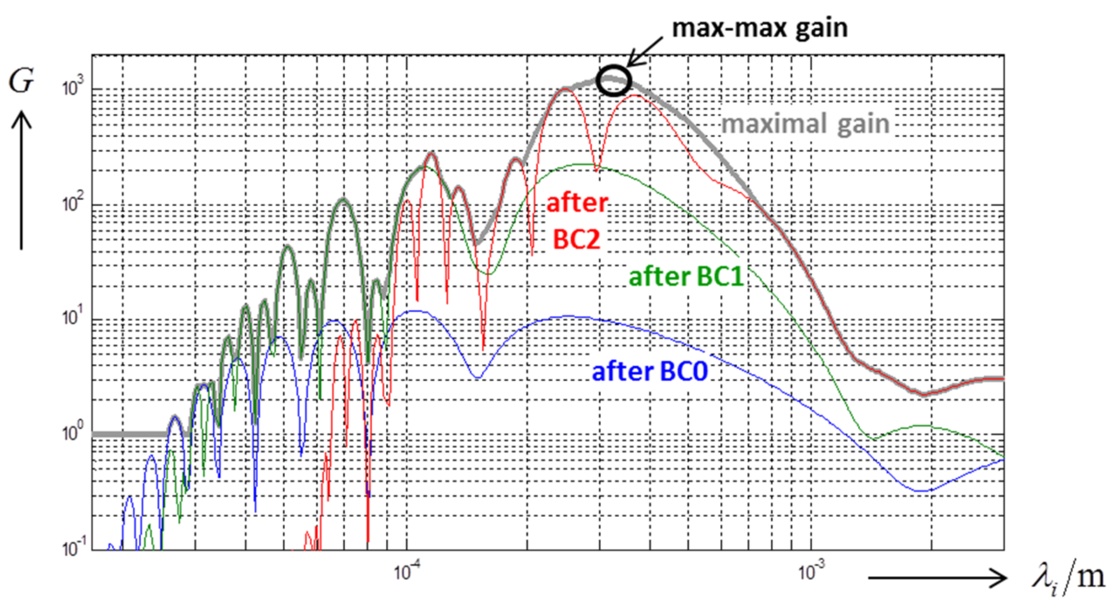
$$G = \frac{\tilde{I}(z)}{I(z)} \frac{I(0)}{\tilde{I}(0)}$$ gain factor, amplification of **relative** modulation

$z =$ length along linac

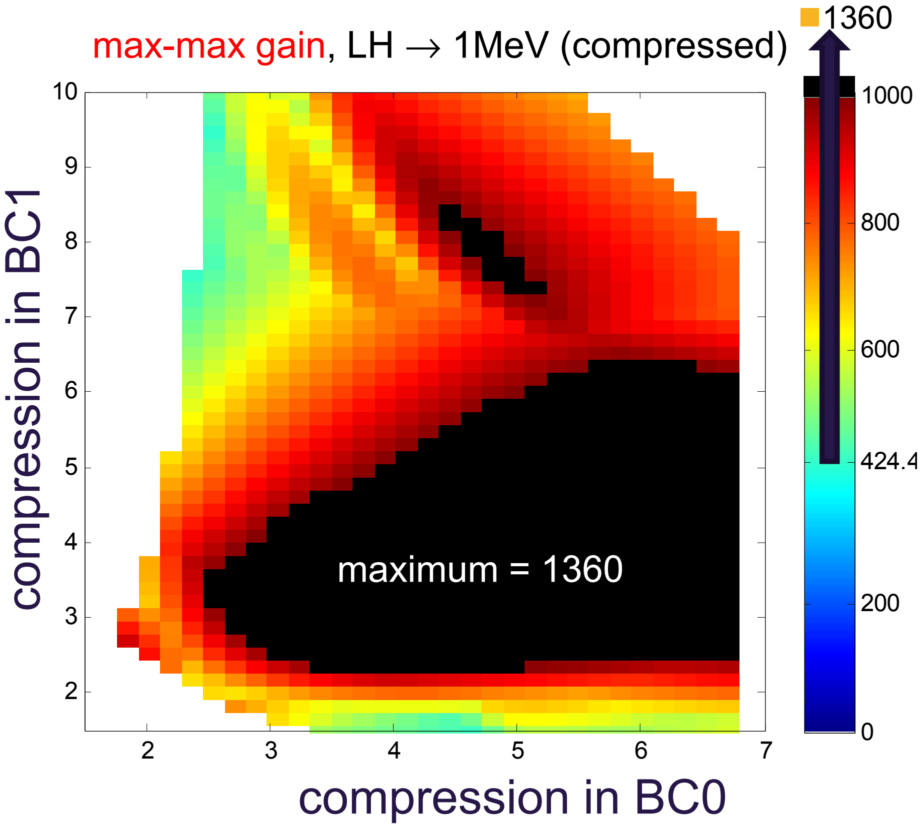
$\lambda_i =$ wavelength of initial density modulation

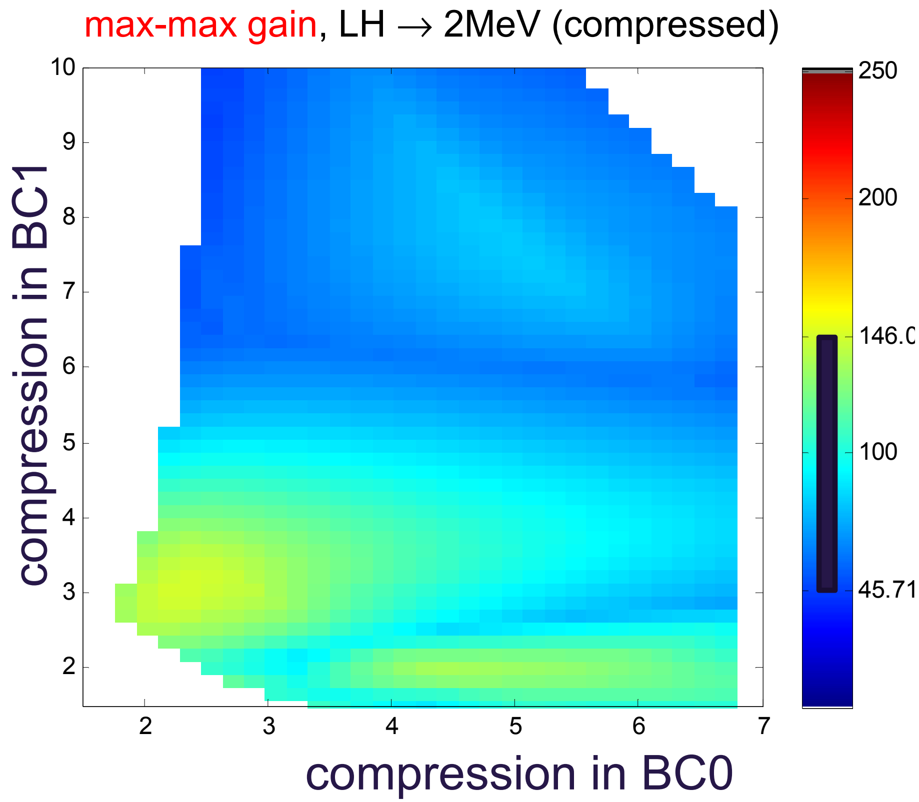
$K =$ kernel depends on **impedance**, current, optics, rf settings, spectrum of uncorrelated **energy spread**, … ← **laser heater**

example:
E-XFEL

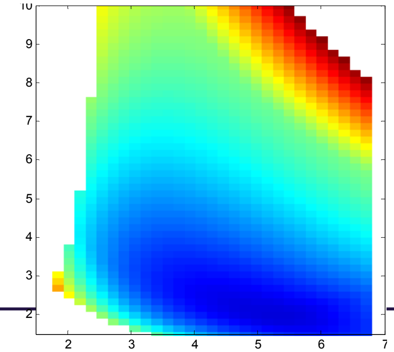


Micro-Bunching Instability Gain



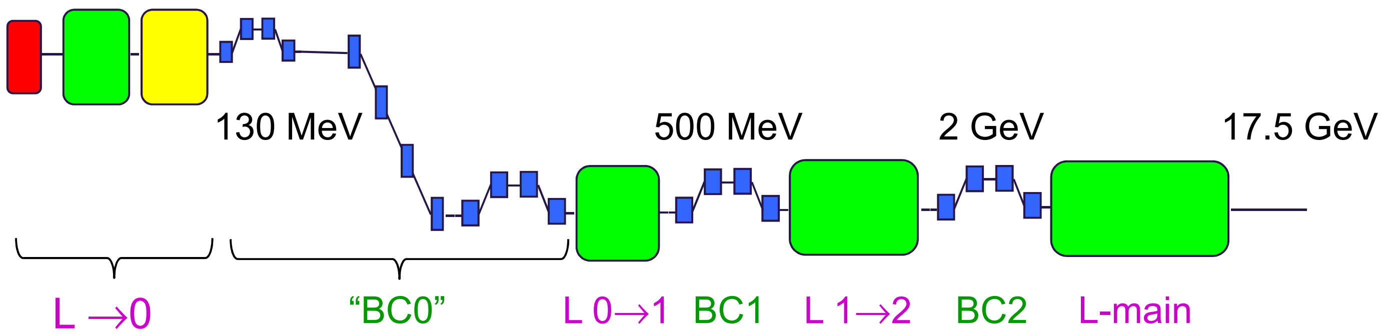


$$S_{\mathrm{rms}} = \sqrt{\sum S_n^2}$$



European XFEL Working Point for 1 nC, 5 kA, Total Compression Factor: 100

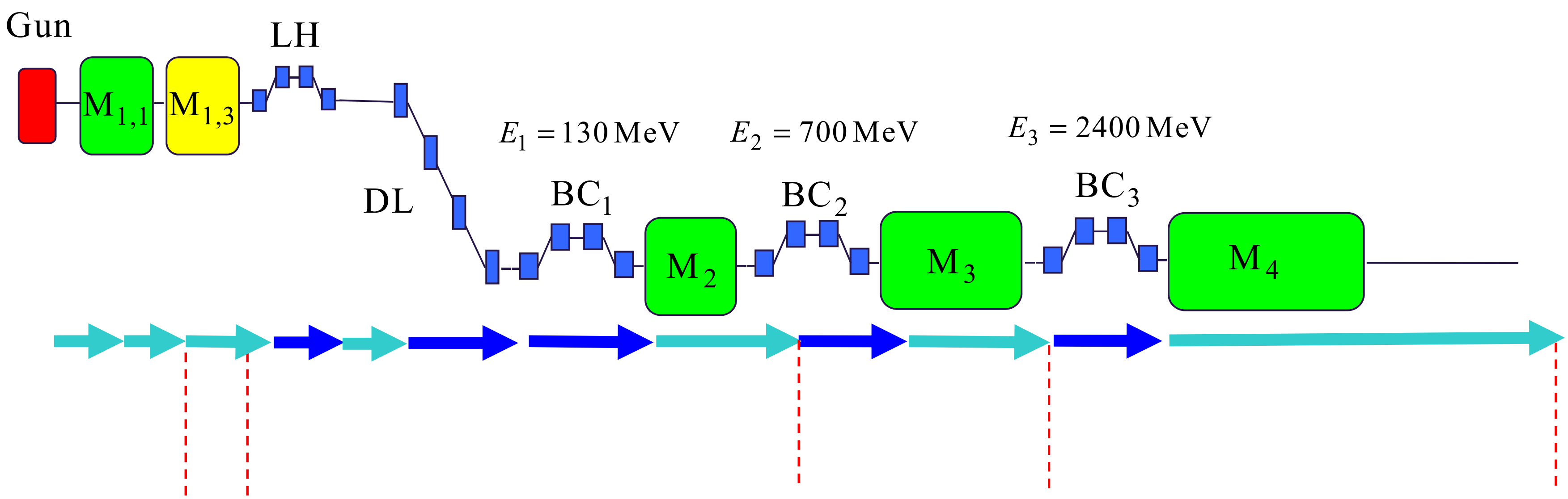
- three stage compression (E-XFEL)



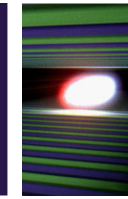
- BC energies: pre defined
- compression factors: free, but total compression fixed (=100)
- higher derivatives of total compression: pre defined
- compression parameter: R56, from rf stability and micro-bunching gain optimization, constraints from RF, BC, maximal ΔE

High Level Simulation

Full 3D simulation method (**200 CPU, ~10 hours**)

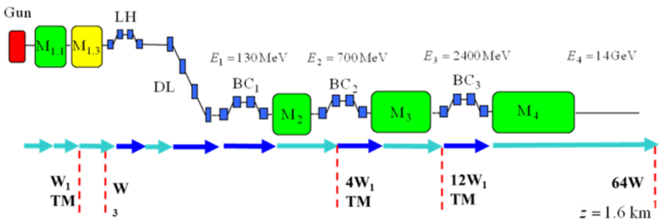


- **ASTRA** (tracking with 3D SC) since 2011: ASTRA with wakes
- **CSRtrack** (tracking with CSR, "projected" model)

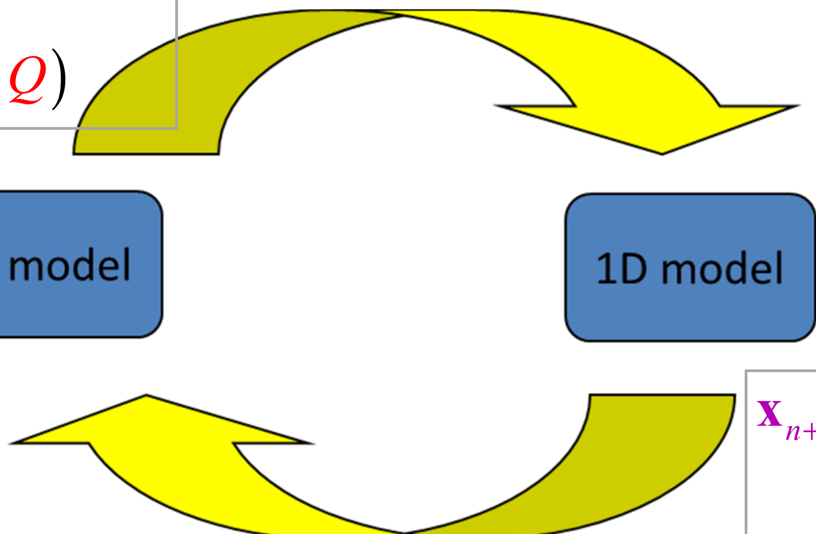


Iterative Process to find Working Point

Full 3D simulation method (**200 CPU, ~10 hours**)



$$\mathbf{y}_n = f_Q\left(\mathbf{x}_n, \mathbf{p}, Q\right)$$

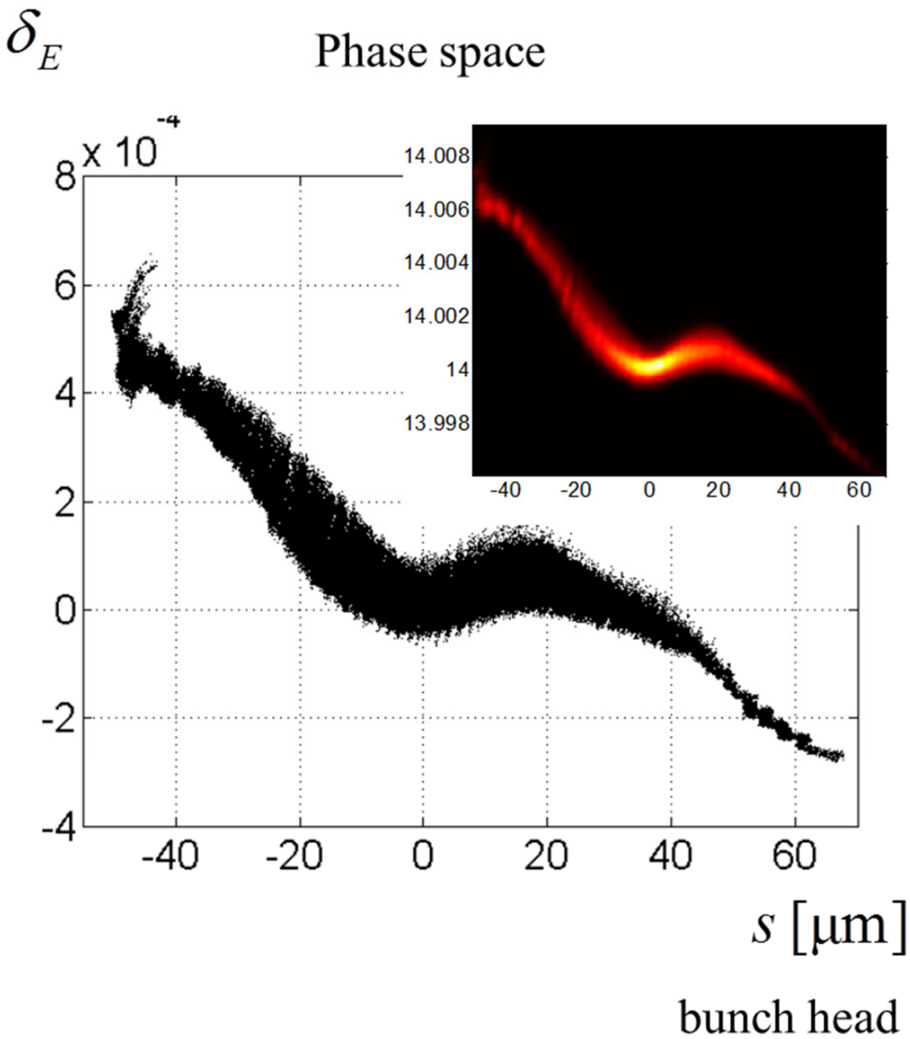


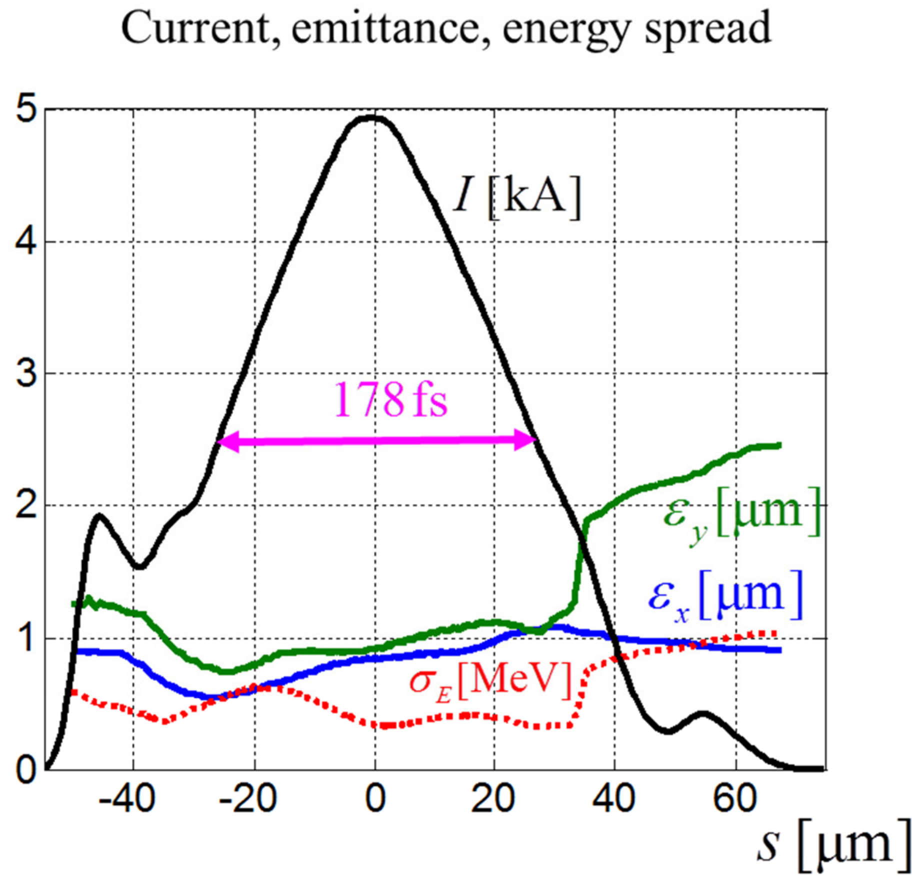
$$\mathbf{x}_{n+1} = g\left(\mathbf{y} - \mathbf{y}_n + f\left(\mathbf{x}_n, \mathbf{p}\right), \mathbf{p}\right)$$

↑ (use low level inverse function)

I.Zagorodnov, M.Dohlus: A Semi-Analytical Modeling of Multistage Bunch Compression with Collective Effects, Phys. Rev. STAB, 2011.

European XFEL BC Exit: 1 nC, 5 kA, Total Compression Factor: 100





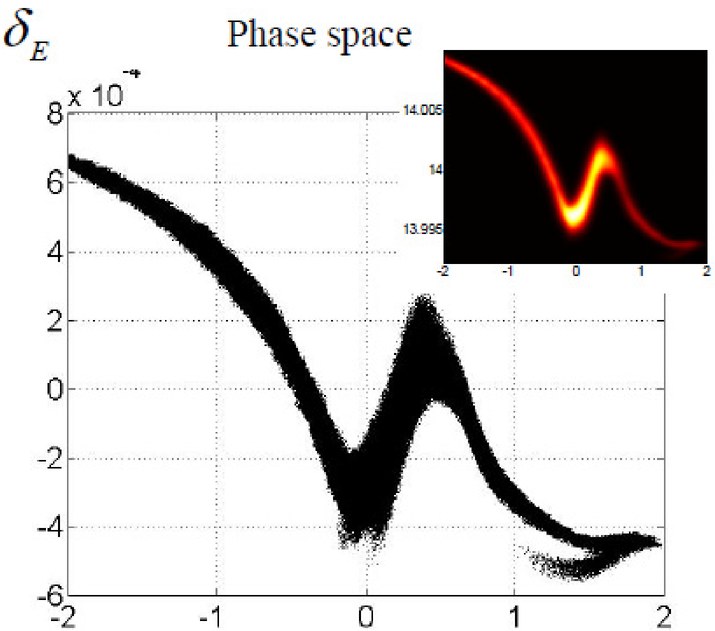
$$\varepsilon_x^{proj} = 0.9\ [\mu m]$$

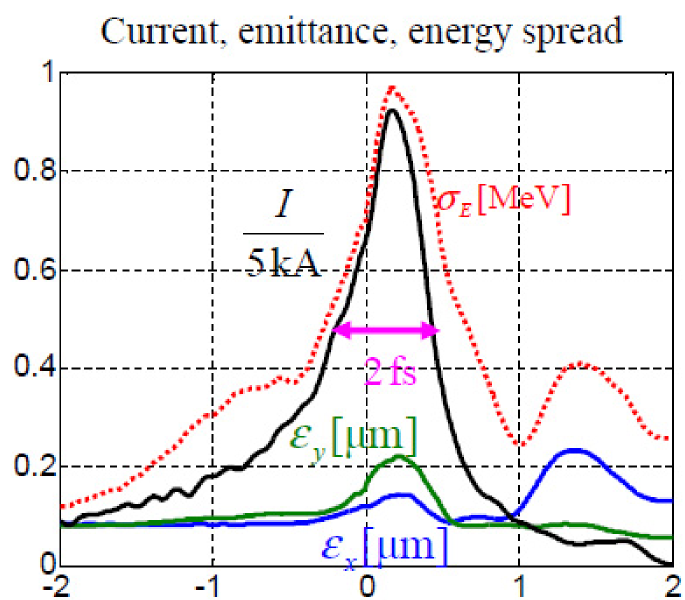
$$\varepsilon_y^{proj} = 3.5\ [\mu m]$$

Q = 20 pC

XFEL beam dynamic simulations for different charges (full)

Q=20 pC





s [µm]

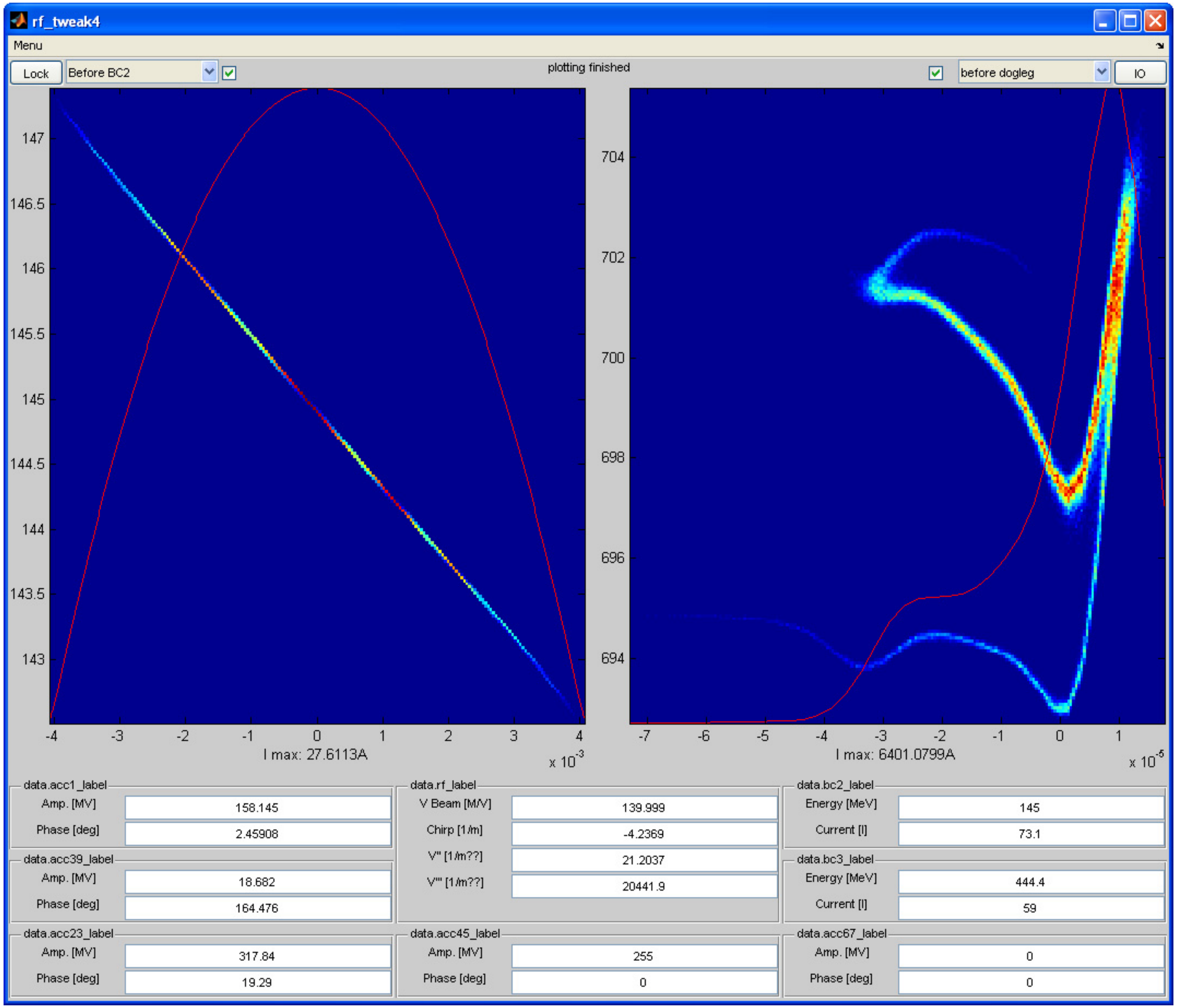
s [µm]

bunch head

$$\varepsilon_x^{proj} = 0.14\ [\mu m]$$

$$\varepsilon_y^{proj} = 0.26\ [\mu m]$$

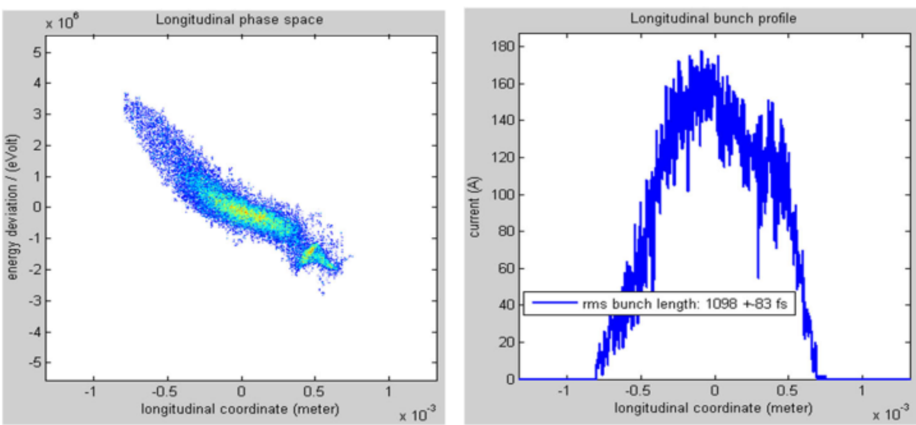
Fast Model for longitudinal Phase Space

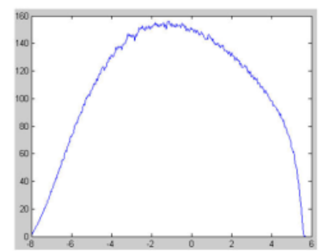


FLASH Compression Studies

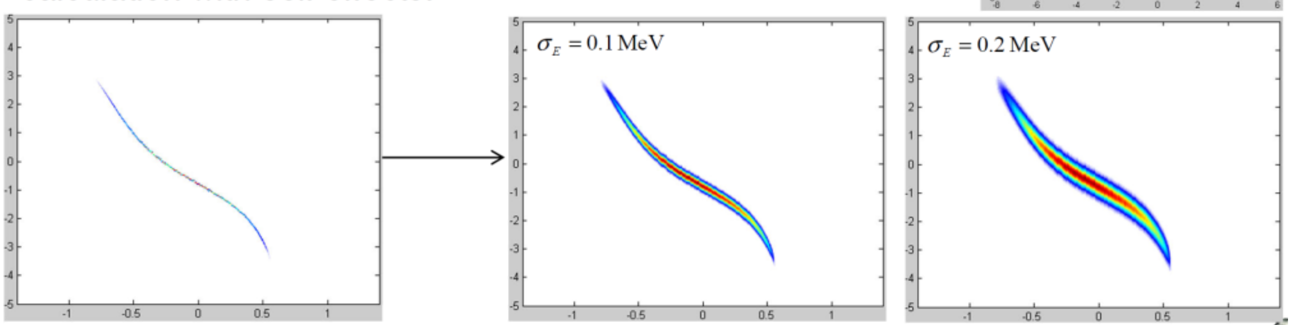
- Further understanding of the physics high density electron bunches; comparison of detailed phase space measurements at FLASH with simulations

LOLA measurement:





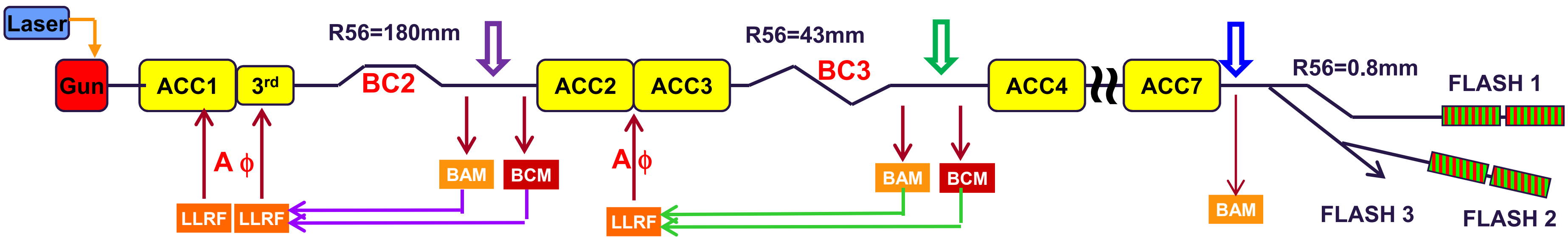
calculation with self effects:

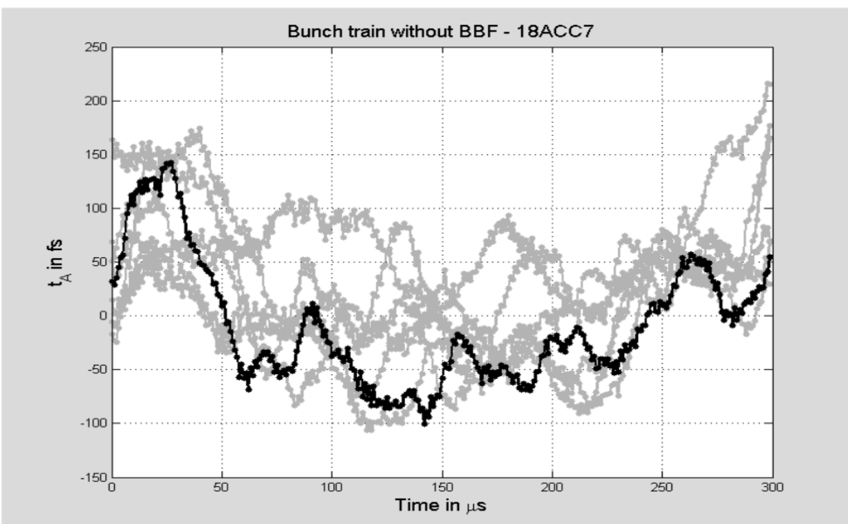


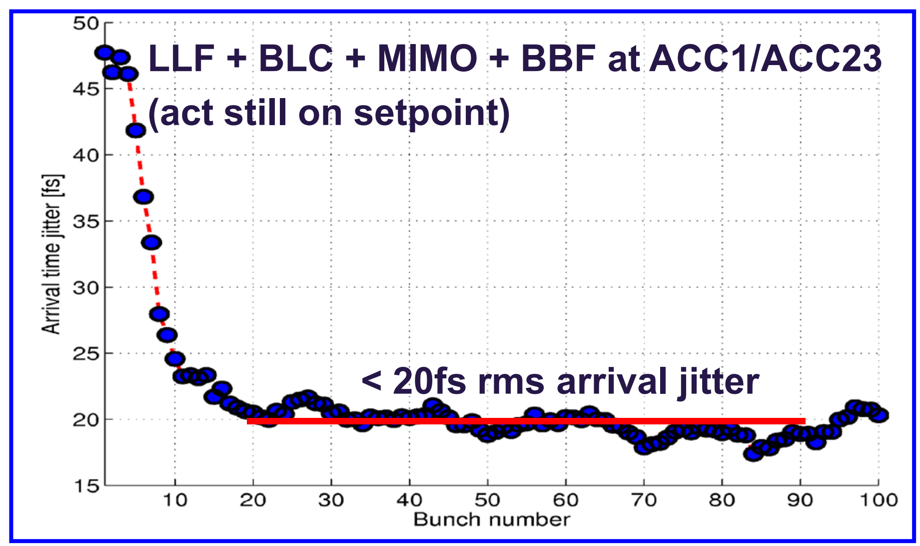
Stabilization

Beam Based Feedbacks for control of longitudinal parameters

- Measurements of beam arrival time (BAM) and bunch compression (BCM) feedback on RF parameters
- Concept implemented and tested at FLASH (intra-train arrival time and slow 5x5)



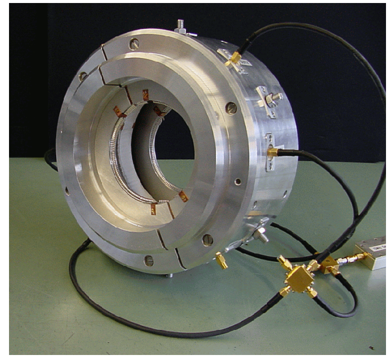




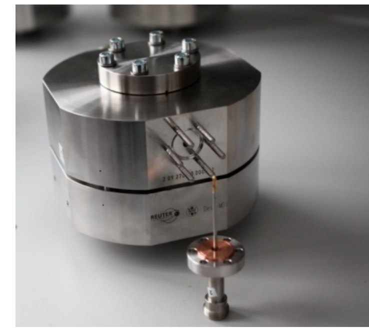
Beam Diagnostics

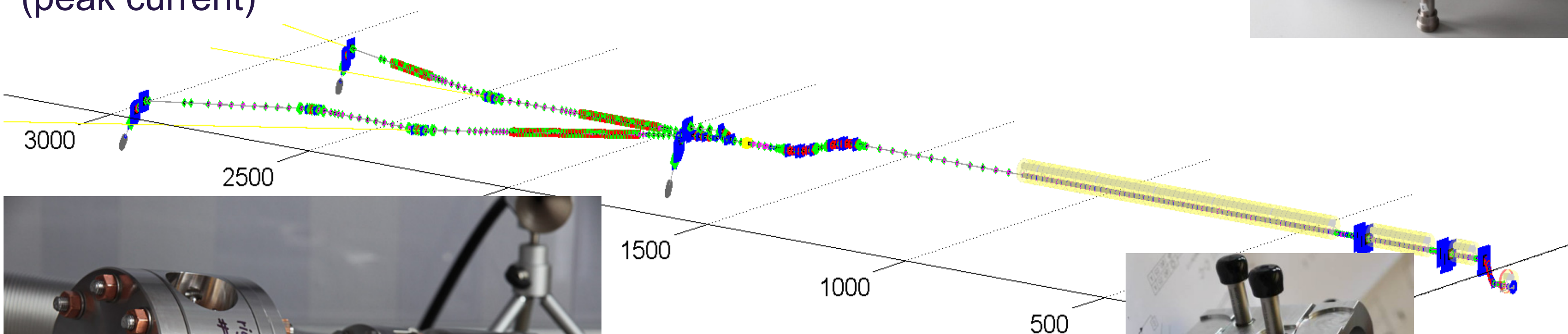
Coherent Radiation Diagnostics (peak current)

Current Monitor

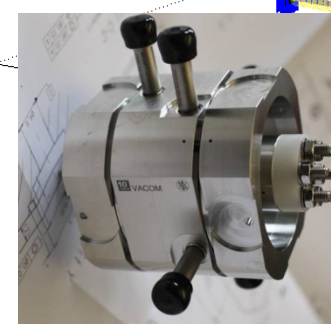


Dark Current Monitor (also very sensitive charge monitor)



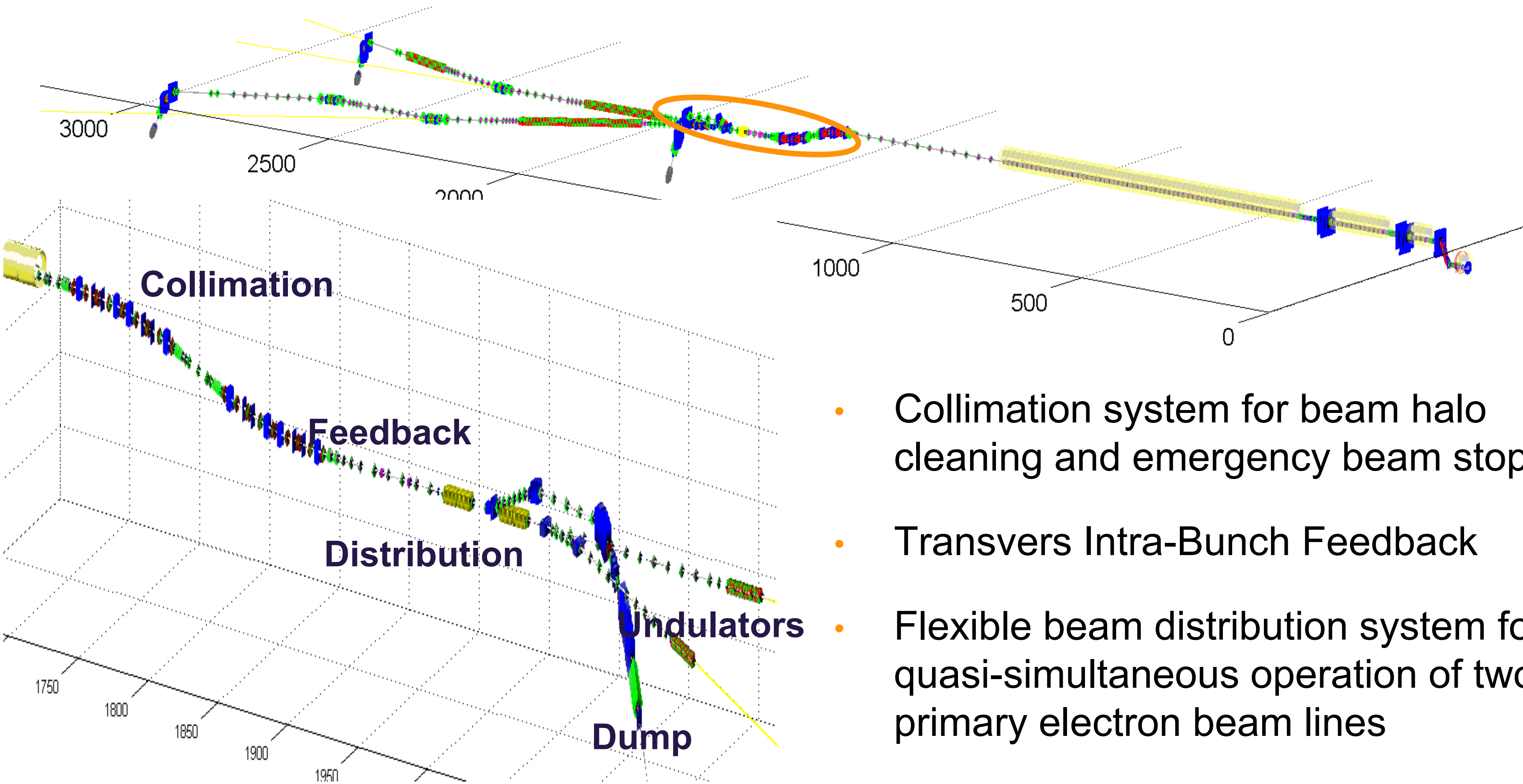


Beam Arrival Time Monitor



Beam Position Monitor

Collimation & Beam Distribution

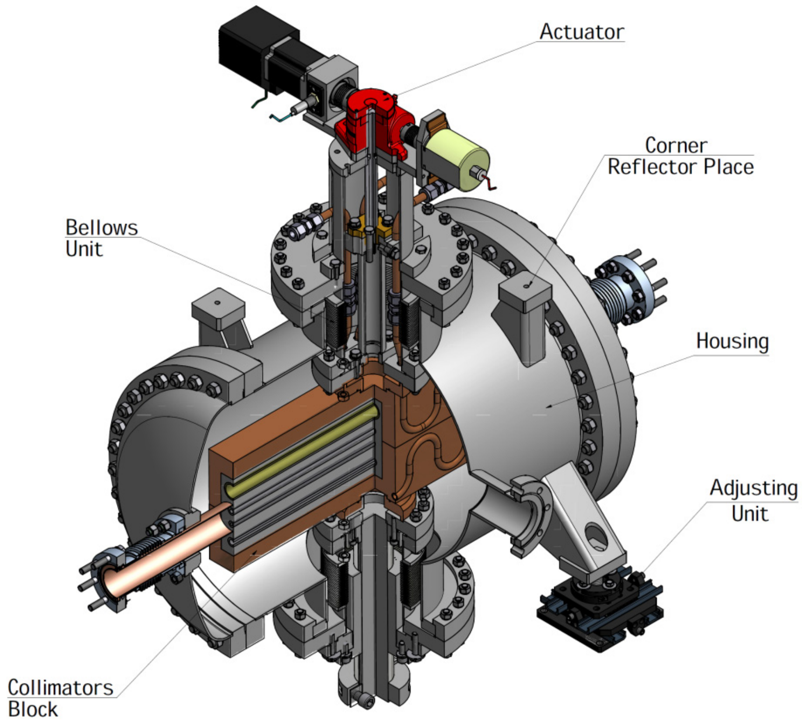


- Collimation system for beam halo cleaning and emergency beam stop
- Transvers Intra-Bunch Feedback
- Flexible beam distribution system for quasi-simultaneous operation of two primary electron beam lines

Collimation

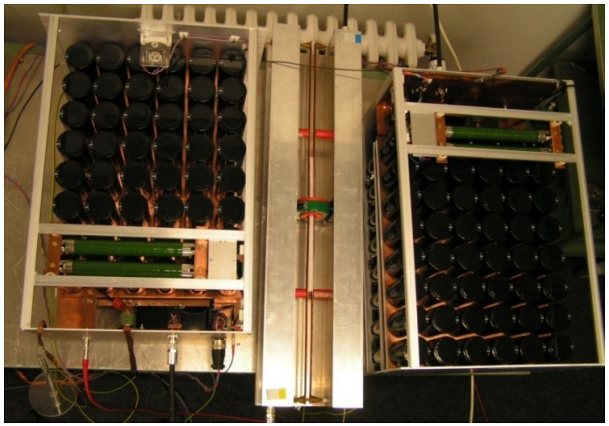
- Downstream equipment protection: survival of direct hit of up to 100 bunches
- Collimation of up to 12 kW average power in beam halo (over short time)
- 50 cm long collimator blocks with different radii (2mm smallest)

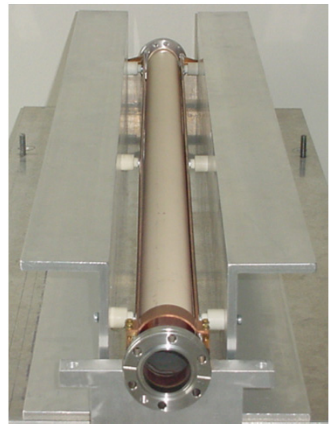
XFEL Collimator



Beam Distribution

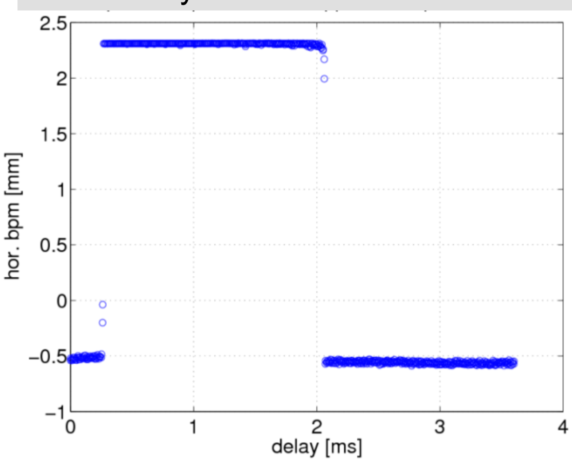
- Development of ultra-stable flat-top pulser
- Pre-Series production 2012

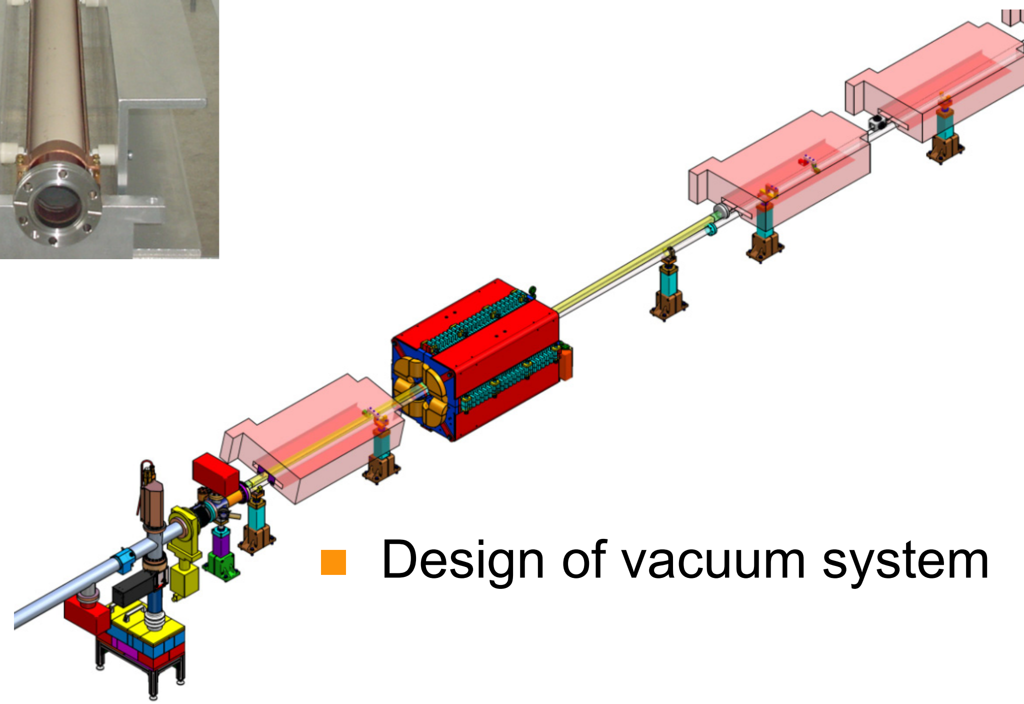




- Design of septum magnet

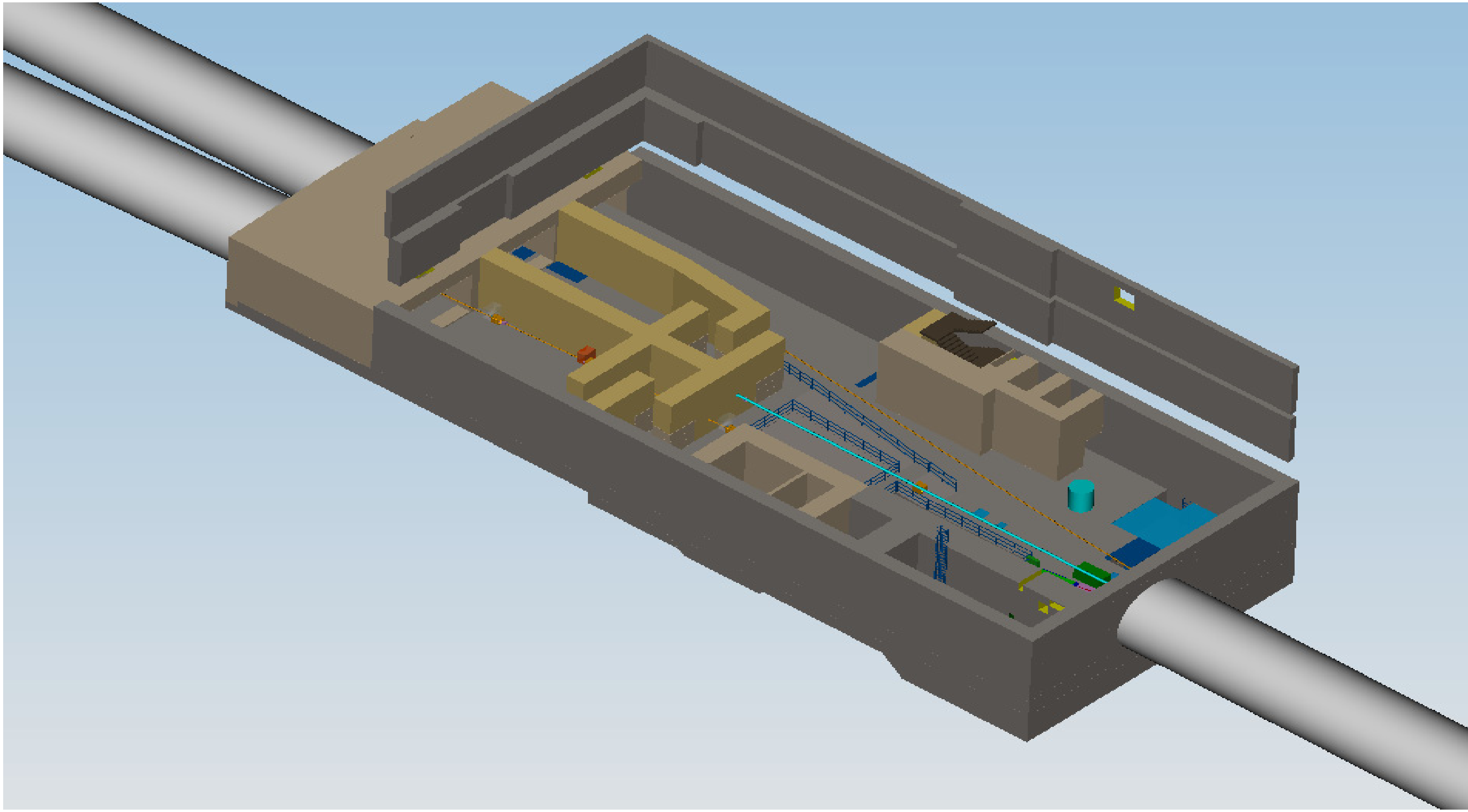
Stabiltity measurements at FLASH





- Design of vacuum system

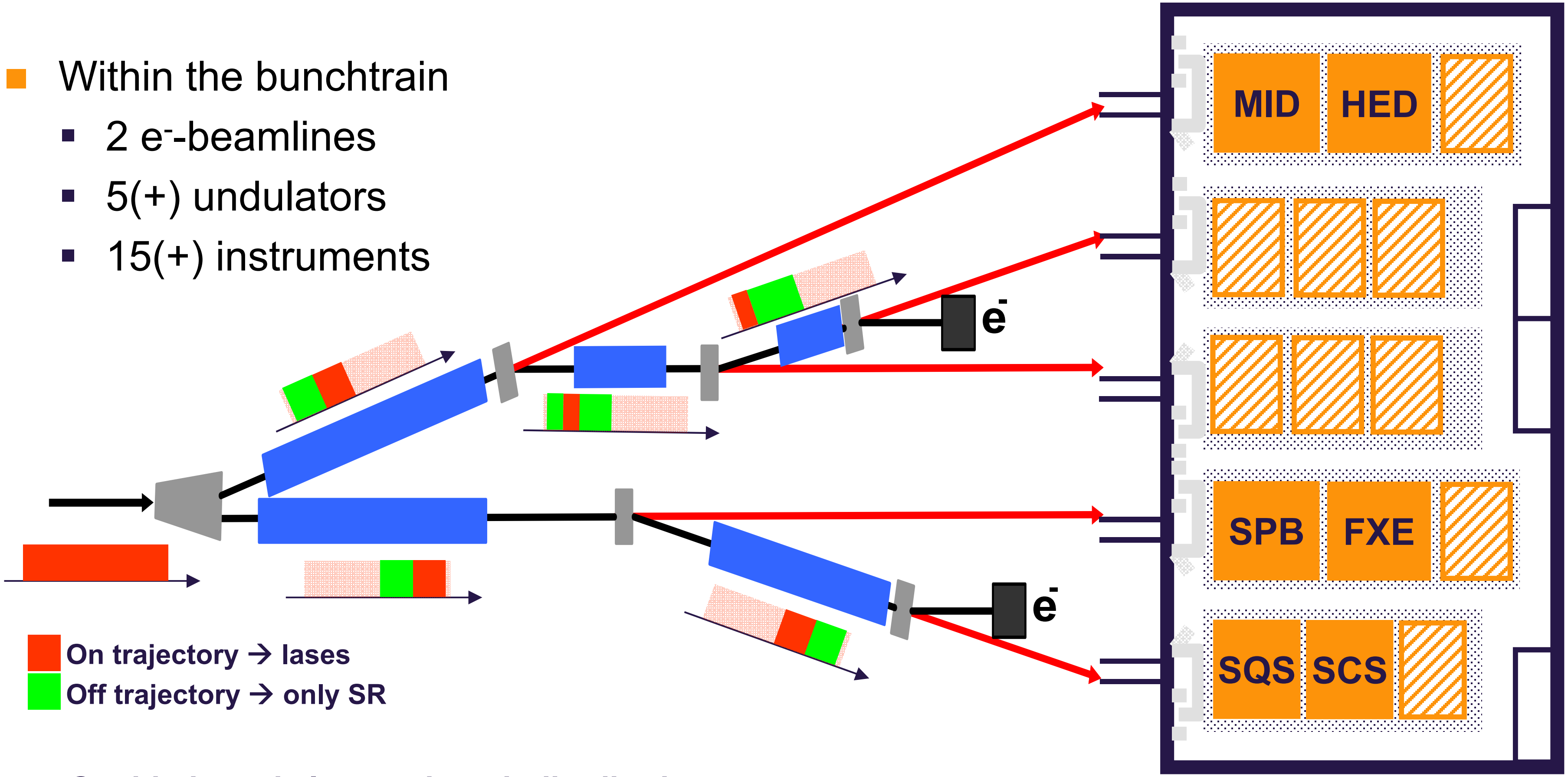
Beam Distribution Shaft – XS1



Beam Distribution Shaft – XS1

Simultaneous operation of many instruments

- Within the bunchtrain
  - 2 e⁻-beamlines
  - 5(+) undulators
  - 15(+) instruments



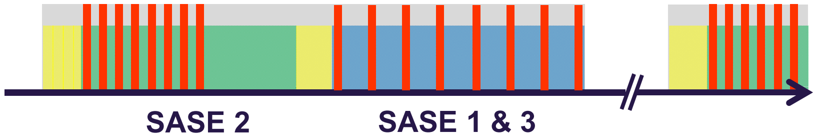
Boxes only placeholders !

Sophisticated electron bunch distribution

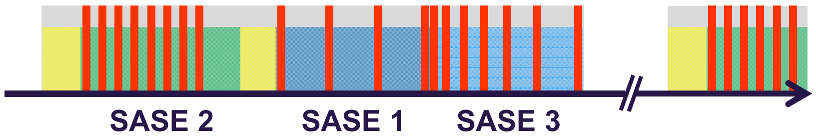
- **27.000 bunches/sec to 5 beamlines**
- **in average 10-20 Hz and ~500 pulses/train**
- **using kicking methods to make bunches lase only in dedicated undulator**

Electron bunch distribution to 2 BL / 5 undulators

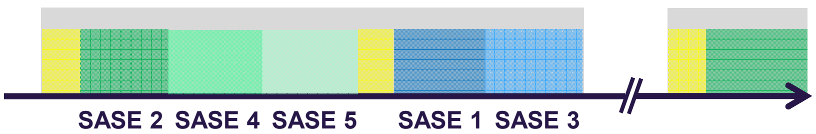
- e-beam distribution to 2 beamlines
  - Slots for feedback & switching
  - Equal splitting on both e⁻-BL



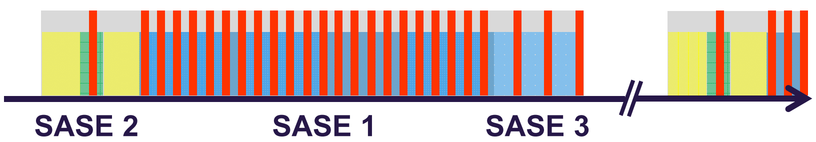
  - Equal splitting on 3 undulators



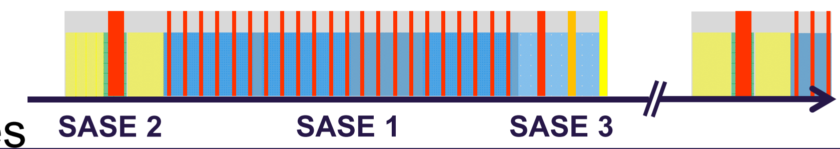
  - Equal splitting on 5 und. (future)



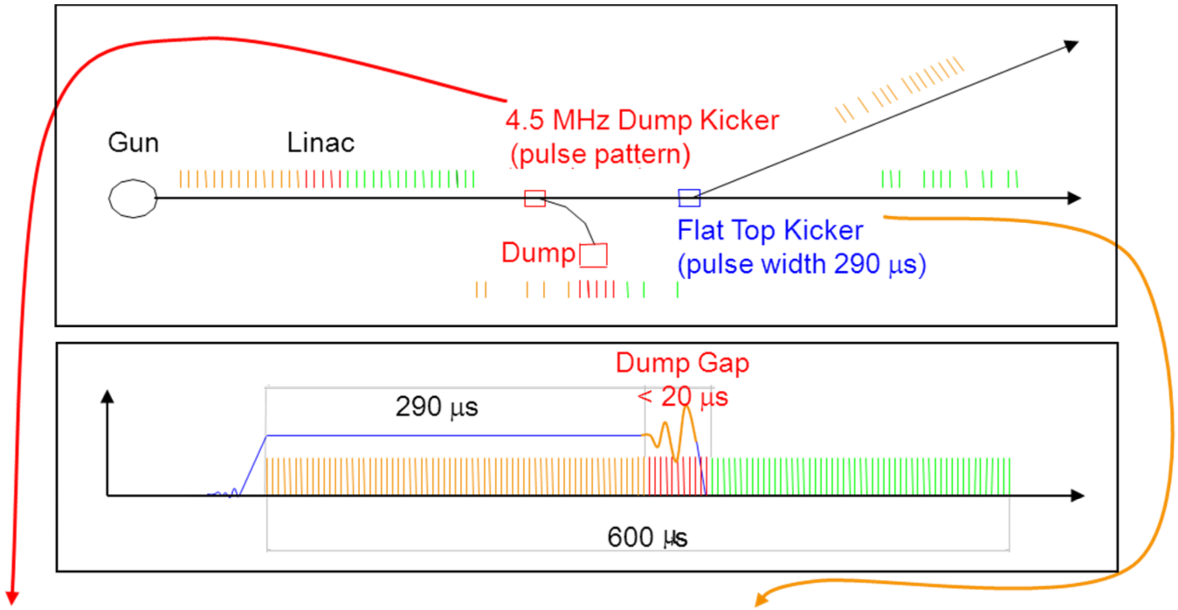
  - Asymetric splitting



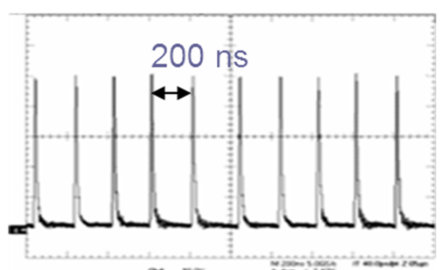
  - Specific electron bunch properties



Pulse Distribution

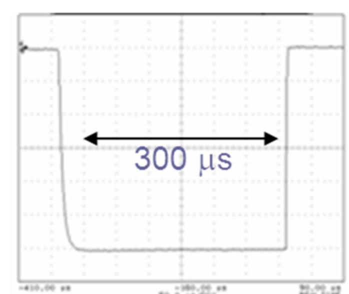


- low accuracy (>1 %)
- 4.5 MHz burst operation



example:
pulser prototype measurement

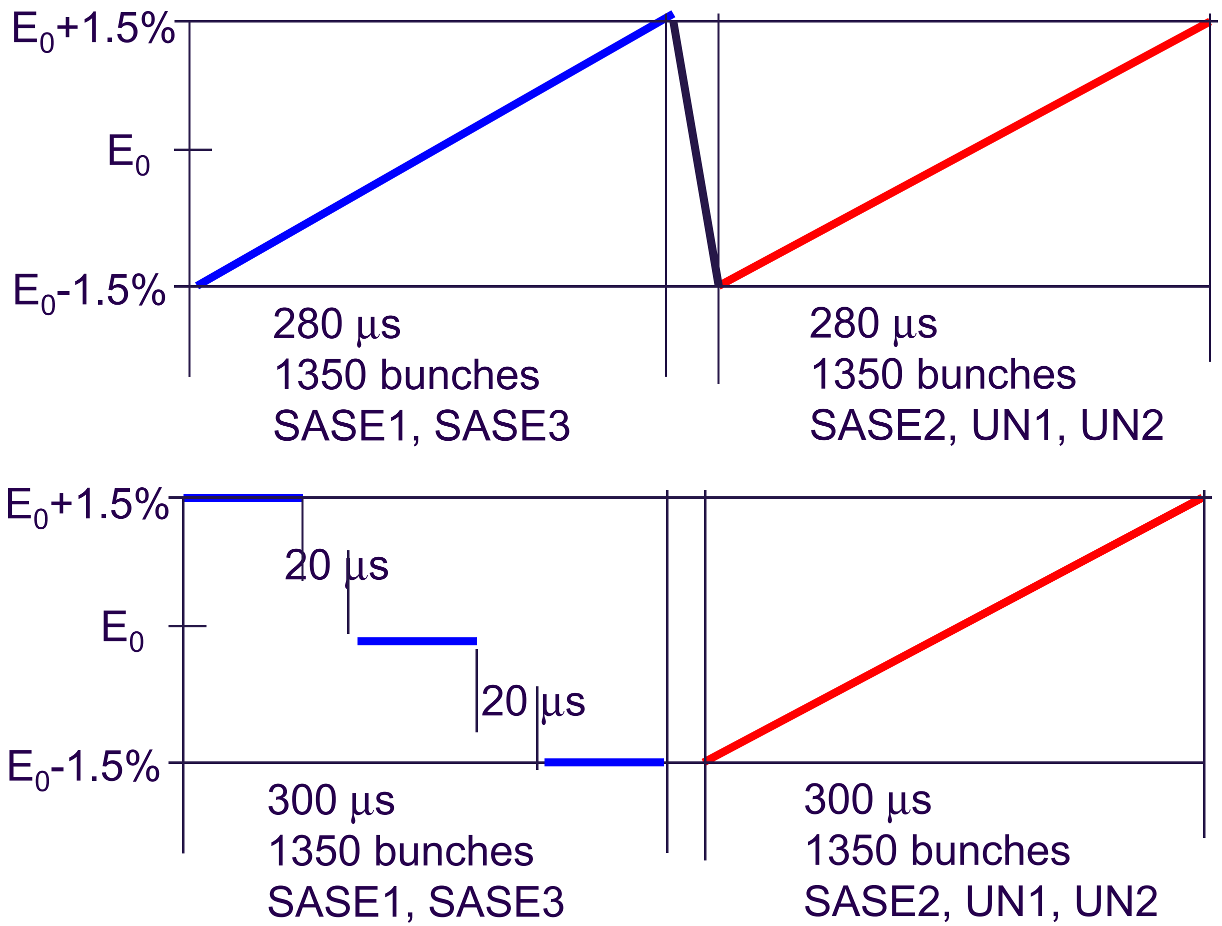
- high accuracy (< 0.01 %)
- 10 Hz operation



example:
pulser prototype measurement

European XFEL

Energy Variation – Within Pulse



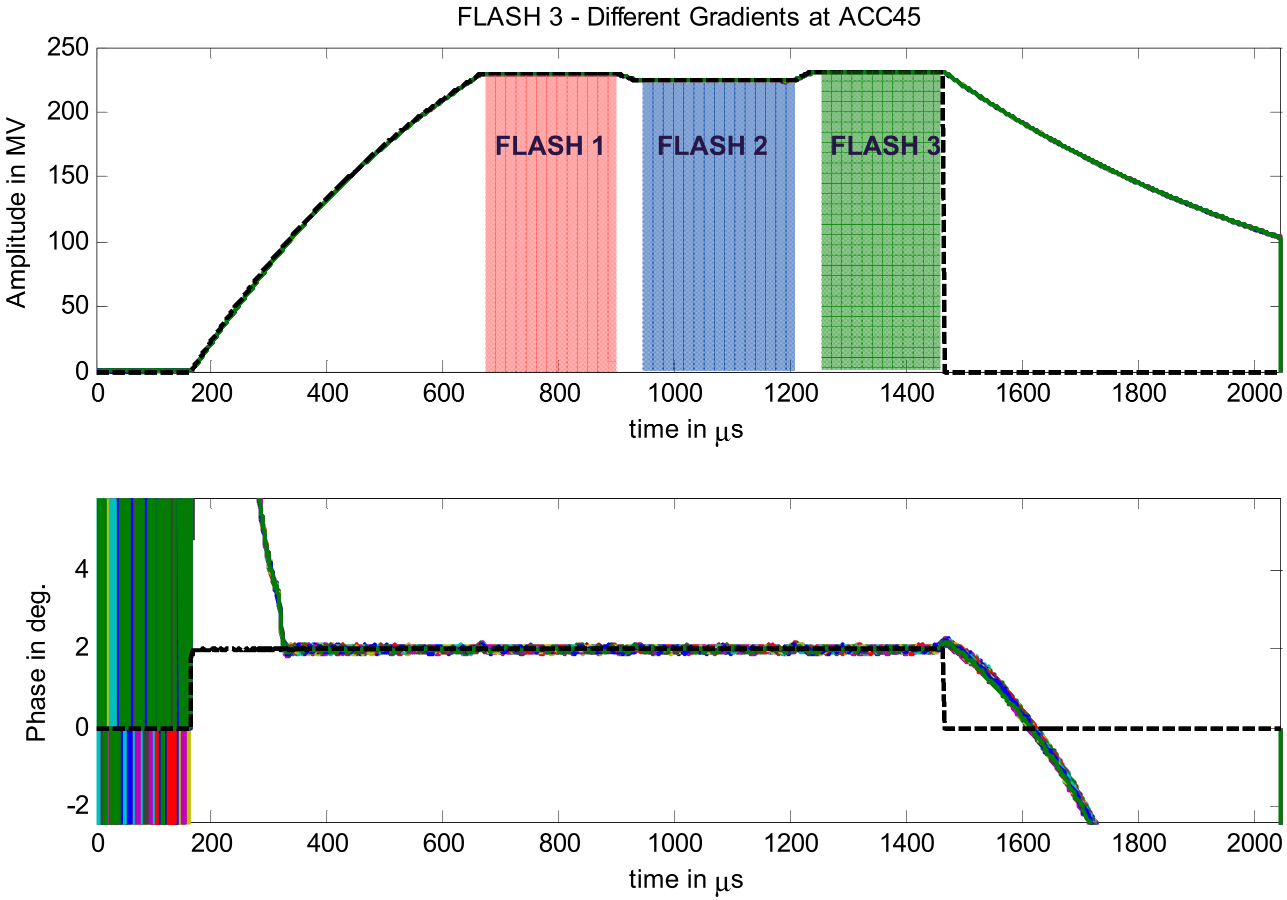
$\Delta E/E_{max} = 3\ \%$

$\Delta E/E = + 10^{-4} / \mu s$

$- 10^{-3} / \mu s$

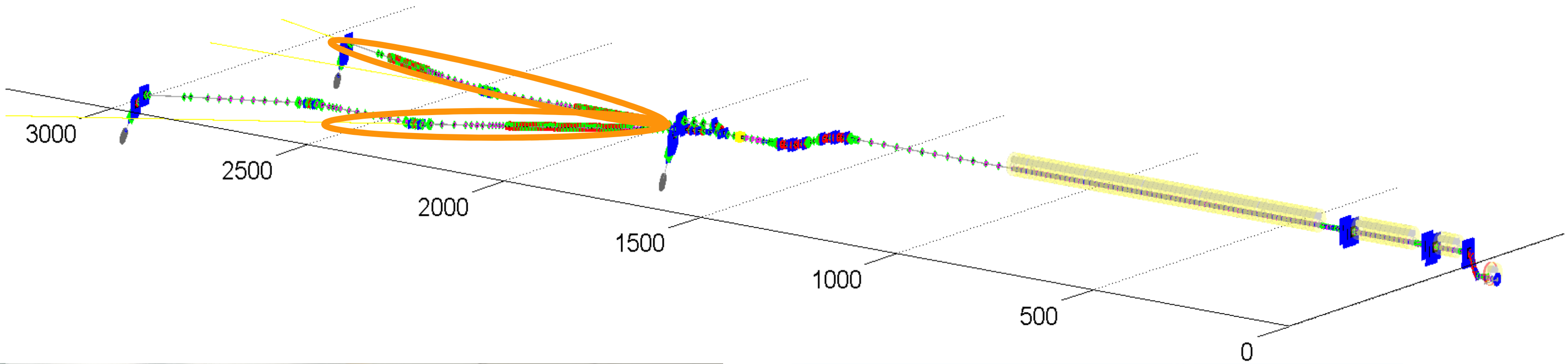
Multiple – gradient/phase operation

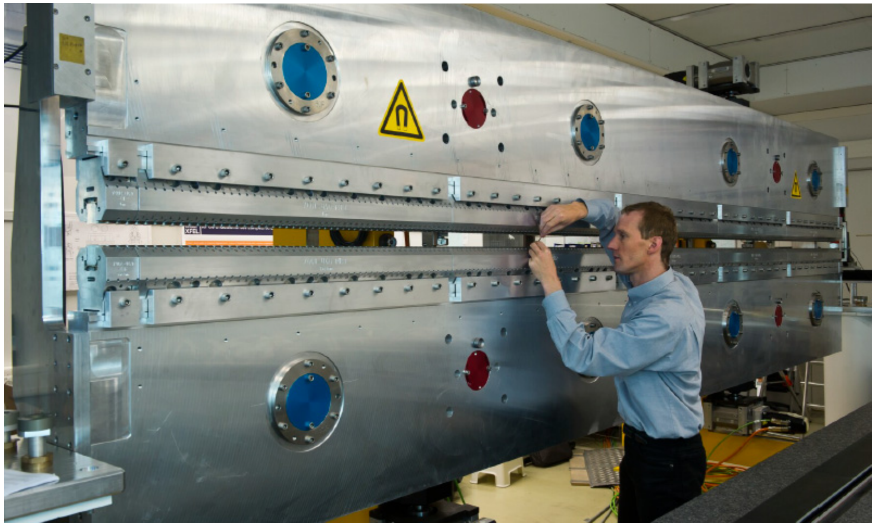
- **Preparation of software for FLASH 1 & 2 & 3 operation!**

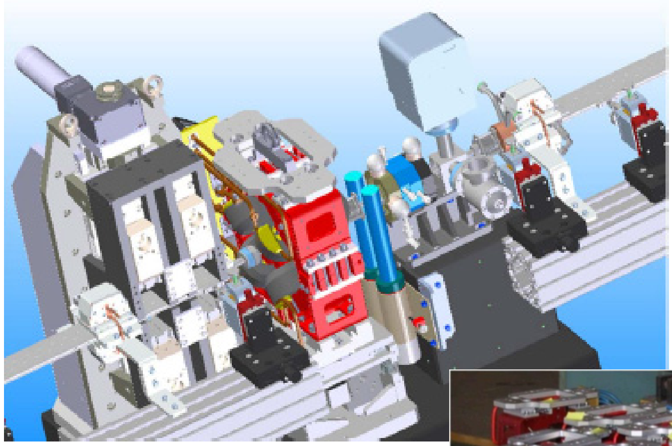


- Used gradient steps -2% and + 3% with 40us transient time
- Set-up time < 10 sec

European XFEL – Undulators

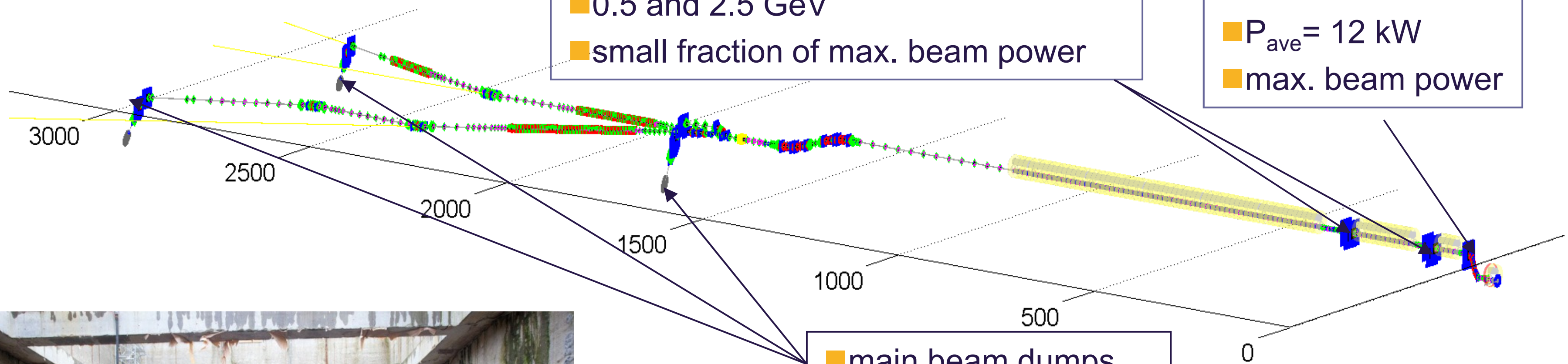






Pre-series arrived &measured, series ordered (total 35+35+22)

Beam Dumps

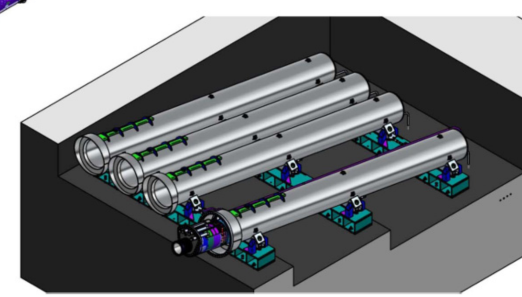


- bunch compressor diagnostic dumps
- 0.5 and 2.5 GeV
- small fraction of max. beam power

- injector dumps
- 130 MeV
- P_{ave}= 12 kW
- max. beam power

- main beam dumps
- up to 25 GeV
- P_{ave}= 300 kW
- 1/2 max beam power

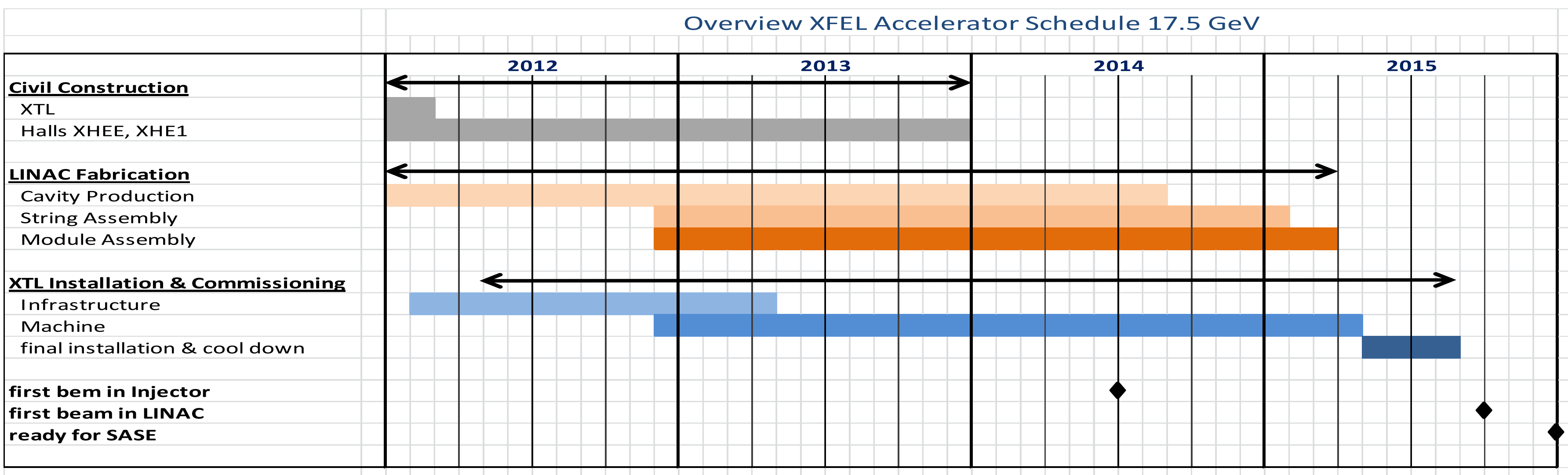
Design of the main dump (Qty 5)



Production readiness reviews for all beam dumps finished

Schedule

- Construction, infrastructure planning and ramp up of accelerator component fabrication on track
- Working hard to finish installation in time for
  - start of injector commissioning mid 2014
  - start of linac commissioning mid 2015
  - observe first SASE by end of 2015

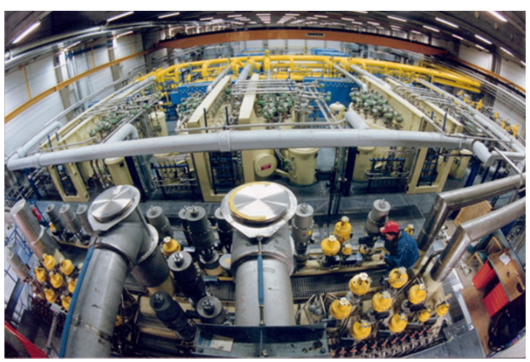


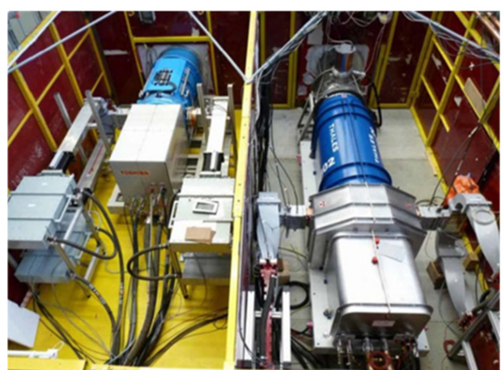

Thank you for your attention!

Repetition Rate Variation Limits

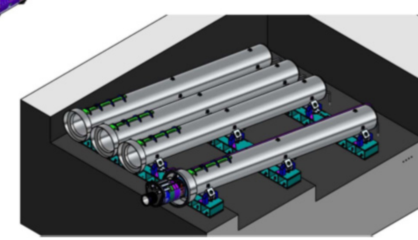
- cryo-losses: $P_{loss} \approx N_{modules}(P_{static} + c\, f_{rep} T_{total} V_{acc}{}^{2}) < 2\ \mathrm{kW}$ for all, $< 30\ \mathrm{W}$ single module
- rf system: $P_{kly,peak} \approx \frac{N_{bunches} C_{bunch}}{T_{pulse}} V_{acc} \#_{modules}\, f_{reg} < 10\ \mathrm{MW}$

  $P_{kly,ave} \approx P_{kly,peak} f_{rep} T_{total} < 150\ \mathrm{kW}$
- dump: $P_{beam} = f_{rep} N_{bunches} C_{bunch} E_{beam} < 300\ \mathrm{kW}$



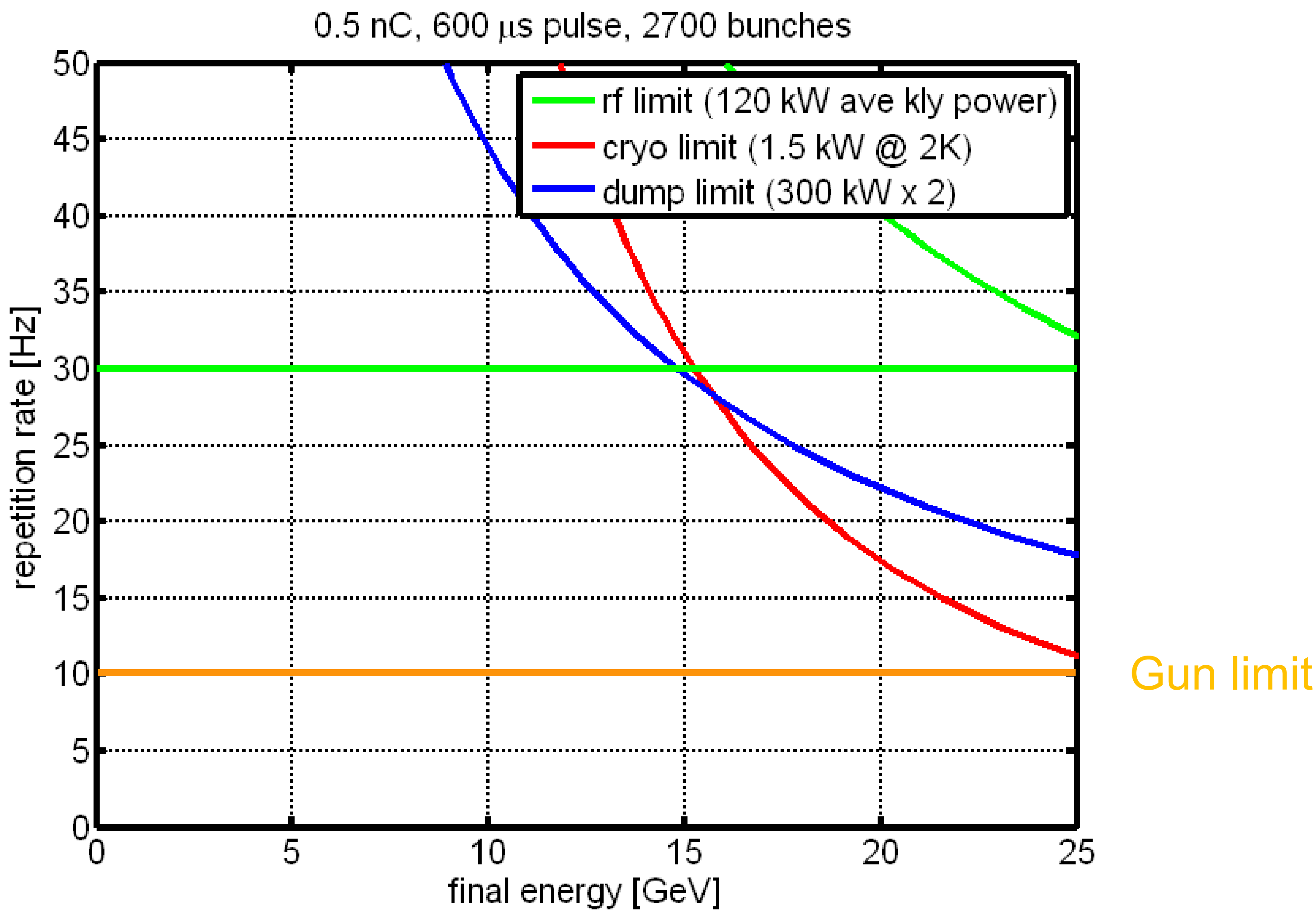


Design of the main dump (Qty 5)



European XFEL

Repetition rate variations



CW or Near CW Operation

- From dump

$$P_{beam} = f_{rep} N_{bunches} C_{bunch} E_{beam} < 300\ \mathrm{kW}$$

- From Cryo-plant

$$P_{loss} \approx \#_{modules}(P_{static} + c\ f_{rep} T_{total} V_{acc}{}^{2}) < 2\ kW$$

- From new IOT (inductive output tube) based RF system

$$P_{kly} \approx \frac{N_{bunches} C_{bunch}}{T_{total}} V_{acc} \#_{modules}\ f_{reg} < 120\ kW$$

ACCELERATORS | PHOTON SCIENCE | PARTICLE PHYSICS

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

DESY

URL: http://www.desy.de/news/@@news-view

13.07.2011

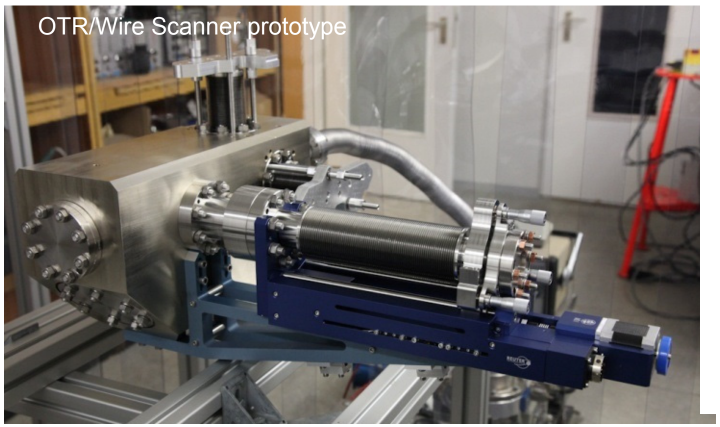
The first continuous wave and long-pulse operation of the XFEL-type cryomodule

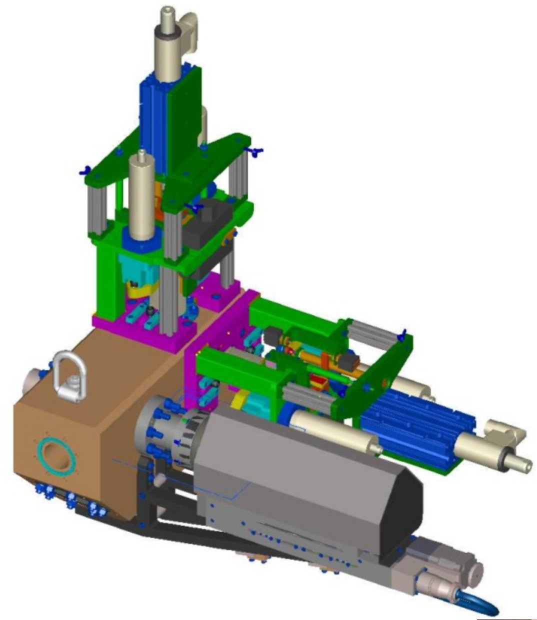
Continuous wave (CW) and long-pulse (LP) operation modes of the XFEL superconducting linac are an attractive future option to enhance the experimental potential of this European facility, being currently under construction. On Wednesday 7 July 2011, a two-week test was finished in which the XFEL-type cryomodule, a building block of the XFEL linac, for the first time was operated successfully in both, CW and LP mode with accelerating gradients up to 5.5 MV/m and 11.5 MV/m, respectively.

Beam Diagnostics: Screens and Wires

Beam Size Measurements

- ~ 50 Screens
- 12 Wire scanners





- 2nd design iteration for wire scanners
- Issue with Coherent OTR from compressed bunches:
  - gated camera
  - spatial separation
- Screen material tests at MAMI performed