Asymmetric Dual Axis Cavity for ERL: recent developments and possible applications

I.V. Konoplev[1], A. Seryi[1], A. Lancaster[1], K. Metodiev[1], G. Burt[2] and R. Ainsworth[3]

[1] *John Adams Institute, Department of Physics, University of Oxford, Oxford, UK*
[2] *Cockcroft Institute, Lancaster University, Lancaster, UK*
[3] *Fermilab, Batavia, Illinois, USA*

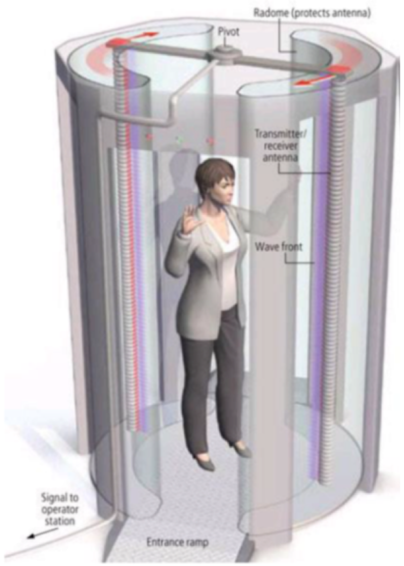
Outline

- Introduction: applications outside research community
- Asymmetric Energy Recovery LINAC
  - Basic concept:
    - Eigenmodes and Eigenmodes field structures
    - Numerical studies
  - Recent experimental studies:
    - Experimental techniques used
    - Results observed and comparison with theoretical predictions
- Conclusion

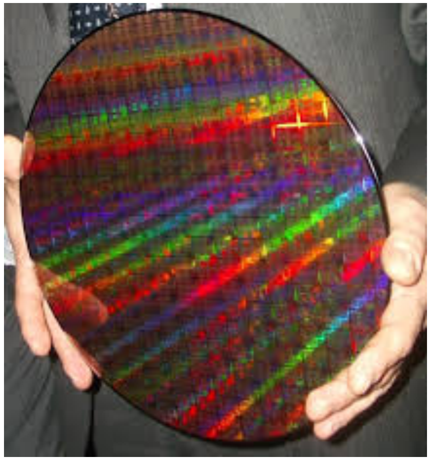
Motivation

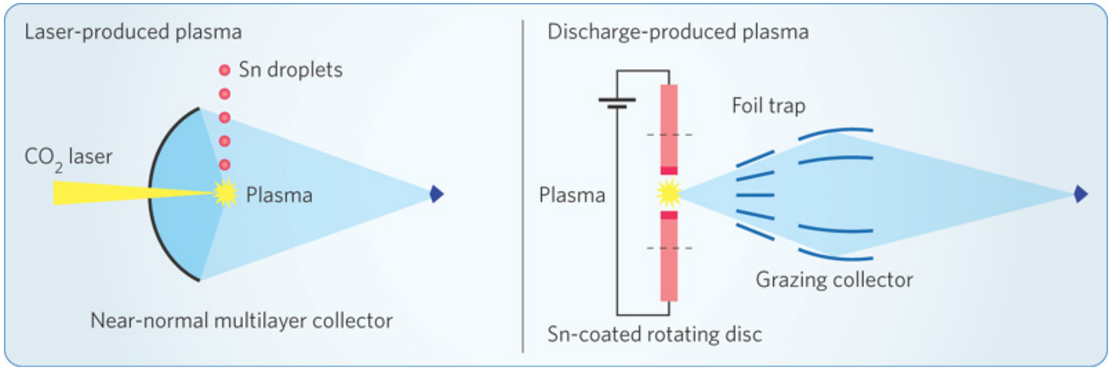
Application in Ultra-High Intensity source of coherent radiation

THz Application: security



X-ray Application: lithography





OPPORTUNITY – THz Applications

THz Application: Produce radiation at high power (up to 1MW) from 0.1 THz to 10 THz

No company can currently produce high power THz in this range, therefore a unique product.

Markets (outside research laboratories):

- Cargo Screening: The World Market for Explosives, Weapons, and Contraband Detection Equipment (EWC) is estimated to be some $2.1 billion annually[1]
- Replacing X-ray scanners: The global security screening market is expected to reach $9.10 Billion by 2020[2]
- Non-contact imaging of coatings and composites, material quality control, drug formulation

[1]The Market for Explosives, Weapons and Contraband (EWC) Detection Equipment – HIS Technology, 2014 Edition
[2]Security Screening Market - Analysis and Forecast 2013-2020 – MarketsandMarkets, 2014 Edition

OPPORTUNITY – EUV Applications

X-ray Application: Generating electron beams of typical energy of 10-30 MeV/peak current above 1A to generate high flux (10^{18} -10^{20} photon per second) of soft X-ray radiation to 1nm to 10nm wavelengths range

No company can currently produce this high flux at around 10nm. In addition, the system is more energy efficient and has the flexibility of going to an even lower nm range.

Markets (outside research laboratories):

- Non-destructive sources and material/medical diagnostics research market
- Lithography for the £332 billion Semiconductor Industry: $7 billion market in 2014[3]

[3]Investor Day, ASML Small Talk London - 2015

Examples of Industrial Companies involved

- Cargo scanning: BAE Systems, Rapiscan, Smiths Detection, Varian

Currently these companies can't produce high enough power THz in various ranges

- Semiconductor Industry - Lithography: ASML, Ultratech, Canon

Currently these companies can't produce around 10nm X-rays at higher power and don't have the flexibility of lower nm ranges

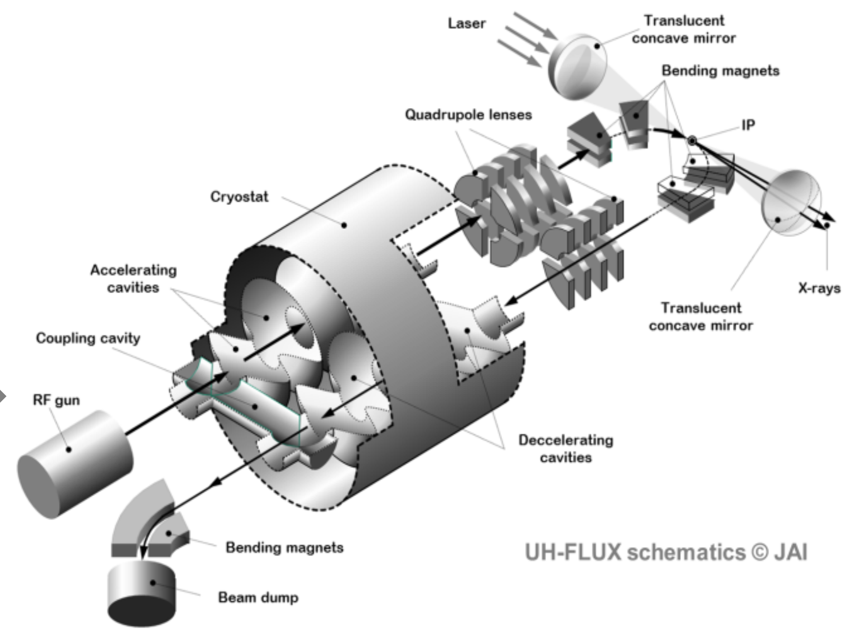
UH- FLUX

Ultra high flux compact source of THz and X-ray

Very large current designs

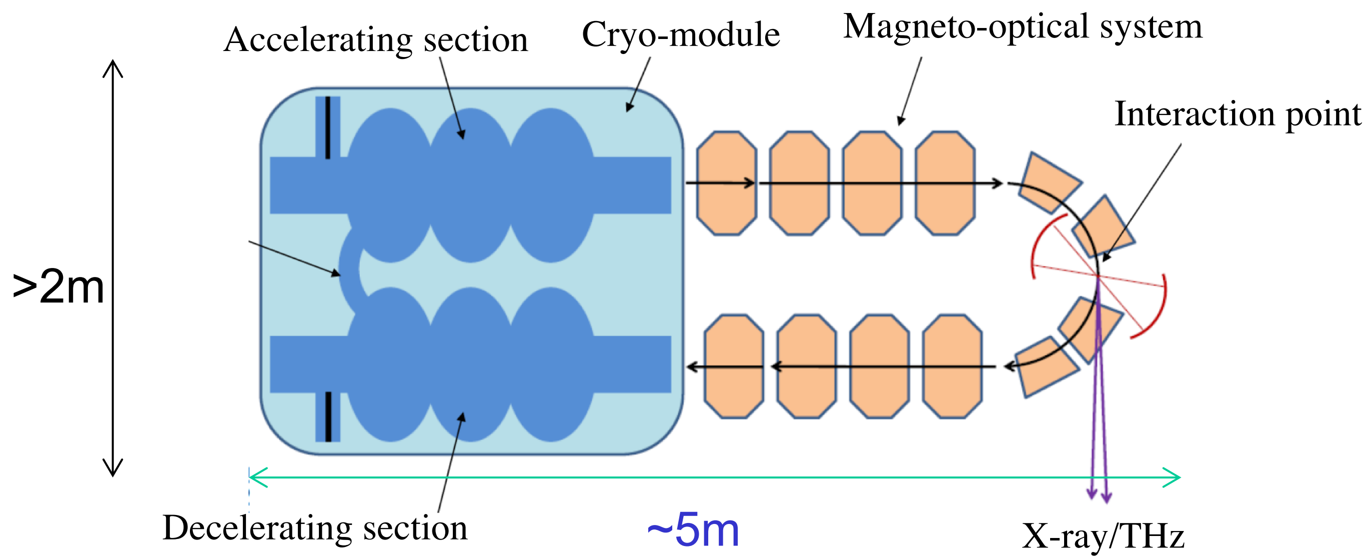
100 metre +

Oxford Design: AERL



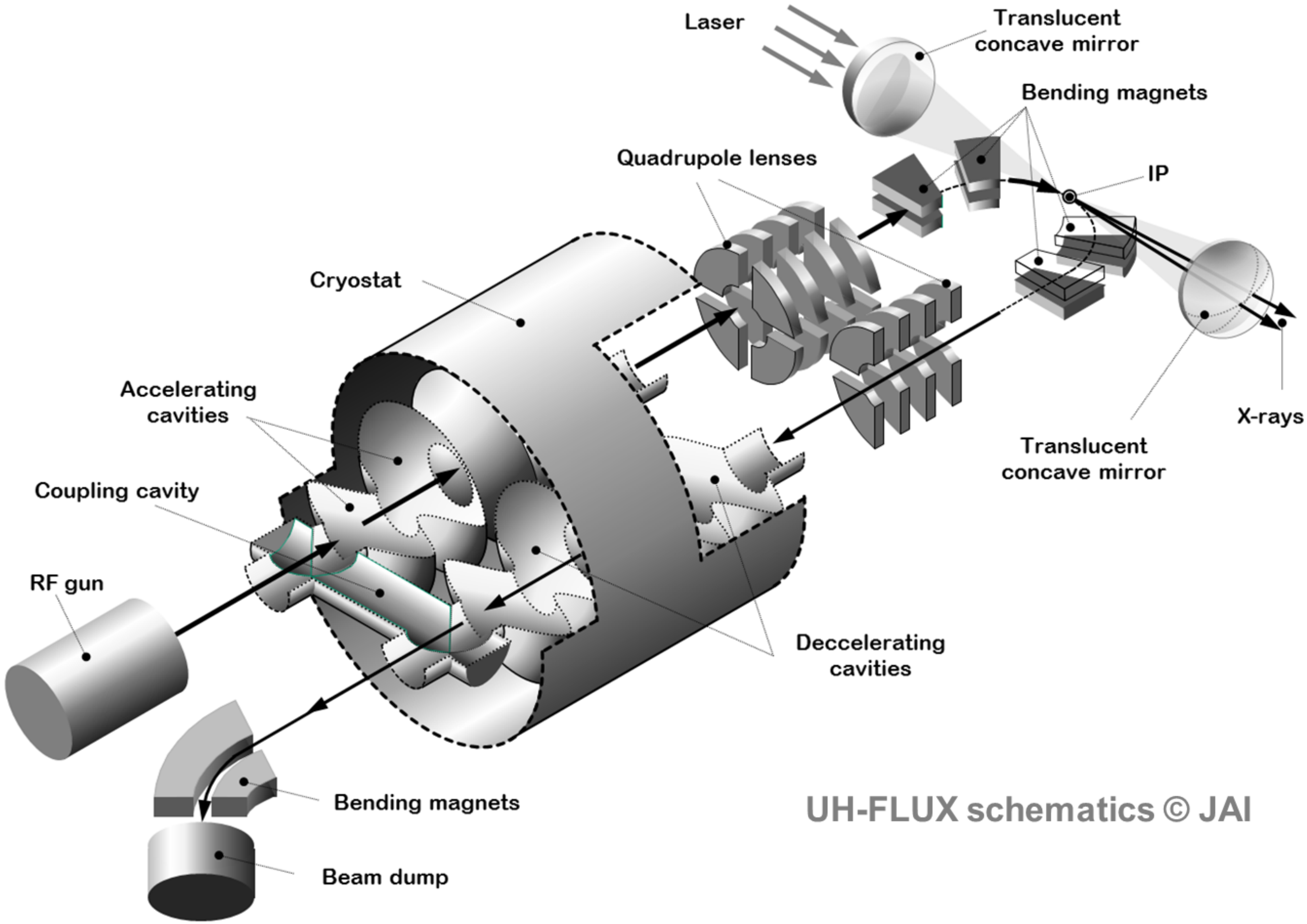
5 metre

UH-FLUX: AERL



- **Collaboration of UK centers JAI, CI and STFC**
  - **To surpass any existing designs**
- **[1] International (PCT) Patent Application No. PCT/GB2012/052632 (WO2013/061051) filed on the 26th October 2012**
- **[2] Oxford University Isis Project No. 11330 – “Asymmetric superconducting RF structure” (UK Priority patent application 1420936.5 titled ‘Asymmetric superconducting RF structure’ filed on the 25th November 2014**

UH-FLUX: AERL

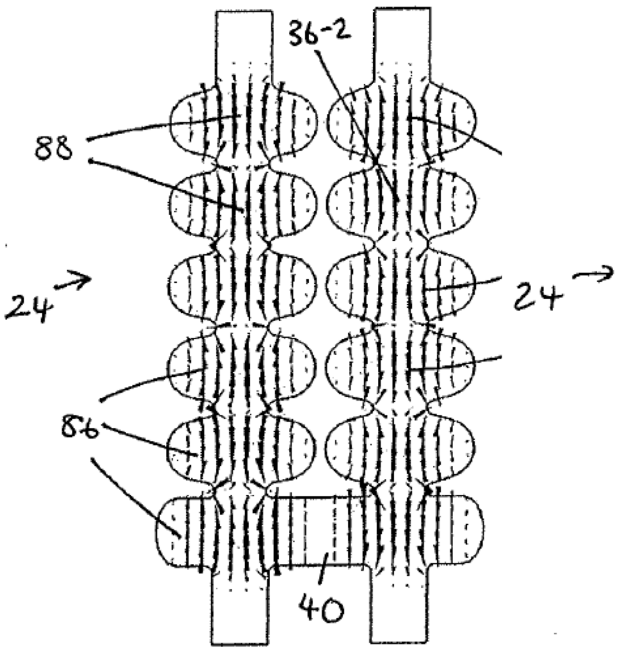


UH-FLUX schematics © JAI

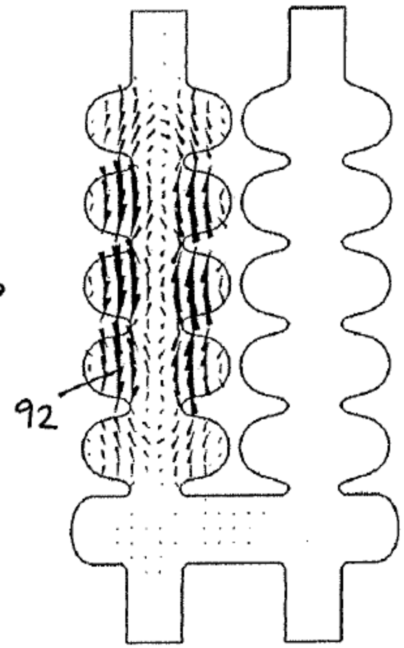
UH-FLUX: AERL

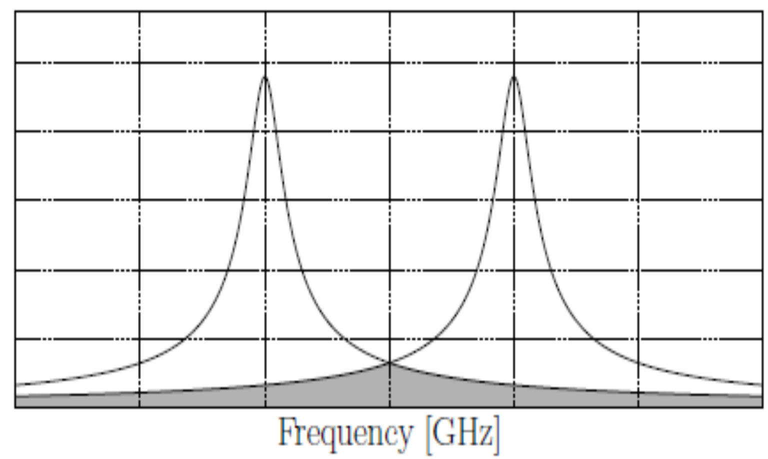
Decoupling all modes except the accelerating mode to maximize the beam current

Acc. mode



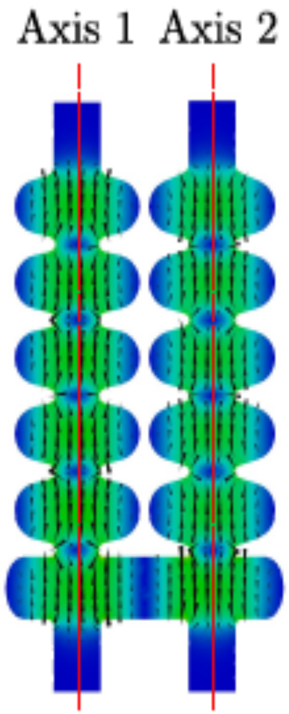
One of transverse modes



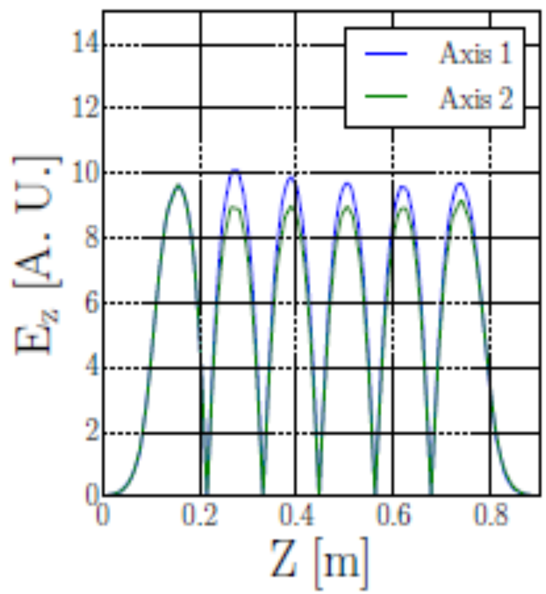


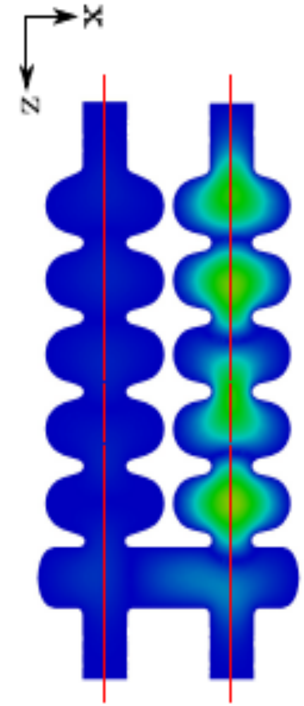
UH-FLUX: AERL 11 Cell cavity

Electric field contour plot of operating eigenmode at 1.3GHz

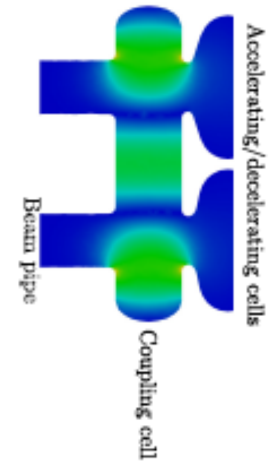


Operating field flatness @1.3GHz





Electric field contour plot of resonant coupler eigenmode at 1.48GHz

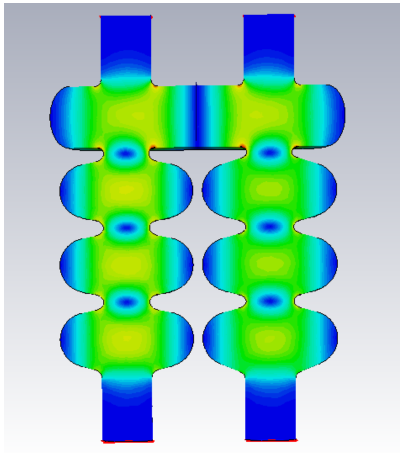


Electric field contour plot of dipole eigenmode at 1.73GHz

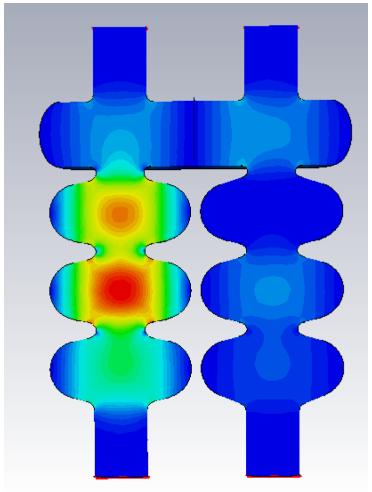
Results observed using ACE3P

UH-FLUX: AERL 7 Cell cavity

Operating mode



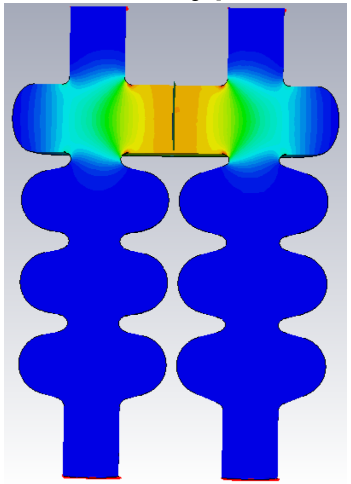
$f = 1.300144\ GHz$



$f = 1.279688\ GHz$

Parasitic LOM
Mode type-1

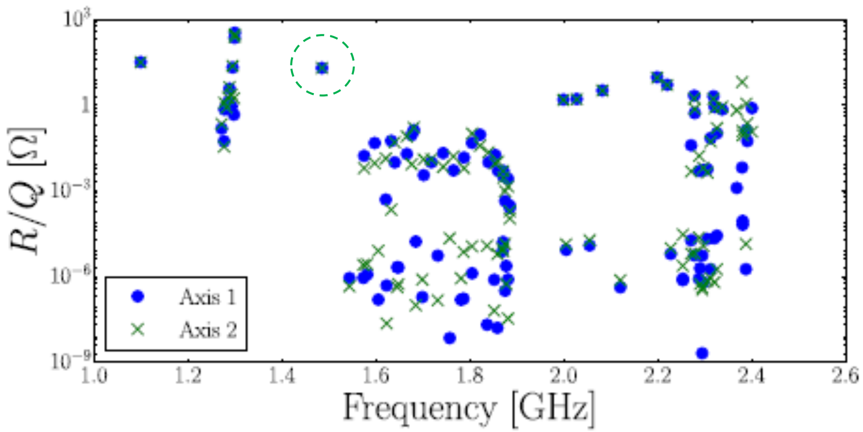
Parasitic LOM
Mode type-2

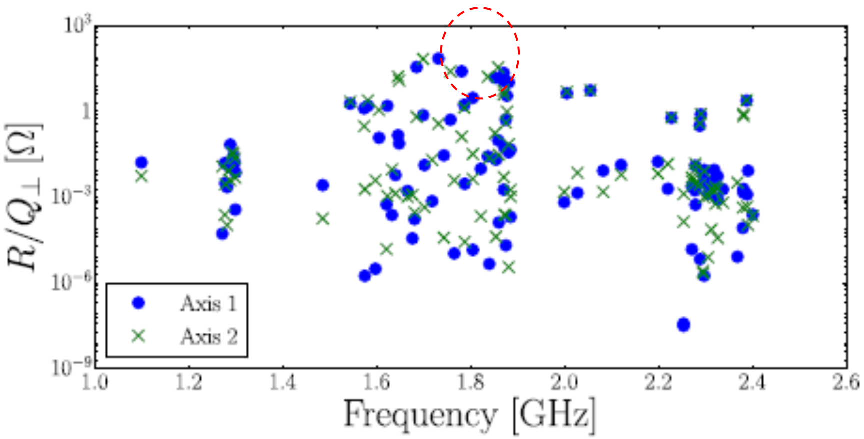


$f = 1.099712\ GHz$

Results observed using CST- Microwave studio

Eigenmodes of the 11 Cell cavity



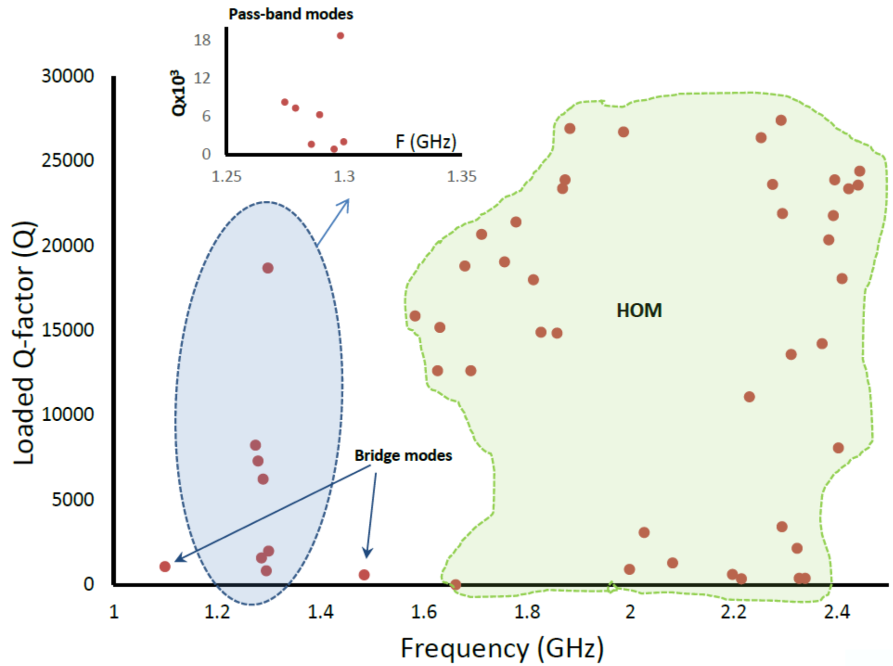


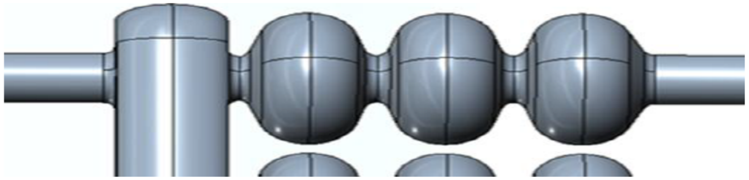
Frequency GHz	Axis 1 R/Q Ω	Axis 2 R/Q Ω	Axis 1 $R/Q_{\perp,x}$ Ω	Axis 2 $R/Q_{\perp,x}$ Ω	Axis 1 $R/Q_{\perp,y}$ Ω	Axis 2 $R/Q_{\perp,y}$ Ω
Highest R/Q						
1.3	348.71	301.51	0.0675	0.0365	0.0074	0.0
1.29943	231.71	247.59	0.0014	0.0059	0.0003	0.0048
1.09966	32.622	32.367	9.5769	9.0660	0.0166	0.0055
1.29532	21.075	23.878	0.0014	0.0267	0.0281	0.0333
1.48554	20.337	20.429	12.094	12.360	0.0026	0.0001
Highest $R/Q_{\perp,x}$						
1.70216	0.0035	0.0127	65.207	0.8680	0.0134	0.0004
1.74343	0.0211	0.0069	61.997	0.4792	0.0294	3.8679
1.87193	0.0050	0.0029	35.500	0.0810	0.0555	0.0002
1.85436	0.0181	0.0091	17.329	0.3260	0.0208	4.2119
1.48554	20.337	20.429	12.094	12.360	0.0026	0.0001
Highest $R/Q_{\perp,y}$						
1.73192	5.4419	1.4736	0.0005	0.0001	72.089	0.3764
1.68526	1.6890	9.9178	0.0024	1.8274	36.312	0.6537
1.78142	1.5499	8.7076	0.0039	0.0070	25.636	0.1329
1.87103	1.6368	7.9211	4.8525	0.0037	22.491	4.0005
1.8523	7.7902	6.4131	0.0033	0.0001	15.388	0.1740

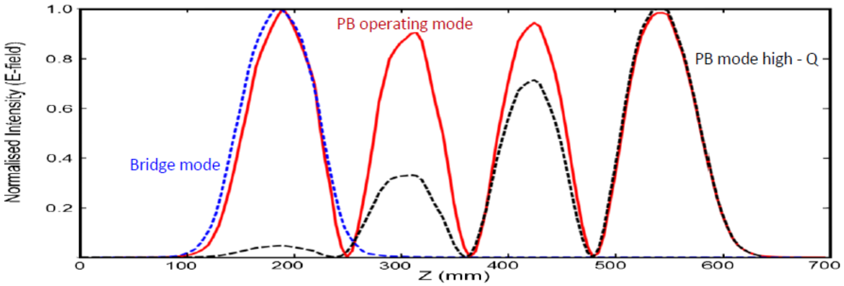
$$R/Q_{\perp,n} = \frac{|V_{\perp,n}(r)|^2}{\omega_n U_n}$$ Different for different axes

$$R/Q_n = \frac{|V_{\parallel,n}(0)|^2}{\omega_n U_n}$$ Different for different axes

Eigenmodes of the 7- Cell cavity







- **Proof of the concept experimental studies**
  - **Aluminium 7 cells cavity**
  - **Copper 11 cells cavity**
  - **Preliminary results**

Experimental studies

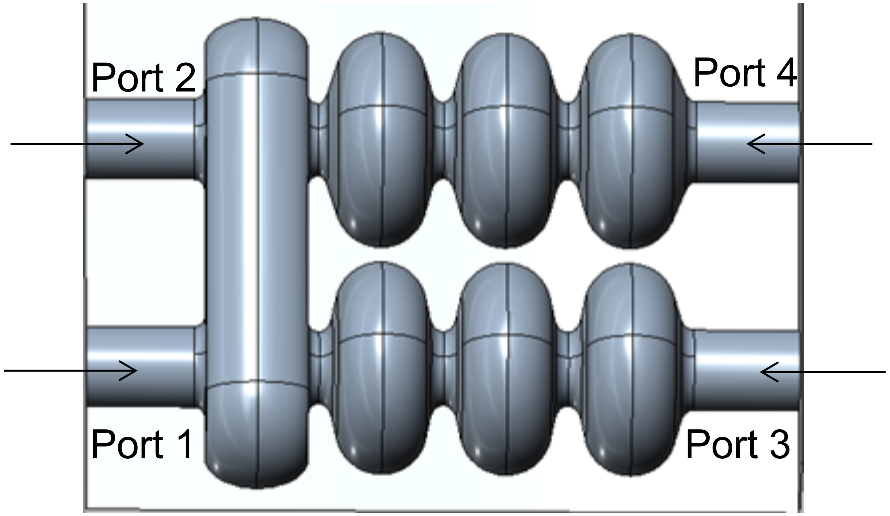
- 7 cell cavity prototype is machined using computer controlled lathe from 2 blocks of solid aluminium.
- The cavity is to develop RF techniques of such cavities study
- Conduct preliminary RF measurements

- 11 cell full scale cavity copper prototype is machined using conventional technology.
- Machined using similar process developed for SCRF cavities.
- The cavity will be tested to conduct detailed RF studies of EM properties and compare with numerical predictions and experimental data from 7-cell cavity measurements

Both cavities will be used to develop full scale ready to use SCRF cavity for AERL

Preliminary experiments

Measurements: Reflection $S_{11}^{\,i}$ from all ports (i) using $\underrightarrow{\text{dipole}}$ antenna



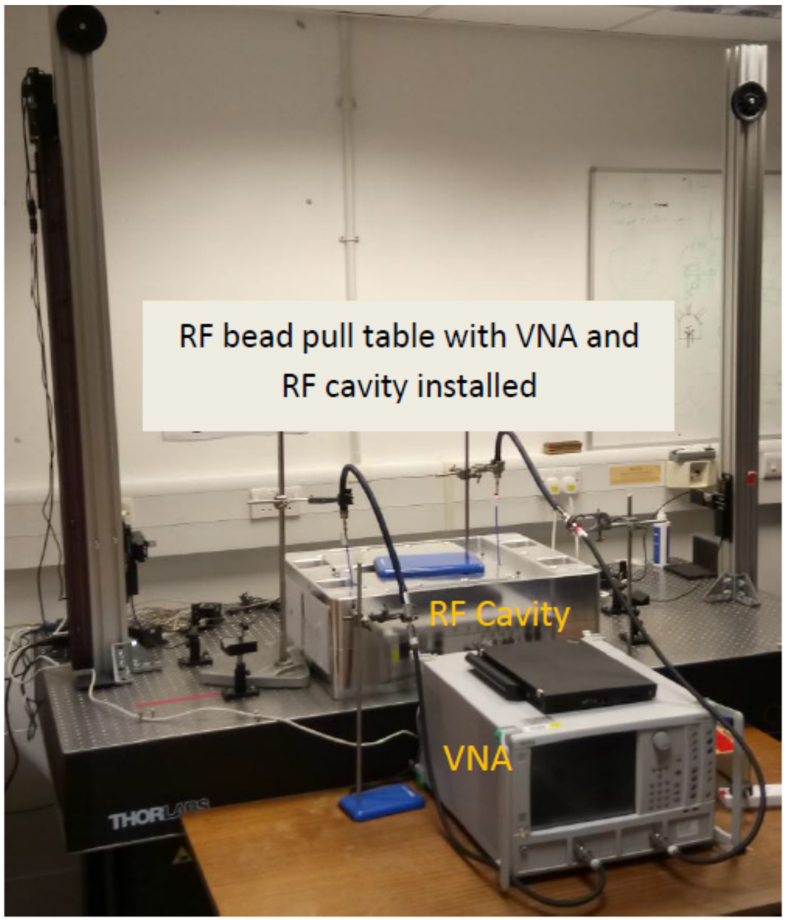
Aim:

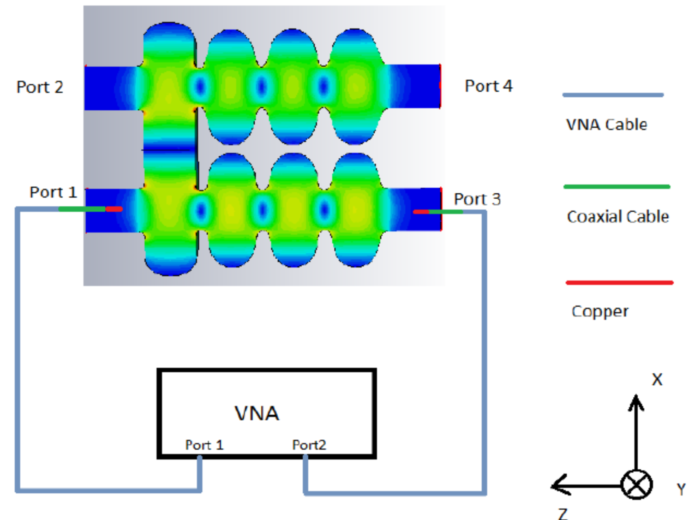
- to identify the cavity modes: operating and HOMs
- To compare with numerical data generated by CST Microwave studio

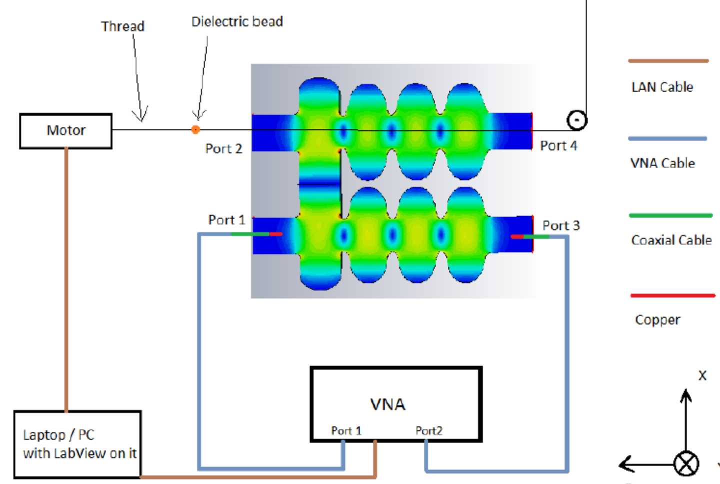
The antennas were inserted through the ports and positioned at different locations and S_{ii} measurements were taken

Starting measurements

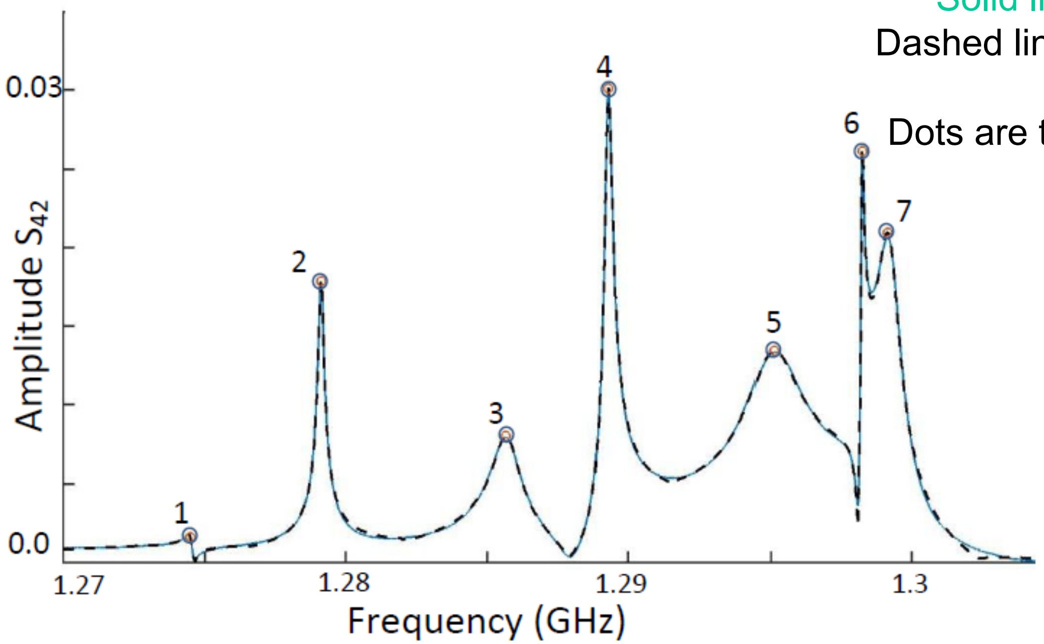
Measuring S_{11} and S_{21} parameters as well as field structure







Method used to measure Q-factor



Solid line - measured S_{21} characteristic

Dashed line - best fit based on Fano model of coupled oscillators

Dots are the eigenmodes positions predicted by CST MS

Fano model of coupled oscillators

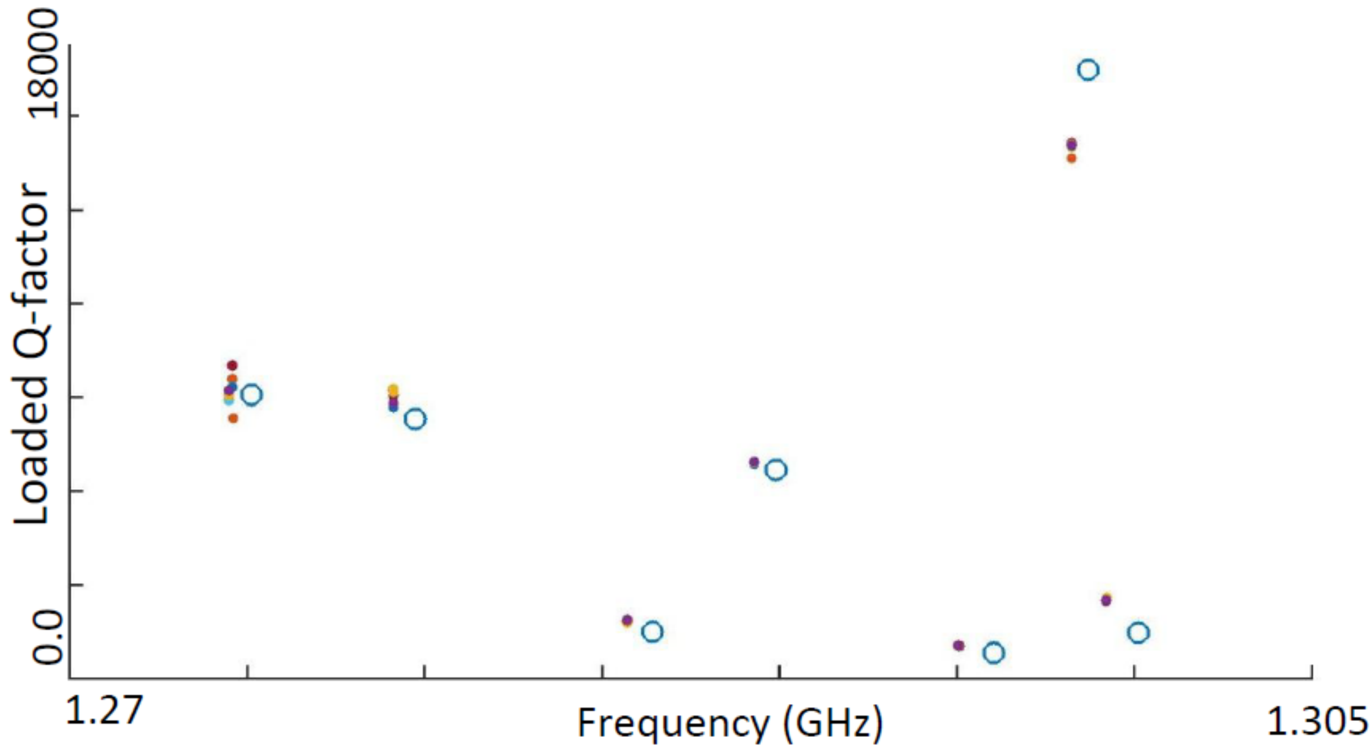
$$\ddot{x_a} + \gamma_a \dot{x_a} + {\omega_0^a}^2 x_a + g x_b = 0 \quad \ddot{x_b} + \gamma_b \dot{x_b} + {\omega_0^b}^2 x_b + g x_a = 0$$

$$S_{ij} = \sum A_n(\Omega_0^n, \Gamma_n, G_n, \omega)$$

$$S_{21} = A_1 + A_2\omega + \sum_{n=1}^{N} |S_{21max}| \left(G_n + 2\frac{\omega - \Omega_0^n}{\Gamma_n}\right) \Big/ \sqrt{1 + 4\left(\frac{\omega - \Omega_0^n}{\Gamma_n}\right)^2}$$

Measurements of Q-factor

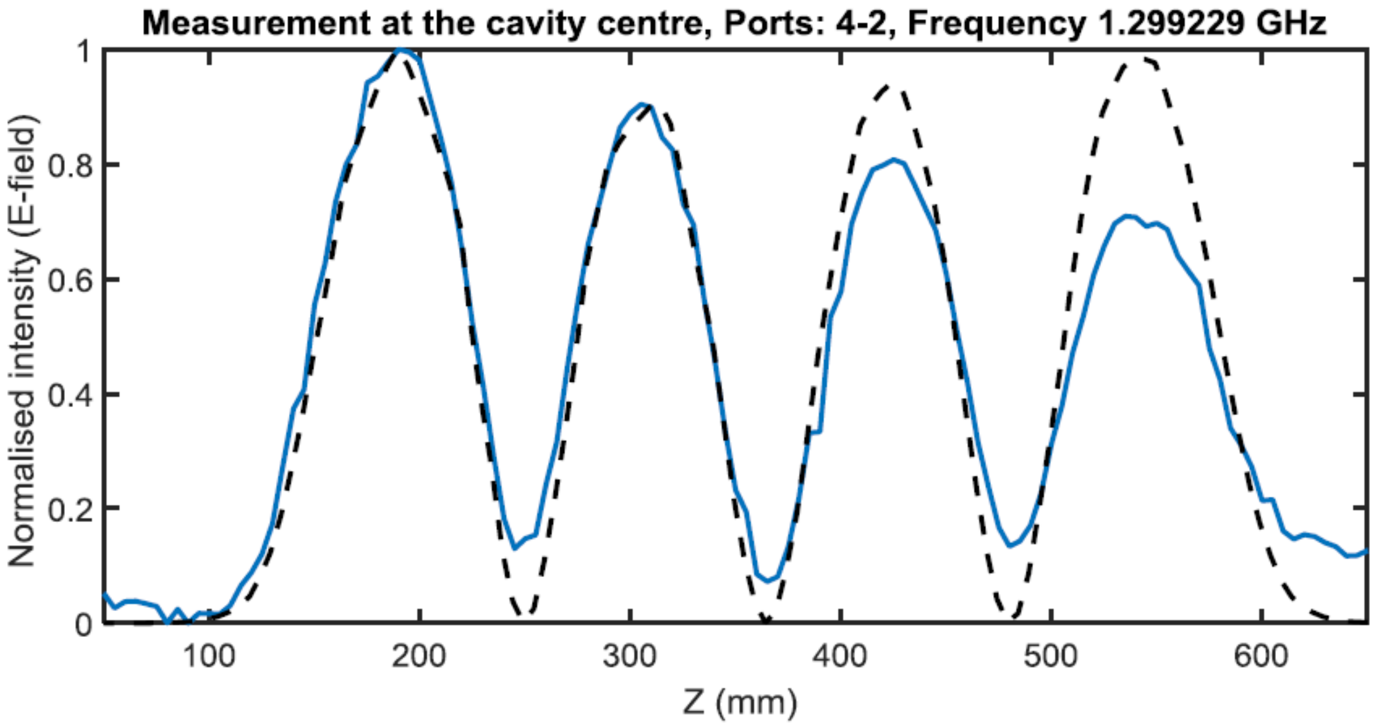
Comparison of measured eigenmodes Q factor (solid dots) and predicted by CST Microwave Studio



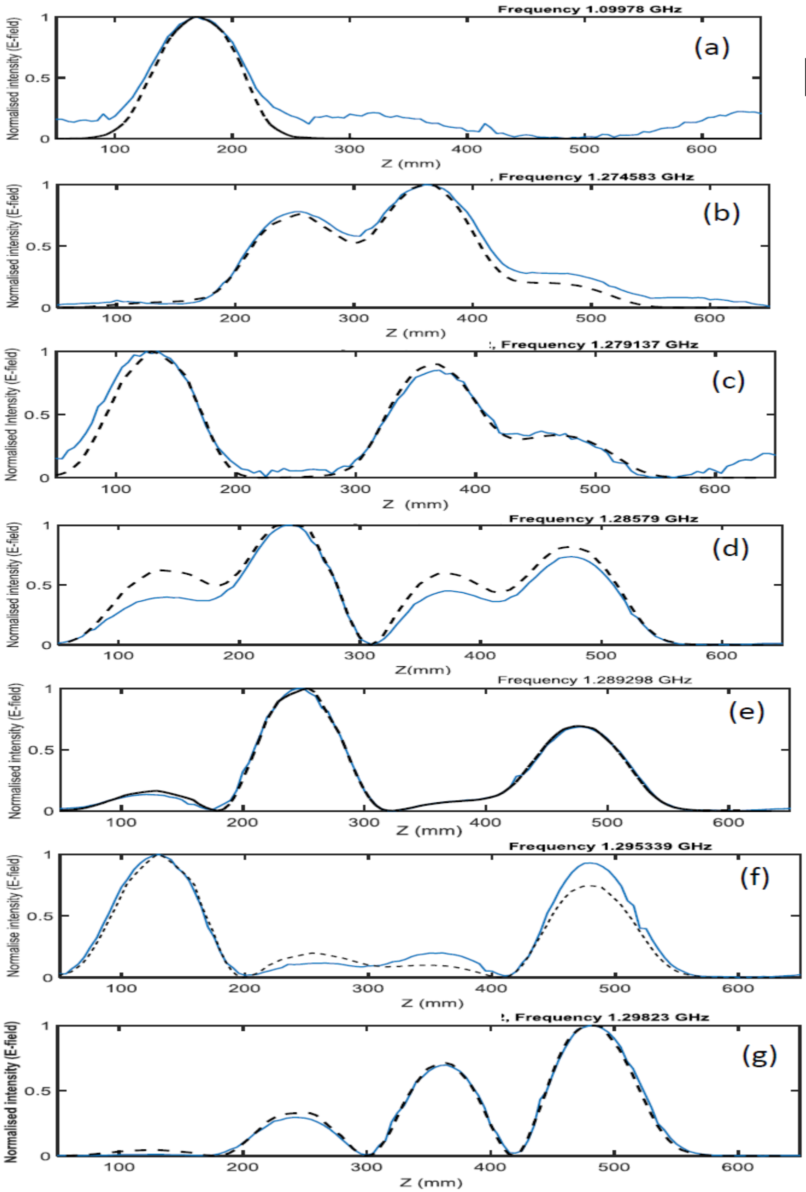
Experimental studies: Operating mode field structure

Field flatness:

Solid line – experiment
Dashed line - predictions



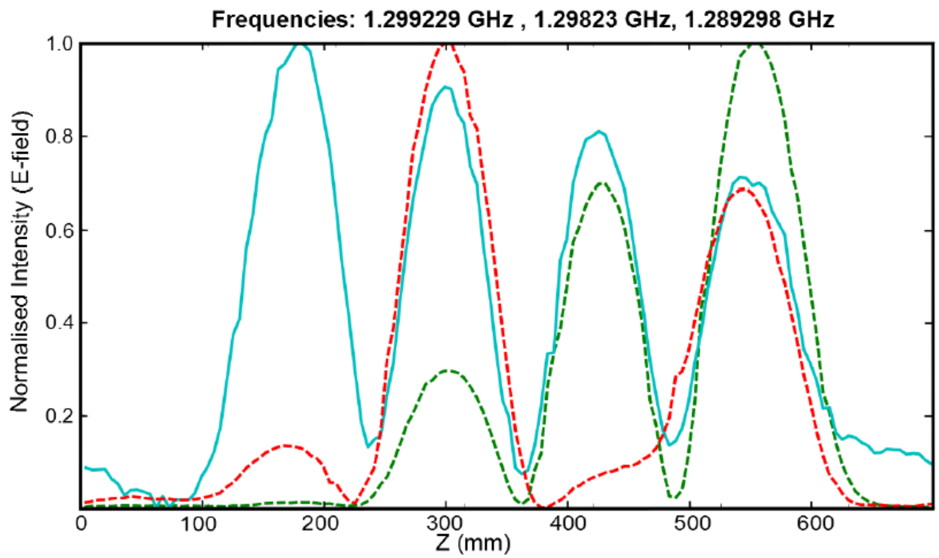
Experimental studies: modes field structure



Pass Eigenmodes Fields' structures:

Solid line – experiment

Dashed line – prediction



Operating mode – solid line

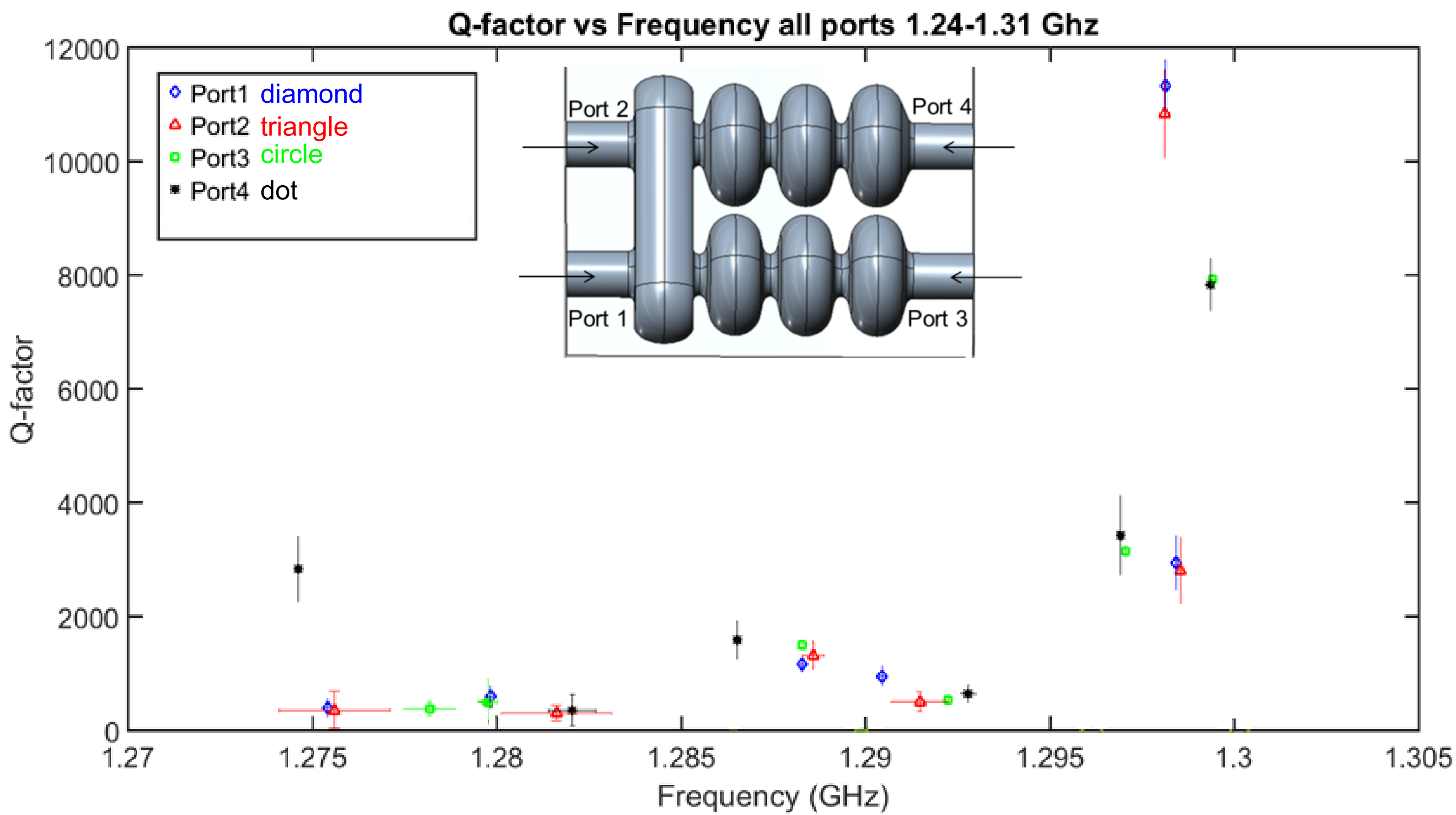
Neighbouring modes dashed lines

Conclusion

- Motivation for new ERL system capable of driving Ampere level average electron beam current has been discussed
- Dual axis 7 cell and 11 cell asymmetric cavities were demonstrated and basic concept was discussed
- Results of numerical studies of both cavities were shown
- The results of RF studies of 7 cell cavity were shown and good comparison with numerical predictions was demonstrated.
- The next steps will be RF study of 11 cell cavity and comparison of the results with the results of numerical studies and experimental studies of 7 cell cavity.
- Gaining funds to continue the development of the AERL system.

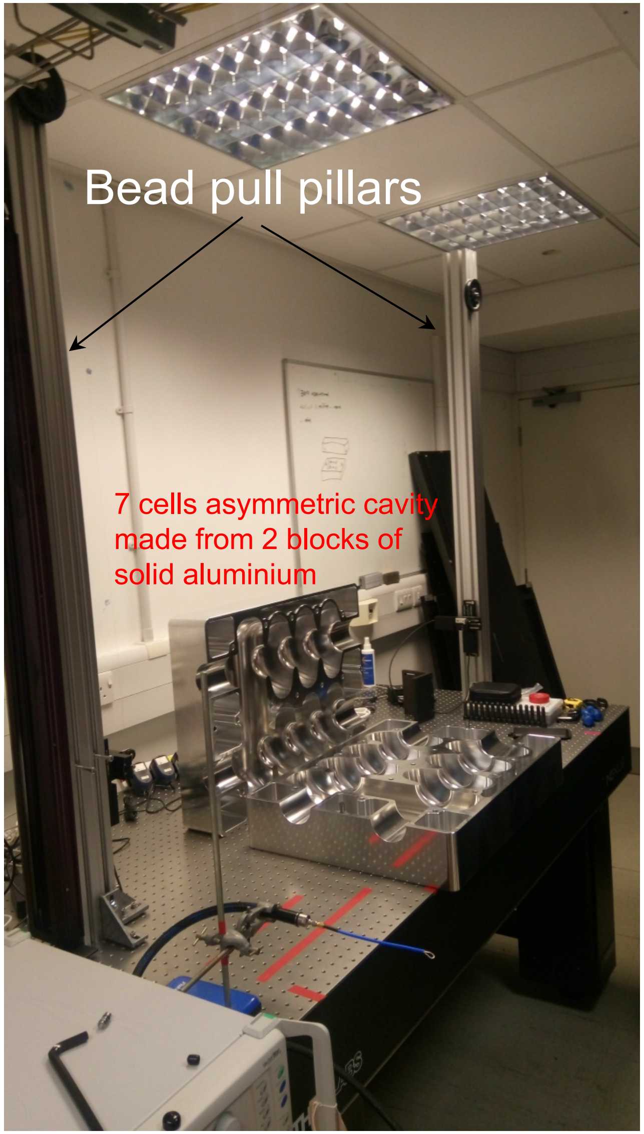
Thank you

Preliminary studies of Q-factor



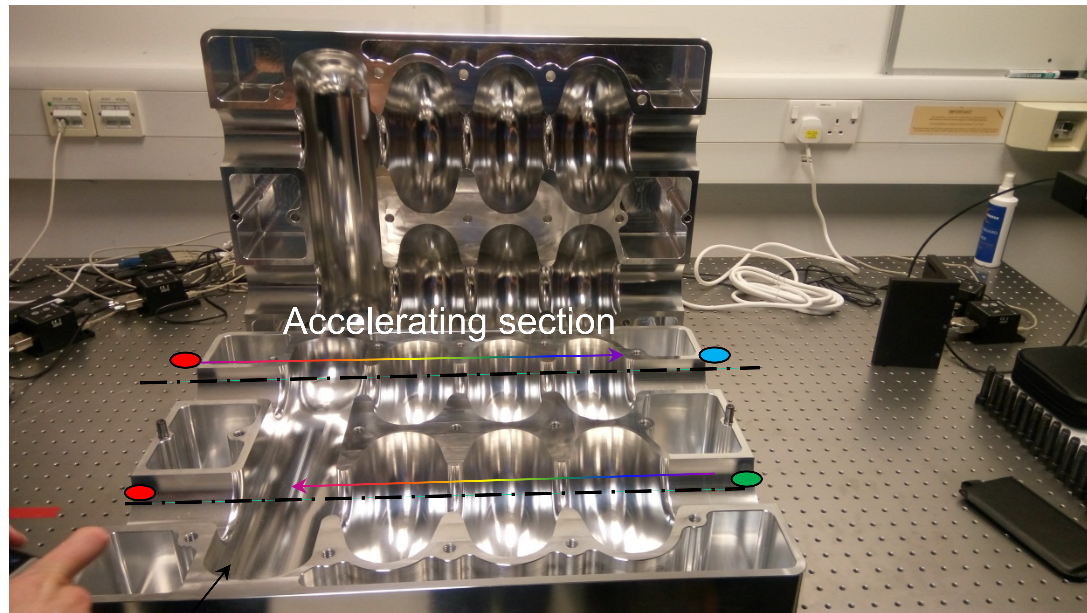
Scaled down prototype of the cavity

7 cells cavity: 3- accelerating; 3 decelerating and coupling cavity



VNA

Bead pull RF measurements test bench

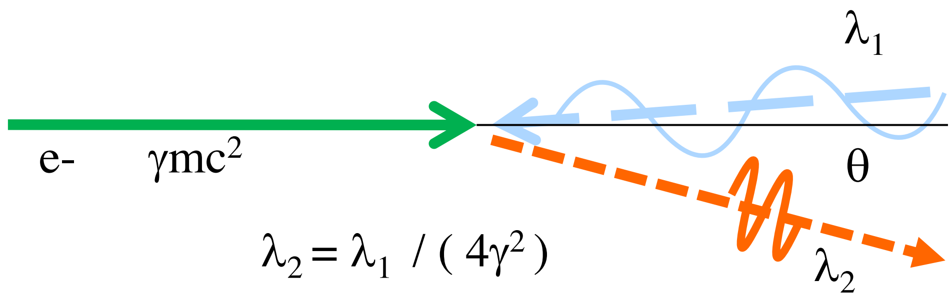


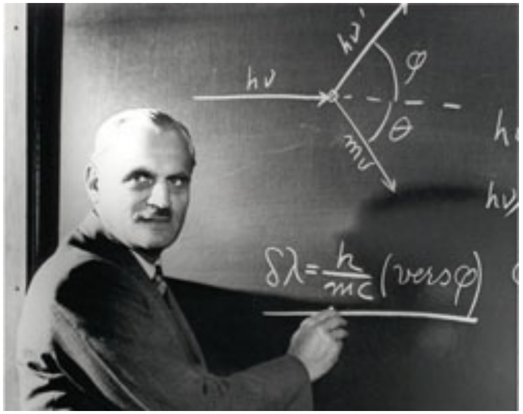
Resonant coupler

Decelerating section

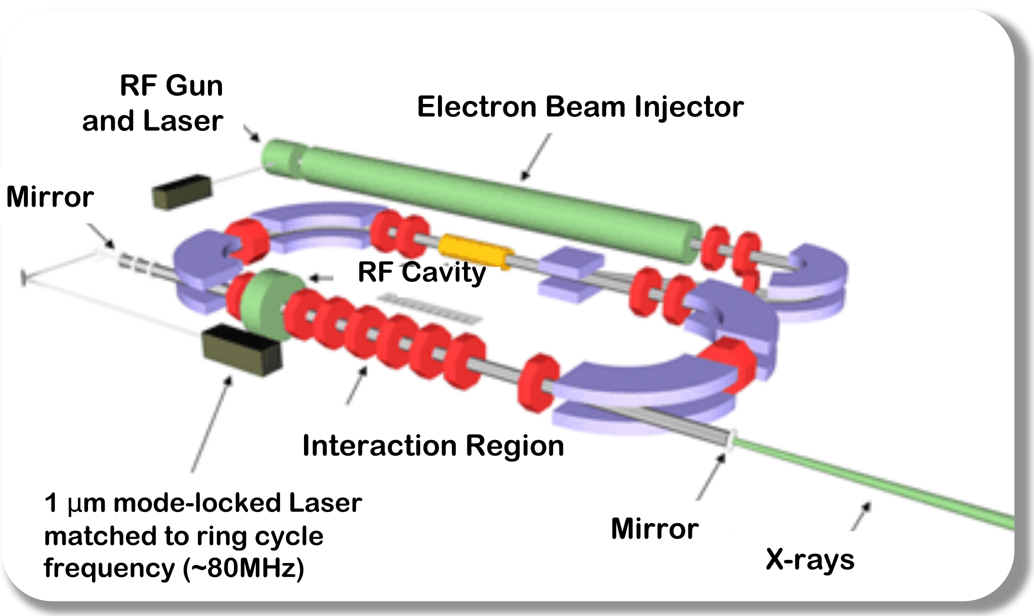
Compton light sources

Based on the reflection of photons from accelerated electrons with an energy transfer to photons





Arthur Compton



Lyncean Technologies, Inc.

Compact X-ray light source

25 MeV accelerator
X-ray tuneable from a few keV up to 35 keV

Fits in a 10x25 ft room