Study of vacuum RF Breakdown in strong magnetic field

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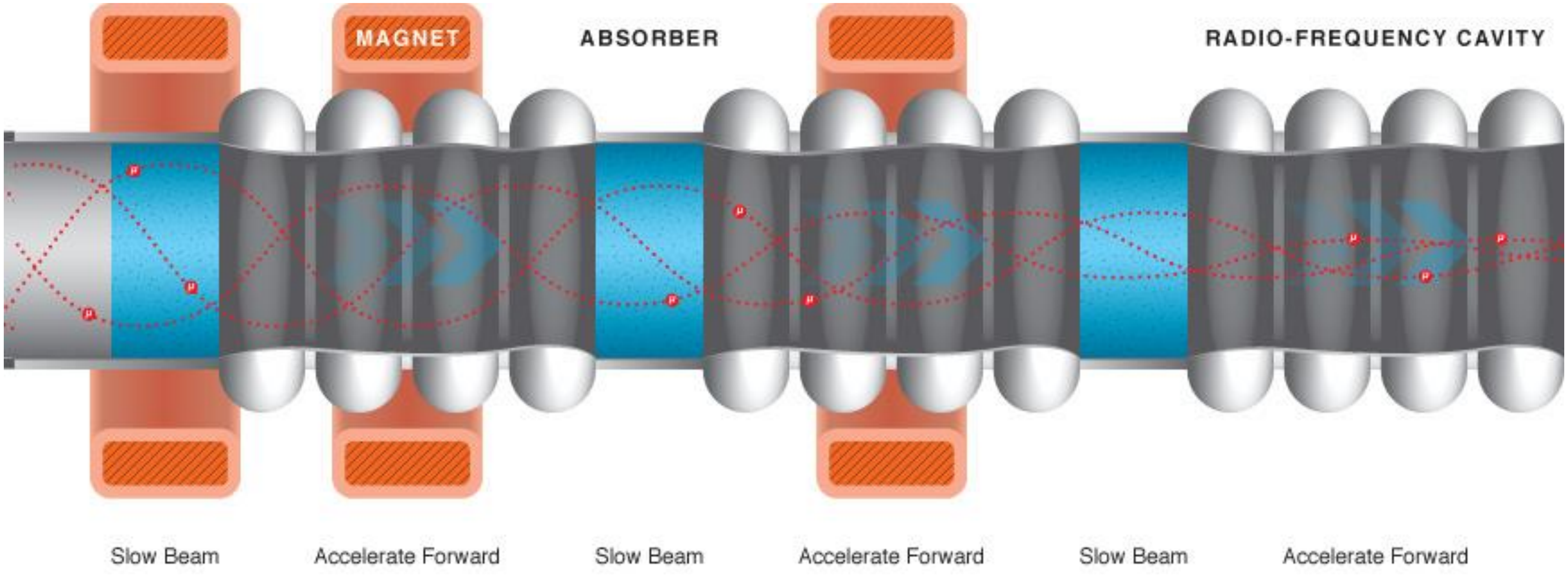
Outline

- Statement of the problem
- Model explaining deterioration of gradient in strong B field
- Modular cavity program
- Experimental results
- Analysis

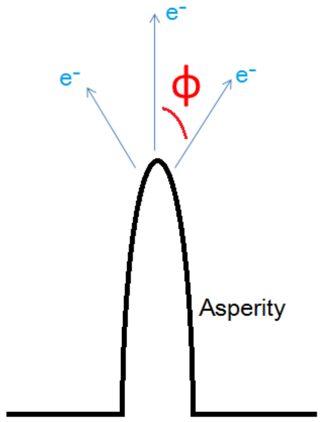
Motivation: Muon cooling channel



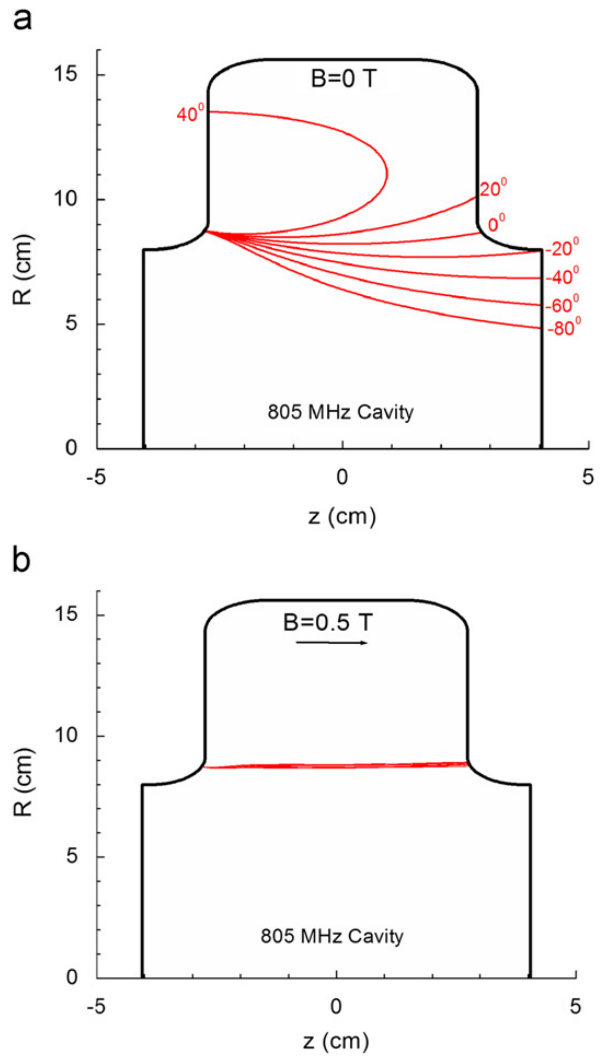
It was experimentally shown that presence of multi-Tesla magnetic increases the breakdown rate

[Safe operating gradient = maximum gradient: breakdown rate < 10^{-5}]

Model explaining deterioration of gradient in strong B fields

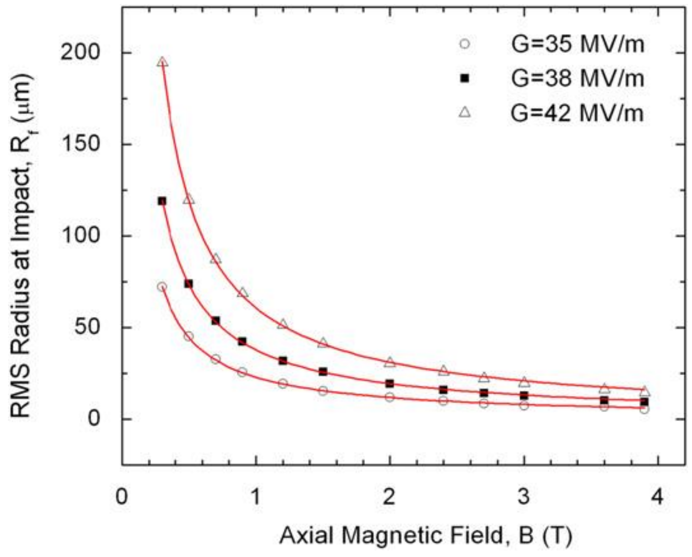


- Electron field emission from surface imperfections
- B field focuses dark current into beamlets
- **Beamlets cause pulsed heating that leads to surface damage**



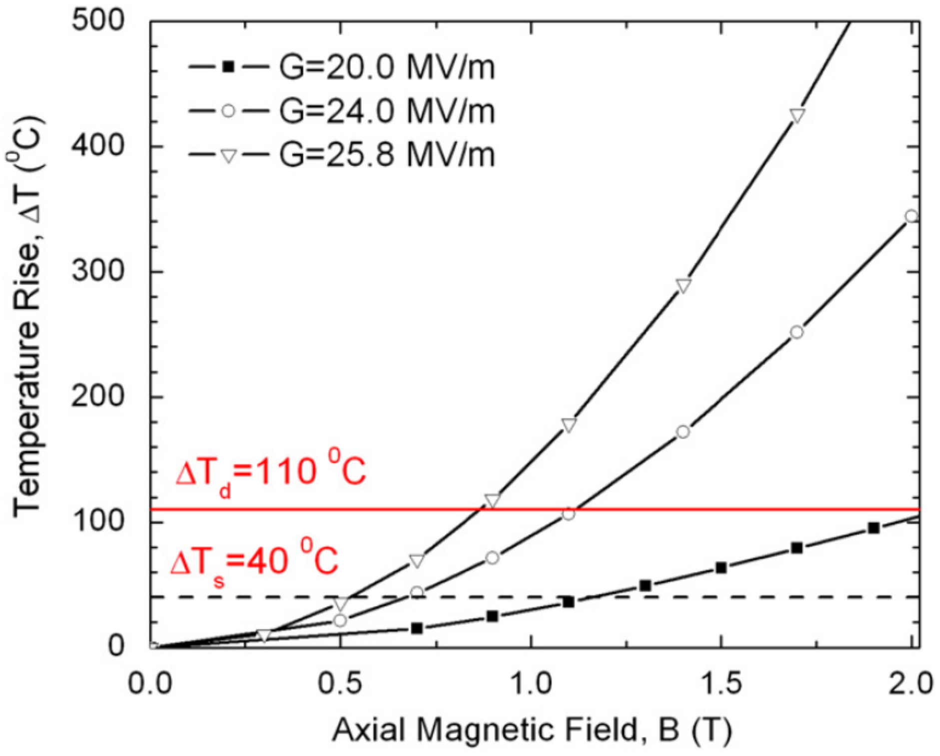
Potential mitigations:

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

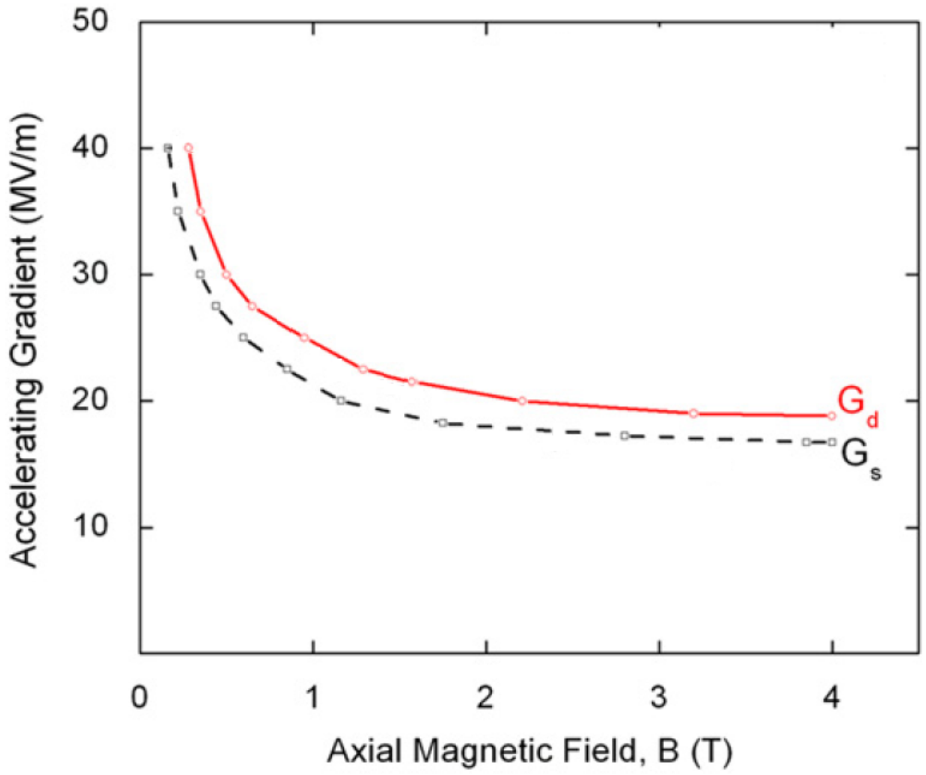


D.Stratakis , J.Gallardo, R.Palmer, Nucl. Inst. Meth. A 620 (2010), 147-154

Mechanical stress on the metal is induced due to temperature rise



Temperature rise model for 805MHz copper pillbox



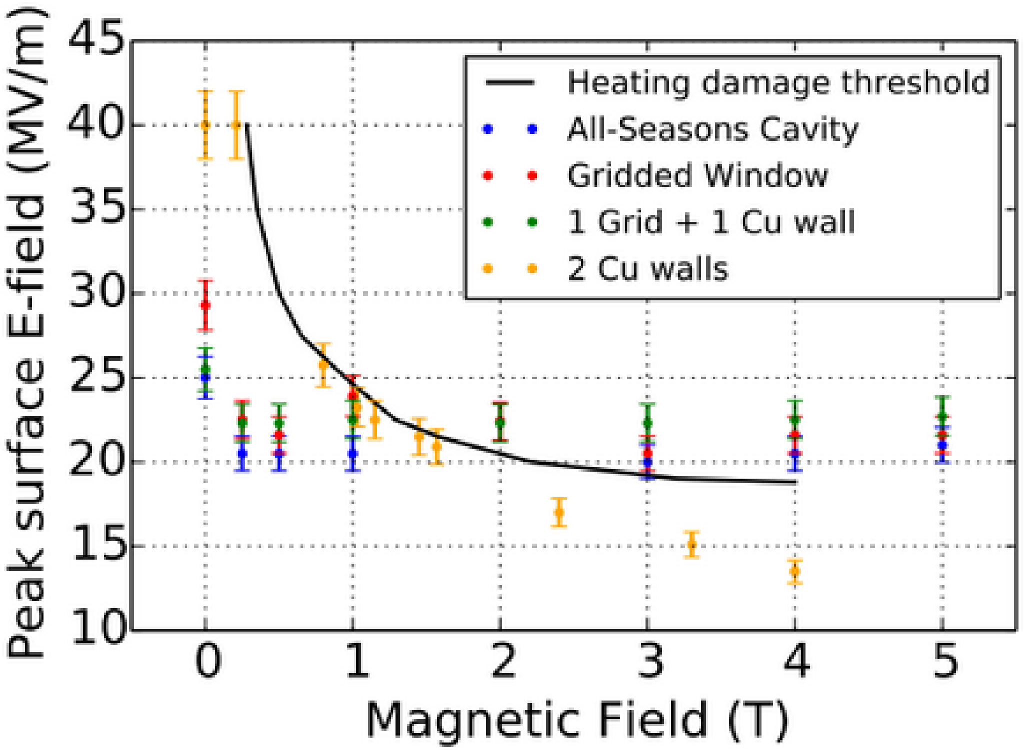
Model prediction of max safe gradient in external magnetic field G_s

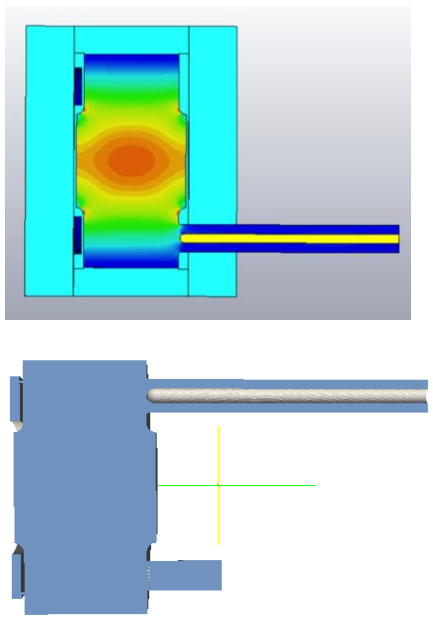
ΔT_s - safe pulse heating temperature for copper
ΔT_d – required temperature for surface fracture

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

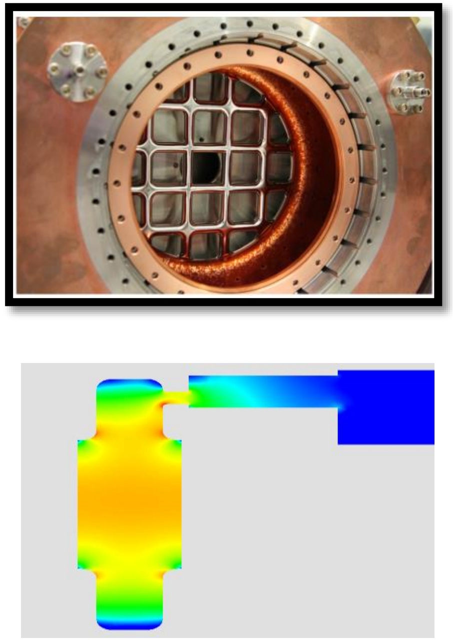
Model of a breakdown in strong B field – prediction vs experiment

High power behavior of previous cavities





"All-Seasons" cavity



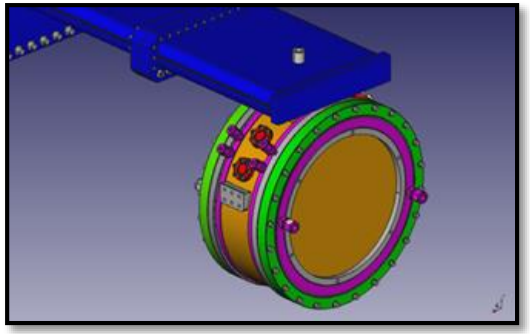
Pillbox cavity

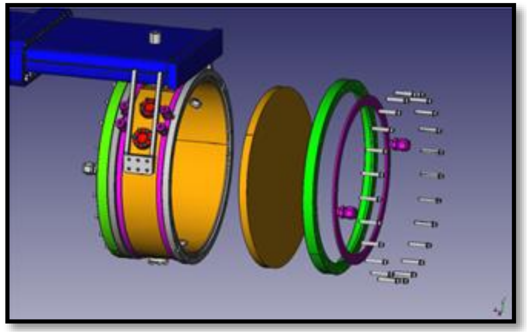
Study of breakdown with better control over systematic error is required.

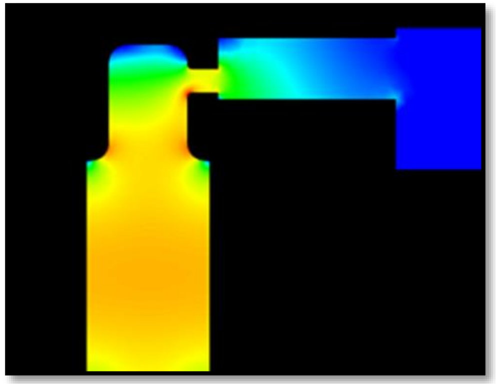
Factors that may affect the fit quality:

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

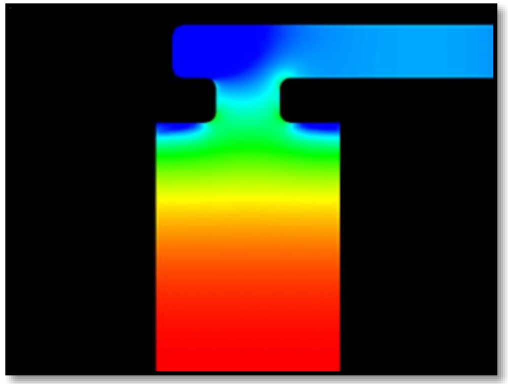
Modular cavity







Old pillbox cavity



Modular cavity

- End walls can be un-mounted easily, allows for material swap
- The gap length can also be varied by replacing the cavity body
- Low E fields in the coupler region

- 805MHz, pillbox geometry
- Water cooling lines

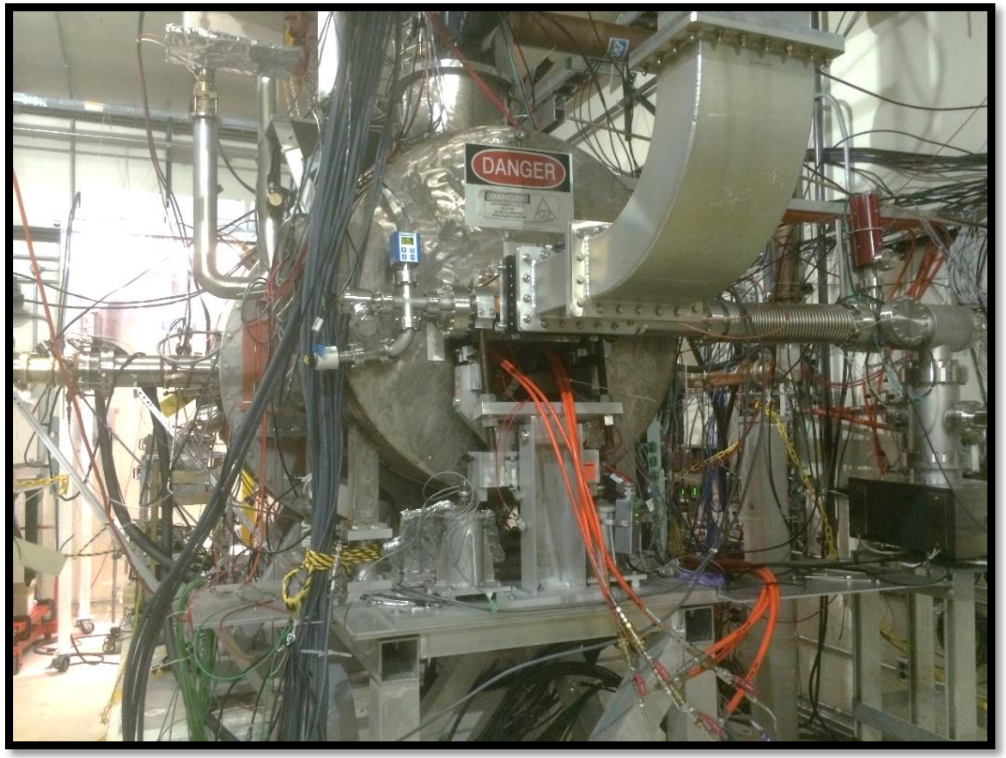
Modular cavity: measurements

- Maximum safe operating gradient in zero and non-zero external B field
- Surface damage formation process dependence on the run conditions
- Effect of high power conditioning sequence on breakdown in strong magnetic fields
- Field emission study to verify the model of beamlet heating (Be endplate program)
- Surface evolution studies

Mucool Test Area (MTA)

Facility built specifically for muon cooling hardware R&D

- Capacity to test 201 and 805MHz cavities in fields up to 5T
- H- beamline can be commissioned through the center of the 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



MTA hall: solenoid magnet with inserted 805MHz modular cavity

Recent experimental programs

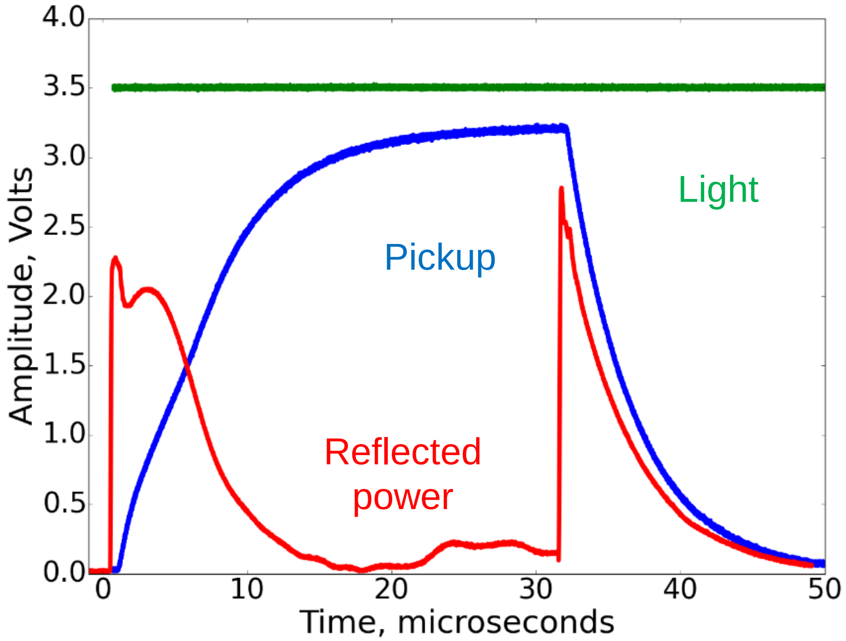
- 805MHz: Modular cavity, high-pressure gas-filled cavity
- 201MHz: pillbox MICE cavity

Spark detection algorithm

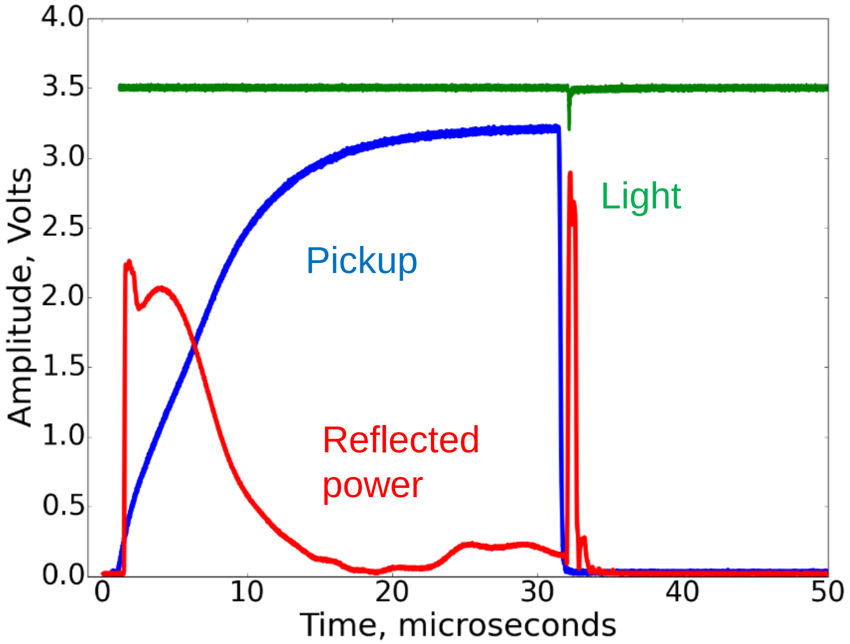
Automated system for spark detection - logical OR between:

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

Normal event



Breakdown event



Figures of merit

Parameter	Range of values
Frequency	805MHz
Mode	TM010
Pulse length	30µs
Repetition rate	5-10 Hz
Stored energy	Up to 20J
Quality factor	~20,000
Pillbox gap length	10cm
Pillbox radius	15cm
Vacuum pressure	~10^{-8} Torr

Copper endplates experimental program

High-power runs with copper endplates: summary

- First B=0T run: Apr – Oct 2015
  - Maximum Safe Operating Gradient of **45 MV/m**
  - Ran for ~13M pulses, 130 sparks detected

← Surface inspection

- First B=3T run: Dec 2015
  - Stable operation below **12 MV/m**
  - Ran for ~5M pulses, 55 sparks detected

← Surface inspection

- “Conditioning” B=0T run: Jan – Feb 2016
  - Conditioned up to **22 MV/m**
  - Ran for ~14M pulses, 460 sparks detected

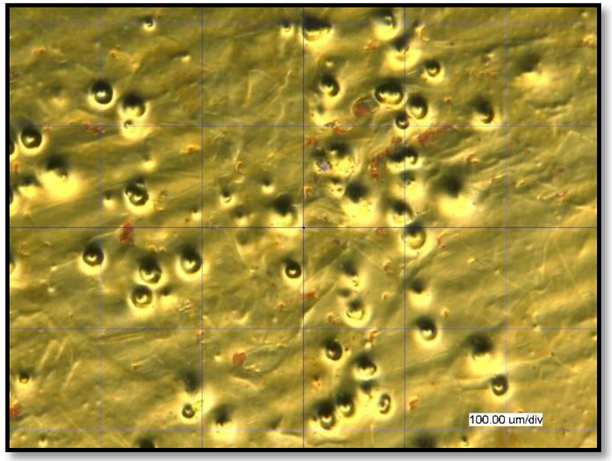
← Surface inspection

- Second B=3T run: Apr 2016
  - Maximum Safe Operating Gradient of order of **10 MV/m**
  - Ran for ~3M pulses, 81 sparks detected

Inspection after first B=0T run

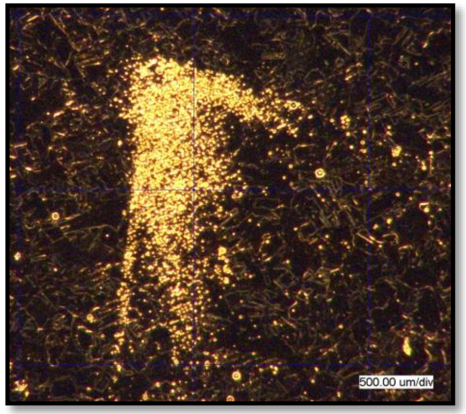
- Cavity ran up to ~50MV/m
- **130** breakdown events detected
- Documented ~400 damage features
- Damage is relatively "non-violent" and flat
- No correlation between damage on opposing endplates observed - asymmetry

Type 1

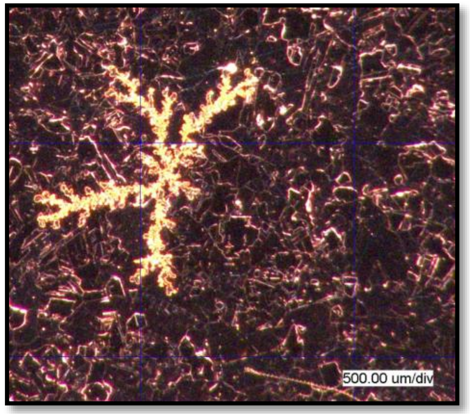


400µm

Examples of most common types of damage



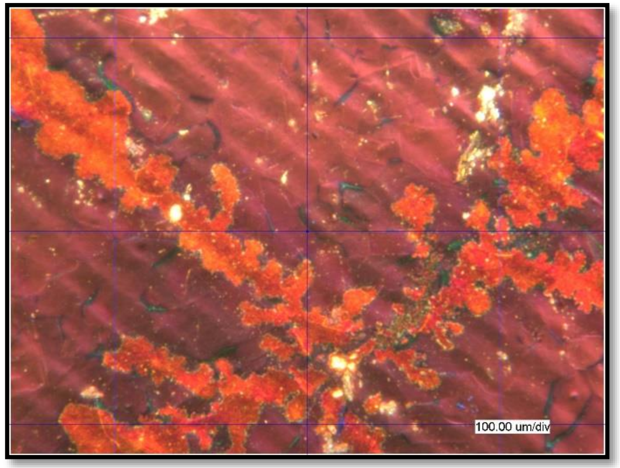
Type 1
Count : > 250



Type 2
Count: 92

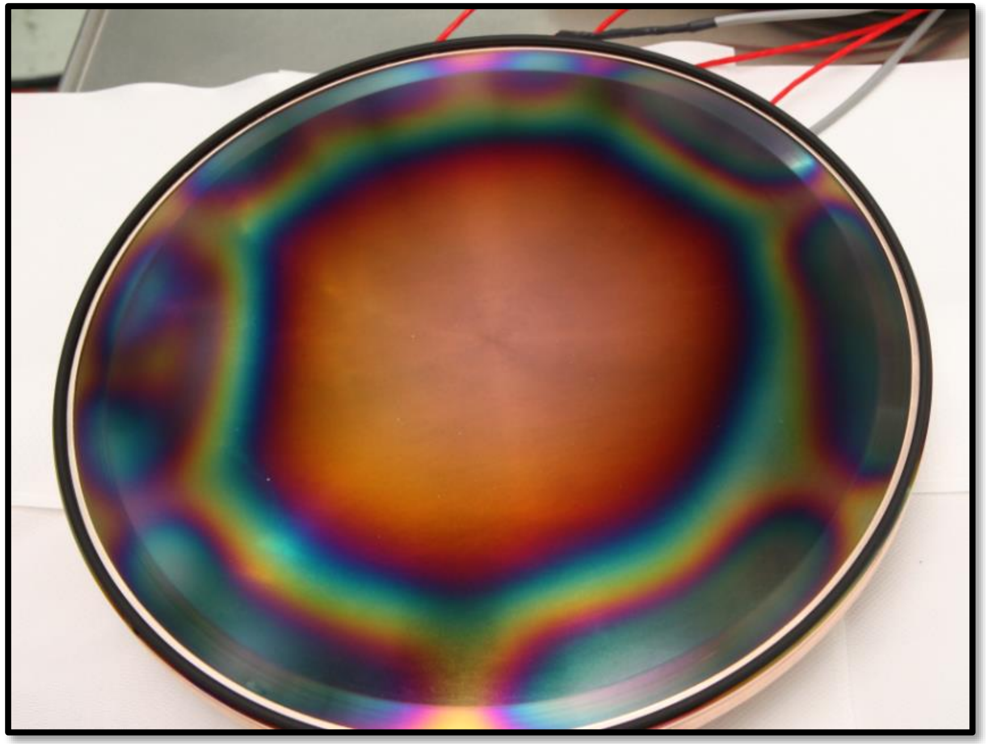
1mm

Type 2

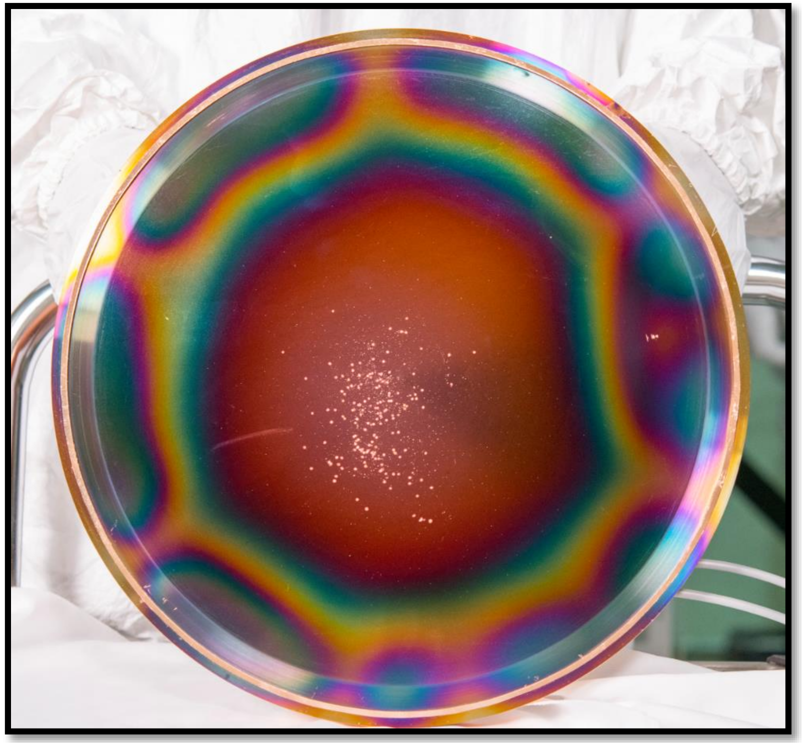


200µm

Inspection after B=3T run



Downstream endplate after B=0T run



Downstream endplate after B=3T run

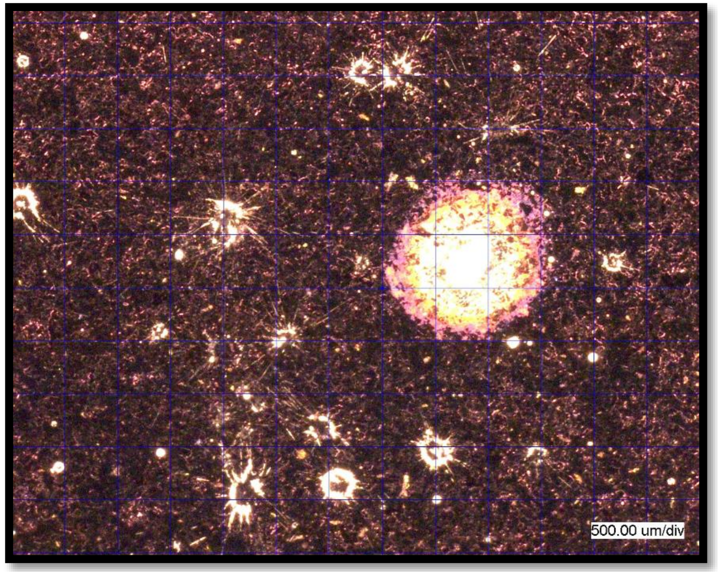
First time inspections were carried out separately after run at zero magnetic field and run at high magnetic field

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

Inspection after first B=3T run: damage microstructure

Typical BD pits

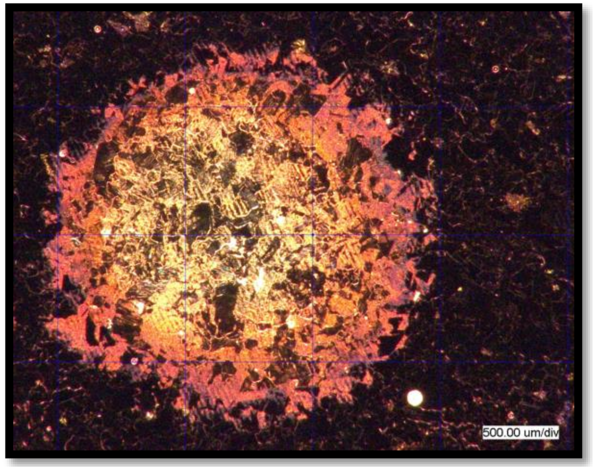
- Similar to BD damage we observed in other cavities
- Characteristic pit diameter ~1.5mm
- Traces of splashing



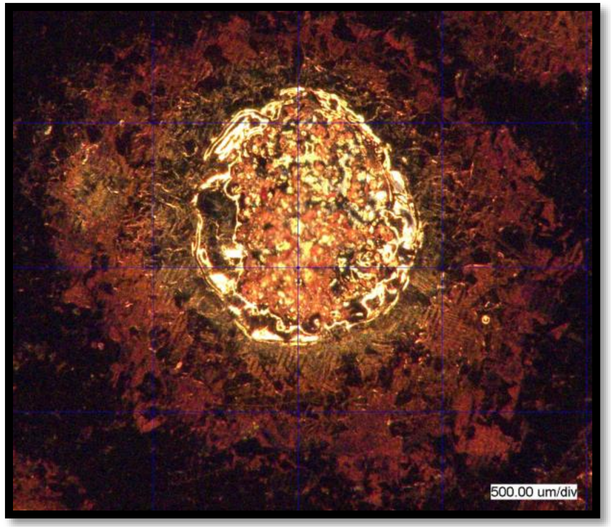
5mm

splashing

Flat structure

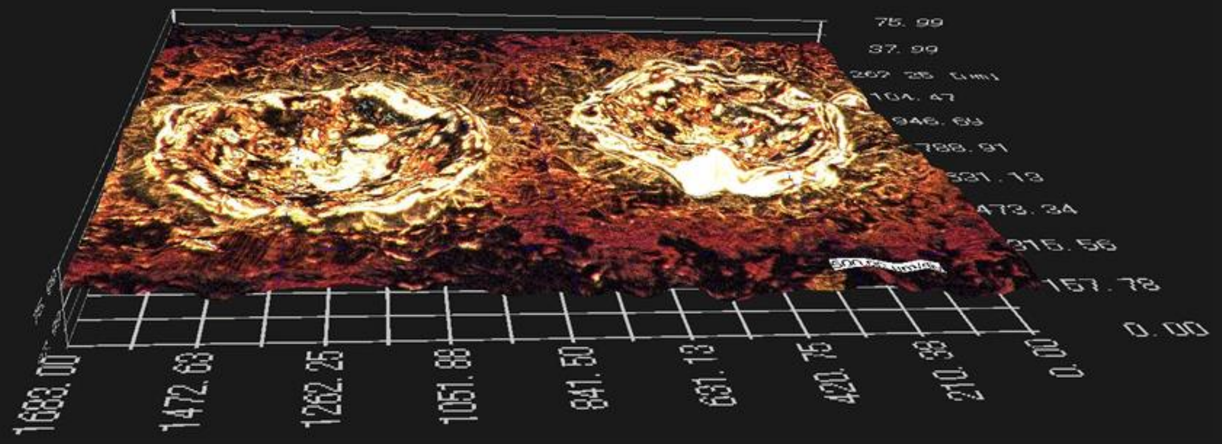


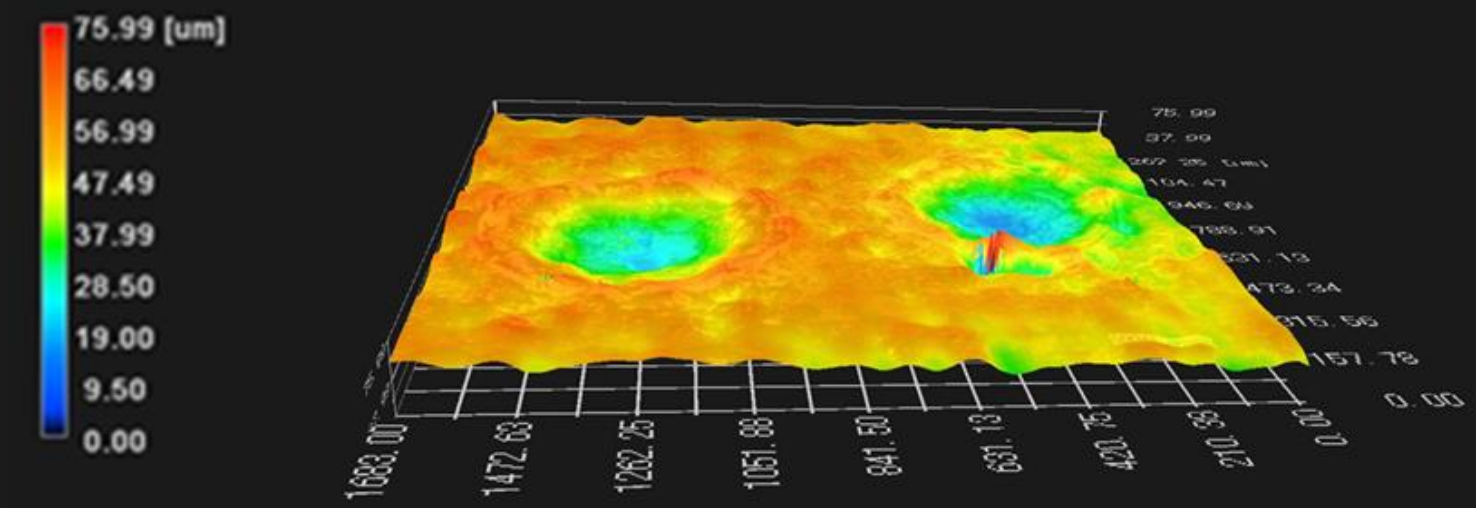
Structure with melted core



2mm

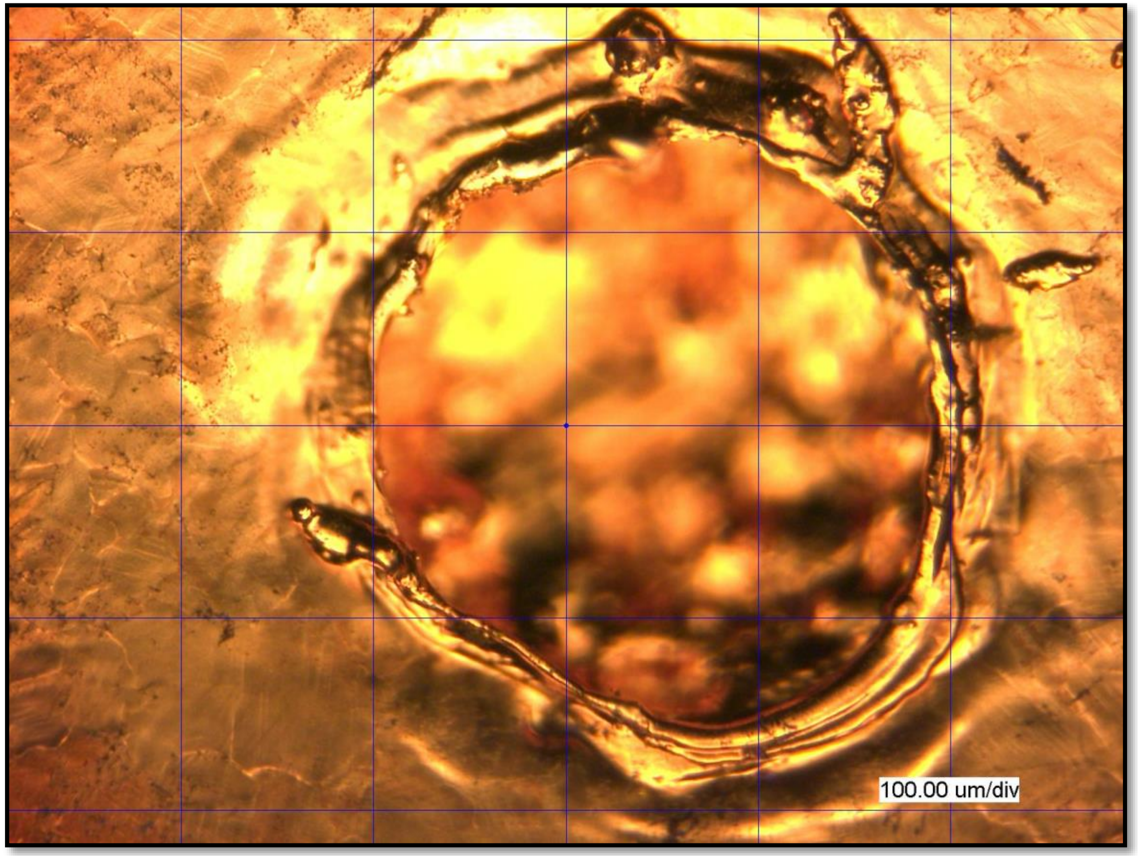
Inspection after B=3T run: 3D imaging



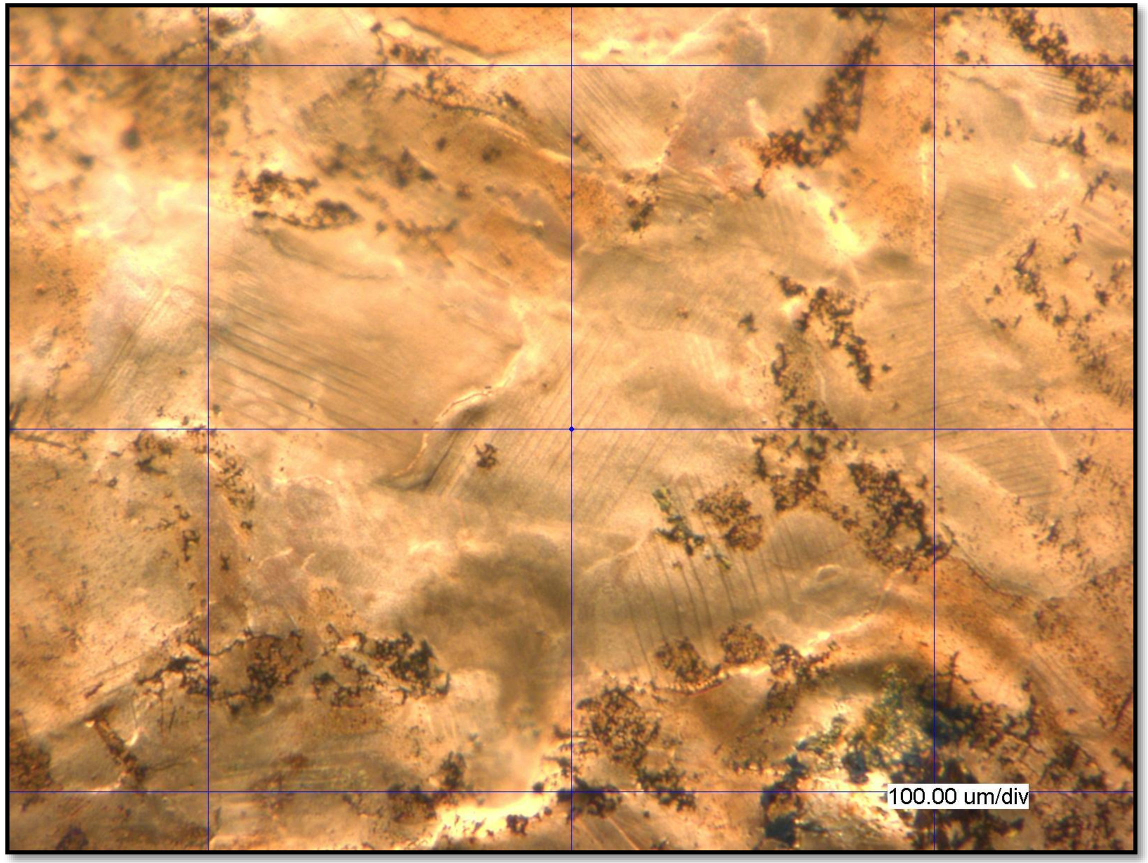


- Damage is much more "violent" than after B=0T
- Melted bulk of copper
- Craters up to ~0.5mm in diameter and up to ~ 60um in depth
- SEM analysis will be possible in the future

Damage microstructure



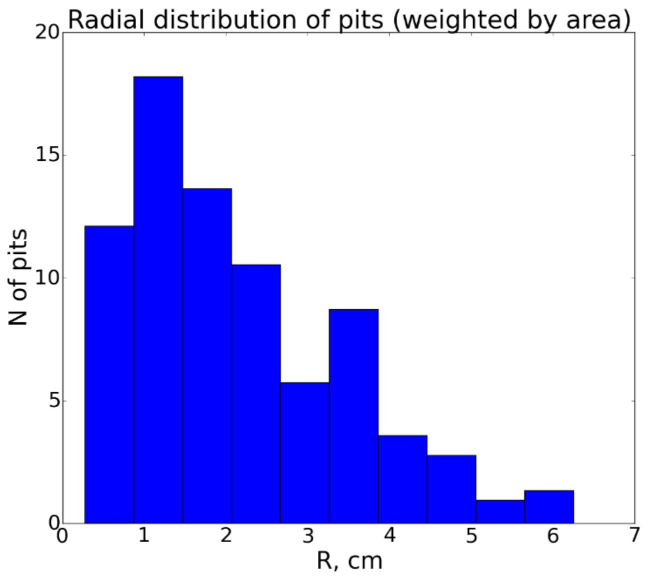
Crater edges

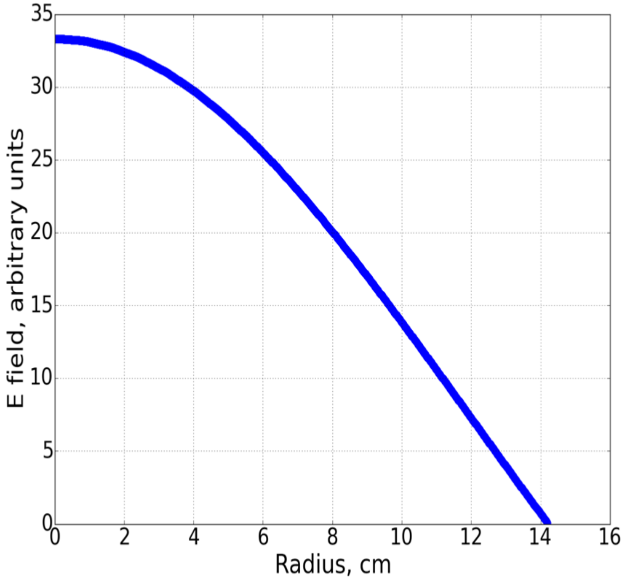


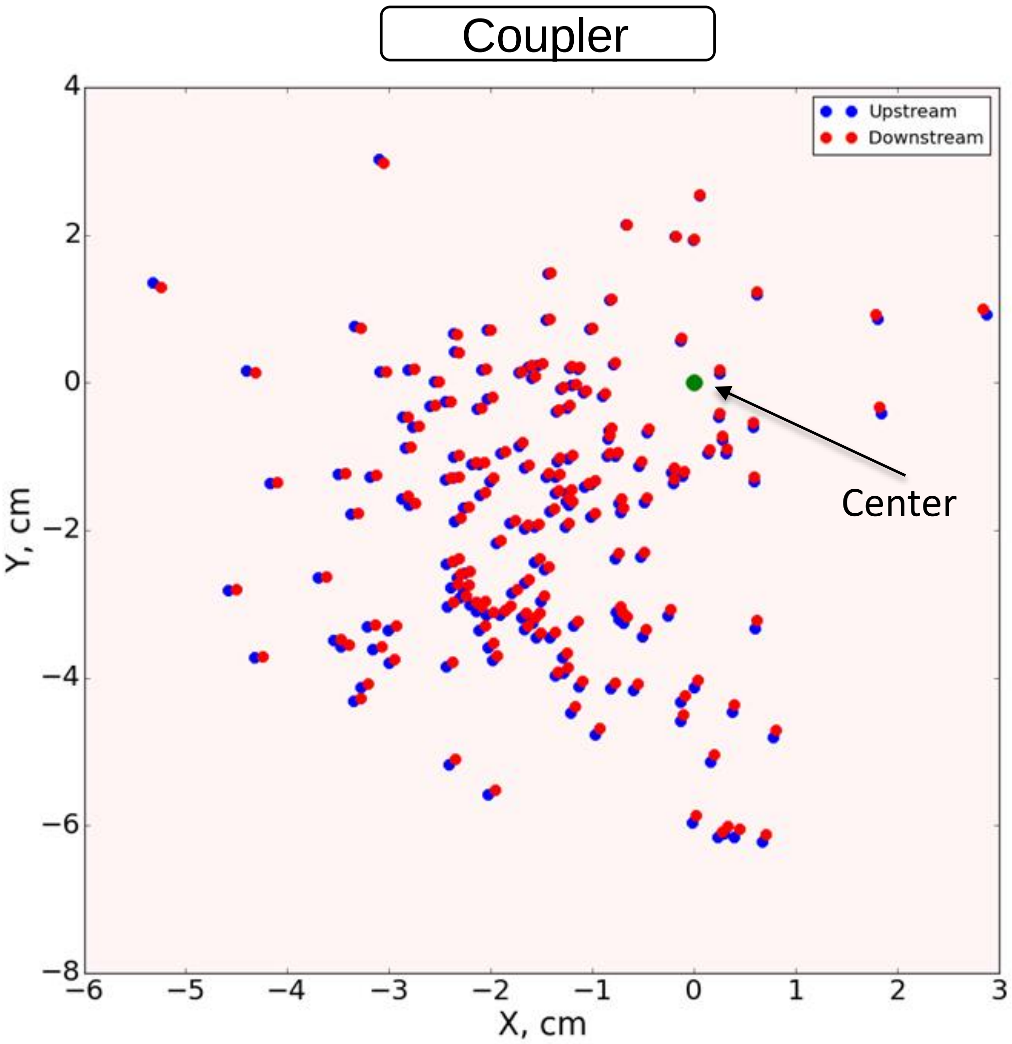
Core center

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





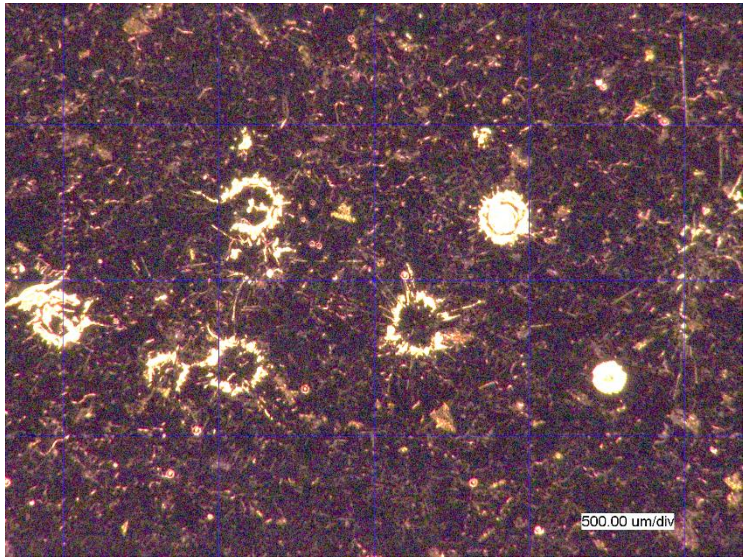


Map of damage pits

Inspection after B=0T conditioning run

Processed up to 22MV/m in >10M pulses, inflicting ~460 sparks

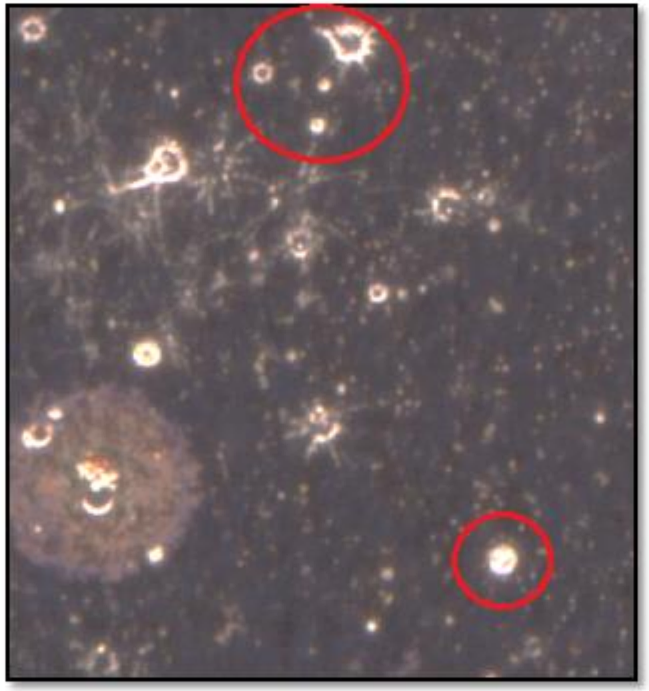
No new damage sites observed
Some splashing traces disappeared



2mm

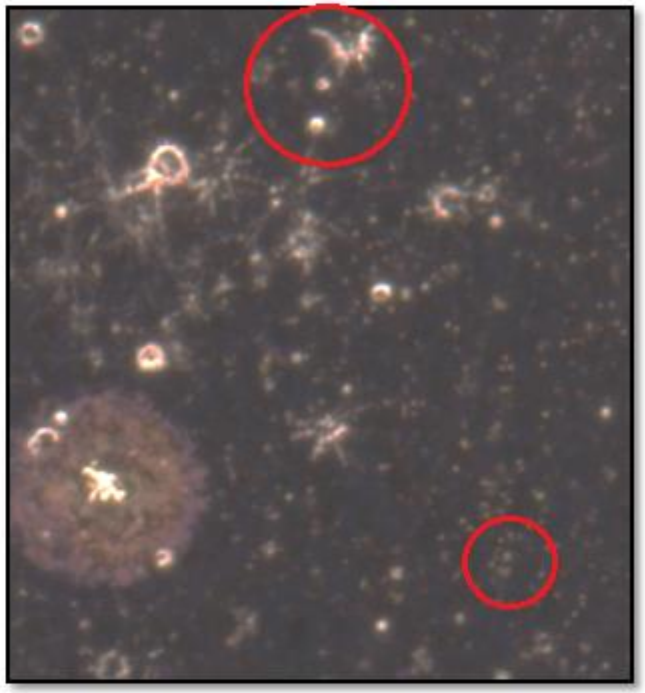
Microscopic image of splashing pattern after B=3T run

Before



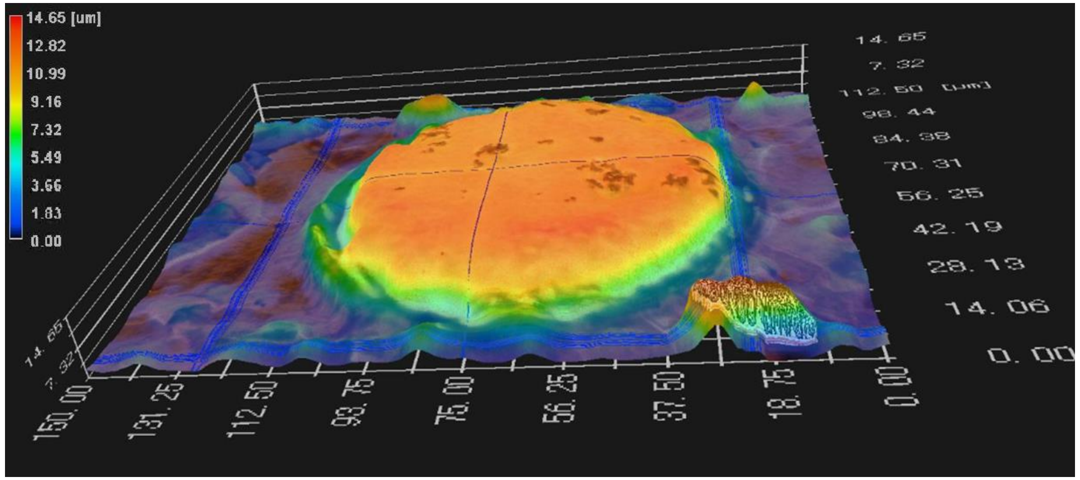
8mm

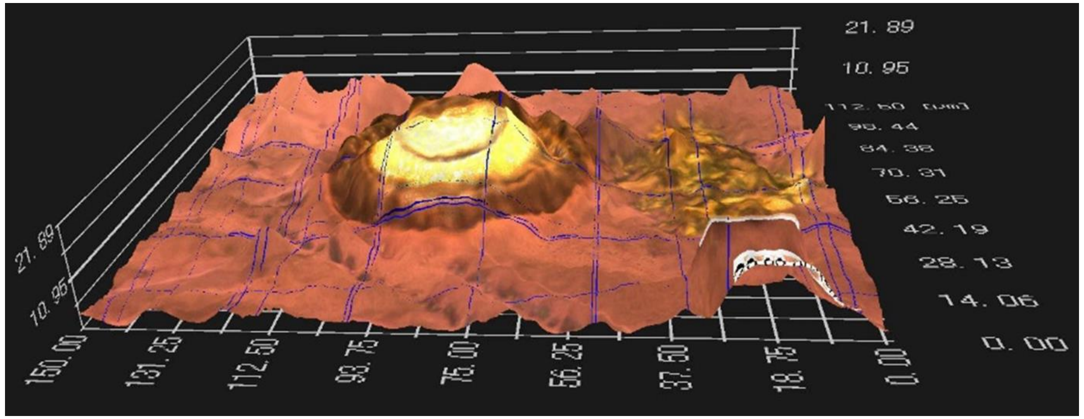
After



Closer look at splashing patterns

Melted copper "drops"

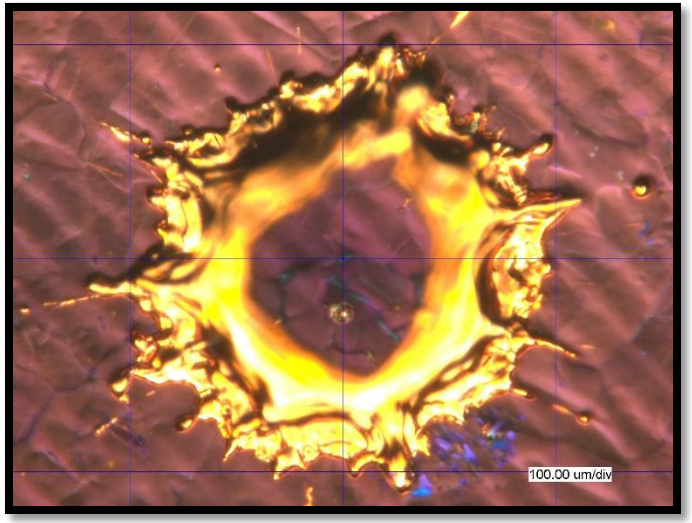




(Units – microns)

- Features that are being processed out during conditioning
- Splashes mostly lack directionality, often ~cm away from closest BD pit
- Characteristic time to solidify and cool down: 0.1 – 1s

300 µm

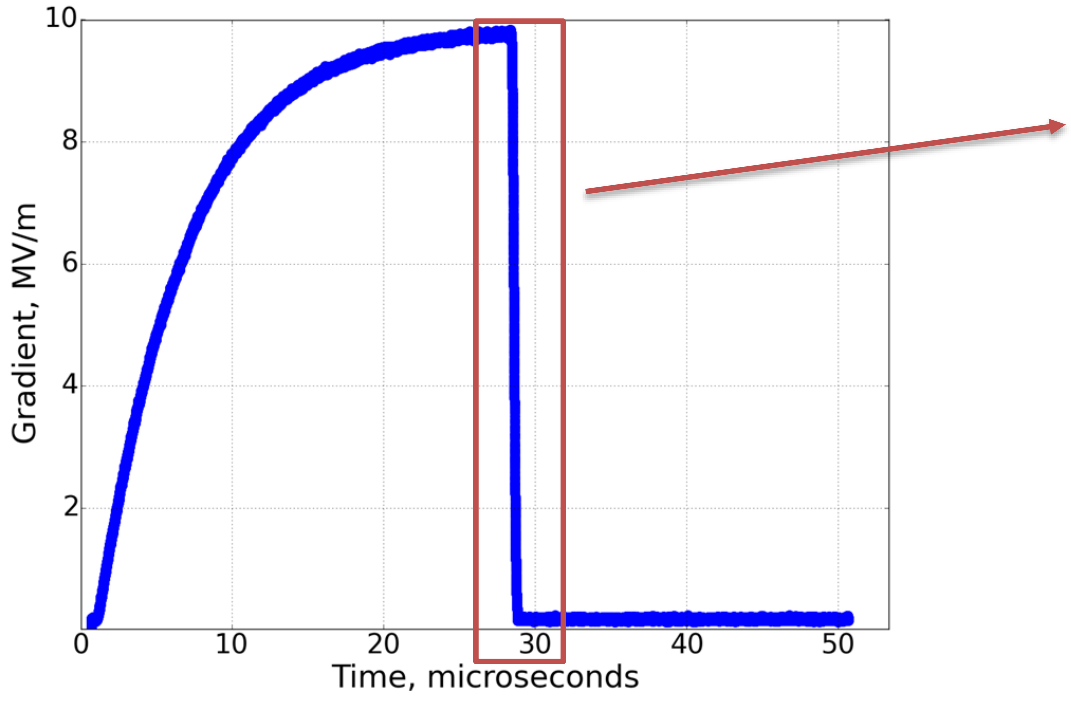


Common type of damage feature – splash with hollow center

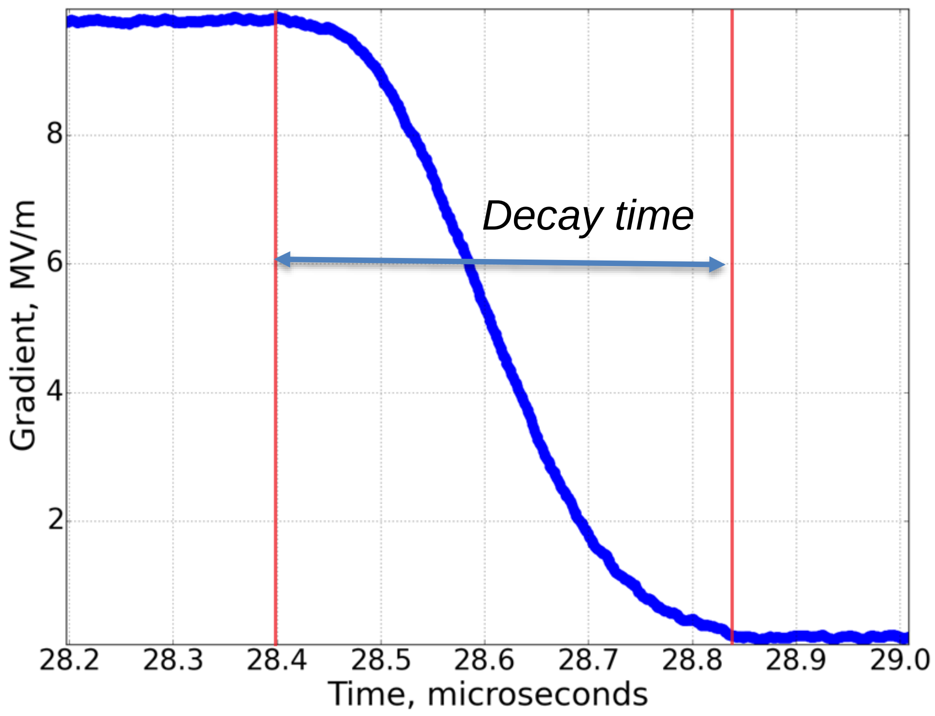
Ongoing analysis: breakdown characterization

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 – exponential fit



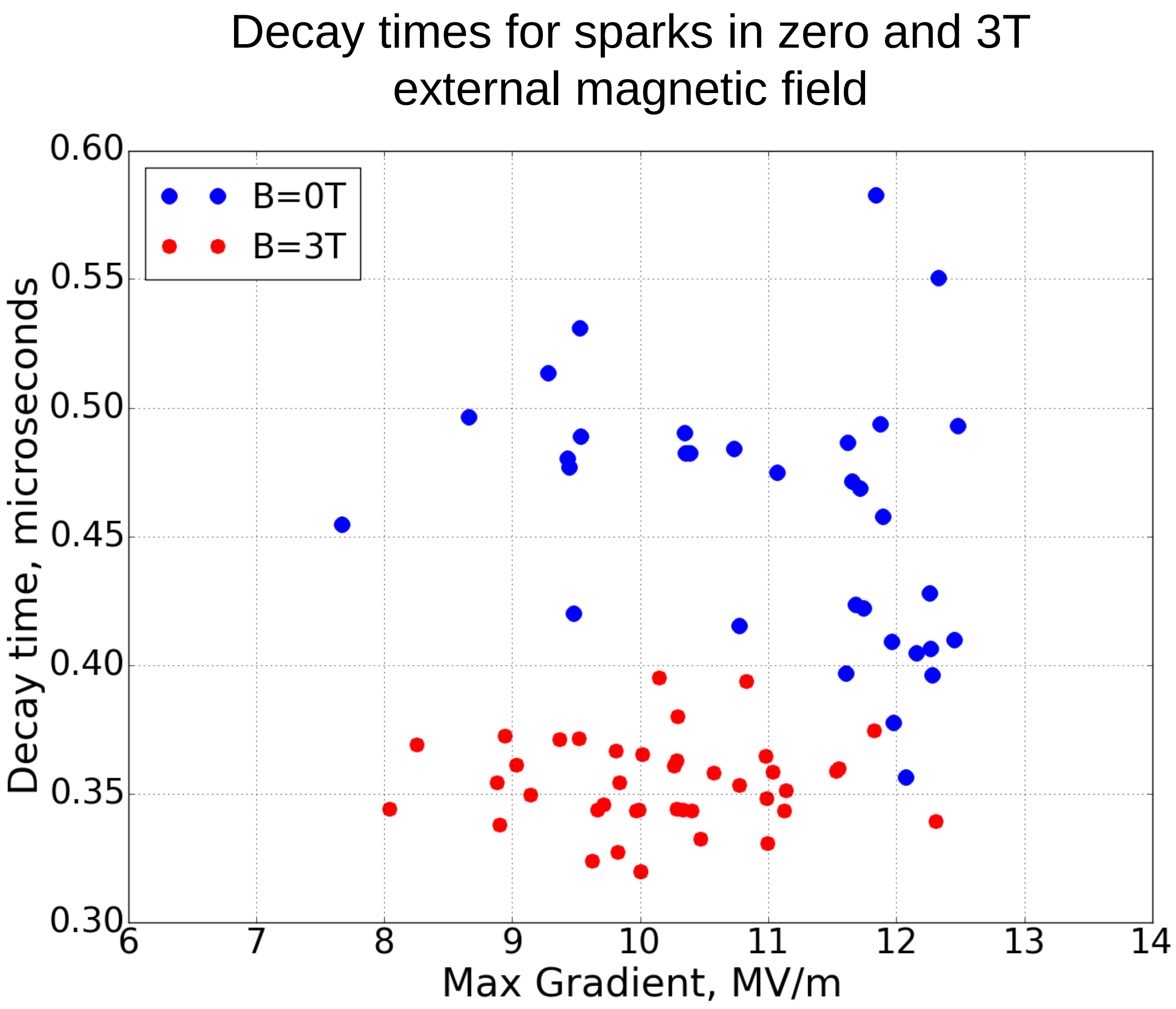
Energy dissipation during breakdown events

- 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

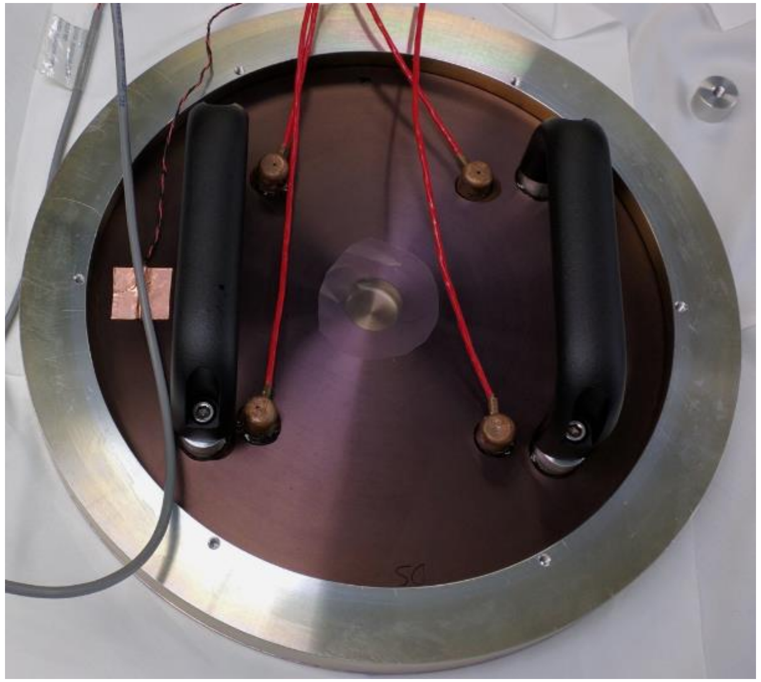
  1. Based on “violent” type of damage we observed in B=3T

  2. Due to focusing of dark current beamlets: higher arc currents and hence lower impedance



Acoustic spark localization

- Goal: correlate **location** and **time** of each spark. That would help in understanding the surface evolution processes during operation.
- Microscopic surface inspection gives answers to the first one
- Spark detection system is responsible for the latter
- Acoustic system is aiming to bridge the gap between these two

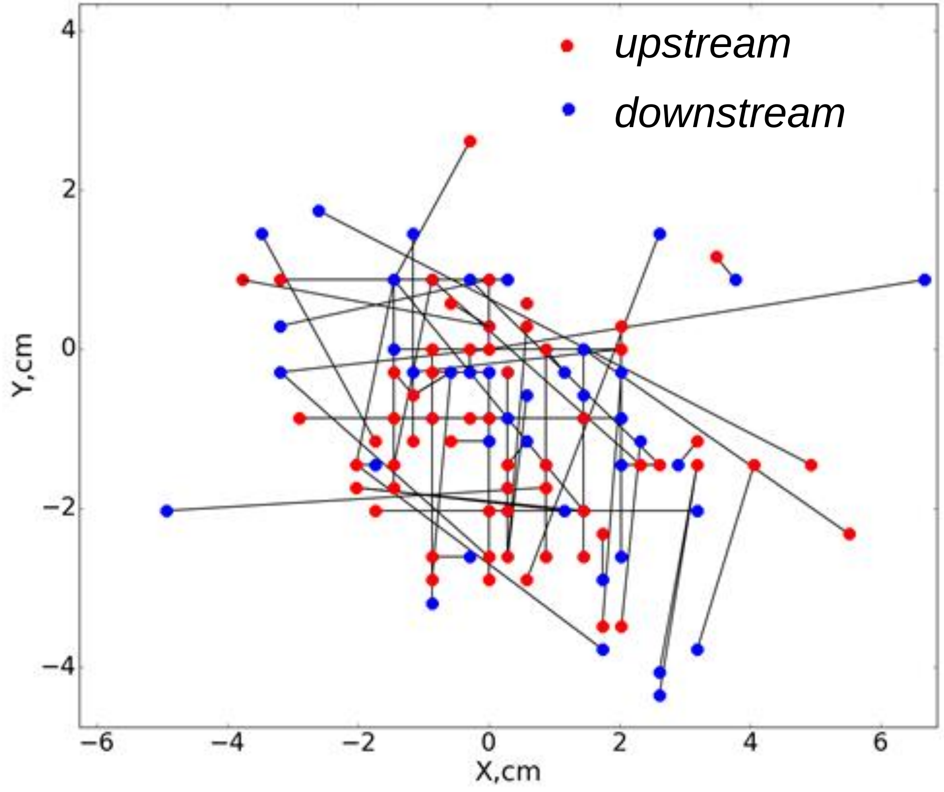


Downstream endplate with microphones attached

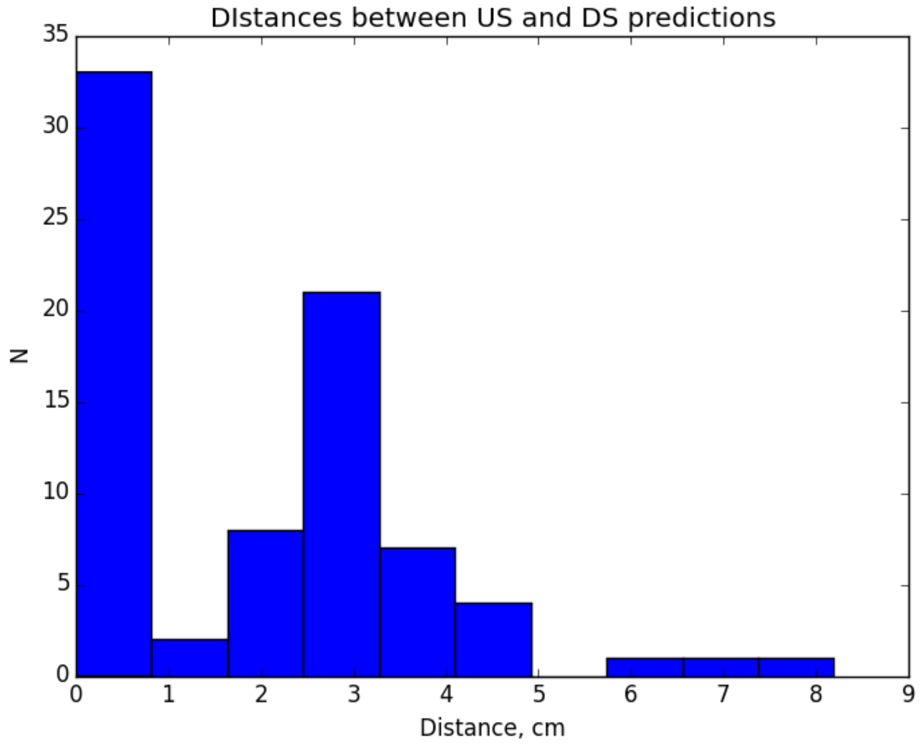
Acoustic predictions

Recall: perfect one-to-one damage match

Acoustic predictions map: corresponding locations connected



- All predictions are within 7cm from the center of the endplate (R=14cm) – good agreement with damage distribution
- Error bar of measurement ~ 2cm



Be endplates experimental program

Be endplate program: motivation

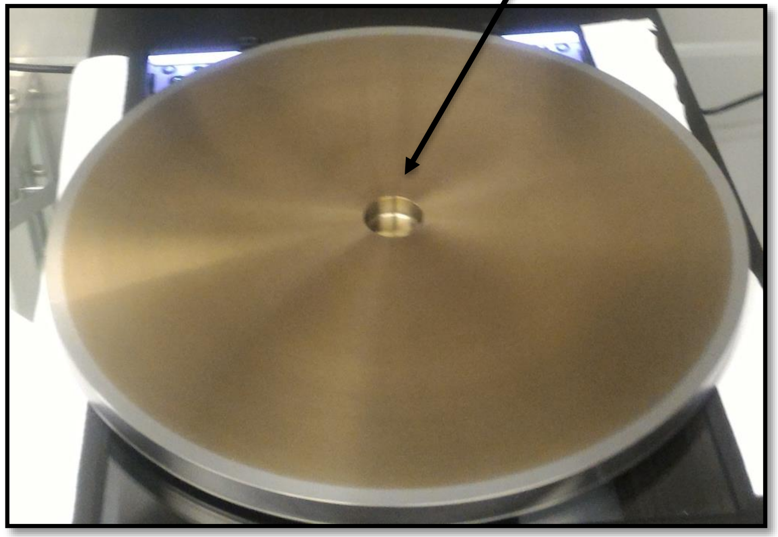
Radiation length of Beryllium (~35cm) for electrons in MeV energy range is significantly higher than of copper (~1.4cm)

According to our model, that implies less effect of dark current electrons on a surface and hence, potentially lower breakdown rates per gradient.

Measurements enabled by Beryllium:

- Direct measurement of dark current (Faraday Cup)
- Dark current transverse emittance (film/glass)
- Study of surface evolution

2mm-thick window

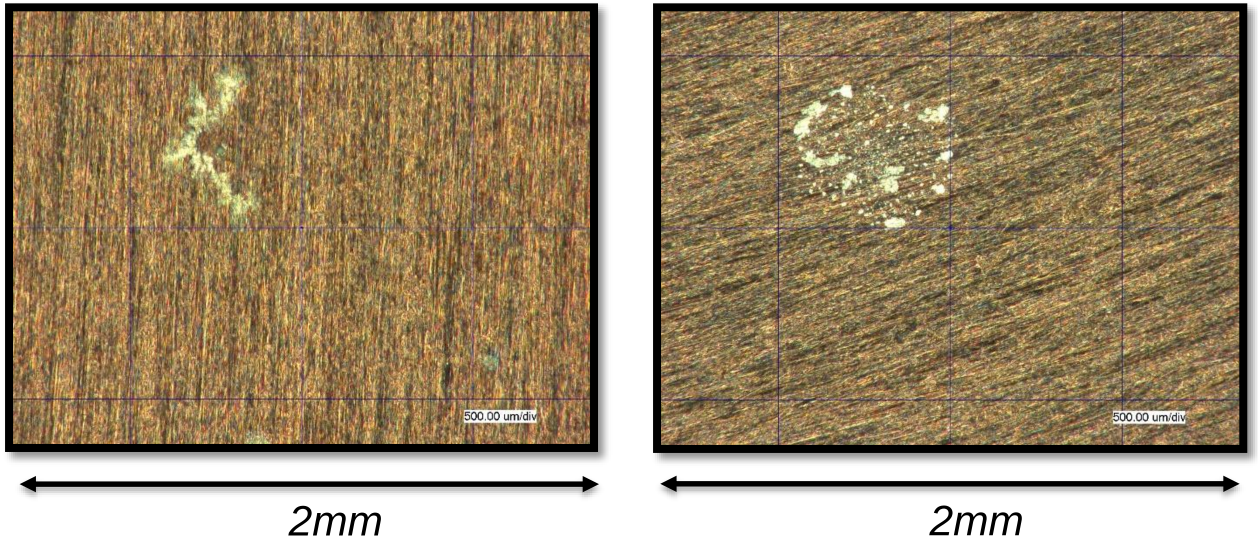


Exterior of Be endplate

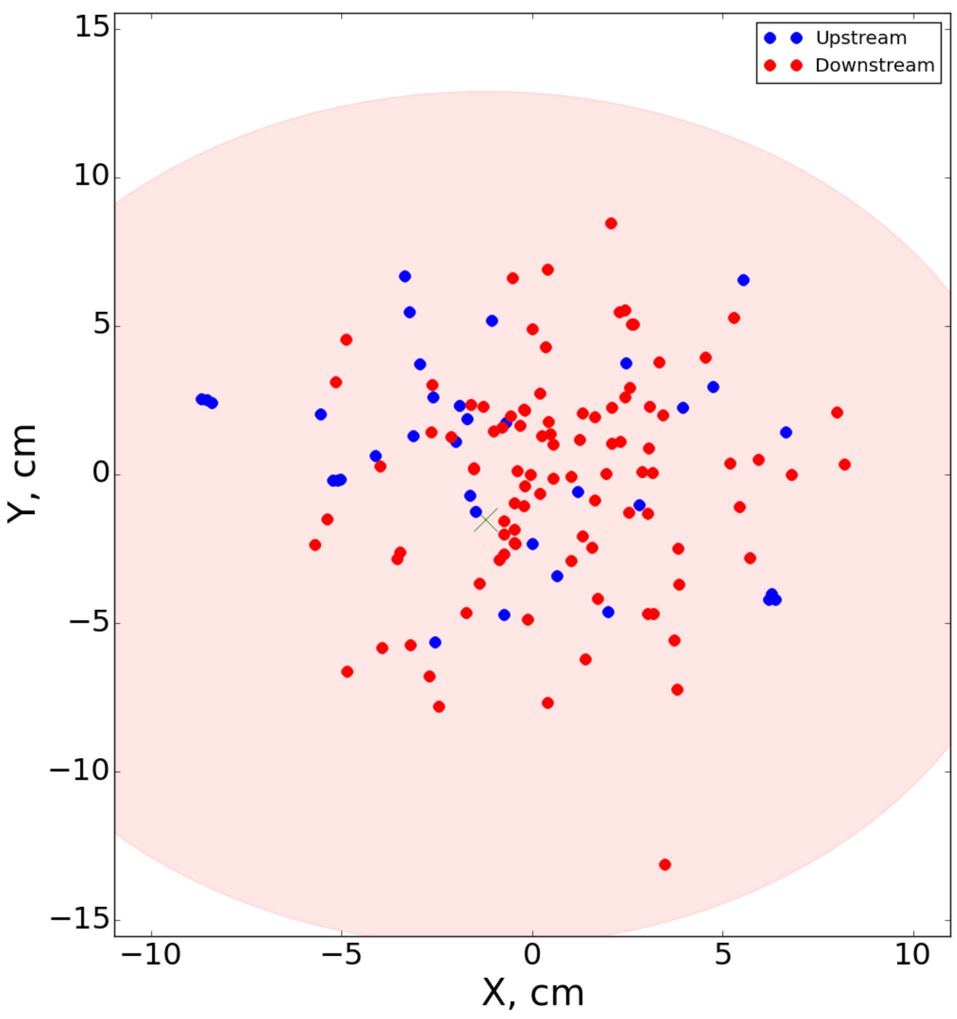
First B=0T high-power run results

- Safe operating gradient of 37MV/m established
- 11M RF pulses accumulated
- Detected 160 breakdown events
- Observed ~ 135 damage spots (subjective counting)

Asymmetry between endplates' damage



Damage distribution map



Conclusion

- 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 inspection revealed unique damage characteristic of operation in B=3T: violent nature of breakdown pits and perfect one-to-one correspondence between pits on opposing endplates
- Lower radiation length of Be will allow for more detailed field emission and surface evolution studies

Thank you for your attention