SRF Photo Injector Development for the European XFEL

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- CW RF photo-injector for EuXFEL
- DESY L-band SRF gun
- Beam dynamics optimization of the CW injector
- Recent beam dynamics results
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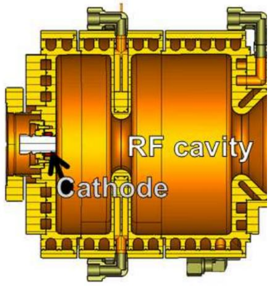
European XFEL in CW mode

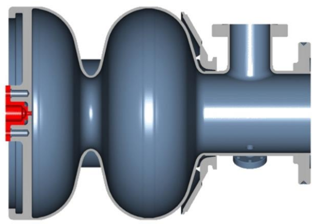
Foreseen CW layout

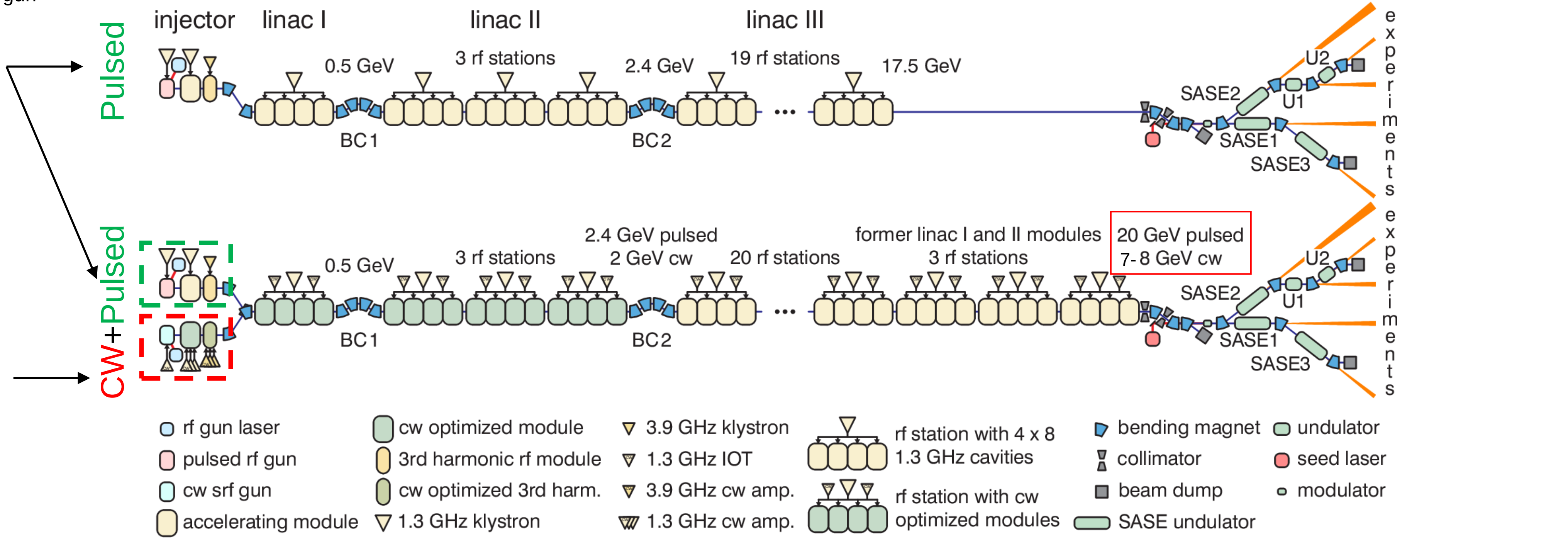
- Separate CW injector part with the accelerating gradient of 16 MV/m
- Modules optimized for CW operation (~16 MV/m) keeping high gradients (up to 32 MV/m) for the pulsed operation in L1 and L2
- 12 out of the 16 present modules from L1 and L2 will be added at the end of L3 (operating in CW at about 7 to 8 MV/m)

Normal conducting 1.3 GHz RF gun



SRF 1.3 GHz gun





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

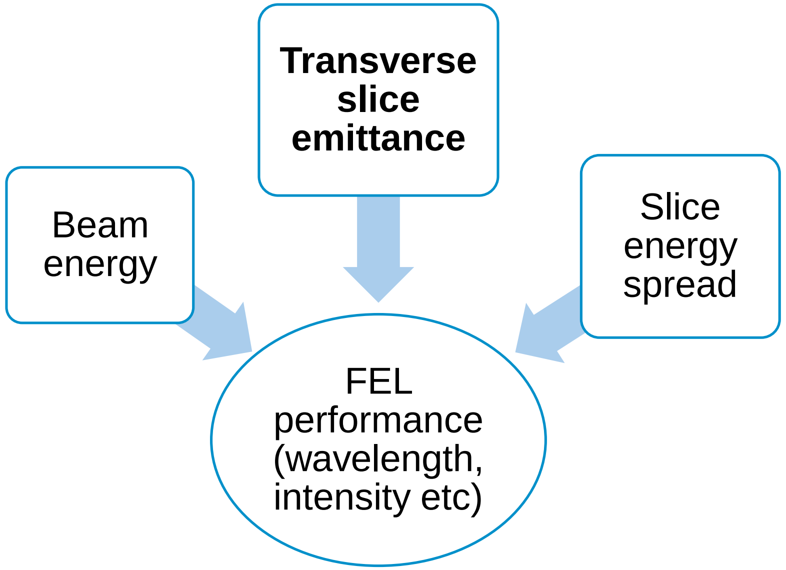
CW RF photo-injector for EuXFEL

Superconducting L-band RF gun and normal conducting QWR RF gun

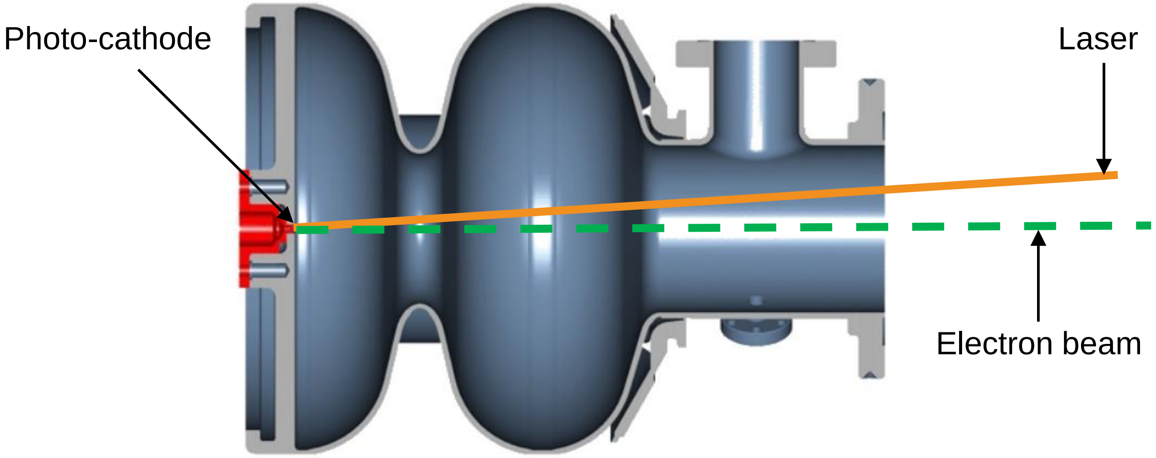
CW RF photo-injector for EuXFEL

RF gun for the FEL

- Beam quality originating from the gun defines overall performance of the FEL machine
- Short bunches with low transverse 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:

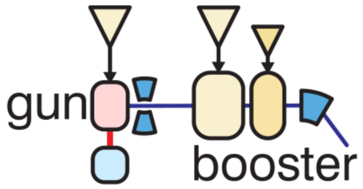


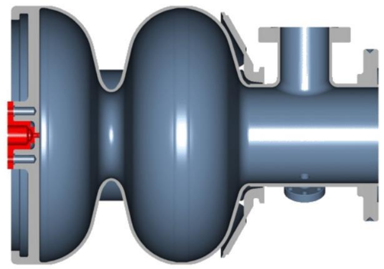
Wish: FEL with 20 keV in CW - > **transverse slice emittance at the level of 0.2 µm; 100 pC**

CW RF photo-injector for EuXFEL

Why L-band SRF gun is preferable in CW for EuXFEL?

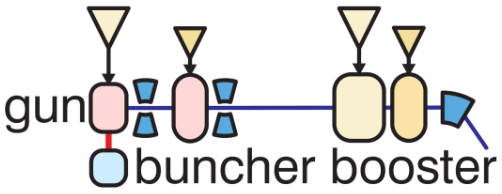
CW L-band SRF gun

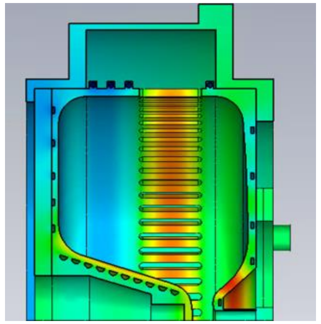




- High frequency 1.3 GHz
- High peak electric field on axis 40 – 60 MV/m
- **High energy beam > 4 MeV**
- **Short bunches – matching main linac**
- High gradient is required for low slice emittance
- Further RnD is required

CW low frequency normal conducting gun (QWR cavity)





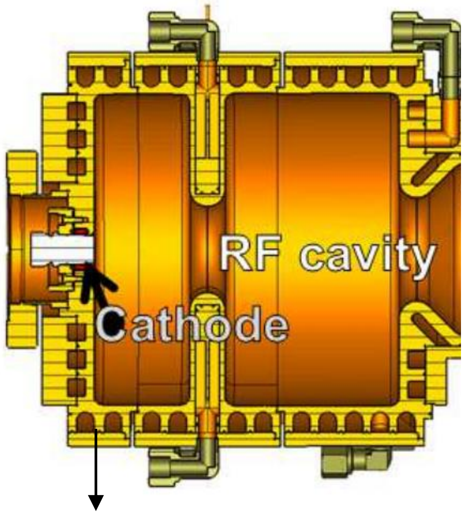
- Low frequency < 250 MHz
- Low and medium peak electric field on axis < 30 MV/m
- Low energy < 1 MeV
- Long bunches – buncher required
- Low slice emittance
- State-of-the-art technology
- Back-up solution for CW EuXFEL – studied at PITZ

CW RF photo-injector for EuXFEL

DESY SRF gun in CW mode

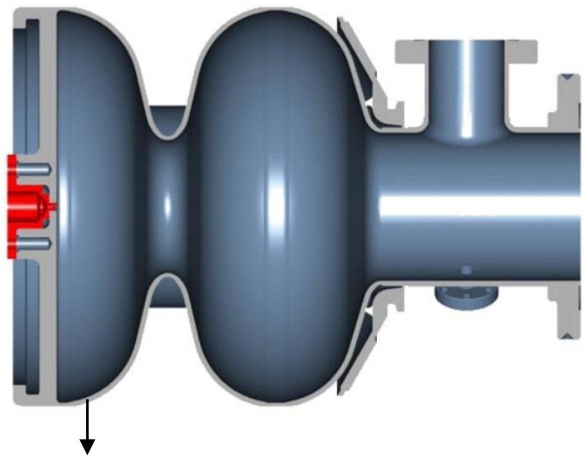
- Idea suggested in 2005*: keep everything as simple as possible
- Gun design which would produce bunches similar to what we have in pulsed mode
- General challenge for SRF guns: cathode insertion
    - Load lock system (HZDR, HZB, KEK)
    - All superconducting gun – approach followed by DESY
    - Superconducting cathode (lead) is inserted via the cathode plug

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



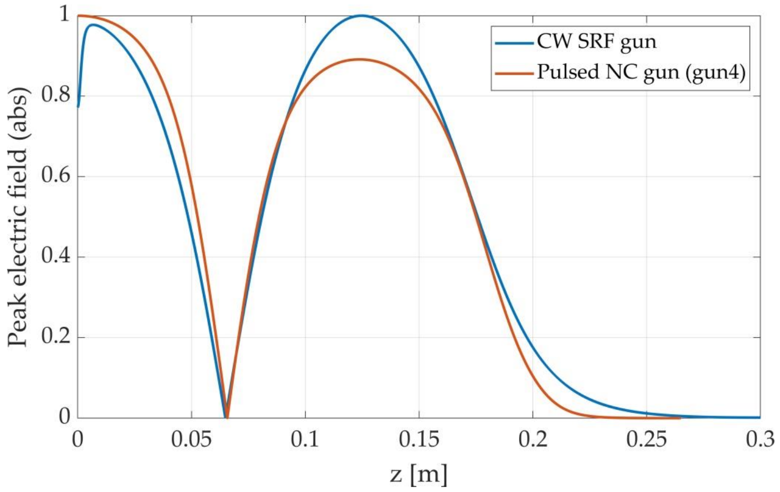
Copper

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



Niobium

Electric field on axis:



*) 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

RnD history, RF shape, peak electric field, cathode

DESY L-band SRF gun

RnD history

16G1:

- Nb as the cathode material
- low quantum efficiency
- lead proposed as the cathode material
- lead coating at the back wall - unsuccessful
- cavity surface preparation must be decoupled from the cathode preparation using a cathode plug

16G2:

- cathode plug screwed to back wall, sealed with indium
- the cavity achieved the required gradients in vertical tests at DESY
- after many cathode insertions the backwall in the region of cathode plug became mechanically unstable and no longer leak tight

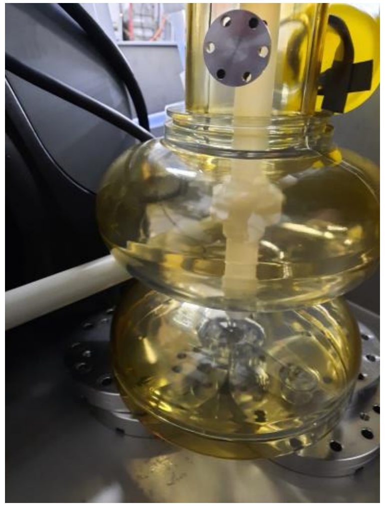
16G3/4:

- backside mechanically reinforced, improved cathode plug design
- backside without deformation, leak tight
- poor RF performance up to October 2020
- after EP at KEK 55 MV/m demonstrated in vertical test

DESY L-band SRF gun

RnD history and current status

16G5/6:
- plane backwall, no cathode opening
- evaluate backwall cooling
- improved the BCP removal at the back wall became much more homogeneous
- mechanical tolerances added up resulting in not tunable cavities
- measurements of the 16G6 with detuned field flatness – up to 48 MV/m for 0-mode in the half cell



16G7/8:
- foreseen to overcome field flatness issue of G5/6
- acceptable field flatness demonstrated
- more homogenous removal by main BCP due to improved "edging head“
- next steps: fine BCP and VT

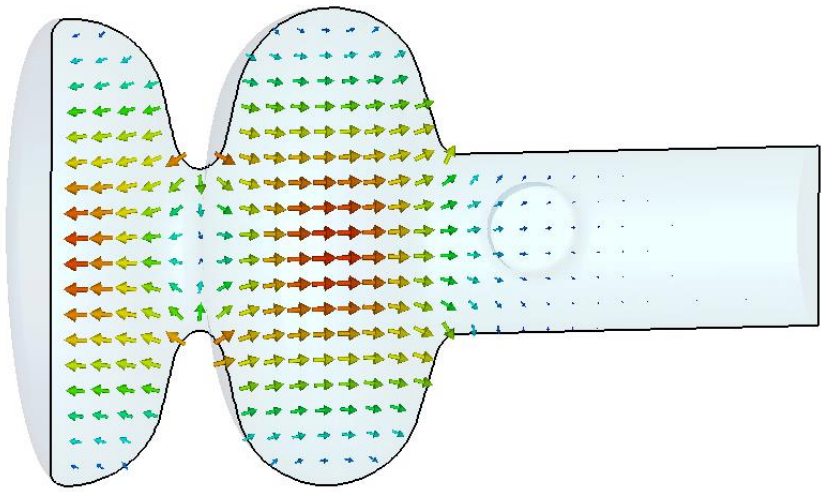
16G9/10:
- incorporating all lessons learned
- backwall of G3/4, RF shape of G7/8
- work is performed at drawings, specification, etc.
- contacting vendors for offers started
- first VT foreseen in the summer 2021

DESY L-band SRF gun

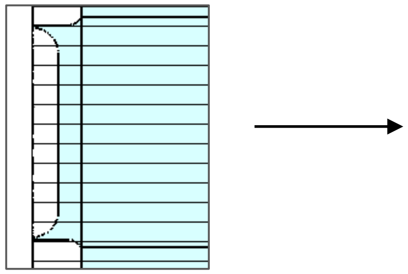
RF shape

- Gun version 16G10 (RF shape of 16G7)
- 1.6-cell TESLA cavity operated
- Operating frequency 1.3 GHz; TM_{010}

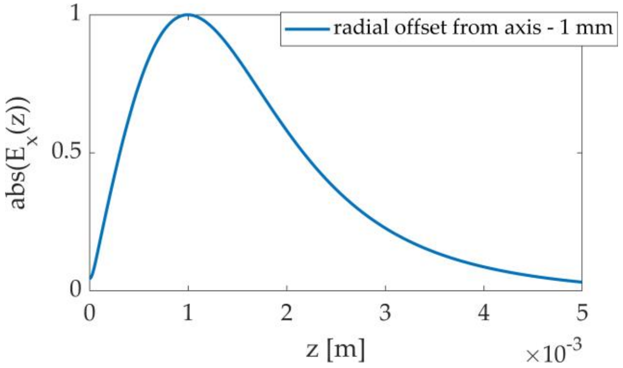
Electric field distribution of the TM_{010}; phase advance - π:



Retracted cathode (450 µm):



Transverse electric field near cathode:



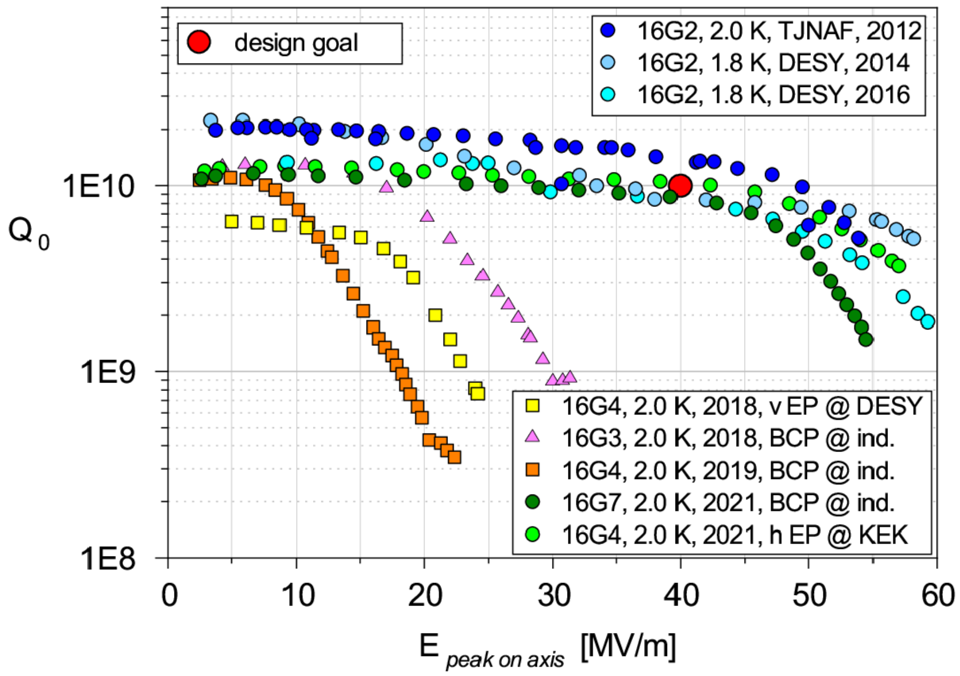
- Cathode retraction is a beneficial approach for the transverse emittance compensation
- Positive impact confirmed for longitudinal Gaussian; transverse radial uniform laser profile
- Impact when the beam is formed by longitudinal flat top; transverse truncated Gaussian at 1 sigma is not clear - under investigation

DESY L-band SRF gun

Peak electric field

- Results of vertical tests
- Figure of merit Q vs Ep
- Peak electric field of 40 MV/m up 60 MV/m demonstrated in vertical tests
- Still do be demonstrated in horizontal tests

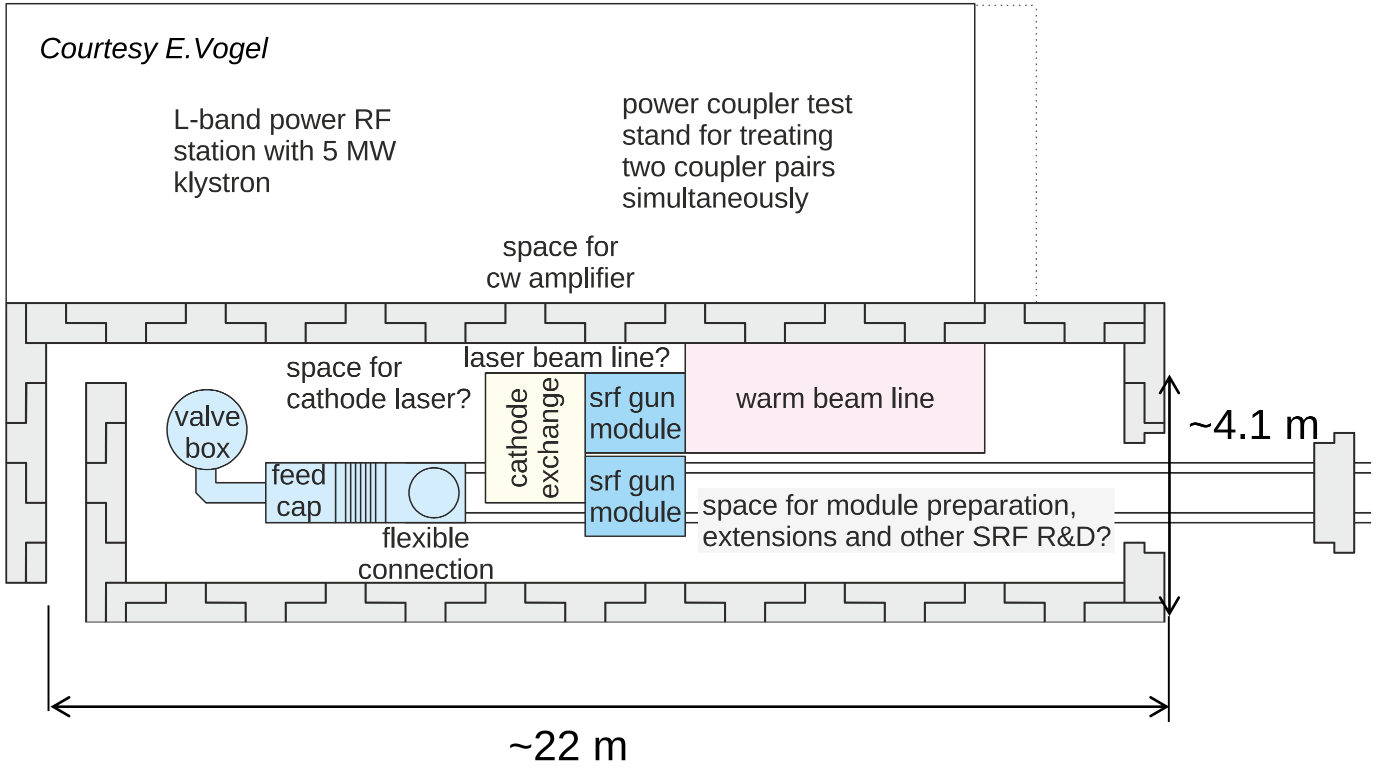
Vertical test results



DESY L-band SRF gun

Experimental horizontal test stand for L-band SRF guns

- Horizontal test stand will 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

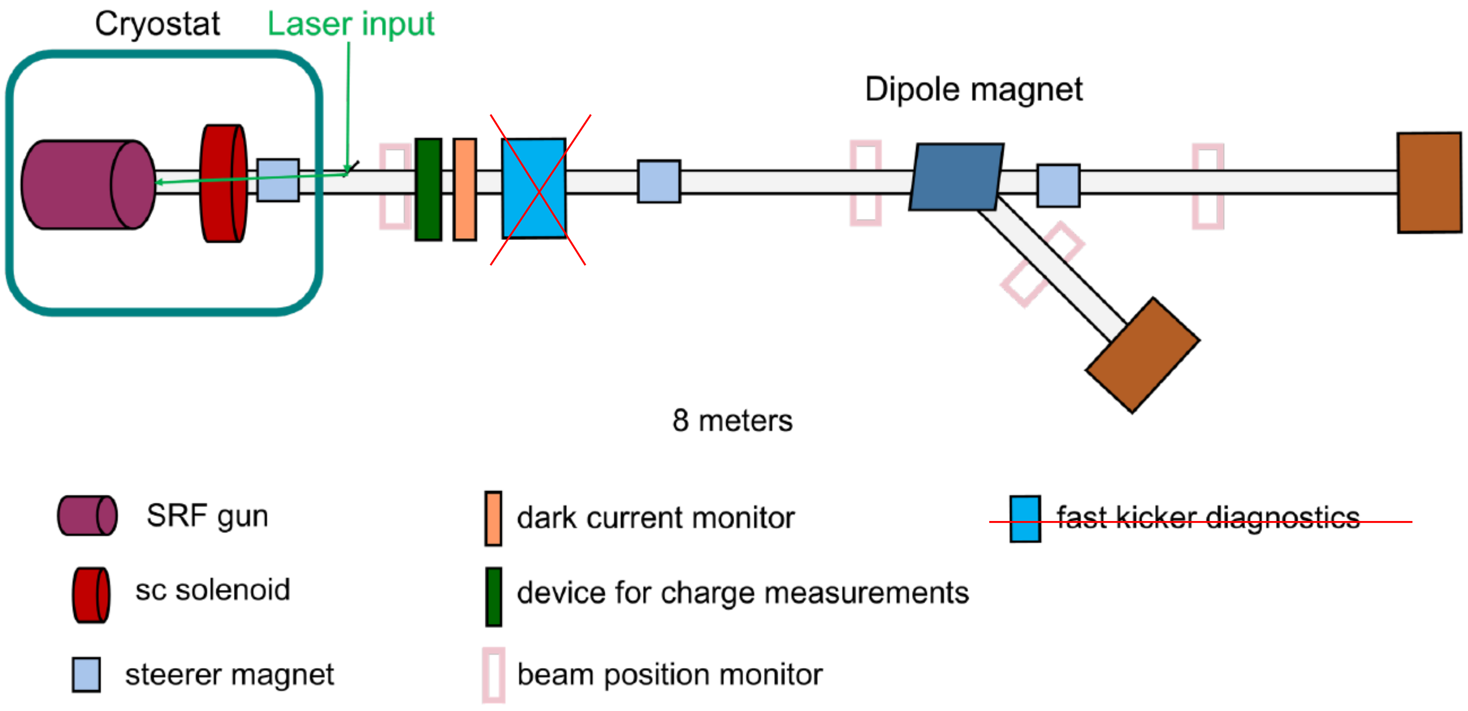


AMTF bunker XATB3:

DESY L-band SRF gun

Experimental horizontal test stand for L-band SRF guns

- the test stand shall be expandable in several steps
- basic aim: evaluation of the SRF gun performance prior to the installation in the CW linac and R&D of CW L-band SRF guns



Operating parameters

- SRF gun frequency 1.3 GHz
- bunch charge 100 pC
- bunch repetition rate 10 Hz to 1 MHz
- beam energy 3.5 to 6 MeV

Measurements

- RF parameters of the SRF gun
- bunch charge
- dark current
- beam energy
- transverse projected emittance

Challenges

- control system and real time data display in CW
- space limitations in the AMTF bunker

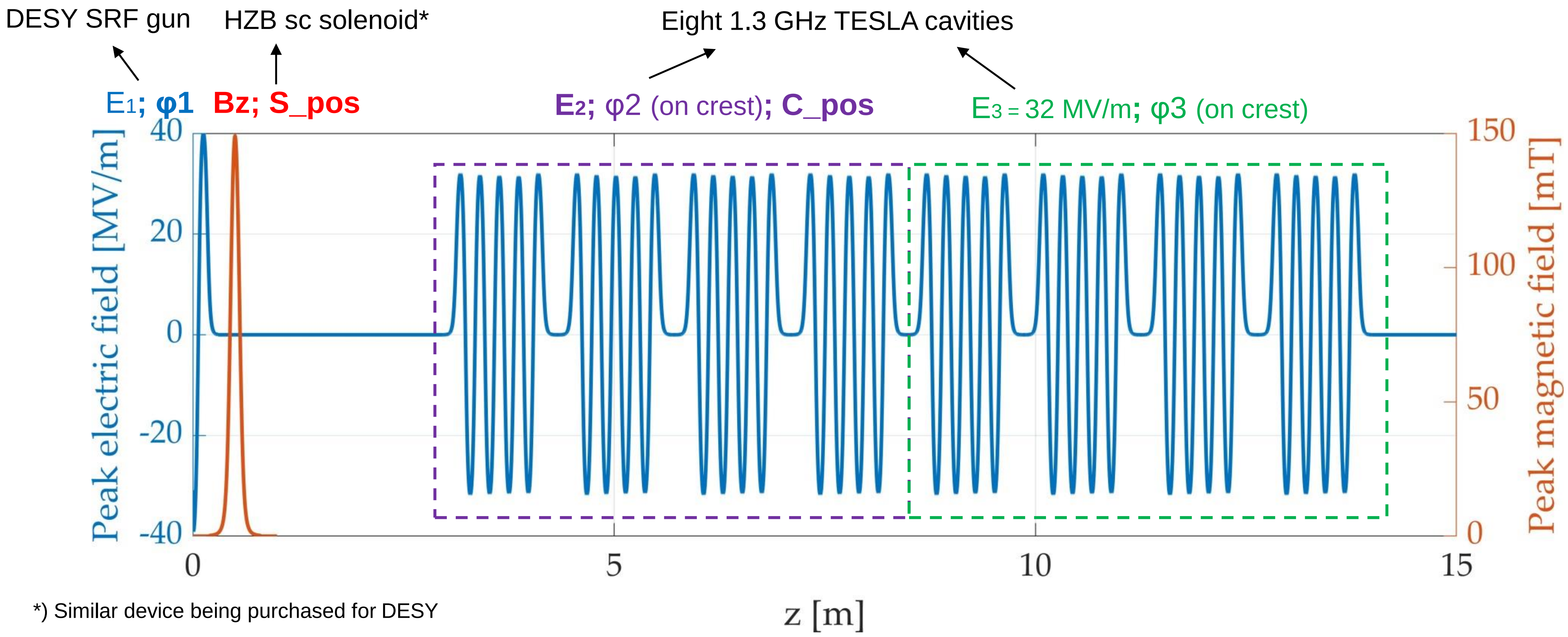
Beam dynamics optimization of the CW injector

Some recent results

Beam dynamics optimization of the CW injector

Injector setup for the optimization

- Multi-objective optimization carried out using LBNL C++ code
- ASTRA for beam dynamics simulations; 10 000 particles per run; interesting cases recalculated with higher accuracy
- Goal: minimize transverse projected emittance and bunch length at 15 [m] for 100 pC bunces

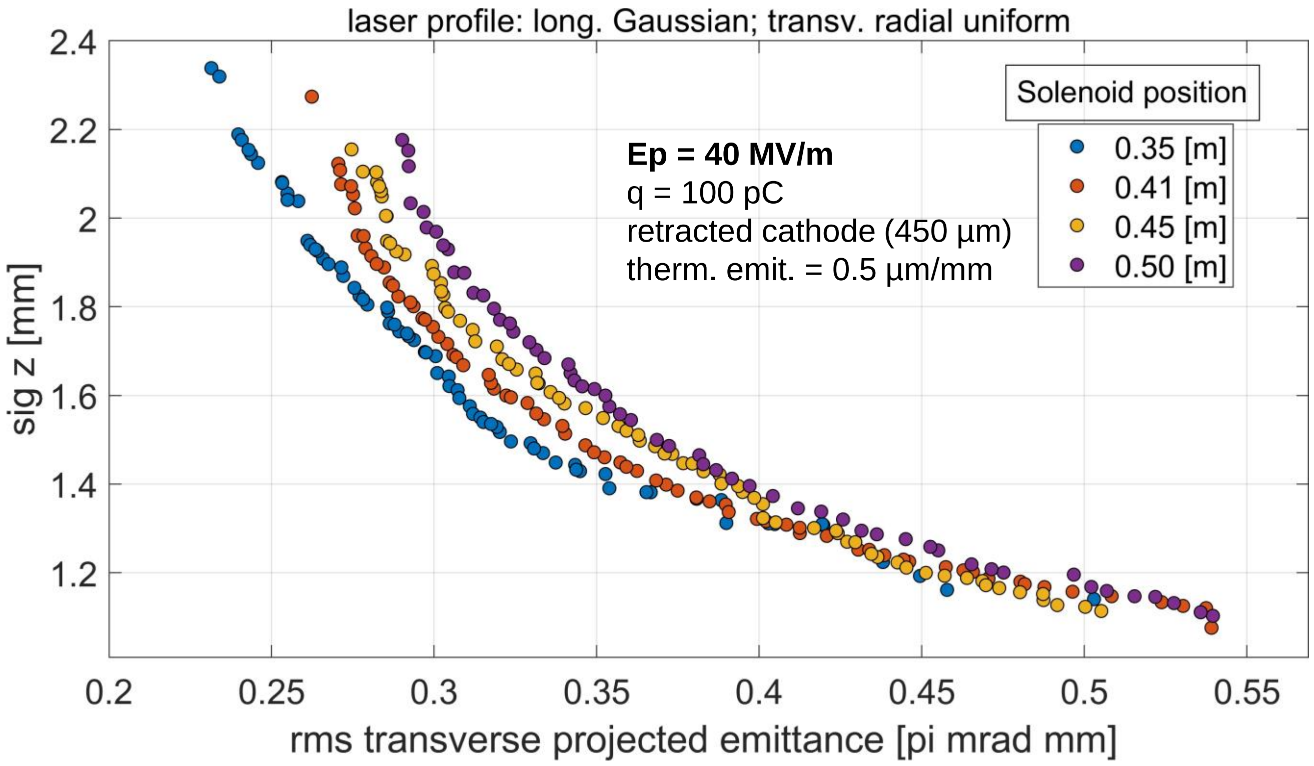


*) Similar device being purchased for DESY

Beam dynamics optimization of the CW injector

Position of the solenoid

- Result of the optimization - Pareto front
- Final position of the solenoid depends on constrains
- Solenoid field must not perturb superconducting state of the SRF gun
- Boundaries for choosing solenoid position definition are not final
- Allocating solenoid closer to the cathode yields better results

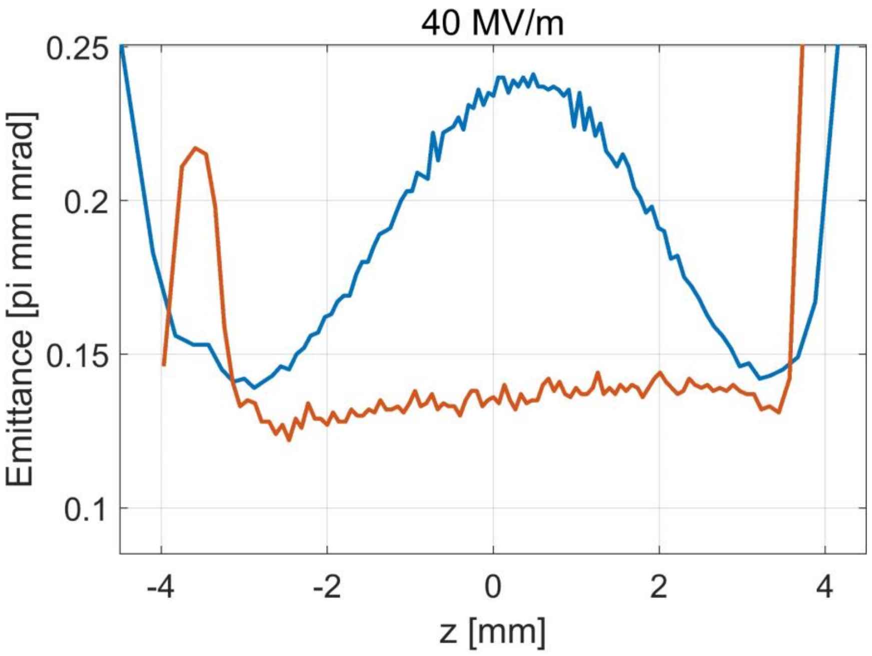


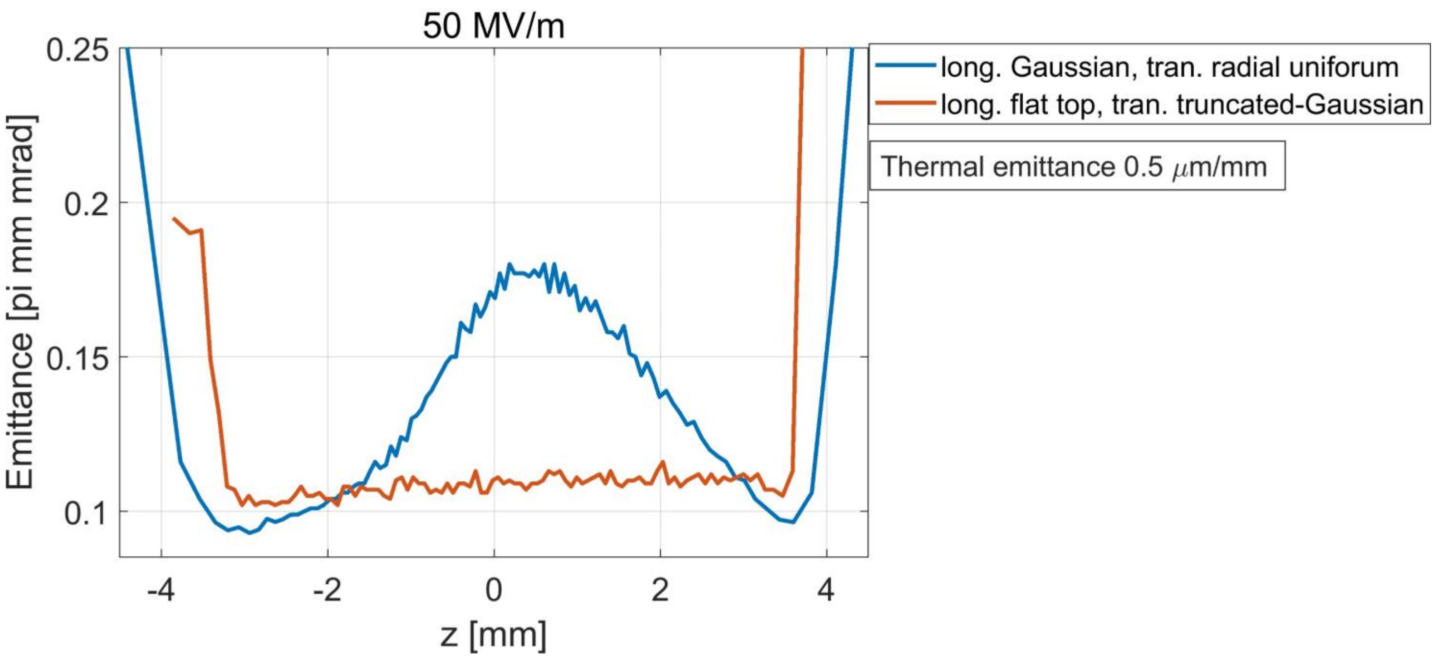
- Considered laser profile yields transverse emittance at the level of 0.3 µm (with low thermal emittance!)
- Consider advanced laser shaping
- Consider shorter solenoid length and allocate it as close as possible to the cathode
- Consider scenario with Ep = 50 MV/m

Beam dynamics optimization of the CW injector

Recent data concerning beam dynamics

- Transverse truncated-Gaussian (at 1 σ) laser profile allows to obtain smaller transverse slice emittance in comparison to radial uniform*
- Higher peak electric field at the cathode (i.e. on axis) allows to further minimize the transverse emittance
- Transverse core slice emittance is below 0.15 μm for the considered parameters and preferable laser profile





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

Conclusion and outlook

- SRF L-band gun is a preferable solution for the CW EuXFEL
- RnD of the DESY SRF gun is ongoing, upcoming new prototypes incorporate all previously learned lessons, 40-60 MV/m achieved in VT, horizontal tests needed and foreseen
- Final layout of the SRF gun will be confirmed soon w.r.t gained experience during RnD
- We have started beam dynamics studies: optimization of the CW injector, start-to-end simulations including microbunching phenomena
- Possibility to reach slice emittance at the level of 0.2 µm and below has been demonstrated in simulations (under several assumptions) – to be verified experimentally using test stand
- Low thermal emittance, laser shaping, solenoid configuration and the peak electric field in the gun are decisive factors to reach low transverse slice emittance