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Paolo Craievich :: on behalf of SwissFEL team :: Paul Scherrer Institut

Overview of the SwissFEL Injector design and performances

XLS Injector Road Map – INFN/LNF, 13-15 November 2019

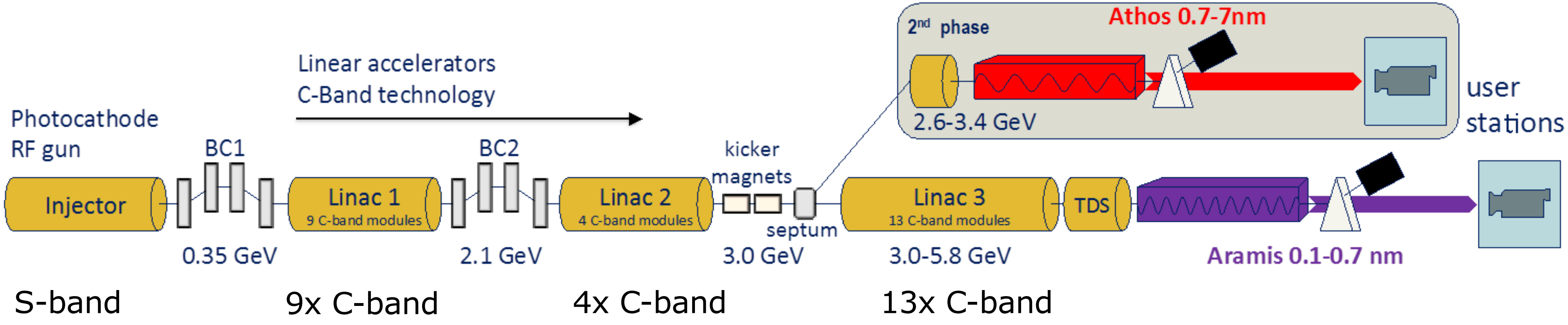
Credits

- The work presented in this section has been carried out by the SwissFEL team:
    - A big acknowledgment goes to all the colleagues who contribute to it (and, I hope, cited in a right way in the talk).
    - To prepare my slides, I have especially used material from: Simona Bettoni, Eduard Prat, Philip Dijkstal, Sven Reiche, Laser Group (Carlo Vicario et al.), Thomas Schietinger, Marco Pedrozzi, Qiao Geng
- In this talk I have summarized studies done at PSI in the last 9 years and in particular measurements performed in:
    - SwissFEL Injector Test Facility (SITIF): from 2010 to 2014
    - SwissFEL: from Summer 2016 to now

Outline

- **RF source and photocathode**
  - 2.5 cell S-band gun
  - Laser system and shaping
- **Definition of the working point**
  - Emittance measurements and minimization
- **RF jitter and beam stability**
  - Improvement of RF Gun Field measurements
- **Linearization in BC1**
  - Using passive devices
- **What's next at SwissFEL injector?**

Introduction to the SwissFEL



Main parameters

Wavelength	0.1 nm–5 nm
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs (rms)
e^- Energy (0.1 nm)	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz
Overall length	740 m

ARAMIS

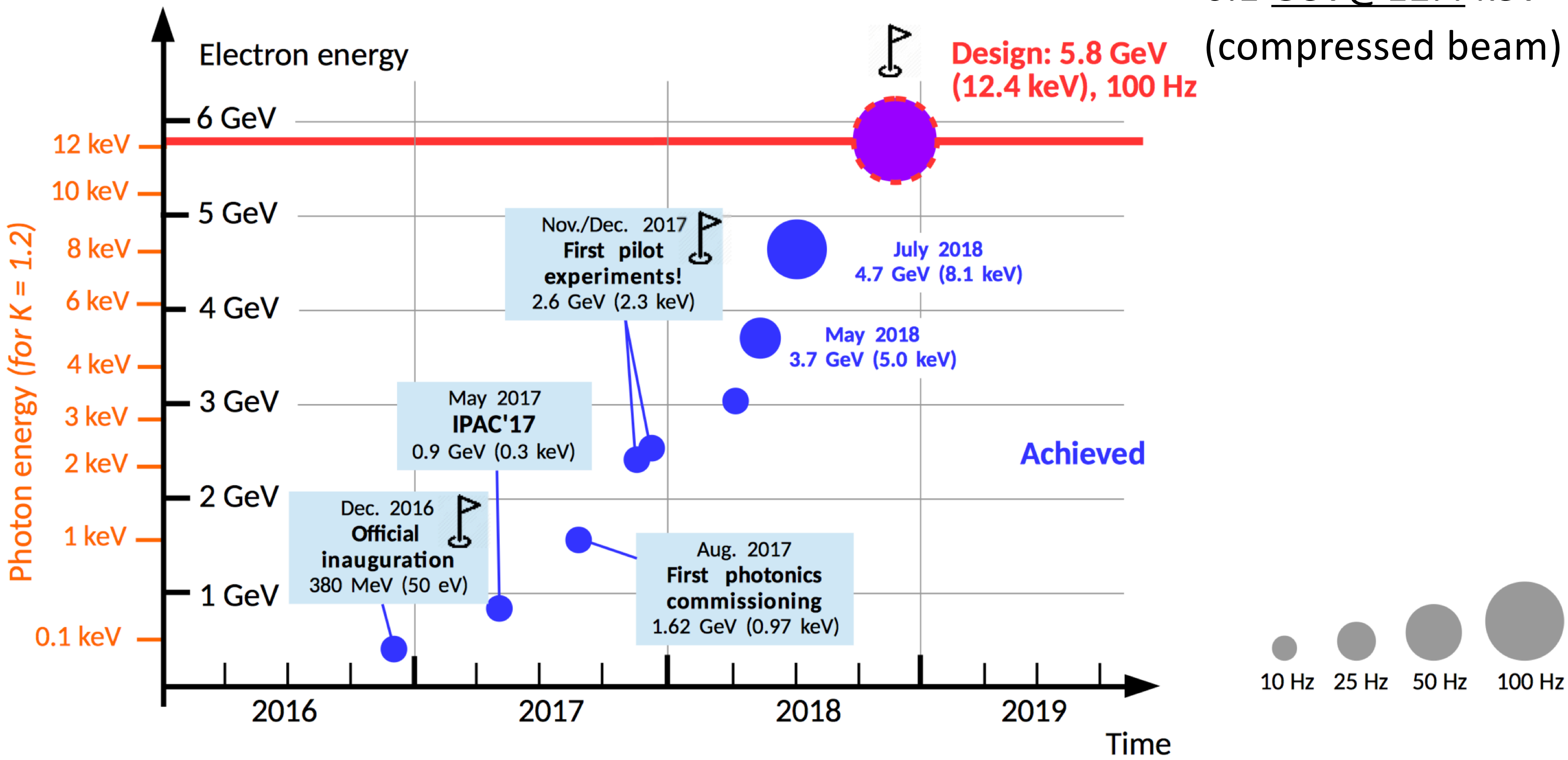
- Hard X-ray FEL, λ=0.1 - 0.7 nm (12-2 keV)
- Linear polarization, variable gap, in-vacuum undulators
- User operation from 2018

ATHOS

- Beam Energy 2.7 – 3.3 GeV
- Soft X-ray FEL, λ=0.65 - 5.0 nm (2-0.2 keV)
- Variable polarization with Apple-X undulators (2-m long)
- Commissioning starts in December 2019

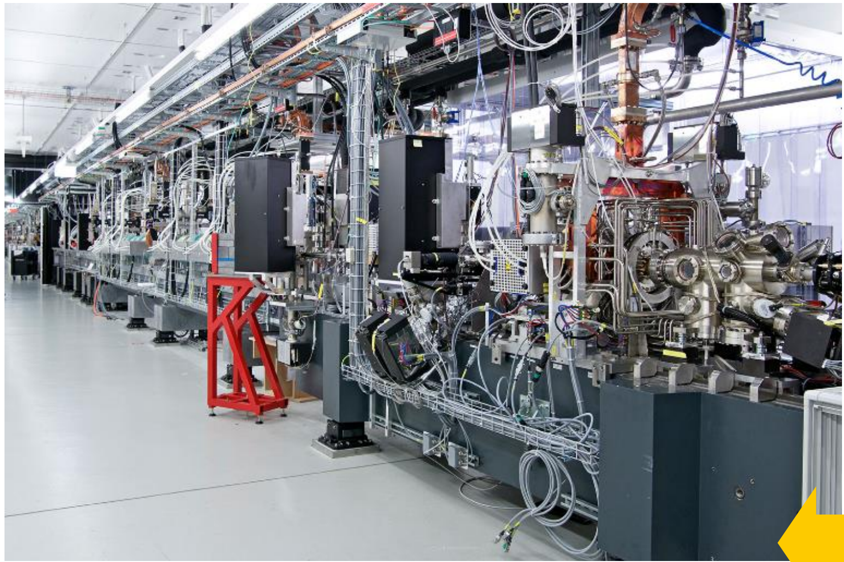
Machine Evolution

6.1 GeV@12.4 keV
(compressed beam)



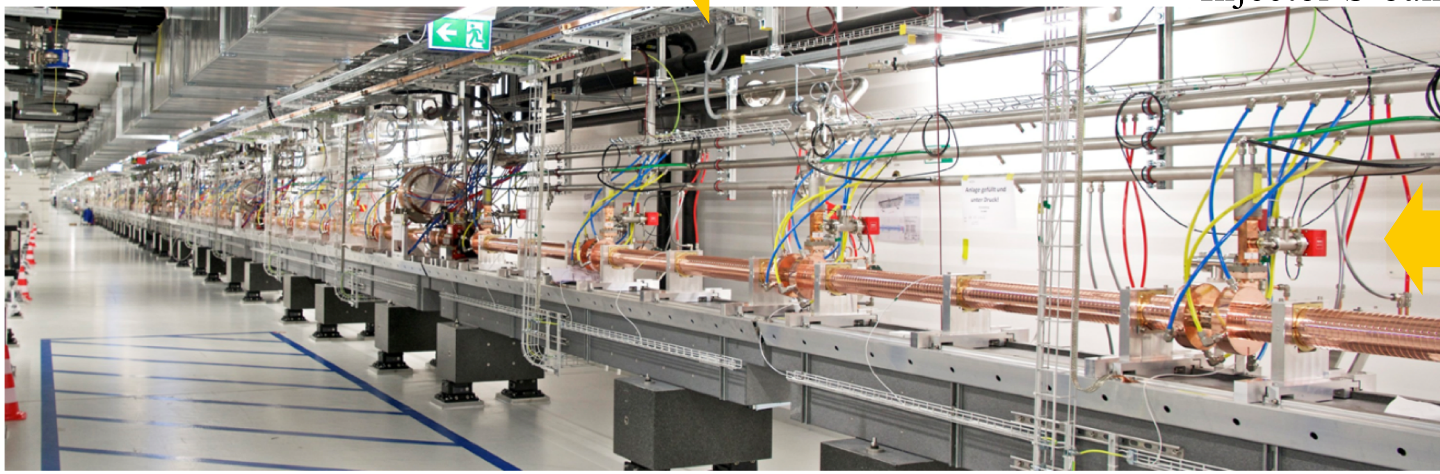
Courtesy of T. Shietinger

SwissFEL RF System in Tunnel



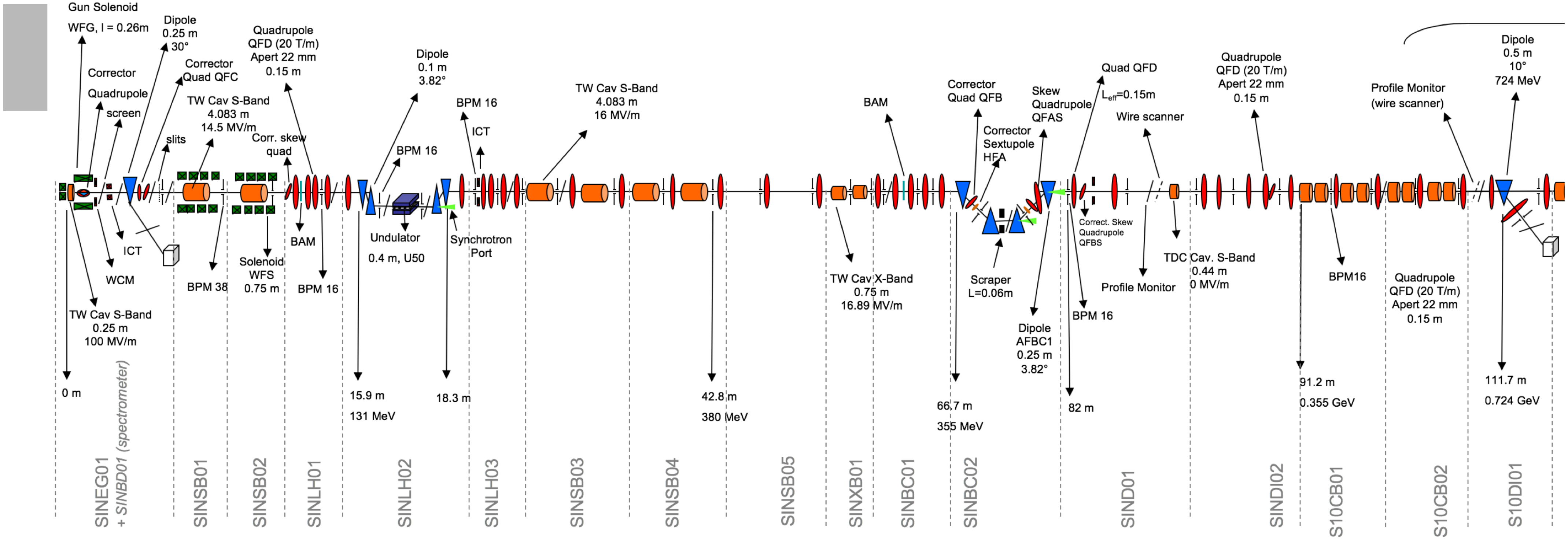
RF Gun

Injector S-band



Linac
C-band

SF injector (similar layout in SITF)



2.5 cell S-band RF gun

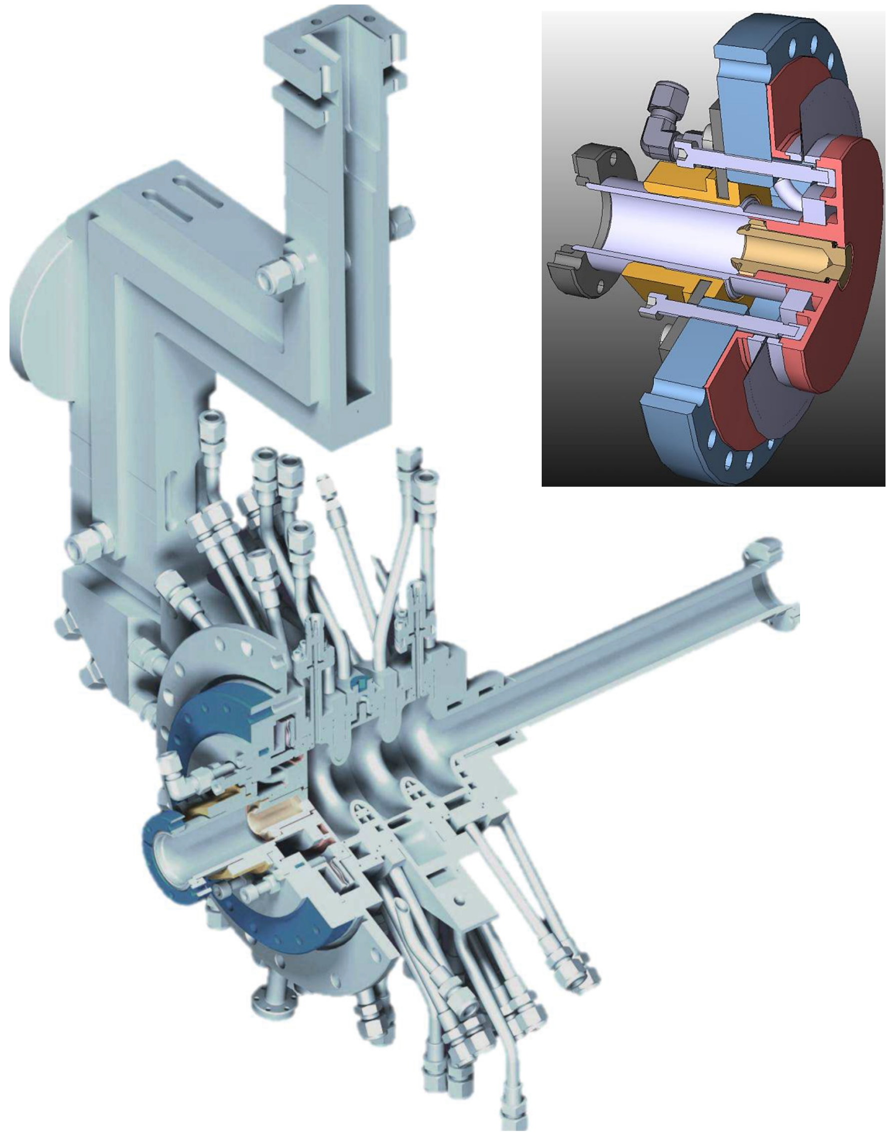
- Best design features from LCLS and CTF/PHIN RF guns adopted
- Machined “on tune” according to HFSS
- No tuning plungers
- No tuning step during machining
- Quadrupole compensated symmetric coupler
- Load lock chamber

Parameter	HFSS	Measurement
π-mode frequency (MHz)	2 997.912	2 997.912
β-coupling	1.98	2.02
Quality factor Q_0	13630	13690 ± 100
Time constant (ns)	485	481
Mode separation (MHz)	16.36	16.20
Field balance (%)	>98	>98
Operating temperature (°C)	57.7	53.0

RF and mechanical design: PSI

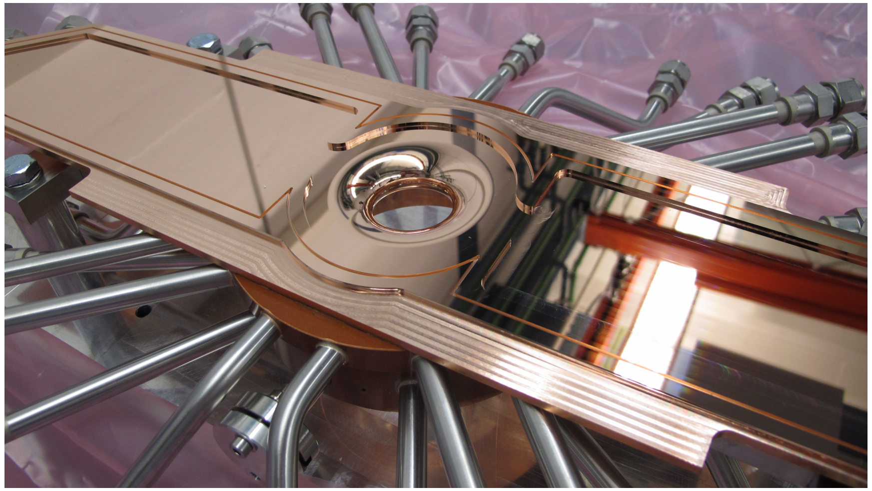
Fine machining cavities : VDL

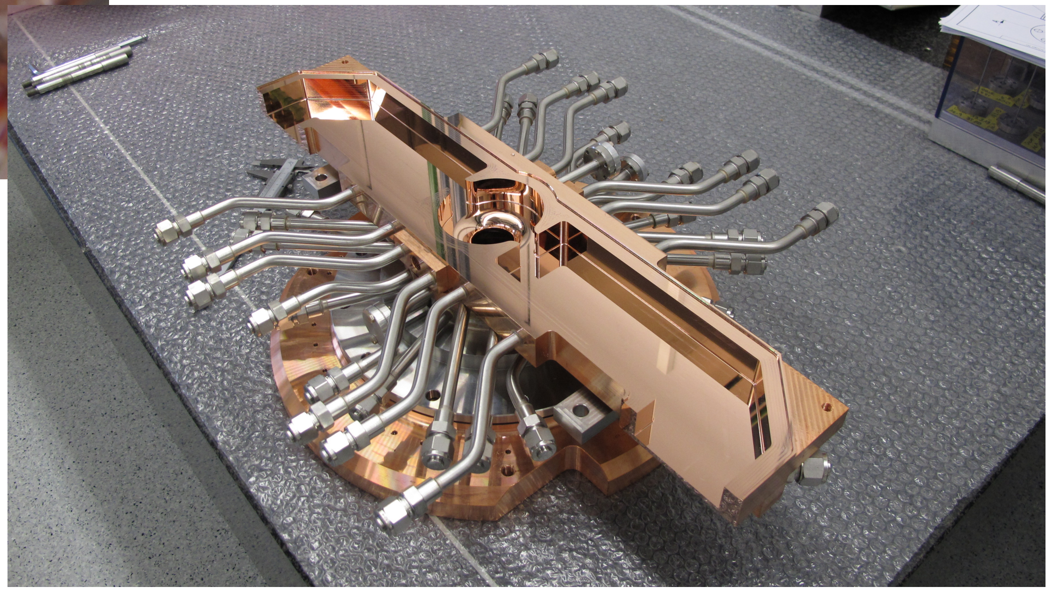
Pre-machining & brazing: PSI workshop



7.1 MeV @16 MW, 1μs, 100 Hz

From RF design to copper





Cooling system was design for operation at 400 Hz

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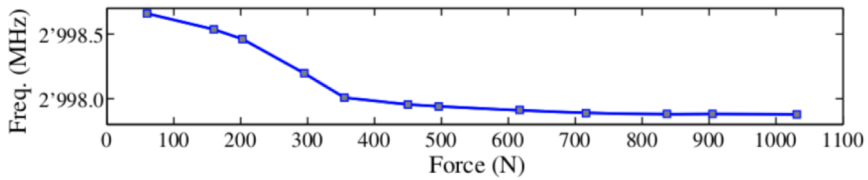
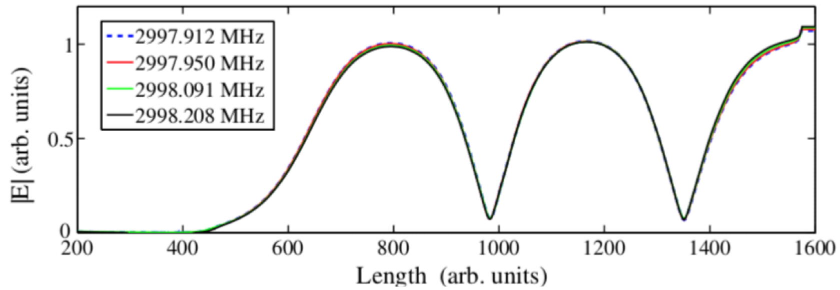
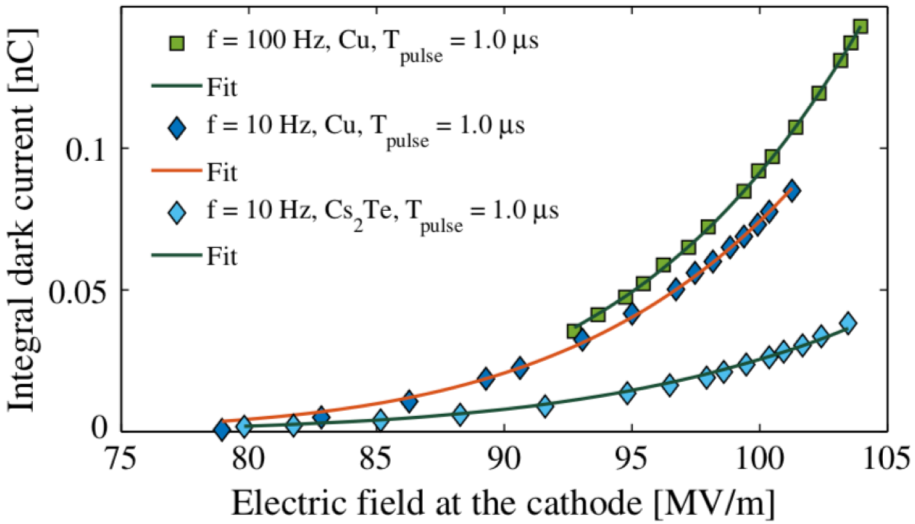
Field balance and dark current







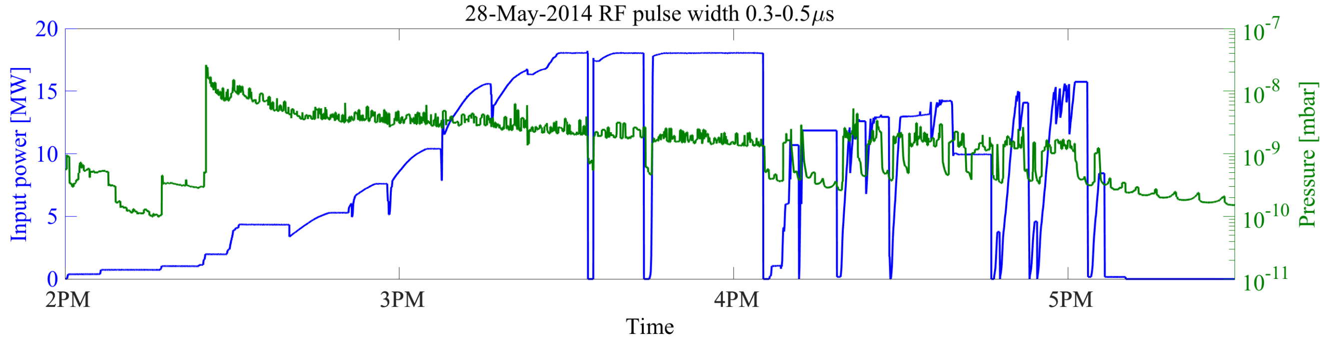
→ frequency spectrum and field balance verified with the bead-pull method

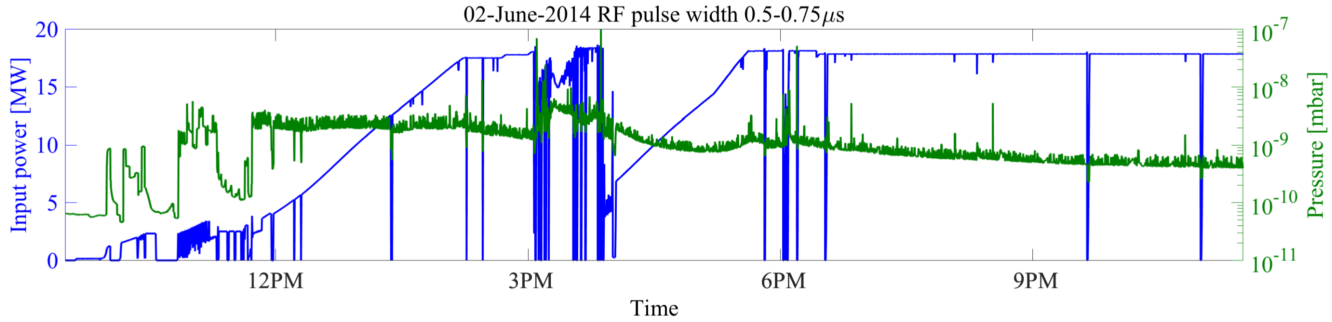
→ frequency and field balance as a function of the force applied to the cathode plug

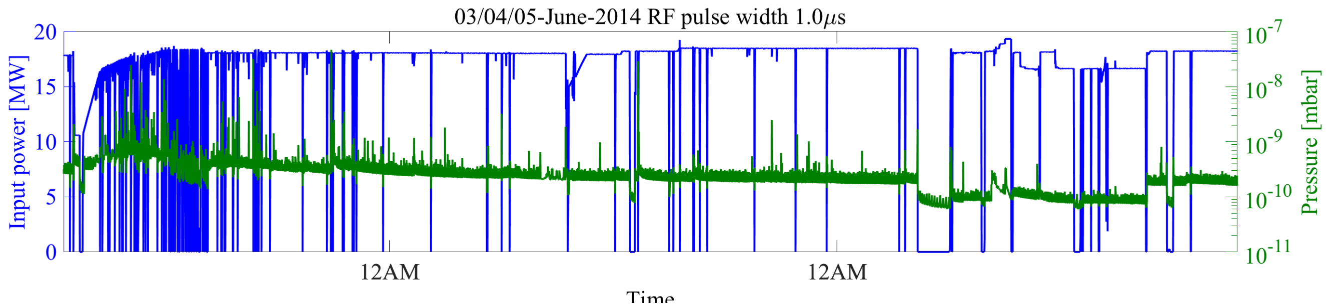
→ on- axis electric field profiles for different positions of the cathode plug

→ Dark current versus electric field at cathode gun, rep. rate 10/100Hz, Cu and Cs2Te

RF conditioning at SITF



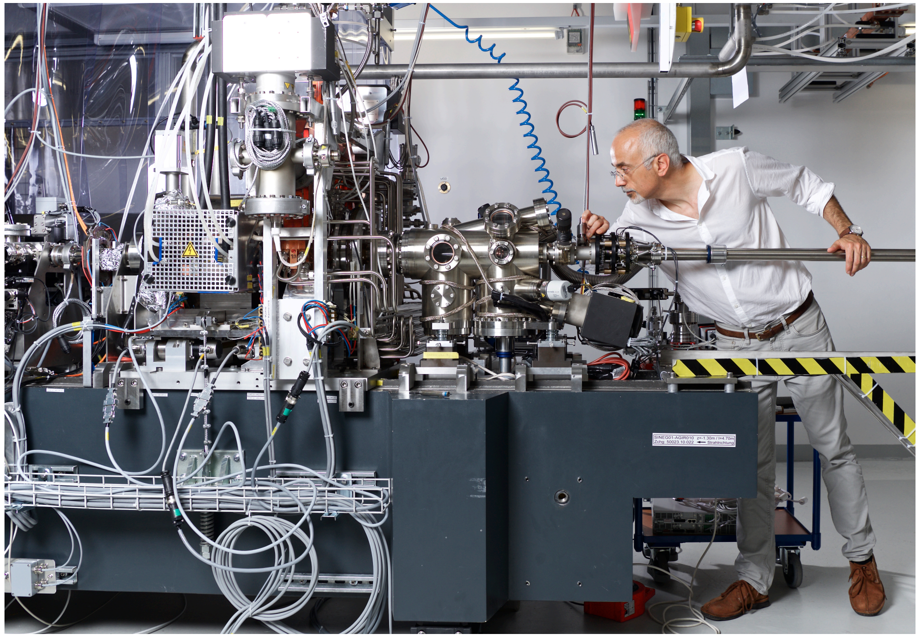


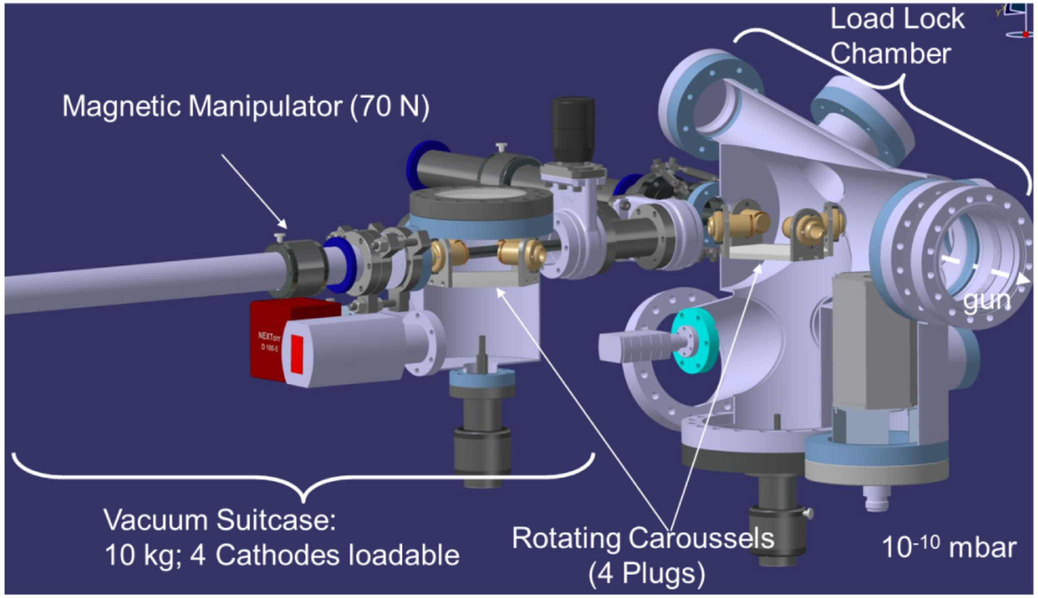


Blue lines: RF power

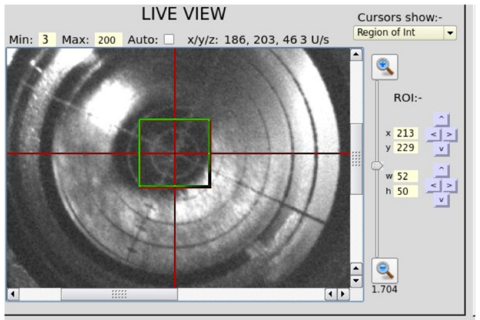
Green: vacuum pressure

Gun installed in SwissFEL



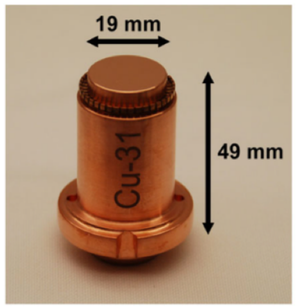


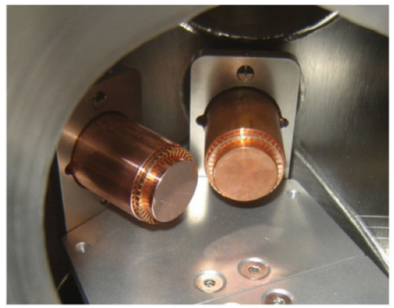
Vacuum suitcase connected to the load-lock, showing the cathode transfer principle and the storage carroussels..



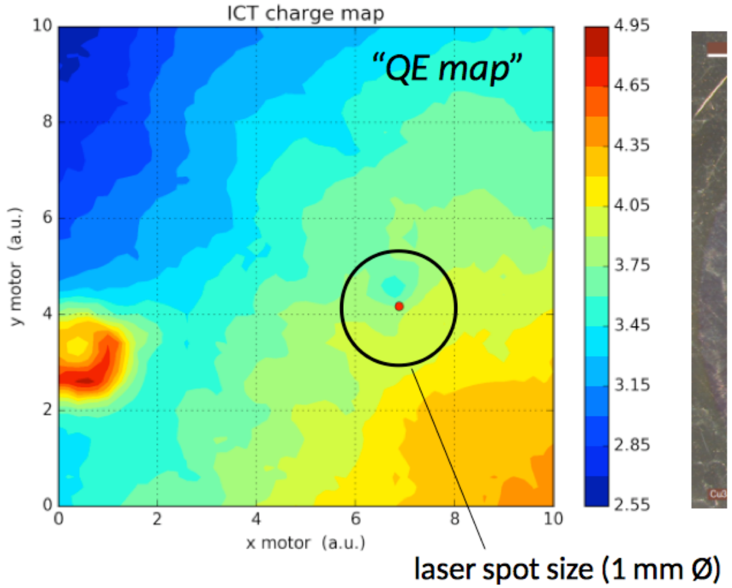
Laser alignment cathode

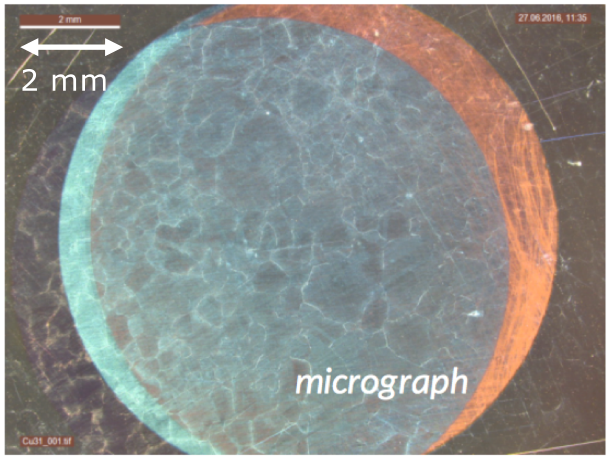
Cs2Te coated copper cathode, QE ~0.7%



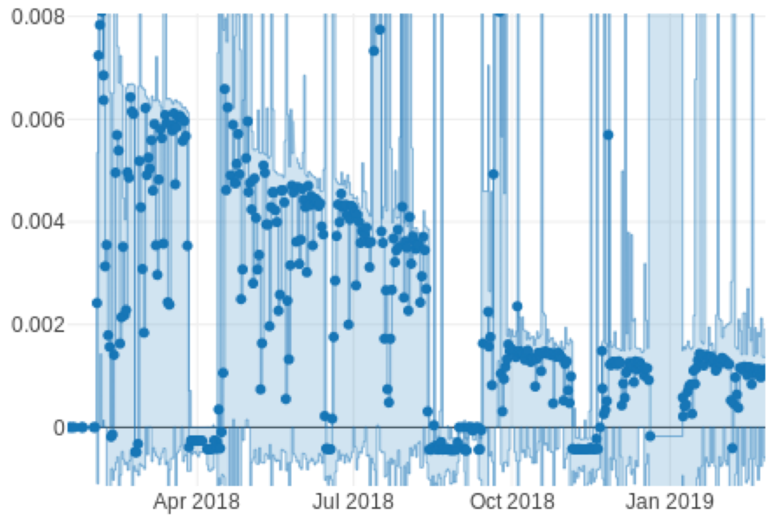


Cs2Te coated copper cathode





- Cs2Te coated copper cathode installed since July 2017.
- Quantum efficiency stable at about 0.7% with uniform distribution around the laser spot until spring 2018
- The apparent QE of Cu_31 is now around 0.1%. The QE has dropped after the shutdown of November 2018 around 0.1% (still good for the operation)



Courtesy of R. Ganter

- This summer we replaced the cathode

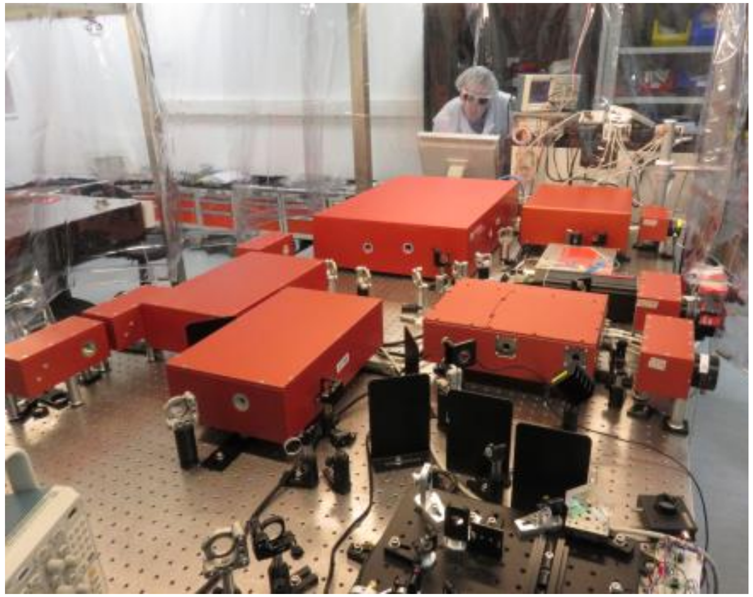
Photocathode laser

➢ ALCOR Yb:CaF_2

(**A**dvanced **L**aser for photo-**C**athode and **O**ptical **R**eplica):

Photocathode (λ=260 nm):

- Energy up to 500 μJ (at cathode 0.05-1 μJ for QE~2-0.1%)
- 0.65 FWHM gaussian pulses
- 3.3-10 ps flat-top by **stacking**
- 7-11 ps gaussian by **UV stretcher**
- UV laser stability at the cathode better than 0.8 % rms



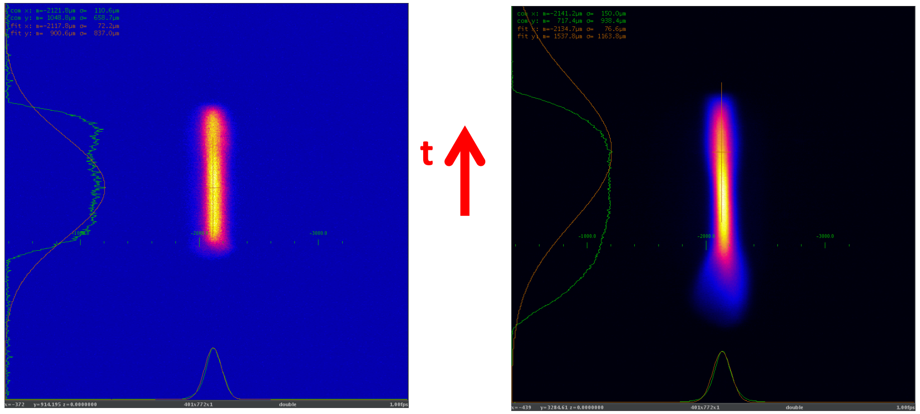
- ❖ Solid state Yb:CaF2 (Ytterbium:Calcium Fluoride) chirped pulsed amplifier with excellent stability and uptime
- ❖ Variable circular aperture allows optimization of beam size on cathode (low emittance)
- ❖ Approximate flat top profile with pulse stacking – beam based profile optimization
- ❖ Systematic comparison pulse-stacked versus stretched Gauss profile.
- ❖ Standard operating procedure for routine gun-laser check – fundamental for stability and reproducibility of the facility

Courtesy of C. Vicario et al.

Laser shaping (laser group): Cu vs Cs_2Te

Longitudinal:
- ❖ Optimization done manually and tuned with a simplex based code
- ❖ Used the uncompressed low charge beam (closest to the bunch profile at the cathode)

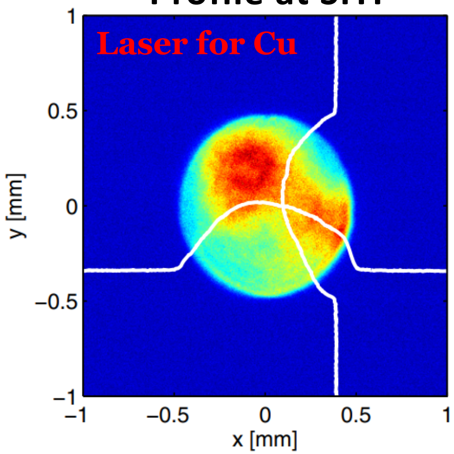
Q = 15 pC (L_t = 10 ps FWHM) Q = 200 pC (L_t = 10 ps FWHM)



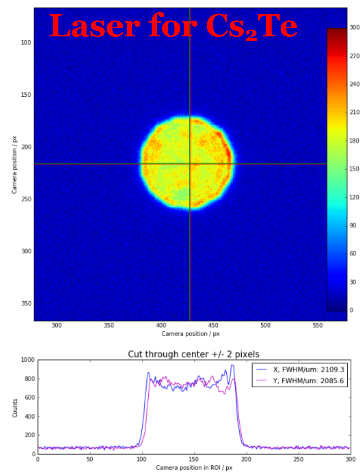
Transverse:
- ❖ Transverse shaping because of a large QE a lot of laser intensity can be used
- ❖ Important to have enough reserve of energy for the manipulations of the laser beam in order to have a good homogeneity.

Courtesy of C. Vicario et al.

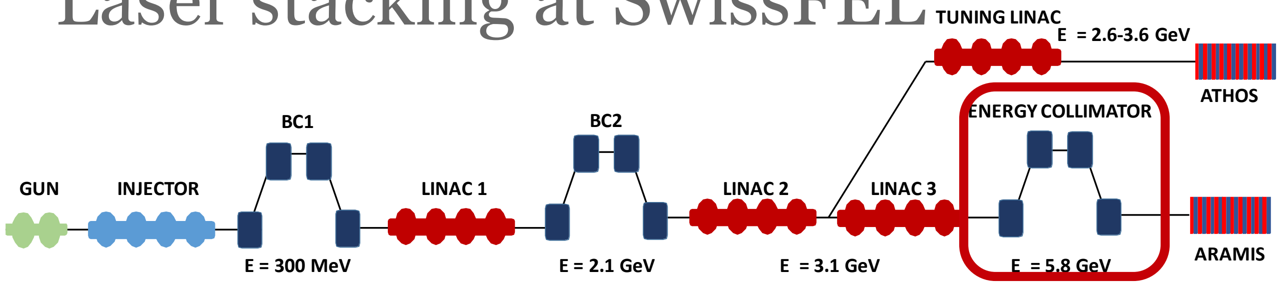
Profile at SITF



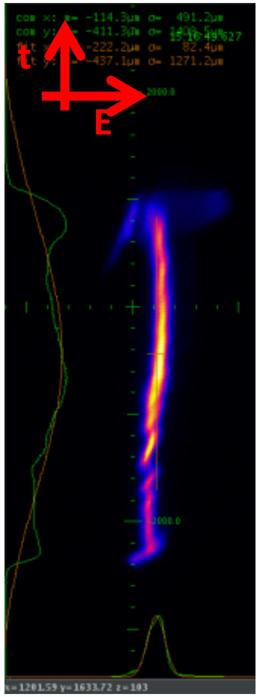
Profile at SwissFEL



Laser stacking at SwissFEL



Beam longitudinal phase space measured at high energy

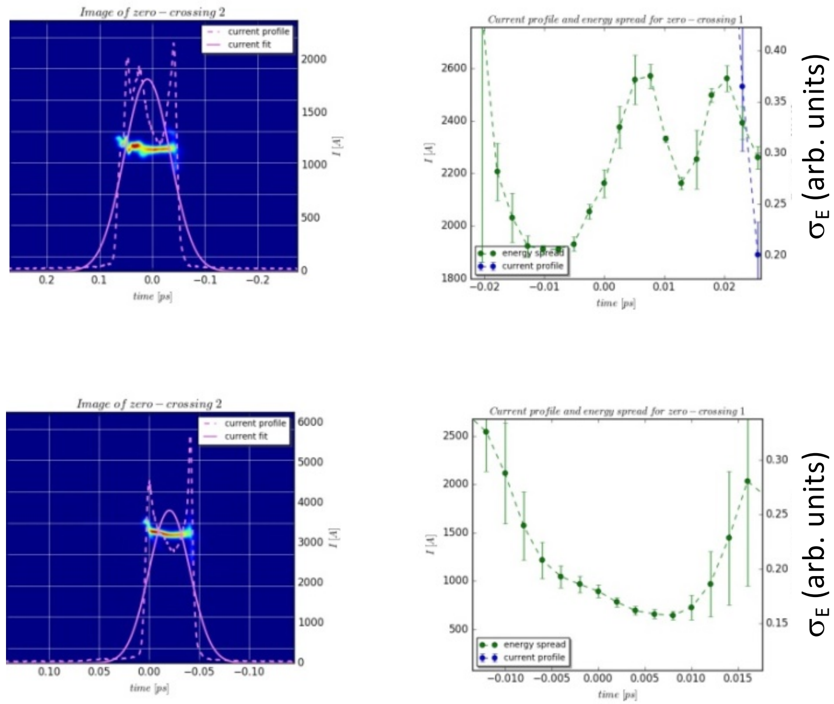


STACKING

- Energy structures still present
- Current modulation observed
- LH not efficient at this wavelength

GAUSSIAN

- Smoother profile
- LH not necessary



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Definition of the working point

Injector working point optimization

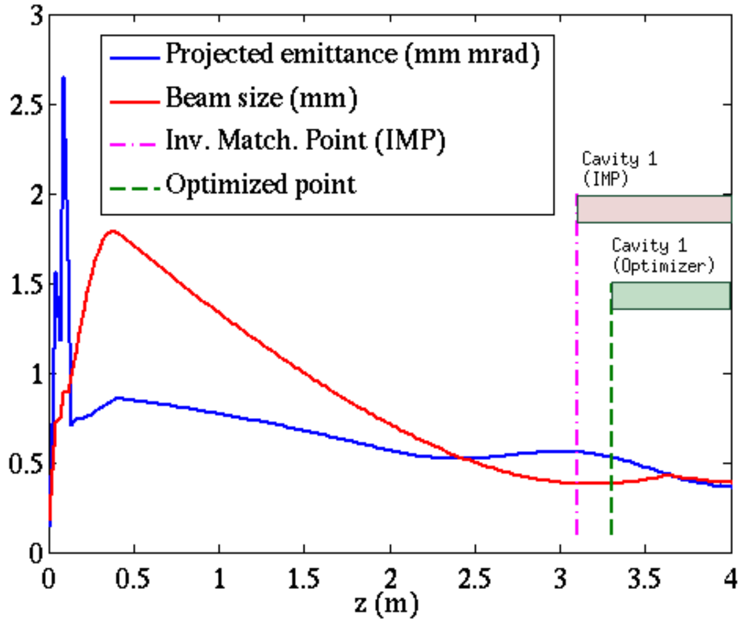
Figure of merit (FOM) optimized is a weighted combination of the mean optics mismatch and slice emittance over ¾ of the bunch duration:

$$FOM = w1\left(\langle\zeta\rangle_{MID-PART} - 1\right) + w_2 \langle\varepsilon\rangle_{MID-PART}$$

where the mismatch parameter is calculated as:

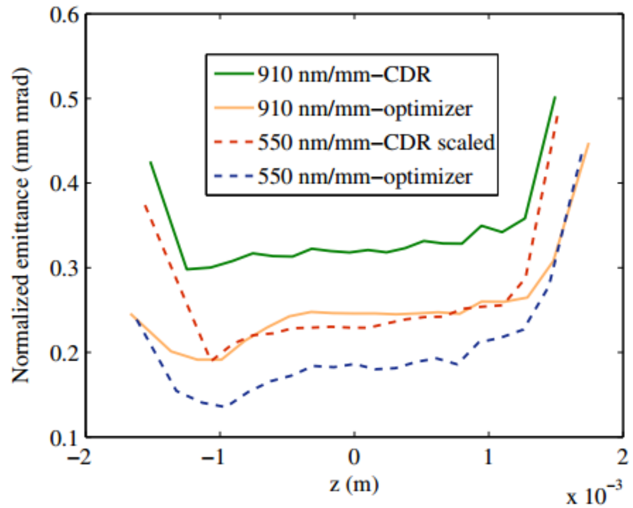
$$\zeta \equiv \frac{1}{2}\left(\beta_0\,\gamma - 2\,\alpha_0\,\alpha + \gamma_0\,\beta\right)$$

where *_0 indicates the values of the projected bunch and α , β, γ are the Twiss parameters



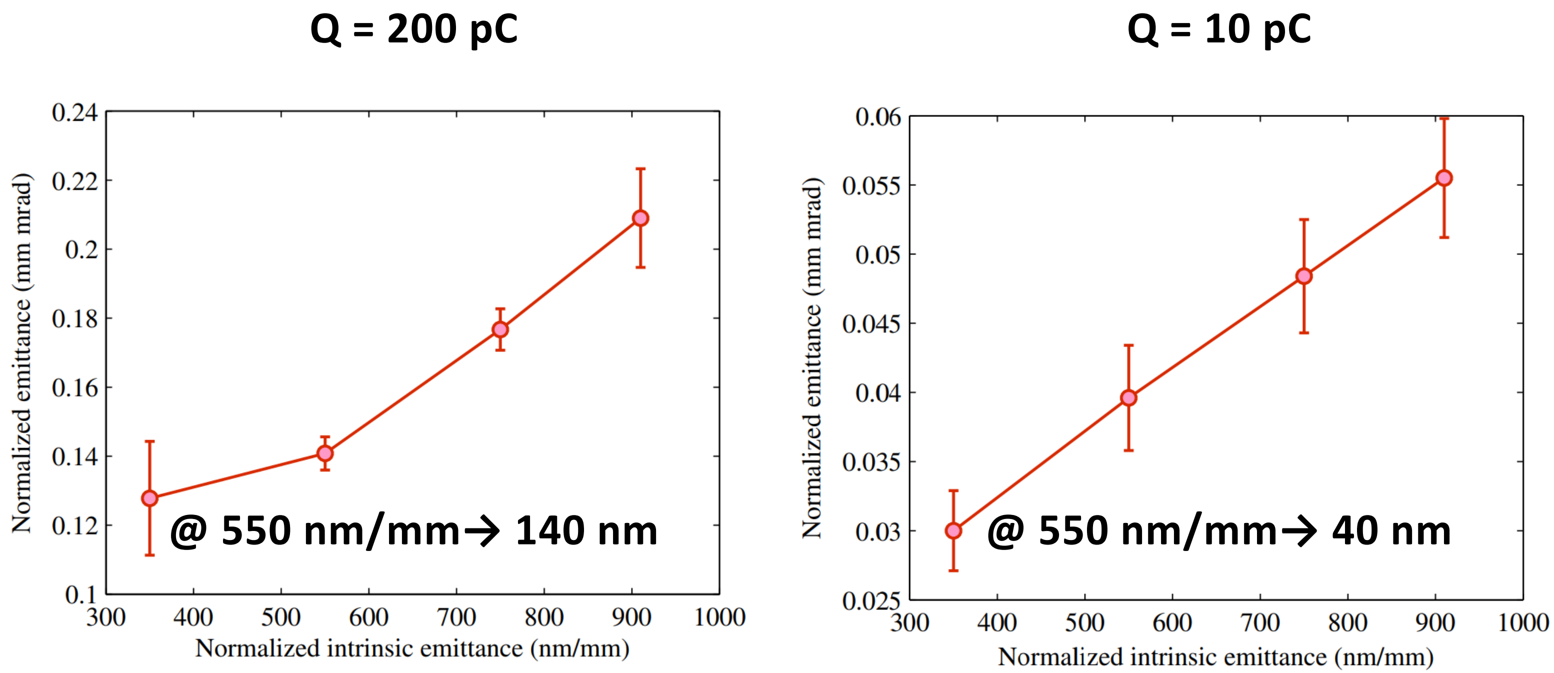
Reduction of the design emittance compared to the CDR (novel working point and measured thermal emittance)

Optimal working point corresponds to a slightly different condition than the invariant envelope (booster located more downstream)



Courtesy of S. Bettoni

Design emittance for SF



One of the highest brightness source for FEL hard X-ray facility
About 70% of the total emittance is given by the intrinsic emittance

S. Bettoni et al., PRST AB 18, 123403 (2015)

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Emittance measurements (1)

- Transversely coherent FEL radiation is generated when $\frac{\varepsilon_n}{\gamma} \le \frac{\lambda}{4\pi}$

ε_n : normalized emittance, γ :Lorentz factor, λ : FEL wavelength

- If the normalized emittance is reduced:
  - The final beam energy can be decreased → more compact and cheaper accelerator ☺
  - Higher radiation power and shorter undulator line for a given beam energy ☺

- The thermal emittance is a significant contributor of the final beam emittance. It can be expressed as (neglecting tilted surface effects):

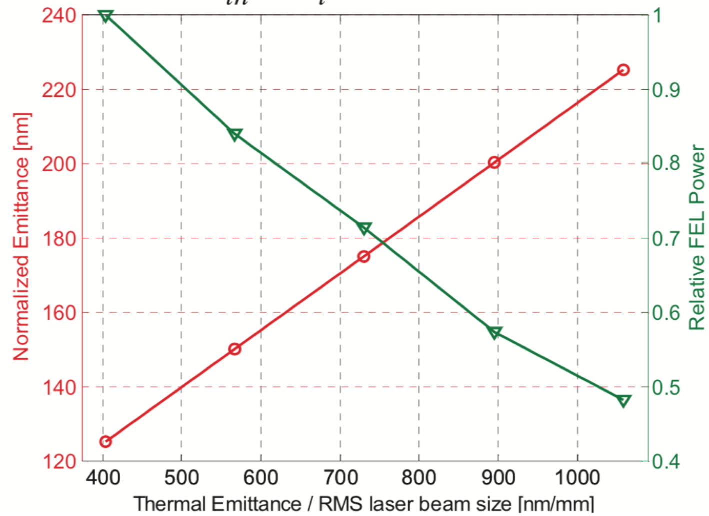
$$\varepsilon_{th} = \sigma_l \sqrt{\frac{\phi_l - \phi_{eff}}{3 m_0 c^2}}$$

σ_l rms laser beam size,

ϕ_l: laser photon energy,

ϕ_{eff} effective work function

Relative FEL power vs normalized thermal emittance $\varepsilon_{th} / \sigma_l$ for SwissFEL (200 pC)



Emittance measurements (2)

$$\varepsilon_{th} = \sigma_l \sqrt{\frac{\phi_l - \phi_{eff}}{3m_0c^2}}$$

Effective work function $$\phi_{eff} = \phi_w - \phi_s = \phi_w - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_c(\varphi)}$$

ϕ_w material work function ϕ_s Schottky effect

β Enhancement factor (surface properties)

$E_c(\varphi)$ Field on the cathode at injection phase φ

Expected effective work functions: ~4.0 eV for copper, ~3.6 eV for cesium telluride

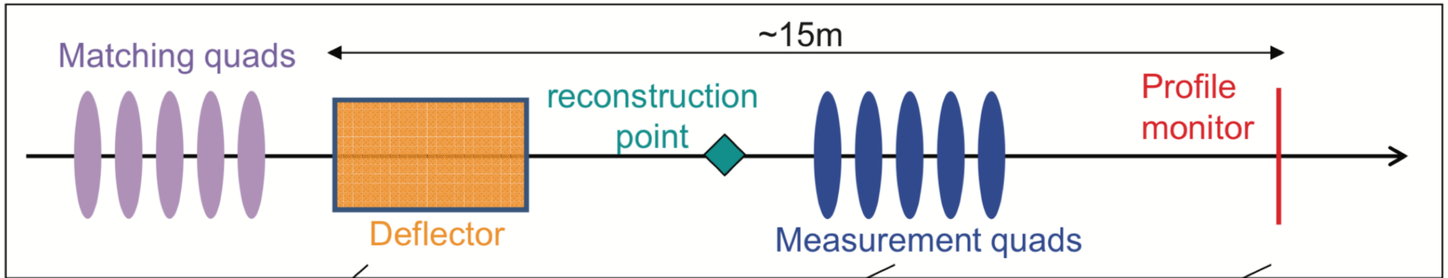
When E_c varies in a small range for a metal photocathode $$QE \propto (\phi_l - \phi_{eff})^2$$

The effective work function can be determined by measuring the **QE as a function of the phase (Schottky scan)** OR the **QE as a function of the laser energy (wavelength scan)**

Refs:
D. H. Dowell and J. Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009).
K. Flöttmann, TESLA FEL Report No. 1997-01, 1997.
Z. M. Yusof, M. E. Conde, and W. Gai, Phys. Rev. Lett. 93, 114801 (2004).
H. J. Qian et al, Phys. Rev. ST Accel. Beams 15, 040102 (2012).

Slice emittance measurements at SwissFEL (1)

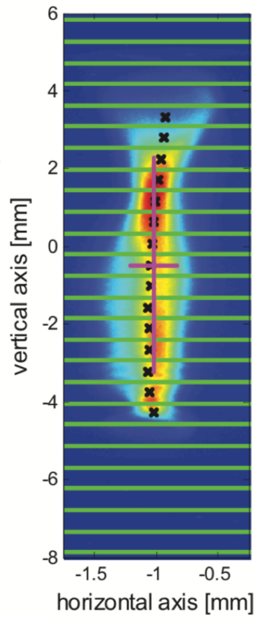
The beam is **deflected** in one direction as a function of time and the slice parameters in the other direction are reconstructed using 2D profile monitors.



Deflection.
The streaking can be done:
1. Using an RF Transverse Deflector (TD) (y)
2. Introducing dispersion to an energy chirped beam (x and y)

Optics. The optics are scanned using 5 quads between the transverse deflector and the observation point

Image analysis.
The beam is split into slices, using the centroid from Gauss fit as a reference. Per each slice the beam size from Gauss fit is obtained.



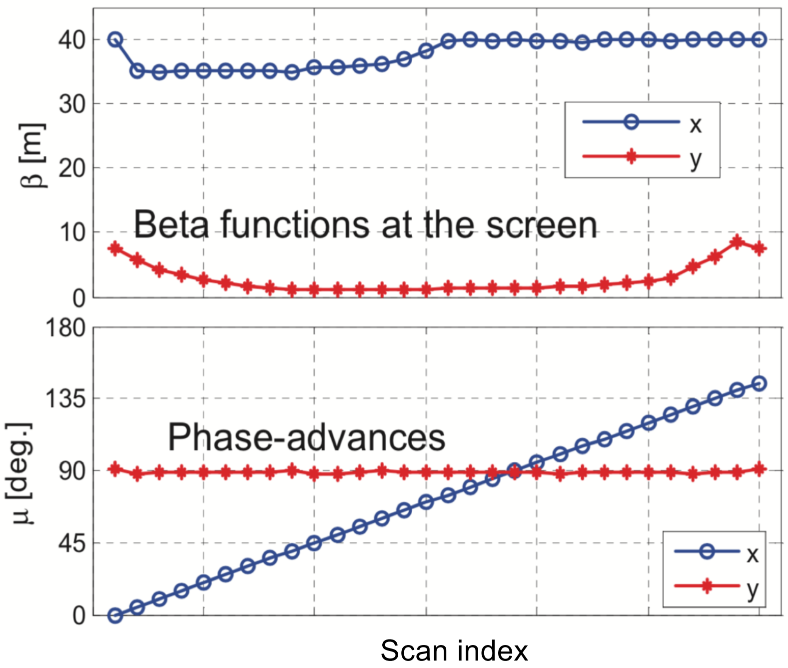
Emittance/mismatch determination.
From the beam sizes per each optics the emittance and optics are obtained per each slice.

Courtesy of E. Prat

Slice emittance measurements at SwissFEL (2)

5 quadrupoles are used to:
- ➢Scan phase-advance in the meas. plane
- ➢Optimize longitudinal resolution
- ➢Keep beta-functions at the PM under control

Optics example for TD measurements



$$\text{Longitudinal resolution} \propto \frac{\sqrt{\varepsilon_y}}{\sum_i \sqrt{\beta_{y_{TD_i}}} \cdot \sin(\Delta\mu_{y_{TD_i \to PM}})}$$

β_{yTDi} : β-function at the deflector *i* in the streaking direction
$\Delta\mu_{yTDi \to PM}$: vertical phase-advance in the streaking direction between deflector I and profile monitor
ε_y= emittance in the streaking direction

Long. resolution (assuming , ε_y=0.5μm, E=250MeV)
TD: **~4 μm** (V=5MV)

Courtesy of E. Prat

Emittance resolution, errors and matching

- SwissFEL profile monitor (YAG)
  - Beam size resolution is ~15 μm, equivalent to an emittance resolution of **2-3 nm** (E=250MeV)
  - Signal to noise ratio is good enough to measure slice emittance for bunch charges of less than **1pC**

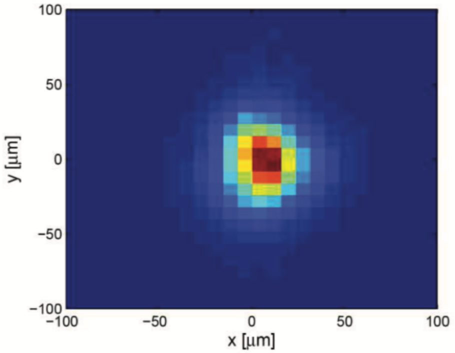
Errors

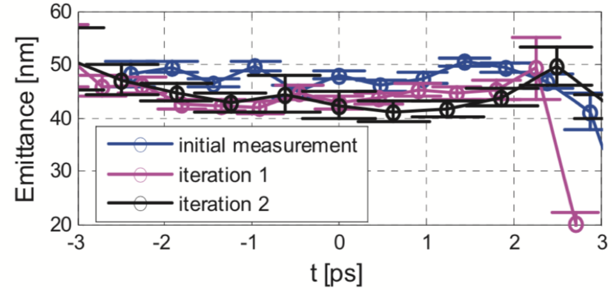
- Statistical errors from beam size variations (what is shown in the error bars of the measurements). For 5% of beam size measurement error this is below 3% (if $\Delta\mu_x$=10deg).
- Systematic errors expected to be below 5%:
  - Screen calibration (~1%→~2%) and resolution
  - Energy and quadrupole field errors (<1%)
  - Optics mismatch
  - Others (e.g. errors associated to Gauss fit)

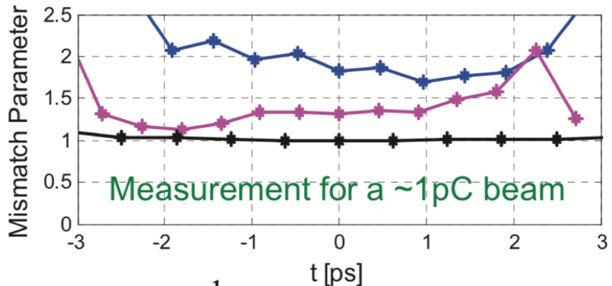
Matching

- Beam core is always matched to exclude errors due to optics mismatch
- Matching of the core works normally in 1-2 iterations
- Successful matching gives us confidence in the obtained emittance values

Beam image close to screen resolution limit



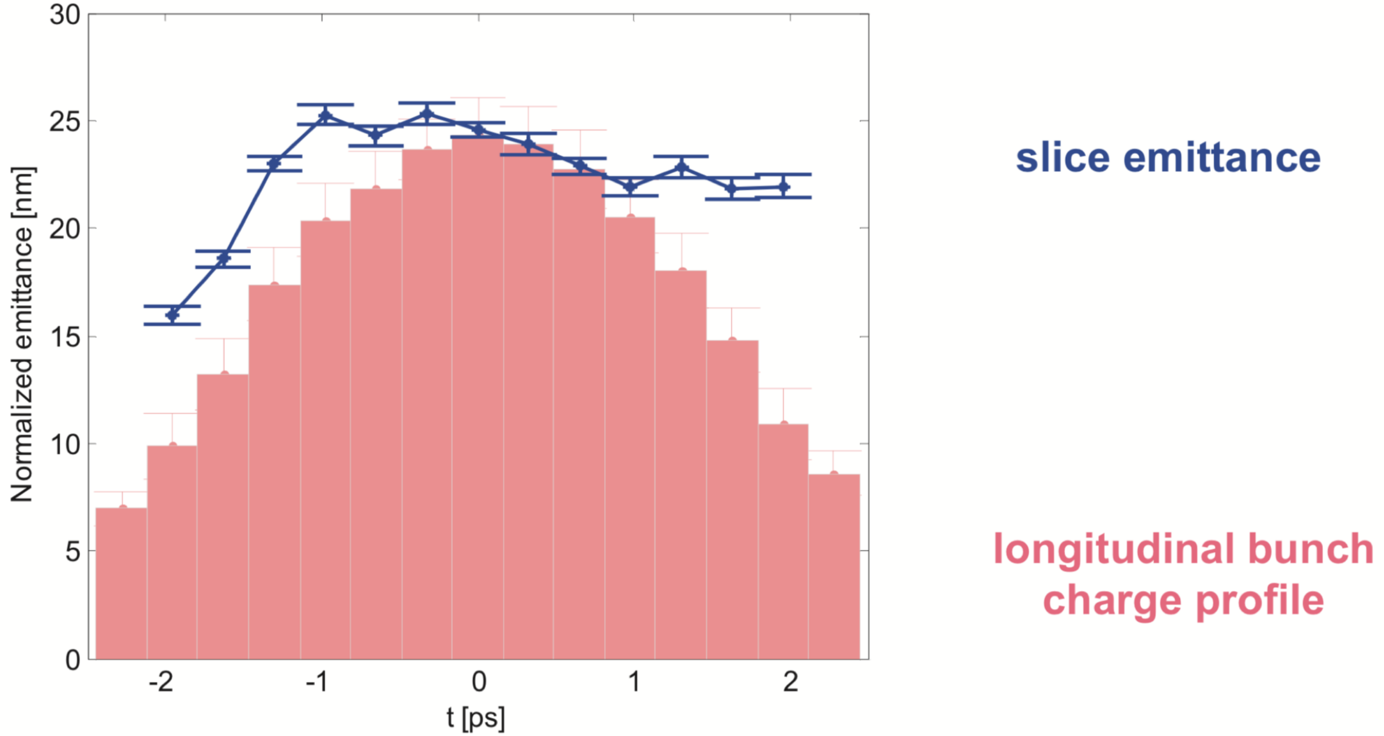




$$M = \frac{1}{2}(\beta\gamma_D - 2\alpha\alpha_D + \gamma\beta_D)$$

Courtesy of E. Prat

Smallest measured emittance



- Measurement done for a total bunch charge of about **30 fC**
- Measurement done with low gradient (E=3.7 MeV) and smallest laser aperture (rms laser beam size around 50 μm)
- Core slice emittance **< 25 nm**

Courtesy of E. Prat

Source characterization

Thermal emittance measurements as a function of

- Laser wavelength
- Field at the cathode
- Cathode material: copper and cesium telluride

Procedures

- Emittance: The thermal emittance is defined as the core slice emittance when space-charge and rf effects are negligible. The normalized thermal emittance $\varepsilon_{th} / \sigma_l$ is reconstructed by measuring the emittance as a function of the rms laser beam size
- The effective work function can be alternatively reconstructed from:
  - Wavelength scan (QE vs laser wavelength)
  - Schottky scan (QE vs rf phase)
- The QE is measured by recording the charge at a calibrated BPM (2.6 m downstream of the gun) as a function of the laser intensity.

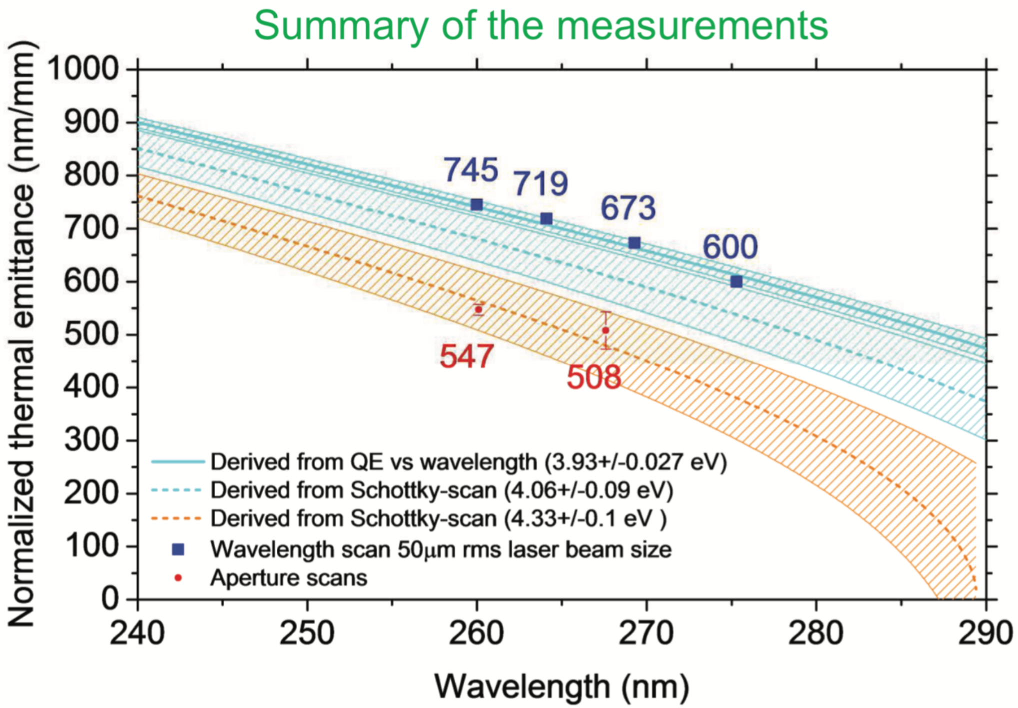
Used lasers

- Ti:Sapphire laser + OPA (wavelength dependence measurements)
- ND:YLF laser (all the rest)

Used cathodes

- Copper: cath_3 (laser dependence), cath_19 (field at the cathode dependence)
- Cesium telluride: cath_13 and cath_8

Laser wavelength dependence

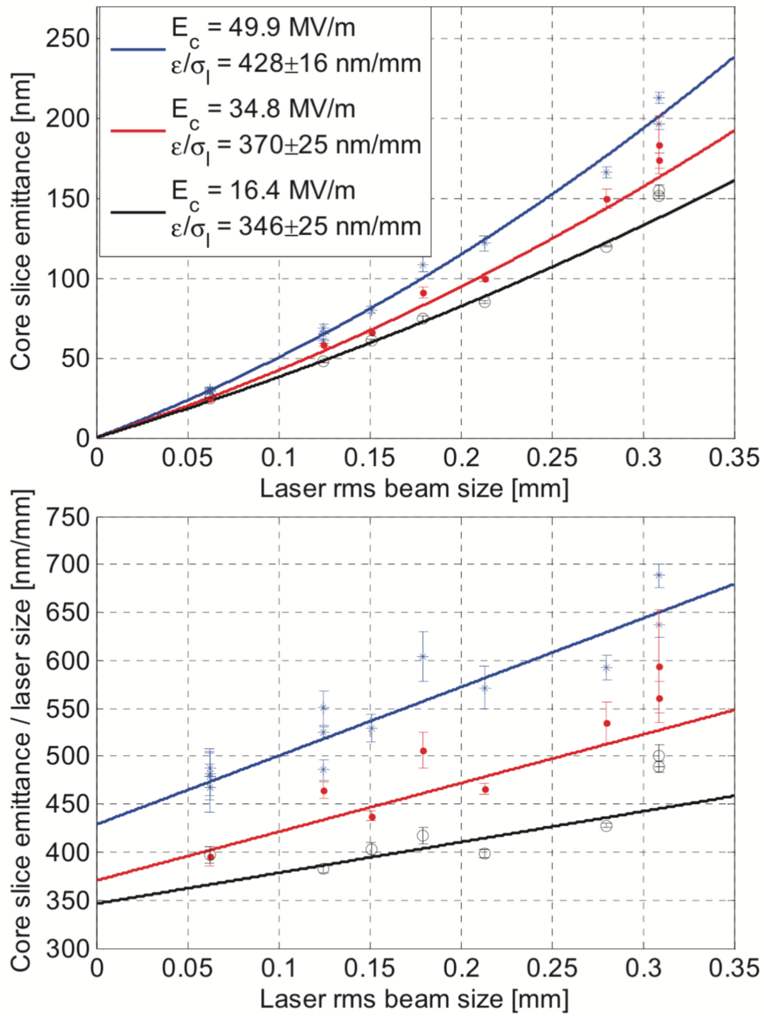


- Measurements agree well with expected work functions
- Wavelength dependence as expected by theory $\varepsilon_{th} / \sigma_l \propto \sqrt{\phi_l}$
- Wavelength-scans and Schottky-scans can be used to reconstruct the normalized thermal emittances
- Same cathode show different work function after one month of operation

Field at the cathode dependence

Field at the cathode [MV/m]	Normalized thermal emittance [nm/mm]	Quadratic component [nm/mm2]
49.9	428±16	716±84
34.8	370±25	508±137
16.4	346±25	321±105

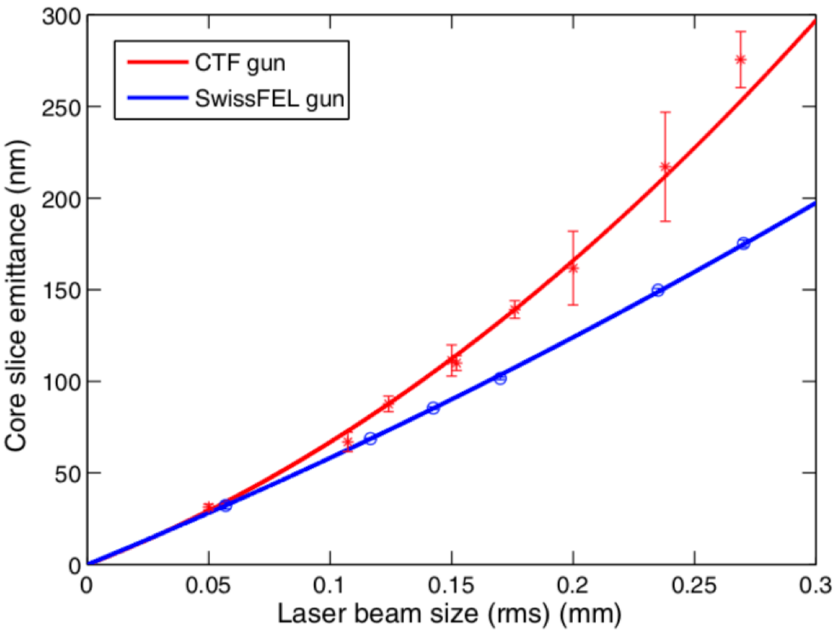
- Quadratic component decreased as a function of the gradient → higher order effects are due to rf
- Normalized thermal emittance changed as a function of the gradient as expected by theory $\varepsilon_{th} / \sigma_l \propto E_c(\varphi)^{1/4}$



E. Prat et al., PRST AB 18, 063401 (2015)

Quadrupolar field effect

- Most of our intrinsic emittance measurements were performed with the CTF gun
  - → symmetric rf feed design to avoid dipolar kicks, but has no compensation of quadrupolar fields
  - → These quadrupolar fields lead to a quadratic rise of the emittance as a function of the laser spot size.
- SwissFEL gun: quadratic effect is less pronounced (racetrack shape in the coupler cell)



Courtesy of E. Prat

Normalized thermal emittance

Cathode	Measurement day	$\varepsilon_{int}/\sigma_l$ (raw) [μm/mm]	Laser wavelength [nm]	Cathode field [MV/m]	$\varepsilon_{int}/\sigma_l$ (normalized) [μm/mm]
Cu-3	30 October 2012	0.51 ± 0.04	267.6	50	0.57 ± 0.04
Cu-3	31 October 2012	0.55 ± 0.01	260.1	50	0.53 ± 0.01
Cu-19	25 September 2013	0.44 ± 0.02	262.0	50	0.44 ± 0.02
Cu-19	04 April 2014	0.40 ± 0.03	262.0	50	0.40 ± 0.03
Cu-22	13 June 2014	0.58 ± 0.03	262.0	76	0.54 ± 0.03
Cs_2Te-8	04 April 2014	0.54 ± 0.06	262.0	50	0.54 ± 0.06
Cs_2Te-17	08 October 2014	0.54 ± 0.01	266.6	76	0.54 ± 0.01
Cs_2Te-17	08 October 2014	0.50 ± 0.02	266.6	76	0.51 ± 0.02
Cs_2Te-17	08 October 2014	0.52 ± 0.02	266.6	76	0.53 ± 0.02

Measurements at other labs (Cu): **~900 nm/mm**

H. J. Qian et al, Phys. Rev. ST Accel. Beams 15, 040102 (2012)

Y. Ding et al, Phys. Rev. Lett. 102, 254801 (2009)

normalized to a laser wavelength of 262.0 nm and to a cathode field of 50 MV/m

E. Prat et al., PRST AB 18, 043401 (2015)

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References

- ❖ E. Prat et al., PRST AB 17, 104401 (2014)
- ❖ M. C. Divall et al., PRST AB 18, 033401 (2015)
- ❖ E. Prat et al., PRST AB 18, 043401 (2015)
- ❖ E. Prat et al., PRST AB 18, 063401 (2015)
- ❖ S. Bettoni et al., PRST AB 18, 123403 (2015)
- ❖ M. Schaer et al., PR AB 19, 072001 (2016)
- ❖ *T. Schietinger et al., PR AB 19, 100702 (2016)*
- ❖ S. Bettoni et al., PR AB 19, 034402 (2016)
- ❖ S. Bettoni et al., PR AB 21, 023401 (2018)

Emittance minimization

Source emittance contributions:

- Cathode emittance
- Space-charge forces
- RF fields at the gun

Optimized with

- Gun RF gradient (maximum)
- Laser transverse size
- Gun solenoid field
- Distance between gun and booster

Emittance growth sources

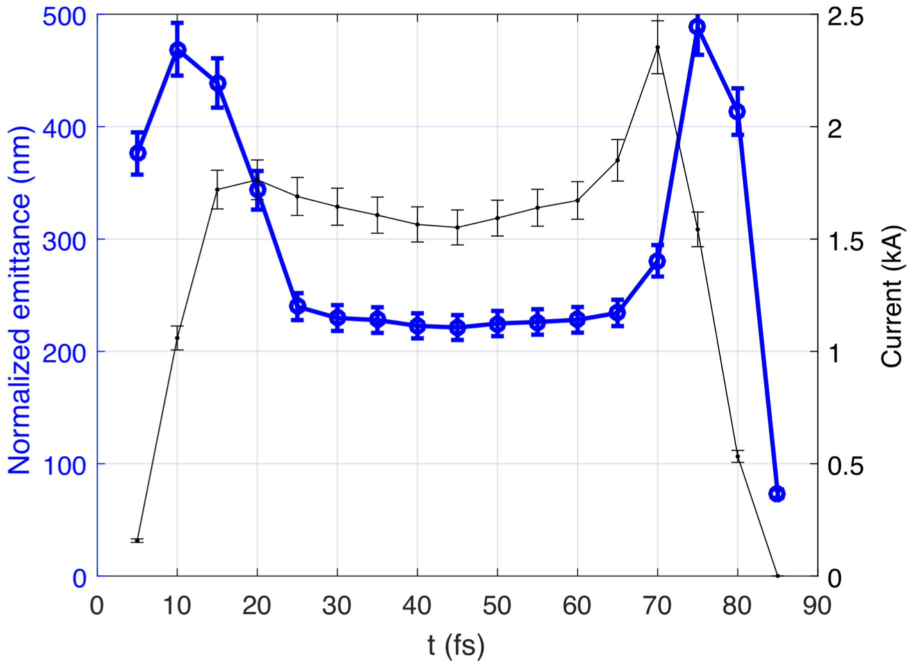
- Transverse coupling
- Beam tilt (x-z correlation)
- Coherent Synchrotron Radiation

Mitigated with

- Coupling correction
- Beam tilt correction
- Compression setup
- Optics in the bunch compressors

Measured emittances in SwissFEL

Normalized slice emittance measurement after nominal compression for a beam charge of 200 pC at 6 GeV



Measured normalized emittances for 200 pC and 10 pC at different linac location

200 pC	Uncompressed	After BC1	After BC2
σ_t (ps)	≈3	≈0.4-0.5	≈0.03-0.04
I (A)	≈20	≈120-150	≈1500-2000
Slice (nm)	≈150 (140)	≈200	≈200
Proj. horizontal (nm)	≈200 (210)	≈250	≈400
Proj.vertical (nm)	≈200 (210)	≈250	≈300
10 pC	**Uncompressed**	**After BC1**	**After BC2**
σ_t (ps)	≈1.4	≈0.2	≈0.003
I (A)	≈2.5	≈18	≈1200
Slice	≈60 (40)	≈80	≈100
Proj. horizontal (nm)	≈90	≈90	≈180
Proj. vertical (nm)	≈90	≈90	≈90

Lowest emittance for an X-ray FEL measured (to our knowledge)

Courtesy of E. Prat et al. – submitted PRL (accepted)

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Few fixed points

❖ Emittance

- Normalized thermal emittance ~ **550 nm/mm**
- Dependencies with the photon injector parameters measured
- Design optimization + low thermal emittance → **high brightness** injector
- Systematically correct for the coupling (quad and skew quad corrector in the gun solenoid)

❖ Cs_2Te vs Cu photocathode

- Similar thermal emittance, but Cs_2Te semiconductor gives orders of magnitude larger QE
- Better **uniformity** of the **transverse** laser profile
- Cs_2Te acts as a low band pass filter for the laser profile → less **microbunching instability**
  - **Simona is preparing a paper on this topic**
- Also with the very good longitudinal profile and Cs_2Te the stacking configuration does not look promising for FEL

RF jitter and Beam Stability in the SF linac

Proceedings of FEL2019, Hamburg, Germany - Pre-Release Snapshot 29-August-2019 13:00 CEST

RF JITTER AND ELECTRON BEAM STABILITY IN THE SwissFEL LINAC

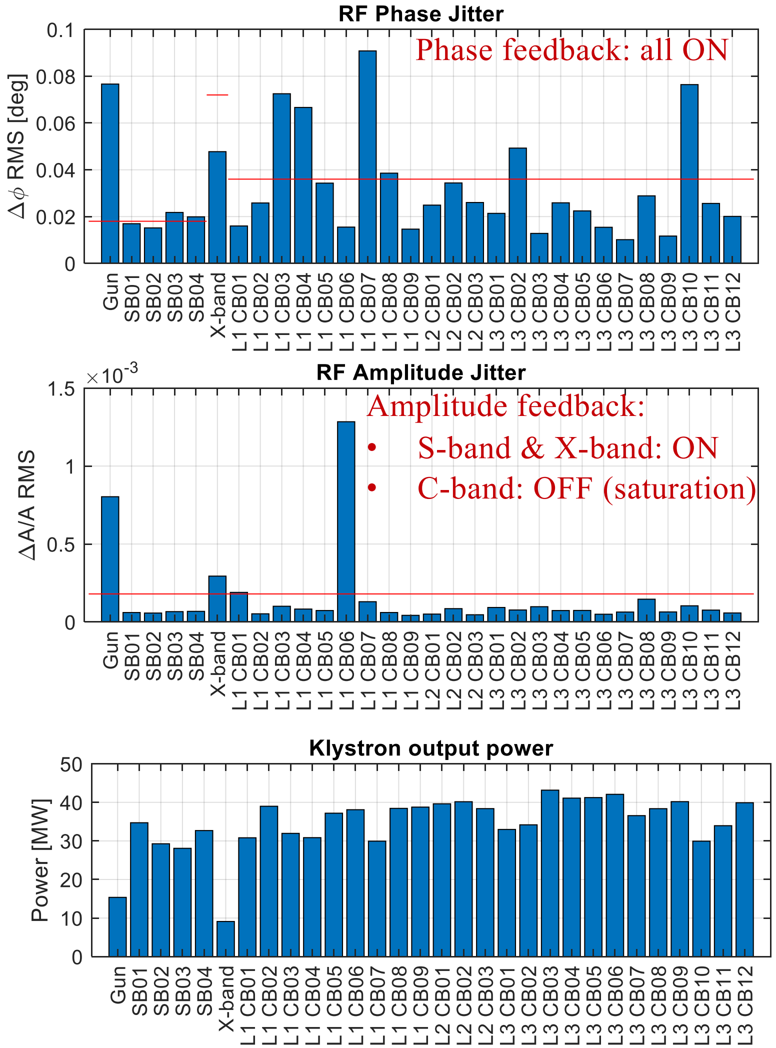
Z. Geng#, P. Craievich, R. Kalt, J. Alex, C. H. Gough, T. Lippuner, M. Pedrozzi, F. Löhl, V. R. Arsov, S. Reiche, E. Prat, Paul Scherrer Institut, Villigen PSI, Switzerland

Aramis beam stability requirements (RMS):

- Peak current (bunch length): < 5 %
- Beam arrival time: < 20 fs
- Beam energy: < 5e-4

RF Station	Phase Tolerance (rms)	Voltage Tolerance (rms)
S-band (2.9988 GHz)	0.018 degS	0.018 %
C-band (5.7120 GHz)	0.036 degC	0.018 %
X-band (11.9952 GHz)	0.072 degX	0.018 %

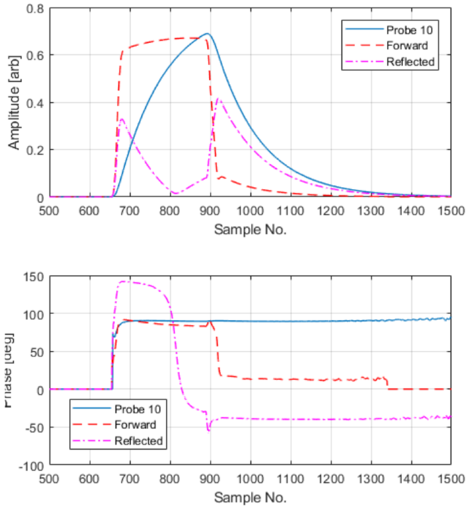
Station Pulse-to-pulse Amplitude and Phase Jitter



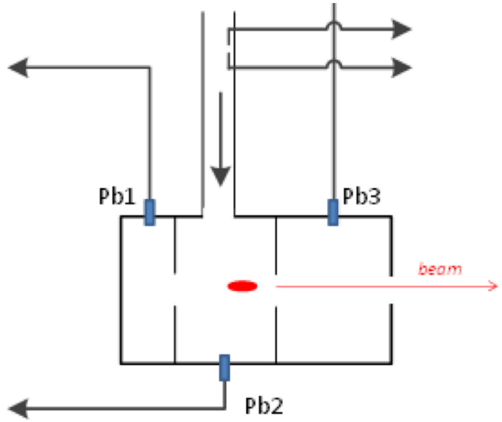
- ❑ RMS jitter is calculated with the 10-min amplitude/phase data with beam (RF rep. rate 100 Hz, statistics with beam rate 25 Hz).
- ❑ Gun measurement problem:
  - Contains high-frequency noise (not averaged in pulse) and other passband mode (π/2-mode): **beam feels less jitter**.
  - *Problematic cavity probes.*
- ❑ Linac1 C-band #6 pre-amplifier failed and resulted in large amplitude drift in open loop operation.
- ❑ Large phase jitter in some C-band stations – BOC and klystron multipacting.

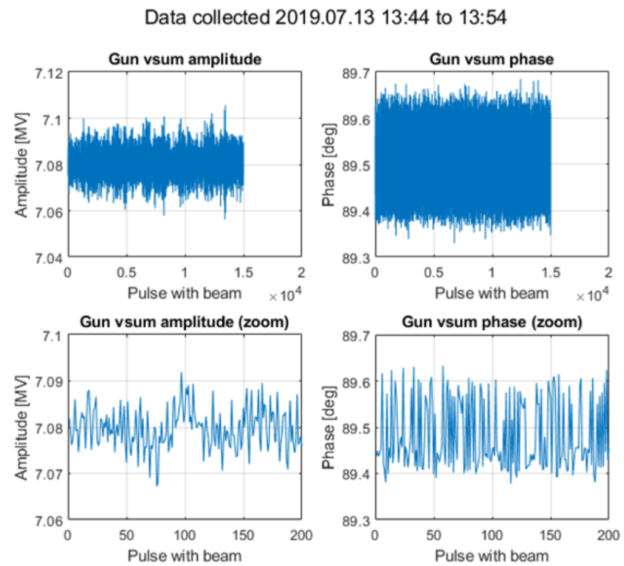
Data collected from SwissFEL at July 13, 2019 13:44–13:54

Example: RF Gun Amplitude and Phase Jitter

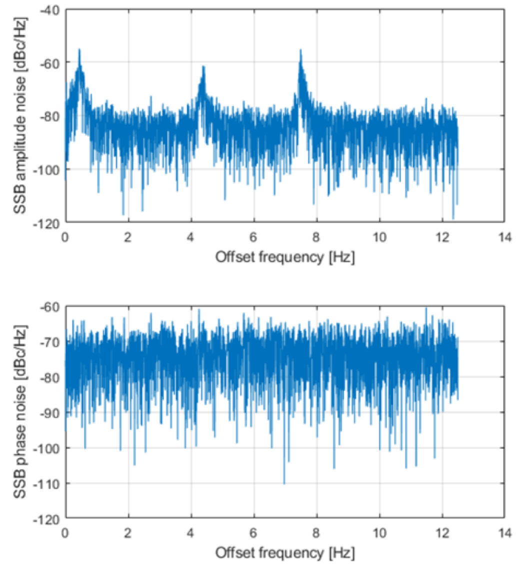


Gun probe, forward and reflected waveforms.





Amplitude and phase pulse-to-pulse data of Gun cavity field (vector sum of probe signals).



Spectrum of amplitude and phase pulse-to-pulse data.

Possible sources of resonant peaks:

- ❑ Cavity probe is sensitive to the mechanical vibration major caused by cooling water flows.
- ❑ Pass-band mode signal aliased back to the Nyquist band of beam repetition rate (25 Hz).

Courtesy of Q. Geng

Improvement of RF Gun Field Measurement

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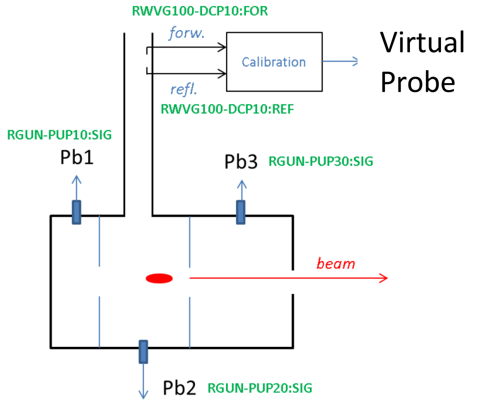
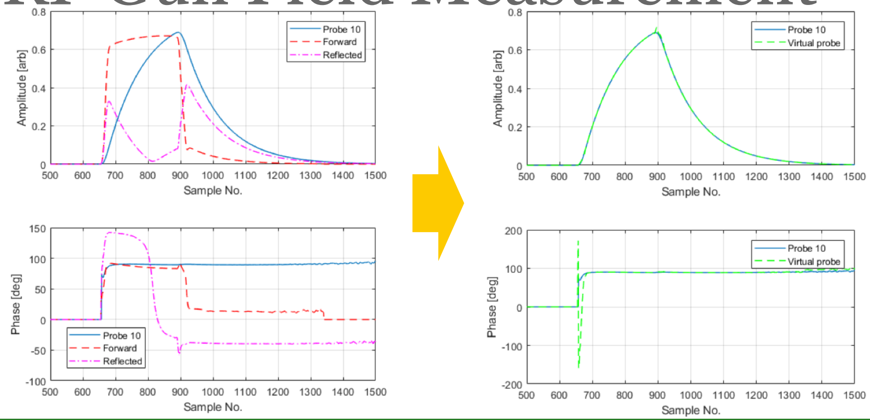
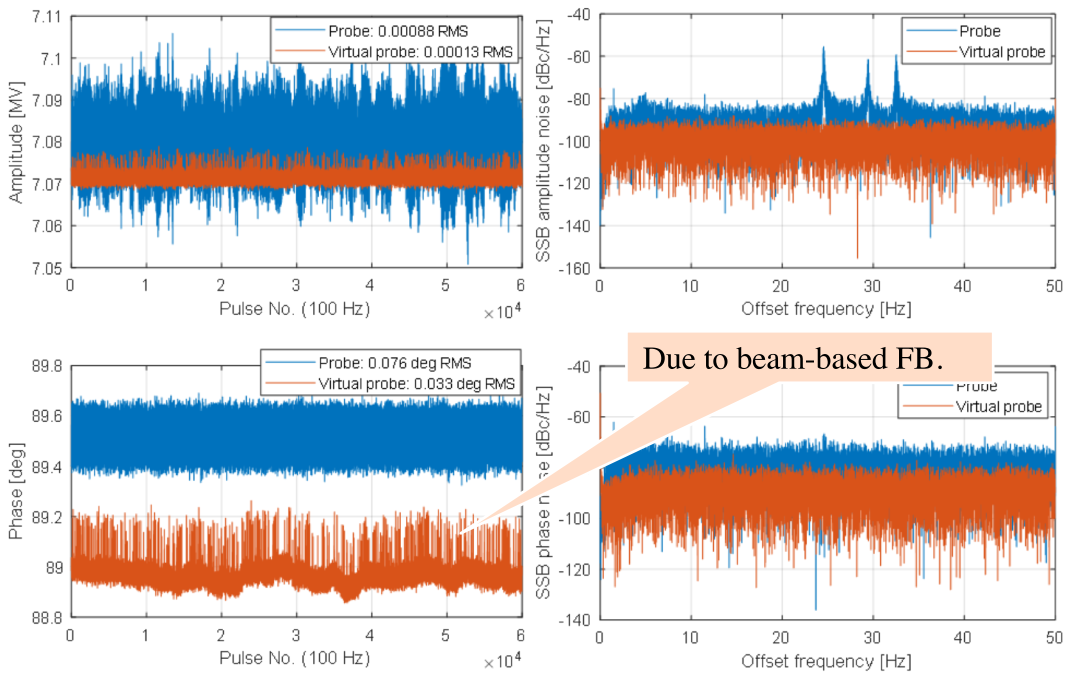
Use virtual probe to replace the probe signal.







Construction of virtual probe:

Vector sum of measured forward and reflected signals:

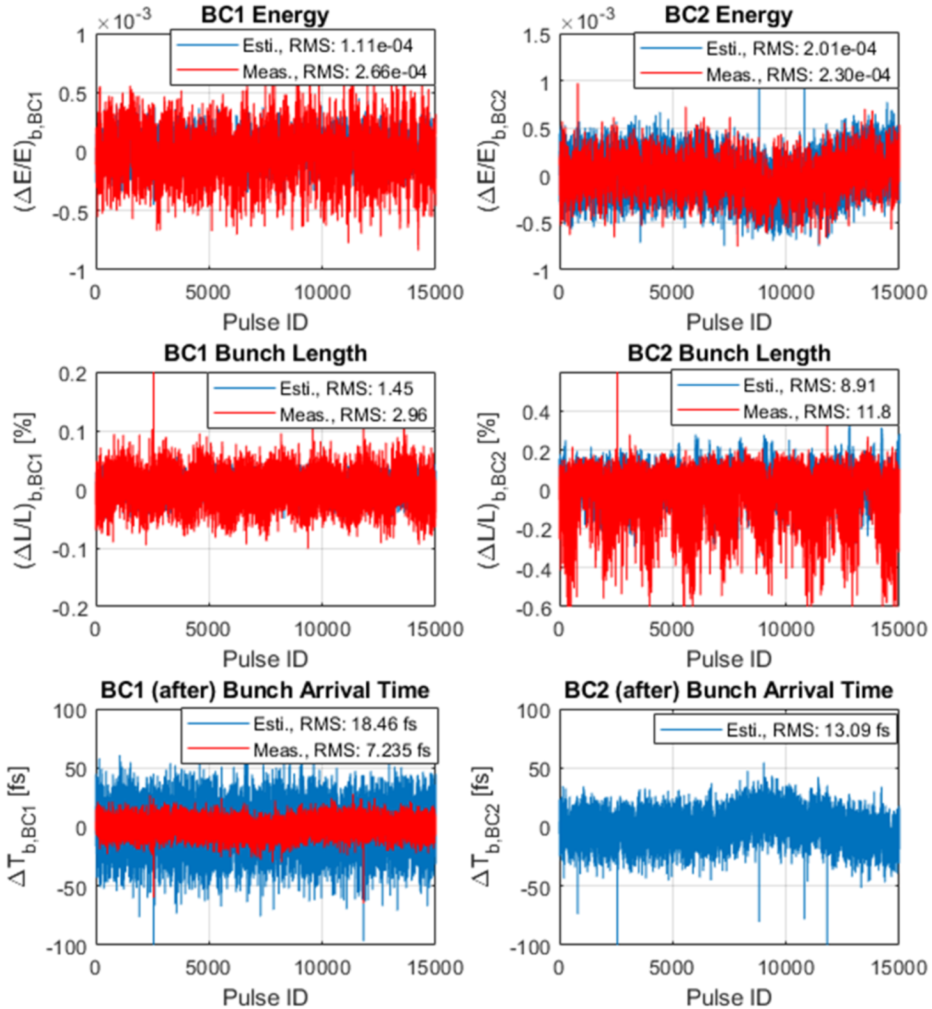
$$\left.\begin{aligned} \mathbf{v}_{for} &= \mathbf{a}\mathbf{v}_{for,mea} + \mathbf{b}\mathbf{v}_{ref,mea} \\ \mathbf{v}_{ref} &= \mathbf{c}\mathbf{v}_{for,mea} + \mathbf{d}\mathbf{v}_{ref,mea} \end{aligned}\right\} \Rightarrow$$

$$\boxed{\begin{aligned} &\mathbf{v}_{probe} = \mathbf{v}_{for} + \mathbf{v}_{ref} = \mathbf{m}\mathbf{v}_{for,mea} + \mathbf{n}\mathbf{v}_{ref,mea} \\ &(\mathbf{m} = \mathbf{a} + \mathbf{c},\ \mathbf{n} = \mathbf{b} + \mathbf{d}) \end{aligned}}$$

Calibration of m and n:

Linear fitting with the "Pb1" and measured forward and reflected signals.

Estimation and Measurement of Beam Jitters



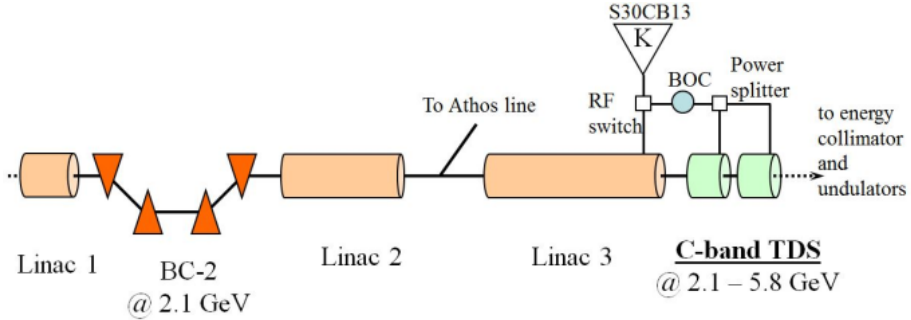
- Beam jitters can be predicted from RF measurements via the response matrix and directly measured with beam diagnostics.
- When collecting data, all longitudinal feedbacks **OFF**.

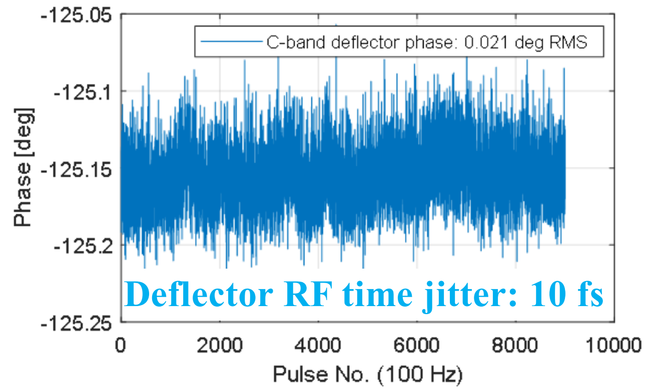
At BC2 Exit:

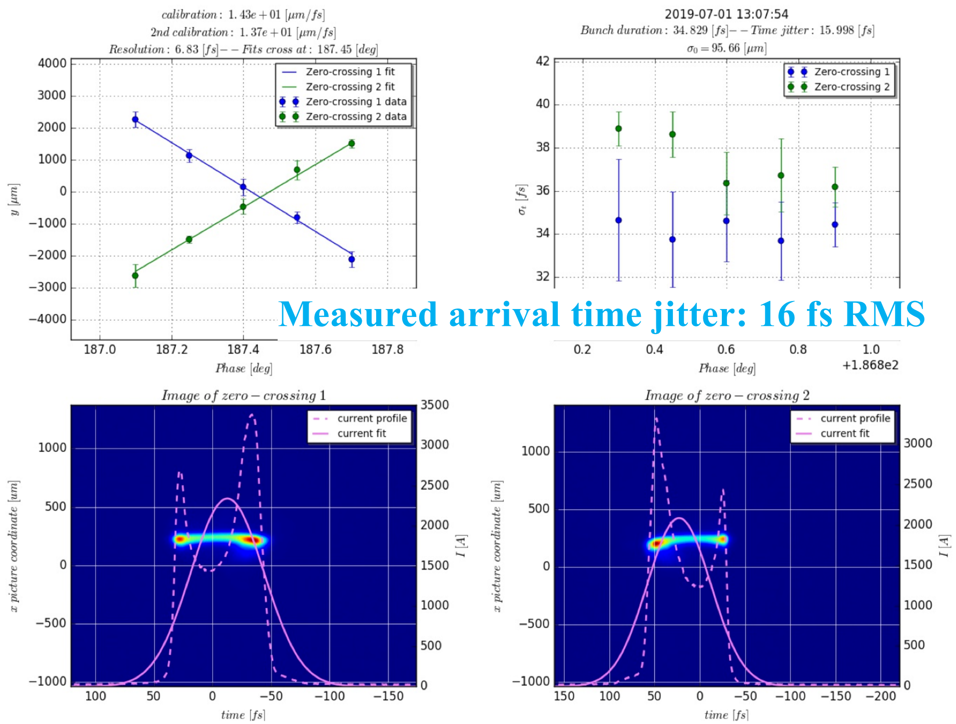
- Measured beam energy jitter: 2.3e-4 RMS (goal: 5e-4)
- Measured bunch length jitter: 11.8 % RMS (goal: 5%)
- Measured arrival time jitter (see next page): 13 fs RMS (goal: 20 fs)

Data collected from SwissFEL at July 13, 2019 13:44–13:54

Bunch Arrival Time Mea. with C-band Deflector







Measured arrival time jitter: 16 fs RMS

Estimated actual bunch arrival time at the end of Linac 3 of SwissFEL:

$$t_{b,RMS} = \sqrt{16^2 - 10^2} \approx 13 \text{ fs}$$

BC2 bunch-length jitter:RF-beam Jitter Correlation

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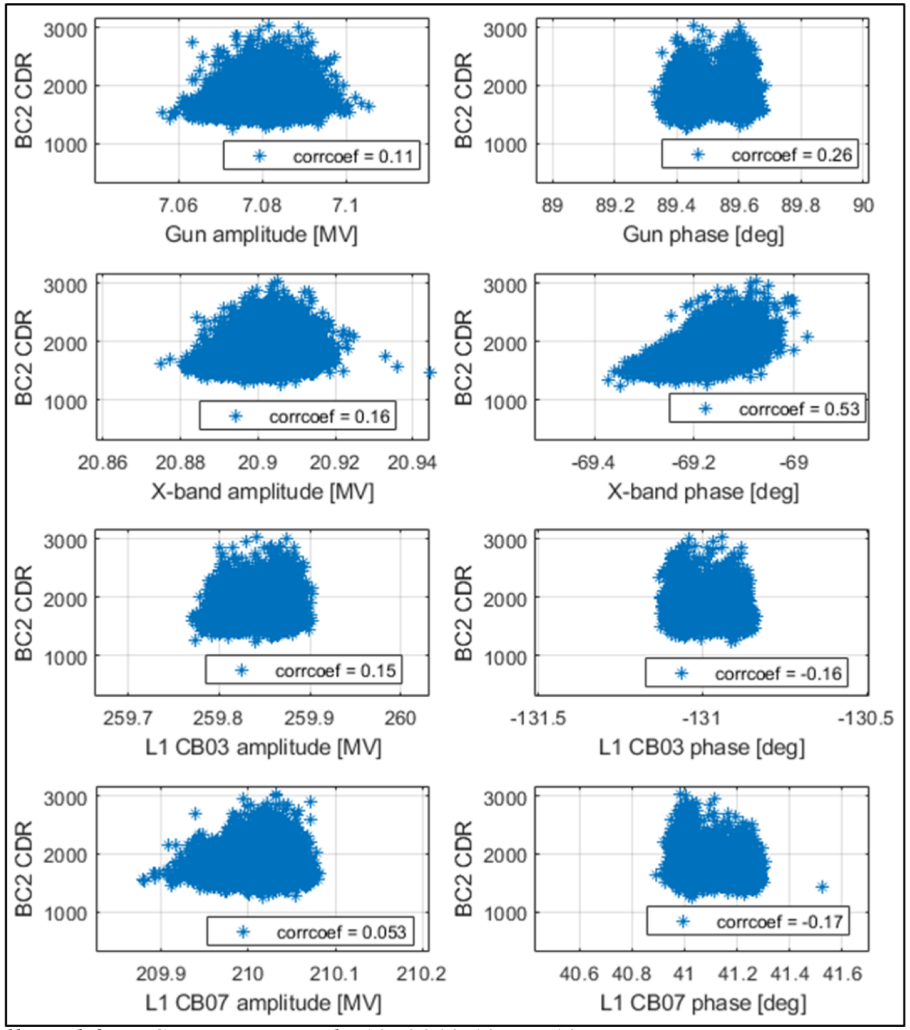
Correlation between bunch length jitter measured with CDR (BCM) and jitter sources.



Data collected from SwissFEL at July 13, 2019 13:44–13:54

- The correlation strength shows the potential RF stations that have large jitter and require improvements.
- Conclusion from the correlation on right side:
  - *RF Gun stability need improvement;*
  - X-band stability needs special focus – need to be improved even better than the original stability specification in CDR;
  - Linac 1 C-band phase stability (mainly due to BOC multipacting) needs improvement.

RF jitter and Beam Stability (comments)

Summary :

- SwissFEL RF system has reached its nominal working point: 5.8 GeV energy gain @ 100 Hz. Linac3 can provide 2 spare RF stations in hot-standby.
- Most RF stations satisfy the stability requirements*. Improvements are needed for the RF Gun, X-band* and several Linac 1 C-band stations. The X-band phase jitter is one of the major sources for the bunch length jitter and a tighter stability requirement should be applied.

Outlook for Future:

- Stability improvement:
    - Improve the X-band stability by improving the pre-amplifier (already replaced) and modulator;
    - Understand and mitigate the phase jitter synchronous to beam (e.g. Linac1 #7);
    - Mitigate all the C-band stations with BOC multipacting.
    - Evaluate the drifts in RF reference distribution system and LLRF system.

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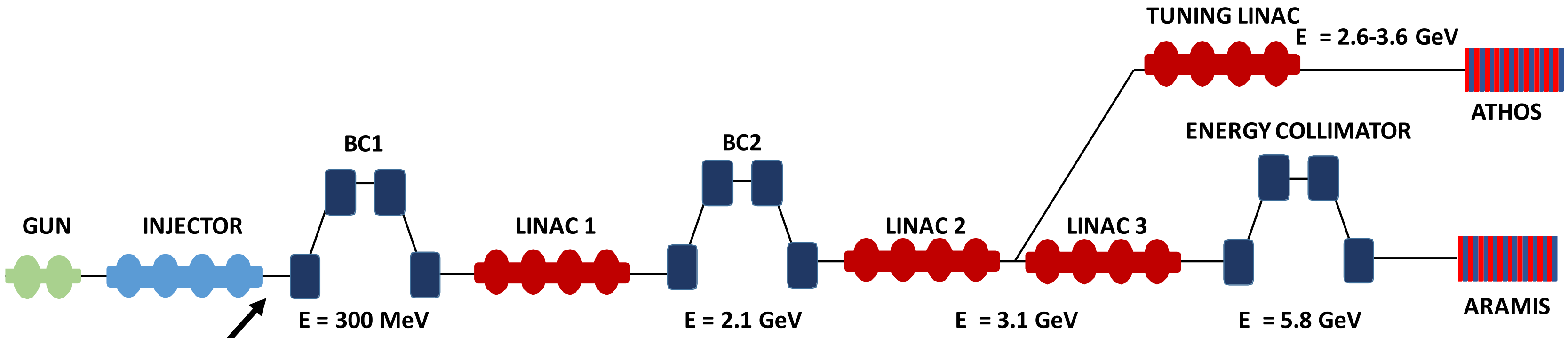
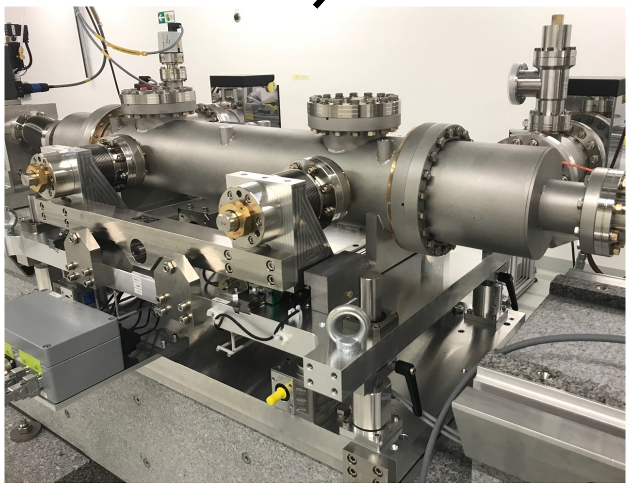
Beam manipulation using passive devices i.e. linearization in BC1

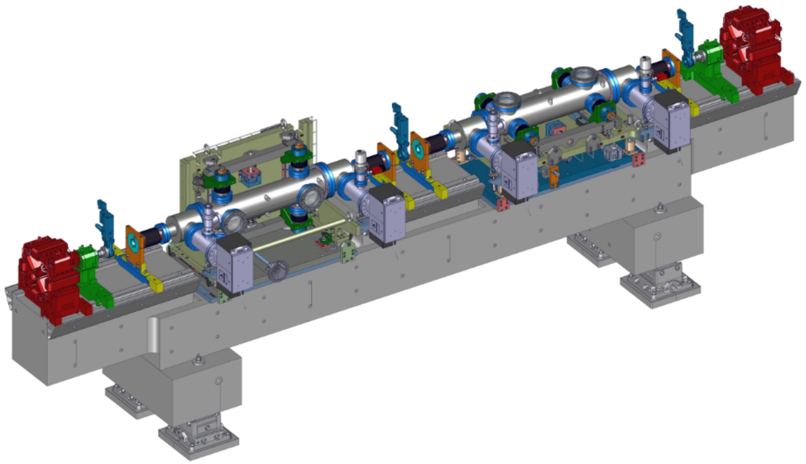
Just one comment on the X-band active system for the linearization: we are using two 70-cm long X-band structures in order to limit the RF from the klystron (~10 MW)

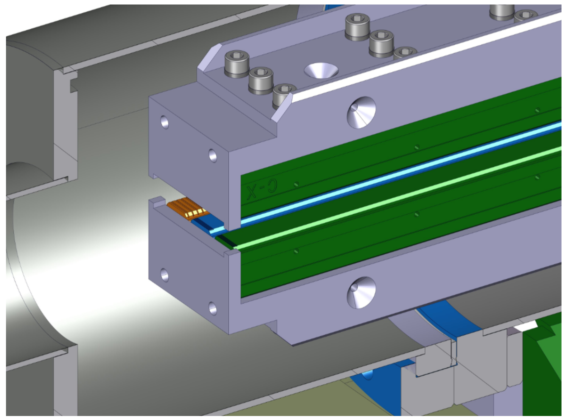
Beam manipulation using passive devices



3 different metallic corrugation: dechirper, linearizer, 2-color generation







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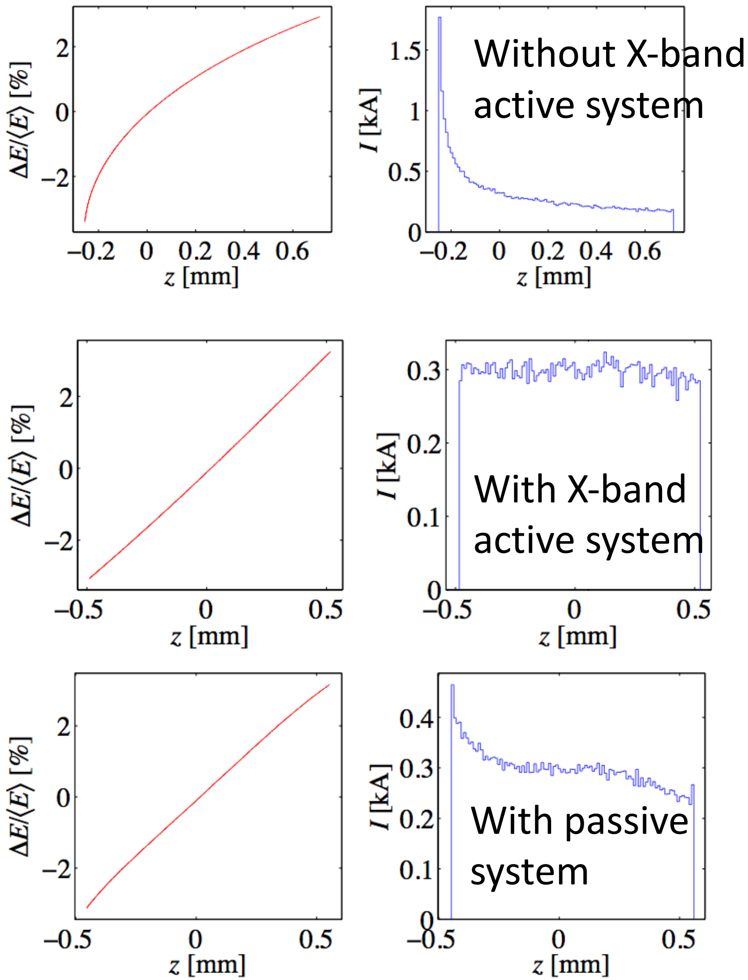
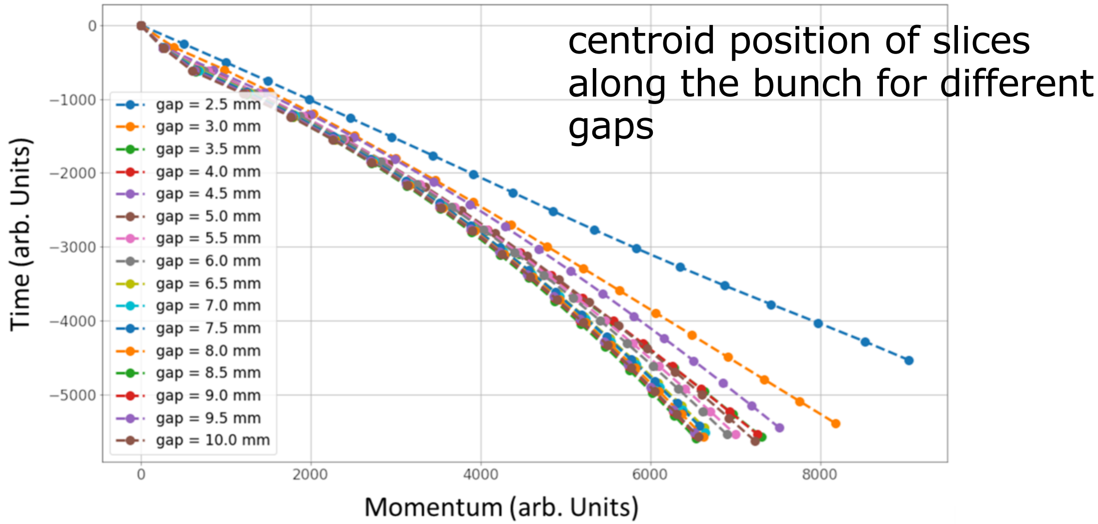
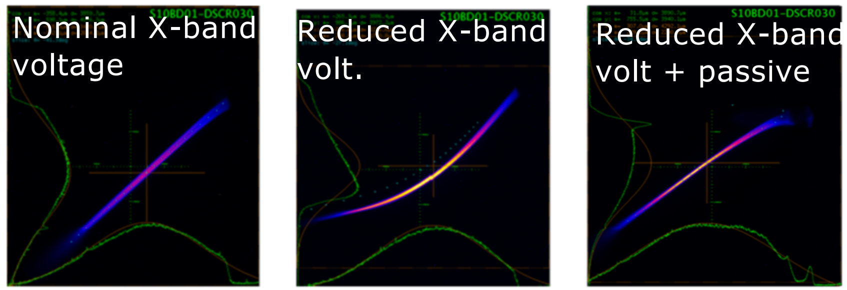
Beam manipulation: linearization



Measured beam longitudinal phase space



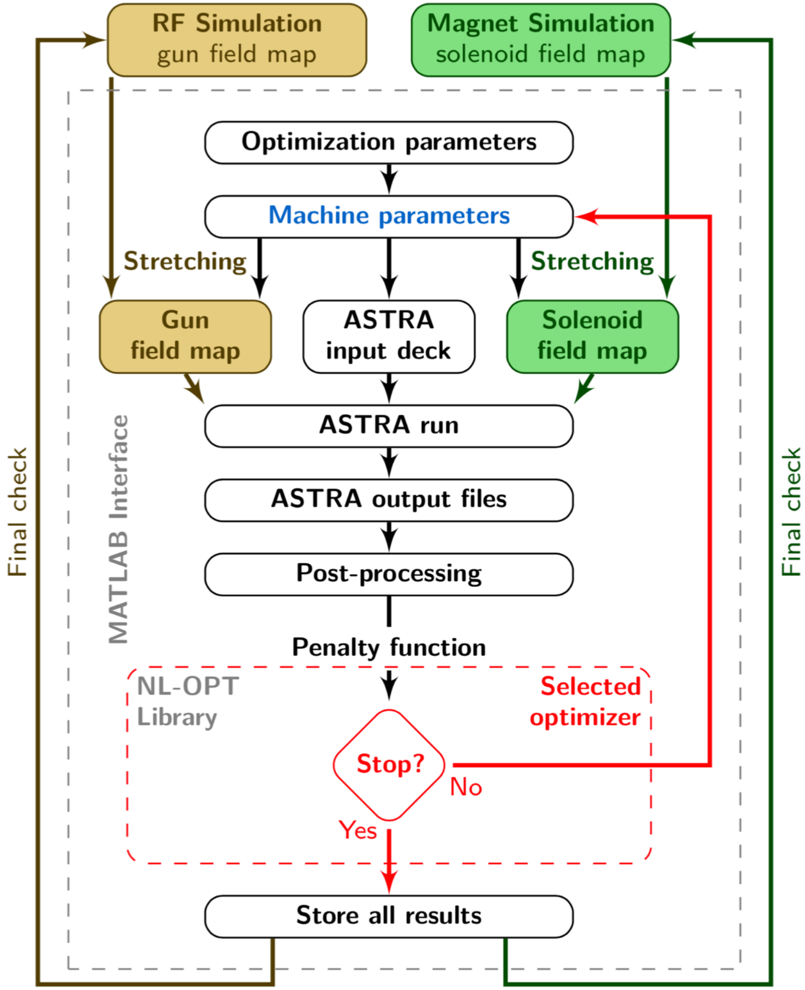


Passive structures at gap = 2.5 mm

S. Bettoni et al., IPAC 2019, MOPGW07

What’s next at SwissFEL injector?
i.e. SwissFEL Electron Source: Margins of Improvement?

Injector Optimization: Combining RF and Beam Dynamic



Penalty function

$$f_p(\bar{B}_n, \bar{\zeta}) \equiv -C_1\left(\bar{B}_n - \bar{B}_{n,0}\right) + C_2\left(\bar{\zeta} - \bar{\zeta}_{off}\right)$$

Brightness $B_n \equiv \dfrac{I_{peak}}{\varepsilon_{x,n} \cdot \varepsilon_{y,n}}$

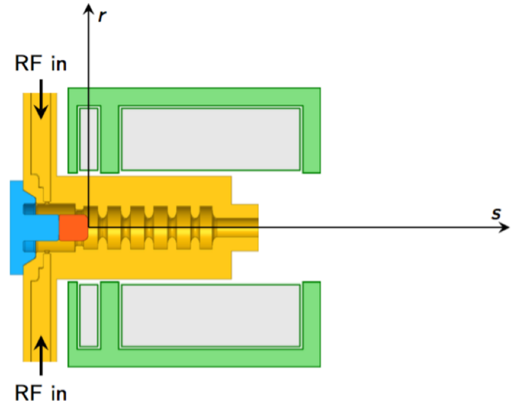
Parameters to optimize

- Machine operation
  - Laser pulse length
  - Laser transverse size
  - Gun phase
  - Gun solenoid field strength
  - First booster position
  - First booster gradient
  - ...
- RF and Magnet design
  - First cell length
  - Regular cell length
  - Last cell length

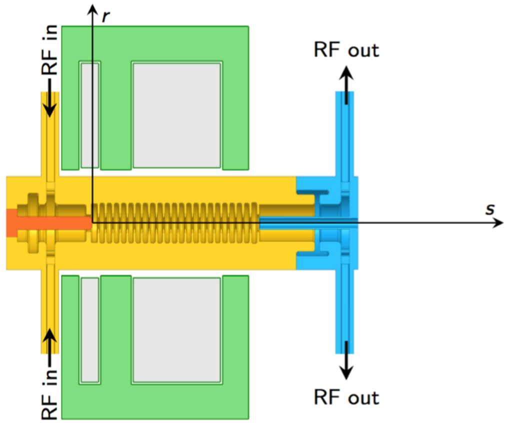
M. Schaer et al, PR AB 19, 072001 (2016)

What's next? RF Travelling-Wave Electron Gun

- Motivation: exploring new designs of electron source at C-band frequency that could represent a future upgrade of the SwissFEL injector.
- Approach: higher electric field at cathode with shorter RF pulses



Setup		SwissFEL Gun 1 reference	C-Band SW Gun	C-Band TW Gun 60°	120°
E_{kin}	[MeV]	6.6	9.8	12.0	12.7
I_{peak}	[A]	20	41	48	41
$\varepsilon_{x,n}$	[μm]	0.21	0.22	0.21	0.22
$\bar{\varepsilon}_{x,n}$	[μm]	0.14	0.17	0.13	0.15
$\bar{\zeta}$		1.14	1.03	1.13	1.09
B_n	[TA/m^2]	450	850	1050	870
$\bar{B}_n$	[TA/m^2]	965	1480	2940	1840
f_p		−1	−1.5	−2.0	−1.4



- Brightness a **factor 3** higher than the SwissFEL
- Peak current a **factor 2** higher than SwissFEL gun
- Very conservative value of the field at cathode (**135 MV/m** with a filling time **< 100 ns**)
- With 200 MV/m → Brightness 3870 (TA/m2) (**factor 4 higher**)

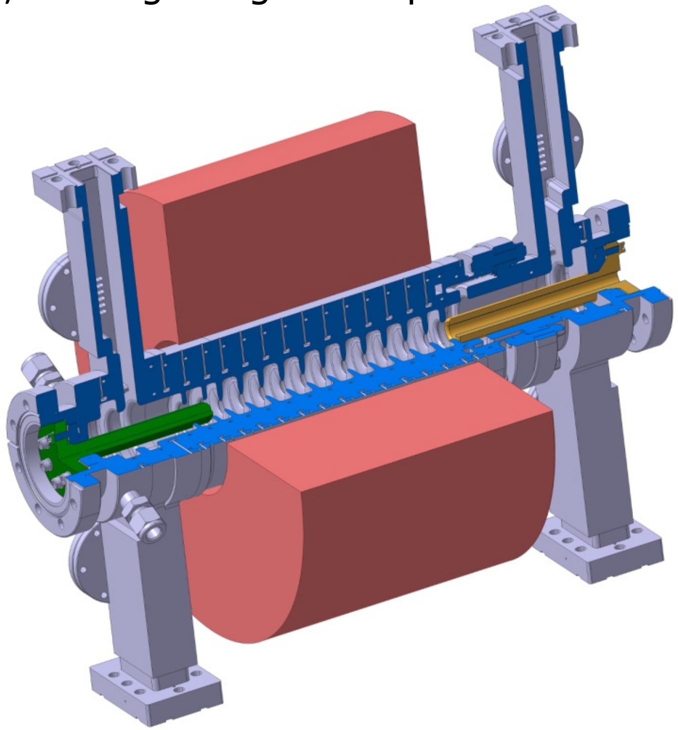
M. Schaer et al, PR AB 19, 072001 (2016)

C-band RF Travelling-Wave Electron Gun

An innovative coaxial RF coupling from the cathode side enables

- the placement of the focusing solenoid around the cathode with a simplified magnet design that integrates main and bucking coil
- the elimination of the quadrupole components of the RF fields in the region where the beam is accelerated
- the introduction of gaps with vanishing RF fields, making the gun compatible with the load-lock system without the need of special RF contacts

C-band TW Gun	
Frequency	5.712 GHz
Phase advance per cell	60 deg/120 deg
# cells	21/10
Structure length	215/220 mm
Q	4700/10000
Filling time	73/90 ns
Iris radius	5.5 mm
Group velocity	0.95/079 % of [c]
Nominal gradient	135 MV/m
Nominal power	57.9/37.4 MW
Repetition rate	100 Hz



M. Schaer et al., PR AB 19, 072001 (2016).

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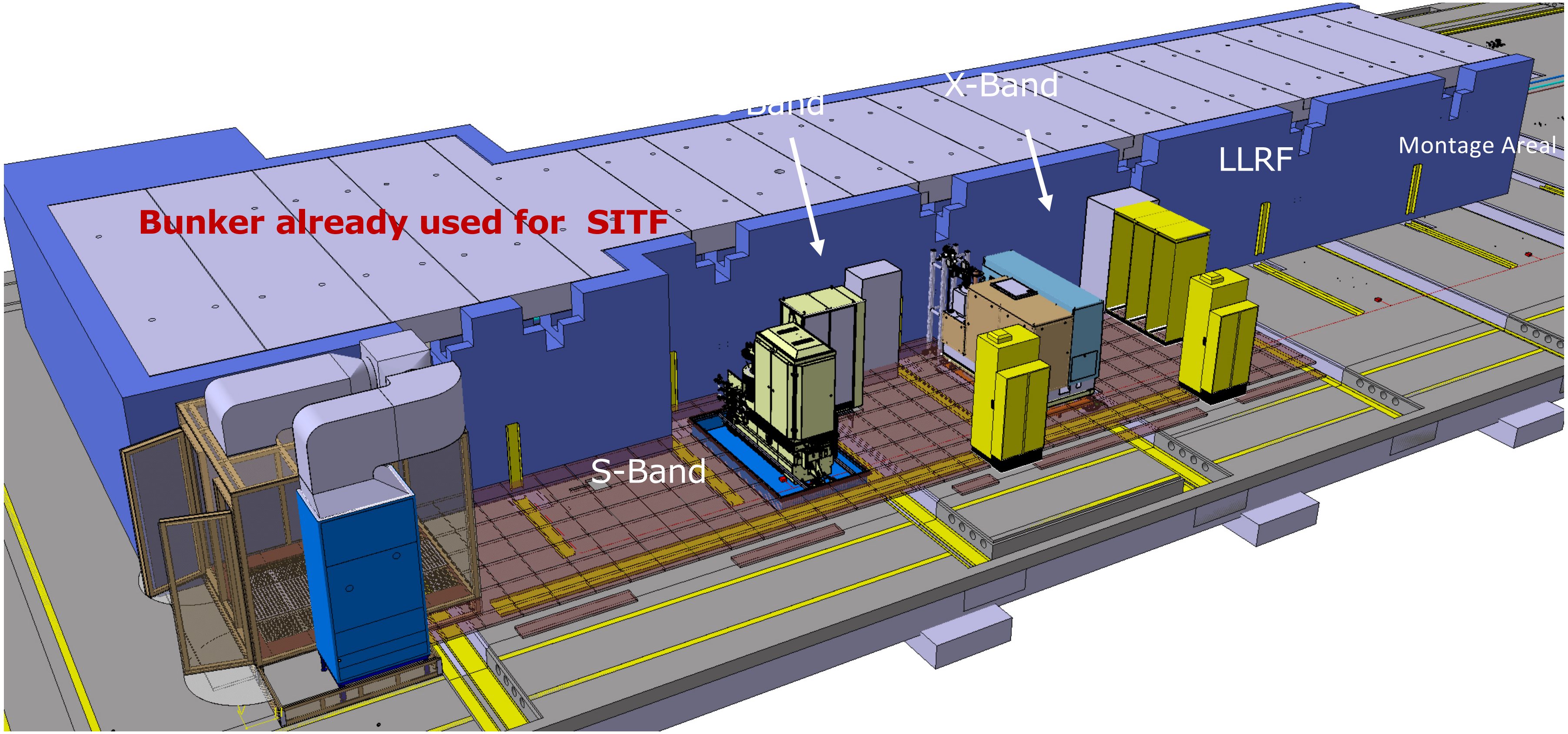
WLHA: RF test facility for SwissFEL upgrade



Wir schaffen Wissen – heute für morgen