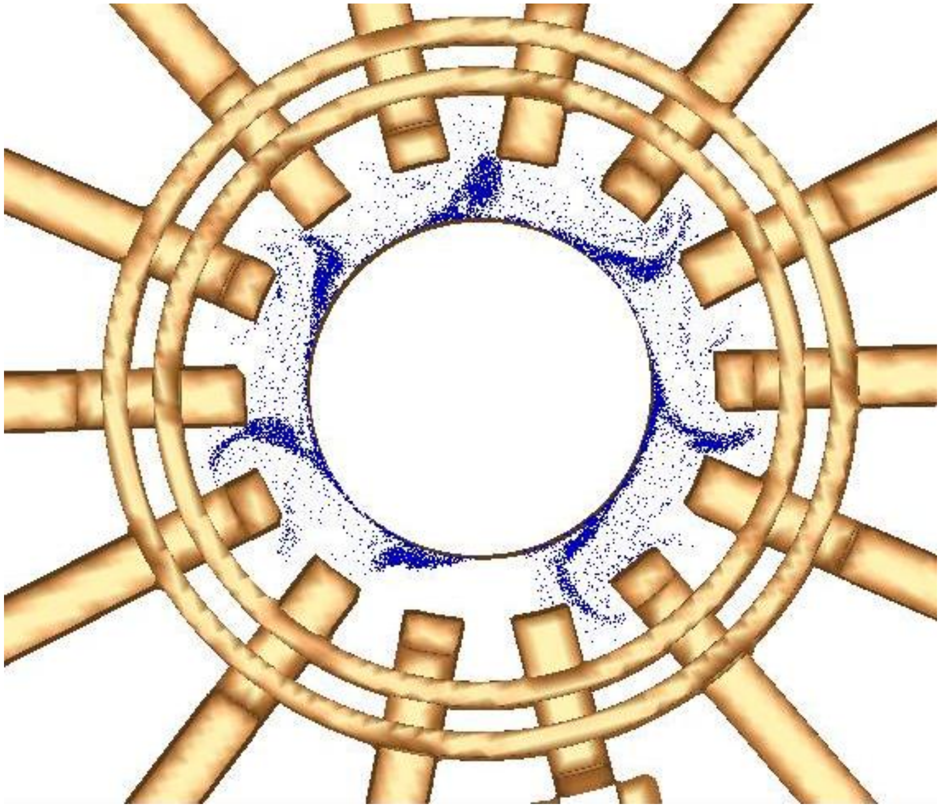
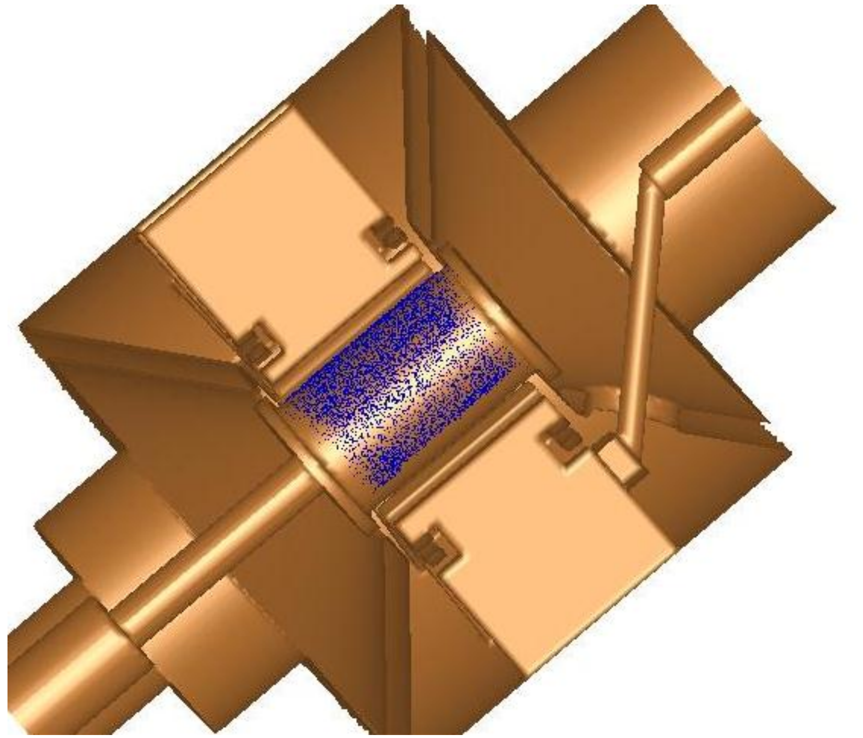
sLHC

A magnetron solution for proton drivers

Amos Dexter





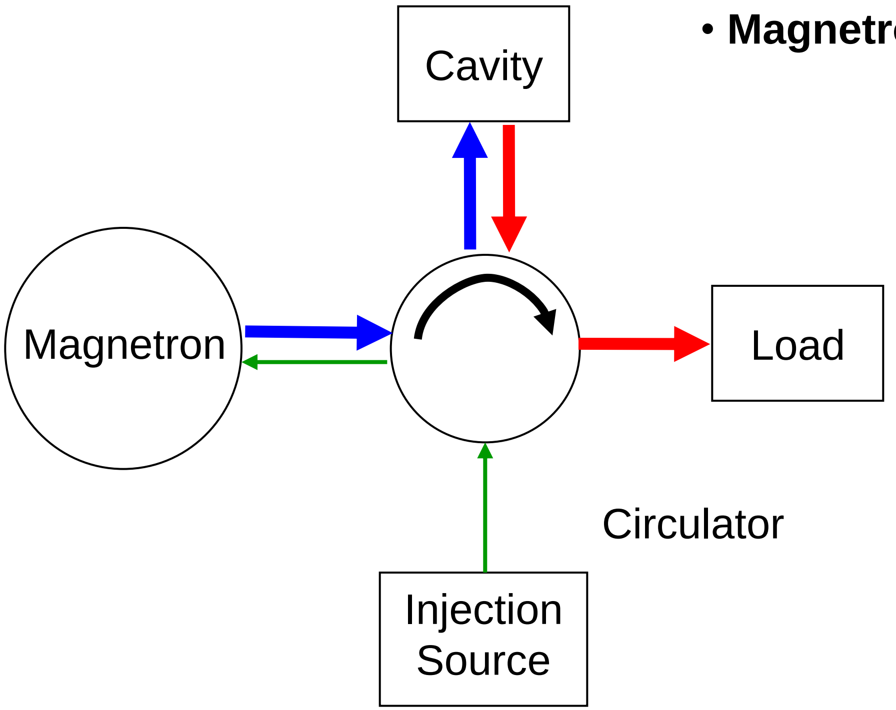
Simulation Using Tech-X's VORPAL e.m. code

Collaborations

Lancaster	Richard Carter, Graeme Burt, Ben Hall, Chris Lingwood
JLab	Haipeng Wang, Robert Rimmer
CEERI	Shivendra Maurya, VVP Singh, Vishnu Srivastava
TechX	Jonathan Smith
CERN	?
ESS	?

The Reflection Amplifier

- Linacs require accurate phase control
- Phase control requires an amplifier
- Magnetrons can be operated as reflection amplifiers



Compared to Klystrons, in general Magnetrons

- **are smaller**
- **more efficient**
- **can use permanent magnets (at 704 MHz)**
- **utilise lower d.c. voltage but higher current**
- **are easier to manufacture**

Consequently they are much cheaper to purchase and operate

J. Kline "The magnetron as a negative-resistance amplifier," *IRE Transactions on Electron Devices*, vol. ED-8, Nov 1961

H.L. Thal and R.G. Lock, "Locking of magnetrons by an injected r.f. signal", *IEEE Trans. MTT*, vol. 13, 1965

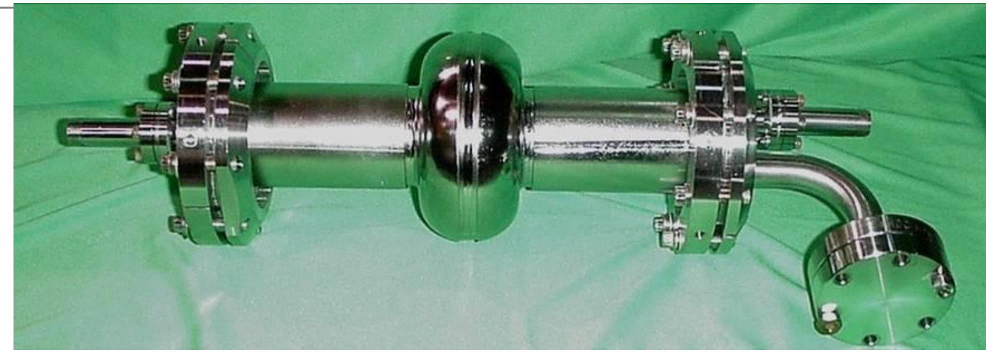
The Royal Academy of Engineering

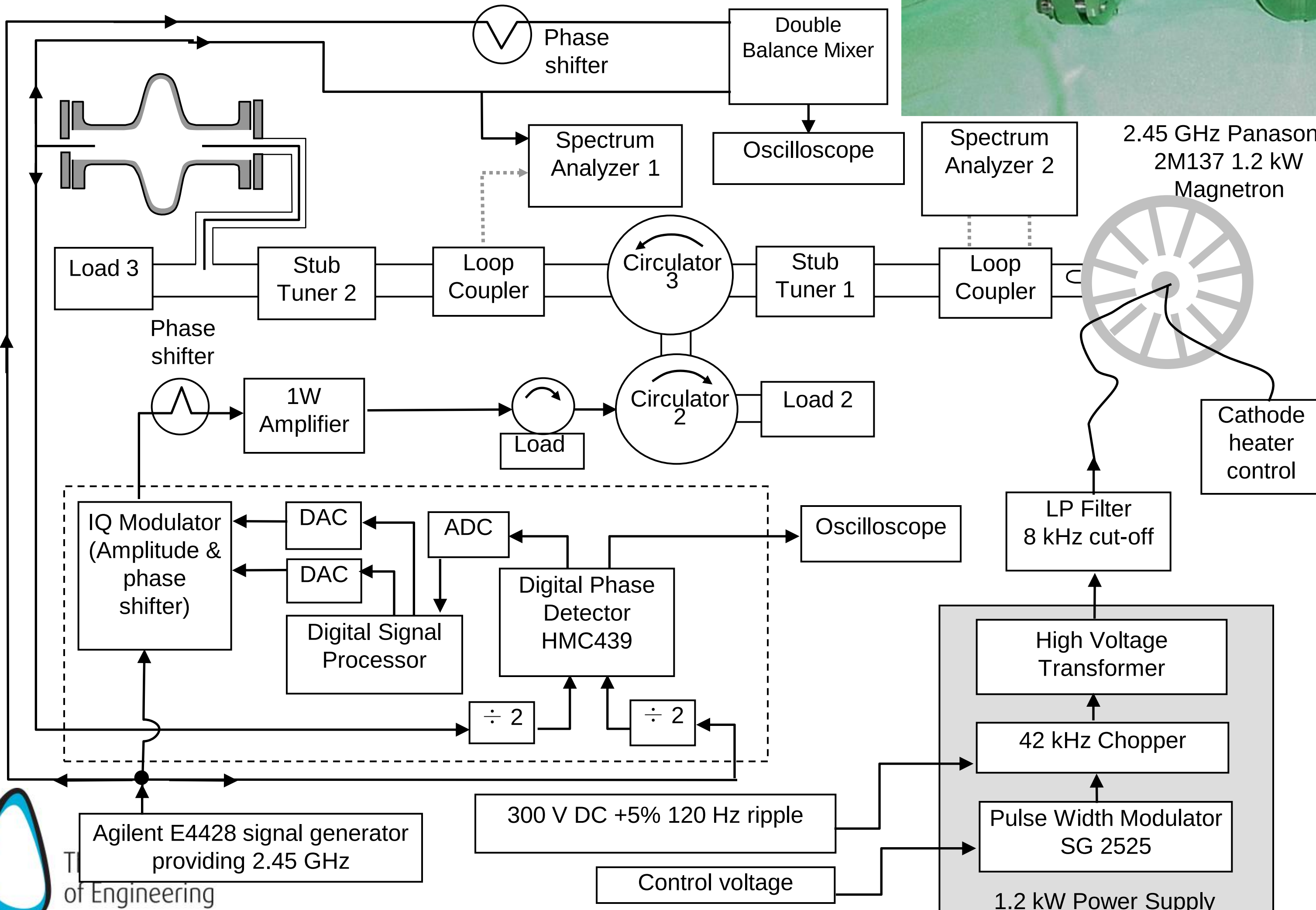
sLHC

Proof of principle

The Cockcroft Institute
of Accelerator Science and Technology

Demonstration of CW 2.45 GHz magnetron driving a specially manufactured superconducting cavity in a VTF at JLab and the control of phase in the presence of microphonics was successful.

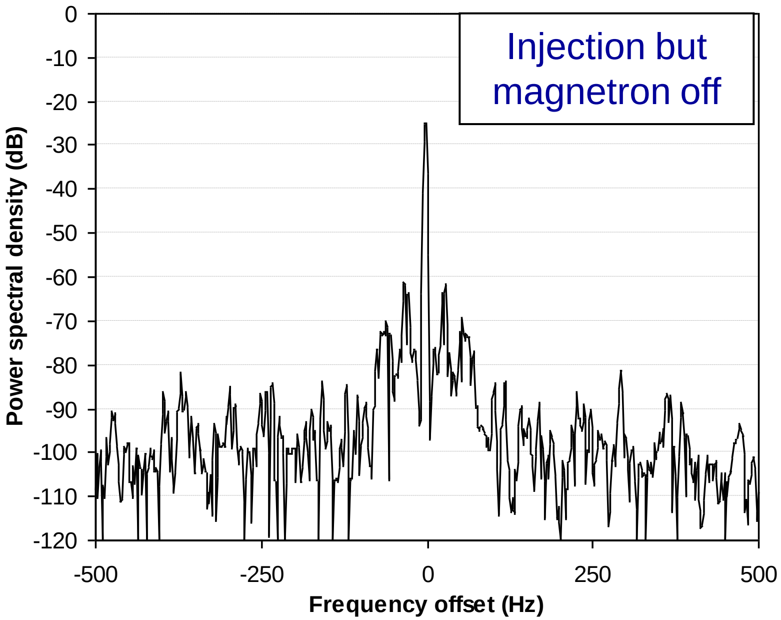


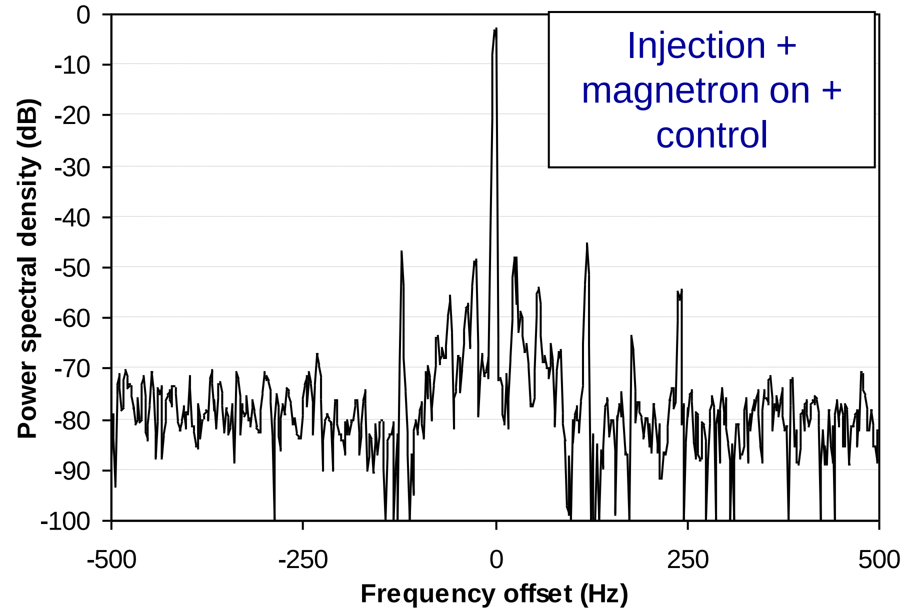


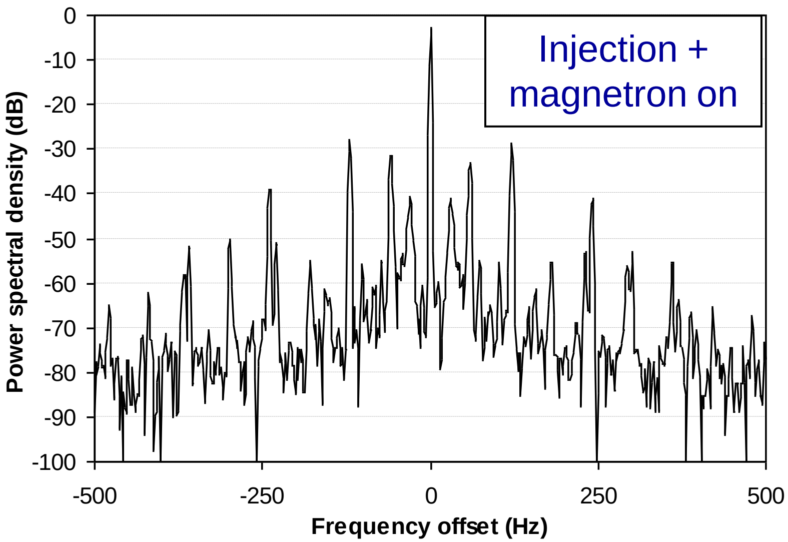
Jefferson Lab

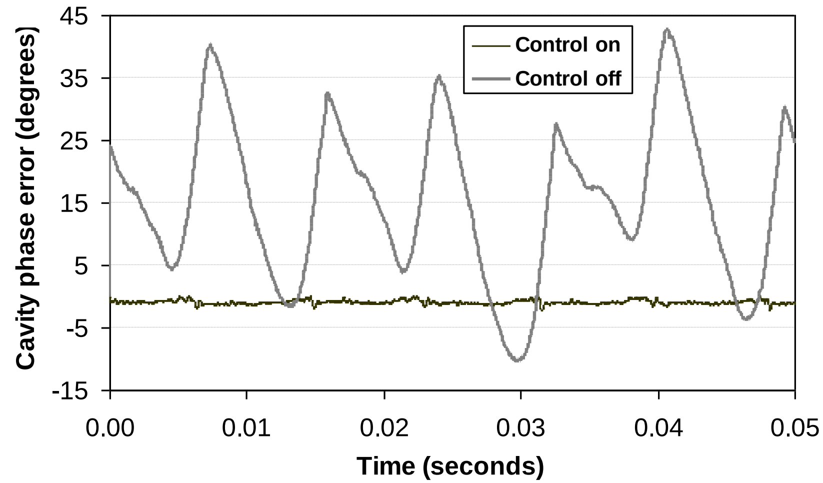
LANCASTER UNIVERSITY

SCRF cavity powered with magnetron









Next Steps

- **Development of a 704MHz Magnetron (440kW – 880kW)**

  Collaboration with CEERI, Pilani, India

- **Procure standard modulator**

  Hope to use klystron modulator with different pulse transformer however rate of voltage rise is tightly defined. Need to deal with impedance change on start up. The CI have a suitable 3 MW magnetron modulator for short pulses up to 5 micro-seconds and could be used for characterisation

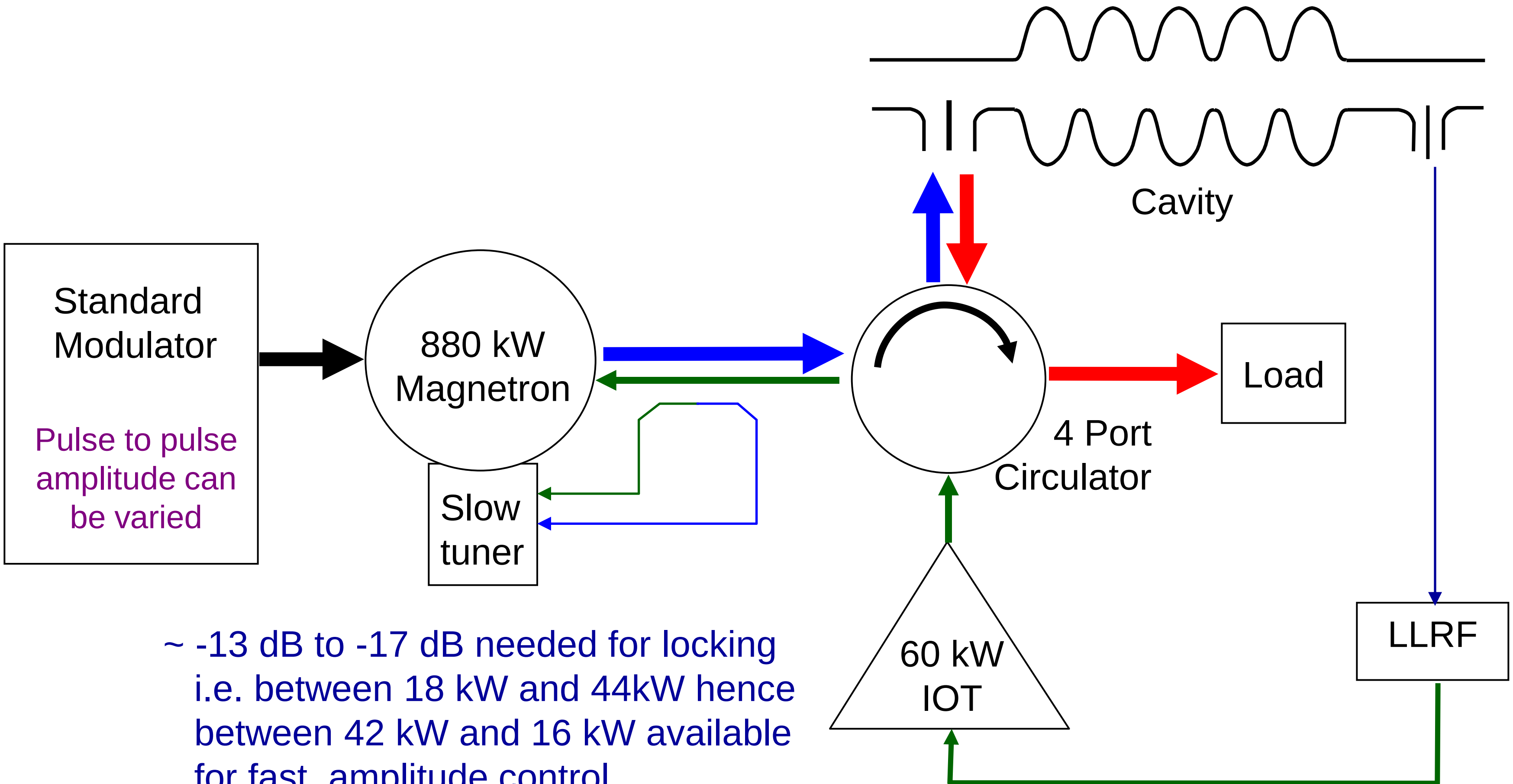
- **Establish test station with Television IOT as the drive amplifier**

  Could be used for conditioning SPL and ESS components

- **Understand locking characteristics of new magnetron**
- **Commission advanced modulator with in-pulse current control**
- **Establish minimum locking power**
- **Establish two magnetron test stand**
- **Develop LLRF for simultaneous phase and amplitude control**

Layout using one magnetron per cavity

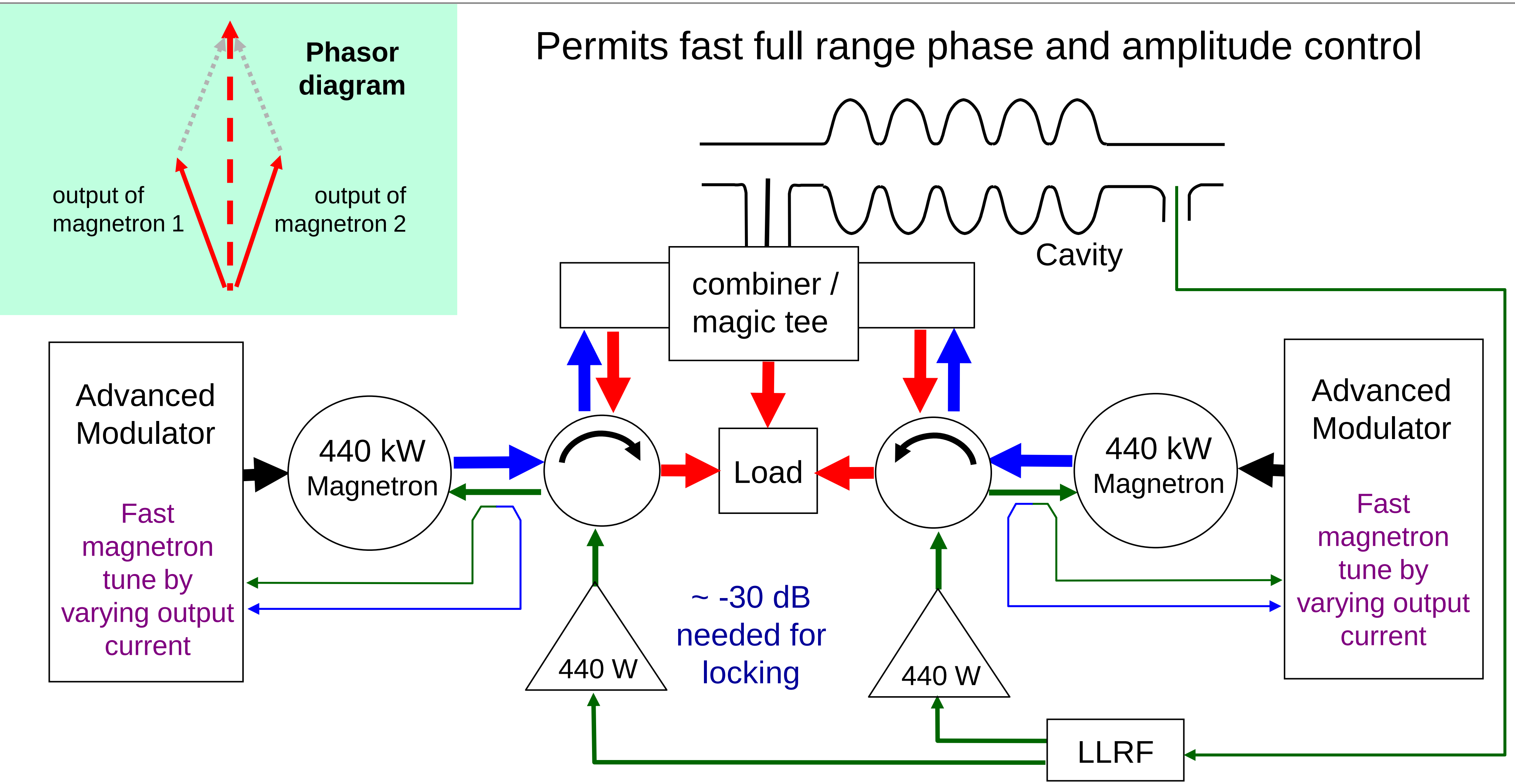
Permits fast phase control but only slow, full range amplitude control



~ -13 dB to -17 dB needed for locking i.e. between 18 kW and 44kW hence between 42 kW and 16 kW available for fast amplitude control

Could fill cavity with IOT then pulse magnetron when beam arrives

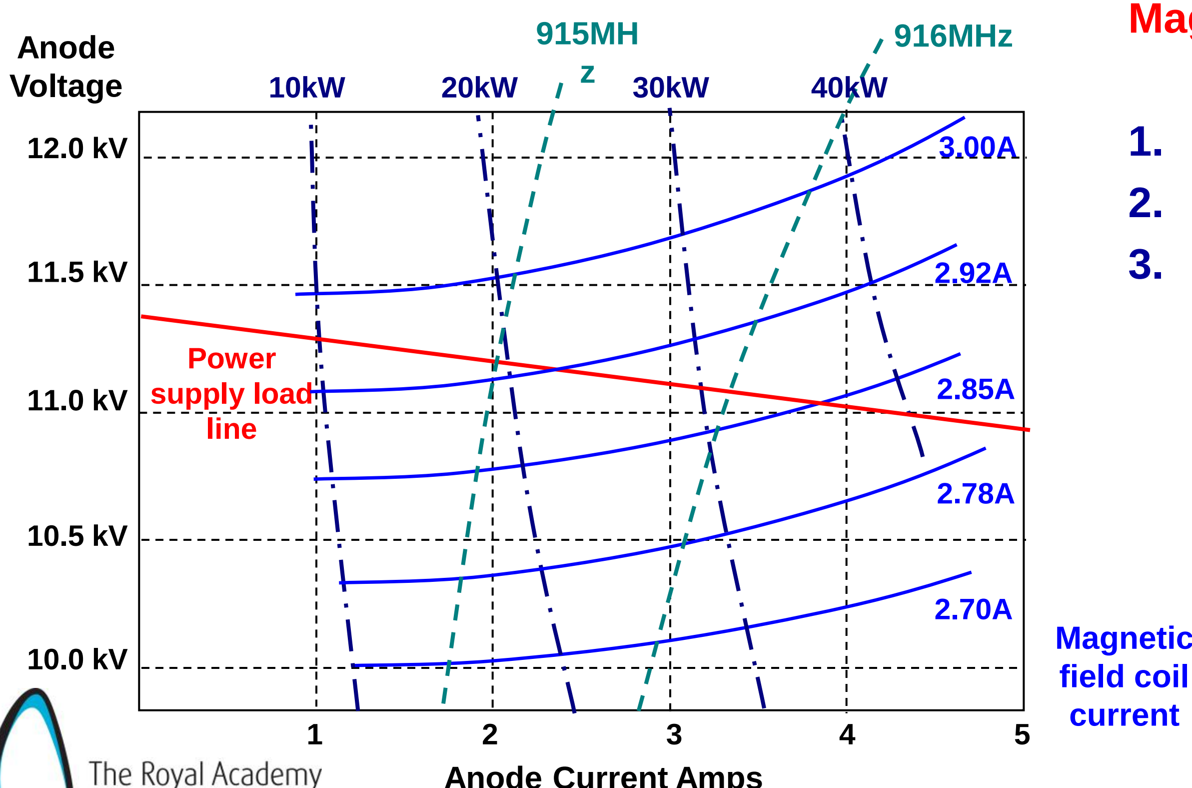
Layout using two magnetrons per cavity



Reflection Amplifier Controllability

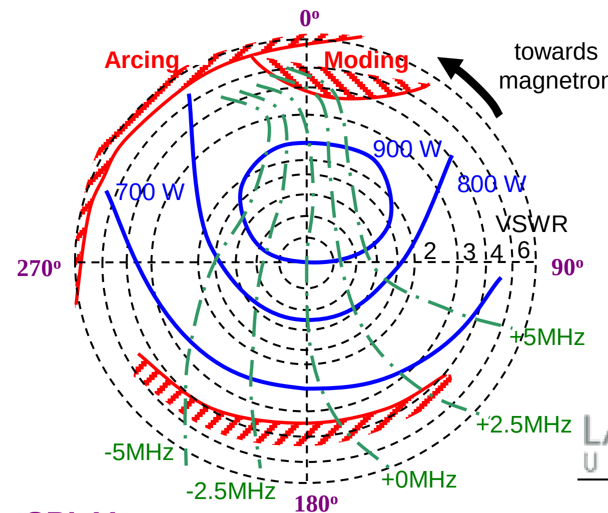
sLHC

1. Phase of output follows the phase of the input signal
2. Phase shift through magnetron depends on difference between input frequency and the magnetrons natural frequency
3. Output power has minimal dependence on input signal power
4. Phase shift through magnetron depends on input signal power
5. There is a time constant associated with the output phase following the input phase



Magnetron frequency and output vary together as a consequence of

1. Varying the magnetic field
2. Varying the anode current (pushing)
3. Varying the reflected power (pulling)



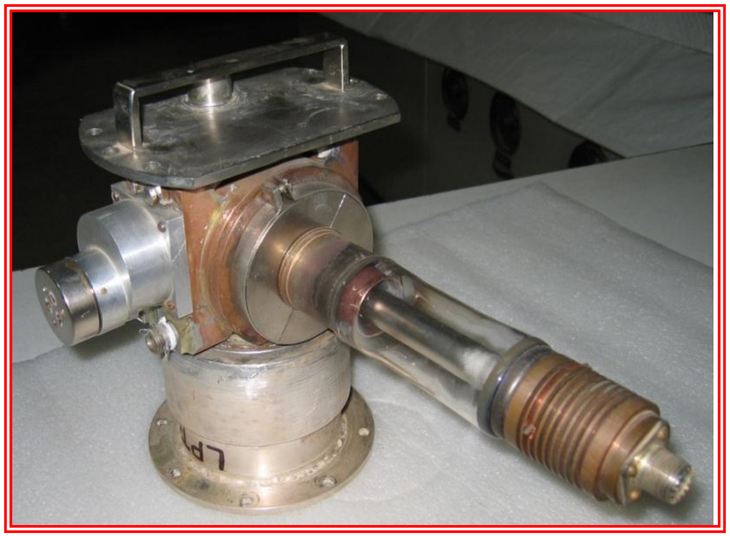
SPL11

CEERI Collaboration

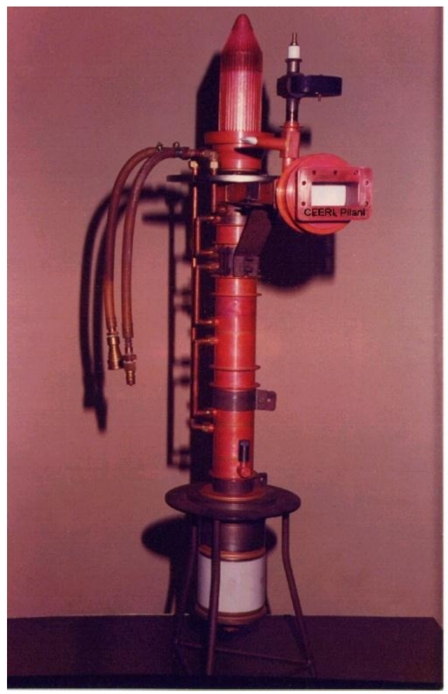
Dr Shivendra Maurya of the Microwave Tube Division, CEERI, PILANI, India visited Lancaster University from 1st August to 31st November to start work on the design of a suitable magnetron.

This visit has been funded by the Royal Academy of Engineering.

If there is sufficient interest CEERI will seek funding to manufacture the magnetron. CEERI already manufacture a range of tubes mainly for use in India.



S-band, 3.1 MW Pulse Tunable Magnetron for Accelerator



5 MW (pk), 5kW(avg) S-band Klystron as RF amplifier for injector microtron in Synchrotron Radiation Source

at RRCAT, Indore

Specification of initial device

Frequency	704 MHz
Power	200 kW to 1 MW
Pulse length	5μs to 5 ms (for max power)
Max average power	100 kW
Efficiency	> 90% above 500 kW
Magnet	NyFeB (< 0.5 T)
External Q	~ 50 (for ease of locking)
Mechanical Tunability	~ 5 MHz
Cathode heating	indirect and controllable

CERN sLHC

Approximate Calculations

Using standard theory one can estimate Magnetic field, anode and cathode radii from requirement data (frequency 704 MHz, efficiency >90% and power

Power output	W	5.26E+05	1.00E+06	Given
Overall efficiency target		0.9066	0.9210	Assumed
DC power	W	5.80E+05	1.09E+06	Derived
DC impedance	Ohms	1615	1615	Guessed
Anode voltage		30611	41876	Derived
Anode current		18.954	25.930	Derived
Cathode plus circuit losses		4.00%	4.00%	Estimated
electronic efficiency		94.66%	96.10%	Derived
V anode over V threshold		1.25	1.25	Assumed
V threshold	V	24488	33501	Derived
Modified Slater factor		1.96	2	Assumed
Number of Vanes		14	14	Assumed
Anode radius	m	0.02400	0.02401	Calculated
Cathode radius	m	0.01775	0.01774	Calculated
Anode height	m	0.05536	0.05536	Assumed
Cathode current density	A/m^2	3070	4202	Derived
Electric field	V/m	9.79E+06	1.34E+07	Derived
Voltage field product	kV/mm^2	299.6	559.8	Derived
B	T	0.30477	0.41331	Calculated

$$\eta_e \approx \frac{B+0.5B_o}{B+1.5B_o}$$

$$B_o = 4\frac{m}{e}\frac{\omega_{rf}}{N}\frac{1}{1-(r_c/r_a)^2}$$

$$V_o = \frac{2m}{e}\left(\frac{\omega_{rf}}{N}\right)^2 r_a^2$$

$$\frac{V_{th}}{V_o} = 2\frac{B}{B_o} - 1$$

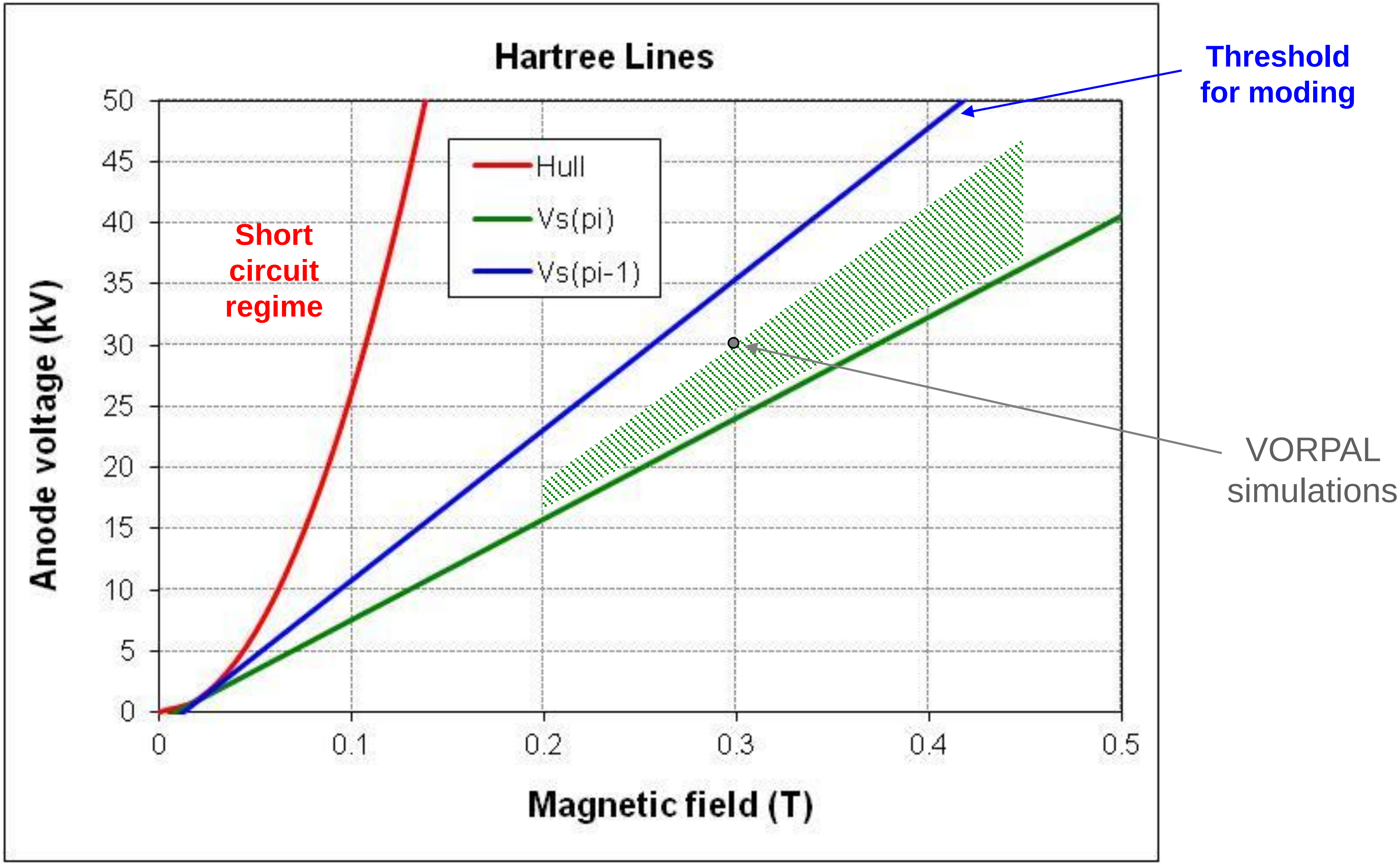
$$S_F = \left(\frac{r_a - r_c}{r_a + r_c}\right) N \sqrt{1-\frac{V}{V_c}}$$

$$V_c = V_o\left(\frac{B}{B_o}\right)^2$$

Should be able to use same block for efficient generation at both the 500 KW and 1 MW level

The Cockcroft Institute of Accelerator Science and Technology
The Royal Academy of Engineering
LANCASTER UNIVERSITY

Expected operating range



VORPAL Predictions at 30 kV

Take

B = 0.3 T,

V_a = 32 kV,

I_c = 60 A

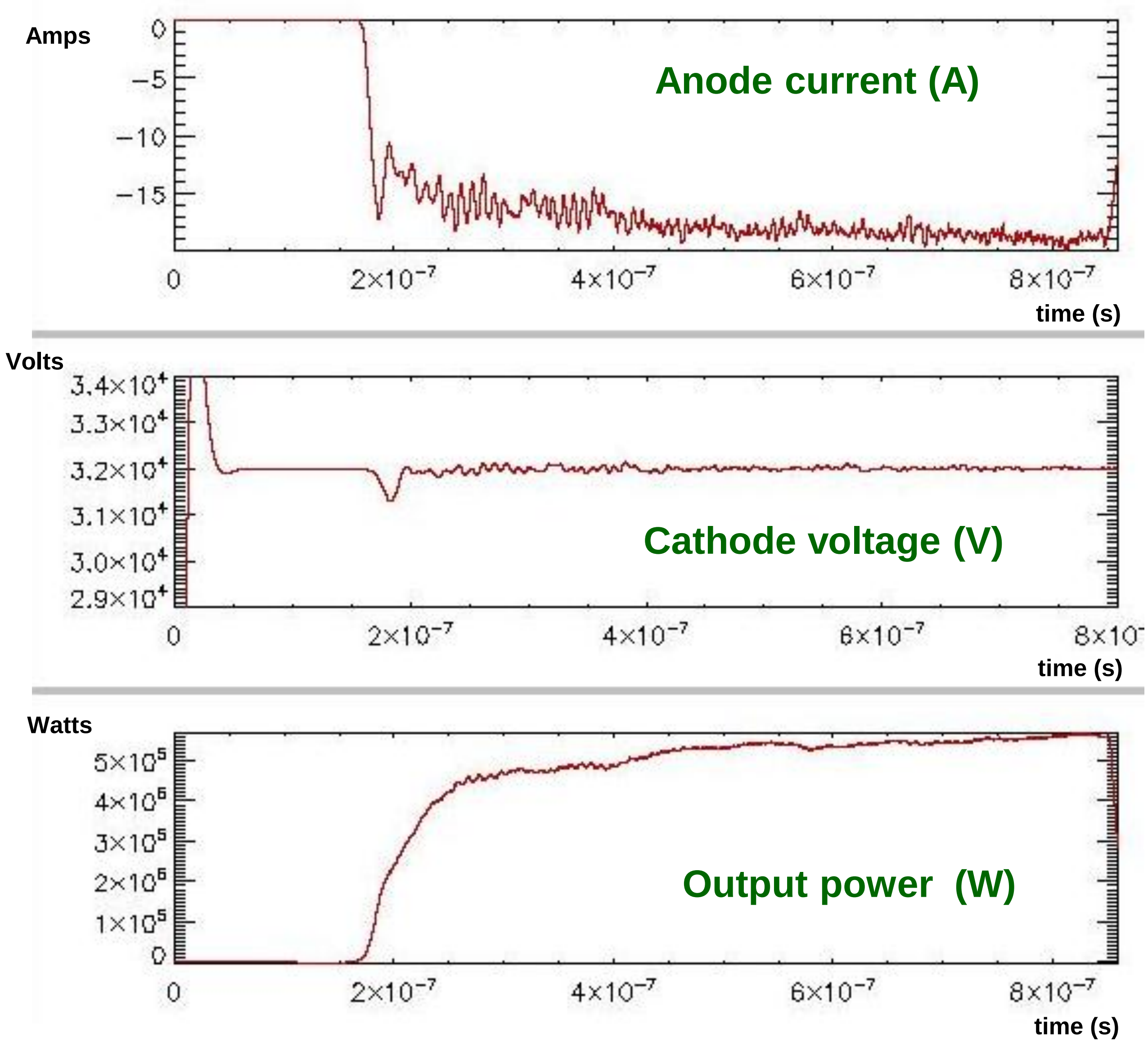
Predict

I_{anode} = 19 A,

Efficiency = 92%,

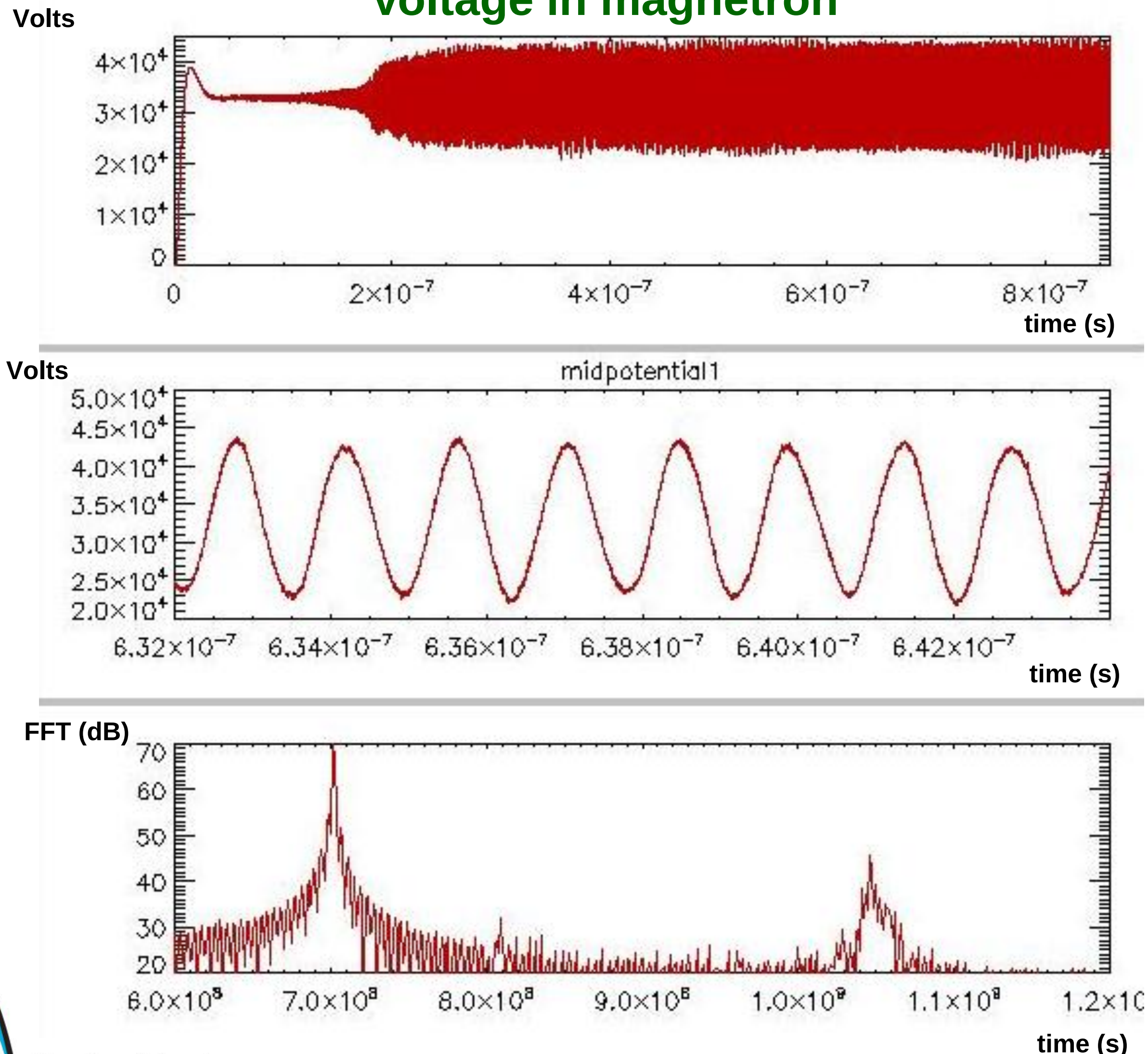
Power = 560 kW

Z = 1684 Ω



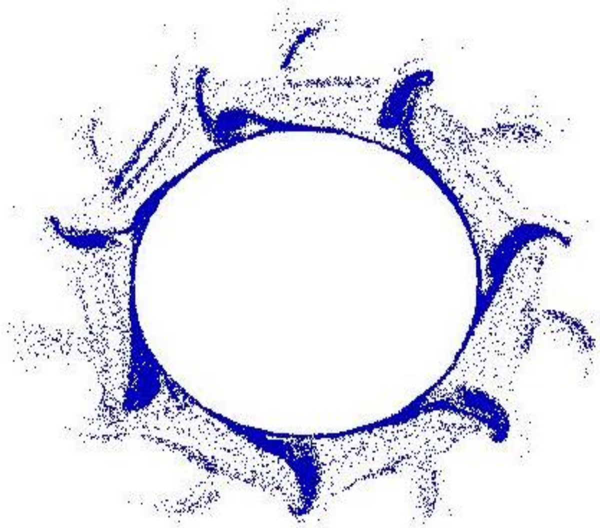
Moding Issues

Voltage in magnetron

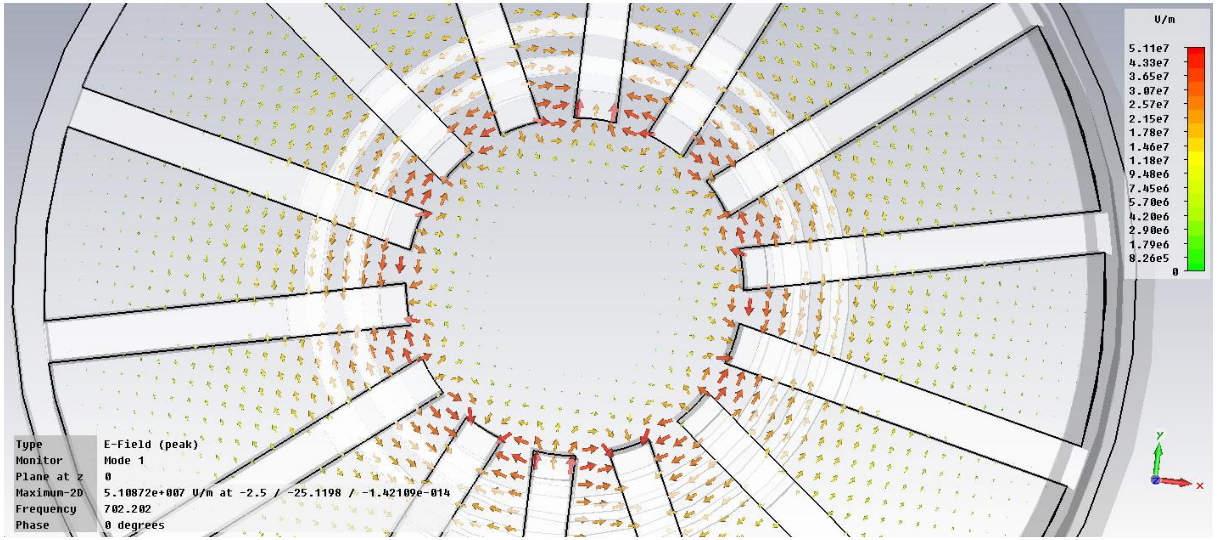


Excitation in the mode at 1060 MHz might be a problem.

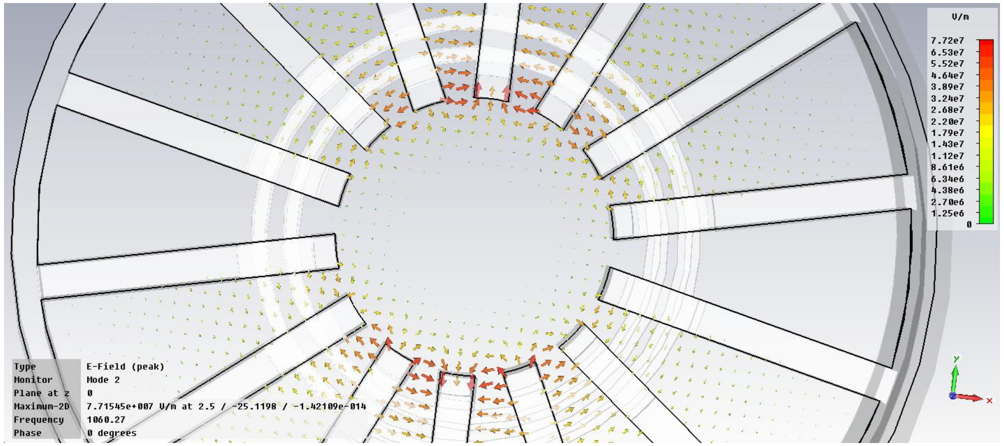
We think the coarse mesh or other issues with the simulation might exacerbate the issue.

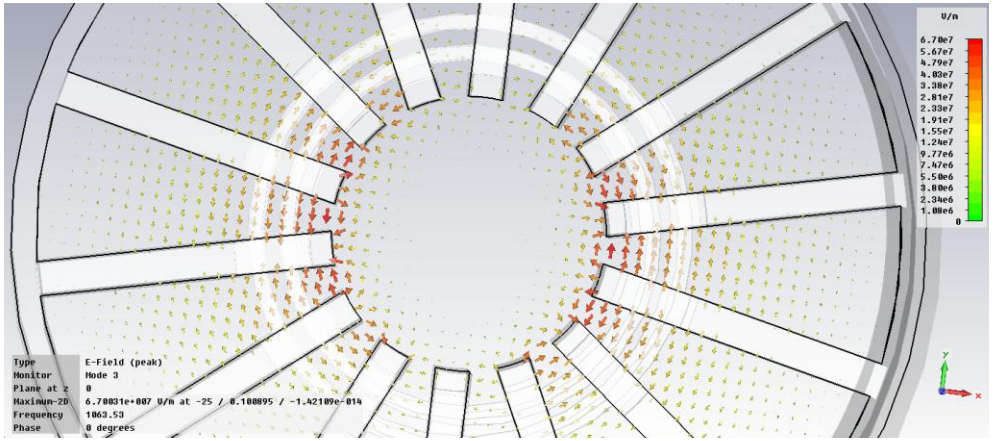


MWS modes



π mode at 702 MHz





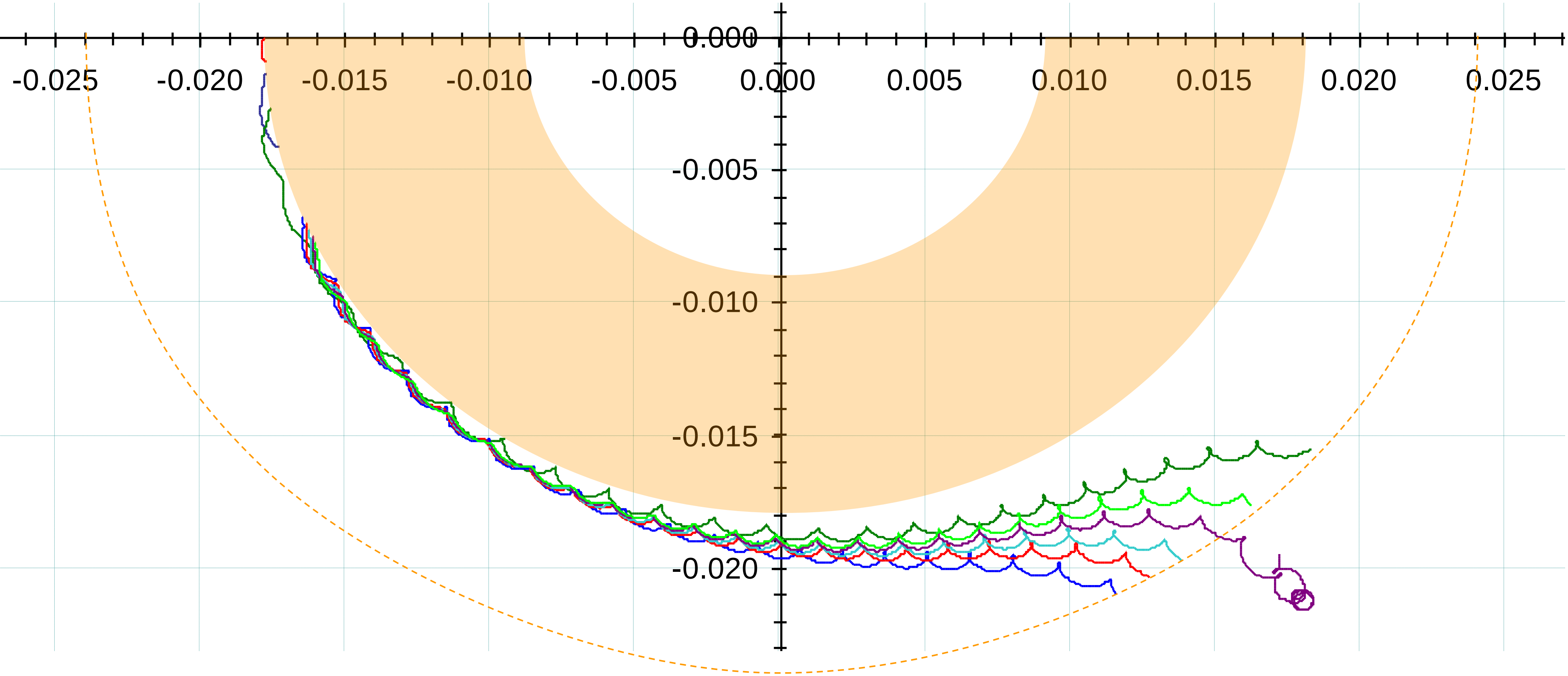
$\pi-1$ mode at 1060 MHz

$\pi+1$ mode at 1063 MHz

Efficient Orbits

The Cockcroft Institute of Accelerator Science and Technology

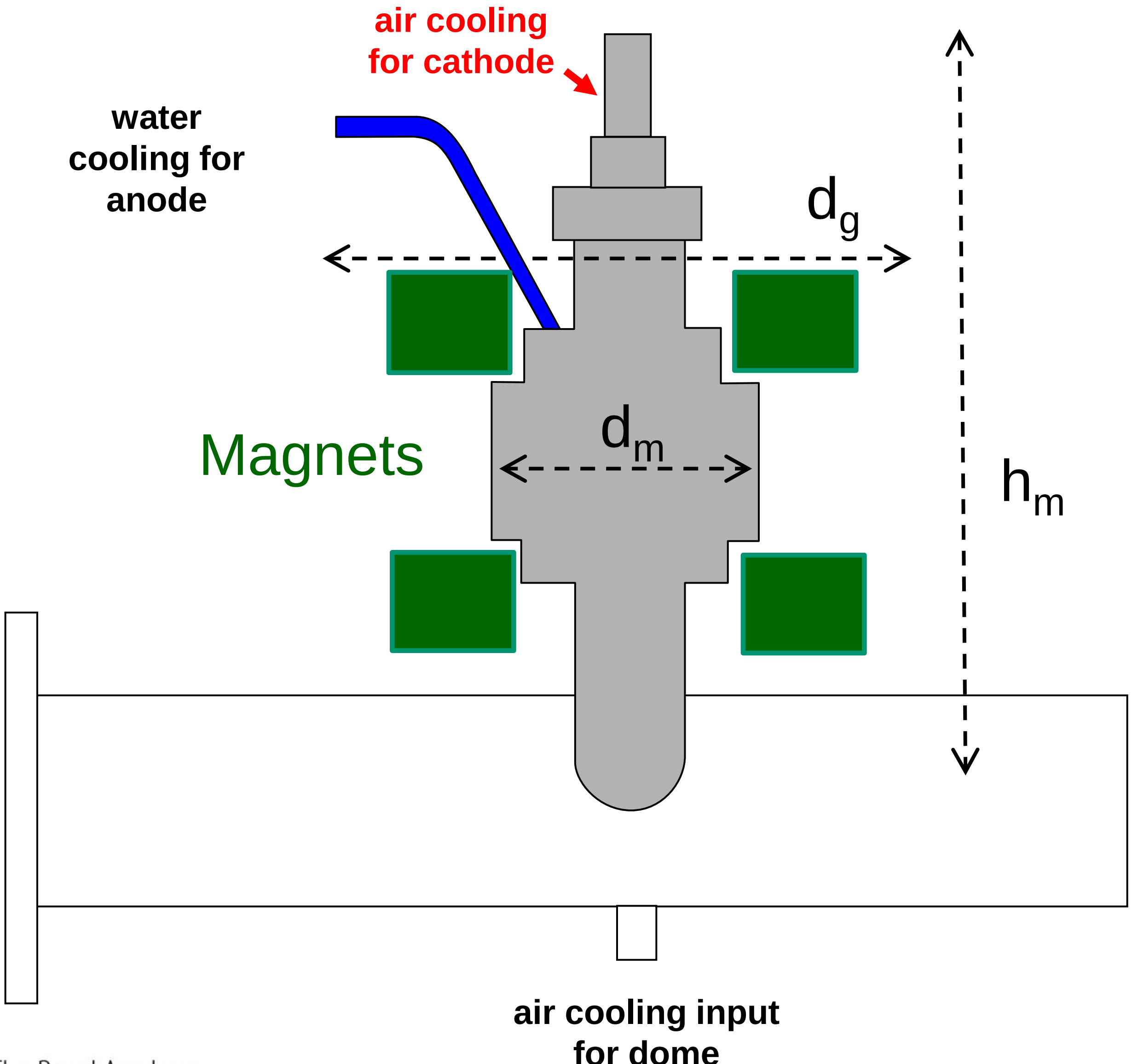
An efficient orbit should have no loop



The Royal Academy of Engineering

LANCASTER UNIVERSITY

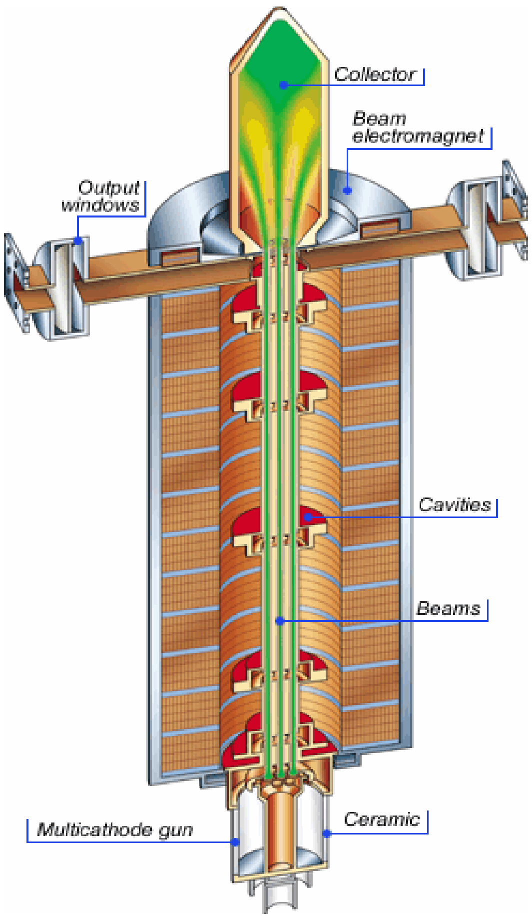
Magnetron Size



	704 MHz
d_g	~ 360 mm
d_m	~ 165 mm
h_m	~ 650 mm
cost	£8000

If magnetron design is similar to industrial design with similar tolerances and can be made on same production line then cost may not be much more

High Efficiency Klystrons



Images courtesy of Thales Electron Devices

- Design of high efficiency klystrons for ESS in collaboration with CLIC
  - Similar Klystrons (704.4 MHz, 1.5 MW, 70% efficiency) allow synergetic activities with CLIC.
  - Focus on understanding of bunching process and space charge in the output cavity.
  - Using evolutionary algorithms to improve optimisation
  - New design concepts to achieve optimum beam modulation
  - Single and Multiple beams investigated

EUROPEAN SPALLATION SOURCE