# RF breakdown in strong magnetic fields

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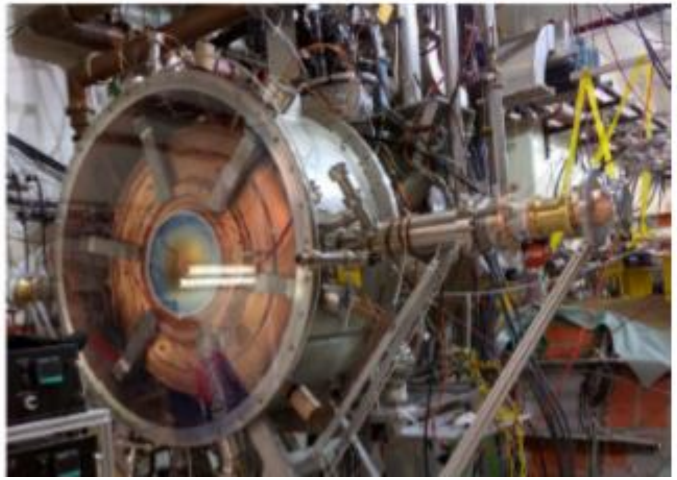
# RF for Muon Collider

MuCol

## Challenges:

- Short muon lifetime requires rapid phase space control
  - Ionisation cooling proven by MICE
    - High magnetic field to guide the beam surrounds the RF system
    - The magnetic field strongly increases the tendency to RF breakdown, which limits the cavity electric field

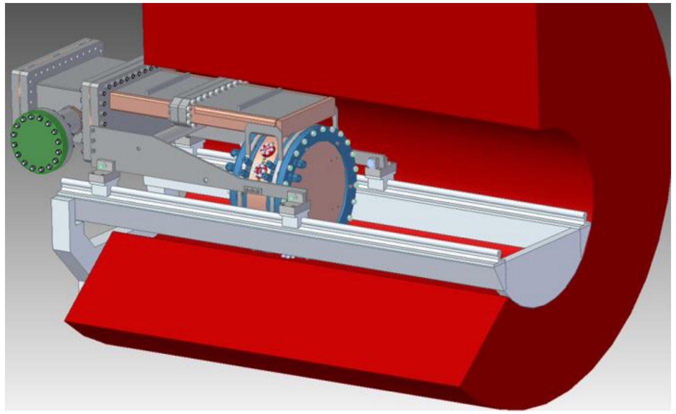


MICE 200 MHz RF module prototype: 4T, **10 MV/m**, 1ms@1Hz

## State-of-the-art solutions:

- Using carefully chosen material for RF cavity
- Filling the cavity with high-pressure gas
- Optimizing the cavity structure

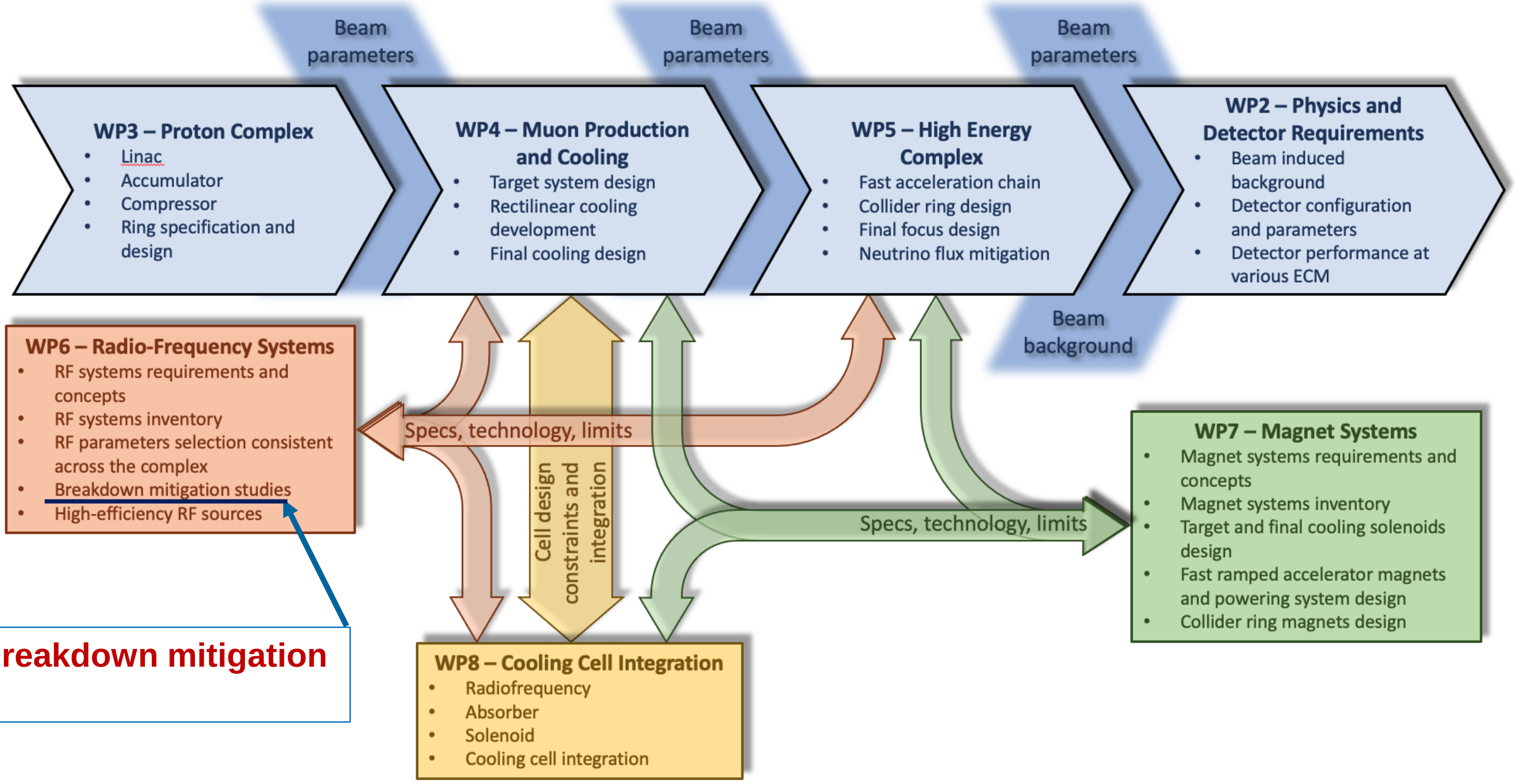
The breakdown process involves complex physics and a wide range of experimental parameters, which makes comprehensive understanding difficult.



Fermilab's MuCool Test Area(MTA), 805 MHz beryllium walls, 3T, >50 MV/m, 32us@10Hz

[1] D. Bowring, PRAB, 23, 072001, 2020.

# Interfaces between MUCOL WP's




**WP6.3 Breakdown mitigation studies**

# Task 6.3: Break-down mitigation studies for muon cooling cell cavities

Led by CEA, partners include INFN, CERN, Lancaster, Southampton and Strathclyde

**Objectives:**

- define cavity parameters & RF properties to minimize breakdown in a high magnetic field

**Methodology:**

- Enhance theory and models of breakdown in strong magnetic field
- Define and conduct suitable experimental tests (DC and RF) to study the influence of control parameters
  - RF frequency, E field, RF pulse length, B field, material (Cu, Be, Al), temperature, surface preparation, conditioning algorithms, and others
- Provide design and cost of a few RF test stands for the above tests to be included in the European Laboratory Directors Group (LDG) roadmap

# Research plan at Strathclyde

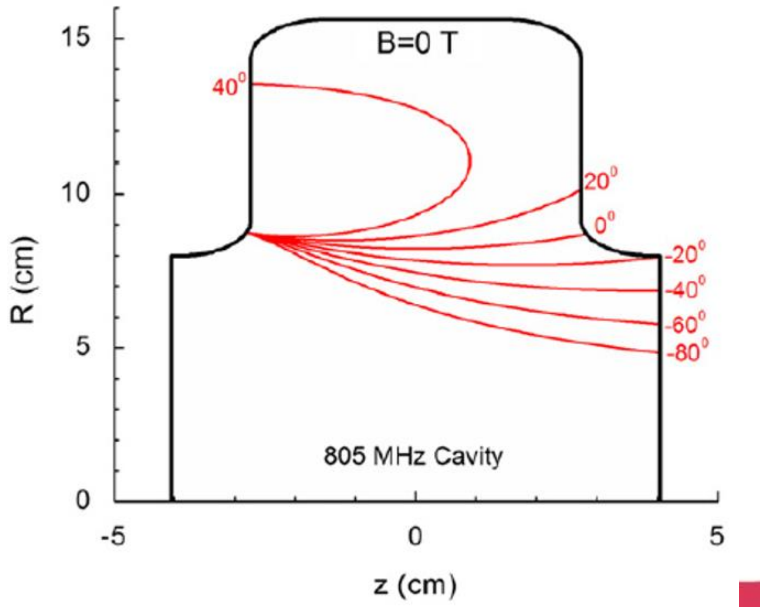
PhD student Robert Kyle started in July 2023. Main research focus is breakdown mechanism and mitigation based on theoretical and simulation studies. The research tasks include:

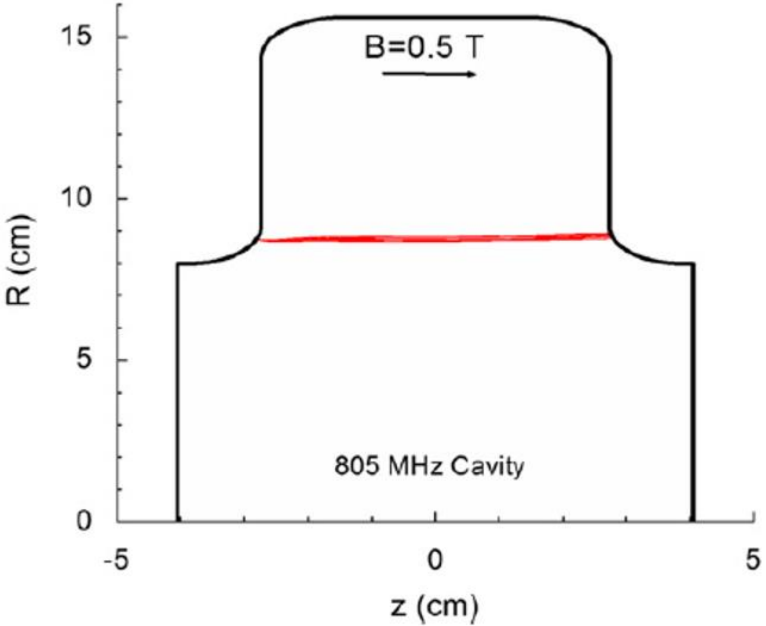
- **T1:** Summarise analytical description of the breakdown limit as a function of the control parameters
- **T2:** Breakdown simulations cross check with different packages; Identify the weak points of the cavity
- **T3:** Investigation of various solutions including high-pressure gas, low-density material, and cavity structure optimisation.
  - Re-optimise the shape of the acceleration cavity based on T2 to reduce the BRD.
- **T4:** Breakdown experiments and AI-enhanced data analysis to benchmark T1-T3
  - RF breakdown test stands: Daresbury/Saclay?
  - DC breakdown test stands: CERN/Strathclyde?

# RF breakdown simulations

Different simulation packages will be benched mark to research the breakdown physics at different levels, with significant requirements of computing resource and time.

- Astra + SuperFish (fast particle tracking)
- CST Particle Studio (field emission, multipactor)
- XOOPIC/Vsim (field emission + plasma ionization process)



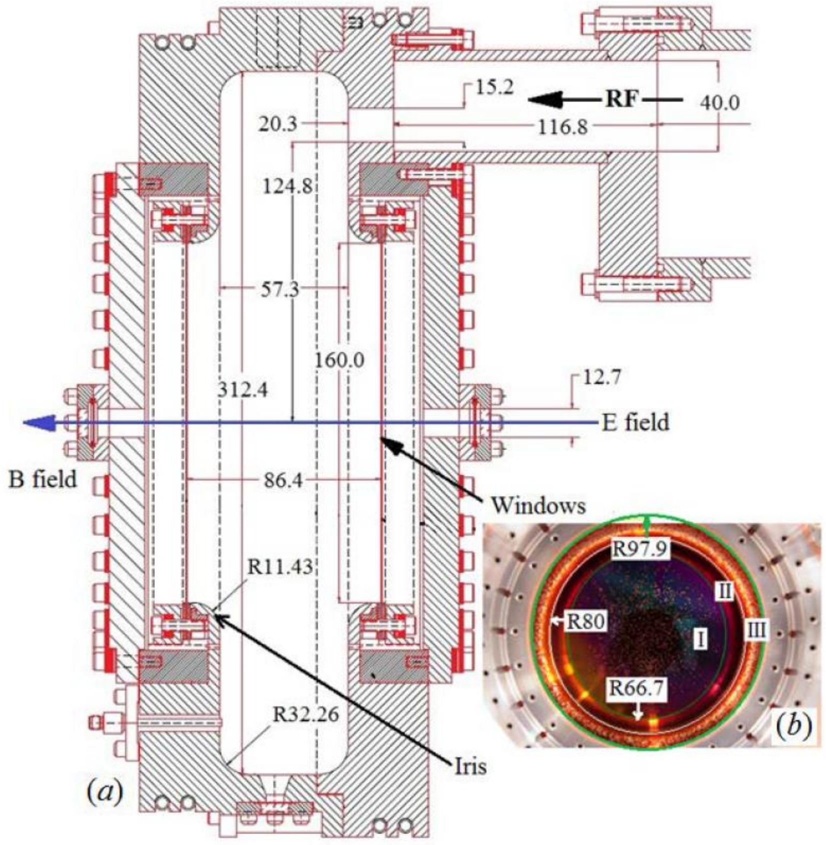



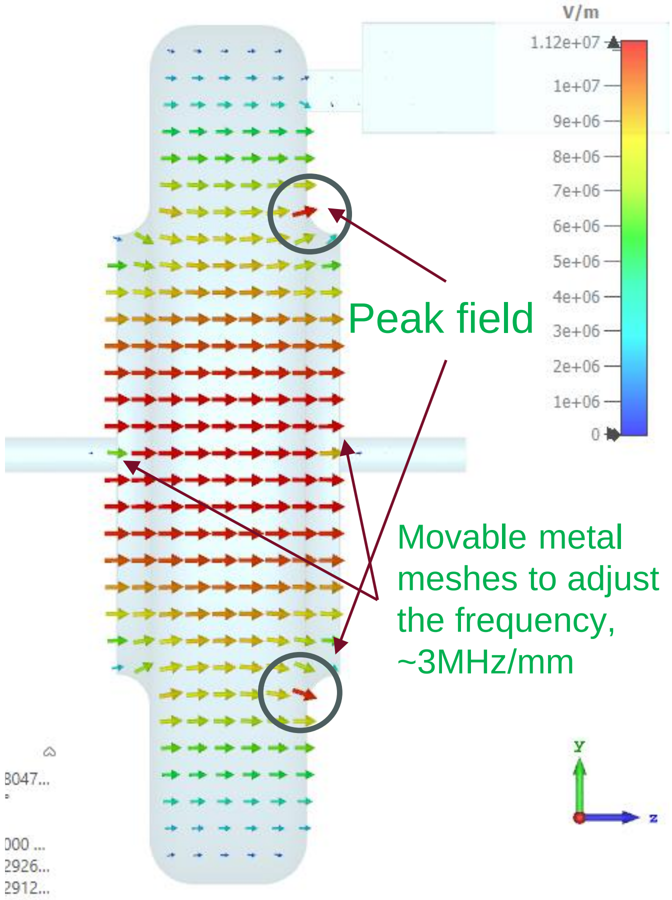

The first step is to replicate simulations from the published paper

[1] D. Stratakis, Effects of external magnetic fields on the operation of high-gradient accelerating structures, NIMPRA, 620, p147-154, 2010.

# Preliminary simulations - CST

## Validation of an 805MHz accelerator cavity




Next steps:

1. Postprocess the field distribution to get the maximum field points.
2. Apply the field emission model and B field to the model.
3. Multipactor simulation of secondary electron emission with/without B field.
4. Cavity shape re-optimizing

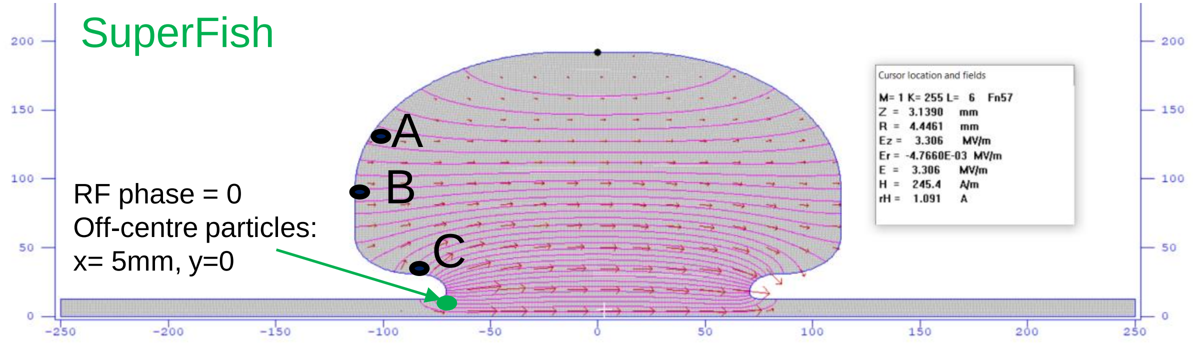
Potential challenges:

1. accurate field emission model
2. Multi-physics simulation may be needed to include thermal
3. How to quantify better shapes (current? Peak field strength? Trajectories?)

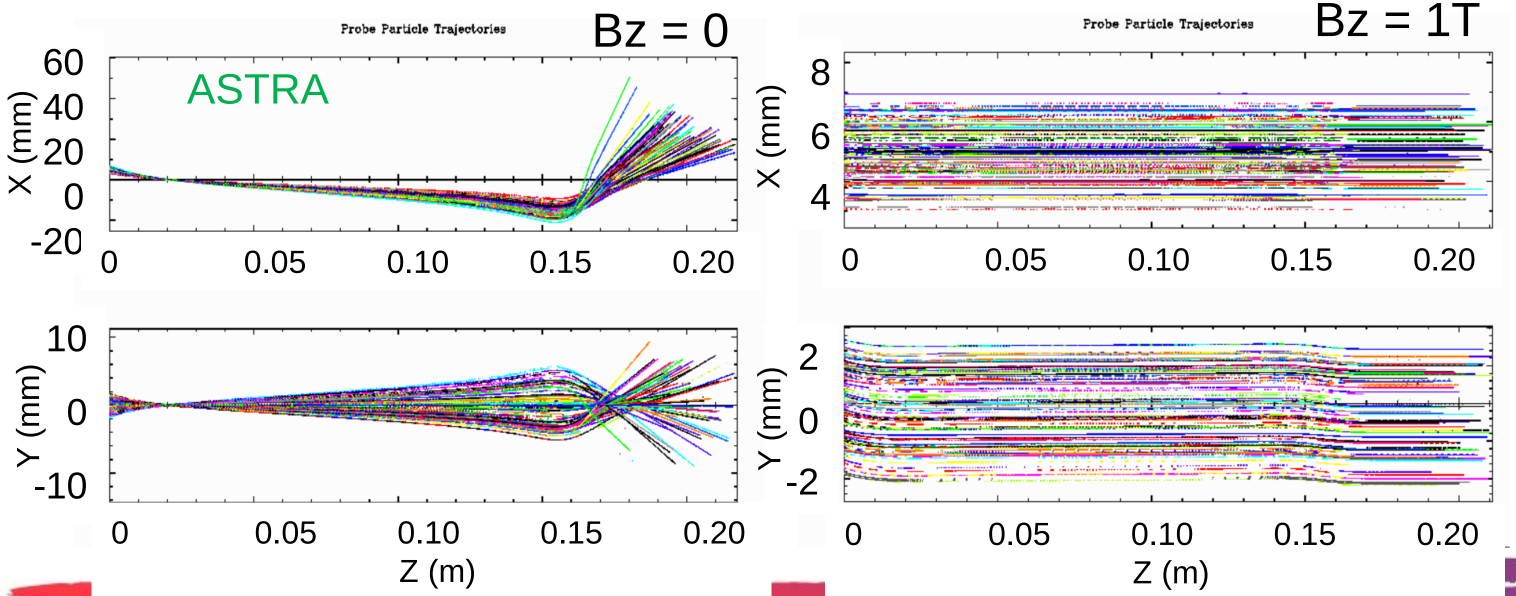

[1] M.R. Jana, et. al, Investigation Of Breakdown Induced Surface Damage On 805 MHz Pillbox Cavity Interior Surfaces, NAPAC2013, 2013

# Preliminary simulations – ASTRA

Example of a 600MHz cavity, not for Muon acceleration




Particle trajectories calculated with ASTRA look reasonable.
The B field has a big impact on the particle trajectories.

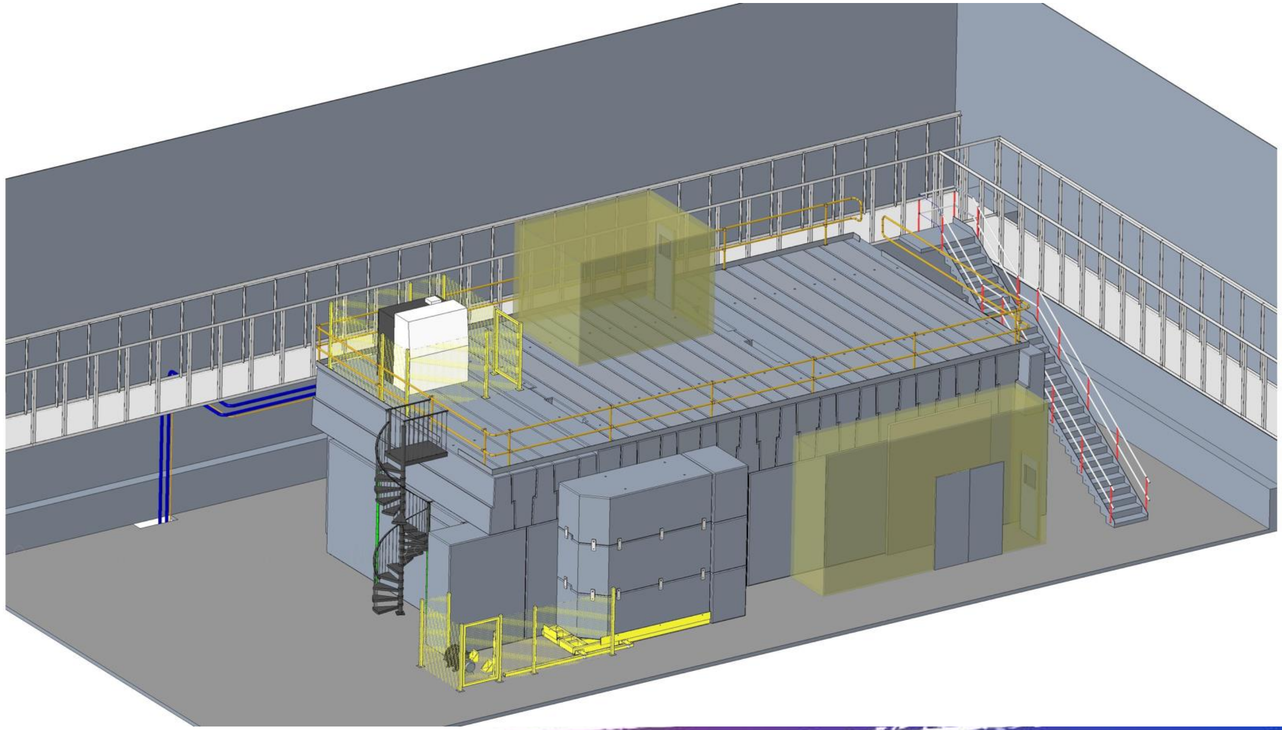



Questions to be solved:

1. ASTRA takes the on-axis field distribution. It is suspected that the off-axis field, e.g. points A-C, can be calculated correctly. Further investigation is required.
2. 3D field mapping may be used.
3. ASTRA does not have the field emission model, needed to generate the particles separately. [opportunity to add optimised, self-consistent emission model.]
4. Integrate SuperFish + ASTRA into automatic cavity shape optimisation

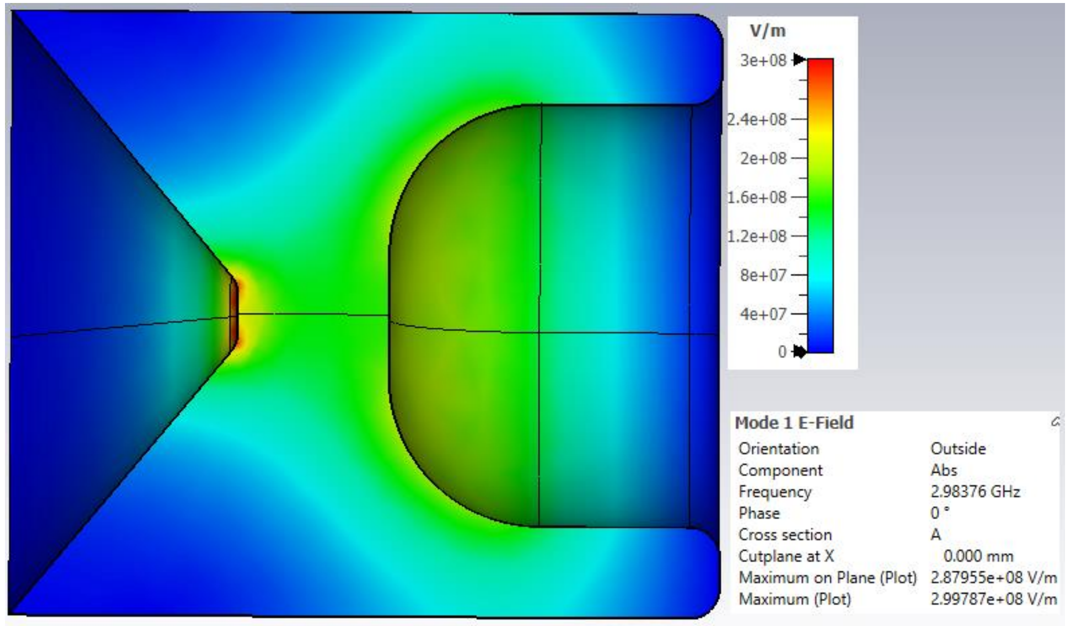
# Daresbury CI RF bunker

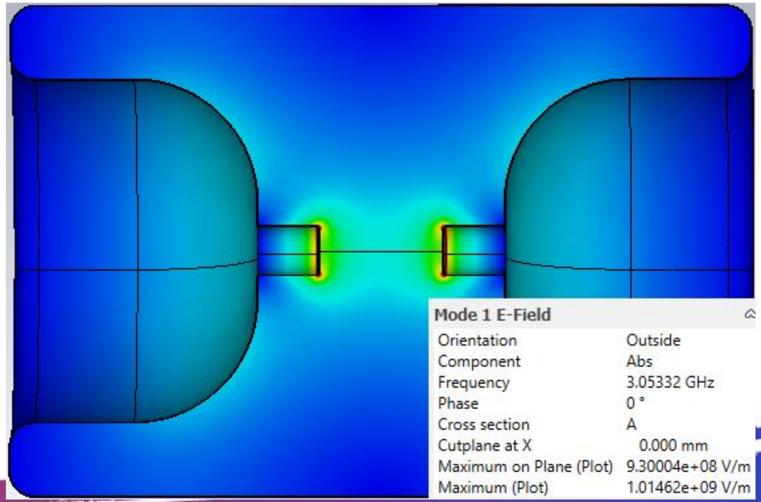
- Lancaster: RF testing & cavity design, Klystron design
- Strathclyde: Physics of breakdown & cavity design
- Southampton: Solenoid Design and construction
- STFC: Mechanical design, controls, lower B field testing on CLARA gun



# Possible S band cavity schemes

- Intend to have flexible scheme
  - Compatible with confines of likely magnet
- Diagram shows 40mm diameter system
- Cone/tips concentrates field strength
- Readily changeable endcap
  - Vary material easily
  - Asymmetric material test
  - Asymmetric fields
- Exploring options for compact nominally symmetric system
  - To compare with asymmetric scheme



# Conclusion

- Our goal is to support the Muon Collider working with other partners to address the physics questions on RF breakdown
  - Focus for the moment is on modelling to support future experiments
  - Interpretation of existing outcomes
- Keen to support development of further breakdown experiments
  - Should resources be found to support
  - Extend parameter space of dataset
  - Contribute to data processing