Potential for UK interest in Muon Collider RF

RF vacuum surfaces in strong magnetic fields

Background

- Vacuum breakdown (DC and RF) have been subject to much research
  - Complex physics (and wide range of experimental parameters) makes comprehensive understanding difficult
  - Significant commonality observed between DC and RF behaviours
- Gradients of many 10's MV/m are regularly achieved with well prepared surfaces
- Adding magnetic fields regularly reduces achievable gradients
- Muon accelerators require cooling channels immersed in strong magnetic fields
  - Alternating sections of deceleration and acceleration required to manage phase space
  - Strong focussing required in deceleration sections to ensure cooling dominates heating

Background

- In RF discharges B –fields have been noted to
  - Increase dark current
  - Require re-conditioning of cavities
  - May inhibit conditioning and limit peak E field
  - Increase risk of sparking
- 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 cathode 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
  - Resulting in 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)
  - Complex cooling dynamics in magnetically confined scenarios

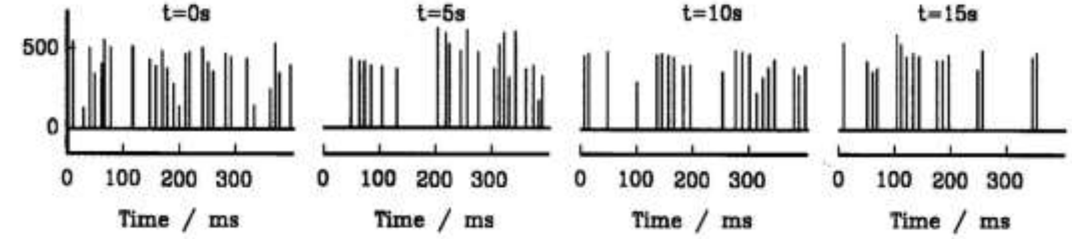
State of the Art

- Bowring et al (PRAB 2020) demonstrated 50 MV/m @ 805 MHz & 3 T
    - Used Be surfaces predicted 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 ptl windows
    - Copper prepared using polishing techniques
    - TiN coating of critical areas (including couplers)
- 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

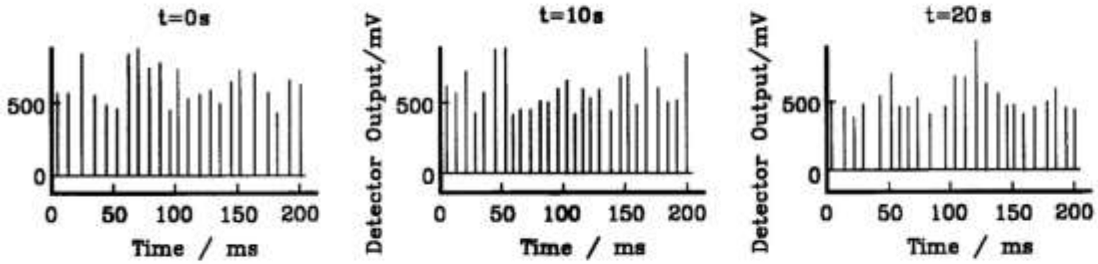
Links to DC Vacuum Spark Dynamics

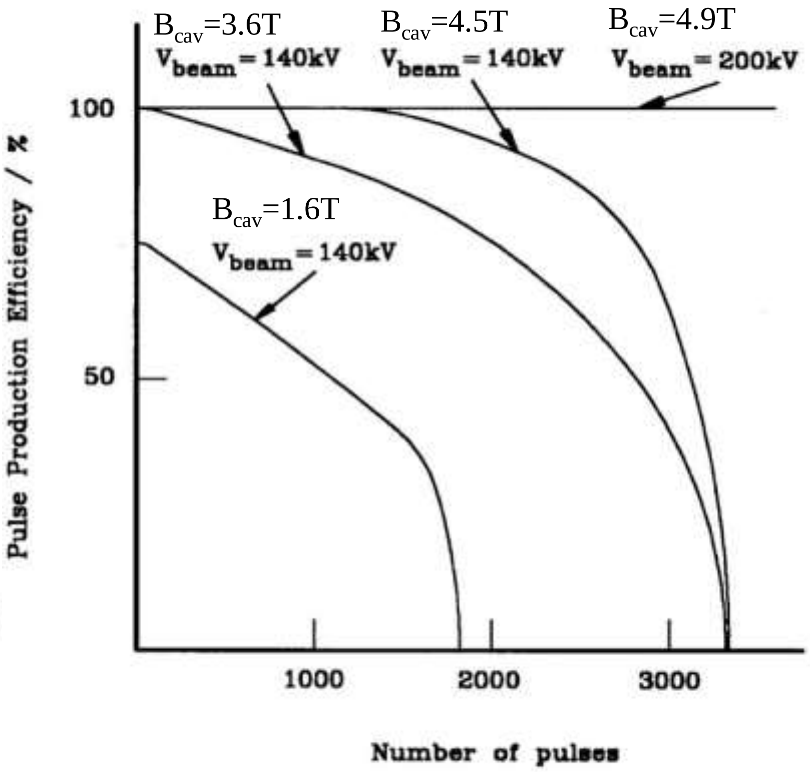
- Spark et al investigated high PRF cathode erosion in vacuum sparks
  - Showed sensitivity of ‘critical field’ and ‘cathode polishing’ of knife edge emitters to B-field

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



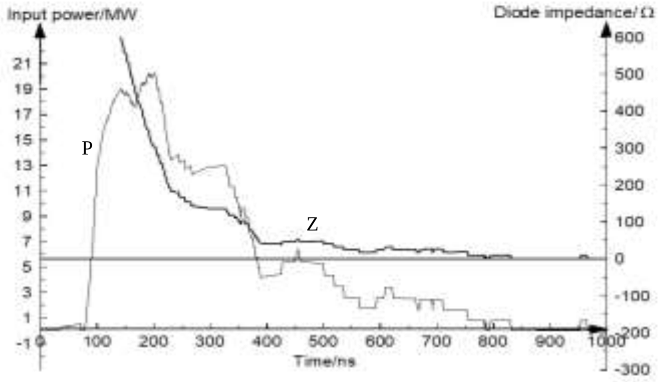
B_{cav}=4.5T, V_{beam}=140kV

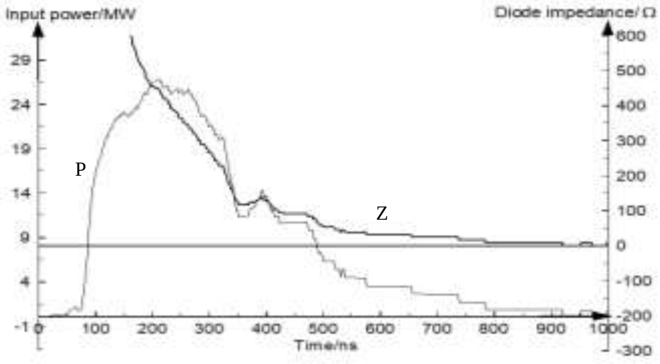


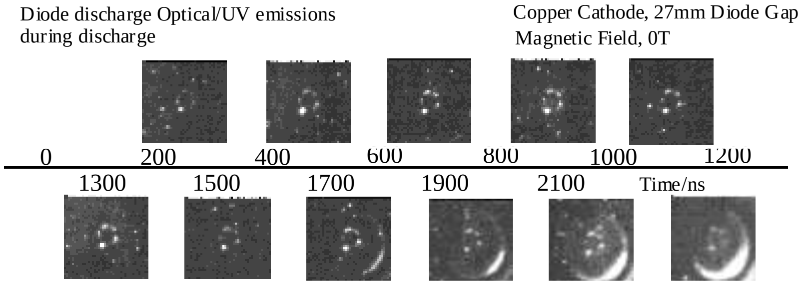


Links to DC Vacuum Spark Dynamics

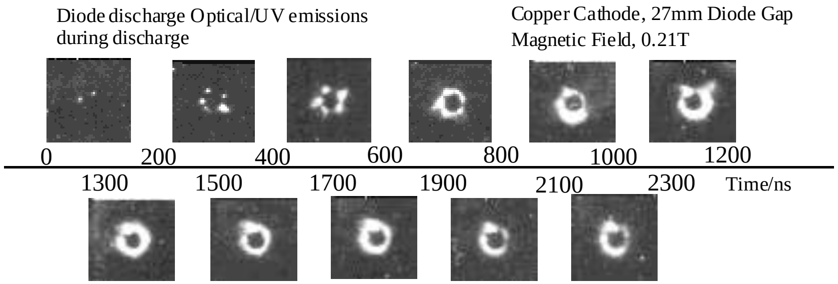
- Ronald et al investigated pulsed vacuum sparks
  - Showed sensitivity of cathode flare plasma (distribution and intensity) to B-field in knife edge emitters






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

Motivation

- Muon accelerators highlighted in 2020 European strategy update
- Muon collider collaboration formed under CERN leadership
  - Motivates fundamental and underpinning research
- MAP and MICE research highlighted complex interactions between cavity breakdown/dark current and B fields
  - Opportunity for fundamental research building on this work
  - Study surface / breakdown physics over a range in:
    - Frequency;
    - magnetic field (magnitude/polarisation);
    - surface preparation.
  - Impact in accelerator physics, vacuum electronics and potentially wider.

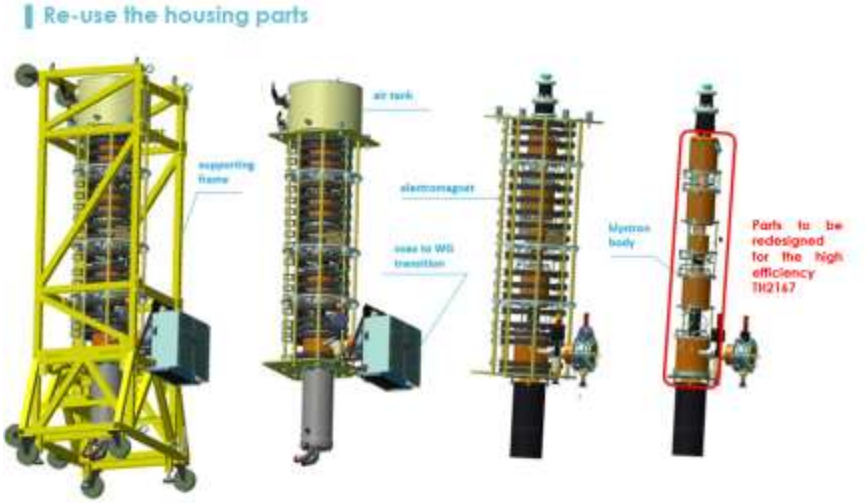
Engagement potential?

- Equipment availability:
  - Powerful RF/microwave systems, 1-100GHz;
    - Realistically minimum frequency ~ 3GHz, except possibly at RAL
  - Graeme Burt (Lancaster) working with Daresbury on cavity test facility
    - Potential to include magnetic fields – but only NC – SC not feasible in sensible timeframe – needs some thought
  - Complement existing US research at 201 and 805 MHz; Planned Saclay initiative
  - Extend range as underpinning basic physics research
- Interest in Strathclyde and Lancaster
- Opportunity for international collaboration
    - E.g. Saclay initiative
    - Extension of FNAL:MTA research
- Opportunity for cross disciplinary impacts and application pull through

High Efficiency RF Drive Amplifiers

HE-Klystron activities

- Under development for LHC
  - will give the LHC a higher power overhead to cope with transients
  - Lancaster chose the core stabilization method to achieve high efficiency for this requirement
- For other applications alternative models may be relevant



Project	$\approx \eta$	Technology	Design status	System status	Industrial partner	Prototype schedule
LHC 400 MHz, 350 kW CW	70% *)	CSM	completed	ongoing	Thales	18 months
FCC 400 MHz 600 kW CW	88%	TS MBK or CSM	ongoing		Thales?	36 months
FCC 800 MHz 1.3 MW CW	88%	TS MBK or CSM	ongoing		Thales?	
ILC 1.3 GHz 10 MW pulsed	85%	TS MBK	completed		Thales/Canon/CPI	
CLIC 1 GHz 24 MW pulsed	85%	TS MBK	completed		Thales/Canon/CPI	
X-band 8 MW pulsed	56%*)	COM	completed	completed	Canon	12 months
X-band 50 MW pulsed	70%*)	COM	completed	completed	CPI	24 months
36 GHz 2.5 MW	35%	HOM MBK	completed	completed	On hold	

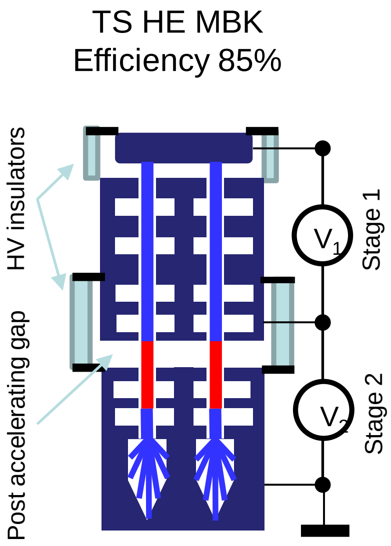
Two-Stage Multi Beam Klystron (TS MBK) technology (CLIC & FCC).

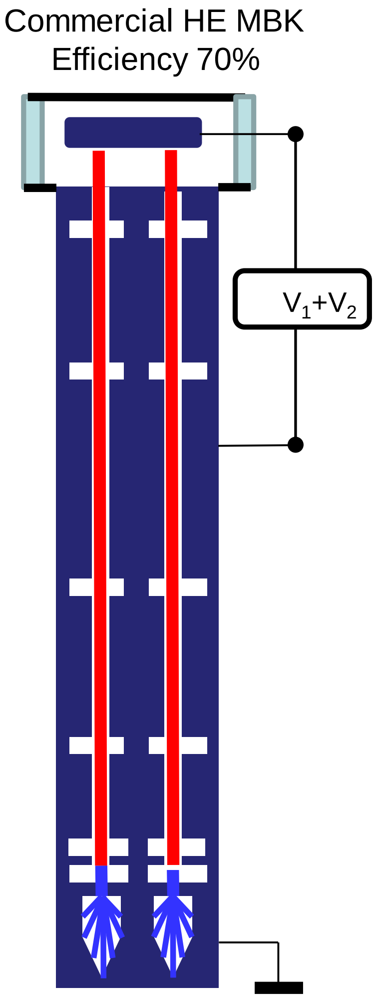
Specific features

1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing $\Delta p/p$) along the short DC voltage post-accelerating gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

Additional advantages:

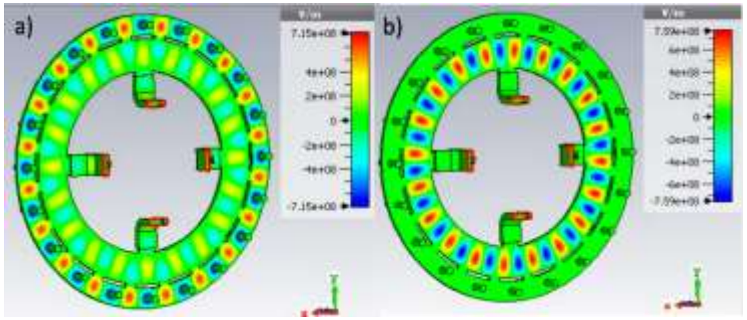
1. The second HV stage can be operated in DC mode. Thus simplifying the modulator topology (cost/volume) and increasing the modulator efficiency (in pulsed mode).
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.
3. Gap's accelerating DC voltage is a natural barrier for reflected electrons. Improved tube stability.


TS HE MBK
Efficiency 85%

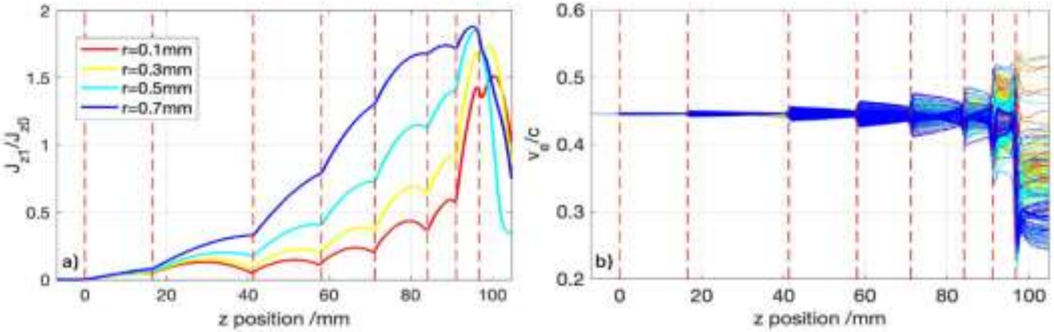

Commercial HE MBK
Efficiency 70%

HOM MBK for Ka-band

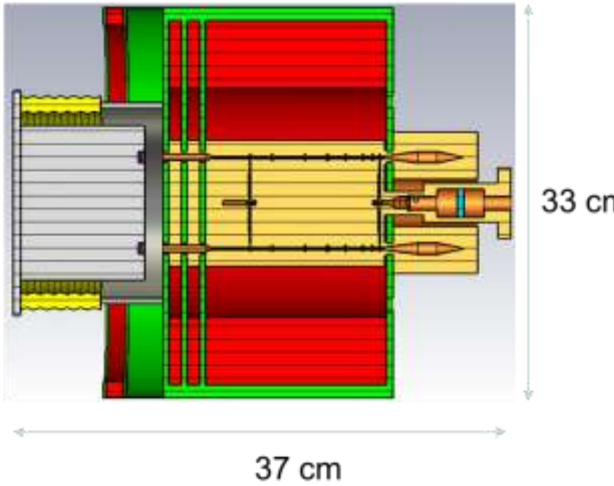
RF Source	Klystron	
Beam Voltage	60	kV
Beam Current	120	A
Efficiency	35	%
Bandwidth	50	MHz
Repitition rate	1	kHz
Magnetic field	0.55	T
Magnet diameter	33	cm
Oil tank required?	No	
Length	37	cm
Phase stability @ 100 ppm mod. Stab.	0.38	deg
Amplitude stability	1	%
Output Power	2.5	MW

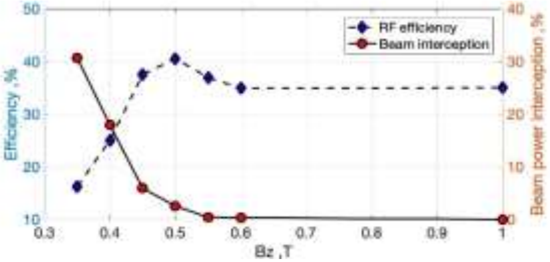


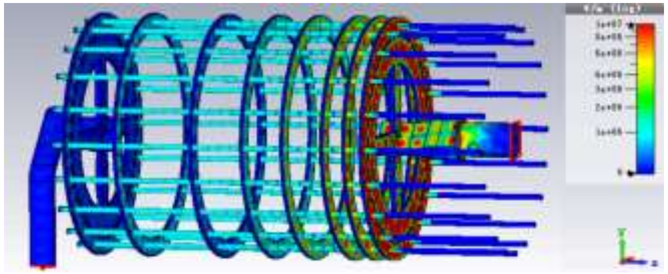
- $TM_{20,1}$ mode chosen for a 20 beam MBK
- Couple via an external waveguide wrapped around the inside of the cavity fed to two feed waveguides



- There is some beam interception in the last cell so a higher magnetic field is required. We find 0.55 T gives an efficiency above 35% while limiting beam loss.







Opportunity

- Muon Collider Needs
  - Depending on scheme….
    - Drive proton linac 402.5/805 MHz or 352/704MHz or 325/650MHz
    - Muon Cooling 325/650MHz or 352/704MHz
    - Main MC accelerator these plus possibly 1300MHz
  - High efficiency drivers critical to overall system budget
    - Can also be expected to enhance tube reliability or performance
    - Current η~50-64% (occasionally 70%)
- Opportunity to refine klystron designs for new performance points
  - Higher power
  - Pulsed operation