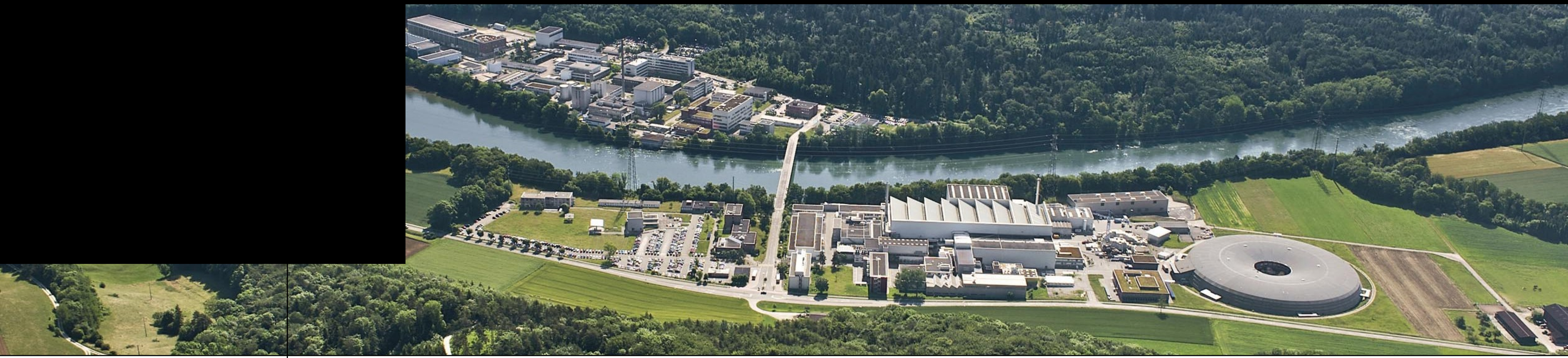


Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut
Sven Reiche

The SwissFEL Project and the SwissFEL Test Facility at PSI

SwissFEL
A Compact X-ray Facility

Optimizing the FEL (Namely Brilliance)

Photon Brilliance

$$B = \frac{\#\, photons}{\Delta T \cdot \Delta\omega/\omega \cdot \Delta x \cdot \Delta x' \cdot \Delta y \cdot \Delta y'}$$

Fourier Limited ~λ *Diffraction Limited* ~λ^2

Electron Brilliance

$$B = \frac{Q}{\Delta T \cdot \Delta E/E \cdot \varepsilon_x \cdot \varepsilon_y}$$

Quantum Limit

$$\left(\frac{2Q}{e h^3} \right)$$

FEL Process converts electron brightness into photon brightness

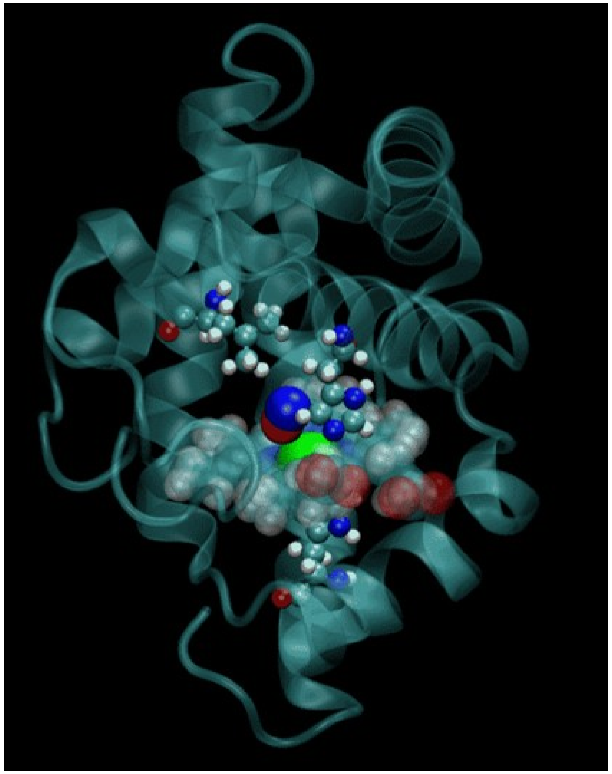
Electron brightness can be much smaller but needs only to be smaller than photon brightness:

$$N_{ph} E_{ph} / \Delta T \approx \rho N_e E_e / \Delta T \qquad \frac{\Delta E}{E} < \rho \qquad \frac{\varepsilon_N}{\gamma} < \frac{\lambda}{4\pi}$$

High Current — Low Energy Spread — Low Emittance

SwissFEL Design Strategy

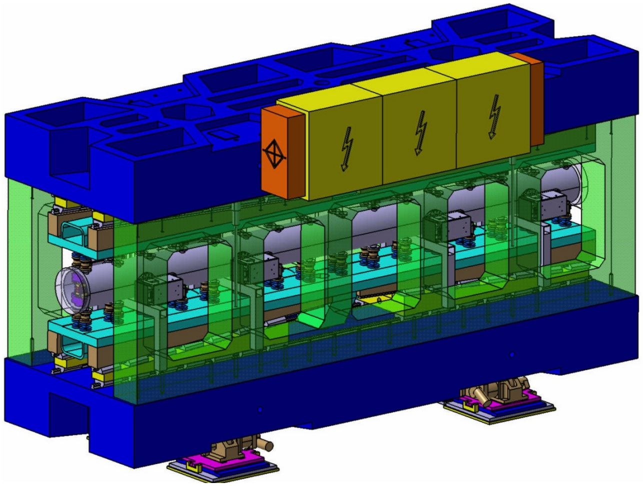
1) Reaching 1 Ångstrom Wavelength for Atomic Resolution



2) Compact Undulator to lower Beam Energy

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

→ **E ~ 6 GeV**



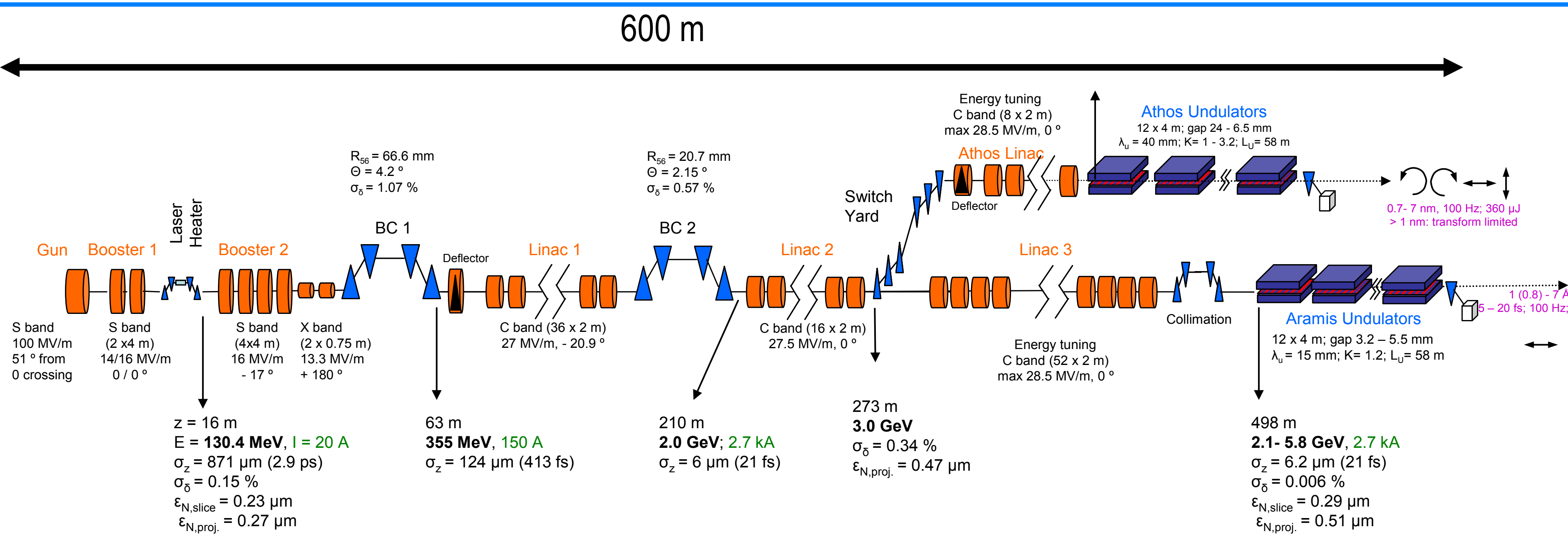
3) Low emittance electron beam source

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

→ **ε_n ~ 0.3 mm mrad**

4) Efficient beam generation, acceleration and compression

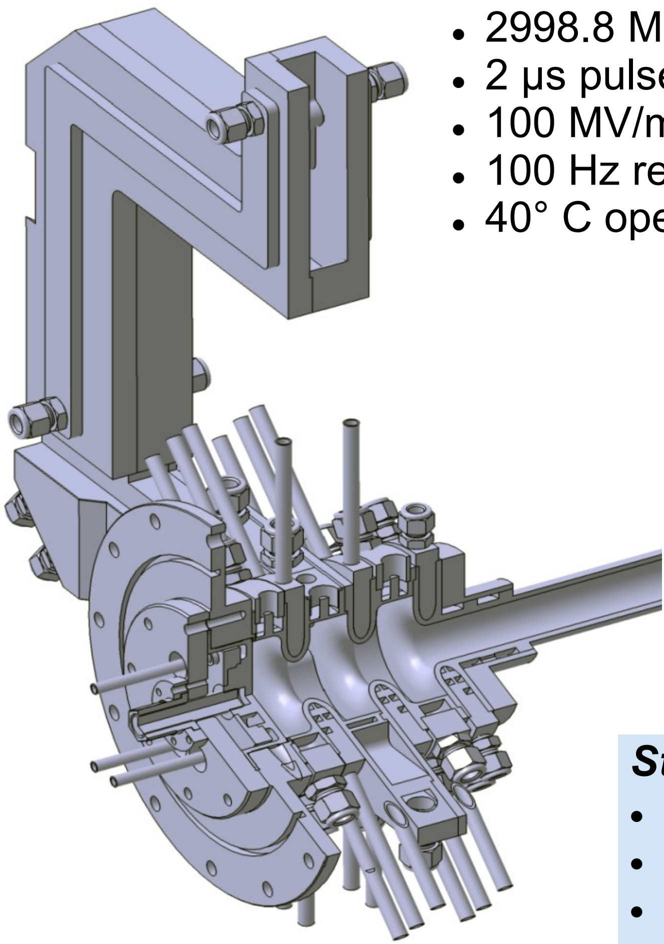
Layout SwissFEL



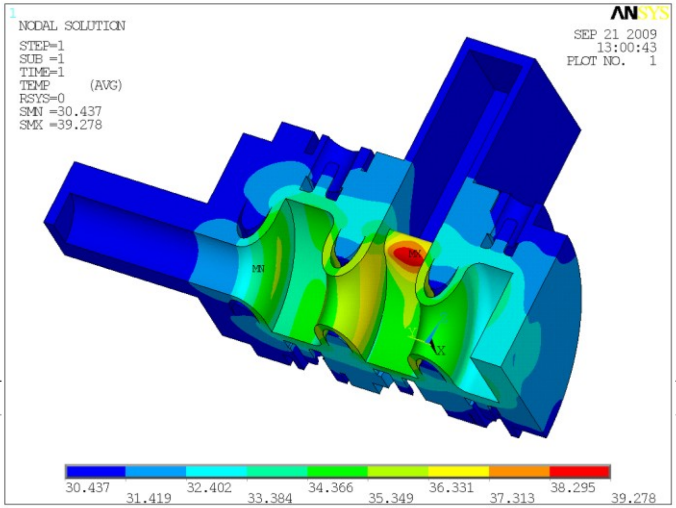
Technology choice:

- RF photo-electron gun (2.5 cell), S-band
- 2 Stage compression at highest energy possible to minimize RF tolerances
- C-band linac (less RF stations, real estate and mains power than S-band, chirp removal after BC 2)
- X-band for linearizing phase space before BC 1
- 2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz
- Laser Heater to mitigate microbunch instability

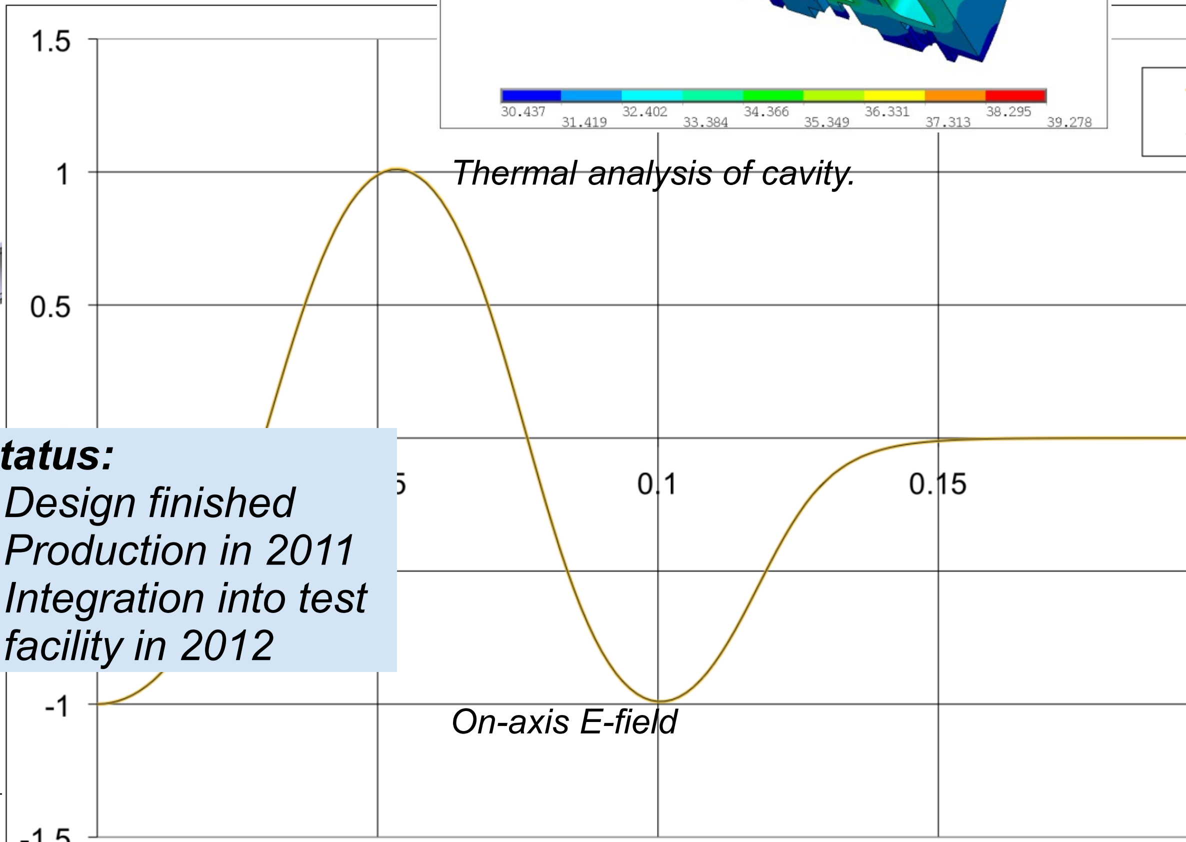
PSI-developed RF Gun



- 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.

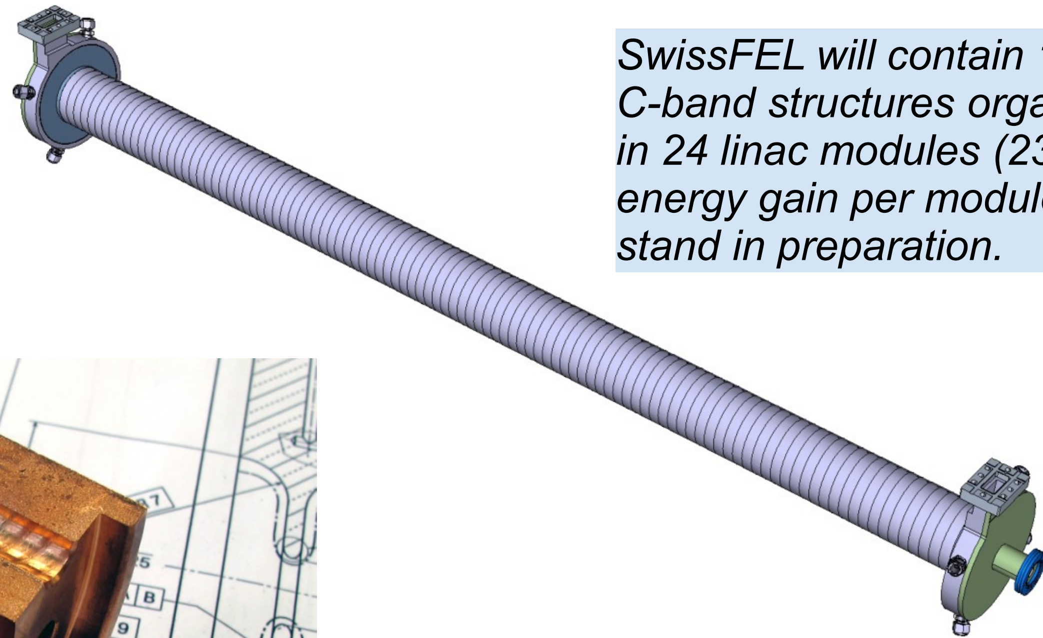


On-axis E-field

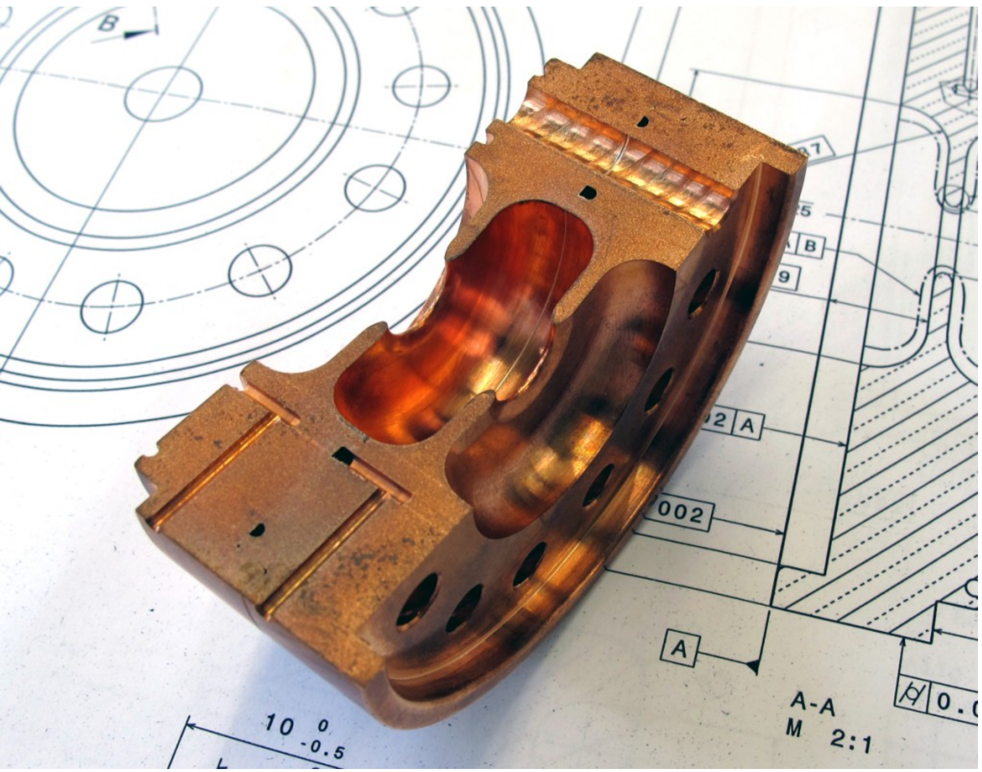
Status:
- *Design finished*
- *Production in 2011*
- *Integration into test facility in 2012*

Main Linac: C-band technology

- 2050 mm long structure
- 113 cells per structure
- 5712 MHz (C-band)
- 28.8 MV/m gradient

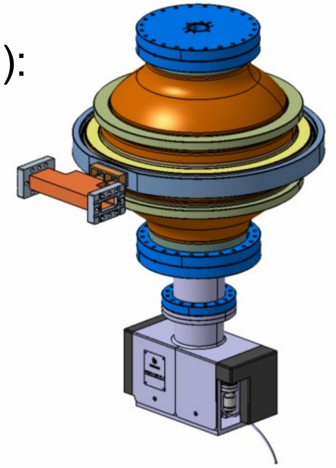


SwissFEL will contain 104 C-band structures organized in 24 linac modules (236 MeV energy gain per module). Test stand in preparation.



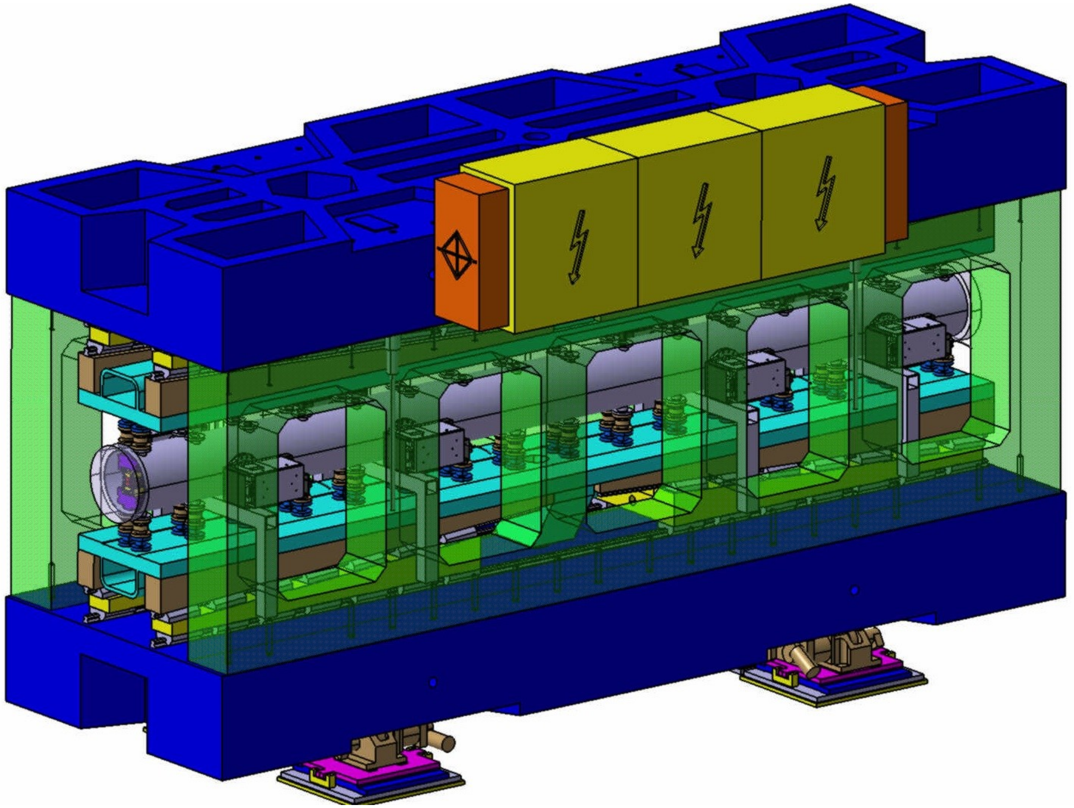
Pulse compressor (SLED):

- accumulates the energy of the incoming “long” pulse and releases a short pulse
- 40 MW, 2.5 μs → 120 MW, 0.5 μs
- Q = 220'000



Undulator development (hard X-ray)

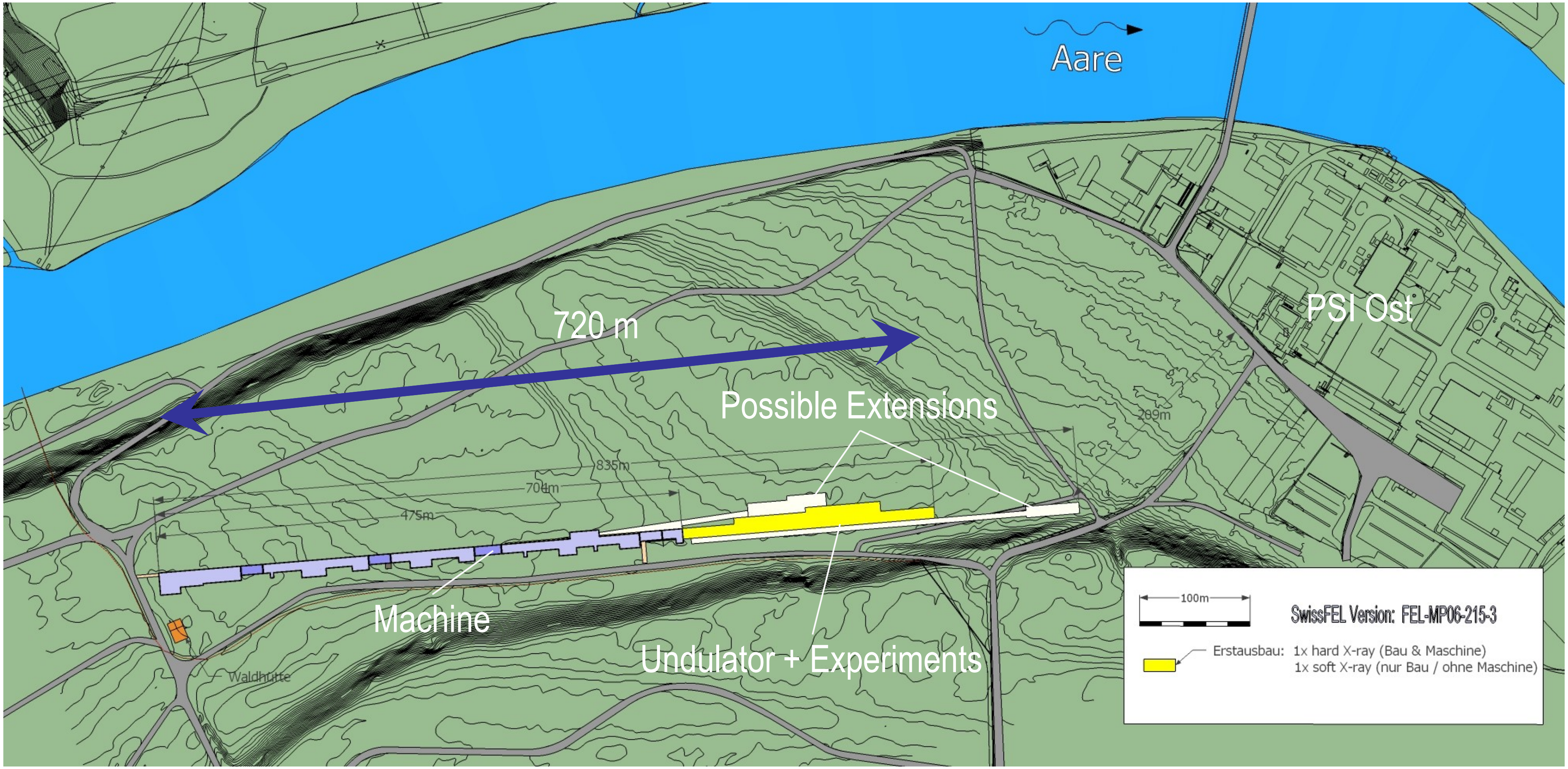
- Hybrid in-vacuum undulator
- 266 periods, each 15 mm
- Magnetic length 3990 mm
- Magnetic material: $Nd_2Fe_{14}B$ + diffused Dy
- Gap varies between 3 and 20 mm
- At a gap of 4.2 mm, maximum B_z is 1 T



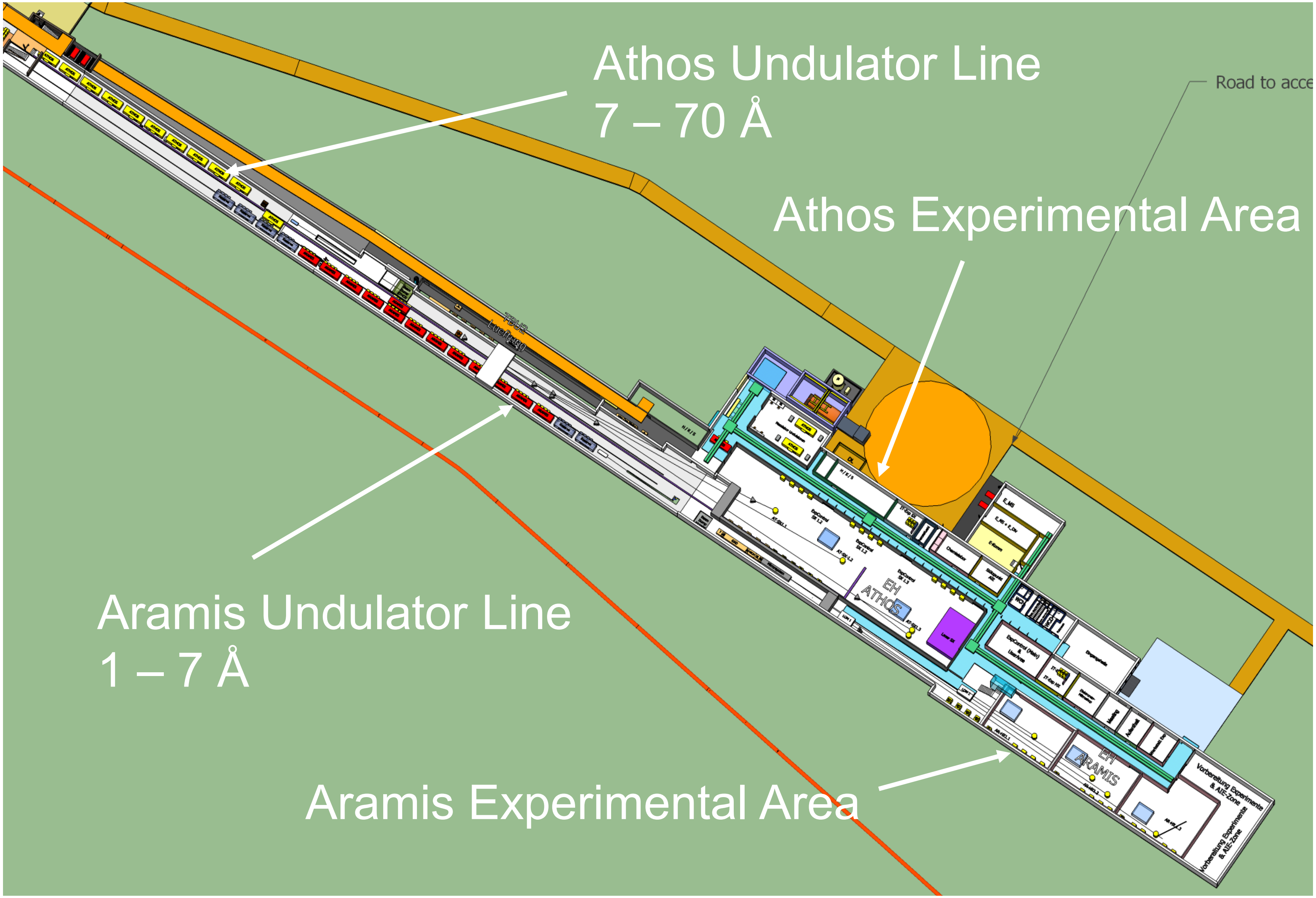
The SwissFEL ARAMIS beamline will comprise 12 undulators of this type. Test of prototype foreseen in injector test facility.

SwissFEL Building

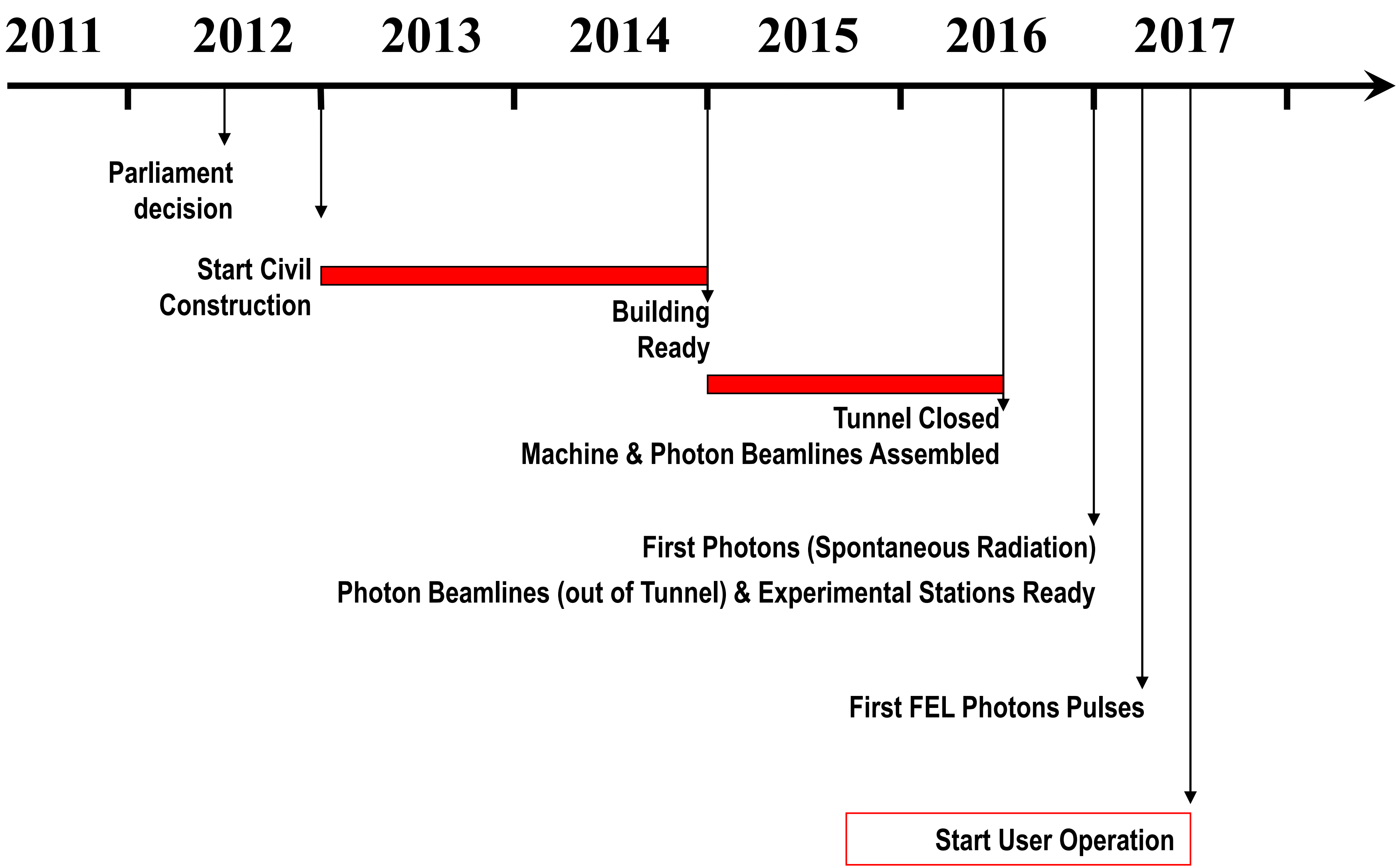
SwissFEL Site



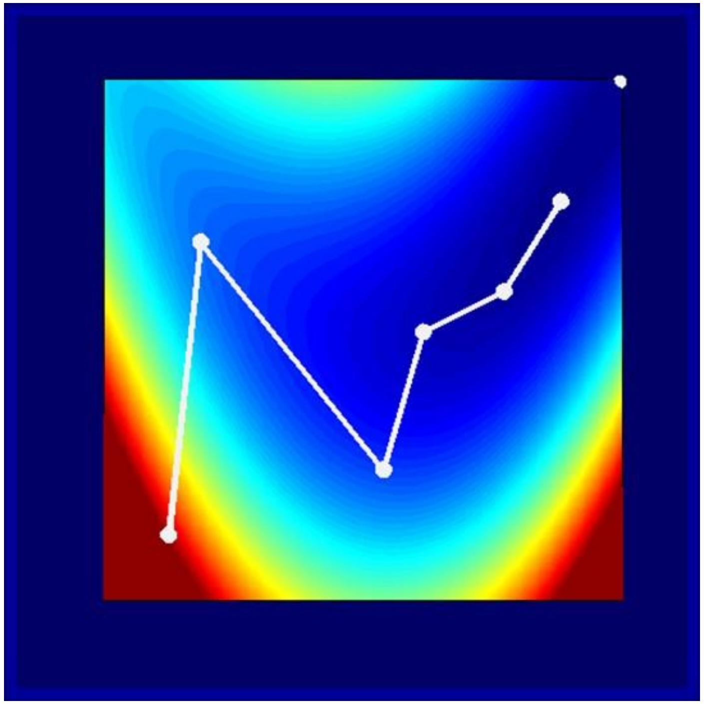
SwissFEL Layout



SwissFEL Timeline

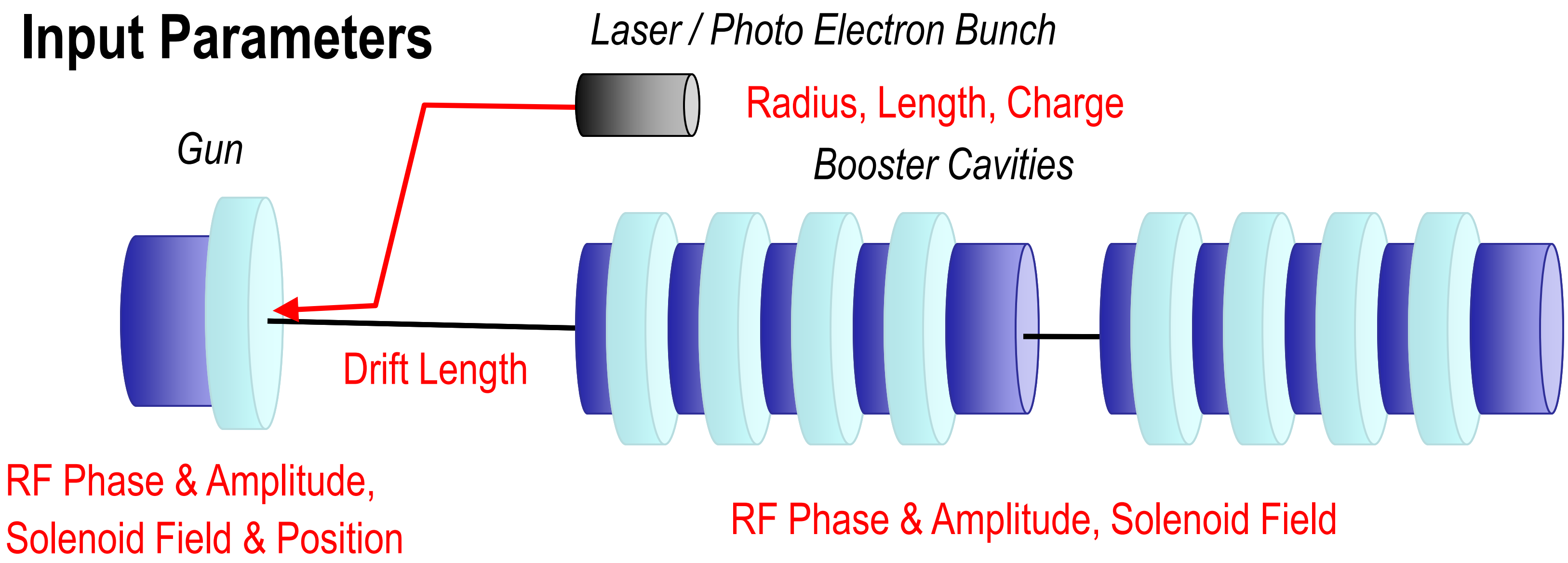


Gun Optimization (work done by Simona Bettoni)



Gun Optimization

Input Parameters



Optimization

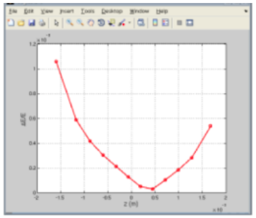
- Minimal Slice Emittance
- Minimal Projected Emittance
- Minimal Slice Mismatch Parameter
- Minimal Slice Energy Spread

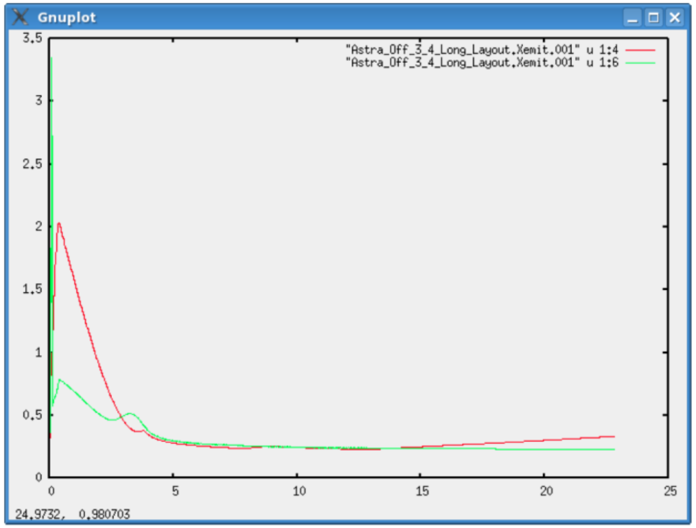
Constraints

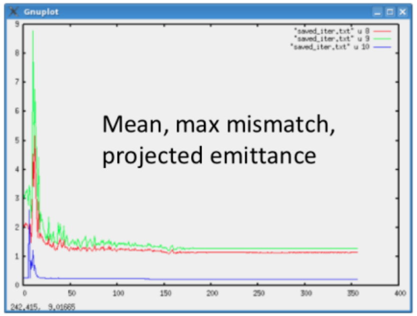
- Charge = 200 pC
- Peak Current > 20 A
- E > 120 MeV
- Gun gradient 100 MV/m

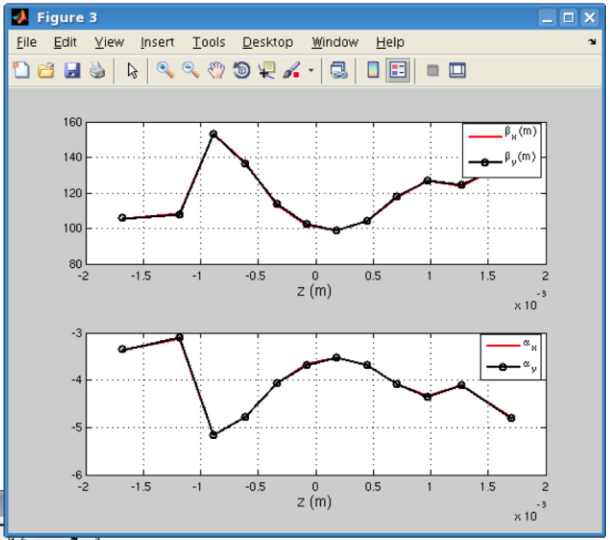
SwissFEL Optimization Result (Courtesy of S. Bettoni)

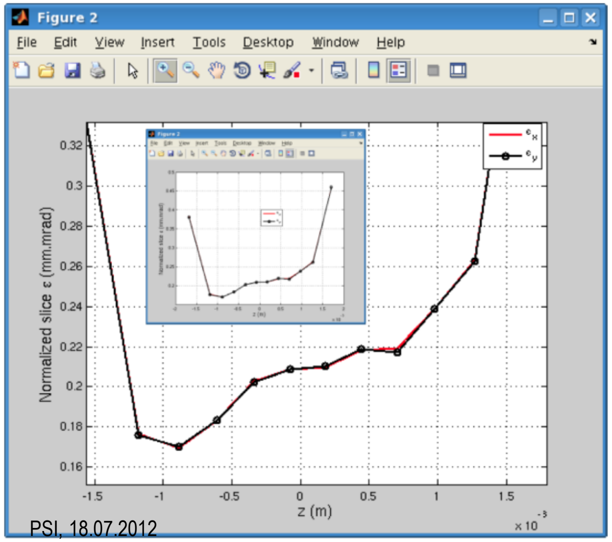
I try to re-optimize starting from Opt_8, but **I fix pulse_length = 10 ps**.
par_start = [phi_gun coeff_sol_1_a coeff_sol_2 sigma shift_cav1 maxB(1) coeff_sol_1_b];
path: /gpfs/homefelsim/bettoni_s/Astra_sim/SwissFEL_gun/Opt_16

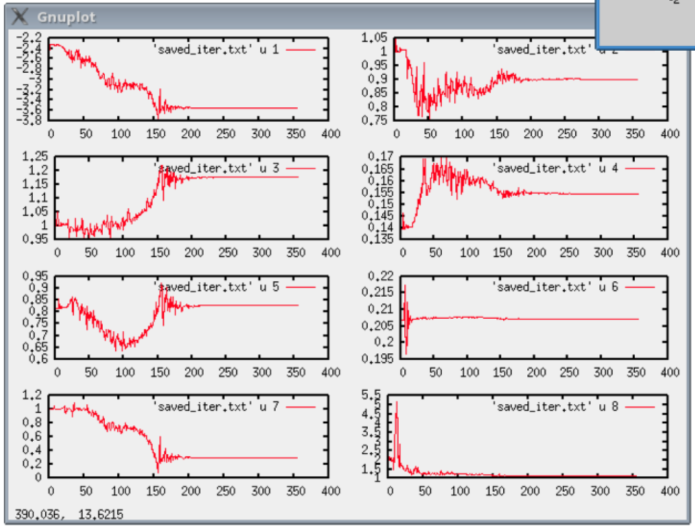












Projected (mm.mrad)	Slice (mm.mrad)
0.23	<~0.17 (average = 0.2)

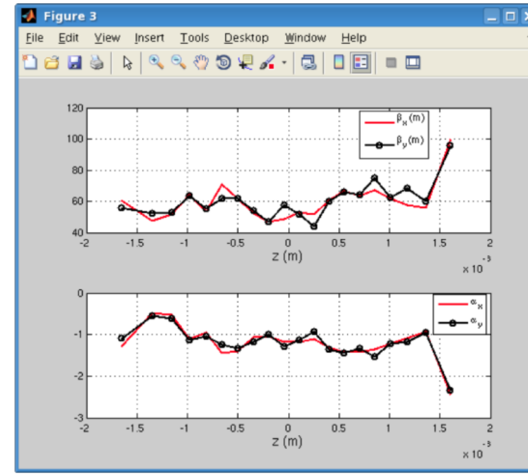
Final sigma = 0.134 mm

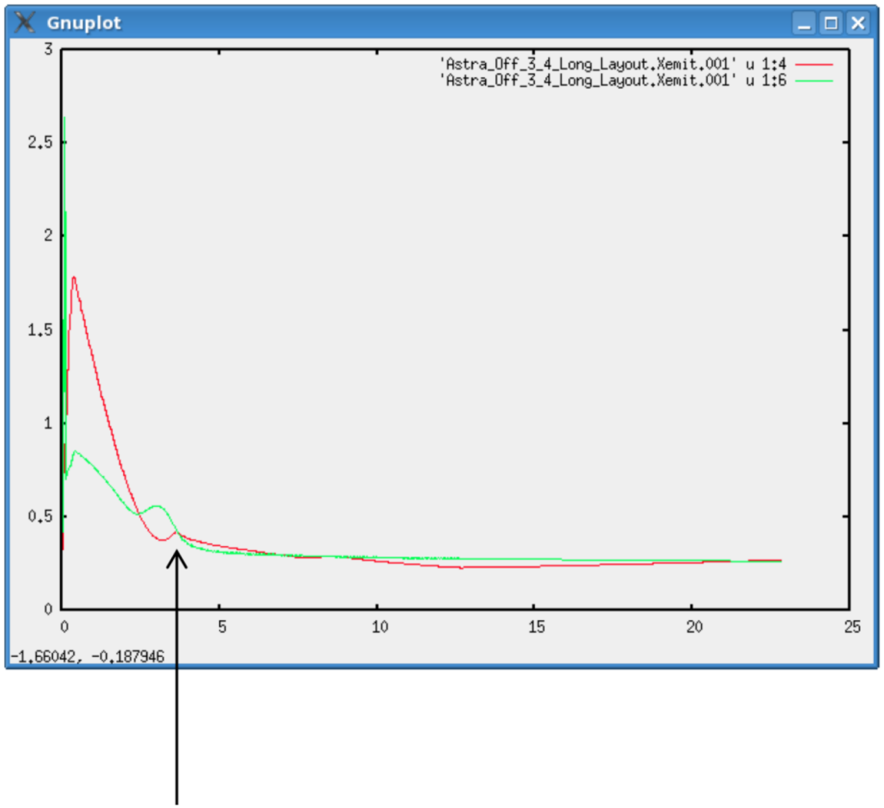
Reducing the Mismatch (2nd Optimization)

Start from Opt_16_bis, but with less parameters to vary and minimize the max mismatch calculated in range_z = +-2 mm.

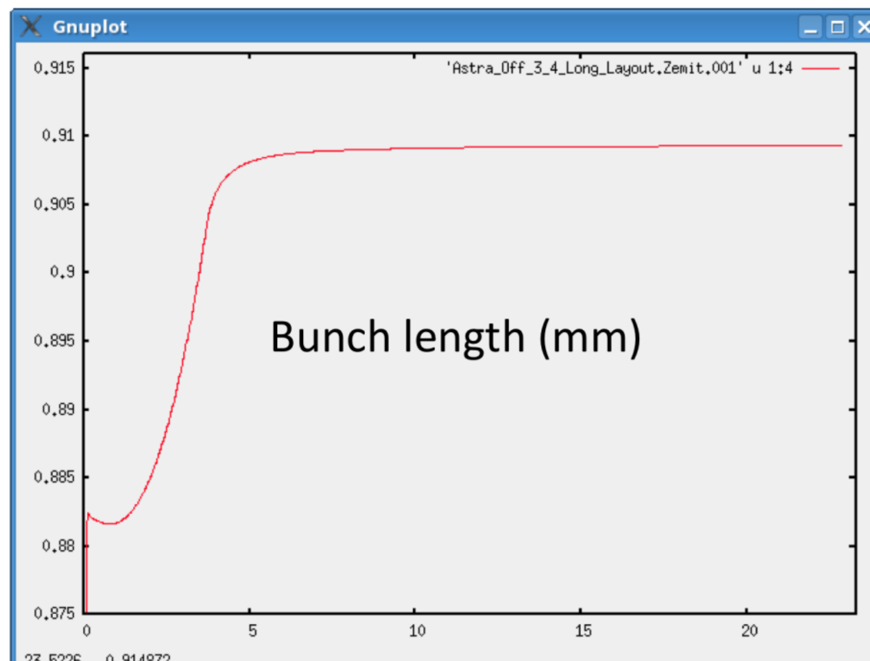
par_start = [sigma shift_cav1 maxB(1)];

path: /gpfs/homefelsim/bettoni_s/Astra_sim/SwissFEL_gun/Opt_23

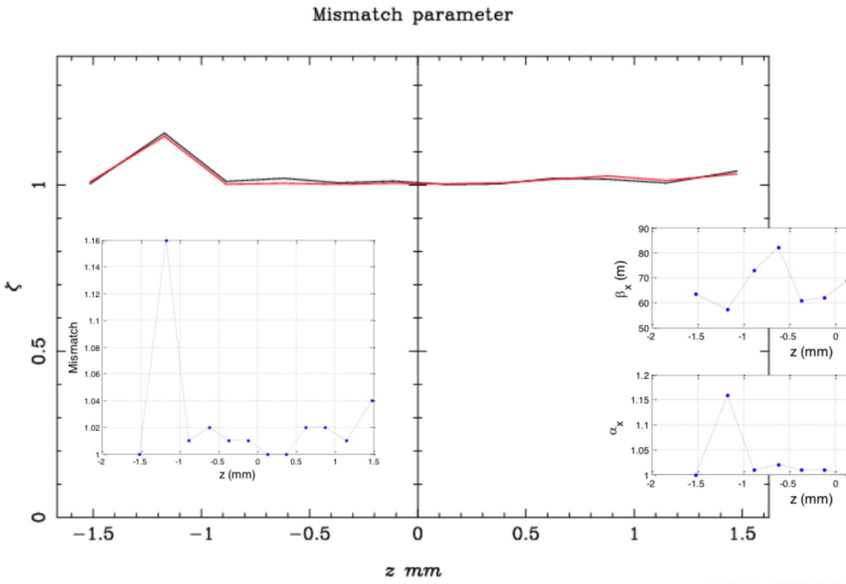


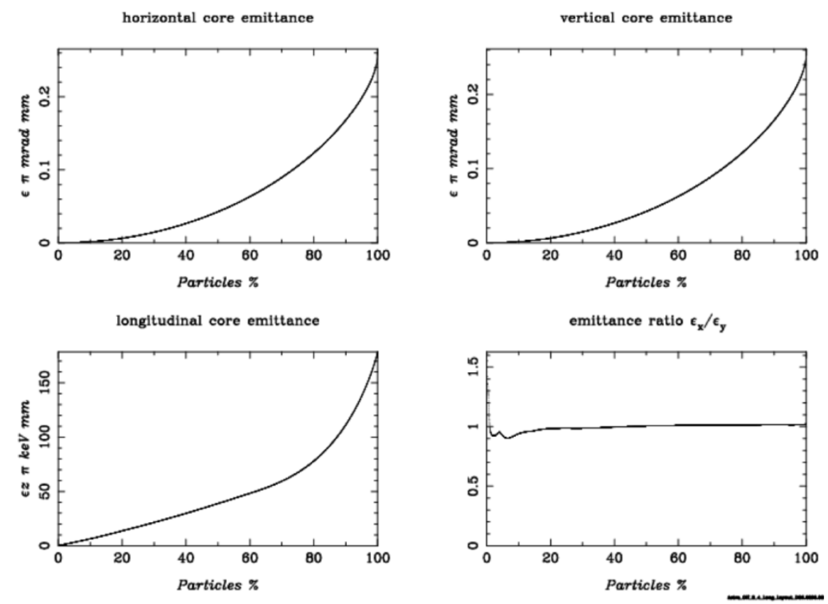


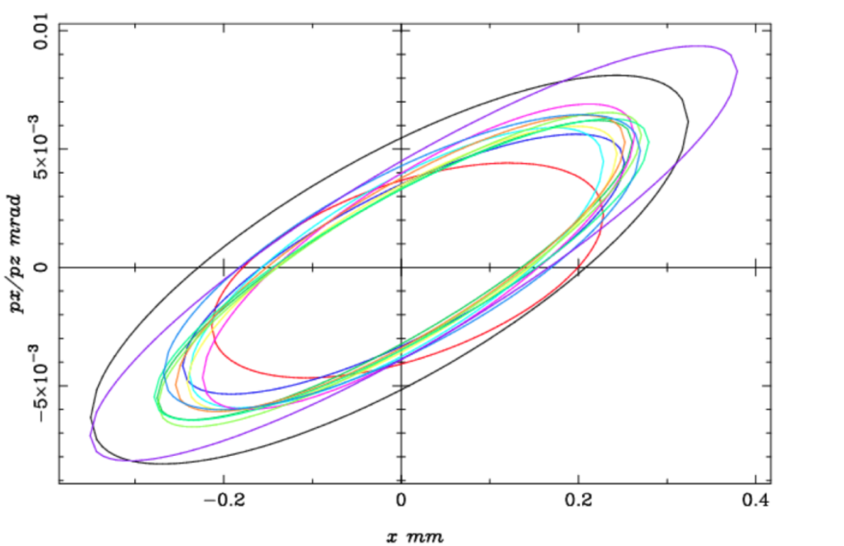
Position SB01 = 3.5974 m

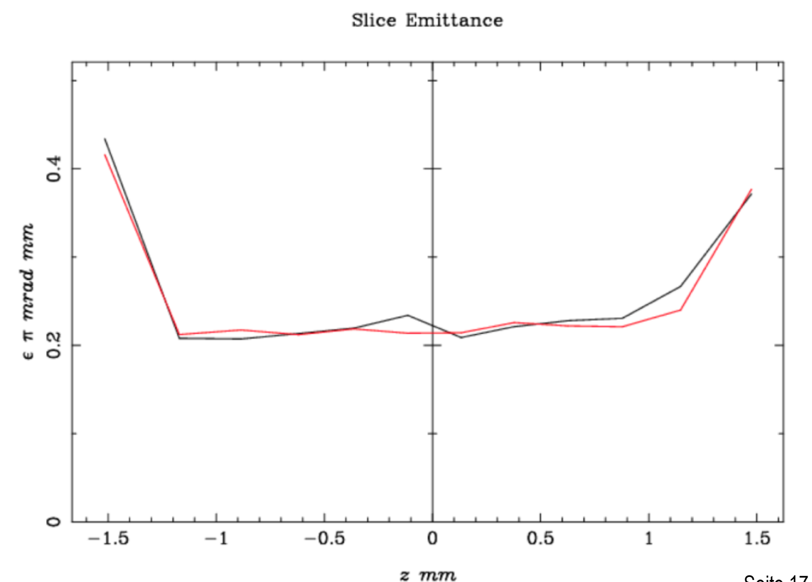


Current Design Case with SwissFEL Gun







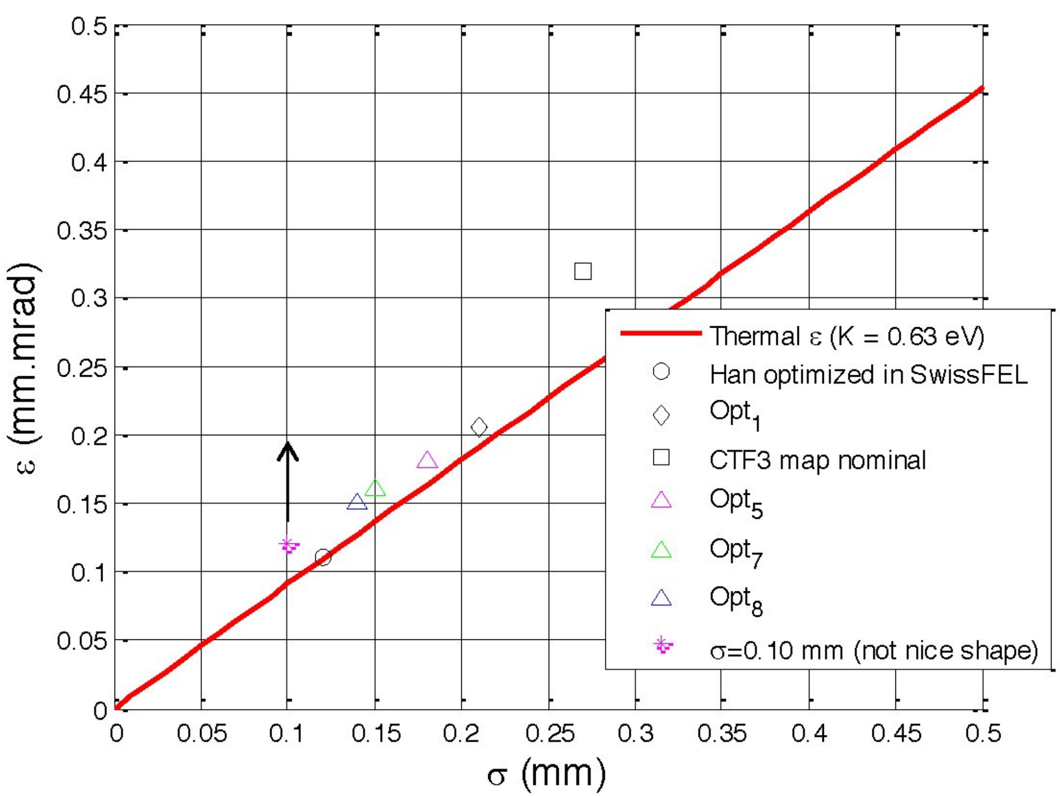


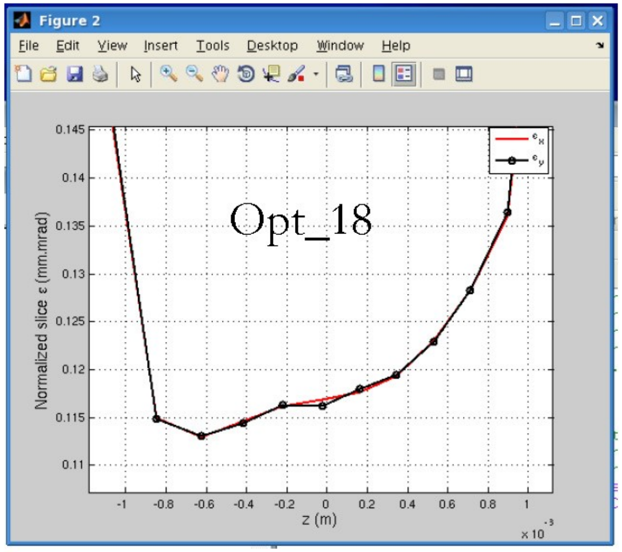
Considering the Han Gun Design

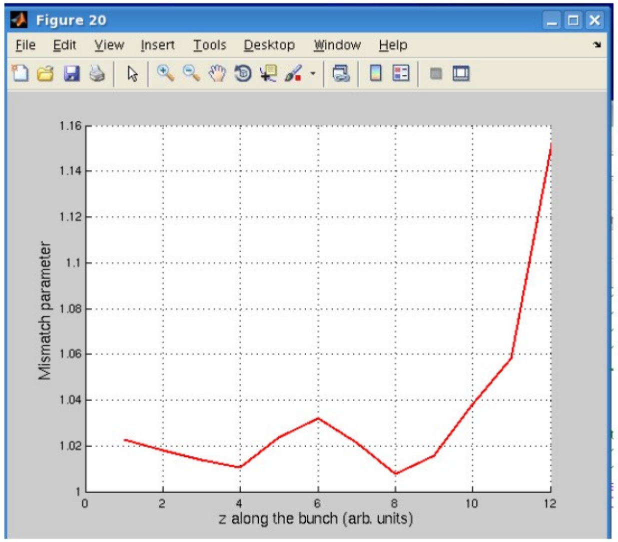
Considering new gun with door knob coupler:

- Solenoid is shifted closer to cathode
- Allows for higher charge density
- Reduced spot size and emittance

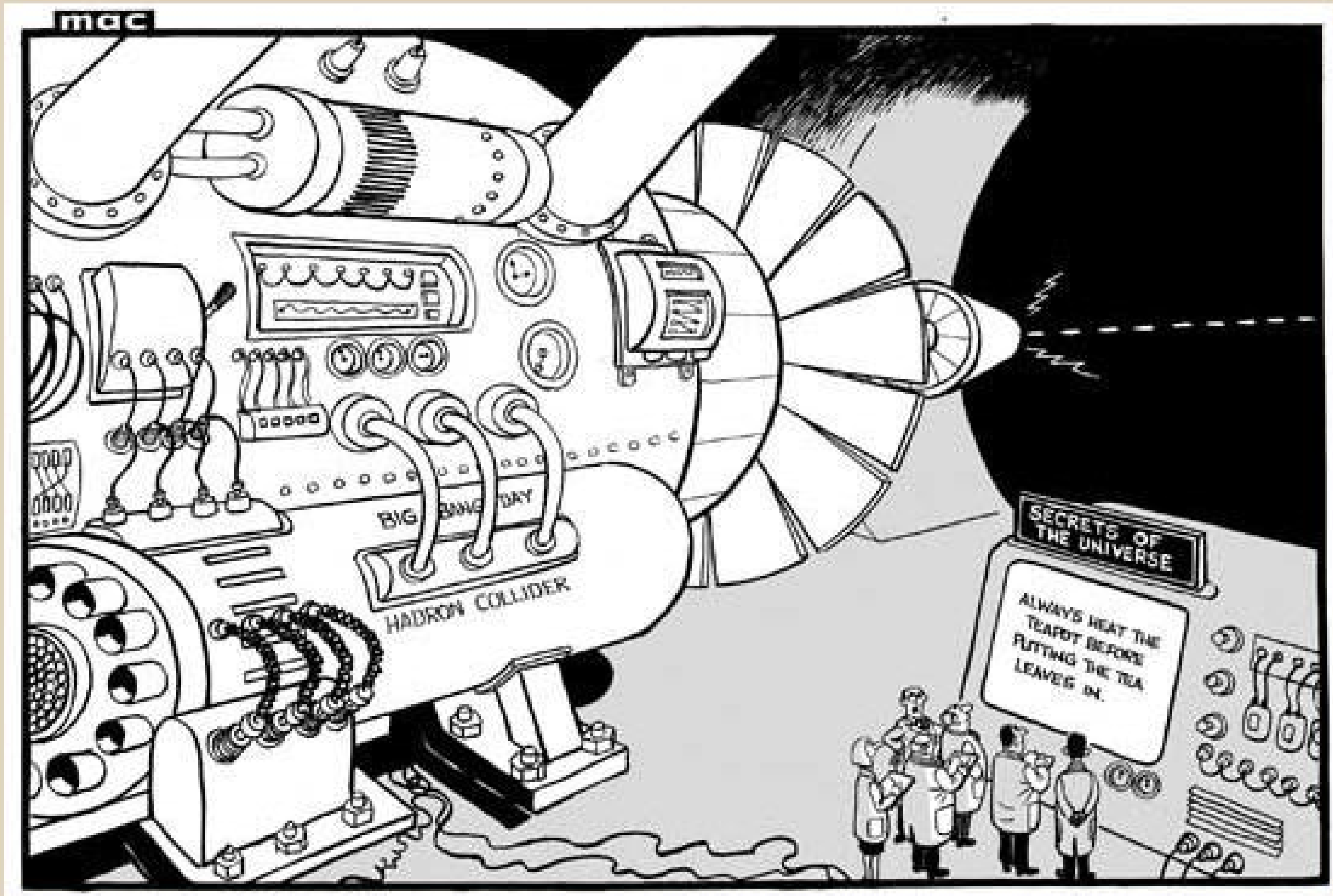
New optimization of shorter pulse + larger spotsize







SwissFEL Injector Test Facility

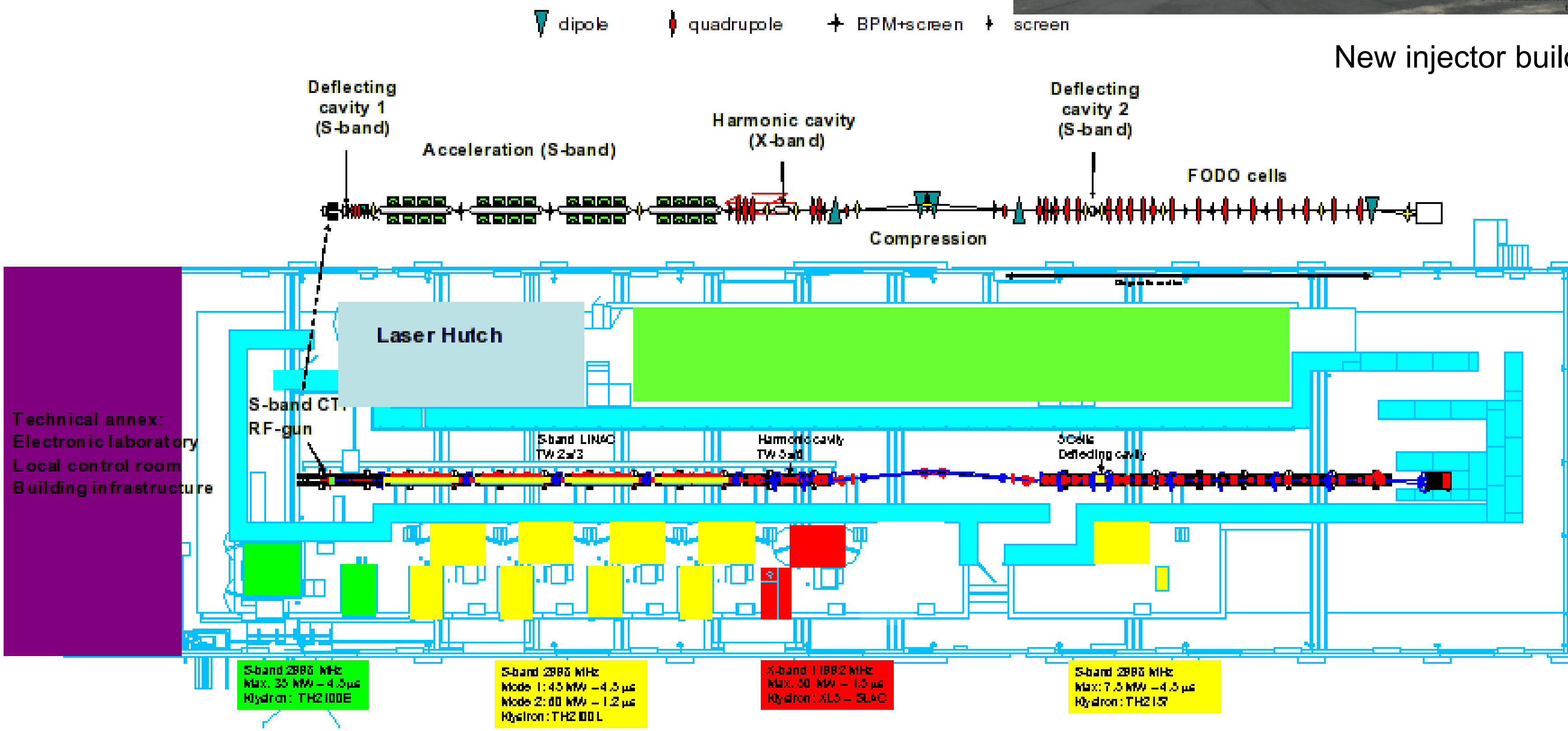


"Remind me. How much did we spend on this machine?"

SwissFEL Injector Test Facility

- Electron gun and first accelerating section (first ~50 m of SwissFEL)
- Test of components and procedures needed for SwissFEL
- Will be moved to final SwissFEL location in 2015


New injector building

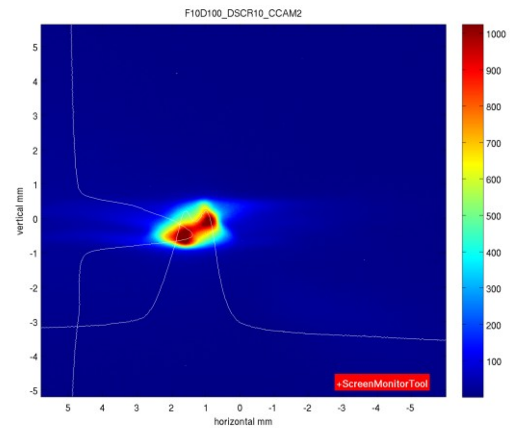


SwissFEL Injector Test Facility

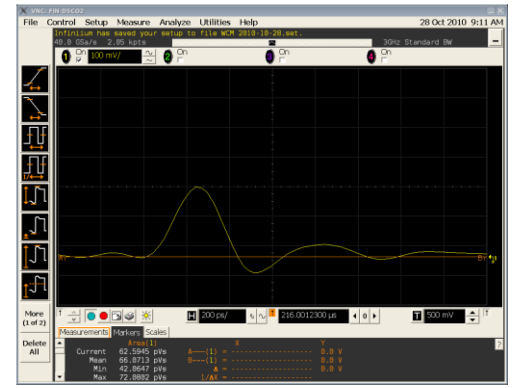
Official inauguration (24 August 2010)

Keep it simple for the Federal Councillor: one button, two signals

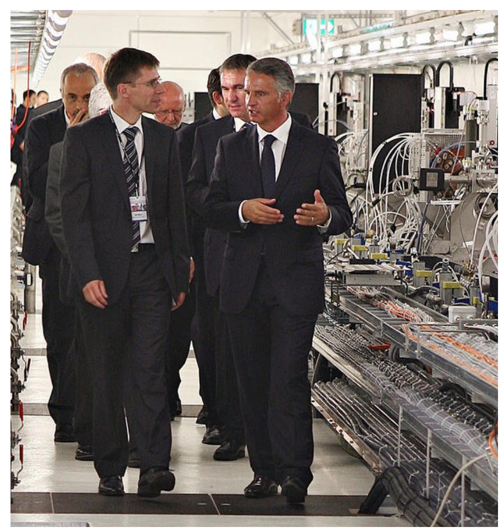
Button connected to laser shutter.



Beam on LuAG screen in front of beam dump.



Signal from Wall Current Monitor after the RF gun.



Visit to the injector tunnel.

The Burkhalter beam:

- ~35 pC charge
- ~160 MeV energy
- ~0.5 MeV energy spread

250 MeV Injector Time Schedule

Months shown for each year: January, February, March, April, May, June, July, August, September, October, November, December

2011

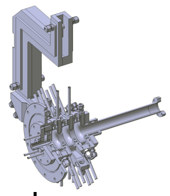
- BC Installation
- RF Problems
- priority to beam operation
- complete modulator repairs

2012

- Done √
- Integration FINSB04 & THz diag.
- Re-com. RF and gun laser
- 250 MeV
- Slice & fs Compression
- FAT x-band modulator
- Modulator assembly and diode tests
- Assembly X-band cavity + load lock Gun
- RF commissioning
- First potential window but schedule requires a deep verification

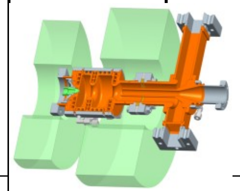
2013

- Integration U15 experiment. Integration new RF-gun
- Production starting. Schedule being analyzed (critical)



2014

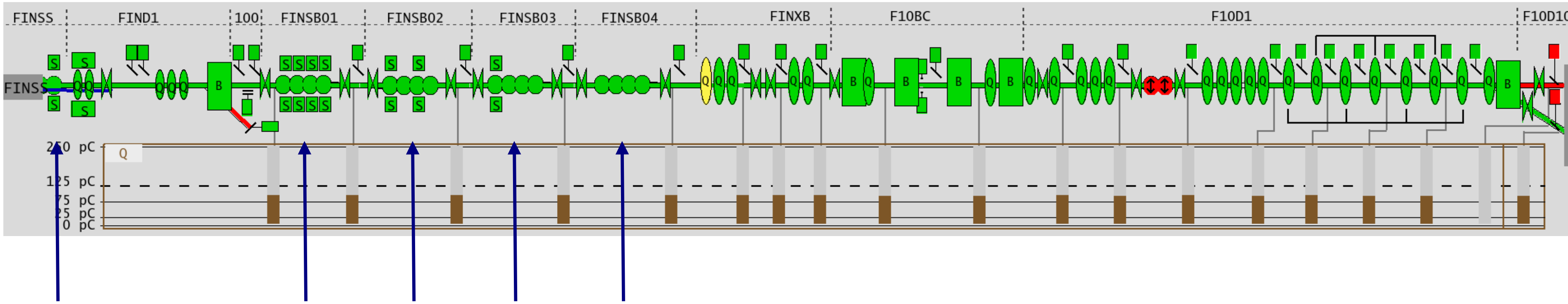
- Option integration alternative RF-gun
- Possible collaboration with Diamond. Implementation critical! Priority to first SwissFEL gun.



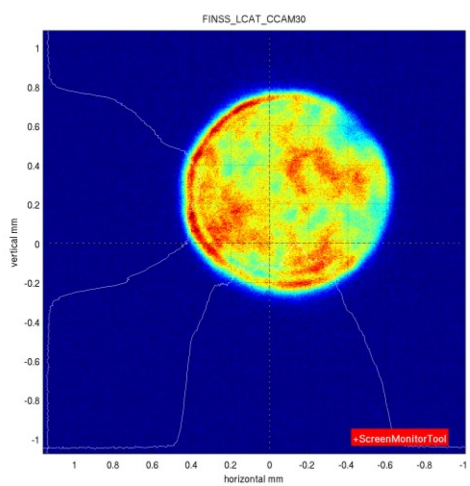
- Concept: Three months before bulding ready dust free stop Facility and preparation hardware for move.

Milestones: Beam Energy

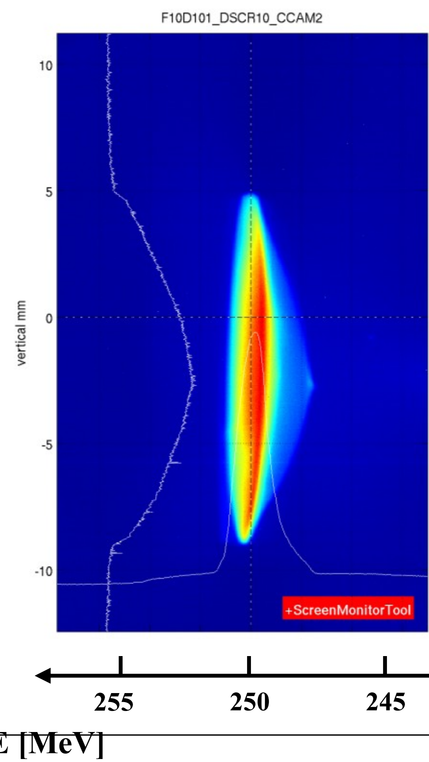
Preconditions



Gun + 4 S-Band Cavities in Operation



Pulsar laser
(transverse profile)

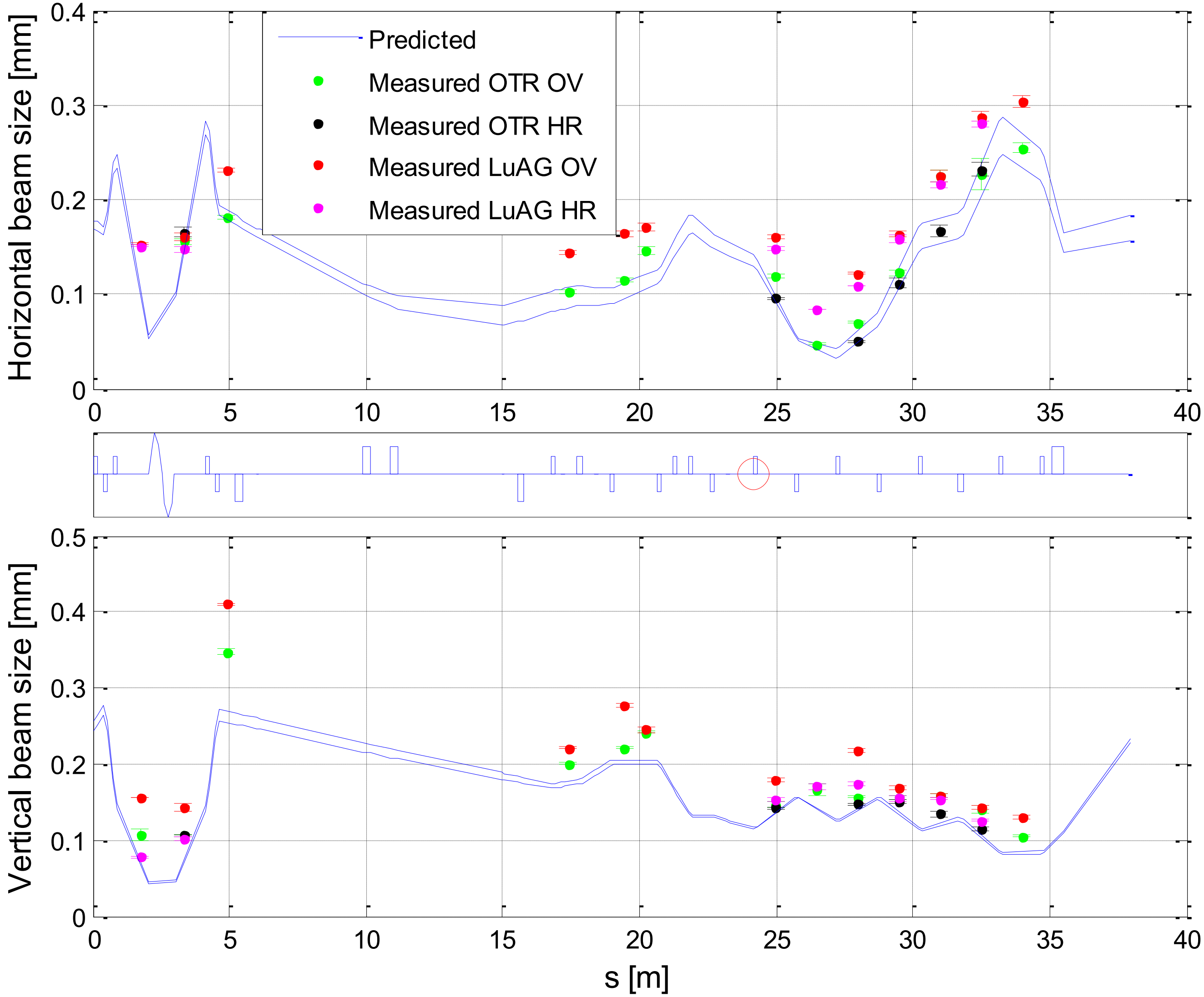


Beam energy ≥ 250 MeV
(first reached on April 11)

(for bunch compression studies energy limited to ~230 MeV)

Milestones: Beam Optics (M. Aiba/N. Miles)

Beam optics matched and understood (using OTR screens)



Milestones: Emittance (B. Beutner)

Projected emittance

Main method: "single-quad scan" (E. Prat)

- *Phase-advance scan with single quad:* use last matching quad upstream of FODO section to generate phase advance simultaneously in x and y. Possible if optics at quad fulfils some conditions (matching is crucial):
  - $\beta_x = \beta_y = \beta_0, \alpha_x = \alpha_y = \alpha_0$ (same optics x and y)
  - $\alpha_0 \times L = \beta_0$ (L is distance to observation screen)
- Beam size measurement with screen downstream of FODO section.

Alternative method: "multi-quad scan"

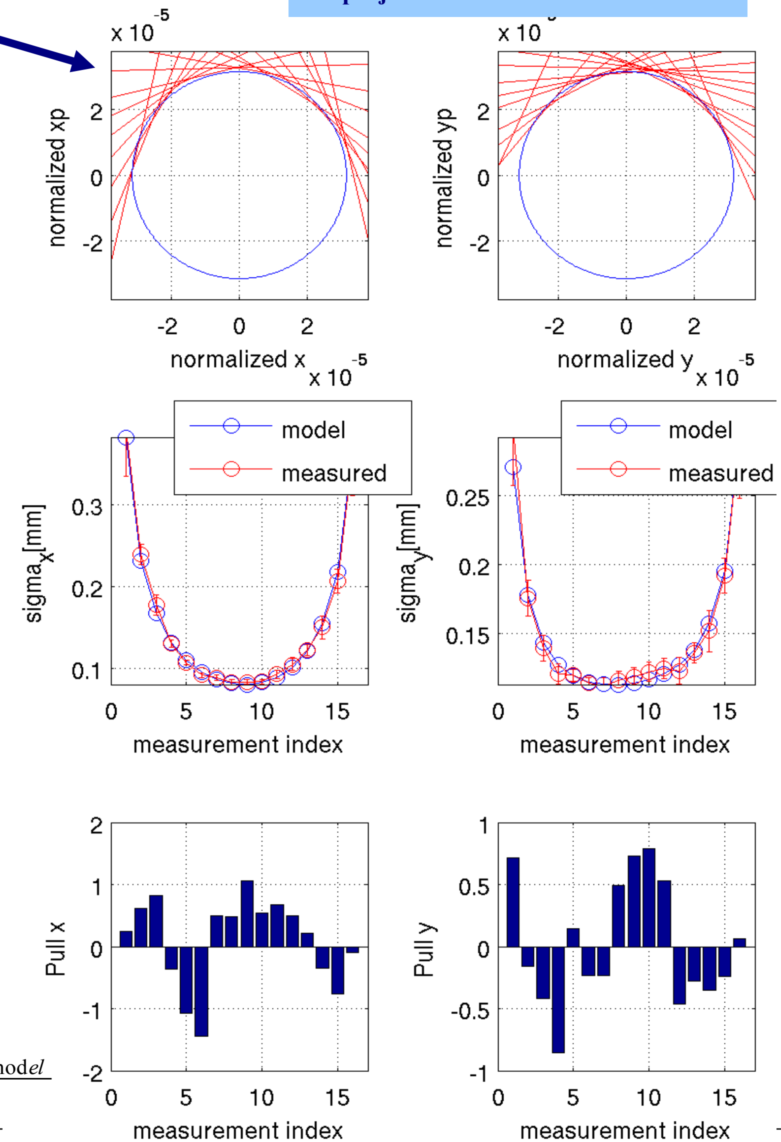
- *Phase-advance scan with three quads:* use three quads upstream of FODO section to generate phase advance, first in x then in y, while keeping the beam size under control.
- Beam size measurement with screen downstream of FODO section.

(No longer used: "FODO scan")

Optimization (parameter study) ongoing...

200 pC

$\varepsilon_{proj}(x) = 0.45$ mm mrad
$\varepsilon_{proj}(y) = 0.44$ mm mrad



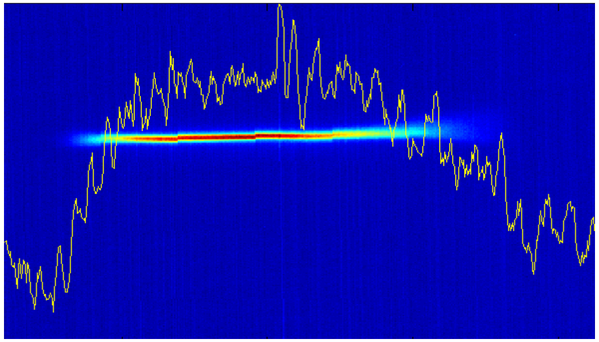
$\frac{\sigma_{meas} - \sigma_{model}}{\delta_{statistic}}$

Milestones: Slice Emittance (E. Prat)

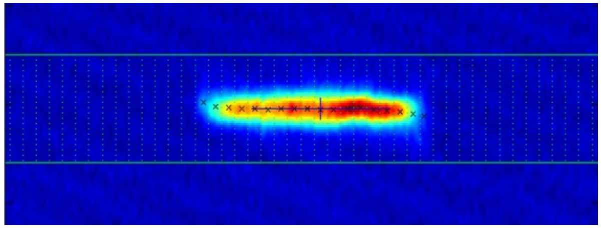
Slice emittance

Method:

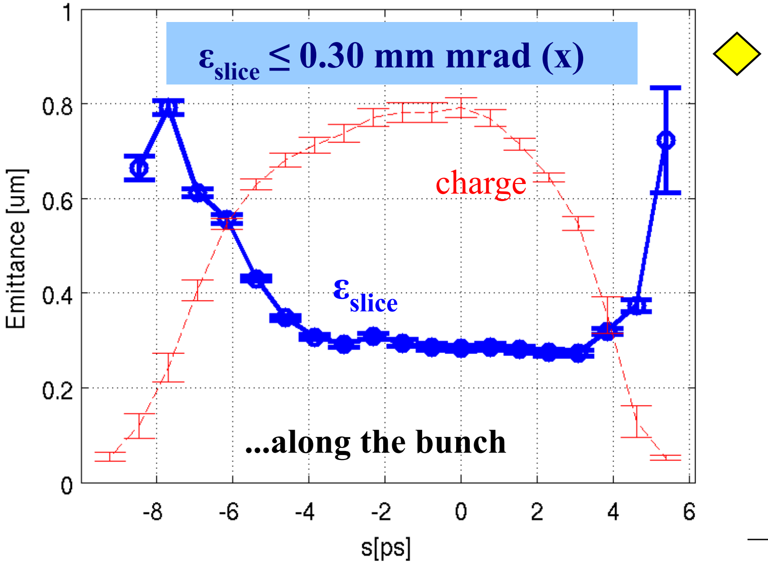
- *Transverse deflection ("streaking"):* the bunch is streaked in the transverse deflecting cavity, then recorded on a screen downstream of the FODO section.
- *Phase-advance scan:* change optics using five matching quads between transverse deflecting cavity and FODO section:
  - Generate regular phase advance in x
  - Keep beam size under control
  - Keep longitudinal resolution constant
- *Slice analysis:* split beam into slices (use centroid from Gauss fit as reference). Beam size from Gauss fit to slice profile.
- *Transverse deflector calibration:* change deflector phase at each optics setting to obtain individual mm ↔ ps calibration for each optics setting (add the data for increased statistics).
- *Mismatch parameter:* determined for each slice, checked against central slice and design optics.



streak



slice

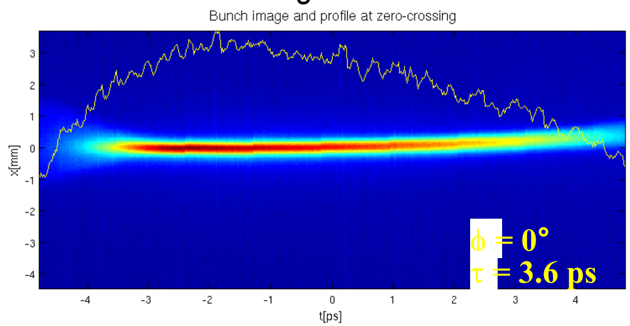


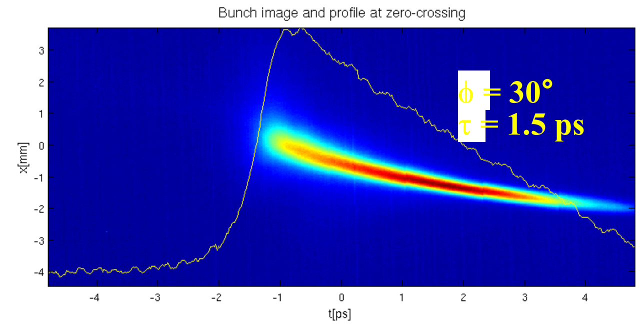
Milestones: Compression (B. Beutner)

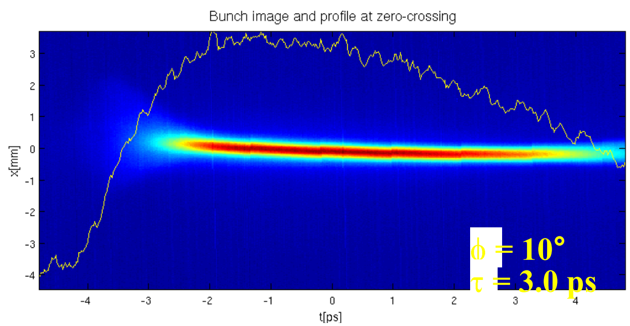
Missing X-band structure

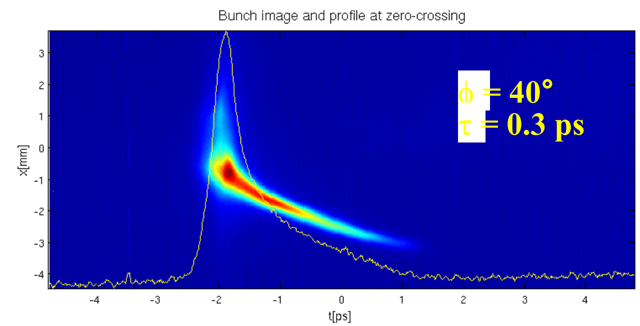
φ: phase in FINSB03/04
τ : bunch length

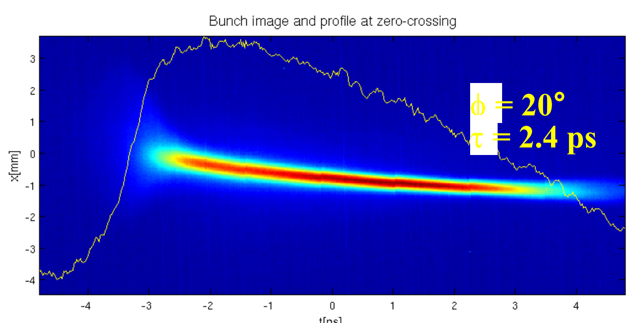
First demonstration of bunch compression (April 18, Jaguar laser)
Bunch length (rms from Gauss fit) reduced from
3.6 ps to 200 fs.
BC angle 4.07° (R56 = –46.19 mm rad2)

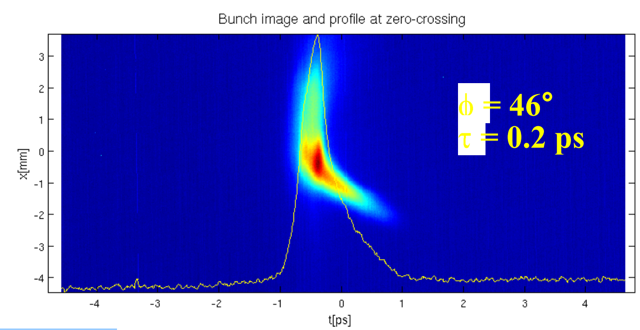












3.6 ps → 200 fs (rms)

Fighting the Coupling (M. Aiba)

- Motivation:
  - Asymmetric emittance in hor. and ver. plane persists
    - Solved partially by FINSB01 BBA: typically 0.4/0.6 → 0.4/0.5 μm
    - The remaining asymmetry because of coupling? Let's try to correct
- Correction:
  - General optics correction approach

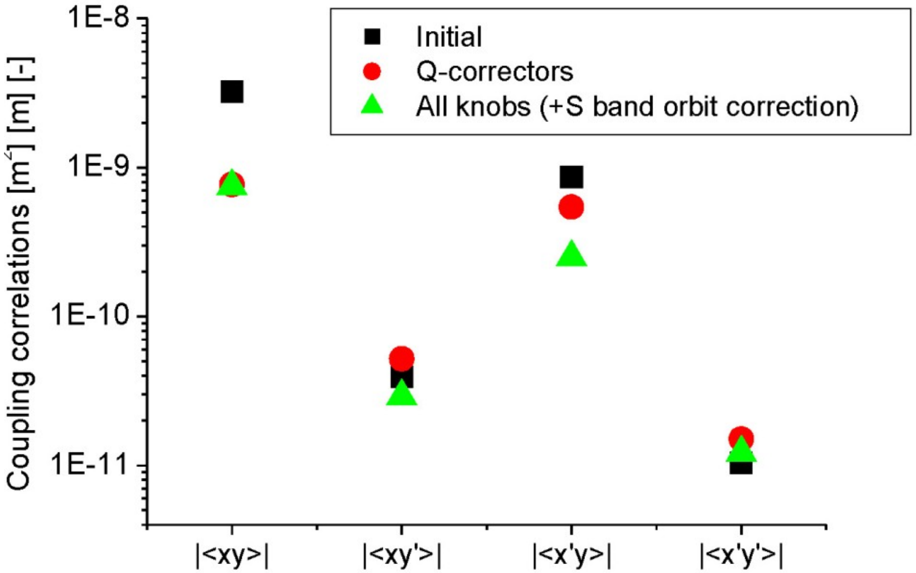
$$\vec{P} = S\vec{C} \rightarrow \vec{C} = S^{-1}\vec{P}$$

$\vec{P}$: *Beamparameters to be corrected*
$<xy>, <xy'>, <x'y>, <x'y'>$
S : *Sensitivity matrix*
$\vec{C}$: *Corrections*

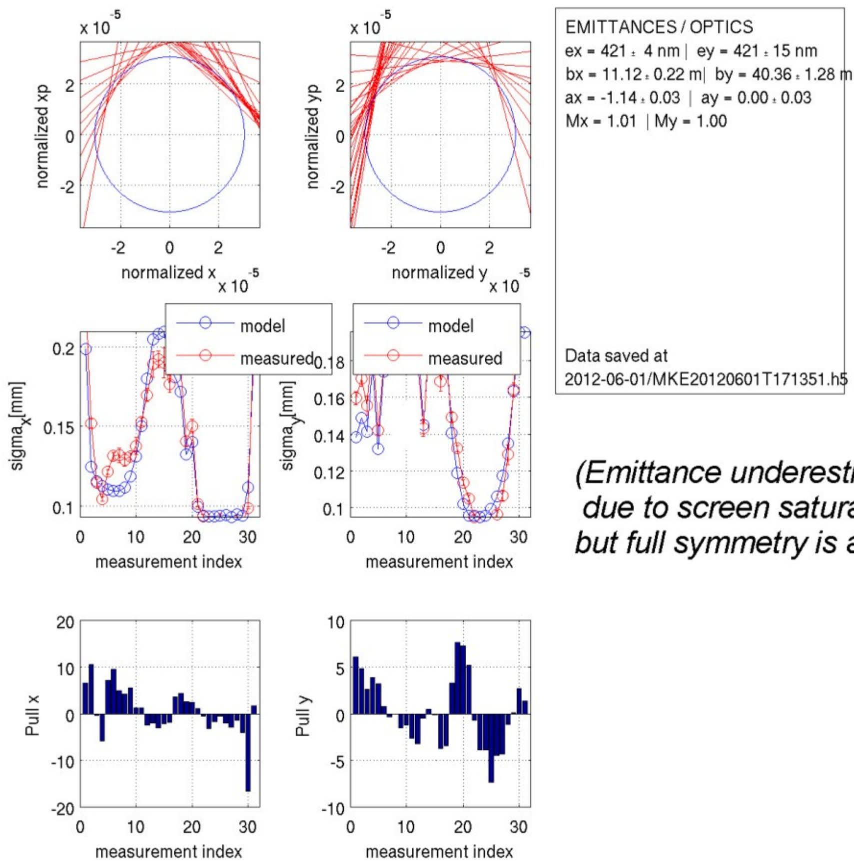
  - Sensitivity matrix taken from the machine
- Knobs: $\vec{C}$
  - Quad correctors of gun solenoid: FIND1-MCQR10 / FIND1-MCQS10
  - Solenoid pairs (increase one of them and decrease the other) of FINSB01 and FINSB02:
    FINSB01-MSOL10 + FINSB01-MSOL20
    FINSB02-MSOL10 + FINSB02-MSOL30
  - (Two skew quad correctors available in addition for SwissFEL)

Fighting the Coupling (M. Aiba)

- Beam results:
  - Coupling correction



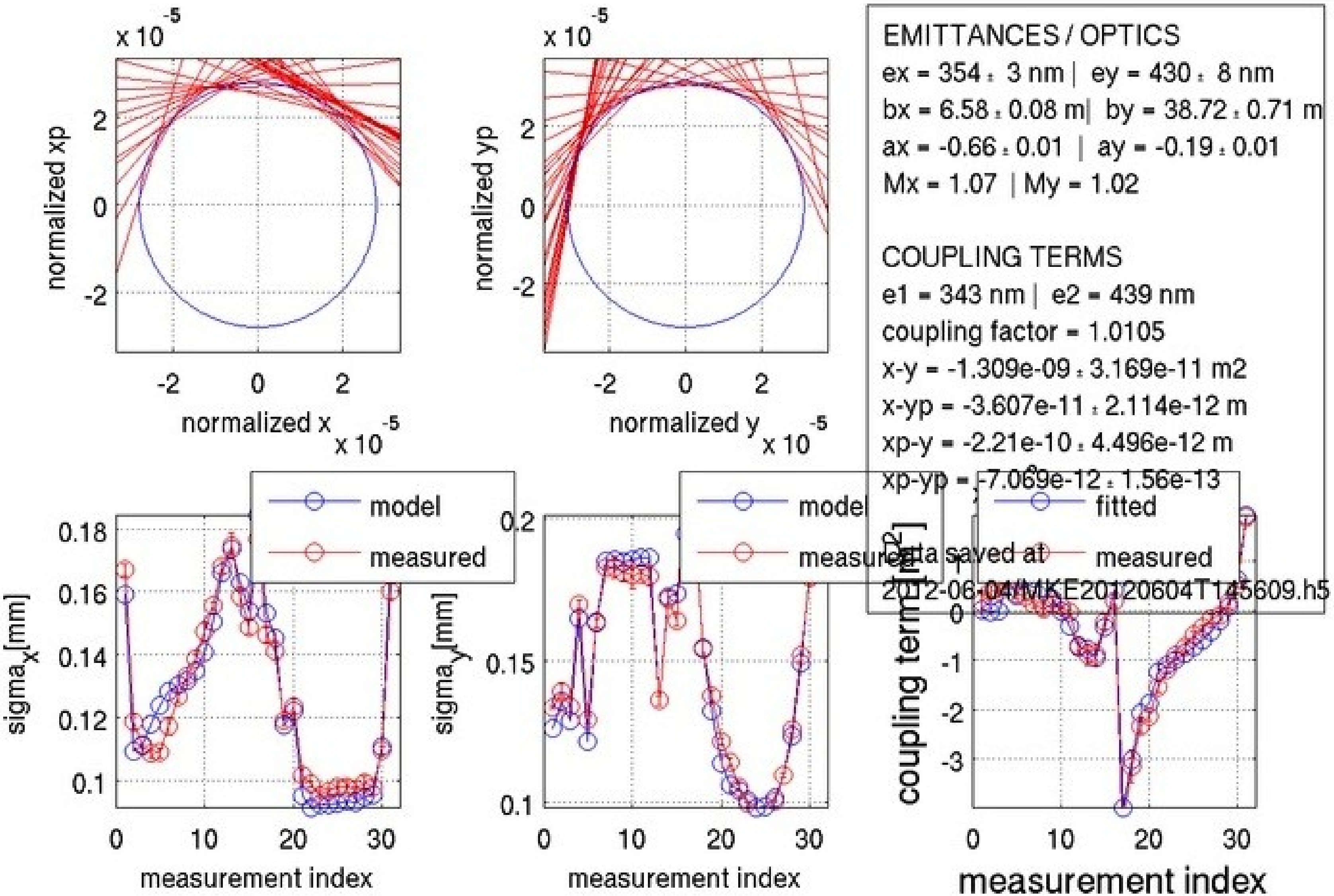
Typical emittance measured with correction:



(Emittance underestimated due to screen saturation, but full symmetry is achieved)

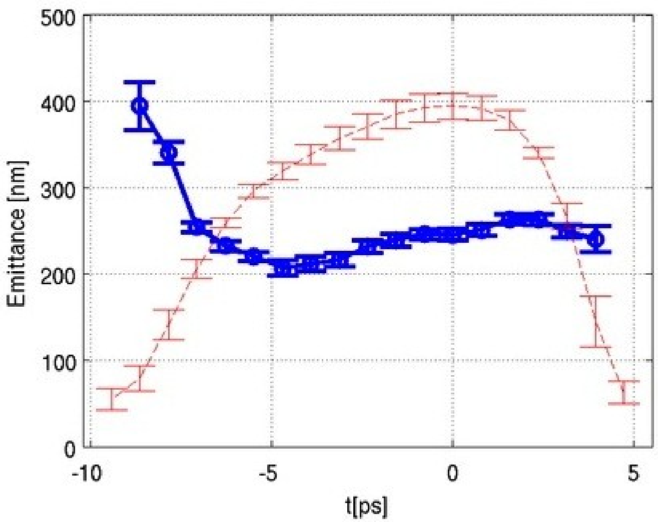
- What we learned:
  - Coupling correction works
    - Suggests lower field in the first solenoid and higher in the second
  - 100 or 200 μm orbit displacement in S-band has some impact on the emittances (up to 0.1 μm increase)

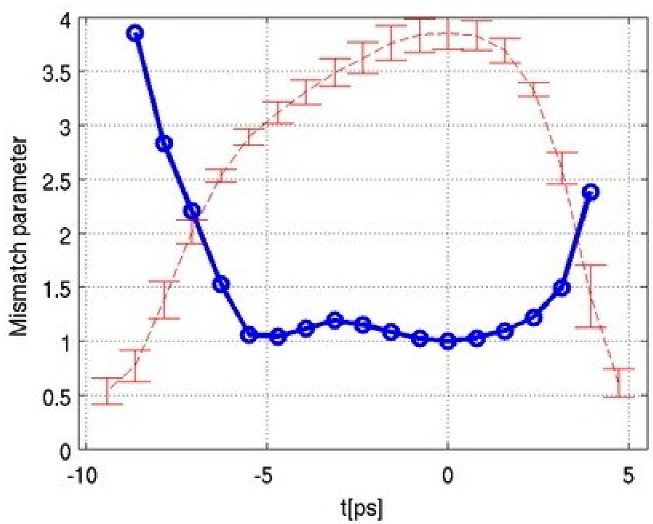
Best Emittance Measurements (Logbook)



Best Emittance Measurements (Logbook)

Slice Emittance





CORE SLICE EMITTANCES / OPTICS
ex = 246 ± 6 nm
bx = 6.33 ± 0.21 m
ax = -0.65 ± 0.04
Mx = 1.08

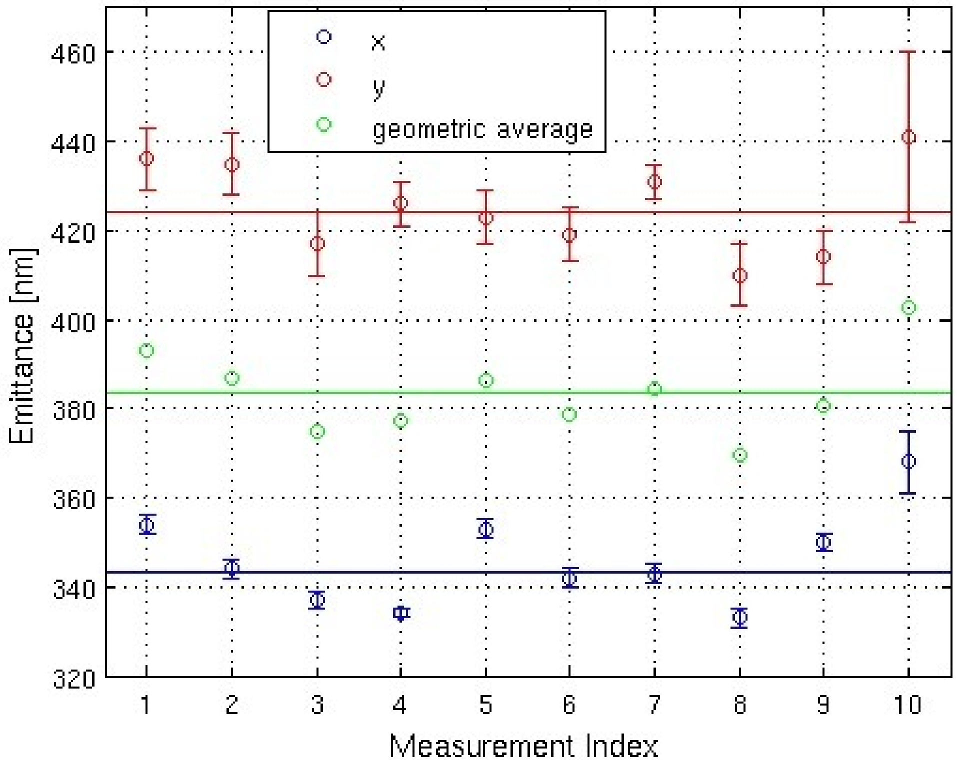
PROJECTED EMITTANCES / OPTICS
ex = 288 ± 8 nm
bx = 7.41 ± 0.27 m
ax = -0.67 ± 0.05
Mx = 1.04

Slice emittance better than prediction with Astra:

- Cut of halo particles ?
- Lower thermal emittance (currently matched to LCLS results)

To be studied

consistency of emittance measurement



Summary

SwissFEL

- Final permission by Swiss government in fall 2012 (very likely)
- 5 years of construction and commissioning
- 1 hard X-ray line (1-7 Å) in 2017/ 1 soft X-ray line (0.7-7 nm) in 2019
- Option to add one more hard and soft X-ray beamline

Gun Optimization

- Improvement upon „Massimo“ working point
- Door know Coupler allows for better emittances: more current from cathods to reduce required compression in linac (stability and microbunch instability)

SwissFEL Test Injector

- Major milestones achieved in April this year
- X-band and „controlled“ compression end of this year
- Unknow coupling limits current emittance optimization.

Acknowledgement

SwissFEL Beam Dynamics

- Simona Bettoni (Injector/Gun Optimization, Microbunch Instability)
- Bolko Beutner (RF Tolerances, Bunch Compression)
- Masamitsu Aiba (Beam Based Alignment, Feedback)
- Natalia Miles (Linear & non-linear beam optics)
- Eduard Prat (Diagnostic Optics, FEL self-seeding)
- Frederic Le Pimpec (Dark current studies, collimator)
- Sven Reiche (FEL performance, SwisSFEL lattice)
- Thomas Schietinger (Section head, Commissioning Leaders)

Thanks to BD Alumnis (Anne Oppelt, Yujong Kim), BD Students, SwissFEL Diagnostics and RF Group, STFC Beam Dynamics group and, in particular,

- Marco Pedrozzi (Head of SwissFEL Test Injector)
- Hans Braun (SwissFEL Project Leader)