Third Harmonic Cavity Design for the Electron-Ion Collider

IOP PAB 2026

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S. Toole s.j.toole@lancaster.ac.uk

G. Burt, Z. Conway, R. Rimmer

Motivation for an Electron-Ion Collider

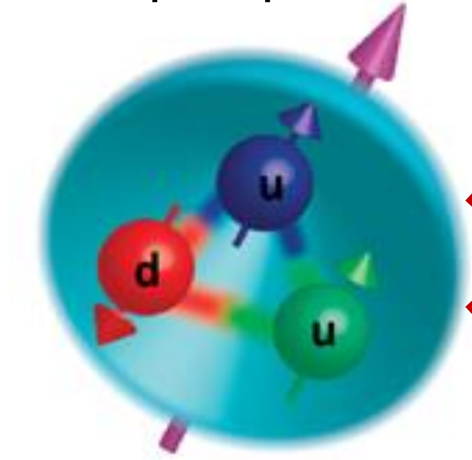
Quark and gluon orbital angular momentum

Protons, were thought to derive their ½ spin primarily **from their constituent valence quarks, uud**

Gluon spin

$$\frac{1}{2} \approx \frac{1}{2}\Delta\sum(\Delta u+\Delta d+\Delta s)+\Delta G+L_Q+L_G$$

Valence quark spin



$\frac{1}{2}$

In 1988, deep inelastic scattering (DIS) experiment revealed valence quarks contribute **less than 30% of proton spin**[1]

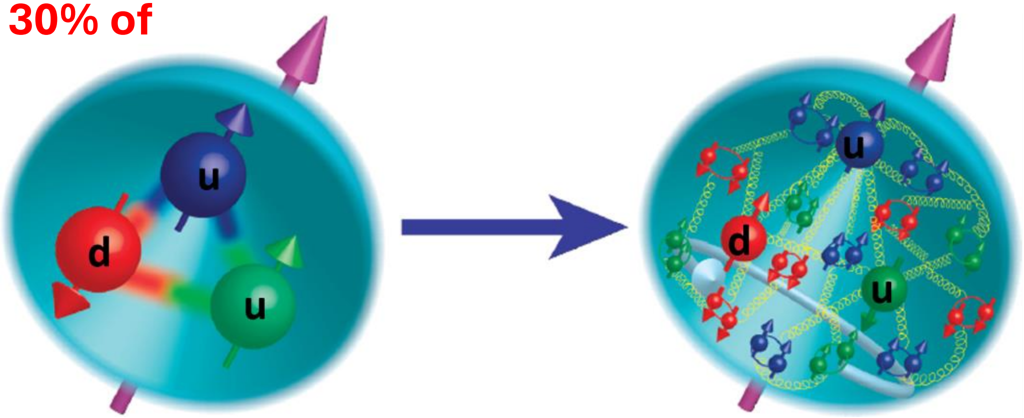
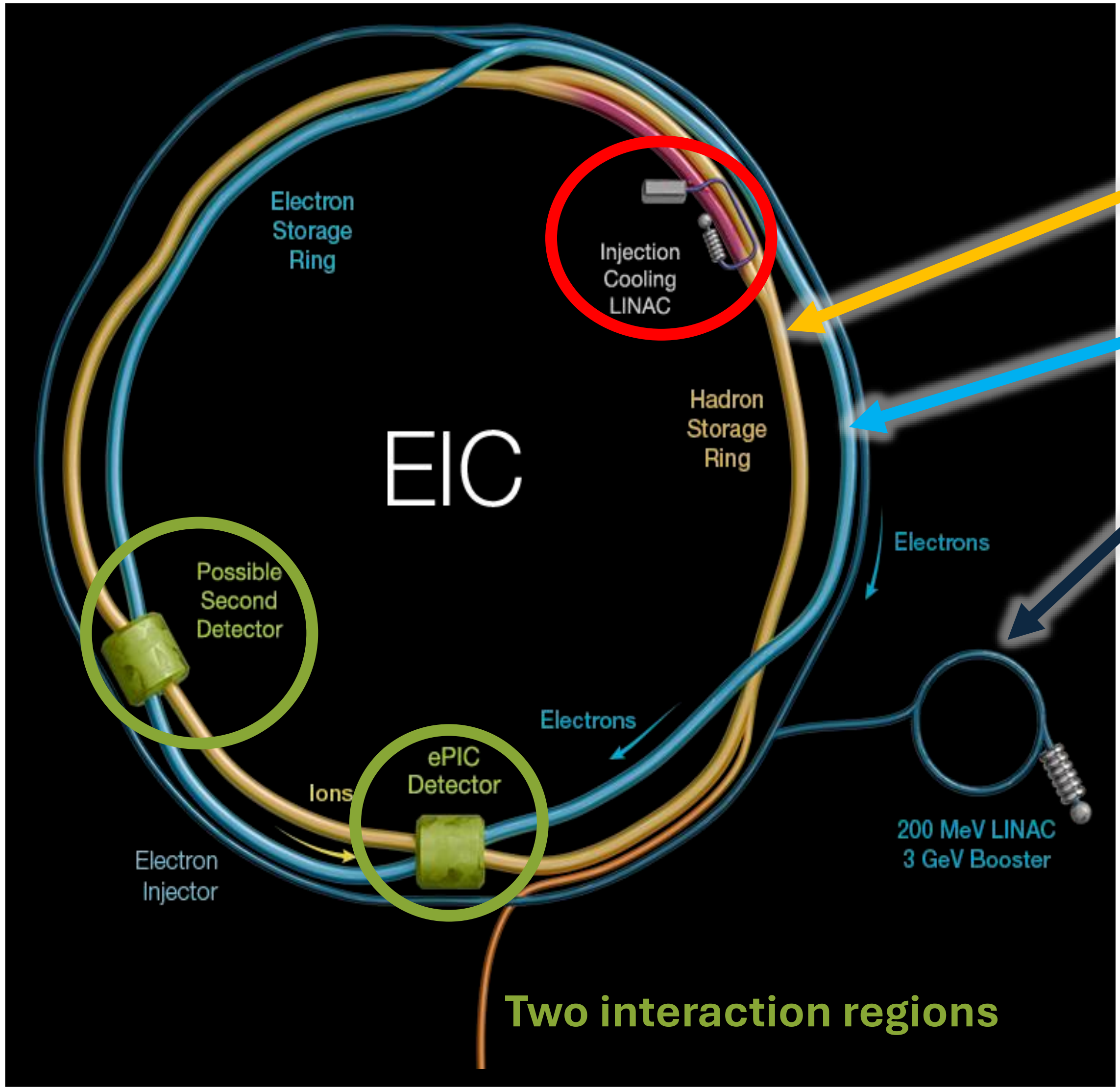


*Figure 1: Evolving understanding of proton spin origin. (**Left**) proton was composed of three valence quarks, with total spin ½. (**Right**) proton contains quarks, as well as a gluonic sea of quark-antiquark pairs; the total spin is composed of that of the elementary spins[2].*

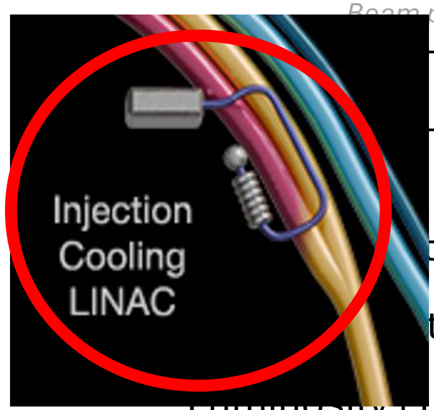
[1]"Lipkin, Harry J. 1988. "Flavor Symmetry, EMC Results and the Spin Content of the Proton." Physics Letters. B 214 (3): 429–33; [2]White Paper on the Electron-Ion Collider in Preparation for the NSAC Long Range Plan." 2023

The Electron Ion Collider



The existing 3.4km rings of the **Relativistic Heavy Ion Collider** are used to build:

- **Hadron Storage Ring (HSR):** storing polarised protons at energies 41-275 GeV.
- **Electron Storage Ring (ESR):** storing polarised electrons at energies 5 GeV -18 GeV.
- **Rapid-Cycling Synchrotron (RCS):** a pre-injector to accelerate polarised electrons from 200MeV to 5 GeV-18 GeV[4].



Beam parameters operating at maximum luminosity[4].

	e^-	p^+
[GeV]	10	275
[A]	2.5	1
tion [%]	≥70	
Luminosity [$10^{34} cm^{-2} s^{-1}$]	1	

[3]Bnl.gov. (2017). The EIC Machine., Satogata, T. (2023). [4]EIC Parameter List Summary. [online] EIC.JLAB. Available at: https://eic.jlab.org/Documents/EIC-General/EIC_ParameterList.pdf.

Coherent Electron Cooling

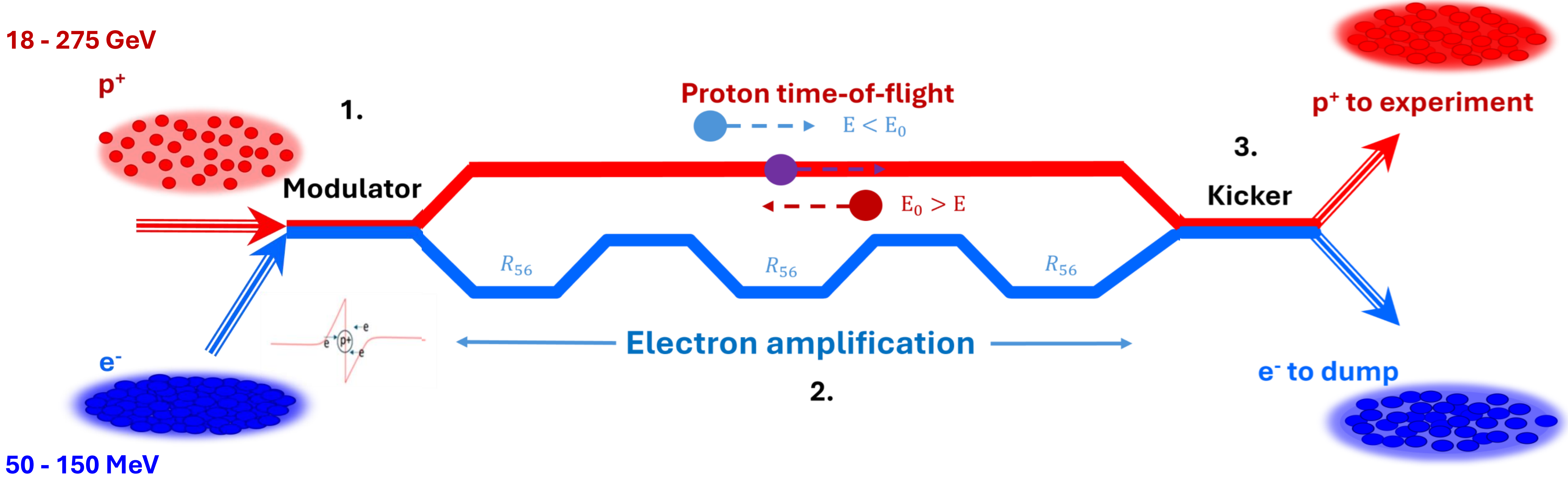
A future upgrade

Heavy ions do not have an intrinsic damping mechanism to counteract emittance growth when subjected to long stores in collider rings

Emittance growth occurs due to: **Intra Beam Scattering → Degrades luminosity**

Vertical emittance grows from $\mathbf{0.3\mu m}$ **to** $\mathbf{2.5\mu m}$ **in 2 hours**[5]

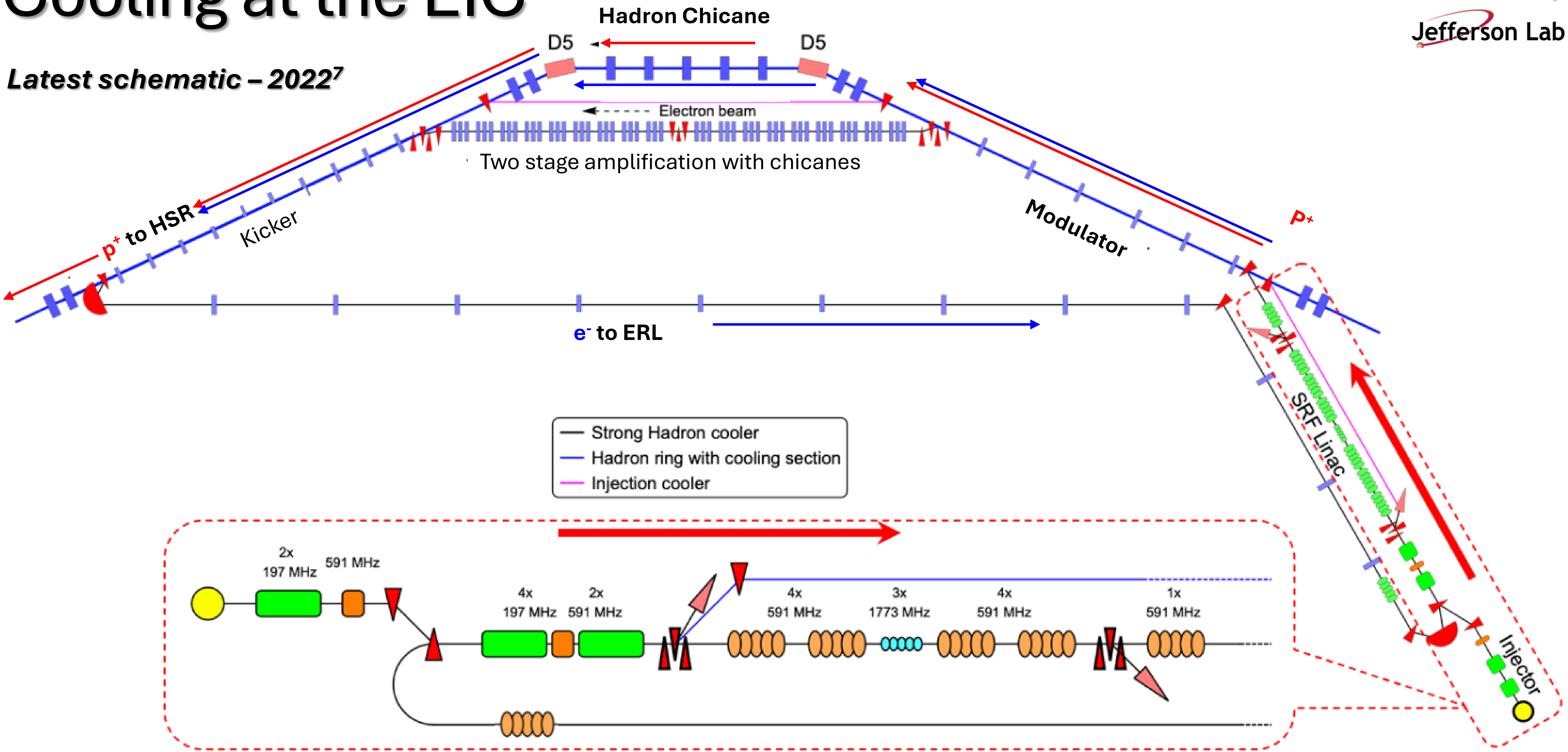
External **fast cooling mechanism required** to counteract this[6]



[5]COHERENT ELECTRON COOLING PHYSICS FOR THE EIC. doi:https://doi.org/10.18429/JACoW-IPAC2024-THYD1
[6]Ratner, D. (2013). Microbunched Electron Cooling for High-Energy Hadron Beams. Physical Review Letters, 111(8). Bergan, W.F., Mayes, C., Wang, N. and Stupakov, G. (2024).

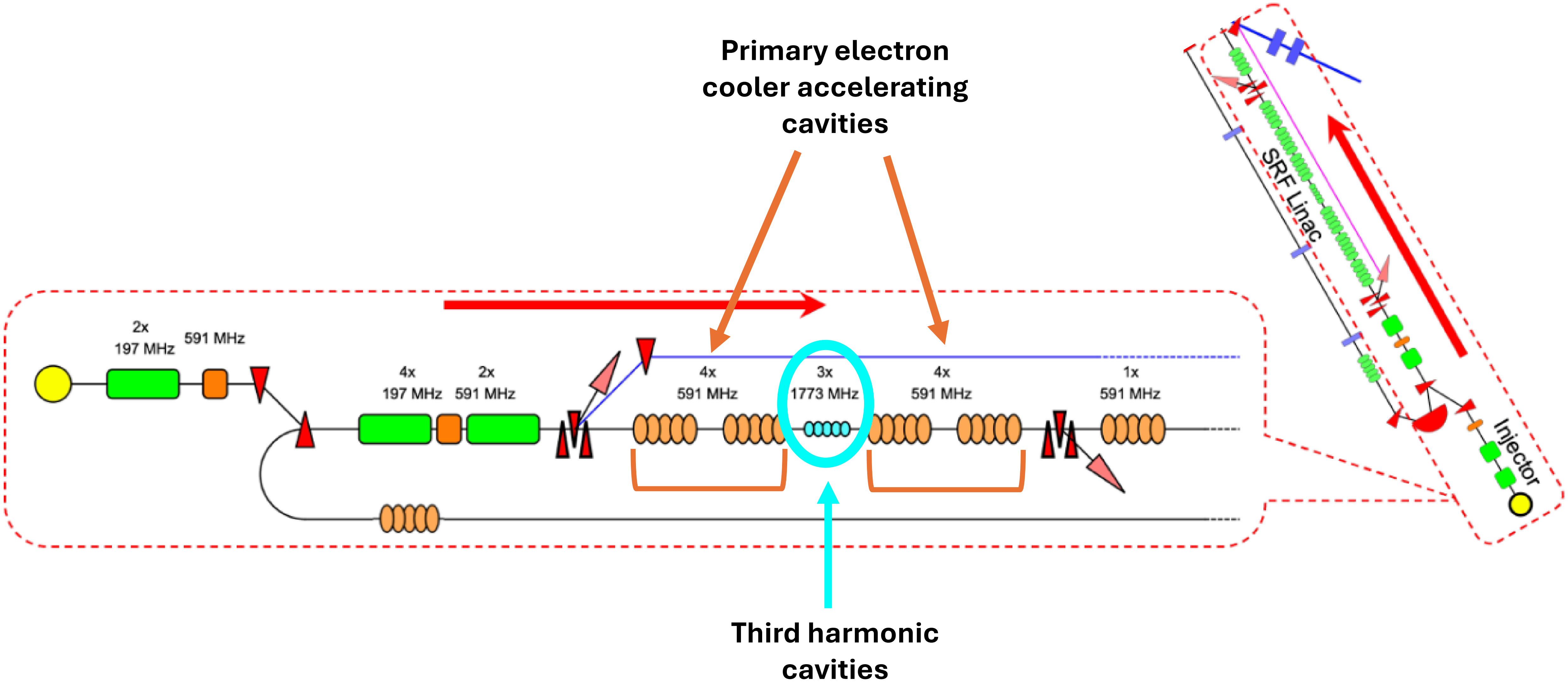
Cooling at the EIC

Latest schematic – 2022[7]



[7]Wang, E, W Bergan, F Willeke, S Benson, K Deitrick, Thomas Jefferson, C Mayes, D Douglas, C Gulliford, and N Taylor. n.d. "ELECTRON ION COLLIDER STRONG HADRON COOLING INJECTOR and ERL.

Cooling at the EIC



[7]Wang, E, W Bergan, F Willeke, S Benson, K Deitrick, Thomas Jefferson, C Mayes, D Douglas, C Gulliford, and N Taylor. n.d. "ELECTRON ION COLLIDER STRONG HADRON COOLING INJECTOR and ERL.

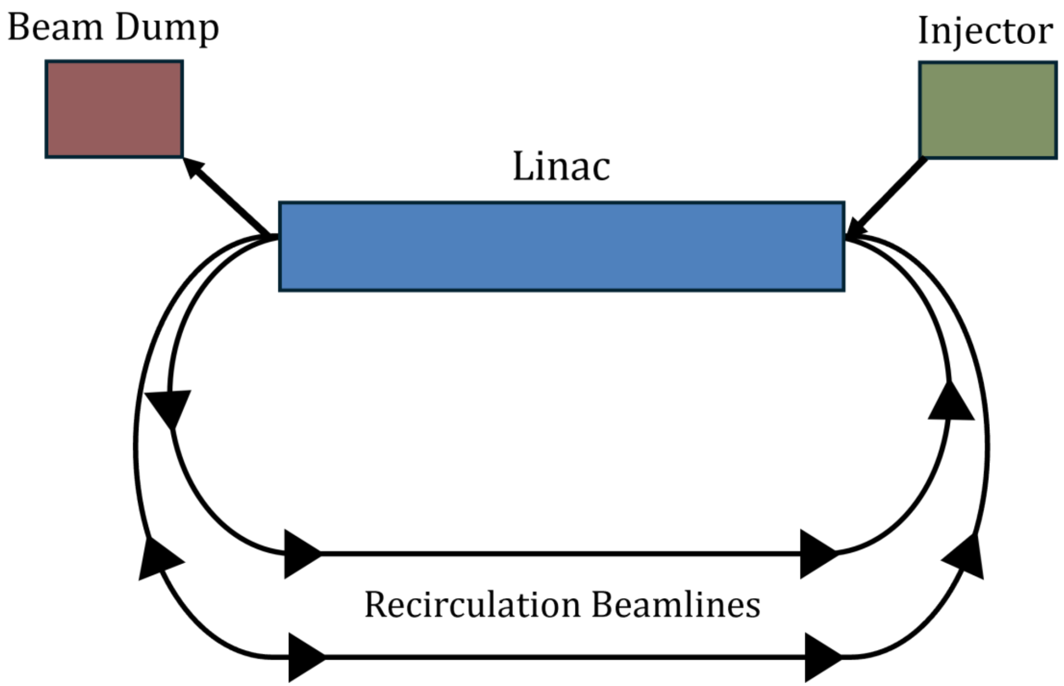
Energy Recovery Linacs & BBU

ERL operation

1. Beam accelerated by SRF cavities

2. After use, beam is recirculated back to cavities with π phase difference

3. Beam is decelerated, returning its energy back to cavities



Beam Break Up Instability

Bunch enters cavity off axis → Deflecting HOM is excited → Bunch experiences transverse kick → Bunch returns to cavity with larger transverse offset → Bunch receives another transverse kick → Bunch decelerated, HOM energy grows → Bunch enters cavity off axis

Positive feedback loop

Limits maximum operable beam current

Compromises complete energy recovery

Deflecting modes must be sufficiently damped

Motivation for Third Harmonic Cavities

Cooler **electron bunch length is 4-5 cm,** occupying 36 degrees of 591 MHz RF voltage

- **Curved electron bunch**
- **Poor cooling efficiency**

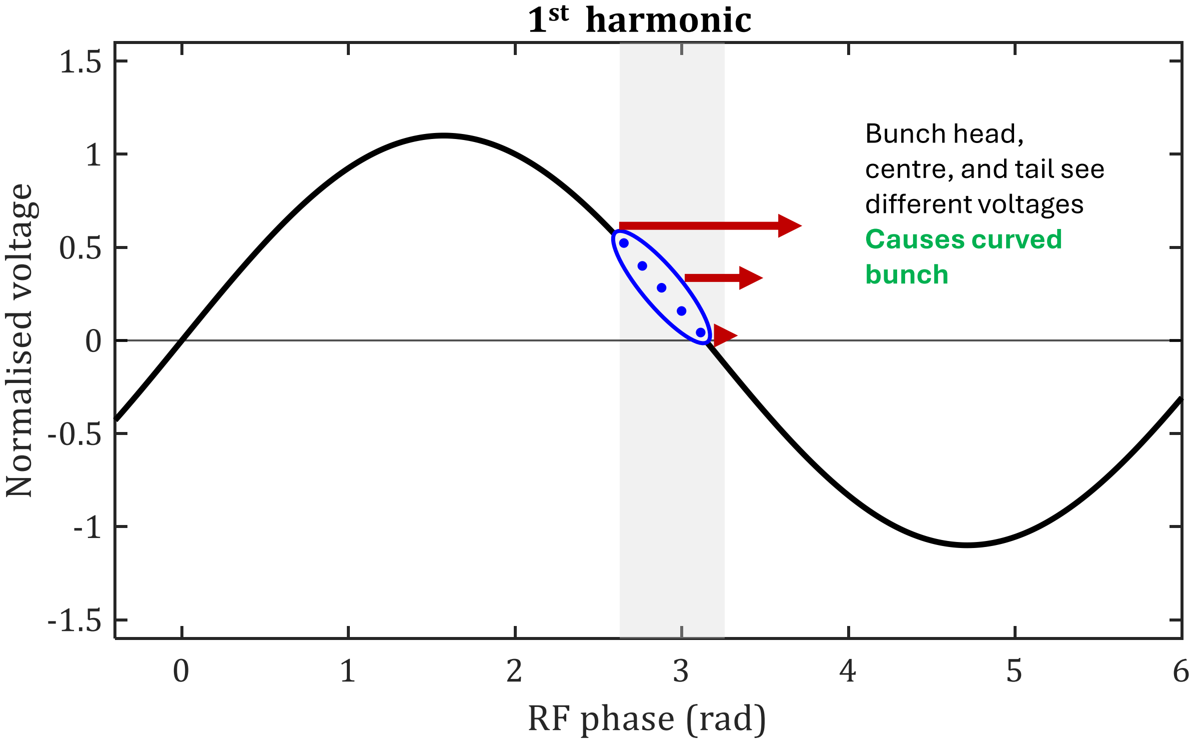
1st harmonic

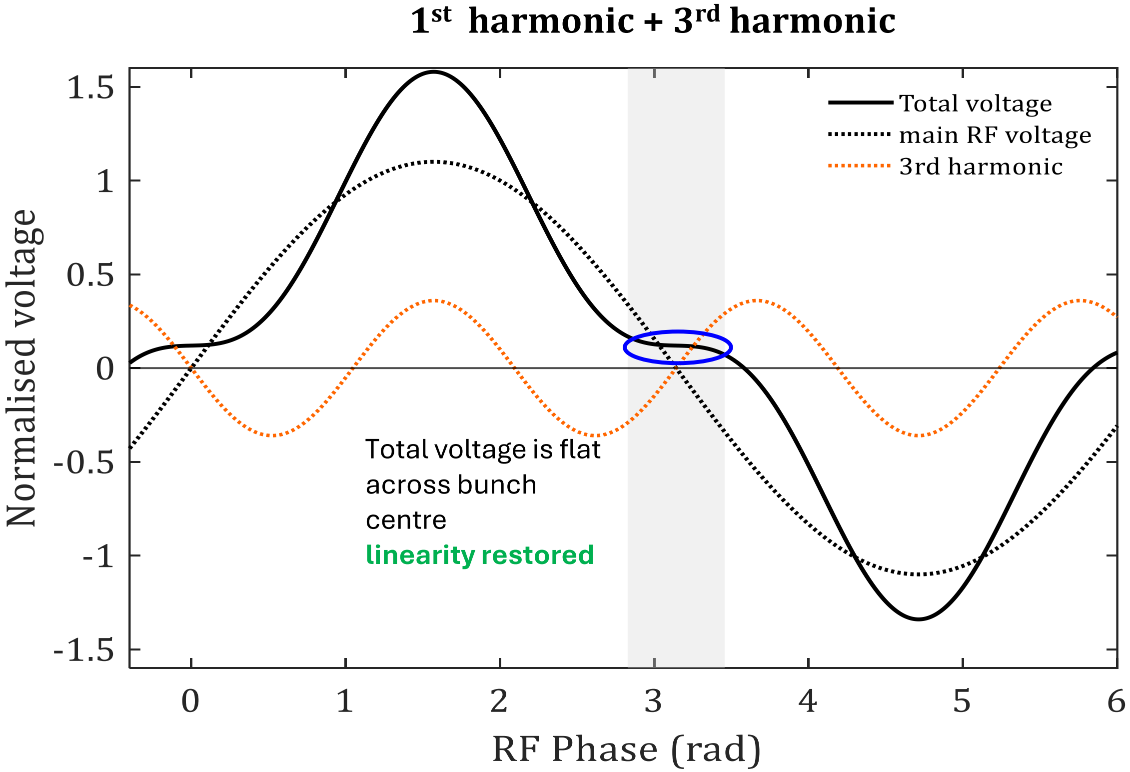
$$V(\phi) = V_{RF}[\sin(\phi + \phi_s)]$$

$$\boxed{\phi = \frac{\omega_{RF}}{c} z + \phi_s}$$

1st + 3rd harmonic

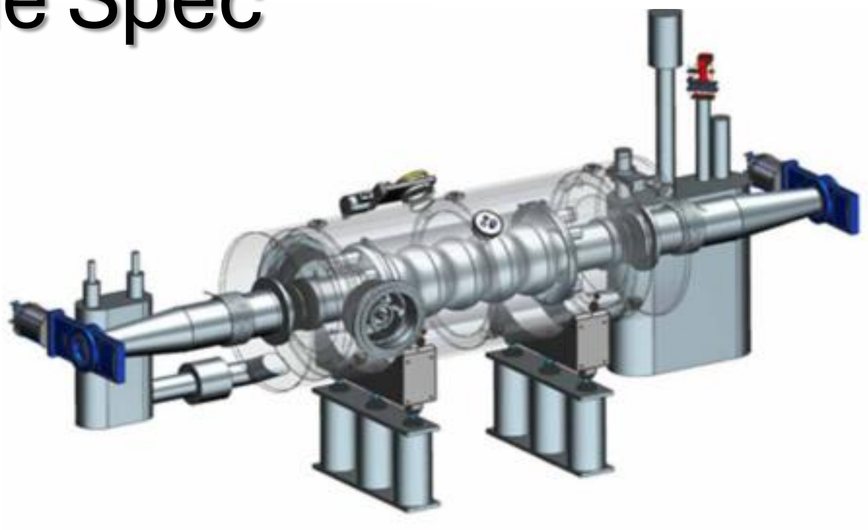
$$V(\phi) = V_{RF}\left[\sin(\phi + \phi_s) + \frac{V_3}{V_{RF}}\sin(n\phi + n\phi_h)\right]$$





[8] Byrd, J.M., Baptiste, K., De Santis, S., Kosta, S., Lo, C.C., Plate, D., Rimmer, R.A. and Franks, M. (2000). Design of a higher harmonic RF system for the Advanced Light Source. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, [online] 439(1), pp.15–25. doi:https://doi.org/10.1016/s0168-9002(99)00892-x.

1773MHz Cavities: The Spec



591MHz SRF 5-cell cavity module for the ERL cooler[10]

Parameter	Value
Frequency [MHz]	1773
$V_{5\text{-cell}}$ [MV]	6.33
E_{pk}/E_{acc}	2.77
B_{pk}/E_{acc} [mT/MV/m]	5.54
E_{acc} [MV/m]	15.4

[9] Rimmer, R. (2021). An Overview of RF Systems for the EIC. *JaCoW*. doi:https://doi.org/10.18429/JACoW-IPAC2021-MOPAB385
[10] Rimmer, R. and Daly, E. (2022). CAVITY AND CRYOMODULE DEVELOPMENTS FOR EIC. JaCoW. doi:https://doi.org/10.18429/JACoW-eeFACT2022-WEXAS0101

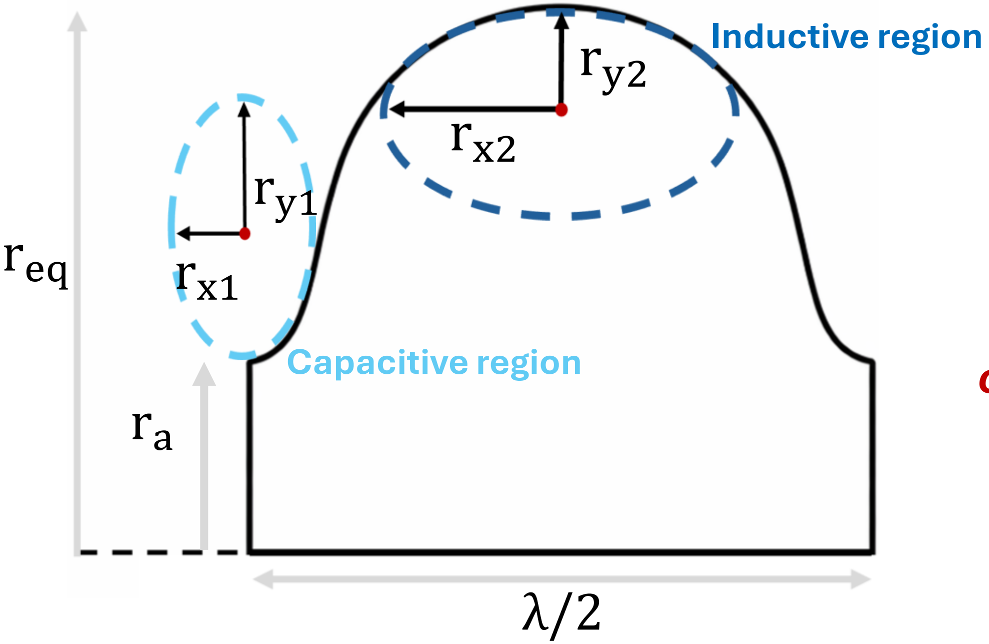
Single Cell Optimisation

CAVITY OPTIMISATION GOALS

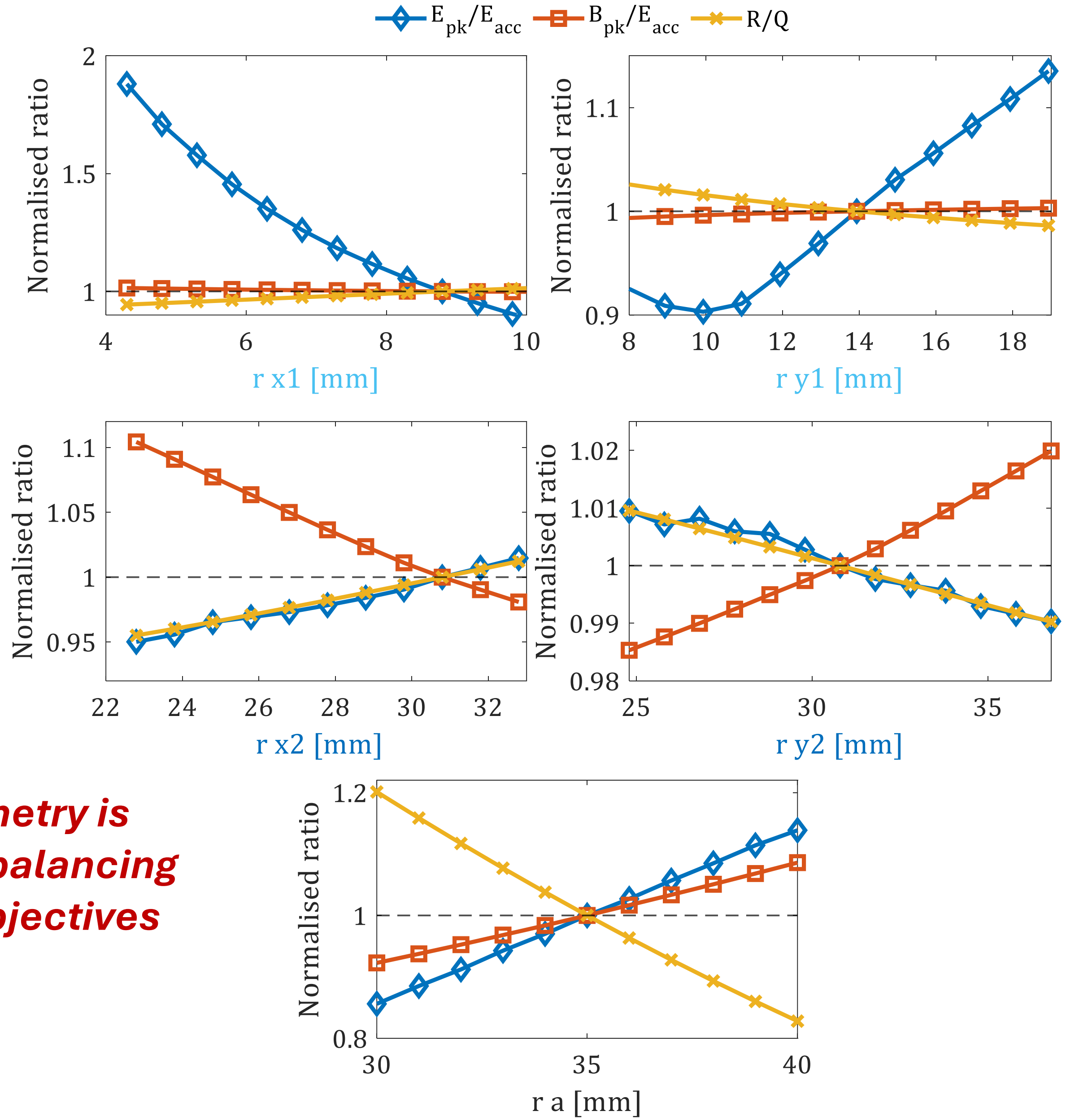
1. **Epk/Eacc** – surface electric field required to produce E_{acc} ↓

2. **Bpk/Eacc** – surface magnetic field required to produce E_{acc} ↓

3. **R/Q** – how **efficiently** RF energy is transferred to beam ↑



Cavity geometry is optimised by balancing competing objectives



Multi-Objective Optimisation

Cavity design requires **simultaneous optimisation of conflicting objectives**

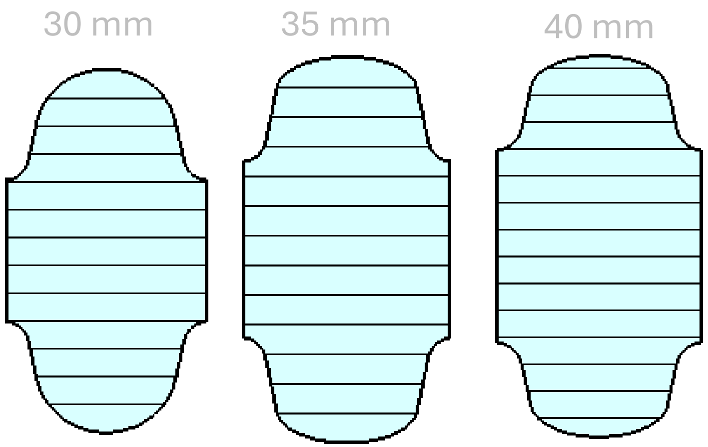
A design is Pareto-optimal if one objective cannot be improved without degrading another.

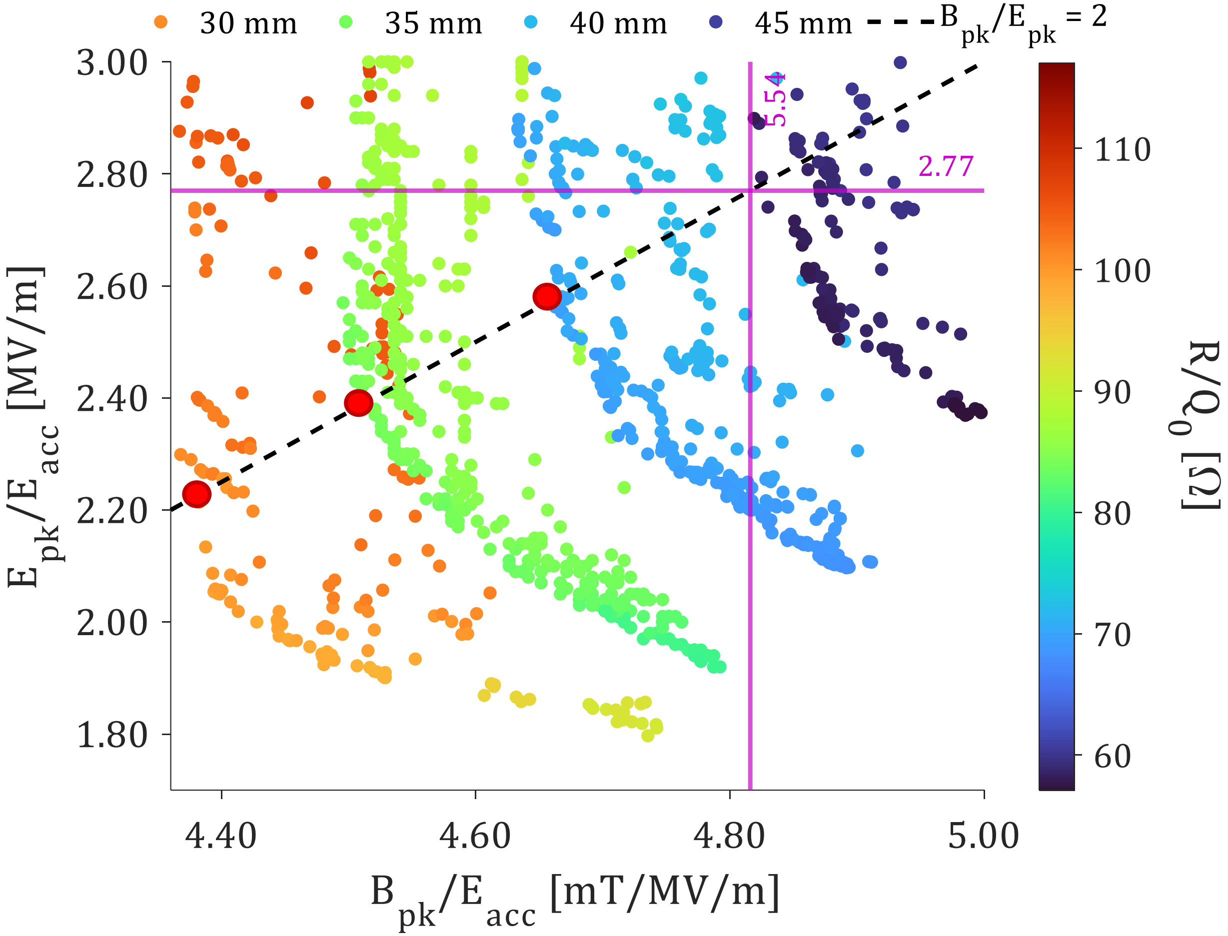
Design objectives:

$$\text{min.} \begin{cases} E_{pk}/E_{acc} \\ B_{pk}/E_{acc} \end{cases}$$
$$\text{max.} \{R/Q$$

- Multi-objective genetic algorithm is used to identify a set of Pareto-optimal geometries satisfying objectives
- Each point is an individual design candidate from the optimisation process, where cell elliptical parameters were varied with increasing aperture radius.

Candidate geometries

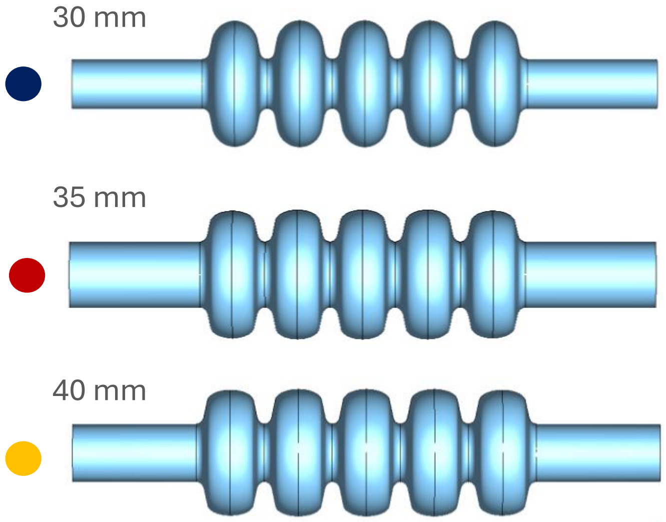




Trapped Mode Analysis

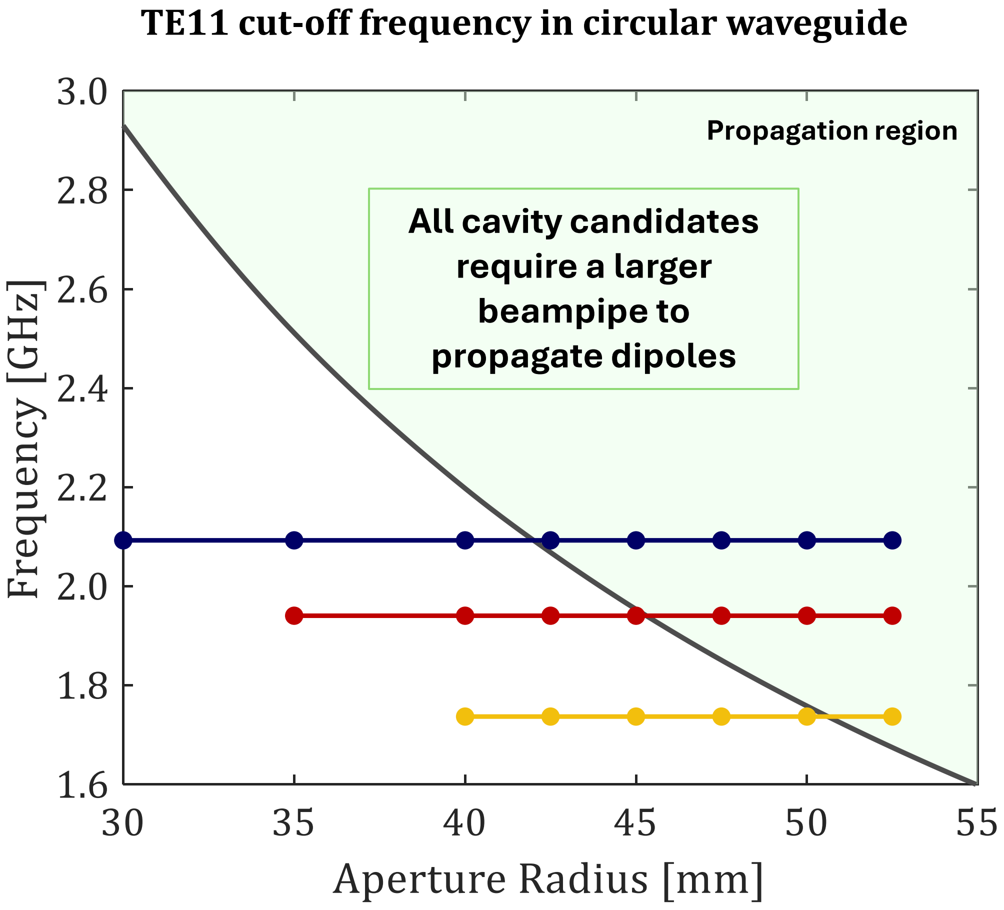
Initial studies of dipole behaviour begins with a **standard 5-cell structure**

cavity aperture radius = beampipe radius



Lowest HOM frequency is trapped within all candidates

Beampipe radius sets TE11 cut-off frequency

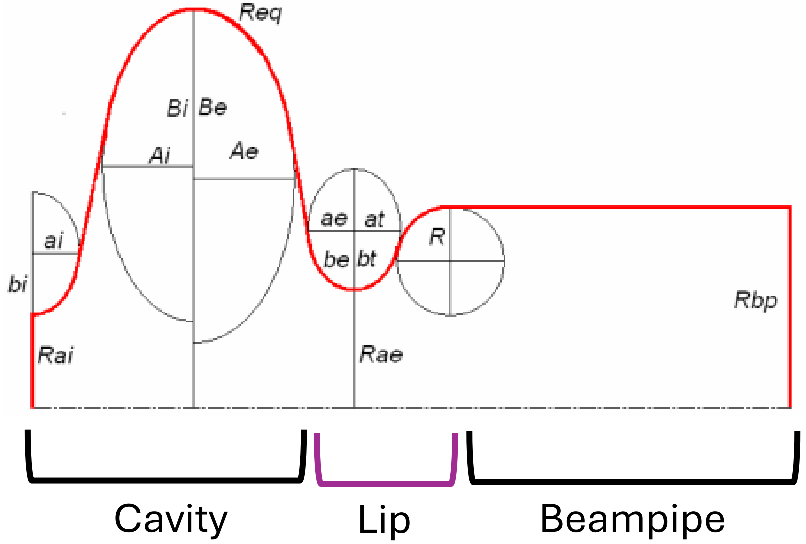


Each 5-cell configuration satisfies

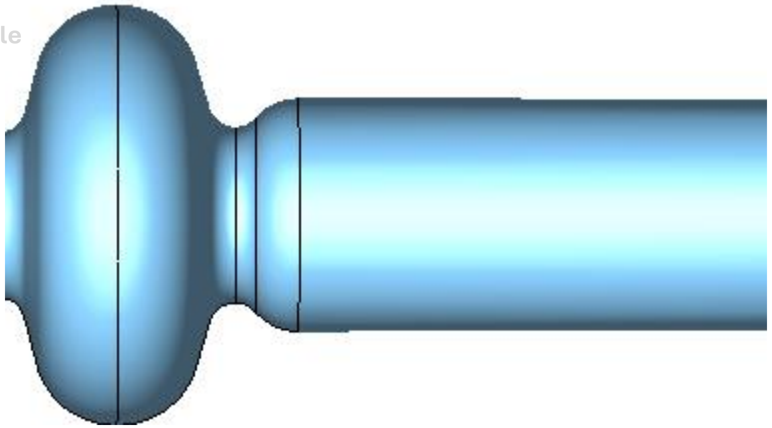
- ✓ Field Flatness ≥98%
- ✓ Transit Time Factor ≥ 0.7
- ✓ Evenly distributed surface fields across all cells (close to 1:1)

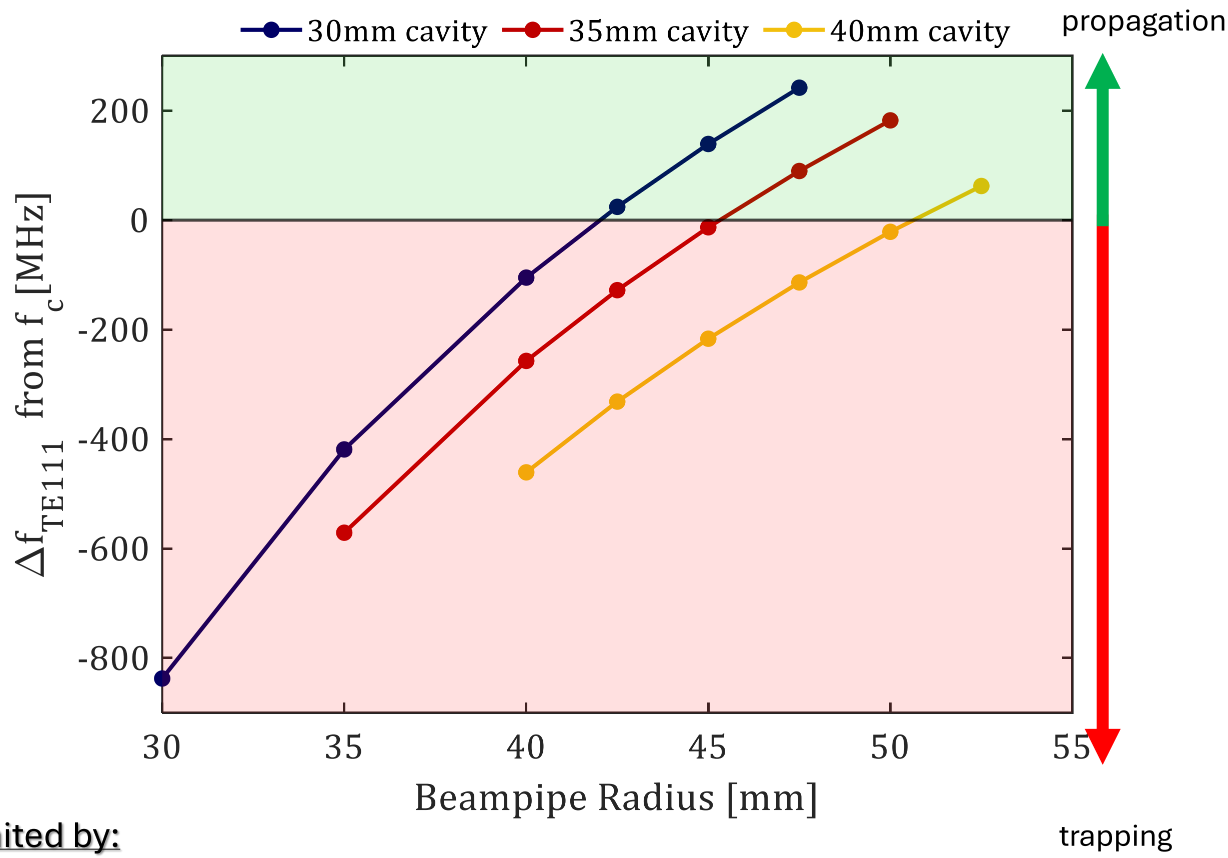
Trapped Mode Analysis

Using a larger beampipe requires an optimised 'lip' transition between cavity and beampipe



example





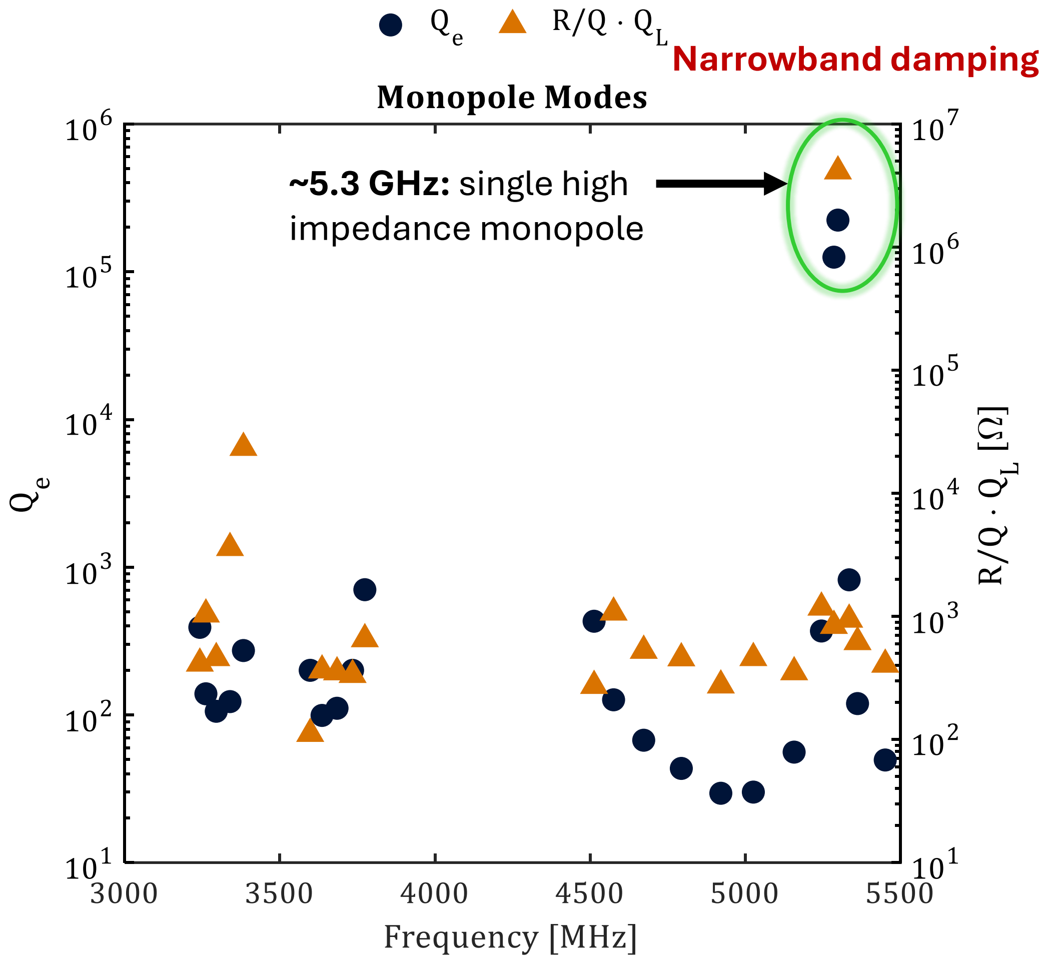
<u>Maximum aperture limited by:</u>

- Evanescent decay of TM010 mode into beampipe
- TM010 cut-off
- Cavity sandwiched between 591 MHz cavities –beampipe will have to taper down

Baseline HOM Spectrum

BLA configuration based on beampipe optimised for TM010 trapping ($Q_e > 10^{10}$)

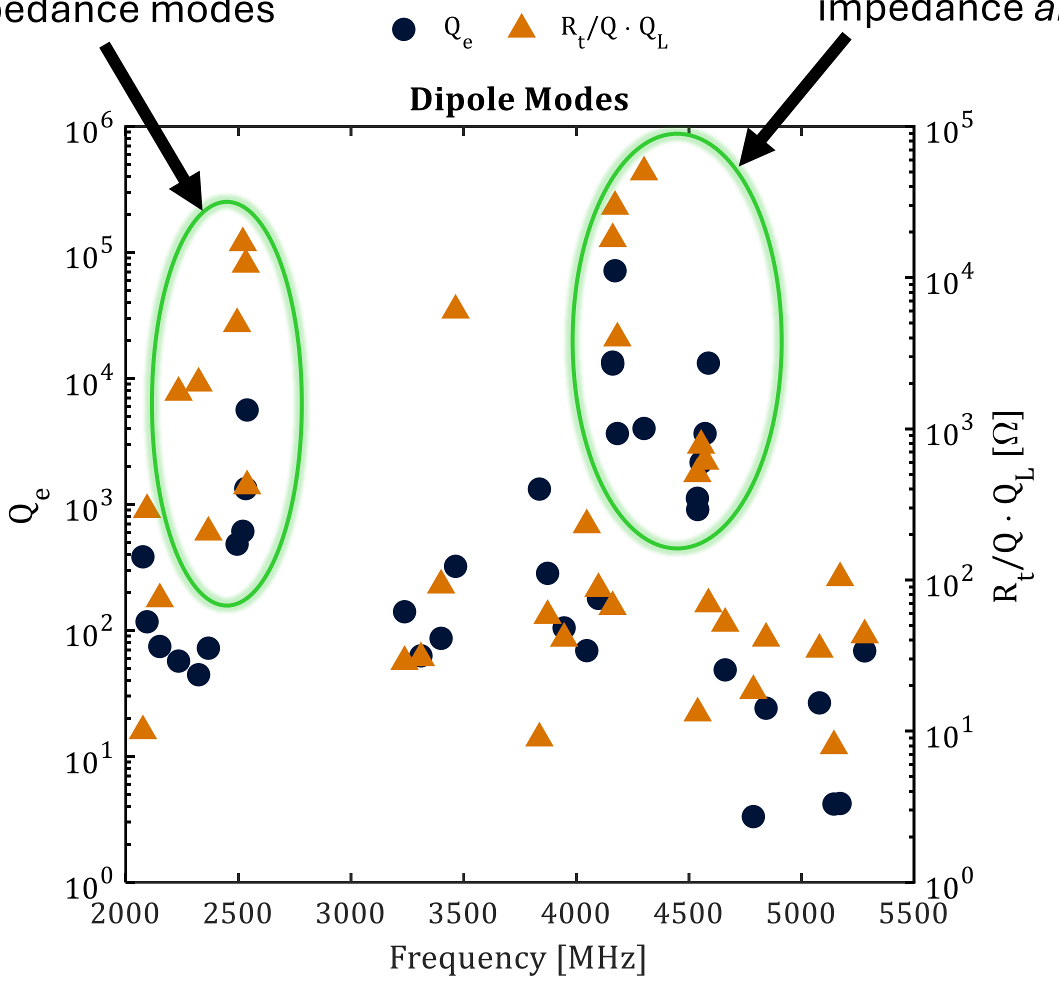
Narrowband damping



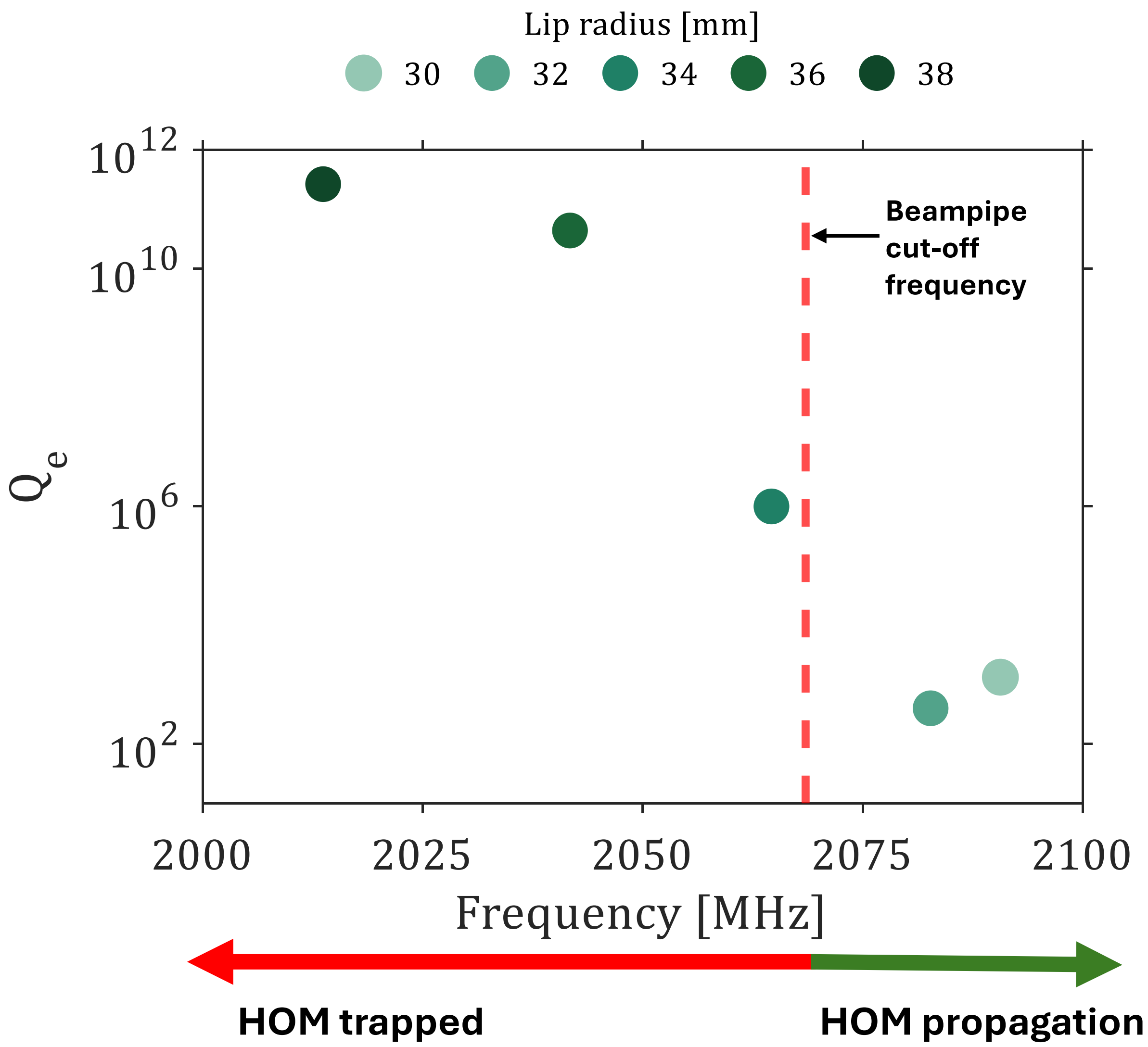
2 GHz band: high impedance modes

Requires broadband damping

4.1-4.4 GHz band: high impedance *and* Q_e



Lowest Dipole Frequency Propagation



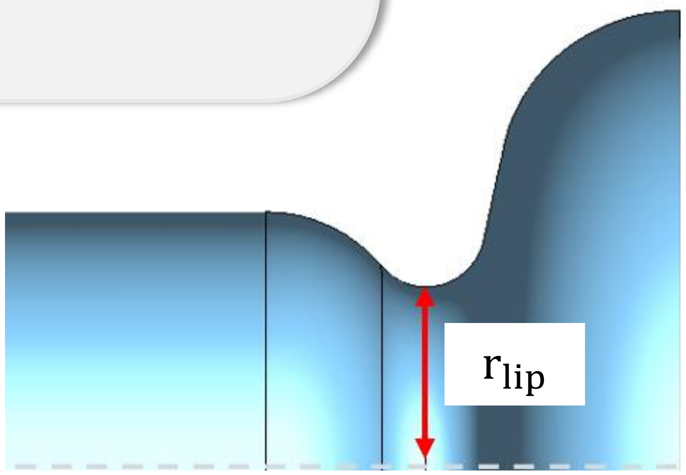
Key Takeaway

Lip radius determines whether the first dipole is trapped or propagates

- ➢ Using a <u>smaller lip increases dipole frequency to push above cut-off</u>

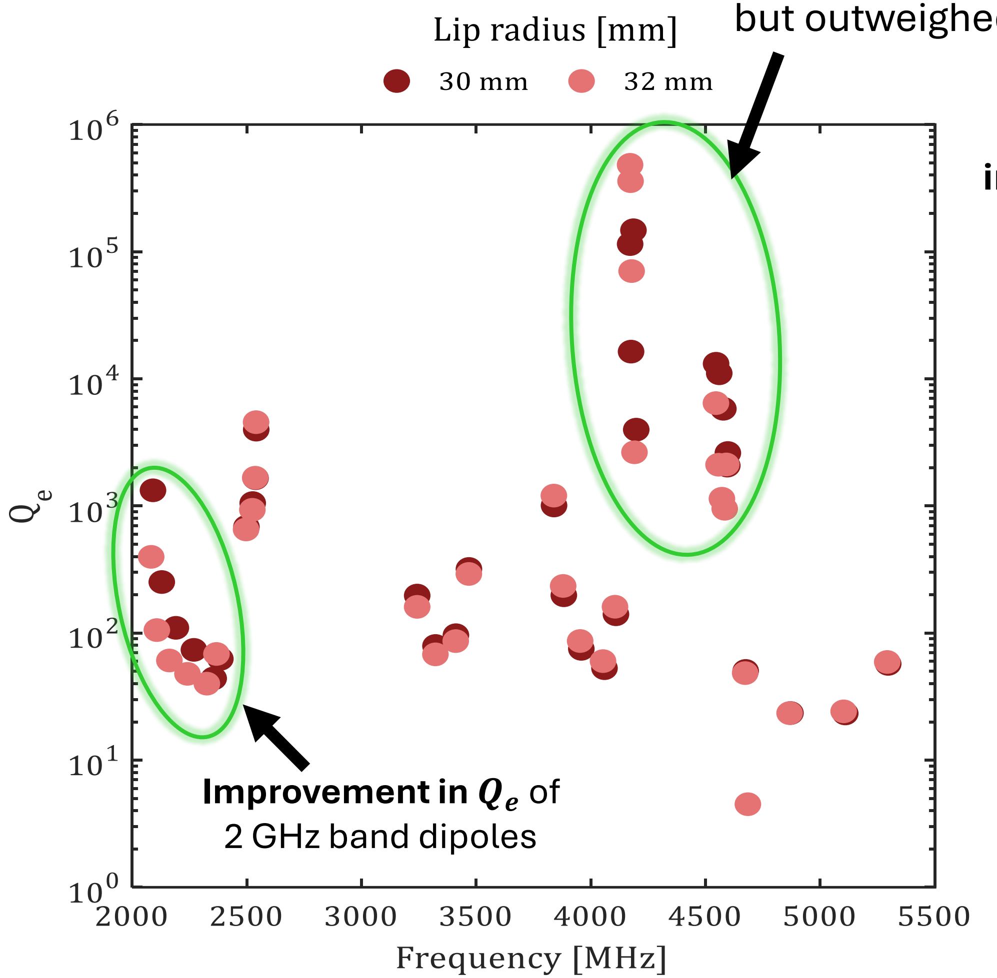
- 30 mm and 32 mm lip shows promise for damped Q_e however,
- **Q_e and impedance dipole response to lip radius 2.0GHz – 5.4 GHz** must be evaluated

Lip radius defined from beamline axis



Mode Trapping in Bottleneck Geometry

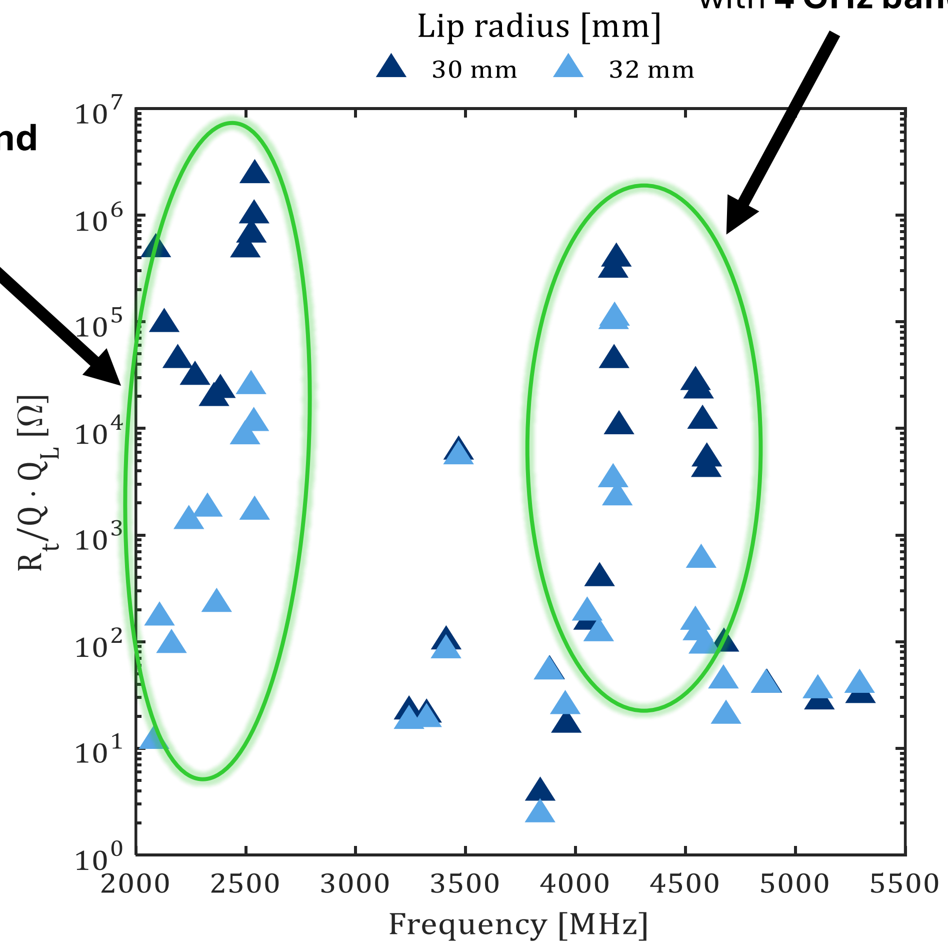
Balanced Q_e behaviour, but outweighed by a...



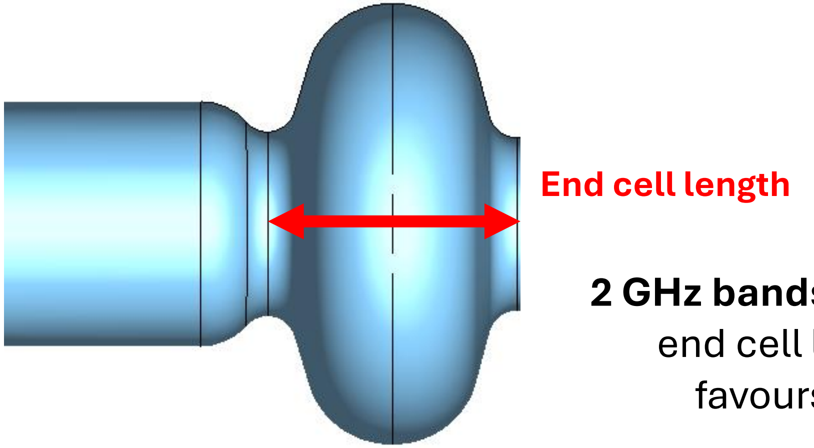
Improvement in Q_e of 2 GHz band dipoles

A huge impedance improvement GHz band with larger lip

Same improvement seen with **4 GHz band**

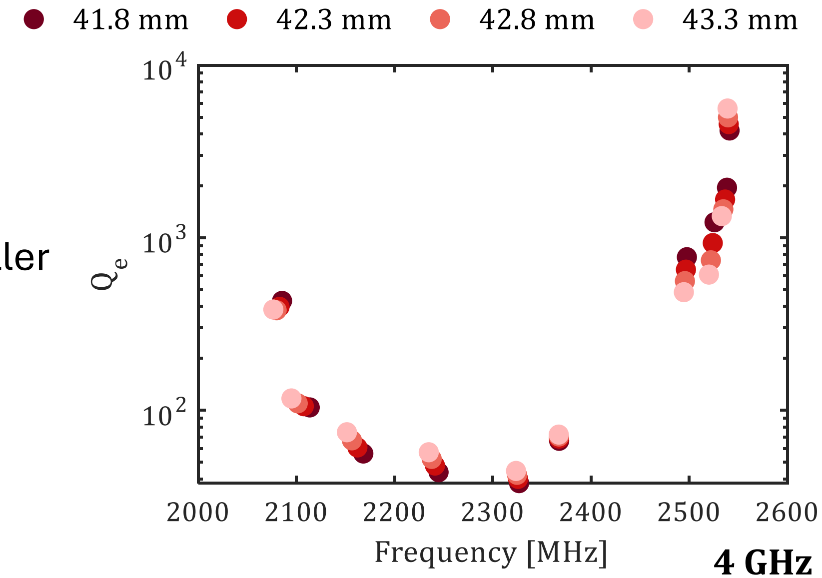


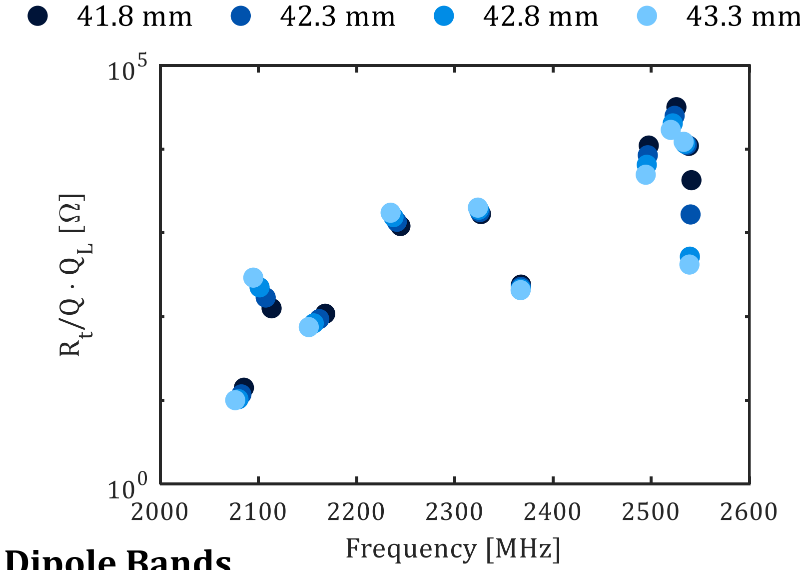
End Cell Optimisation for Dipole Damping



2 GHz bands: smaller end cell length favours Q_e

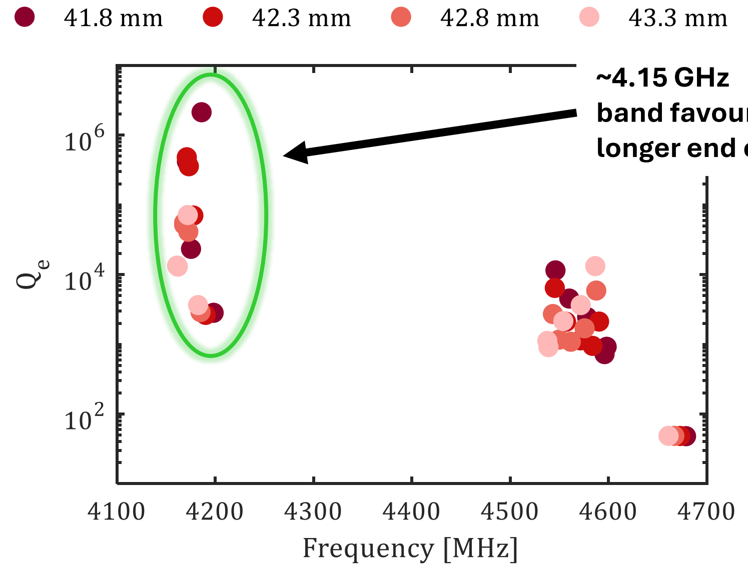
First Dipole Passband



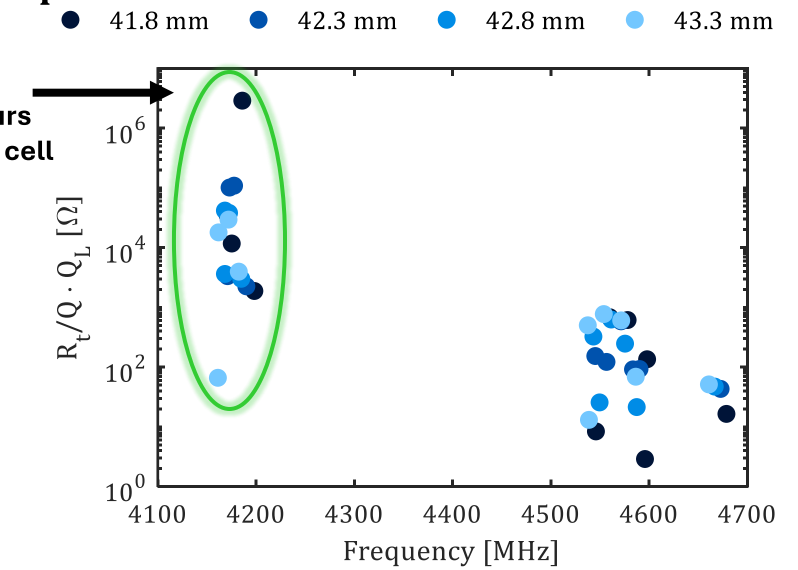


4 GHz Dipole Bands

4 GHz bands: longer end cell length **improves both Q_e and impedance**



~4.15 GHz band favours longer end cell



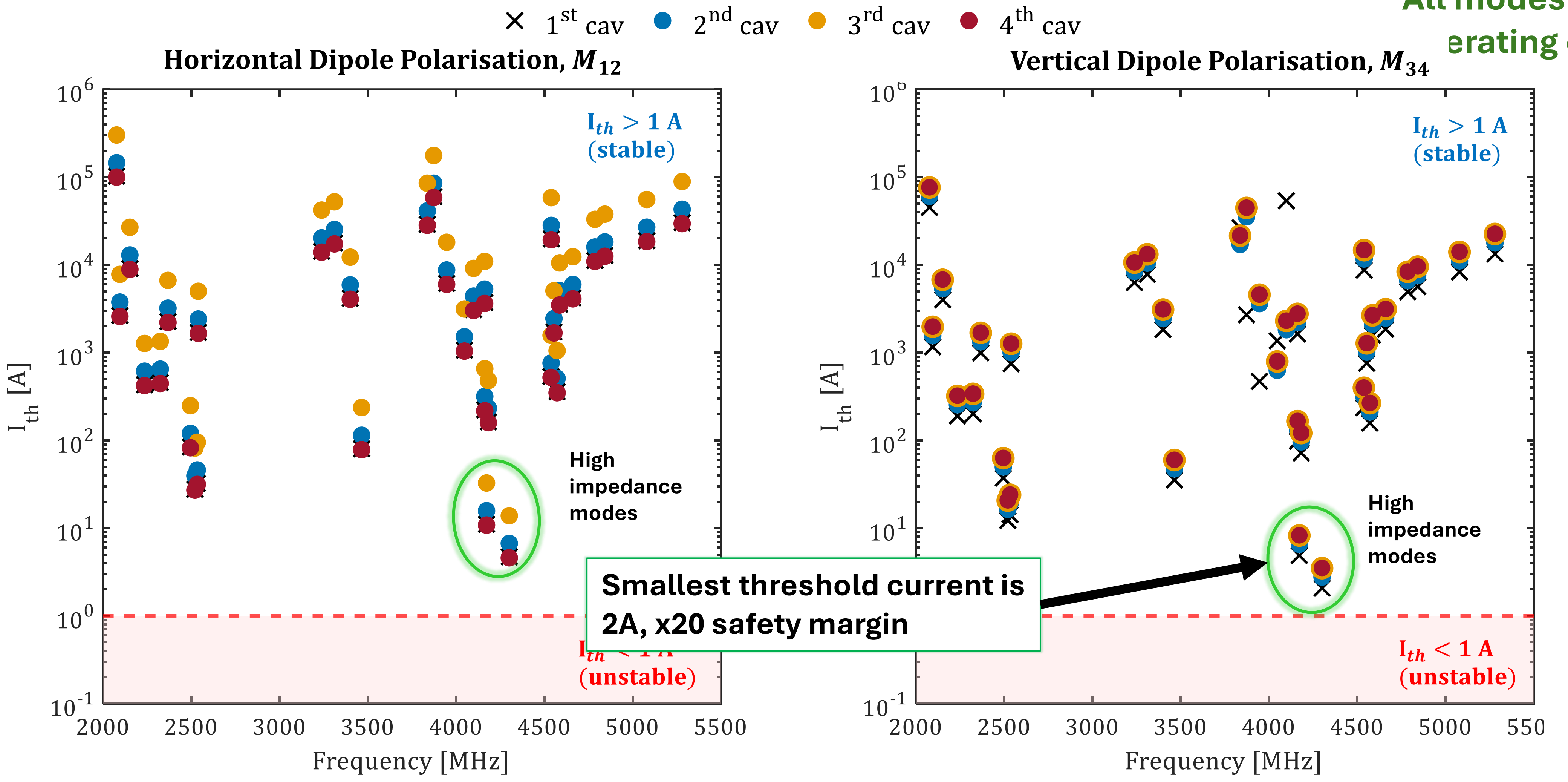
We require broadband damping of Q_e and impedance, with stronger impedance weighting for BBU

longer end cell preferred

Beam Break-Up Instability

Minimum beam current to drive regenerative beam break up for each cavity[11] *(I_b= 100 mA)*

All modes stable at erating current



Threshold currents calculated using cavity R_t/Q, Q_L, HOM frequency, and lattice recirculation optics (M_{12}, M_{34})

[11] *S. Sentiyaz (2025) BBU Parameters for EIC-ERL, Private communication,*

Waveguide Consideration

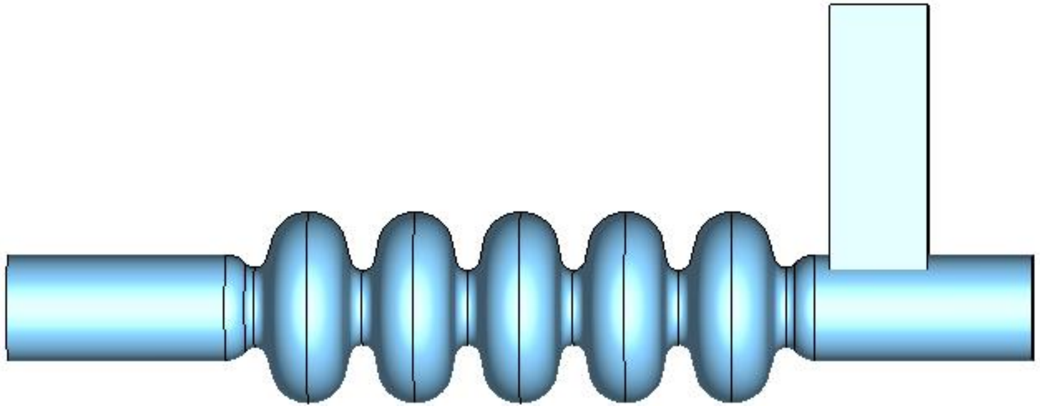
Beampipe absorber shows **good promise for damping dipole modes**

however,

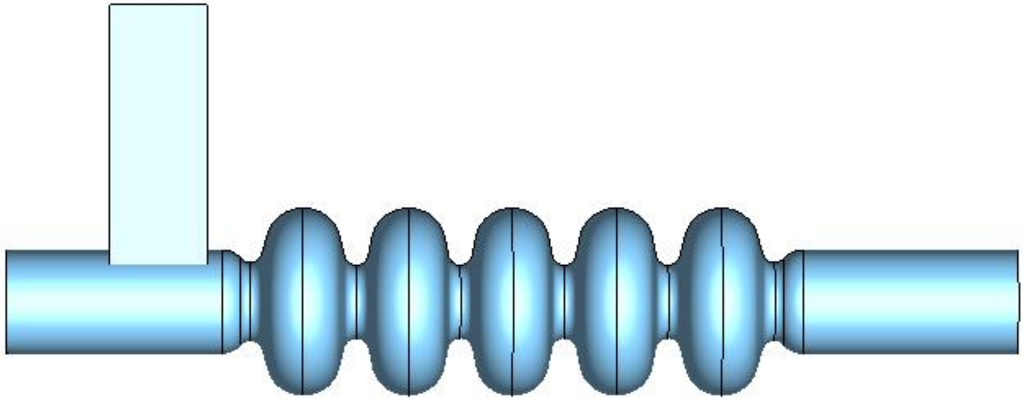
In a recirculatory machine, **available beamline real estate is limited** → Beamline absorber requires warm section → **Requires more space**

Can adding a waveguide provide equivalent or improved HOM damping than a BLA?

Possible configuration



BLA – CAV – WG



WG – CAV – WG

- **Break rotational symmetry** → introduce hybrid modes → **complex WG system**
- **Local field enhancement** around beampipe-WG interface
- **Multipacting**

Summary

- Developed 5-cell 3rd harmonic cavity for EIC cooler
- Optimised end-cell and cavity-beampipe geometry for built-in HOM damping
- All BBU threshold currents at least 1 order of magnitude above I_{th}

Future Work

- Evaluate if a waveguide provides improved damping for optimisation of space utility
- Perform thermal simulations of BLA with ferrite HOM loads
- Change of direction – coaxial coupler for EIC crab cavity

Thank you for listening

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S. Toole s.j.toole@lancaster.ac.uk

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Back-up Slides

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S. Toole s.j.toole@lancaster.ac.uk

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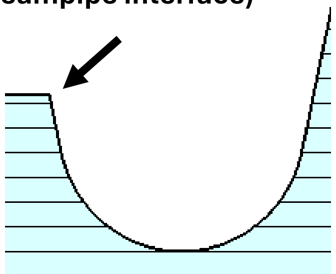
Multipacting in the Beampipe

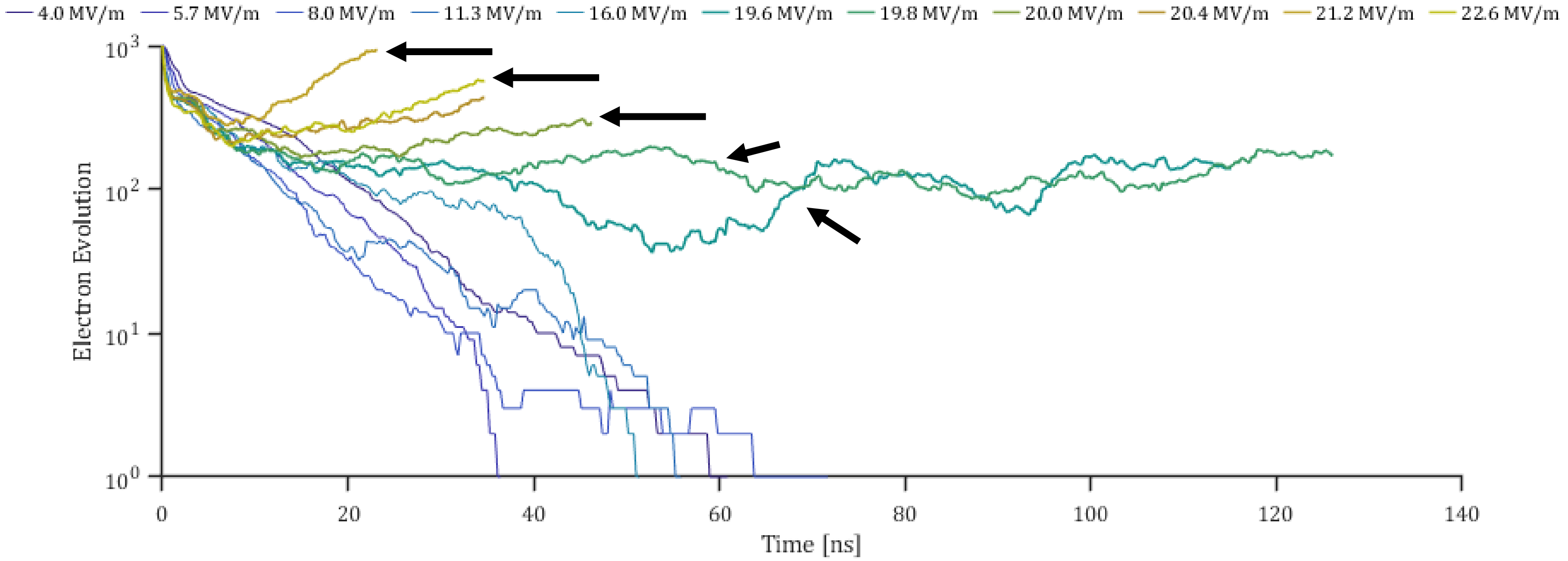
Table X: SEY parameters of high purity Nb following 300˚ C bakeout.

Parameter	Value
SEY_{max}	1.5
SEY_0	0.8
Impact energy at first crossover [eV]	75
Maximum impact energy [eV]	300
Initial number of electrons	1000

Unoptimised lip (cavity-beampipe interface)



Multipacting field levels



Operating $E_{pk} = 35MV/m$

*Figure 10: Electron evolution starting from a homogenous distribution of 1000 electrons as a function of rising E_p surface fields on **5-cell cavity with no lip optimisation**. Nb (2K) SEY curve: 300˚ C bakeout.*

Diagnosing MP in the Beampipe

It is energetically favourable for electrons to exist in a local electric minima due to the associated lower potential (Φ), which attracts electrons

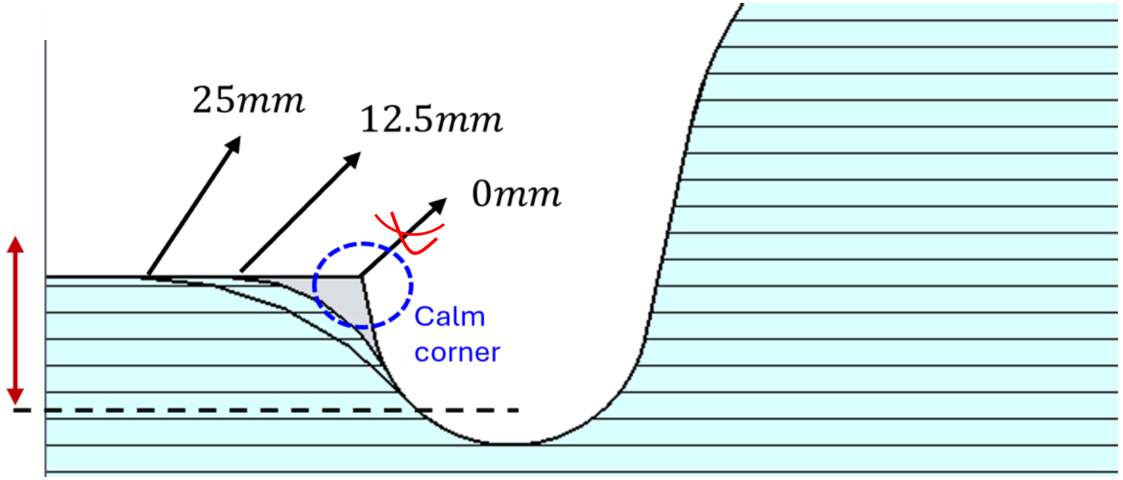
$$\Phi_{well} = \left(\frac{\eta}{2\omega_0}\right)^2 \cdot |\mathbf{E}_{\mathbf{minima}}|^2$$

$$\boxed{\eta = \frac{e_e}{m_e} r_0(t)}$$

Miller force

$$\ddot{r}_0(t) = -\nabla\Phi$$

‘Calm corners’ are eliminated by encouraging electron drift in the direction of the decaying field.



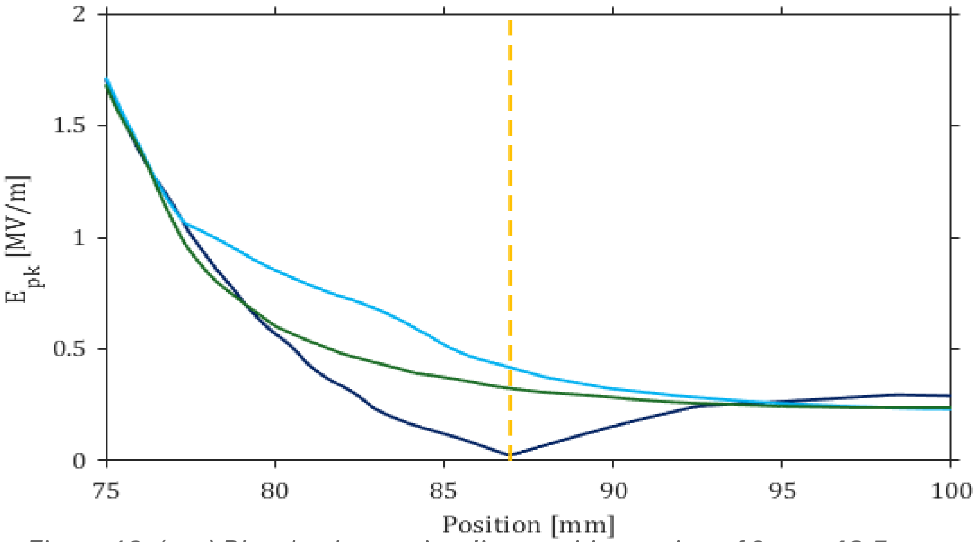


Figure 12: (top) Blend at beampipe-lip transition region of ***0mm, 12.5mm, and 25mm*** *(bottom) Elimination of electric field minima at MP location.*

[1]*Sergey Belomestnykh, and Valery Shemelin. 2008. “Multipacting-Free Transitions between Cavities and Beam-Pipes.” Nuclear Instruments and Methods in Physics Research Section a Accelerators Spectrometers Detectors and Associated Equipment 595 (2): 293–98. https://doi.org/10.1016/j.nima.2008.05.041*

BBU ERL Parameters

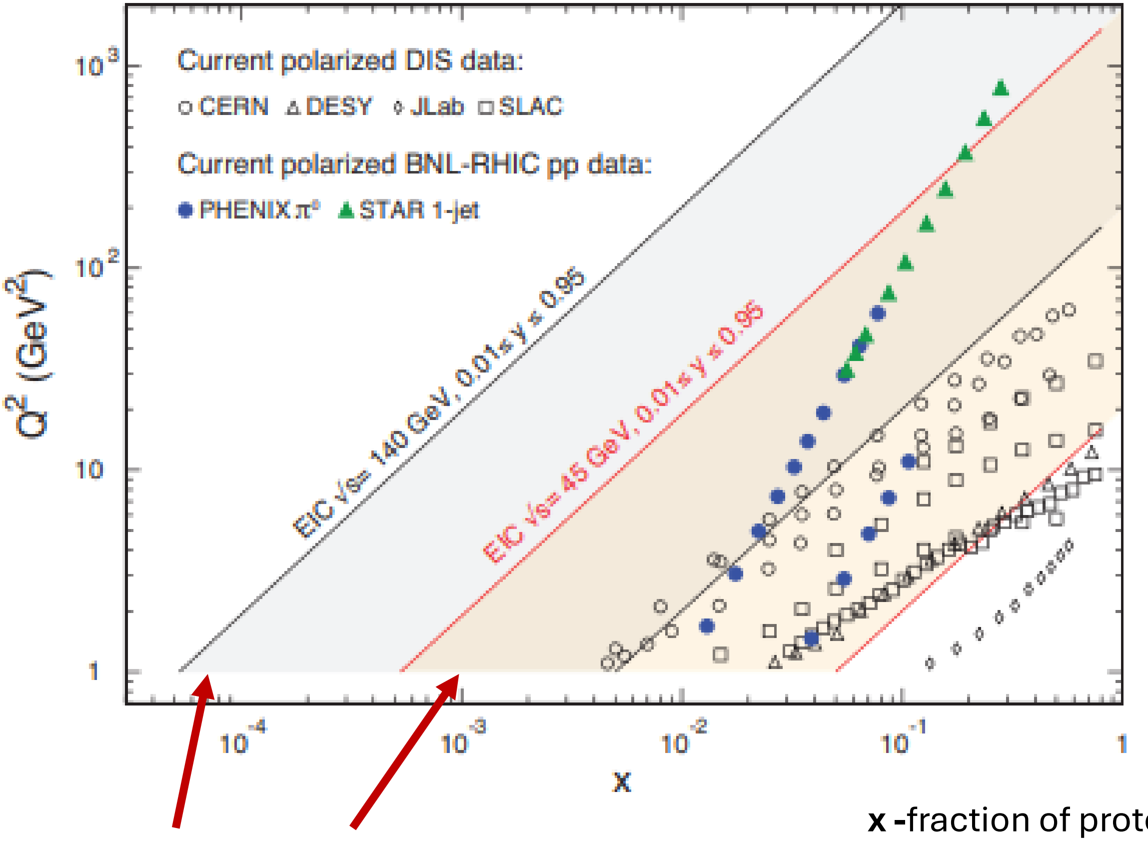
$$\boxed{I_{th} = \frac{-2E}{\left(\frac{\omega}{c}\right)\left(\frac{R_\perp}{Q_0}\right) Q_l M_{12} \sin(\omega T_r)}}$$

Cavity	Energy [MeV]	M_{12}	Energy [MeV]	M_{34}
1st	25.052	-2.40998727	25.025	5.47015190
2nd	26.462	-1.79034846	26.462	4.32234179
3rd	27.899	0.9118264	27.889	3.61400521
4th	29.336	2.89340006	29.336	3.77933567

Revolution time = 2.526298722343194e-06 s

EIC DIS data

Q^2- negative squared four momentum transfer carried by the exchanged virtual photon during scattering event



Achieving this region requires **maximising total available energy at collision point**

x **-**fraction of proton momentum carried by a struck quark or gluon (Bjorken scaling variable)