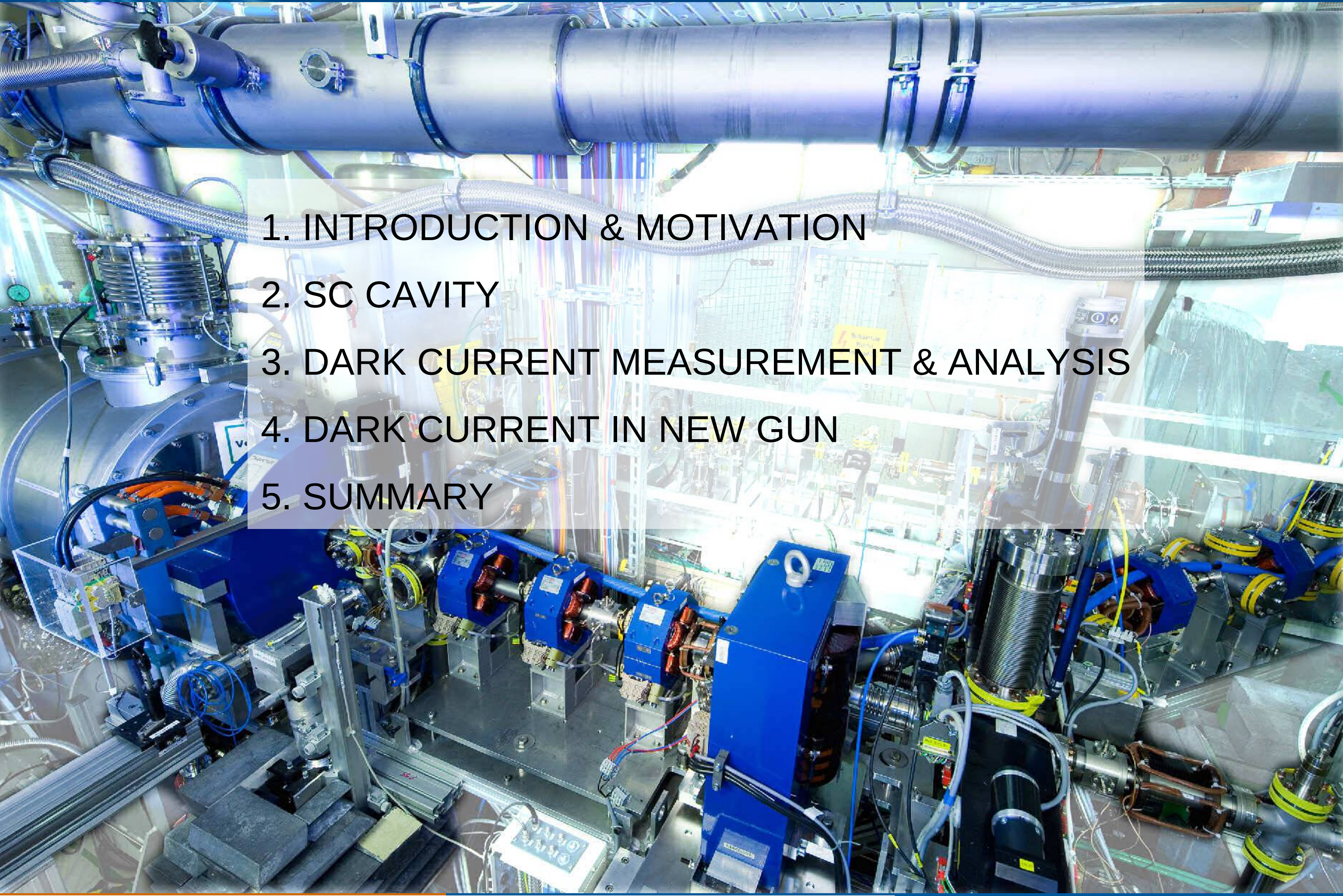
J. Teichert
A. Arnold, P. Lu, P. Murcek, G. Staats, H. Vennekate, R. Xiang (HZDR)
T. Kamps, R. Barday (HZB)

Dark Current in Superconducting RF Photoinjectors -Measurements and Mitigation

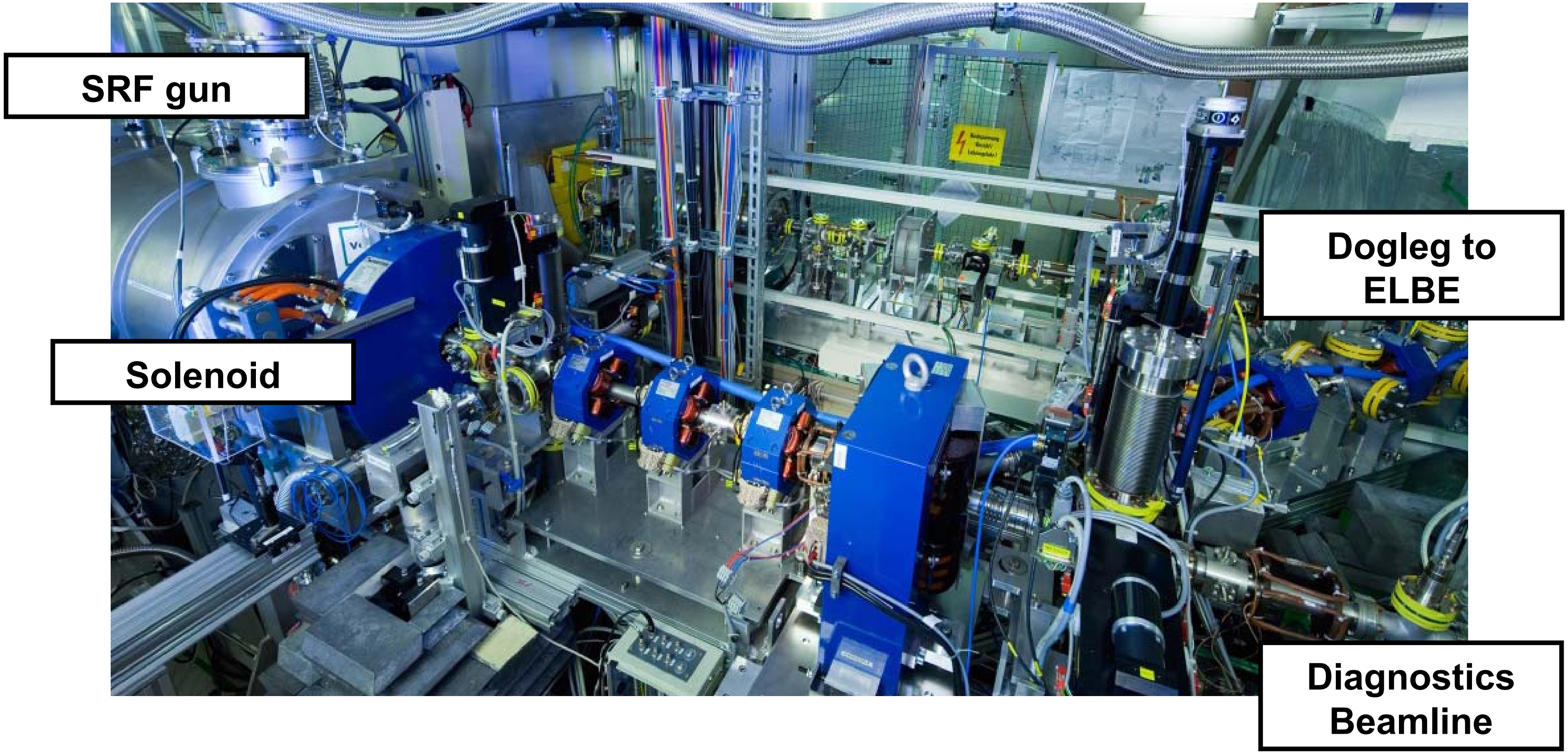
The 53th ICFA Advanced Beam Dynamics Workshop on
Energy Recovery Linacs "ERL-2013"
9 – 13 September , 2013, BINP, Novosibirsk, Russia

OUTLINE

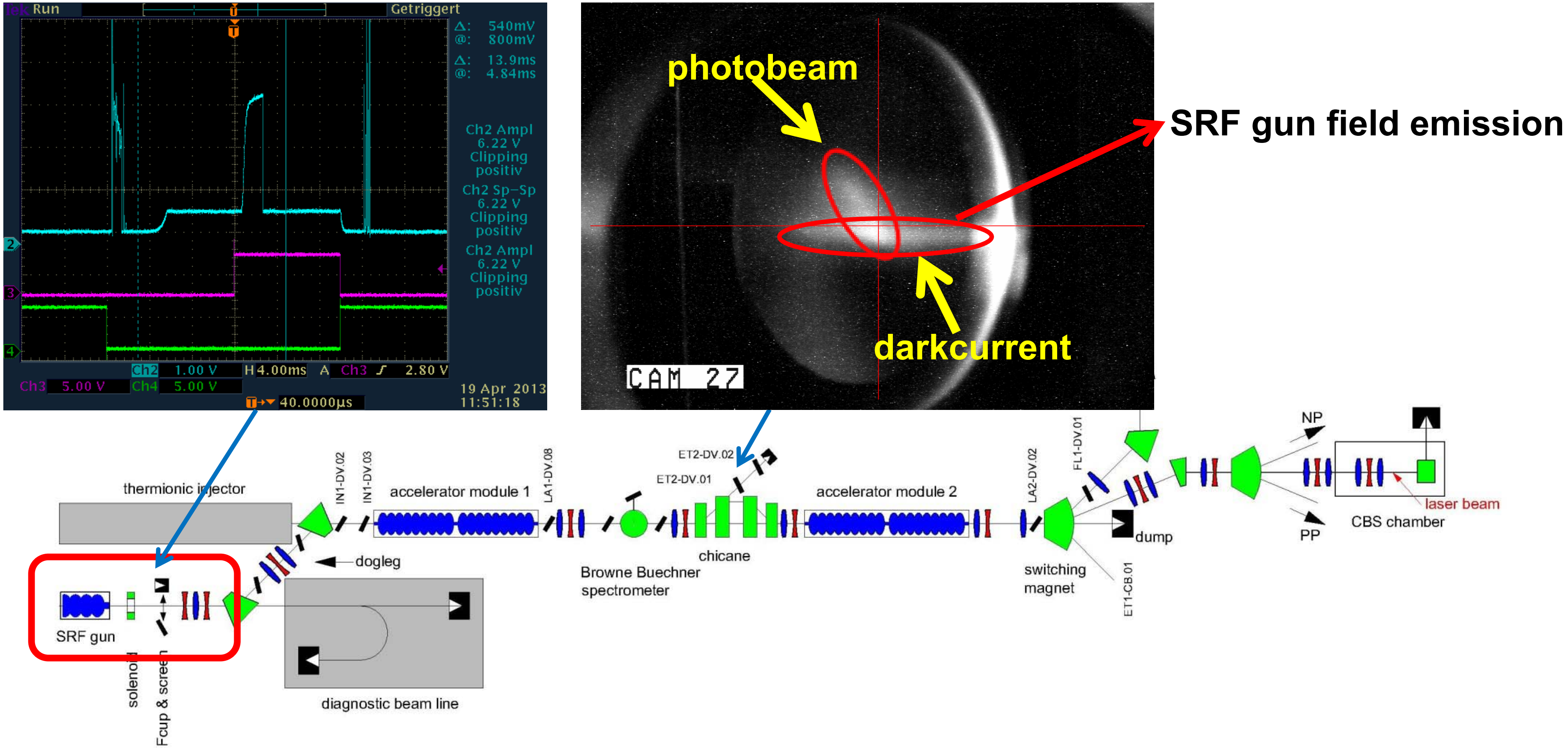


1. INTRODUCTION & MOTIVATION
2. SC CAVITY
3. DARK CURRENT MEASUREMENT & ANALYSIS
4. DARK CURRENT IN NEW GUN
5. SUMMARY

INTRODUCTION & MOTIVATION



INTRODUCTION & MOTIVATION



Dark current produces beam loss that increases radiation level and activation

causes damages to accelerator components

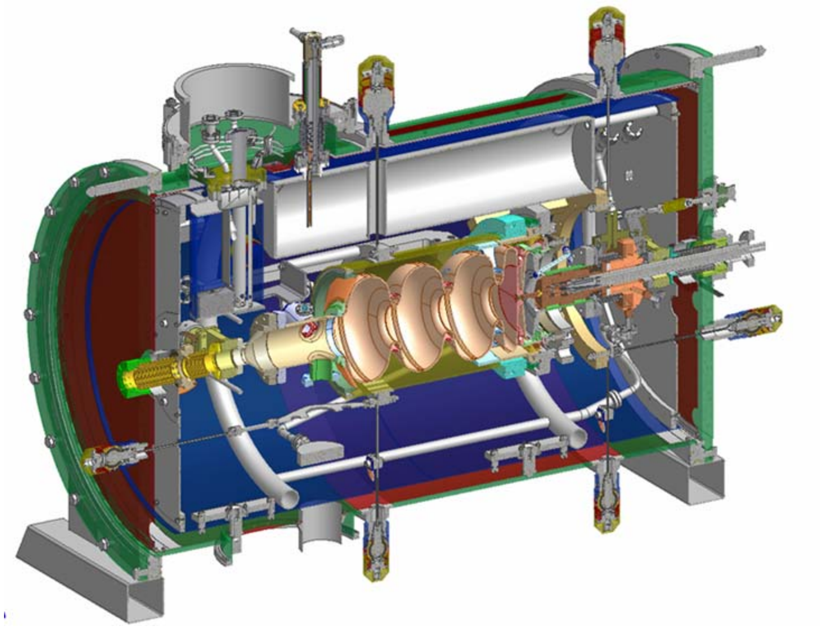
produces additional background for users

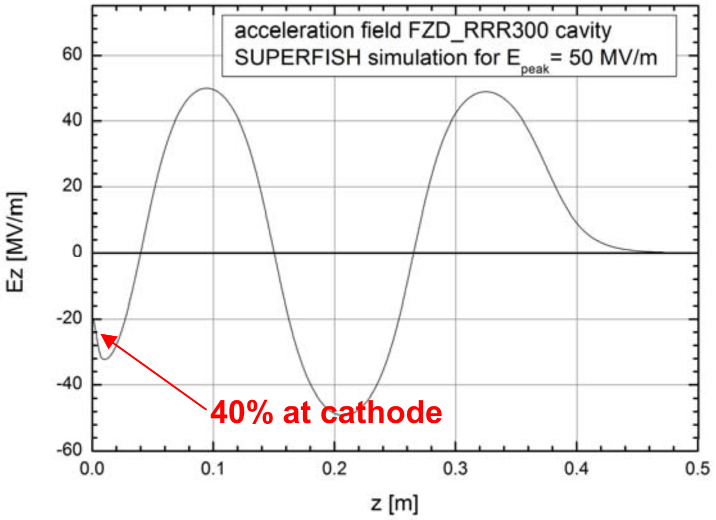
increases RF power consuming and heat load for cavity

cathode lifetime

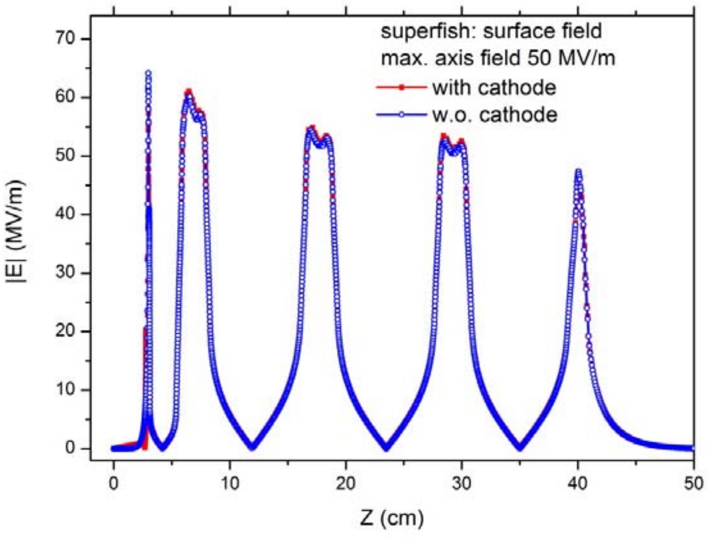
……

RF CAVITY





field profile on axis



surface electric field

SRF gun design

medium I_{ave}: 1 - 2 mA (< 10 mA)

high rep-rate: 500 kHz, 13 MHz

low and high bunch charge: 80 pC - 1 nC

low transverse emittance: 1 - 3 mm mrad

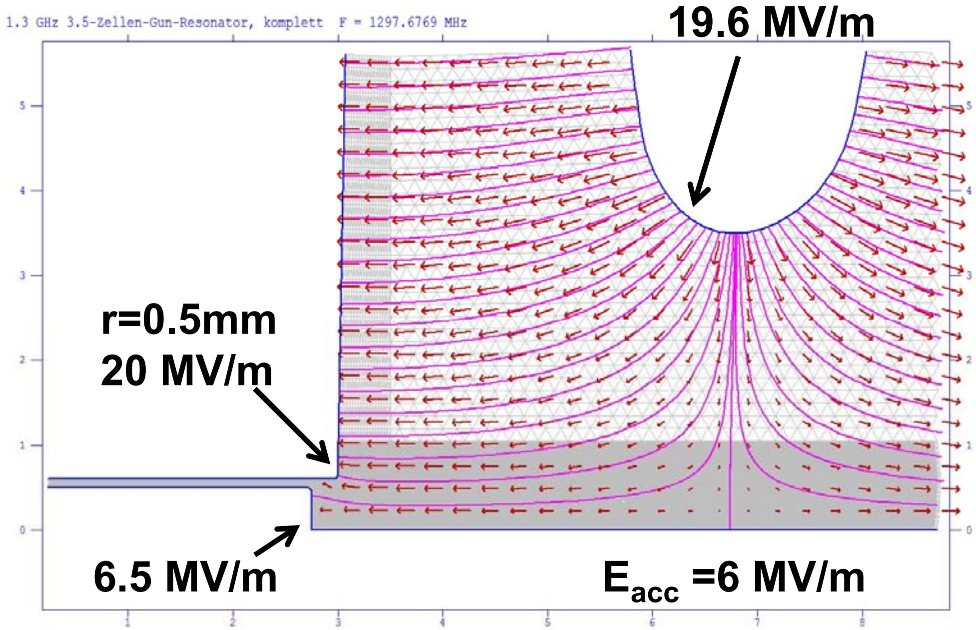
high energy: ≤ 9 MeV, 3½ cells (stand alone)

highly compatible with ELBE cryomodule (LLRF, high power RF, RF couplers, etc.)

LN$_2$-cooled, exchangeable semiconductor photocathode

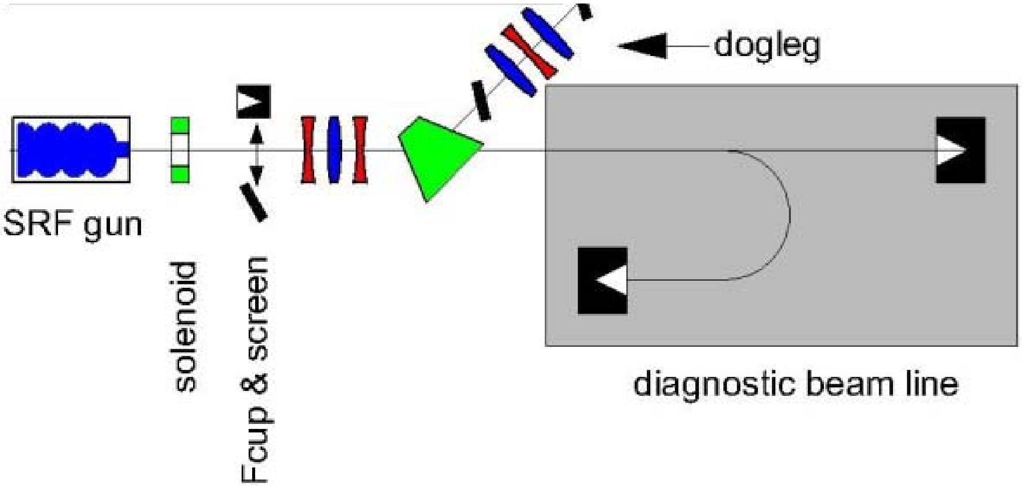
RF CAVITY

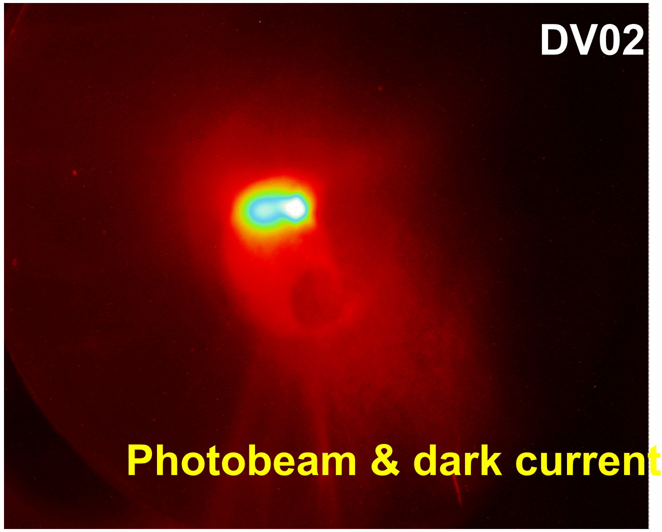
gun operation mode	CW	pulsed RF
acceleration gradient	6.0 MV/m	8 MV/m
electron kinetic energy	3 MeV	4 MeV
peak field on axis	16.5 MV/m	21.5 MV/m
peak field at cathode (2.5 mm retracted)	6.5 MV/m	8.4 MV/m
cathode field at launch phase (10°)	1.1 MV/m	1.5 MV/m
cathode field at 10° and -5 kV bias	2.2 MV/m	2.6 MV/m
cathode field at 90° and -5 kV bias	7.6 MV/m	9.5 MV/m

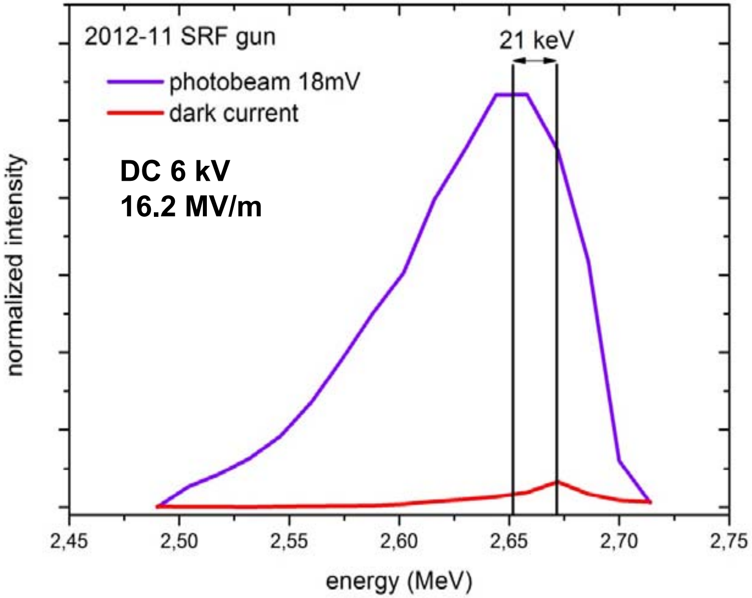


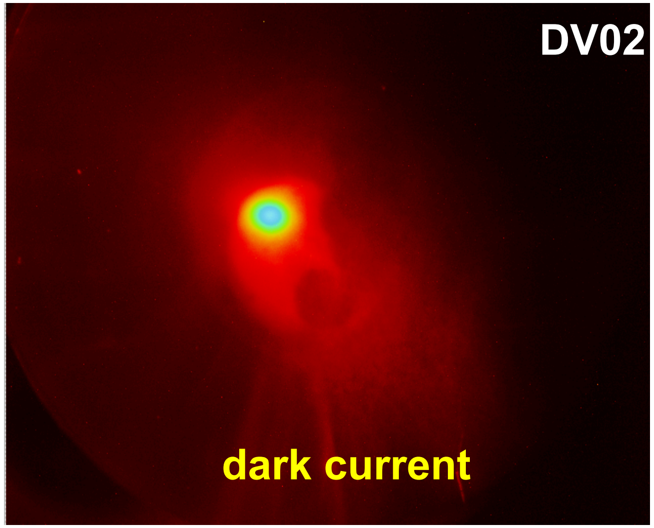
most possible zone of field emission:
the rim of cathode hole
Cavity iris
half cell wall
Cs_2Te emitter layer
cathode rim

DARK CURRENT MEASUREMENT AND ANALYSIS



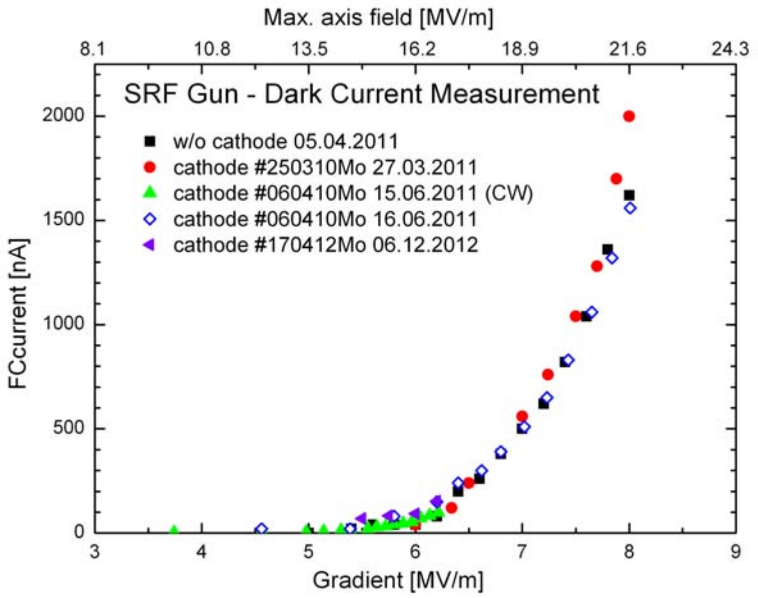


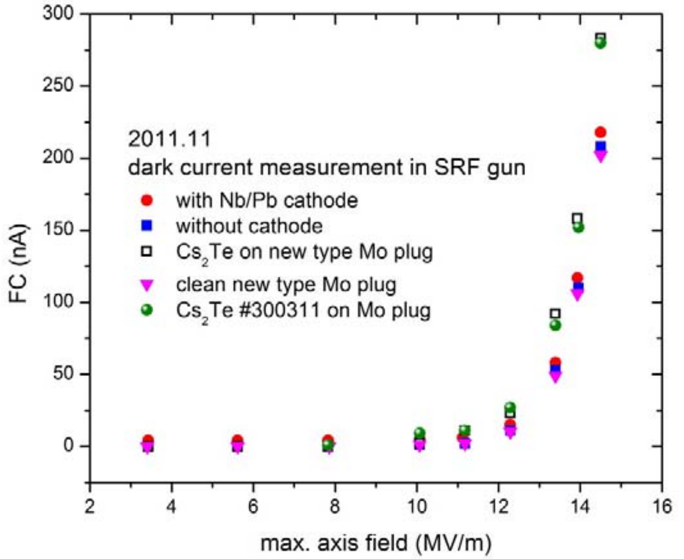




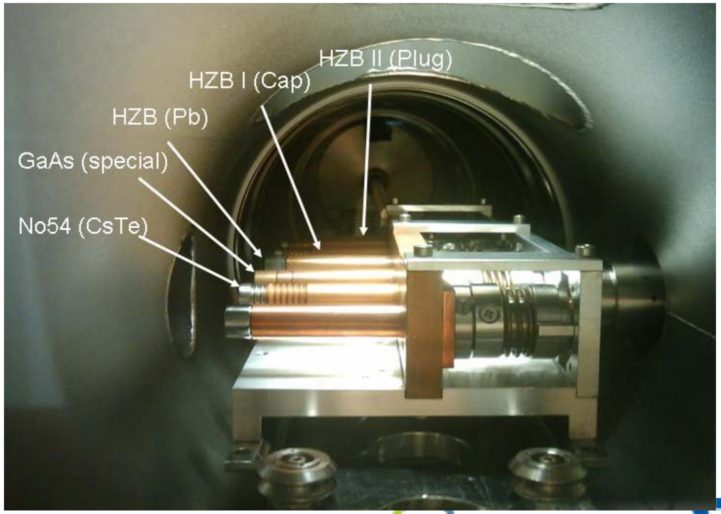
DARK CURRENT MEASUREMENT AND ANALYSIS

Dark current in Faraday cup (~1.5 m from cathode) versus gradient for different cathodes





- **about 20 % dark current from cathode, 80% from cavity**
- **only cathodes with Cs$_2$Te layer have dark current, exception: #060410Mo, but without direct comparison**



DARK CURRENT MEASUREMENT AND ANALYSIS

Fowler Nordheim formula for field emission current:

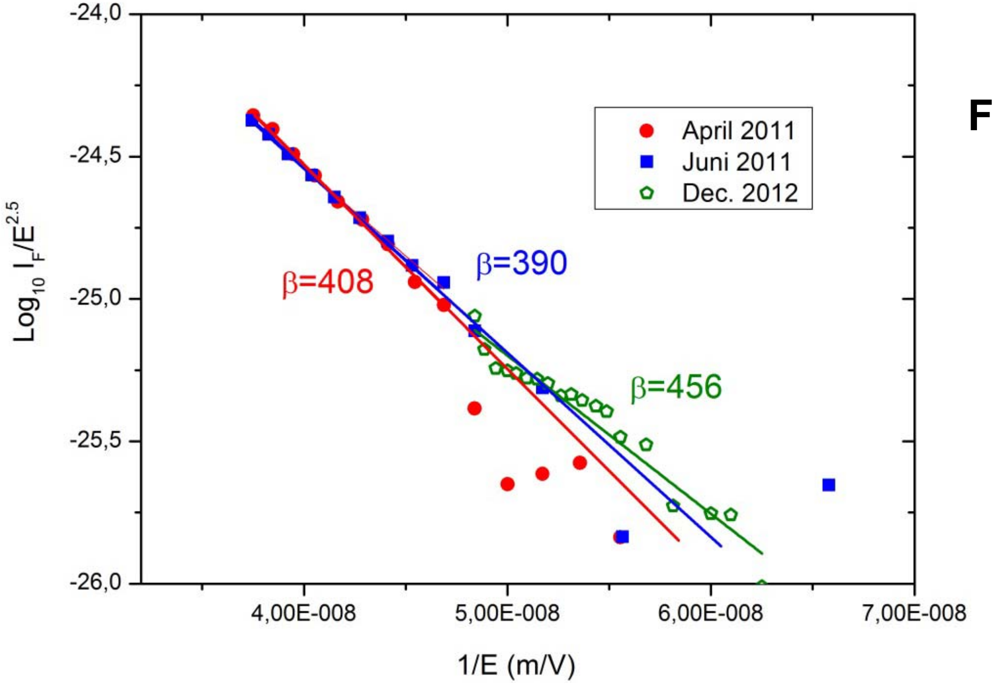
$$I_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\emptyset^{-0.5}} A_e \beta^2 E^2}{\emptyset} e^{-\frac{6.53\times10^9 \emptyset^{1.5}}{\beta E}}$$

Fowler Nordheim plot for RF fields:

$$\frac{d(log_{10} I_F/E^{2.5})}{d(^1/_E)} = -\frac{2.84 \times 10^9 \emptyset^{1.5}}{\beta}$$

E: surface field amplitude in V/m, ϕ: work function in eV, β: field enhancement factor.

(J.W. Wang and G.A. Loew, SLAC-PUB-7684 October 1997)



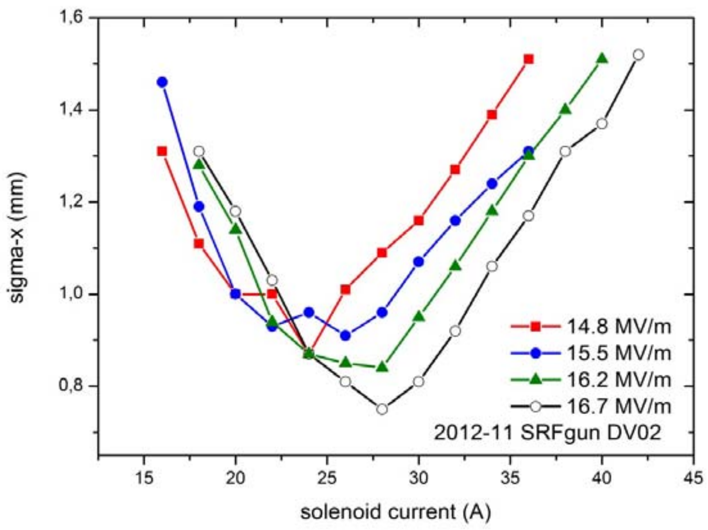
F-N plots for the SRF gun cavity

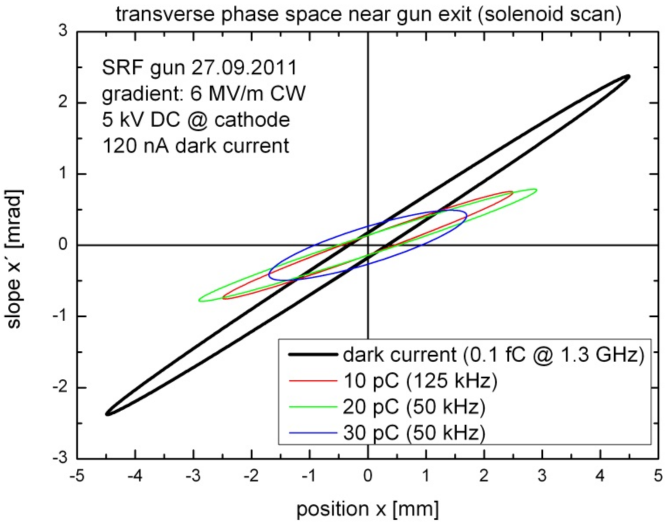
ϕ_{Nb} = 4.3 eV
β ≈ 400

Sharp emitter

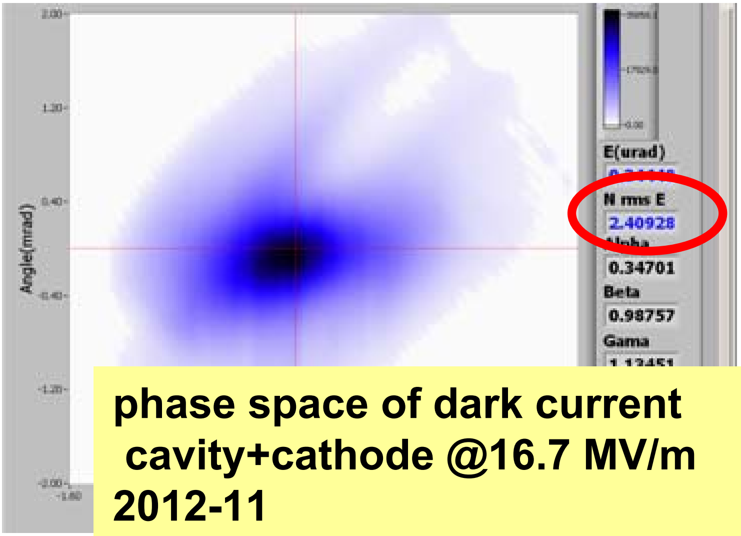
DARK CURRENT MEASUREMENT AND ANALYSIS

Solenoid scan





Slit scan



E(urad)

N rms E

2.40928

Alpha

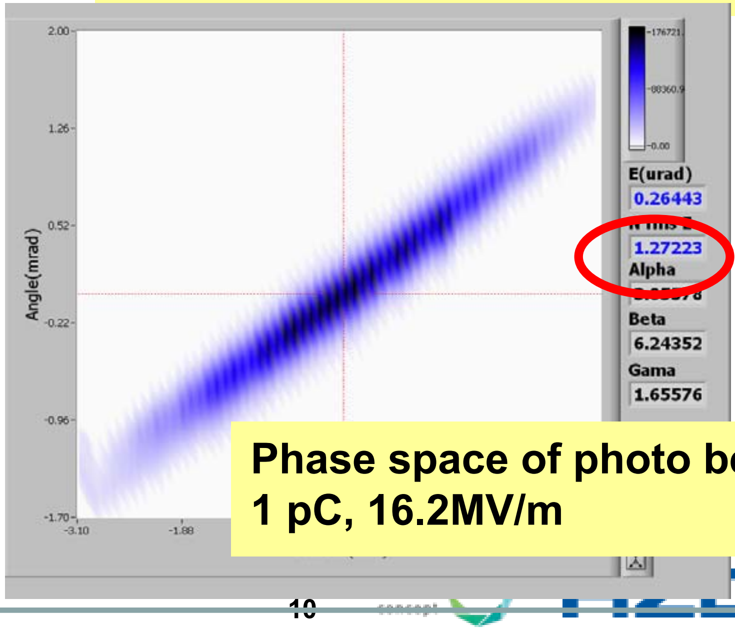
0.34701

Beta

0.98757

Gama

phase space of dark current cavity+cathode @16.7 MV/m 2012-11



E(urad)

0.26443

1.27223

Alpha

Beta

6.24352

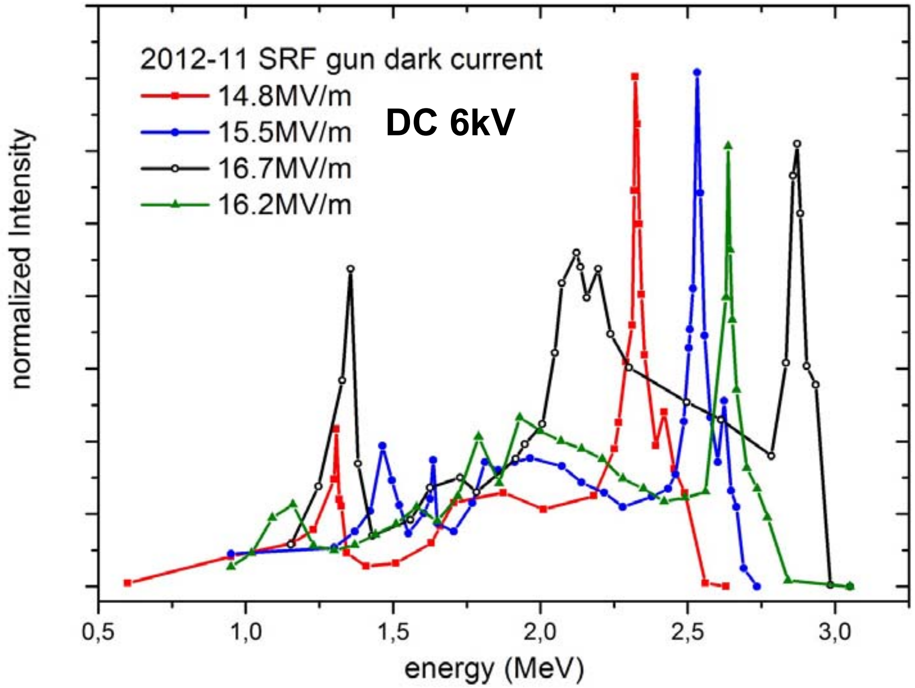
Gama

1.65576

Phase space of photo beam 1 pC, 16.2MV/m

DARK CURRENT MEASUREMENT AND ANALYSIS

Dark current energy spectrum with cathode #170412Mo



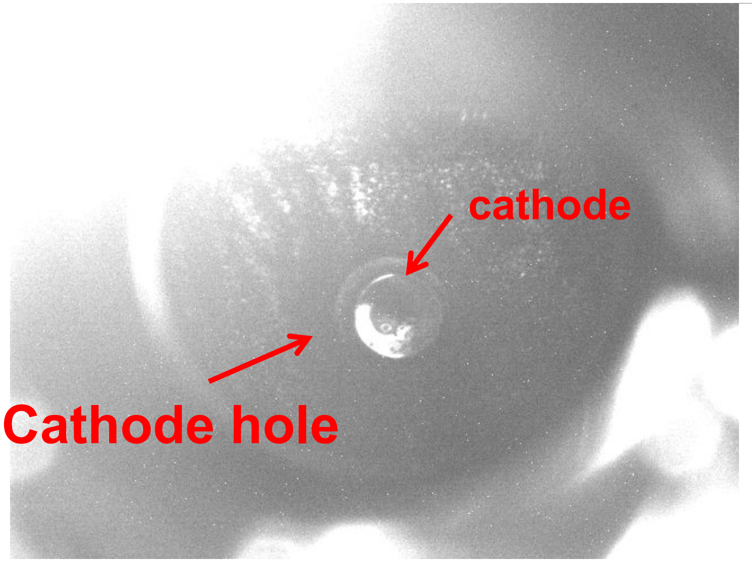
Measured with dogleg dipole + YAG screen,
normalized according to the total dark current measured from Faraday cup.

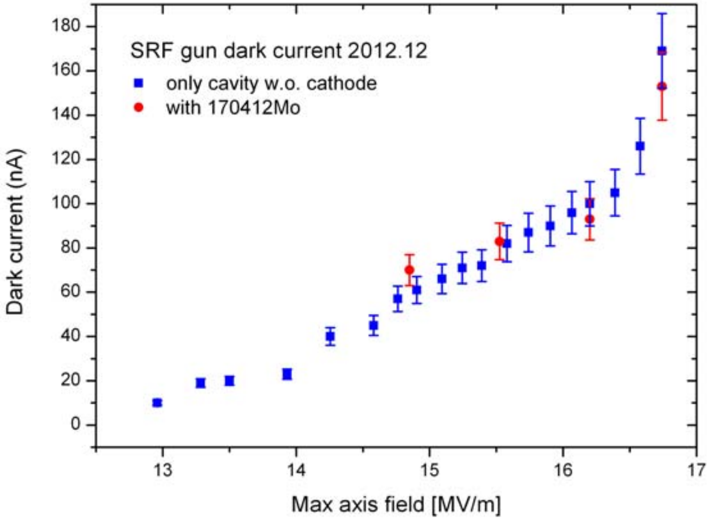
Different energy ⇔ different position?

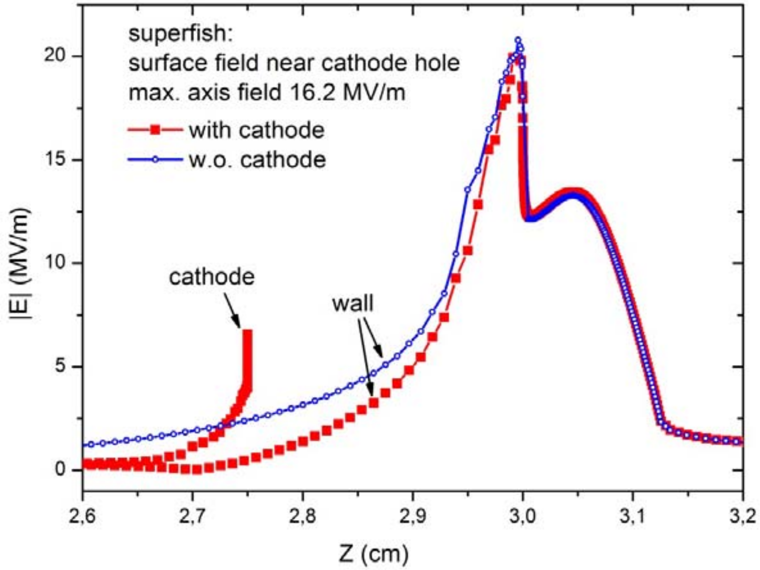
Simulation needed.

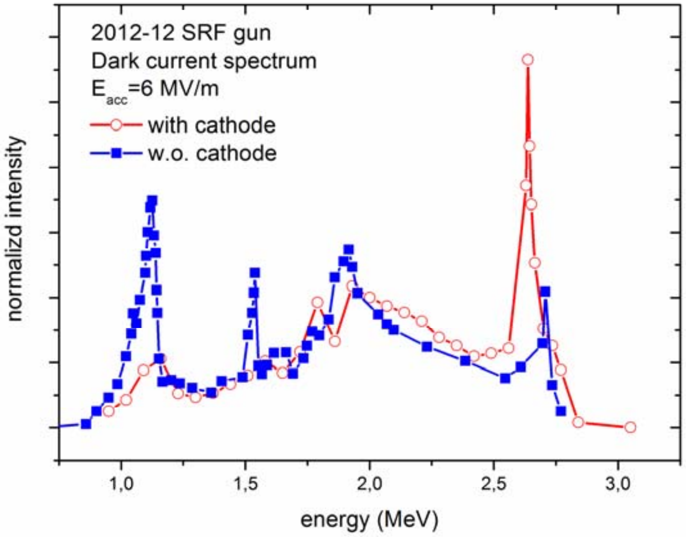
Max. axis gradient	Energy @ peak	Energy spread @ peak	peak/ total	Current @ Main peak
14.8 MV/m	2.3 MeV	140 keV	24.6 %	17 nA
15.5 MV/m	2.53 MeV	140 keV	20.8 %	17 nA
16.2 MV/m	2.64 MeV	146 keV	16.3 %	15 nA
16.7 MV/m	2.87 MeV	145 keV	12.9 %	20 nA

DARK CURRENT MEASUREMENT AND ANALYSIS



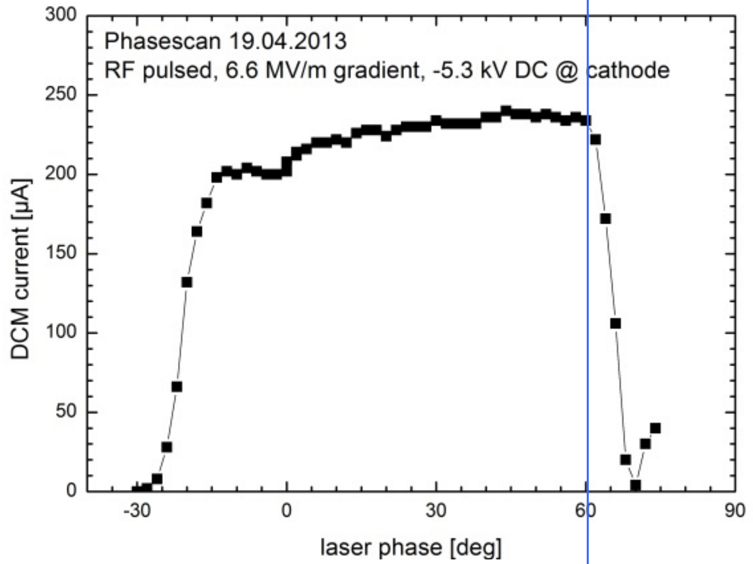


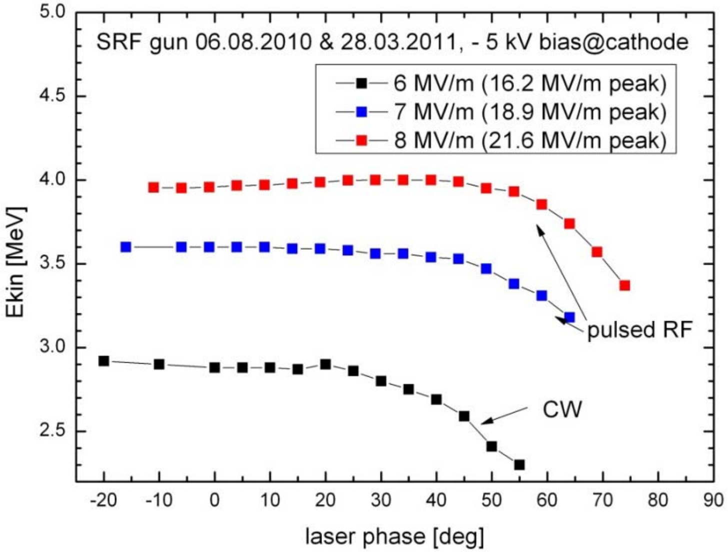


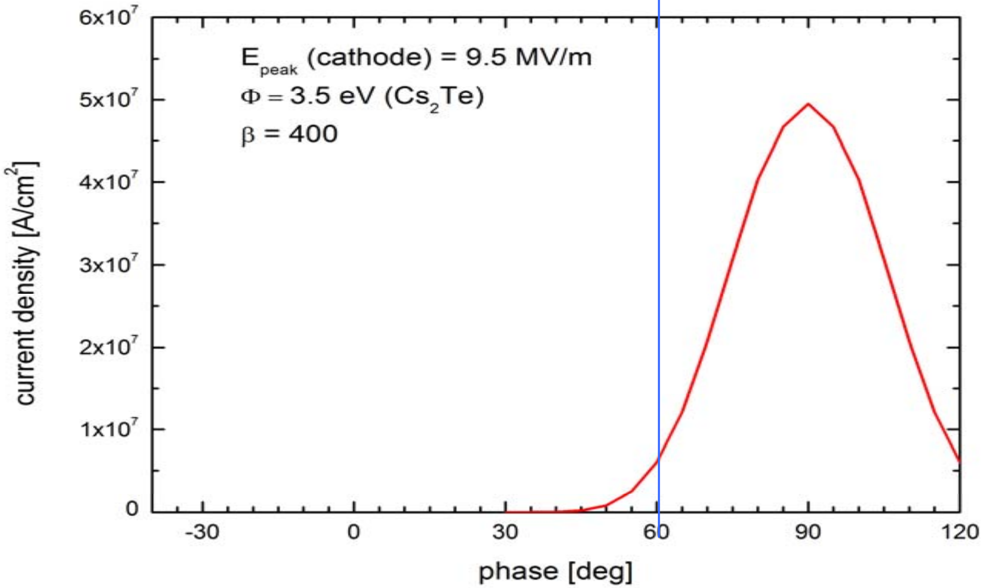


DARK CURRENT MEASUREMENT AND ANALYSIS

Measured phase acceptance of the gun



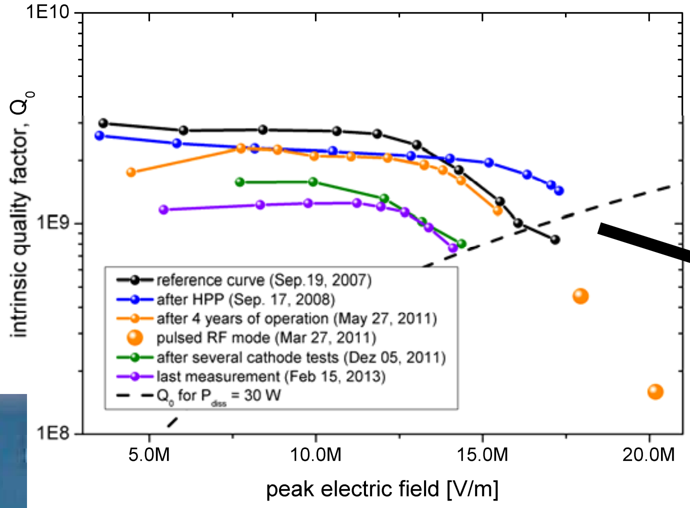




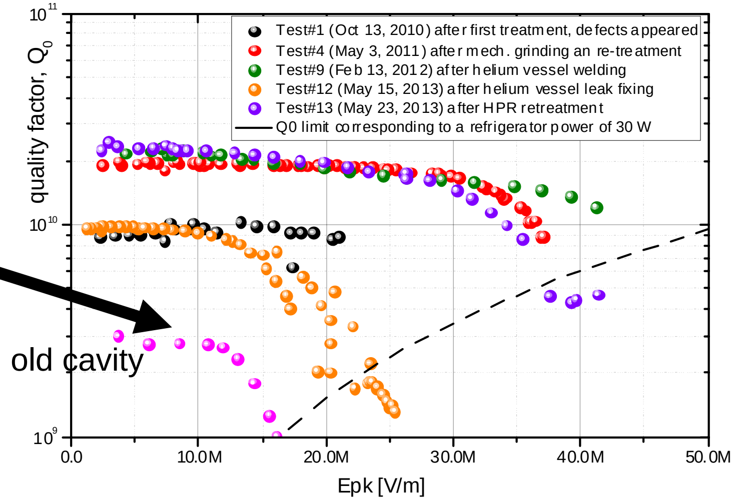
Simulated RF phase dependance of dark current

DARK CURRENT IN NEW GUN

existing cavity in SRF gun at ELBE with high field emission



new cavity built and tested at JLAB

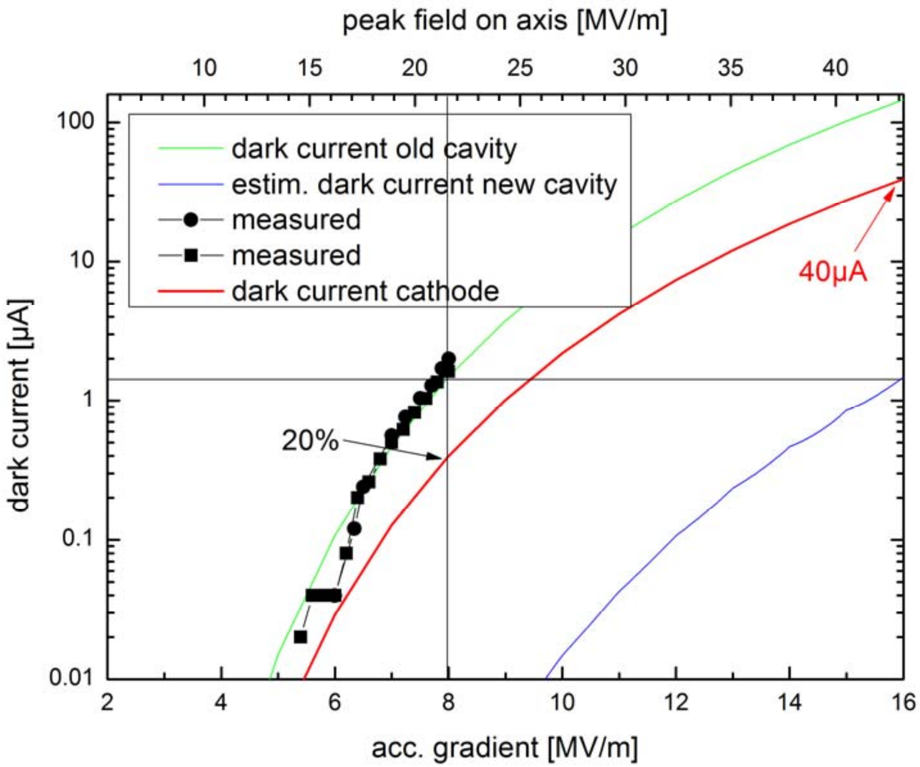


Maximum fields (pulsed):
E_{acc} = 8 MV/m
E_{peak} = 21.5 MV/m

Maximum fields for operation
E_{acc} = 16 MV/m
E_{peak} = 43 MV/m

DARK CURRENT IN NEW GUN

Extraction of Fowler Nordheim results for new cavity:



- **New cavity will be operated at 16 MV/m. Here we expect lower field enhancement factor β for the new cavity. For instance, the same dark current as for the old cavity @ 8 MV/m (blue curve)**
- **FN fit for 20 % of dark current emitted from cathode (φ = 3.5 eV for Cs_2Te, 40% peak field) and extrapolation to 16 MV/m (red curve) gives 40 μA cathode dark current**

DARK CURRENT IN NEW GUN

For cathodes used in SRF gun:

If one wants a low unwanted beam ~µA in CW accelerators with SRF guns, there will be a need for photo cathodes with low dark current

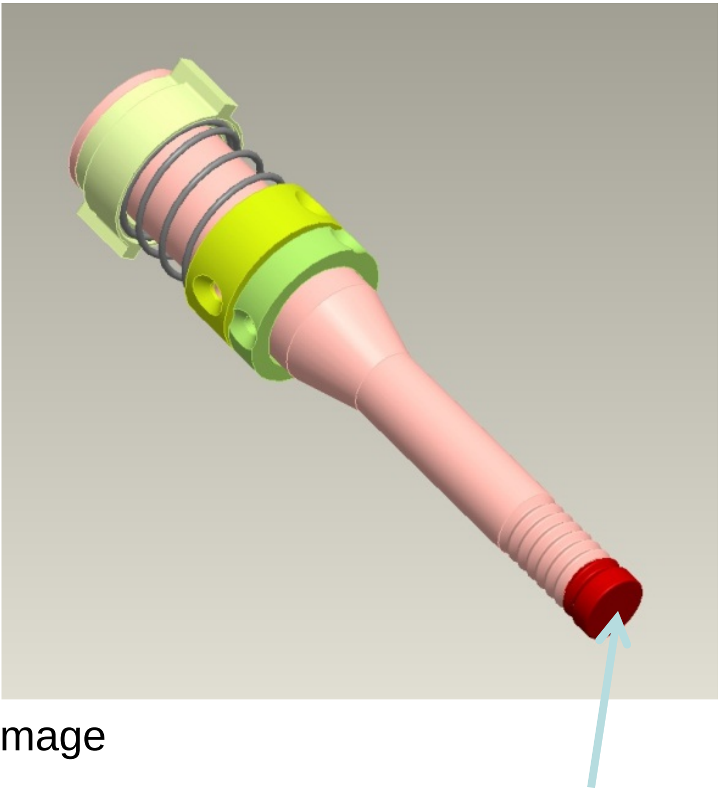


photo emission layer (Cs_2Te)

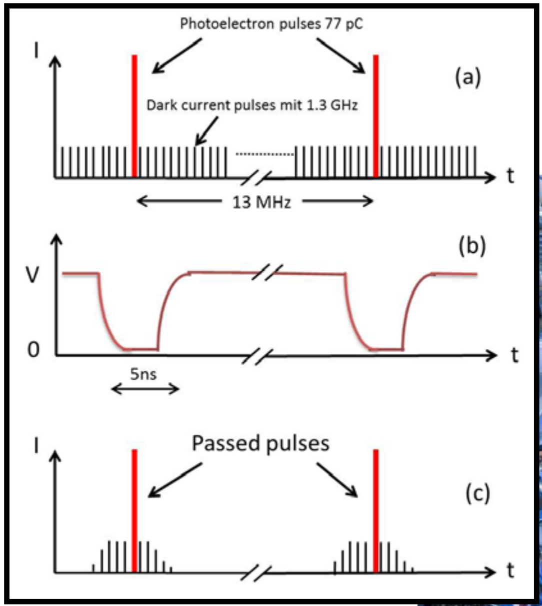
Photo cathode optimization parameters:

QE,
life time (charge & operational lifetime), thermal emittance (roughness)
roughness & field emission

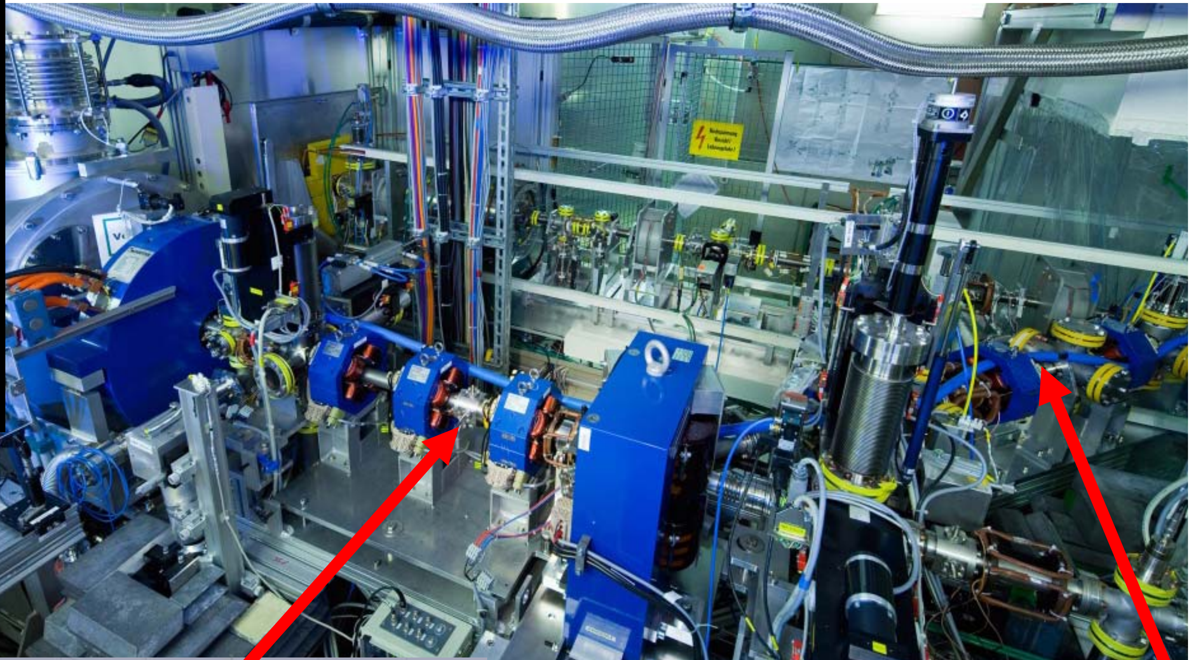
But how to reduce field emission?

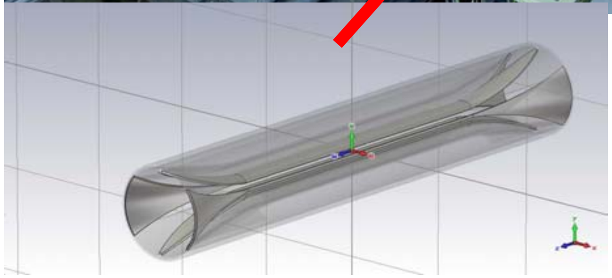
- proper handling to prevent dust particles and surface damage
- proper materials for plugs and smooth surface
- photo layer properties
  - roughness, homogeneity, thickness
  - work function
  - crystal size, boundary and structure
  - post-preparation treatment (protection layer, heating, …)
  - pre-conditioning

DARK CURRENT IN NEW GUN



Stripline kicker with 13 MHz CW, 5 ns pulse length,
dark current reduction to ~ 5 %





ca. 250 mm long
10 mm gap

collimator

(horizontal slit)

SUMMARY

- Dark current measurement of the SRF gun at ELBE for different gradients and various photocathodes
- Determination of energy spectrum, transverse phase space and Fowler-Nordheim analysis performed
- Source is field emission at cavity back wall and photocathode (20%)
- Estimation of dark current for new cavity with higher gradient
- Photo cathodes need optimization to lower field emission current
- A dark current kicker is beeing designed for the SRF gun at ELBE

THANK YOU FOR ATTENTION

Acknowledgement

We acknowledge the support of the European Community under the FP7 programme (EuCARD2, contract no 227579, LA3NET contract no 289191) as well as the support of the German Federal Ministry of Education and Research grant 05K12CR1