Dark current measurements at REGAE

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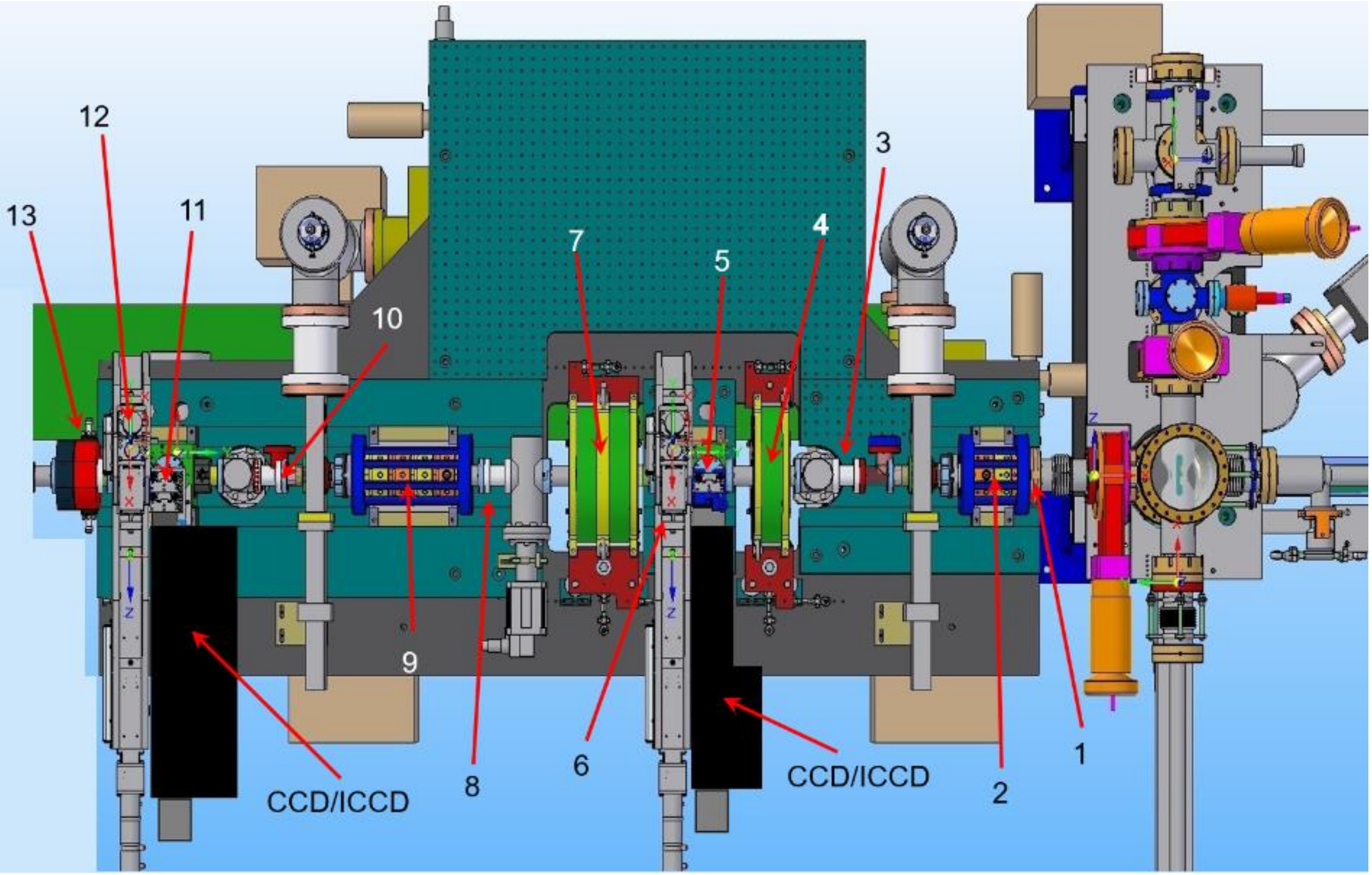
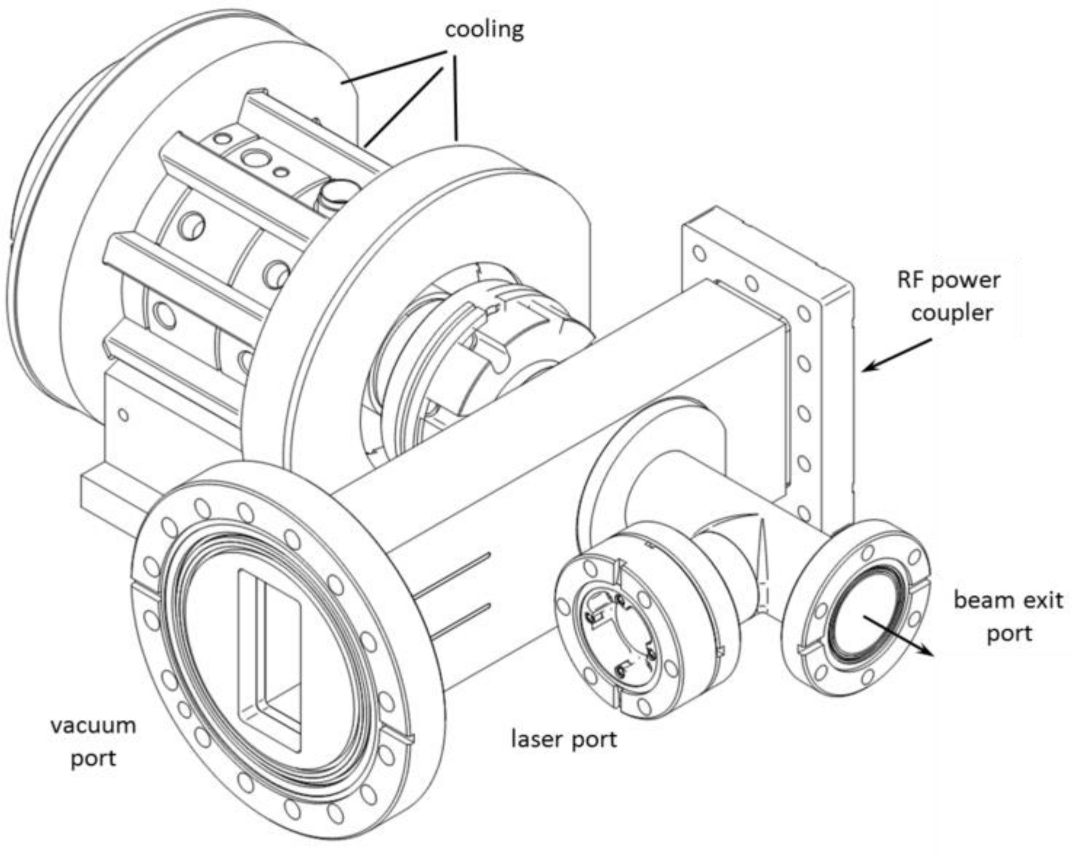
REGAE injector part, almost no change during 2017 upgrade

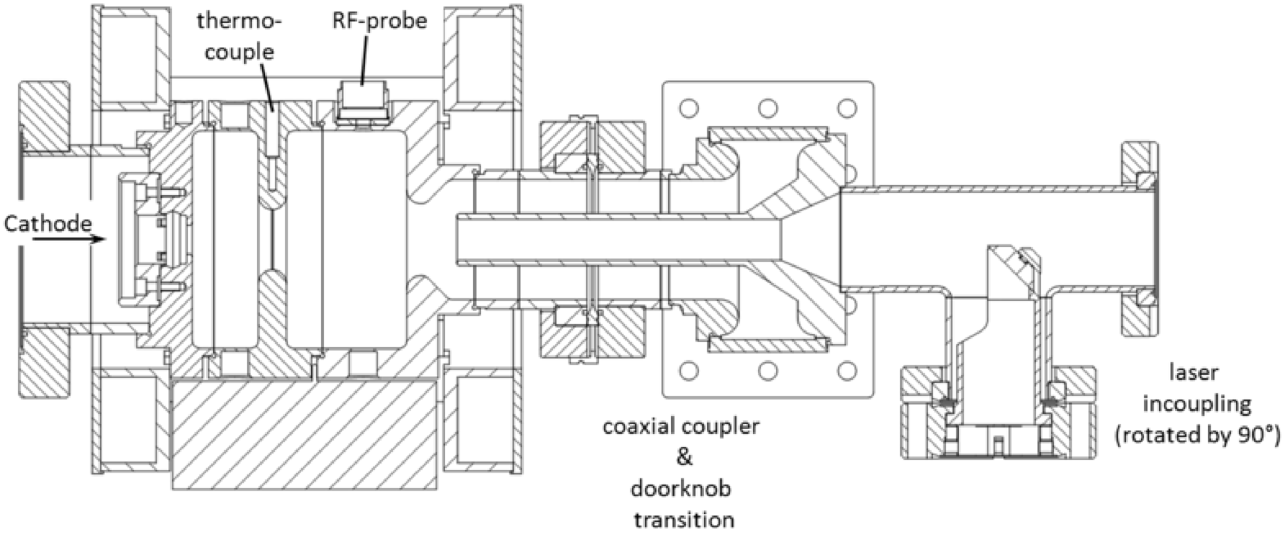
No.	Beam-line element	Position (mm)
1	Cathode	0
2	Gun center	41
3	Steerer pair 1	352
4	Solenoid 1	550
5	Faraday cup and Profile monitor screen	693
6	Collimator 1	773
7	Solenoid 2	930
8	Steerer pair 2	1192
9	Buncher	1360
10	Steerer pair 3	1654
11	Faraday cup and profile monitor screen	1899
12	Collimator 2	1979
13	Cavity monitor	2069



REGAE gun design



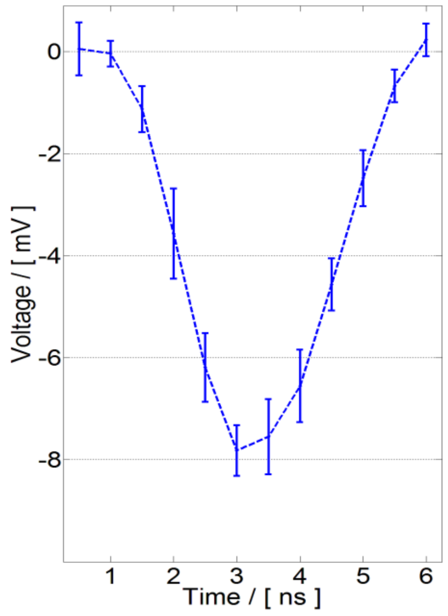
The REGAE rf gun is derived from the rf gun family developed for FLASH, PITZ and XFEL. REGAE operates at S-band frequency (3 GHz), while the FLASH rf gun is designed for L band (1.3 GHz) thus the cavity dimensions have been scaled accordingly.
The laser beam is coupled in with an in-vacuum mirror through the inner axis of the coaxial coupler through which also the electrons leave the gun.



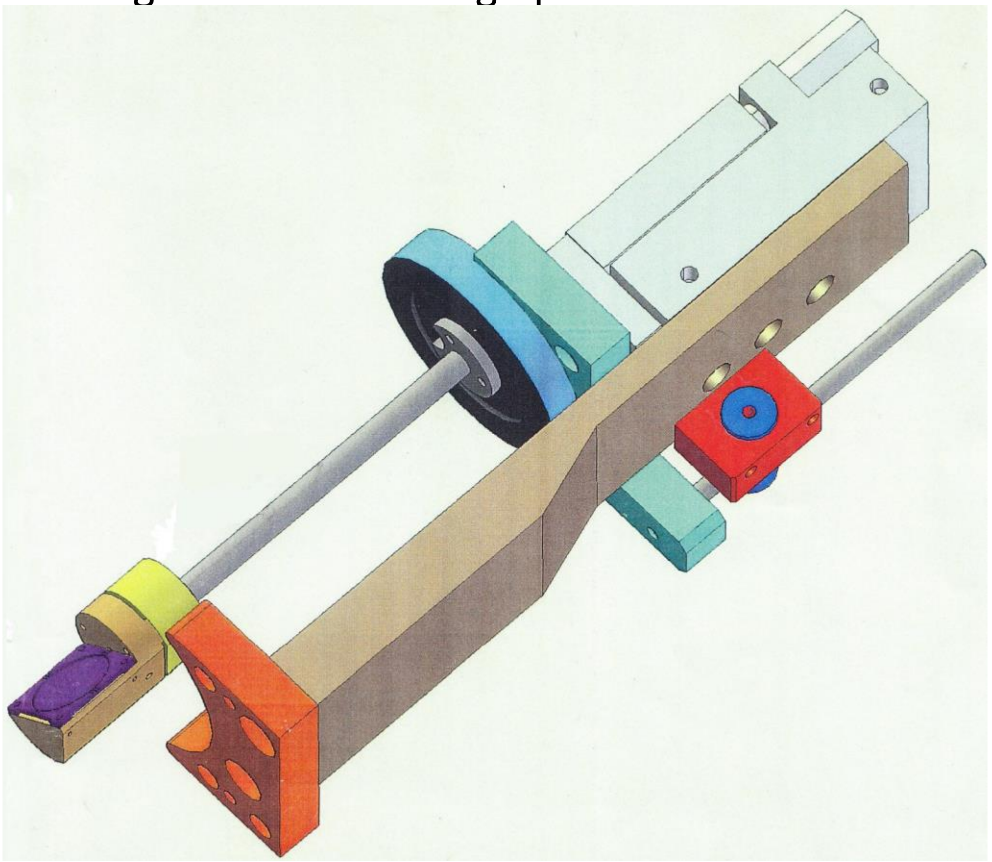
Faraday-cups as electron-beam charge-monitor

As the most ordinary tool to measure charges, REGAE uses the well-known principle of a Faraday cup. The design of the Faraday cups – adopted from FLASH – employs a copper block which at the same time is used as a holder for a scintillator thus enabling simultaneous charge measurements and transversal diagnostics. Since at the low charge levels required at REGAE beam position monitors are not available, this setup turned out to be very helpful for machine operation too.

The charge collected on the copper block is transferred via a 50 Ω resistor to ground. The voltage pulse over the resistor is measured with a fast ADC.

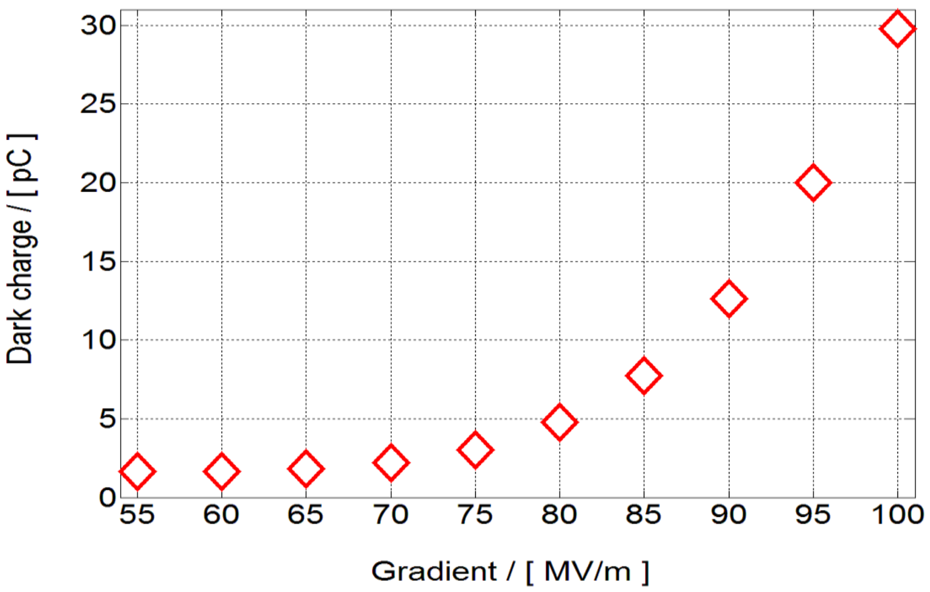


For electron beam charge measurements the cups yield voltage pulses of about 5 ns and a height of 33 mV/pC (with 50 Ω impedance) resulting in a large dynamic range of a few tens of fC to 100 pC.

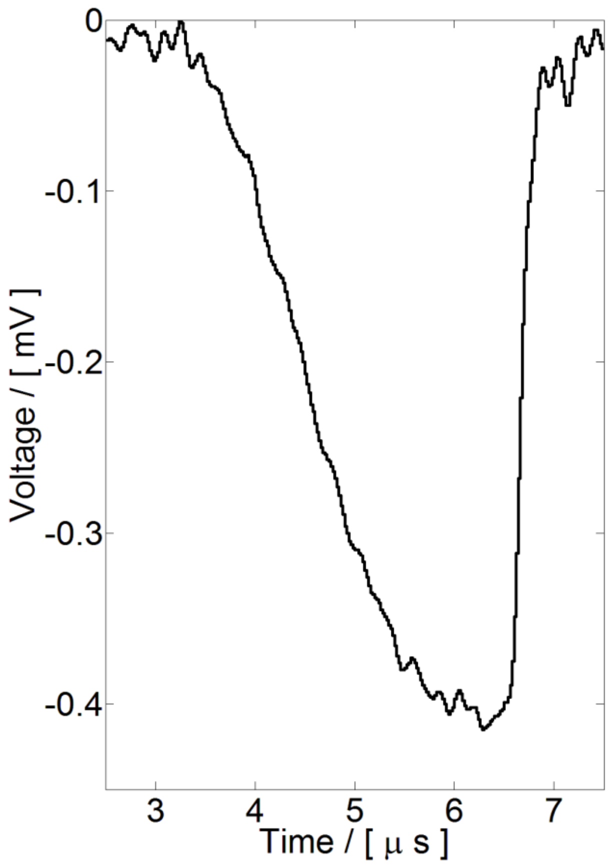


Faraday-cups as dark-current monitor

A dark current voltage signal is shown here. In total a trace of 10 µs (500 points at 50 MHz) can be recorded at each RF pulse in this operation mode. The charge in each bin of 20 ns is below 100 fC in the presented case; the noise level – in front of the pulse – is correspondingly small.



Dark charge vs gradient, first REGAE gun 2013



Dark-current measurement and analysis

This figure shows a typical measured dark current trace. Here 200 shots are averaged, the error bars represent the standard deviation of these 200 shots. Rms deviations are small despite the fact that they include the overall effect of all errors like machine instabilities, statistical behavior of field emission and noise of the measurement device and digitization electronics as well as amplifier noise.

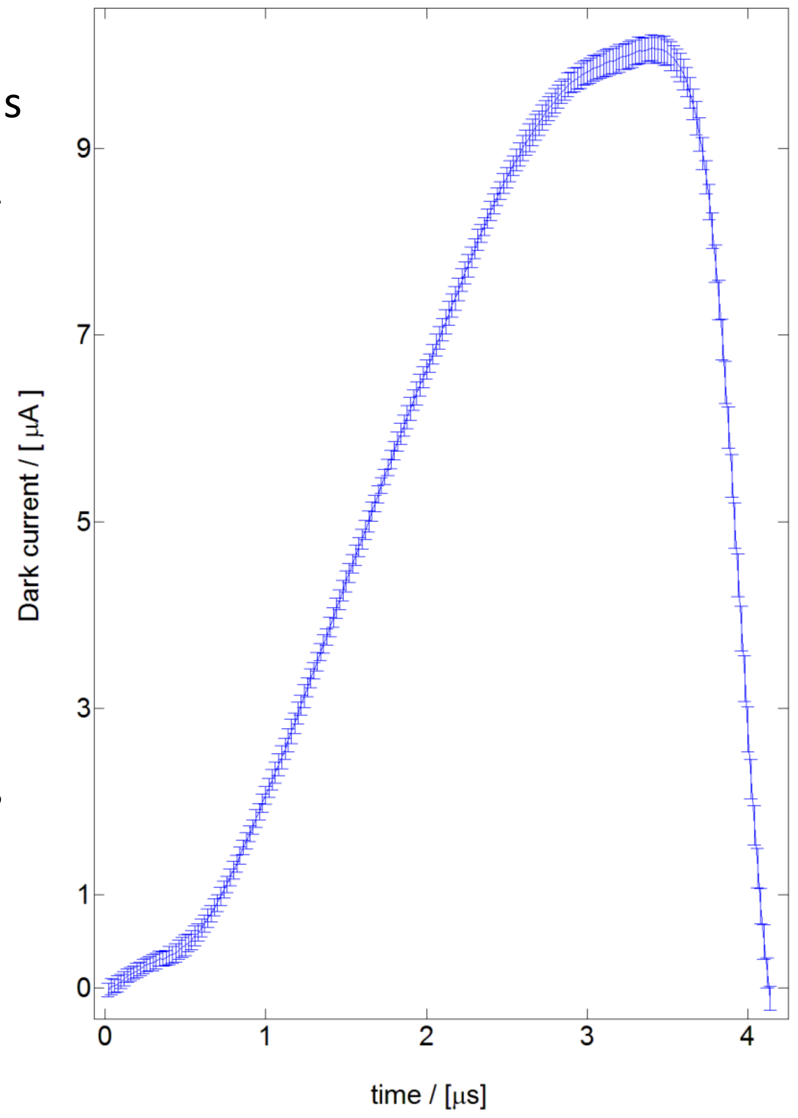
Fowler-Nordheim plots have been created to see whether the measured dark current depends on the field strength as expected from field emission theory. The field emitted current for an alternating field can be expressed as:

$$\bar{I}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\phi^{-0.5}} A_e(\beta E_0)^{2.5}}{\phi^{1.75}} \quad exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_0}\right)$$

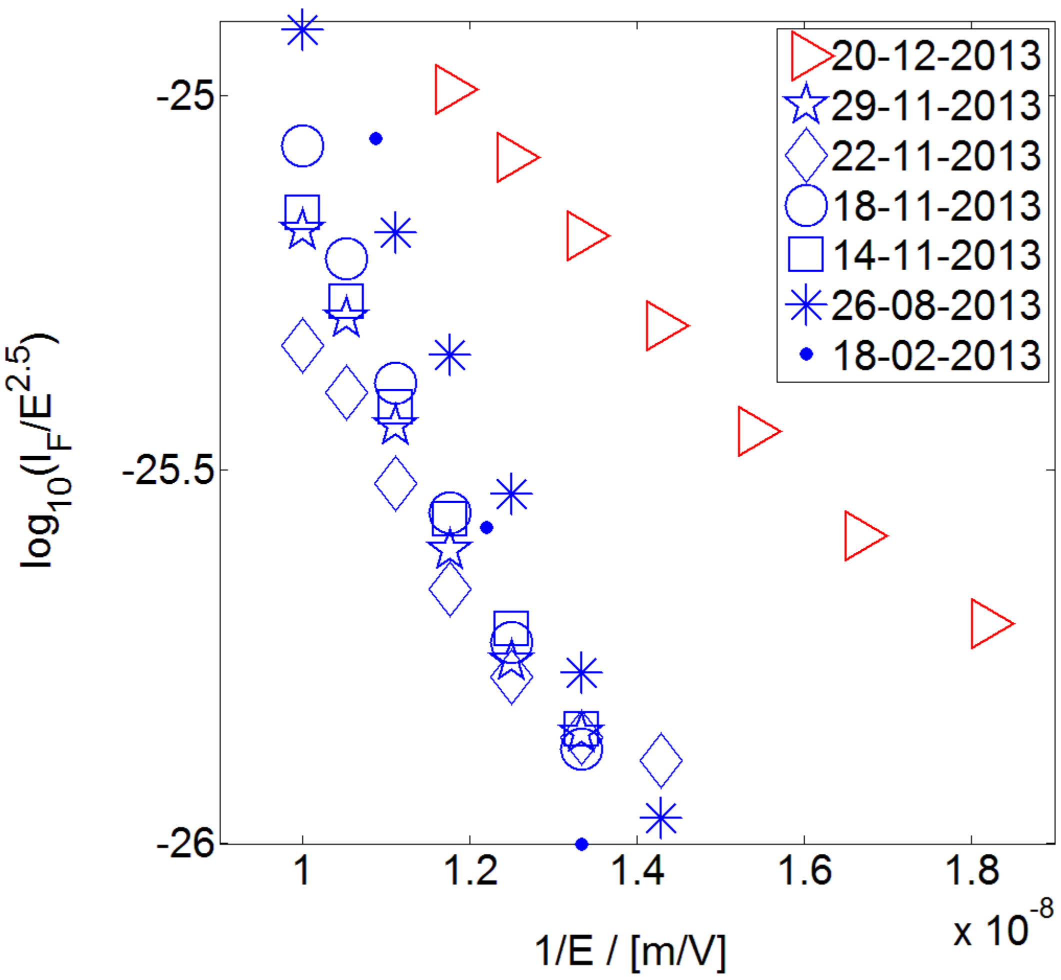
where E is the amplitude of the sinusoidal macroscopic surface field in V/m, β is the enhancement factor and $\bar{I}_F$ is the average field emitted current in amperes from an emitting area Ae in m^2. In a semilogarithmic plot of $\bar{I}_F$ /E^2.5 versus 1/E the data should yield a straight line with β derived from the slope as:

$$\frac{d\left(log_{10}\bar{I}_F/E^{2.5}\right)}{d\left(1/E\right)} = -\frac{2.84 \times 10^9 \phi^{1.5}}{\beta}$$

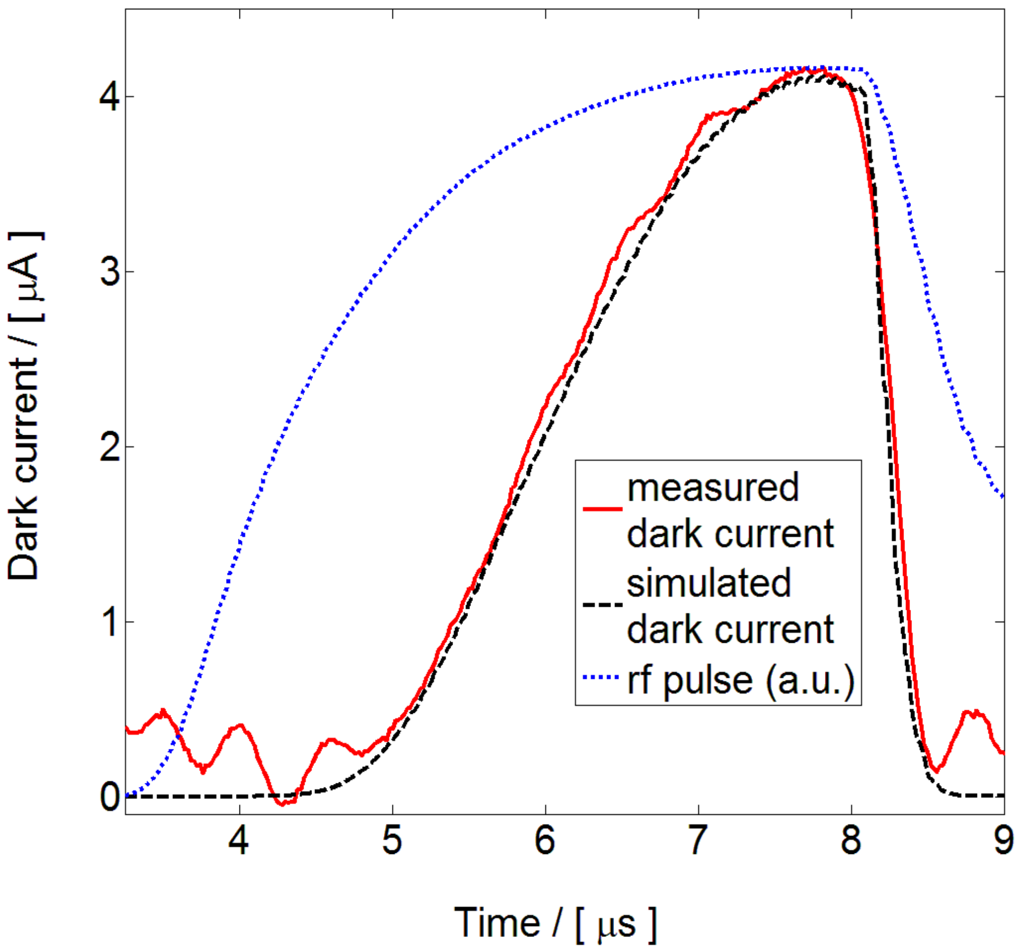
Ae can be deduced from the offset of the line.



REGAE first gun dark-current



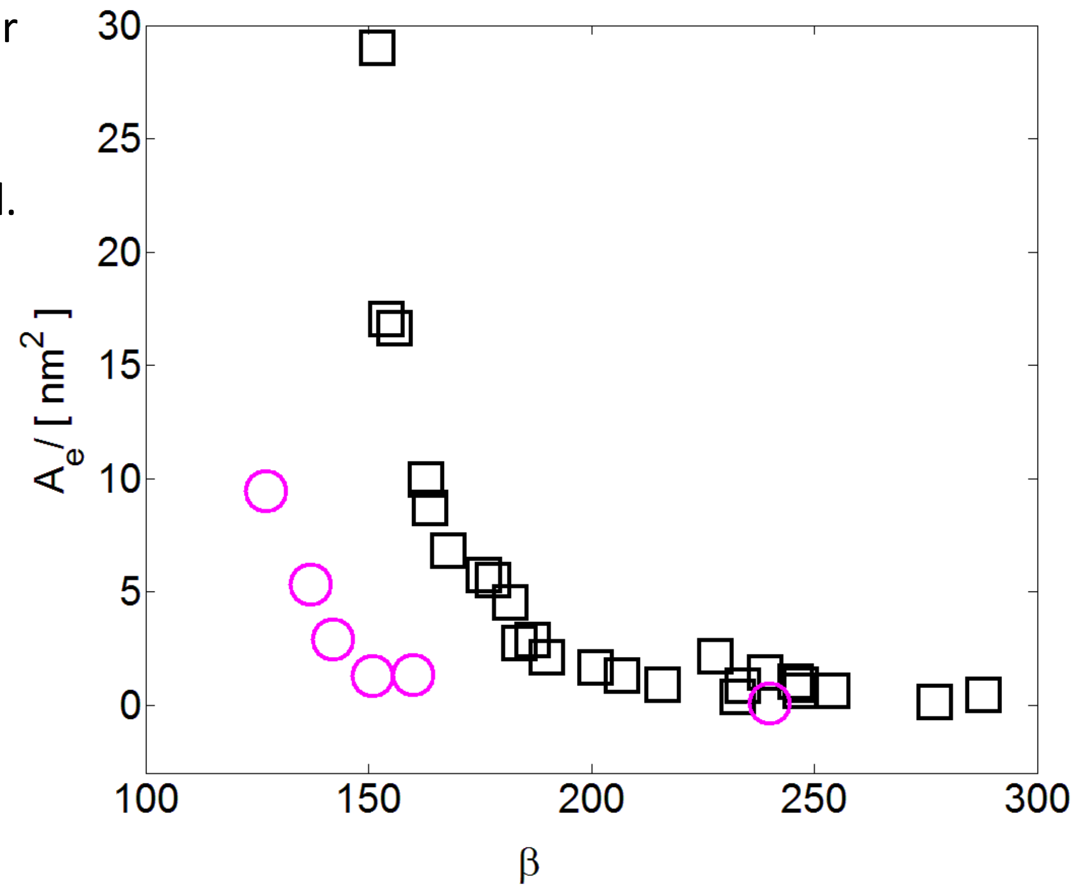
Fowler-Nordheim plot for the period before the vacuum problem. A first measurement result after the vacuum accident is added for comparison.



Measured and calculated dark current within an rf pulse. The dark current pulse appears to be delayed and shortened as compared to the rf pulse.

REGAE first gun dark-current

Compilation of field enhancement factors and effective emitter area Ae for dark current measurements at REGAE (first gun). Circles are for the time before the vacuum problem appeared, squares show results after the vacuum problem had been fixed. All results are found to follow two exponential like curves.



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DARK CURRENT STUDIES AT RELATIVISTIC ELECTRON GUN FOR ATOMIC EXPLORATION – REGAE

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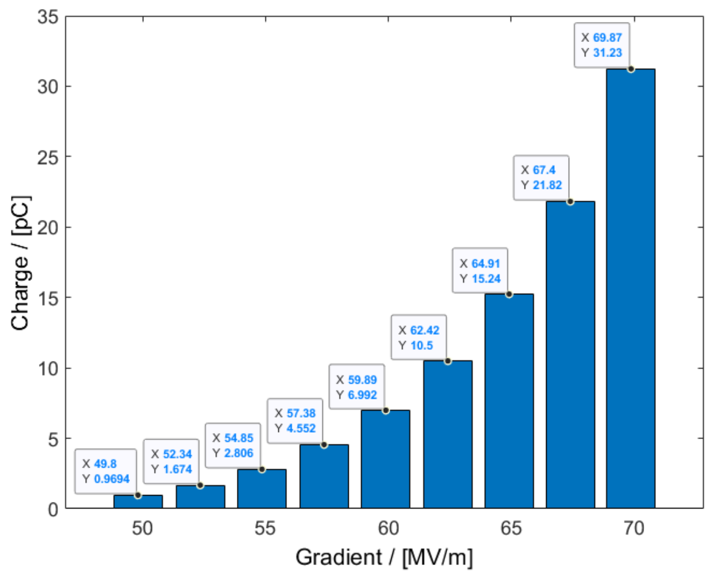
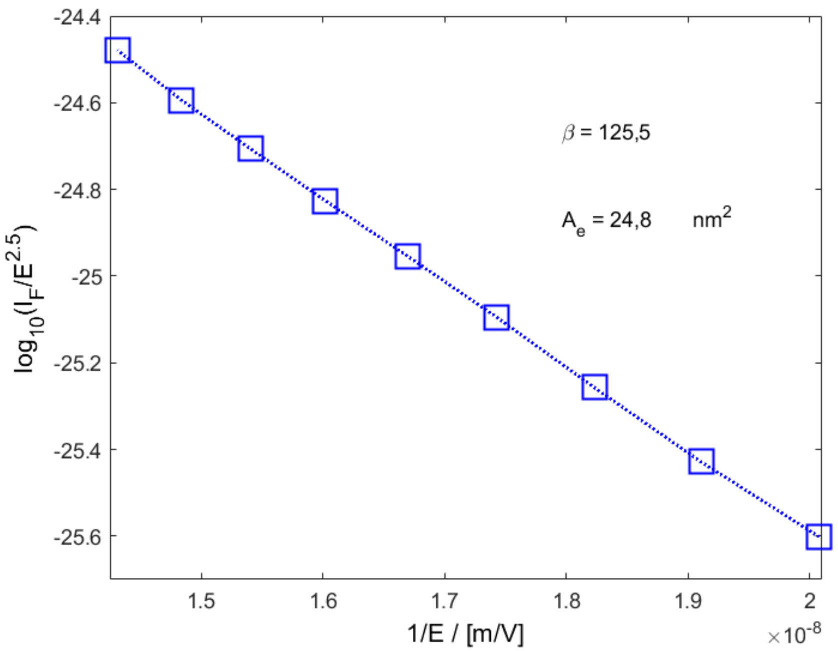
Gun exchanges at REGAE

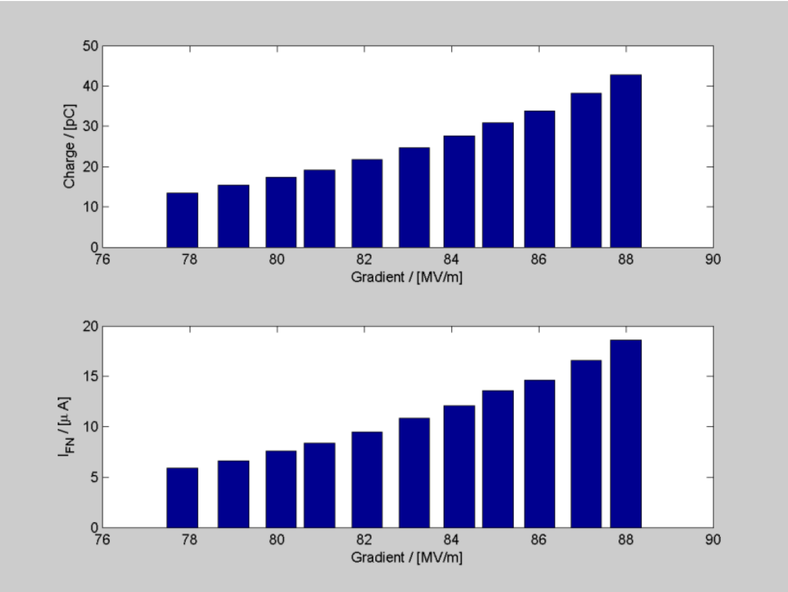
So far we have installed and used four guns at REGAE. Minor modifications happened in the design of RF pick-up antennas, cathode-housing and spring. In terms of dark-current, good performance met with first gun and the best case is 4th gun which is currently in operation.

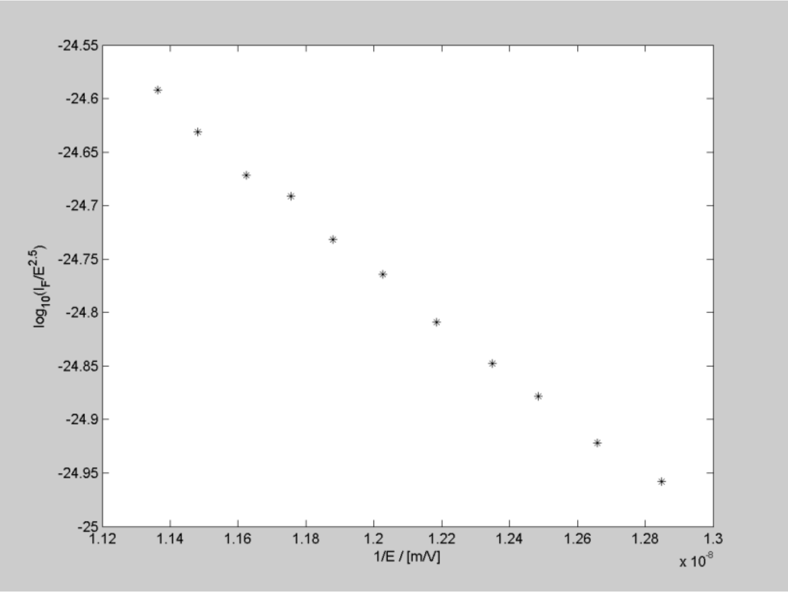




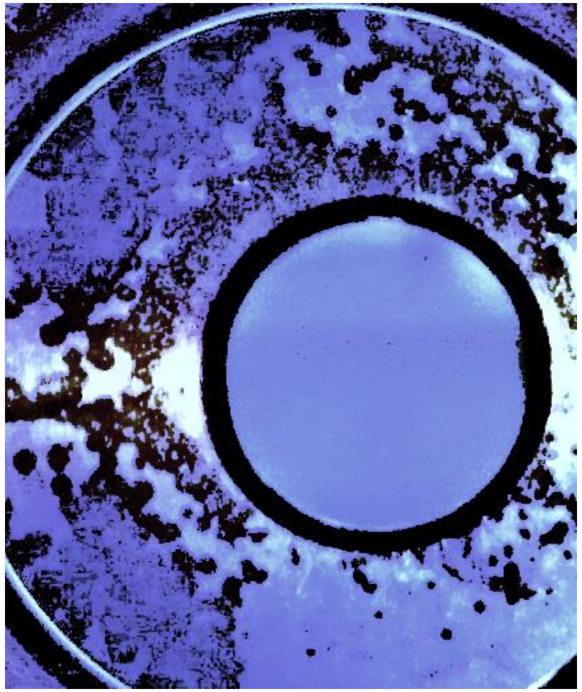
2nd REGAE gun encountered very early problem in the RF probe which has got a temporary fix but could not exceed 70 MV/m otherwise a lot of vacuum activity.

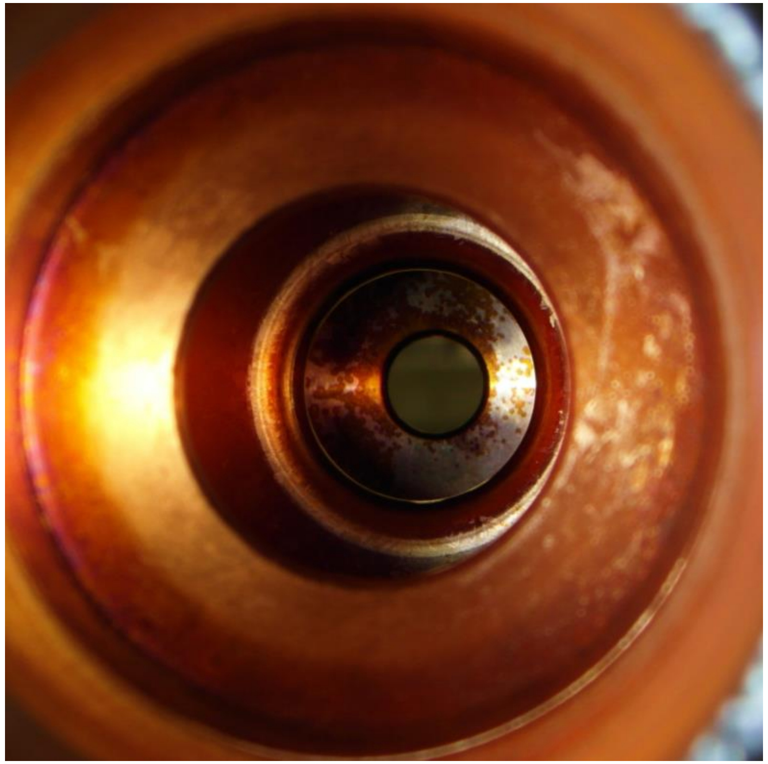
Gun exchanges at REGAE





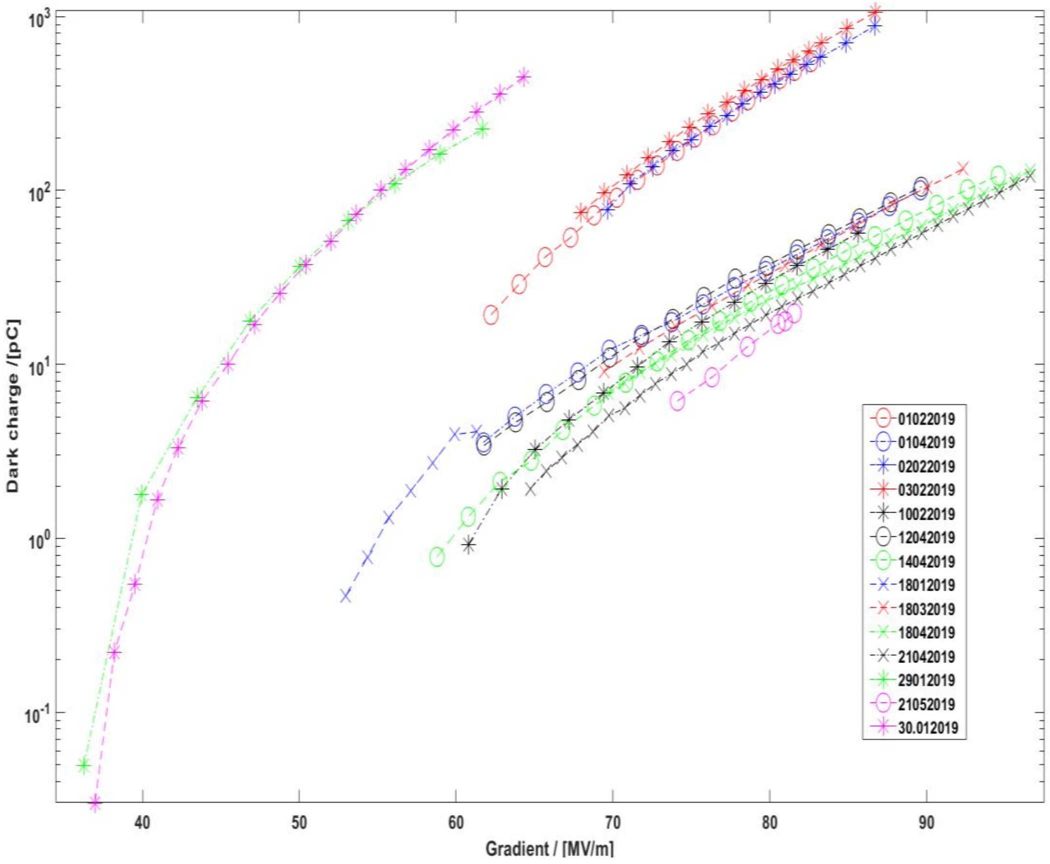
Third REGAE gun was performing better. During efforts towards commissioning/conditioning to higher gradients several time new emitters have got active. We tried conditioning (in parallel to experiments operation) over long period but at the end found out that over large areas of the gun cavity there were stains and efforts to clean them were not successful therefore had to give up this gun too.

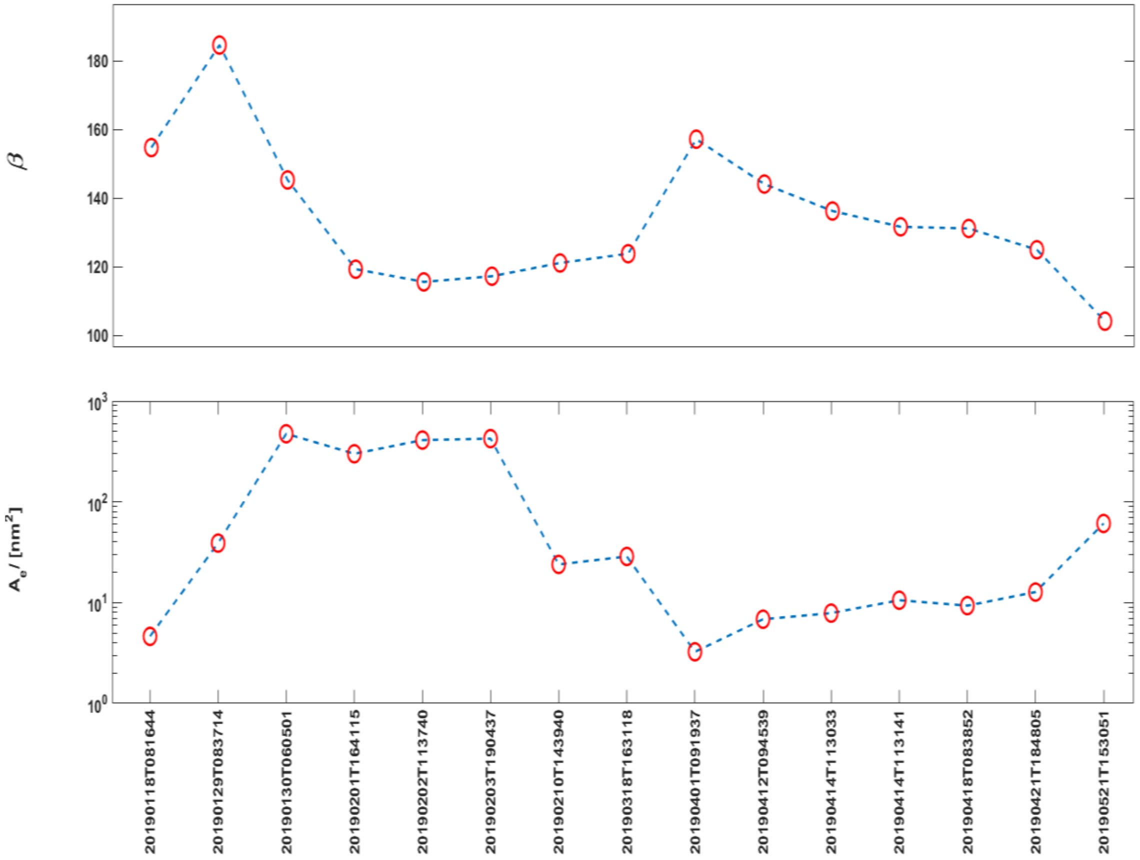




Gun exchanges at REGAE

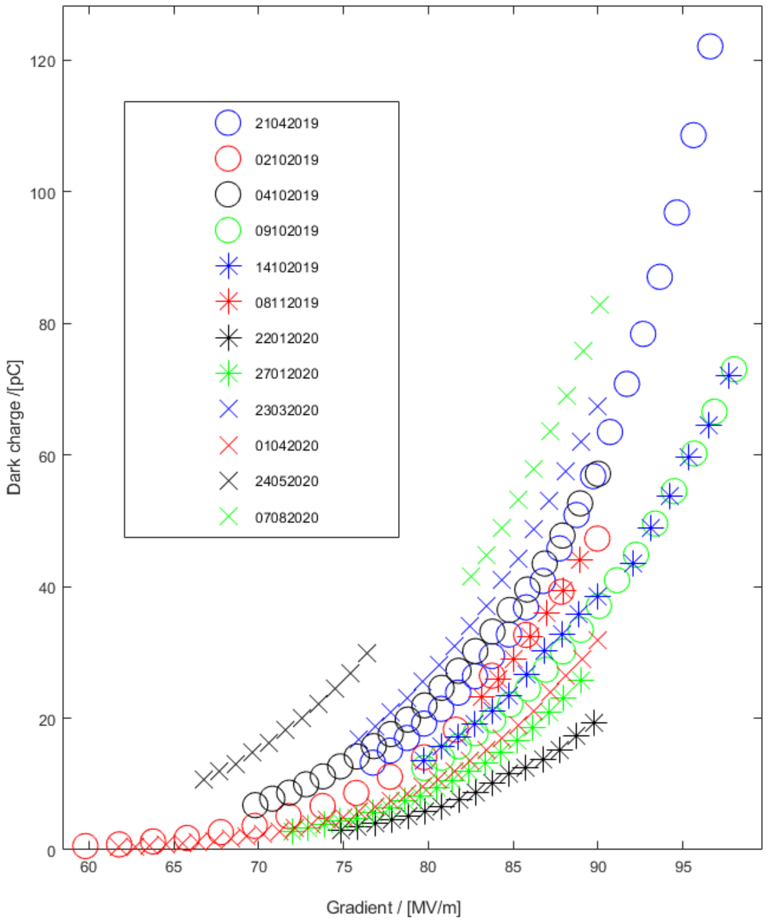
Since about five years the 4th gun is installed at REGAE. There has been two times need to clean this gun. Once performance was degrading gradually due to problems with spring and exchange of cathodes. Dark charge measurements were performed during conditioning. In the following the outcome of Fowler-Nordheim analysis is plotted as they develop over time.

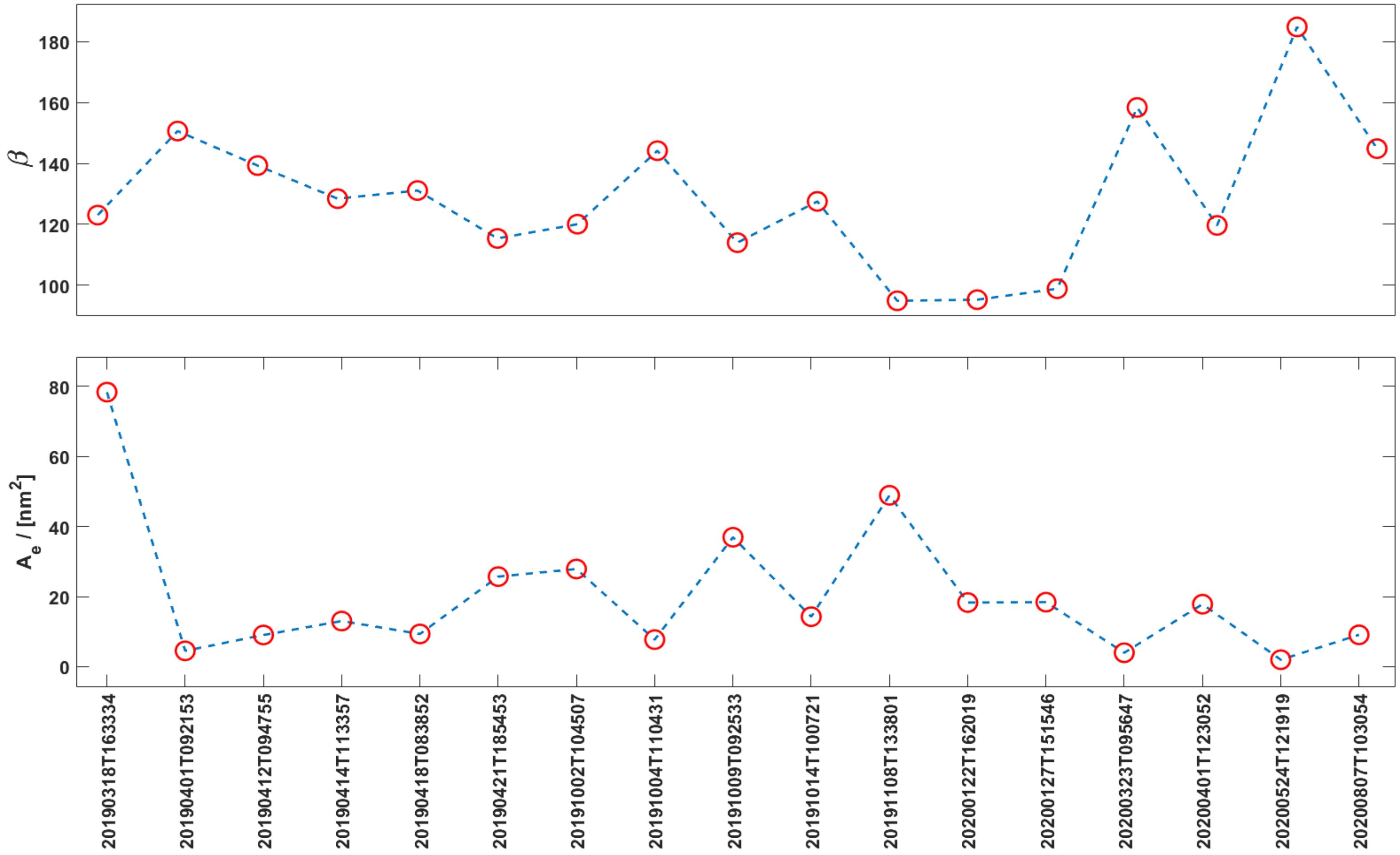




REGAE 4th gun

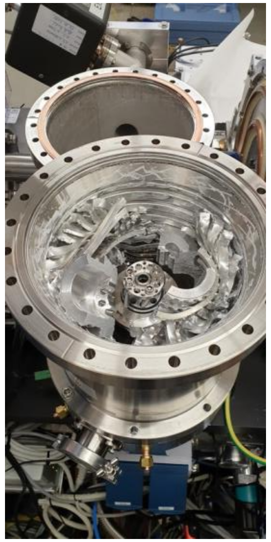
Over almost one and half a year there were several times need to repeat conditioning of the gun due to changes of spring or klystron/modulator/RF-window problems etc. but in general gun was in operation and good condition.

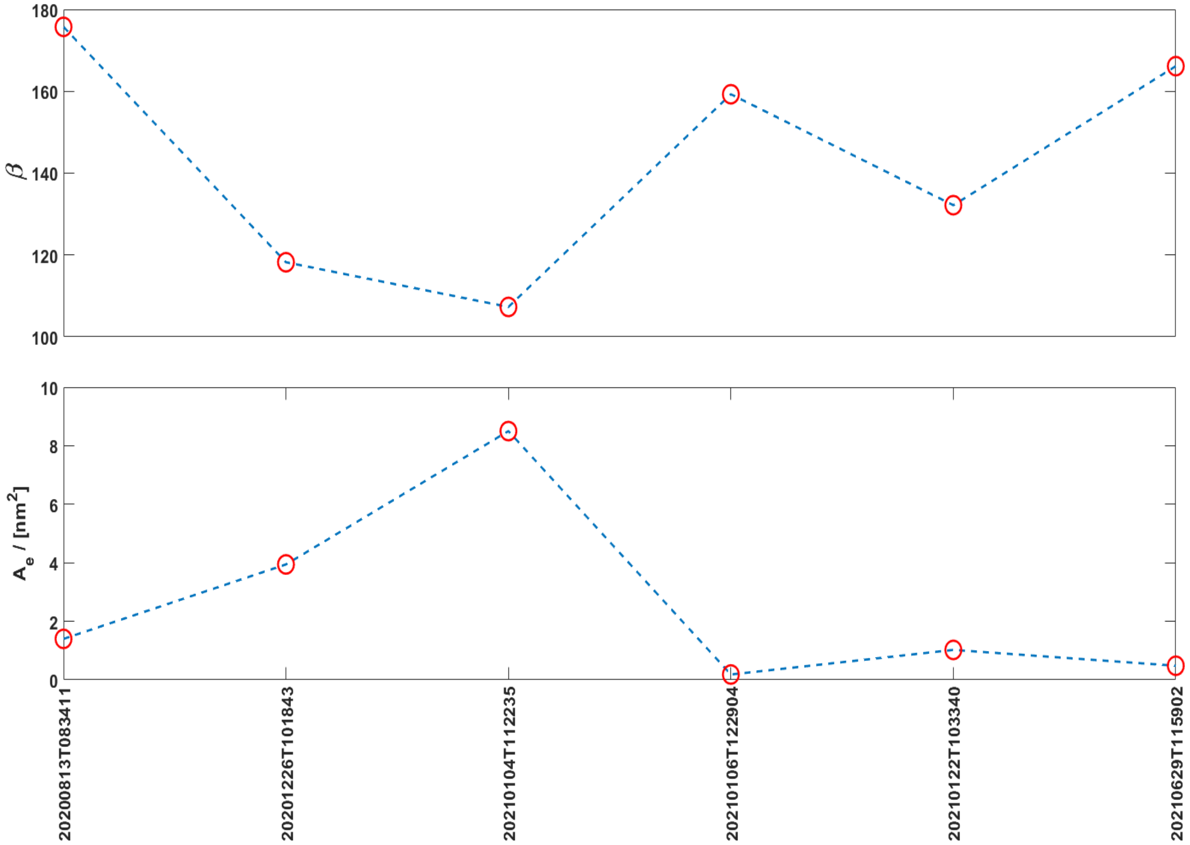


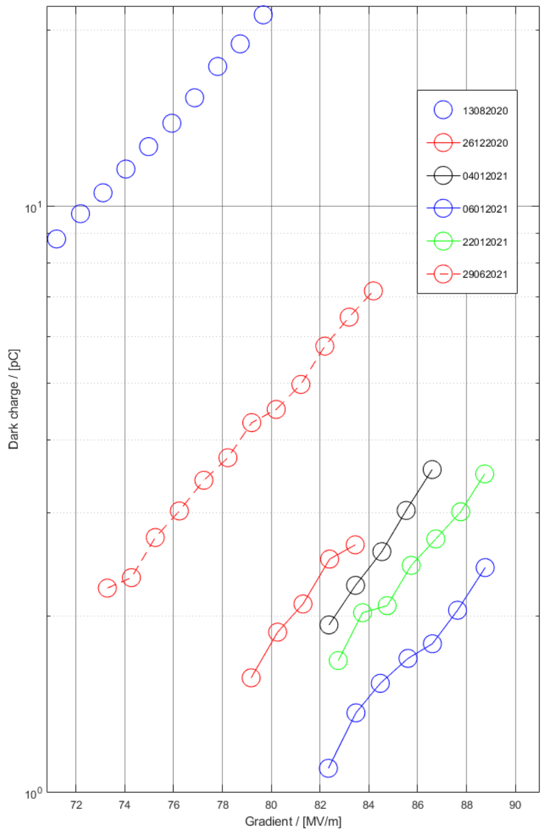


REGAE 4th gun

On 15.10.2020 a vacuum accident happened at REGAE. Gun was affected too. We tried ordinary cleaning once. After installation result was not convincing and decision was made to go through a full cleaning process. This time in very early steps of conditioning we observed different behavior, dark charge level was very low. Conditioning progress was fast and the outcome was hard to believe. Maximum dark charge was close to 1 pC in gradient exceeding 80 MV/m. Since then gun is running at this record low dark charge level.

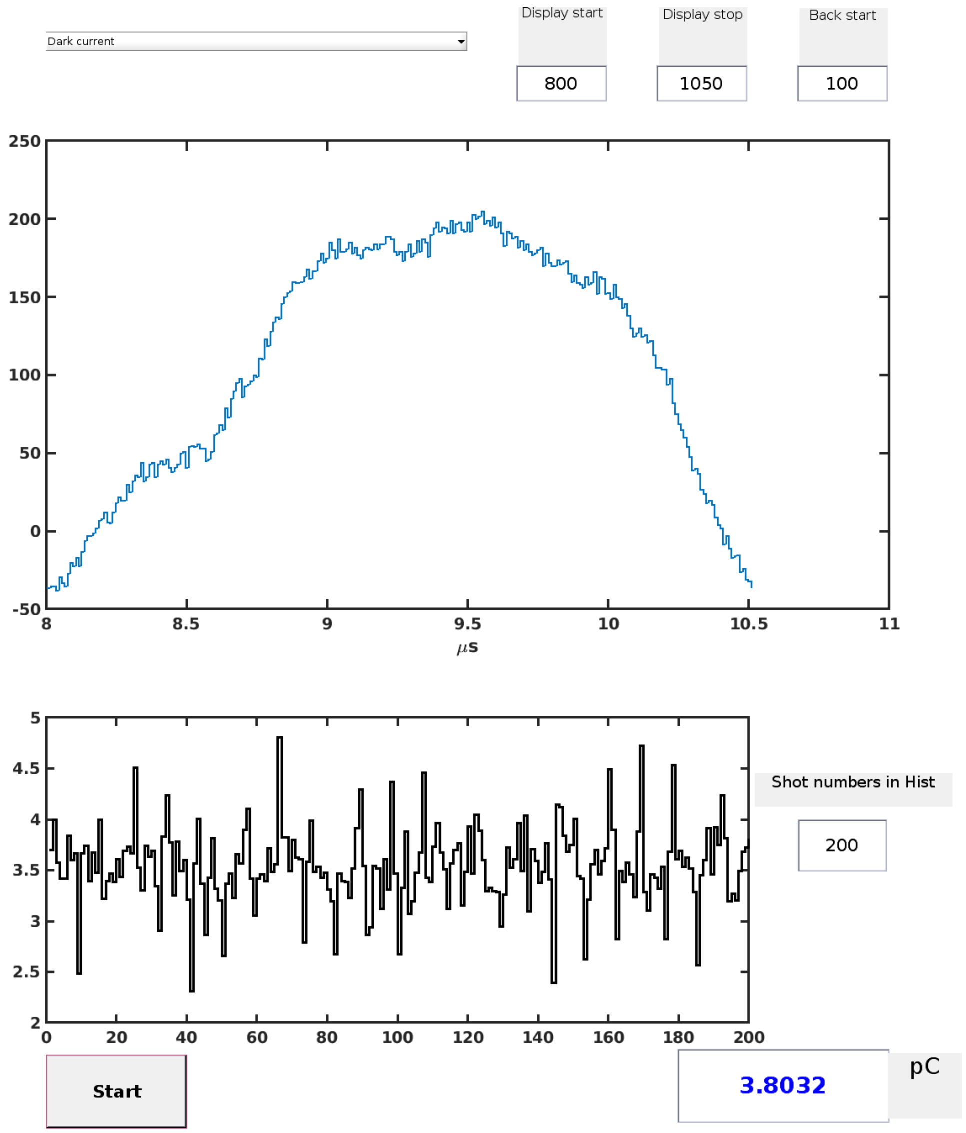




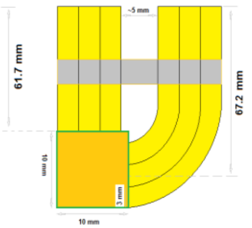


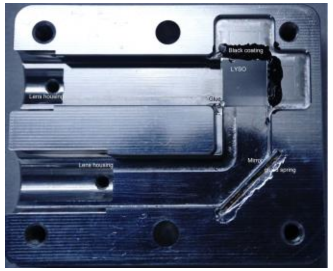
REGAE 4th gun

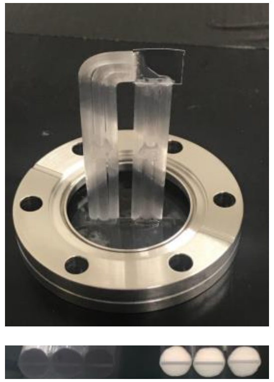
Recently we integrated a second µTCA to be used mainly for data acquisition synchronized to the electron-bunch. Data can be collected into DAQ system with highest rep-rate of REGAE (50 Hz). Our cavity-charge-monitor as well as dark-current signals are connected to ADC cards of this µTCA. Stability of electron-beam-profile/diffraction-pattern, pump-laser-profile/intensity can be studied in a shot-to-shot basis. In this figure snapshot of dark-current app at a gradient of 80 MV/m is shown.

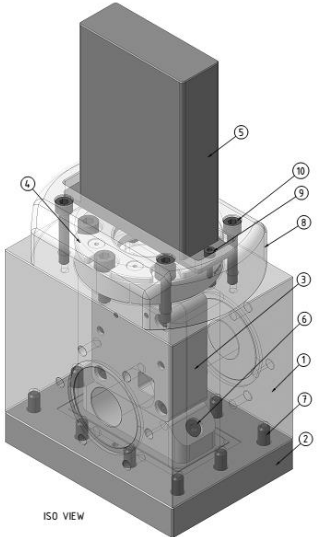


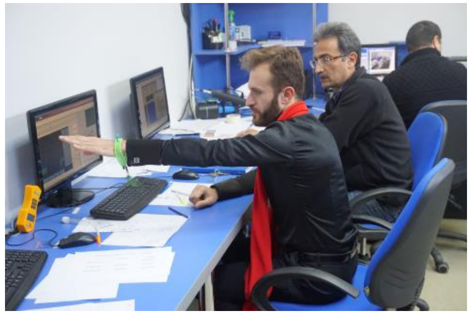
Quick tour to ULCBPM test at AREAL

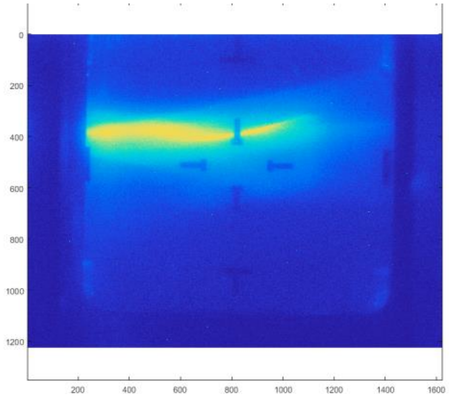




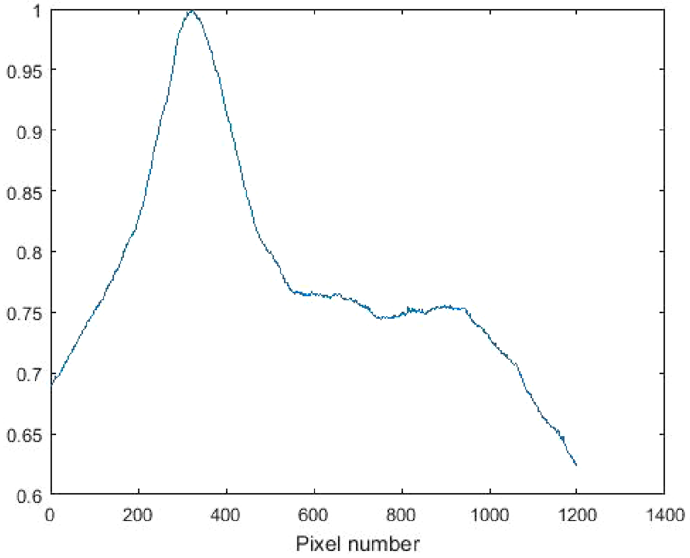


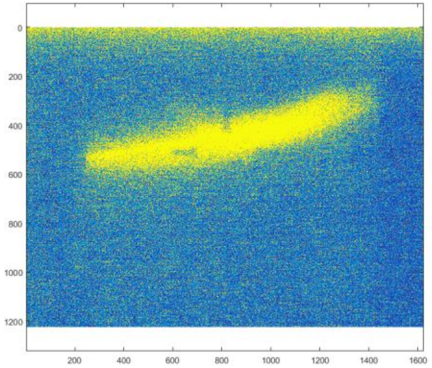




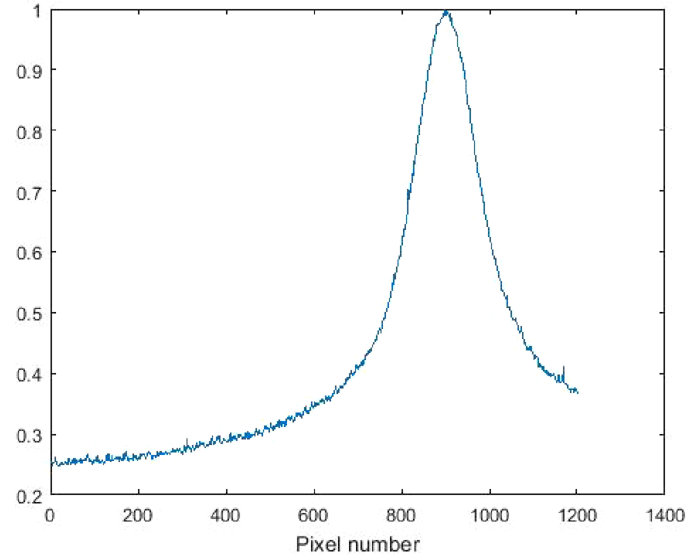


4MeV E-beam



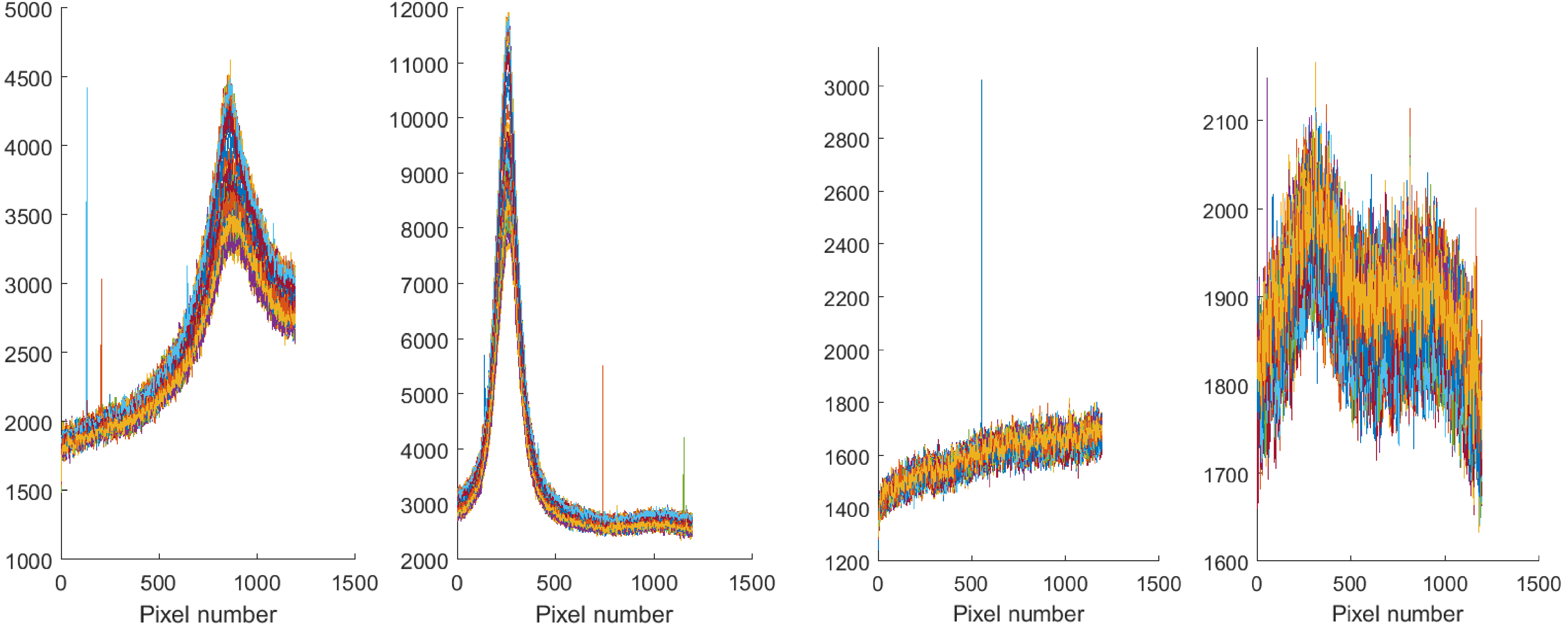


1MeV E-beam



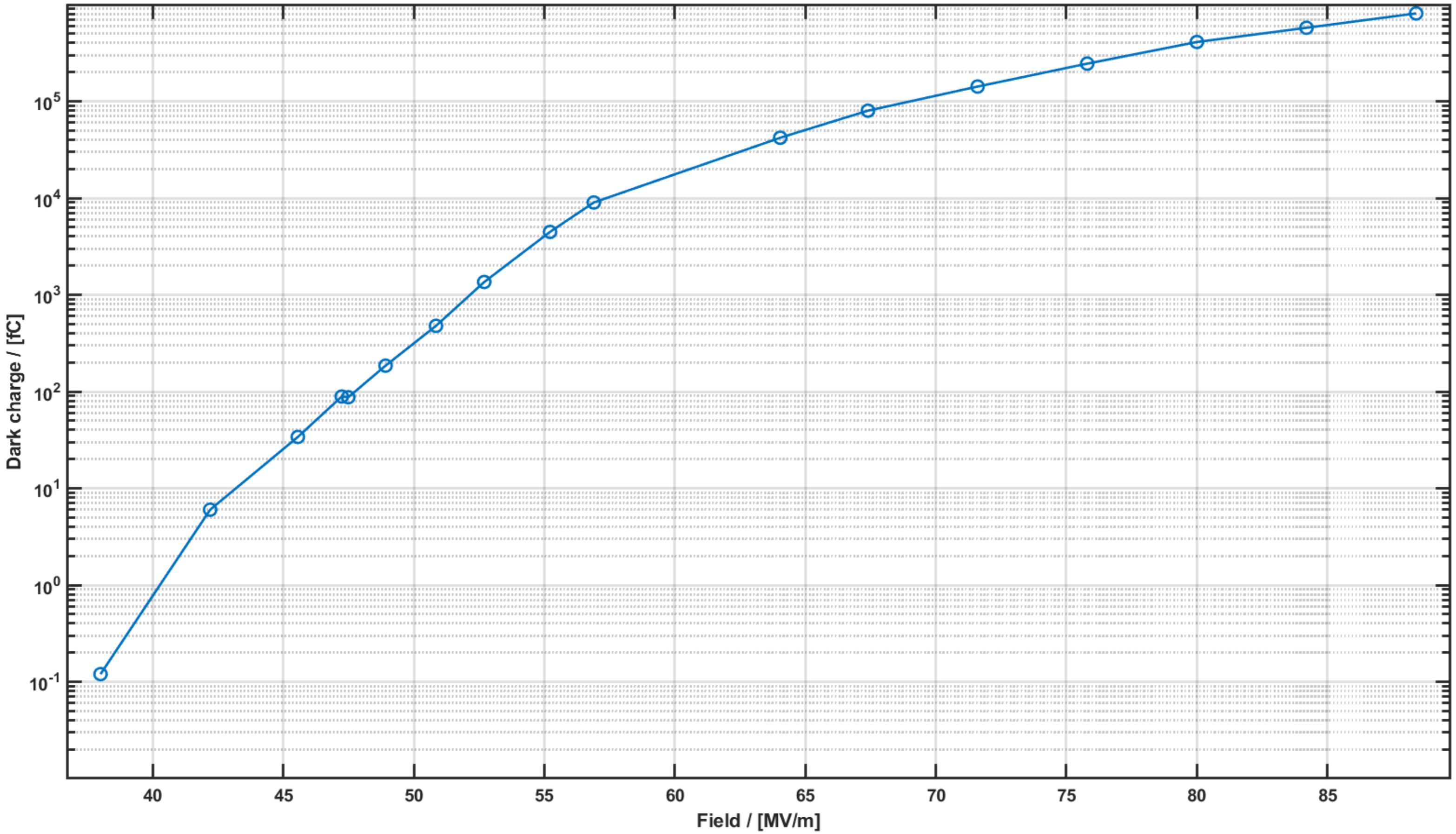
Quick tour to ULCBPM test at AREAL

Laser on (left) / off (right) during one of measurement at AREAL May 2019



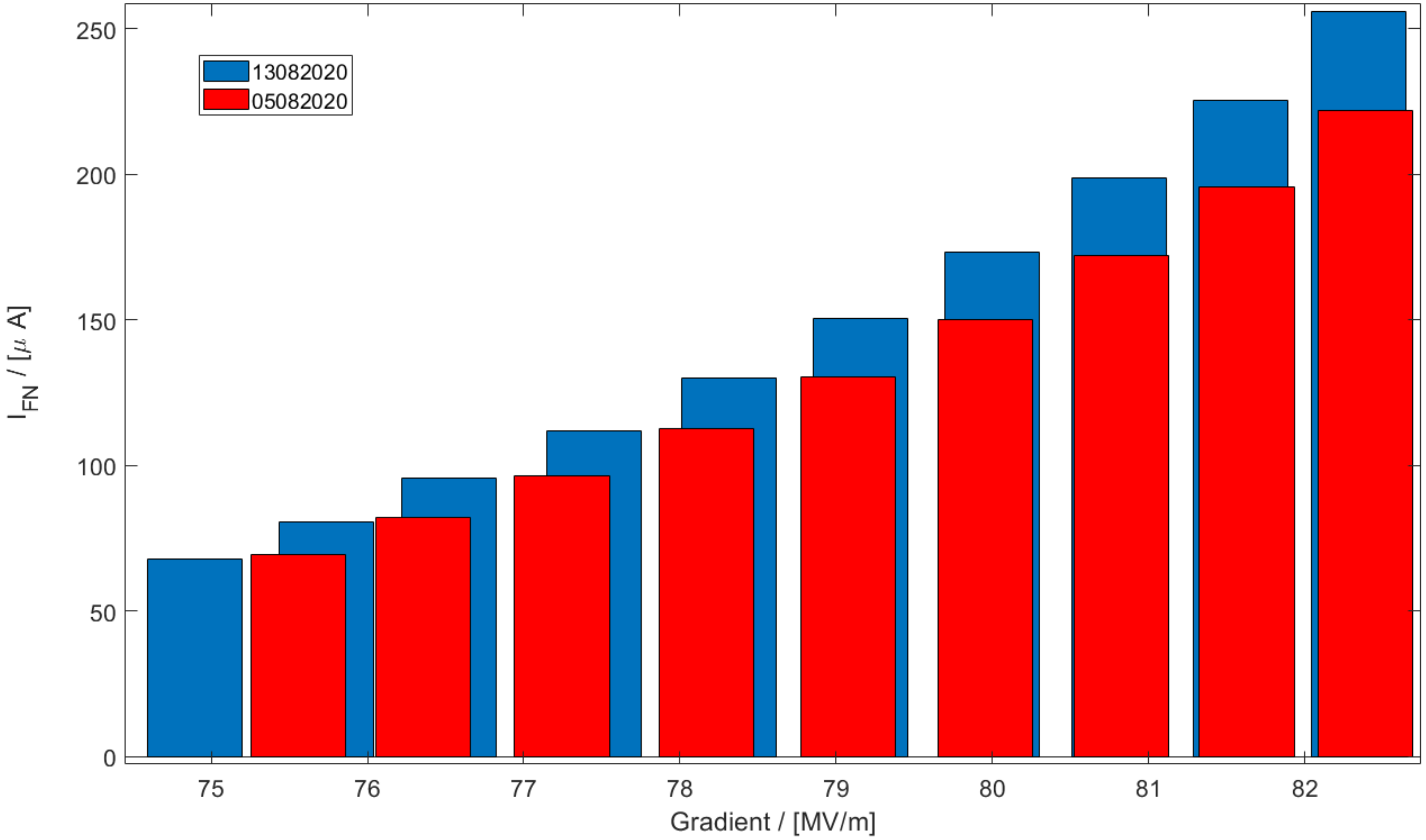
AREAL gun, the repaired REGAE first gun

First REGAE gun has been installed after repair and minor modification at AREAL.
During commissioning of an Ultra-low-charge BPM at AREAL May 2019 we measured dark-charge. For the high-field range we used Faraday-cup while for lower fields, where Faraday-cup signal was below noise, we used Ultra-low-charge BPM. We tried to cover an overlap in measured dark-charge with both techniques therefore could combine results to produce the following result.

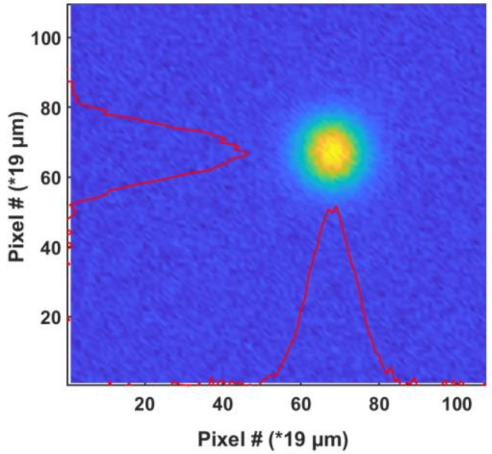


Another REGAE-type gun, this time at ARES

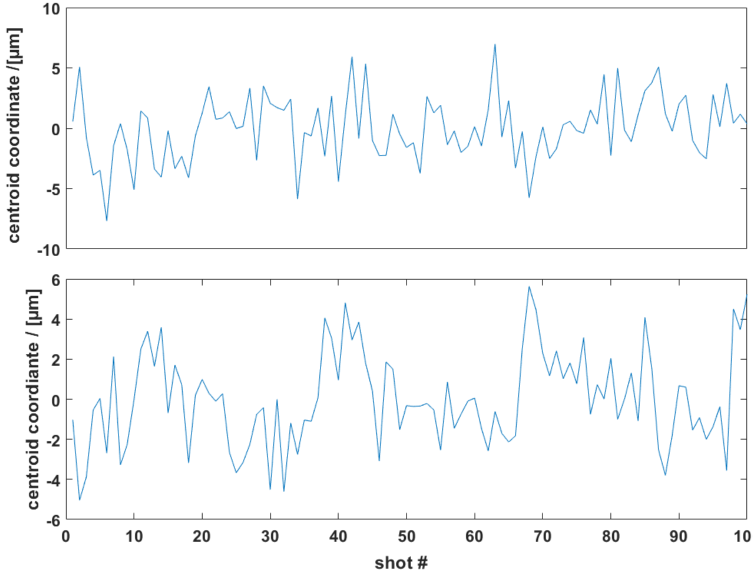
ARES (**A**ccelerator **R**esearch **E**xperiment at **S**INBAD) started conditioning a REGAE-type gun in 2020. The achieved performance in terms of dark current was (and is) suboptimal.

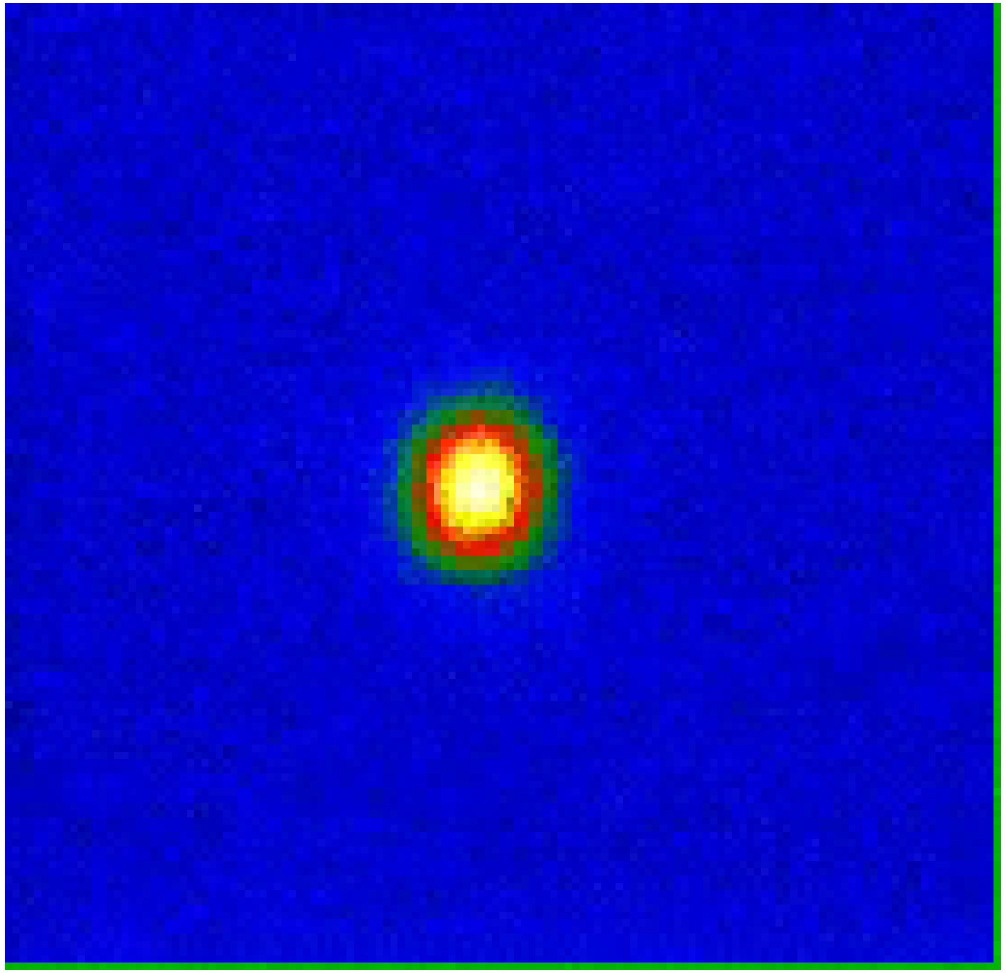


REGAE electron beam last Friday!

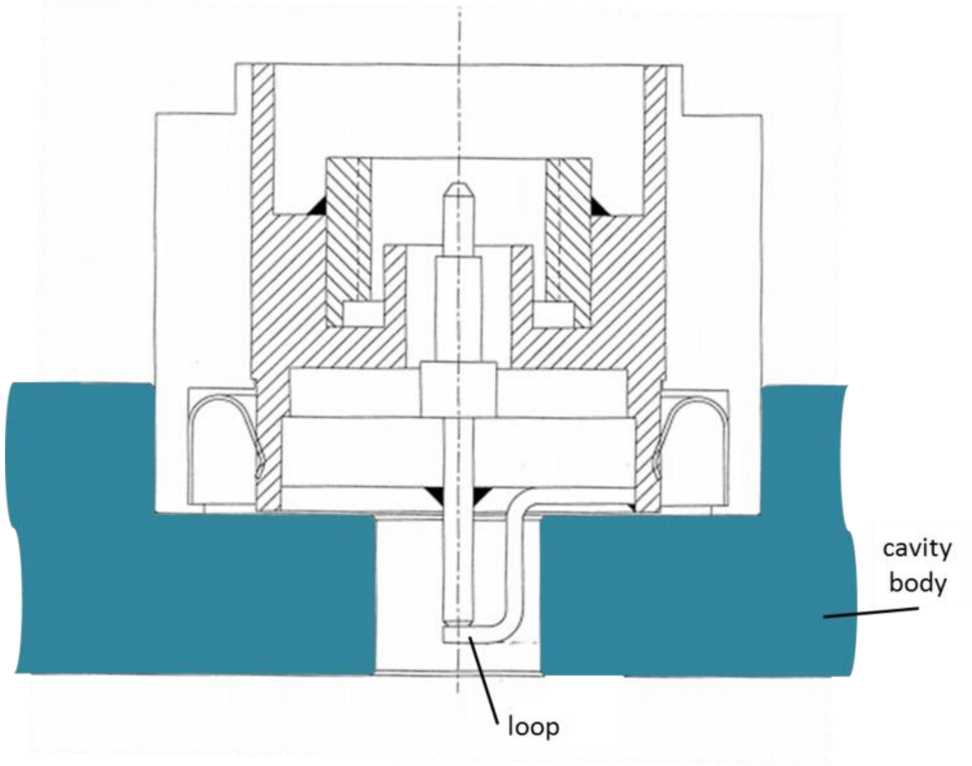


rms size ~120μm
P2P / {σ} < 10%





THANKS


cavity
body
loop