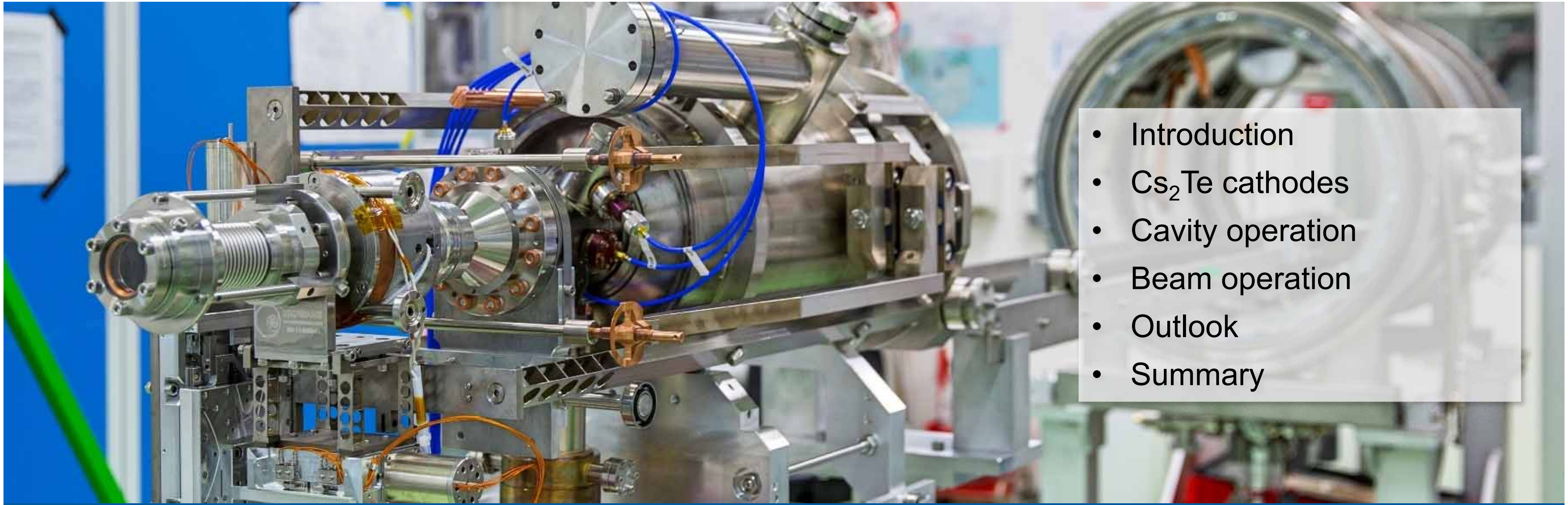

- Introduction
- Cs_2Te cathodes
- Cavity operation
- Beam operation
- Outlook
- Summary

OPERATIONAL EXPERIENCE FROM 8 YEARS OF ELBE SRF GUN II

The 21st International Conference on Radio-Frequency Superconductivity (SRF 2023)
25 to 30 June 2023 at the Amway Plaza Hotel in Grand Rapids, Michigan, USA.

Institute für Strahlenphysik · FWKE / ELBE · Dr. André Arnold · a.arnold@hzdr.de · www.hzdr.de

On behalf of the ELBE SRF gun group

HZDRs pioneering work over the last 20 years

Historical overview		
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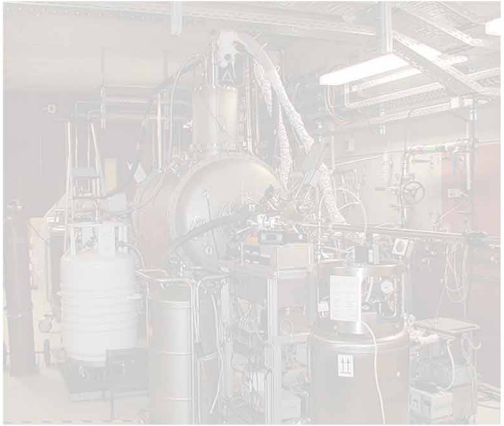
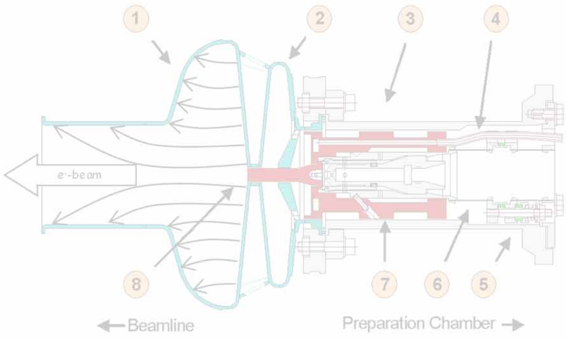
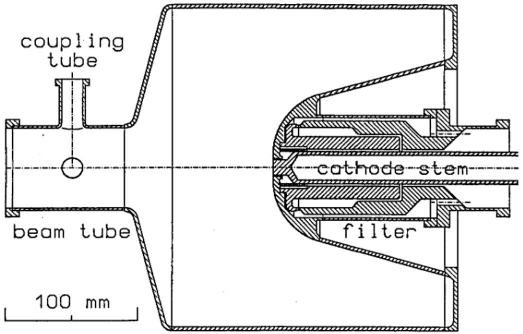




Cavity: Niobium ½ cell, TESLA 1.3 GHz
Cathode: Cs_2Te (262 nm, 1 W laser) thermally isolated, LN_2 cooled

Cavity: Nb re-entrant type 500 MHz
Cathode: Cs_3Sb (532 nm, 1 W laser) electrically isolated, LHe cooled



Cavity Material	High RRR Nb
Frequency	500 MHz
Peak Surface E/E_C	1.1
Peak Surface B/E_C	2.4 $\frac{mT}{MV/m}$
G factor Cavity	90 Ω
G factor Cathode	390 MΩ
Q_0 at 4.2 K	10^9
Acc. Distance	10 cm

H. Chaloupka et al., Proc. 4th SRF Workshop, KEK, Japan, 1989

A. Michalke et al., Proc. of 5th SRF Workshop, DESY, Germany, 1991

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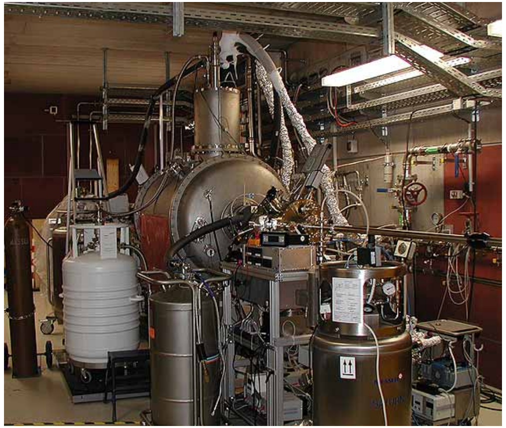

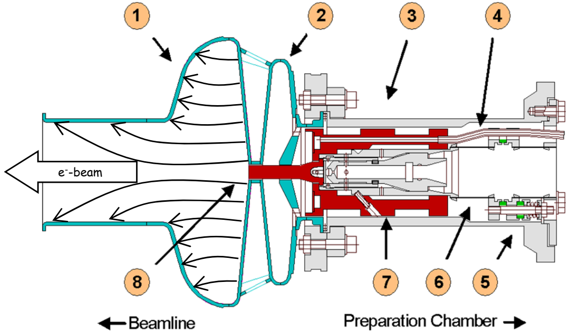

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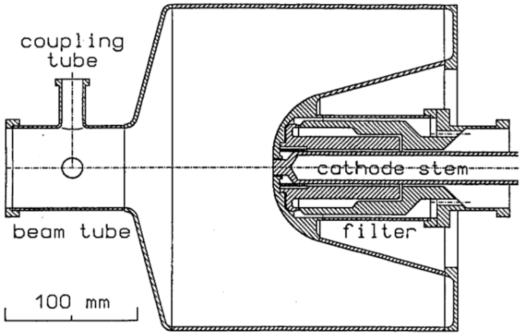

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DRESDEN concept HZDR

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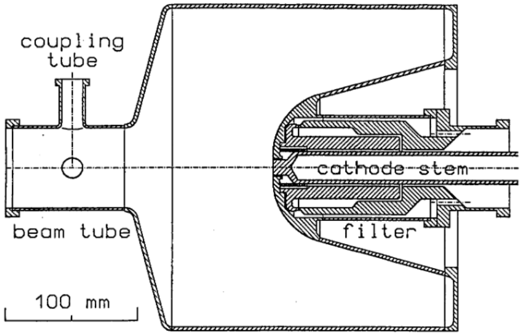

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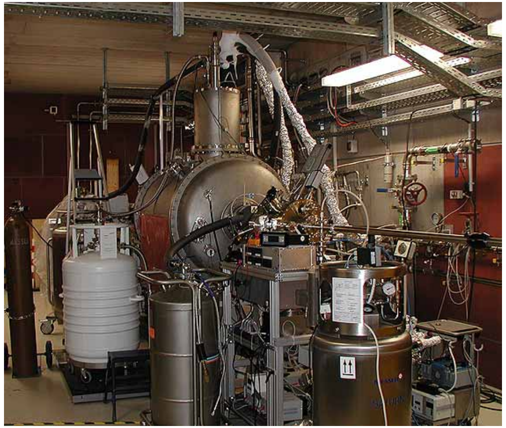

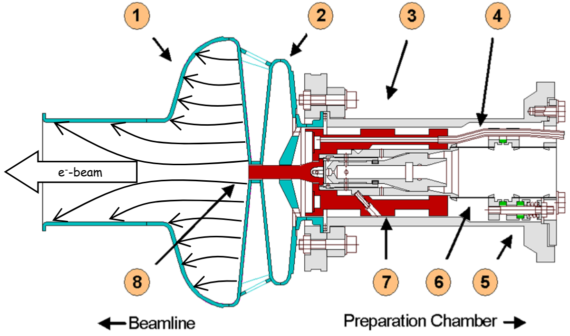

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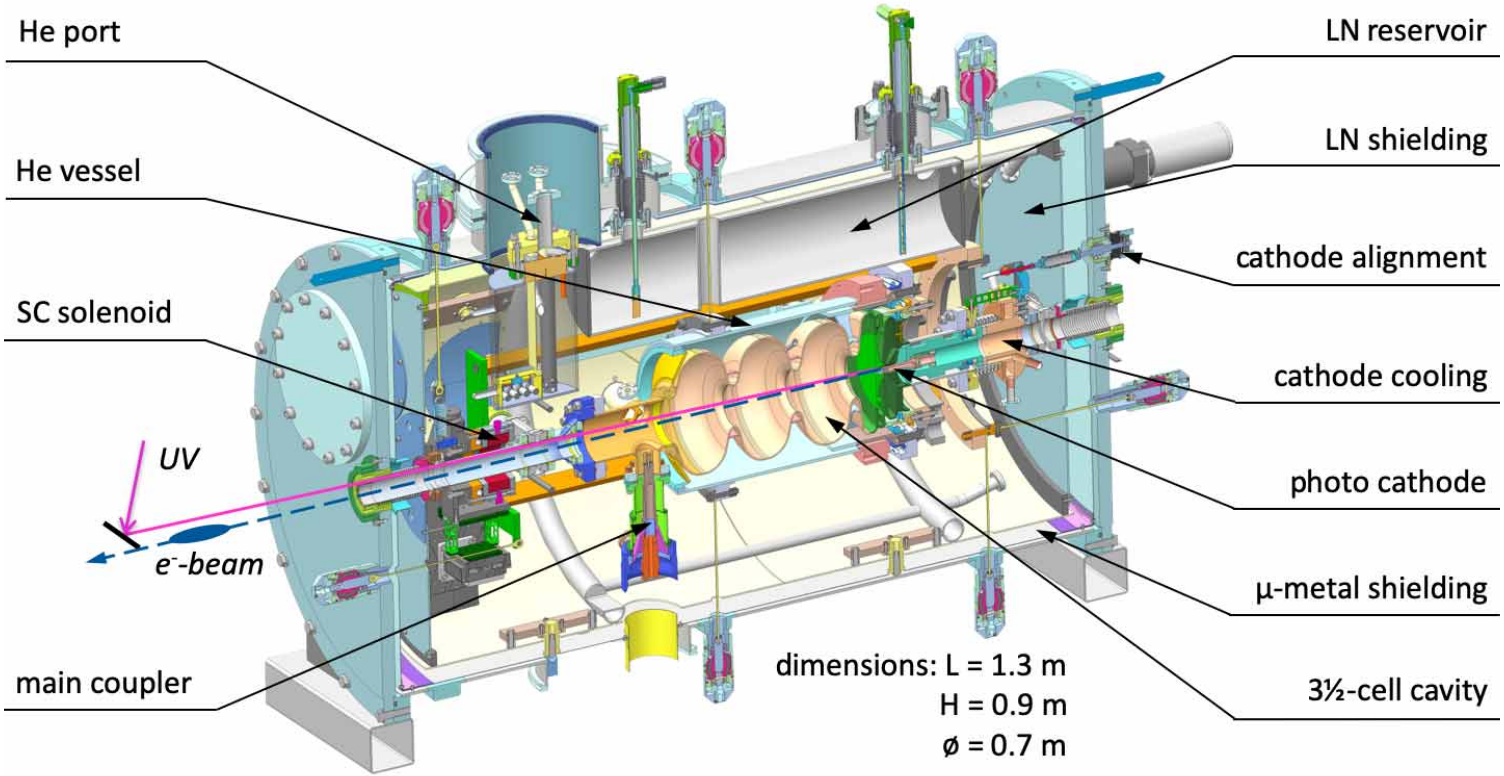
Cryomodule of ELBE SRF gun II



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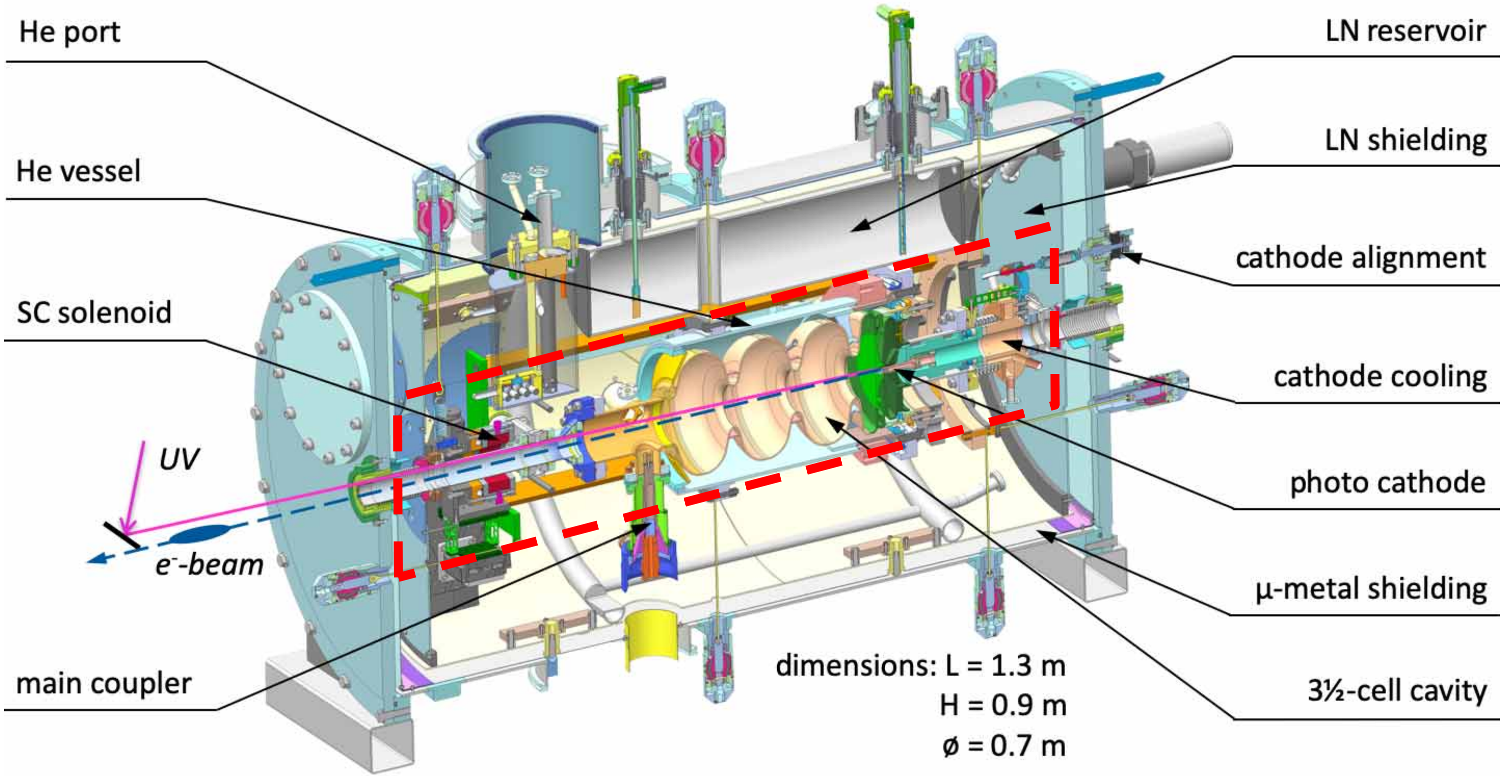
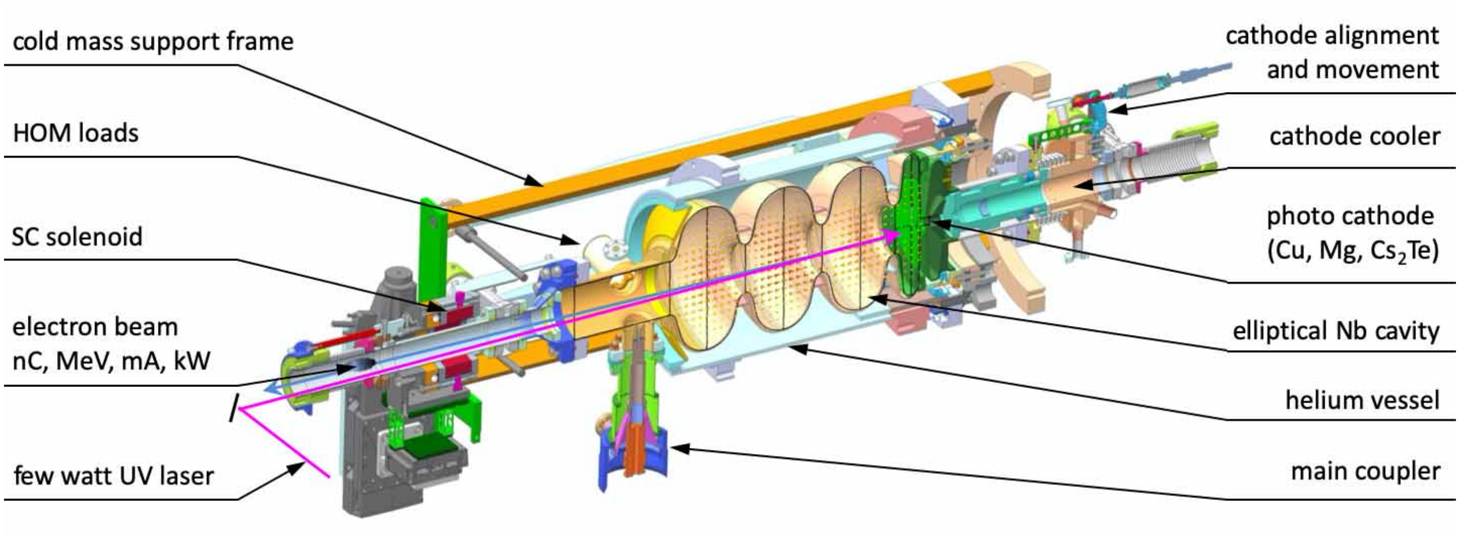


Coldstring



cold mass support frame
HOM loads
SC solenoid
electron beam
nC, MeV, mA, kW
few watt UV laser
cathode alignment
and movement
cathode cooler
photo cathode
(Cu, Mg, Cs_2Te)
elliptical Nb cavity
helium vessel
main coupler

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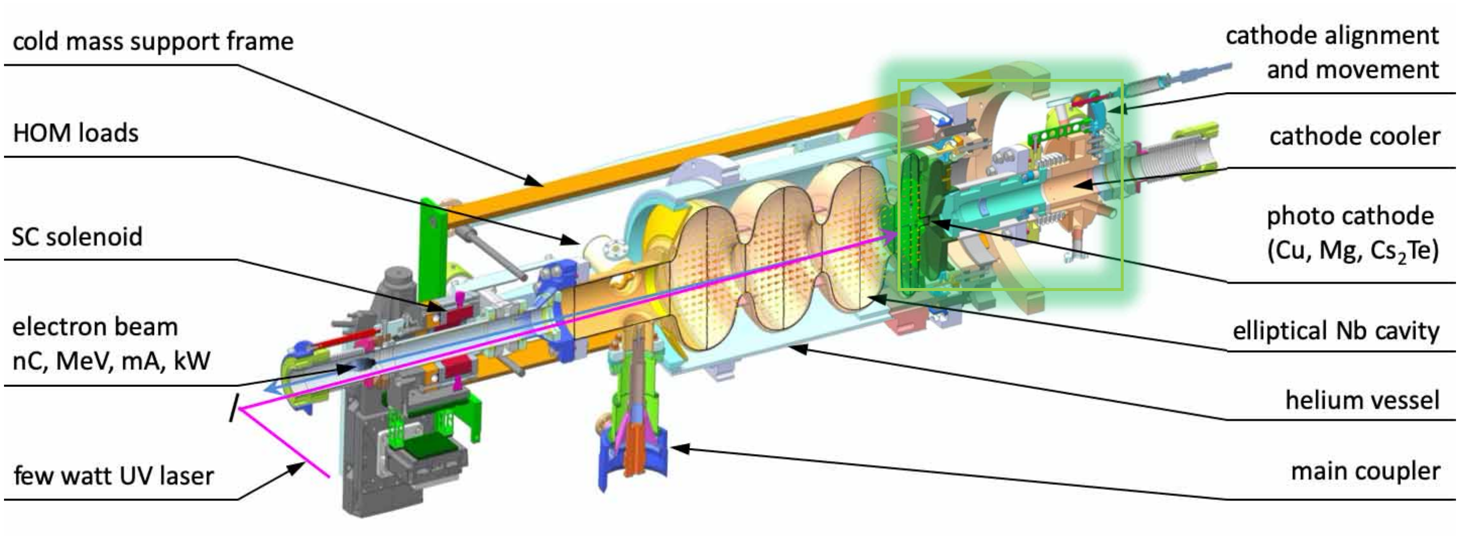

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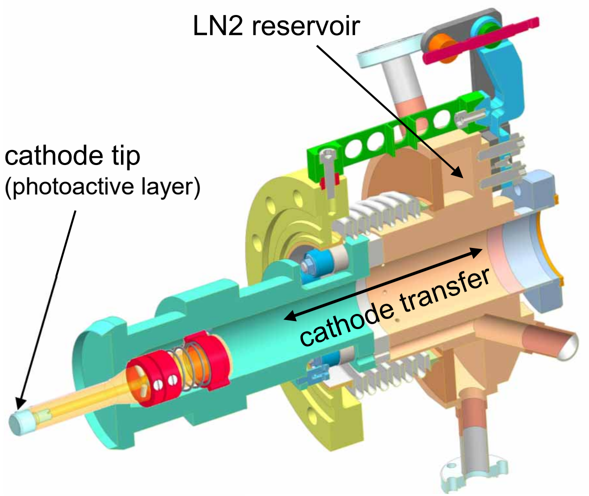
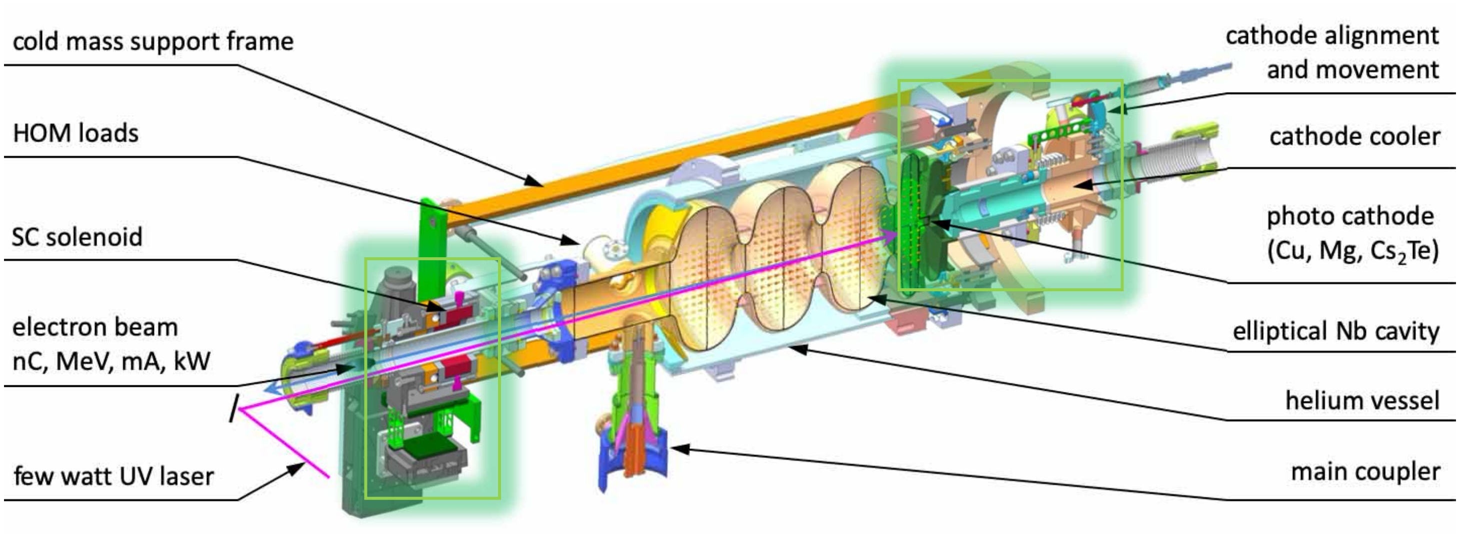
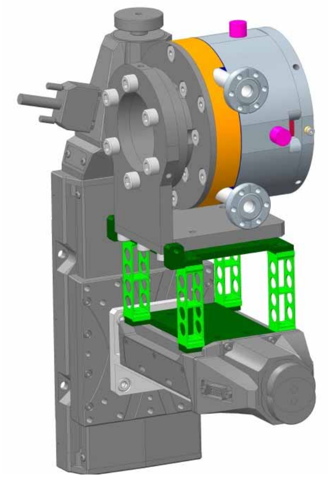


LN2 reservoir
cathode tip
(photoactive layer)
cathode transfer

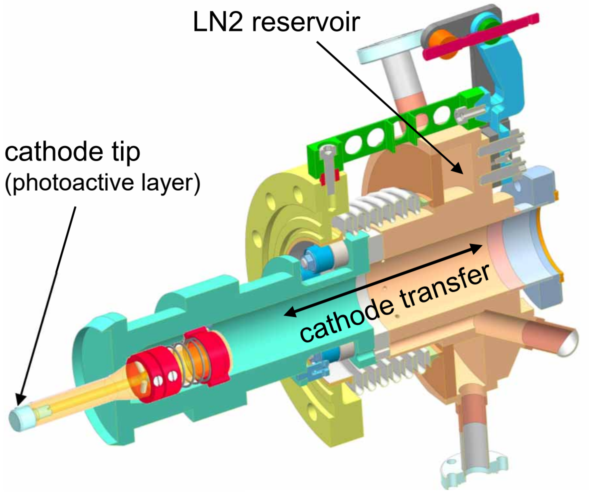
Coldstring



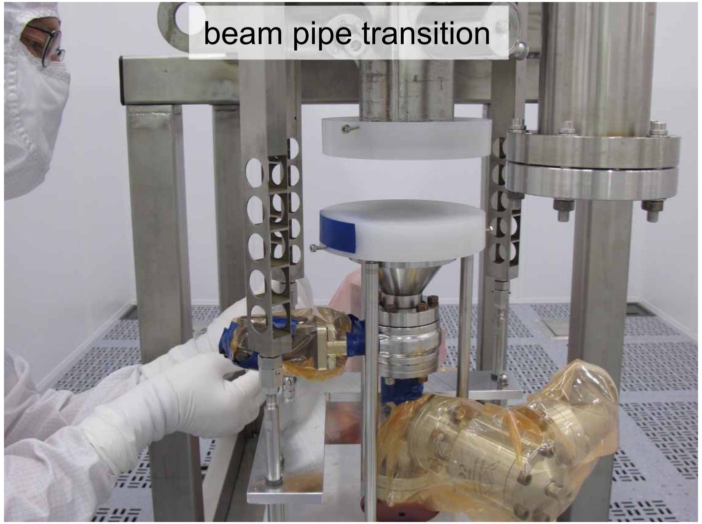


- Cs_2Te, Cu, GaAs, Mg cathodes
- cathode cooling by LN to 77 K
- cathode transfer into the cold gun
- therm. and electrical isolation
- DC bias up to 7 kV to suppress MP
- moveable (±0.6 mm) by remote stepper for best RF focusing

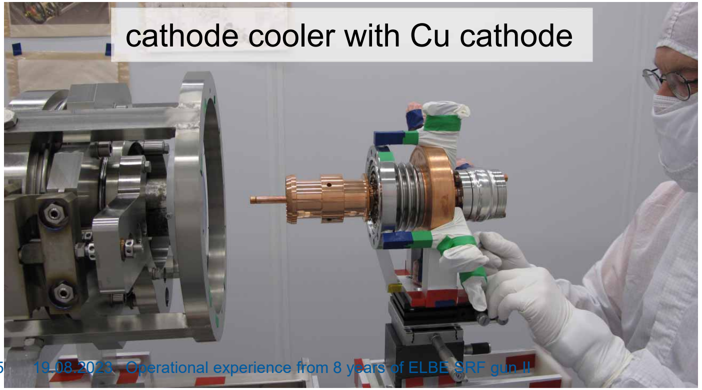
- SC solenoid $B_{z,max}$=0.5 T @ 10 A
- Remote controlled xy-table (77 K)



Cold mass cleanroom assembly at JLab



Cavity was built at JLab by P. Kneisel / G. Ciovati and many others helped!



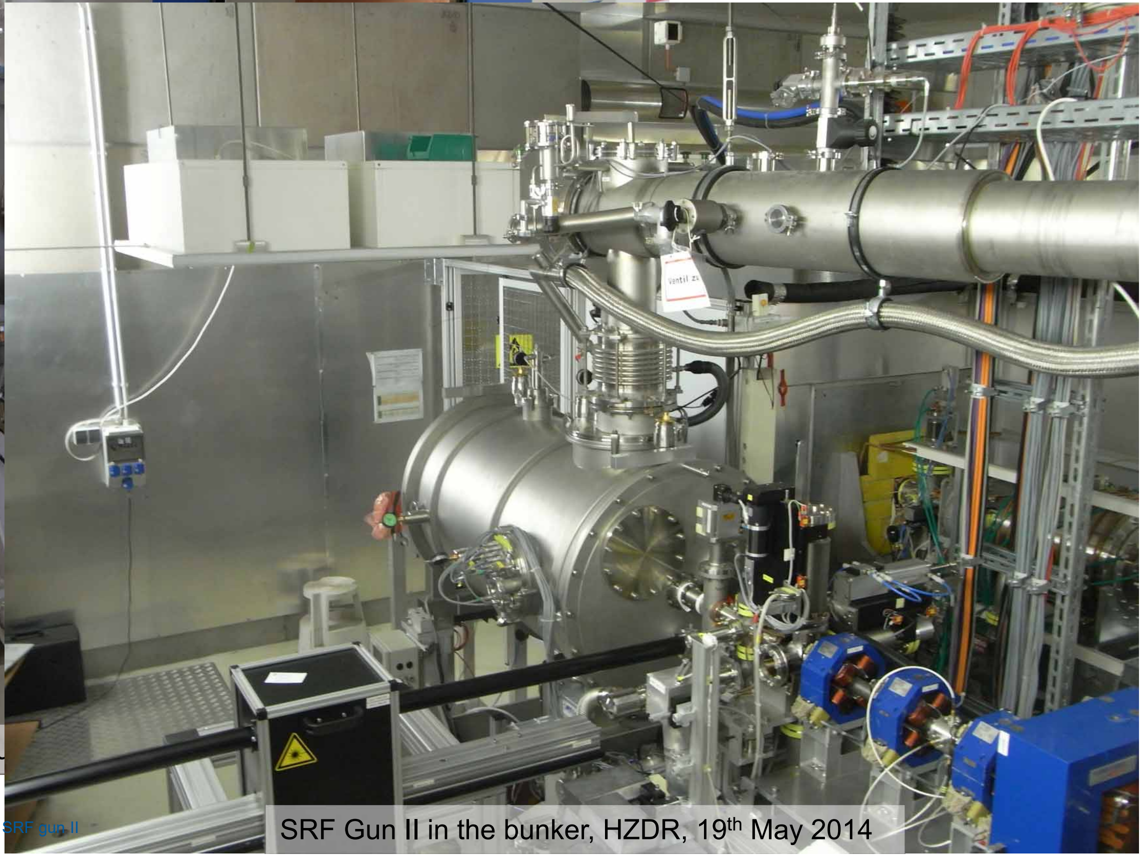
Cryomodule assembly at HZDR

“procession” of SRF Gun II into the bunker, HZDR, 5th May 2014

DRESDEN concept HZDR

Cryomodule assembly at HZDR

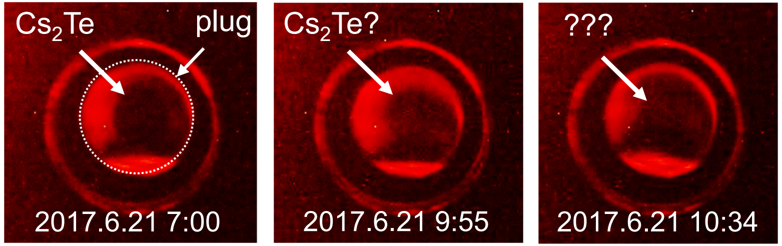
“procession” of SRF Gu



SRF Gun II in the bunker, HZDR, 19th May 2014

HZDR

Cathode overheating, total loss of Cs_2Te



- **Problem:** Cathode overheating in the 2nd week operation, total loss of Cs_2Te layer in the gun, FE + drop of cavity Q0
- **Investigation:** all thermal contacts of cathode insert: (#1) Mo plug and Cu body, (#2) Cu body and Cu cooler, (#3) Cu cooler and LN2 reservoir (ceramic in between)
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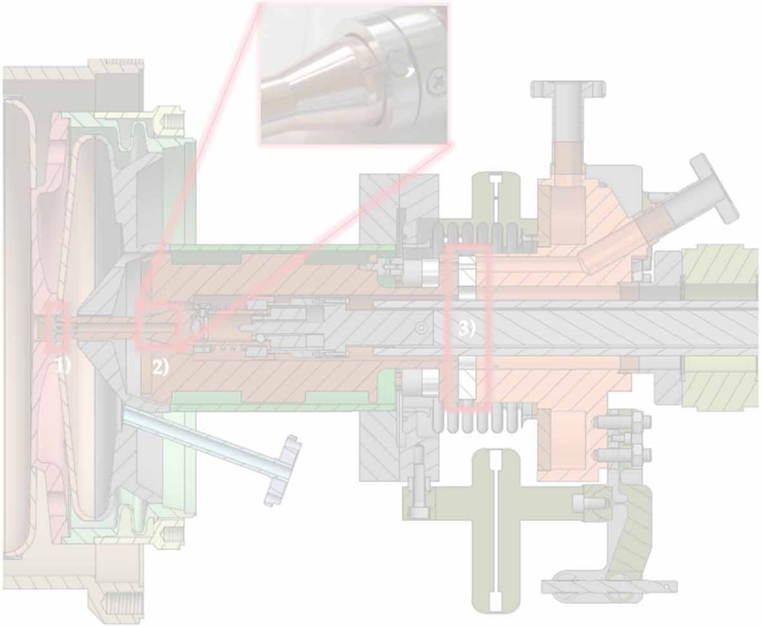

- **Finding:** Mo plugs getting loose after thermal cycle to 400 °C (during cathode prep.) and cool down to 77K in the gun! Reason is the different expansion coefficients of Mo and Cu.

- **Solution:** Cu plugs (as substrate) torqued with 2.5 Nm on cathode body (temp. increase with RF neglectable)

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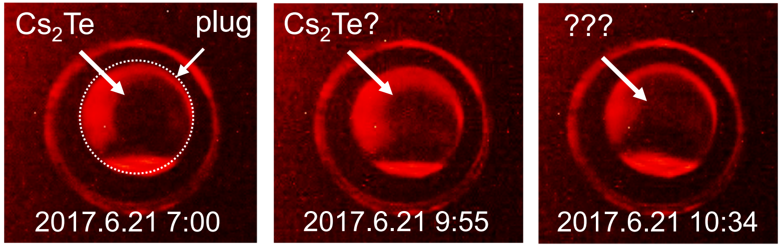

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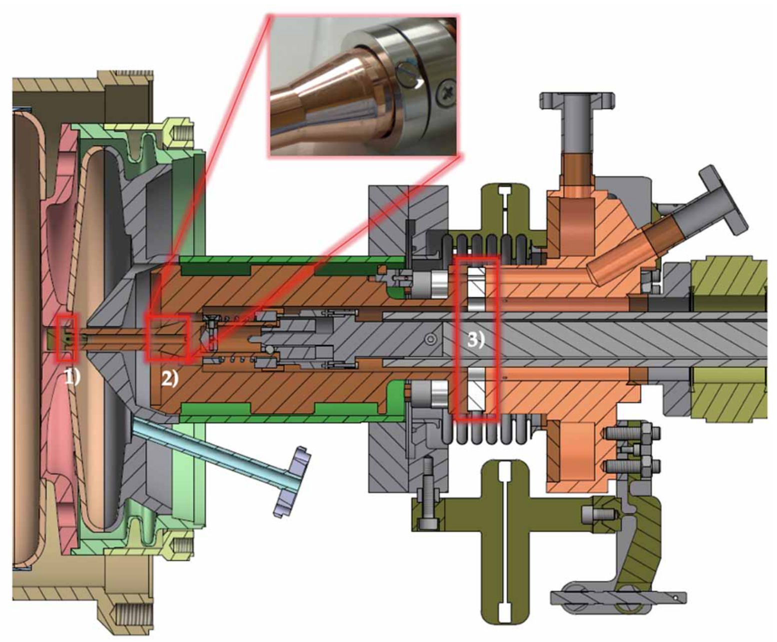

DRESDEN concept HZDR

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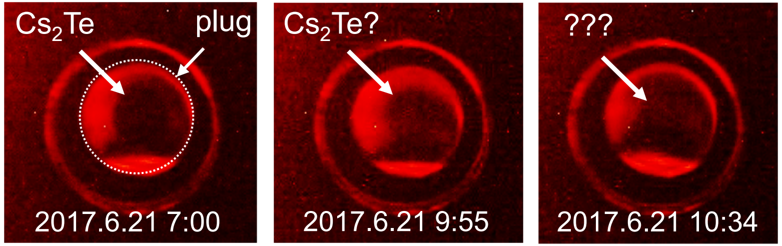

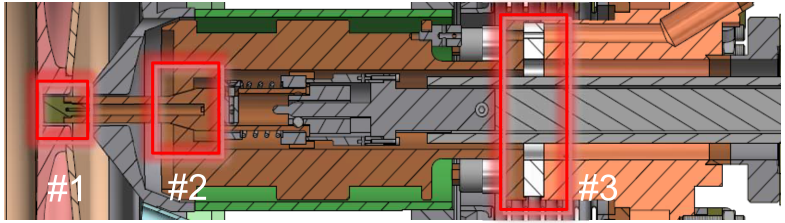

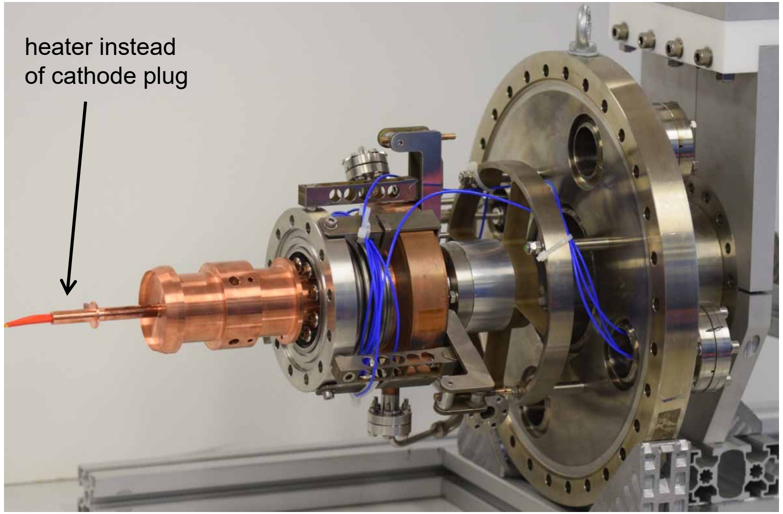

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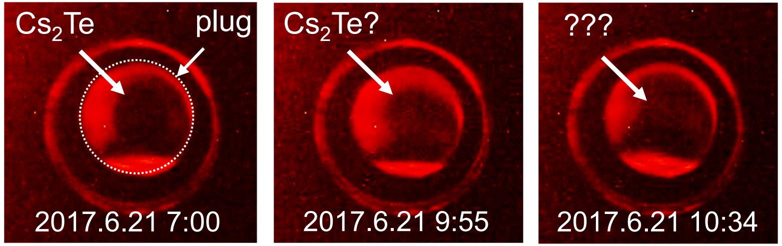

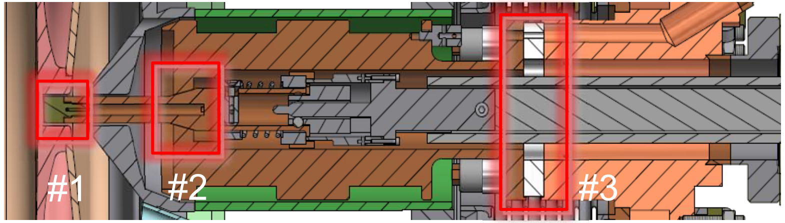

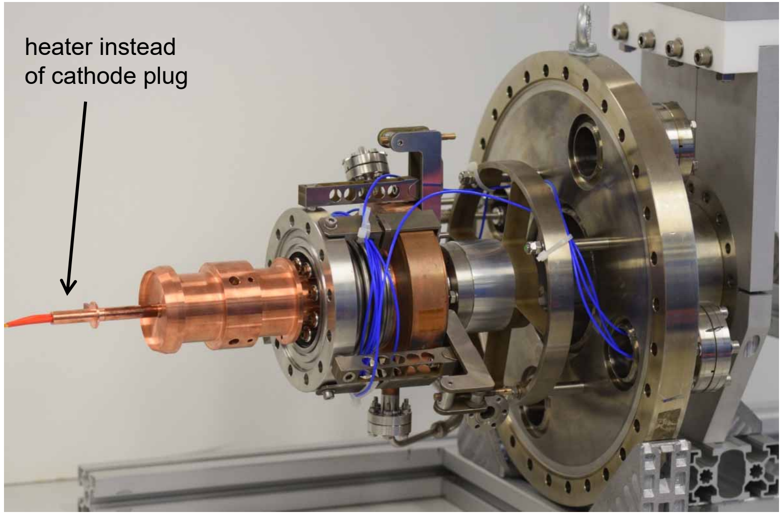

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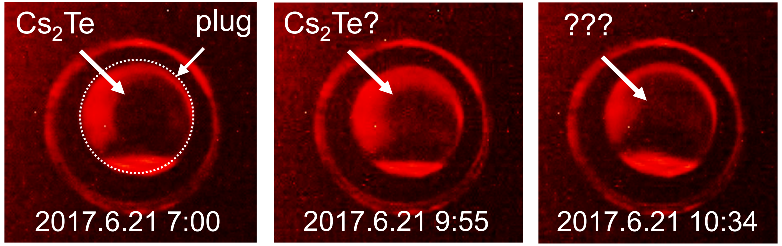
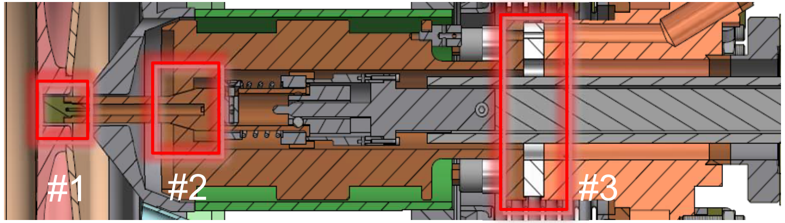
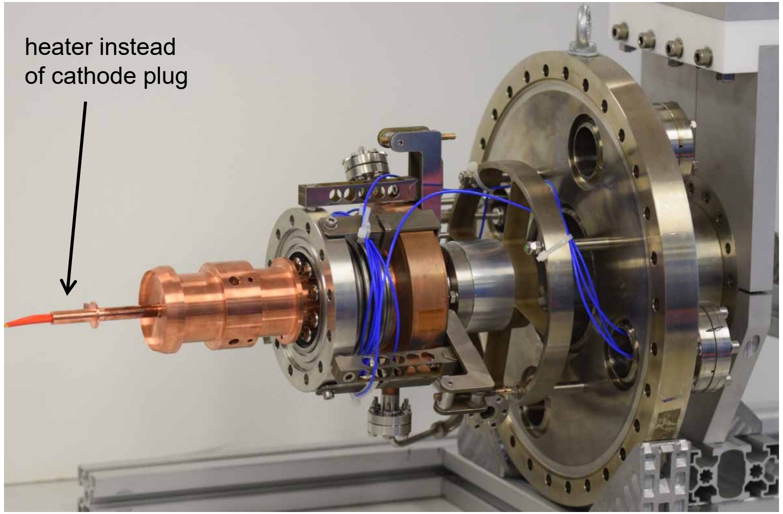
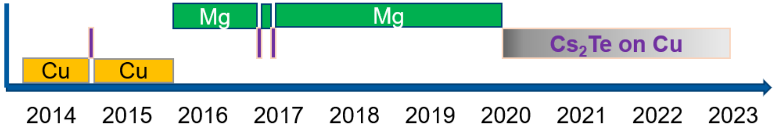




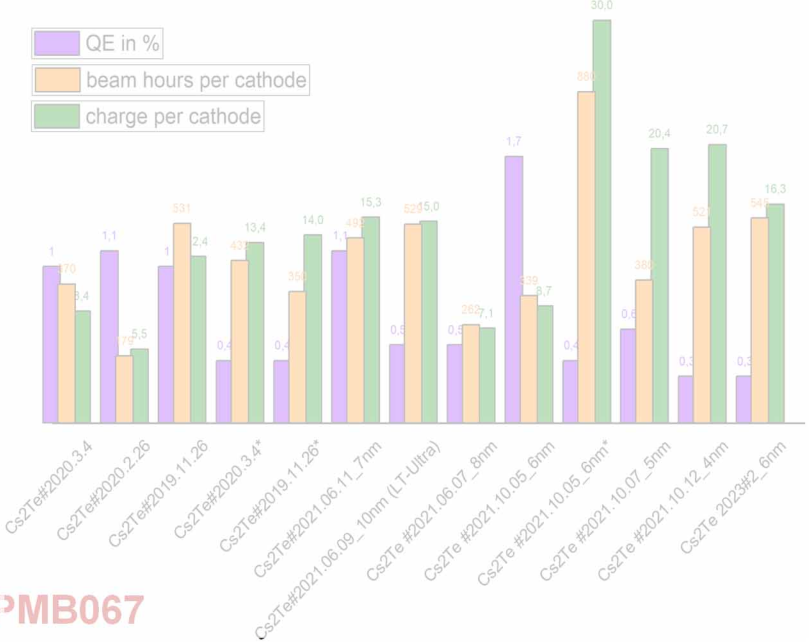


Cathode experiences

- 30 cathodes (2 Cu, 12 Mg, 16 Cs_2Te)
- since 2020 13 Cs_2Te on Cu (solved excessive heating of plug)
- Cs_2Te preparation is done in-house (already since 2007)
- QE remains stable at a few percent during storage for month
- Cathodes are transferred under UHV into the cold gun cavity
- In the gun all cathodes behave differently in terms of multipacting, QE during operation and lifetime / robustness
- on average per cathode 15 C in 500hr beam time and ¼ year in the gun (typ. limited by warm up of LHe machine)



Pure Cu plug | Cs_2Te on Mo plug | Mg (laser cleaned) | Cs_2Te on Cu plug



SRF gun II with cathode transport and transfer system, HZDR

See also poster MOPMB067

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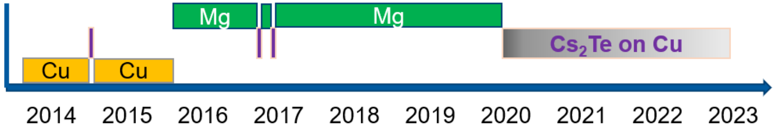

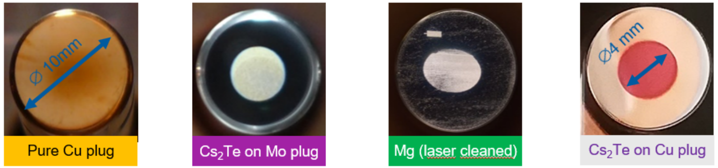

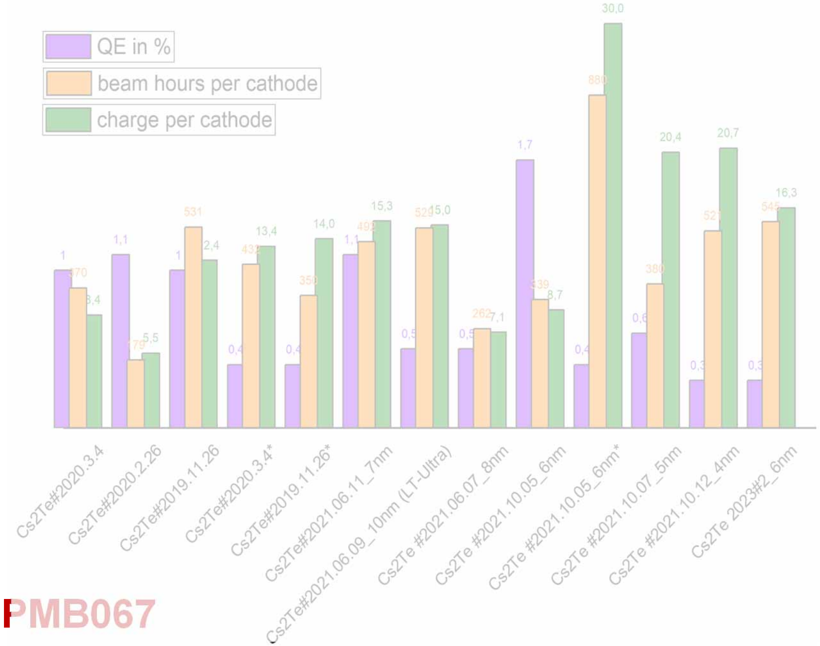

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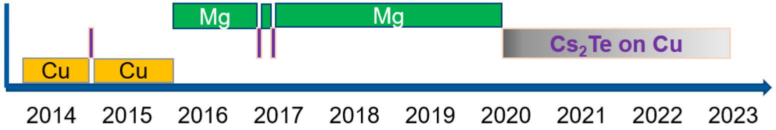

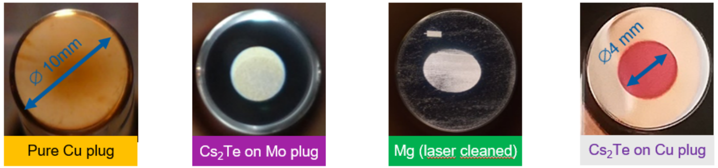

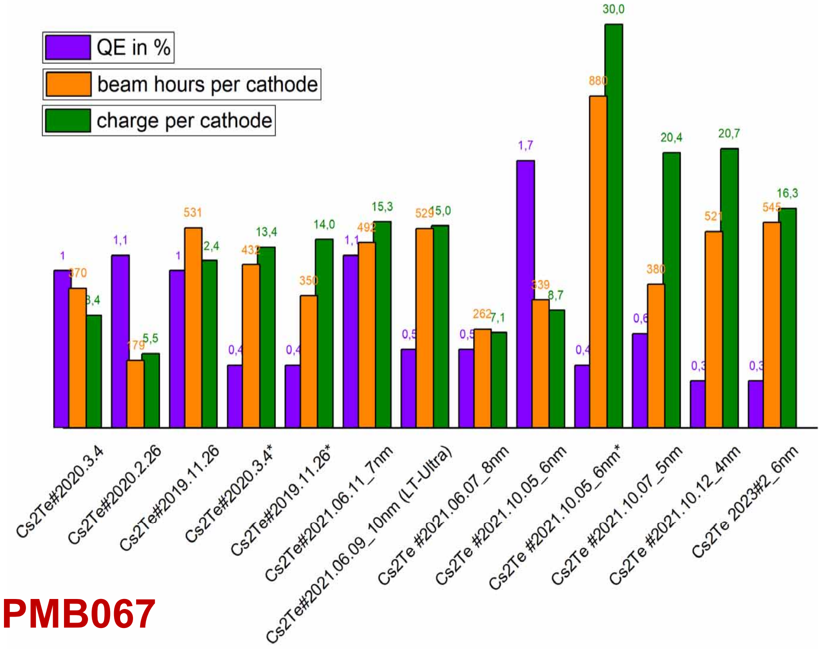

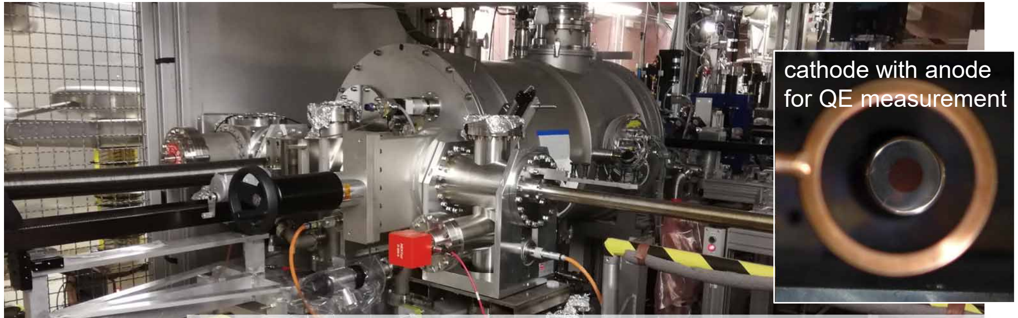

SRF gun II with cathode transport and transfer system, HZDR

See also poster MOPMB067

Cathode experiences (cont'd.)

Two effects during SRF operation

1. Fast QE drop when RF is loaded with a new cathode
    - Only few multipacting events combined with vacuum rise and electron shower that travels towards gun exit
2. Slow QE decay / distribution change during charge extraction
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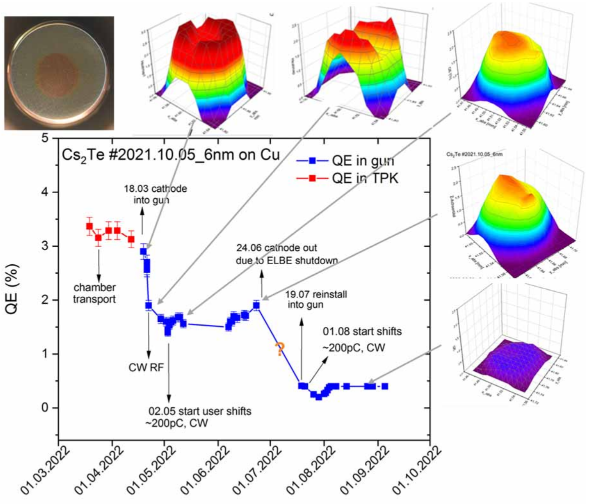
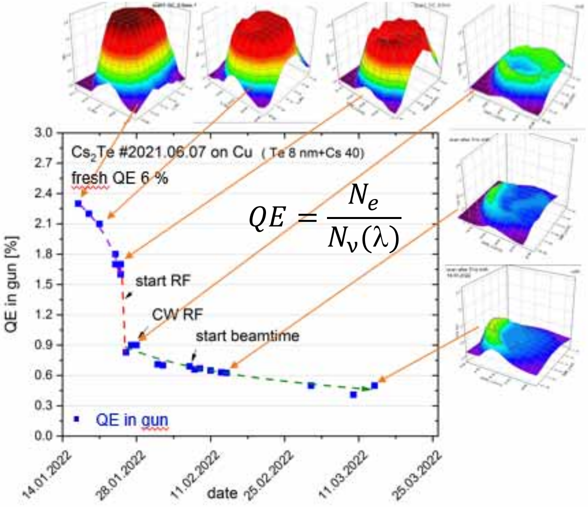
Next steps

- in vacuum sample transport for XPS* study
- Mo brazed on Cu with good therm. contact

See also poster MOPMB085

*XPS: X-ray photoelectron spectroscopy





Cathode experiences (cont'd.)

Two effects during SRF operation

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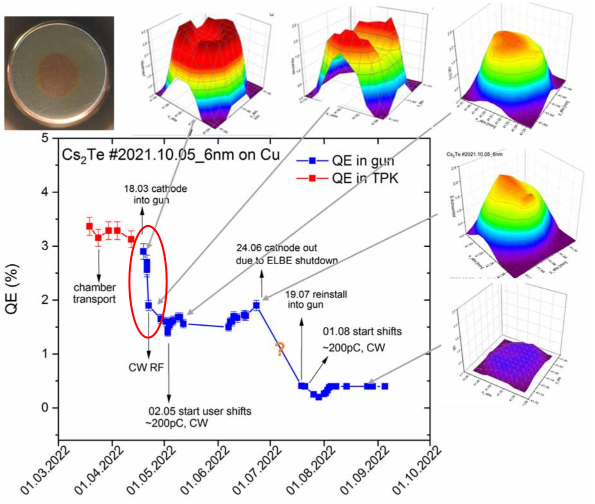

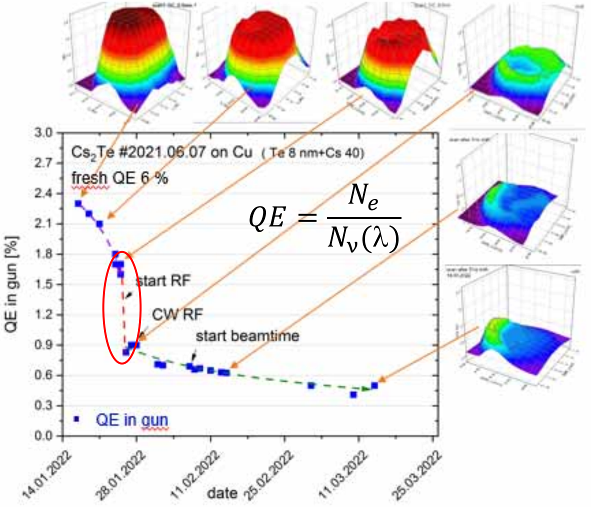

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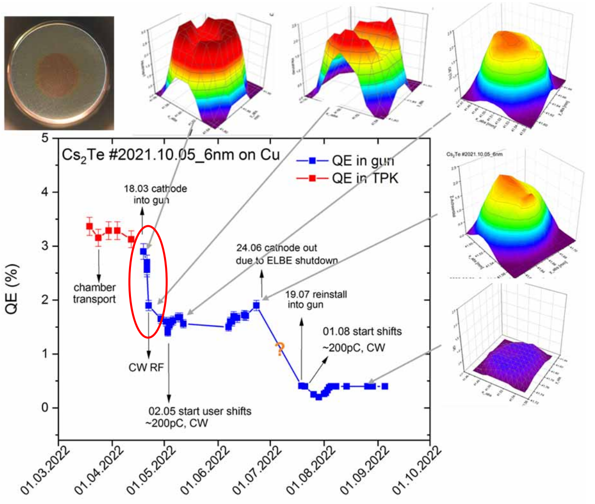

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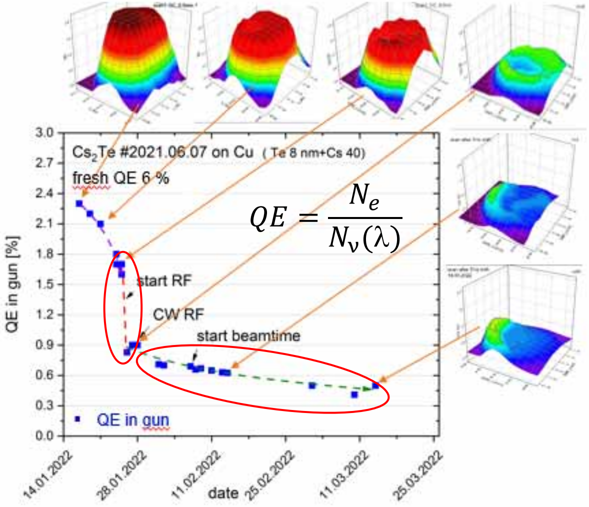

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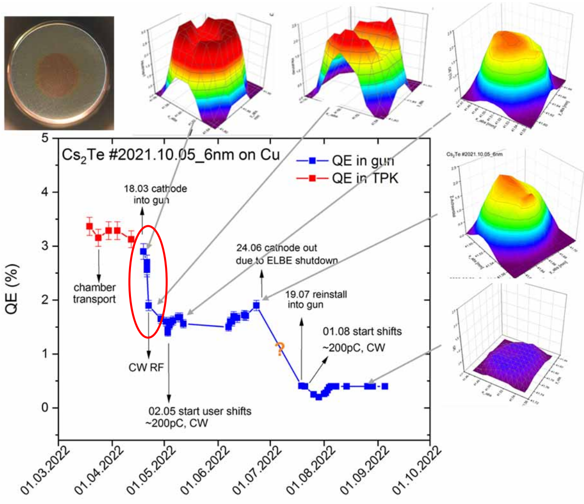

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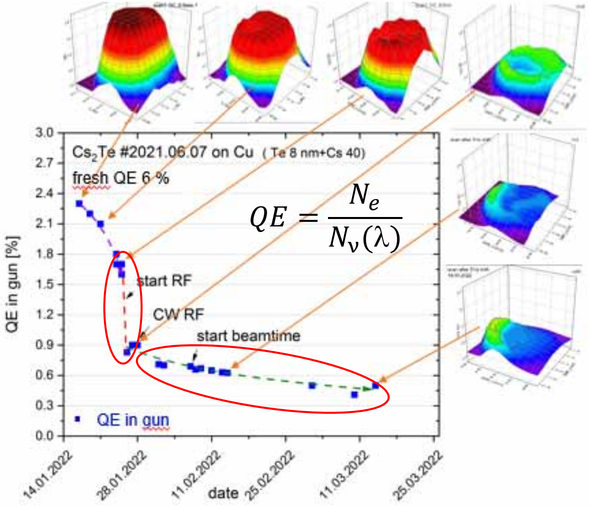

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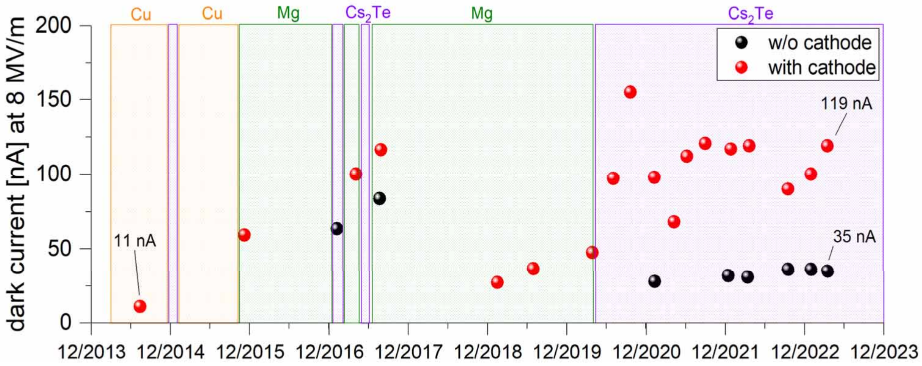
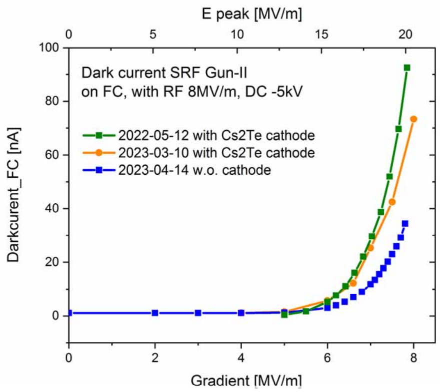
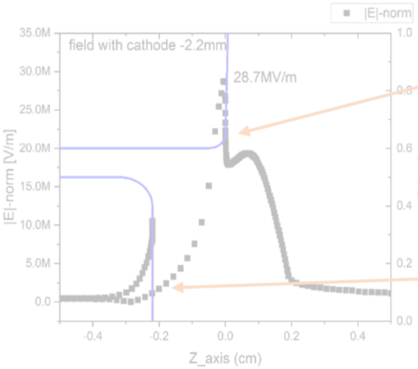
*XPS: X-ray photoelectron spectroscopy

Dark current (at 1.4 m downstream the cathode)

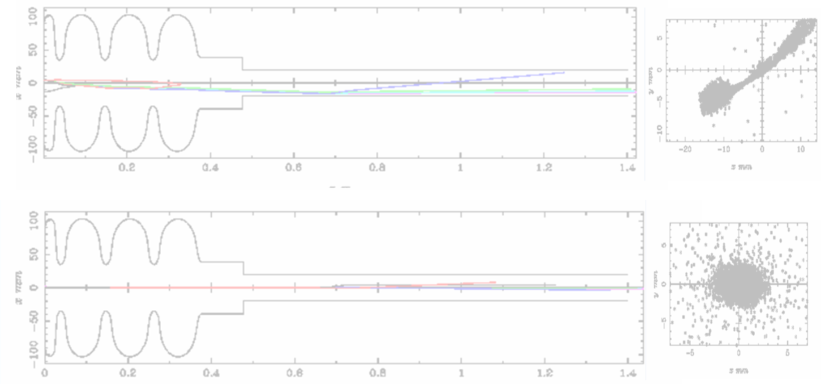
- Typ. dark current
  ~ 120 nA @ 8 MV/m
- 70% from cathode, but unclear whether from the Cs_2Te layer or substrate
- 30% from near the hole in backplane
- Less dark current and no MP with Mg & Cu



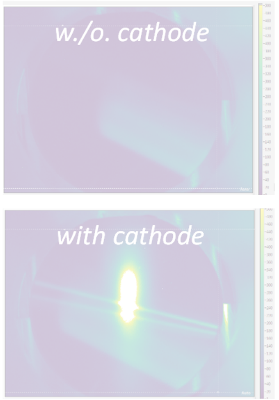




cathode hole
r=6mm



cathode
r=2mm



YAG screen 1.4m downstream

courtesy R. Xiang

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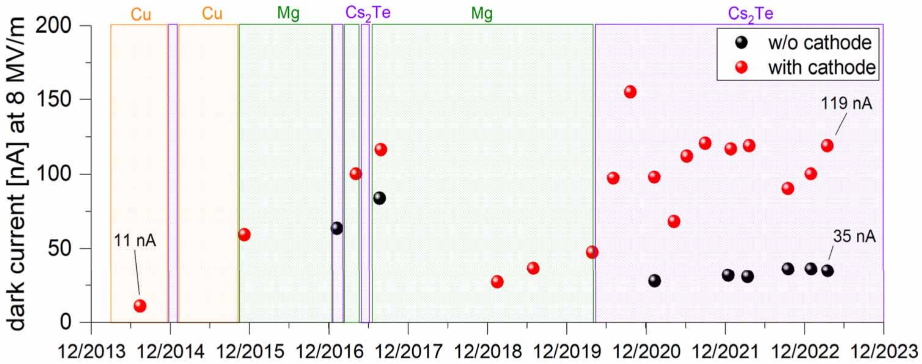

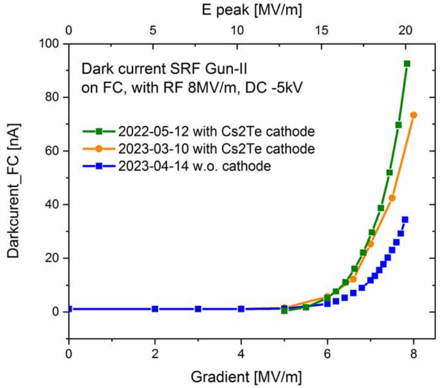

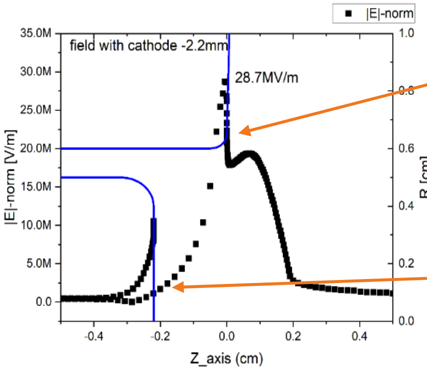

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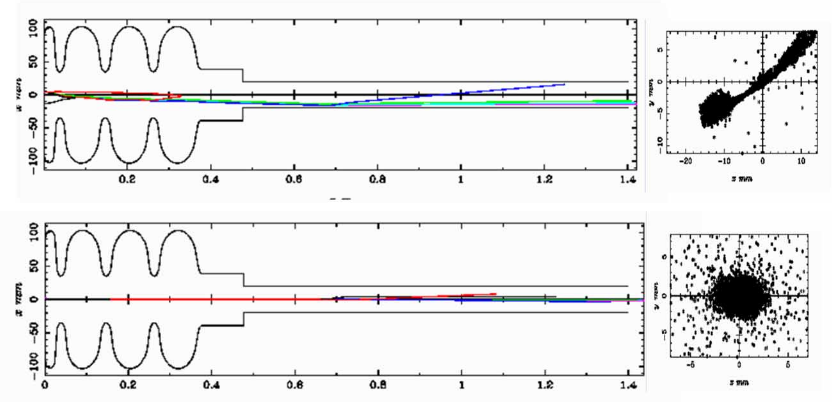

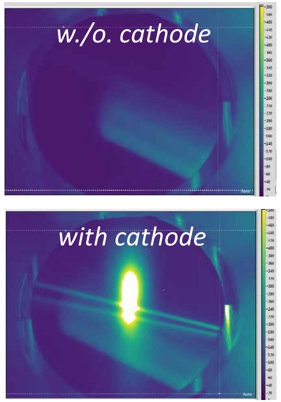

YAG screen 1.4m downsteam

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DRESDEN concept HZDR

SRF performance (selection)

QvsE

- in last vertical test at Jlab E0=37 MV/m was achieved,
- -30% loss due to clean room assembly and shipping
- -20% loss because of overheating of 1st Cs_2Te (2015)
- up today no additional degradation despite 30 cathodes

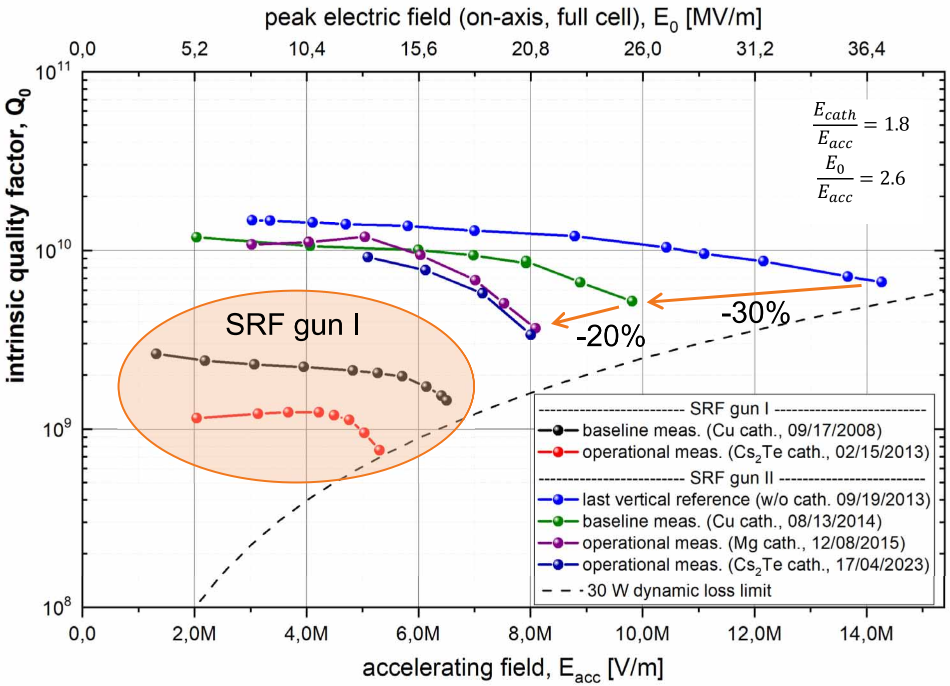
Microphonics

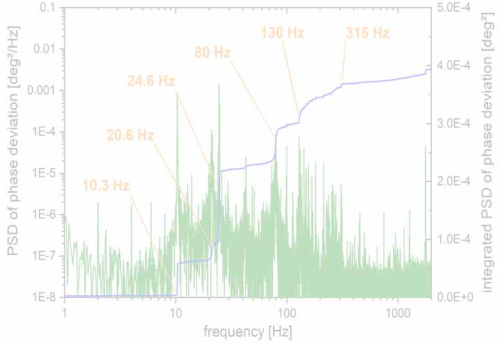
- σ_f = 6.6 Hz (RMS); 24.6 Hz membrane pumps, 20+130 Hz compressors of LHe machine, 10+80 Hz unknown
- σ_φ=0.02° at 1.3 GHz or timing jitter σ_t=43 fs (in loop)

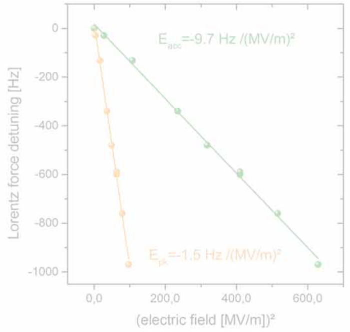
Lorentz Force (LF) detuning

- k_0 = 1.5 Hz$(MV/m)^{-2}$, 6x higher than for TESLA 9 cell [1)]
- LF detuning vs. E0 for each mode clearly point on weak half cell as reason, stiffeners are not satisfactory
- Δf = 650 Hz for E_{acc} = 8 MV/m, because of bandwidth of BW = 200 Hz tuning while changing gradient is essential

Helium pressure sensitivity: 155 Hz/mbar (stability of LHe machine is 0.2 mbar pk-pk)







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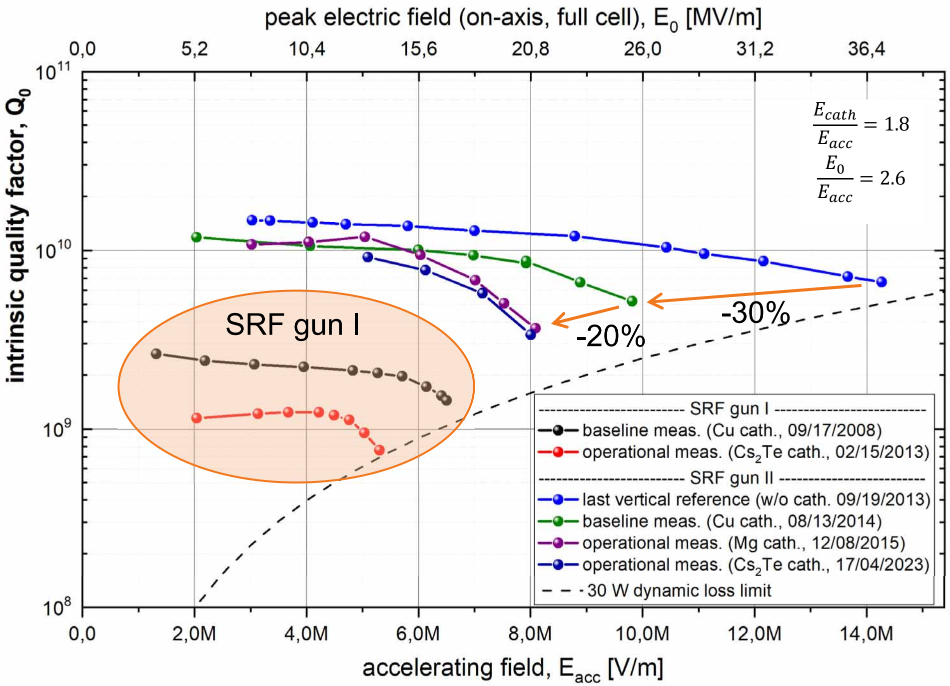

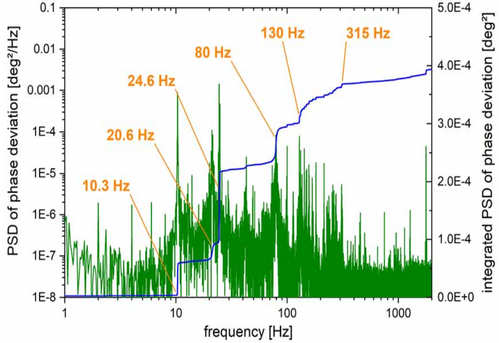

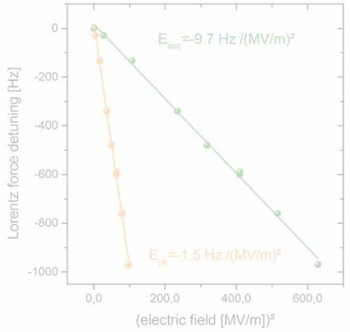

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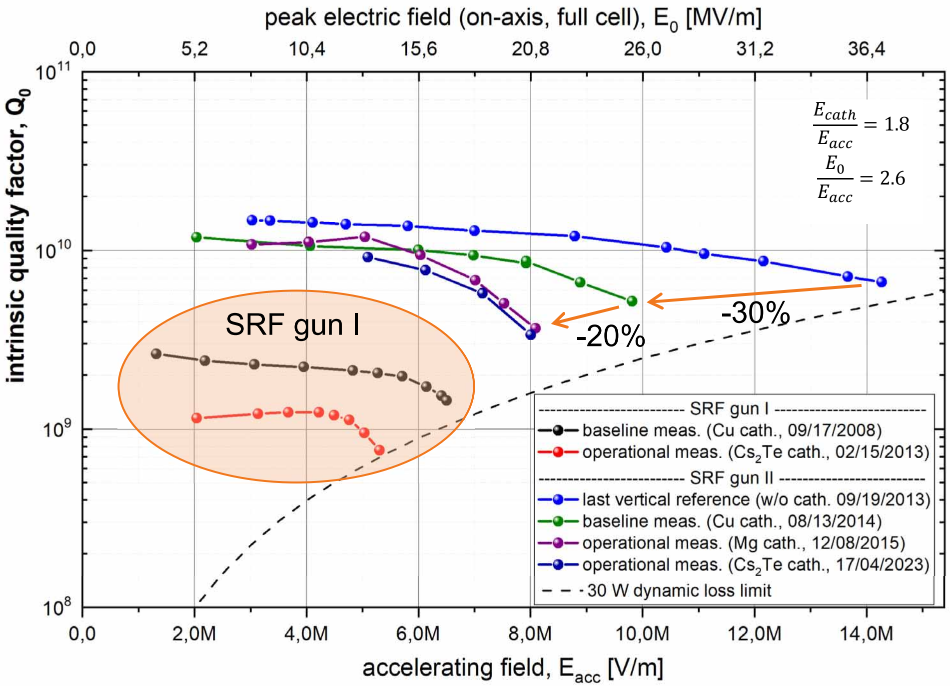

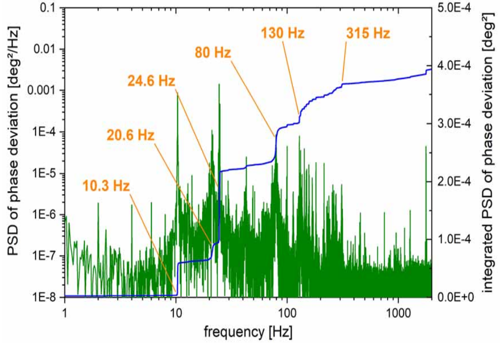

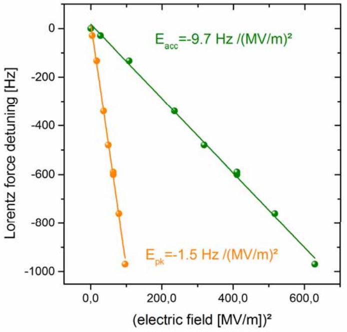

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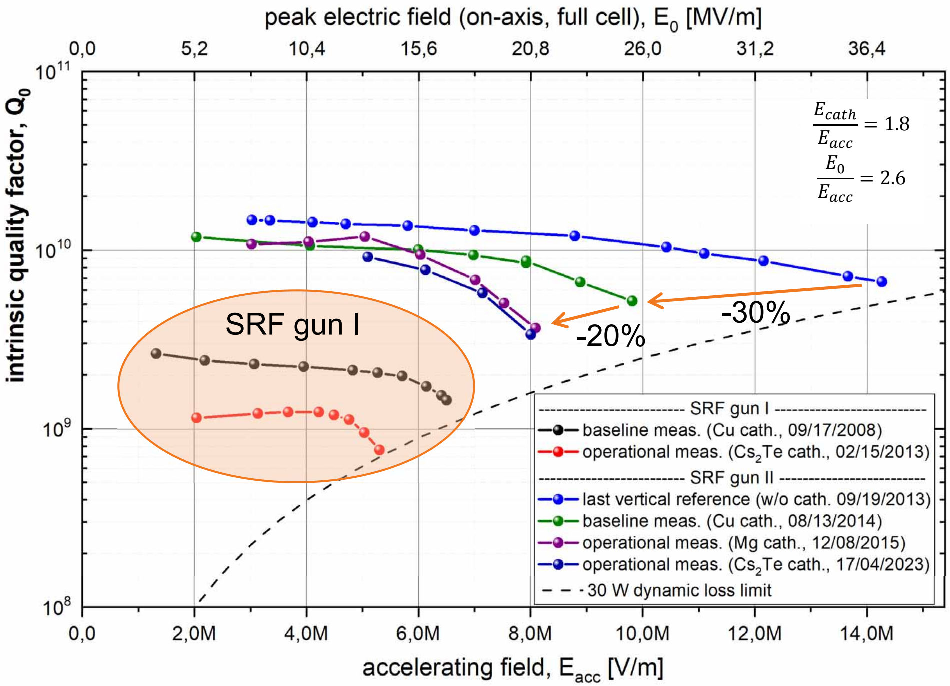

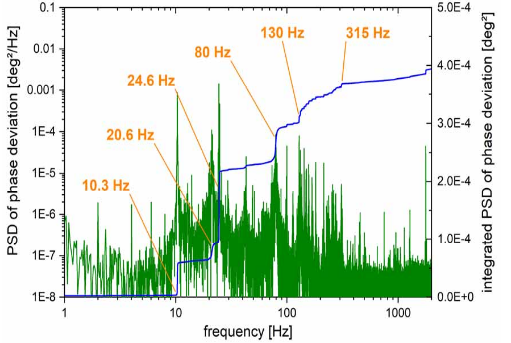

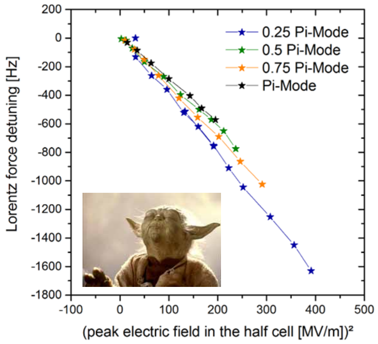

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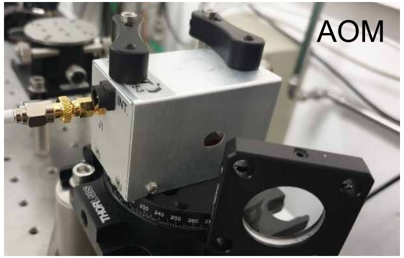
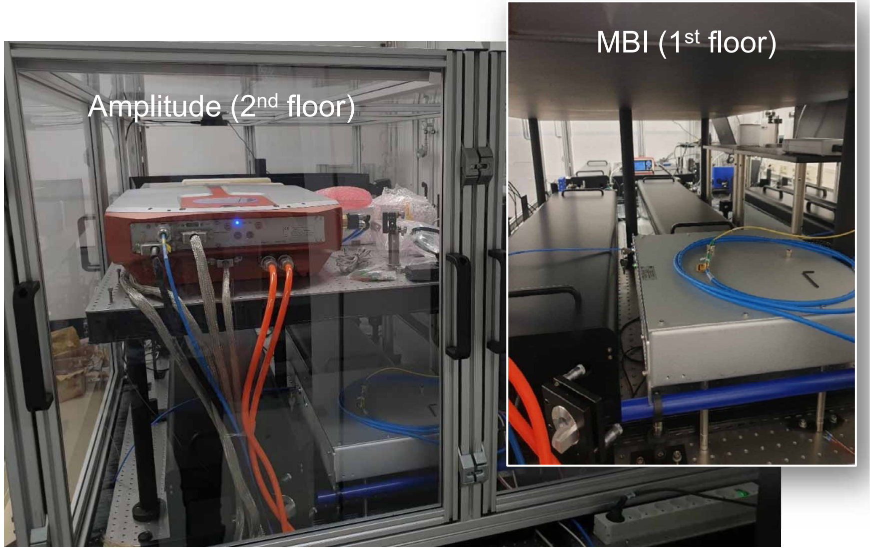
Photocathode laser(s)

- UV laser operated at constant power (thermal equilibrium)
- UV laser power adjusted by attenuator (waveplate/polarizer)
- Fast chopping in UV (up to MHz) for e-beam setup by AOM (acousto optical modulator, Isomet M1365-aQ215-3)
- Laser transport equipped with the 2 fast shutters in a row (AOM and Uniblitz) for redundancy in machine safety





Parameter	New Laser *) (Amplitude)	Old Laser 2 (Max Born Institue)
4th harmonic	257 nm	262 nm
Oscillator	39 MHz, fiber	52 MHz, free space
Pulse rep. rate	0…1 MHz (divider of 39 MHz)	10…500 kHz in 7 steps and 13 MHz
UV pulse energy	>10 µJ @ 100 kHz >2 µJ @ 1 MHz	5 µJ @ 100 kHz
UV pulse length, FWHM	up to 7 ps, variable	5 ps
jitter (10 Hz - 1 MHz)	70 fs	150 fs

*) not ready for user beam, still issue with synchro-lock

Operational experiences (selection)

- Main reason of failures is water (both infrastructure and chiller)
- Degradation of mirrors, lenses, waveplate/polarizer, conversion crystals within weeks of operation (depends on power density)
- Frequent maintenance and re-adjustment mandatory (1 FTE)

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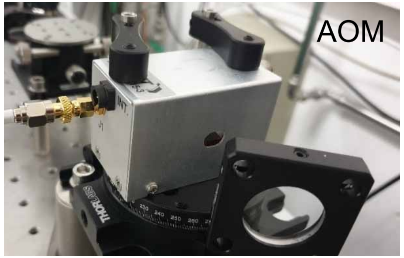

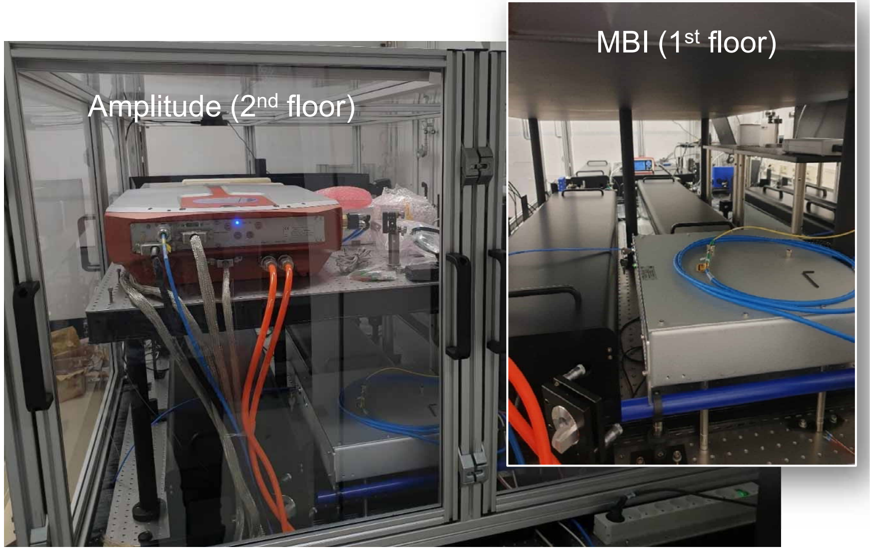

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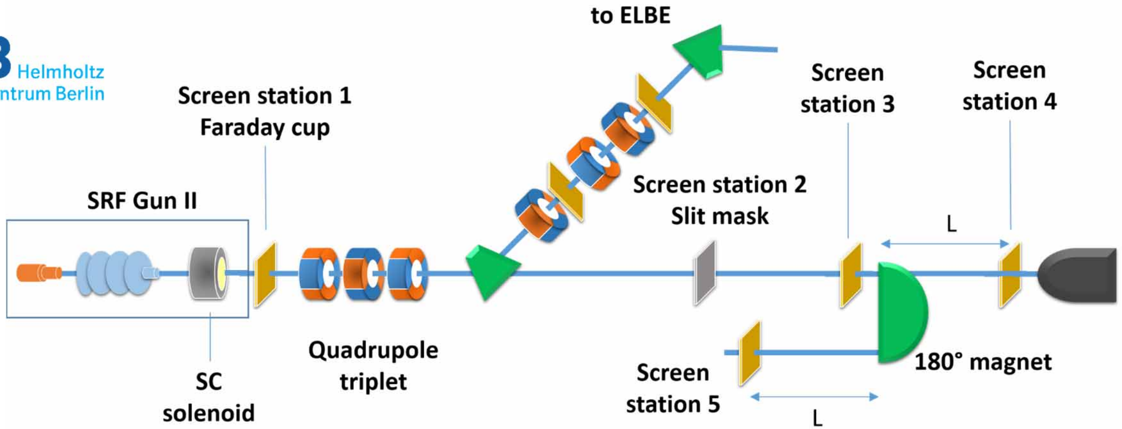
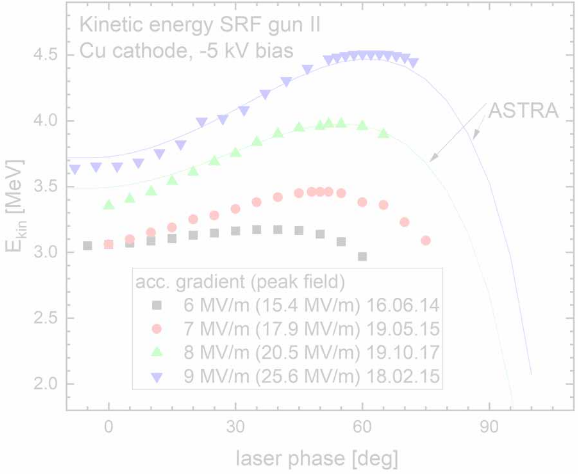
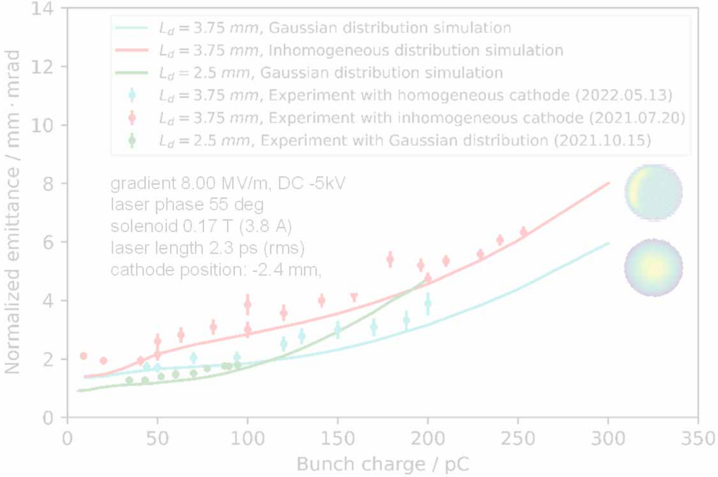


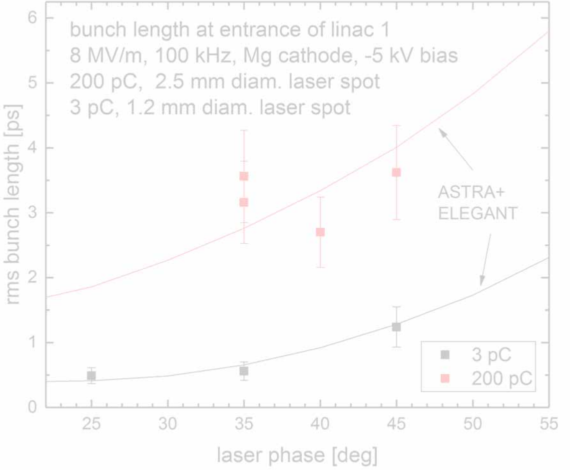
OP parameter	SRF gun II
energy (pc)	4.5 MeV
SRF gun gradient	8 MV/m
cathode field	14.4 MV/m
bunch charge	0 – 250 pC
transv. emittance	1.3 – 6.3 µm
energy spread	5 – 25 keV
micro pulse rate	25 – 250 kHz
beam current (CW)	60 µA
laser pulse length	2.3 ps
dark current	<100 nA



Ma, S., Ph.D. thesis of University Hamburg, 2022.



Bunch length by RF zero-phasing technique



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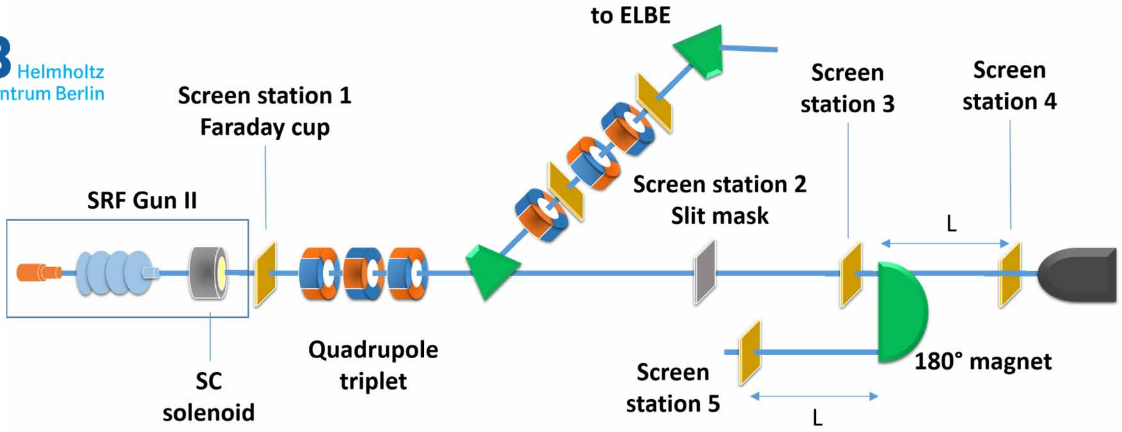

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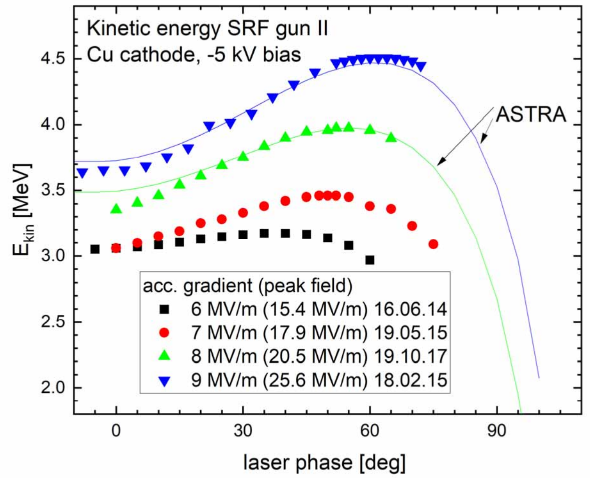

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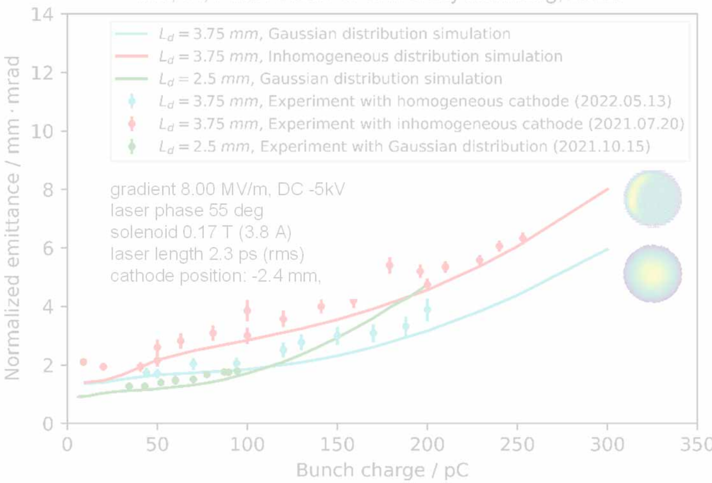

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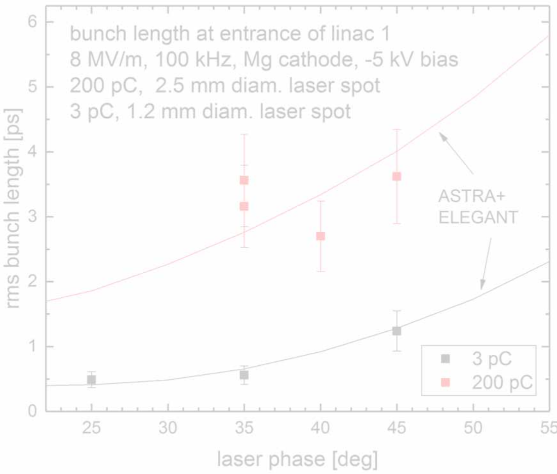
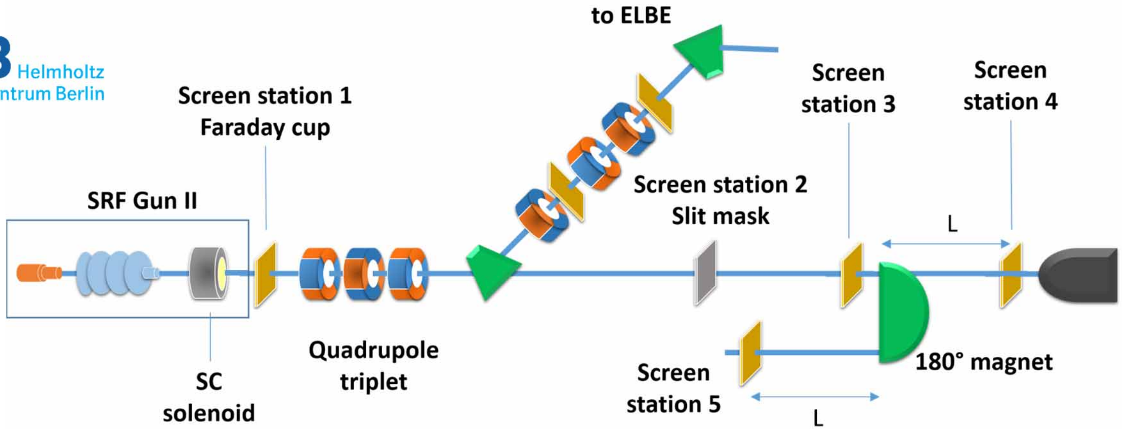


Beam performance

HZB Helmholtz Zentrum Berlin



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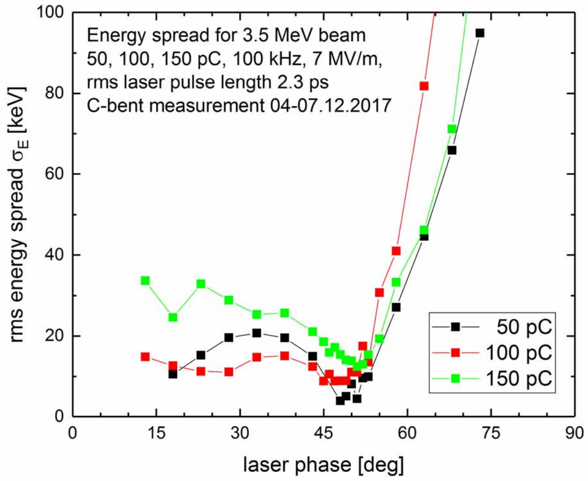

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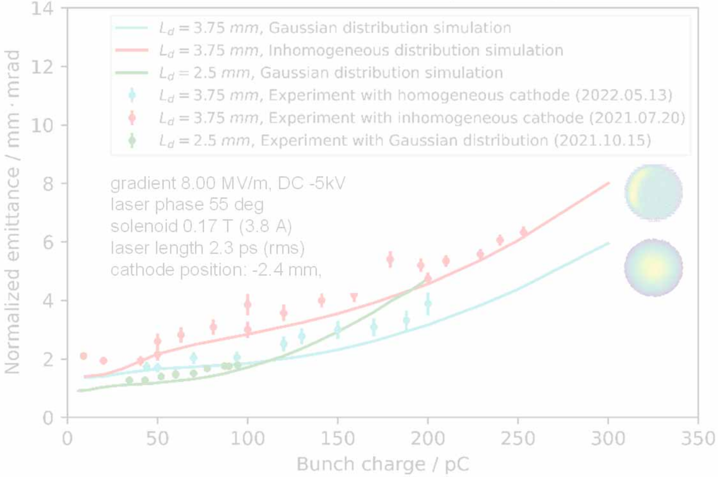

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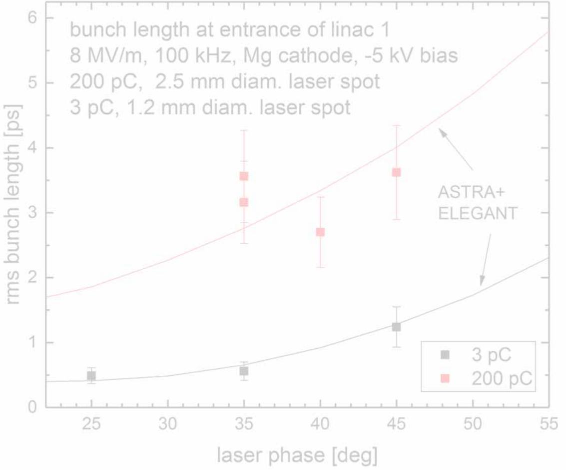

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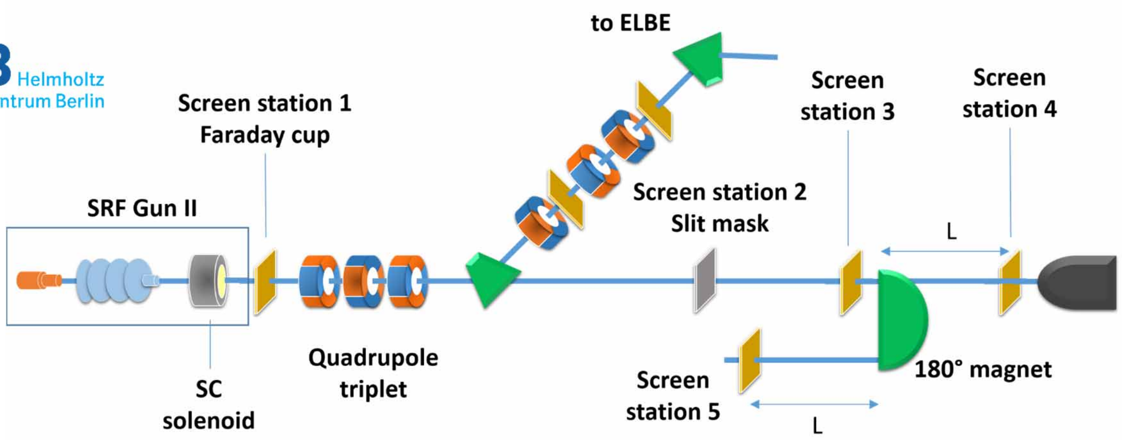
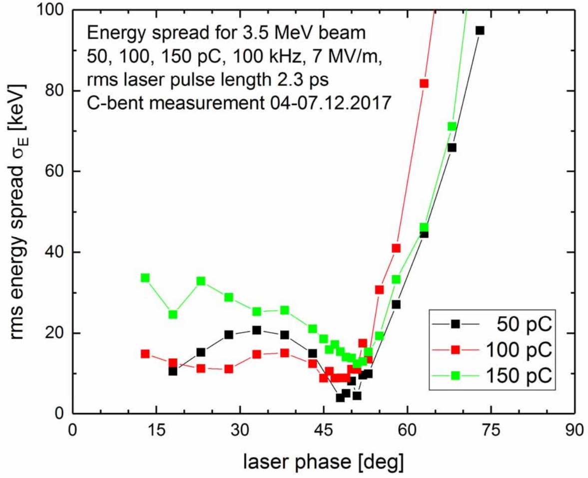
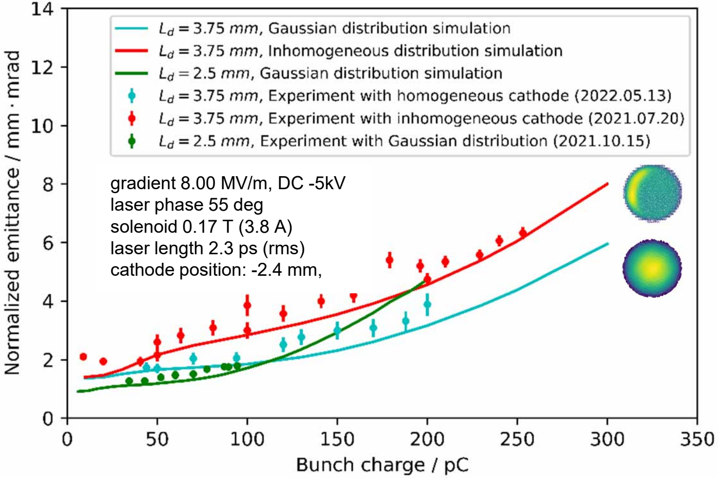
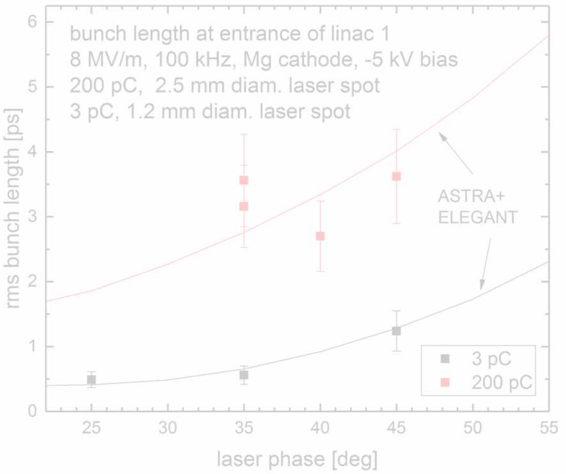




Ma, S., Ph.D. thesis of University Hamburg, 2022.



Bunch length by RF zero-phasing technique



Beam performance

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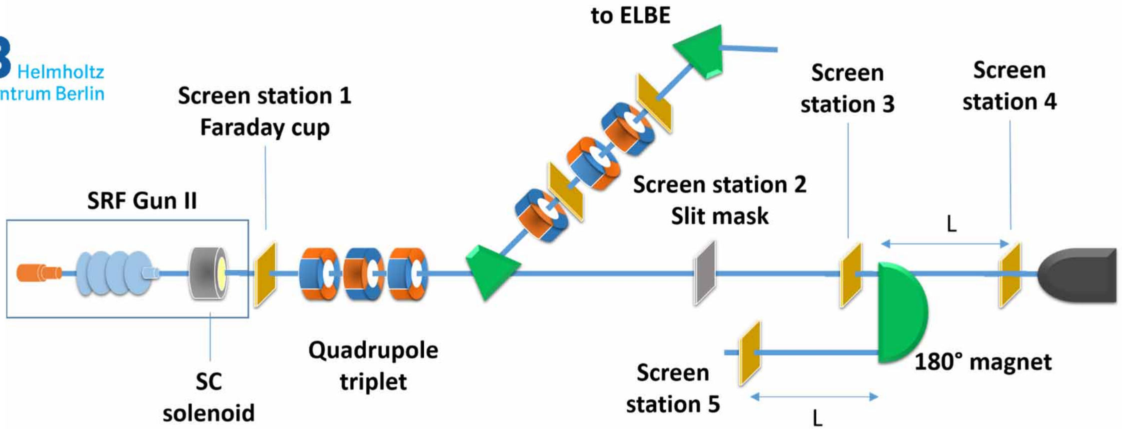

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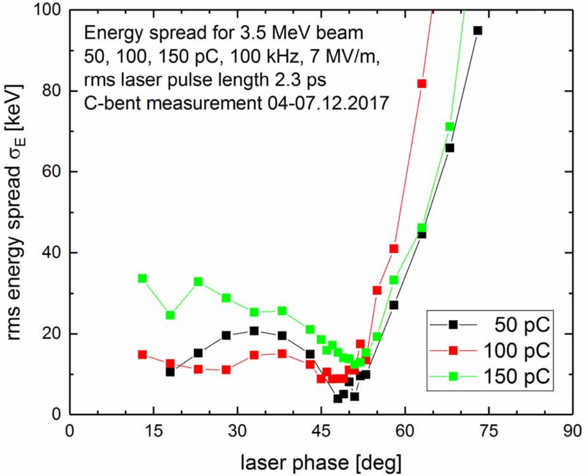

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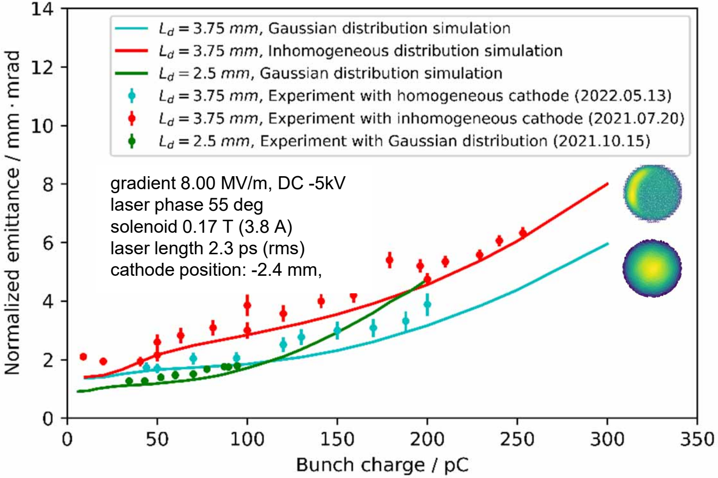

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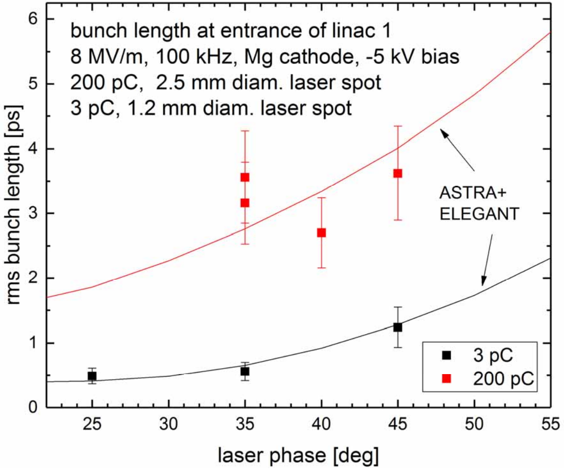

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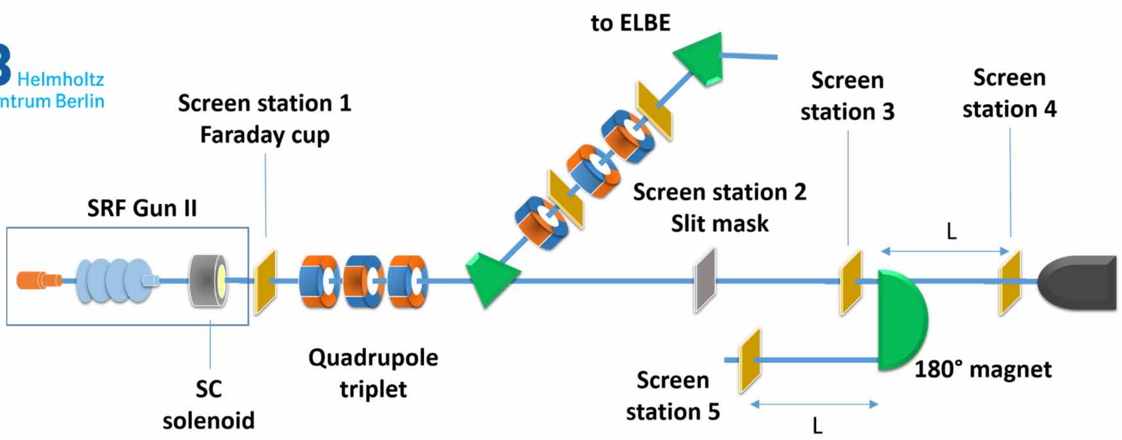

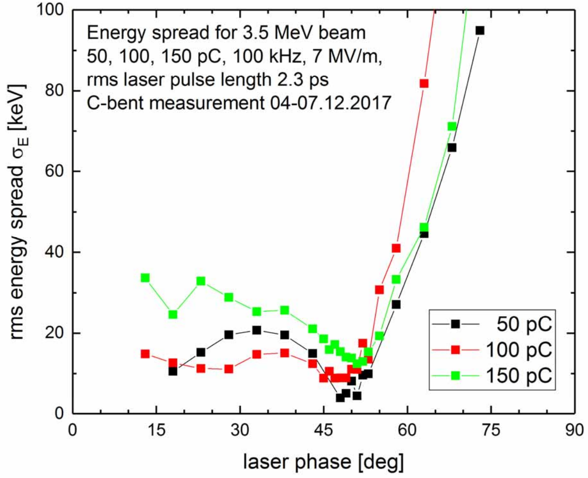

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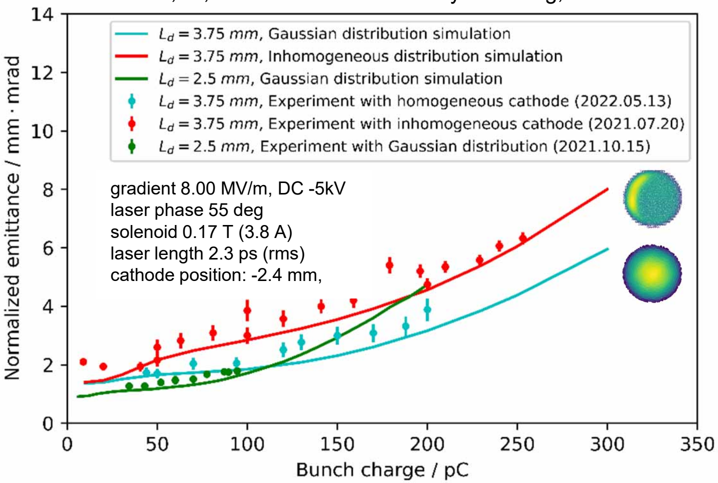

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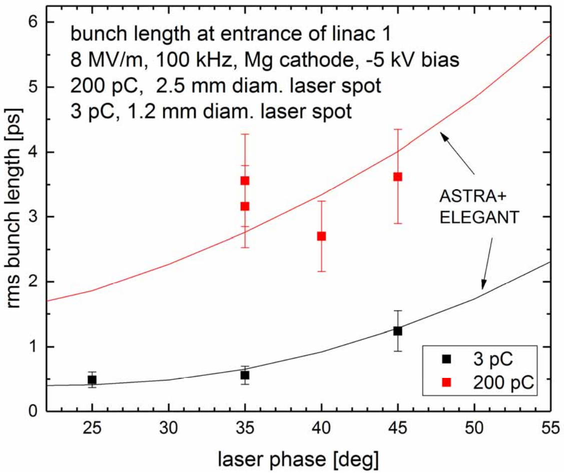

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- Reliable operation over days w/o any trips
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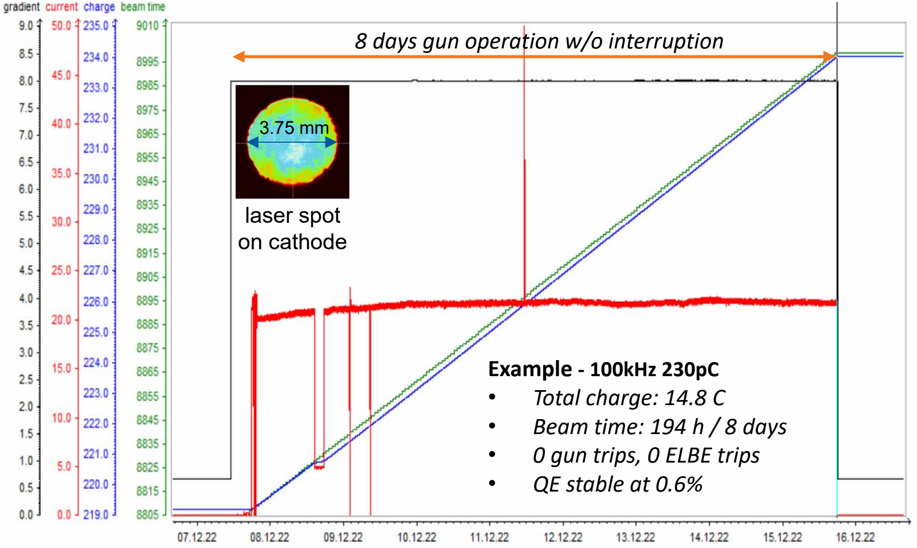
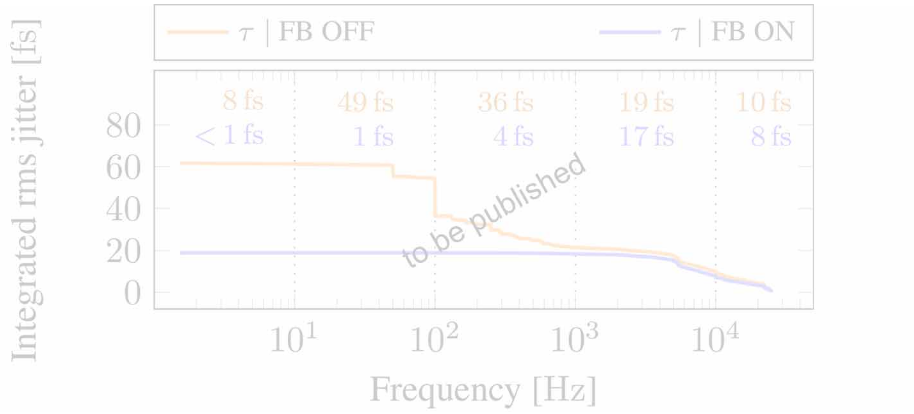
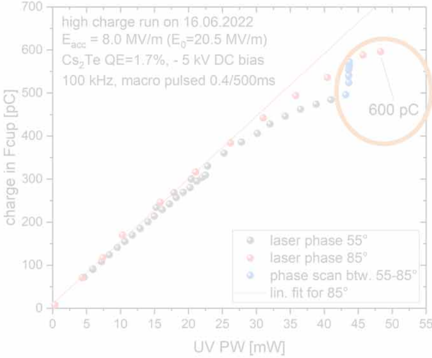
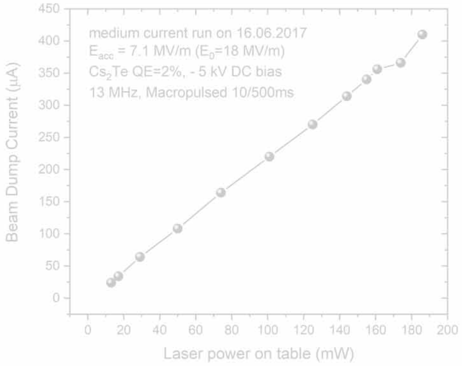


A. Maalberg, M. Kuntzsch, K. Zenker and E. Petlenkov, "Regulation of electron bunch arrival time for a continuous-wave linac: Exploring the application of the H2 mixed-sensitivity problem", *Phys. Rev. Accel. Beams*, under review.







DRESDEN concept HZDR

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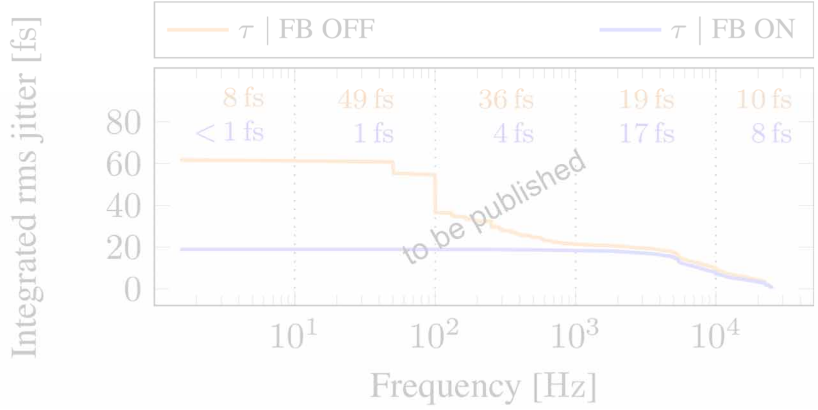

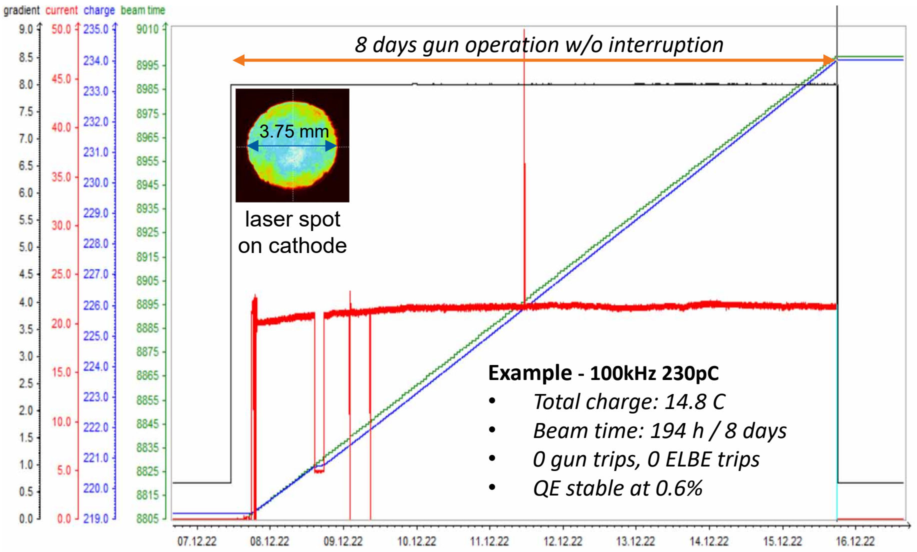

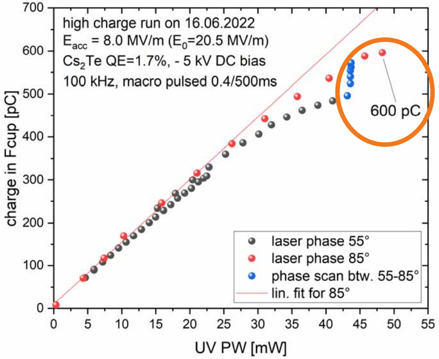

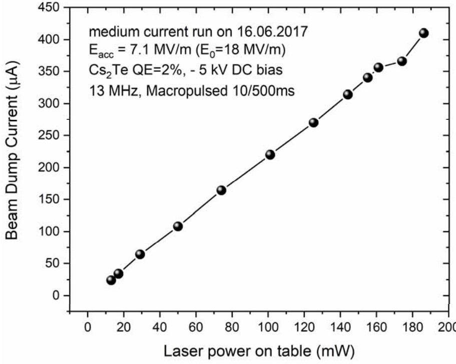

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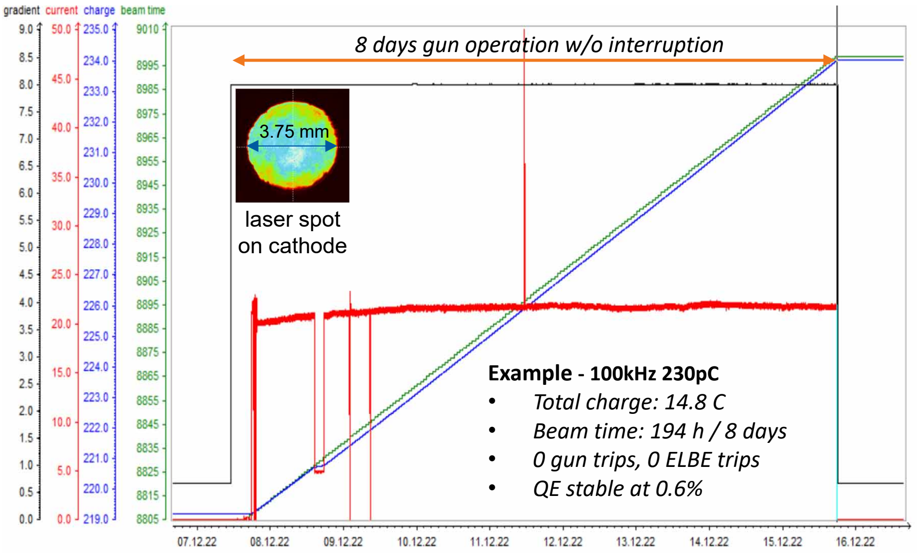

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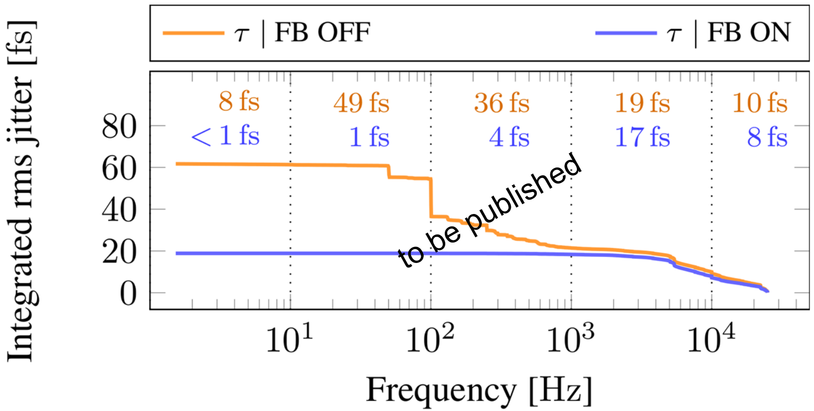
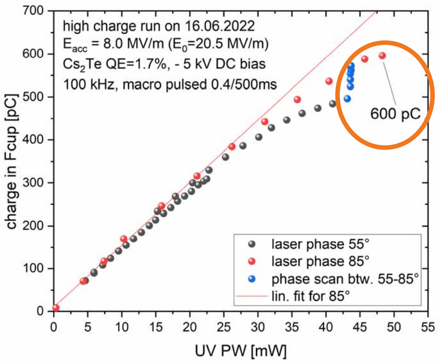
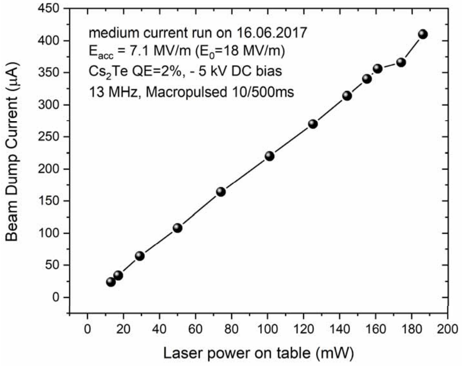


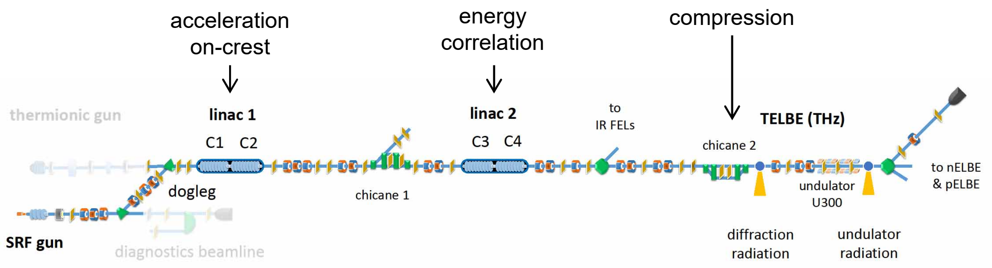


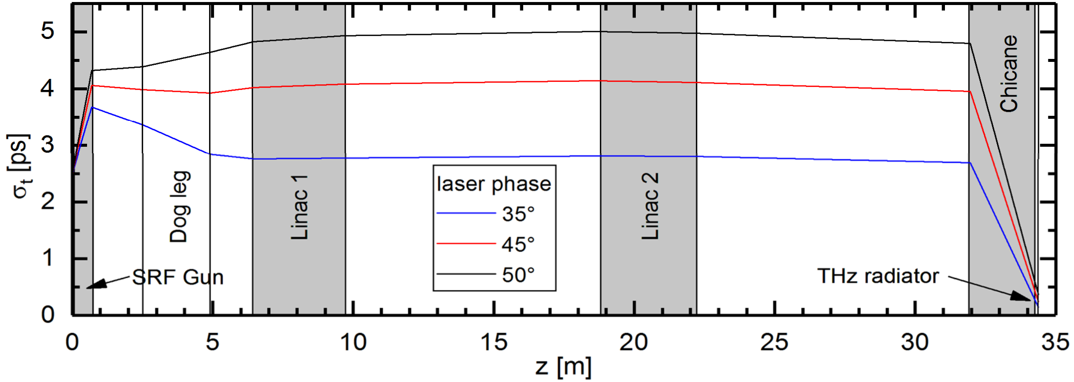


DRESDEN concept HZDR

THz – most demanding experiment

$$E_{THz} \sim F(\omega, \sigma_z) N^2$$





- SRF gun delivers 4 MeV beam with 200 - 250 pC
- CW operation with 10, 50, 100, 250 kHz rep.-rate
- acceleration to 26 MeV, imprint of correlated energy spread and compression to some 100 fs
- THz radiation with frequencies 0.05 – 2.5 THz
- pulse energies ≤10µJ (≤1 THz), few µJ (≤2.5 THz)
- pulse energy fluctuations are typ. 3.5 %
- synchronization to external systems typ. 75 fs (including the laser jitter, w/o feedback)

100% of all THz shifts and up to 40% of all ELBE user shifts (4500h w/o MD) are served by SRF gun

J. Teichert et al. PRAB 24, 033401 (2021)

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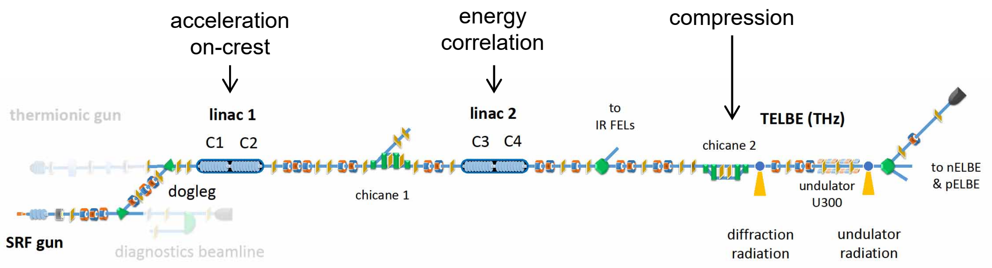

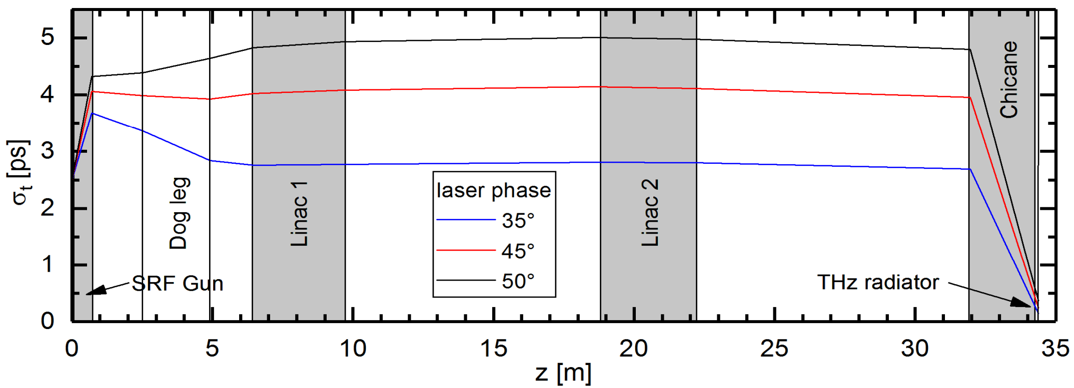

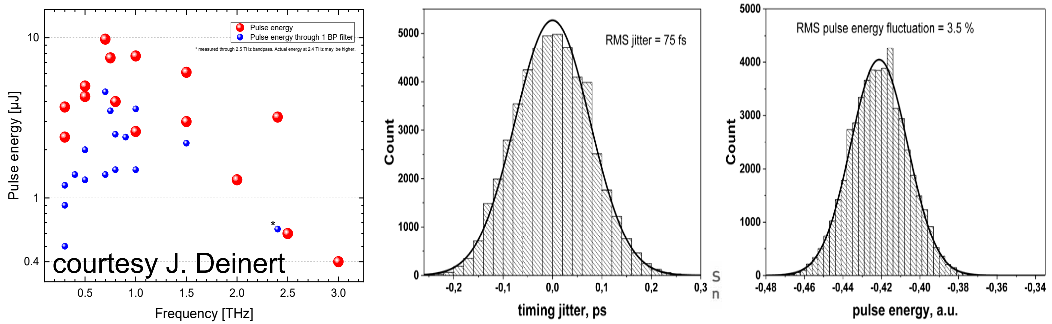

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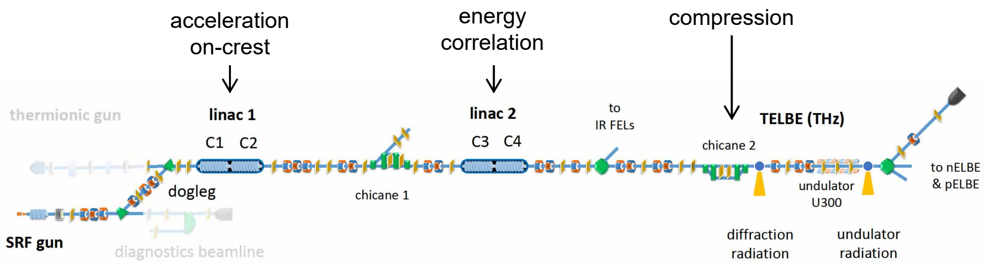
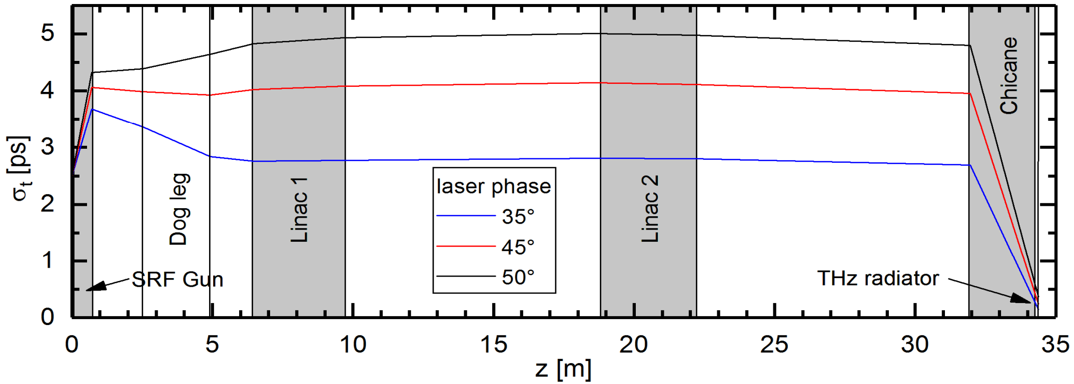
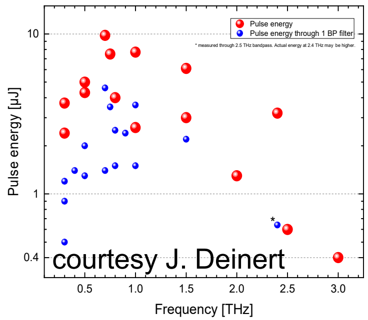
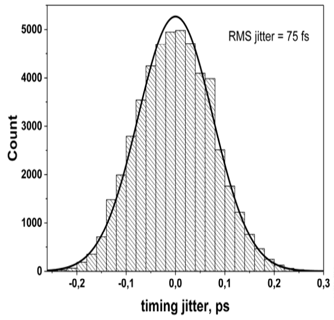
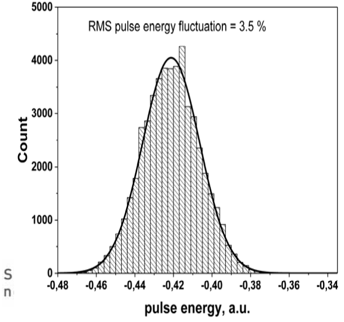






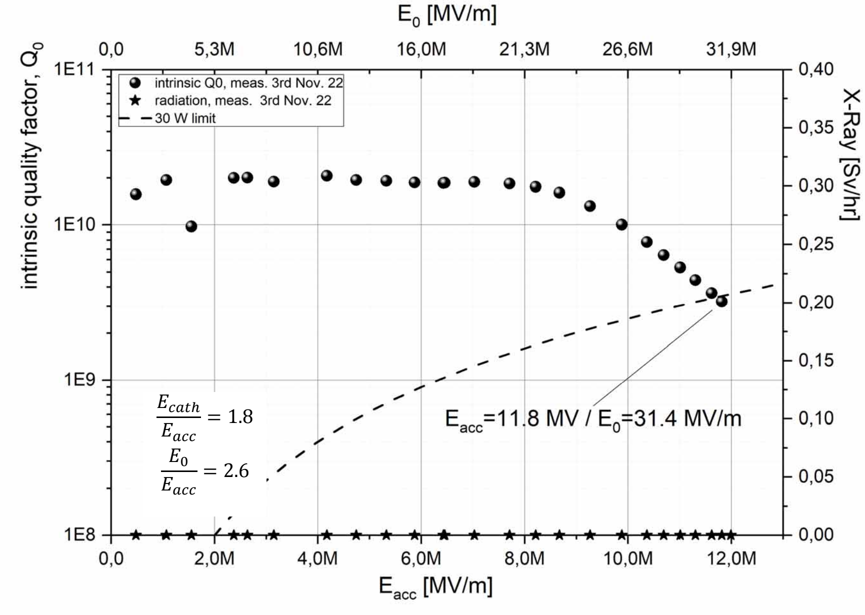




Outlook - SRF Gun III

Goal: <u>**(re-)establishing 30 MV/m**</u> of old SRF gun I by using HZB infrastructure

- ✓ high pressure rinsing (HPR) with special nozzle for gun cavities
- ✓ cavity cleanroom assembly of all auxiliaries for vertical test
- ✓ **achieved 30 MV/m** in small test dewar in HoBiCaT bunker
- ✓ in parallel, the cryomodule was completed and cold tested
- – cold mass cleanroom assembly at HZB or HZDR “just” missing



cavity ready for vertical test

HPR with special gun nozzle

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SRF gun III cold test in the bunker (w/o cavity)

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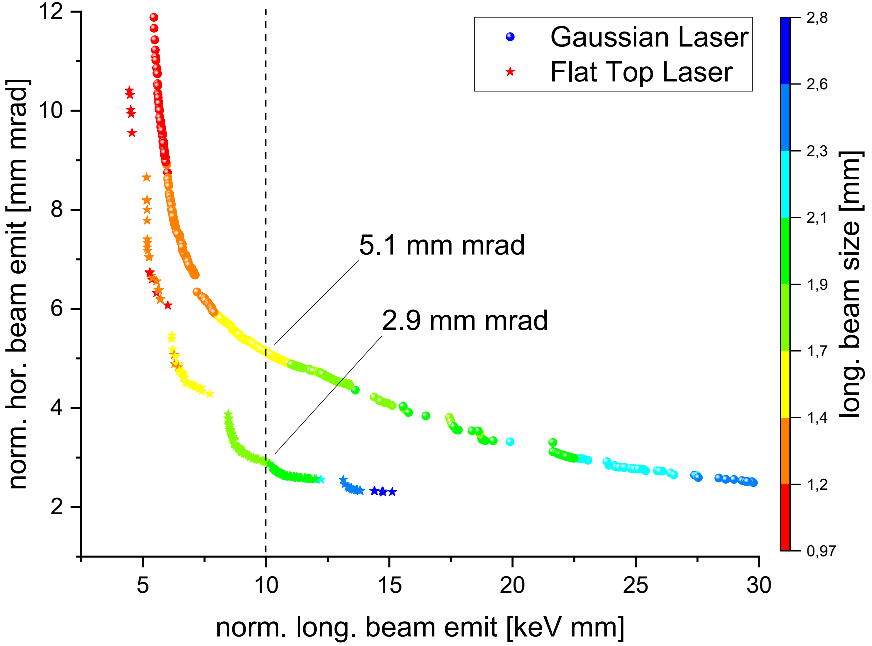
Outlook - SRF Gun III for 1nC

- ASTRA tracking and Pareto optimization for transverse and long. emittance at 4 m, beam size ≤ 5mm, no particle loss
- Many knobs: solenoid field, long. laser pulse length, transverse laser size (top hat), cathode position (-4 to 0 mm), RF phase (10°-90°), DC field (±5kV); only solenoid position (0.7 m) and cavity field (30 MV/m) are fixed
- 50% higher gradient would allow 5 times higher bunch charge at the same transverse emittance and ideally up to 25 times higher THz pulse energy
- 1 nC in CW is basic requirement for ELBE successor DALI (Dresden Advanced Light Infrastructure)



SPEA2 algorithm provided by J. Völker and E. Panofski
Eva Panofski, *Beam Dynamics and Limits for High Brightness, High Average Current Superconducting Radiofrequency (SRF) Photoinjectors*, Humboldt-Universität Berlin, thesis, 2019.

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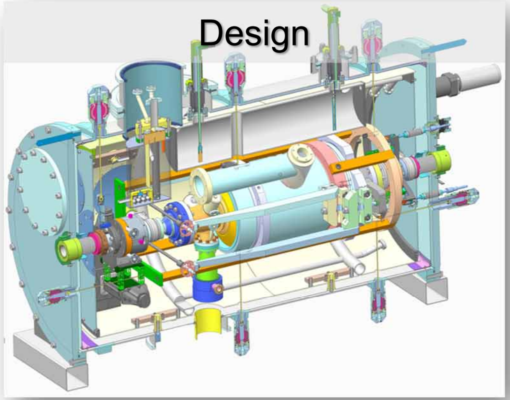
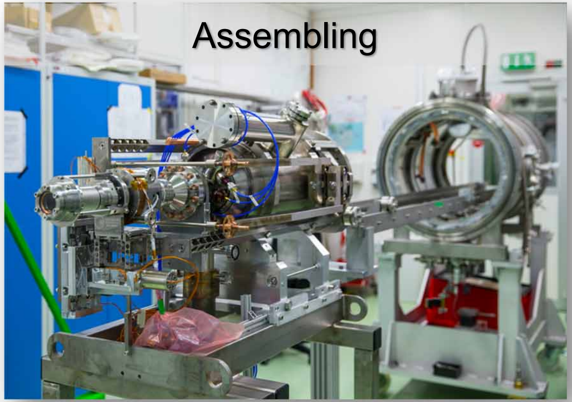
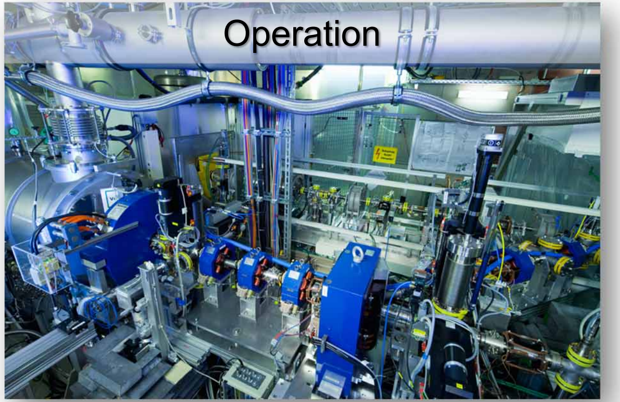
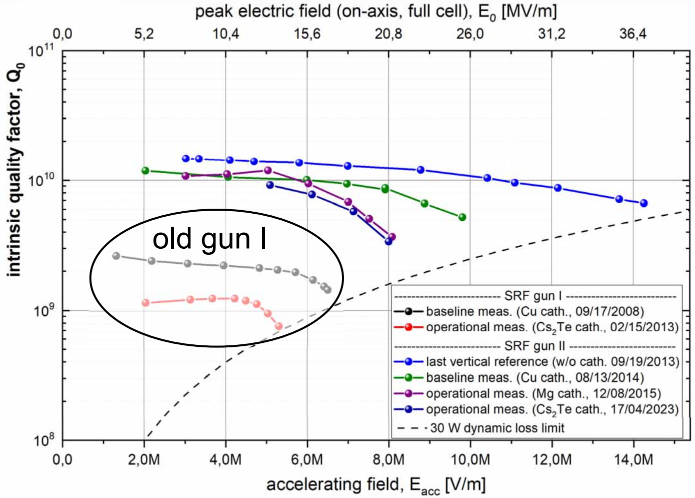
Summary







- >15 yrs. of experience in designing, assembling and operation of an SRF gun including save and particle-free cathode exchange
- 30 cathodes (2 Cu, 12 Mg, 16 Cs_2Te) w/o cavity degradation
- On average per cathode 15 C in 500 hr beam time, ¼ year in gun
- Very reliable and stable user operation (1800h per year)
- No show stopper but questions about cathode / cavity interplay



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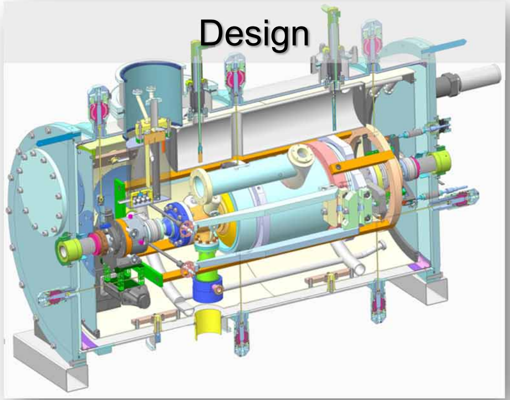

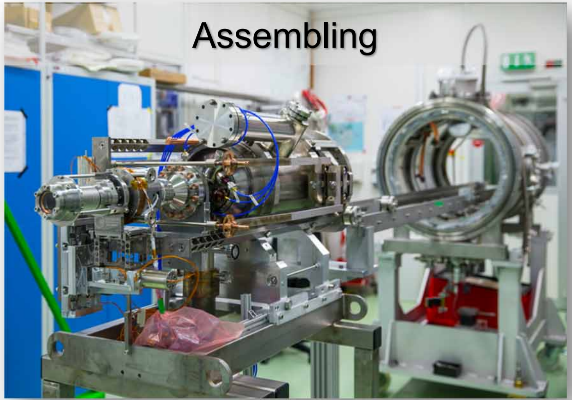

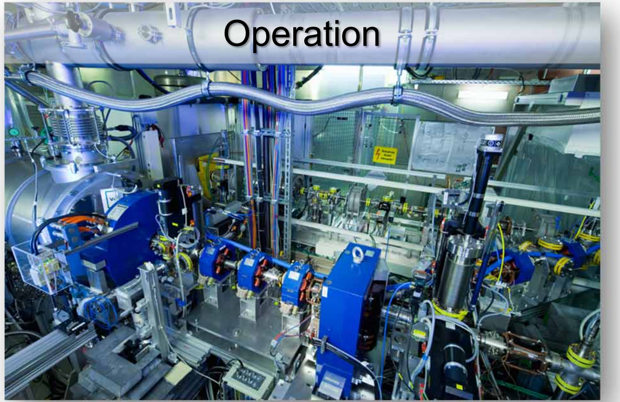

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