Study of vacuum RF Breakdown in 805MHz pillbox cavity in strong magnetic field

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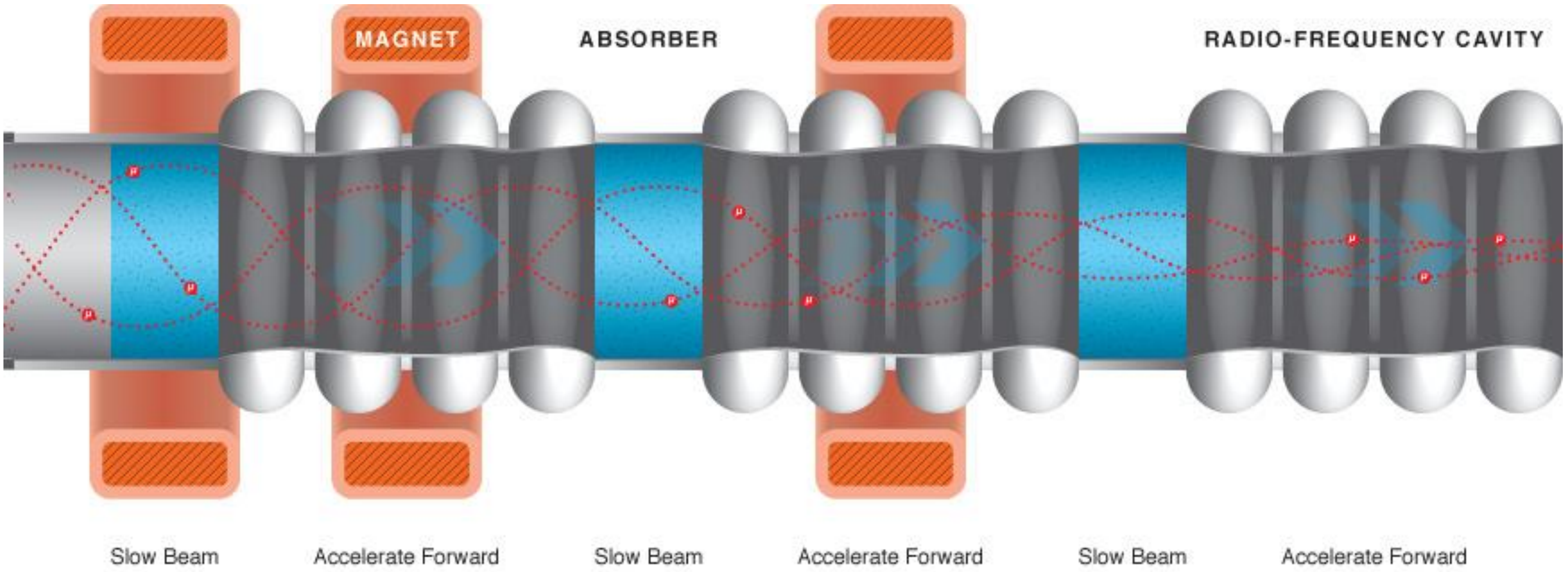
Today you will hear about

- Statement of the problem
- MTA work overview
- Modular cavity program
- Experimental results
- Analysis and future plans

BD in strong magnetic fields - applications

- Any RF system in external magnetic field
- RF gun design
- Klystron lifetime
- Tokamak conditioning
- Muon cooling channel

Example: Muon cooling channel

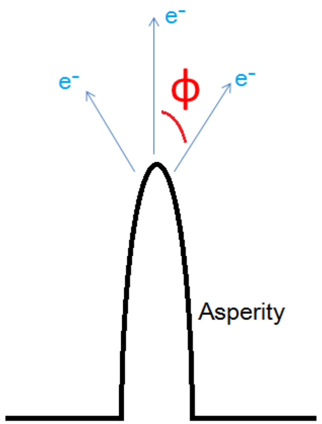


Problem roots

- Muon has a lifetime of 2.2μs
- Designs of cooling channel require accelerating gradient of tens MV/m
- Gradient is restricted by RF breakdown (BD)
- Breakdown rate should be kept small. Maximum gradient with BD rate lower than 10^{-5} defines the safe operating gradient (SOG)
- It was experimentally shown that strong magnetic fields decreases max safe operating gradient

RF Breakdown - “conventional wisdom”

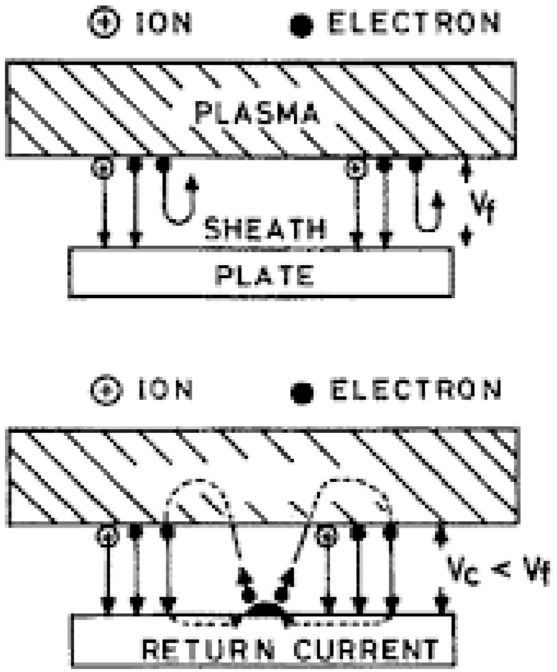
- Metallic protrusions on RF surface create high E field regions
- That leads to enhanced filed emission currents
- Increasing density of surrounding plasma sheath
- Eventual arc - breakdown



- Several groups worldwide (Fermilab, SLAC, CERN, ANL etc.)
- Extensive particle simulation efforts
- More attention to X-Band and higher frequency structures

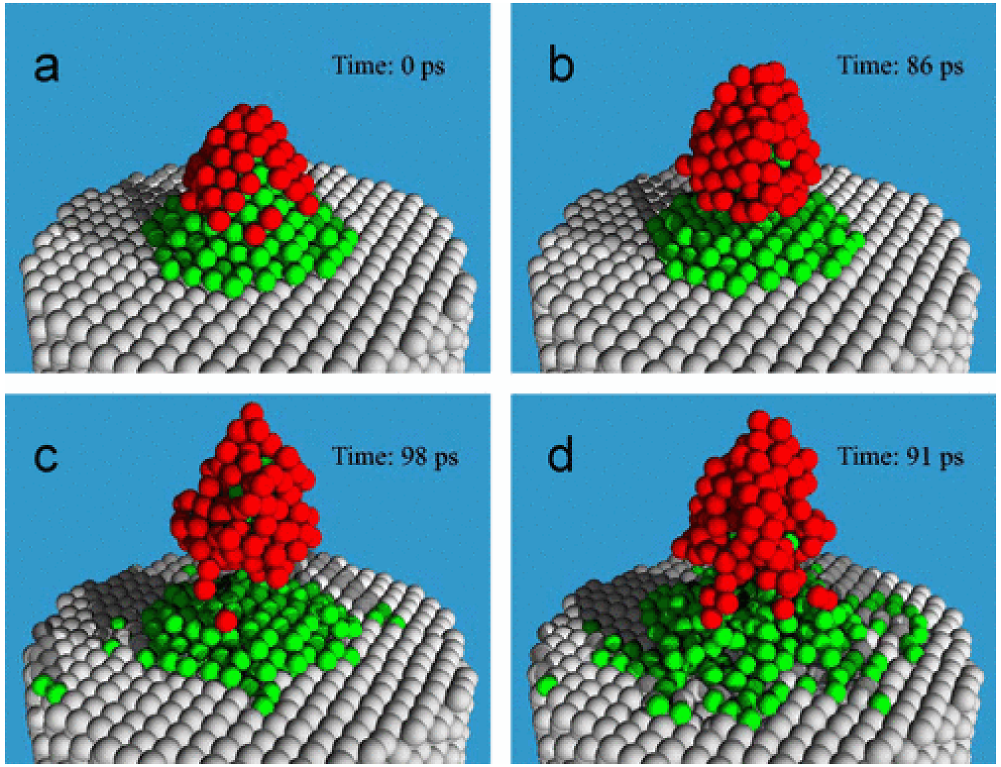
Approaches various groups are taking to study a problem of breakdown

Unipolar arc model



F.Schwirzke, Unipolar arc model, Journal of Nuclear Materials 128 & 129 (1984) 609-612

Example of molecular dynamics approach

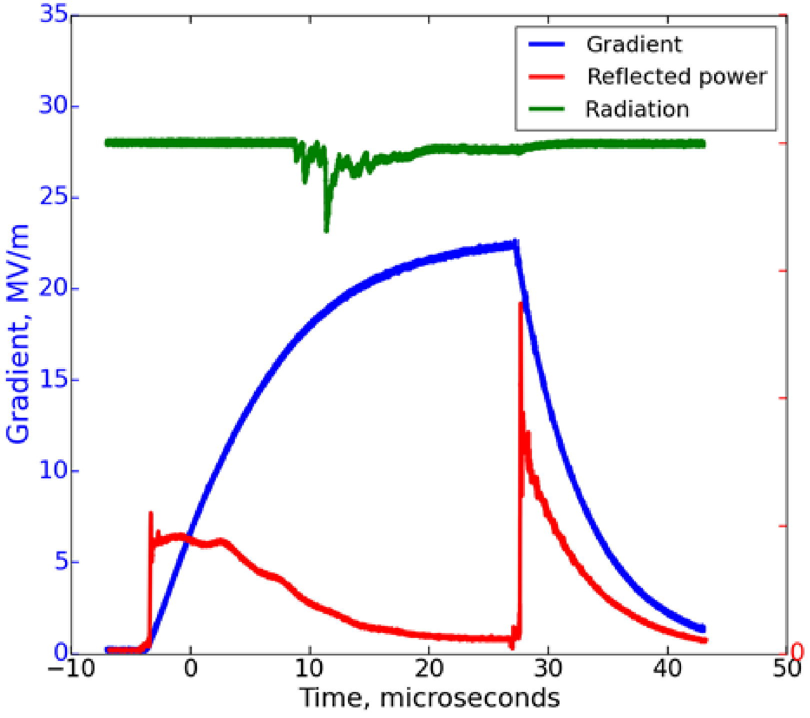


J.Norem et al. *New mechanism of cluster-field evaporation in RF breakdown, Phys. Rev. ST Accel. Beams* ***7****, 122001*

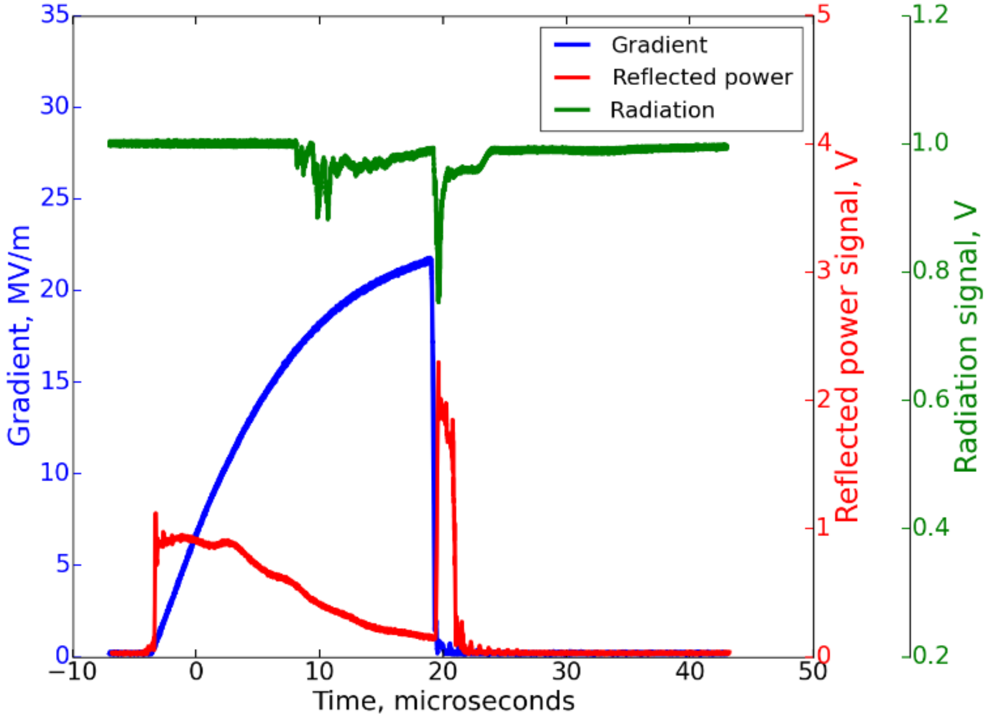
Observation of breakdown event

- Drop in pickup voltage
- Burst in vacuum
- Spikes in radiation, field emission
- Early spike in reflected power
- Sound

Normal pulse



Breakdown pulse



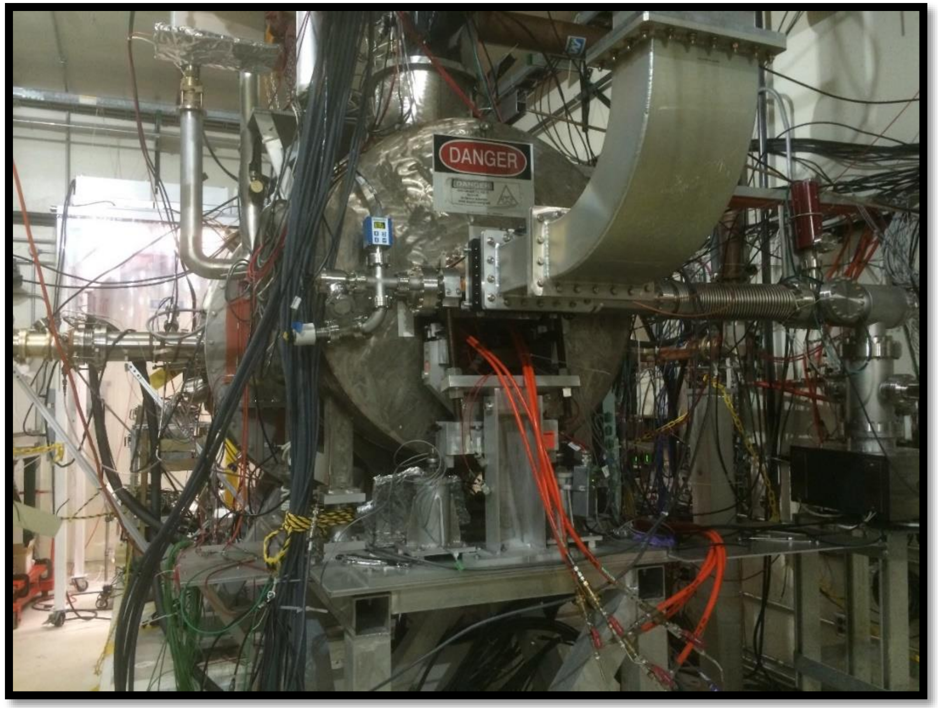
Mucool Test Area (MTA)

Facility built specifically for muon cooling hardware R&D

- Capacity to test 201 and 805MHz cavities in strong magnetic field
- H- beamline passes through the center of magnet bore
- Infrastructure for clean room assembly and inspection
- Extensive instrumentation for BD characterization
- Run control system to detect breakdown events and record relevant data streams

Current experimental programs

- 805MHz: Modular cavity, high-pressure gas-filled cavity
- 201MHz: pillbox MICE cavity



MTA hall: solenoid magnet with inserted 805MHz modular cavity

Data acquisition and run control system

- Trigger system for breakdown detection
- Fast oscilloscopes to record time sensitive signals <- Labview
  - Cavity pickups
  - Light signal from optical fibers
  - Scintillators (X ray detection)
  - Forward and reflected power
- Vacuum pressure data
- Temperature sensors
- Spark acoustic localization

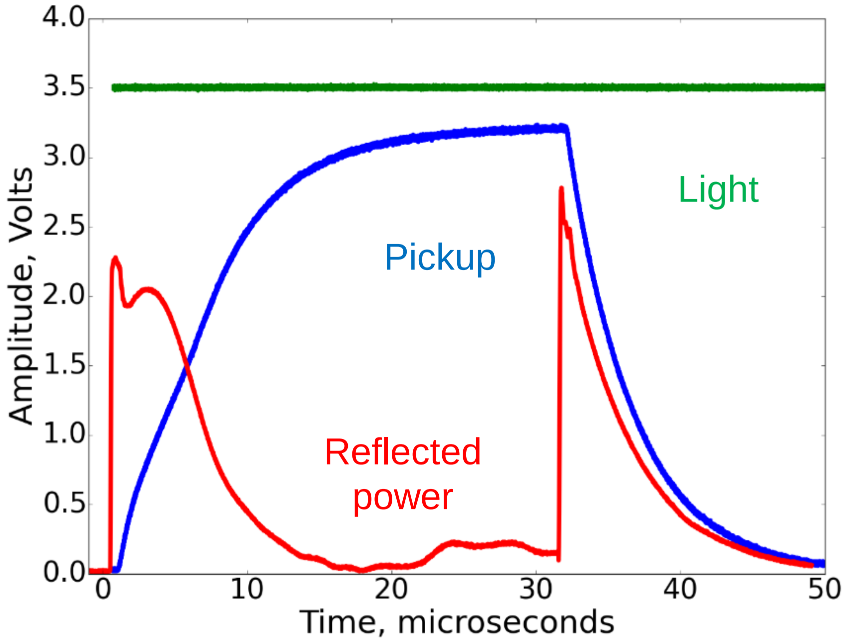
Run control station at the linac gallery

How do we detect sparks?

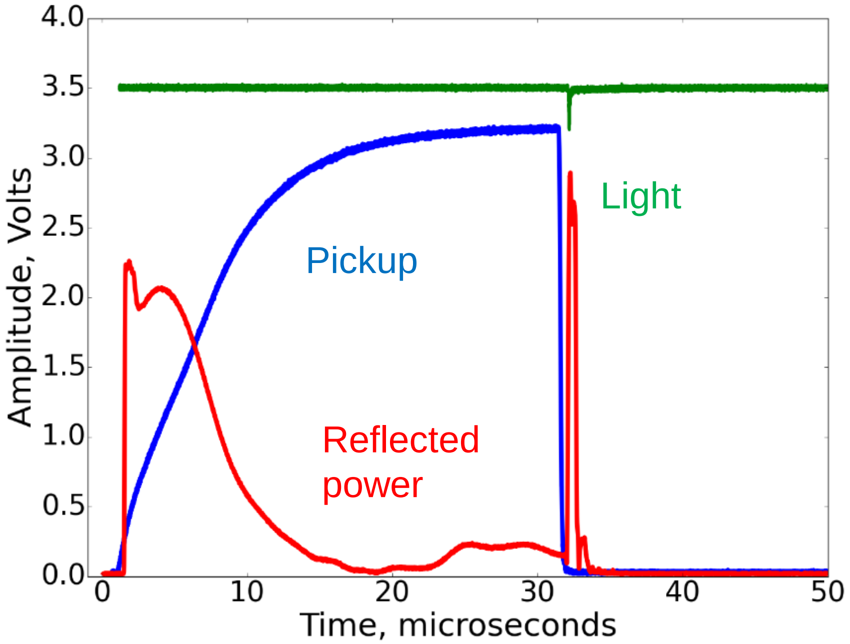
Automated system for spark detection - logical OR between:

- Abrupt drop in pickup voltage
- Flash of light from optical ports
- Early spike in reflected power

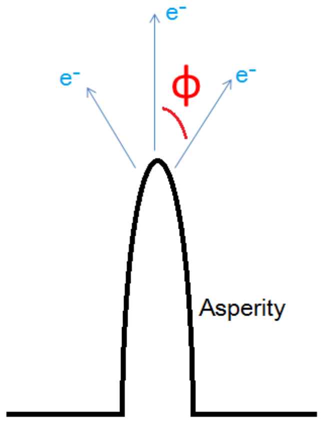
Normal event



Breakdown event



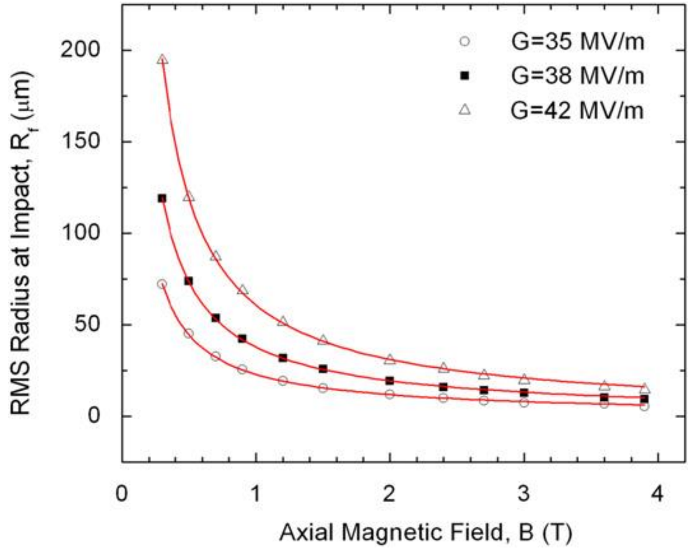
Model explaining deterioration of gradient in strong B fields

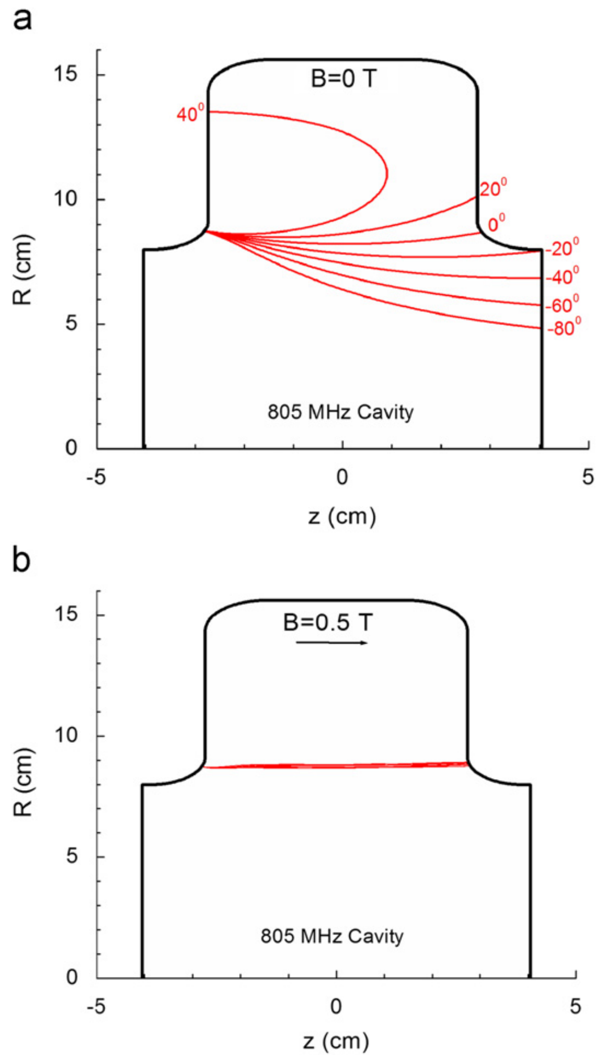


- Electron field emission from surface imperfections
- B field focuses dark current into beamlets
- **Beamlets cause pulsed heating that leads to surface damage**

Potential mitigations:

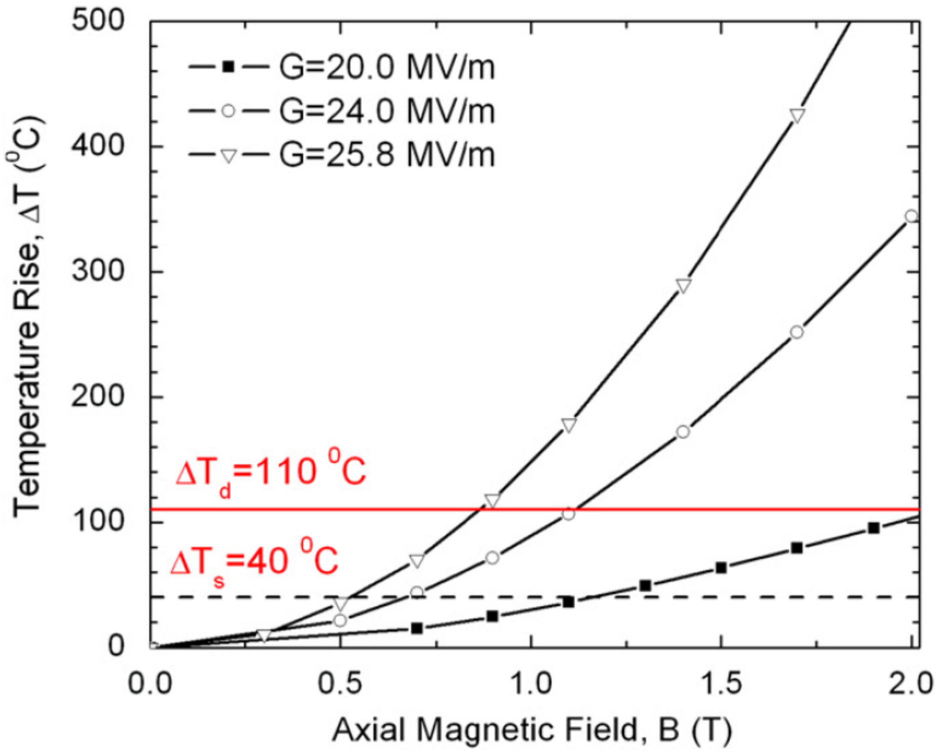
- Surface treatment
- Use higher radiation length materials (Be)
- Decrease impact energy of electrons
  - Longer RF gap
  - Change B || E configuration



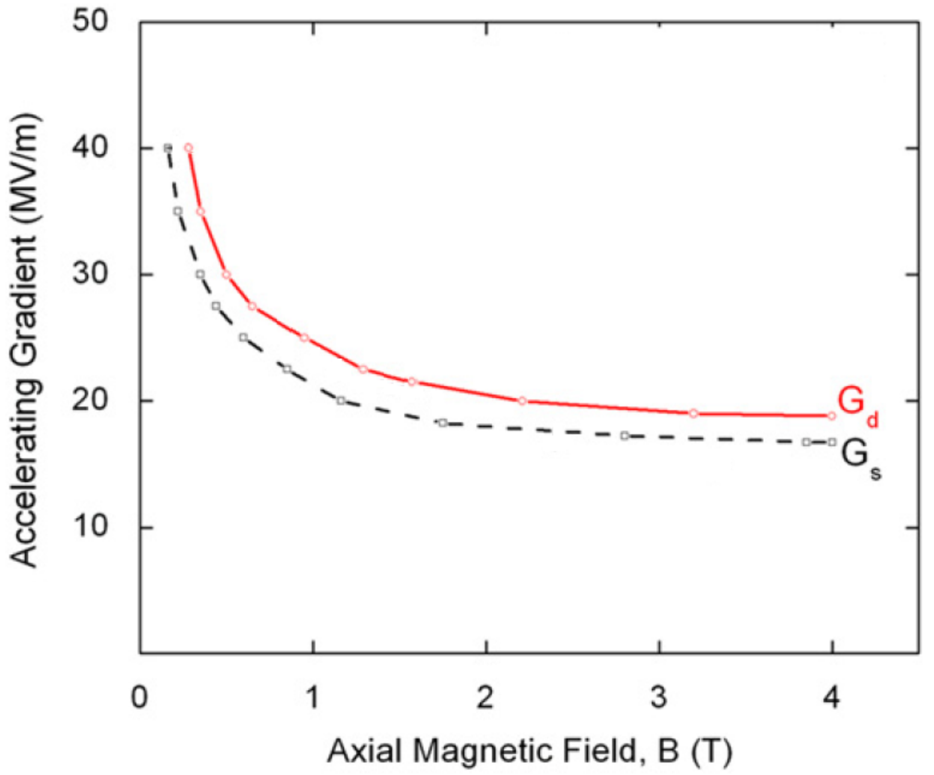


D.Stratakis , J.Gallardo, R.Palmer, Nucl. Inst. Meth. A 620 (2010), 147-154

Mechanical stress on the metal is induced due to temperature rise



Temperature rise model for 805MHz copper pillbox



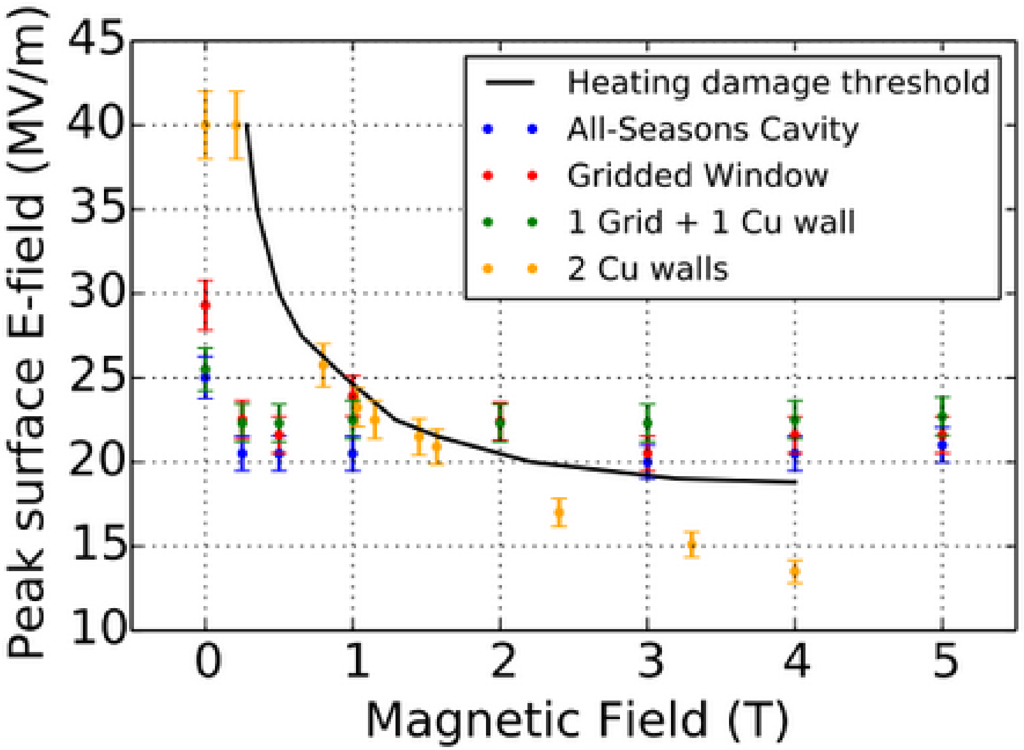
Model prediction of max safe gradient in external magnetic field G_s

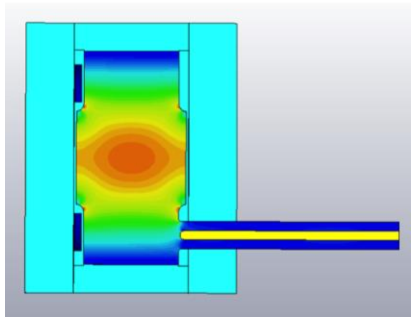
ΔT_s - safe pulse heating temperature for copper
ΔT_d – required temperature for surface fracture

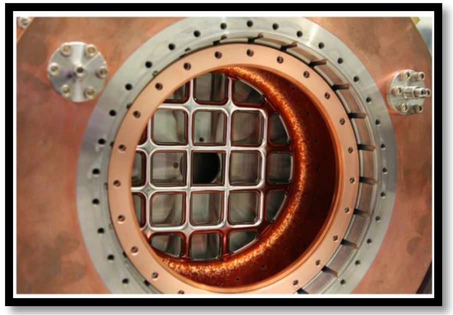
D.Stratakis , J.Gallardo, R.Palmer, Nucl. Inst. Meth. A 620 (2010), 147-154

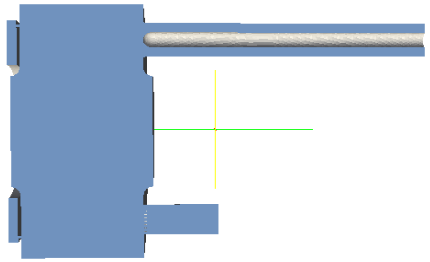
Model of a breakdown in strong B field – prediction vs experiment

High power behavior of previous cavities

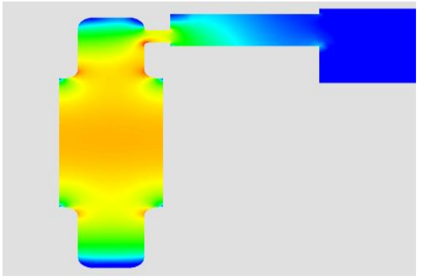








All-Seasons Cavity



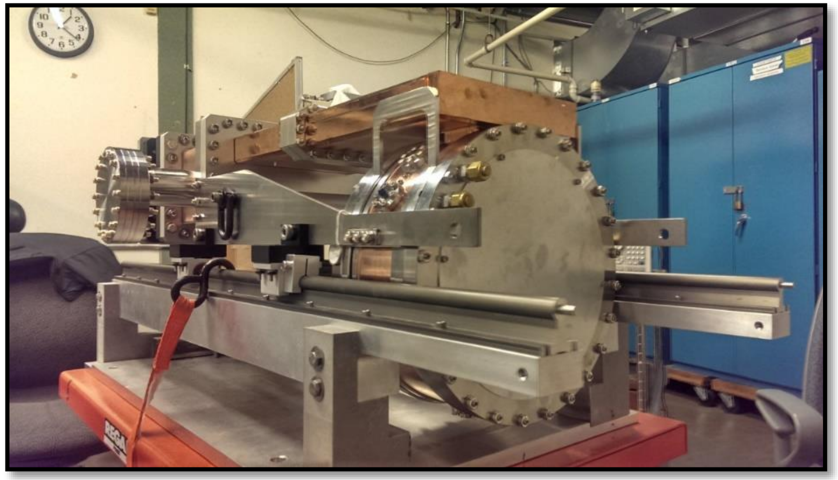
Pillbox cavity

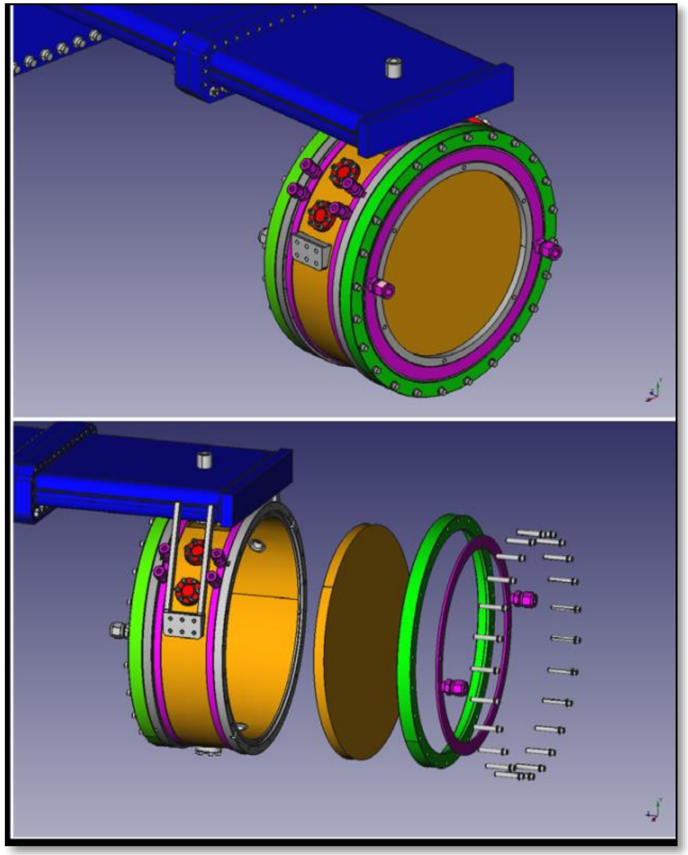
Study of Breakdown with better control over systematic error is required

Factors that may affect the fit quality:

- Conditioning history
- Local field enhancement around coupler regions
- Surface treatment

Modular cavity





- Pillbox geometry
- End walls can be un-mounted easily
- Allows for end wall material swap
- Low E fields in the coupler region
- Water cooling lines
- Center section could be replaced or extended to different gap length

Modular cavity has unique measurement capabilities

- Allows for careful control over experimental conditions
- Evaluate different materials
- Perform frequent inspections to track surface state

Goal: to build a coherent picture of processes

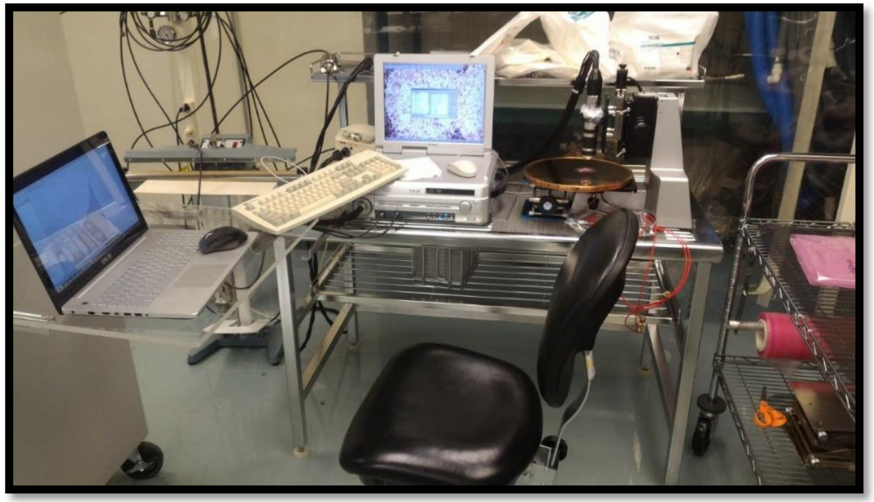
inside the cavity during breakdown

Modular cavity: measurements we aim to make

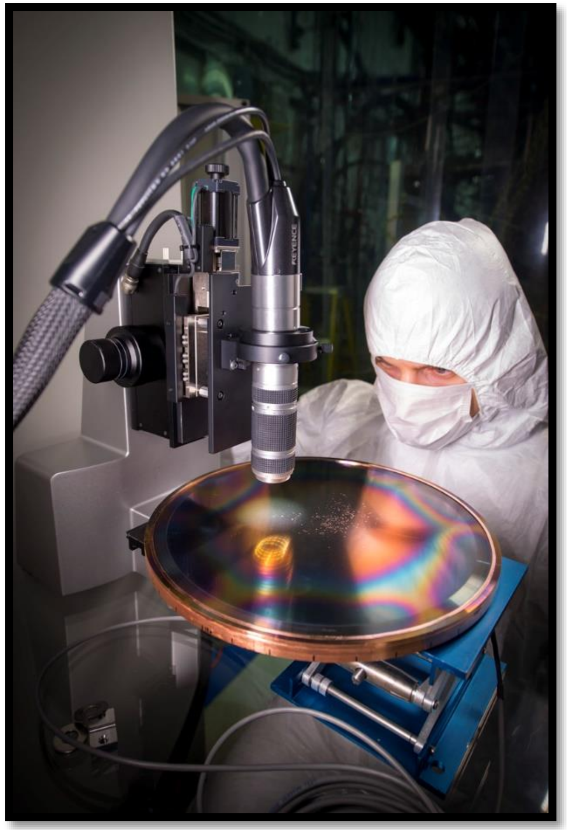
- Maximum safe operating gradient in zero and non-zero B field
- Damage formation process dependence on the run conditions
- How does the high-power conditioning sequence affect breakdown behavior in strong magnetic fields?
- Field emission study to verify the model of pulsed heating
- Study of surface evolution process

Surface microscopic study

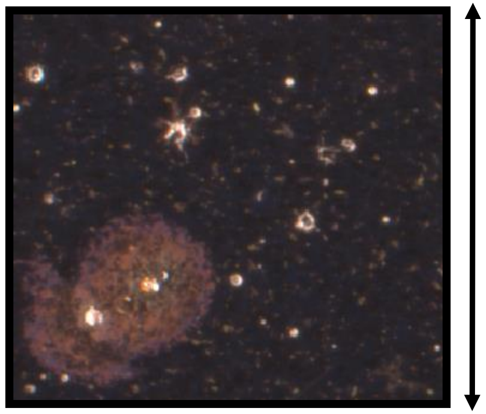
Cabinet is designed to operate in a portable clean room.



Inspection setup at A0 clean room

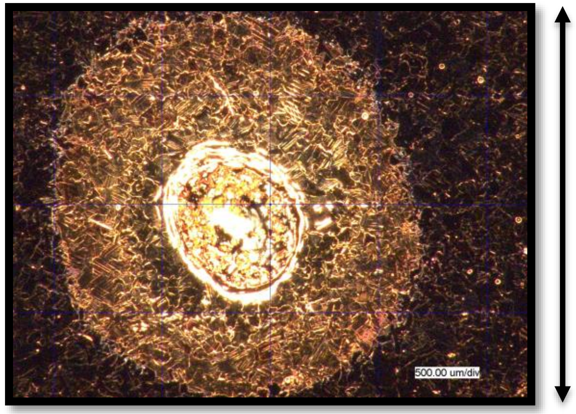


Inspection process



5mm

Example of scanned image



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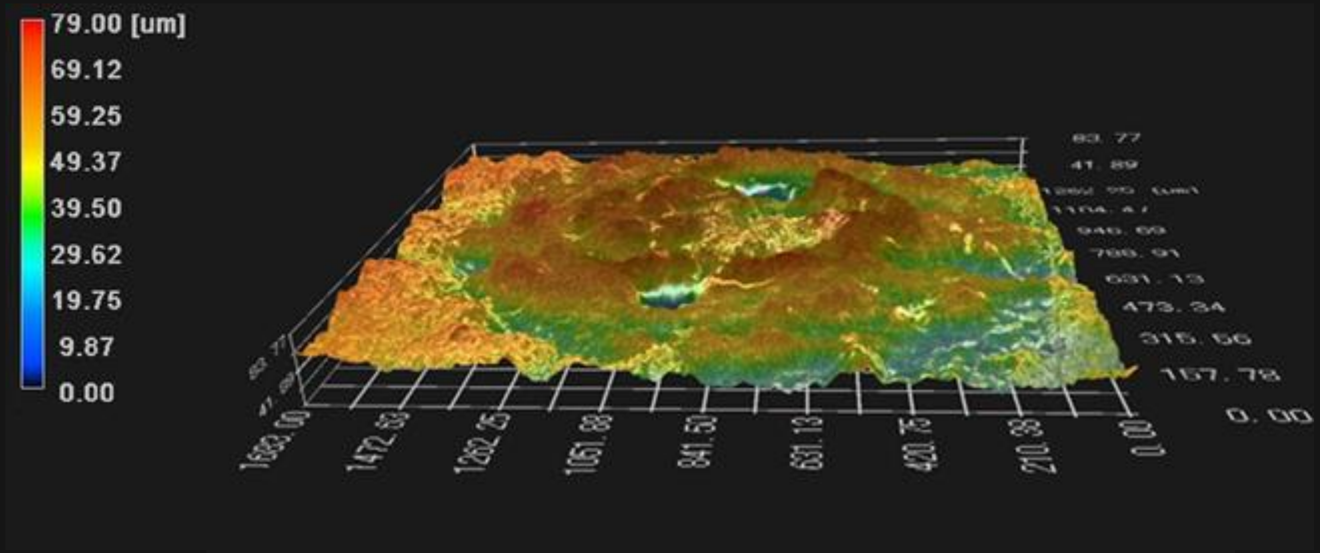
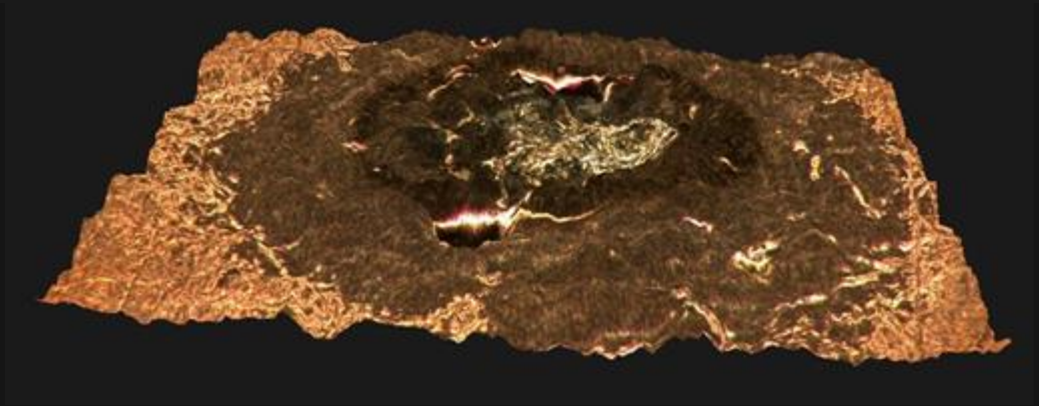
Microscopic image of damage

We have the ability to do 3D imaging





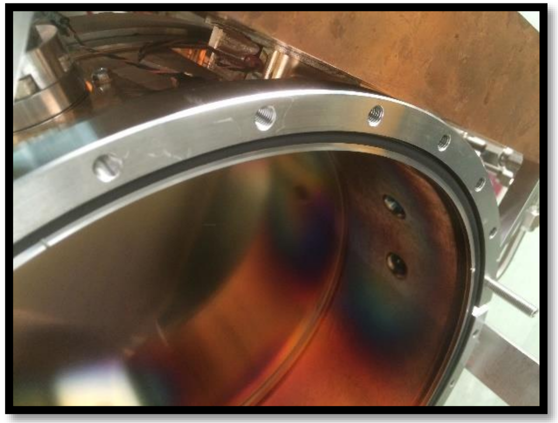
Depth From Defocus (D.F.D.) to construct 3d model

Estimate deposited energy by amount of melted material

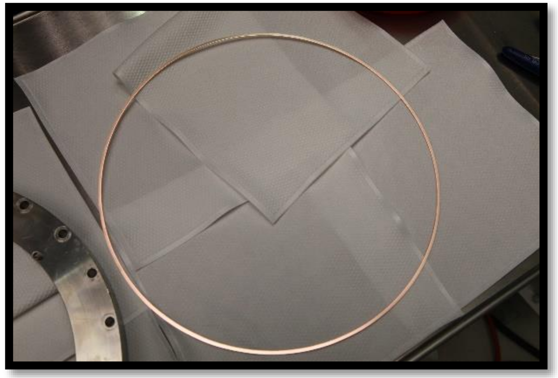
Quantitative estimation of breakdown pit structure

Surface roughening from BD may induce future sparks

MC: consistency of Qs and resonant frequency



Vacuum and RF seals



Copper gasket for RF contact

Date	f_o, MHz	Q
02-Feb-16	804.58	22,400 ± 300
26-Jan-16	804.59	21,900 ± 300
20-Jan-16	804.58	22,100 ± 300
22-Dec-15	804.49	23,000 ± 300
3-Dec-15	804.54	23,000 ± 300
14-Oct-15	804.32	23,000 ± 300

Measured RF parameters of Modular cavity

Modular cavity: run history, preliminary results

- First B=0T run: April – October 2015
  - Maximum Safe Operating Gradient of order of 45MV/m
  - 130 sparks detected
- First B=3T run: December 2015
  - Stable operation below 12MV/m
  - 55 sparks detected
- “Conditioning” B=0T run
  - Conditioned up to ~22MV/m inflicting 460 sparks
- Second B=3T run
  - In progress. Stable operation below 12MV/m

Establishing safe operating gradient: algorithm

Maximum safe operating gradient (SOG) - maximum surface gradient for which the breakdown rate is below 10^-5

1. Ramp up until spark happens at gradient G
2. Hold at G to establish the estimate of BD rate

    If estimated BD rate is much lower than 10^-5, return to step 1

    If estimated BD rate is higher than 10^-5, stay at G

3. Determine BD rate by observing at least 10 sparks at fixed gradient

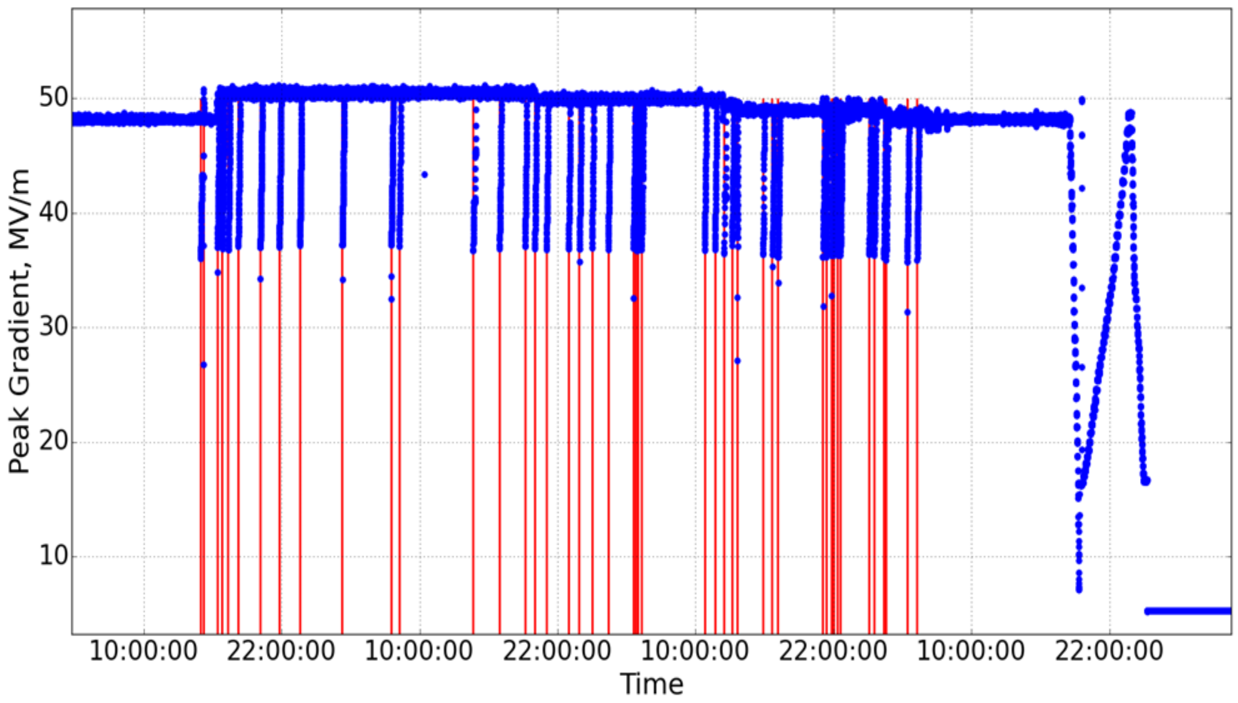
    If determined BD rate is > 10^-5, take a dG step back

    If determined BD rate is <10^-5, continue from step1.

Comment: time constraint consideration may our effect choices

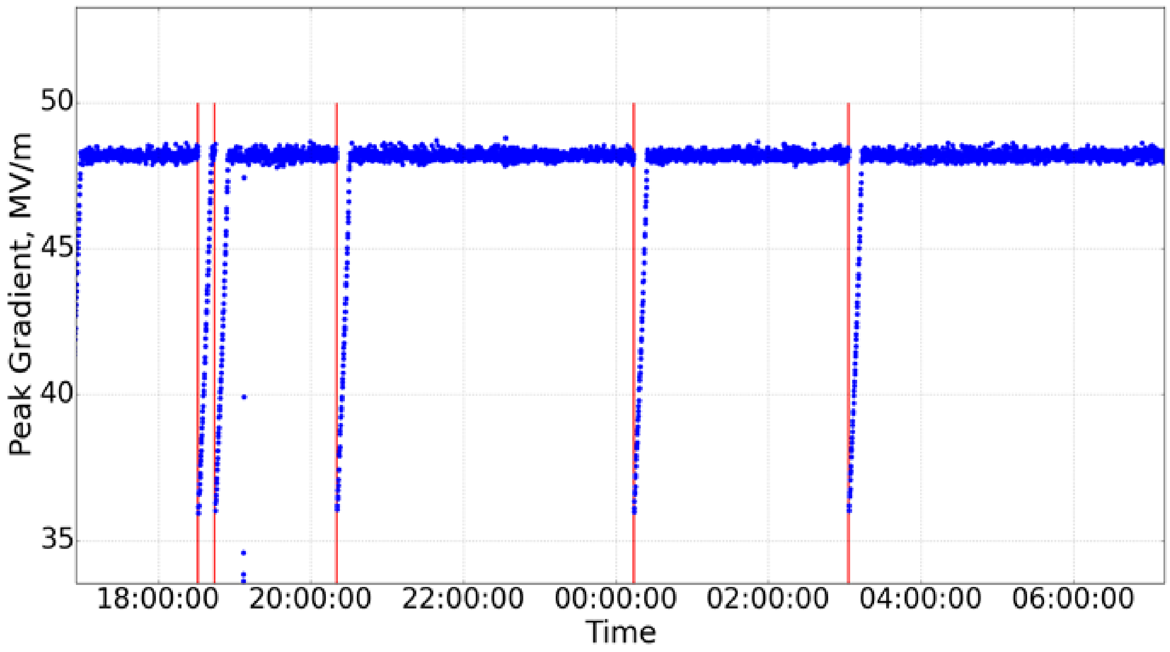
Establishing Safe Operating Gradient (SOG)

Run history at the end of first B=0T, showing process of establishing SOG



Red lines mark spark events
Blue dots represent measurement of gradient in 10s intervals
(Gradient is logged at 1Hz)

Zoomed-in part of the graph, illustrating breakdown events

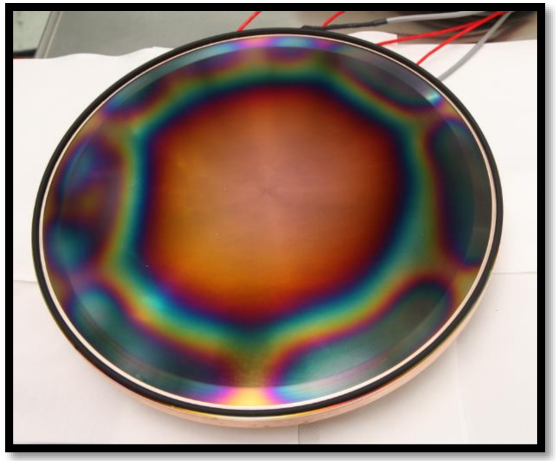


Run control software automatically cuts power by 3dB when a spark is detected

Inspection after first B=0T run

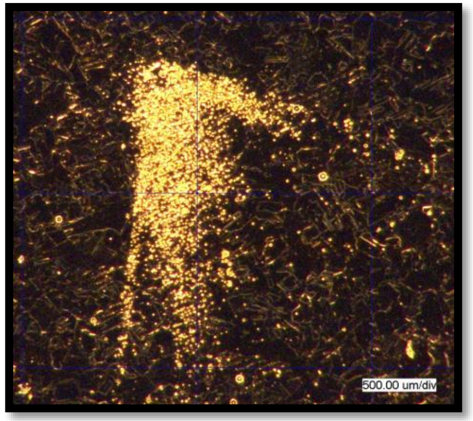
- Cavity ran up to ~50MV/m
- 130 breakdown events detected

- Documented ~500 damage features

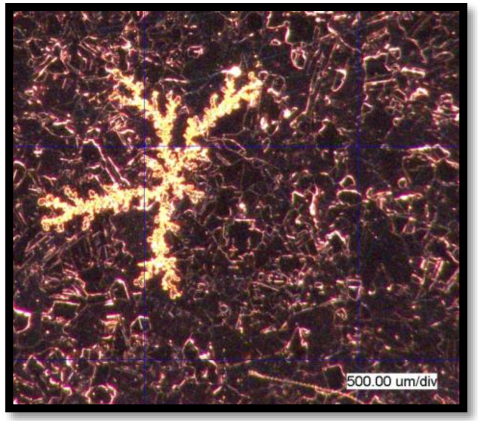


Downstream endplate

Examples of most common types of damage

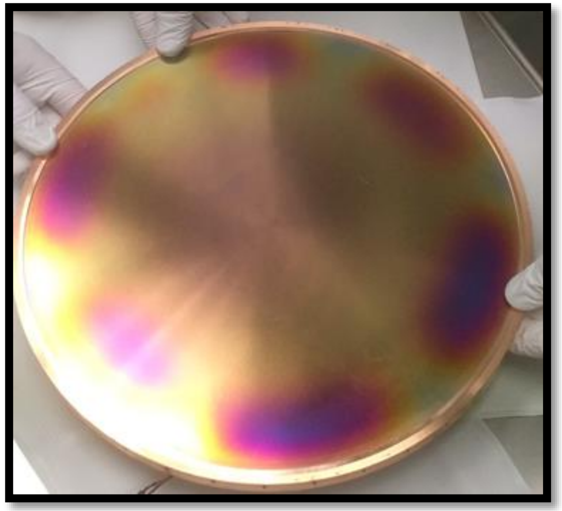


“cluster”



“fractal”

1mm

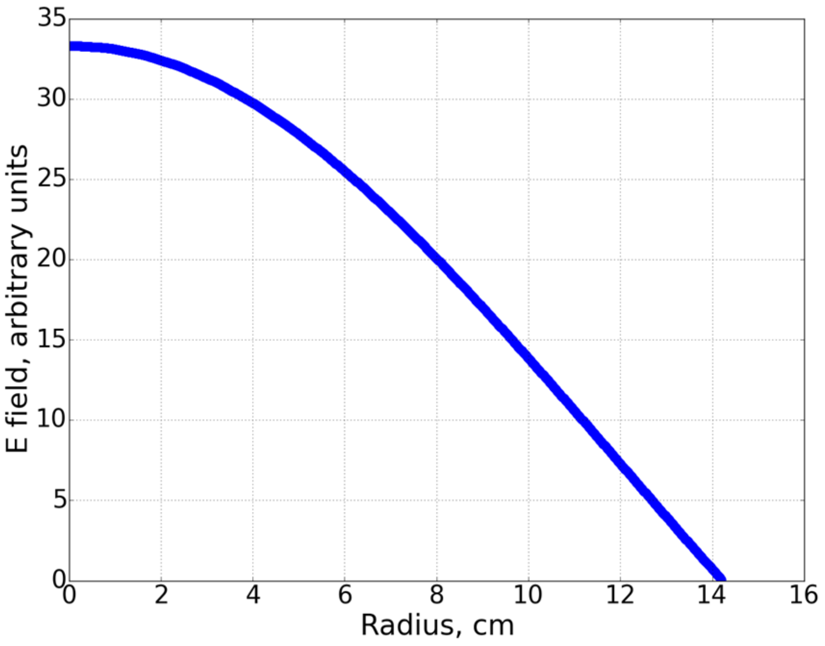


Upstream endplate

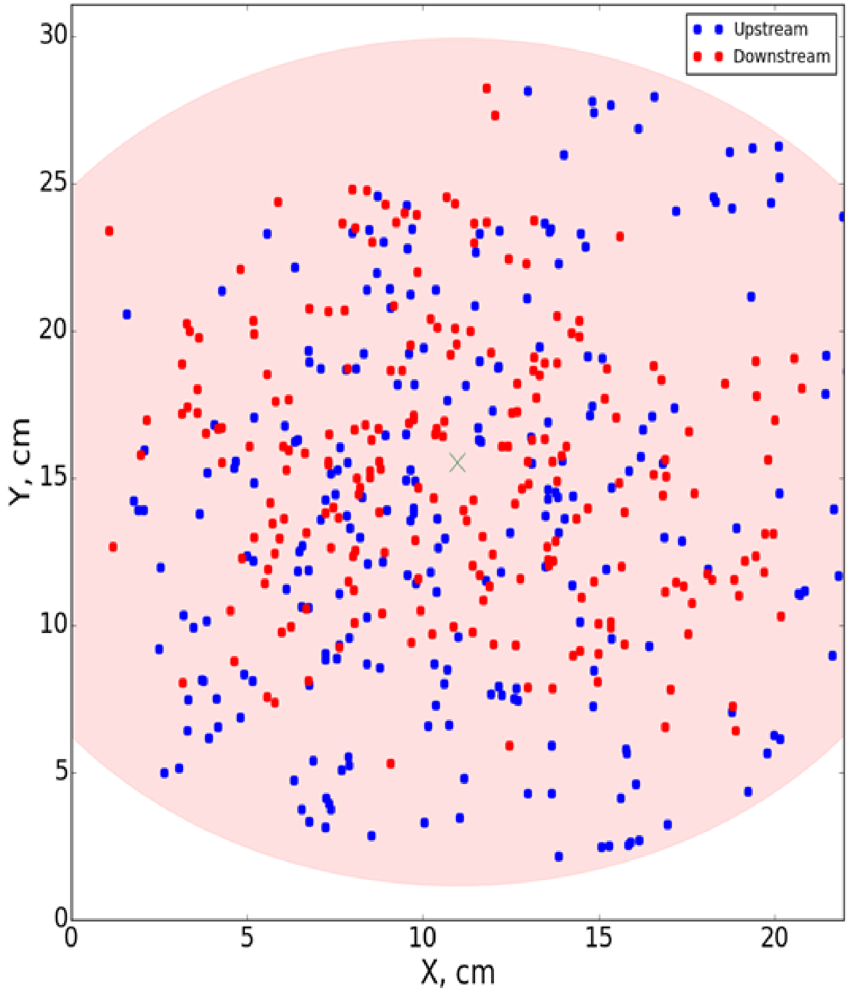
Inspection after first B=0T run

- Damage distributions on both endplates does not correlate with each other
- Distribution is uniform and does not follow Bessel-like E(R) dependence

Simulated E(R) dependence



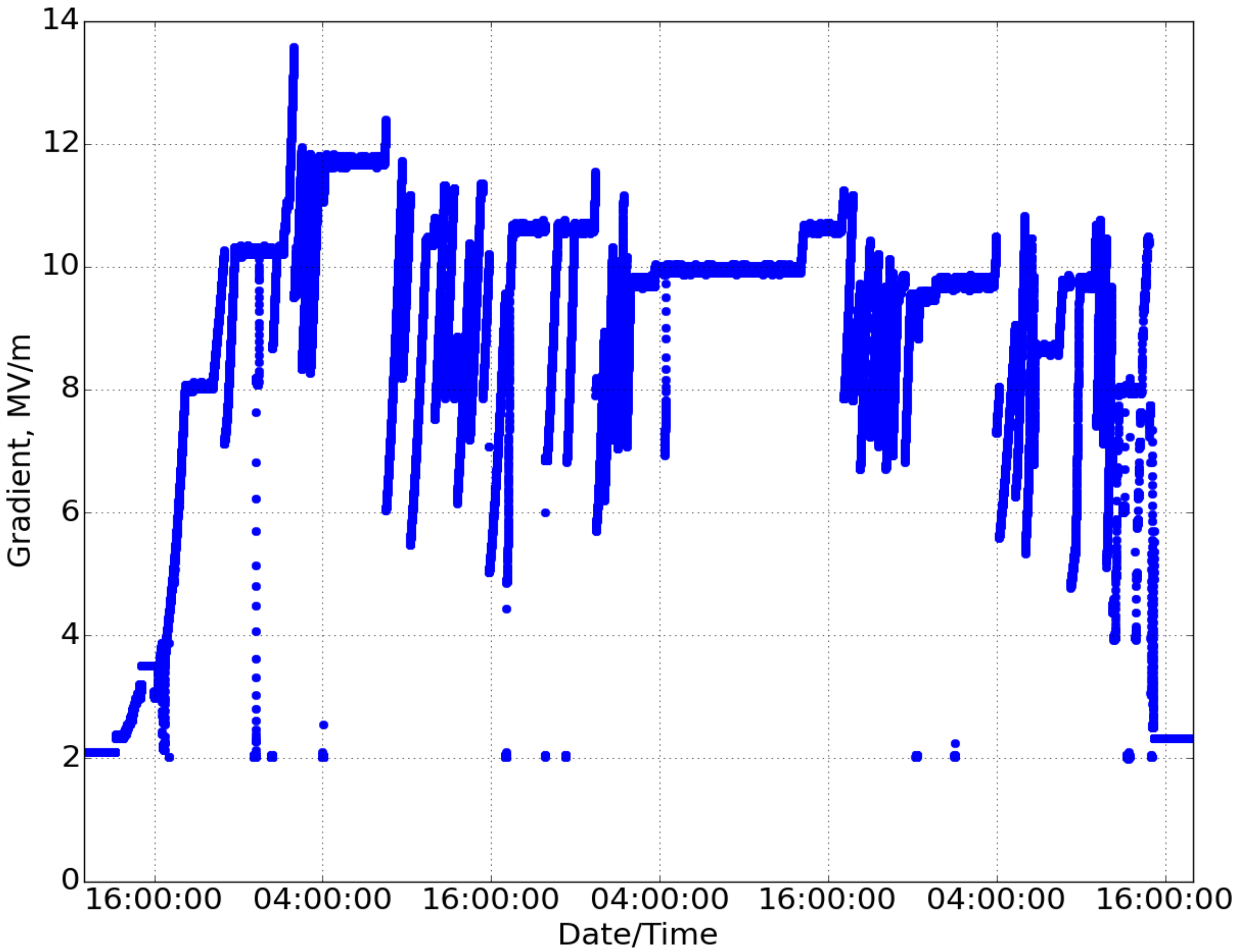
Map of observed damage sites



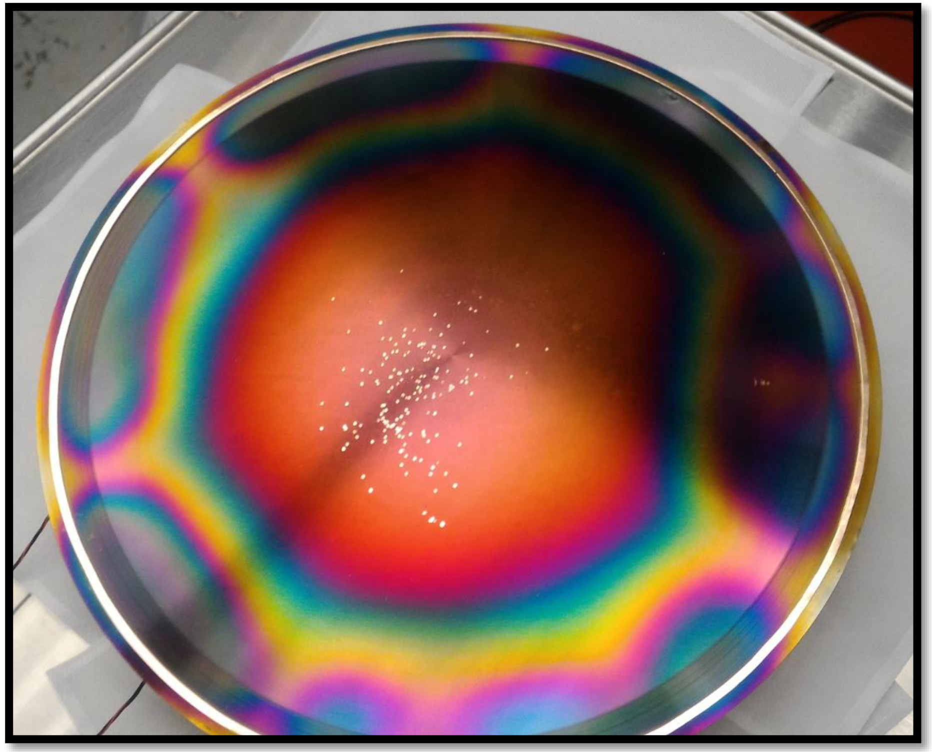
First high power in B=3T magnetic field

- Accumulated 2.5 Million pulses
- Detected 55 sparks
- End-of-run stable running below 12 MV/m
- Deterioration of gradient in time
- Run was stopped for inspection

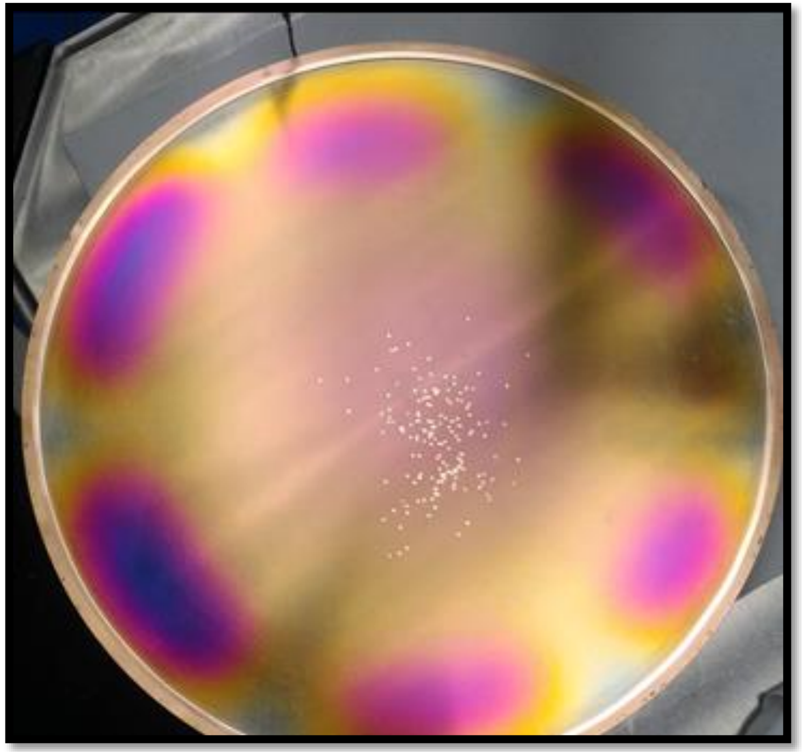
Gradient history Dec 12th – 18th



Inspection after first B=3T run



downstream



upstream

First time inspections were carried out after run with zero magnetic field and run with high magnetic field

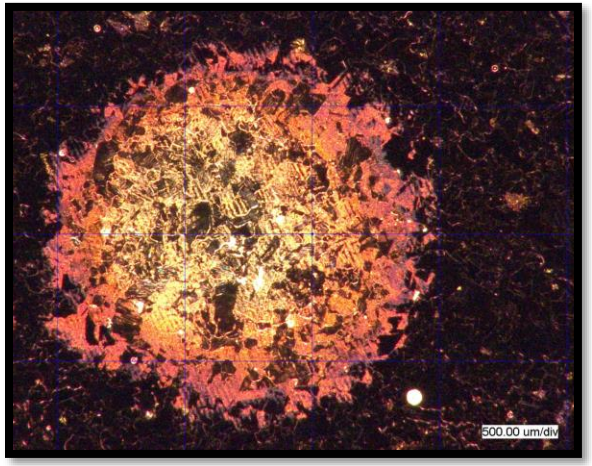
All clearly visible damage was inflicted during B=3T run (!)

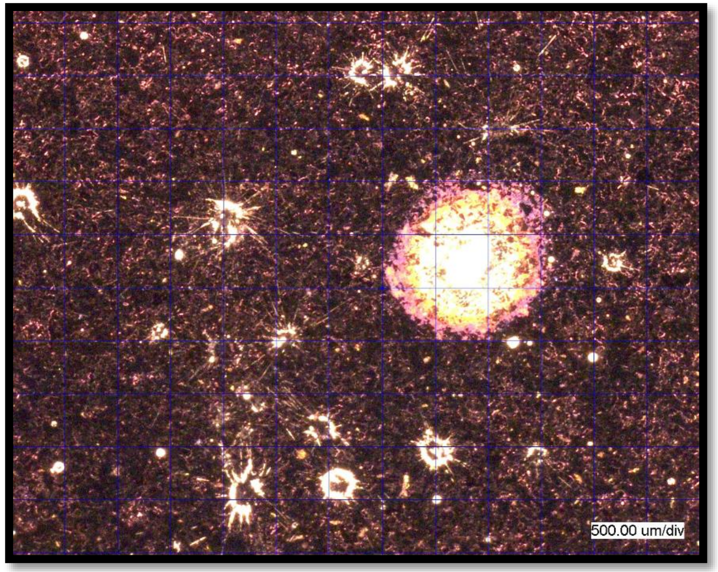
Inspection after first B=3T run: damage microstructure

Typical BD pits – we call them “volcanos”

- Similar to BD damage we observed in other cavities
- Characteristic pit diameter ~1.5mm
- Traces of splashing

Flat “volcano”

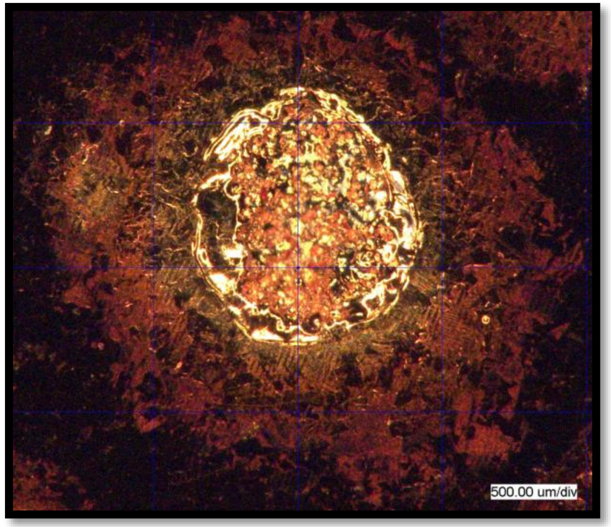




5mm

splashing

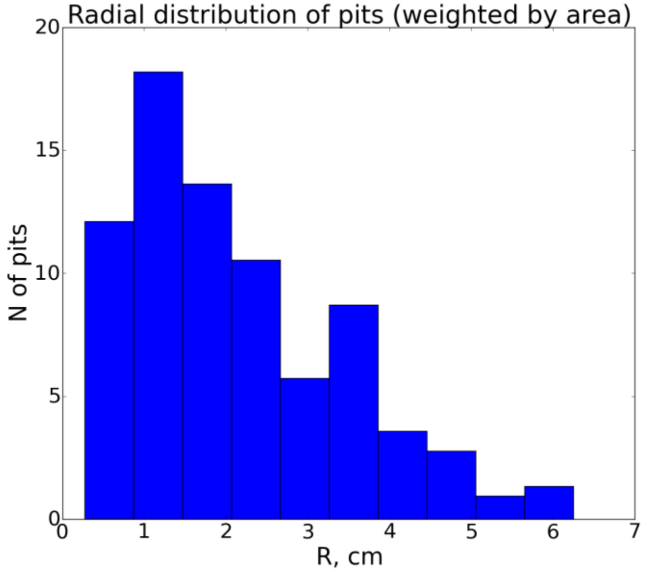
“Volcano” with crater

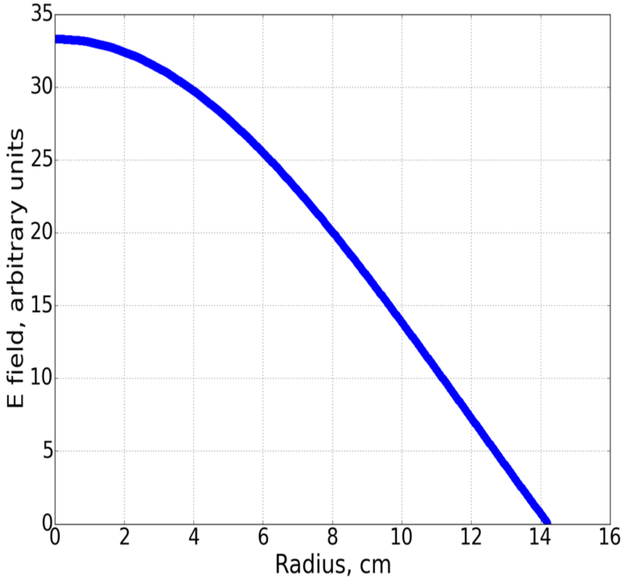


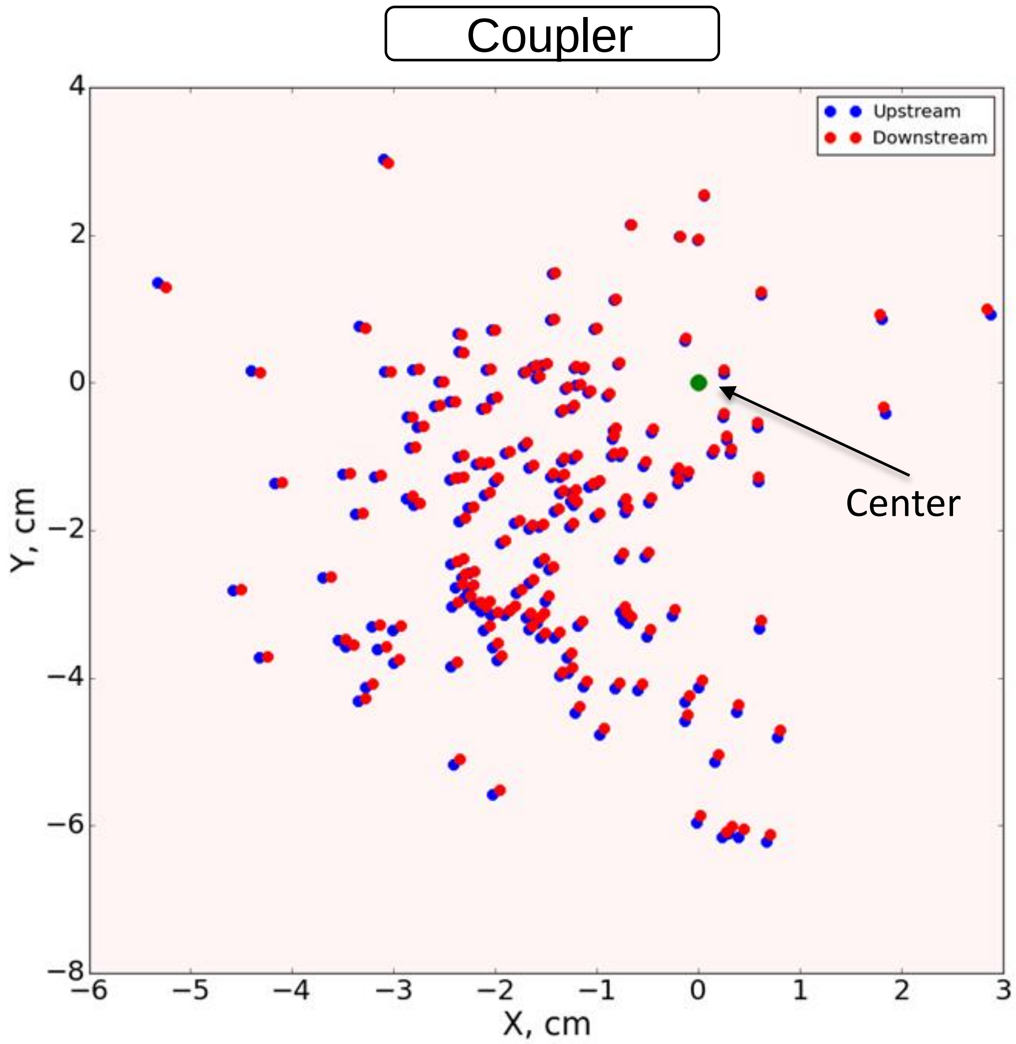
2mm

Inspection after B=3T run: damage pattern

- **Perfect 1-to-1 correspondence between 168 pits on each endplate**
- Detected 55 sparks, but observed 168 damage sites
- Damage distribution is in agreement with E(R) dependence

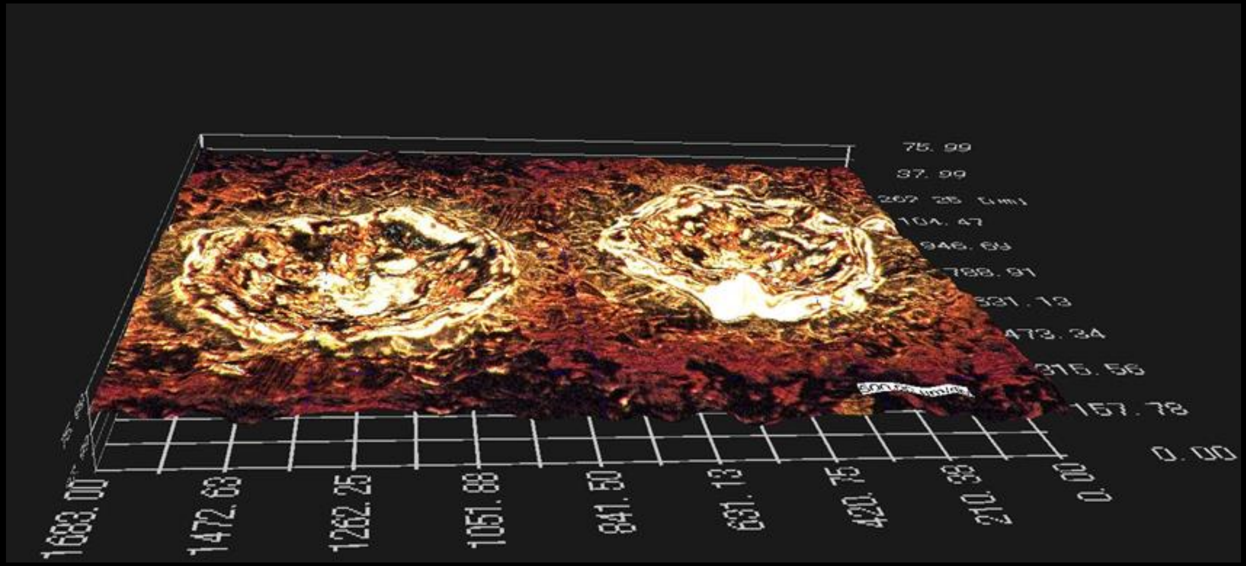


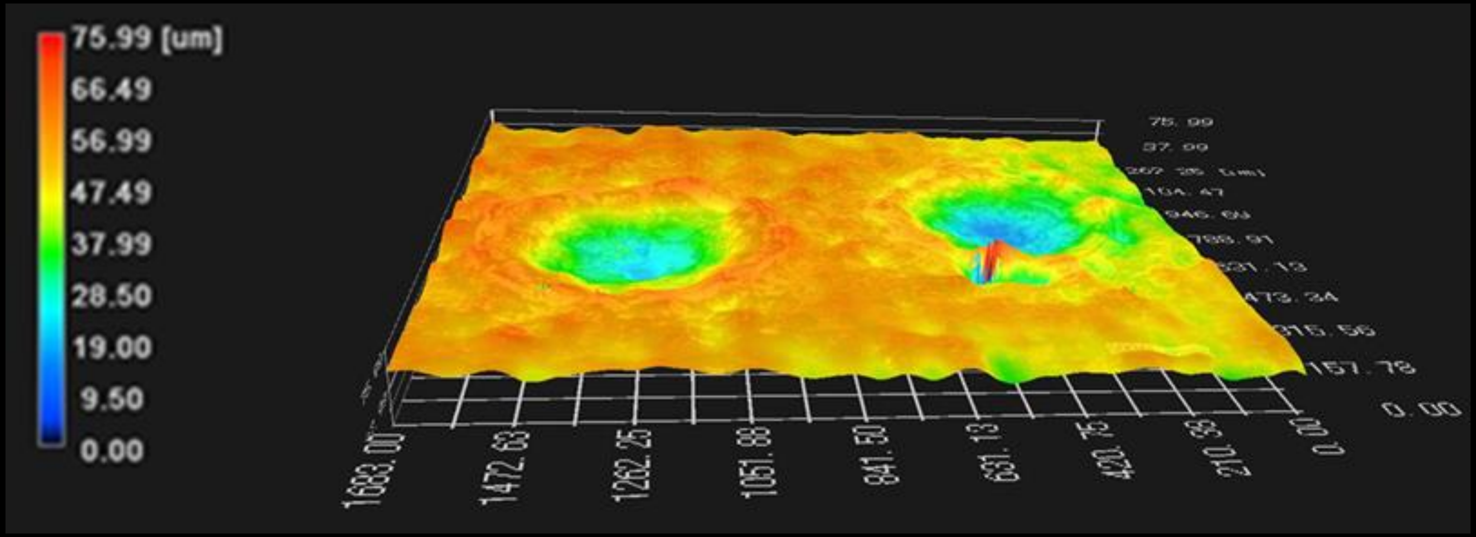




Map of "volcanos"

Inspection after B=3T run: 3D imaging



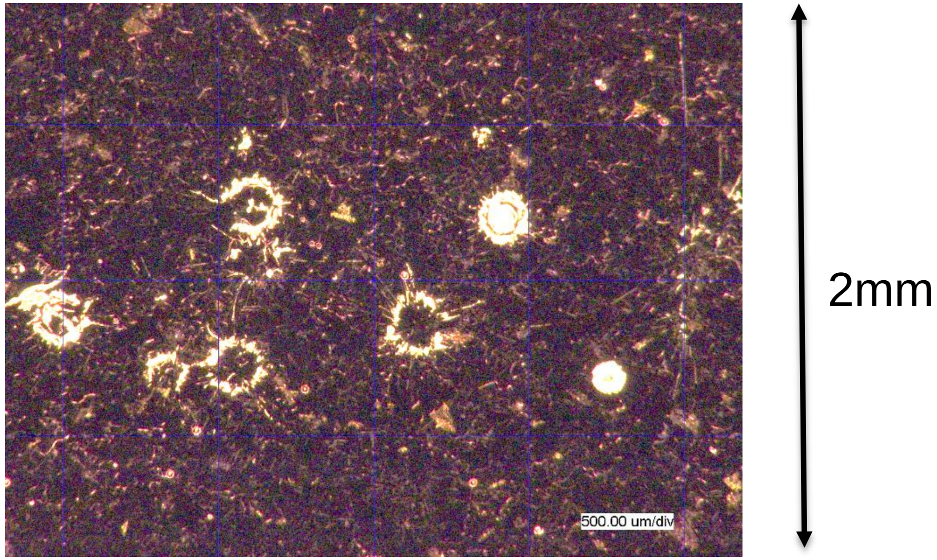


- Damage is much more “violent” than after B=0T
- Melted bulk of copper
- Craters up to ~0.5mm in diameter and up to ~ 60um in depth
- SEM analysis will be possible after we retire copper endplates in May

Inspection after B=0T conditioning run

Processed up to 22MV/m in >10M pulses, inflicting ~450 sparks

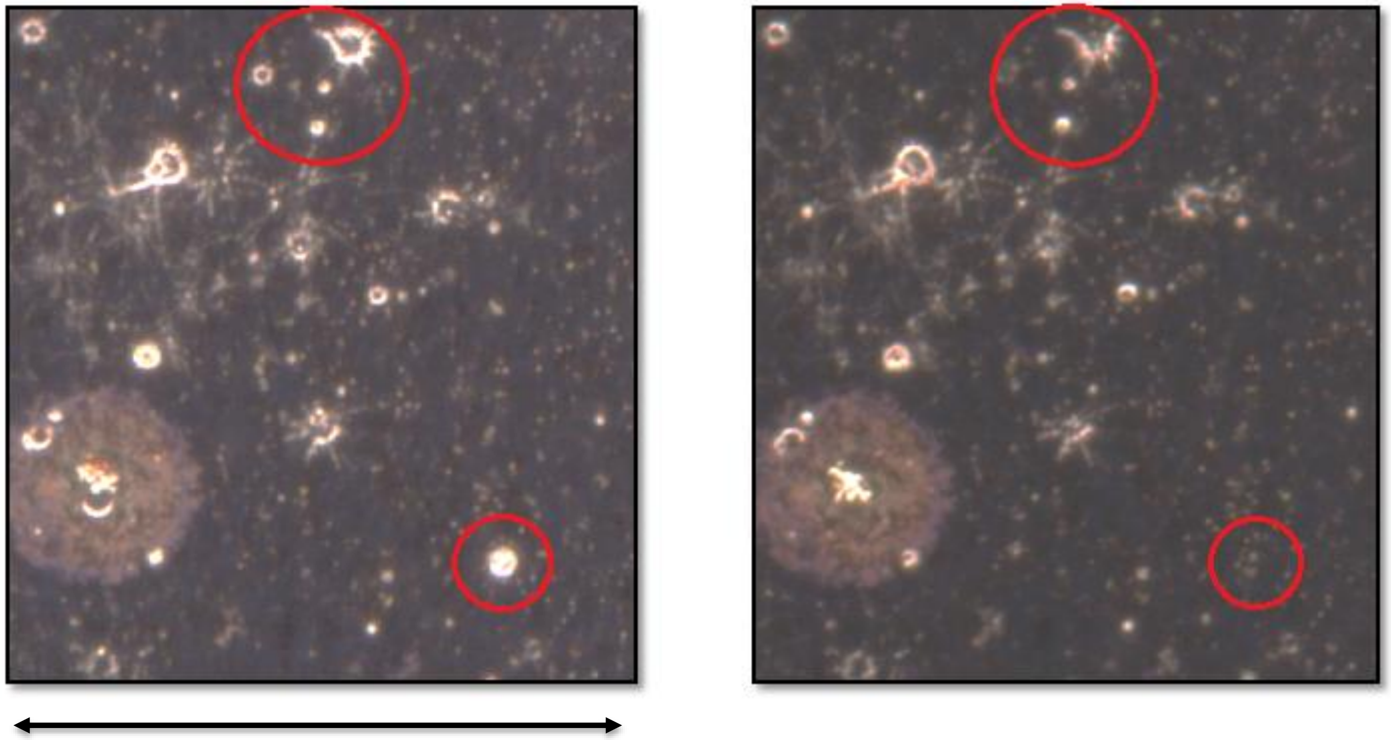
No new damage sites observed
Some splashing traces disappeared



Microscopic image of splashing pattern after B=3T run

Before

After



Experimental results Apr’15 – Apr’16: summary

“cluster” “fractal”

- First B=0T run:

  SOG > 40MV/m, ~130 sparks

  – Inspection: ~500 features inspected. Most common: fractals (92) and clusters (>200)

- First B=3T run:

  SOG < 12MV/m, 55 sparks

  – Inspection: damage pattern of volcanos, 168 pits on each endplate, perfect 1-to-1 match

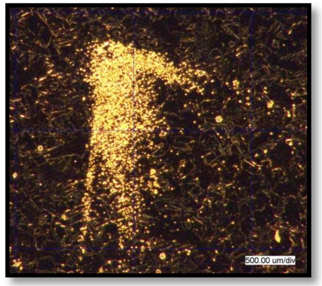
  – Copper splashing

- B=0T “conditioning run”:

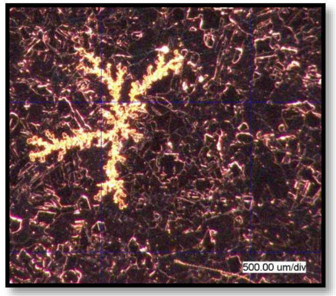
  Conditioned up to ~20MV/m, inflicted ~500 sparks

  – Inspection : no new BD sites, some of splashing got evaporated, slight changes in volcanos

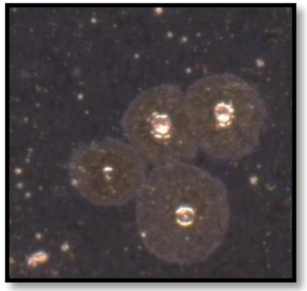
“cluster”



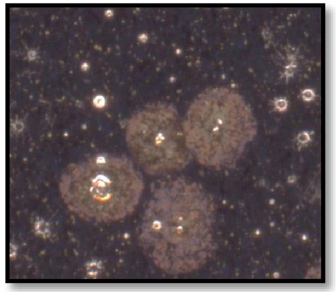
“fractal”



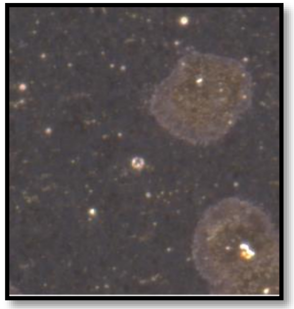
upstream



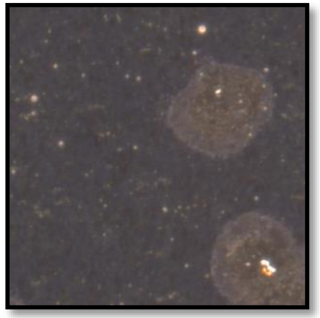
downstream



before



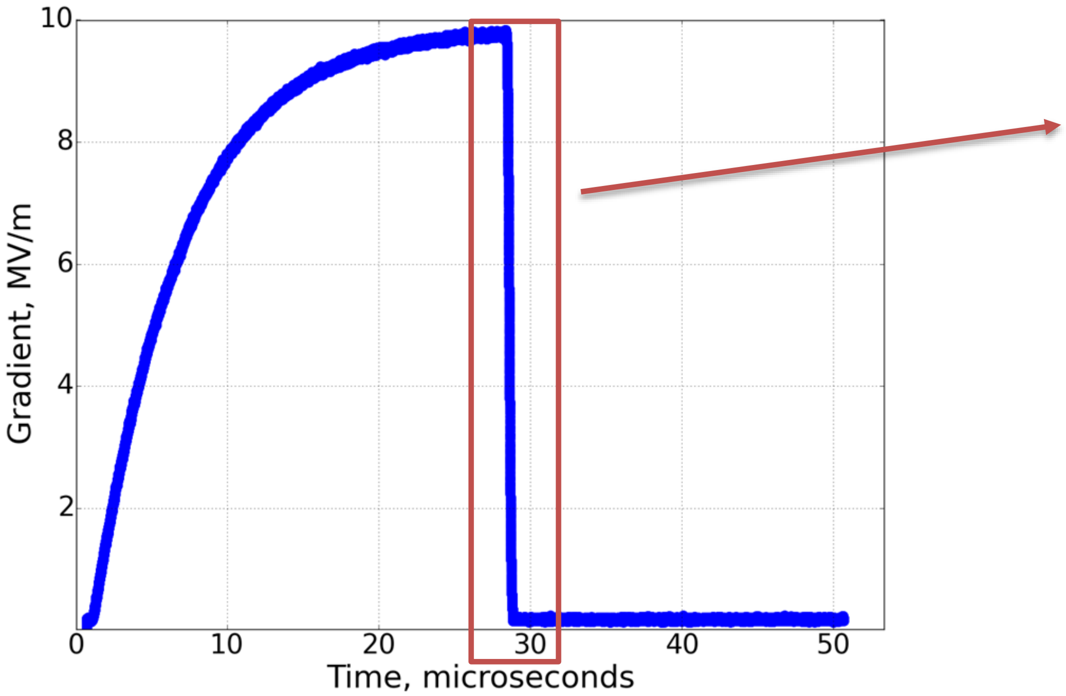
after



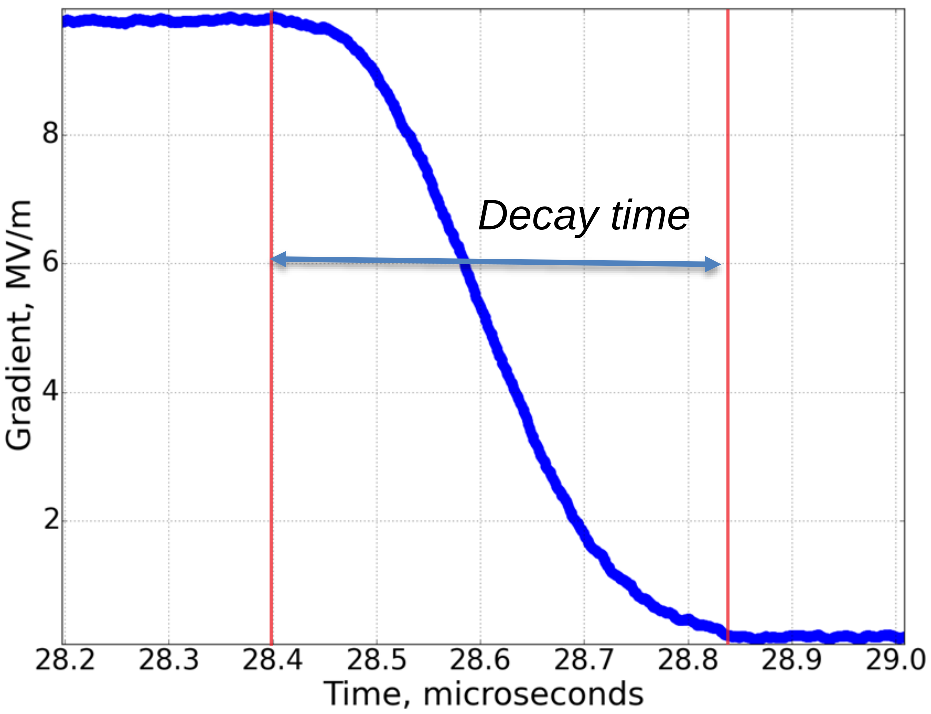
Ongoing analysis: Breakdown characterization

We observed drastically different damage after B = 0T and B = 3T runs, which implies different energy deposition mechanisms. Does the data support it?

Envelope of pickup signal during breakdown event



Decay time – cavity loses 95% of the stored energy



Energy dissipation during breakdown events

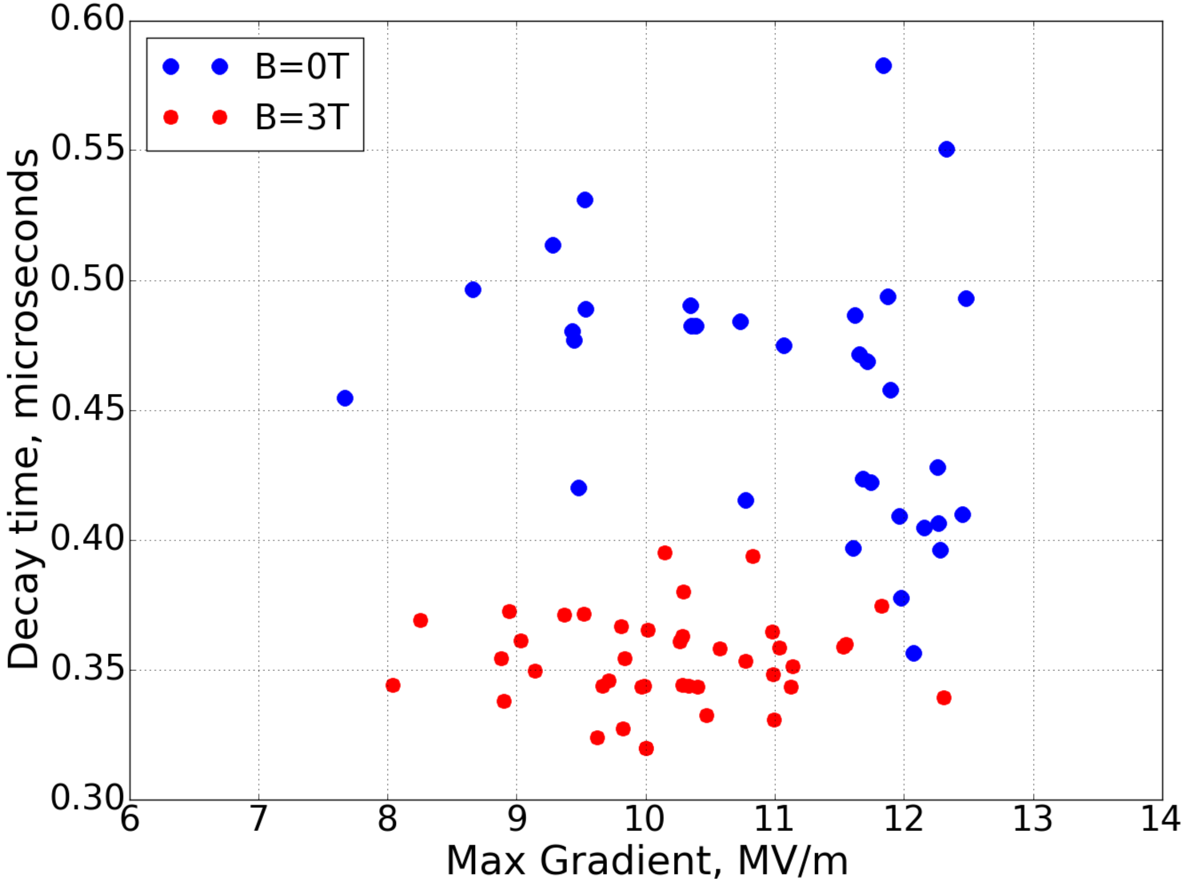
- Decay time in B=3T is 30% smaller on average → Implies that energy deposition mechanism is more efficient in strong magnetic field

- That is what we have expected to see

  1. Based on "violent" type of damage we observed in B=3T

  2. Due to focusing of dark current beamlets: higher arc currents and hence lower impedance (Quantative analysis ongoing)

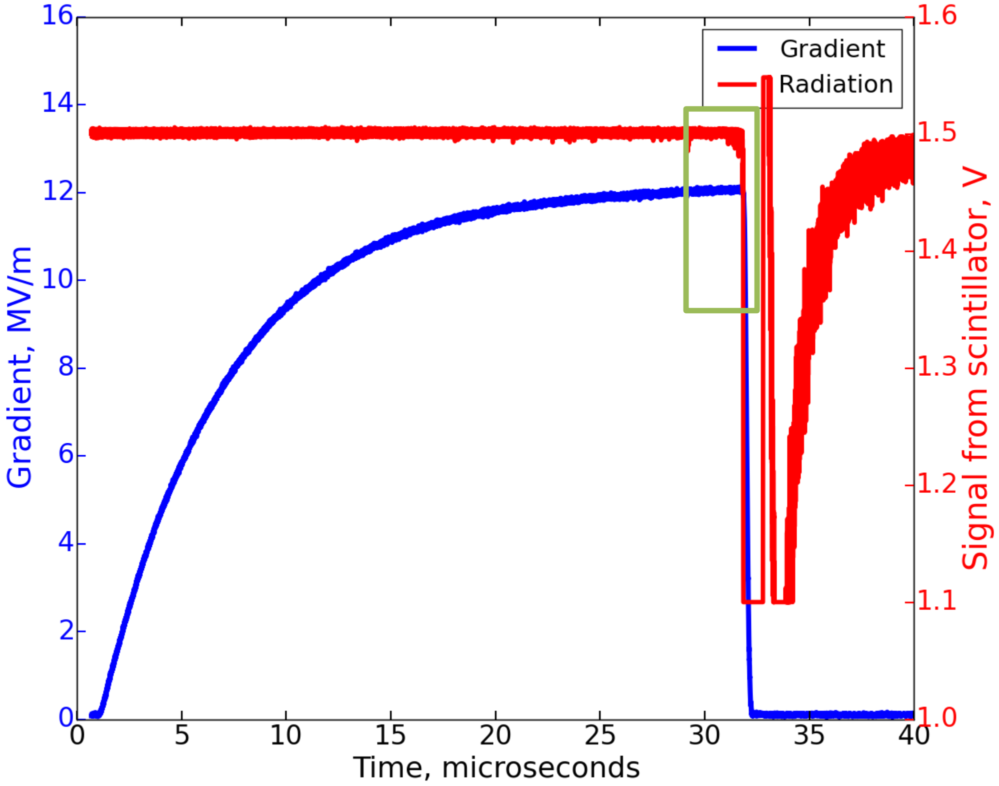
Decay times for sparks in zero and 3T external magnetic field



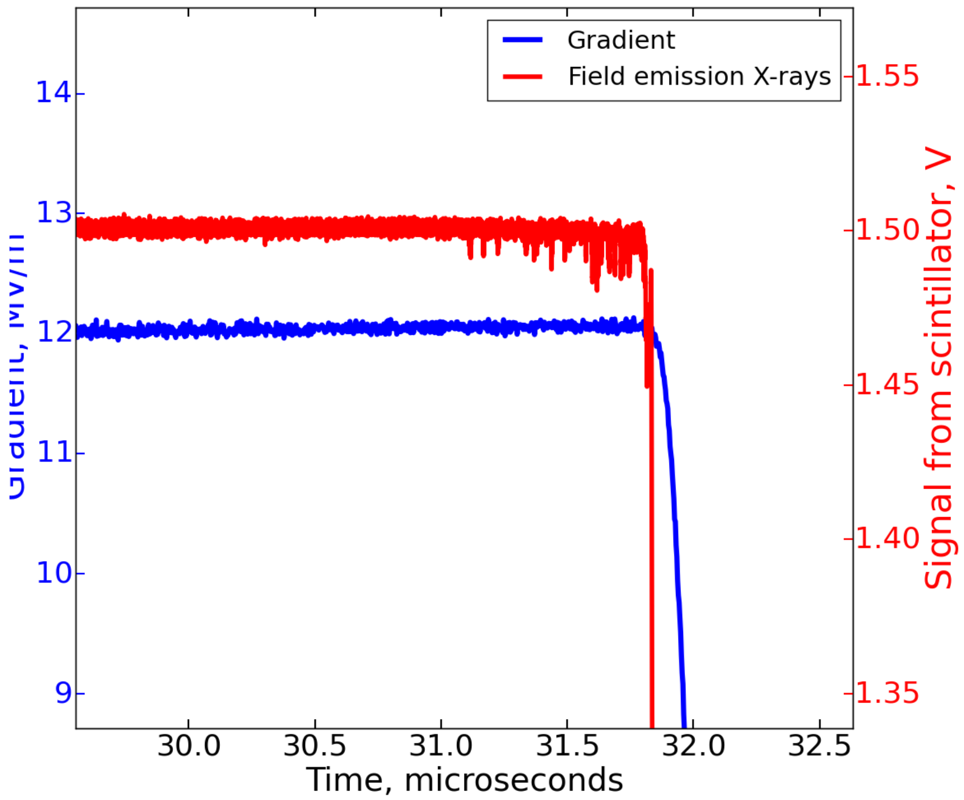
Breakdown precursors: how is breakdown triggered?

We expect to see increase in field emission current just before the breakdown

Rise time of “fast” scintillators allows to measure radiation signal with sub-RF cycle precision



Zoom-in



Analysis: surface evolution in time

Analysis is ongoing. Results are preliminary

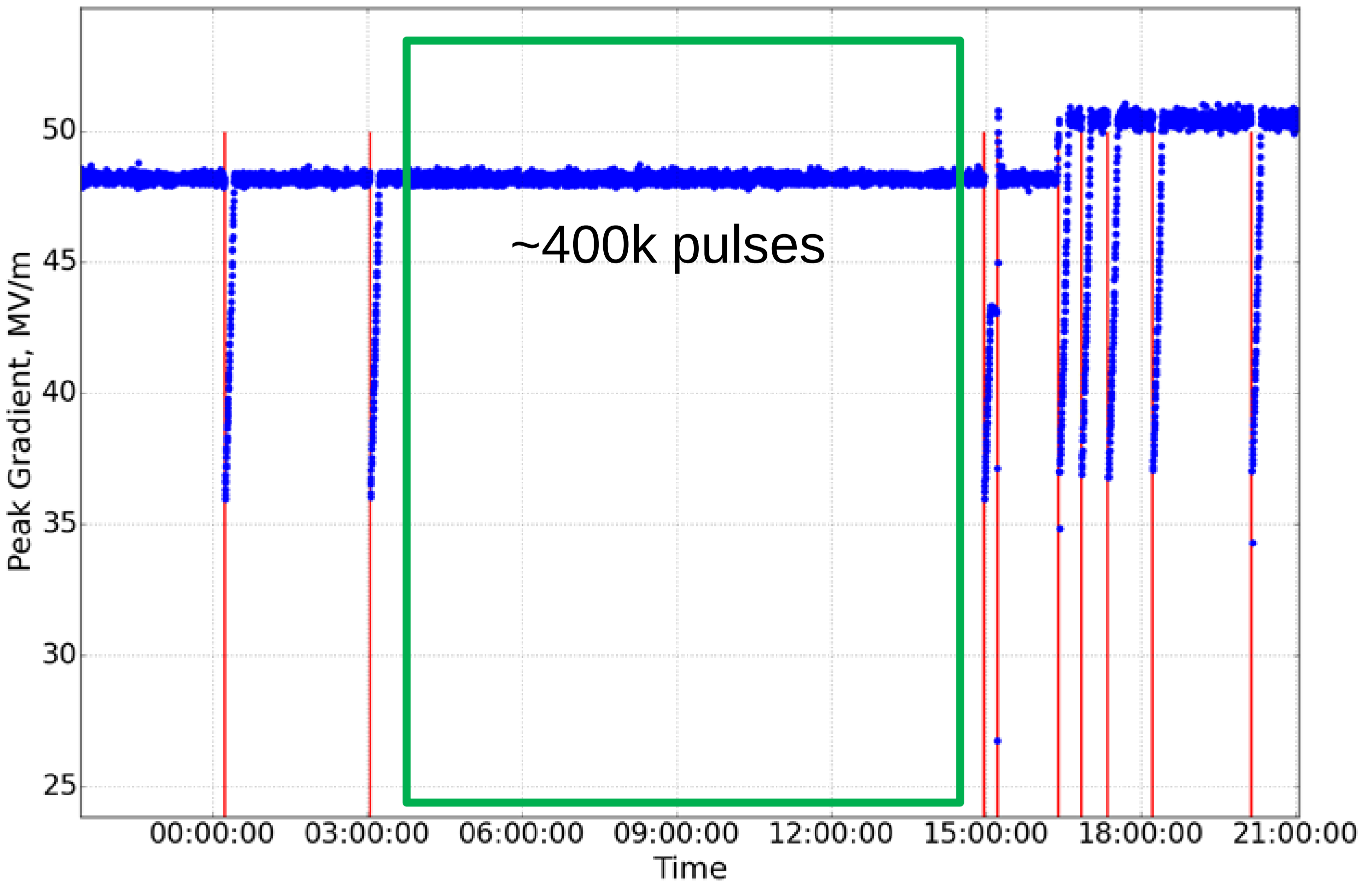
Can we make qualitative statements about surface condition from the data that we are collecting?

Chose stretch of data with operation at fixed gradient with no sparks

Using data from Pickup signal, we can calculate the loaded Q value

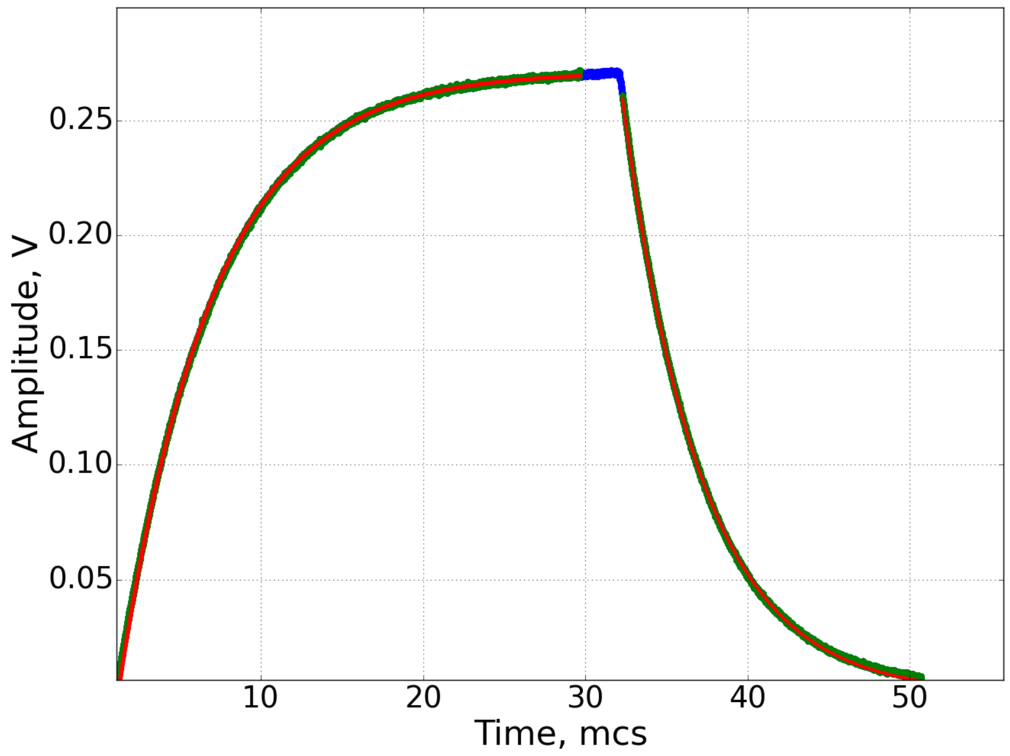
$$Q = \omega \frac{Energy\ stored}{Power\ loss}$$

Gradient history for part of first B = 0T run

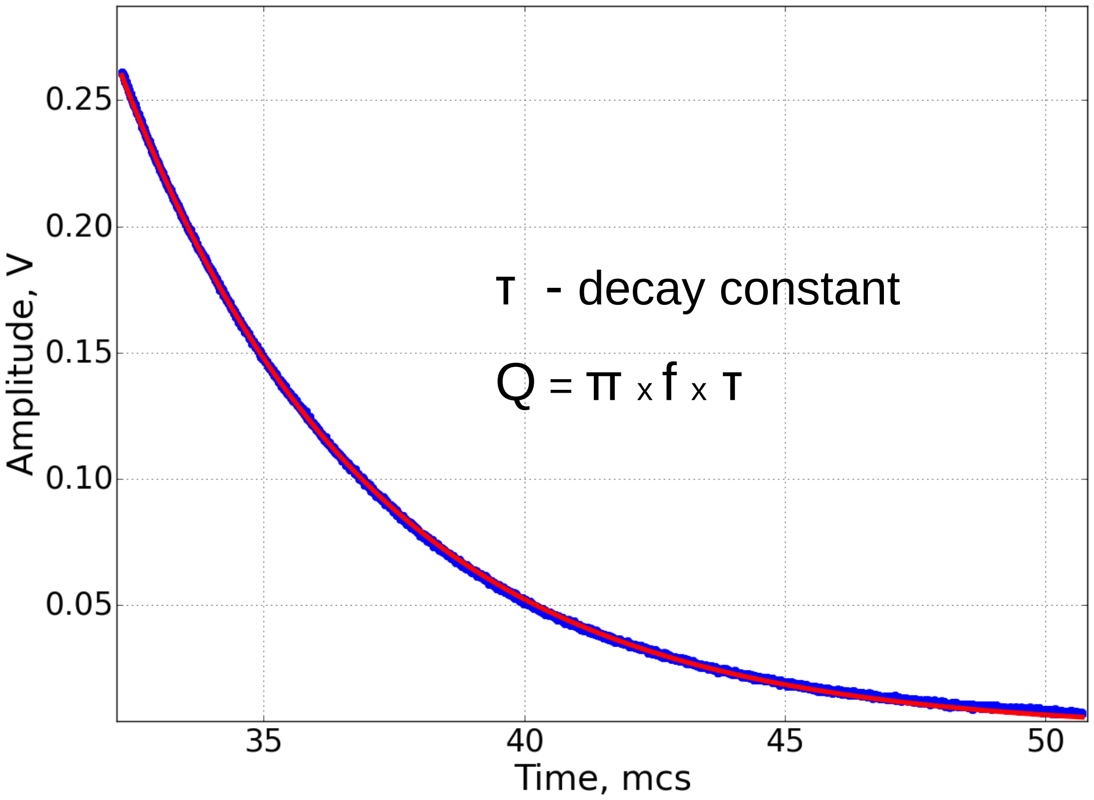


Analysis: Measuring loaded Q

Envelope of the Pickup signal



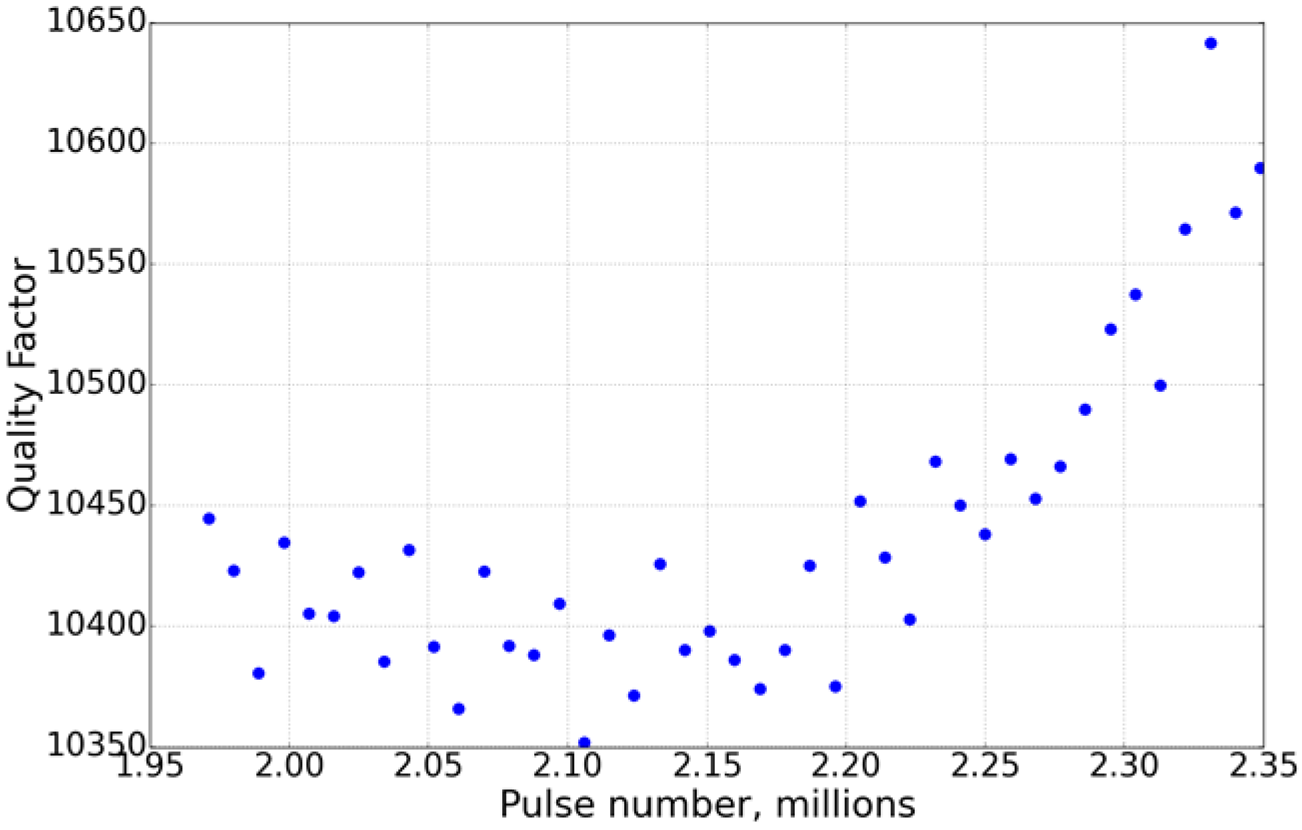
Fitting discharge with decaying exponent



Evolution of quality factors (slide in development)

- Increase Q for fixed stored energy means decrease in power loss in the cavity
- Indication of improvement in surface quality
- Can we correlate that to field emission through radiation data?

Quality factor changing in time



Quantifying field emission

Measuring dark current data can tell us a lot about evolution of surface

$$J = 6.0 \times 10^{-12} \frac{\beta_e^{2.5} G^{2.5}}{\phi^{1.75}} 10^{4.52\phi^{-0.5}} \left(e^{-(6.53\times 10^9 \phi^{1.5}/\beta_e G)}\right)$$

x Area to get current

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

→ Can extract β

$$\log_{10} \; (I_F/E^2)_{E\to\infty} = \log_{10} \left[\frac{1.54 \times 10^{-6} \;\; A_e \beta^2 \;\; 10^{4.52\phi^{-0.5}}}{\phi} \right]$$

→ Can extract area (A_e)

Power dissipated on field emission: $W = I_{avg\ over\ cycle} * E_{impact}$

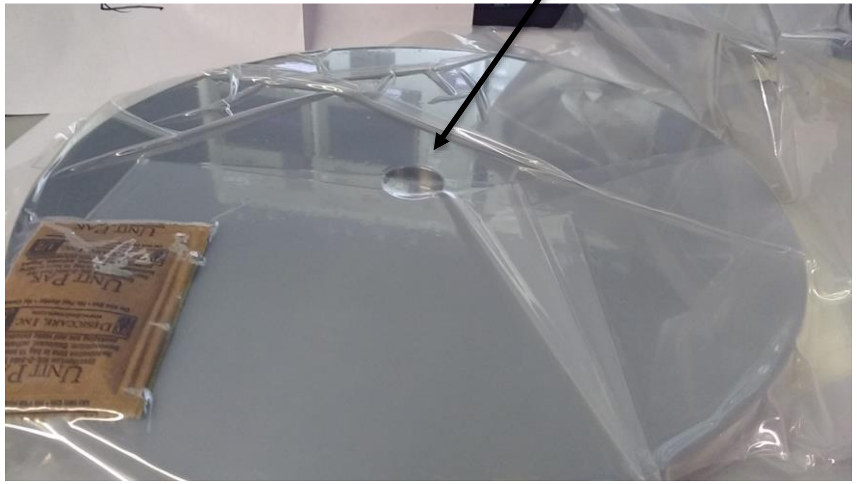
Current setup with thick (1.2cm) copper endplates on does not allow precise measurement of dark current

Next set of measurements will be with Beryllium endplates

Radiation length of Beryllium (~35cm) for electrons in MeV energy range is significantly higher than of copper (~1.4cm). According to our model, that implies less effect of dark current electrons on a surface and hence, potentially lower breakdown rates per gradient.

New set of Be endplates is out for TiN coating, we expect to have it back by the end of April. There are several measurements enabled by Beryllium:

- Direct measurement of dark current (Faraday Cup)
- Study of surface evolution (next slide)



Beryllium endplate in a sealed bag

Next experimental steps: Be endplates

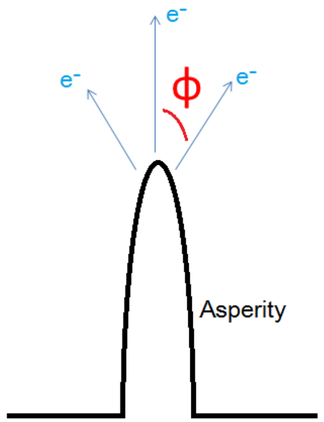
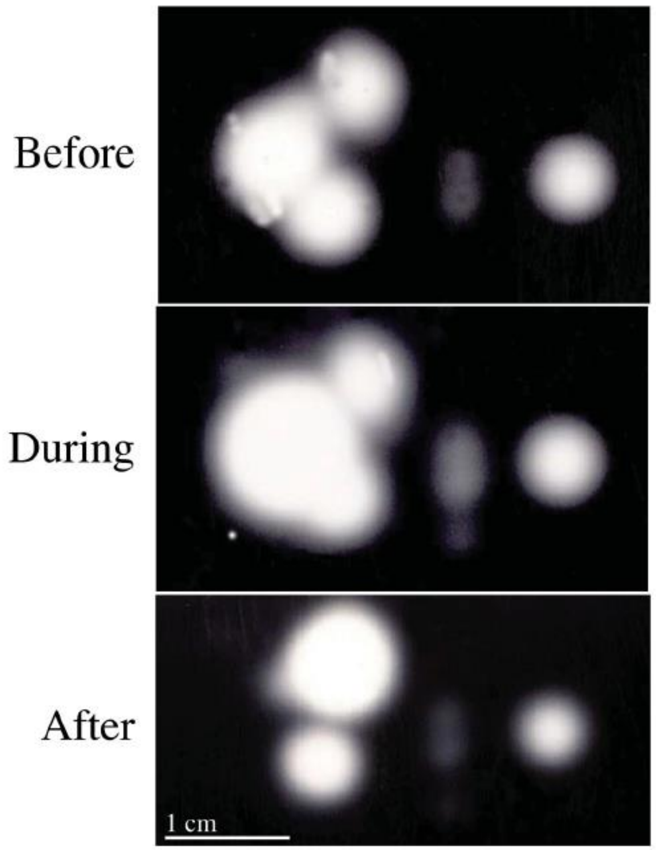


Photo film measurements

- Estimating transverse size of dark current beamlets
- Will give us an estimate of transverse momentum of electrons leaving field enhanced region
- Can infer characteristic dimensions of surface defects

Polaroid images before, during and after breakdown event



A.Moretti et al., Effects of high solenoidal magnetic field on rf accelerating cavities, Phys.Rev – accelerators and beams. 8,072001 (2005)

Conclusion

- We tested MC in high RF power with and without magnetic field on
- Cavity behaves as intended to:
  - Providing reproducible measurements
  - Allows for relatively fast inspection (turnaround of a week)
  - Breakdown happens where we want it to happen
- Surface inspections revealed new exciting results
- New set of Be endplates is expected to be ready for installation by the end of this month
- Low radiation length of Be will allow for more detailed field emission and surface evolution studies

Thank you for your attention

BACKUP

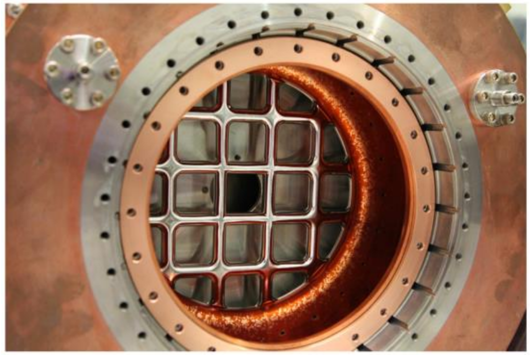
Run history table

Summary of Modular Cavity runs

Run Dates	B field on?	Safe gradient	# Sparks	Number of RF pulses accumulated
Apr 17 – 21 , 2015	0T	>30MV/m	~15	~3M
Aug 17 – Oct 10 , 2015	0T	45MV/m +/- 7MV/m	113	>10M
Dec 11 – 15 , 2015	3T	< 10MV/m	55	~5M
Jan 11 – 19, 2016	0T	> 12 MV/m	37	
Feb 12 –21st	0T	> 20 MV/m	415	
Apr 4th - current	3T	<12 MV/m	80	

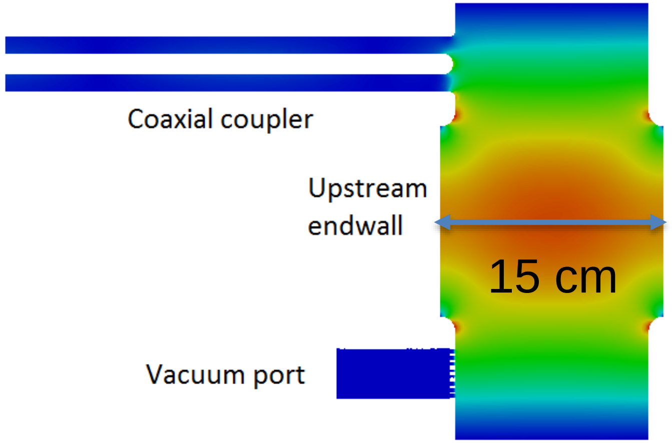
Mitigation techniques

Geometry



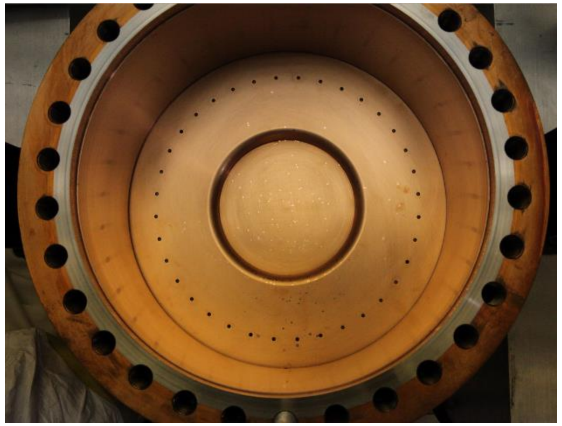
Grid
windows

ASC cavity – longer gap



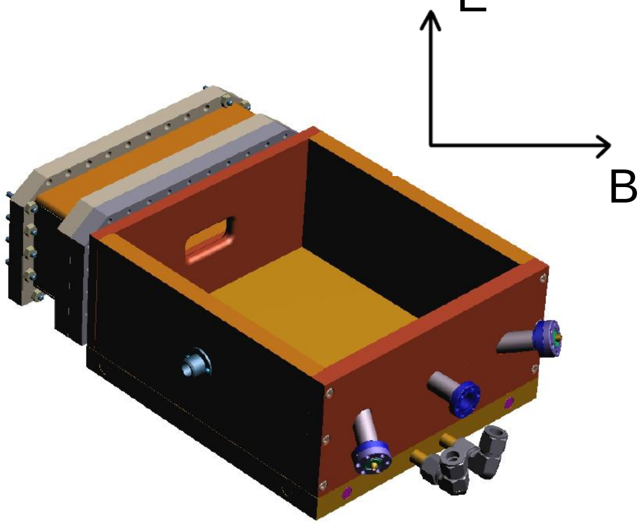
Surface treatment

201MHz cavity - electro polished



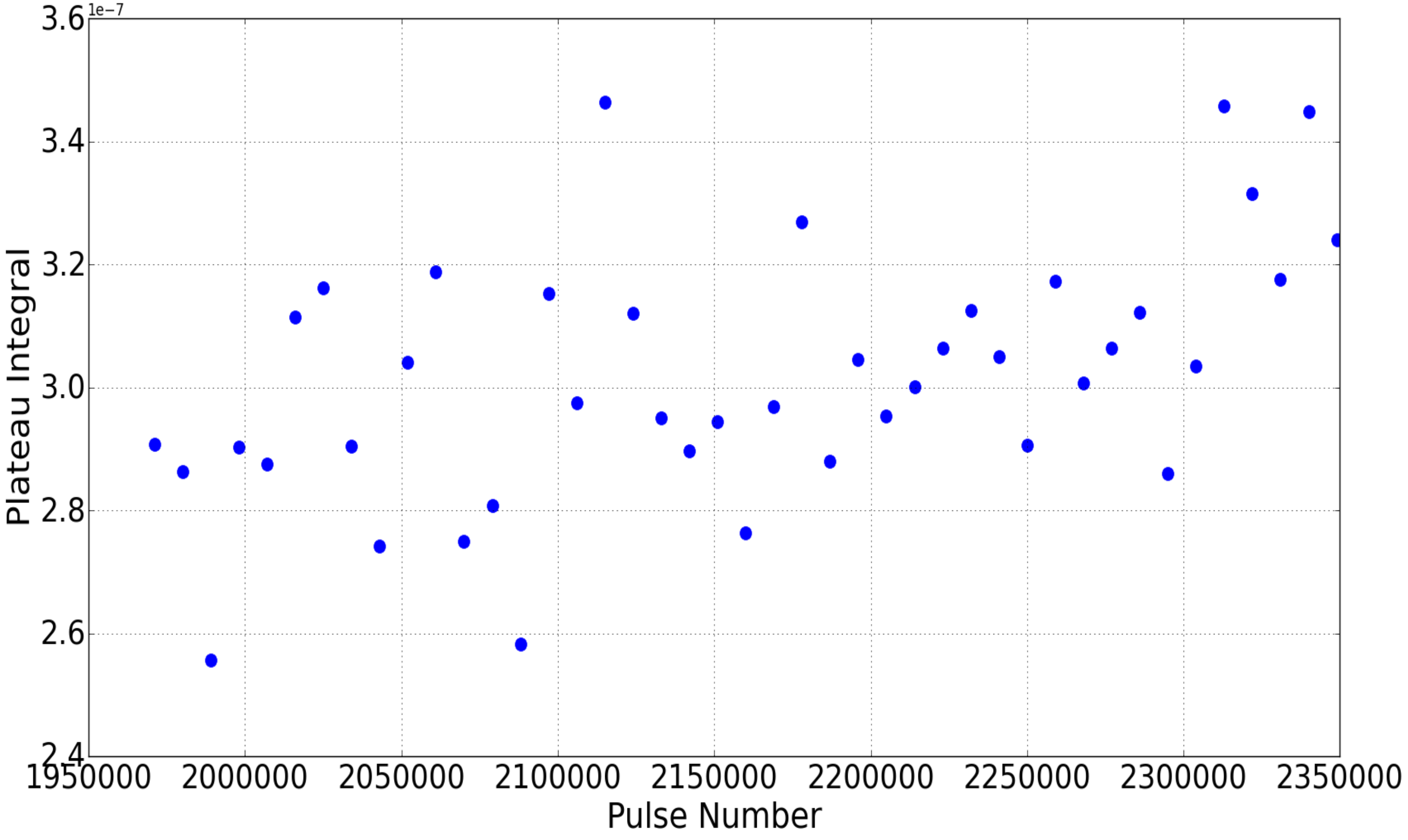
ASC
copper
coating

Magnetic insulation



Magnetic field deflects
dark current electrons
to low E field regions

Comparison to field emission



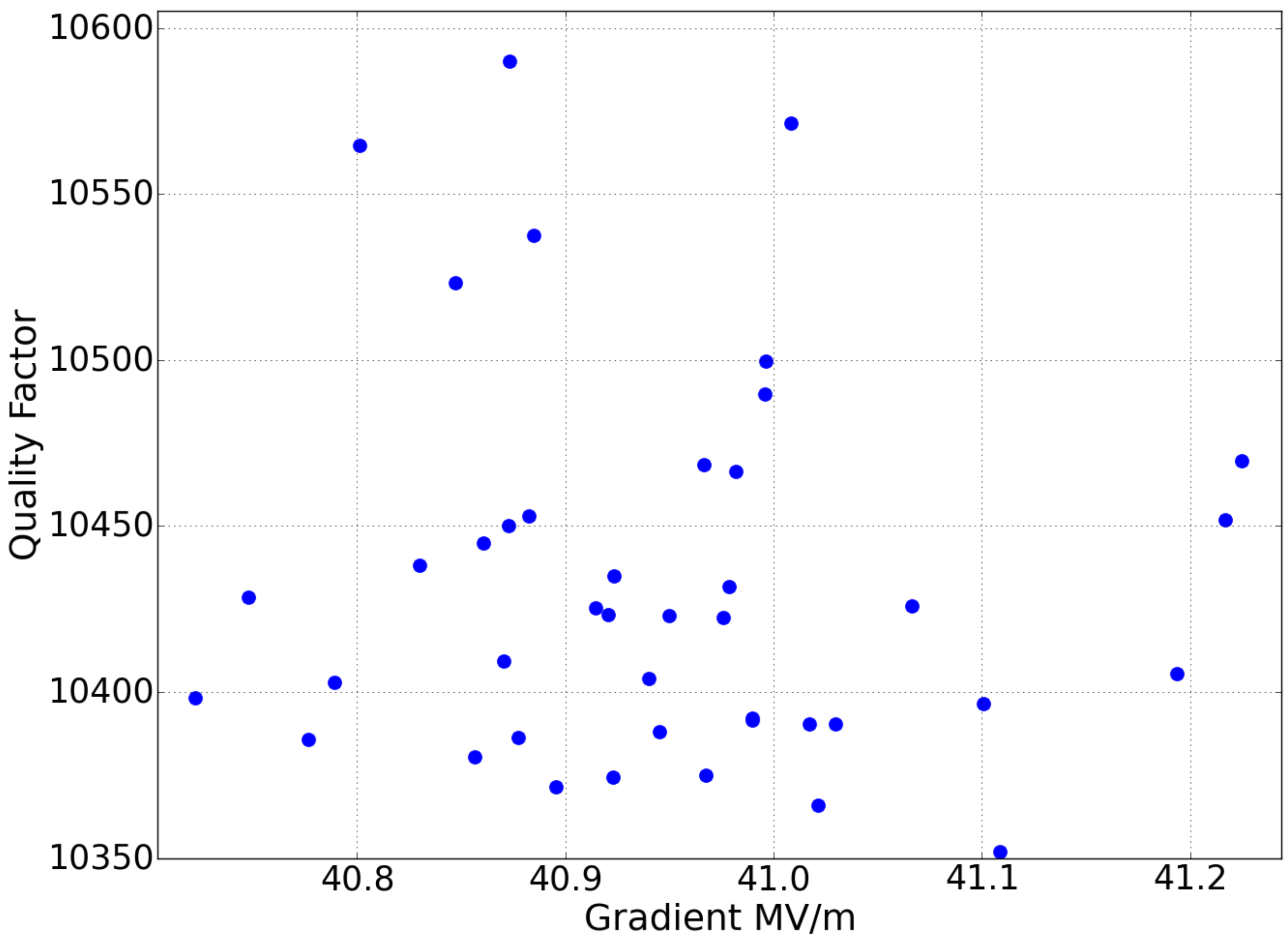
Potential sources of error:

Dark current is not ~ radiation detected in plastic counters

To prevent scope overloading the precision is low

Surface evolution study - sanity check

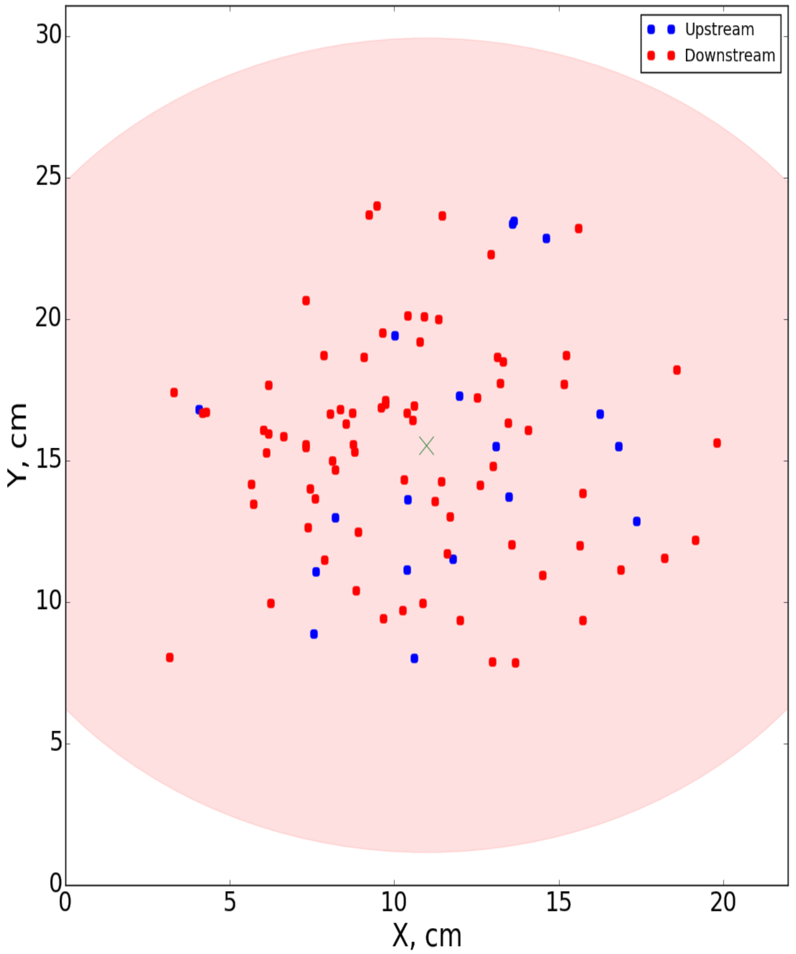
Can we explain trend in quality factors by drift or fluctuations in a gradient?



B=0T high power run: fractals only

- Established baseline SOG for copper endplates in B=0T
- Significant amount of microscopic damage observed
- No one-to-one correspondence between damage on opposing endplate found
- Damage sites are not "canonical"
- Damage is microscopic and "non-violent" – surface roughness is intact

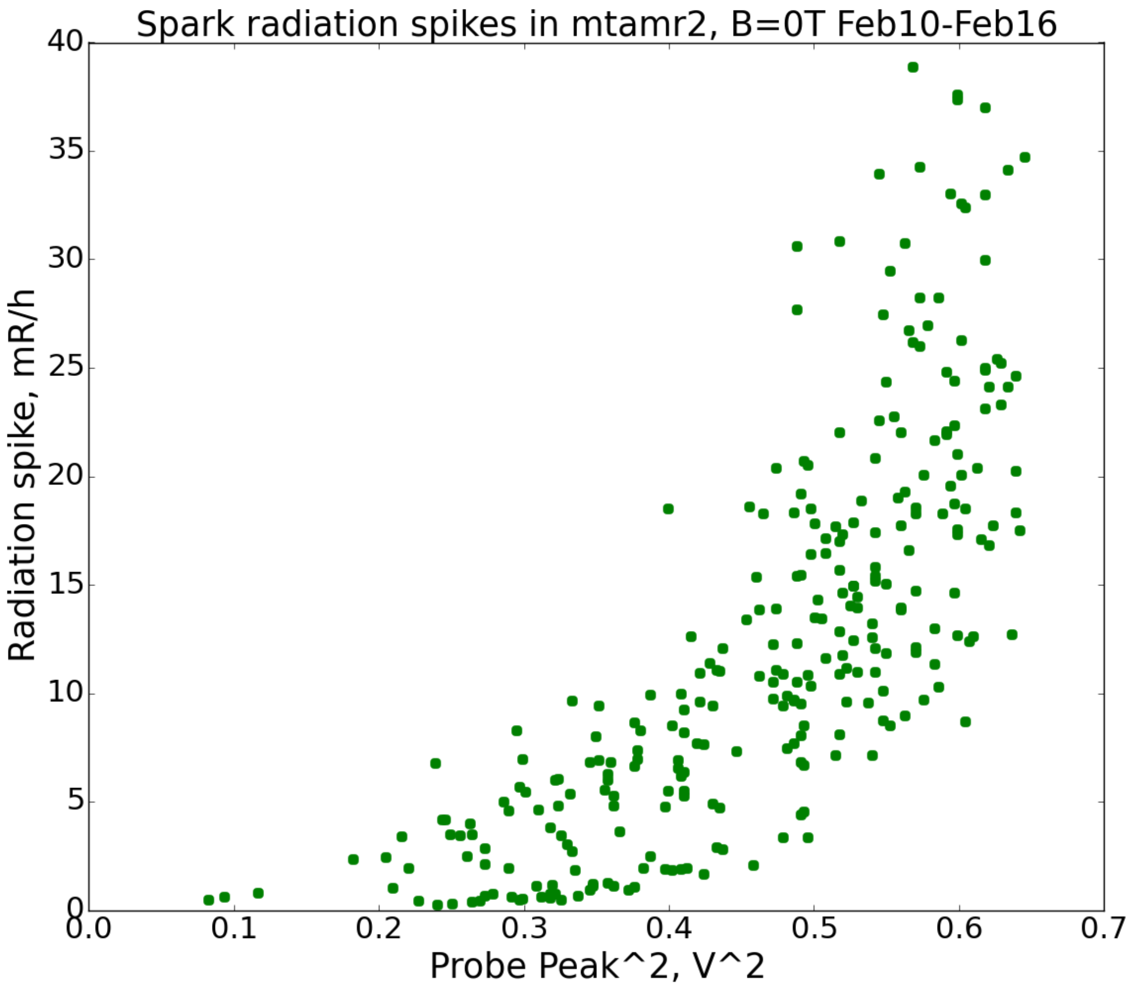
"Fractals"



Ongoing analysis (spark characterization)

Radiation spikes in mtamr2 during breakdown events.

Horizontal axis - stored energy in a cavity



RF Breakdown

- Essentially is a spark in a RF cavity
- Problem for almost any accelerator and beyond
- The field of BD study is not unified in one consistent model