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

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17.11.20

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Content

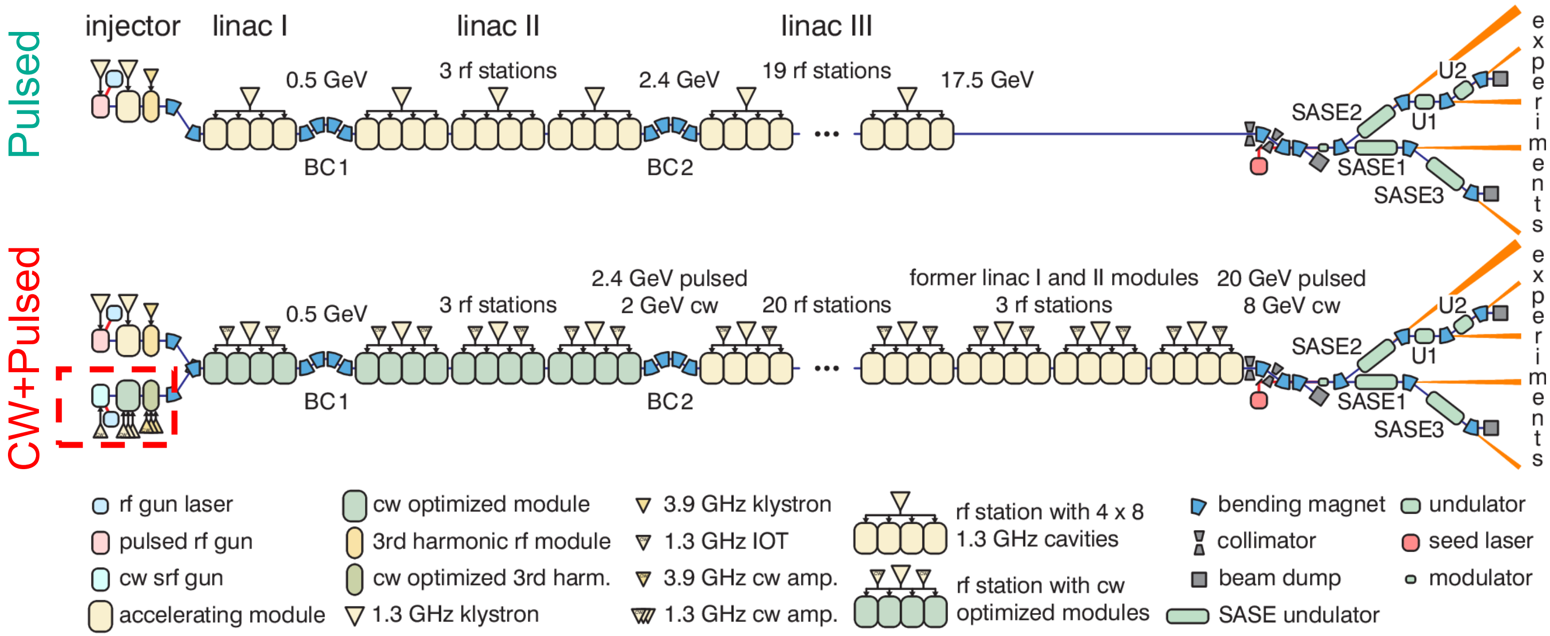
- Motivation and goals
- CW XFEL
- L-band SRF gun
- Superconducting solenoid
- CW XFEL injector
- Optimization algorithm
- Injector optimization
- Discussion and outlook

Motivation and goals

- **Evaluate the performance of the DESY SRF CW L-band gun**
- **Optimization of the CW injector for two objective functions: transverse emittance and longitudinal size of the beam**
- Evaluate initial working points for the CW injector
- Evaluate optimal solenoid position
- **Generate various bunch profiles for further s2e simulations (Ye Chen, Martin Dohlus)**
- Further optimization
- …and more

CW XFEL

- L-band 1.3 GHz SRF gun
- SC solenoid
- 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



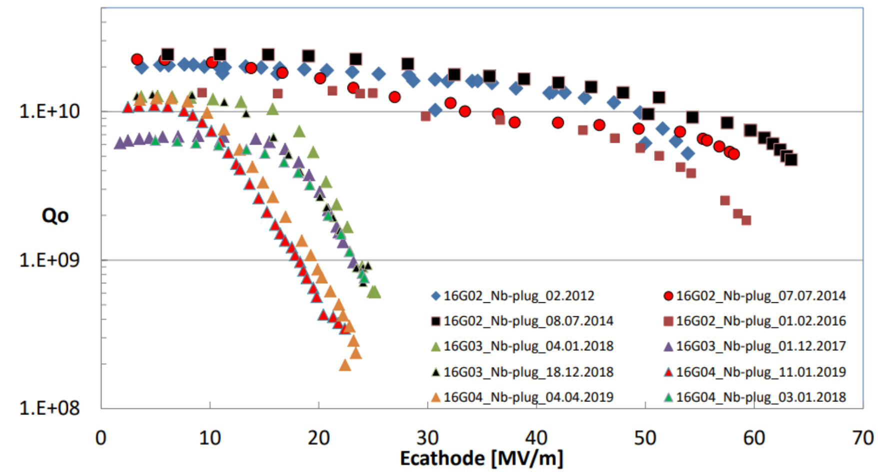
Prospects for CW and LP operation of the European XFEL in hard X-ray regime, R. Brinkmann, E. A. Schneidmiller, J. Sekutowicz, M. V. Yurkov

DESY L-band SRF gun

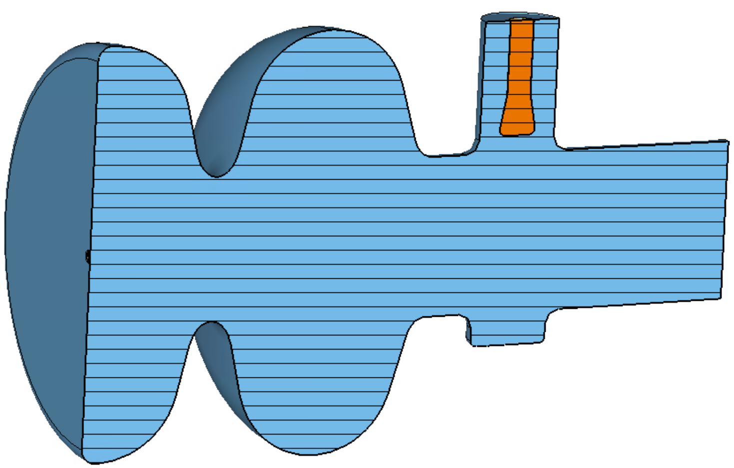
- 1.6-cell TESLA cavity
- Operating frequency 1.3 GHz
- Current gun version – 10
- Experimentally demonstrated possibility of achieving peak field of 60 MV/m; 40 MV/m – repetitively
- G09;10 are being prepared for manufacturing

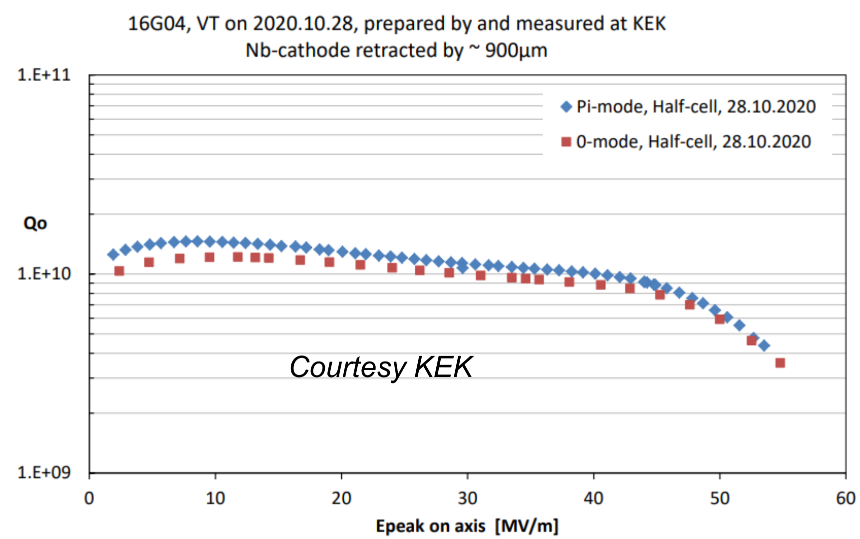
Q vs E:

Courtesy J. Sekutowicz



RF shape of the gun n.10:





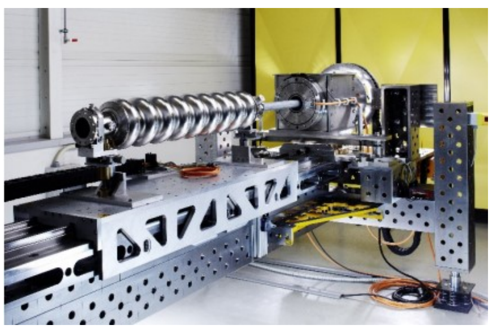
DESY L-band SRF gun

Limit of the accelerating gradient

- Empirical limit for Nb cavity:
  - Magnetic field on the surface of 200 mT – thermal breakdown

Electric field on axis [MV/m]	40	50	60
Magnetic field on the surface [mT]	99.2	123	147

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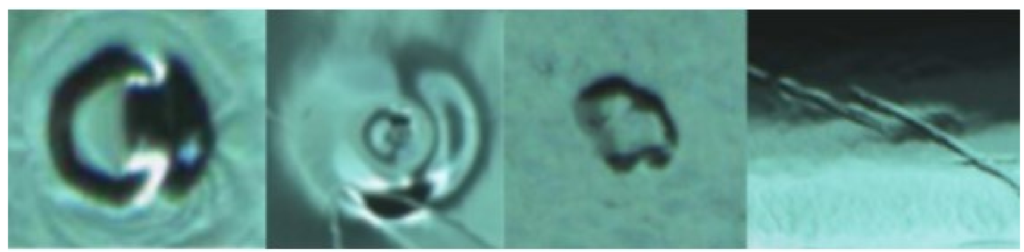
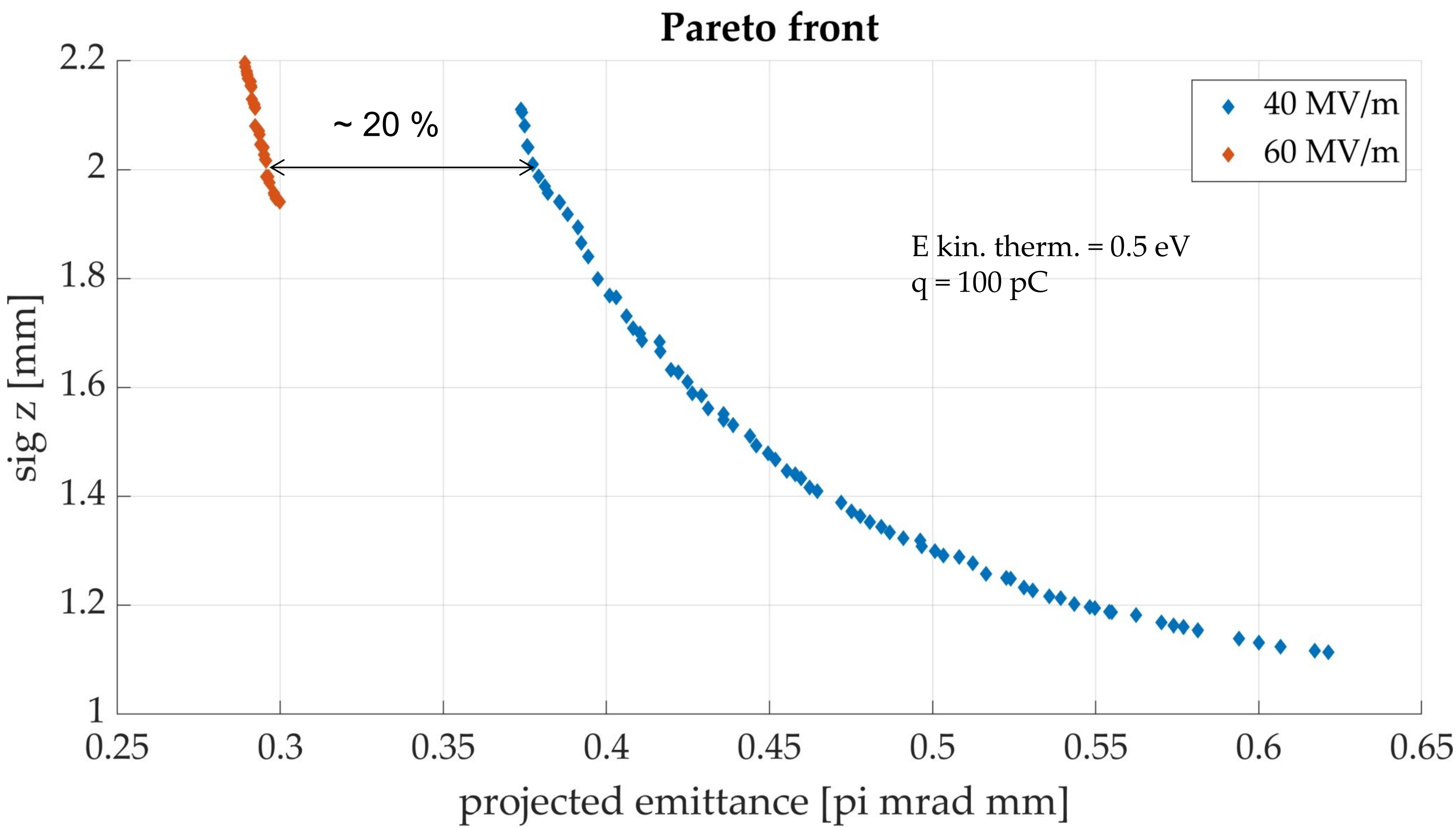


- In 1980s the limit was 3 MV/m – multipacting (technological limitation)
- Many labs are working on various techniques related to surface treatment in order to increase the gradient while maintaining high Q-factor (e.g. A. Grassellino, FNAL)

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

Injector optimization

Gun gradient



L-Band SRF gun

Cathode choice

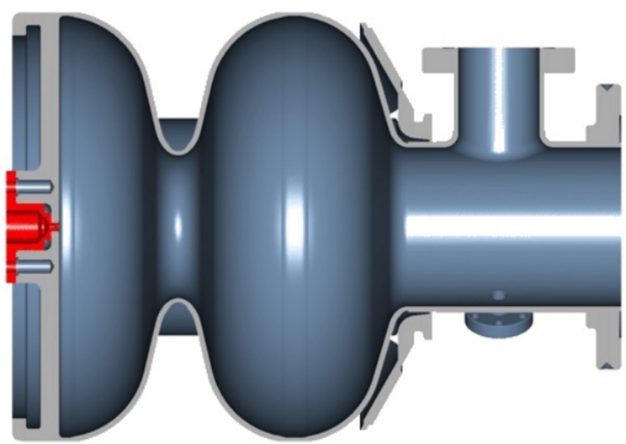
Metallic cathode (e.g. Pb)

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

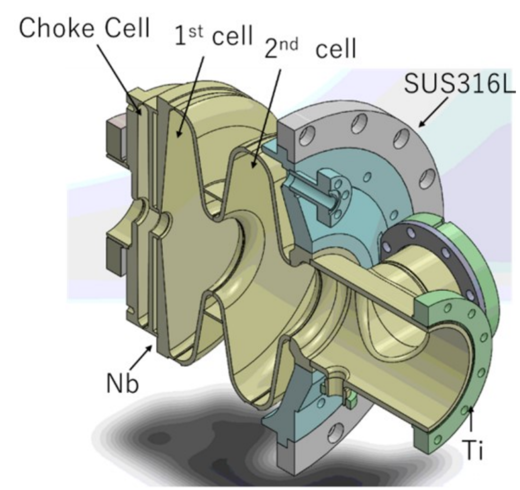
Semi-conductor cathodes (e.g. CsK2Sb)

+ 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

DESY SRF GUN:



KEK (Japan) SRF GUN*:



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

L-Band SRF gun

Thermal emittance of the Pb cathode

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:

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

[1] David H. Dowell and John F. Schmerge, Phys. Rev. Accel. Beams **12**, 074201 (2009).

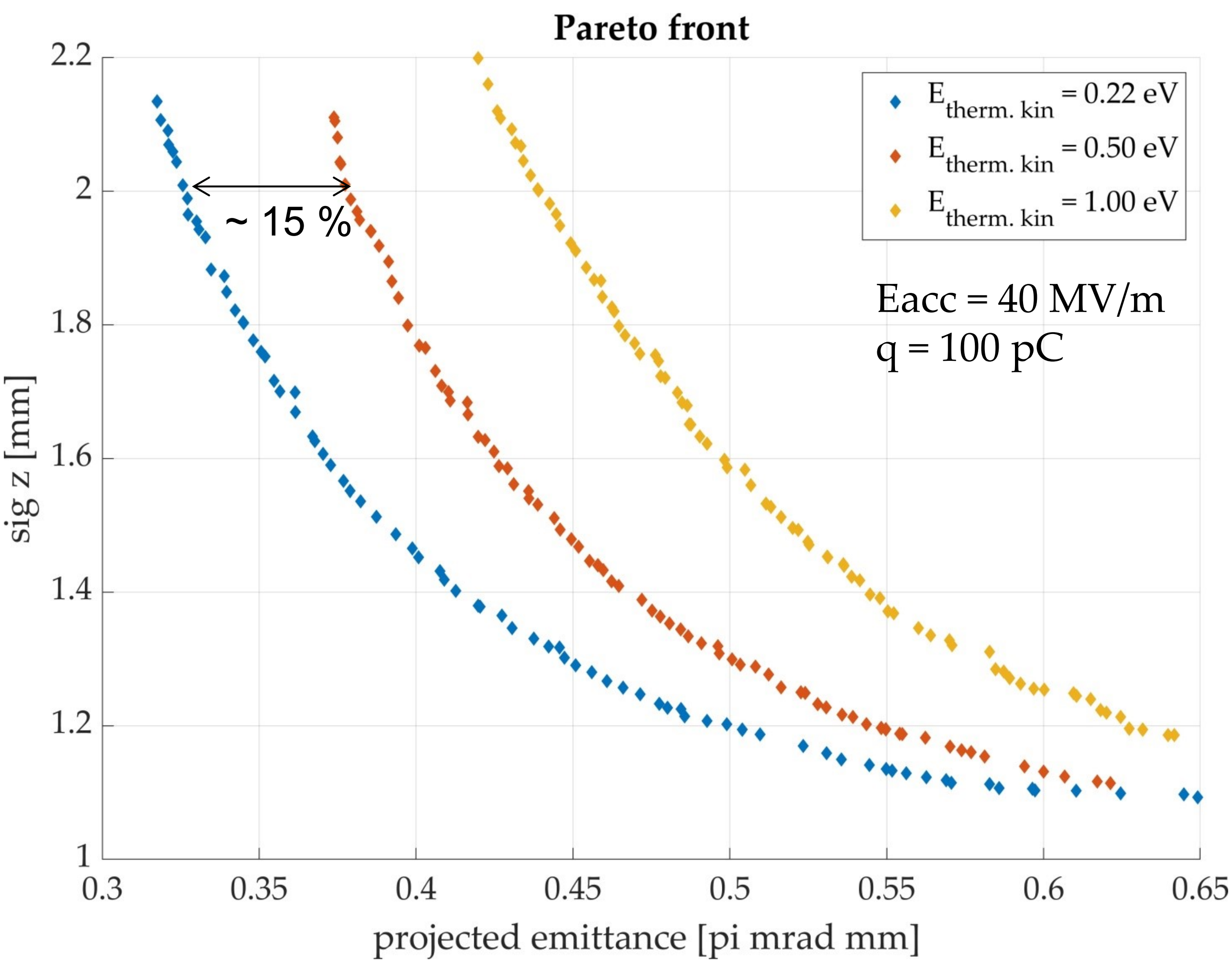
[2] J. Smedley, T. Rao, J. Sekutowicz, Phys. Rev. Accel. Beams **11**, 013502 (2008).

[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*

Injector optimization

Importance of thermal emittance (i.e. quality of the cathode)



Thermal emittance:

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

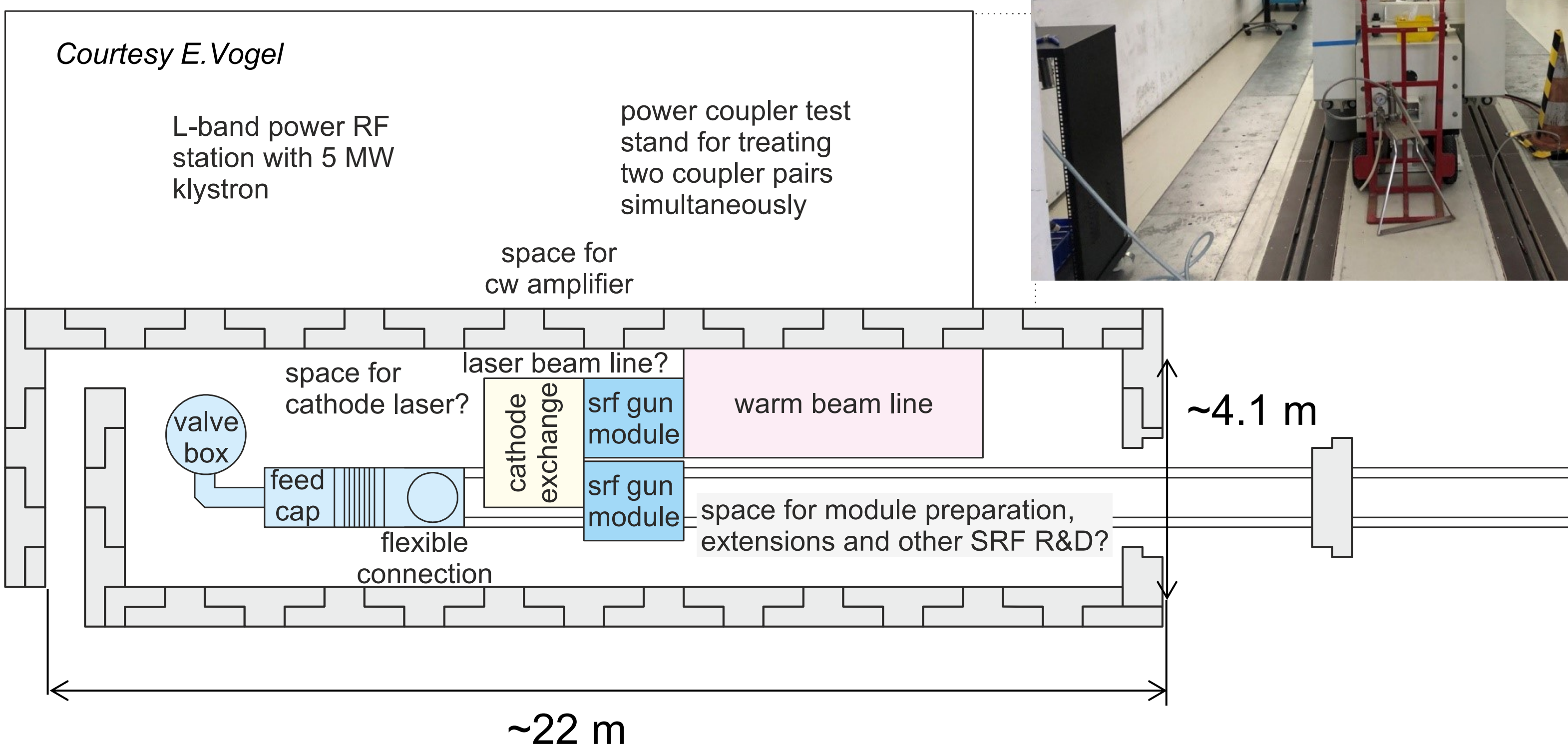
or

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

L-Band SRF gun

L-band SRF gun test stand at DESY

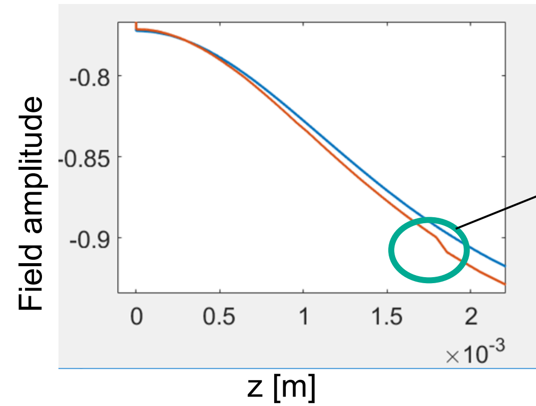
AMTF bunker XATB3



L-Band SRF gun

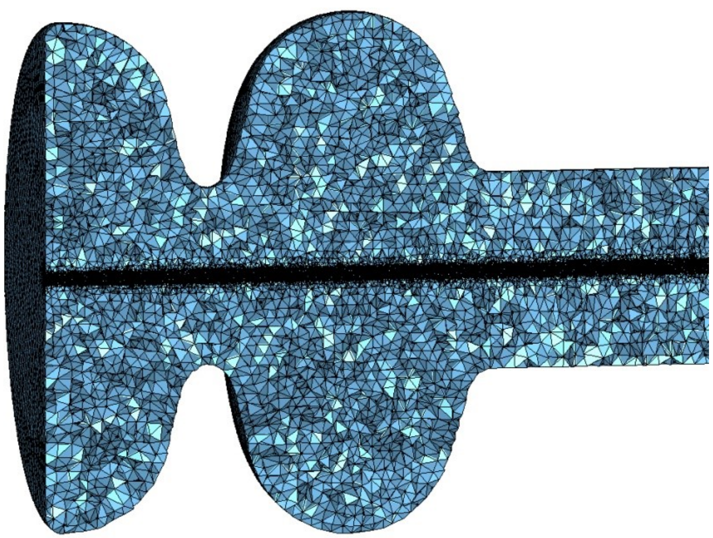
EM field calculation

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

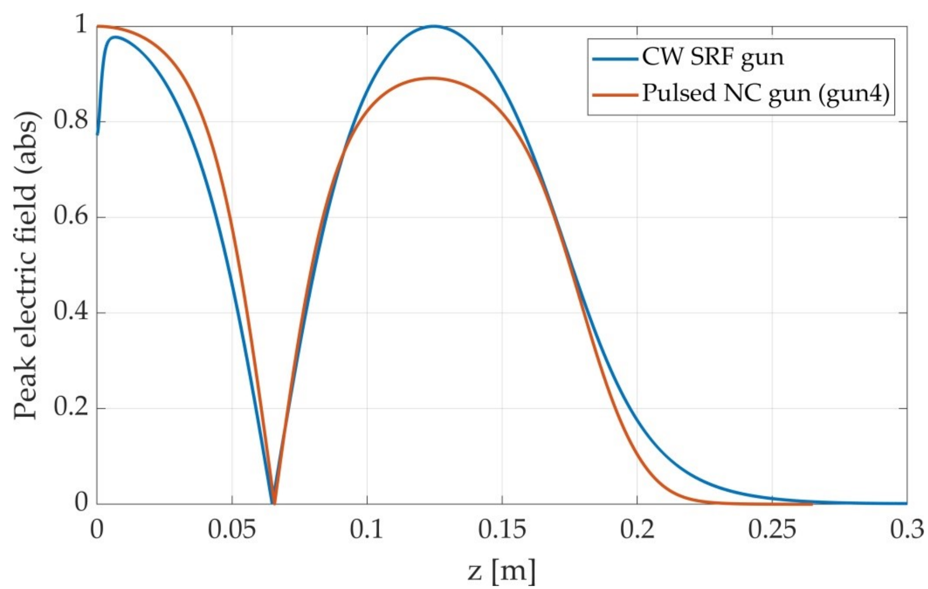


Example of the mesh noise

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

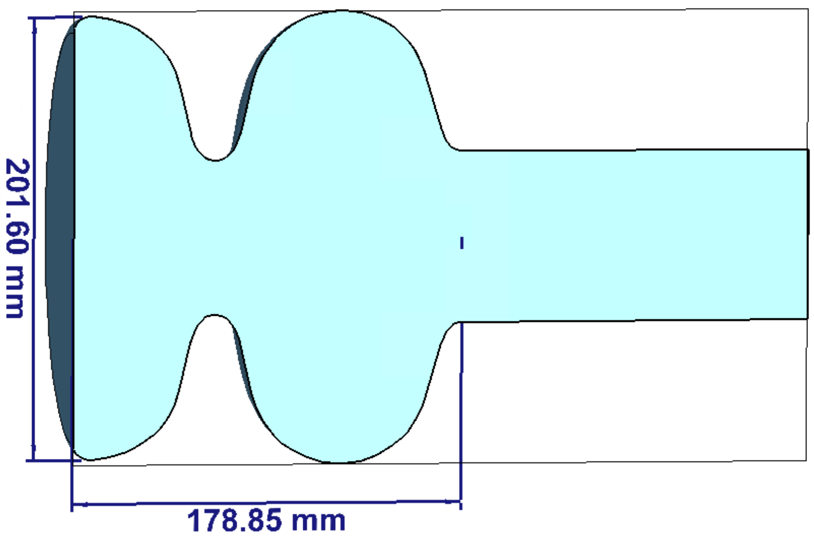


Electric field distribution on axis:

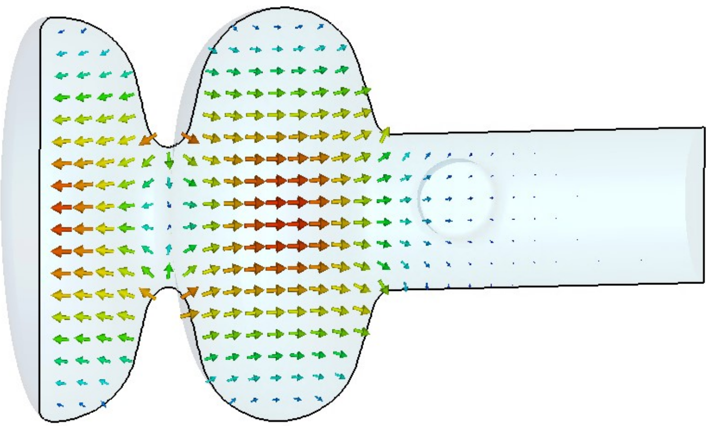


L-Band SRF gun

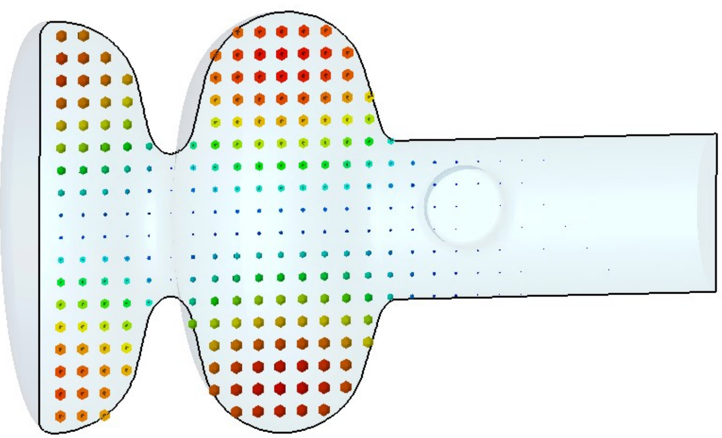
EM field calculation



E-field:



H-field:



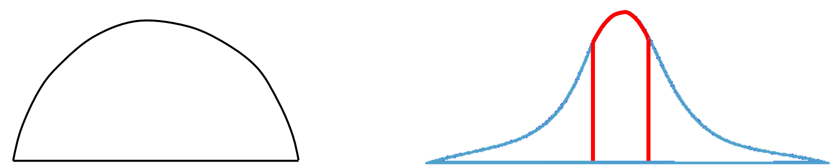
- 1.6 – cell cavity
- 1.3 GHz
- TM_{010}; pi-mode
- Peak field on axis – 40 MV/m

L-Band SRF gun

Laser profile

Longitudinal profile:
- **Gaussian**
- *Flat top*
- *Ellipsoid*

Transverse profile:
- **Radial uniform**
- *Truncated Gaussian*



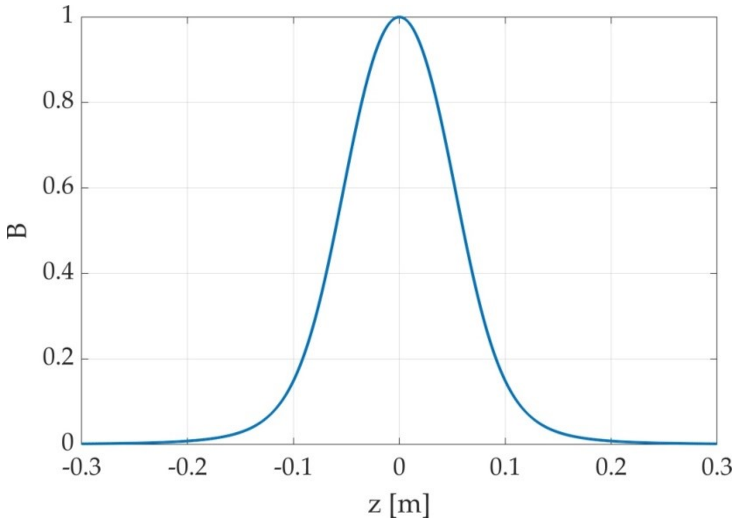
Charge:
- **100 pC**
- *50; 75 pC?*

Uncertainties:
- Maximal laser pulse length (micro bunching and other issues)
- Thermal emittance

Superconducting focusing solenoid

- Data concerning the solenoid received from HZB
- Fields are calculated in POISSON (based on the input from NIOWAVE)
- In operation at gun test stand at HZB
- Compare to other options in future

Distribution of the magnetic field on axis:

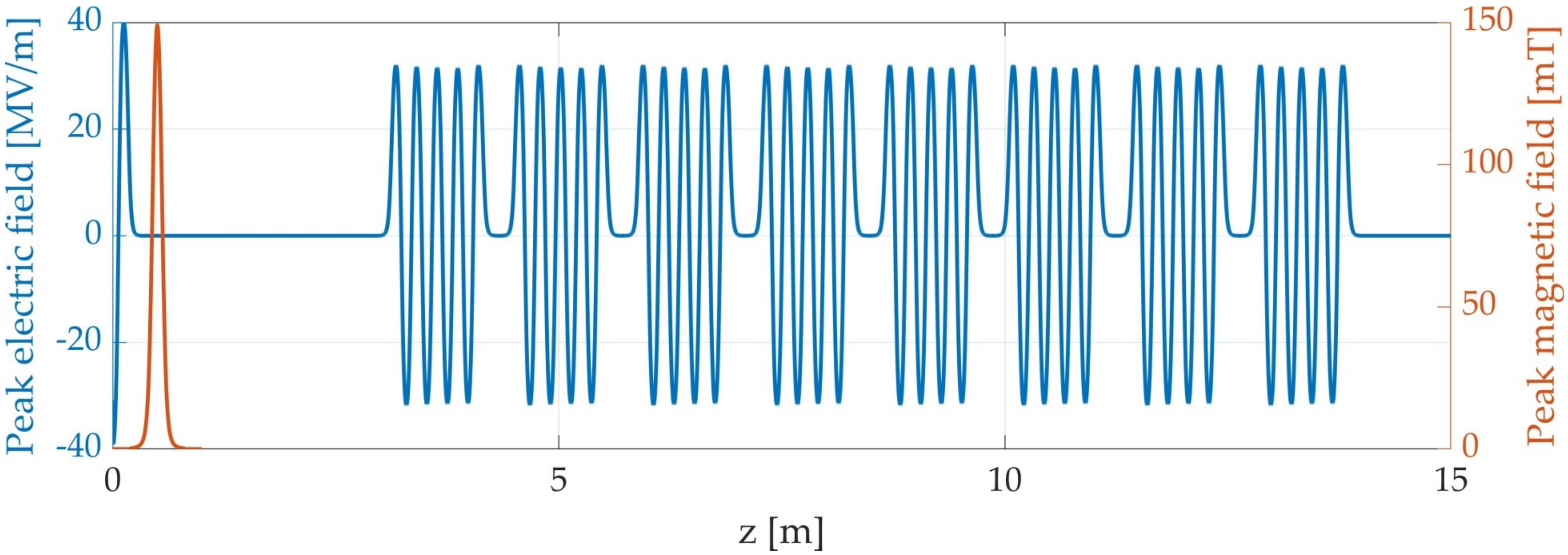


Courtesy HZB

CW XFEL injector

Injector setup for the optimization

- SRF gun #10 (RF shape of the gun #7)
- NIOWAVE solenoid
- Eight SRF 9-cell TESLA cavities

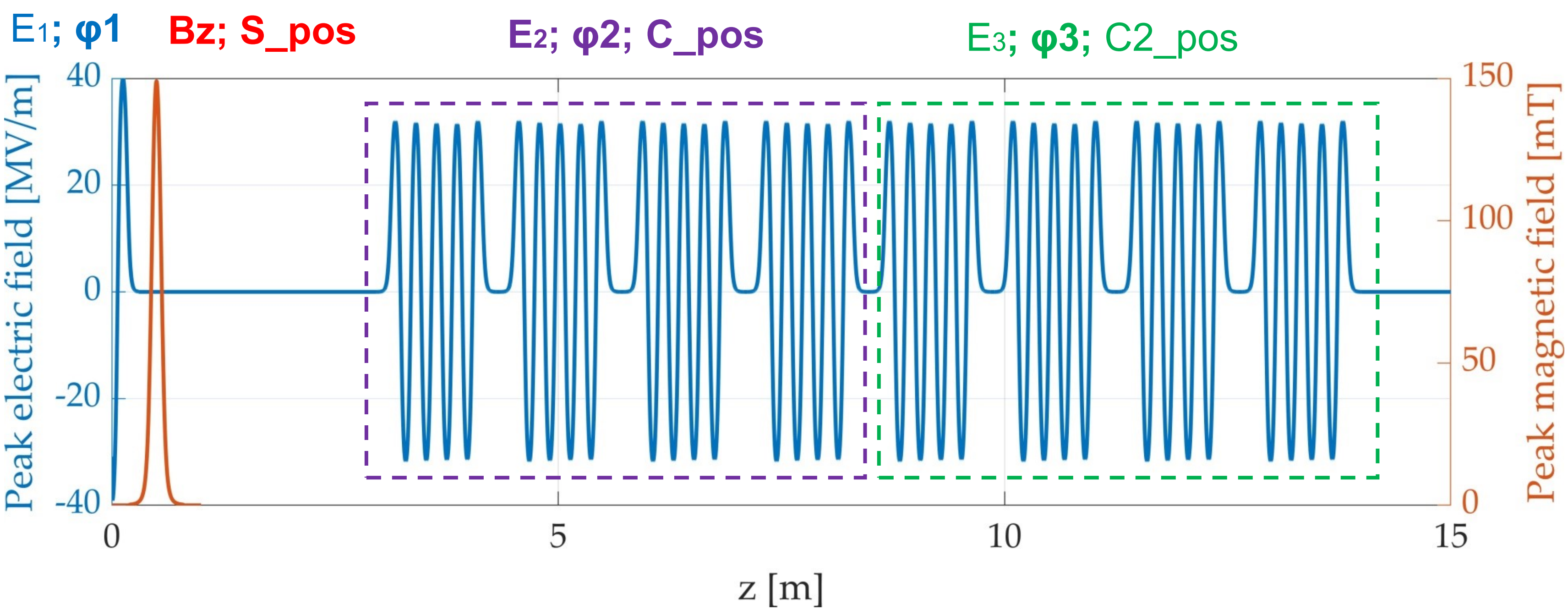


CW XFEL injector

Parameters for optimization

Laser profile:
- Longitudinal laser shape – Gaussian
- Transverse laser shape – radial uniform
- Transverse size – **sig_x/sig_y**
- Pulse duration – **sig_z**

Cathode:
- Pb
- Initial thermal kinetic energy of 0.22
- Charge 100 pC



CW XFEL injector

Objective functions and parameters for optimization

Present:

- In this framework:
  - objective functions: **rms bunch length** and **rms projected emittance**
- 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**

Further on:

- Include peak field in the first module

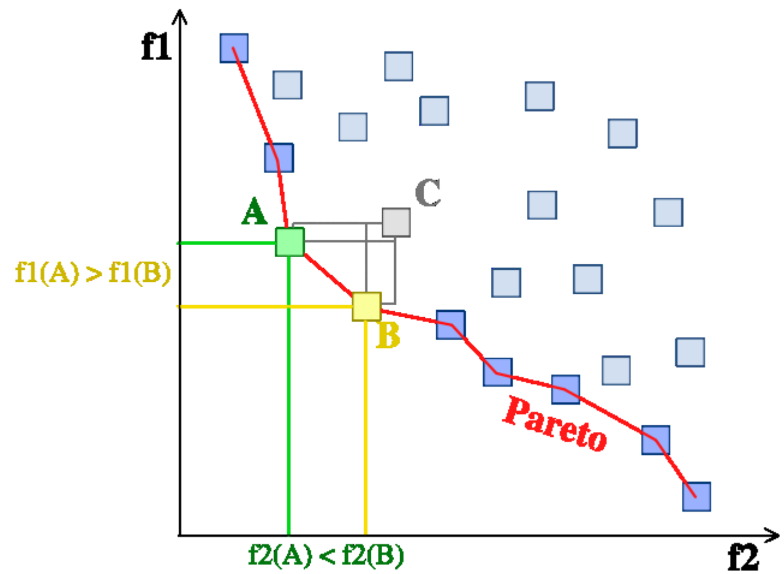
rms laser spot size	sig_x / sig_y
rms pulse duration	sig_z
Gun phase offset from MMGA value	φ_1
Solenoid field	Bz
Position of the first accelerating module	C_pos
Peak field in the first module	E1
Phase offset in the first module	φ_2
Phase offset in the second module	φ_3

Optimization algorithm

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

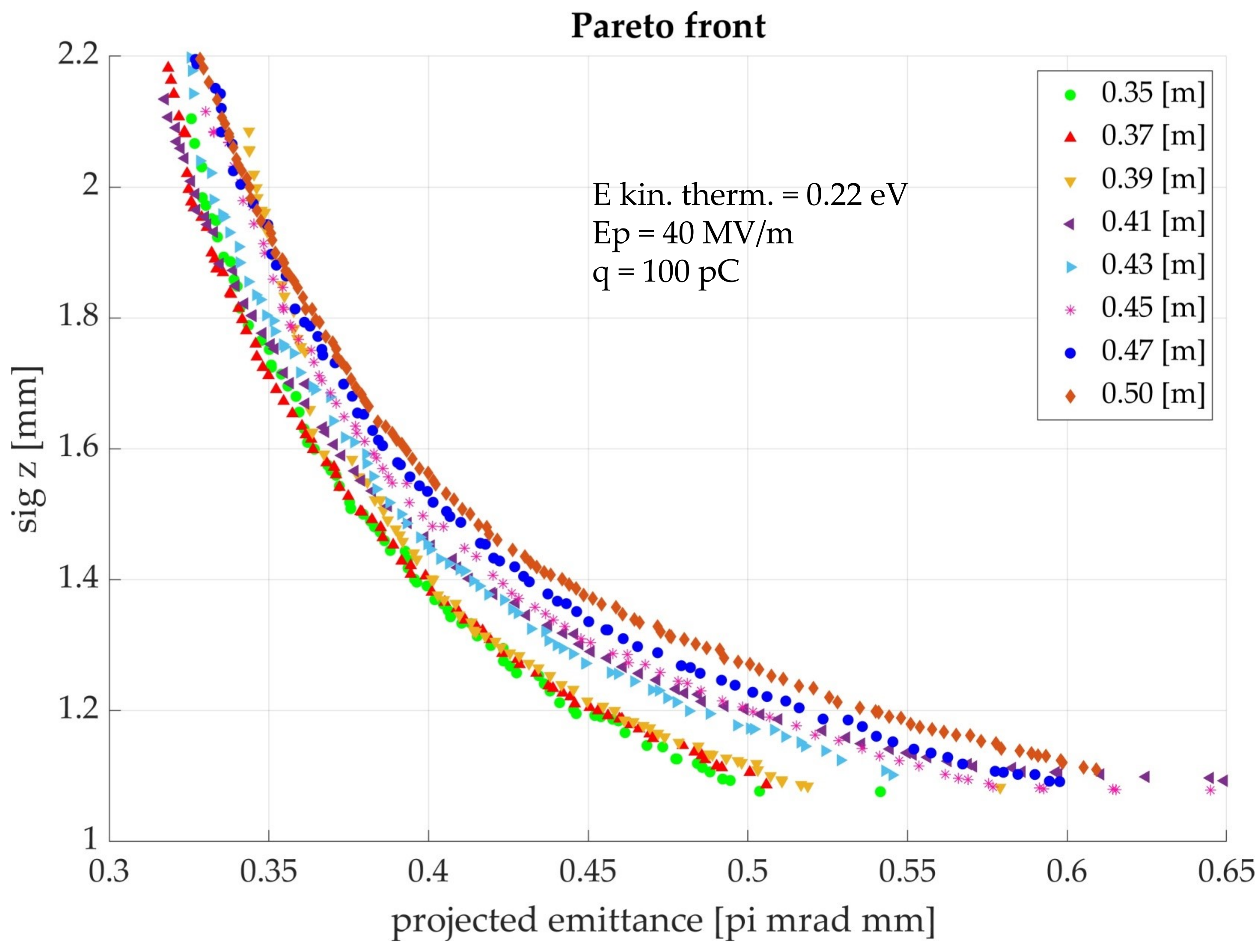
Figure source: wikpedia.org



- In this framewrok:
  - 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

Injector optimization

Solenoid position

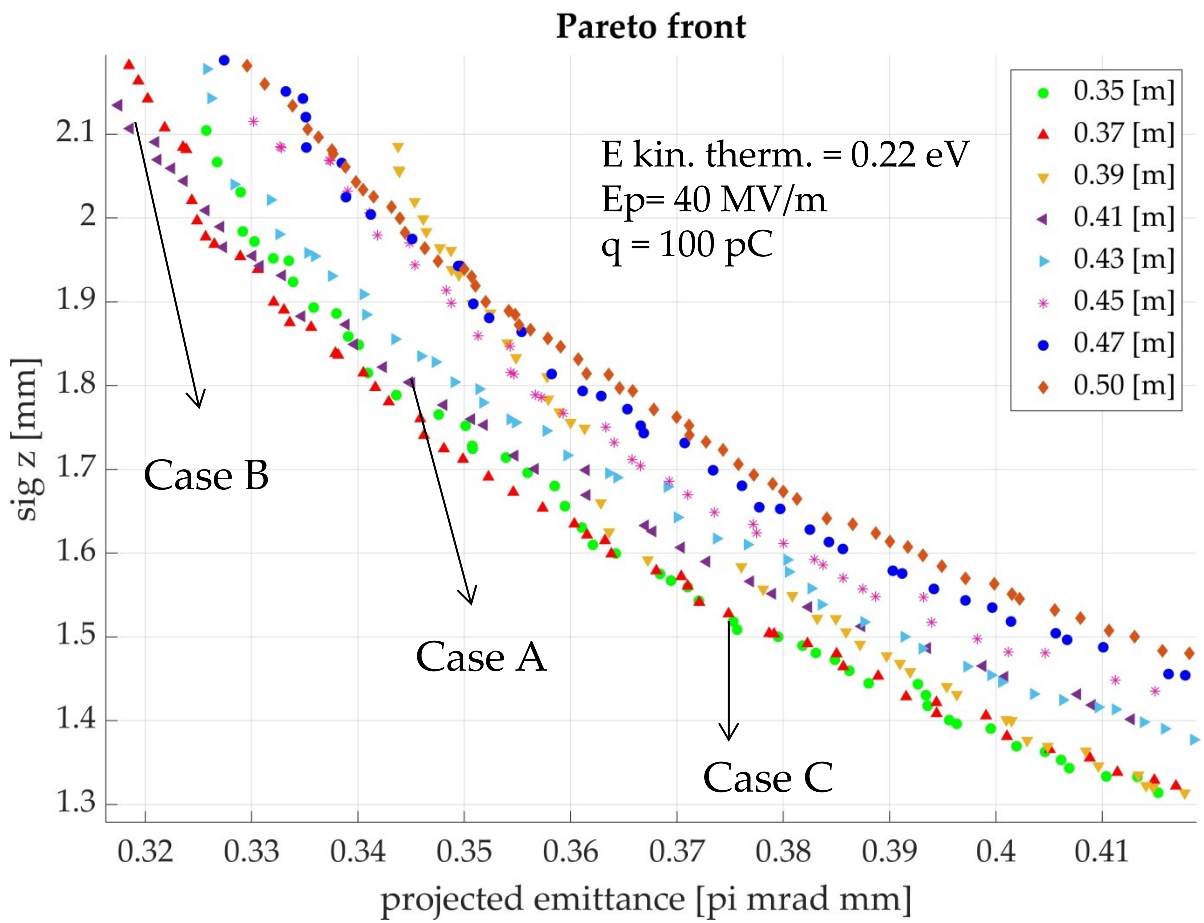


Injector optimization

Solenoid position

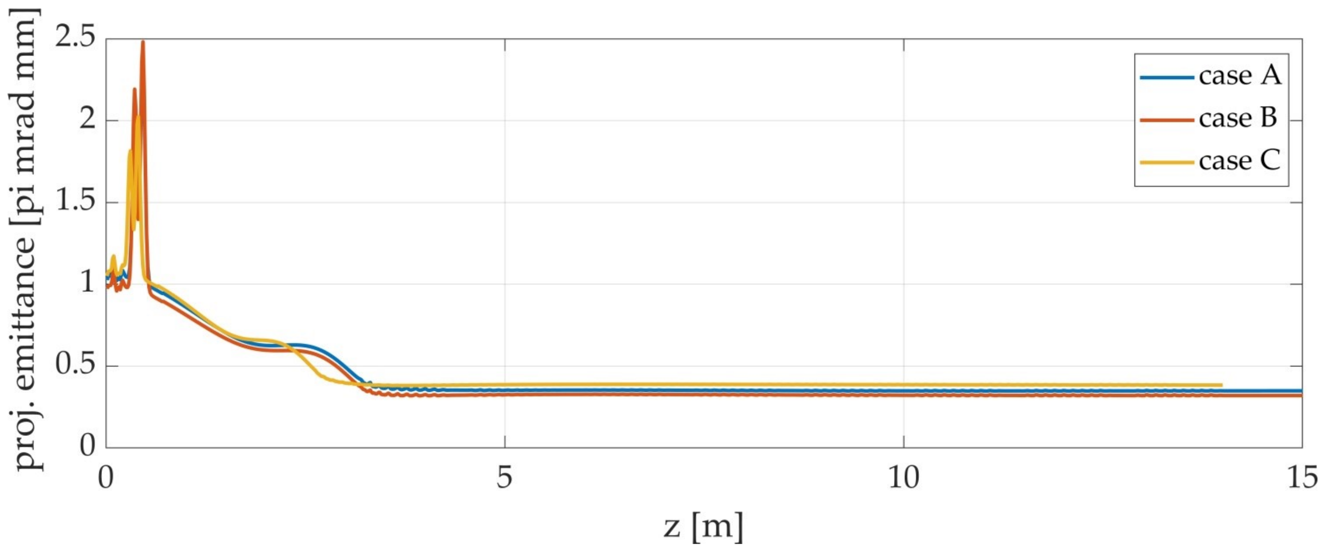
- Geometric constrains in the cryostat will be present
- Positioning of the solenoid closer to the cathode yields better results (with some inconsistency)
- Similar results can be achieved within +- 0.4 meters from the optimal position
- 0.41 [m] seems to be favorable position (to be checked with geometric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

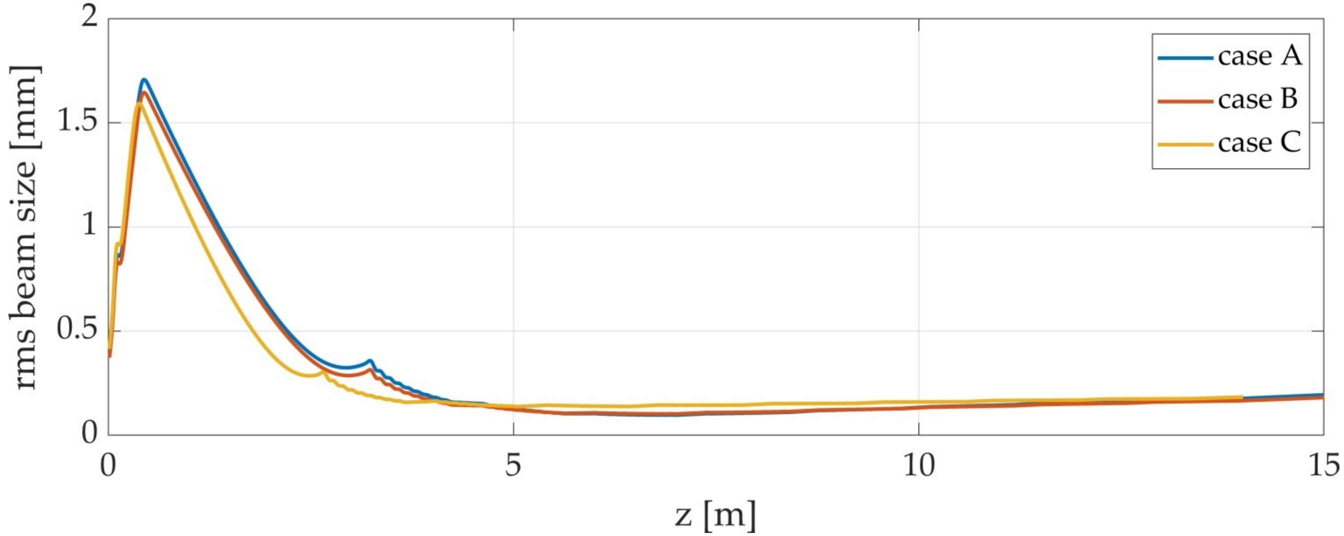
Same results from previous slide but zoomed in:



Injector optimization

Transverse emittance, beam size

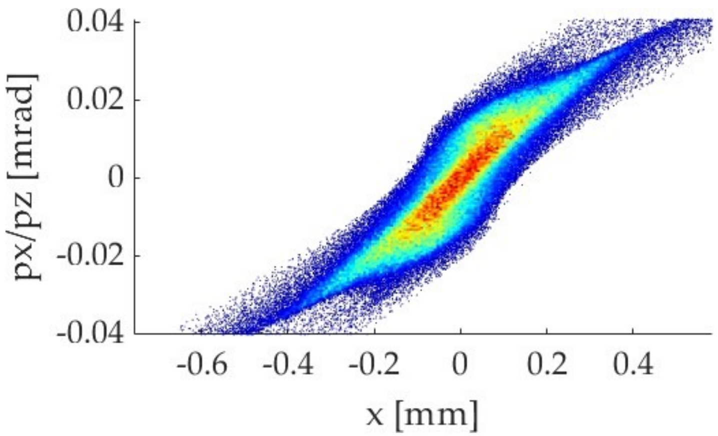




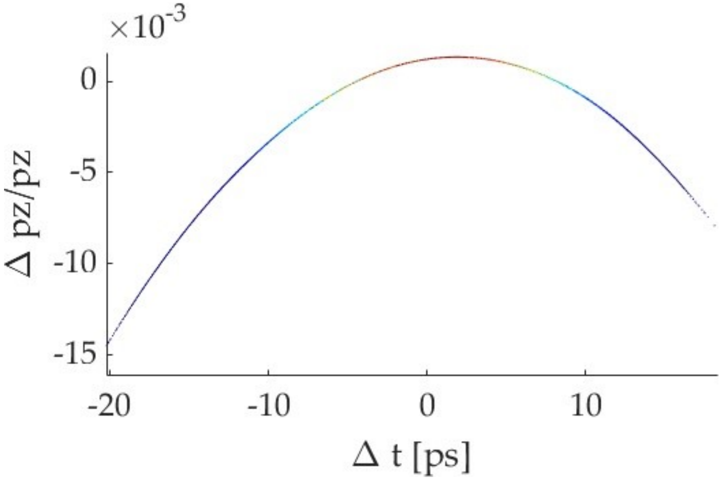
Injector optimization

Case A – larger emittance, smaller bunch length; bunch at 15 m

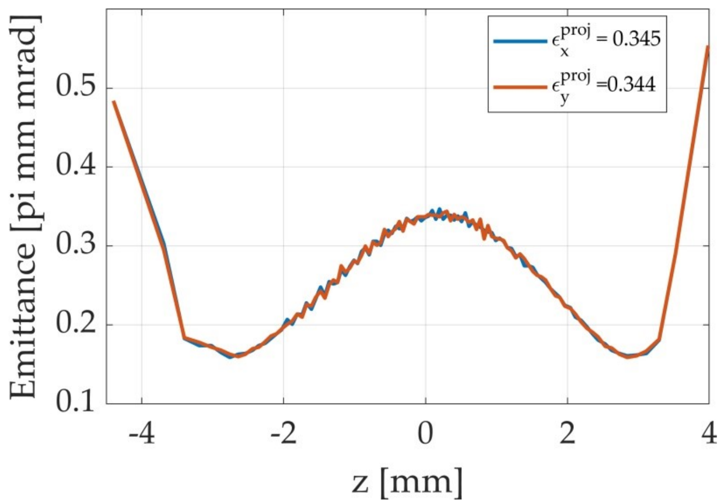
Transverse phase space:



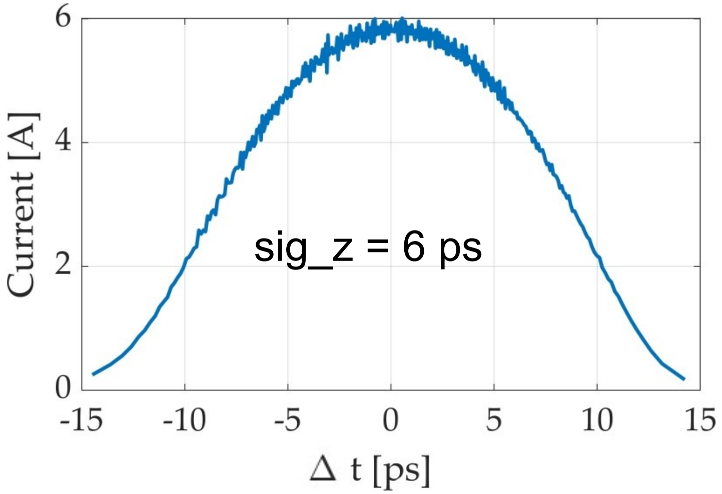
Longitudinal phase space:



Slice emittance:



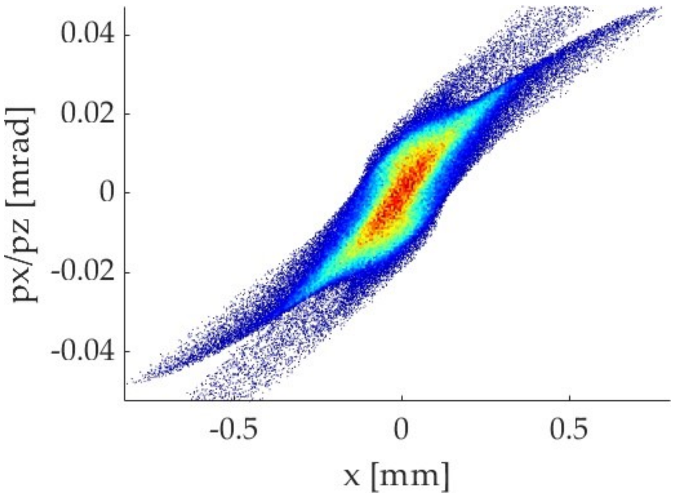
Current:



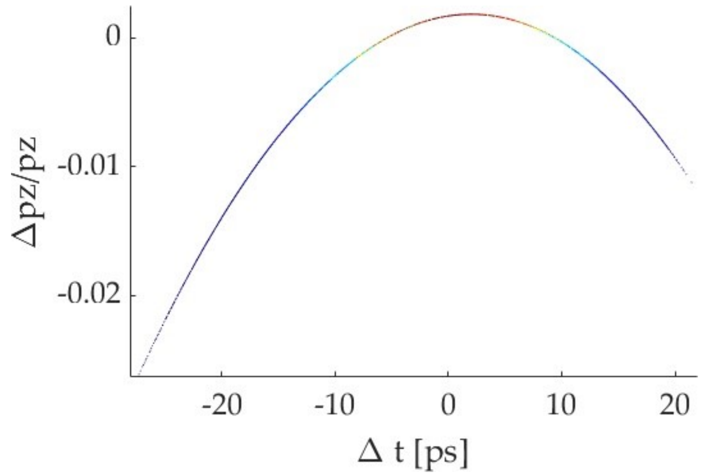
Injector optimization

Case B – smaller emittance, larger bunch length; bunch at 15 m

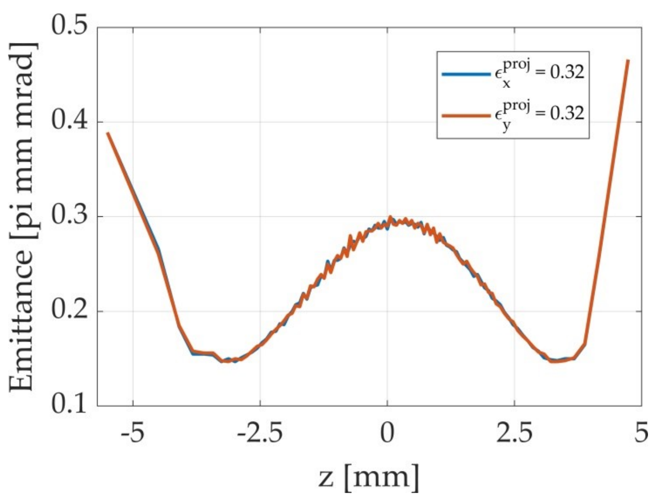
Transverse phase space:



Longitudinal phase space:



Slice emittance:



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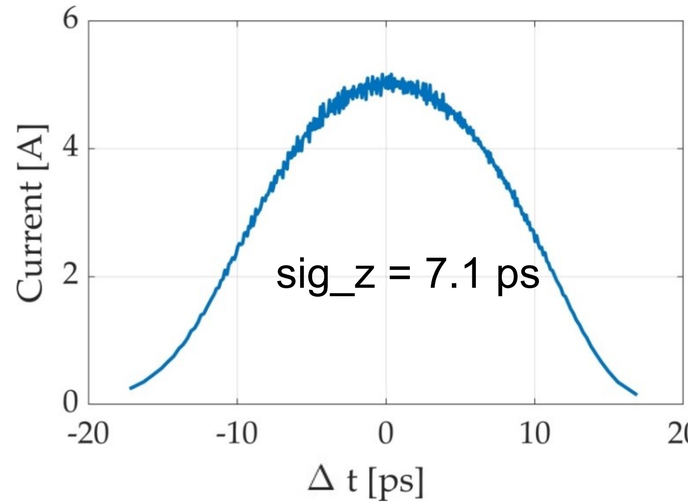
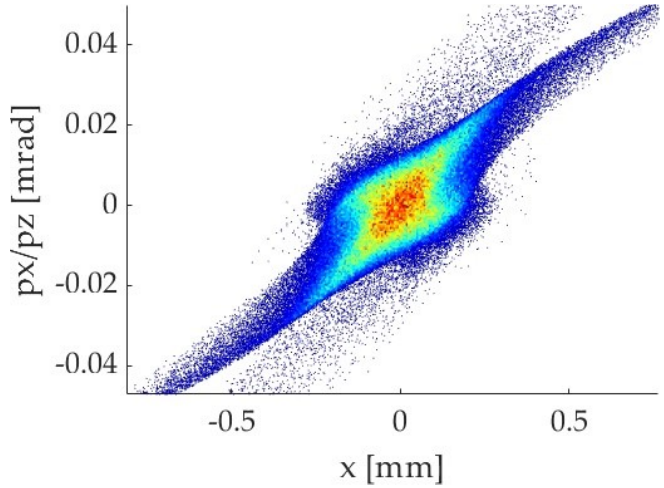


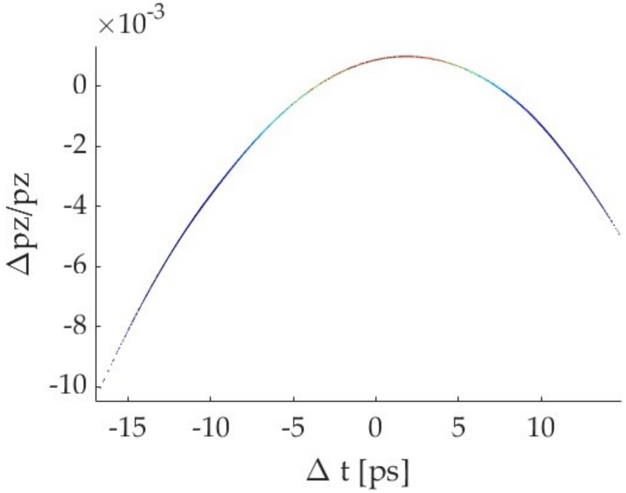
Injector optimization

Case C – largest emittance, smallest bunch length; bunch at 14 m

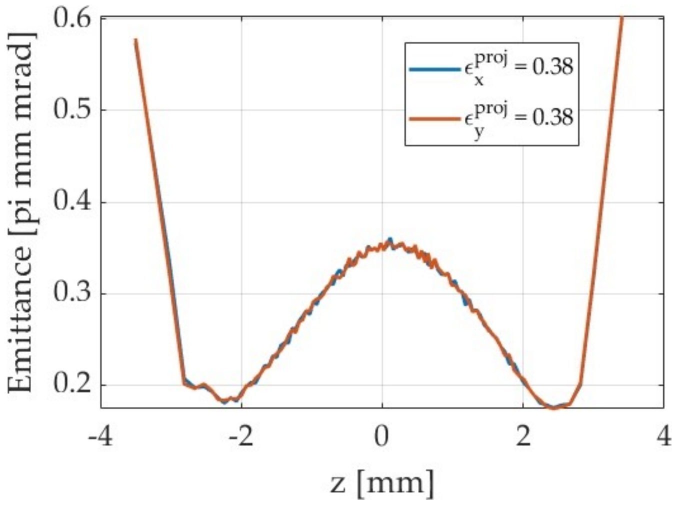
Transverse phase space:



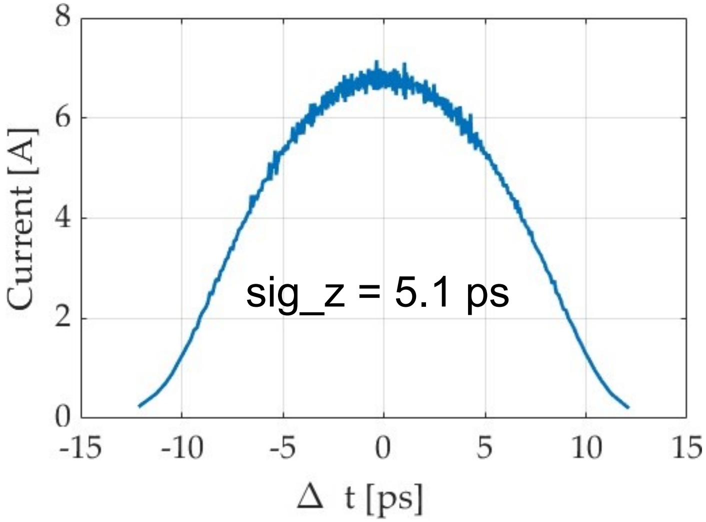
Longitudinal phase space:



Slice emittance:



Current:



Injector optimization

Summary

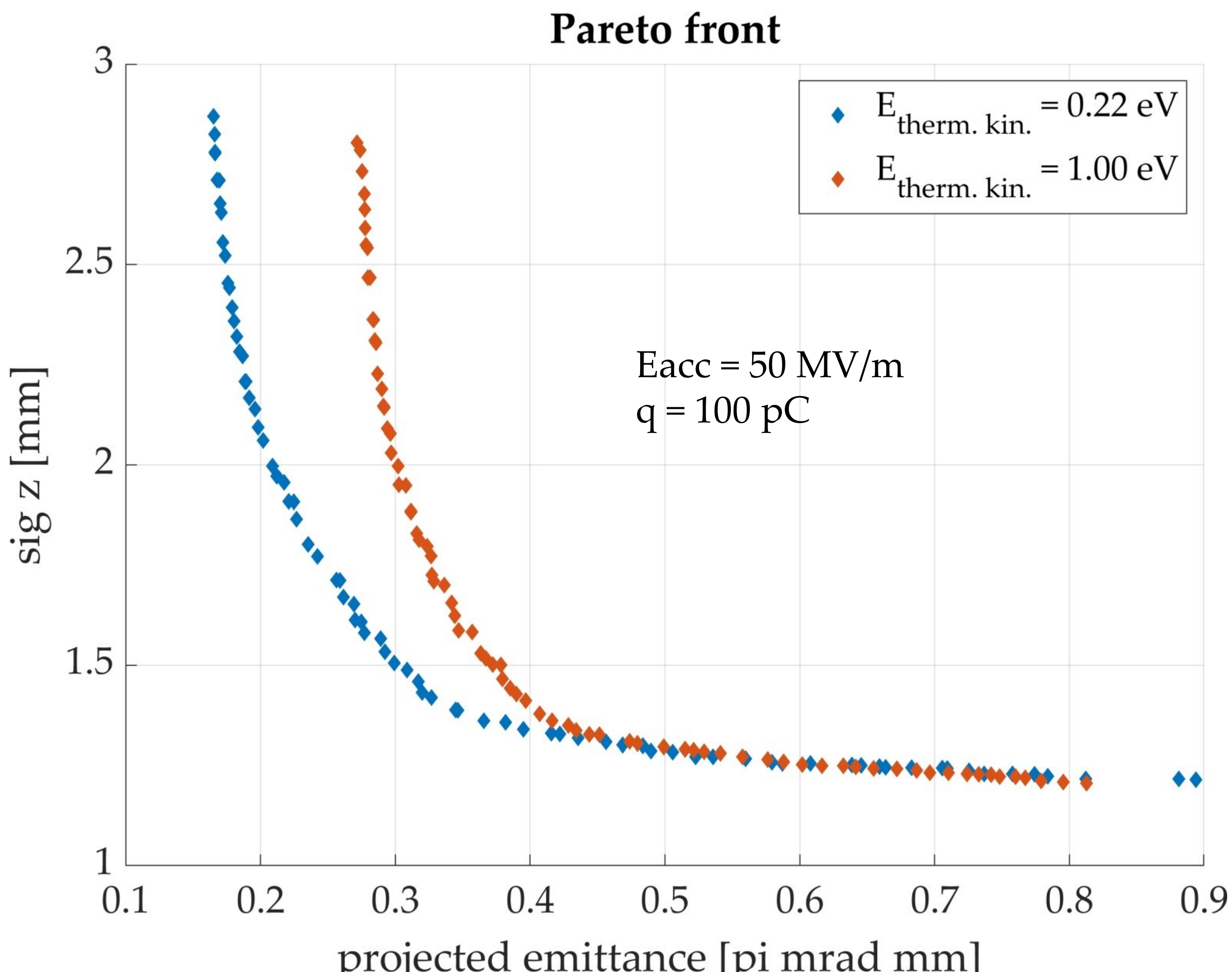
- Laser profile – Gaussian
- Initial thermal kinetic energy 0.22 eV
- Charge – 100 pC

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

- These cases are being analyzed by Y. Chen and M. Dohlus (OCELOT, IMPACT-Z)
- We need to better understand the upper limit of the laser pulse length

Injector optimization

Longitudinal flat top and transverse truncated Gaussian (1σ) laser profile at 50 MV/m



Injector optimization

Coming up next…

For the DESY SRF gun (Pb cathode):

- Consider 50 MV/m and 60 MV/m
- Consider bunch charge of < 100 pC
- Continue optimization with longitudinal FT and transverse truncated Gaussian laser profiles
- Results must be obtained for various thermal emittance values
- Take into account longer pulse (with relatively long laser pulse length -> lower slice emittance)
- *Consider different solenoid field*

For the SRF cavity, which can host green cathodes:

- Selectively repeat optimization for particularly interesting scenarios
- Compare the results

Conclusion

- C++ optimization code runs without problems on DESY Maxwell cluster
- In general, allocating solenoid closer to the cathode yields better results
- The SRF gun gradient is the key for achieving low emittance
- Thermal emittance defines the final emittance
- Longitudinal flat top laser yields better results in comparison to Gaussian

Acknowledgments

- I. Zagorodnov, Y. Chen, H. Qian, X. Li and the colleagues who are involved from the DESY beam-dynamics group

Thank you

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