Operation of the CeC 113 MHz SRF Gun

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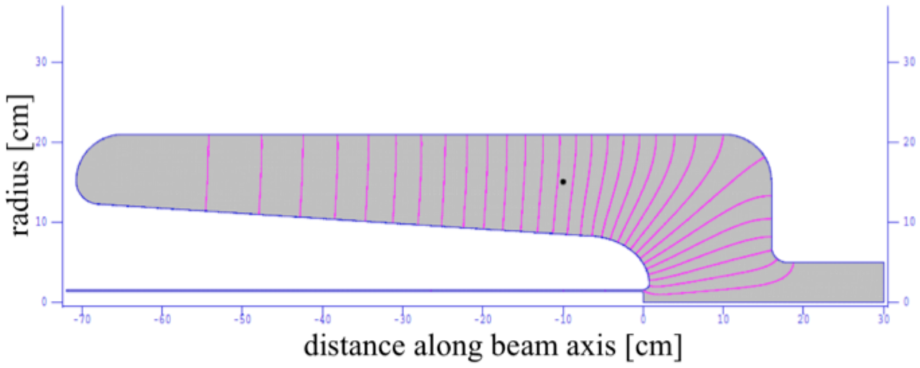
Introduction

- The gun quarter-wave cavity was developed as part DoE SBIR program to be a prototype for the electron cooling
- It was configured as SRF gun with room temperature photocathode for the Coherent Proof-of-Principle Experiment at RHIC
- The aim of the experiment was to demonstrate cooling of single hadron bunch circulating in RHIC

S. Belomestnykh *et al.,* Proc. of PAC’11, TUP051
V.N. Litvinenko *et al*., Proc. of IPAC’12, MOPPD016
D. Kayran *et al.,* Proc. of IPAC’12, MOPPP028

Design Parameters

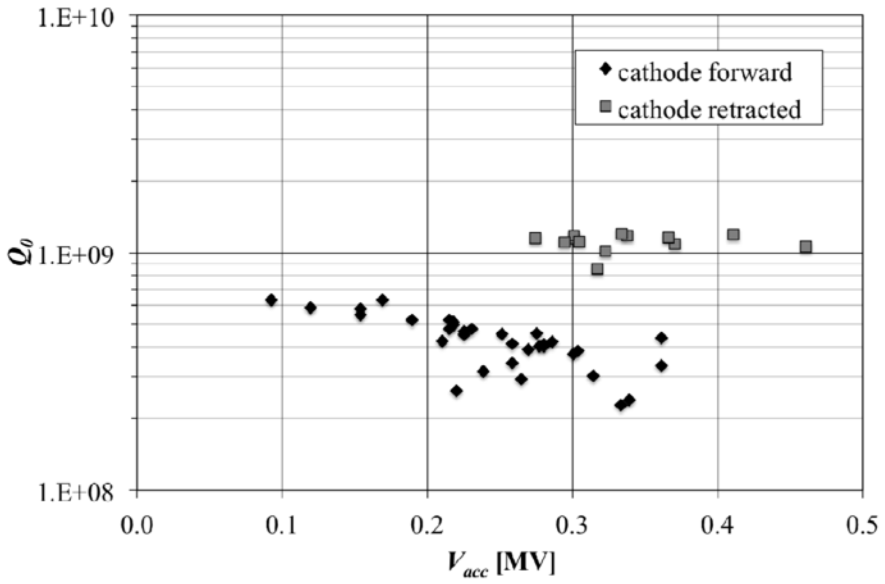


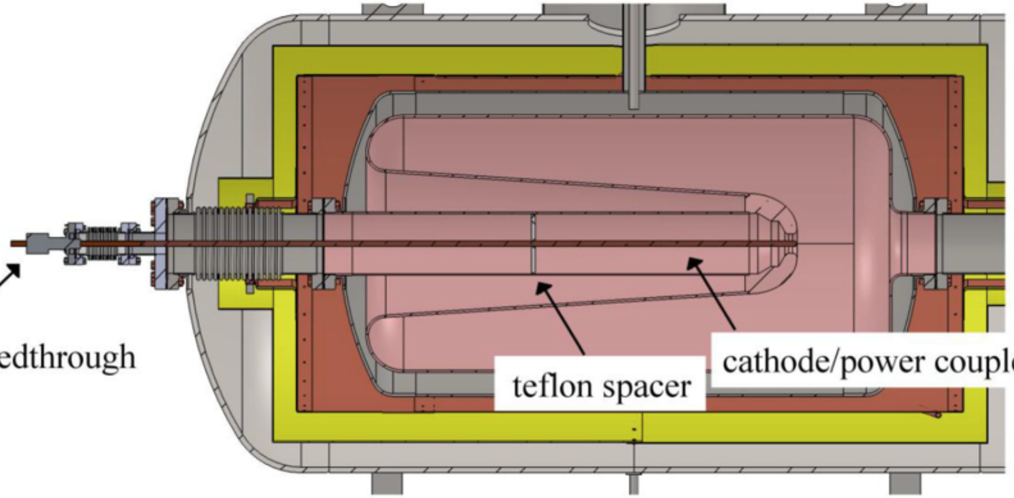
Parameter	Value
Frequency	112 MHz
R/Q (linac definition)	126 Ω
Geometry factor	38.2 Ω
Quality factor Q0 w/o cathode insert	> 3.5×10^9
Operating temperature	4.5 K
E_{pk}/V_{acc}	19.1 m^{-1}
B_{pk}/V_{acc}	36.4 mT/MV
Operating voltage	2 MV

T. Xin *et al.*, Rev. Sci. Instrum. **87**, 093303 (2016)

First Tests

- Due to the size of this cavity, testing in the cryomodule was easier and more efficient than trying to carry out an intermediate test before cryomodule assembly
- The cryomodule's vacuum vessel was made from low carbon steel. The vessel was demagnetized and acted as a magnetic shield.
- Fundamental mode frequency was 113 MHz
- Cooling time was 3.5 hours
- Heat load 7 W
- Observed gap voltage was 0.5 MV limited by allowable radiation levels
- Sensitivity to the helium bath pressure is 10 Hz/mbar

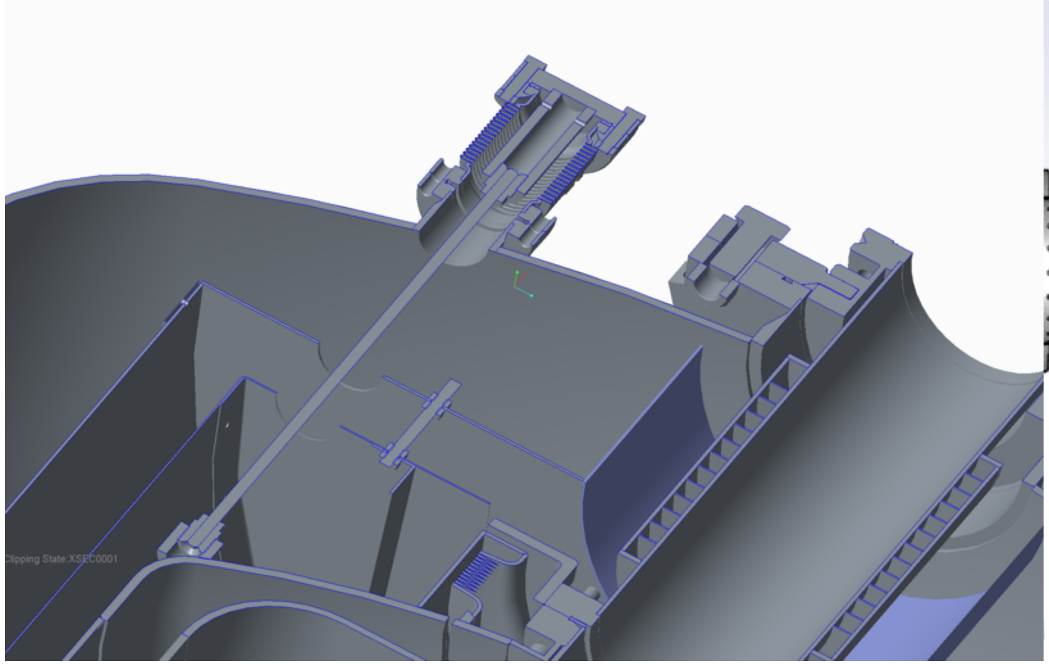


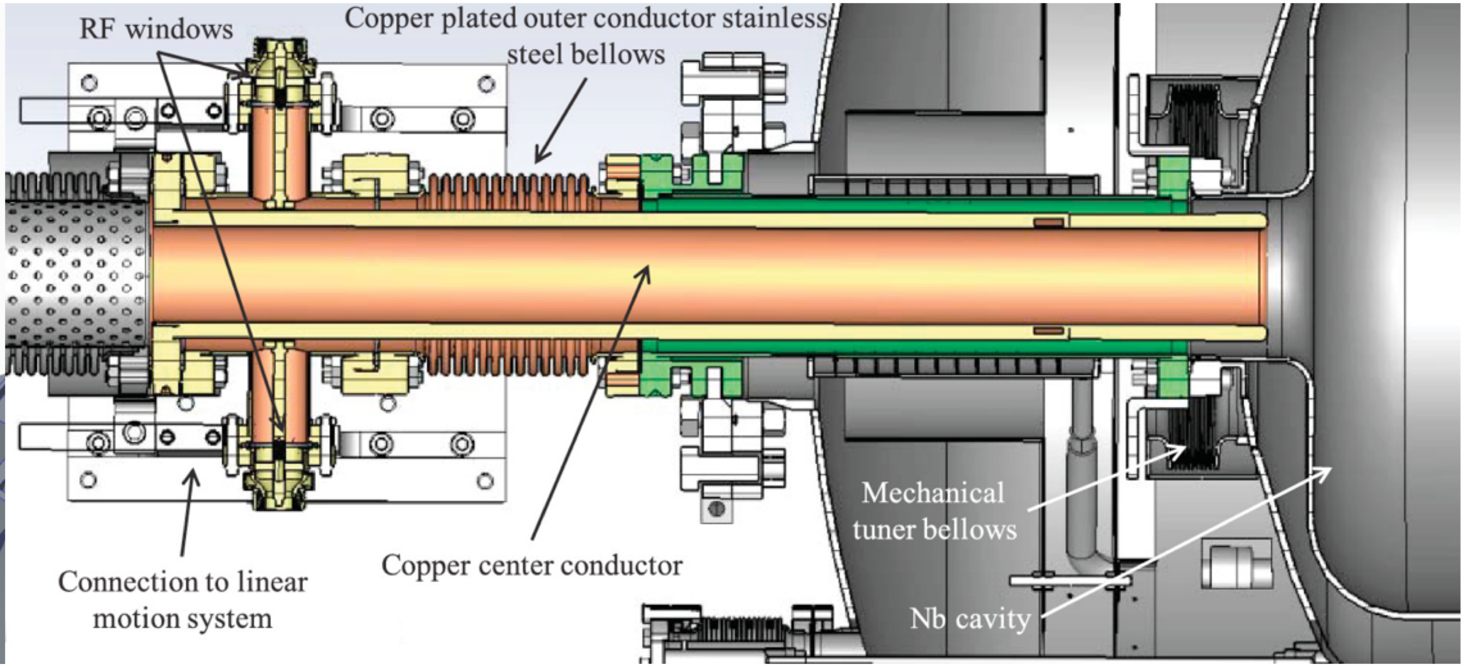


S. Belomestnykh *et al.*, Proc. of SRF'11, MOPO054
S. Belomestnykh *et al.*, Proc of PAC'11, TUP051

Modifications for CeC Experiment

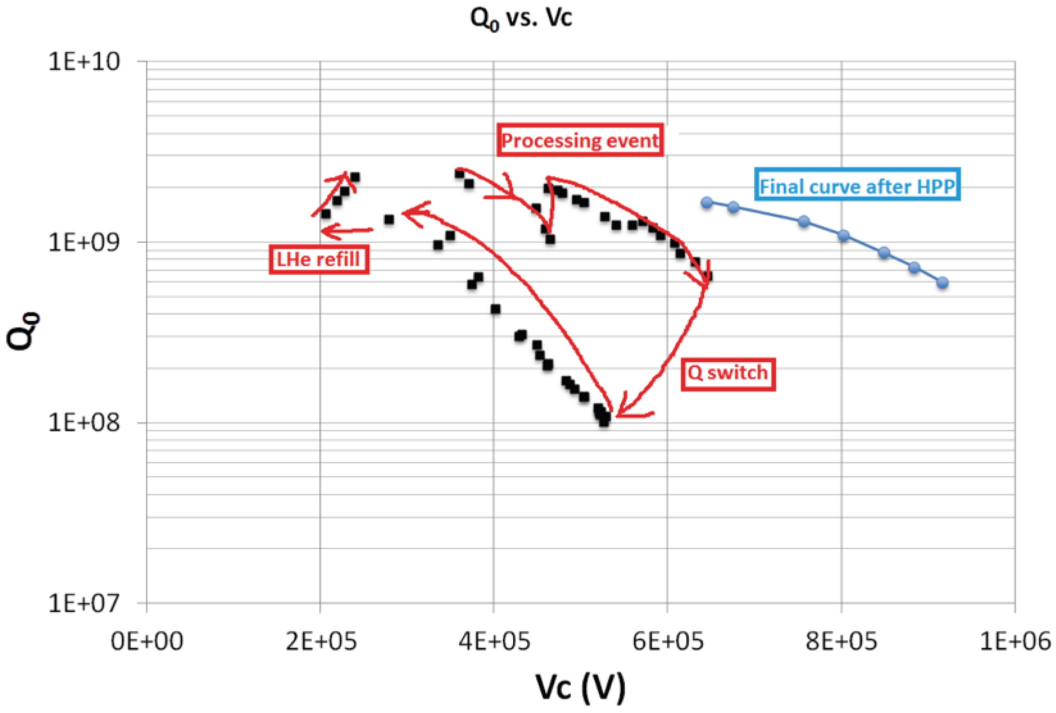
- The low-carbon-steel vacuum vessel was replaced with the stainless steel
- The vacuum vessel has flanges on both ends to allow easy access to inside of the cryostat
- Cryogenic stack was modified to interface with the BNL He refrigeration system
- Two manual coarse tuners provided 80 kHz tuning range to match the harmonic of the RHIC revolution frequency
- Fine tuning is achieved with movable FPC (tuning range >3 kHz)

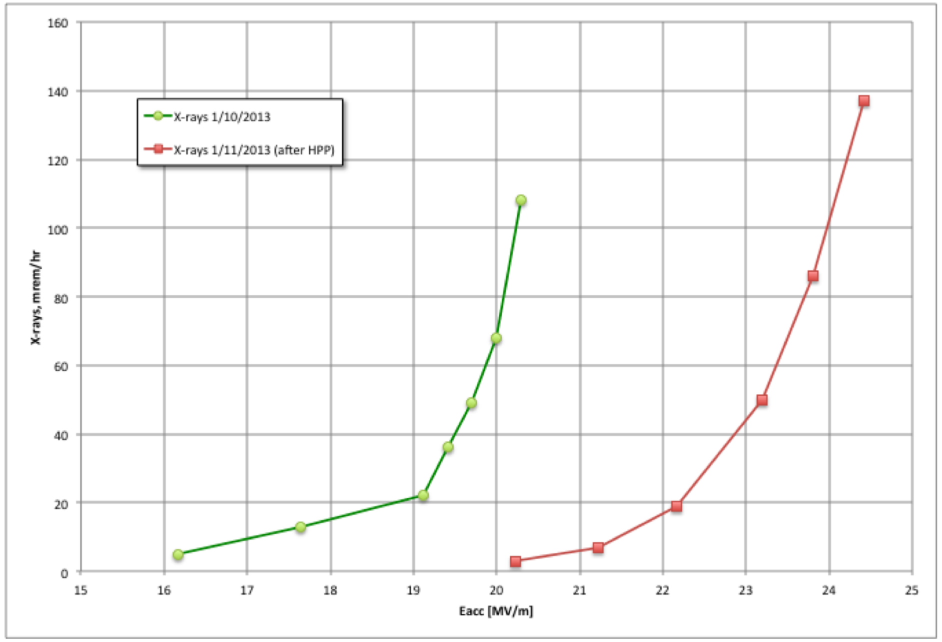




Conditioning

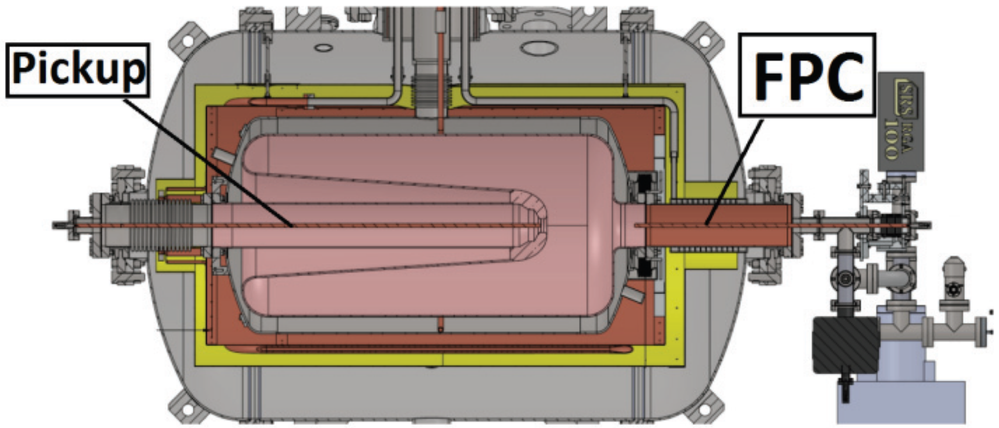
The modified gun was cold tested again at Niowave in December of 2012 and February of 2013. During the test we have encountered multipacting zones at very low fields, which were processed only after we modified the RF input coupler to increase its coupling. Black squares show the processing which includes the activation of emitter and the consequent Q switch. Blue dots show the final Q_0 vs. V_c curve after the high power pulse process.
After processing the gap voltage reached 0.92 MV in CW mode, only limited by the radiation concern at Niowave test facility.



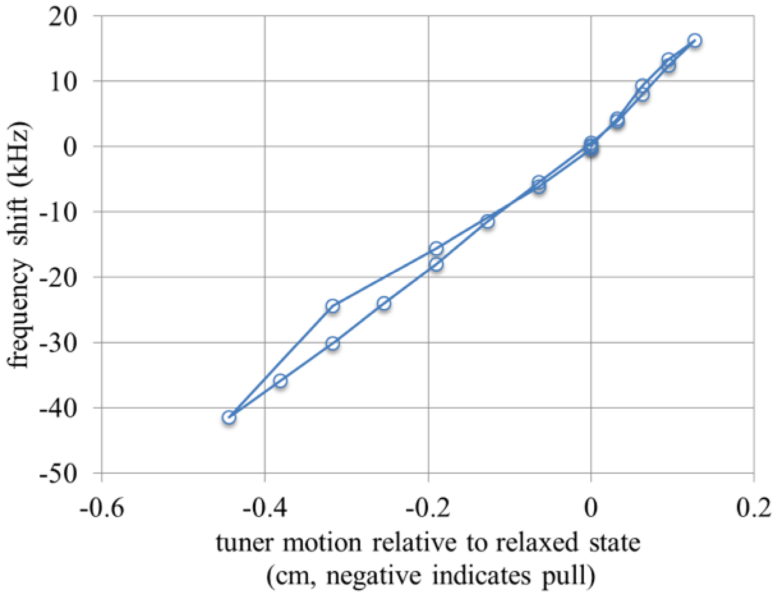


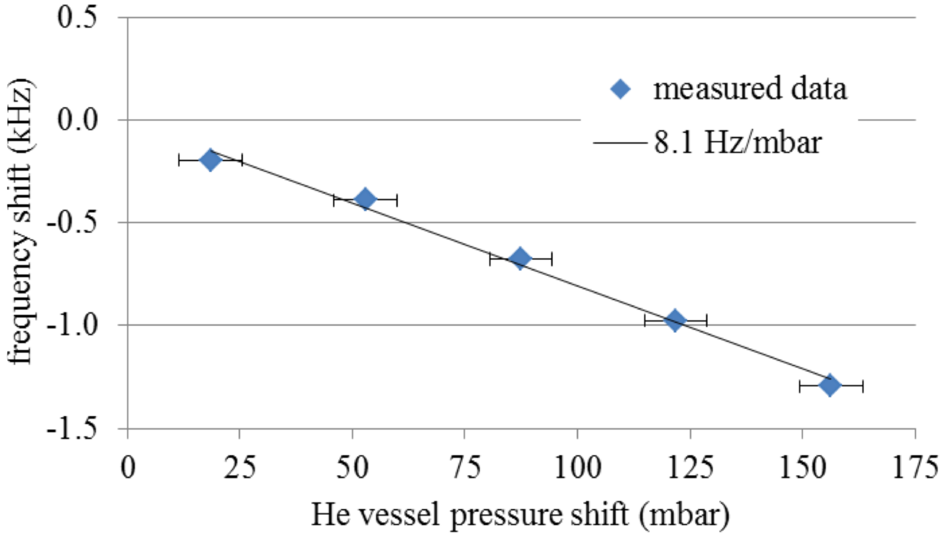
S. Belomestnykh *et al.*, Proc. of SRF'13, MOP016
S. Belomestnykh, Proc. of SRF'13, MOIOB03

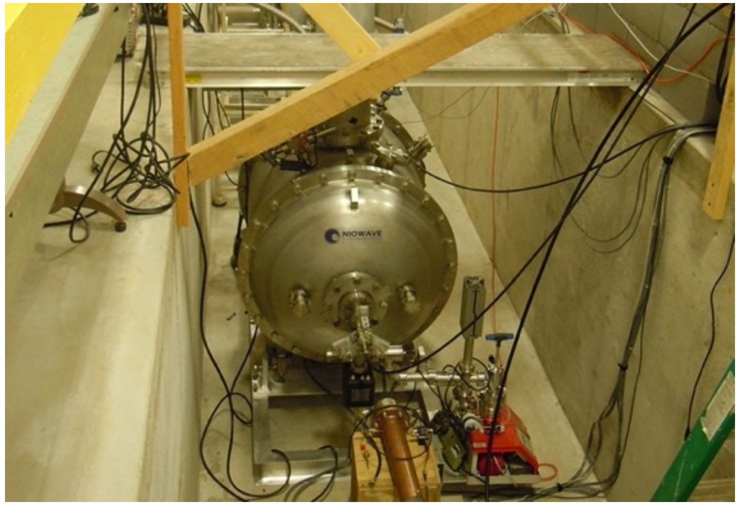
Tests after Modification



A ring down measurement of 3.2 dB in 4.7 seconds
Measured low-field Q exceeded $4{\times}10^9$ (no coupler correction)
Frequency sensitivity to pressure is 8 kHz/mbar

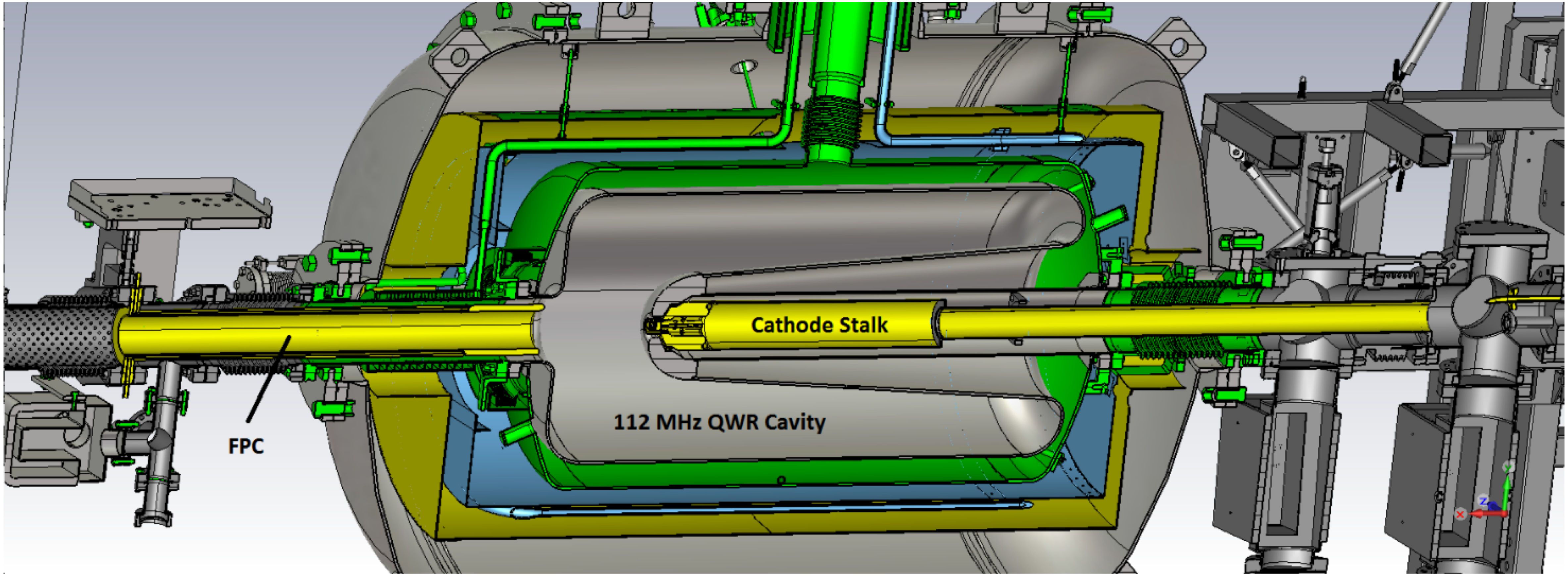




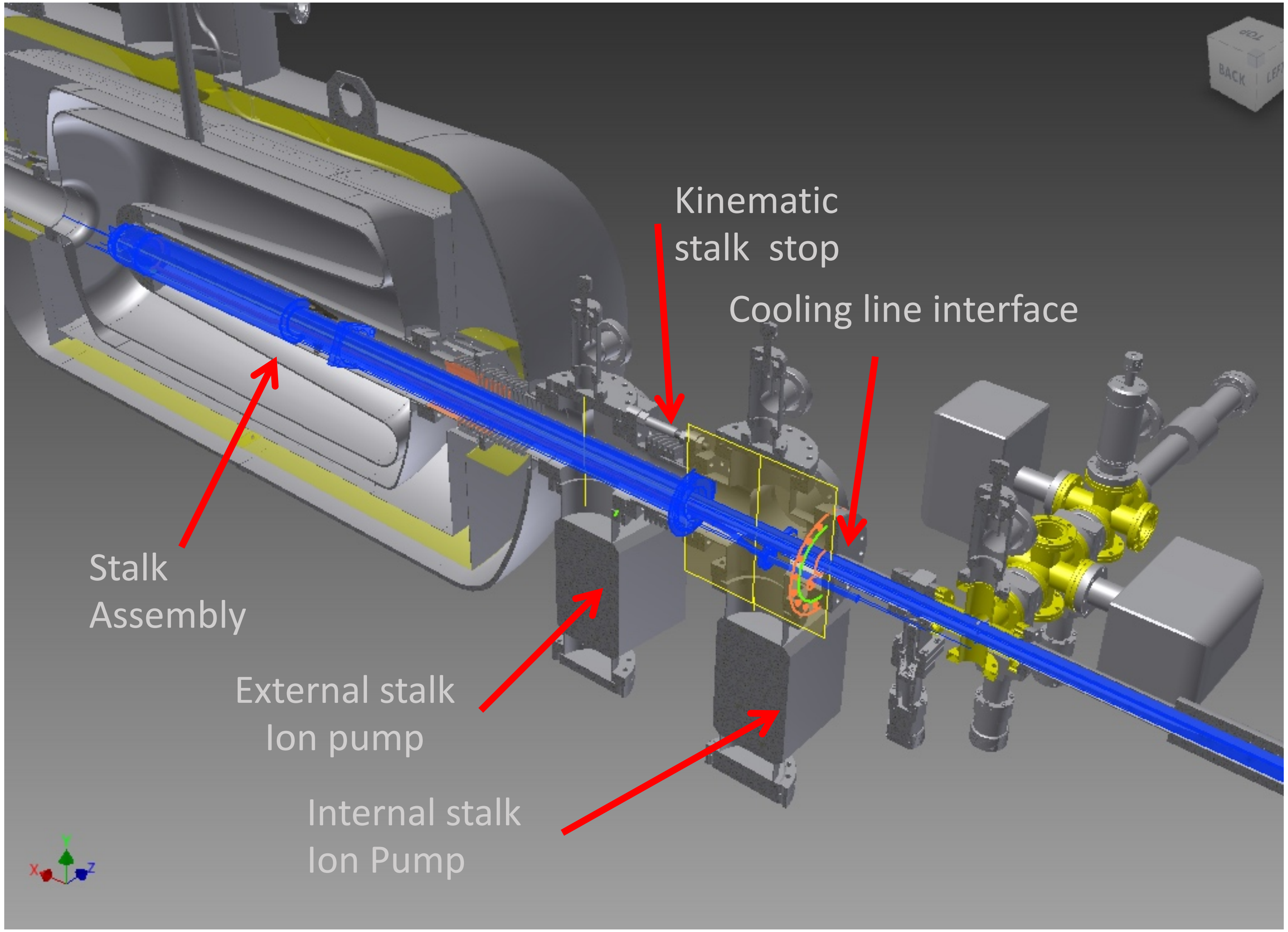


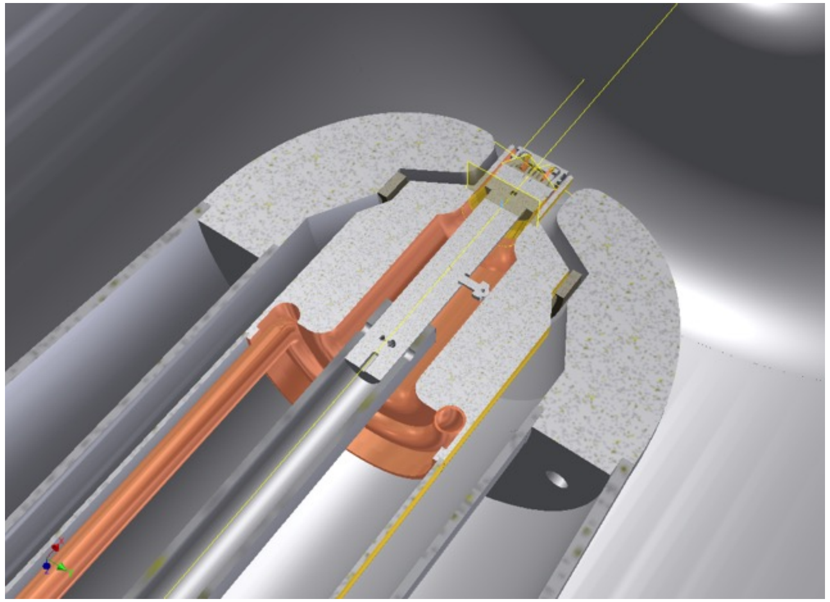
T. Xin *et al.*, Proc. of PAC'13, THPAC35

Cross Section of the Installed Gun



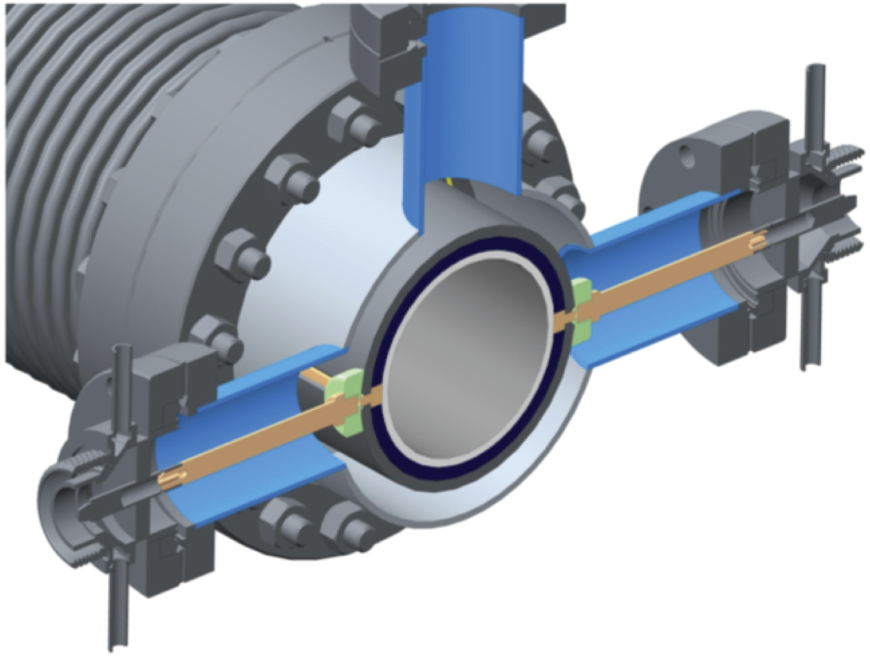
Cathode Injection System Components

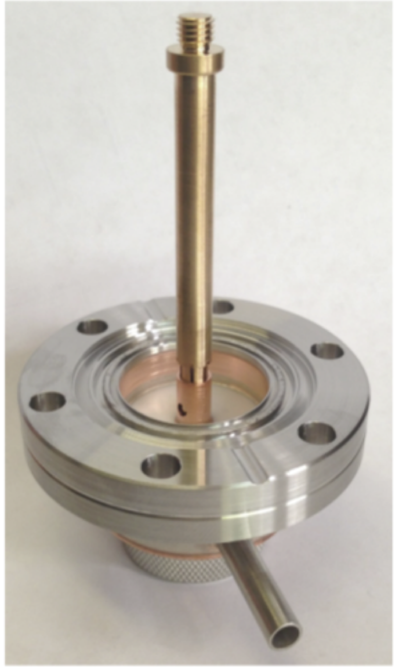


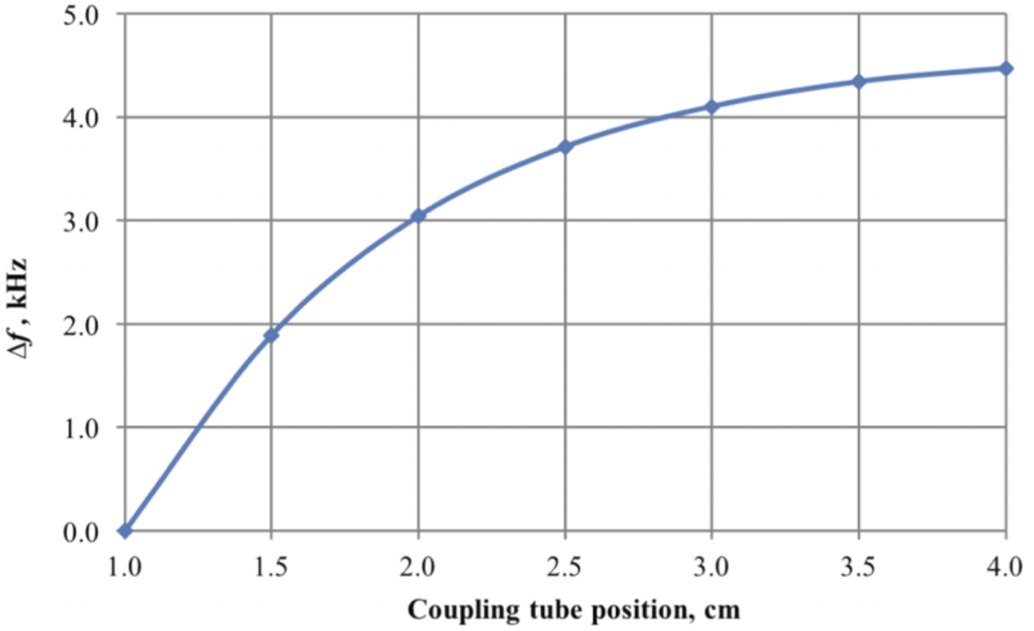


Cathode and stalk position can be adjusted inside the cavity nose for beam dynamics

Fundamental Power Coupler





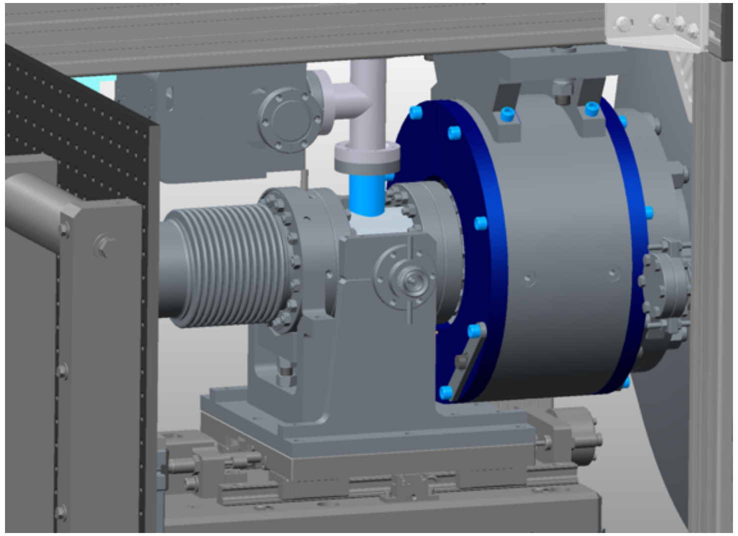


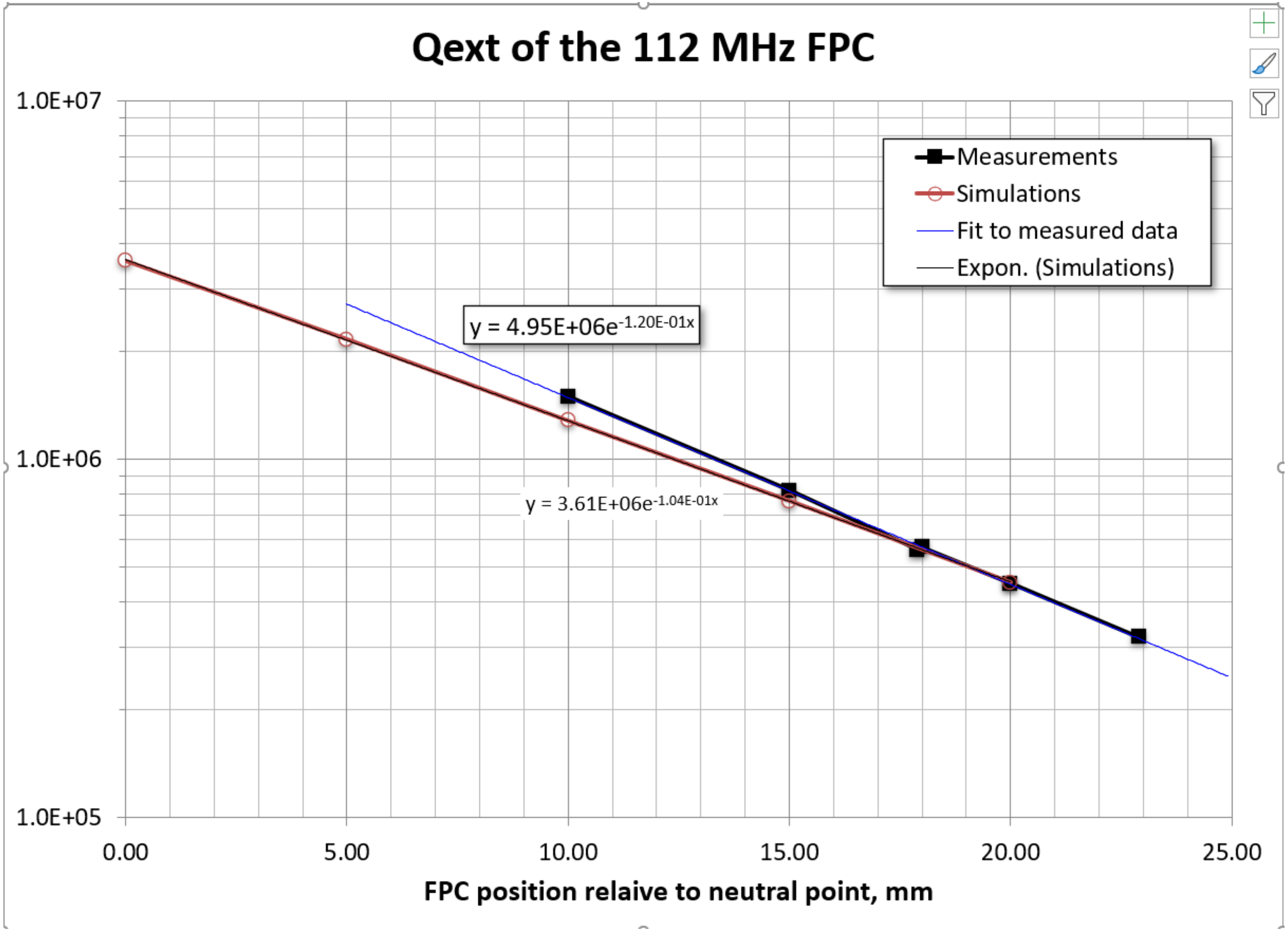
Movable fundamental power coupler serves two purposes:

- Fine frequency tuning (full range 4.5 kHz)
- Coupling adjustment

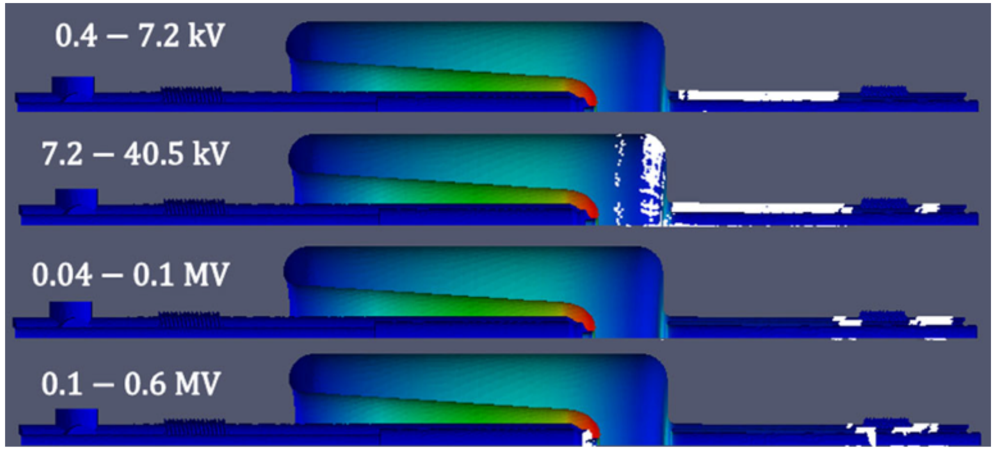
After initial tests and selecting operating frequency the manual tuner was adjusted that nominal FPC position corresponds to the optimal coupling

J.C. Brutus *et al.*, Proc. of PAC'13, WEPAC07



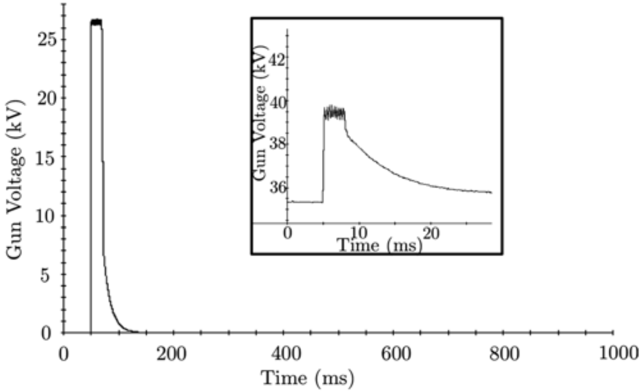

Qext of the 112 MHz FPC
1.0E+07
1.0E+06
1.0E+05
0.00
5.00
10.00
15.00
20.00
25.00
FPC position relaive to neutral point, mm
Measurements
Simulations
Fit to measured data
Expon. (Simulations)
y = 4.95E+06e-1.20E-01x
y = 3.61E+06e-1.04E-01x

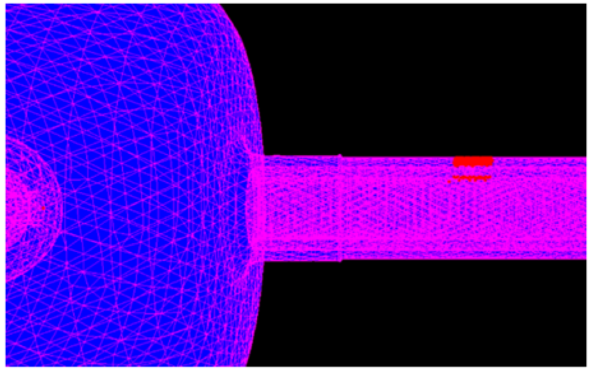
Multipacting

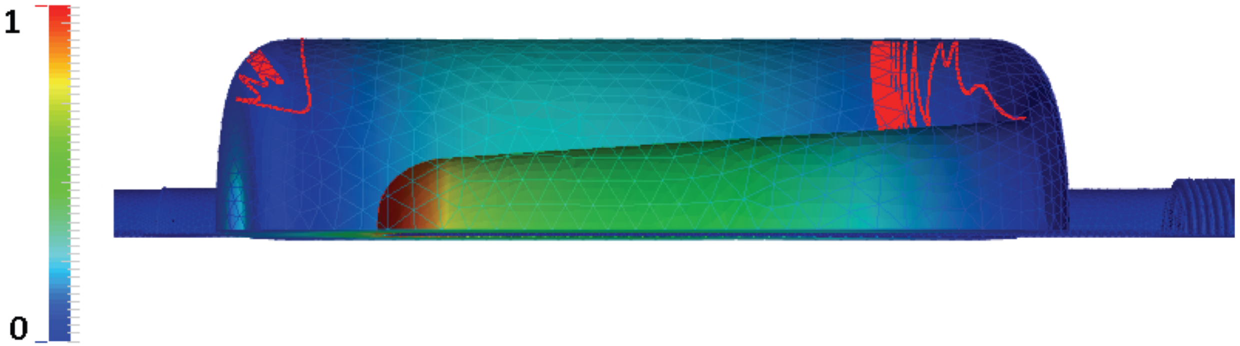


Areas of the gun affected by multipacting (shown in white). Primary electrons are emitted from the surface of the FPC.

T. Xin *et al.*, Proc. of PAC'13, THPAC13
T. Xin *et al.*, Proc. of IPAC'15, TUPMA048
I. Petrushina *et al.*, PRAB 21, 082001

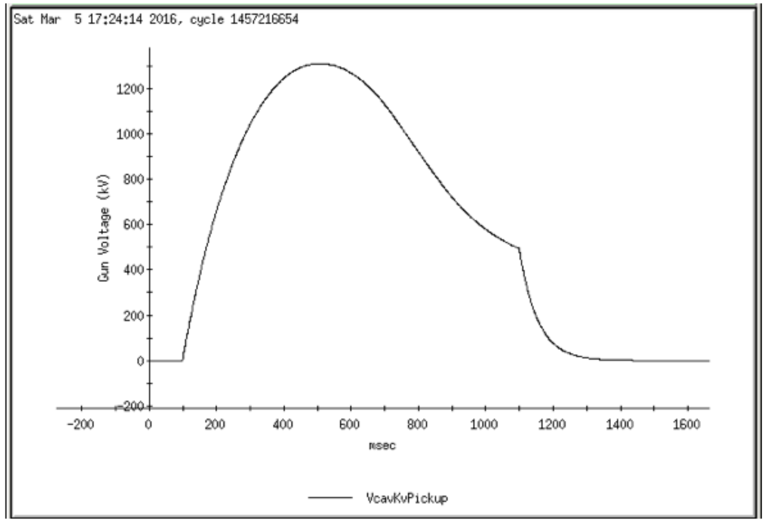




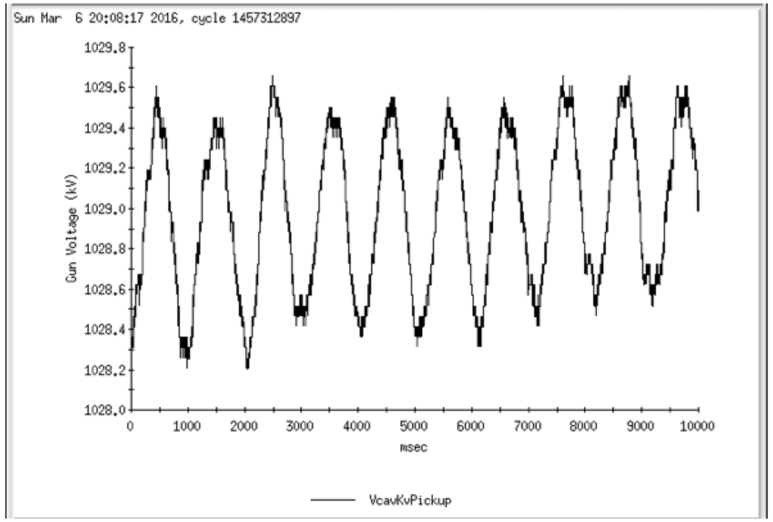


Trajectories of electrons at two multipacting sites (red lines). The left one is under 29 kV gap voltage and the right one appears at 40 kV gap voltage. The color scale indicates the relative strength of electric field.

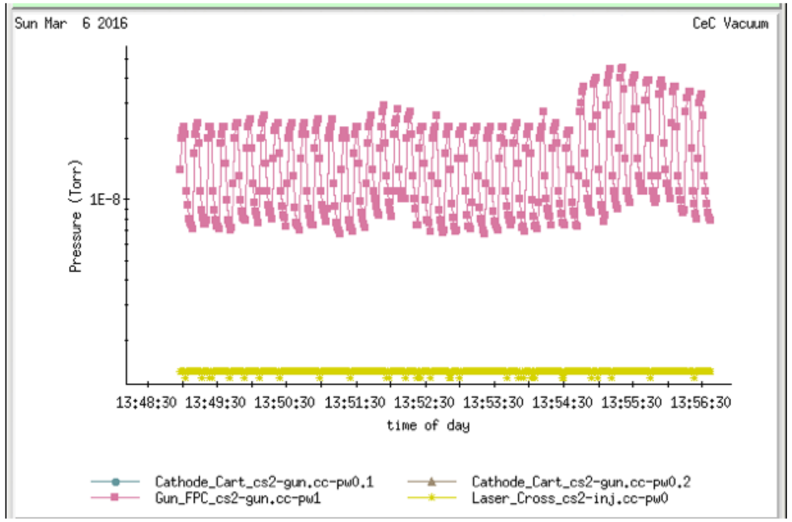
Initial Conditioning



Gun voltage pulse during conditioning

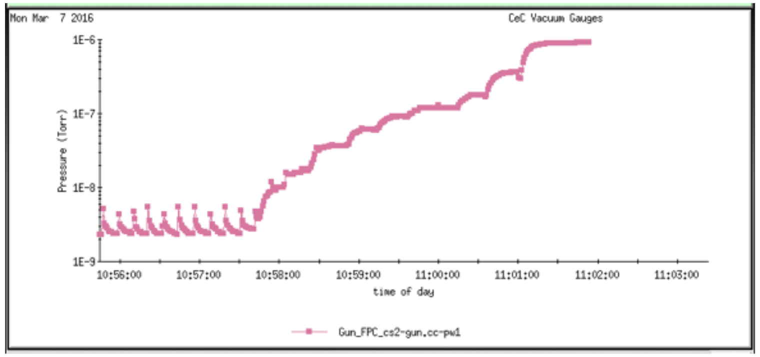


Voltage oscillations due to the thermo-acoustic instability



Vacuum oscillation in the FPV during vacuum conditioning

Cavity conditioning was performed with pulsed vacuum operation followed by condition with helium at 10^{-6} Torr pressure. It took about a month from start with pulse conditioning to generate first electrons.



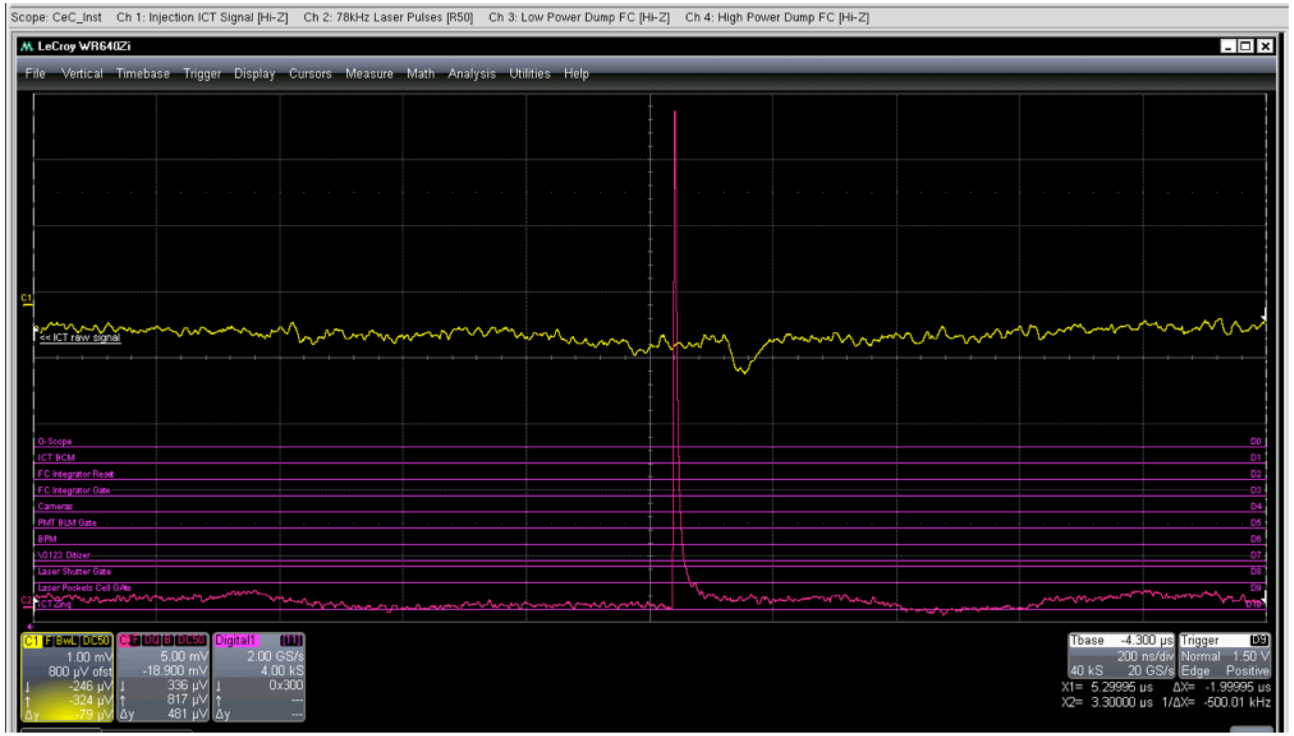
Pressure during helium conditioning

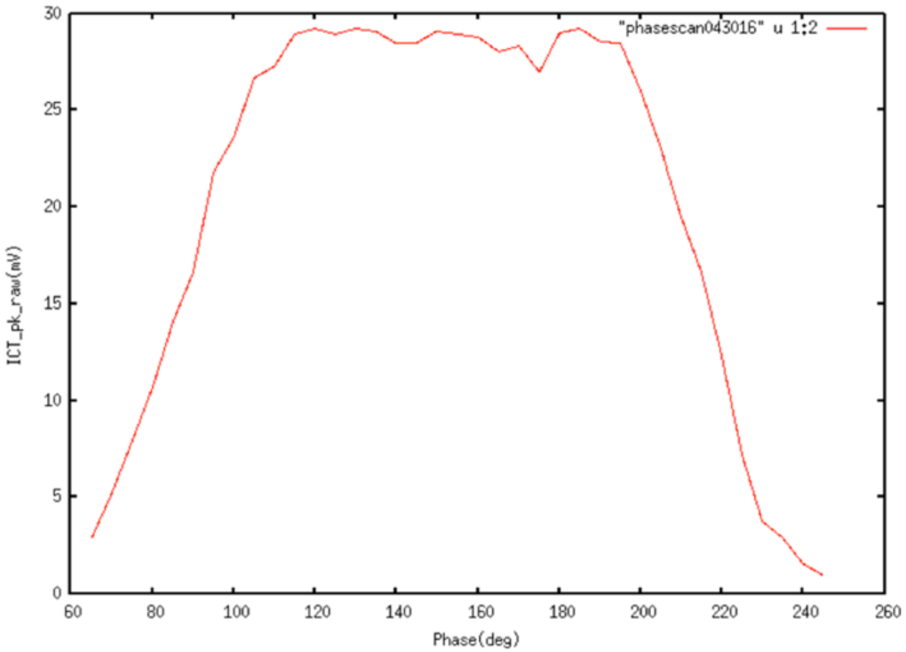
S. Belomestnykh *et al*., Proc. of IPAC’15, WEPWI049

S. Belomestnykh *et al*., Proc. of SRF’15, THPB058

I. Petrushina et al., Phys. Rev. Accel. and Beams, **25**, 092001 (2022)

One of the First Beams

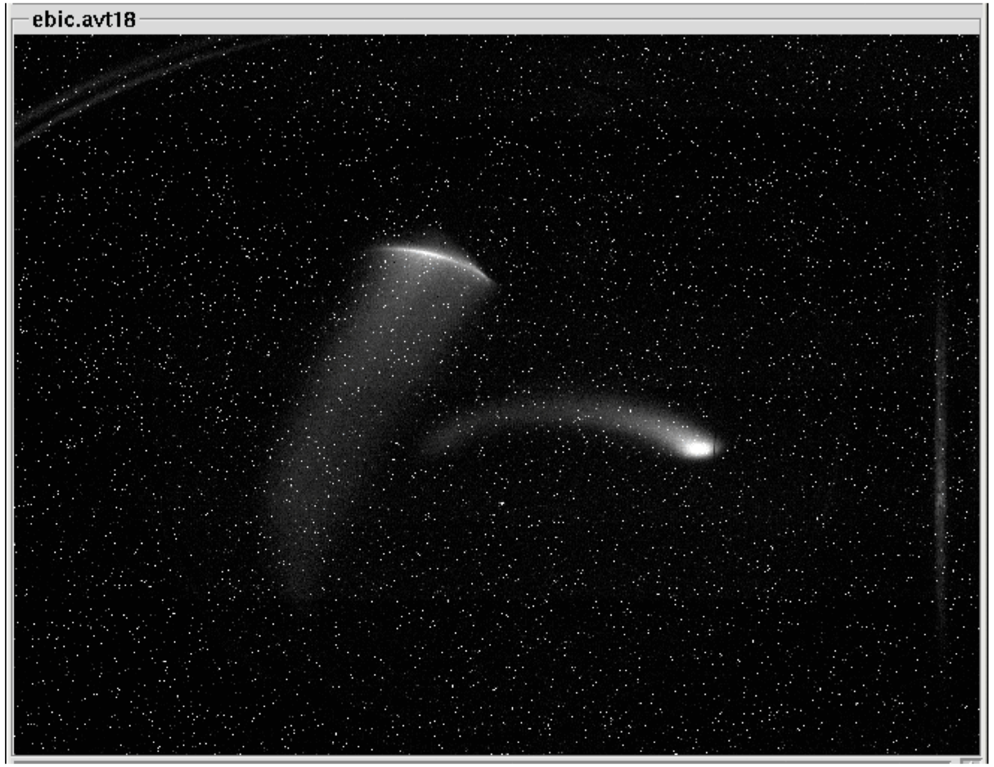


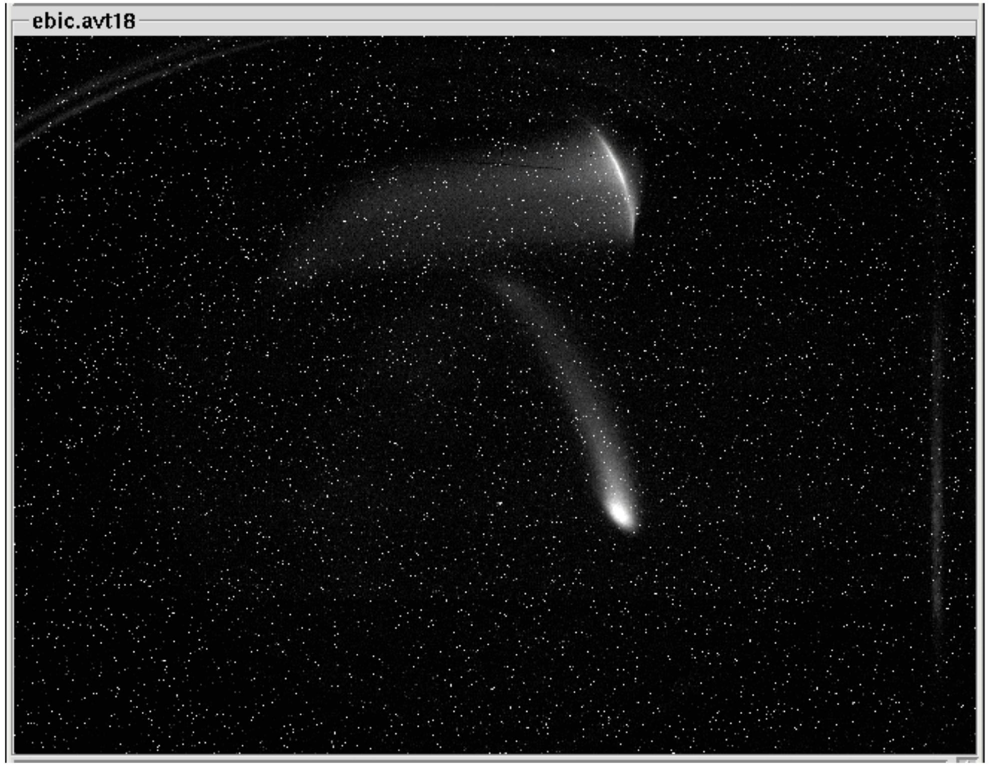


After gun cavity conditioning we have inserted cathode and obtained the first electron beam.
We performed laser phase scan to synchronize laser and gun RF.

I. Pinayev *et al*., Proc. of FEL’15, TUD03
I. Pinayev *et al*., Proc. of NAPAC’16, WEPOB59

First Energy Measurement with Solenoid





April 21 2016
54 degree 1.2 MV
7 g/s helium consumption

We have tried to measure the beam energy using trims but found that measurements inconsistent. Therefore we developed new method based on rotation of the plane of motion by solenoid.

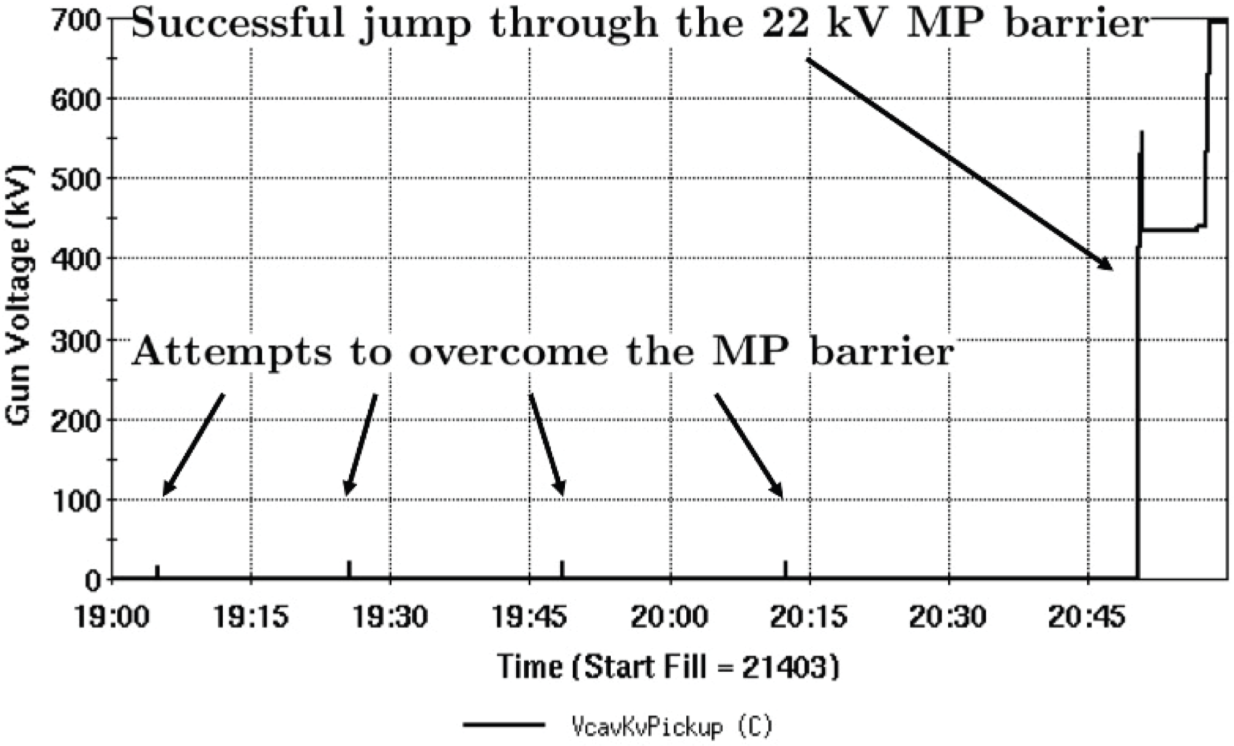
I. Pinayev *et al*., Rev. Sci. Instrum. 84,

Breaking through Multipacting Barriers

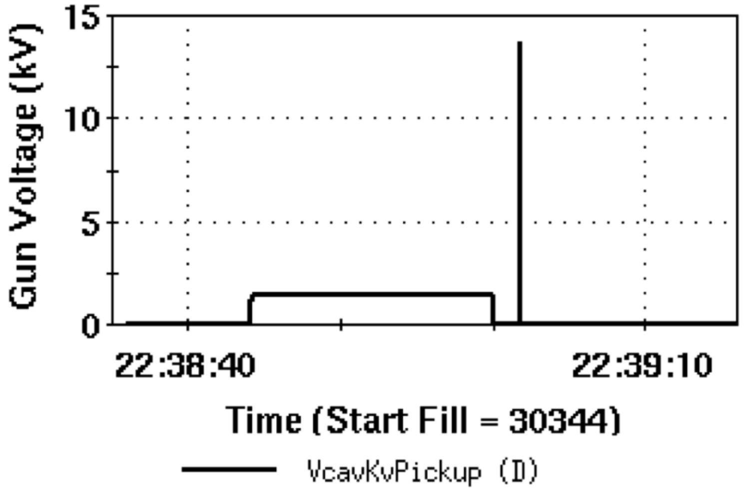
The outgassing during multipacting damages the QE of photocathode. Therefore, we have developed and later automated procedure to overcome the multipacting barriers:

- Close valve to block light
- Turn off solenoid current
- Fully insert FPC (low external Q)
- Drive the cavity at low power below the first multipacting barrier (around 2 kV) for tuning PLL
- Apply short full power pulse. If the voltage exceeds the highest multipacting barrier then full power stays, otherwise it drop to zero.
- Slowly withdraw FPC with gradual decrease of the drive power
- Turn on IQ loop

Increase of PA power from 2 kW to 4 kW also helped

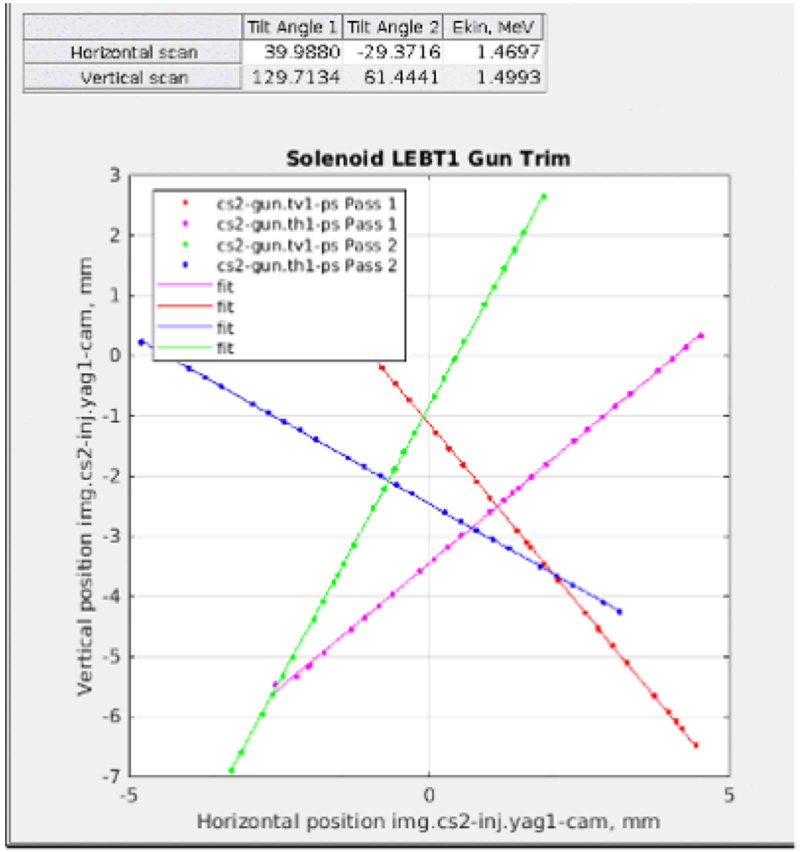


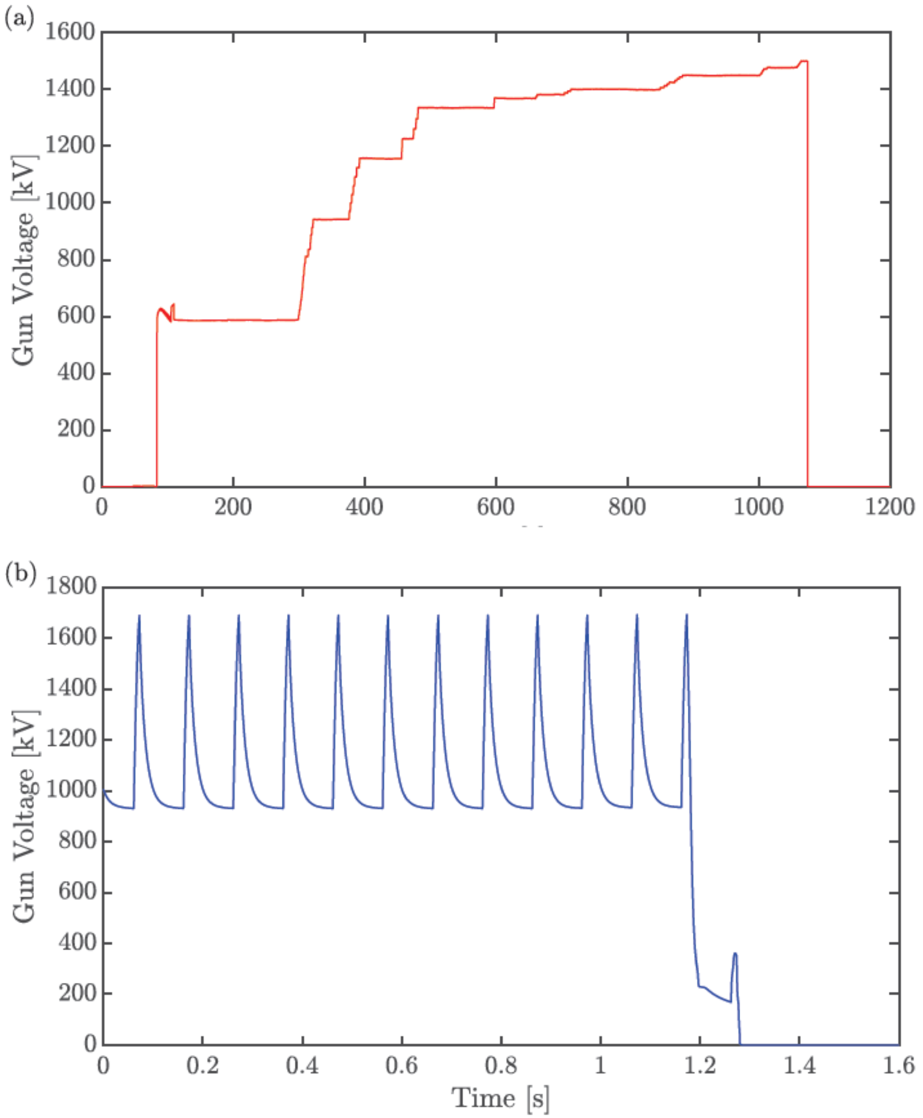
I. Petrushina *et al*., Proc. of IPAC’19, TUPTS079



Achieved Performance

Parameter	Value
CW Voltage	1.5 MV
Pulsed voltage	1.7 MV
Bunch charge	19.7 nC
Idle He consumption	1.4 g/s
1.35 MV He consumption	2.5 g/s
Microphonics ΔF	5-10 Hz



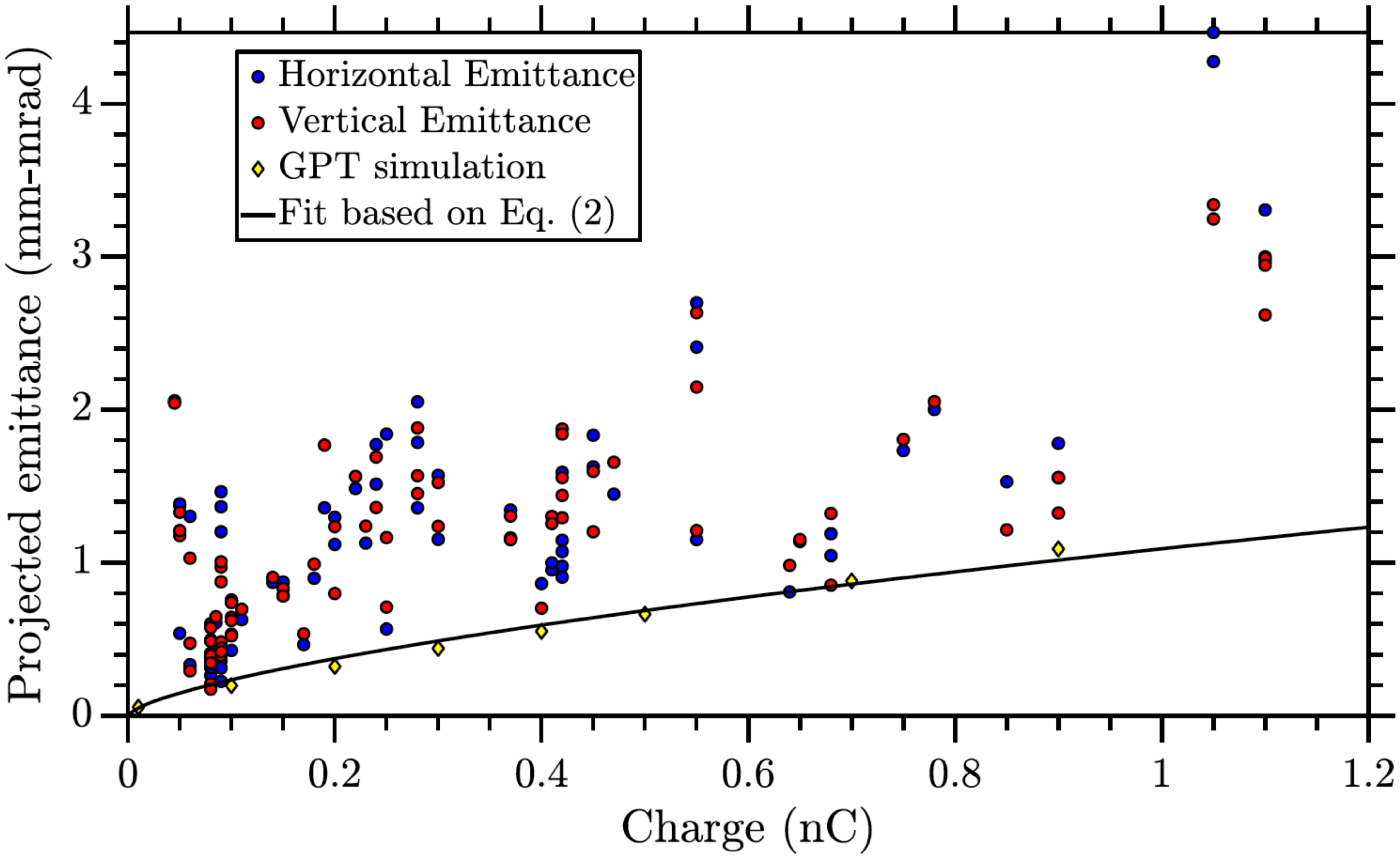


I. Petrushina *et al*., Phys. Rev. Lett., vol. 124, no. 24, p. 244801

I. Petrushina *et al*., Proc. of IPAC'21, WEPAB138

E. Wang *et al*., Scientific Reports, vol. 11, no. 1, pp. 1–9, 2021.

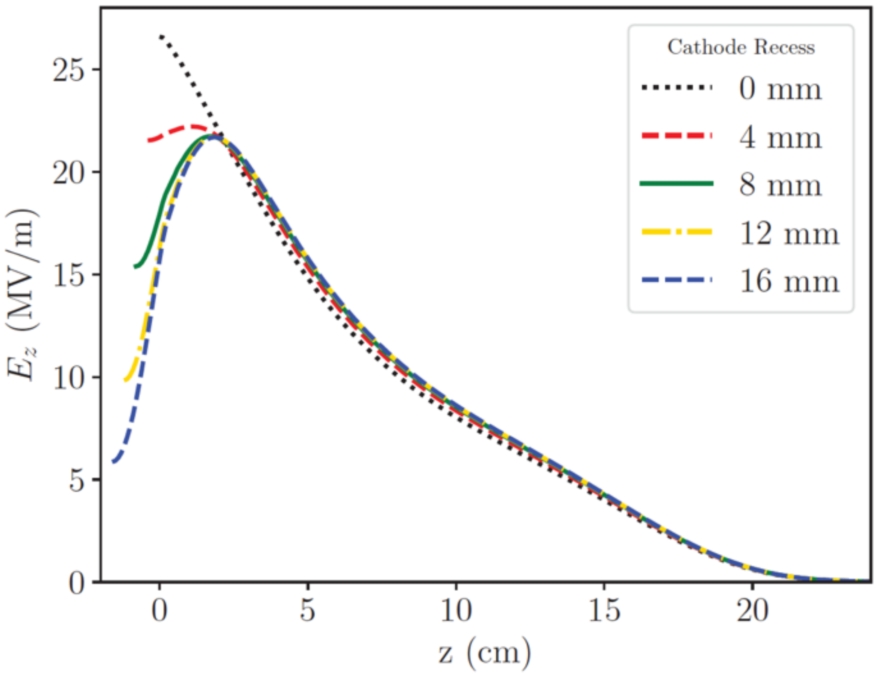
Emittance

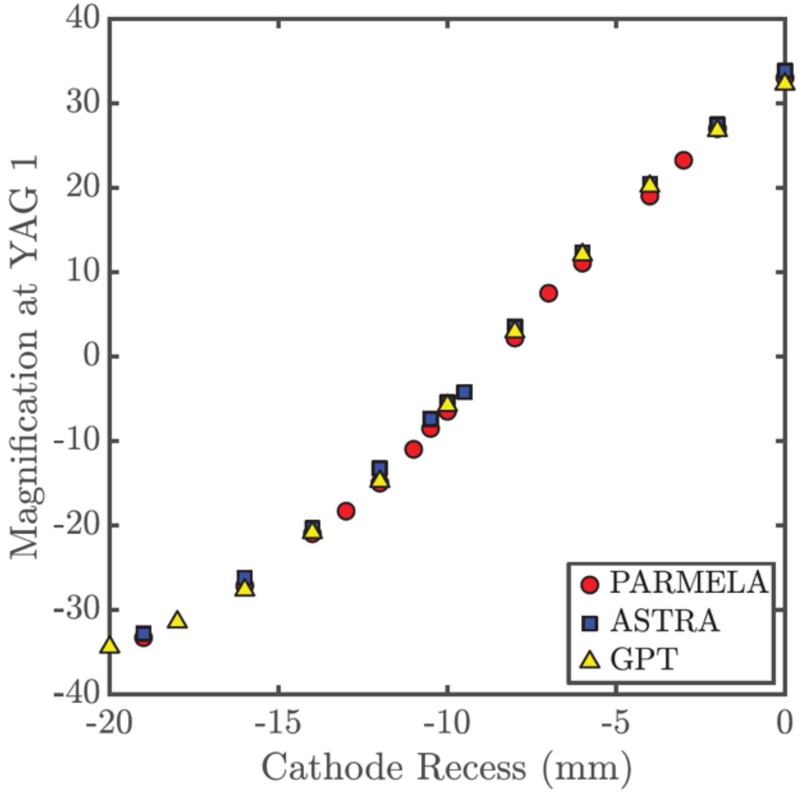


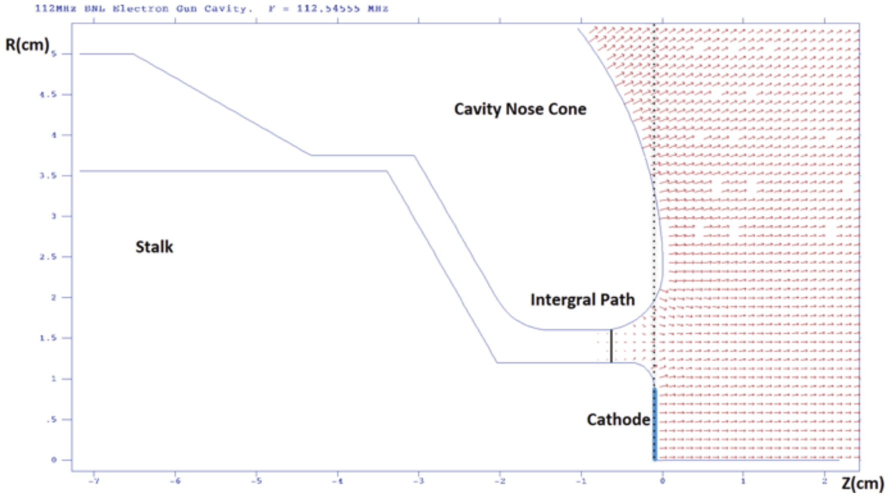
$$\varepsilon_n \propto \frac{\sqrt{E_{MTE}}}{E_{em}} \left(\frac{q}{\Delta t}\right)^{2/3}$$

I. Petrushina *et al.*, Phys. Rev. Lett, **124**, 244801

Measuring Cathode Recess





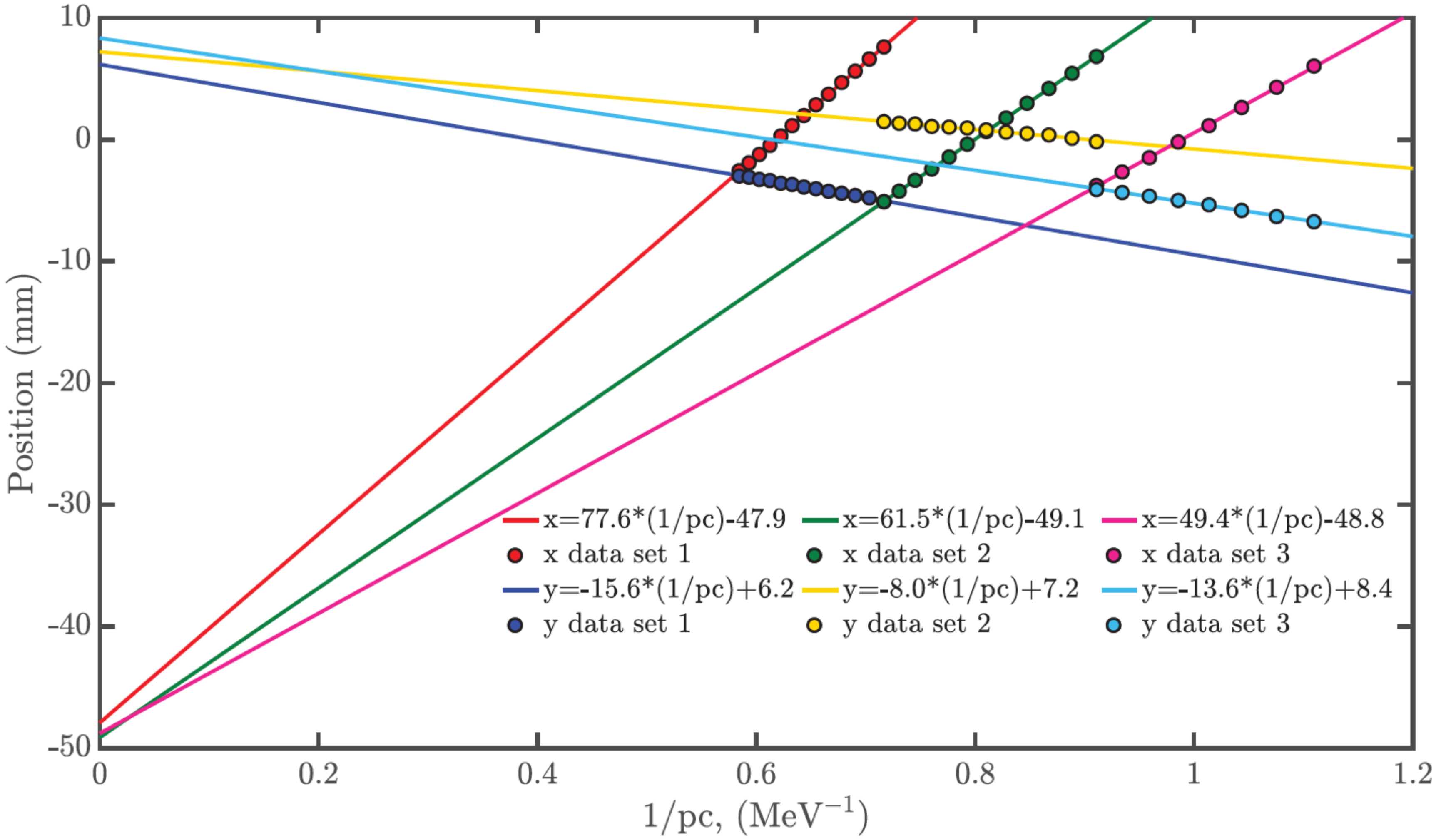


Distribution of the axial electrical field depends on the location of the cathode vs. cavity nose as well as transverse field and, hence, focusing in the gun.

We scan laser spot position on the cathode and measure electron beam position on the profile monitor to extract information on the cathode location.

I. Petrushina *et al.*, Proc. of IPAC’19, WEPRB094

Measuring Gun Axis Tilt



We found that the electron beam leaves the gun at substantial angle.
The measurements were performed varying the gun voltage and measuring beam position on the profile monitor.
Extrapolating beam position for infinite beam energy provides information on the beam angle.

I. Petrushina *et al.*, Proc. of IPAC’19, WEPRB094

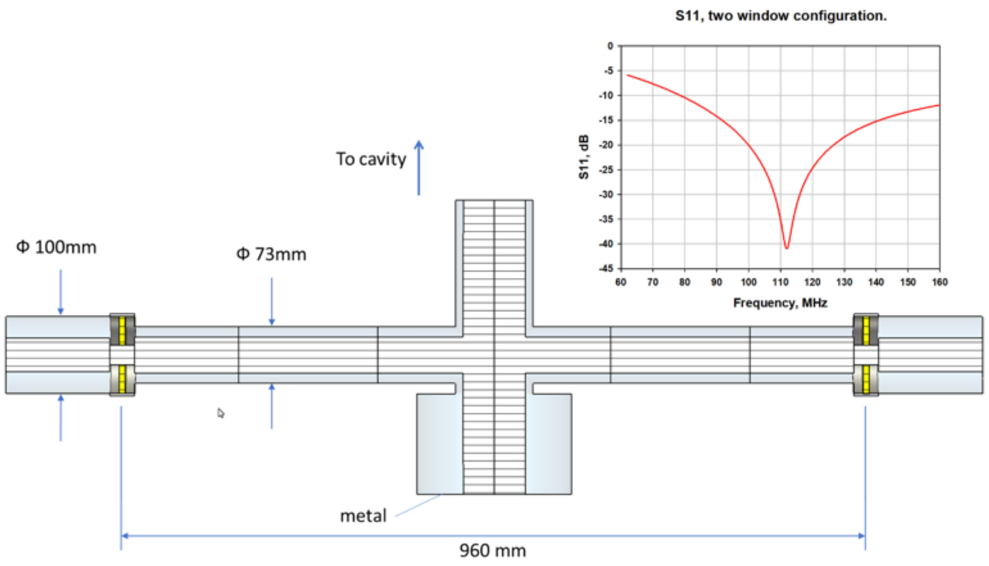
Observations

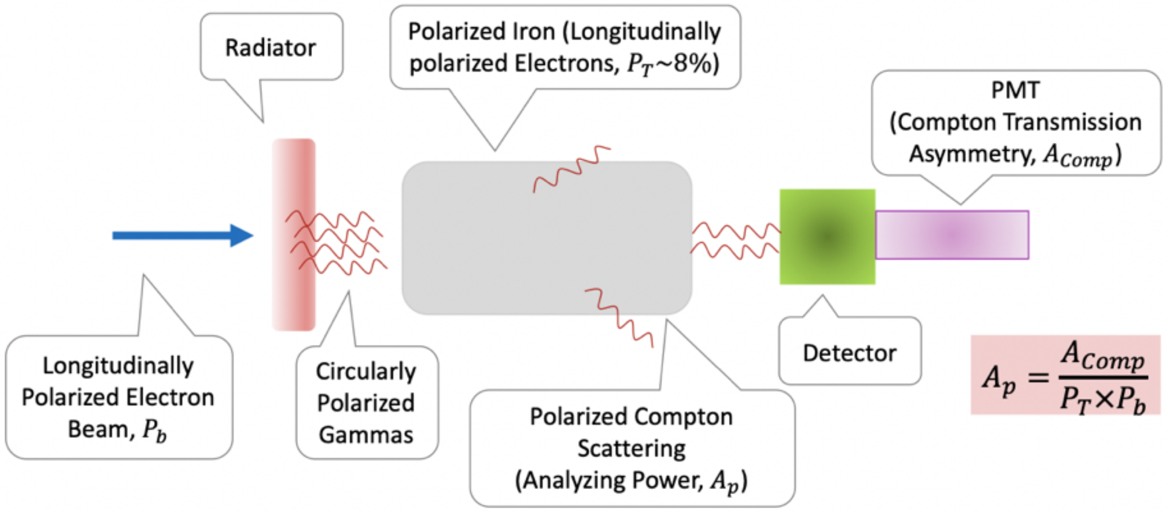
- Cooling of the FPC with effluent helium leads for extension of the cold region when gun is at high voltage. After voltage drop cooling rate decreases and the gases trapped on the surface are being released making sometimes hard to break through the multipacting barrier.
- We also observed increase in QE after turning on electron beam (from the very beginning)
- Contamination of the gun with cathode material can be eliminated by warming up the cavity (released gases neutralize the active components)

Future Plans

There is three-prong proposal for the future development of the SRF gun:

- Development of the in situ gun conditioning
- Demonstration of 1-10 mA CW current
- Operate GaAs cathode for the polarized electron source





I. Petrushina *et al.*, Proc. of IPAC'21, WEPAB138

Hardware modifications:

- Added high-power dump in the diagnostics beamline
- Modified cathode insertion part to achieve high vacuum level required for the GaAs cathode
- Added focusing solenoid for transport of the high-charge beam
- Replaced laser allowing up to 5 MHz pulse rate
- Development of the new 100 kW coupler to generate up to 100 mA
- Development of Compton transmission polarimeter for polarized electron beam