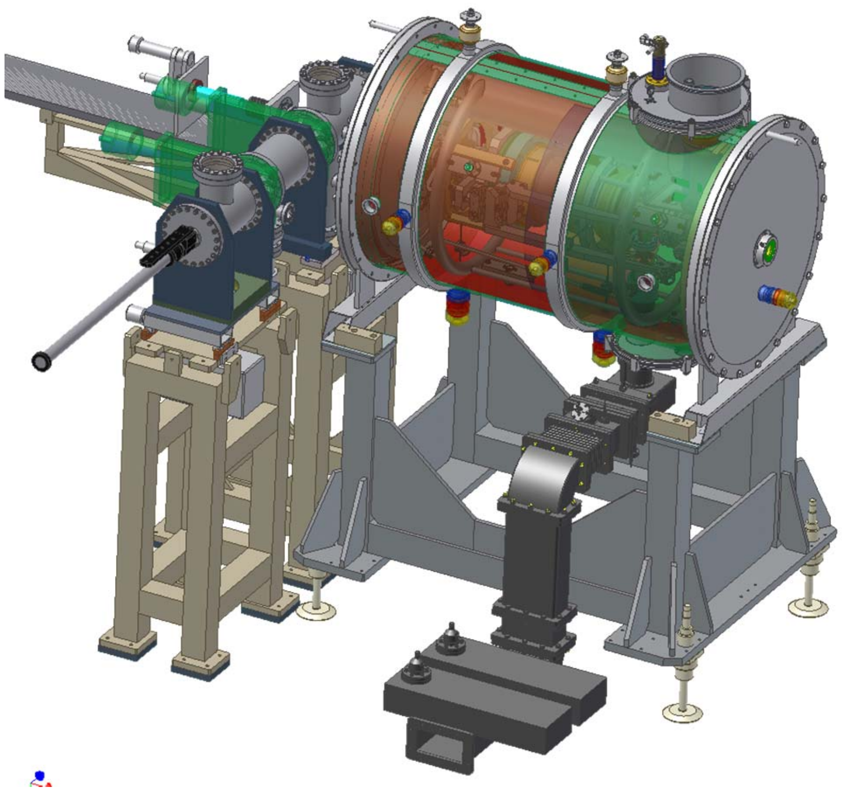


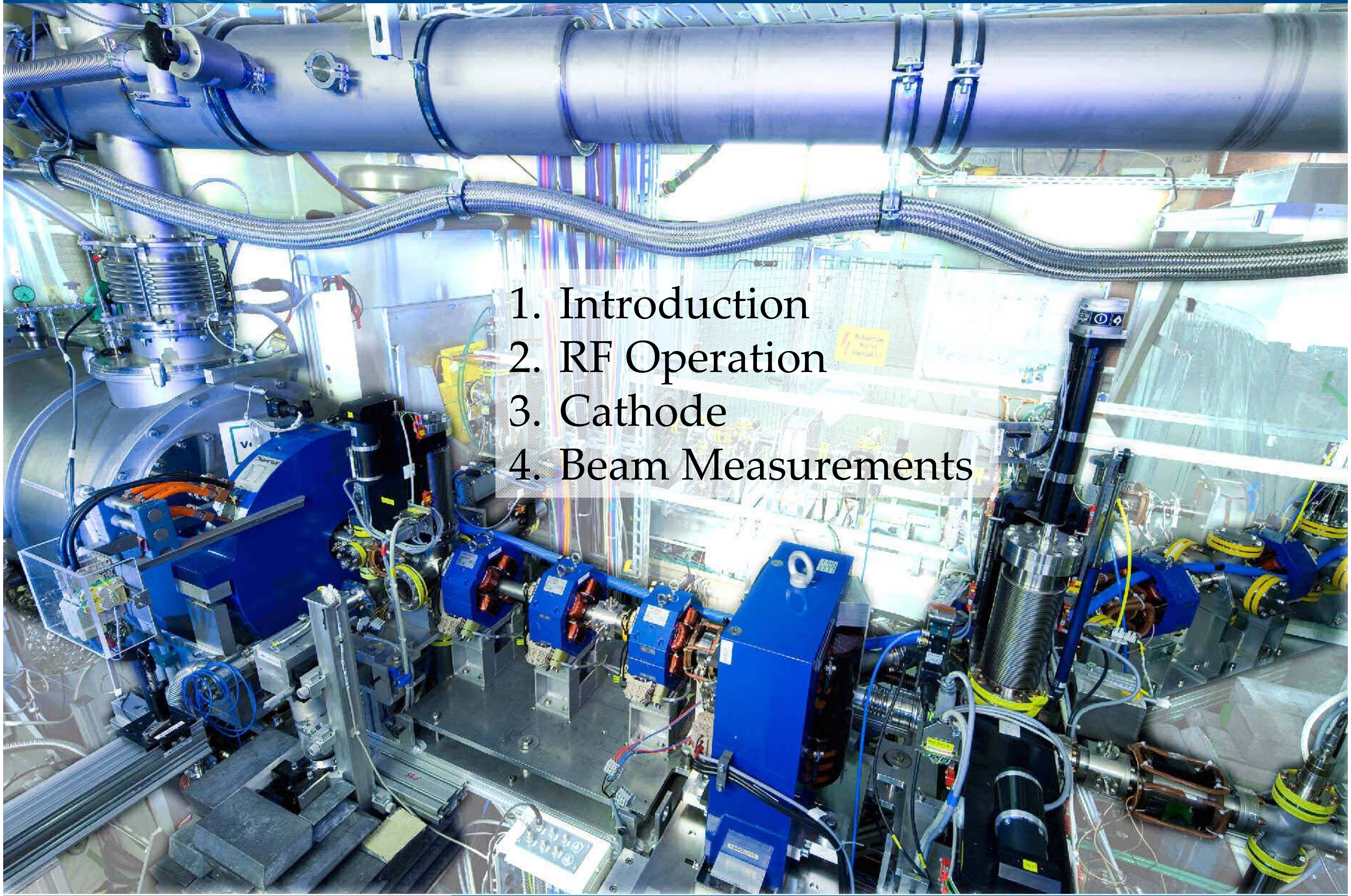
Rossendorf SRF-Gun Operational Experiences

André Arnold
on behalf of the ELBE Crew and the DESY-FZD-HZB-JLab-MBI collaboration

The 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

16-21 October, 2011, Tsukuba, Japan

Outline



1. Introduction
2. RF Operation
3. Cathode
4. Beam Measurements

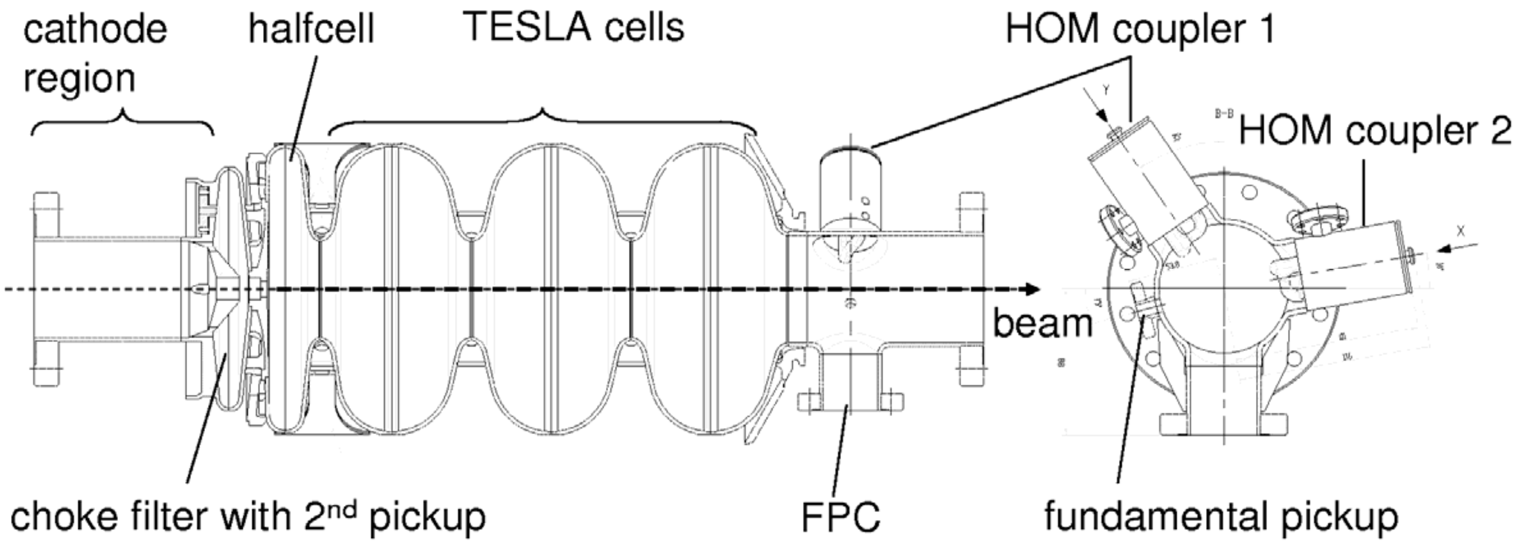
Three operation modes

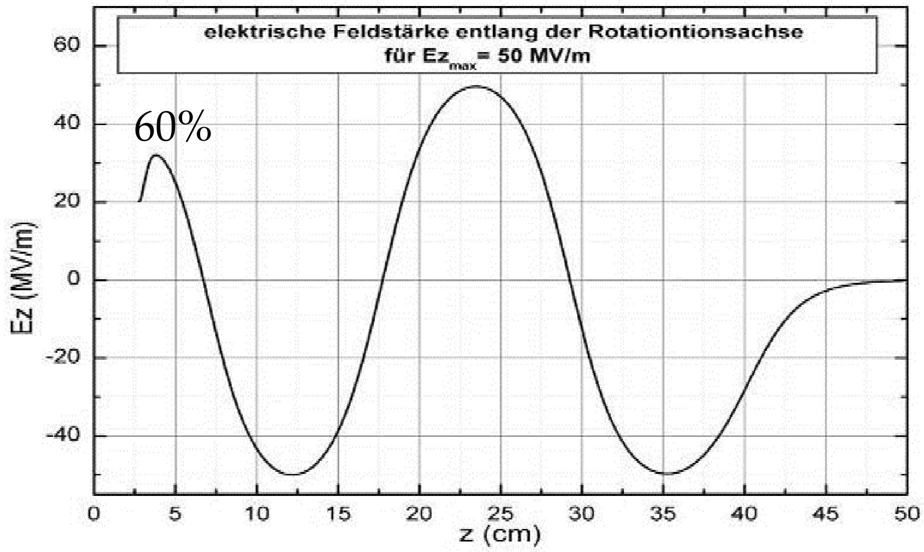
- high peak current operation for CW-IR-FELs with 13 MHz, 80 pC
- high bunch charge (1 nC), low rep-rate (<1 MHz) for pulsed secondary particle beam production (neutrons, positrons for ToF)
- low emittance, medium charge (100 pC) with short pulses for THz-radiation and x-rays by inverse Compton backscattering

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: 9.4 MeV with 3½ cells (stand alone)
- highly compatible with ELBE cryomodule (LLRF, high power RF, RF couplers, He & N2 support, etc.)
- LN_2-cooled, el. isolated, exchangeable, semi-conductor photo cathode

Introduction – Cavity Design

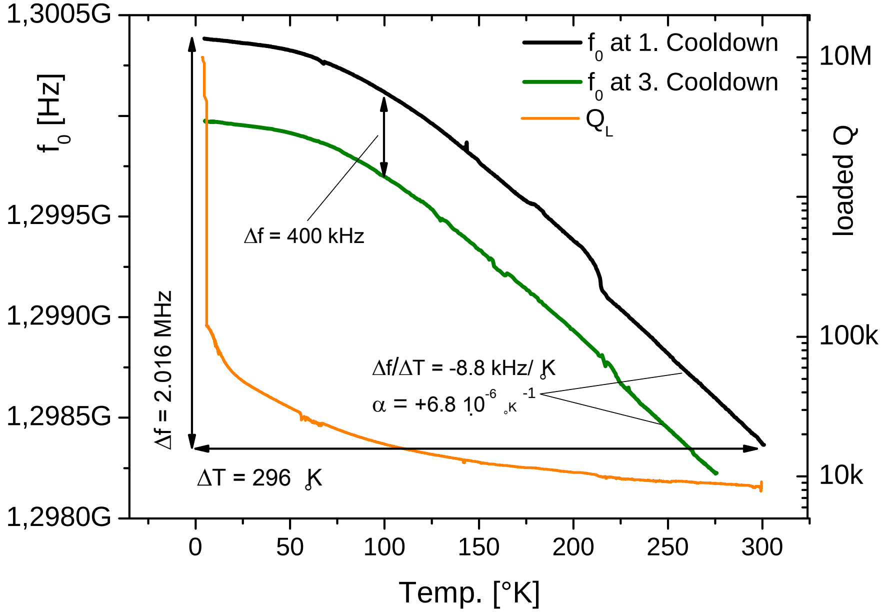


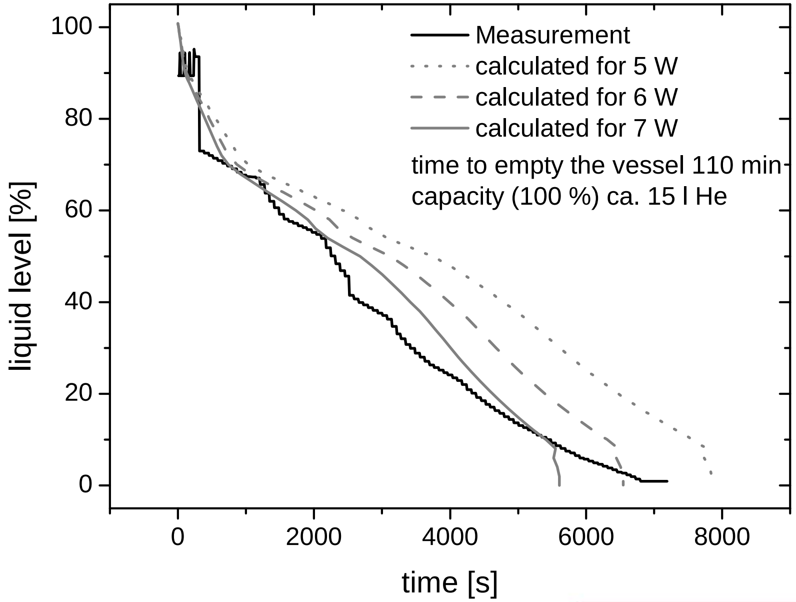


A. Arnold, et al., NIM A 577, 440 (2007)

stored energy U	*32.5 J*
quality factor Q_0	*10^{10}*
dissipated power P_c	*25.8 W*
maximum beam power P_B	9.4 kW
geometry factor G	*241.9 Ω*
accel. voltage V_{acc} accel. gradient E_{acc}	*9.4 MV* *18.8 MV/m*
R_a/Q_0	*166.6 Ω*
E_{peak}/E_{acc}	*2.66*
B_{peak}/E_{acc}	*6.1 mT/(MV/m)*

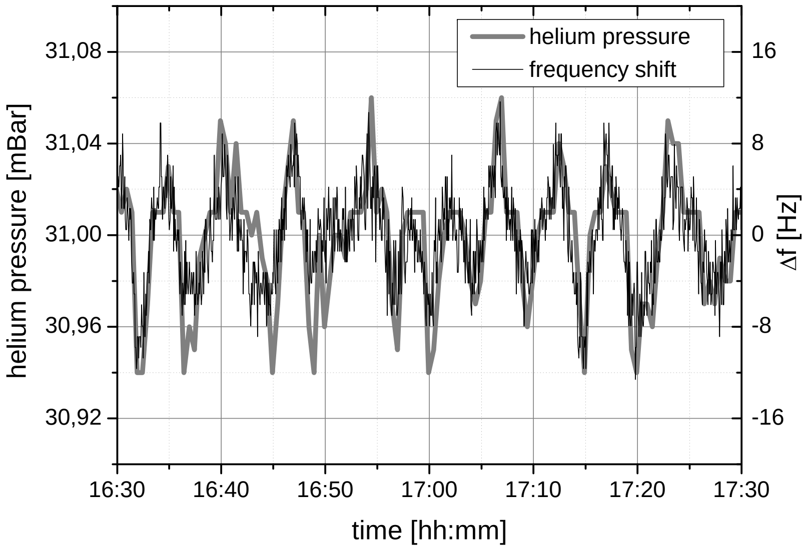
RF Operation – Cool down in 2007



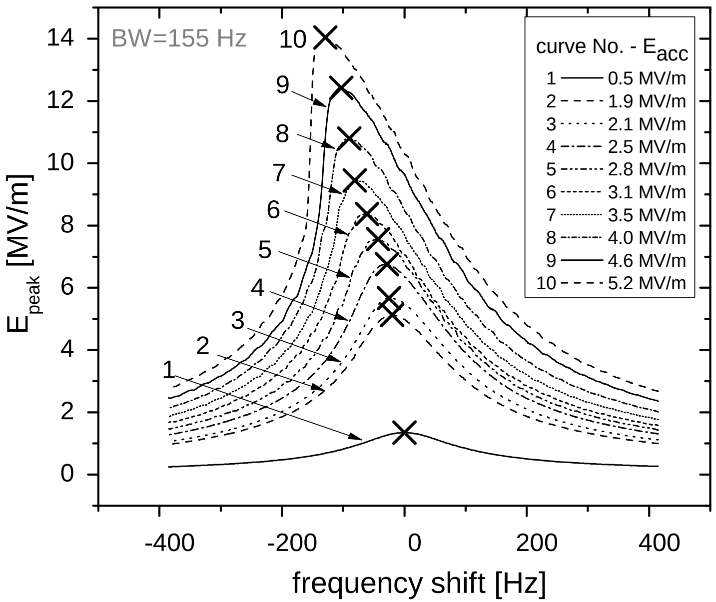


- No problems during cool down
- Frequency shift same as expected from TESLA cells
- After 1st cool down, frequency to high because change of $\Delta\varepsilon_r$ between N_2 filled cavity and vacuum was not considered
- Change in length: $\Delta l/l=-0.155\%$
- Coefficient of thermal expansion: $\alpha_{20}=+6.8\cdot10^{-6}\ K^{-1}$
- Field distribution determined by pass band freq. measurement [A. Arnold, proceedings of SRF07, pp. 689]: *(-62% / 99.4% / -97.5% / 100%) @ 1.3 GHz*
- Static helium heat load measured via boil off curve and comparison with calc.: $P_{static} = 6 - 7\ W$

RF Operation – Pressure Sensibility



a)



- Pressure sensibility evaluated via standard deviation of frequency and pressure

$$\frac{\sigma_f}{\sigma_p} = \frac{4Hz}{0.027mbar} = 150\frac{Hz}{mbar}$$

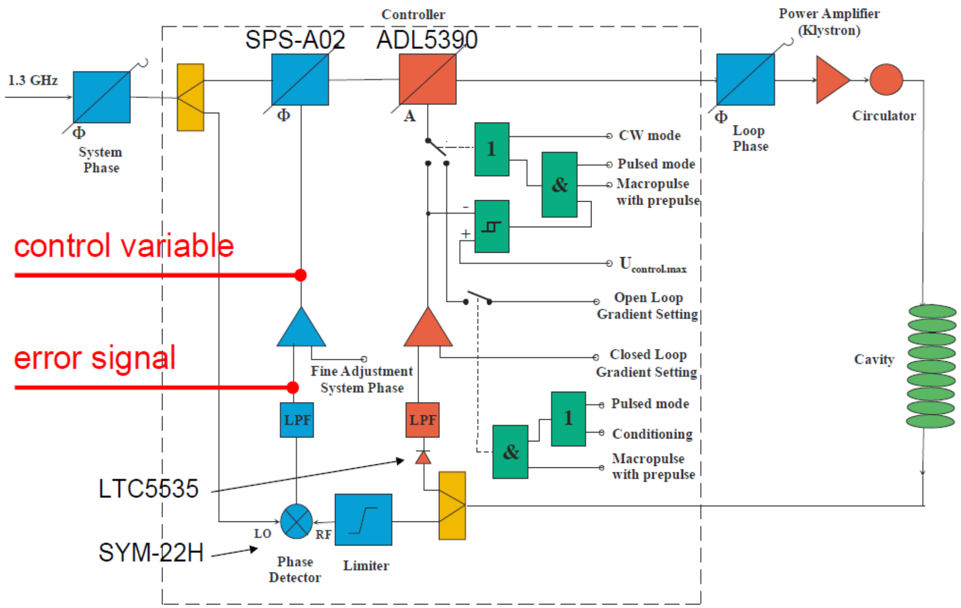
- DESY ~10 *Hz/mbar*, ELBE ~32 *Hz/mbar*
- Because of high bandwidth (~ 160 Hz) and good helium pressure stability (~ 0.1 mbar) operation not critical, but needs to be improved
- Lorentz detuning (CW) using network analyzer with inverse freq. sweep

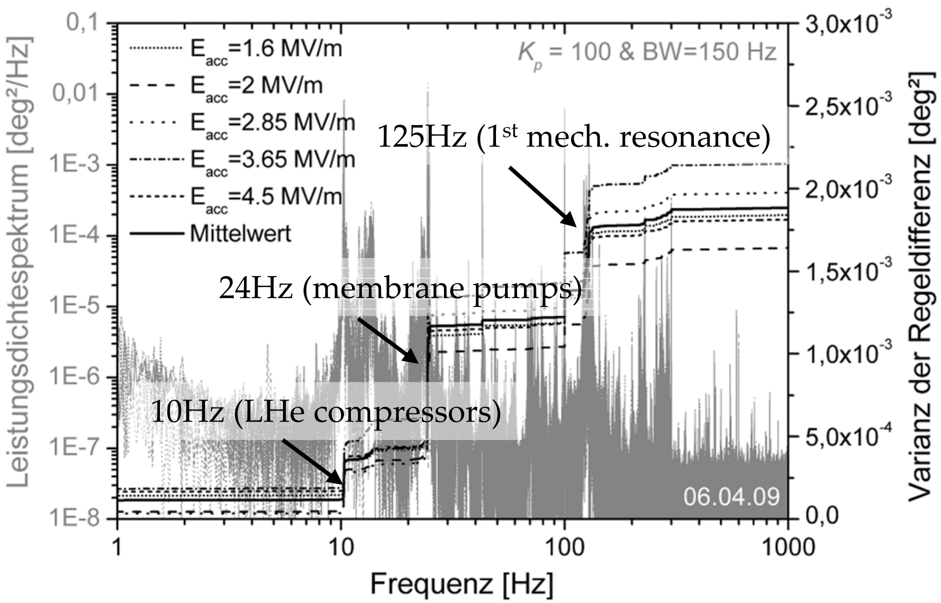
	SRF-Gun	TESLA 9 Zeller
E_{peak}/E_{acc}	2.7	2
k_{peak}	0.69 Hz/(MV/m)²	0.25 Hz/(MV/m)²

reason in both cases: weak half-cell back plane
→ additional stiffener considered at new cavities

DRESDEN concept HZDR

RF Operation – Microphonics





- Microphonics = detuning of the cavity frequency due to mech. vibrations
- LLRF-Controller (here analog) used to counteract amplitude and phase error
- By measuring the error signal of the closed phase loop one gets phase deviation (rms) seen by the beam

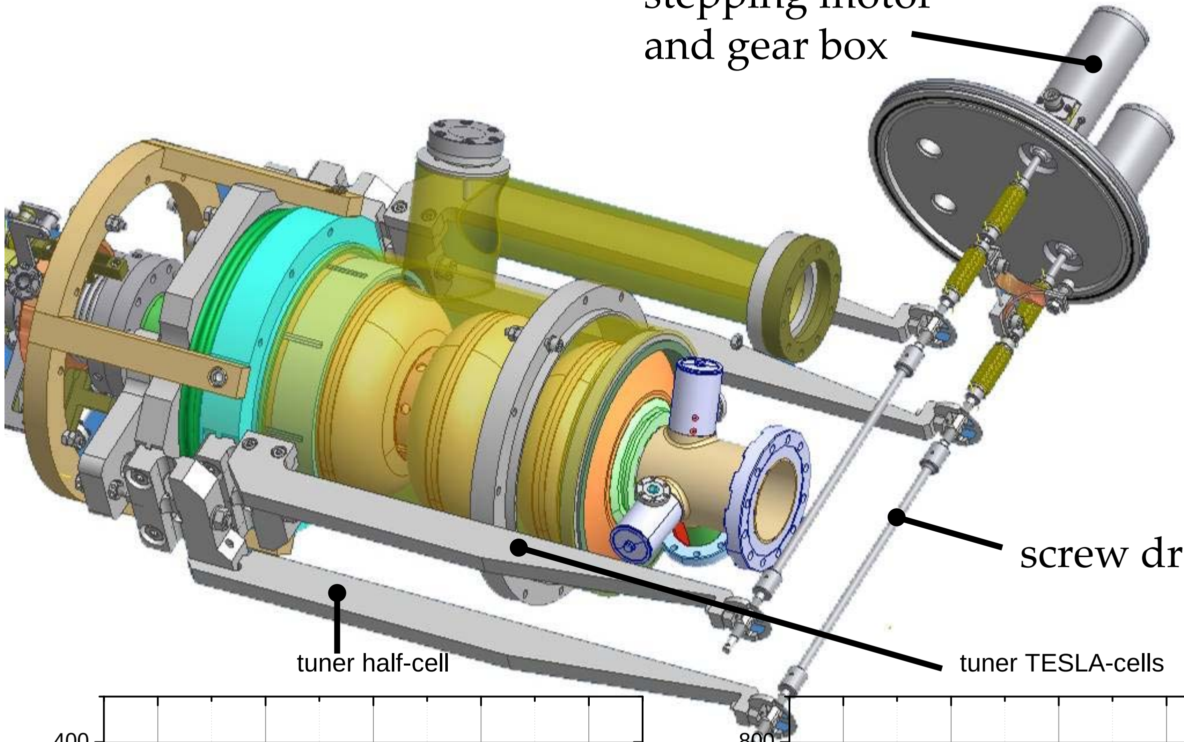
$$\sigma_{ph} = \sqrt{VAR} = 0.0433°$$

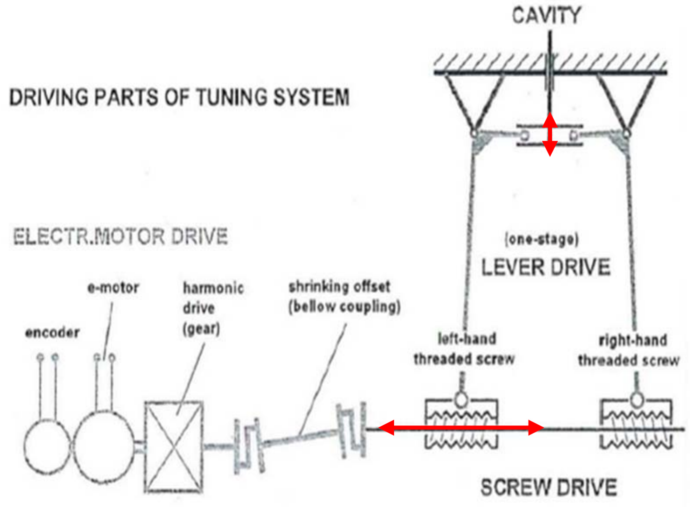
- And with known loop gain K_p the disturbance variable of freq. detuning

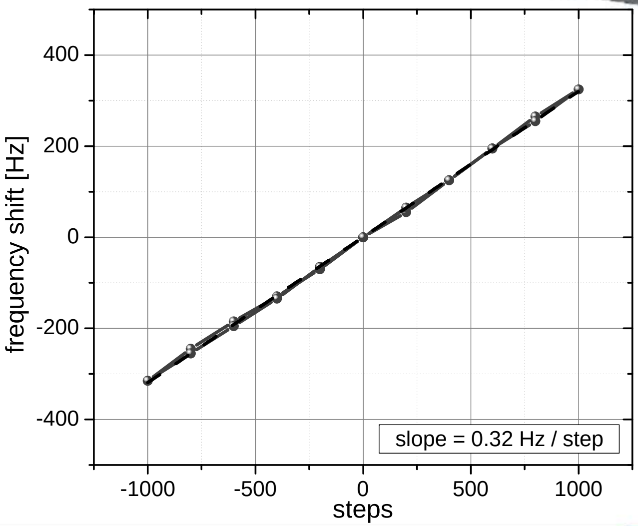
$$\sigma_f = \frac{BW}{2} \tan\left(\sigma_{ph} \cdot \left(K_p + 1\right)\right) = 5.7\,Hz$$

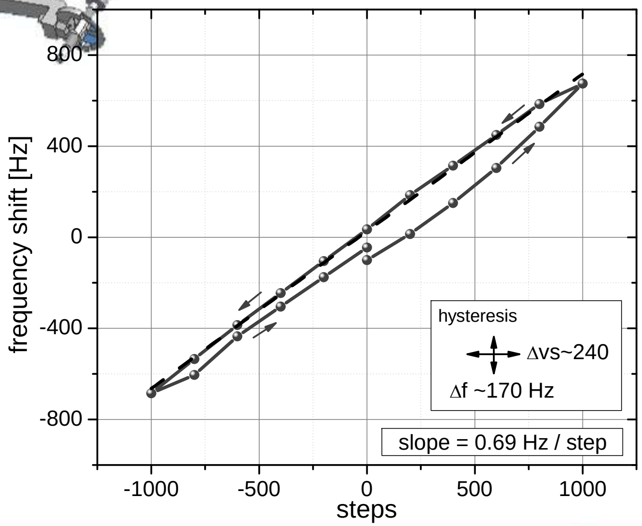
- Significant freq. parts identified by calculation of PSD and integration
- Microphonics is gradient independent
- Residual phase error sufficient for ELBE

RF Operation – Cavity Tuner









measured tuner values

½-cell	TESLA cells
± 78 kHz	± 225 kHz
1.2 nm/step	1.6 nm/step
0.3 Hz/step	0.7 Hz/step

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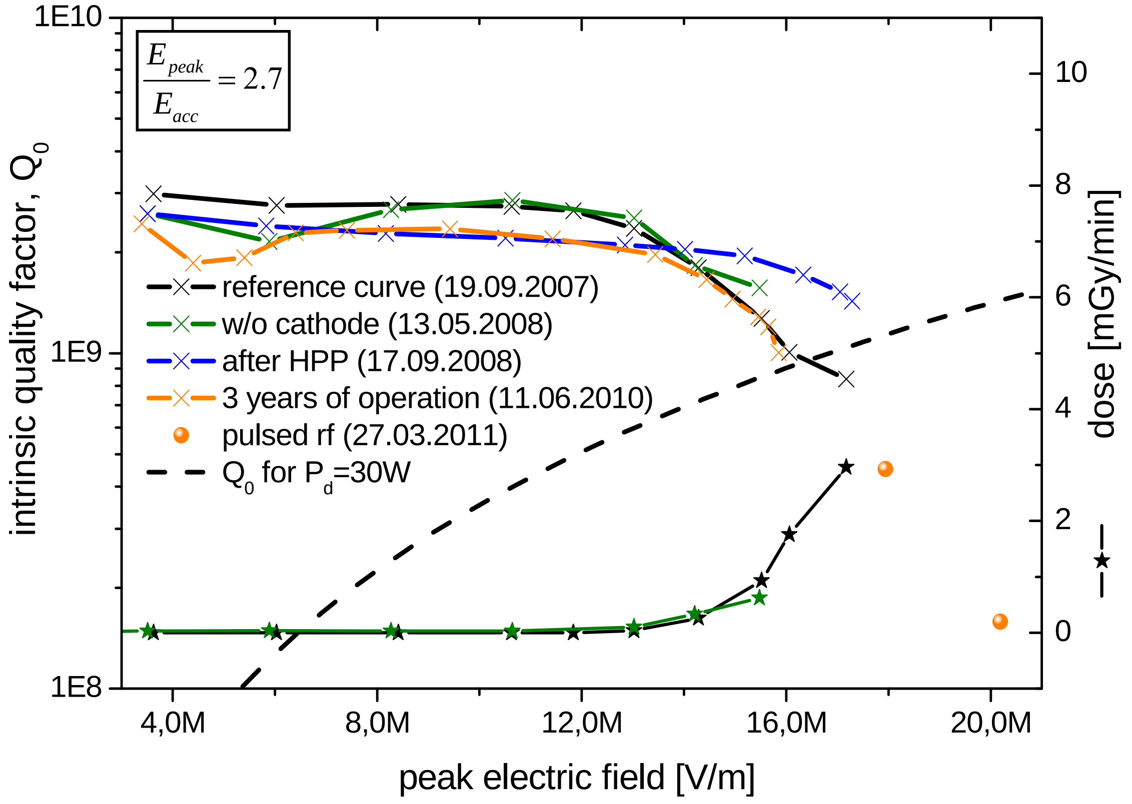
HZDR

RF Operation – In Situ Q_0 vs. E_{pk} @ 2K

HZDR

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



Formulas:

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

- measured Q_0 is 10 times lower than in vertical test

→ cavity pollution during string assembly?

- Maximum achievable field 1/3 of the design value 50 MV/m)
- Cavity performance limited by FE & He consumption

Good News

- No Q degradation seen since 4 years of operation!
- Same performance of cavity with or w/o cathode!

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

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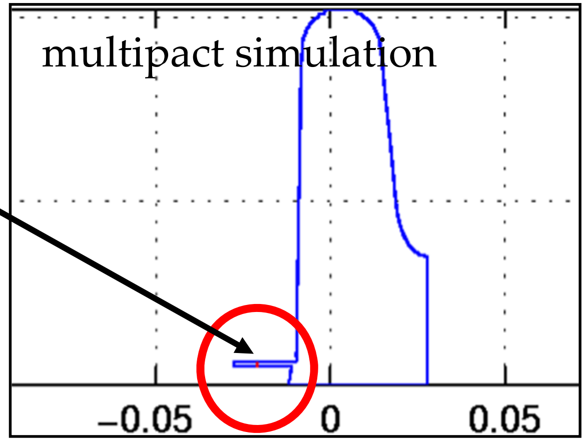
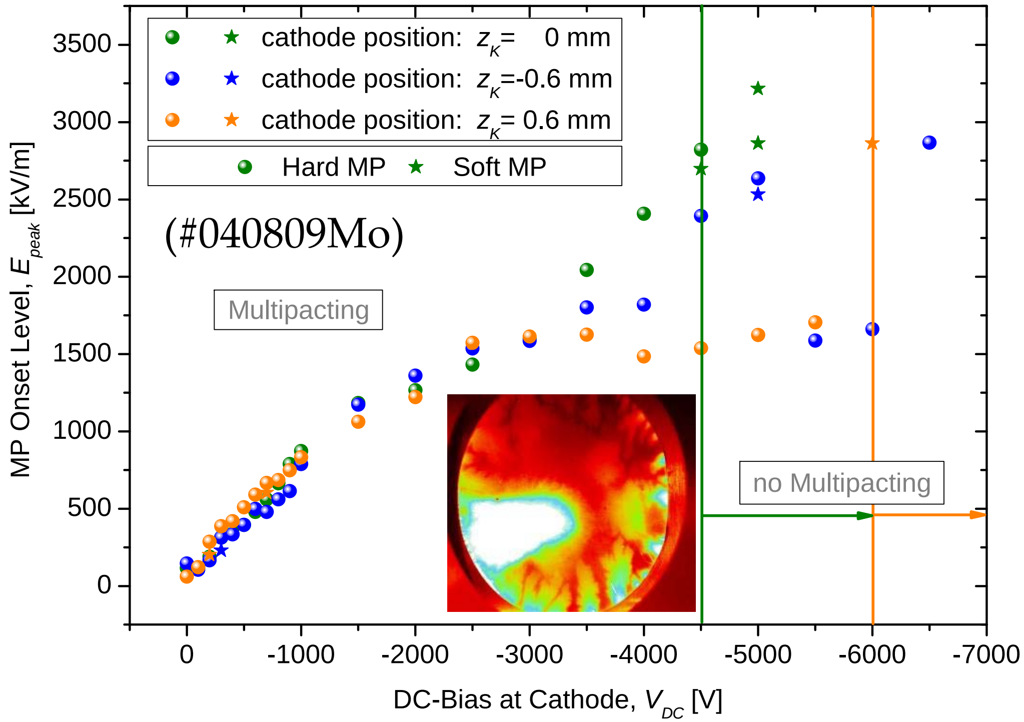
RF Operation – Multipacting at the Cathode

- MP was expected in the gap between cathode and cavity at surface fields of 0.1-0.2 kV/m since the early design stage!
- So biasing of the cathode up to -7 kV was considered in the cathode design (el. isolated)



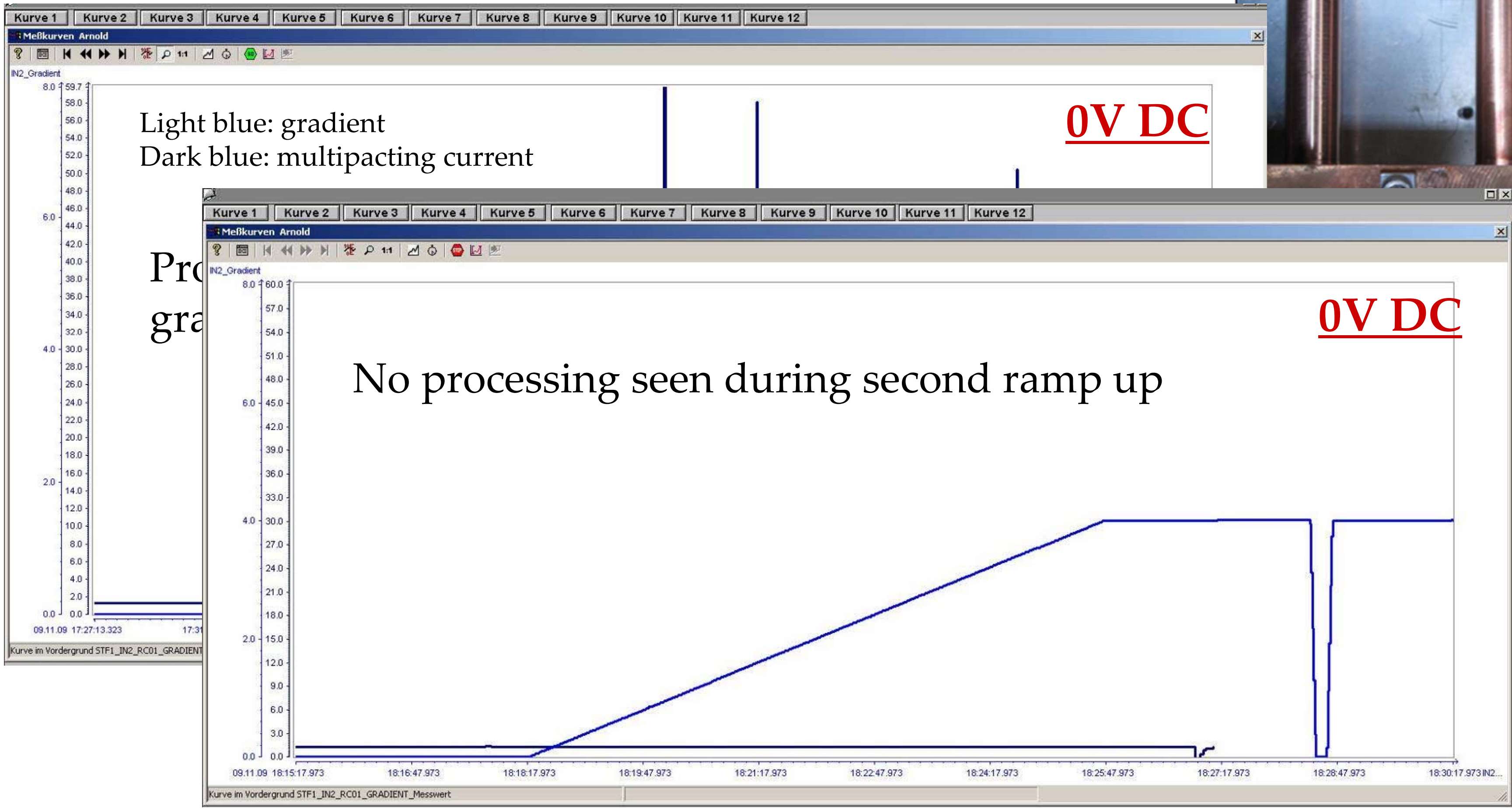


- During increase of RF field, a hard MP barriers are observed, depending on the bias voltage level, the position and the used cathode
- MP characterized by high current (1 mA) measured at the high voltage power supply
- Electron flash at view screens
- Not possible to get above this level not even in pulsed mode and 10kW!

The onset level is different for every single cathode and its position!

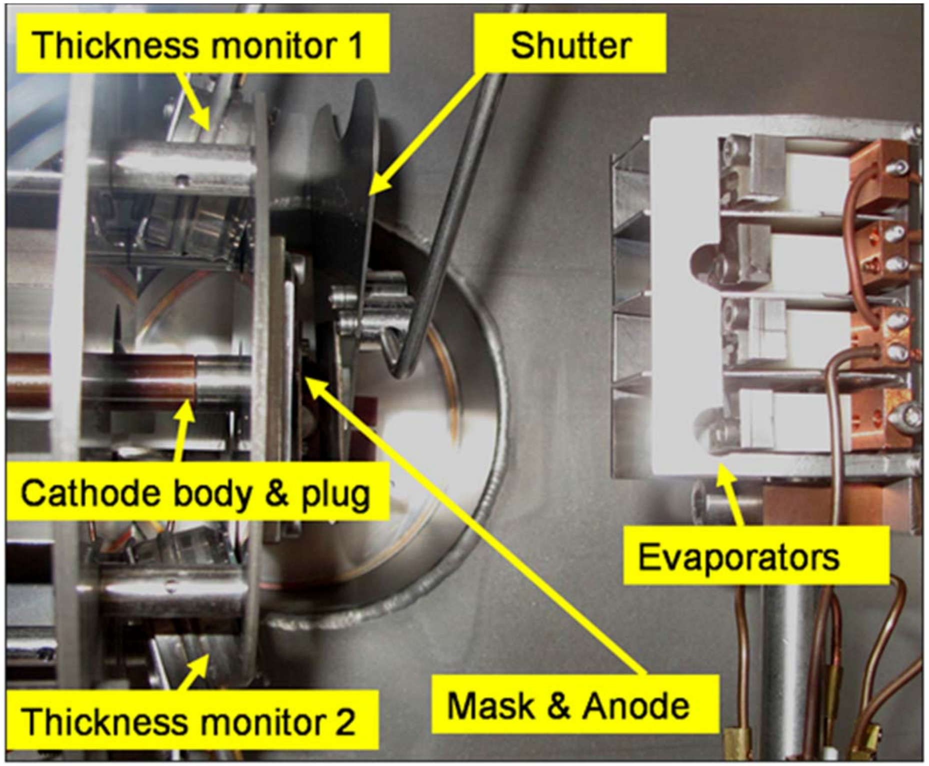
RF Operation – Multipacting Suppression

- Rounding all edges to reduce field enhancement factor
- Anti multipacting grooves to suppress resonant conditions

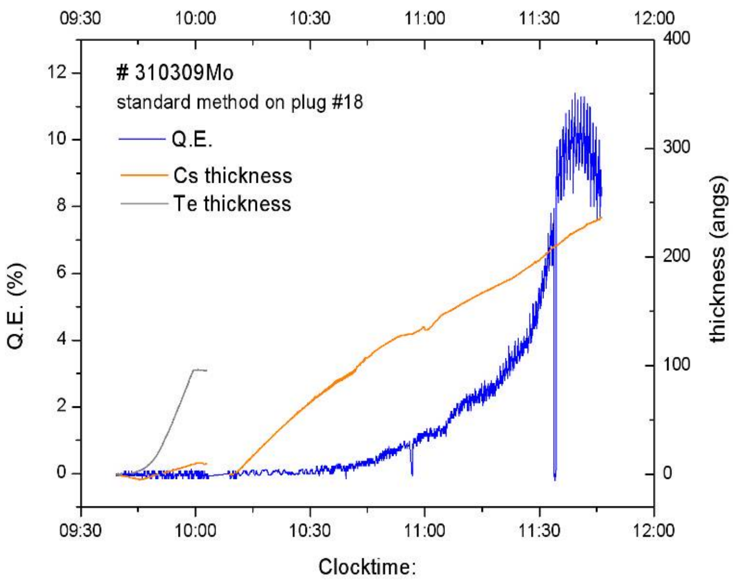


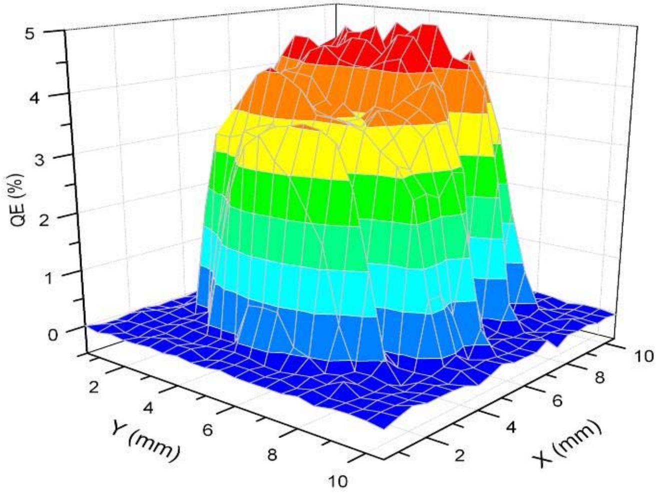
- Coating with TiN to reduce secondary electron yield

Cs_2Te Cathode - Preparation



Inside the 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

Phys. Rev. ST Accel. Beams 13, 043501 (2010)

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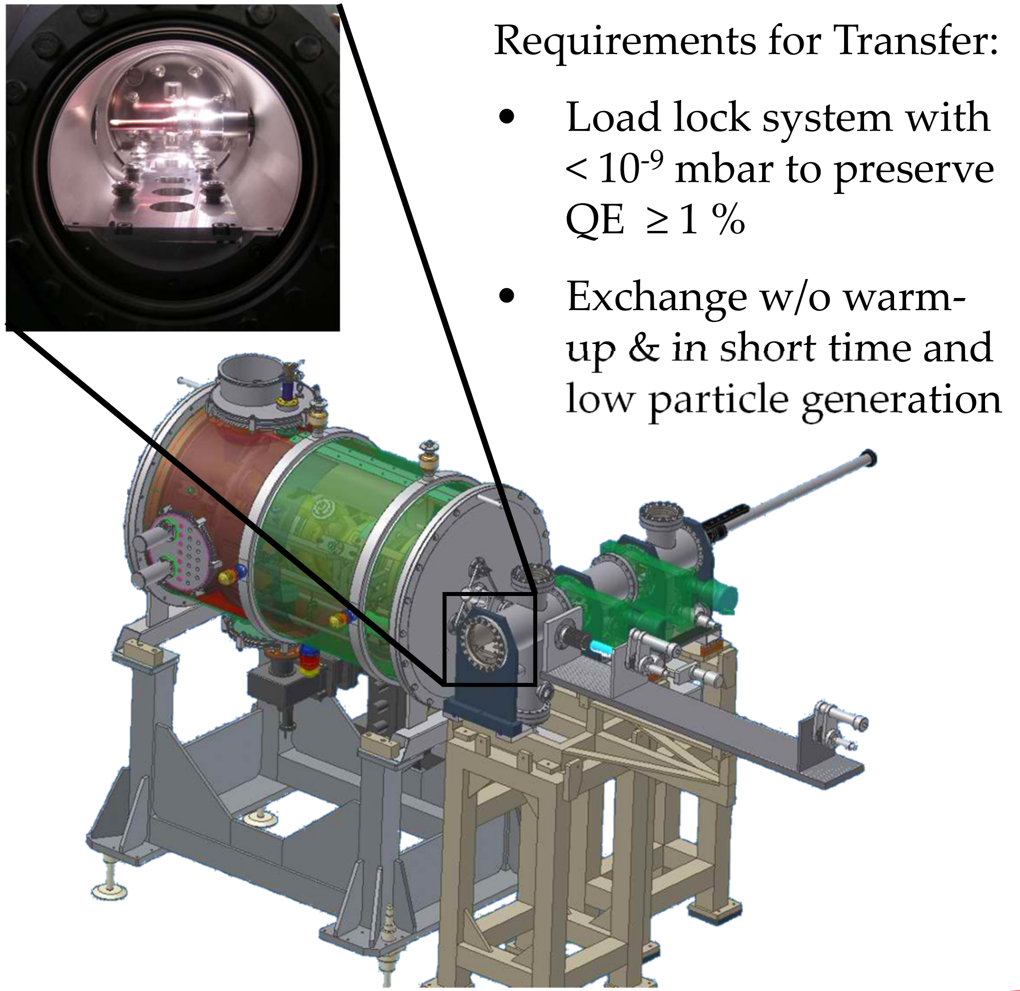
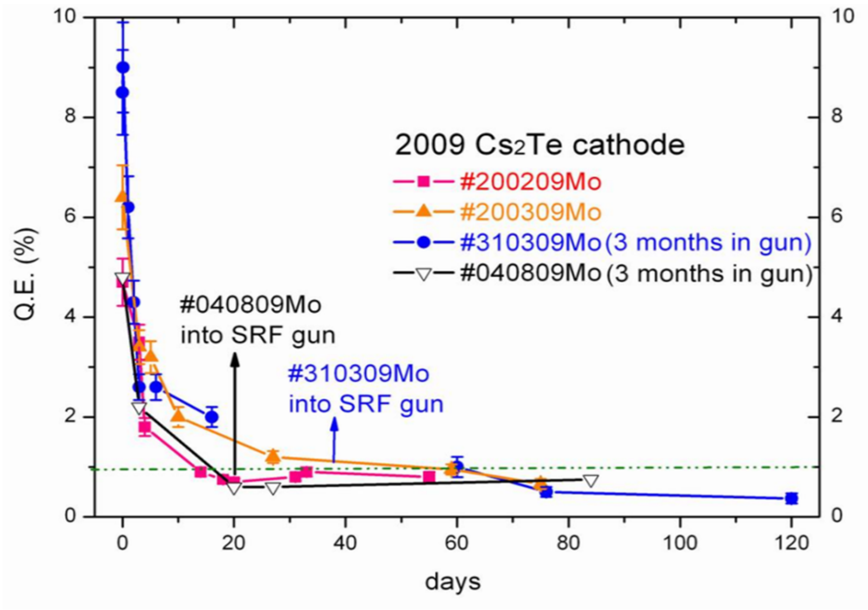
Cs_2Te Cathode - Operation



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	Q.E. in gun
#090508Mo	30	0.05%
#070708Mo	60	0.1%
#310309Mo	109	1.1%
#040809Mo	182	0.6%
#230709Mo	56	0.03%
#250310Mo	**427**	**1.0%**
#090611Mo	From 2011-7-26	1.2%

- fresh QE 15.5%, in gun 1%
- total beam time 1013 h
- extracted charge 35 C

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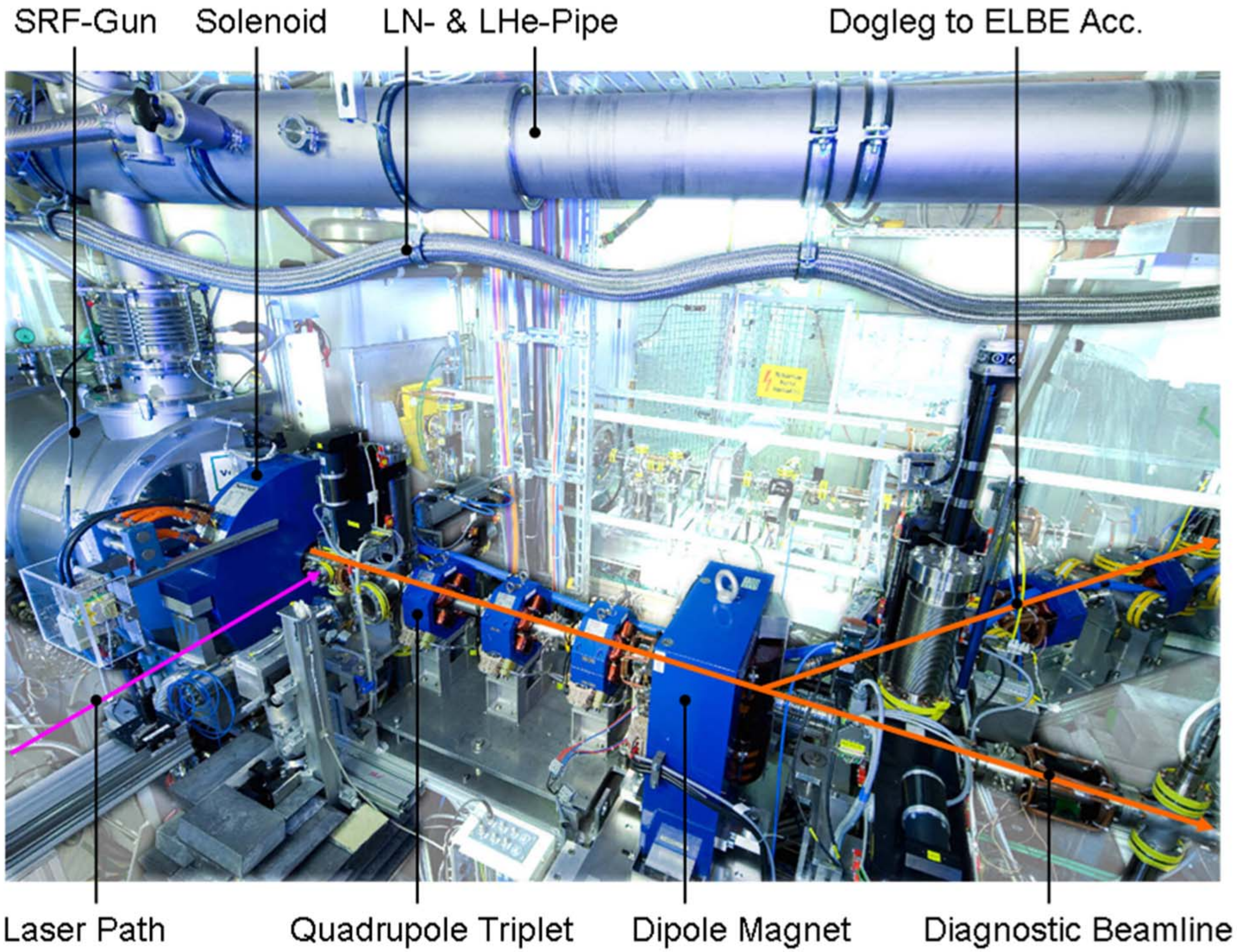
Beam Measurements



Diagnostics Beamline

- Current & charge (faraday-cup & ICTs)
- Transverse emittance (slit mask, solenoid scan)
- Energy and ΔE (C-bent)
- Bunch length (Cherenkov radiator and streak camera or electro-optical sampling)

Dogleg to ELBE

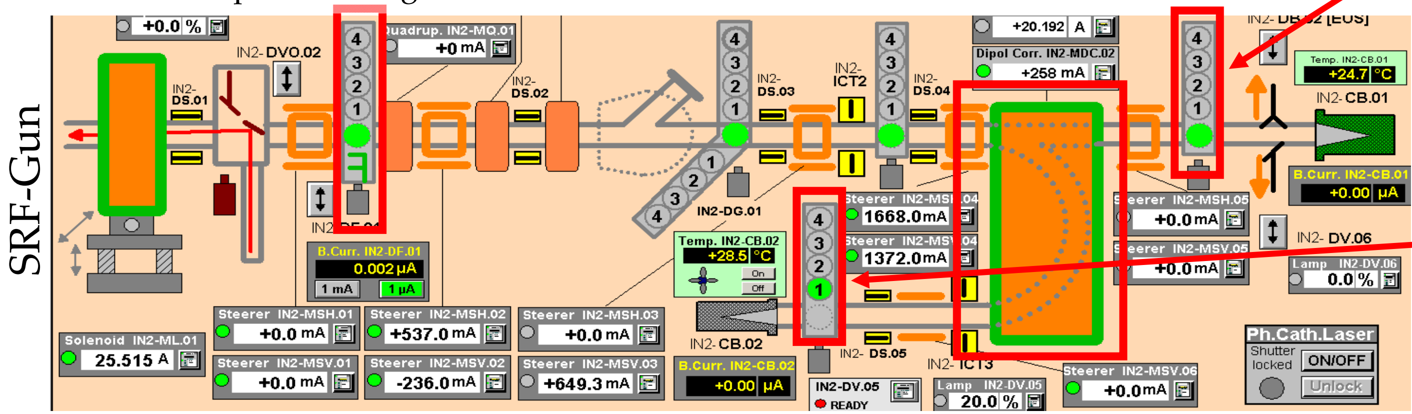
- Achromatic compen-sated connection

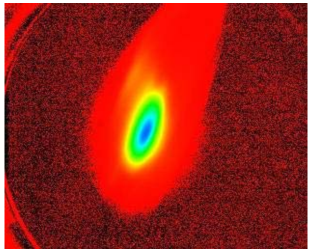
diagnostics beamline designed and built by HZB (BESSY) Berlin

Beam Measurements – Part1

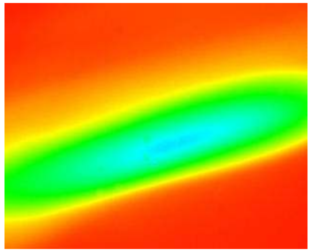
- Schottky scan for different laser pulse energies (15 ps FWHM, ∅ 3 mm flat top): → space charge limit ~300 pC (for 2-3 MeV)
- Energy and energy spread via 180° bending magnet → 3.0 MeV (CW) and 4.0 MeV (pulsed RF)

Control panel of diagnostic beam line



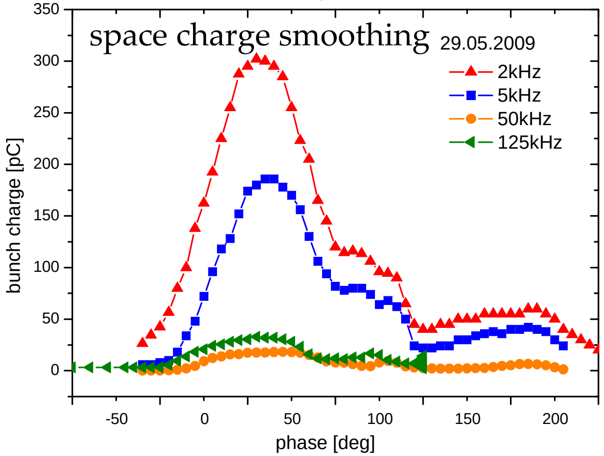


screen DV04 (YAG)
4.4 m from cathode

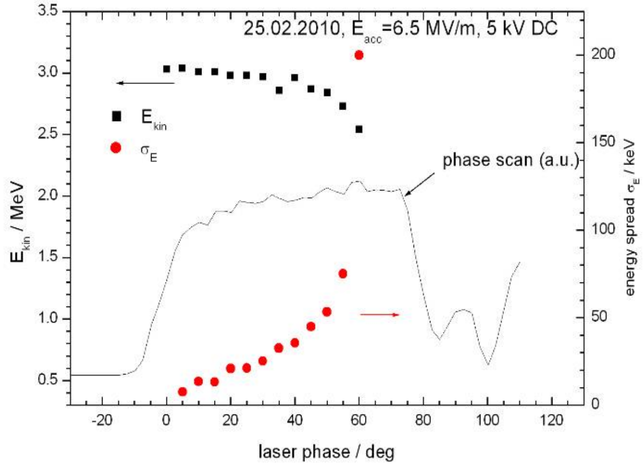


screen DV05 same optical path

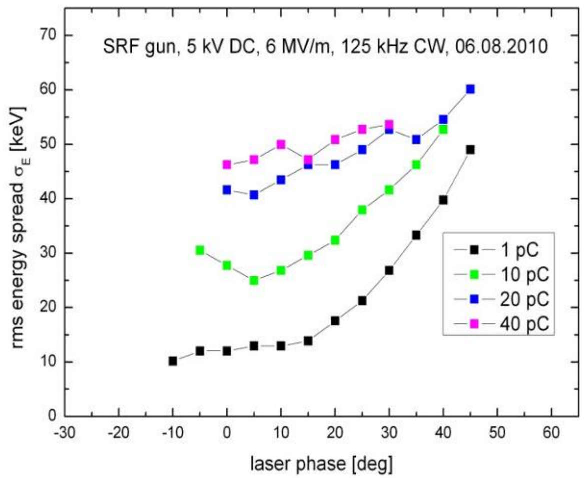
Schottky scan



energy and energy spread @ 5 pC

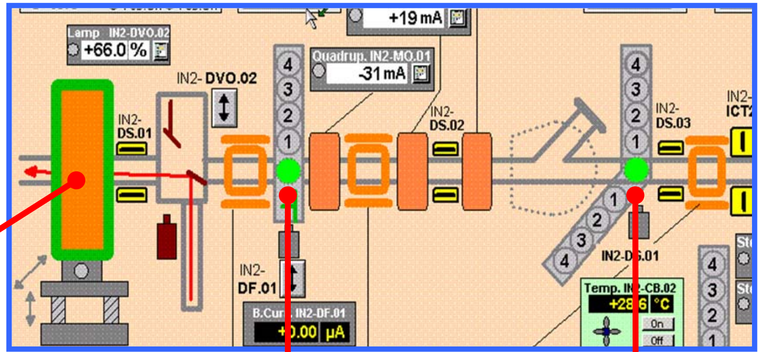


energy spread



Beam Measurements – Part2

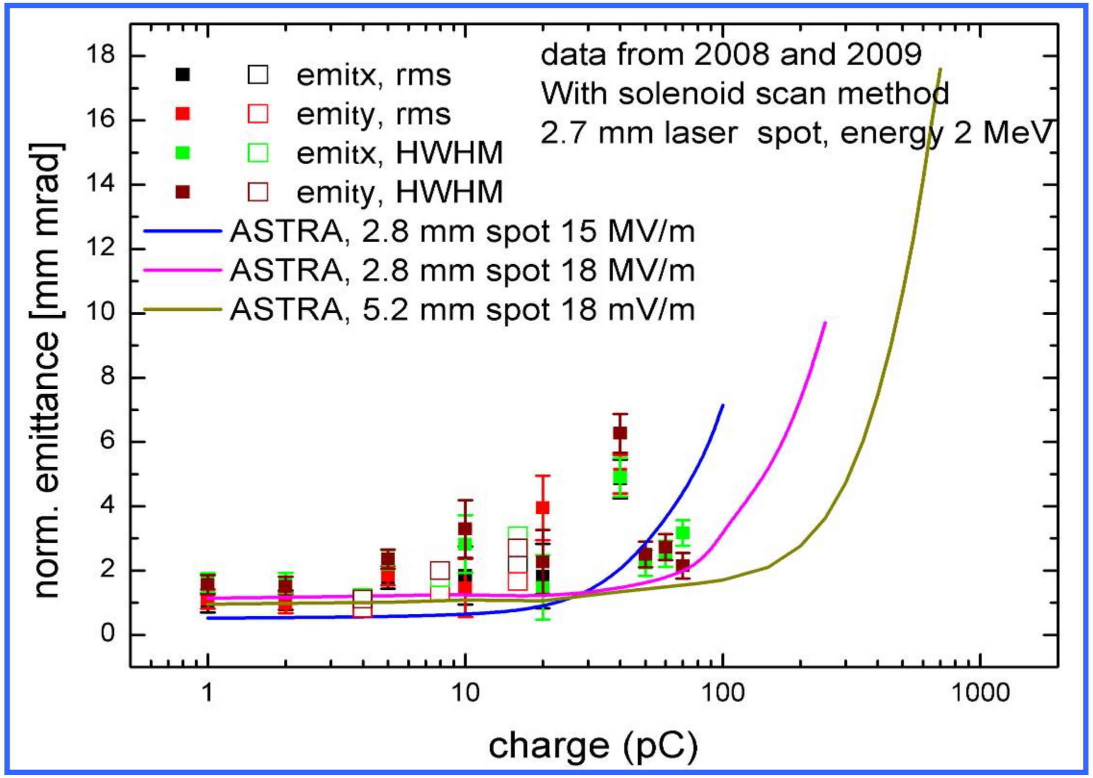
- Transverse emittance with solenoid and quad Scan
- slit mask not useable because design is for 9 MeV
- improved setup needed!

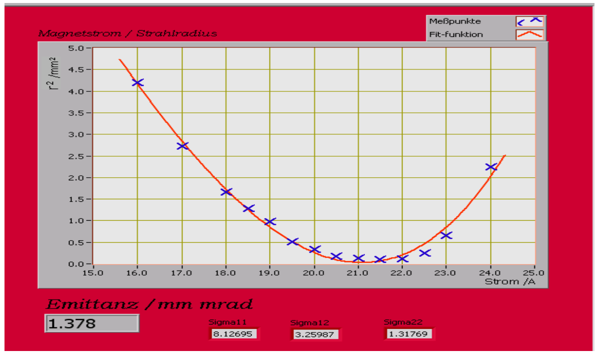


solenoid for
emittance compensation
field precisely measured

screen DV01

screen DV02

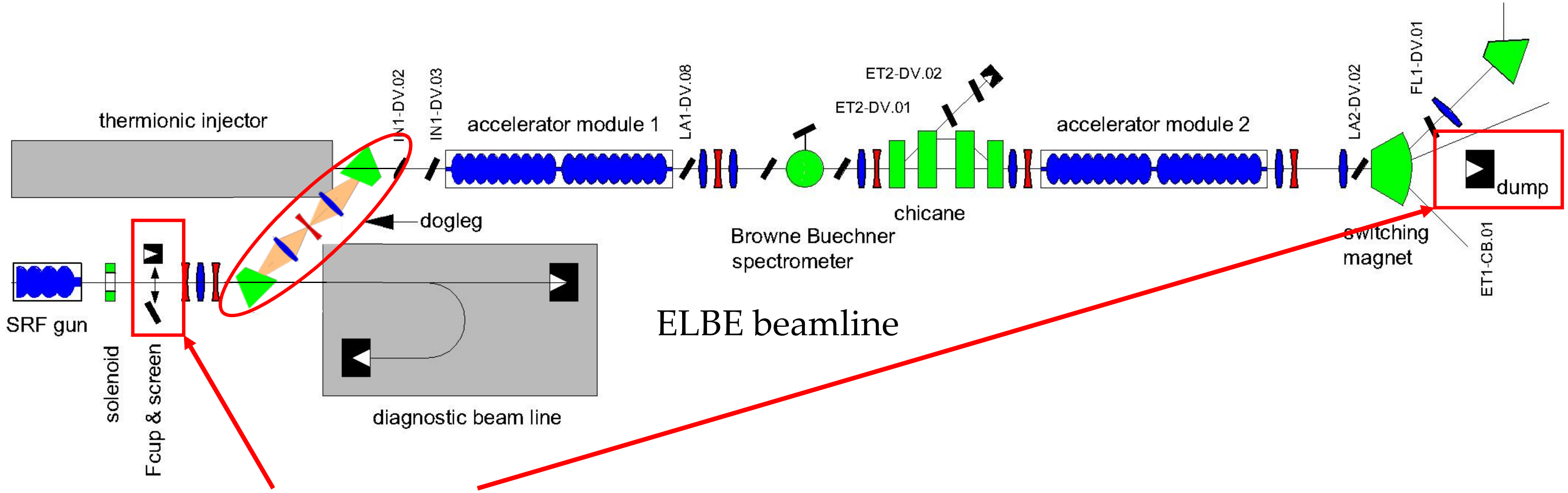




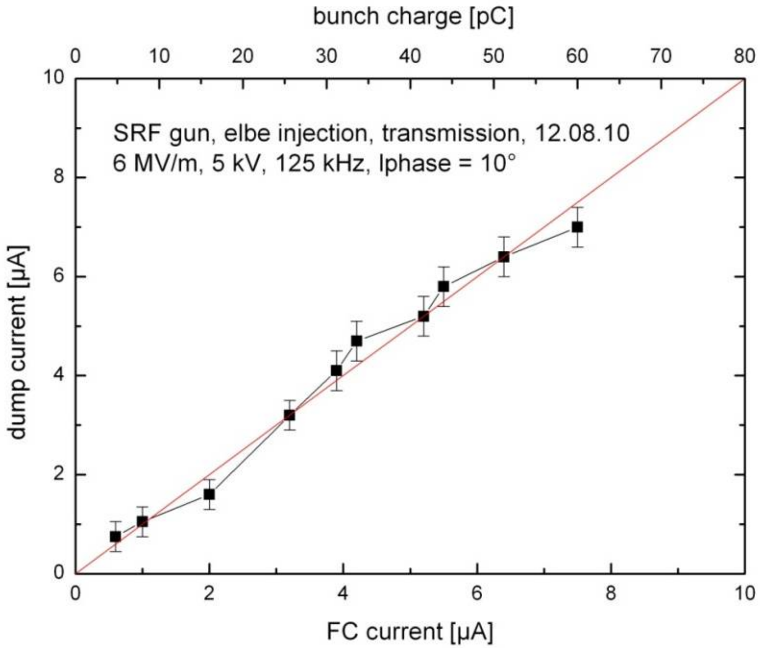
- Good agreement with ASTRA
- measured normalized emittance
  3±1 mm mrad @ 77 pC
- Good enough for ELBE injection

J. Teichert, ERL2009, Ithaca, New York

ELBE - Injection



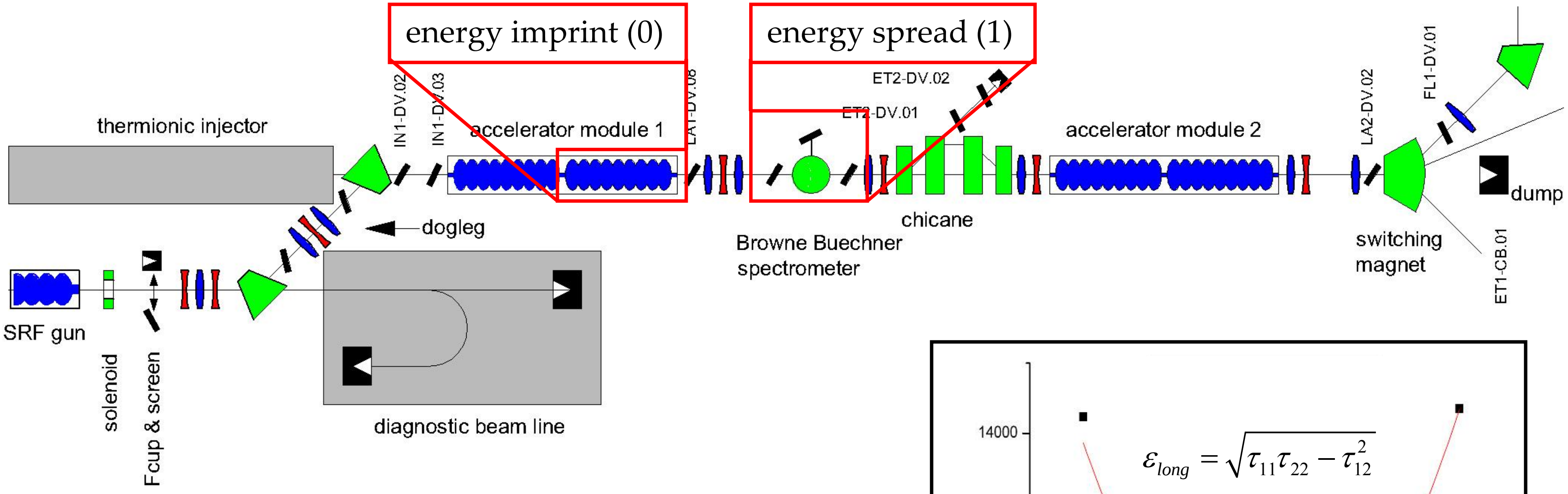
ELBE beamline



- First ELBE Injection Febr. 5, 2010 using achromatic dogleg
- Up to 60 pC with 100% transmission
- Maximum bunch charge injected and accelerated in ELBE: 120 pC @ 50 kHz
- Dogleg acceptance needs low ΔE (correlated ΔE compensated by module 1)

DRESDEN concept HZDR

ELBE - Longitudinal phase space Part 1



general longitudinal beam ellipse

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

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

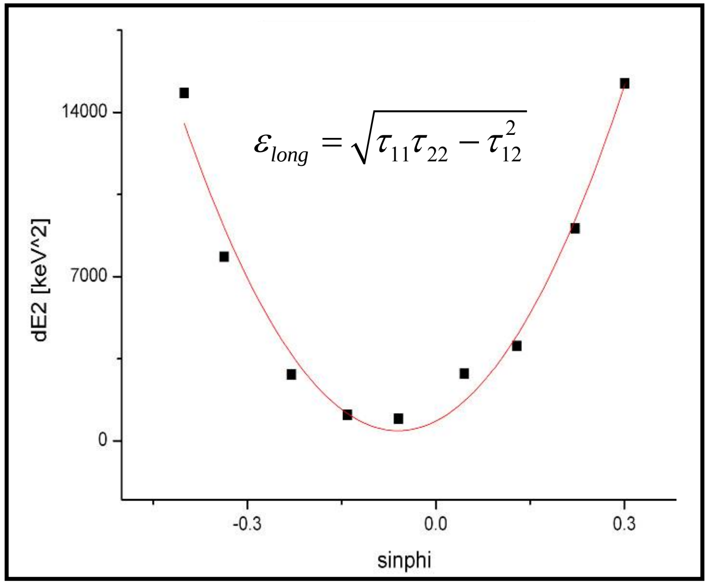
$\sqrt{\tau_{22}} = \sigma_E$ ...rms energy spread (keV)

general cavity transport matrix

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

energy gain $= V_{C2} \cos\left(\varphi_{C2}\right)$

φ_{C2} in reference to crest phase

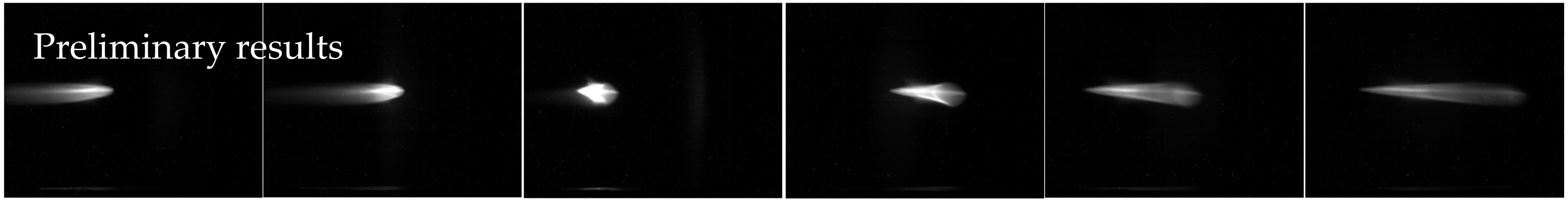


from parabola fit

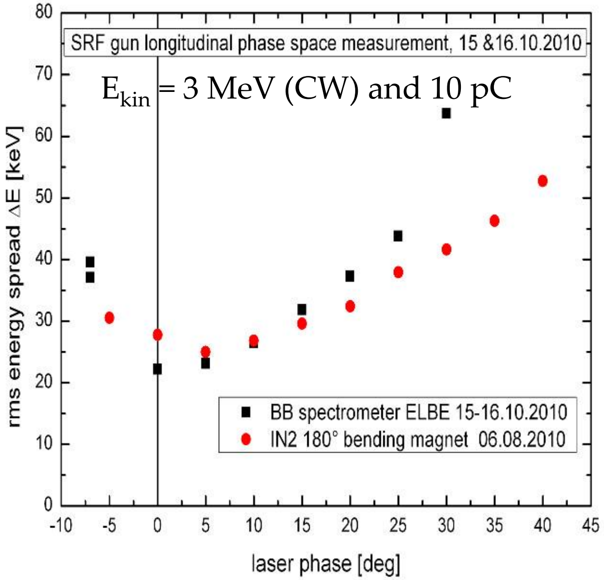
longitudinal beam ellipse at spectrometer:

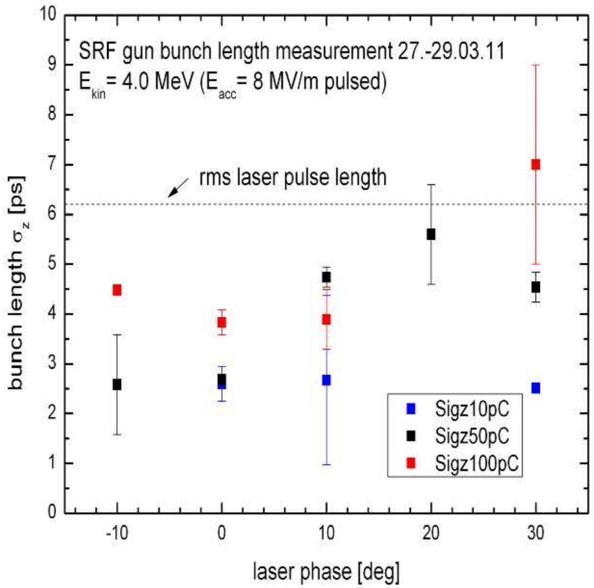
$$T(1) = R_{C2} \cdot T(0) \cdot R_{C2}^T \longrightarrow \tau_{22}(1) = \sigma_E^2(1) = \boxed{\tau_{22}(0)} - 2\boxed{\tau_{12}(0)} V_{C2} \sin(\varphi_{C2}) + \boxed{\tau_{11}(0)} (V_{C2} \sin(\varphi_{C2}))^2$$

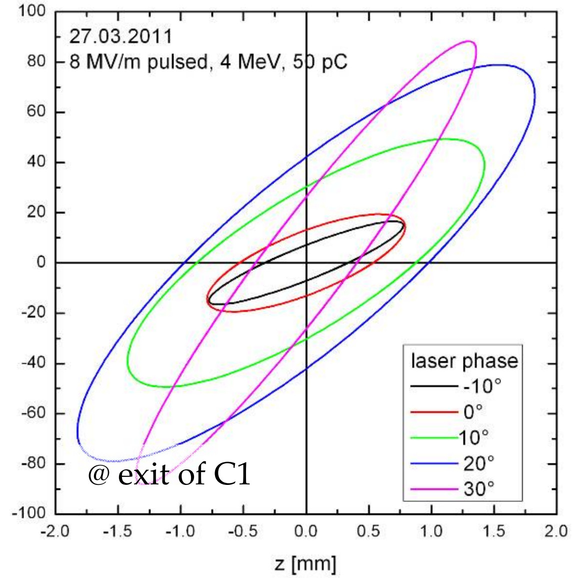
ELBE - Longitudinal phase space Part2



Browne Buechner spectrometer pictures (from SRF gun)

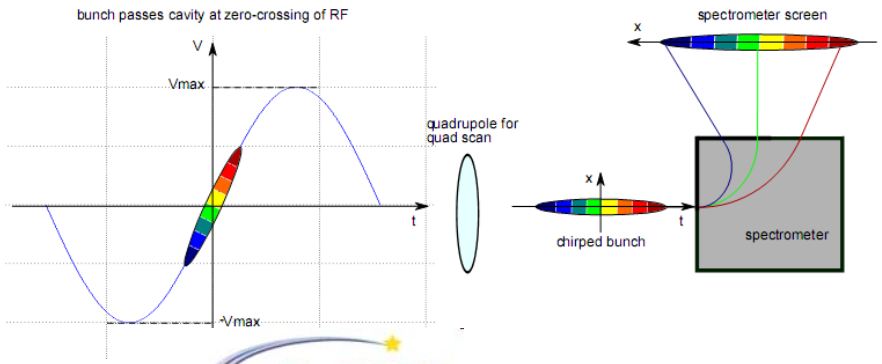






- Same energy spread measured as in the 180° bending magnet of the diagnostic beamline
- Bunch compression in SRF-gun as expected from ASTRA simulation
- So far phase space measured at the exit of cavity 1 but projection to gun in progress
- Successful test of long. phase space measurement for future gun optimization

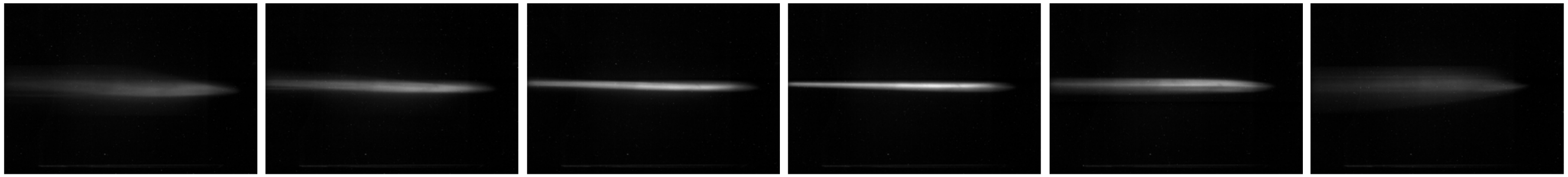
ELBE – Slice Emittance by HZB

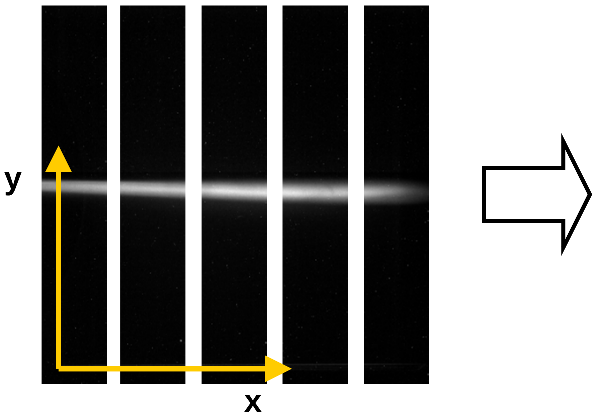


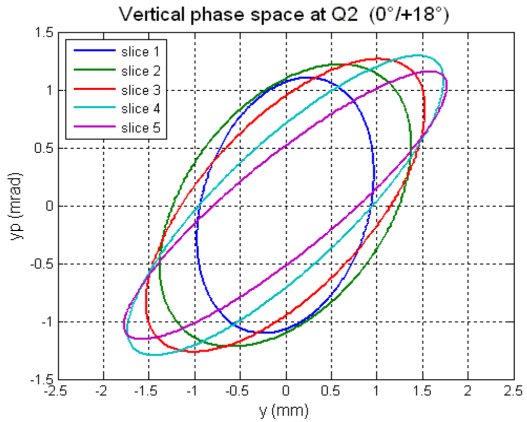
EuCARD

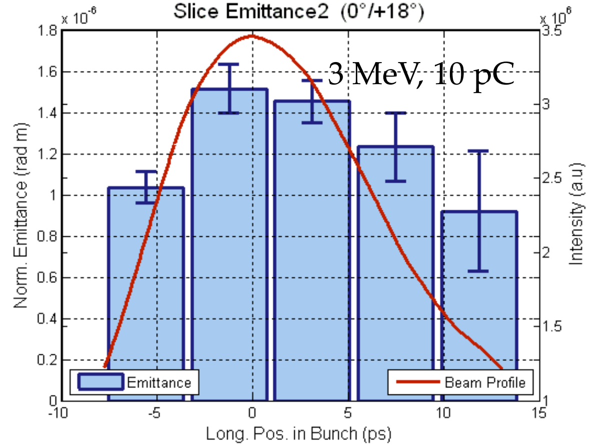
HZB Helmholtz Zentrum Berlin

- Fixed energy imprint for correlation betw. energy spread and long. bunch distribution
- Spectrometer → longitudinal distribution transferred to transverse distribution → longitudinal slices accessible
- Combination with quadrupole scan technique allows to reconstruct the vertical emittance for each slice
- Tool for future emittance compensation





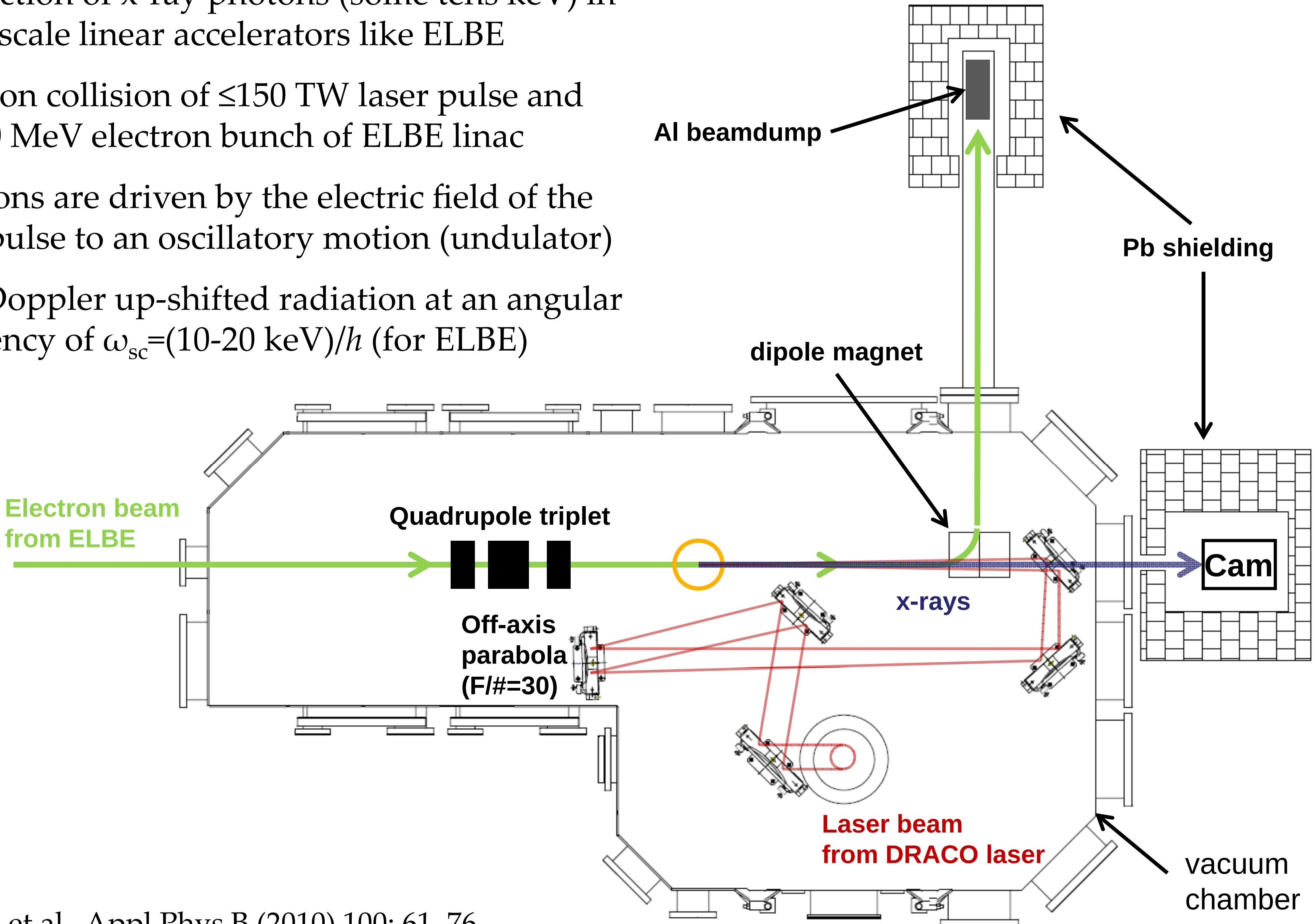




J. Rudolph, et al., Slice-Emittance Measurements at ELBE / SRF-Injector, Dipac2011.

ELBE – Thomson Backscattering (Laser Group)

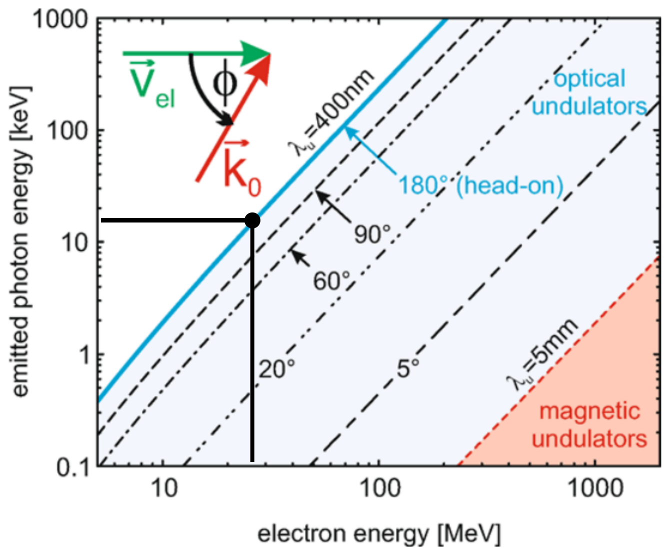
- Production of x-ray photons (some tens keV) in small-scale linear accelerators like ELBE
- Head-on collision of ≤150 TW laser pulse and 20 - 30 MeV electron bunch of ELBE linac
- Electrons are driven by the electric field of the laser pulse to an oscillatory motion (undulator)
- emit Doppler up-shifted radiation at an angular frequency of ω_{sc}=(10-20 keV)/h (for ELBE)

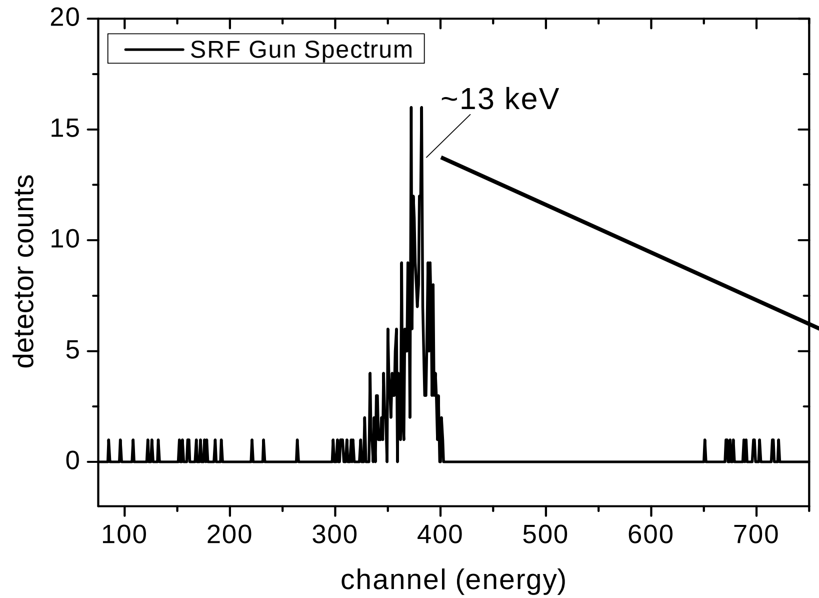


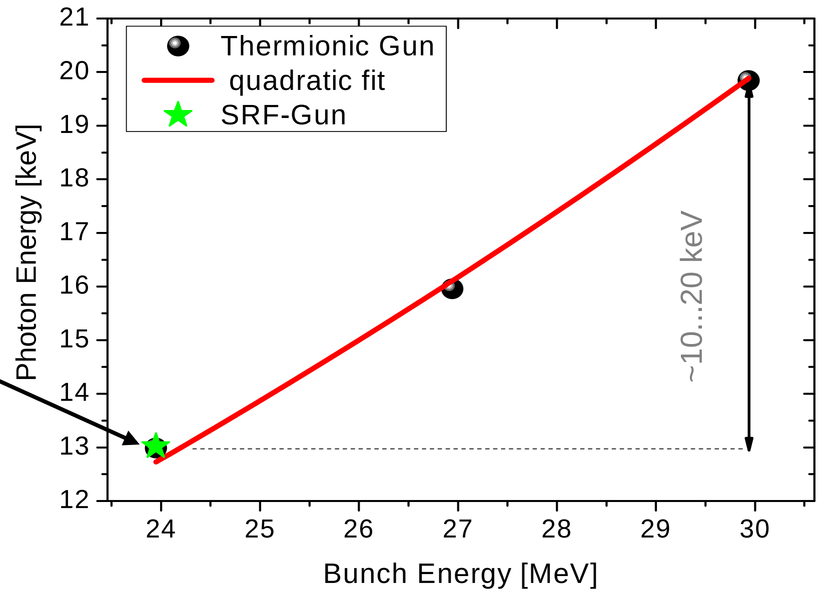
A.D. Debus et al., Appl Phys B (2010) 100: 61–76

- 1^{st} setup ELBE linac with therm. injector than switch to SRF-Gun (E_{acc}=6 MV/m, exit energy 2.85 MeV)
- Switch to 10 Hz single bunch mode (10 pC, 24 MeV) and optimized temporal overlap with laser
- CdTe detector found same X-ray spectrum but lower photon yield than with therm. gun

→ 1^{st} Demonstration of the Reliability of the SRF-Gun during an user experiment with critical needs in terms of bunch phase stability and laser-bunch synchronization







Summary and Outlook

HZDR

- Long lifetime of NC photo cathodes in SRF-Guns (>1 yr, total charge 35 C @ QE = 1%)
- No Q degradation since 4 years (RF operation ≈ 2500 h, beam time ≈ 1400 h)
- Strong MP was defeated by DC Bias and Grooves
- First successful measurements using the ELBE accelerator

  - Slice emittance measurements (J. Rudolph and HZB)

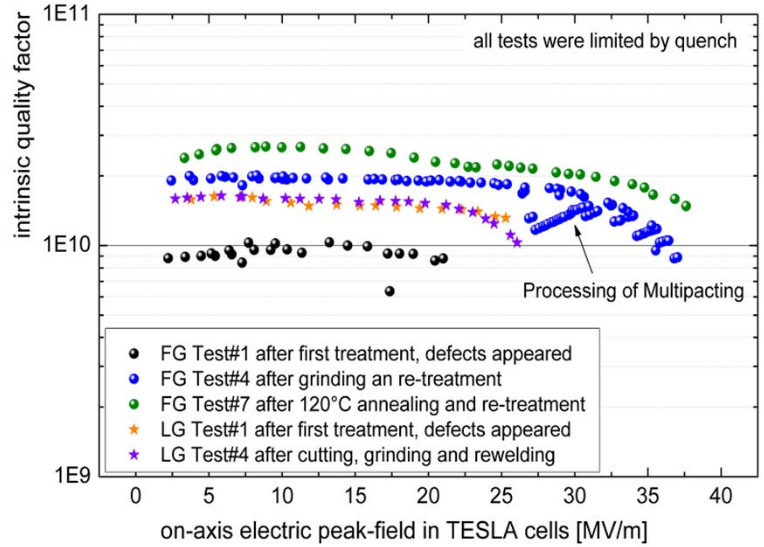
  - Longitudinal phase space

  - Inverse Compton backscattering (Laser Group at HZDR)
- But gun performance limited by low RF-field ($E_{pk} \leq$ 18MV/m and $Q_0 \leq 3x10^9$)

  (so far a problem for all SRF-Guns!)

Outlook 2012

- Installation of upgrade cavity built by **Peter Kneisel and the JLab guys** to twice E_{pk}>35MV/m and Energy to 6-7 MeV
- 13 MHz laser upgrade and start high average current operation (1mA)



Thanks to our collaborators (HZB for diagnostics, MBI for the laser and DESY for their help in preparation and testing the 1st cavity) and thank you for your attention!

ELBE Crew in front of museum of clocks in Glashütte, Germany

Acknowledgement
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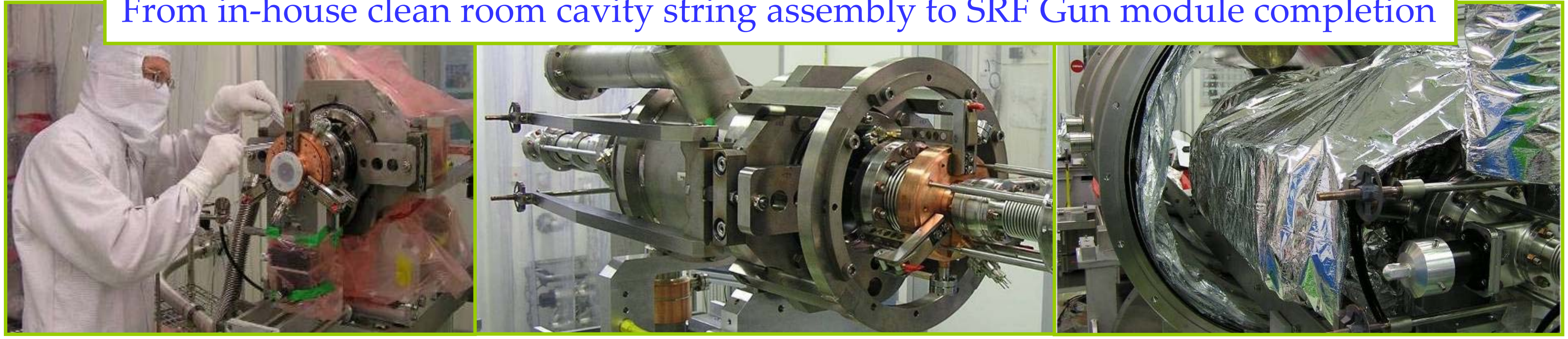
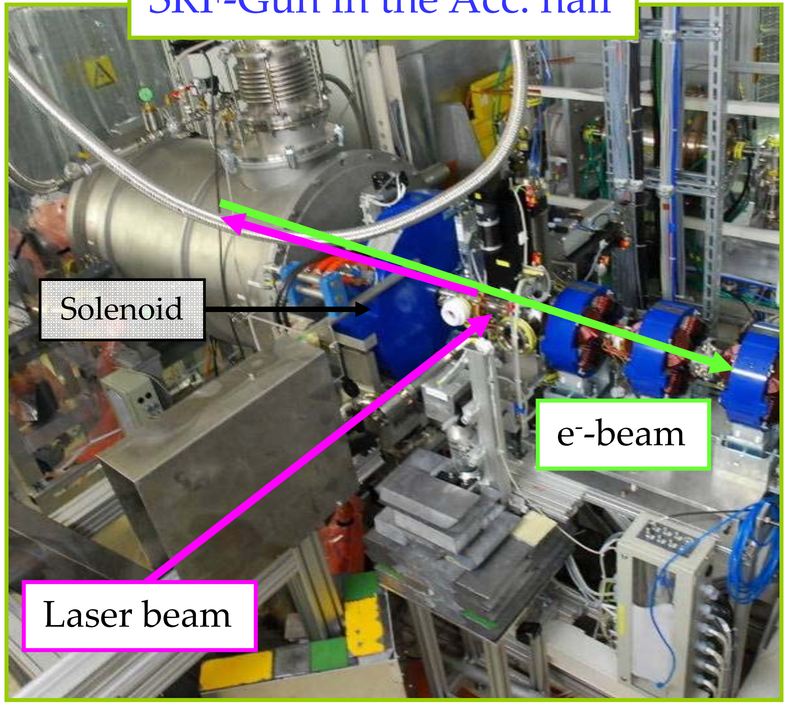
DRESDEN concept

Introduction - Cryostat Assembly

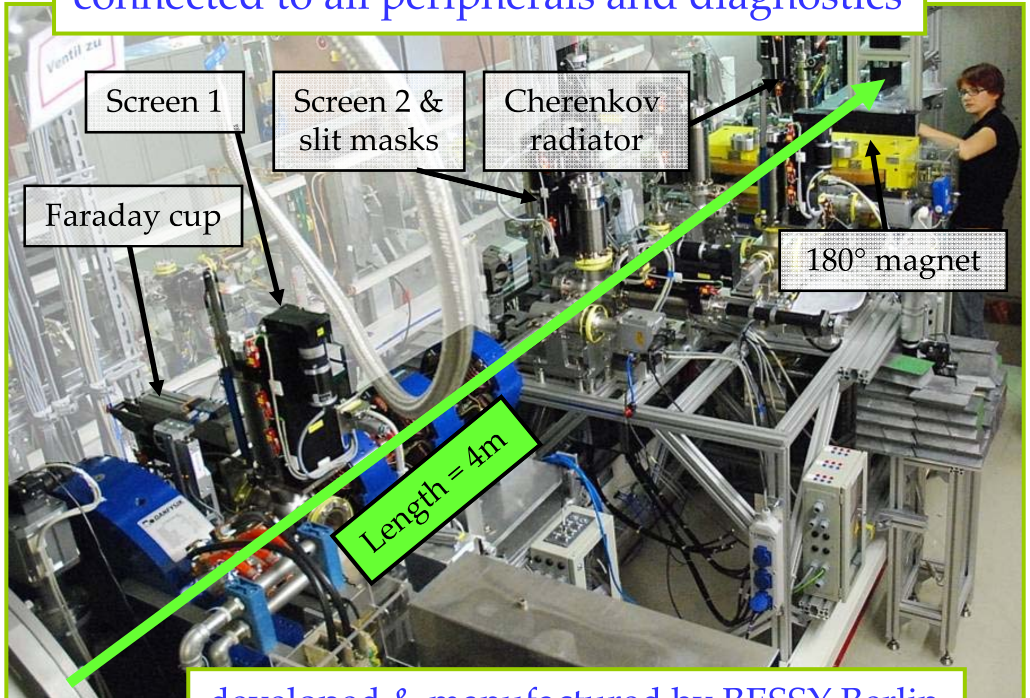
From in-house clean room cavity string assembly to SRF Gun module completion



SRF-Gun in the Acc. hall



connected to all peripherals and diagnostics

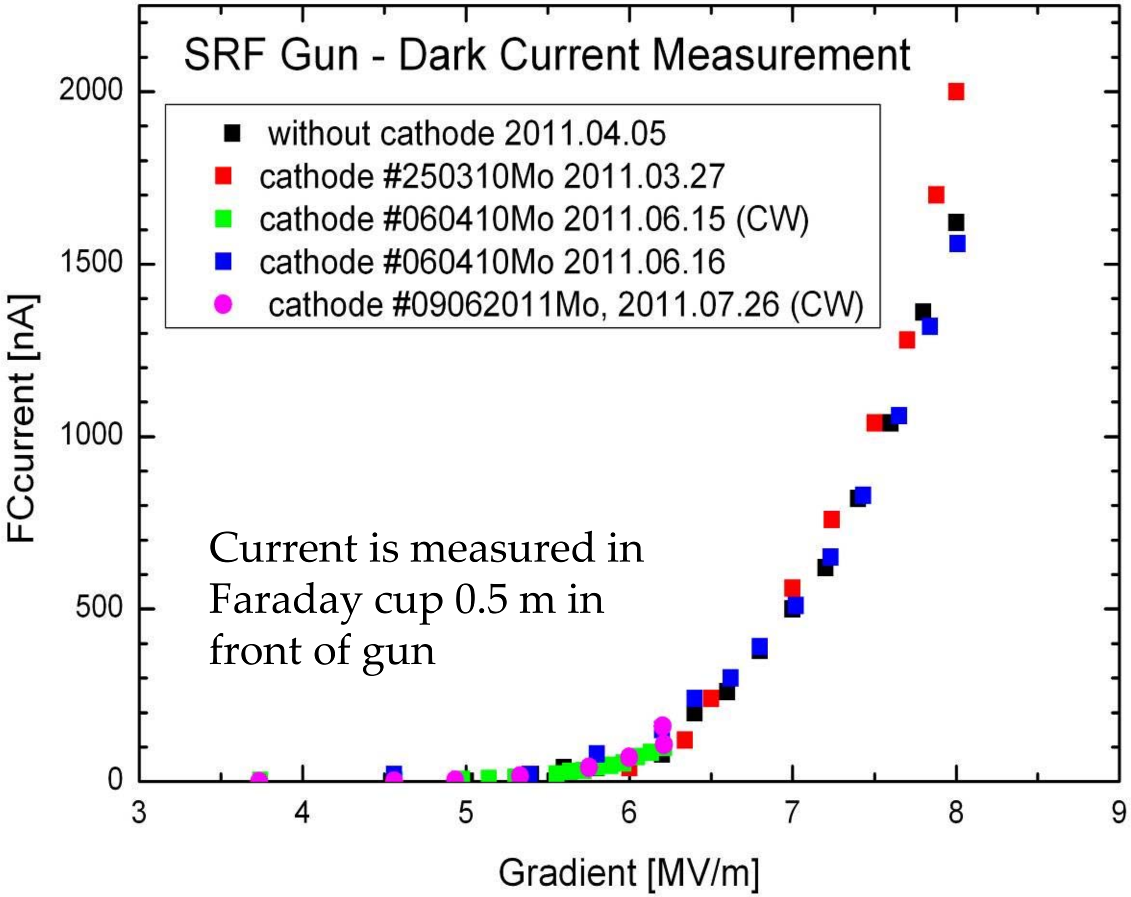


developed & manufactured by BESSY Berlin

RF Operation – Dark Current

An important issue in this context is the dark current

- Operation at high fields especially in pulsed RF regime up to 22 MV/m can increase beam energy to 4 MeV and reduce emittance, but
- Dark current increases to µA level **with mostly the same energy as the photo current.**
- **Most of the current comes from the cavity surface and not from cathode**
- Dark current kicker needed because too much for some experiments e.g. inverse Compton backscattering



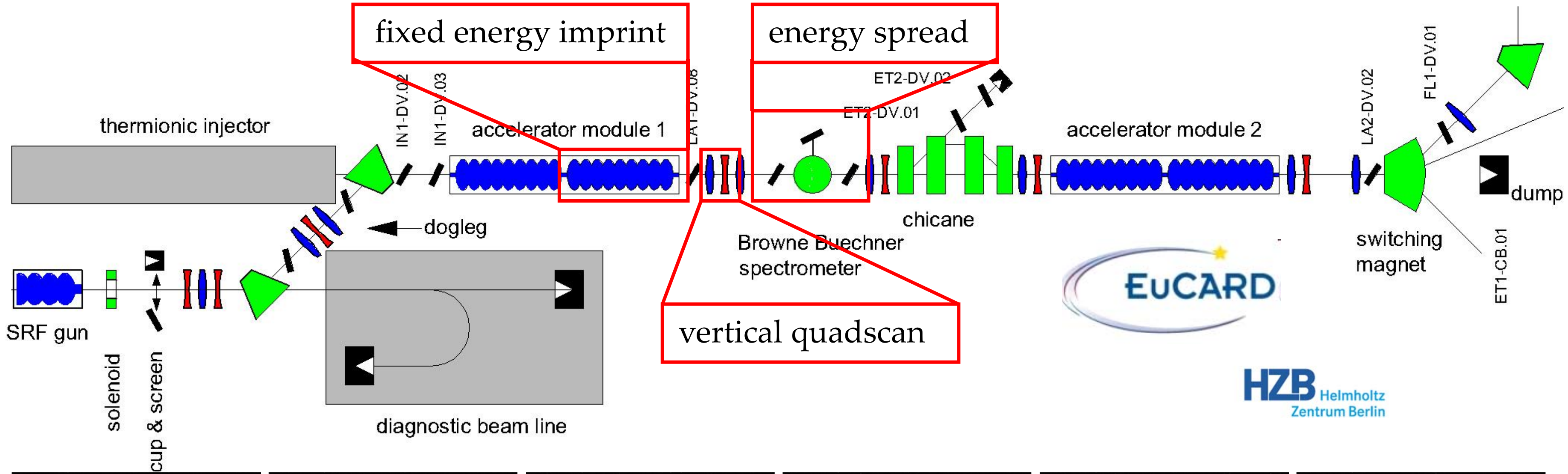
Current is measured in Faraday cup 0.5 m in front of gun

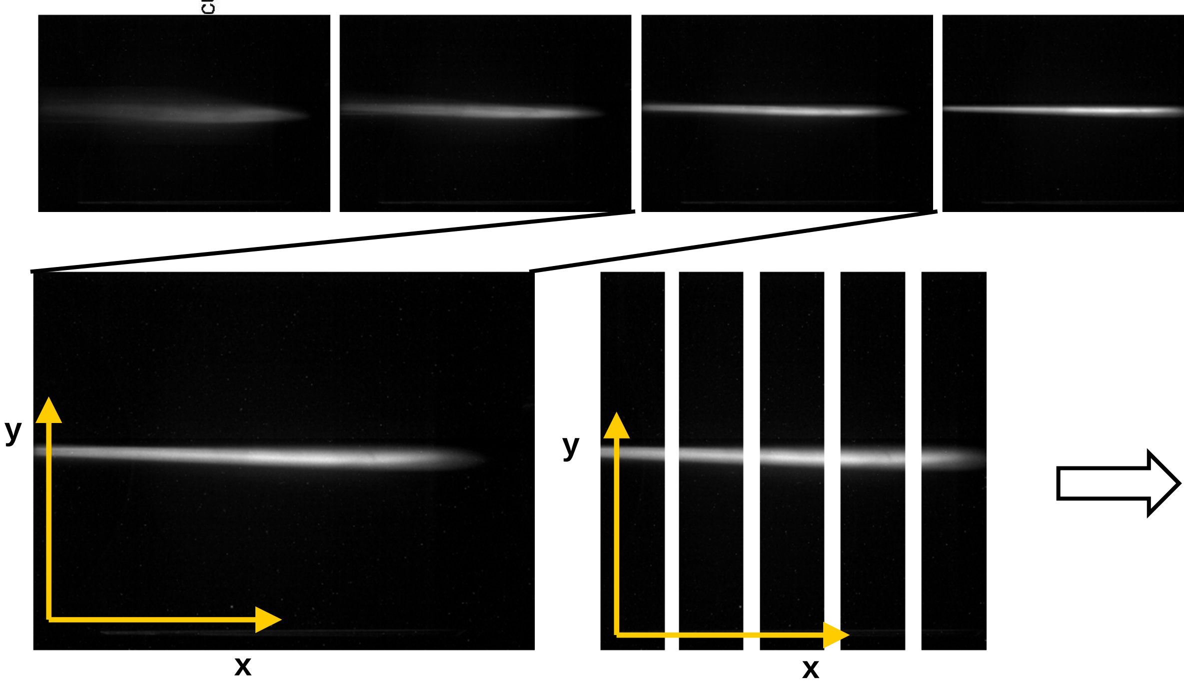
Further investigations within German Gun-Cluster collaboration

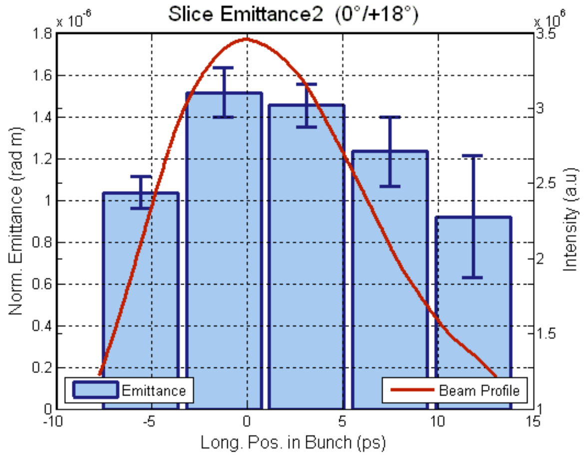
DRESDEN concept

HZDR

ELBE – Slice Emittance by HZB







J. Rudolph, et al., Slice-Emittance Measurements at ELBE / SRF-Injector, Dipac2011.

Cs_2Te Cathode - Summary

Issue	Demonstration for low average current & low energy (3 MeV)	Remarks
stable QE > 1 %	1% for > 1000 h beam time OK	test of cathodes with > 5 % reducing early QE drop
life time in gun	> 1 year OK	
pollution of SC cavity	no Q_0 degradation or increased field emission up to now OK	needs demonstration for high current & gradient ?
extracted charge	≈ 35 C	36 C = 1 mA * 10 h 360 C / cathode is minimum ?
dark current	≈ 120 nA (for 3 MeV or 30 W dissipated power)	needs demonstration for high current & gradient ?
multipacting	shaping of the cathode stem OK	TiN coating planed ?
cathode cooling	< 300 mW laser & low gradient OK	up to 1 mA not critical
easy and quick exchange	cathode exchange needs < 30 min in cold gun OK	Vacuum improvements needed for GaAs and Cs_2KSb ?

SRF Gun Parameter

parameter	present cavity			new "high gradient cavity"	
	measured	ELBE	high charge	ELBE	high charge
final electron energy	2.1 MeV	3 MeV		≤9.5 MeV	
peak field	13.5 MV/m	18 MV/m		50 MV/m	
laser rep. rate	1 – 125 kHz	13 MHz	2 – 250 kHz	13 MHz	≤500 kHz
laser pulse length (FWHM)	15 ps	4 ps	15 ps	4 ps	15 ps
laser spot size	2.7 mm	5.2 mm	5.2 mm	2 mm	5 mm
bunch charge	≤ 200 pC	77 pC	400 pC	77 pC	1 nC
max. aver. Current	1 μA	1 mA	100 μA	1 mA	0.5 mA
peak current	13 A	20 A	26 A	20 A	67 A
transverse. norm. emittance (rms)	3±1 mm mrad @ 80 pC	2 mm mrad	7.5 mm mrad	1 mm mrad	2.5 mm mrad