# RF vacuum surfaces in strong magnetic fields

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# Background

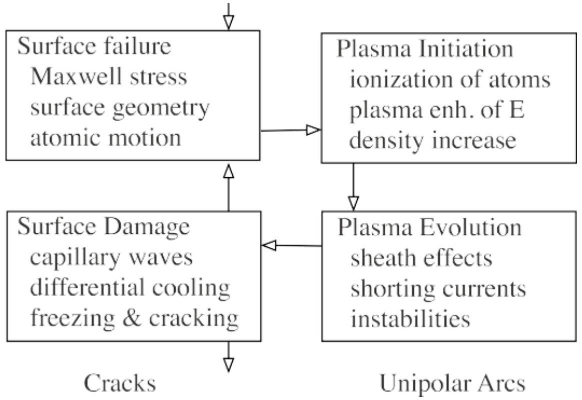
- Vacuum breakdown (DC and RF) have been subject to much research
  - Complex physics (and wide range of experimental parameters)
    - requires systematic study
  - Commonality observed between DC and RF behaviours
- Gradients of many 10’s MV/m are regularly achieved with well prepared surfaces
- Important as field gradient limits are central to the design and costing of a number of accelerator projects
- Adding magnetic fields regularly reduces achievable gradients
  - Higher breakdown probability (BDP) per rf pulse at lower gradients, relative to operation in no magnetic field.
- Muon accelerators require cooling channels immersed in strong B-fields
  - Alternating sections of deceleration and acceleration required to manage phase space
  - Strong focussing required in deceleration sections to ensure cooling dominates heating

# Discharges in Magnetic Fields

- In RF cavities magnetic fields (B-fields) have been noted to
  - Increase dark current
    - diamond machining of surfaces and surface preparation crucial for reducing dark current
    - magnetic field can focus dark current into a beamlet causing more damage
  - Require re-conditioning of cavities
  - May inhibit conditioning and limit peak E field
  - Increase risk of arcing which can happen extremely rapidly (ns scale)
- In DC vacuum breakdown, B – fields have been noted to improve diode insulation BUT also:
  - Increase number of active emission sites
    - suppression of the screening effect
  - Enhance optical emissions from the cathode flare plasma
  - Suppress material polishing in short pulse driven systems

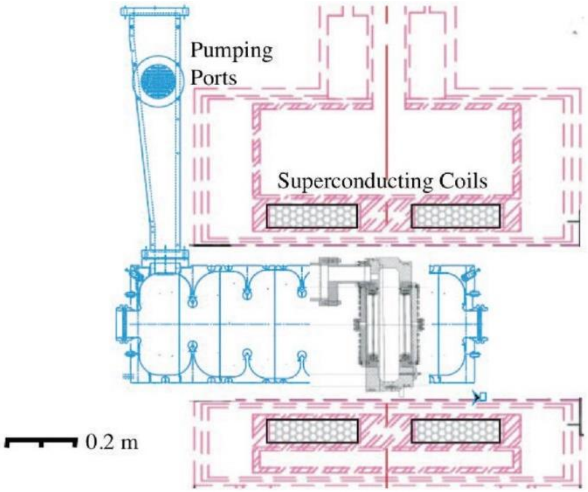
# Processes

- Various authors have contributed to a range of possible mechanisms
  - Norem *et al* and Mesyats *et al* have particularly contributed to RF and DC breakdown models
- Focussing of beams resulting in localised heating on anode surface
  - Can cause localised deterioration in anode which may contribute to emission in reverse cycle
    - Stratakis et al, NIMA 2010, Insepov and Norem J. Vac Sci. Tech. 2013
- Additional magnetic pressure effects on emission sites
  - Leading to enhanced mechanical / thermal failure
    - Moretti et al PRSTAB 2005, Norem et al PRSTAB 2003
- Formation of unipolar arcs
  - Cathode flares formed on single electrode
    - Insepov and Norem J. Vac Sci. Tech. 2013,
    - Mesyats et al (various publications)
  - Complex cooling dynamics in magnetically confined scenarios

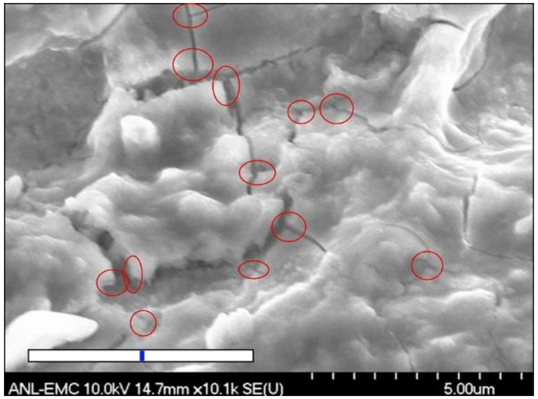


# Understanding RF vacuum arcs (Norem *et al*)

- The lifecycle of the arc can be divided into four parts: trigger, plasma ionization, plasma evolution and surface damage (Norem et al [1]).
  - Process occurs in four stages:
    - (1) local surface fields are high enough so that Maxwell stresses can be comparable to tensile strength causing surface failure
    - (2) field emission ionizes the fragments of surface material, producing a positively charged ion cloud near a field emitter that will increase the field on the emitter
    - (3) an unstable plasma is maintained by field emission and self-sputtering
    - (4) surface damage is caused by Maxwell stresses, thermal gradients, and surface tension on the liquid metal surface



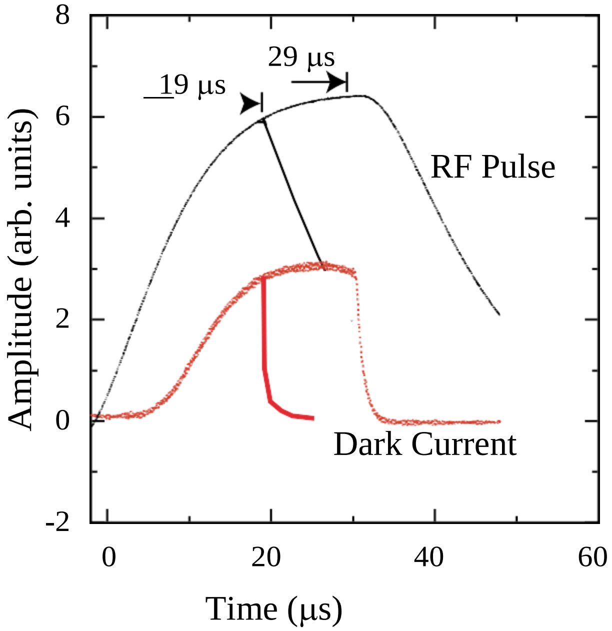
- Six cell 805 MHz cavity (blue) in the superconducting magnet, showing the position of the single cell pillbox cavity with removable surfaces (grey)
  - cracks visible in SEM images of the center of an arc damage spot at a magnification of x10,100.
- Breakdown phenomena needs to verified at other frequencies
  - providing an opportunity to re-examine the modelling & experimental details of vacuum arcs



[1] J. Norem, Z. Insepov and A. Hassanein “An integrated approach to understanding RF vacuum arcs”, Nature Publishing Group, Scientific Reports, 2021-01-27, **11**, (2021). DOI: 10.1038/s41598-021-81947-5

# Magnetic field effects in a multicell, 805MHz cavity, (Norem, Torun *et al*)

- Dark current dark phenomena are almost universally seen in accelerating structures with data available in the 200MHz to 12GHz frequency range, there has been comparatively little systematic study with copper accelerating structures operating in a strong magnetic field.
  - Study using 805MHz cavities operating in the $\pi$ mode, $E_{acc} = \sqrt{33P_{(MW)}}$, maximum surface field is 2.6 times $E_{acc}$ at P= 14MW
  - Cavity was designed to accelerate muons between absorbers in a muon cooling channel
  - Magnet can produce a 5 T field on axis in the solenoidal mode, and in gradient mode the field flips from +3.5 to -3.5 T



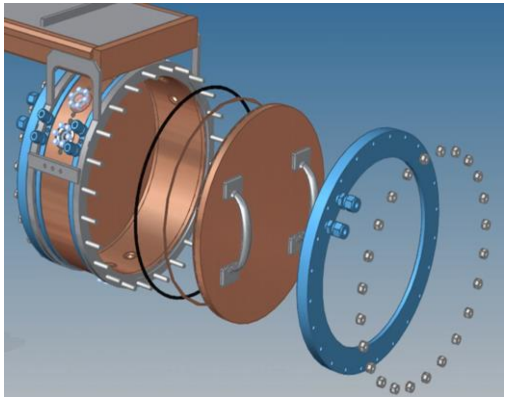
- Breakdown can be explained by field emission arising due to a combination of the electromagnetic stress on the surface of the mechanical structures, and the tensile strength of the material.
  - 2.5 T solenoidal fields on the cavity altered field emission due to mechanical deformation of emitters
  - Dark current ring beamlets were formed as a result of transverse momentum imparted to the electrons by ExB drifts during the non-relativistic part of the acceleration process

[2] J. Norem, V. Wu, A. Moretti, M. Popovic,Z. Qian, L. Ducas, Y Torun and N. Solomey, “Dark current, breakdown, and magnetic field effects in a multicell, 805 MHz cavity”, Physical Review Special Topics-Acelerators and Beams, **6**, 072001, (2003)

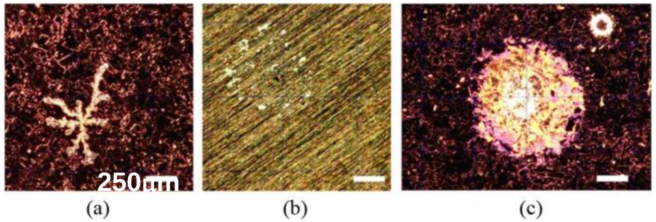
DOI: 10.1103/PhysRevSTAB.6.072001

# Normal-conducting rf cavities in multi-Tesla magnetic fields (Bowring *et al*)

- The damage incurred from breakdown in multi-tesla fields is more severe than damage incurred during operation in no DC magnetic field [3]
  - The breakdown probability of an accelerating structure seems to depend on
    - electron and ion interactions with the metal surface
    - the intensity and distribution of cavity fields and surface currents
    - the extent of pulsed heating and resultant lattice strain



- 805 MHz modular cavity with removable walls
  - to study pulsed heating in copper and beryllium
- Maximum stable operating gradient (SOG) was defined as the peak, on-axis electric field that results in an average breakdown rate of about one in $10^5$ rf pulses



(a) (b) (c)

- Breakdown damage on Be and Cu plates, observed after zero- and three-tesla fields, obtained by digital microscopy.
  - Damage on Cu from zero- tesla run;
  - Damage on Be from zero-tesla run;
  - Damage on Cu from three-tesla run.

[3] D. Bowring, A. Bross, P. Lane *et al*, "Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration", Physical Review Accelerators and Beams, **23**, 072001, (2020)

DOI: 10.1103/PhysRevAccelBeams.23.072001

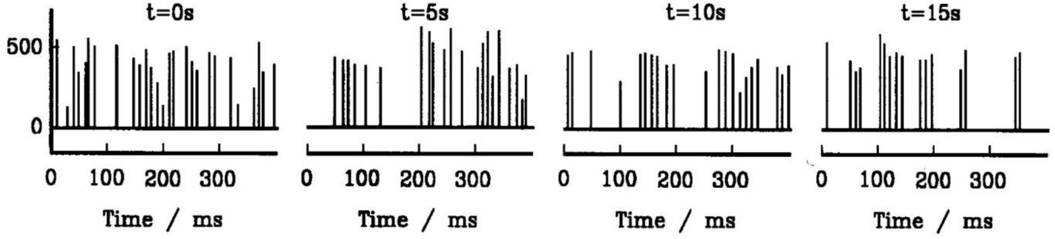
# State of the Art

- Bowring et al (PRAB 2020) demonstrated 50 MV/m @ 805 MHz at 3 T
  - Used Be surfaces which were shown to be more resilient to thermal excursions caused by magnetically confined beams
- Torun et al demonstrated ~16 MV/m @ 201 MHz with fringing B fields
  - Copper cavity with Be windows
  - Copper prepared using polishing techniques
  - No surface damage seen on cavity interiors
  - Somewhat reduced performance in fringe field of solenoid
  - TiN coating of coupler used to mitigate arcing
- Bowring notes more evidence required to robustly demonstrate heating model explanation
  - Scope to extend research to cover additional materials with different thermal responses
  - Also notes open nature of the physical cause of breakdown events
- Norem notes more evidence required at other frequencies
  - Provides an opportunity to examine the modelling & experimental details of vacuum arcs

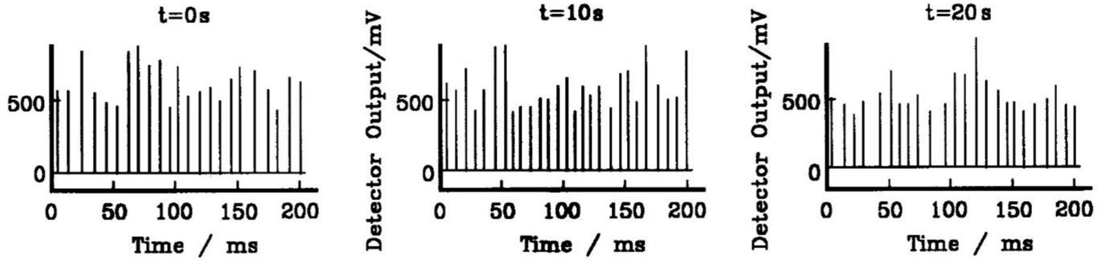
# Links to DC Vacuum Spark Dynamics (Spark *et al*)

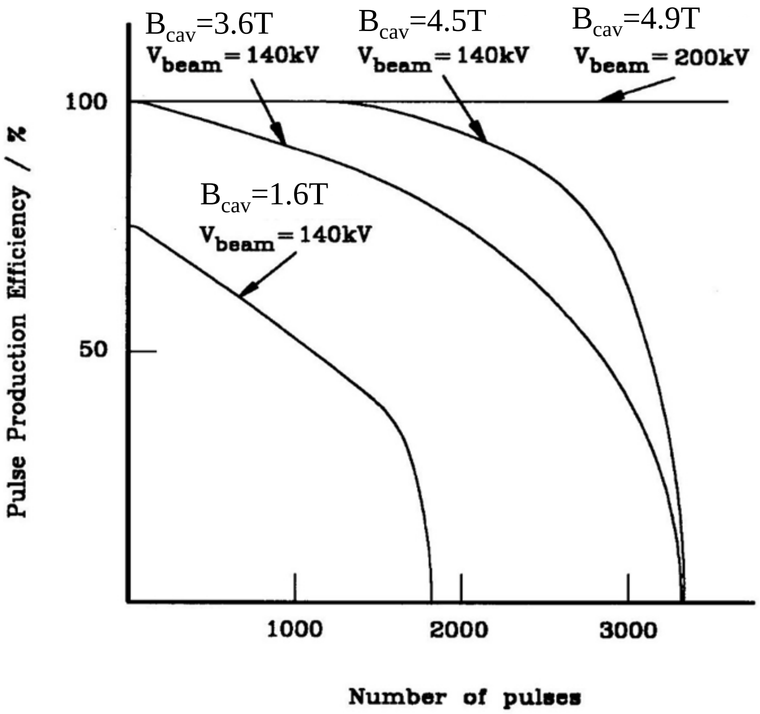
- Spark, Cross, Phelps and Ronald [4] investigated high PRF cathode erosion in vacuum arcs
    - Showed sensitivity of ‘critical field’ and ‘cathode polishing’ of knife edge emitters to B-field

$B_{cav}$=1.6T, $V_{beam}$=140kV



$B_{cav}$=4.5T, $V_{beam}$=140kV

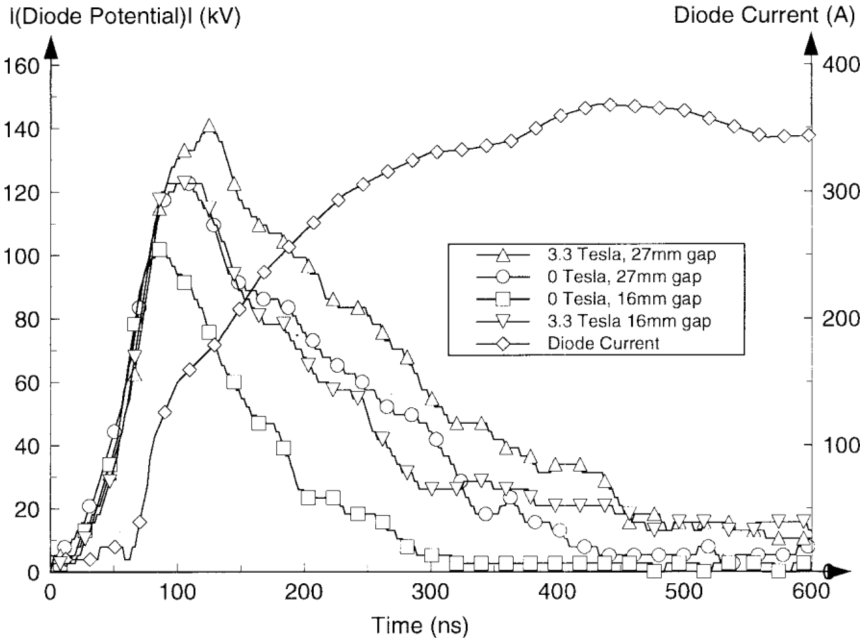


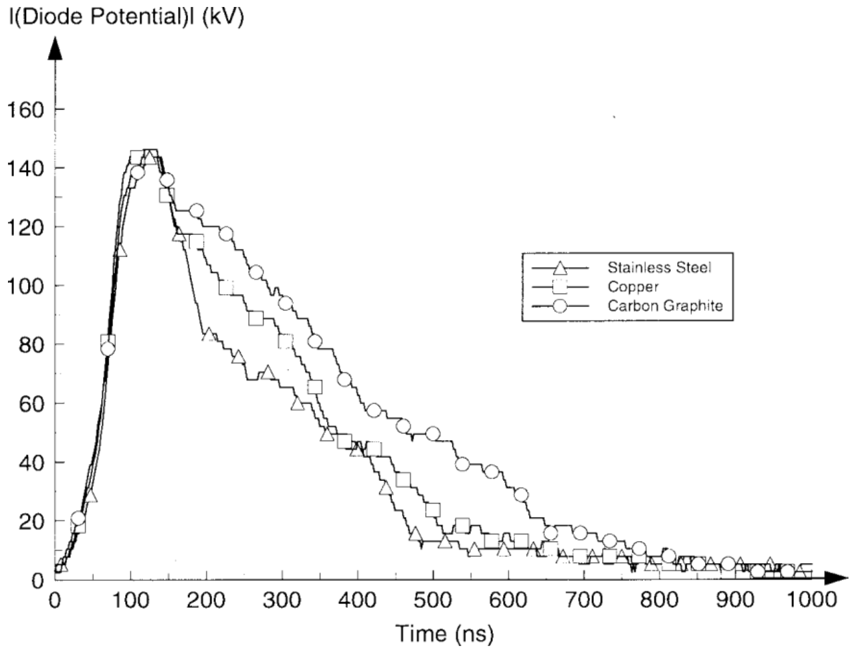


[4] S.N. Spark, A.W. Cross, A.D.R. Phelps A.D.R. and Ronald K. ‘Megawatt, 330Hz PRF tunable gyrotron experiments’, Int. J. of Infrared and Millimeter Waves. 15, No12, pp2003-2017, 1994.

# Links to DC Vacuum Arc Dynamics (Ronald *et al*)

- Influence of the diode gap spacing & the B-field on the collapse of the diode potential
  - Material stainless steel
- Influence of material on rate of collapse of diode potential
  - Anode-cathode gap 27mm
  - B-field 0 Tesla

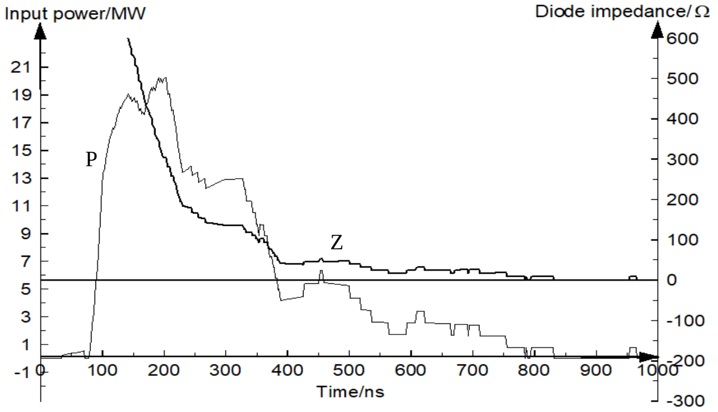


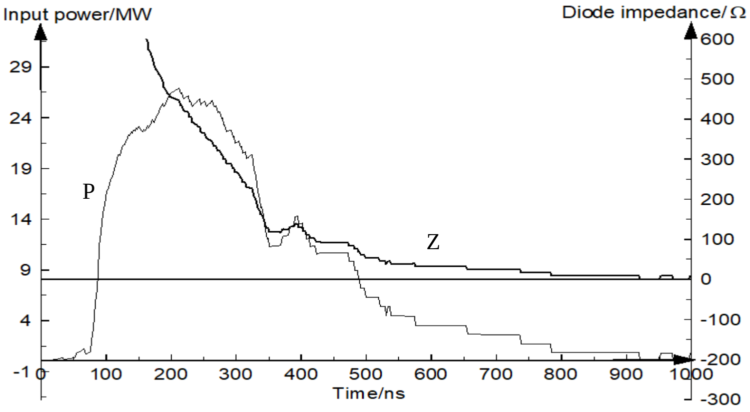


[5] K. Ronald, A.W. Cross, Alan D. R. Phelps et al "Explosive Cathode Experiments", IEEE Trans. on Plasma Science, **26**, No 3, June 1998

# Links to DC Vacuum Arc Dynamics (Ronald *et al*)

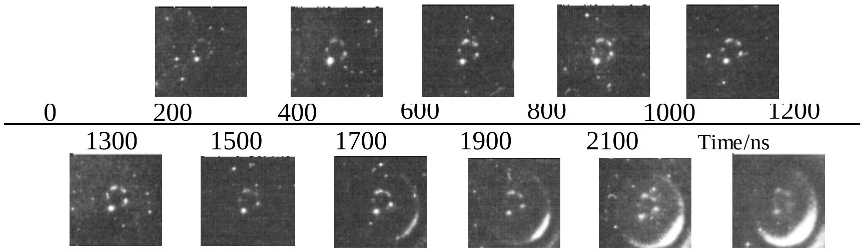
- Ronald et al [5] investigated pulsed vacuum arcs
  - Showed sensitivity of cathode flare plasma (distribution and intensity) to B-field in knife edge emitters





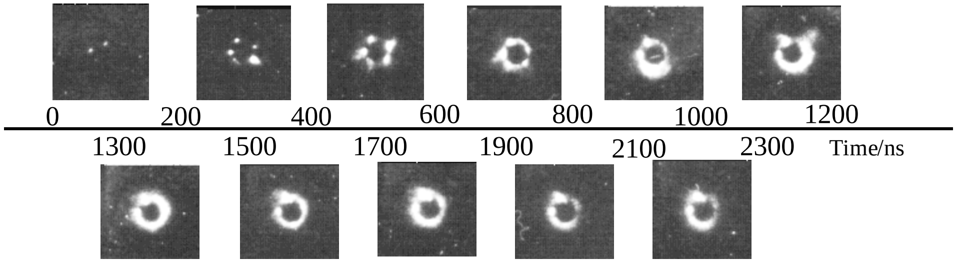
Diode discharge Optical/UV emissions during discharge

Copper Cathode, 27mm Diode Gap
Magnetic Field, 0T



Diode discharge Optical/UV emissions during discharge

Copper Cathode, 27mm Diode Gap
Magnetic Field, 0.21T



[5] K. Ronald, A.W. Cross, Alan D. R. Phelps et al “Explosive Cathode Experiments”, IEEE Trans. on Plasma Science, **26**, No 3, June 1998

# Motivation for Roadmap

- Muon accelerators highlighted in 2020 European strategy update
- Muon collider collaboration formed under CERN leadership
  - Motivates fundamental and underpinning research
- Muon Accelerator Programme (MAP) and Muon Ionization Cooling Experiment (MICE) research highlighted complex interactions between cavity breakdown, dark current and magnetic fields
  - Opportunity for fundamental research building on this work
  - Study surface / breakdown physics over a range of:
    - Frequencies;
    - Magnetic field (magnitude/polarisation);
    - Before and after different surface preparation
  - Impact in accelerator physics, vacuum electronics & potentially wider

# Opportunity

- Equipment availability: Strathclyde, Daresbury & CI:
  - Powerful RF/microwave systems, 0.2-200GHz; FELs, CARM, gyrotron, gyro-TWA, gyro-klystrons, BWO, Cherenkov maser, superradiant sources, magnetrons, klystrons
    - Frequency: 1.2GHz to 200GHz:
    - Power: kWs, MWs, GWs: Pulse lengths: Continuous wave to 300ps
  - Range of magnet systems;
    - Electromagnets, ID 100mm, B-field 0.4T,
    - Superconducting magnets, ID 50mm , B-field 11T
  - Complements existing US research at 201 MHz and 805 MHz;
  - Facilities for surface preparation/analysis.
- Expertise in institutes such as CI, JAI, CERN/CLIC
- Opportunity for international collaboration
- Opportunity for cross disciplinary impacts & application pull through

Thank you for your attention

I’d be happy to answer any questions