Current status of the optimization of the SRF photo injector for the CW European XFEL

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MPY

DESY SRF R&D & DESY and University of Hamburg Accelerator Physics Seminar
16.12.20

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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- DESY L-band SRF gun
- CW EuXFEL injector
- Optimization algorithm
- Injector optimization
- Discussion and outlook

Acknowledgements

• Colleagues who are involved from DESY beam dynamics group, E. Vogel, A. Sulimov, J. Sekutowicz, H. Qian, X. Li

Motivation and goals

- Evaluate the performance of the CW EuXFEL injector based on the DESY SRF CW L-band gun in terms of beam dynamics
- Optimization of the CW injector for two objective functions: transverse emittance and longitudinal size of the beam (i.e. peak current)
- Evaluate initial working points for the CW injector
- Generate various bunch profiles for further s2e simulations (Ye Chen, Martin Dohlus)
- …and more

CW RF photo injectors

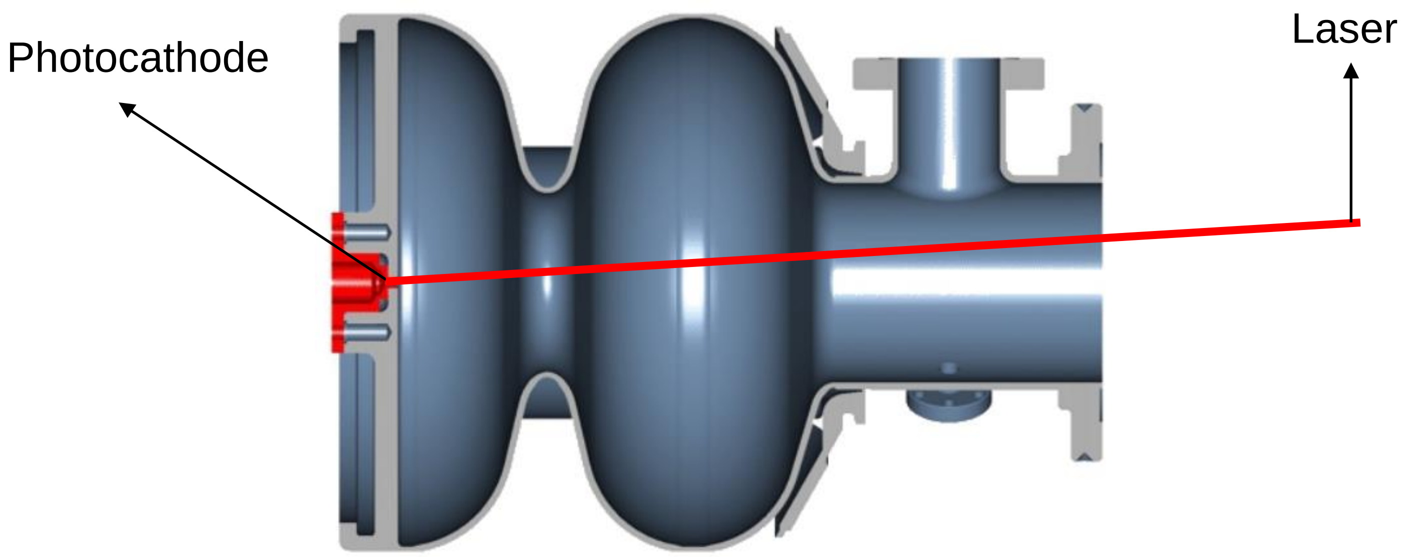
Superconducting and normal conducting RF guns

CW RF photo injectors

RF gun for the FEL

- RF gun is the core part of a photo injector
- Beam quality from the gun defines overall performance of the FEL machine
- Gun should produce short bunches with small slice emittance
- High peak electric field at the cathode required
- Gun must be stable in operation to provide reliable beam time to X-ray users

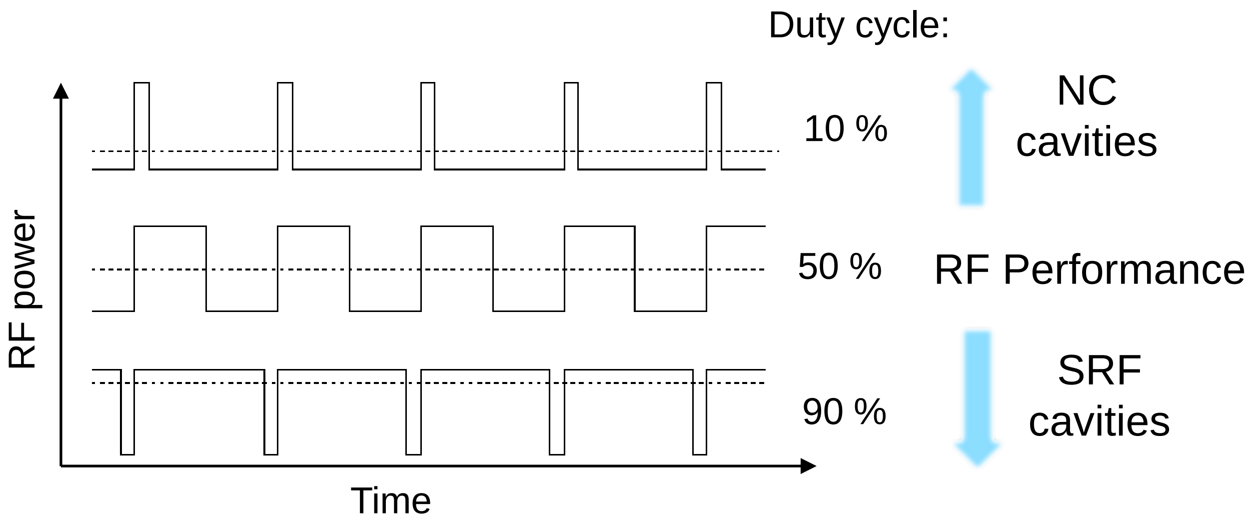
DESY L-band SRF gun:



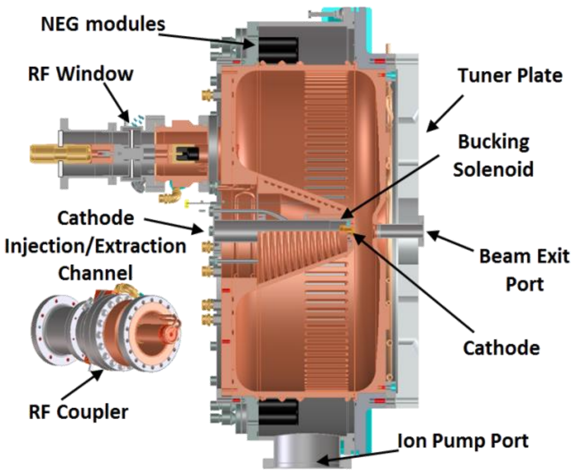
RF photo injectors

Why SRF gun in CW for FEL?

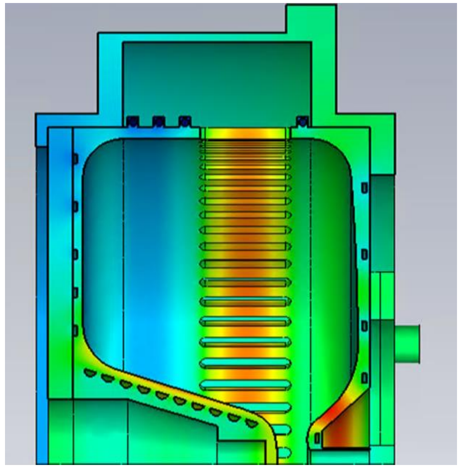
- **Normal conducting RF cavities** (as well as RF guns) perform best in the pulsed regime (i.e. low duty cycle) – up to **60 % of the RF power absorbed in the cavity walls**
- *Normal conducting CW RF guns* are based on the Quarter Wave Cavity (QWR) (f = 100-250 MHz) – **state-of-the-art technology** requires RF buncher and additional focusing solenoid; produces low energy beam with acceptable transverse slice emittance for FEL applications in CW
- Full advantage of **superconducting cavities** is taken in the CW regime or very long pulse regime due to **very low RF losses**
- <u>Superconducting guns have the largest potential to produce the brightest beams due to the highest gradients achievable</u>



LBNL (185.7 MHz)



DESY (216.7 MHz) – backup solution for CW EuXFEL

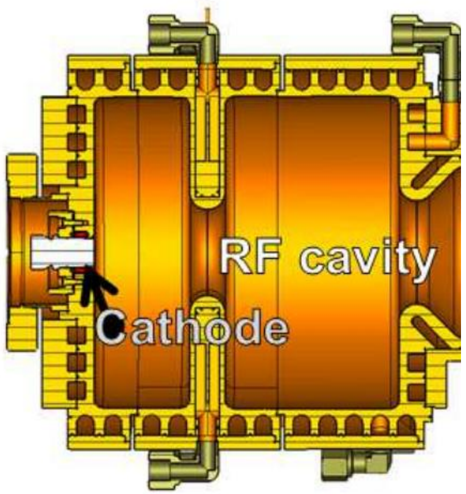


RF photo injectors

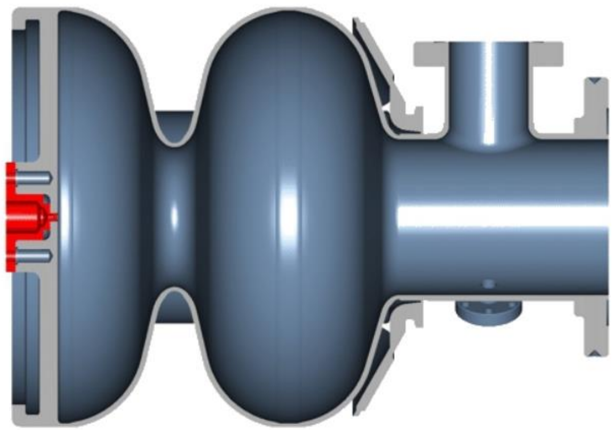
DESY SRF gun in CW mode

- L-band SRF gun with the peak electric field comparable to the pulsed NC gun can produce similar or better beam quality in CW regime

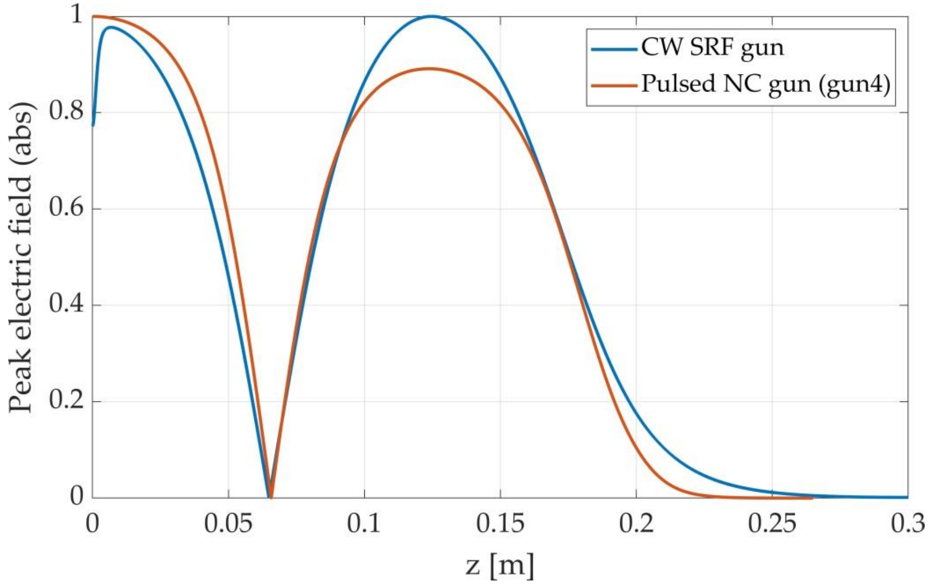
1.3 GHz **nc** DESY **pulsed** RF gun:



1.3 GHz **CW** DESY **SRF** RF gun:



Electric field on axis:



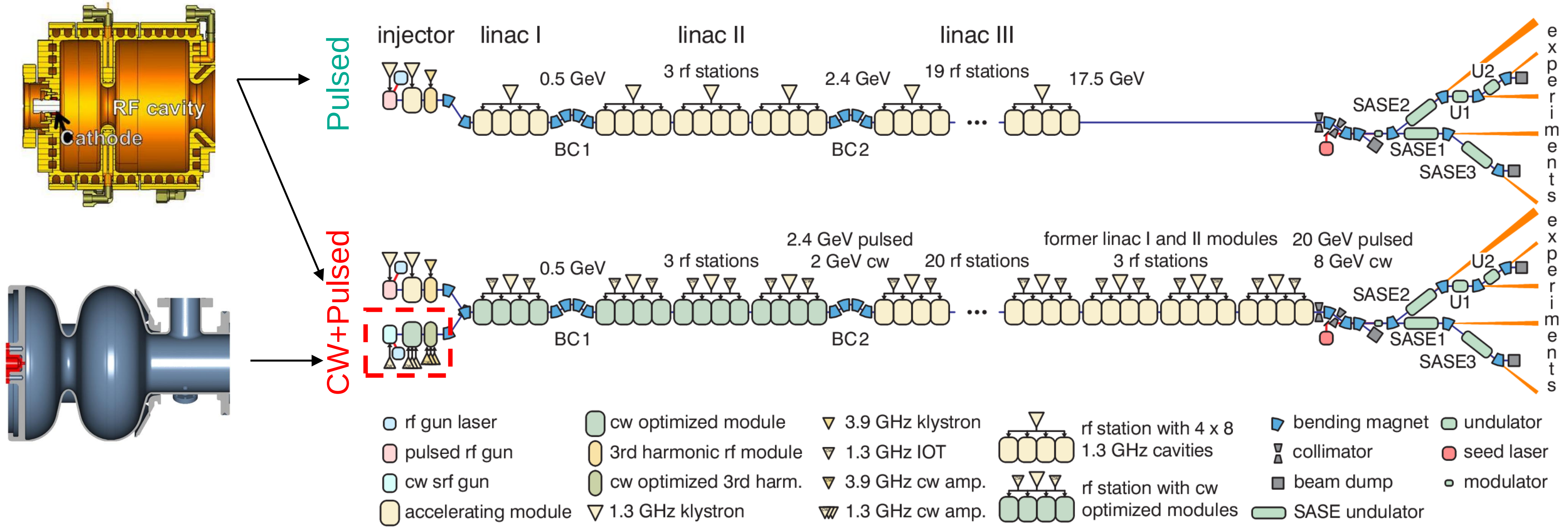
CW EuXFEL

General facts

CW EuXFEL

General facts and foreseen layout

- Continuous wave operation:
  - Accelerating gradient of 16 MV/m in the injector
  - 7-8 MV/m in the L3
  - L3 will be extended by 12 CMs to 96 total
- For the long pulse operation the gradient in the L3 can be increased to 12 MV/m



Prospects for CW and LP operation of the European XFEL in hard X-ray regime, R. Brinkmann, E. A. Schneidmiller, J. Sekutowicz, M. V. Yurkov

DESY L-band SRF gun

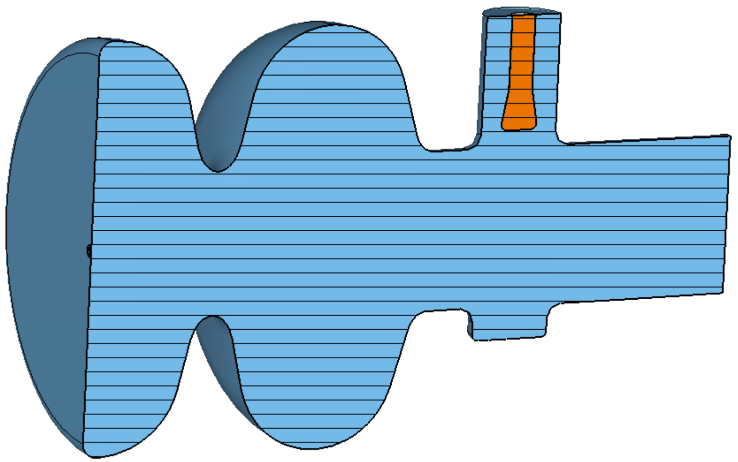
General facts, RF shape, peak fields, cathode

DESY L-band SRF gun

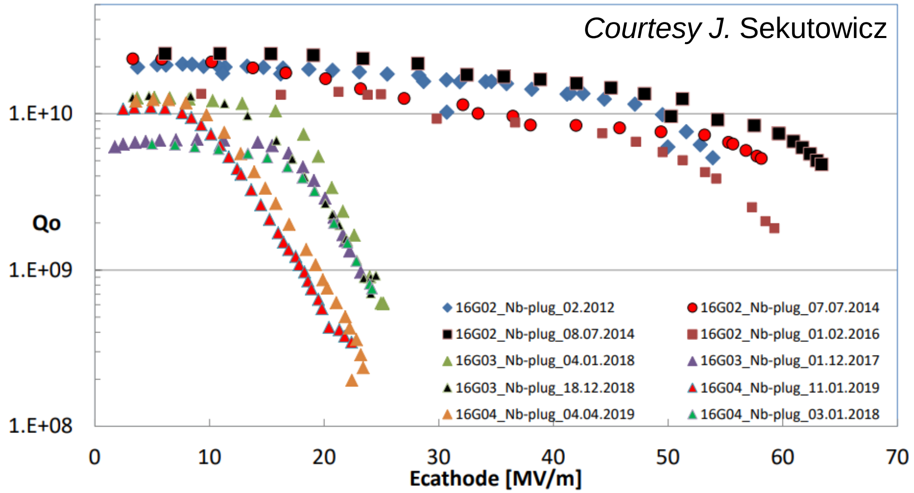
General information

- Idea suggested in 2005*: keep everything as simple as possible
- 1.6-cell TESLA cavity operated at T = 2 K
- Operating frequency 1.3 GHz
- Current gun version – 10
- Experimentally demonstrated possibility of achieving peak electric field of 60 MV/m; 40 MV/m – repetitively
- G09;10 are being prepared for manufacturing

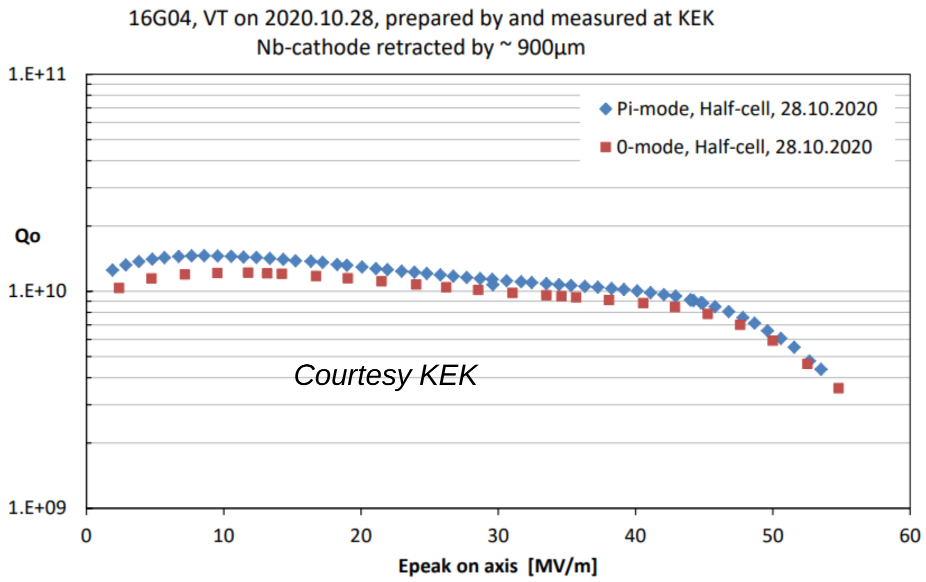
RF shape of the gun n.10:



Q vs E:



Q vs E:



*) SUPERCONDUCTING RF PHOTOINJECTORS; AN OVERVIEW, J.K. Sekutowicz, Proceed. Workshop on "The Physics and Applications of High Brightness Electron Beams", October 9-14,

DESY L-band SRF gun

Limit of peak electric field

- Empirical limit for Nb cavity:
  - Magnetic field on the inner surface of 200 mT – thermal breakdown
- Peak fields for DESY L-band SRF gun:

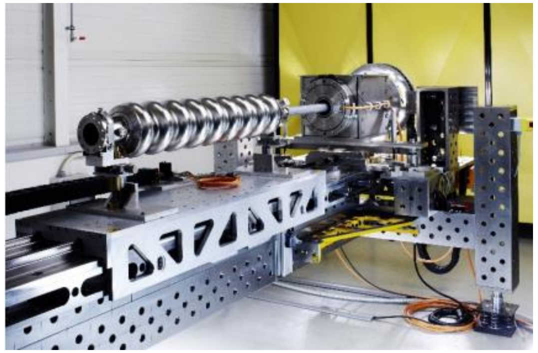
Electric field on axis [MV/m]	40	50	60
Magnetic field on the surface [mT]	99	123	147

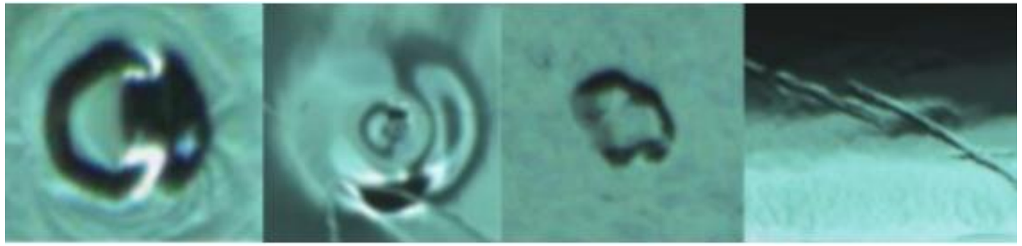
- In 1980s the limit was 3 MV/m – multipacting (technological limitation)
- Currently: mostly field emission, dark current
- Laboratories and institutes are working on various techniques related to surface treatment in order to increase the gradient while maintaining high Q-factor (e.g. A. Grassellino, A. Romanenko @ FNAL)

- Quality of the inside surface of the SRF cavity defines its performance
- Very small defects and imperfections of the inside surface of the SRF cavities can be present

OBACHT (DESY):

(*)





**) D. Bazyl, SRF cavity surface inspection methods, summer student report at DESY - 2014*

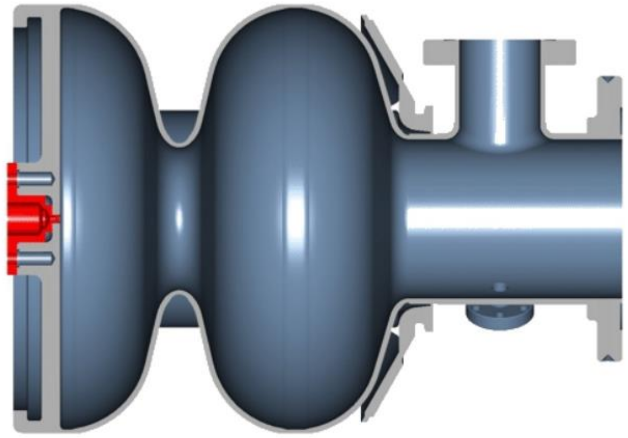
DESY L-band SRF gun

Cathode type

<u>Metallic cathode </u>(sc Pb)

+ Robust
+ Superconducting
+ Long **life time**
- Low QE
- Potentially increased thermal emittance
- High work function (UV light)
- Cathode exchange

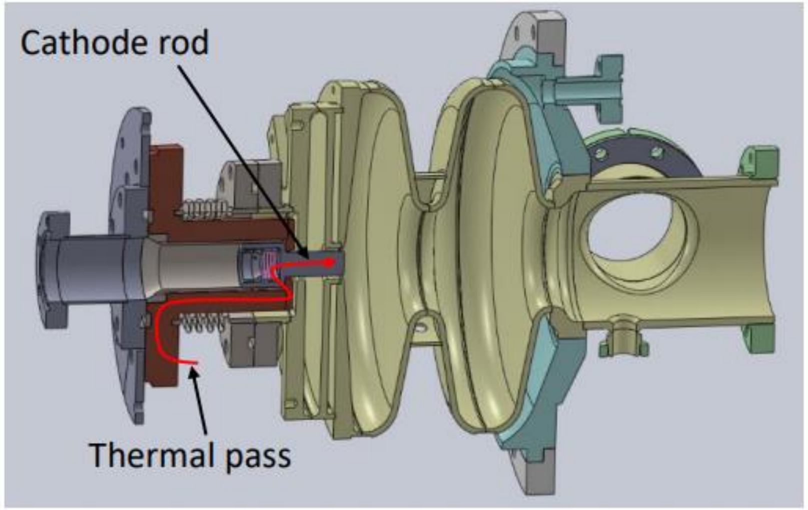
DESY SRF GUN:



Semi-conductor cathodes (e.g. CsK2Sb)

+ High QE
+ **Life time** up to two months demonstrated
+ Lower **thermal emittance**
- Potential deposit of cathode material to the cavity
- Complicated insertion
- Sensitive to vacuum quality

KEK (Japan) SRF GUN*:



*) T. Konomi et.,al. *DEVELOPMENT OF HIGH INTENSITY, HIGH BRIGHTNESS, CW SRF GUN WITH Bi-ALKALI PHOTOCATHODE*

DESY L-band SRF gun

Thermal emittance of the lead cathode

- Superconducting lead cathode
- Several sources reported data concerning QE and thermal emittance

TABLE I: Available data of lead photocathodes and estimations. (*)

	$\hbar\omega$	Φ	QE	σ_x	$\epsilon_n{}^a$
	eV	eV	-	mm	μm
193 nm[b]	6.42	3.88	5.41E-3	0.25	0.322
213 nm[c]	5.82	3.88	2.72E-3	0.25	0.281
258 nm[d]	4.81	4.45	0.90E-4	0.25	0.121
258 nm[e]	4.81	4.37	0.95E-4	0.25	0.134

[b]BNL, tests on samples, no typical cavity treatments, 1 MV/m.
[c]BNL, tests on samples, no typical cavity treatments, 1 MV/m.
[d]HZB, realistic SRF cavity environment, no Schottky.
[e]HZB, realistic SRF cavity environment, a Schottky reduction of 0.08 eV for ~4.8 MV/m.

Thermal emittance:

$$\varepsilon_{x,y} = \sigma_{x,y}\sqrt{\frac{E_{phot} - \phi_{eff}}{3m_0c^2}}$$

or

$$\varepsilon_{x,y} = \sigma_{x,y}\frac{1}{\sqrt{3}}\sqrt{\frac{2E_{kin}}{m_0c^2}}$$

[1] David H. Dowell and John F. Schmerge, Phys. Rev. Accel. Beams **12**, 074201 (2009).
[2] J. Smedley, T. Rao, J. Sekutowicz, Phys. Rev. Accel. Beams **11**, 013502 (2008).
[3] R. Barday, A. Burrill, A. Jankowiak et al., Phys. Rev. Accel. Beams **16**, 123402 (2013).

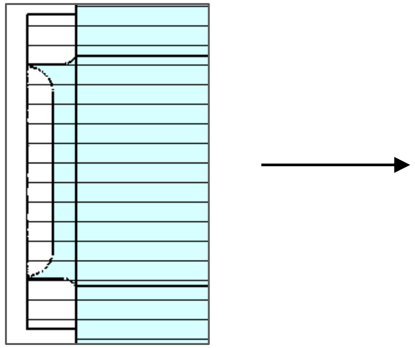
*) *A note on intrinsic emittance for lead photocathodes by Ye Chen on 7.9.2020*

DESY L-band SRF gun

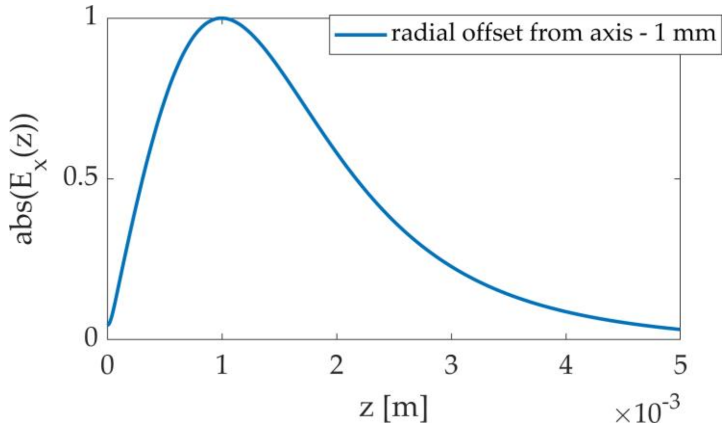
EM field calculation, retracted cathode

- CST MWS for field calculation
- **No coupler**
- Mesh noise close to the cathode can affect beam dynamics simulation

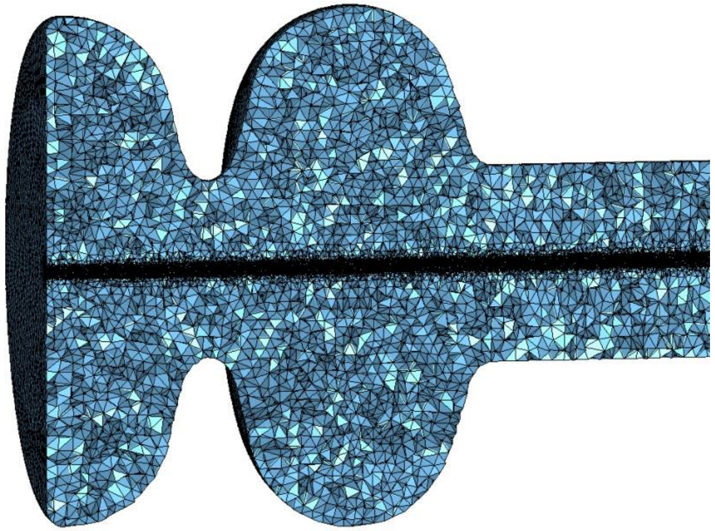
Retracted cathode (450 µm):



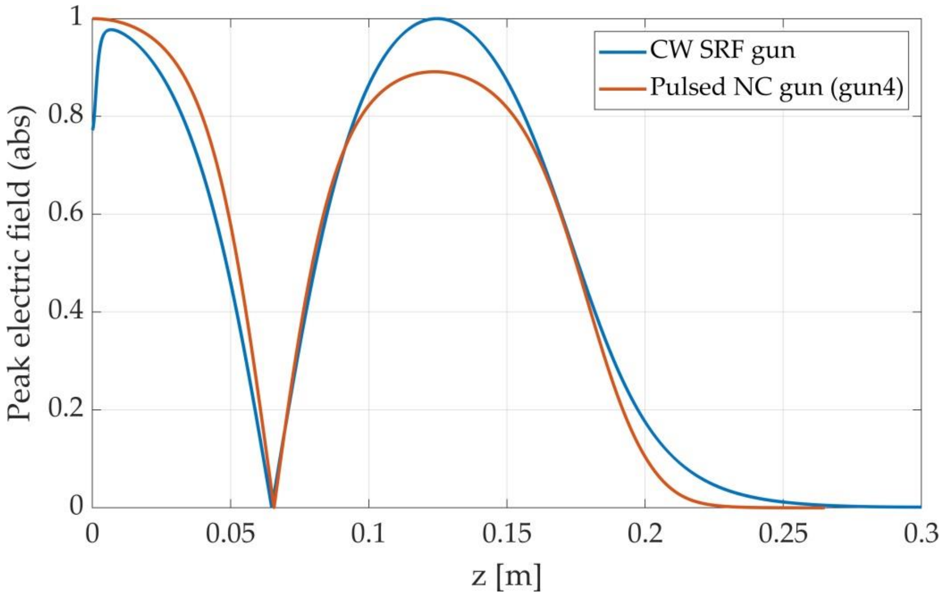
Transverse electric field near cathode:



Refined mesh in the volume which covers the trajectory of the beam:



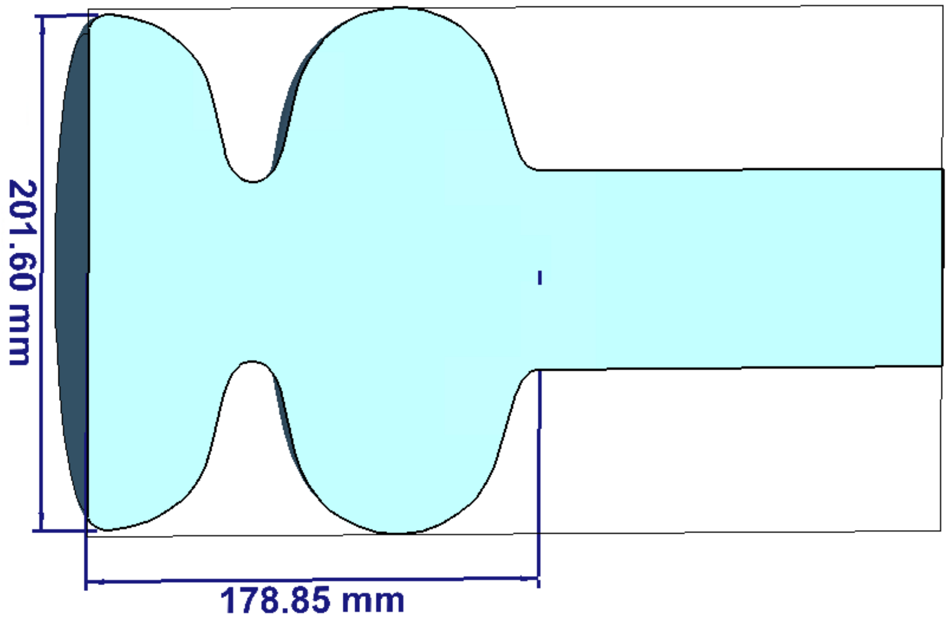
Electric field distribution on axis:



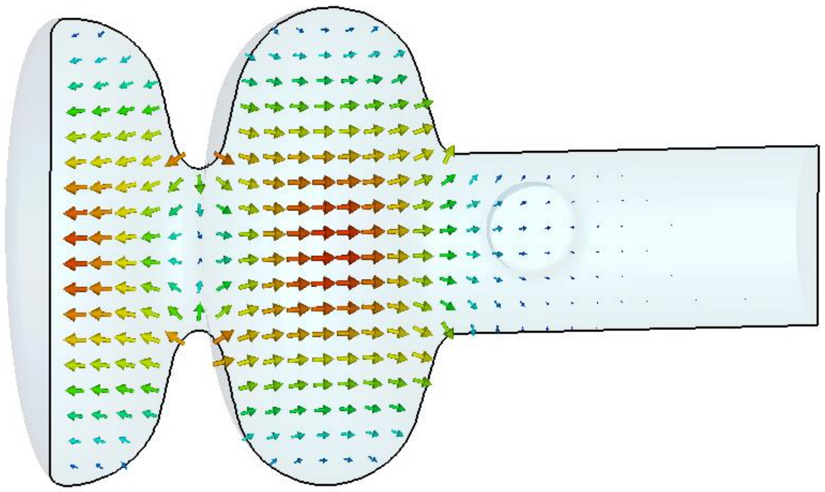
DESY L-band SRF gun

EM field distribution

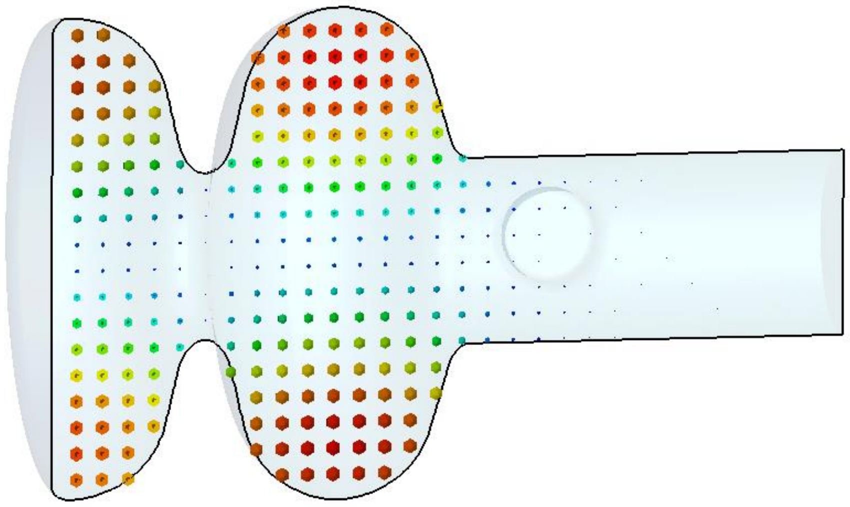
- 1.6 – cell cavity
- 1.3 GHz
- TM_{010}; pi-mode
- Peak field on axis – 40-60 MV/m



E-field:



H-field:



DESY L-band SRF gun

Laser profile

Longitudinal profile:

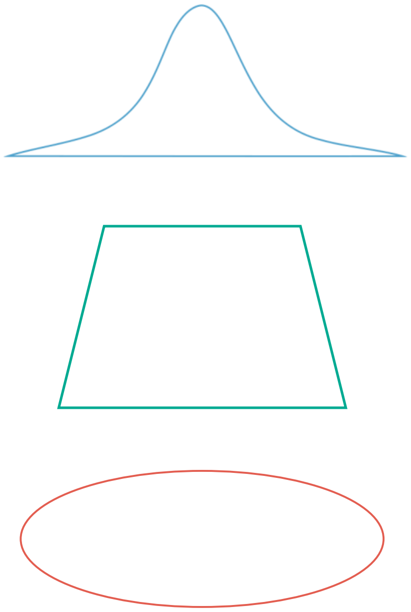
- **Gaussian**
- **Flat top**
- Ellipsoid

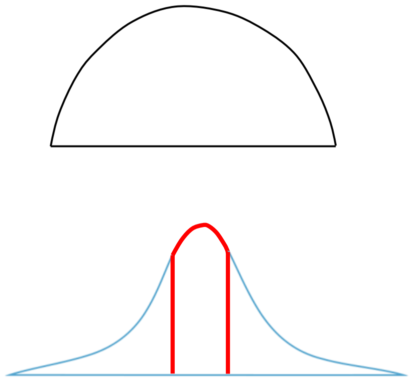
Transverse profile:

- **Radial uniform**
- **Truncated-Gaussian* (1σ)**

Charge:

- **100 pC**
- **50**; *75 pC?*





Uncertainties:

- Maximal bunch length (micro bunching and other issues)
- Thermal emittance
- Additional laser RnD might be required

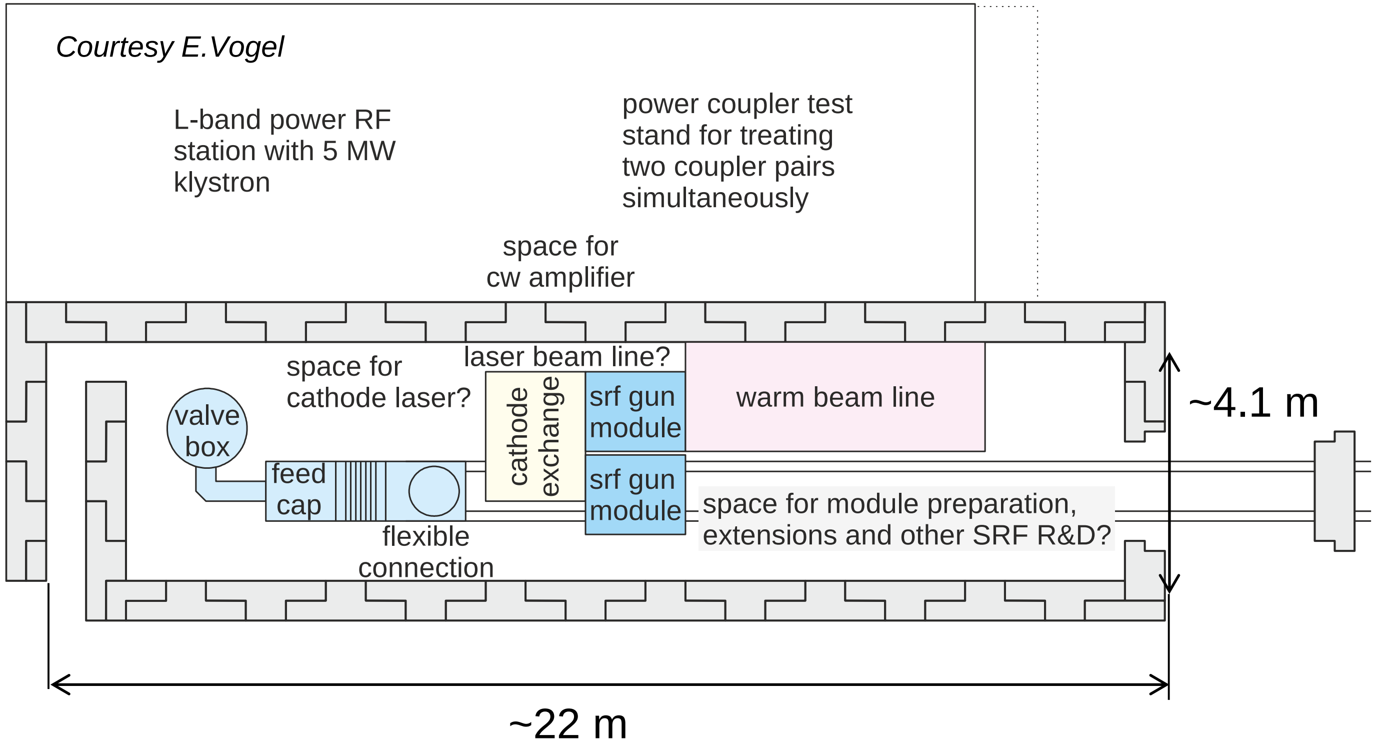
*) "Impact of the spatial laser distribution on photocathode gun operation", Feng Zhou, Phys. Rev., et., al. (DOI: 10.1103/PhysRevSTAB.15.090701)

"Emittance reduction of rf photoinjector generated electron beams by transverse laser beam shaping", M. Gross, H. Qian et., al. (doi:10.18429/JACoW-IPAC2019-TUPTS012)

DESY L-band SRF gun

Experimental horizontal test stand for L-band SRF guns

- Test stand would allow to evaluate assumptions made in beam dynamics simulations
- Characterization of the full 6D phase space of the beam
- Advantage: universal test stand for L-band SRF guns



AMTF bunker XATB3:

CW EuXFEL injector

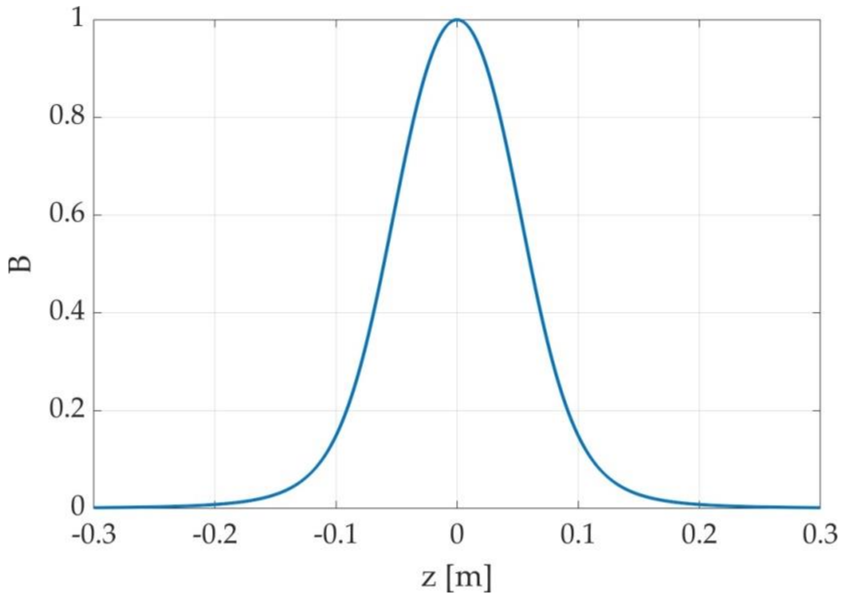
Layout used for optimization

CW EuXFEL injector

Focusing solenoid

- Data concerning the solenoid received from HZB
- Fields are calculated in POISSON (based on the input from HZB)
- Work is on going to purchase the solenoid for the DESY SRF gun

Distribution of the magnetic field on axis:



Photograph of the solenoid:

Courtesy HZB

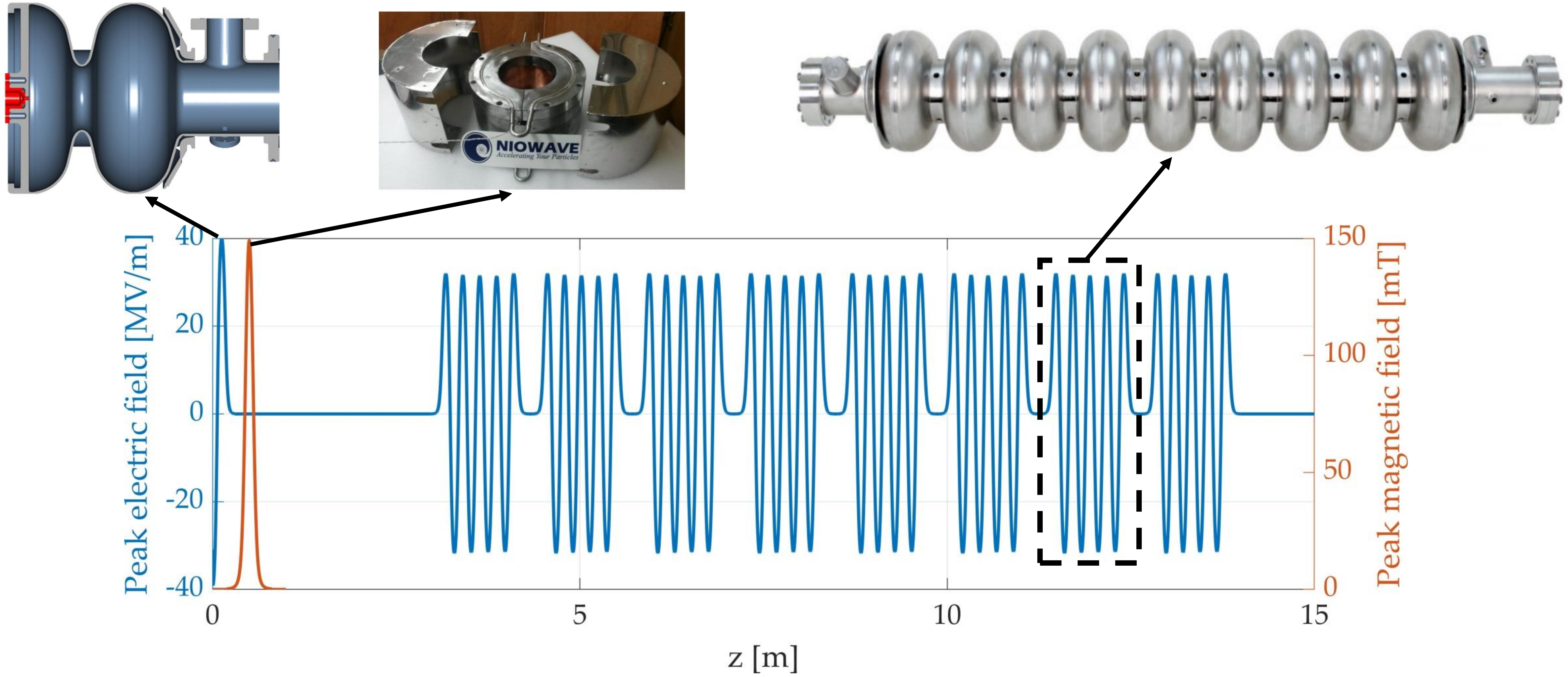
CW EuXFEL injector

Injector setup for the optimization

DESY SRF gun #10

HZB sc solenoid

SRF 9-cell TESLA cavities (x8)

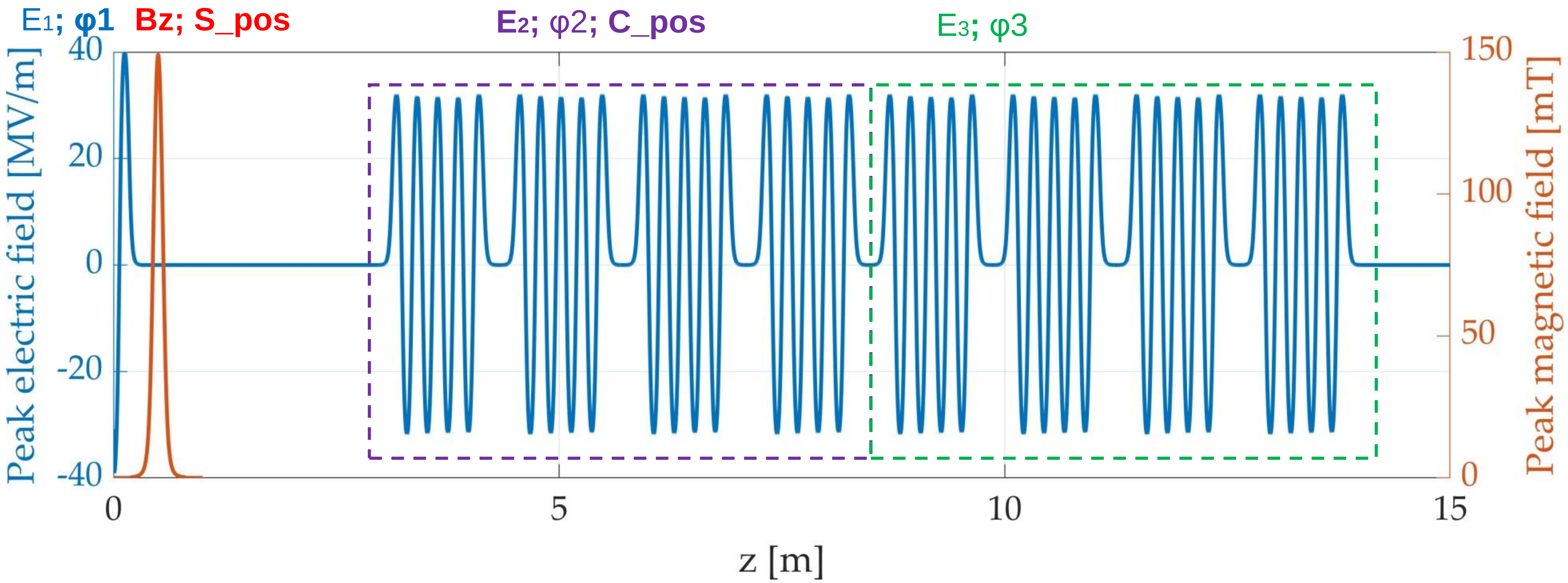


CW EuXFEL injector

Parameters for optimization

Cathode:
- Lead (Pb)
- Initial thermal kinetic energy of 0.22 eV; 1 eV
- Charge 100 pC

Laser profile:
- Longitudinal laser shape – Gaussian
- Transverse laser shape – radial uniform
- Laser spot size (rms) – **sig_x/sig_y**
- Laser pulse duration – **sig_z**



Optimization of the CW injector

Algorithm for optimization and current results

Optimization of the CW injector

Multi-objective genetic optimizer

- C++ code written in LBNL; provided by H. Qian (PITZ)
- NSGA-2: **N**ondominated **S**orting **G**enetic **A**lgorithm
- Code drives ASTRA on cluster
- Population size = number of active CPUs
- Optimization run takes up to 24 hours using reasonable computational recourses (2 nodes x 40 CPUs)
- Run time can be reduced by increasing population size (i.e. number of CPUs)
- Difficulty: the code has been written for LBNL cluster infrastructure; suitable C++ libraries for compilations were unknown

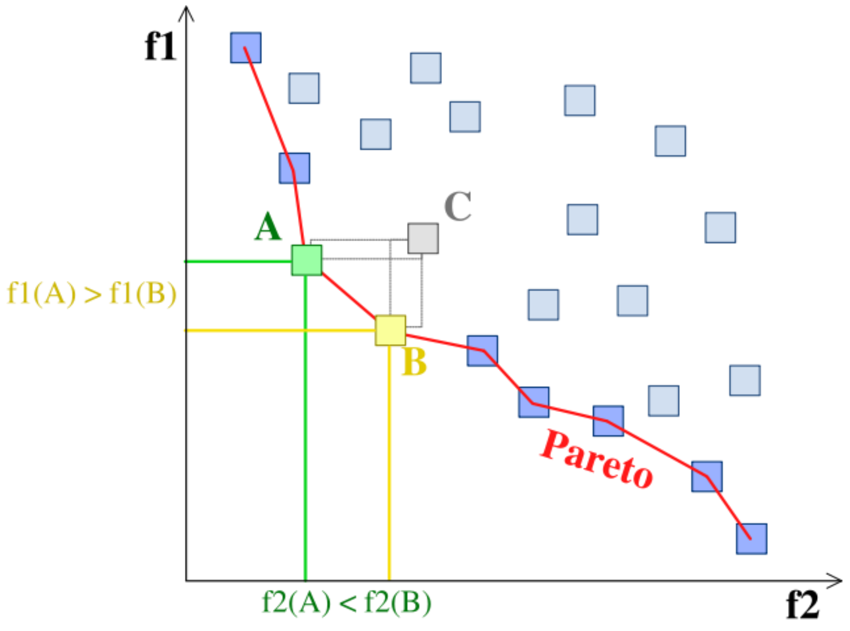


Figure source: wikpedia.org

- In our case:
  - f1 – **rms bunch length**
  - f2 – **rms projected emittance**
- Solution C is not in the Pareto front because it is dominated by A and B
- Solutions A and B do not dominate each other

Optimization of the CW injector

Initial conditions

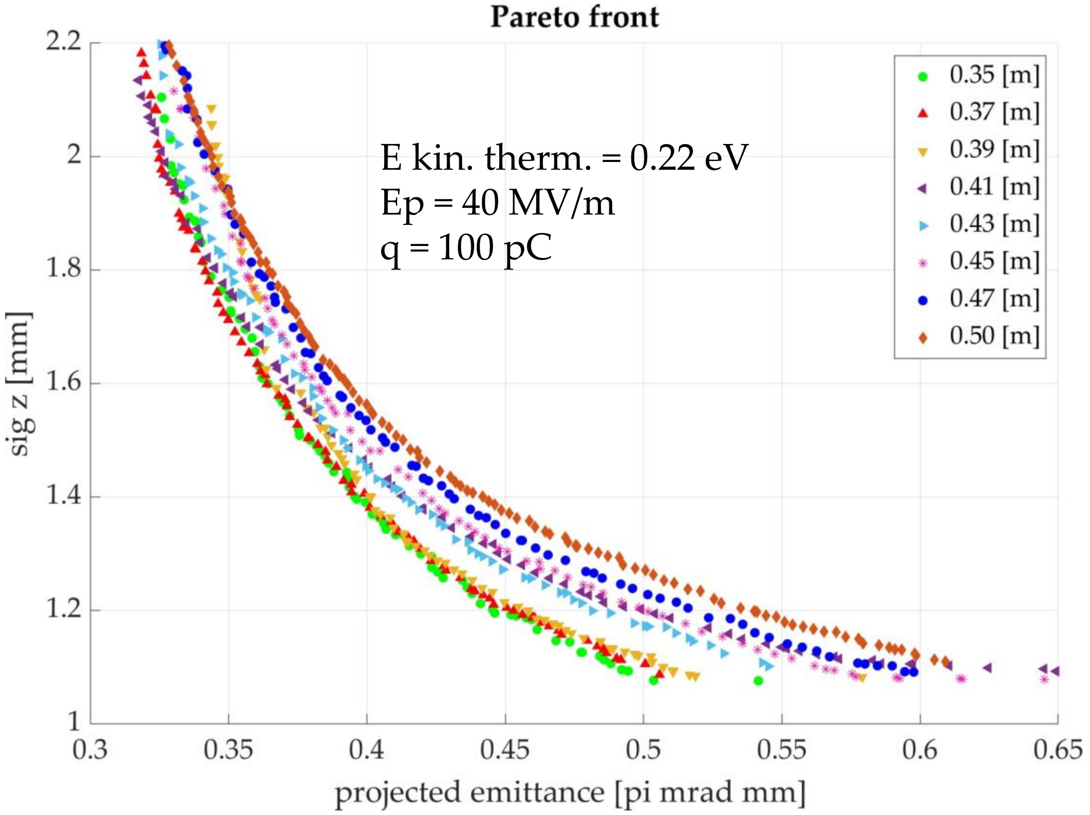
- In this framework:
  - objective functions: **rms bunch length** and **rms projected emittance**
- Particle tracking distance: 15 [m]
- 10000 particles for the optimization purposes; interesting bunch distributions recalculated with 2E5; 2E6 of particles and improved mesh
- Each distribution requires additional refinement with fine mesh and more particles in ASTRA (e.g. 2E6 of particles)
- Five parameters to optimize
- Amplitudes of the first and the second module are set to 32 MV/m
- No phase offset in the first and the second module – they are used further on **for compression purposes in s2e simulations**

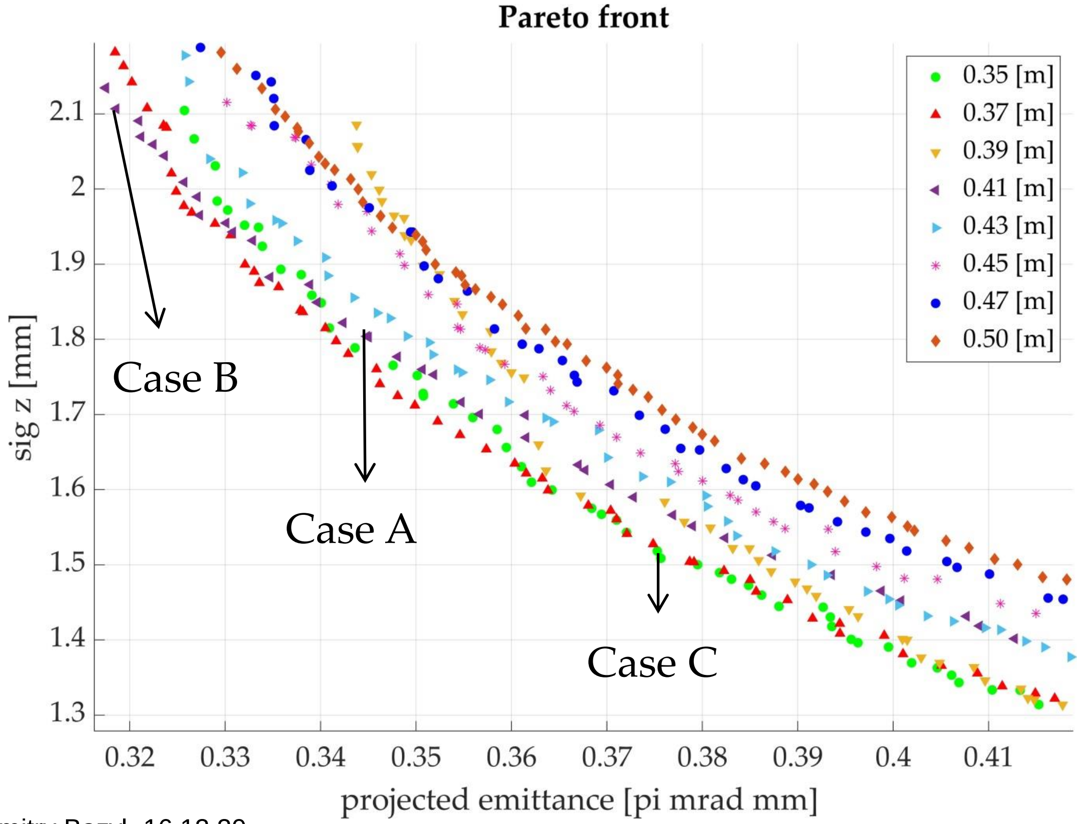
rms laser spot size	sig_x / sig_y
rms pulse duration	sig_z
Gun phase offset from MMGA value	φ_1
Solenoid field	Bz
Position of the first accelerating module	C_pos
Peak field in the first module	E1 / E1
Phase offset in the first module	φ_2
Phase offset in the second module	φ_3

Optimization of the CW injector

Solenoid position

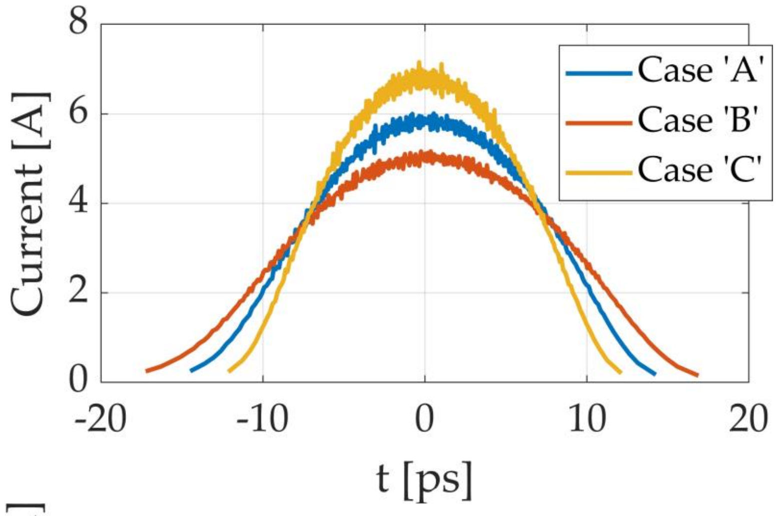
- Geometric constrains in the cryostat will be present
- Positioning of the solenoid closer to the cathode yields better results (with some inconsistency)
- Similar results can be achieved within +- 0.4 meters from the optimal position
- 0.41 [m] seems to be favorable position (to be checked with geometric constrains)

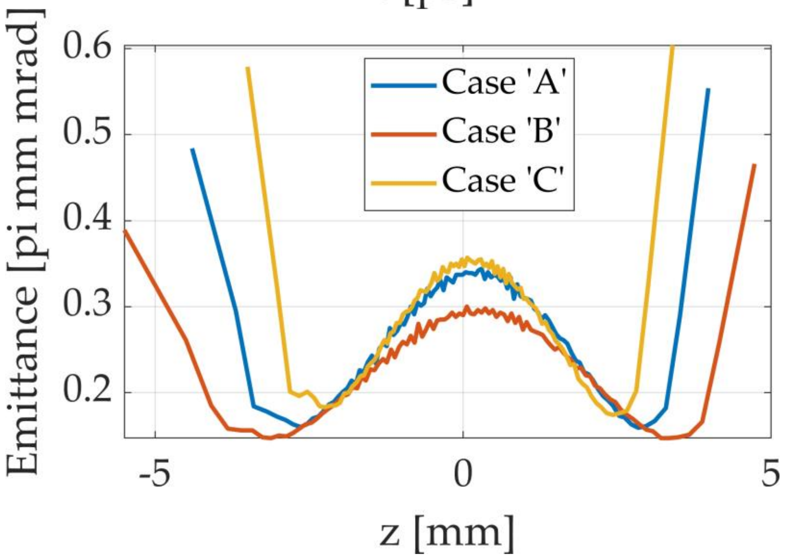


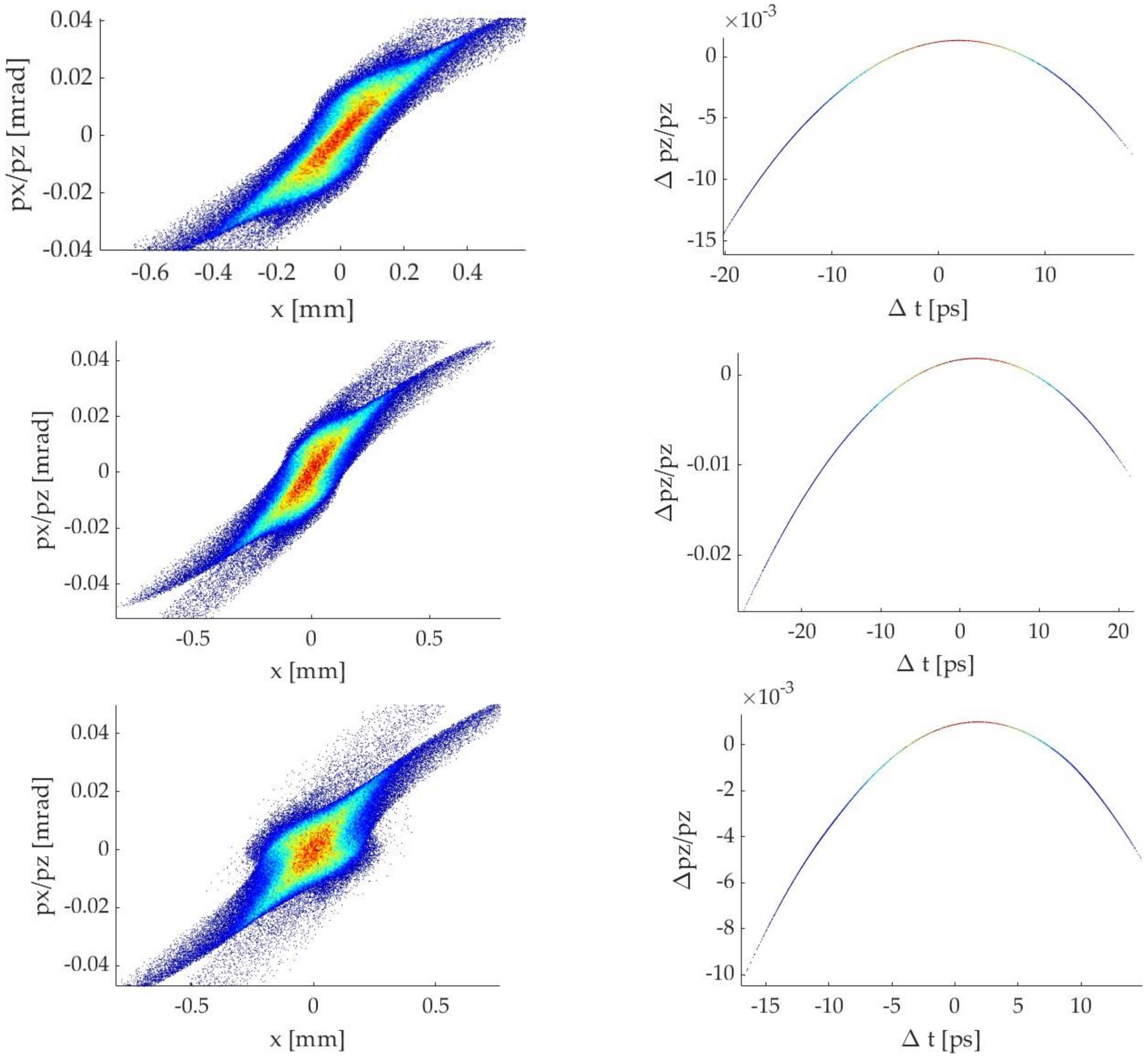


Optimization of the CW injector

A,B,C cases – peak current, slice emittance, phase space at 15 [m] for A,B and 14 [m] for C





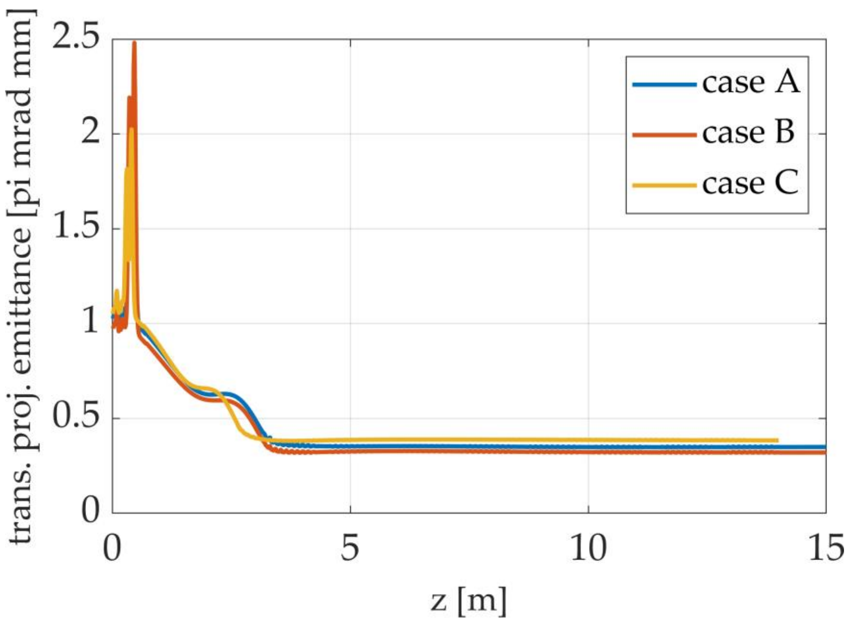


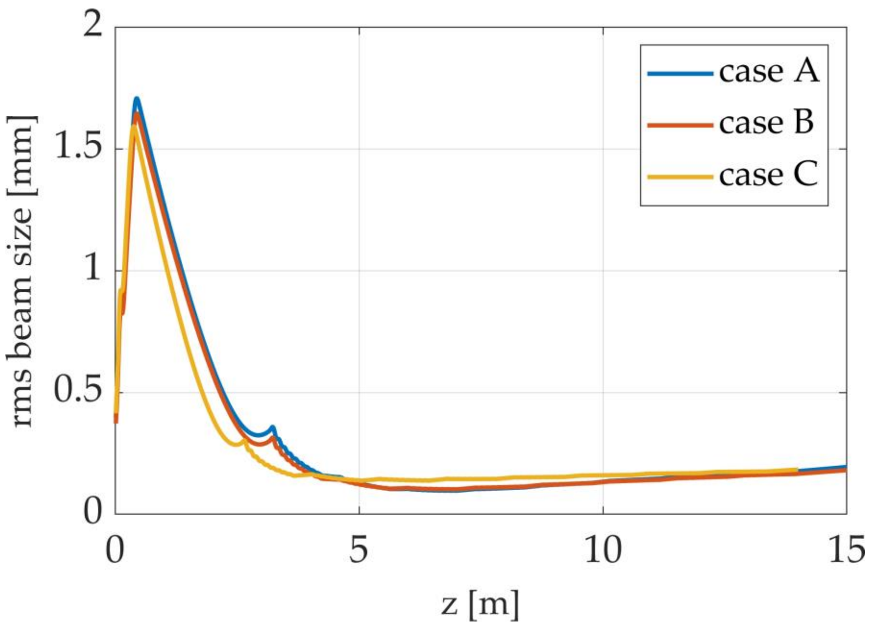
Optimization of the CW injector

Summary for A,B,C cases

- Laser profile – longitudinal Gaussian; transverse – radial uniform
- Initial thermal kinetic energy 0.22 eV (~thermal emittance of 0.5 um/mm)
- Charge – 100 pC
- These cases are being analyzed by Y. Chen and M. Dohlus (OCELOT, IMPACT-Z)
- Microbunching and bunch length limit are under investigation

Paremeter	CASE A	CASE B	CASE C
thermal emittance [pi mm mrad]	0.16	0.14	0.17
rms laser spot size [mm]	0.29	0.26	0.31
rms laser pulse lenght [ps]	7.3	8.7	5.6
transverse. proj. emitt. at 15 m [pi mm mrad]	0.345/0.344	0.320/0.320	0.384/0.384
rms bunch length at 15 m [mm]	1.801	2.132	1.525

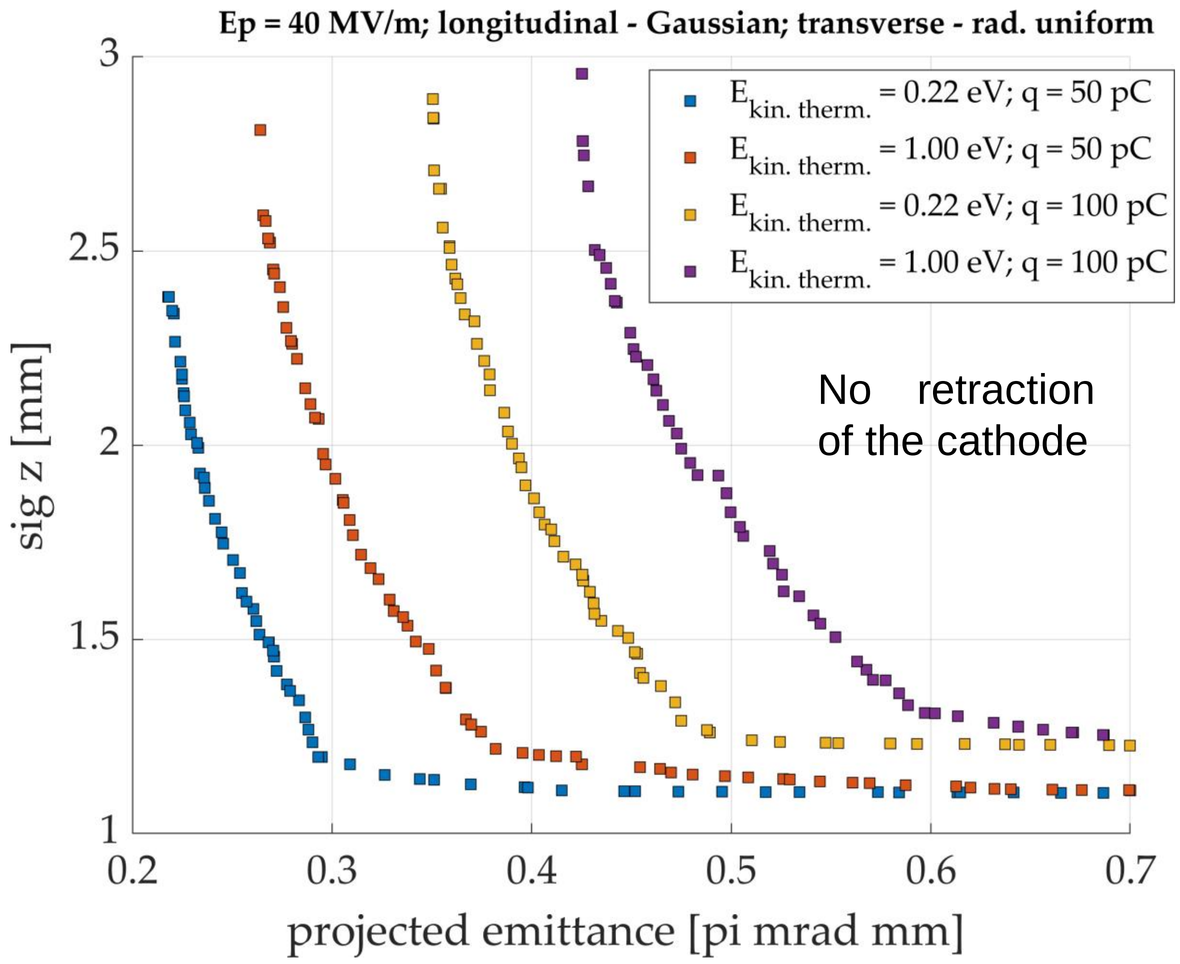




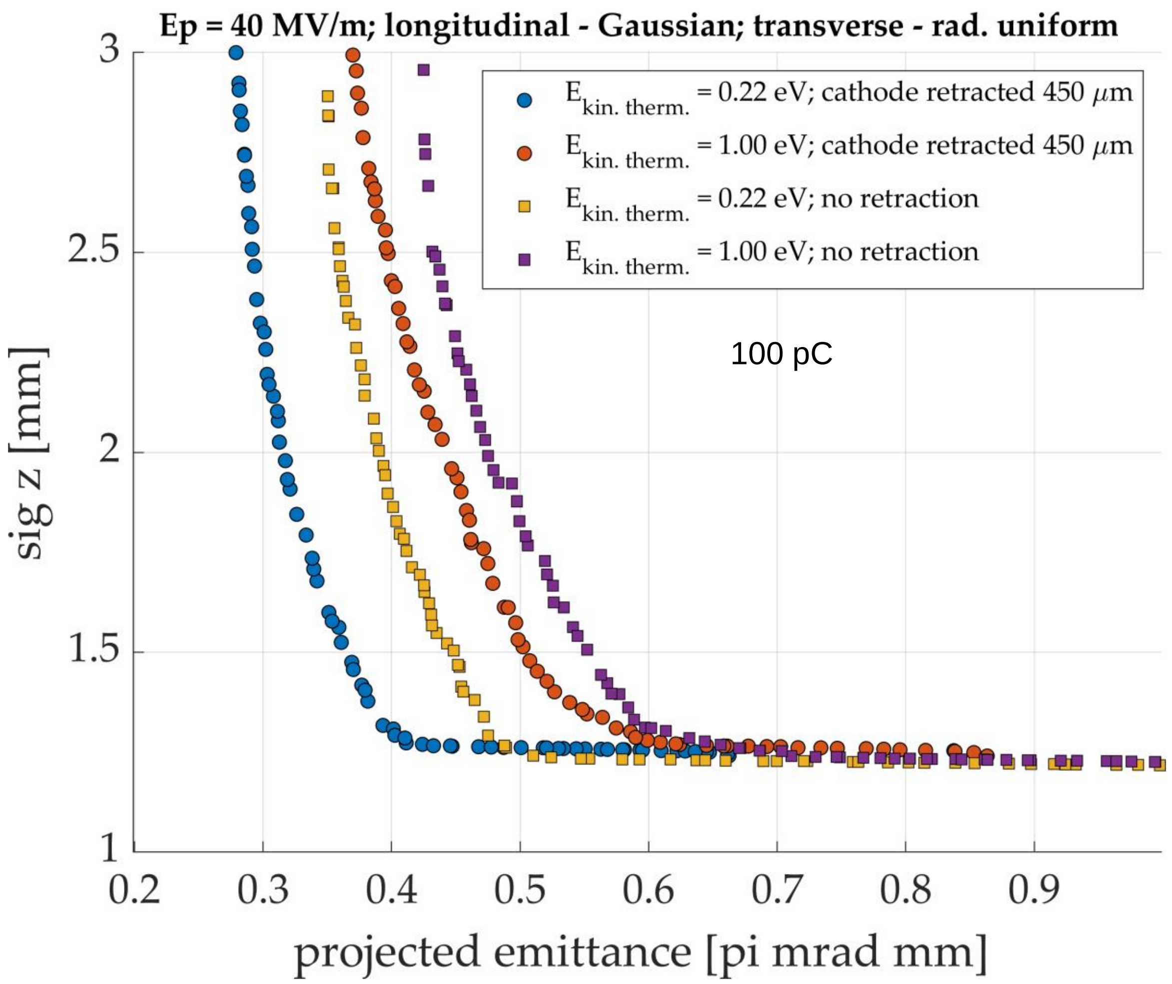
Optimization of the CW injector

Impact of the bunch charge and the cathode retraction on the transverse emittance

50 pC vs 100 pC

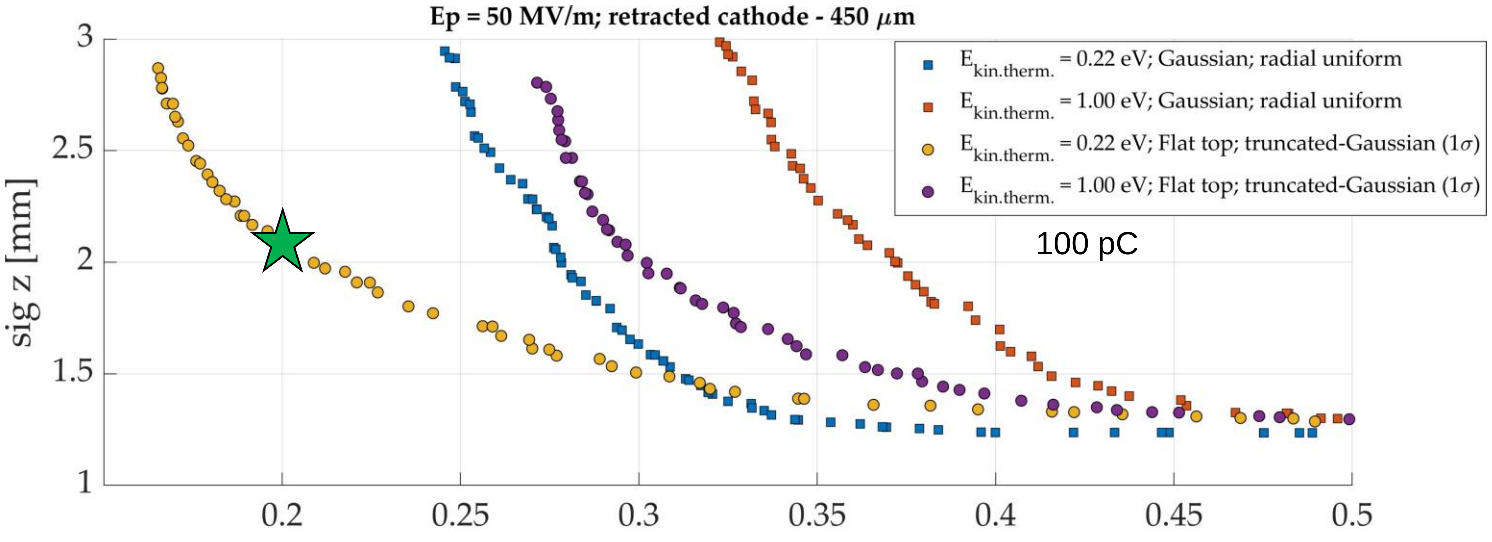


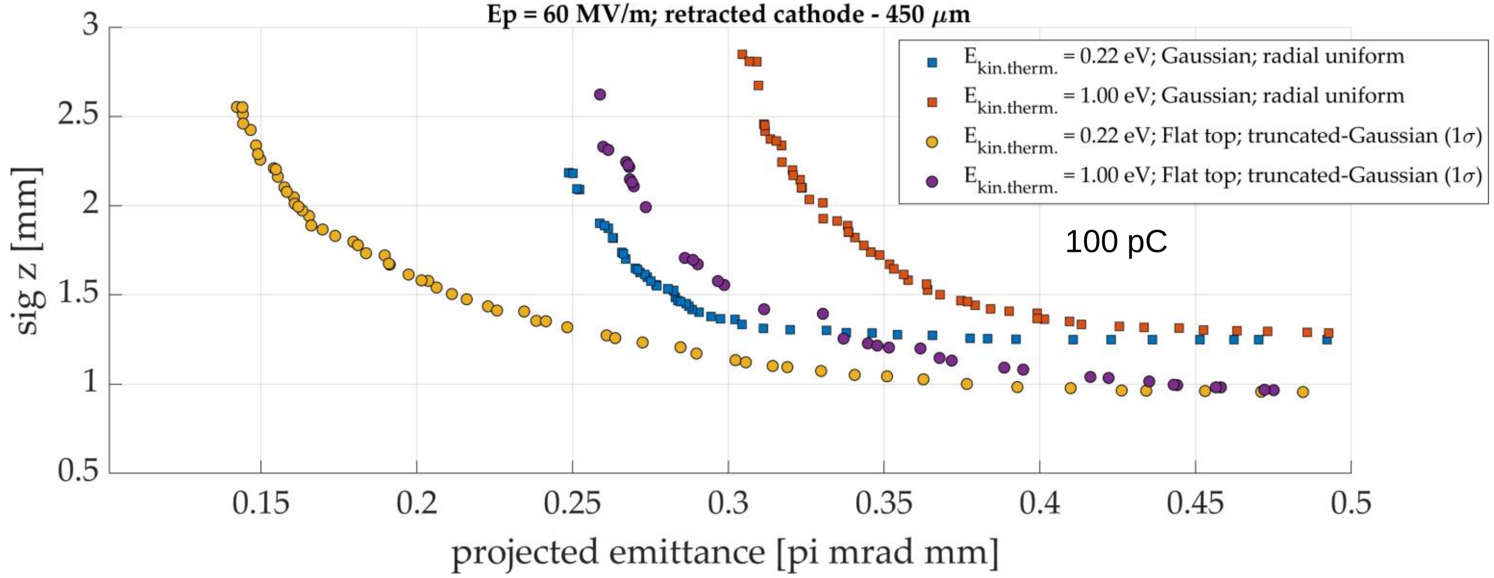
Cathode retraction



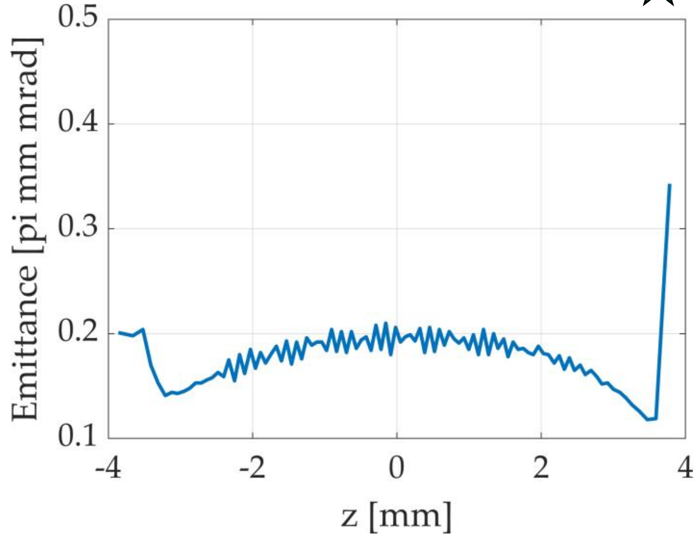
Optimization of the CW injector

Impact of the accelerating gradient on the transverse emittance

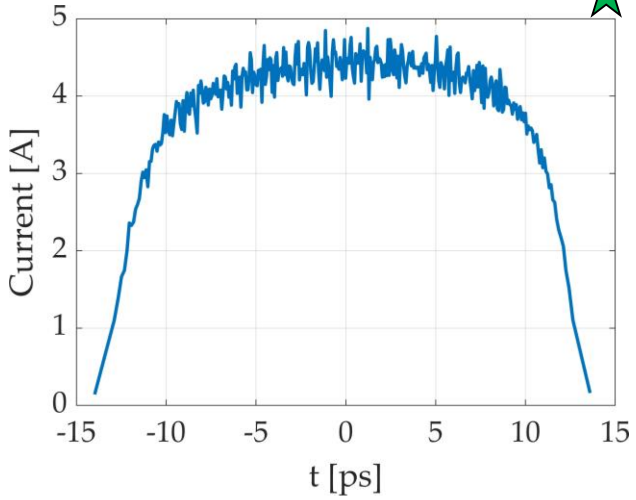




Slice emittance:



Peak current:



Conclusion and outlook (for the first part of this talk)

- SRF L-band gun has a potential to achieve the necessary requirements for the CW XFEL
- **High peak electric field at the cathode** and **low thermal emittance** are the key for achieving **low slice emittance**
- Under several assumptions beam dynamics simulations indicate the possibility of achieving 0.2 [pi mm mrad] of slice emittance **without any modification of the existing injector** (except for the gun and the solenoid) of the EuXFEL; 0.3 [pi mm mrad] under more pessimistic assumptions with ~ 5 [A] at 15 [m] prior compression 3.9 GHz cavity
- All of the obtained bunches are subject to question of transportability in further parts of the linac (including microbunching studies (M. Dohlus))
- Several general topics related to the beam dynamics in the gun require additional investigation

The talk will continue with the further insights concerning s2e simulations from Ye Chen

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