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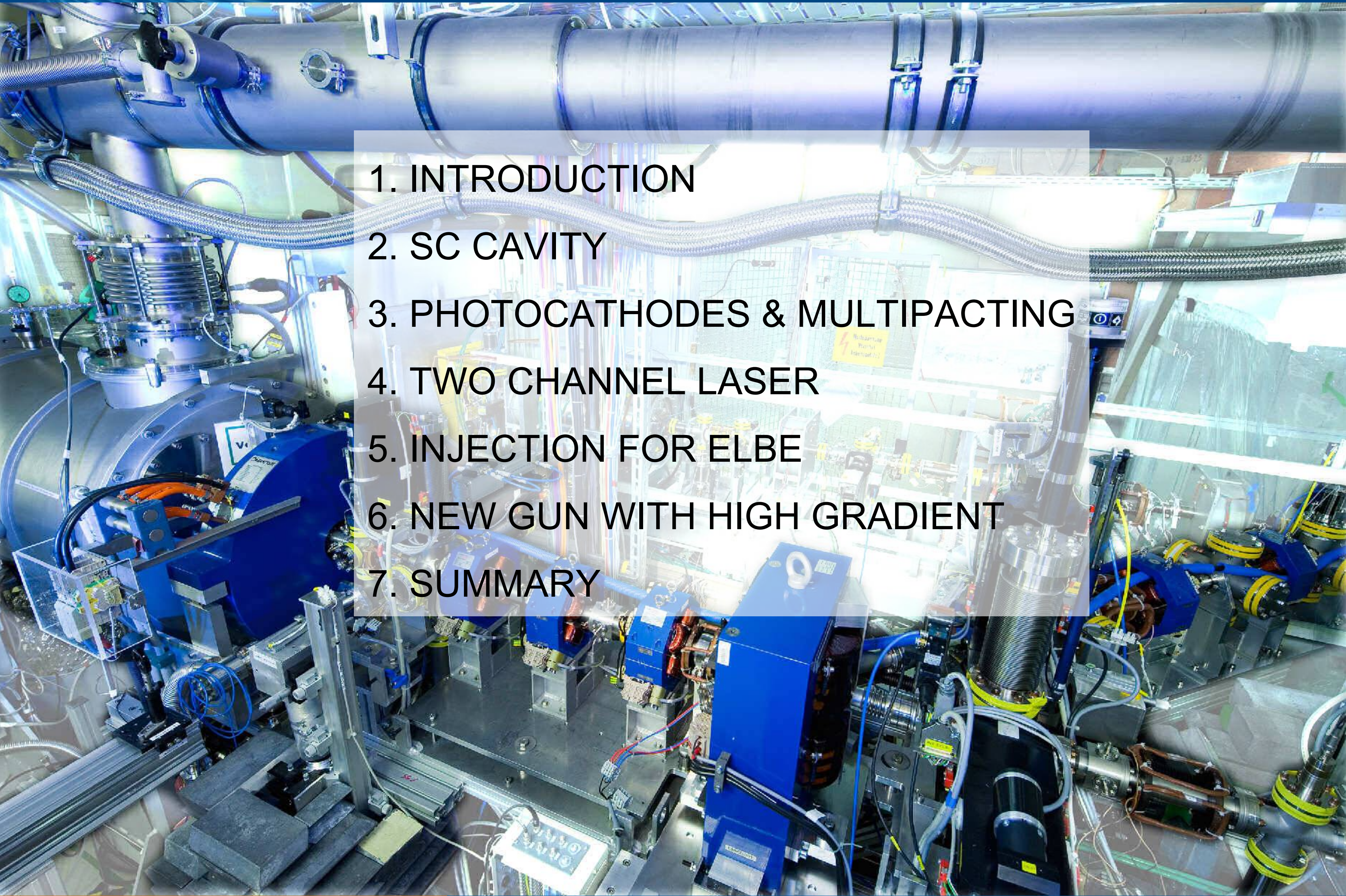
Progress of SRF gun development and and operation at the ELBE accelerator

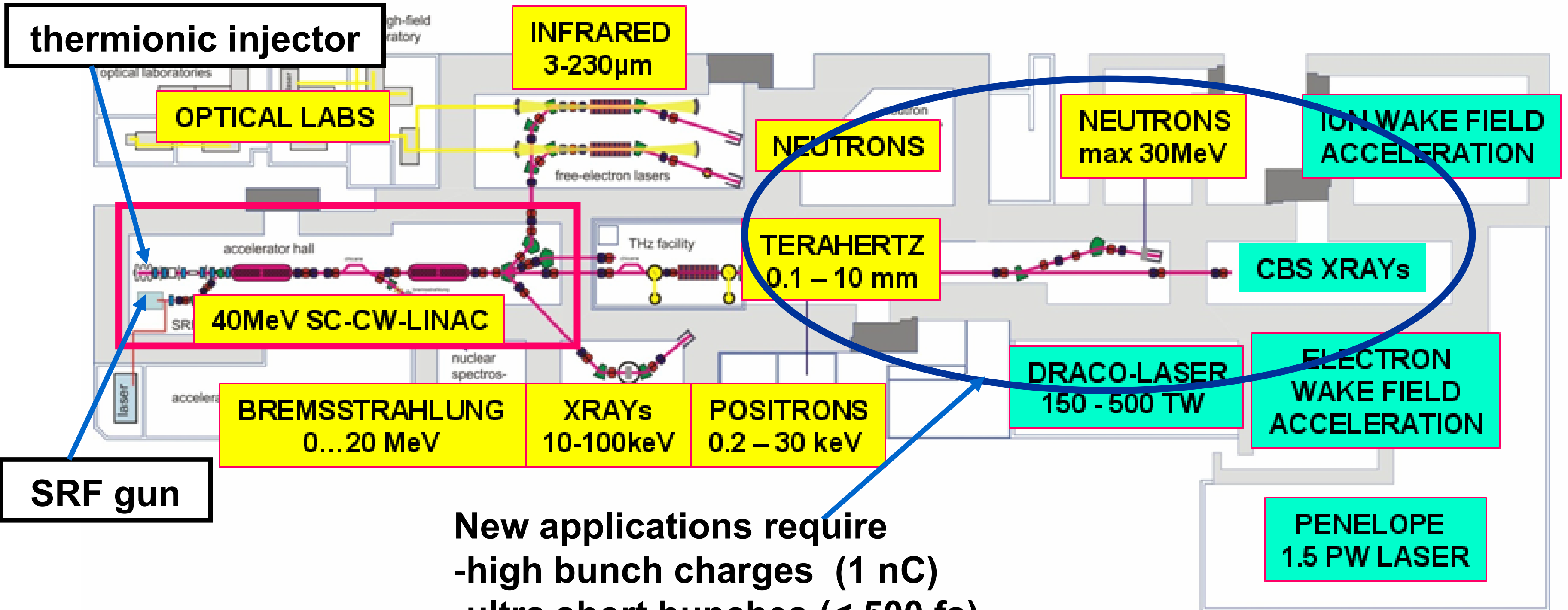
The 53th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs "ERL-2013"
9 – 13 September , 2013, BINP, Novosibirsk, Russia

OUTLINE



1. INTRODUCTION
2. SC CAVITY
3. PHOTOCATHODES & MULTIPACTING
4. TWO CHANNEL LASER
5. INJECTION FOR ELBE
6. NEW GUN WITH HIGH GRADIENT
7. SUMMARY

ELBE User Facility



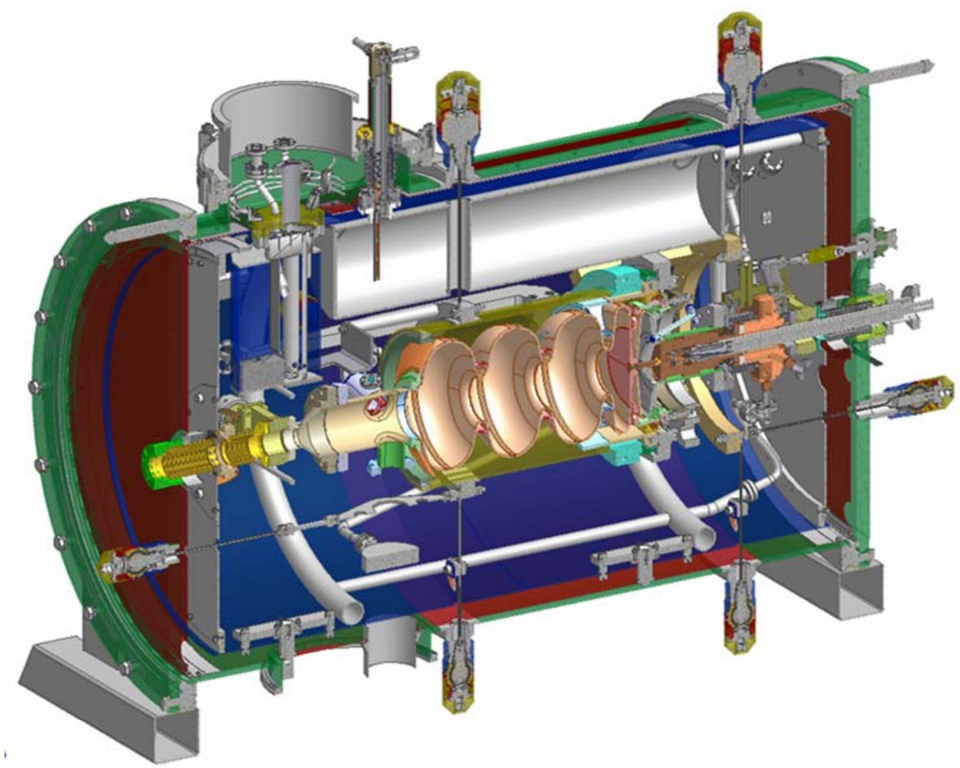
New applications require
-high bunch charges (1 nC)
-ultra short bunches (< 500 fs)
-low transverse emittance (1 mm mrad)

Accelerator Research an Development at ELBE:

Superconducting RF Photoelectron Injector

Application

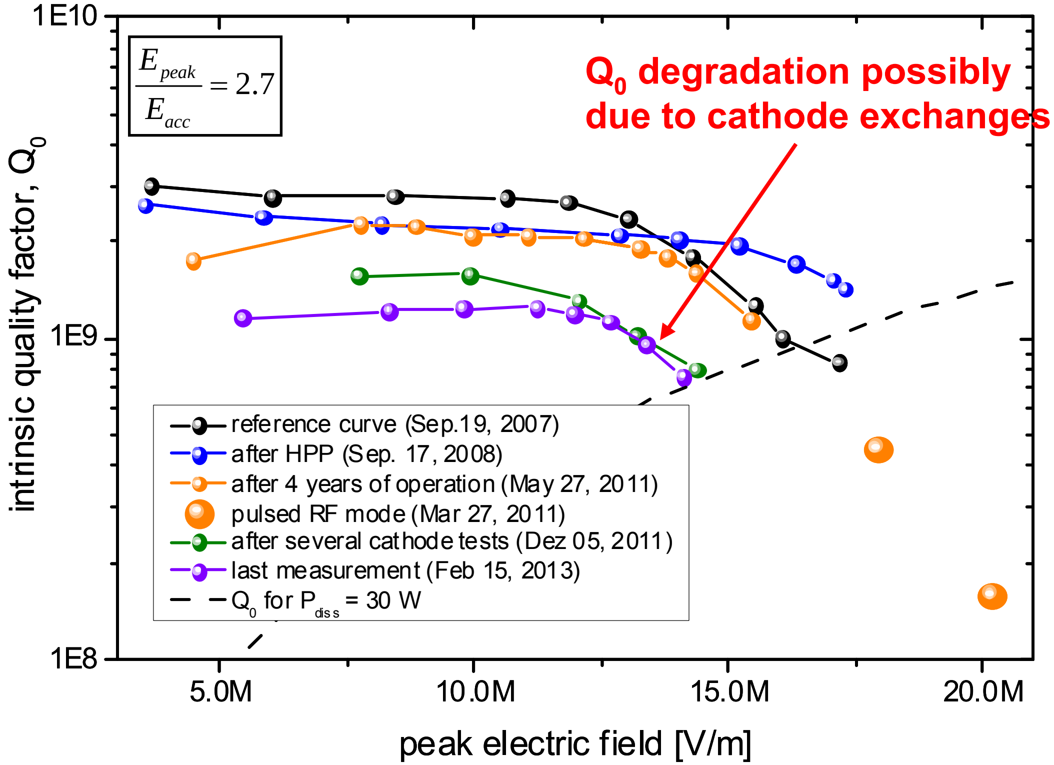
- high peak current operation for CW-IR-FELs with 13 MHz, 80 pC
- high bunch charge (1 nC), low rep-rate (<1 MHz) for pulsed neutron and positron beam production (ToF experiments)
- low emittance, medium charge (100 pC) with short pulses for THz-radiation and x-rays by inverse Compton backscattering



Design

medium average current:
1 - 2 mA (< 10 mA)
high rep-rate:
500 kHz, 13 MHz and higher
low and high bunch charge:
80 pC - 1 nC
low transverse emittance:
1 - 3 mm mrad
high energy:
≤ 9 MeV, 3½ cells (stand alone)
highly compatible with ELBE cryomodule (LLRF, high power RF, RF couplers, etc.)
LN2-cooled, exchangeable high-QE photo cathode

Q vs. E measurement is an important instrument to identify cavity contamination!



Formulas:

$$E_{acc} \overset{\beta \gg 1}{\approx} \frac{1}{L}\sqrt{4P_i 2r_s Q_L} \quad \& \quad Q_0 = \frac{4P_i}{P_d} Q_L$$

Good News

- No Q degradation during the first 4 years of operation!
- Small improvement after HPP (but canceled by thermal cycle)

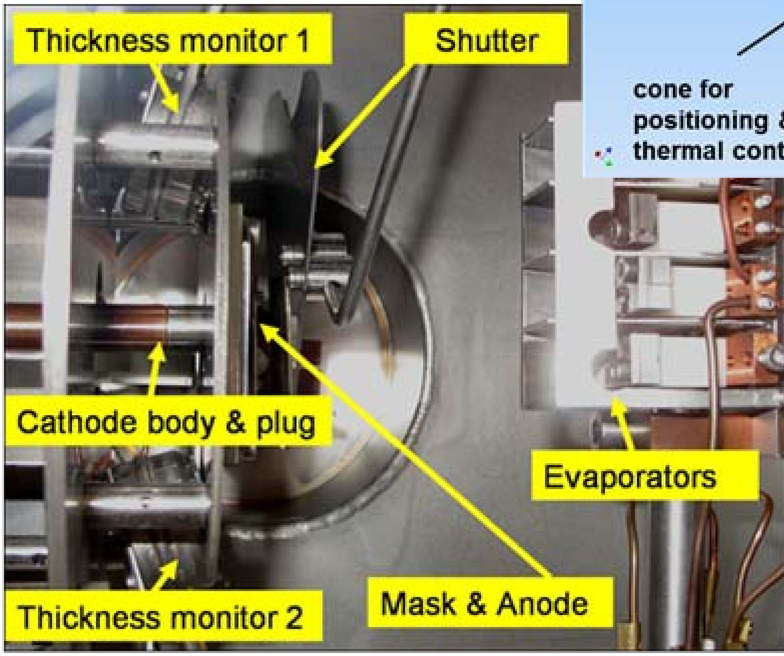
Bad News

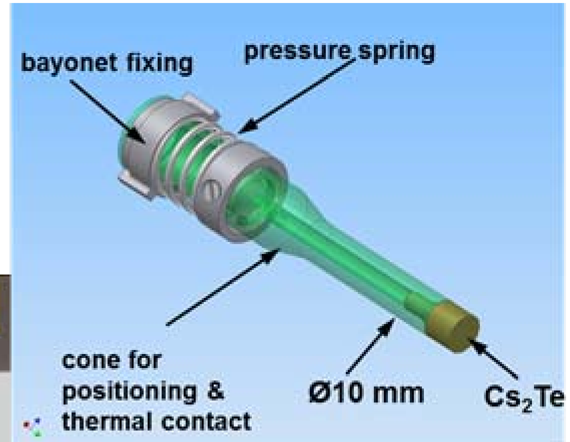
- measured Q_0 is 10 times lower than in vertical test
- Maximum achievable field 1/3 of the design value 50 MV/m)
- Cavity performance limited by FE & He consumption (>30 W)
- performance loss 1 ½ years ago, due to cathode exchanges ?

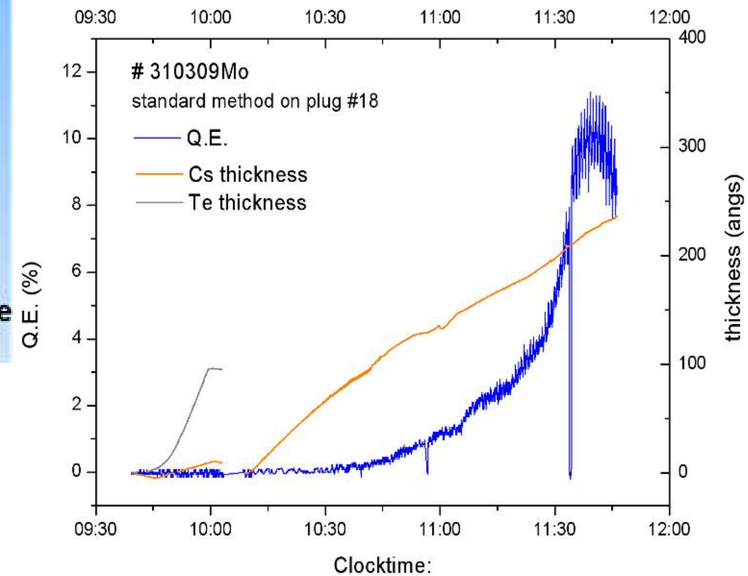
Summary:

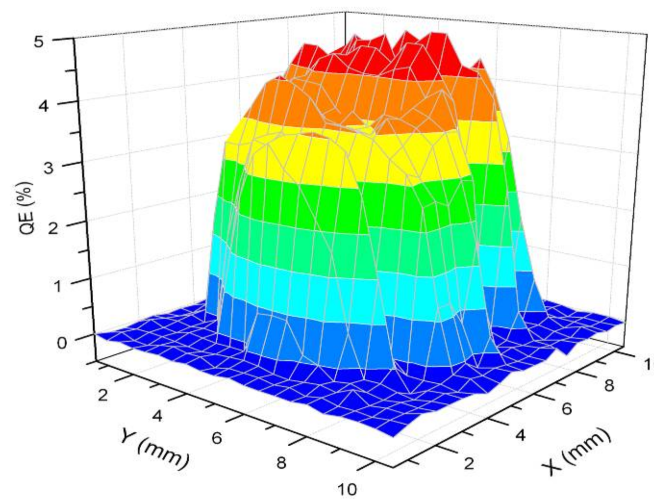
	E_{acc}	E_{peak} on Axis	E_{kin}
CW	6.5 MV/m	17.5 MV/m	3.3 MeV
Pulsed RF	8 MV/m	22 MV/m	4.0 MeV

Inside preparation chamber



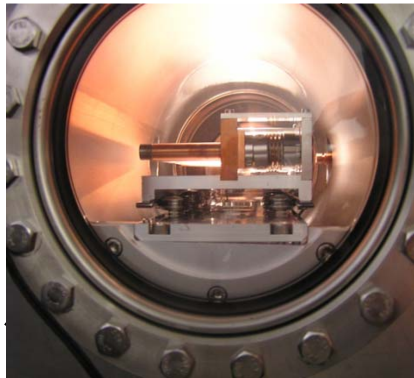


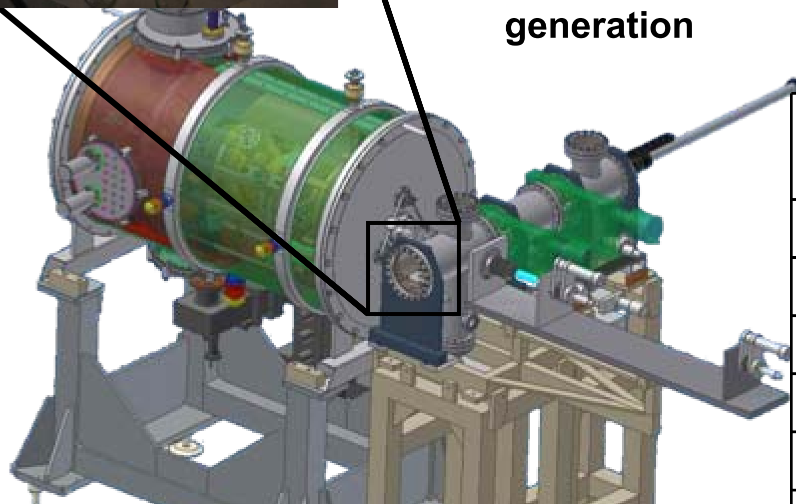




- Cathodes mech. polished and cleaned with Ar^+
- Heated to 120° C and evaporated with Cs and Te (successive- or simultaneously)
- Online thickness and QE measurement
- After prep. also QE distribution scan
- Vacuum requirement: ~10^{-9} mbar

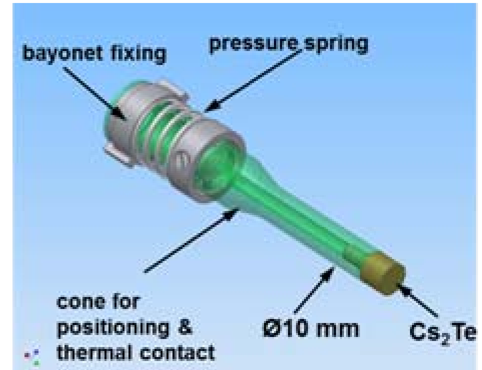
Excellent lifetime of Cs2Te PC in SRF gun





Requirements for Transfer:

- **Load lock system with < 10^{-9} mbar to preserve QE ≥ 1 %**
- **Exchange w/o warm-up & in short time and low particle generation**

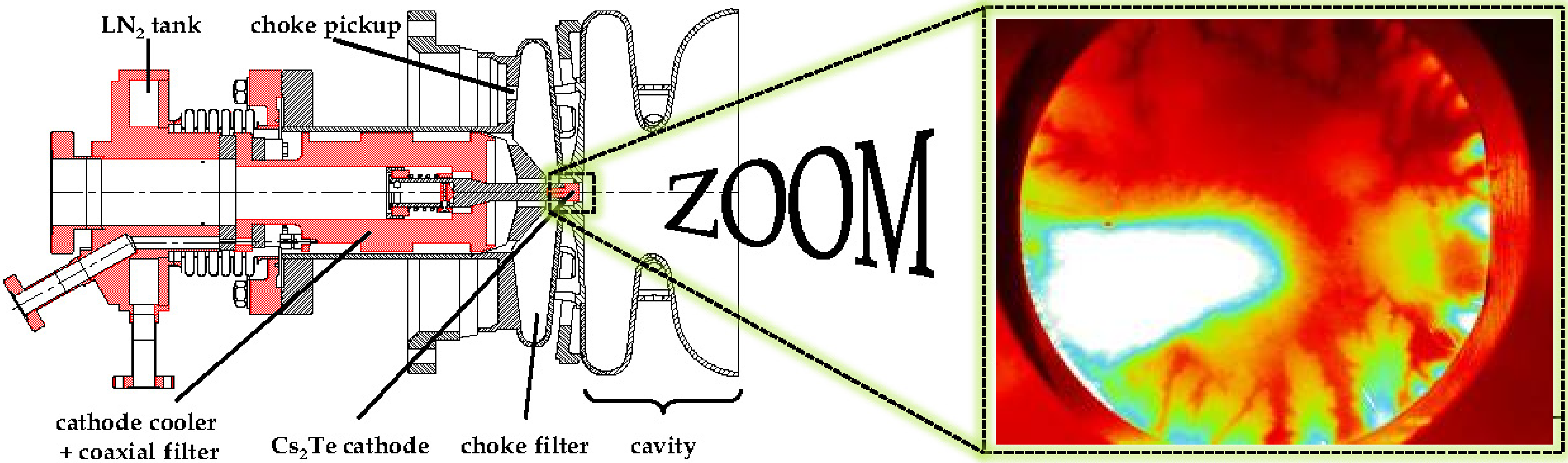


Cathode	Operation days	Extracted charge	Q.E. in gun
#090508Mo	30	< 1 C	0.05%
#070708Mo	60	< 1 C	0.1%
#310309Mo	109	< 1 C	1.1%
#040809Mo	182	< 1 C	0.6%
#230709Mo	56	< 1 C	0.03%
#250310Mo	427	35 C	1.0%
#090611Mo	65	< 1 C	1.2%
#300311Mo	76	2 C	1.0 %
#170412Mo	From 12.05.2012	265 C	~ 0.6 %

- **fresh QE 8.5%, in gun 0.6%**
- **total beam time 600 h**
- **extracted charge 265 C**

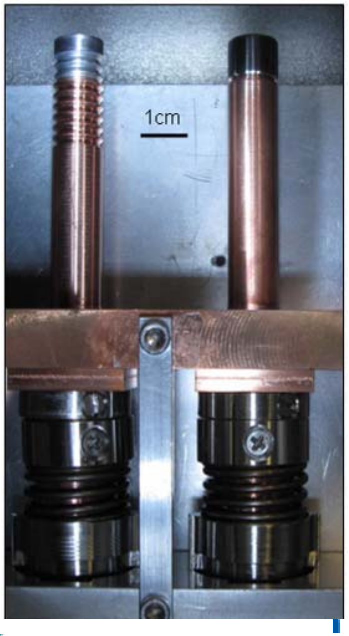
01.08.2013

problems: multipacting, QE drop-down during storage



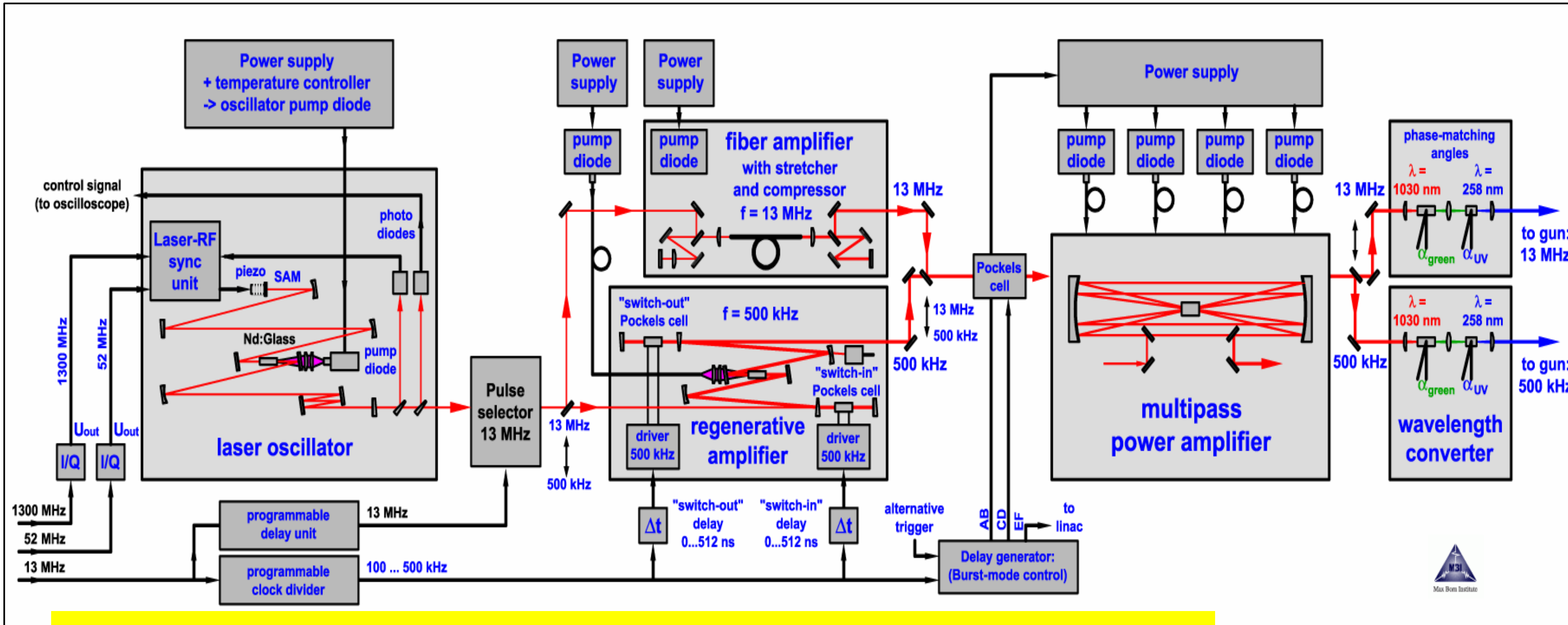
- **MP was expected since the early days of the cavity design!**
- **And indeed it appeared at low field (<1 MV/m) for every Cs_2Te cathode**
- **Characterized by high current (>1 mA, rectified) at the cathode and electron flash at view screens**

- **Biasing of the electrically isolated cathode up to -7 kV usually works (voltage is different for every cathode and position!)**
- **Anti multipacting grooves to suppress resonant conditions and coating with TiN to reduce secondary electron yield doesn't work for Cs_2Te coated cathodes → because of too high SEV due to Cs pollution?**

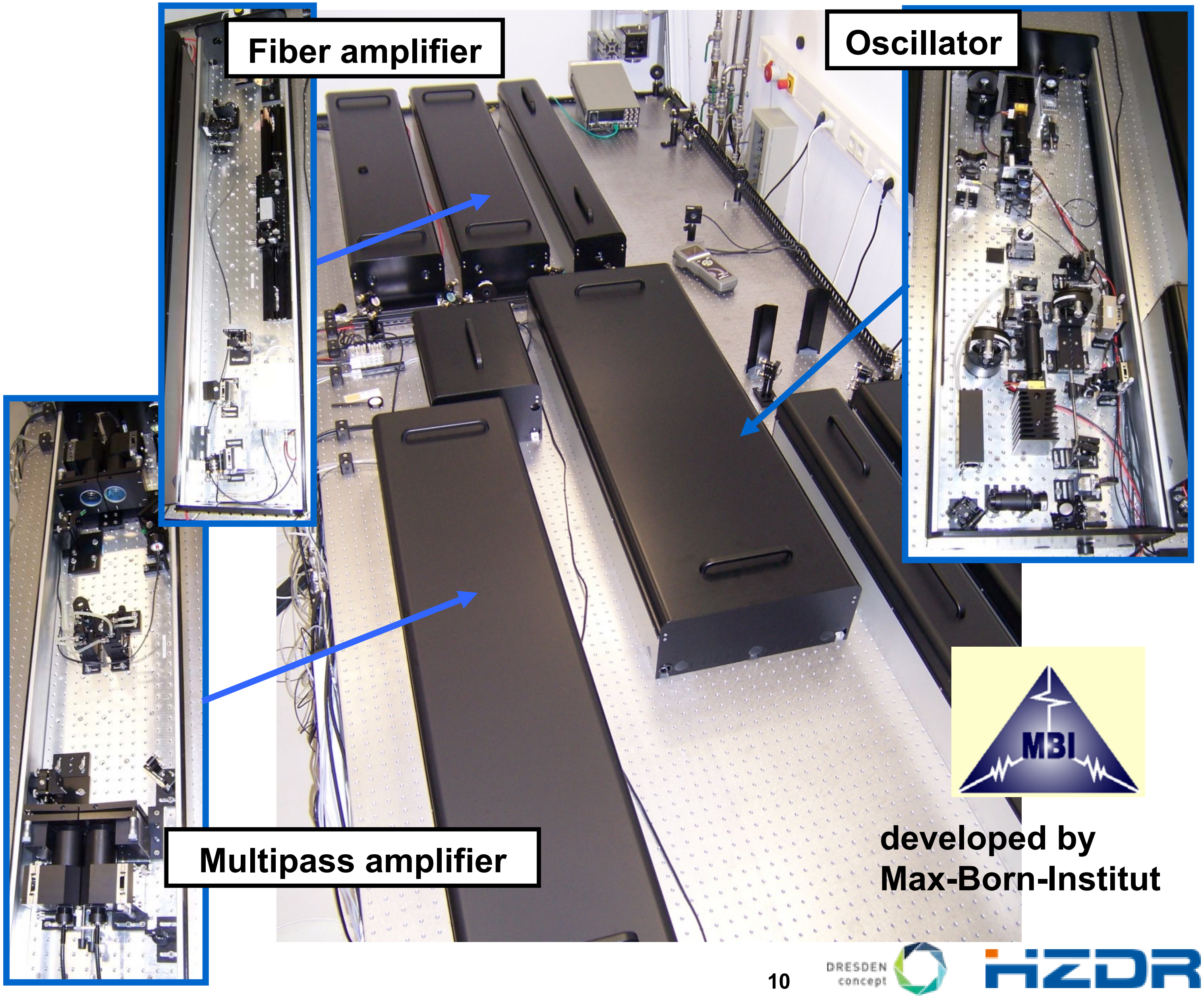


UV Laser system developed by MBI:

- Large flexibility in repetition rate and time structure (burst)
- Conversion to the UV (λ ~ 260 nm) at ~ 1 W power
- Synchronisation with RF of the linac + full remote control of the laser
- Different repetition rates + different pulse durations:
  a) 13 MHz: 3 ps FWHM Gaussian b) 100/250/500 kHz: 12 ... 15 ps FWHM Gaussian



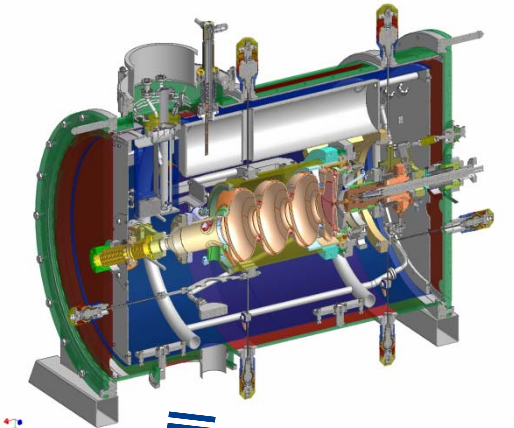
Important
- 13 MHz allow to demonstrate high-current operation of the gun
- Parameters fullfil the requirements for user operation at ELBE

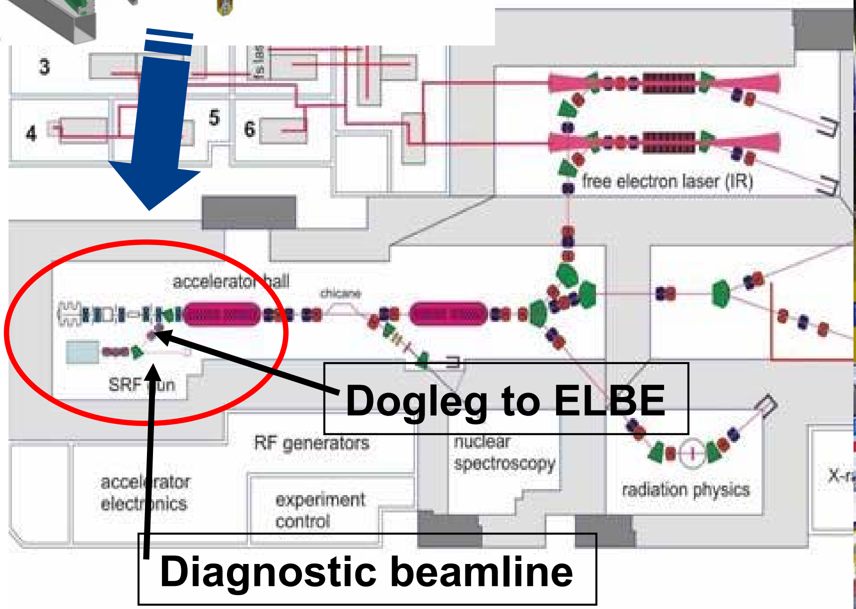


developed by
Max-Born-Institut

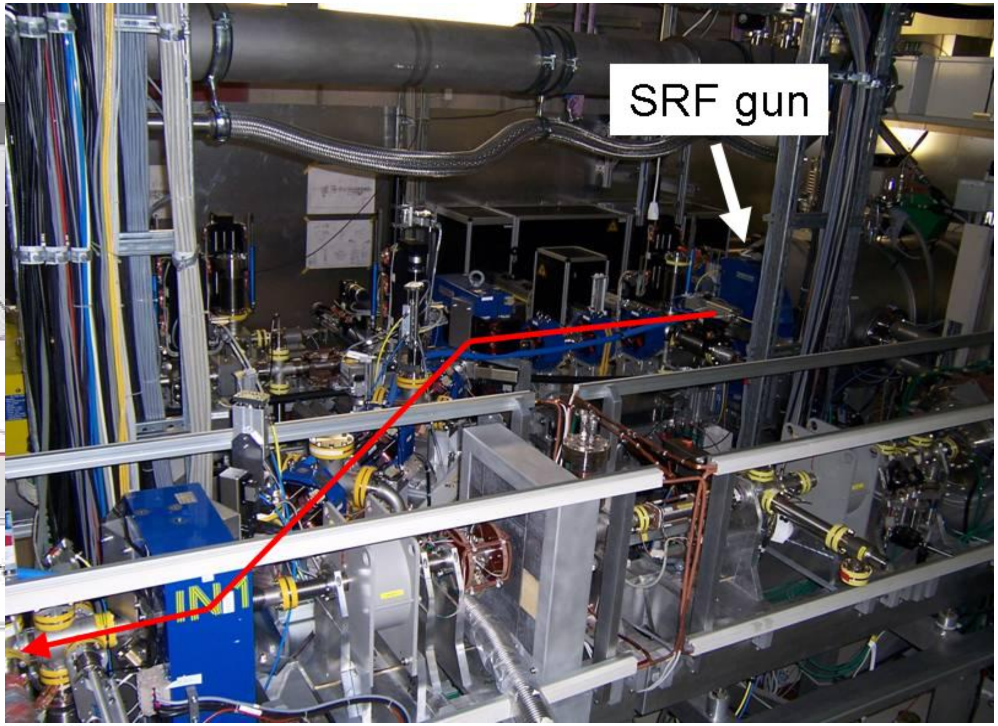
ELBE Superconducting RF Photoinjector

- New Injector for the ELBE SC Linac
- Test Bench for SRF Gun R&D



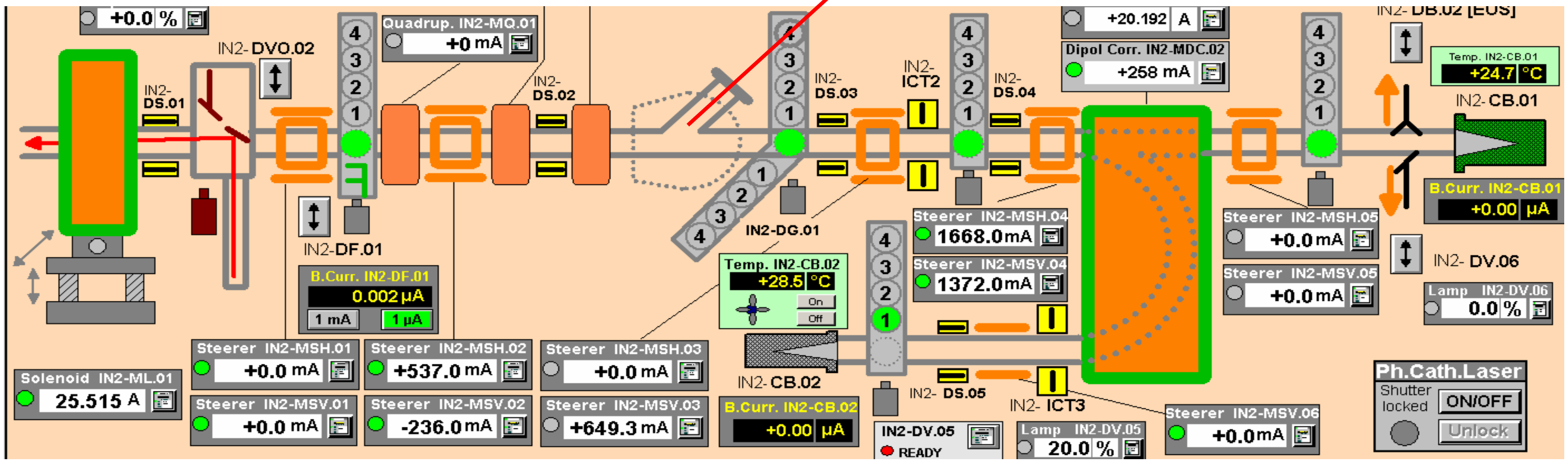


1: Time resolved semiconductor spectroscopy, THz-spectroscopy
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Diagnostic station, IR-imaging and biological IR experiment
4: FTIR, biological IR experiment
5: Near field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal beam deflection spectroscopy



SRF Gun Diagnostics Beamline

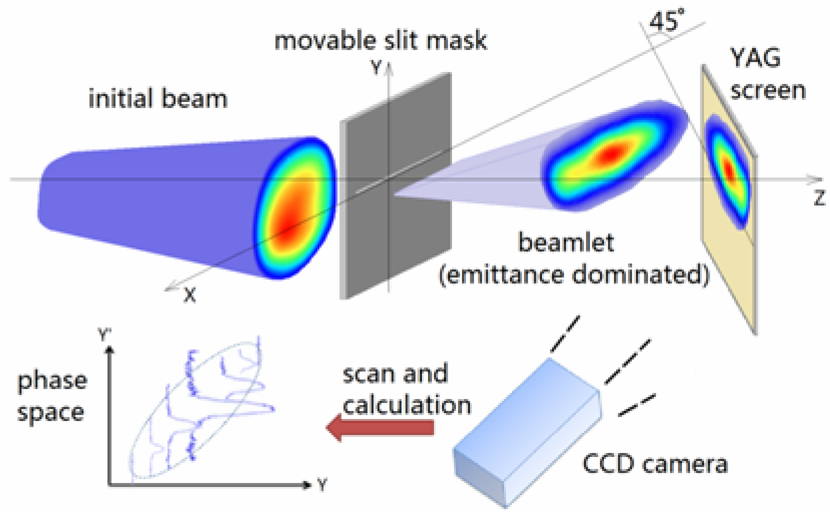
ELBE

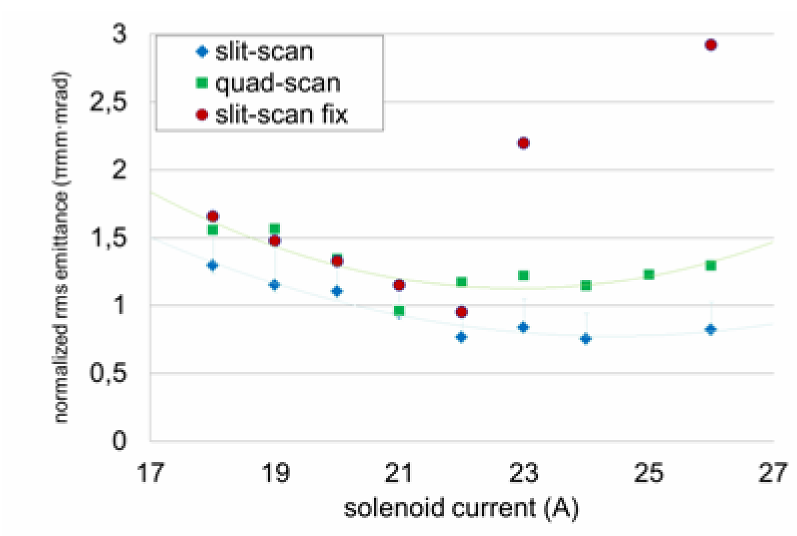


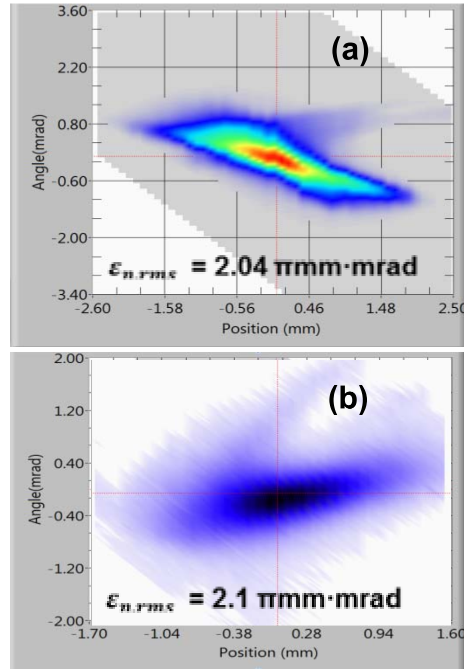
Designed and built by HZB

- Faraday cup: current, bunch charge, dark current
- five screen stations with YAGs and OTRs
- 180° bending magnet: energy and energy spread
- transverse emittance: solenoid, quadrupoles, slit mask
- Cerenkov radiation station: bunch length
- Integrated current transformer (ICT): current, stability
- Beam loss monitors

NEW: Emittance Measurements with Single Slit Scan





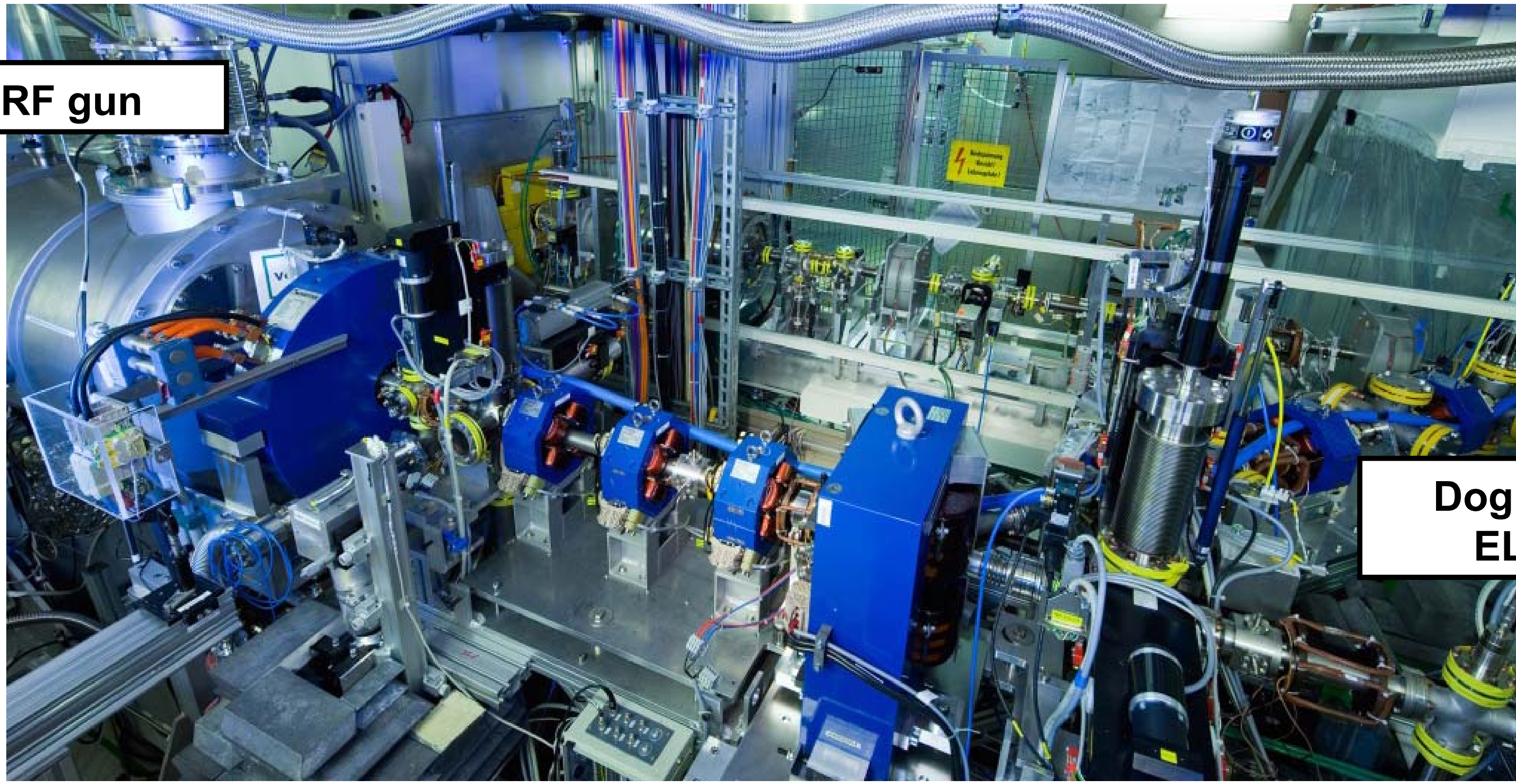


Beam

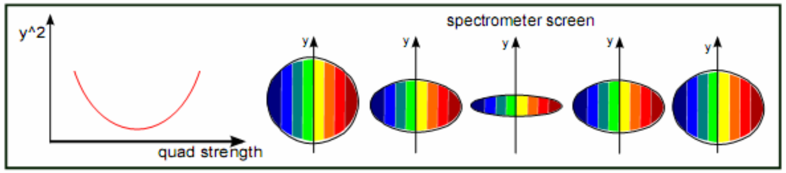
Dark current

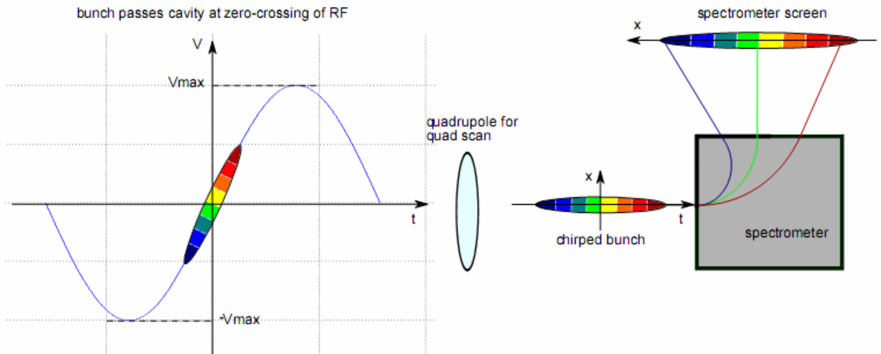
Pengnan Lu

BEAM INJECTION IN ELBE

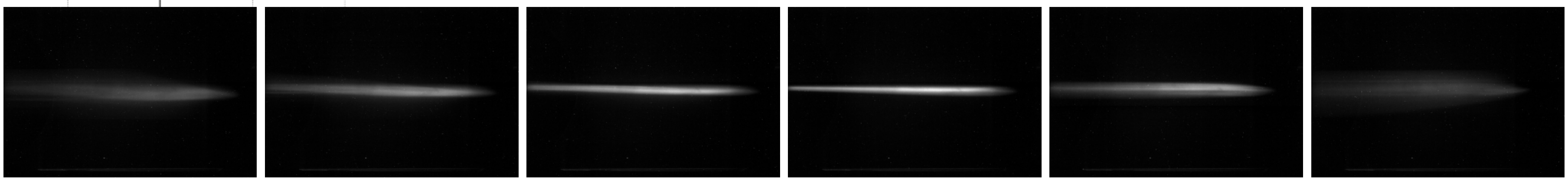


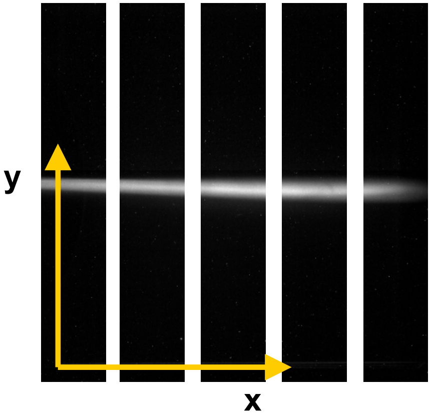
J. Rudolph, T. Kamps, HZB



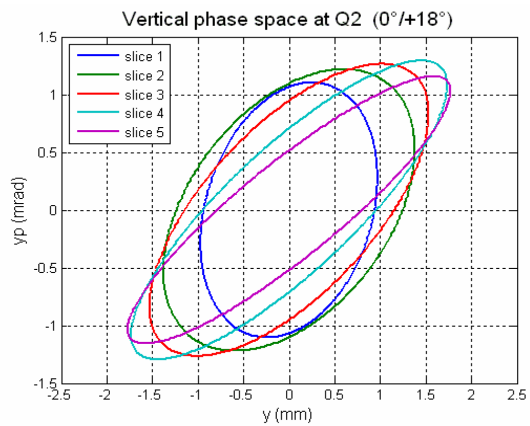


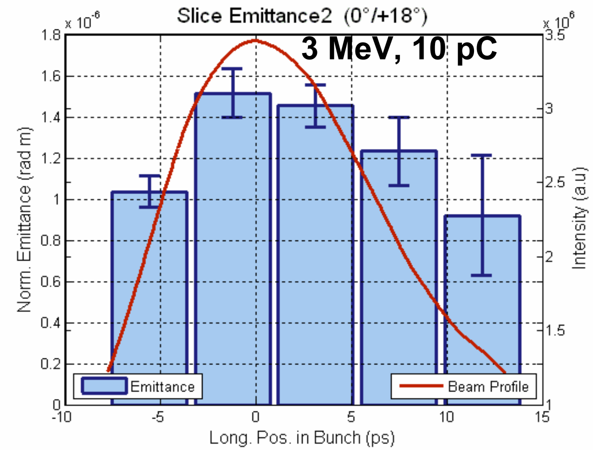
- Fixed energy imprint for correlation betw. energy spread and long. bunch distribution
- Spectrometer → longitudinal distribution transferred to transverse distribution
- Combination with quadrupole scan
- Tool for future emittance compensation



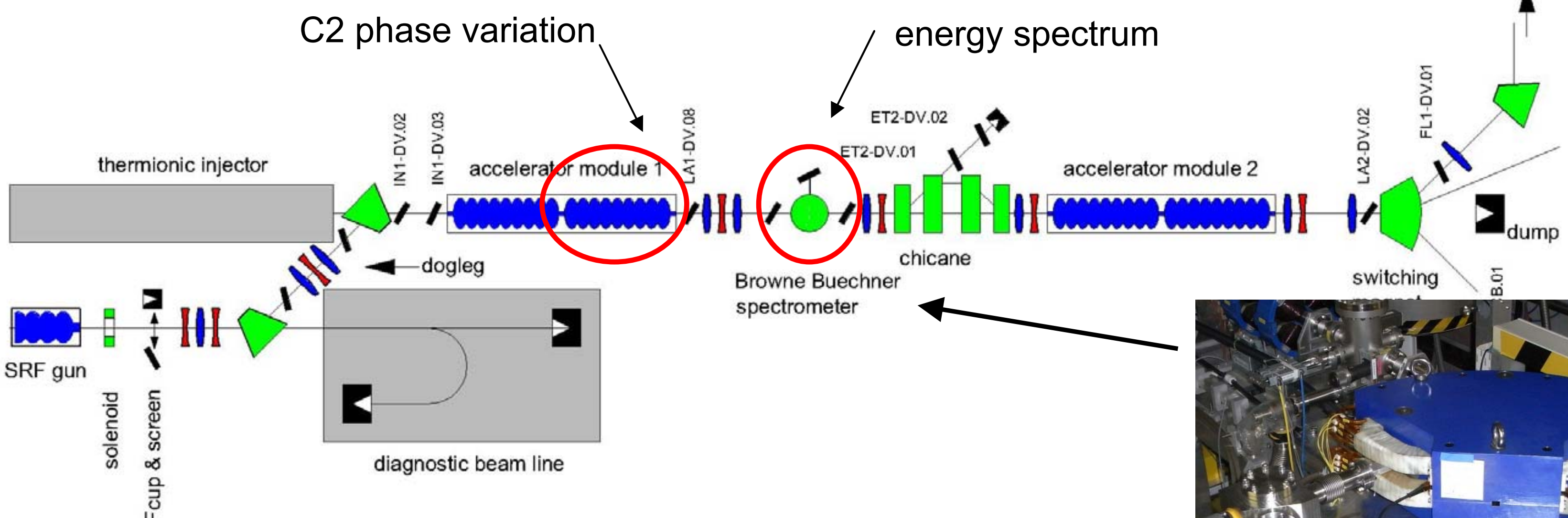


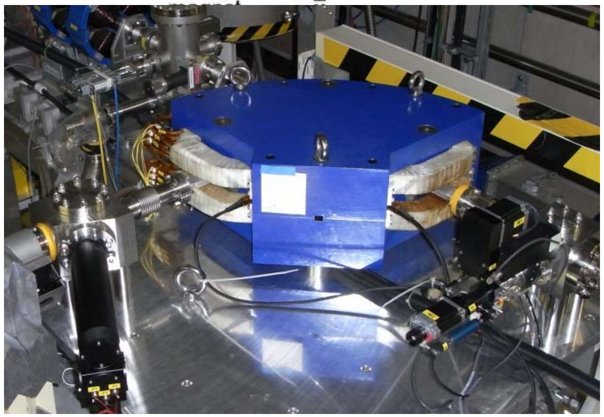
J. Rudolph, et al., Dipac2011





• Method of measurement: phase scan technique using the second ELBE cavity





longitudinal beam ellipse

$$\tau = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{12} & \tau_{22} \end{pmatrix}$$

$$\sqrt{\tau_{11}} = \sigma_t \; rms\ bunch\ length\ (ps)$$

$$\sqrt{\tau_{22}} = \sigma_E \; rms\ energy\ spread\ (keV)$$

cavity transport matrix

$$R_{C2} = \begin{pmatrix} 1 & 0 \\ -\omega_{RF} V_{C2} \sin(\varphi_{C2}) & 1 \end{pmatrix}$$

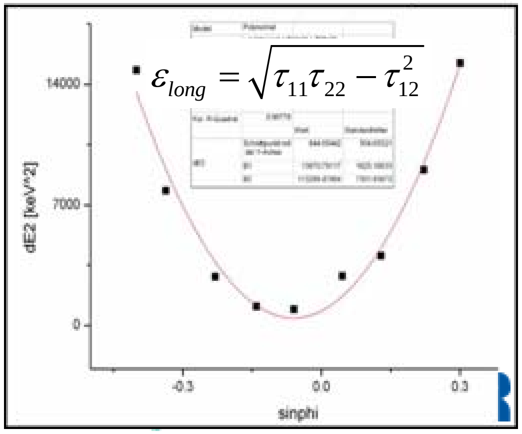
cavity energy boost:

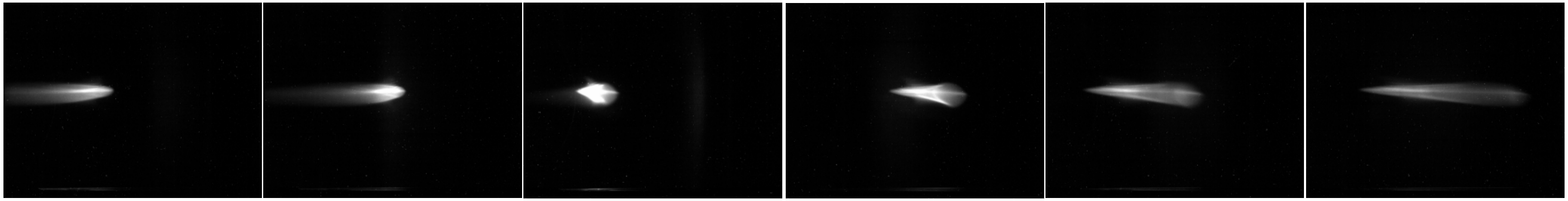
$$V_{C2} \cos(\varphi_{C2})$$

$$\tau(1) = R_{C2} \tau(0) R_{C2}^T$$

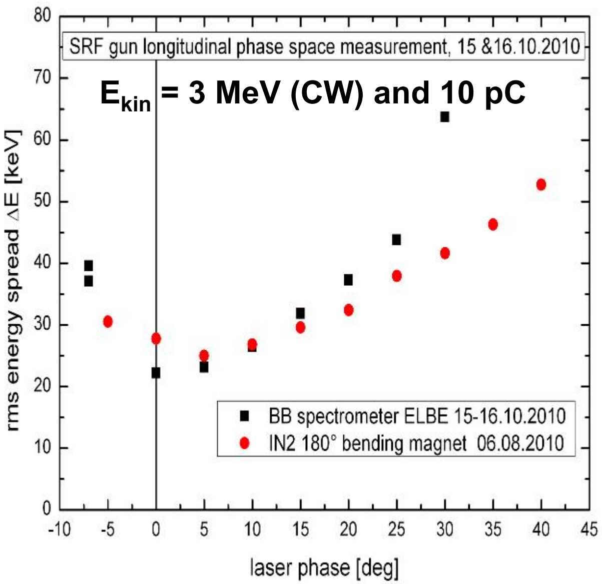
from parabola fit

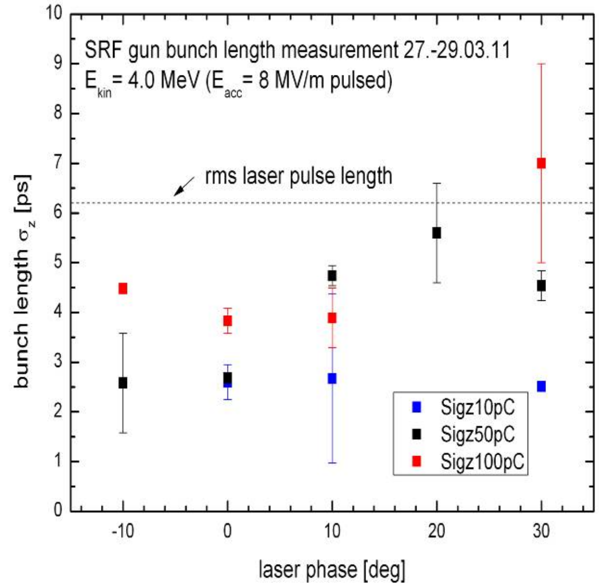
$$\sigma_E^2(1) = \tau_{22}(0) - 2\tau_{12}(0) V_{C2} \sin(\varphi_{C2}) + \tau_{11}(0)(V_{C2} \sin(\varphi_{C2}))^2$$

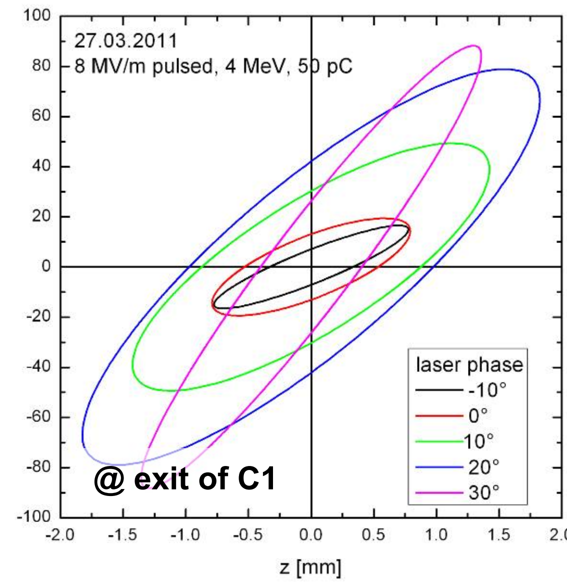




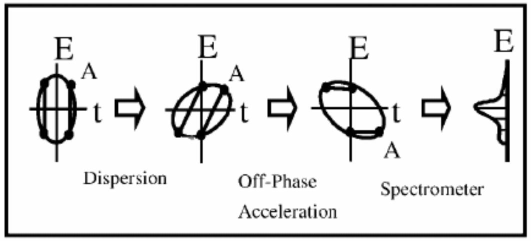
Browne Buechner spectrometer pictures





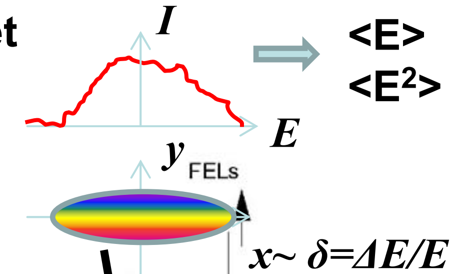


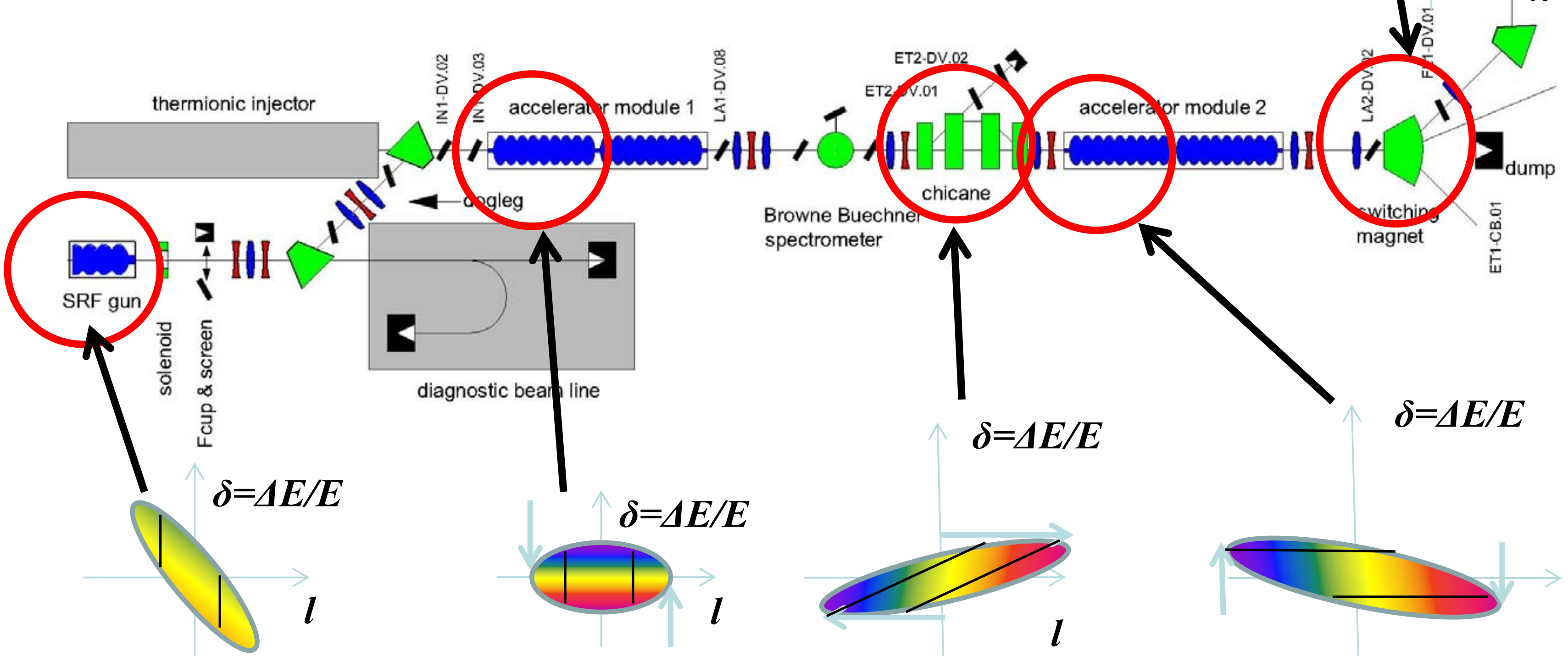
- Same energy spread measured as in the 180° magnet of the diagnostic beamline
- Bunch compression in SRF-gun as expected from ASTRA simulation
- Successful test of long. phase space measurement for future gun optimization



proposed by Ricci, Crosson & Smith (Stanford Univ.)
Nucl. Instr. Meth. A445(2000)333
Phys Rev. STAB 3(2000)032801

dipole magnet and screen are the spectrometer





gun creates bunches with (small) correlated ΔE

C1 corrects correlated ΔE

chicane shears the bunch in l-direction

C3 produces correlated ΔE

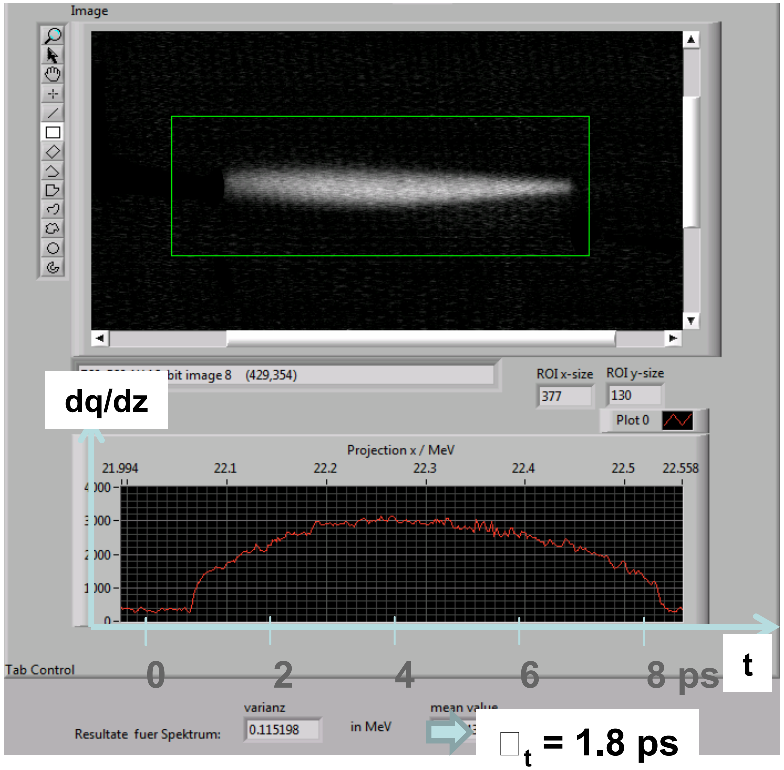
$$\begin{pmatrix} l_3 \\ \delta_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ R_{65} & R_{66} \end{pmatrix} \begin{pmatrix} 1 & \bar{R}_{56} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} l_1 \\ \delta_1 \end{pmatrix}$$

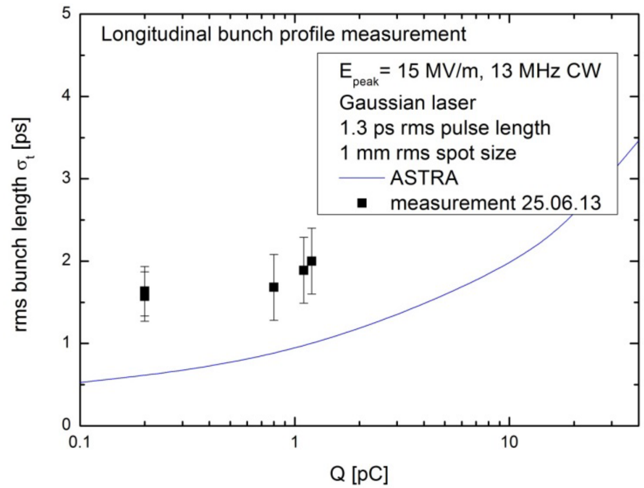
$$\begin{pmatrix} l_3 \\ \delta_3 \end{pmatrix} = \begin{pmatrix} 1 & \bar{R}_{56} \\ R_{65} & \bar{R}_{56}R_{65} + R_{66} \end{pmatrix} \begin{pmatrix} l_1 \\ \delta_1 \end{pmatrix}$$

$$\frac{\Delta E_3}{E_3} = \delta_3 = R_{65} l_1 + (\bar{R}_{56}R_{65} + R_{66})\delta_1$$

initial energy spread removed by $\bar{R}_{56}R_{65} + R_{66} = 0$

time (position in bunch) is uniquely transformed into energy and later into position in a spectrometer

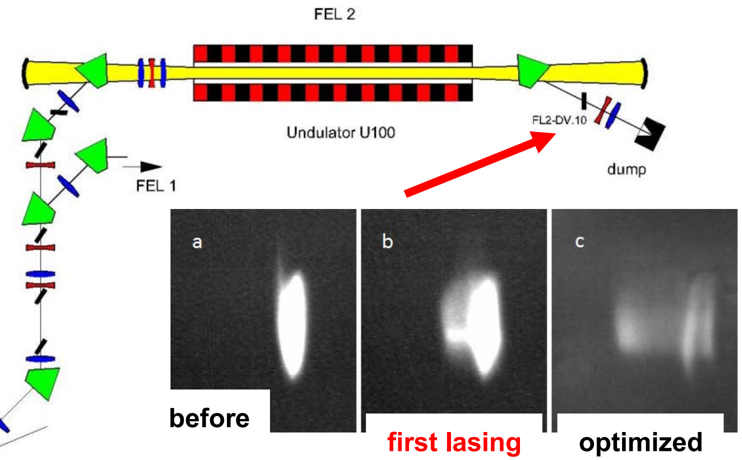




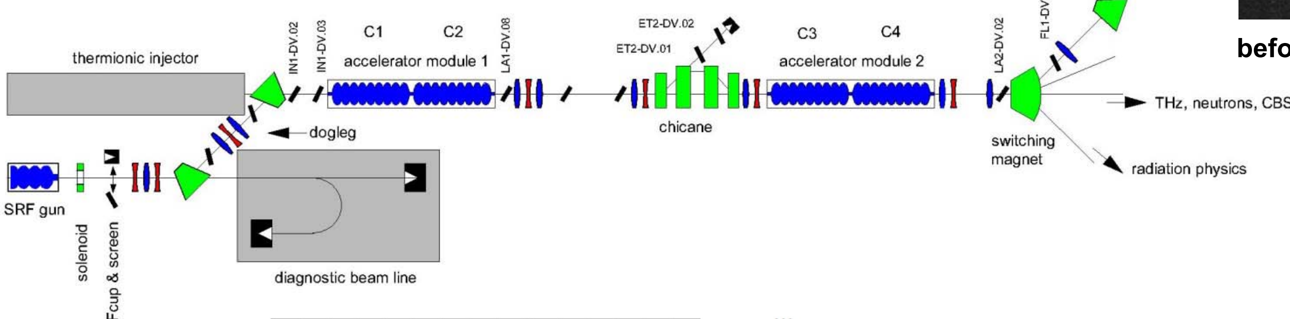
First FEL Operation with SRF Photo Gun at ELBE

E_{kin} at gun exit	3.3 MeV
Micro pulse repetition rate	13 MHz
Macro pulse repetition rate / length	1.25 Hz / 2 ms
Beam energy at FEL	27.9 MeV
Bunch charge / beam current	20 pC / 260 µA
Photo cathode	Cs_2Te
RMS bunch length	1.6 ps
Normal. RMS emittance	1 mm mrad

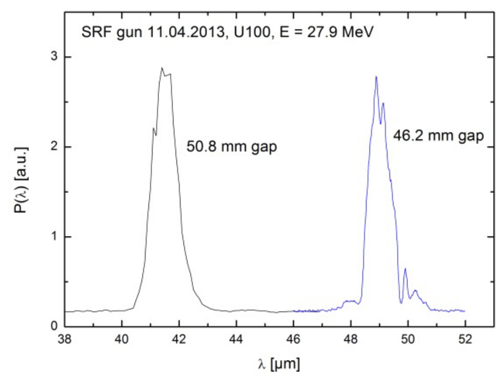
ELBE infrared FEL (20 – 250 µm)



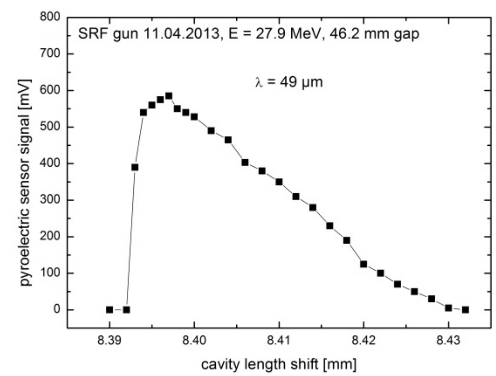
April 11, 2013



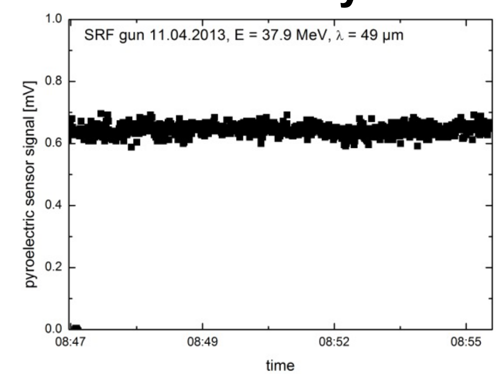
stabilty



FEL spectra



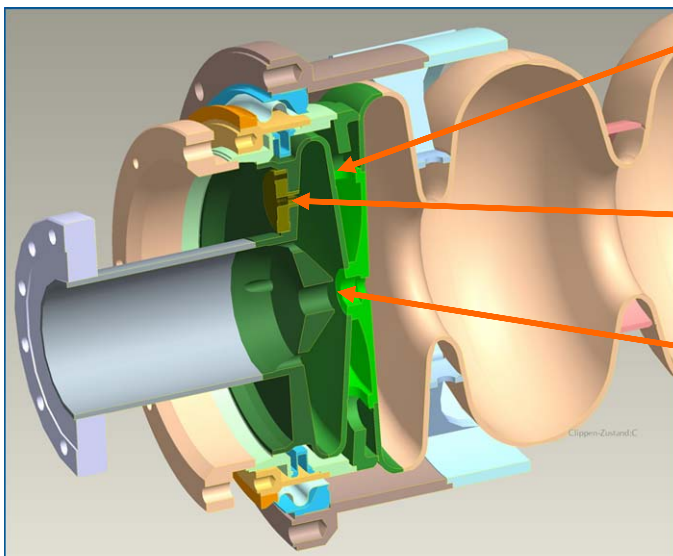
FEL detuning curve



Main aim: approach the design value of E_{pk}=50 MV/m:

- Fabrication of two new cavities in collaboration with JLab (fabrication, treatment, test by P. Kneisel and co-workers)

- Slightly modification compared to old design to:
    - Lower Lorentz force detuning, microphonics and pressure sensitivity
    - Improve cleaning and simplify clean room assembly

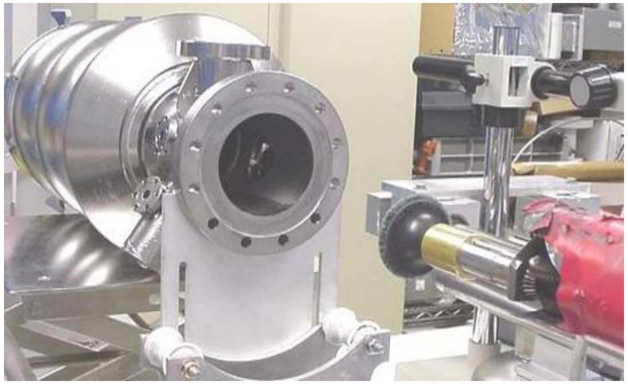


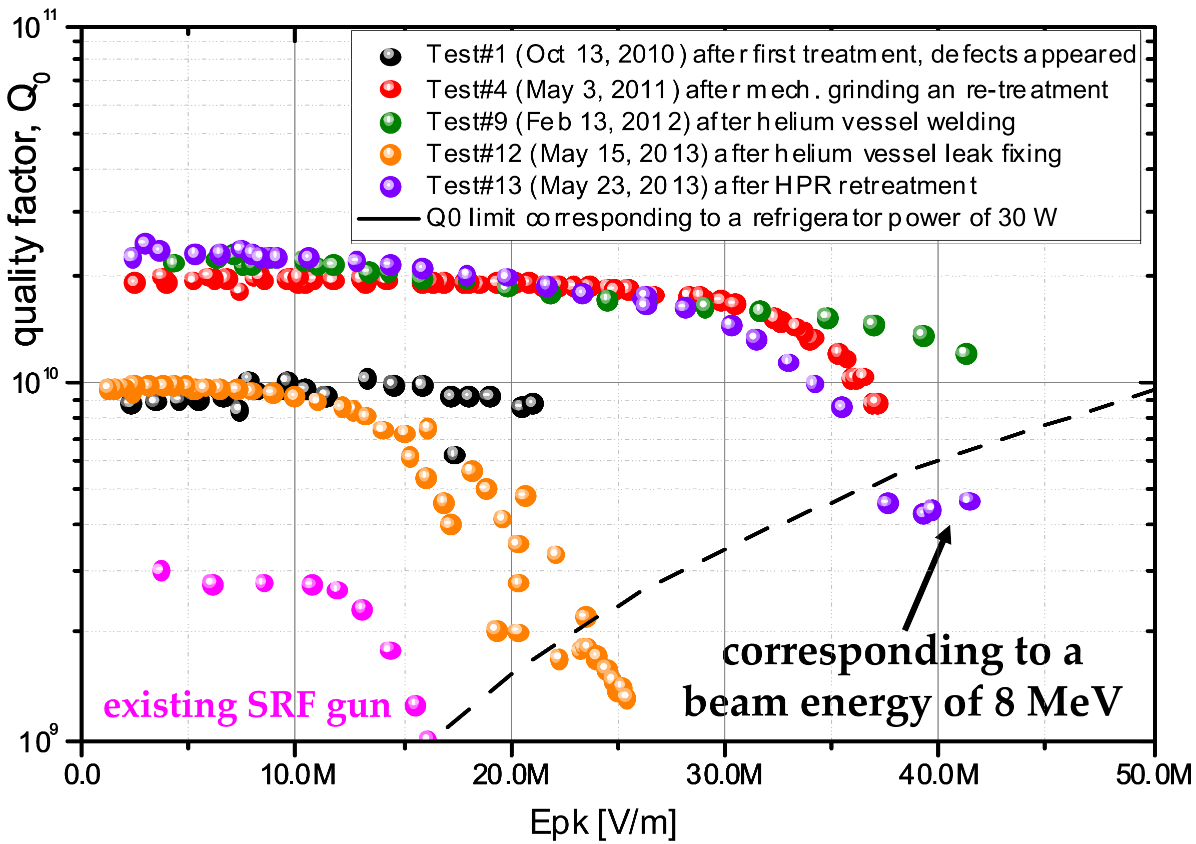
additional half-cell stiffening (light green)

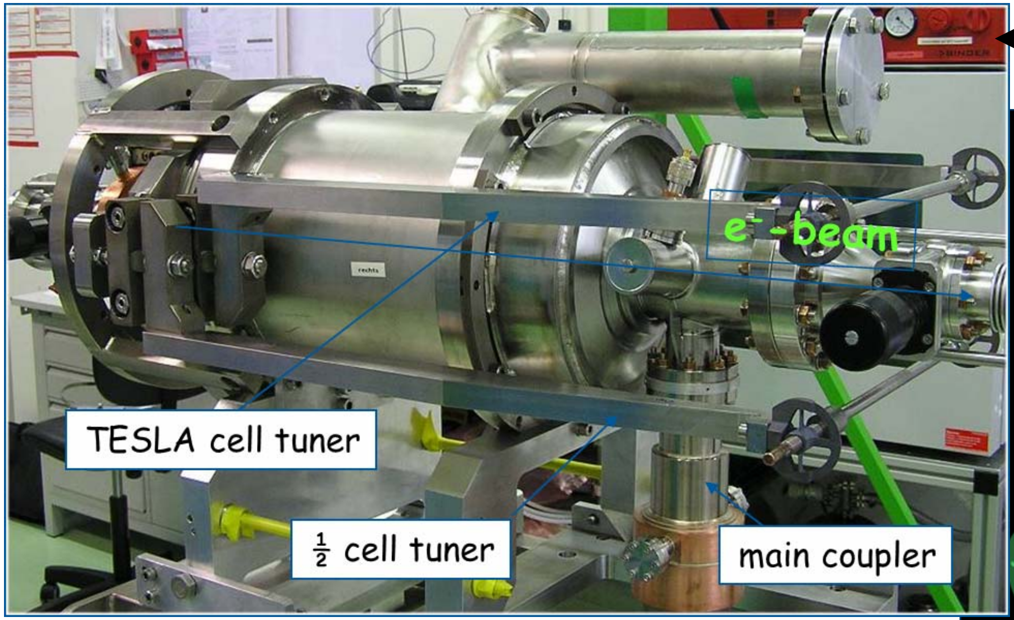
modified choke-cell pick-up flange

larger cathode boring

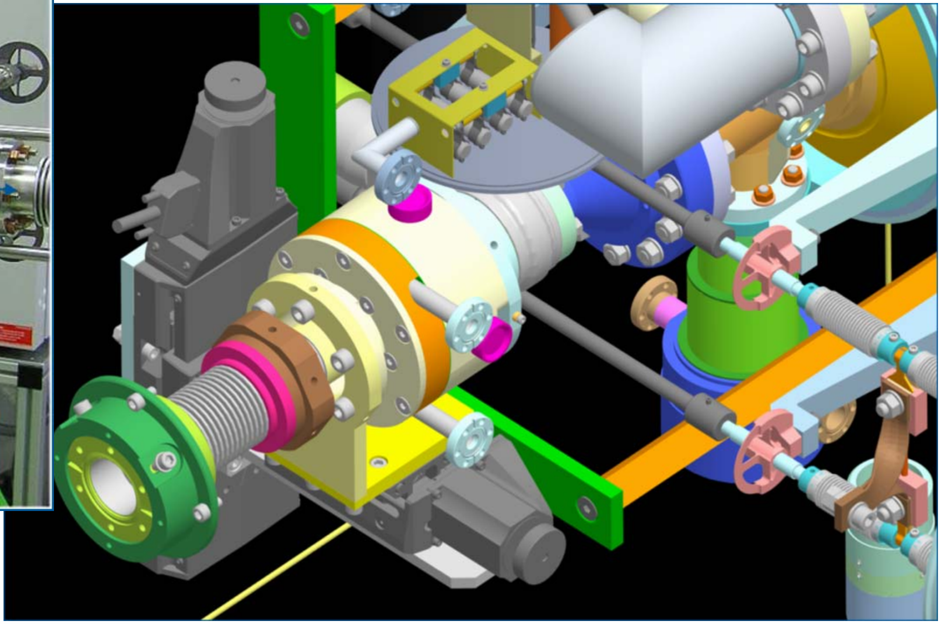
NEW SRF GUN WITH HIGH ACCELERATION GRADIENT

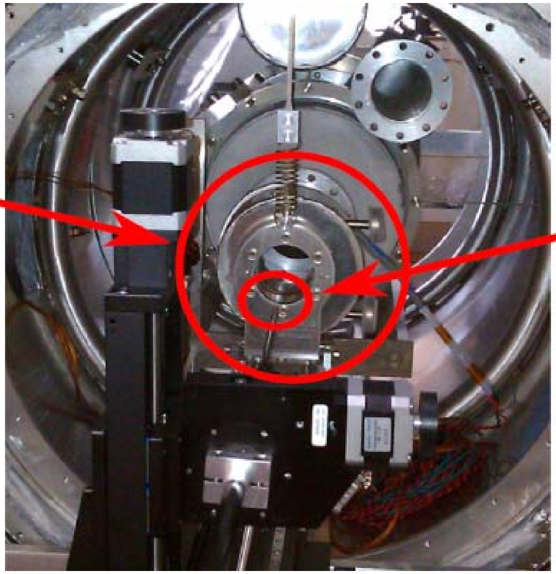






„Old" cold mass of the operating SRF gun





Design for the new cryomodule with
- SC solenoid (2 K) Niowave Inc. (NPS, HZB)
- remote controlled xy-table for alignment (77 K)

Quite recently:
Cryomodule cooldown 77 K & 4.5 K, w/o cavity
SC solenoid reaches spec: 10 A, 0.4 T

CAVITY

- Low acceleration gradient (40 % of design value) due to field emission since commissioning
- No Q degradation of Cavity during first 4 years but then Q-drop due to cathodes?
→ NC cathodes and its exchange are a potential risk for SRF gun cavities

PHOTOCATHODES

- Long lifetime of NC photo cathodes in SRF gun (>1 yr, total charge 260 C @ QE ≈ 1%)
- Multipacting appears for Cs_2Te coated cathodes only, suppression with DC Bias
- Cs_2Te cathodes produces high dark current with similar properties as the photo beam,
→ for higher surface fields 40 μA are expected, which is a problem for CW accelerators

OPERATION @ ELBE

- Despite of low gradient successful experiments and measurements:

Far-IR FEL operation, Compton-backscattering with TW laser, Superradiant THz radiation, Slice emittance, Longitudinal phase space measurements

FUTURE

- RRR300 upgrade cavity (+vessel) tested up to 43 MV/m, cold mass assembly upcoming, new cryomodule with SC solenoid tested

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