Jlab Operational Experience with Photoemission DC Guns

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for

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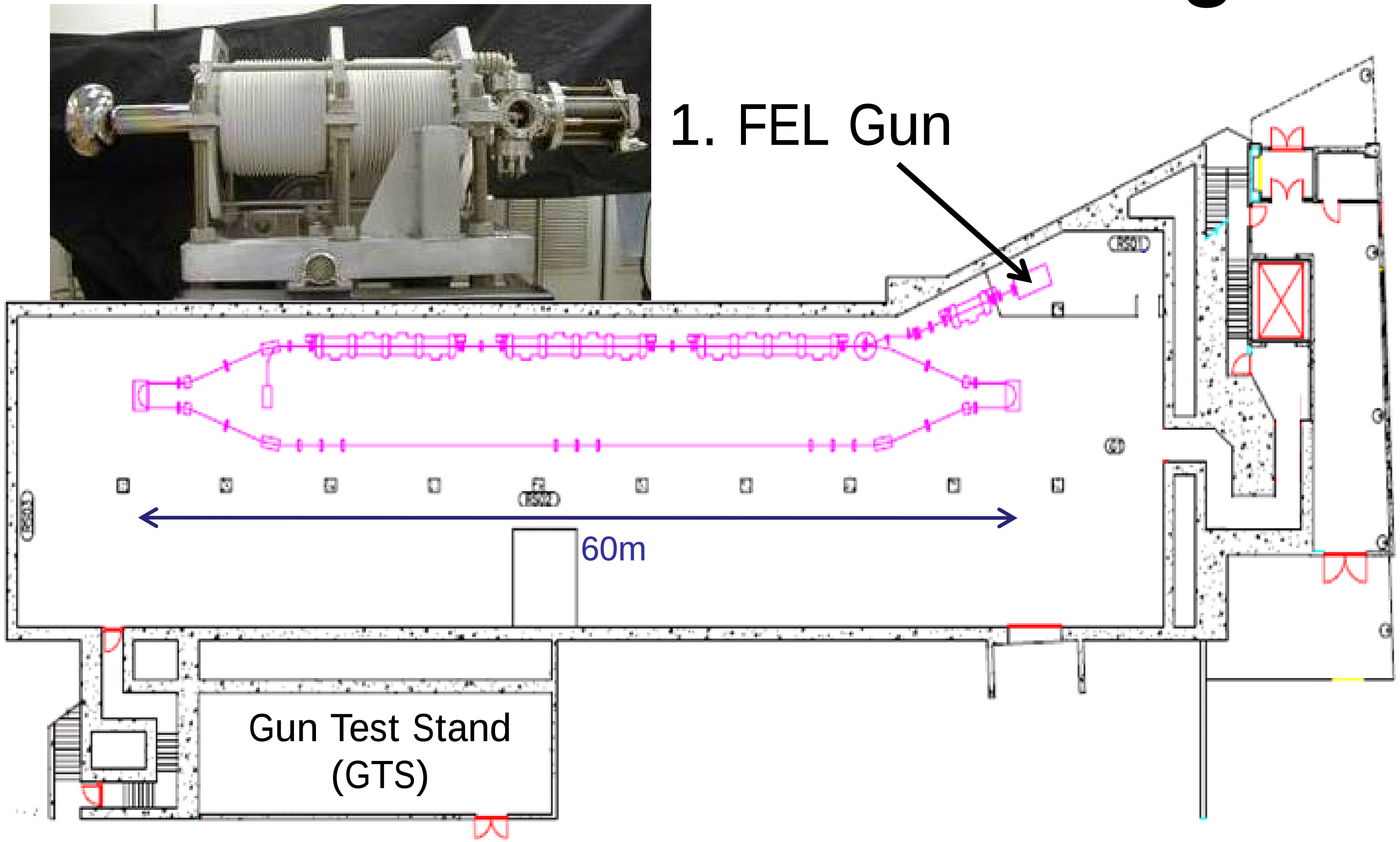
The Jlab FEL operates two DC Photoemission electron guns

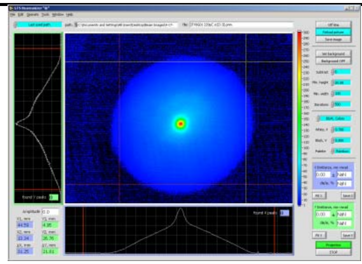


2. Backup gun, test stand with beam characterization beamline

FEL DC Gun "modern" history

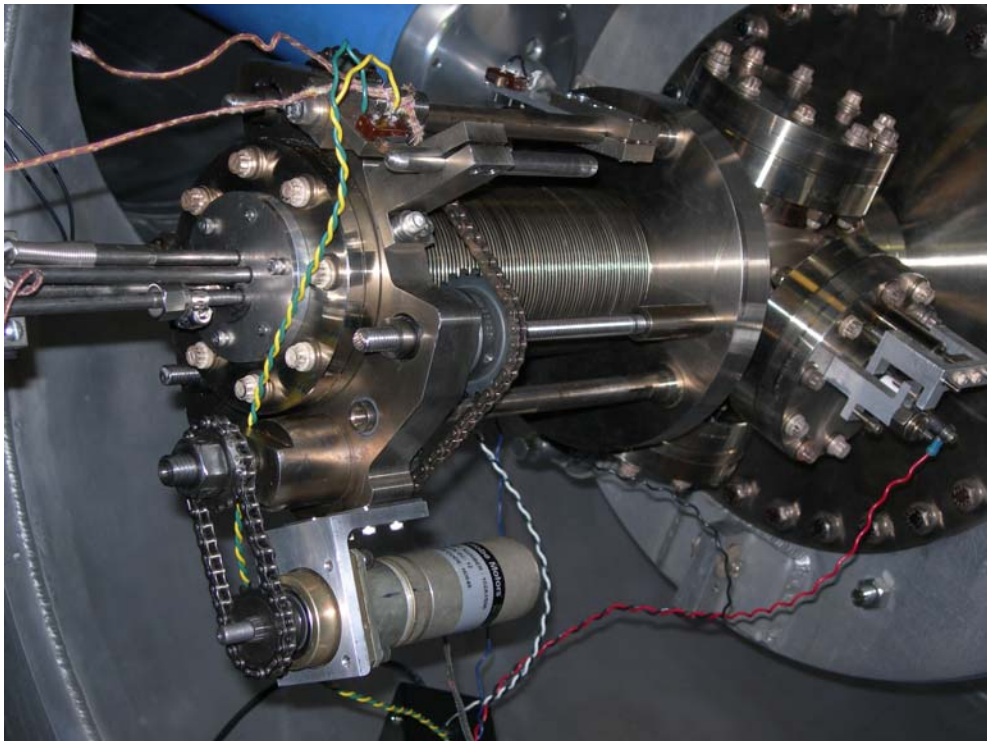
Date	Event
May 2007	Conclusion of 3 years of operations at **<u>350</u>** kV with a single GaAs wafer delivering over ***<u>7000 Coulombs and 900 of CW beam time</u>*** . Opened flange leak at 405kV while testing gun for higher charge studies
Mar. 2008	Punctured insulator at 398kV during conditioning of refurbished gun
Sept. 2008	Rebuilt gun with new insulator, but observed >100 uA of F.E. at 150kV
Oct. 2008	Krypton processed to 375 kV, but too much F. E. from cathode
Nov. 2008	Replaced cathode, F. E. reactivated at 320 kV after gun bake, Kr proc. again
Dec. 2008	No F. E. from cathode, but field emitter re-activated after cathode heat clean punching through ceramic at 350kV.
Dec. 2008 – May 2011	Gun operational at 325kV with injector performance similar as for 350kV, but decreased QE lifetime due to electrode field emission (~25 uA). A motorized cathode retraction system was installed cutting down re-cesiation time from 3 hours to 30 minutes.
May-Sept 2011	Photocathode could not be re-activated and needed to be replaced. Problem: gun and booster gate valves leaked through and booster had to be warmed-up. Replaced valves and entire gun assembly with Wesgo/Morgan bulk resistivity insulator. Achieved 394kV w/Kr before opening leak. Could not recover and delivered some beam at 320kV. Poor cathode lifetime led to replacing entire gun assembly.
Oct. 2011	Rebuilt gun with re-polished GTS gun electrodes, and original FEL gun Pt-implanted insulator. Gun undergoing vacuum bake. Installed new semi-load-lock system for cathode change-out.

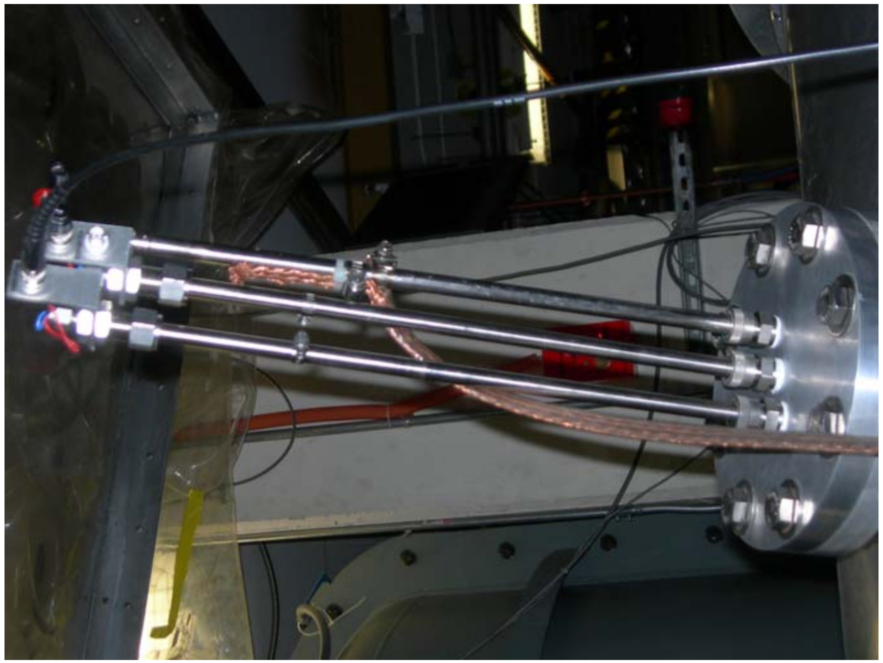
GTS DC Gun history

Date	Event
12/06/2007	With SiON coated electrodes, started HV conditioning, achieved 85 kV the first day
02/01/2008	Achieved **485 kV** after 528 processing-hours under vacuum conditions. At 486kV punched-through ceramic insulator.
02/28/2008	Fixed ceramic leak and ensured gun performance at **460 kV**. Declared HV conditioning done
03/14/2008	First beam at 300kV 
April 2008	Extracted beam up to 375 kV and observed indications of surface charge limit. **1nC demonstration**
2009 - 2010	Multi-slit, second solenoid, kicker cavity ready for installation in expanded diagnostic beam line as soon as $ available for RF power.
Jan. 2010-Nov 2010	$ was not available, but the gun was rebuilt with Wesgo/Morgan bulk resistivity insulator. The Semi-Load-Lock system along with SF6 tanks and corona shields were ready for installation.
Nov 2010-March 2011	Studied Krypton HV processing as a function of pressure. Achieved 440kV in a ew days w/Kr at 5e-6 Torr, when insulator suffered puncture. Continued studies, achieved 500kV for 5 hours and Kr at 1E-4 Torr. Could not reach more than 320kV under vacuum conditions: too much voltage-induced gas desorption led to leak re-opening, loosing gained voltage every time the leak re-opened.
March-May 2011	With electrodes stripped-off their coating, the GTS gun was re-assembled and installed in the FEL injector.

FEL DC Gun cathode retractor mechanism

- System operates by inserting rods into SF6 environment
- Rods deliver electrical power to the motor
- And provide biasing for cathode activations
- System allows cathode QE re-activation w/o opening SF6 tank in 30 min instead of 3 hours.

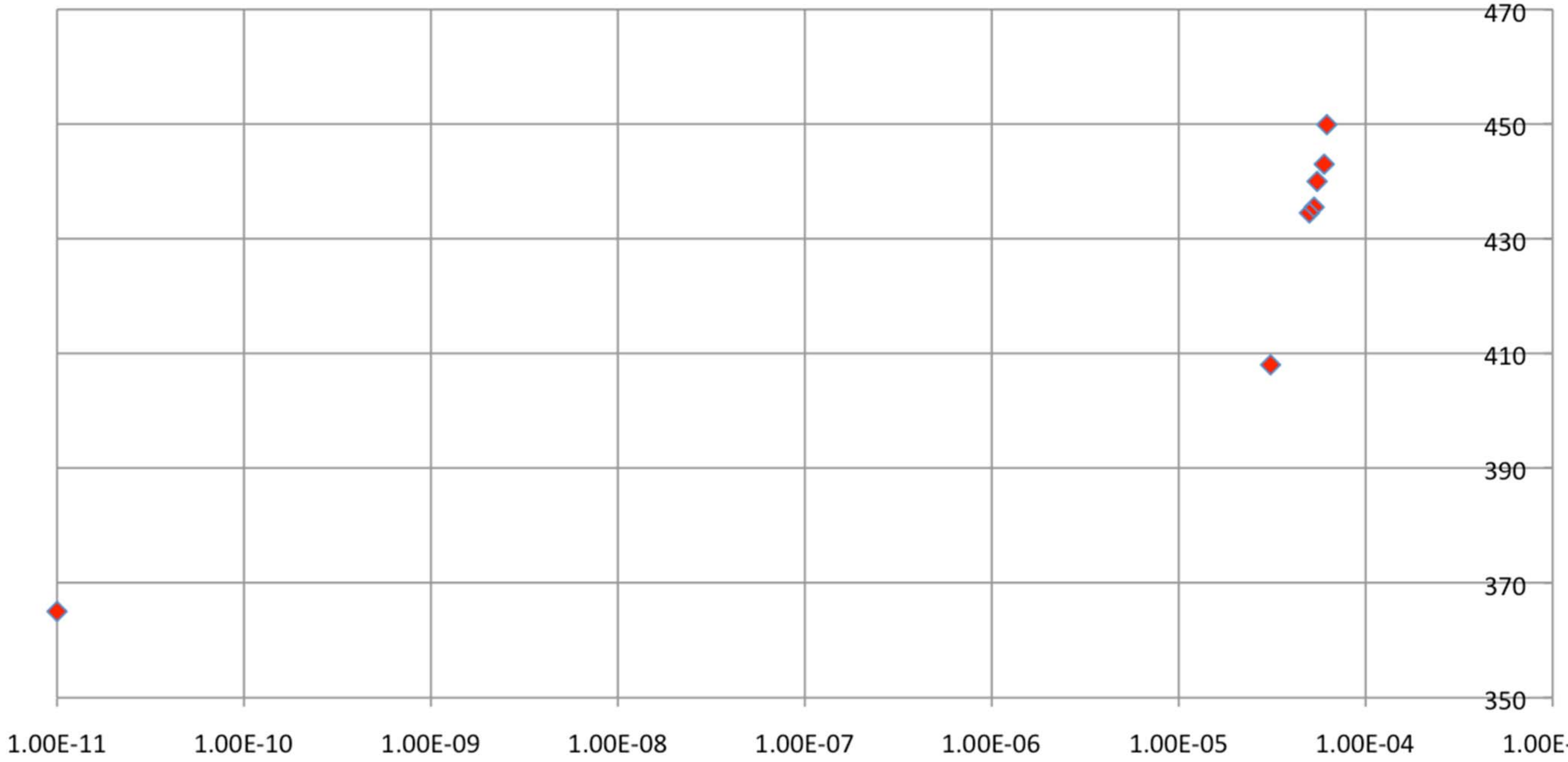




Krypton Processing

- GTS DC Gun
  - Kr is very effective processing field emission
  - Kr has minimal to null effect on voltage-induced gas desorption.
  - It seems that the higher the Kr pressure, the higher the voltage that can be achieved w/o current excursions
  - With increased Kr pressure, the the higher the onset for voltage-induced gas desorption
  - When Kr was evacuated and gun was back to nominal vacuum conditions (5E-11 Torr), there was no field emission but voltage-induced gas desorption was still present.
  - It seems that the SiON coating for suppressing field emission had a large contribution to gas desorption, making voltage processing slower compared to that in bare SS electrodes.
  - Even though field emission was processed under the leak up to 440kV, that voltage could not be achieved under vacuum conditions, as gas desorption was encountered at 320kV. We think that ceramic might charge up with electron-hole pairs due to x-rays produced during voltage-induced gas desorption.

Observations of onset voltage (kV) for gas desorption vs logarithmic Kr pressure (Torr)



This effect has been previously observed

Insulating properties of high vacuum

R. Hawley, B.Sc., Ph.D., A.Inst.P., A.M.I.E.E., A. A. Zaky, B.Sc., M.S., Ph.D., A.Inst.P., A.M.I.E.E., and M. E. Zein Eldine, B.Sc., Ph.D., A.Inst.P., A.M.I.E.E.

Synopsis

Recent experimental work on the insulating properties of high vacuum is systematically reviewed. A résumé of the prebreakdown conduction phenomena is given; in small gaps, the steady prebreakdown currents appear to be due to a modified type of field emission, while in longer gaps the contamination on the electrode surfaces gives rise to an ion-exchange mechanism, which is responsible for the microdischarges associated with these gaps. The parameters affecting the breakdown strength of a vacuum gap, and the different hypotheses postulated to explain the mechanism of breakdown, are considered in detail. No single hypothesis is able to account for all the experimental results reported, but it appears that a transition from one type of mechanism to another takes place as the interelectrode gap is increased.

The paper also considers the important practical aspects of breakdown across solid insulating surfaces in vacuum.

List of symbols

V = voltage
V_B = breakdown voltage
E = nominal stress, V/cm
E_A = actual stress, V/cm
d = gap, cm
d_e = effective gap, cm
m = intensification factor
α, a, b, K = constants
A = average number of positive ions produced by one electron
B = average number of secondary electrons produced by one positive ion
C = average number of photons produced by one electron
D = average number of secondary electrons produced by one photon
G = average number of negative ions produced by one positive ion
H = average number of positive ions produced by one negative ion
G_1 = average number of H^- ions produced by one 250kV H^+ ion
H_1 = average number of H^+ ions produced by one 250kV H^- ion
J = current density, A/cm^2
ϕ = work function, eV

1 Introduction

The increasing interest in the electrical insulating properties of high vacuum is indicated by the number of papers published on the topic (Table 1). In addition to the use in devices such as high-power vacuum switches, electronic valves, particle accelerators and separators, there is the recent requirement for high-voltage apparatus, such as electrostatic generators, to operate in outer space and to make use of the vacuum environment as a dielectric.[1–3]

There have been several papers reviewing both the electrical properties of vacuum and the hypotheses attempting to explain the mechanism of the breakdown process.[4–9] The present paper, while being complete in itself, should be regarded as a supplement to one of the previous papers,[4] as it mainly reviews the experimental results that have become available during the last two years.

Vacuum breakdown between two electrodes is said to take place when the mean free path of any electrons is greater than the distance between the electrodes. Thus the multiplication of charged particles by collision in the space between the electrodes is insufficient to create a self-sustaining discharge. In the gap range normally considered (<1cm) this occurs when the pressure in the gap is less than 10^{-3}torr. If no multiplication of charged particles by collision were to take place, it would be reasonable to assume that vacuum would be a perfect insulator. However, the existence of metallic and insulating surfaces within the vacuum, and the effects of residual gas and oil vapours, complicate the issue so that a sufficiently high applied voltage will cause breakdown.

Although for very small electrode separations (<0·01 mm) the stress for breakdown is high (~10^6 V/cm), it falls rapidly with increase in gap until for long gaps (~100m) it is much[5] smaller (~10^4 V/cm). In this case stress is taken as the voltage to cause breakdown divided by the electrode separation, no allowance being made for stress concentration at asperities on the electrode surfaces. Thus, in discussing prebreakdown conduction and the various vacuum breakdown hypotheses, it is useful to distinguish between the effects occurring in small gaps (<1 mm) at high stresses, and the effects taking place in long gaps at the relatively low stresses.

Table 1

INCREASE IN NUMBER OF PUBLISHED PAPERS ON THE TOPIC OF VACUUM BREAKDOWN

Period	Number of published papers
1911–1915	1
1916–1920	1
1921–1925	3
1926–1930	16
1931–1935	26
1936–1940	14
1941–1945	7
1946–1950	20
1951–1955	92
1956–1960	104
1961–1963	94*

* 3 years only

Paper 4583 S, first received 23 October 1963 and in revised form 13th February 1964. It was presented at the Conference on Dielectric and Insulating Materials, 8th April 1964
The authors are with C. A. Parsons and Co. Ltd., and Drs. Zaky and Zein Eldine are on leave from Alexandria University, UAR

gap current. However, using a 0·5mm gap and copper or nickel electrodes, Mainland[57] has shown that a pressure increase from 10^{-5} to 10^{-4}torr, under continuously pumped conditions, increased the statistical time lag to breakdown. He indicated that this may be caused by molecules interacting with the emitted beam or interfering with the emission process at the cathode.

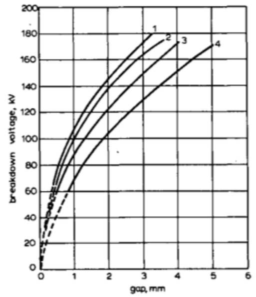


Fig. 4
Effect of electrode geometry (after Pivovar et al.[50])

Electrode material: copper

	Anode diameter	Cathode diameter
1	5	45
2	12	45
3	45	12
4	45	45

With larger gaps, there is a definite pressure effect. In the gap range 1·5–7cm, with a glass cathode and a stainless-steel anode, Murray[48] noted luminous patches on the cathode. The introduction of various gases at a pressure of a few tenths of a millitorr to a few millitorrs caused the luminous patches to disappear and the voltage could then be raised until factors other than the vacuum breakdown limited the applied voltage.

Athold[40], using a 0·16cm-diameter sphere opposite a plane cathode and a gap of 20cm, obtained the results shown in Fig. 5*a*. The breakdown voltage was essentially constant for pressures less than 5×10^{-6}torr, but rose with increasing pressure to a maximum at 5×10^{-4}torr. With further increase in pressure, the voltage fell sharply and a continuous dark discharge took place. Similar results have been repeated by Germain and Rohrbach[58] (Fig. 5*a*).

Ramm[59] noted a similar effect when studying the properties of a bushing for use in an electrostatic particle separator. In the curve he obtained (Fig. 5*b*) each experimental point represents a condition of low current and a few sparks per ten minutes. Again the breakdown voltage rose to a maximum at about 10^{-4}torr. The limit of 600kV in this case was the maximum voltage output of the generators used for the tests.

3.4 Voltage effects

3.4.1 Rate of rise of voltage

Wijker[37] has observed that the impulse breakdown voltage initially decreased with increase in rise time to a minimum at 5μs, and then rose to a maximum between 50μs and 100μs, after which it fell again. Farrall[60] has carried out a theoretical analysis on the effect of rate of rise of applied potential assuming a 'clump mechanism' applies (see Section 4.3). He was unable to explain the effect noted by Wijker, but this may be due to the clump mechanism not being operative in such small gaps.

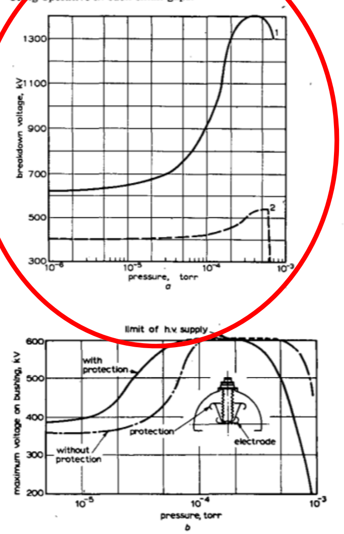


Fig. 5
Effect of pressure on the breakdown voltage of long gaps and across an insulator

a Breakdown in vacuum gap

Electrode material	Gap
1 Stainless steel	20cm (after Arnold et al.[40])
2 Stainless steel	5cm (after Germain and Rohrbach[58])

b Breakdown across an insulator (after Ramm[59])

3.4.2 Frequency

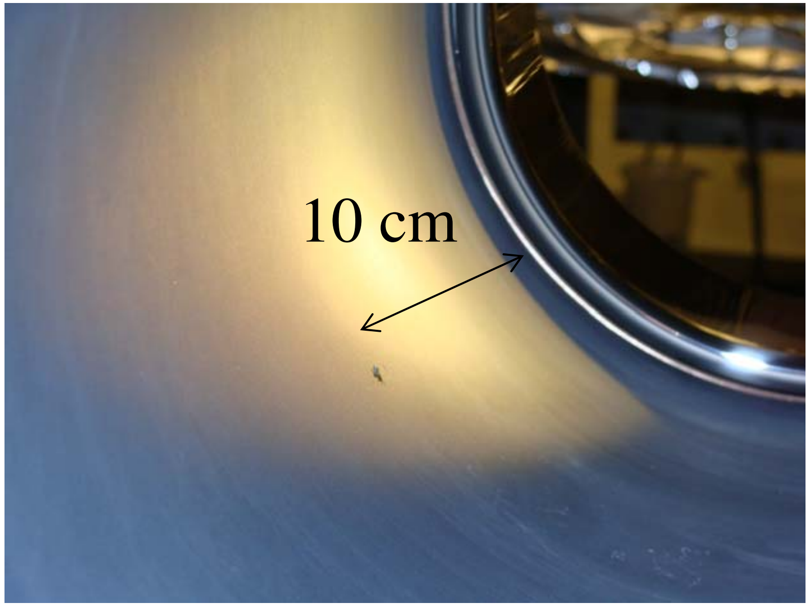
While results for long gaps indicated that increasing the frequency raised the breakdown strength,[4] Little *et al.*[21] showed that, for a small gap, there was no dependence of breakdown voltage on frequency in the range 60c/s–6Mc/s.

3.5 Recovery of the insulating property of a vacuum gap after breakdown

Maitland[61] investigated the rate of recovery of the insulating property of a vacuum gap after a breakdown caused by a 4·5μs pulse. He found that the gap recovered at a rate of about 10kV/μs during the first 5μs and at 0·01kV/μs after about 100μs. He suggested that the incom-

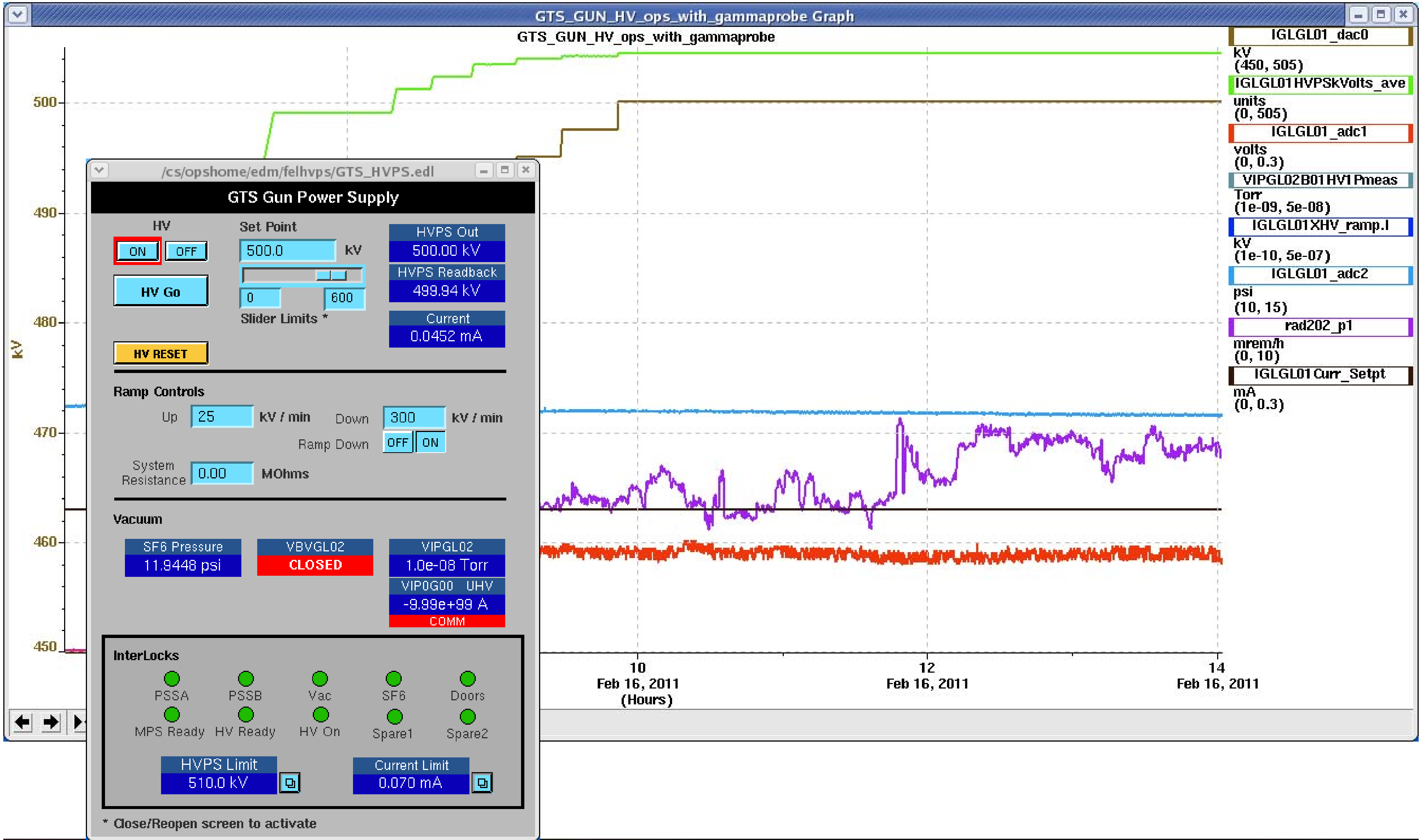
Puncture in the bulk resistivity insulator

Picture of the puncture taken from the inside of the insulator

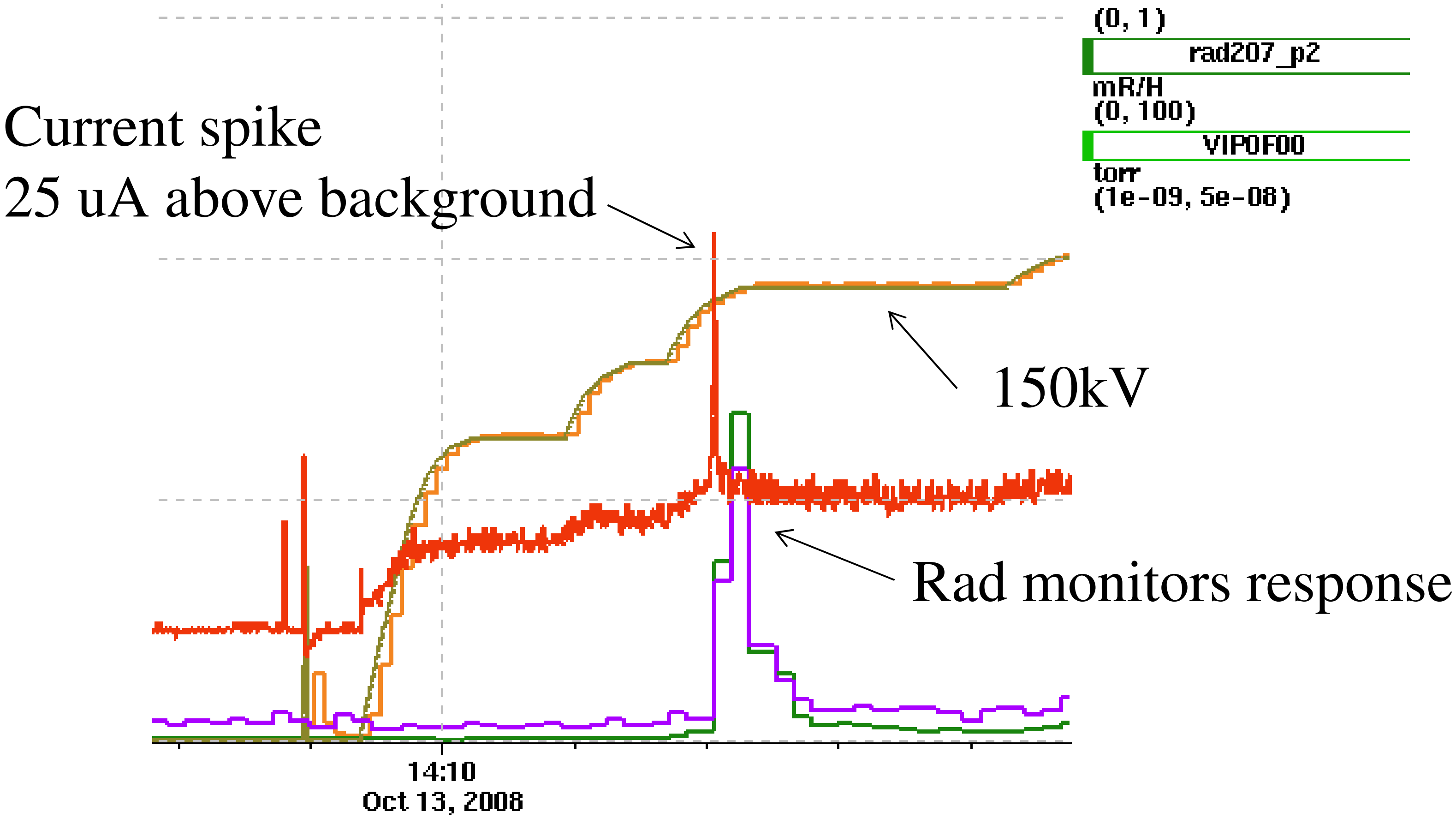


Puncture is about 10 cm from ground-end ring (highest field 12 MV/m @ 500kV

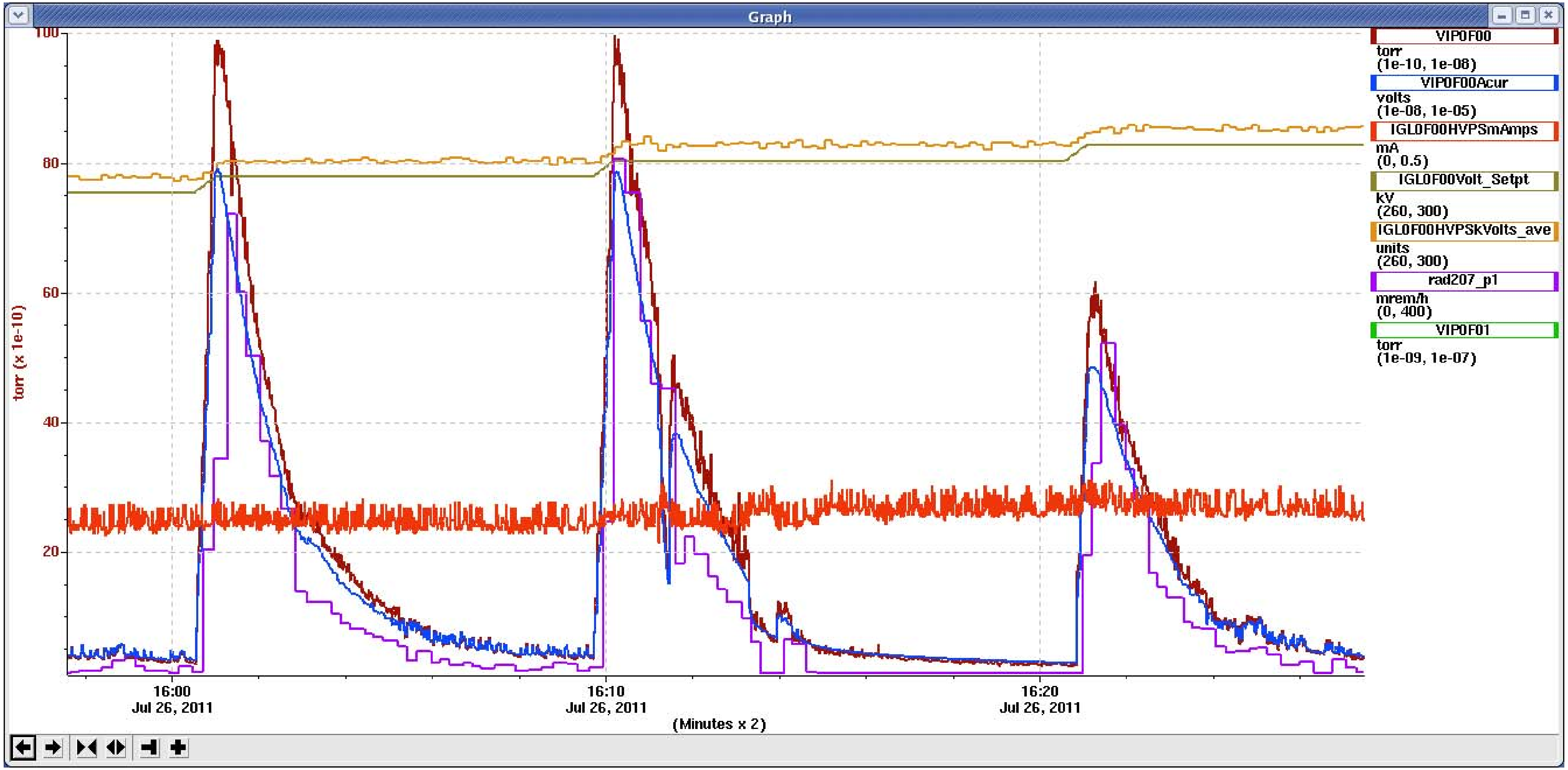
GTS Gun holding 500kV w/Kr at 1E-4 Torr



Typical field emission processing w/Kr at 1e-5 Torr



Typical voltage-induced gas desorption under vacuum conditions



Notice how radiation and vacuum changes with 1 kV steps. Current tracks vacuum and radiation but is only noticeable on strip chart recorder, about 10 uA increase with every kV step.