Study of RF breakdown in strong magnetic fields

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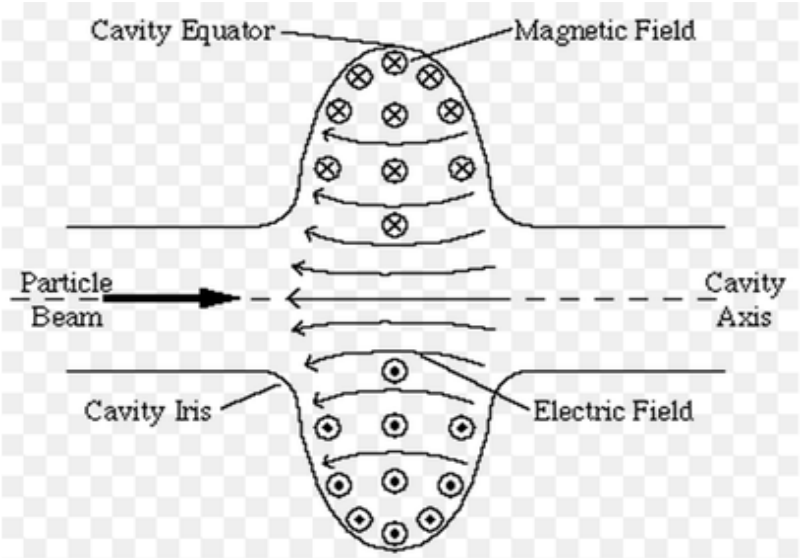
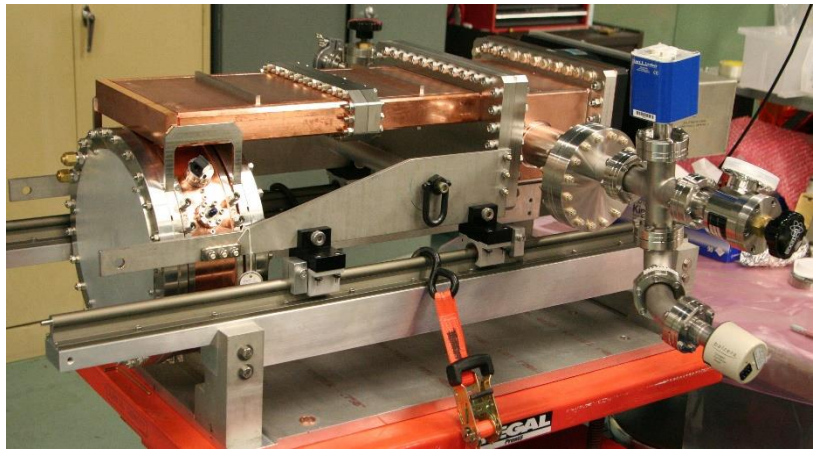
Outline

- Introduction: RF cavities and breakdown
- Problem of RF breakdown in strong magnetic field
- Modular cavity: motivation, design and instrumentation
- Experimental results (*inspection*)
- Summary and conclusion

Introduction: RF cavity and why we need it

- Metallic resonator that allows to “store” high gradient for beam acceleration
- Power transmission: waveguide/coupler
- Vacuum (~ 10^{-8} Torr)
- Accelerating field (gradient) ~ MV/m
- Surface quality control



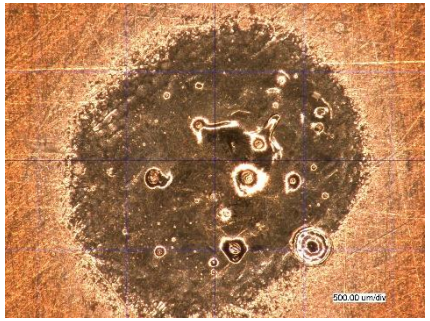


Problem of RF breakdown

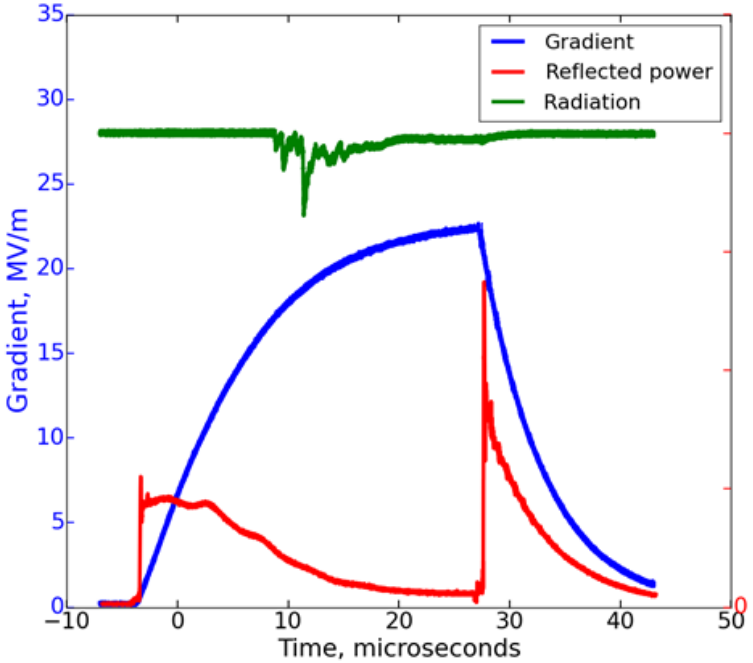
RF Breakdown essentially is a spark inside the cavity.

Why is it a problem?

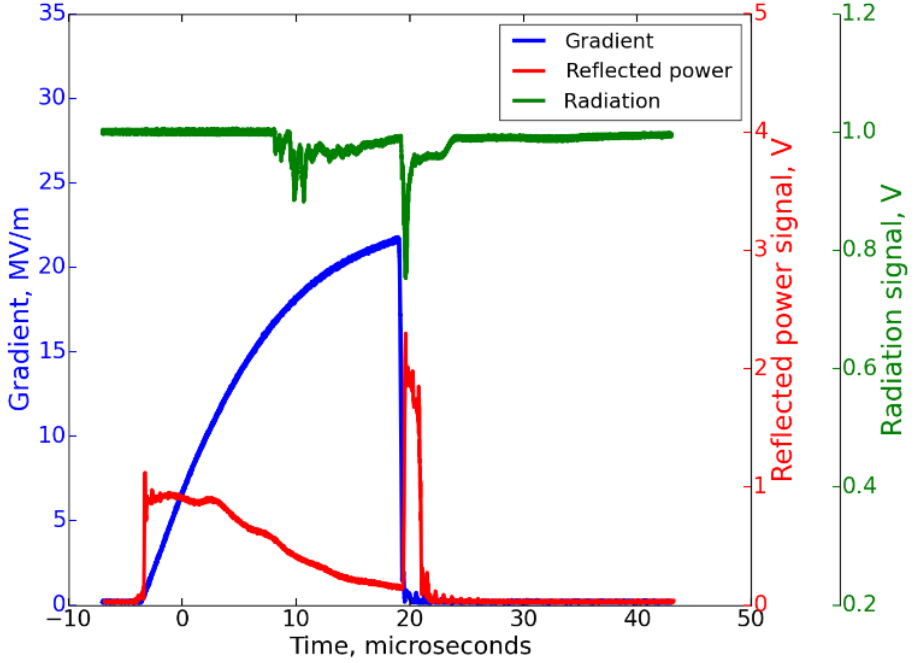
- Discharges all accumulated energy needed for beam acceleration
- Damages surface structure



Normal RF pulse



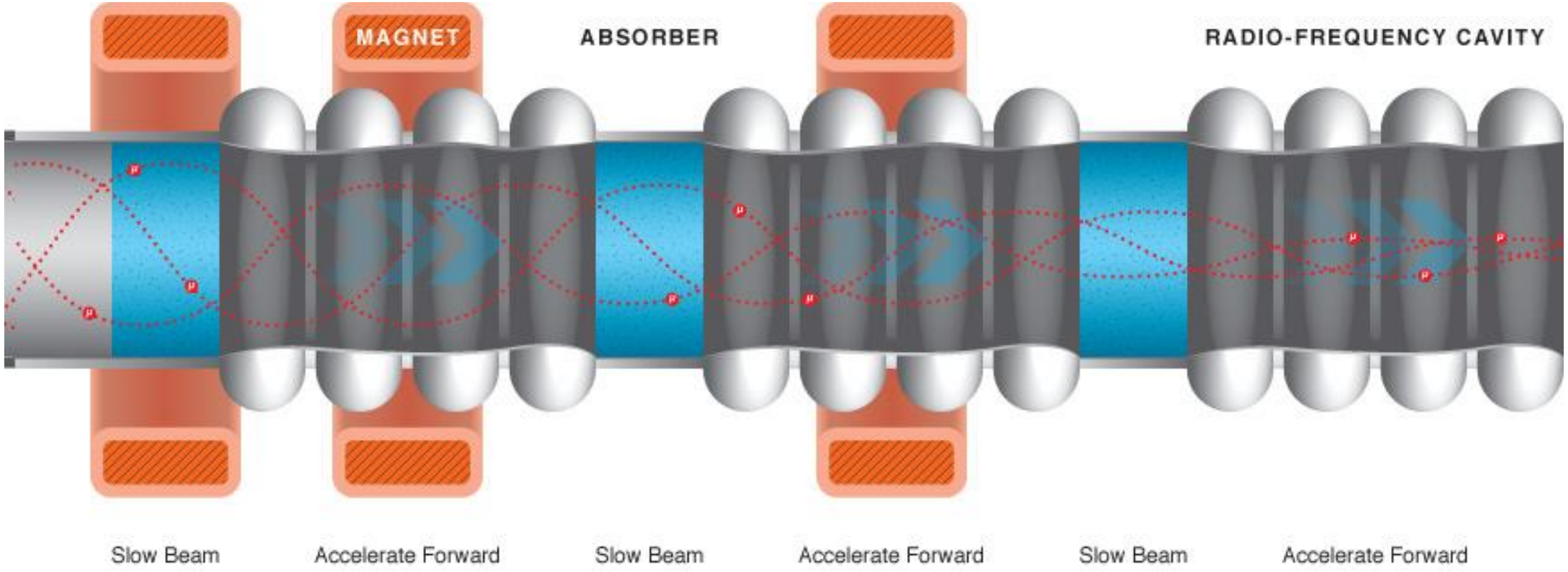
Breakdown RF pulse



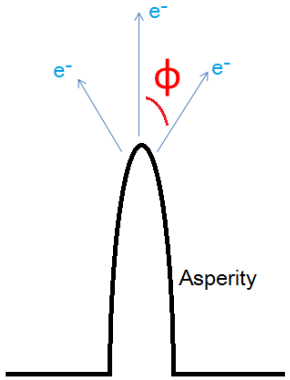
It was experimentally shown that presence of external magnetic field aggravates the problem

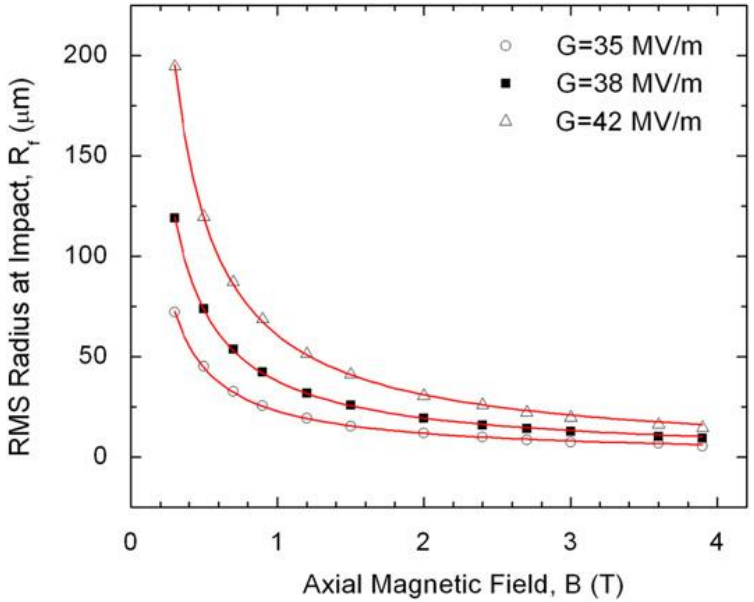
Why do we want to operate cavities in strong external magnetic field?

Muon cooling channel



Why do we see the deterioration of cavity performance in strong B fields?





- Dark current: electron field emission from surface imperfections →
- B field focuses dark current into "beamlets" →
- **Beamlets cause pulsed heating of the surface →**
- Pulsed heating leads to surface degradation →
- Breakdown is triggered

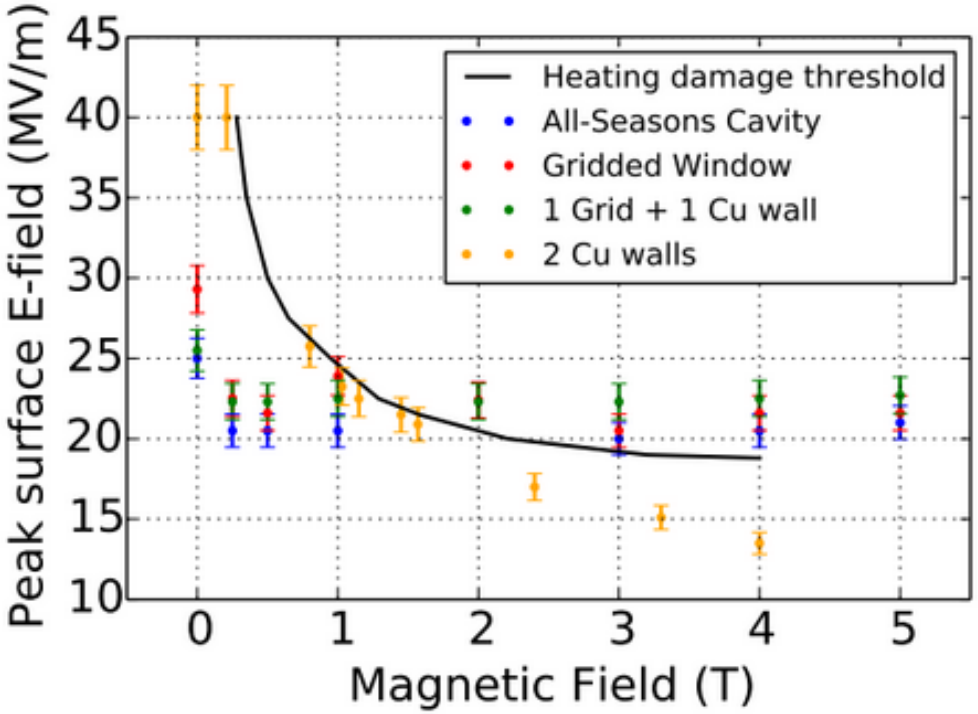
<u>Potential mitigations:</u>

- Surface treatment
- Use higher radiation length materials (Be)
- Decrease impact energy density of electrons

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 805MHz pillbox-like cavities



Factors that may affect the fit quality:

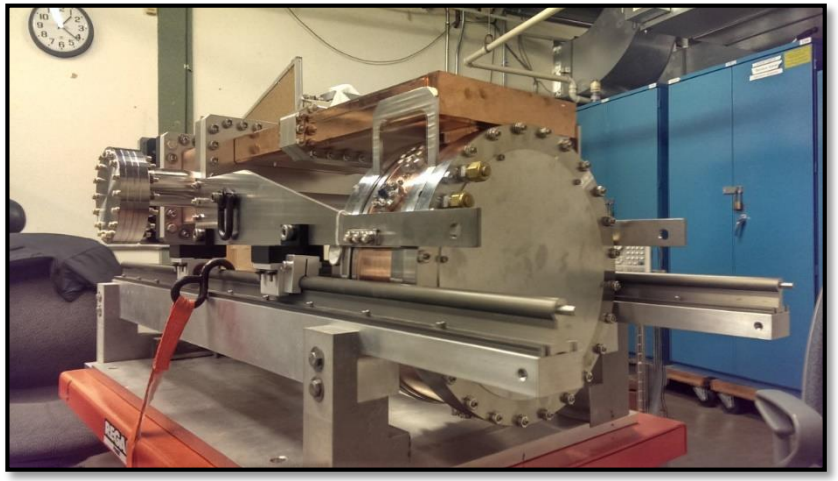
- Conditioning history
- Local field enhancement around coupler regions
- Surface treatment

Study of RF breakdown with better control over systematic error is required

Comment:

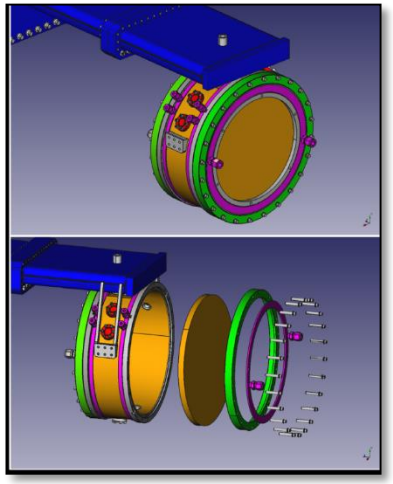
Peak surface field = safe operating gradient = max gradient - max gradient with tolerable breakdown rate

Pillbox “modular” cavity



Unique design features:

- End walls can be un-mounted easily
- Allows for end wall material swap
- Low E fields in the coupler region

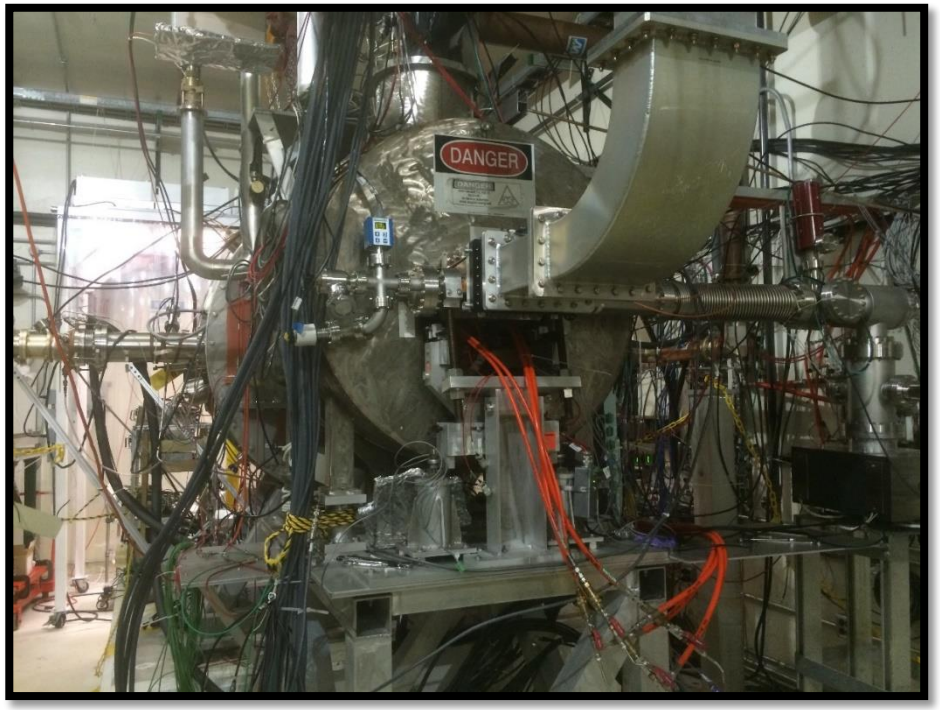


- Allows for careful control over experimental conditions
- Evaluate different materials
- Perform frequent inspections to track surface state

Goal: to build a coherent picture of processes inside the cavity during breakdown

Experimental facility: Mucool Test Area (MTA)

- Capacity to test 201 and 805MHz cavities in strong magnetic field (up to 5T)
- H- beamline passes through the center of magnet bore
- Extensive instrumentation for BD characterization:
  - Trigger system for breakdown detection
  - Fast oscilloscopes to record time sensitive signals (pickups, optical fibers, X ray detection, directional couplers)
  - Vacuum pressure data
  - Temperature sensors
  - Spark acoustic localization



MTA hall: solenoid magnet with inserted 805MHz modular cavity

Experimental results

Modular cavity: run history with copper endplates

- First B=0T run (baseline performance) :
  - Maximum Safe Operating Gradient of 45MV/m
  - 130 sparks detected

← Inspection

- First B=3T run:
  - Stable operation below 12MV/m
  - 55 sparks detected

← Inspection

- “Conditioning” B=0T run:
  - Conditioned up to 22MV/m inflicting 460 sparks

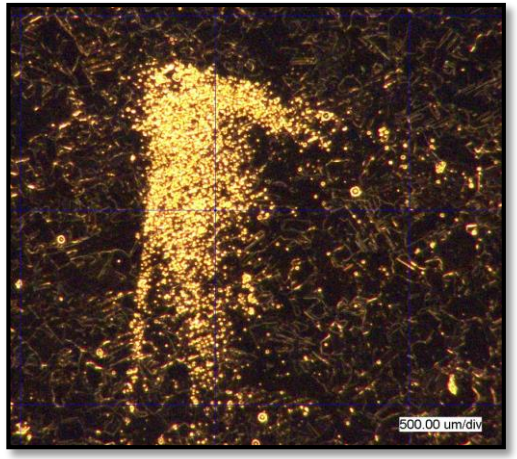
← Inspection

- Second B=3T run:
  - Maximum Safe Operating Gradient of 10MV/m

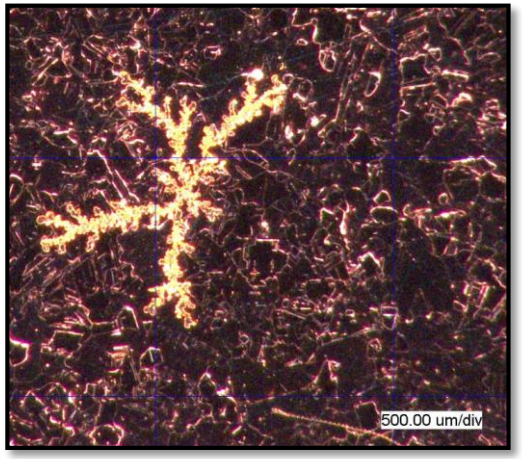
Inspection after first B=0T run

- Maximum gradient 50MV/m, 130 detected sparks
- Damage is “non-violent” and rather flat
- Damage distribution is roughly uniform
- No correlation between damage on opposing endplates

Examples of most common types of damage



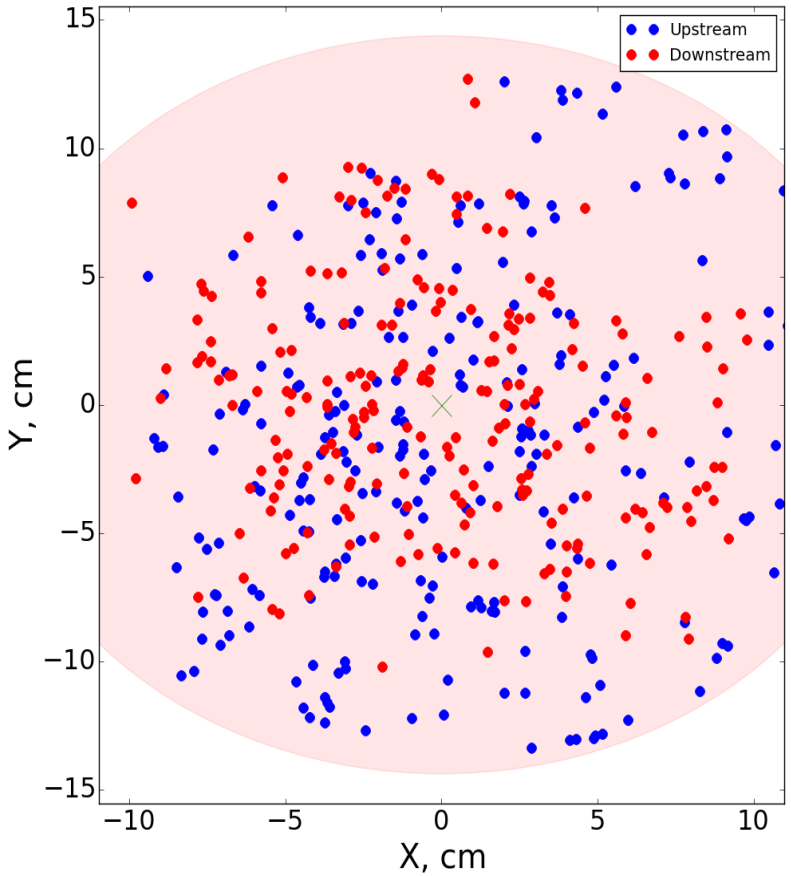
“cluster”
Count : > 250



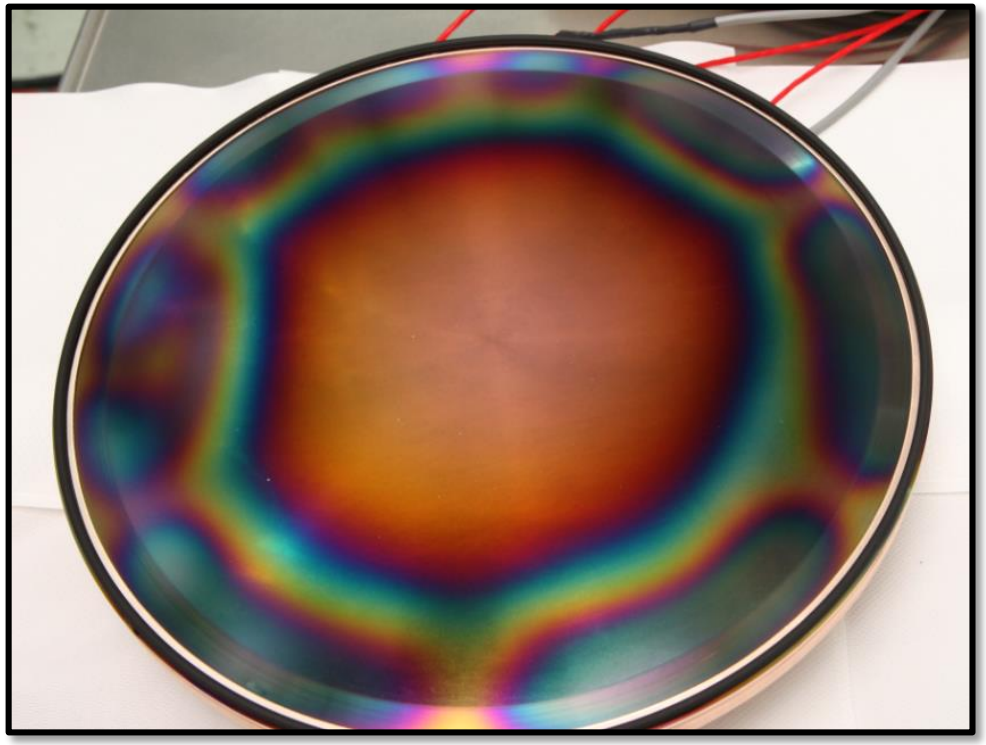
1mm

“fractal”
Count: 92

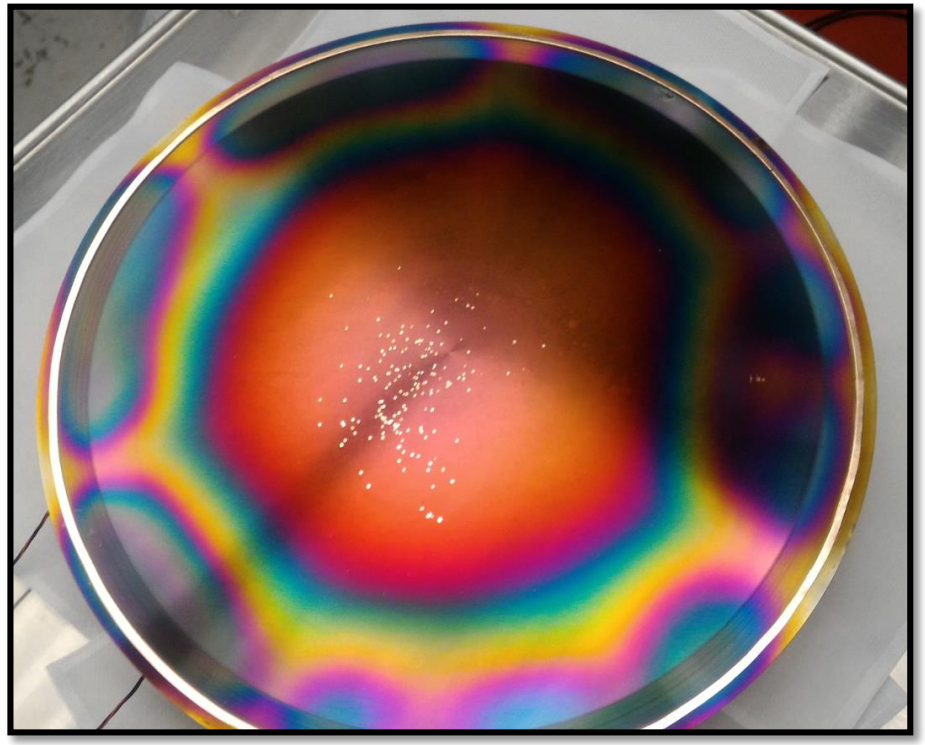
Map of observed damage sites



Inspection after B=3T run



Endplate after B=0T run



Endplate after B=3T run

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

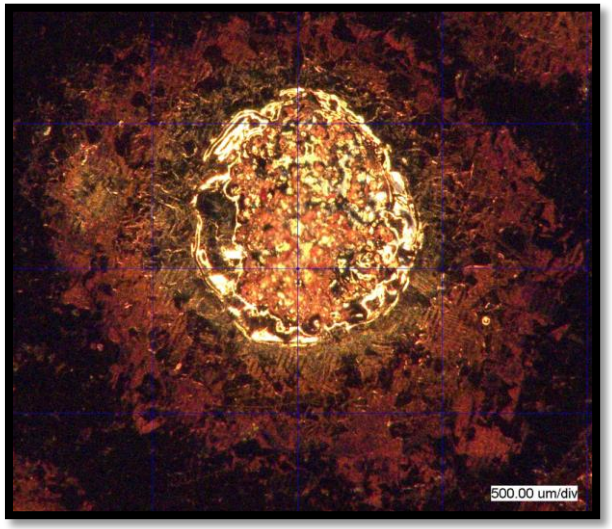
<u>All clearly visible damage was inflicted during B=3T run (!)</u>

Inspection after B=3T run: damage microstructure

Typical BD damage – we call them “volcanos”

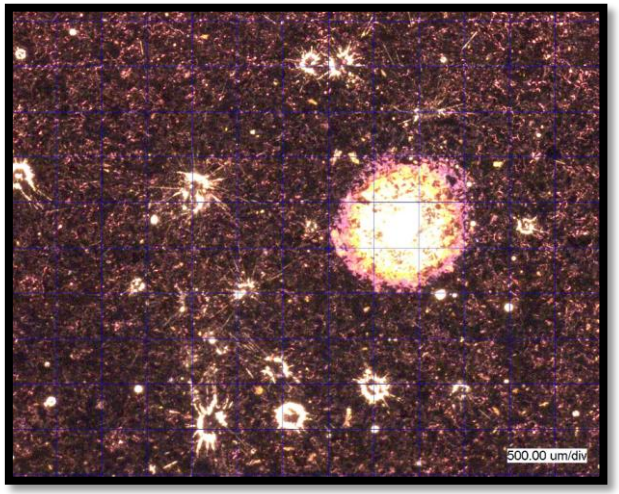
- Characteristic diameter of a volcano ~1.5mm
- Traces of splashing
- Damage is much more “violent”, although stored energy was 16 times lower than in B=0T run

“Volcano” with crater

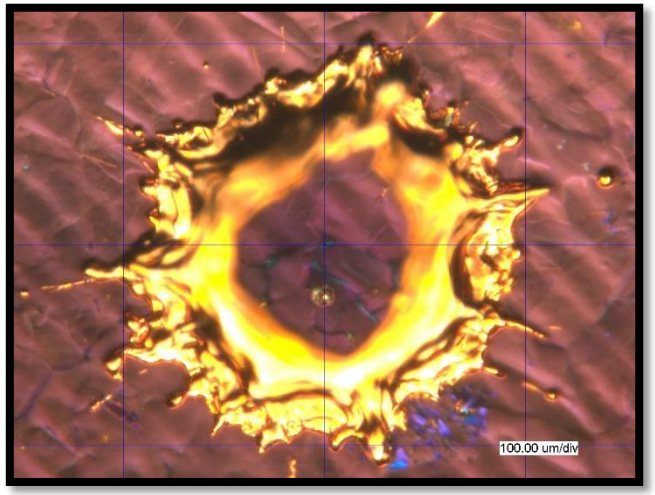


2mm

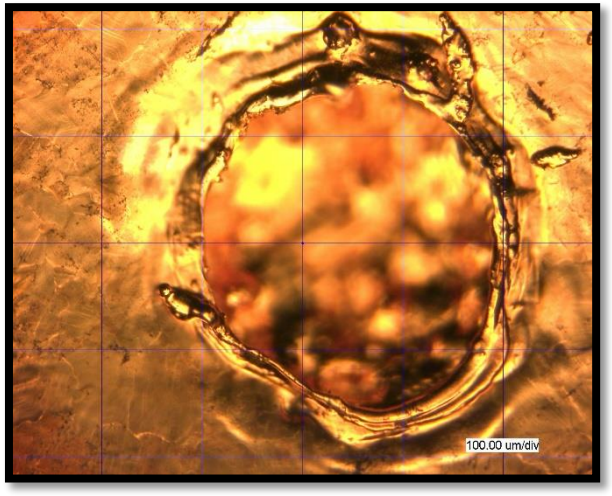
Splashing traces around BD damage



5mm



0.2mm

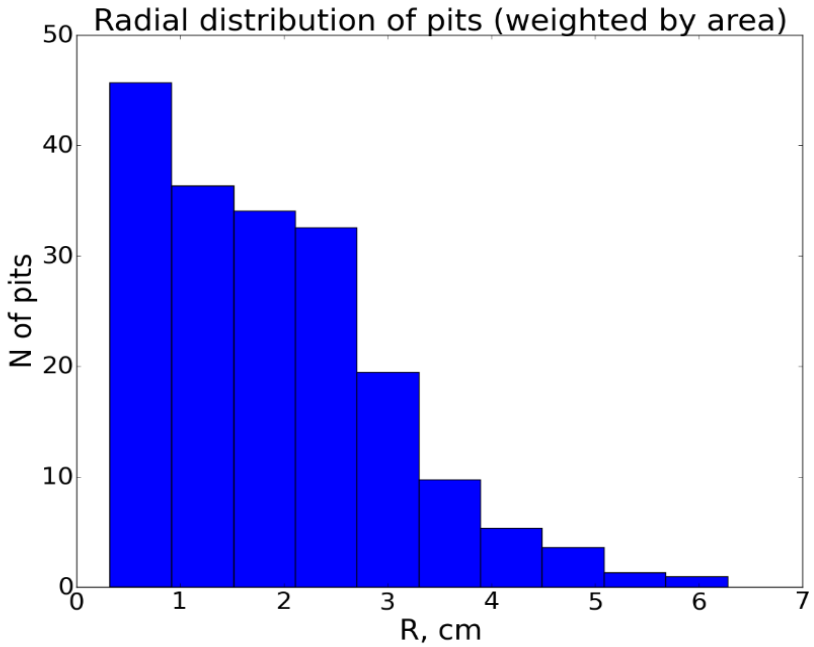


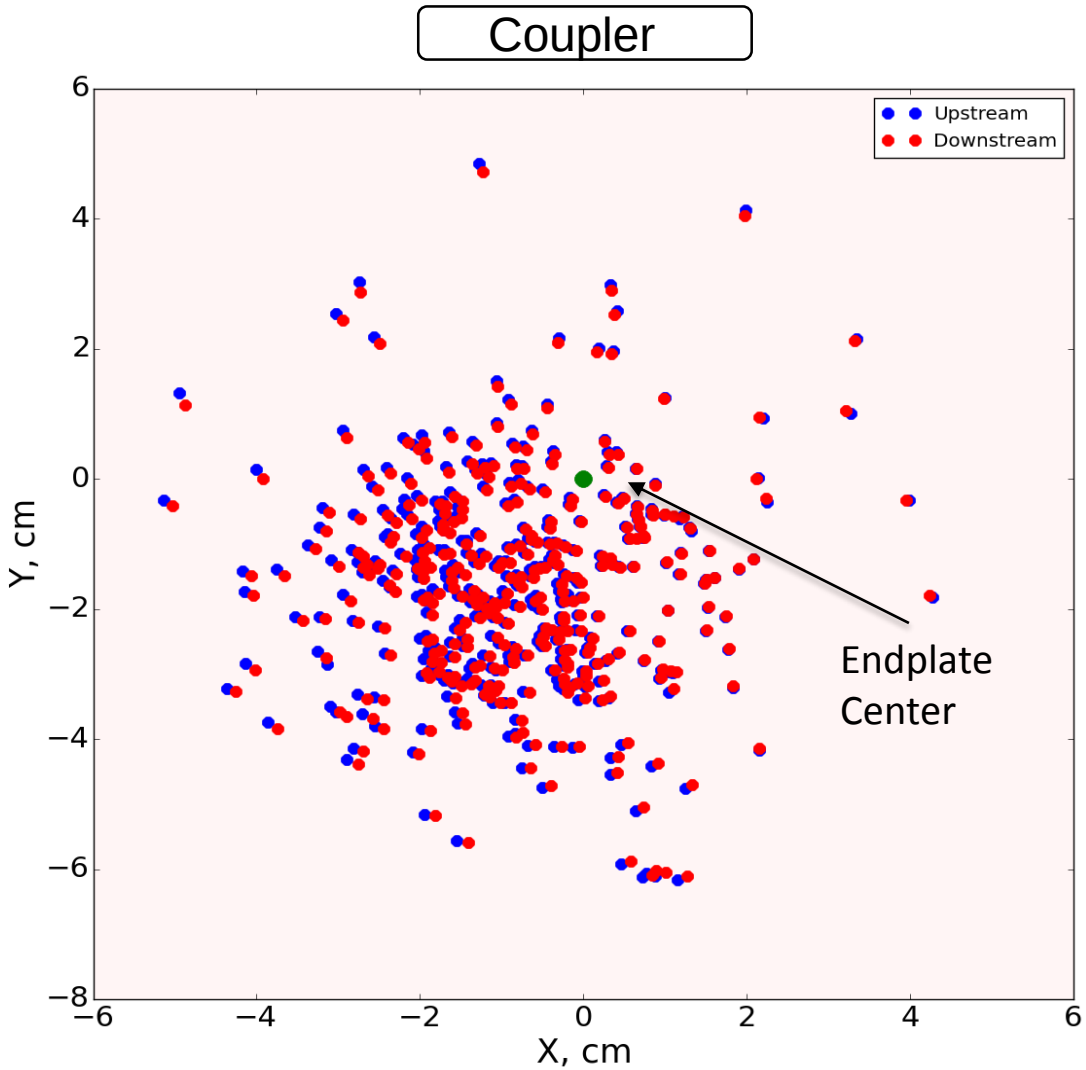
0.5mm

Crater depth ~ 30μm

Inspection after B=3T runs: damage pattern

- **Perfect 1-to-1 correspondence between 354 "volcanos" on each endplate (new result)**
- Damage distribution is denser in high E field region
- Mystery: detected 136 sparks, but observed 354 damage sites



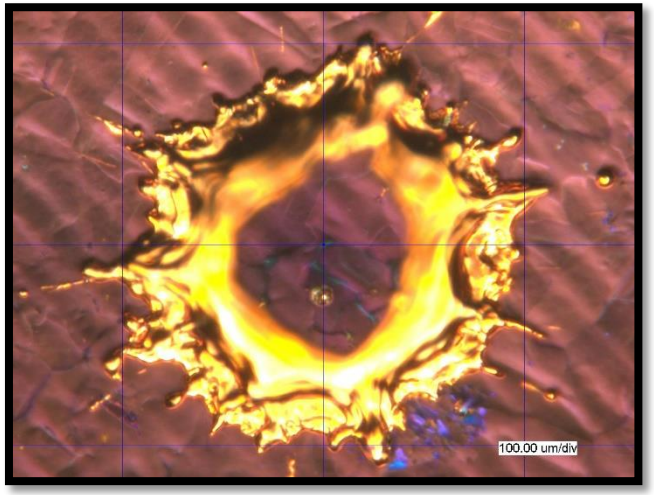


Map of "volcanos"

Inspection after B=0T conditioning run

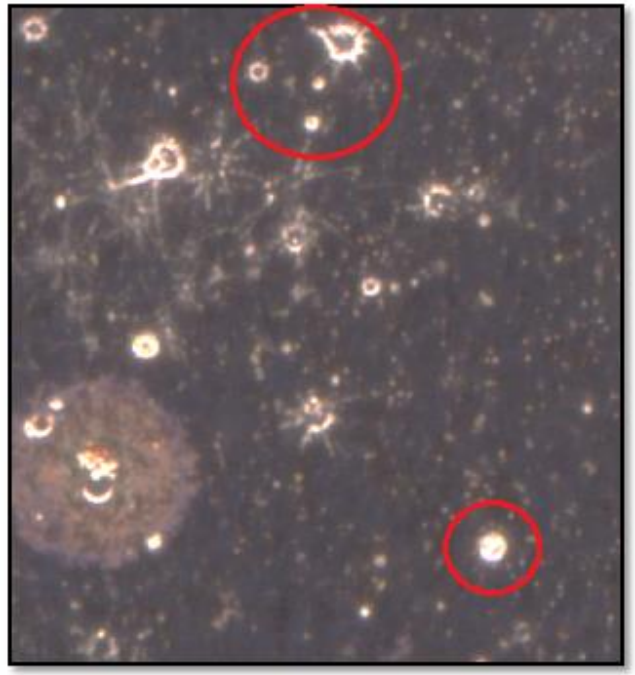
- Ran up to 22MV/m, inflicting ~460 sparks
- No new damage sites observed
- Some splashing traces disappeared

"Splash" after B=3T operation



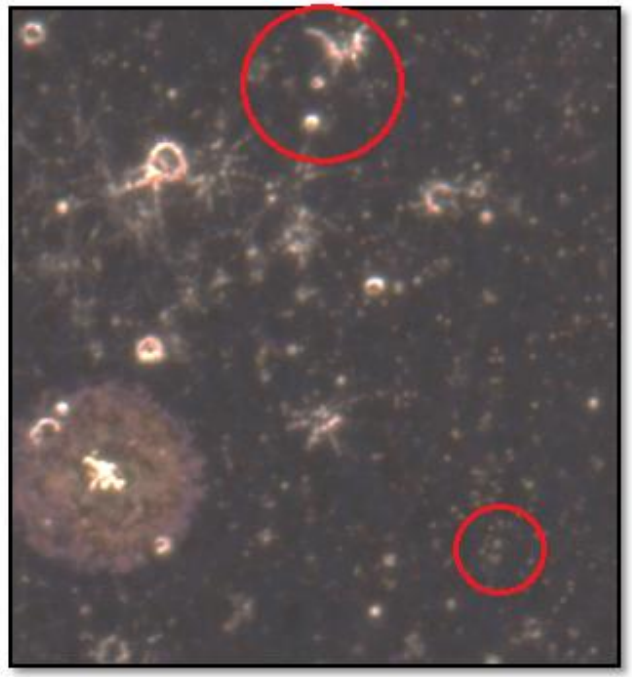
0.2mm

Before



8mm

After



MC high power tests: highlights

- First B=0T run:

  SOG ~ 45MV/m, ~130 sparks detected
  - Inspection: ~500 features inspected. Most common: “fractals” (92) and “clusters” (>250)
  - Damage is non-violent and random

- B=3T runs:

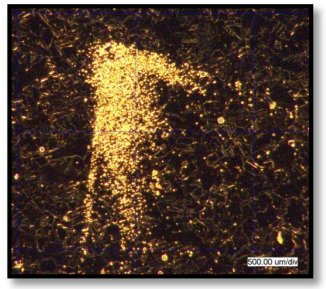
  SOG ~ 10 MV/m, 136 sparks detected
  - Inspection: damage pattern of volcanos, 354 pits on each endplate, perfect 1-to-1 match
  - Copper splashing

- B=0T “conditioning run”:

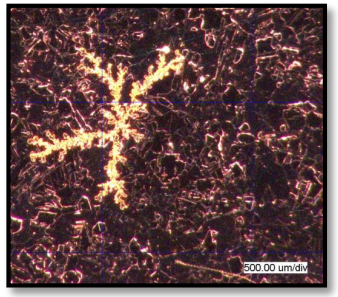
  Conditioned up to 22MV/m, inflicted 460 sparks
  - Inspection: no new BD sites, some splashing traces got eliminated

[SOG = Safe Operating Gradient]

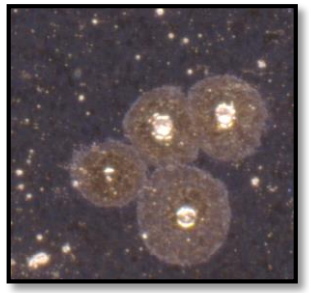
“cluster”



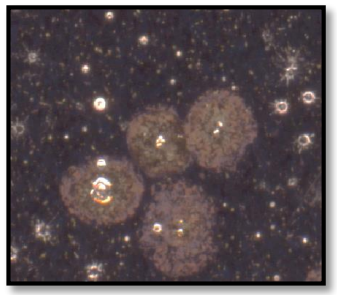
“fractal”



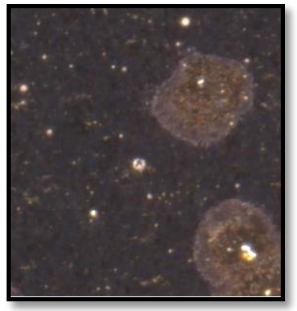
upstream



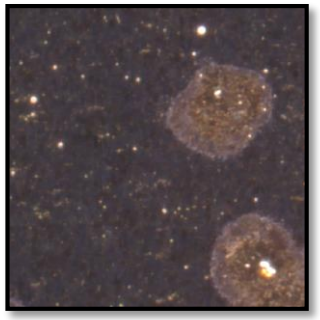
downstream



before



after



Discussion, mysteries, open questions…

- One-to-one correspondence between damage spots in B=3T supports the model of BD being induced by focused dark current
- More violent damage in B=3T also can be explained by focusing

- Mismatch between the number of “volcanos” (N=354) and detected breakdown events (N=134) in 3T operation
- Calculations show that dark current electrons do not cross the cavity gap for gradients <10MV/m. Why do we observe breakdown events at ~8MV/m in B=3T?

- Those are all exciting questions I will be glad to discuss with you if interested
- *Inspection and data analysis is still in progress

Next set of measurements will be with Beryllium endplates

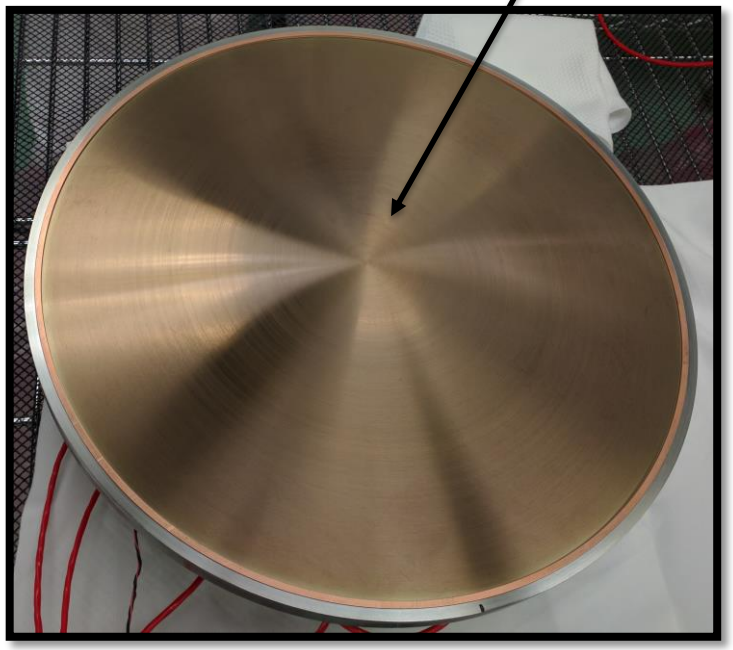
What we expect to observe:

- Radiation length of Beryllium (~35cm) for electrons is higher than of copper (~1.4cm) →
- Mitigation of breakdown triggers on the surface →
- Better gradient performance

There are several measurements enabled by Beryllium:

- Direct measurement of dark current (Faraday Cup)
- Measurement of transverse emittance of dark current beamlets (film/glass)

2.6 mm-thick window



Inner surface of Beryllium endplate

*Beryllium – copper configuration is also being discussed

Conclusion

- We tested 805MHz pillbox modular cavity 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 < week)
  - Breakdown happens where we want it to happen
- Surface inspections revealed new interesting results
  - Analysis is ongoing
- Next high-power runs in B=0T and B=3T will be with Be endplates
- Low radiation length of Be will allow for more detailed field emission and surface evolution studies

Thank you slide

Thank you