R&D towards a 422 MHz highly damped cavity at BNL

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Introduction

- This presentation is based mostly on the work of Wencan Xu, who made most of the calculations.
- The objective of this work is the design of the main linac cavity of the eRHIC ERL.
- The original eRHIC 704 MHz cavities BNL1 and BNL2 were designed by Rama Calaga, using ferrite beam-pipe HOM dampers. BNL1 was built an is now part of the R&D ERL.
- BNL3, also at 704 MHz was intended to be an SPL cavity but more universal. It was designed by Wencan (in interaction with Rama) for coupler-extracted HOM power. The motivation was to reduce the length of the cavity and avoid absorbers in the beam line.
- Two BNL3 cavities were built, one is intended to be used in the CeC experiment, and it tested very well in vertical tests.
- The BNL4 cavity I am describing here is at 422 MHz. The change in frequency is based on various considerations related to the design of eRHIC, including the reduction of HOM power, increase of the BBU threshold, reduction in the transient voltage step, etc.

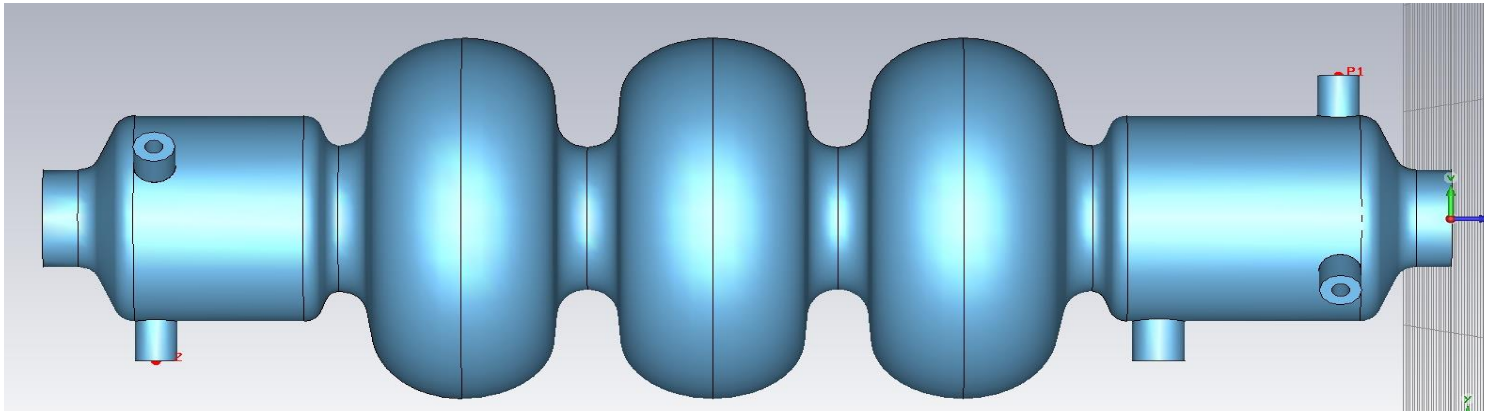
Some previous related LHeC presentations

- LHeC Workshop at Daresbury 22nd and 23rd January 2013
  - Cavity design at 704 MHz
  - Approach to HOM damping with coaxial couplers
- LHeC Workshop in Geneva January 20th and 21st, 2014
  - The BNL ERL and the choice of frequency.

At this meeting I will present progress and plans for further development of cavities at 422 MHz.

5-cell 422 MHz cavity for the eRHIC ERL

- It is a very long multi-cell cavity (2.6 m long).
  - Issues with availability of fabrication and processing facilities.
  - Lack of experience in handling such cavities.
- Motivation:
  - Reduce part count (save money).
  - Improve real-estate gradient (save space in tunnel)
- What are we doing about it:
  - We are building a prototype a 3-cell niobium cavity.
  - We aim to demonstrate a gradient of 18.5 MV/m, $Q_0 > 5 \times 10^{10}$.



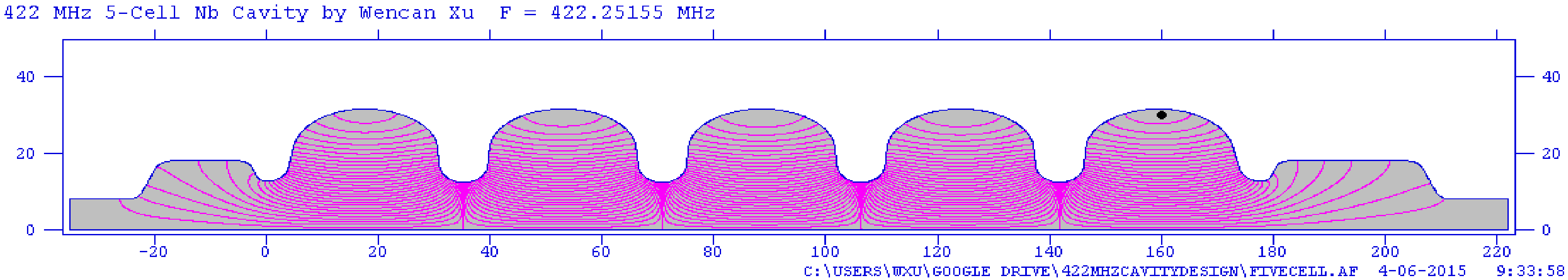
Cavity plans

- A full scale 5-cell eRHIC cavity is being designed, including cavity geometry optimization, analysis of the HOM spectrum and damping scheme, analysis of multipacting in the cavity, mechanical design and optimization of Lorentz detuning factor.
- A 3-cell 422 MHz niobium superconducting RF cavity will be fabricated. We will work closely with the manufacturer to resolve all the potential issues and to make sure every step proceeds correctly. Through this project, the specification and procedure of the eRHIC cavities' fabrication will be determined.
- A performance study and the improvement of the niobium prototype cavity will be carried out with cavity processing and vertical tests. With these tests, the specification for future eRHIC cavities' processing and test procedure will be developed.
- We would like to send an electron beam through the cavity and study the excitation of HOMs.

Parameters for 3 and 5 cell cavities for the eRHIC linac

Parameters	3cell	5-cell
Linac (GeV)	1.325	1.325
Cavity length (m)	1.85	2.56
Gradient (MV/m)	18.5	18.5
Number of cavities	70	42
Cavity spacing (cm)	25	25
Transitions to warm (m)	2x2	2x2
Total (One) linac length (m)	151	122
HOM K_{loss}/cavity (V/pC)	1.4	1.9

Result of design and optimization



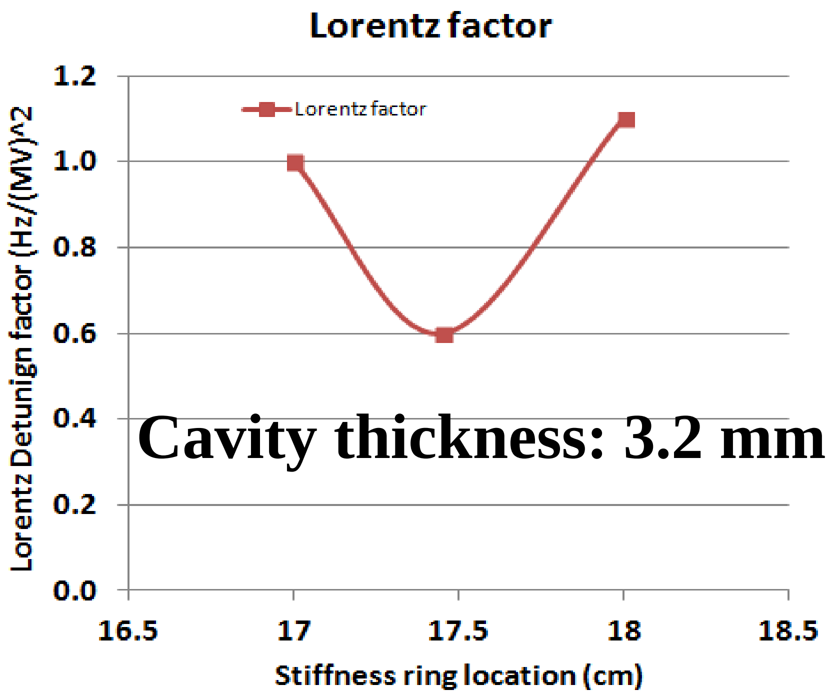
Parameters	BNL 4	BNL4_3cell
Frequency [MHZ]	422.2	422.2
beta	1	1
Cells No.	5	3
Geometry Factor	273	273
(R/Q)/cell [Ω/cell]	100.6	100.6
Epeak/Eacc	2.27	2.27
Bpeak/Eacc [mT/MV/m]	4.42	4.42
Coupling factor [%]	2.83	2.83
Length with HOM damper (cm)	256	1.85
Beam pipe radius (mm)	180	180
Radius after tapered (mm)	80	80
First HOM frequency (MHz)	498	500

Notes:

1. **No multipacting in the cavity and tapers.**
2. **No RF heating issue on the flanges' seals.**
3. **Low loss factor 1.9 v/pC**
4. **Good separation of first HOM from fundamental.**

Mechanical analysis (Thanks to Chien-Ih Pai)

eRHIC Linac cavity frequency table					
Proton	Energy (GeV)	40	50	100	250
	RF frequency (Hz)	4.22E+08	4.22E+08	4.22E+08	4.22E+08
	Delta F to center F (Hz)	-4.18E+04	0	5.58E+04	7.14E+04
Gold	Energy (GeV)	40	50	100	250
	RF frequency (Hz)	4.22E+08	4.22E+08	4.22E+08	4.22E+08
	Delta F to center F (Hz)	-4.01E+04	1.13E+03	5.60E+04	7.14E+04

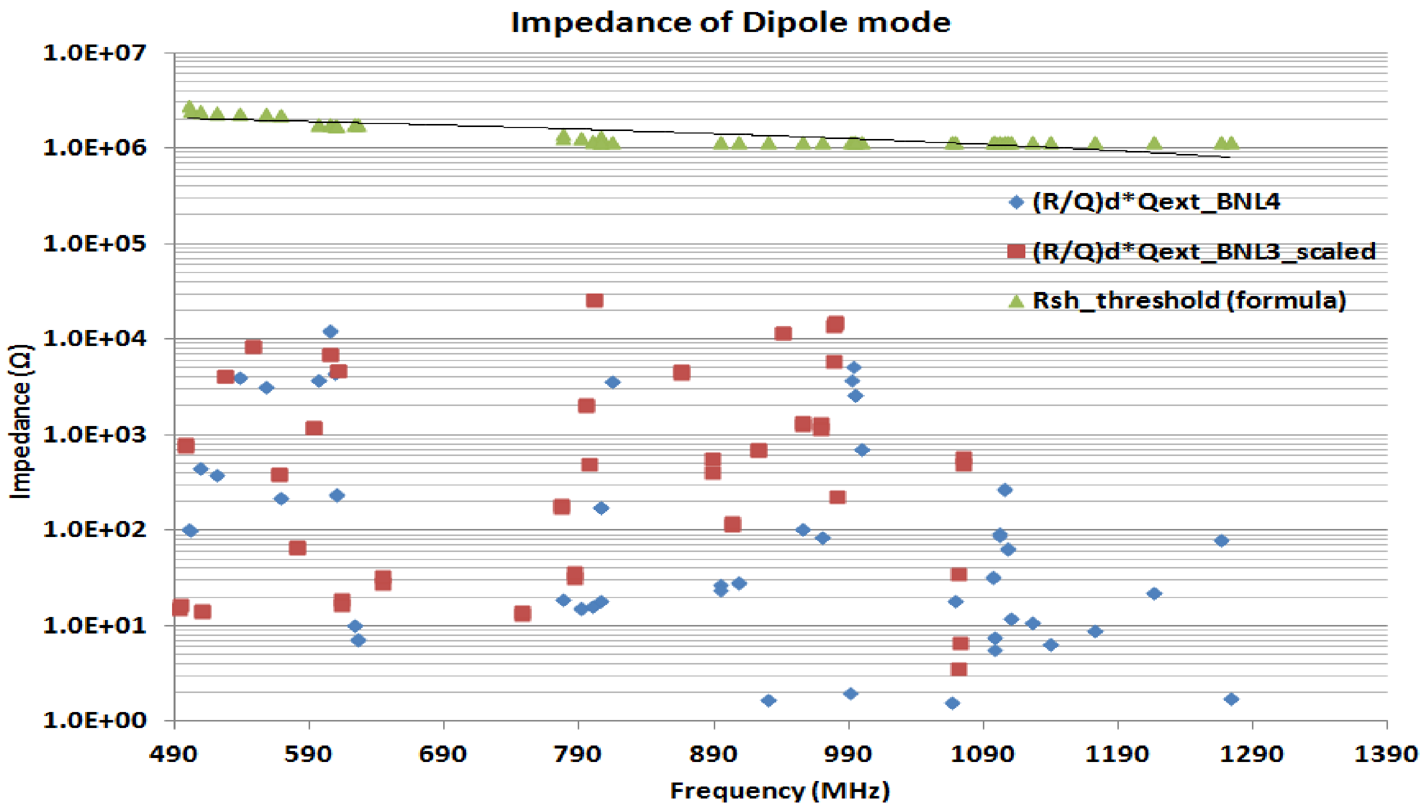


Lorentz detuning factor: 0.6 Hz/(MV/m)^2
Tuning sensitivity: 55 kHz/mm;
So the total tuning will be about 2.05 mm or 113.2 kHz, which is within the allowable stress limit. When the cavity is tuned up to 2.8 mm from neutral position, the stress is 6903 PSI
Note: The minimum strength of RRR=300 Nb specification for cavity at room temperature: 7000 PSI, which will be doubled at 2K.

HOM damping system for the 422 MHz cavity

- Issues at eRHIC:
  - Dipole modes: Beam-break-up beam current threshold.
  - Monopole modes: High HOM power: 7.8 kW per cavity.
  - Large frequency range of HOMs: 0.5 GHz to 30 GHz.
- What are we doing about this:
  - We are designing and we will build a prototype HOM damping system aiming at HOMs' external Q < 50,000, up to 30 GHz.
  - We also plan a full scale 5-cell copper cavity for HOM mode studies.

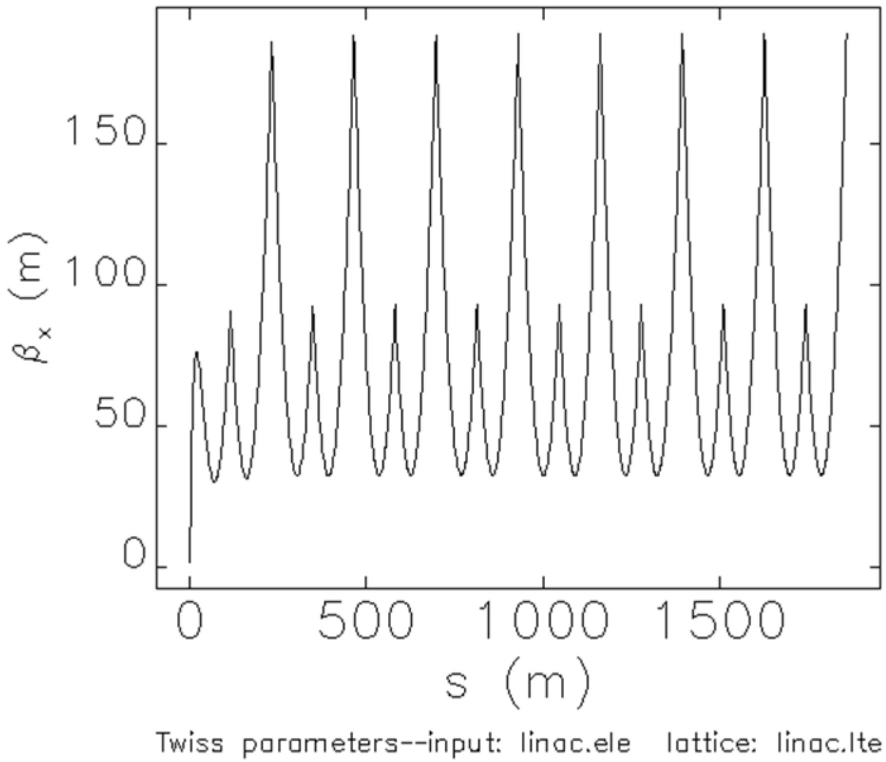
Transverse BBU considerations



1) HOM damping capability: All of the dipole modes' $Qe < 2.5\times10^4$ and all of the monopole modes' $Qe < 1.7\times10^4$.
2) *Beam parameters: 18 mA 16-pass ERL, T_{21}= 150 m*
3) *BNL3_scaled cavity was used for BBU simulation in the eRHIC lattice and its threshold current is well above the eRHIC design beam current.*

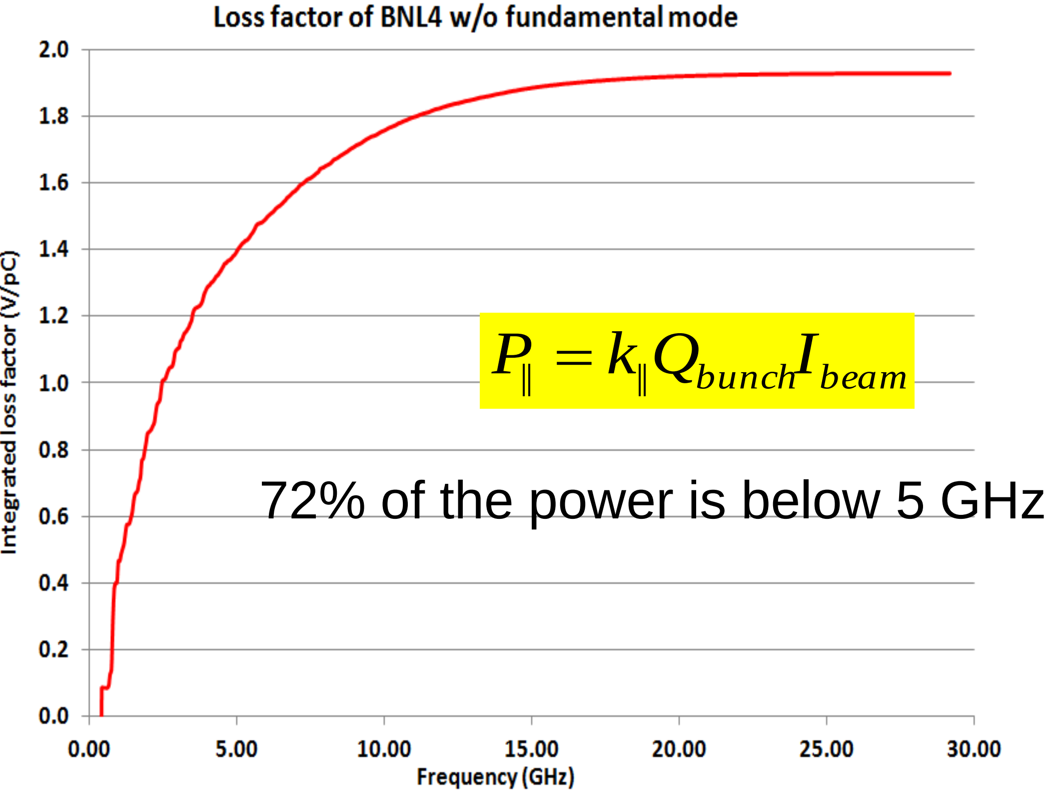
BBU simulation for eRHIC (Thanks to Yue Hao)

- Injection energy 12 MeV;
- Total length of linac 115 meters, and energy gain is 1.322 GeV
- The BBU simulation for the 21 GeV, 16 pass case shows that the threshold is way above the operation current 18 mA;



Δf/f	Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-3	225
1e-2	329

HOM power considerations



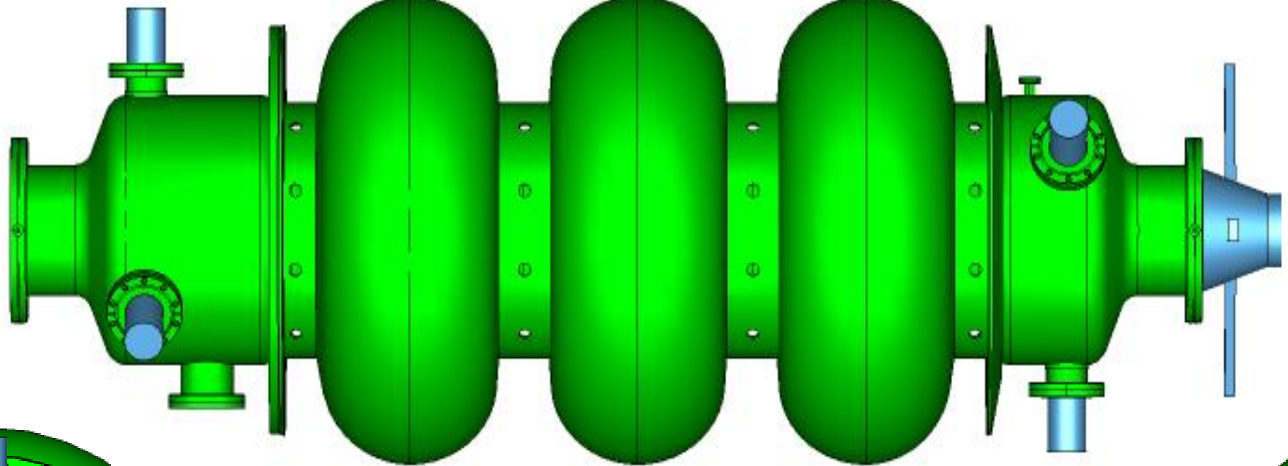
One of the optimization goals of the cavity design was to reduce to loss factor, which led to 1.9 V/pC for a 4 mm bunch length.

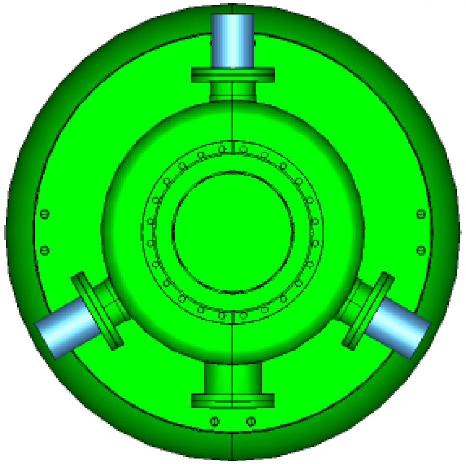
Design	Mode 1	Mode 2	Mode 3
Total energy, GeV	15.9	21.6	9.4
Frequency, *MHz*	422	422	422
Passes	12	16	7
No. of cavity	42	42	42
Gradient, *MV/m*	18.5	18.5	18.5
Linac Length, *m*	128	128	128
Bunch Charge, *nC*	1.06	0.39	1.812
Bunch length, mm	4	4	4
Current in Linac, m*A*	10	3.7	17
HOM power/cavity, *W*	484	87	819
BNL3_scaled (W)	588	106	1140

Our planned HOM damping scheme

To damp the full range of HOM power: Two types of HOM damping.

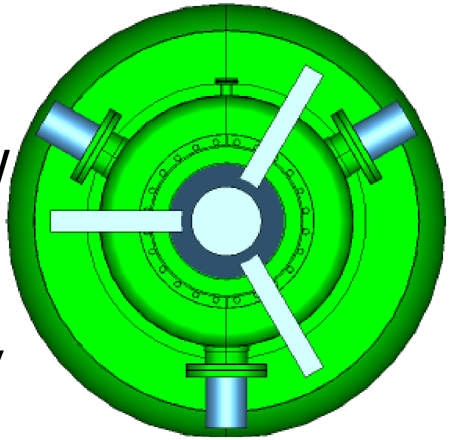
Coaxial-line HOM coupler and waveguide HOM coupler





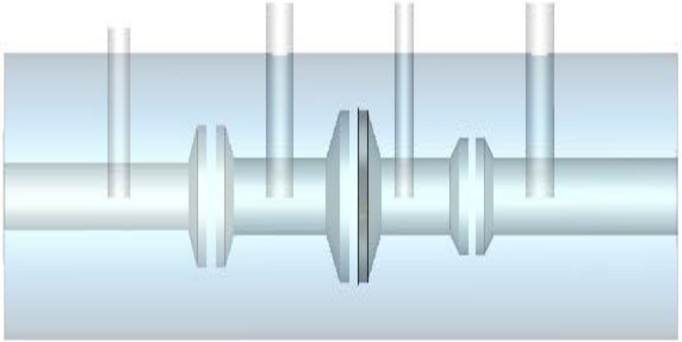
6 coaxial-line HOM couplers on the cavity for low frequency HOMs: ~ 5.6 kW

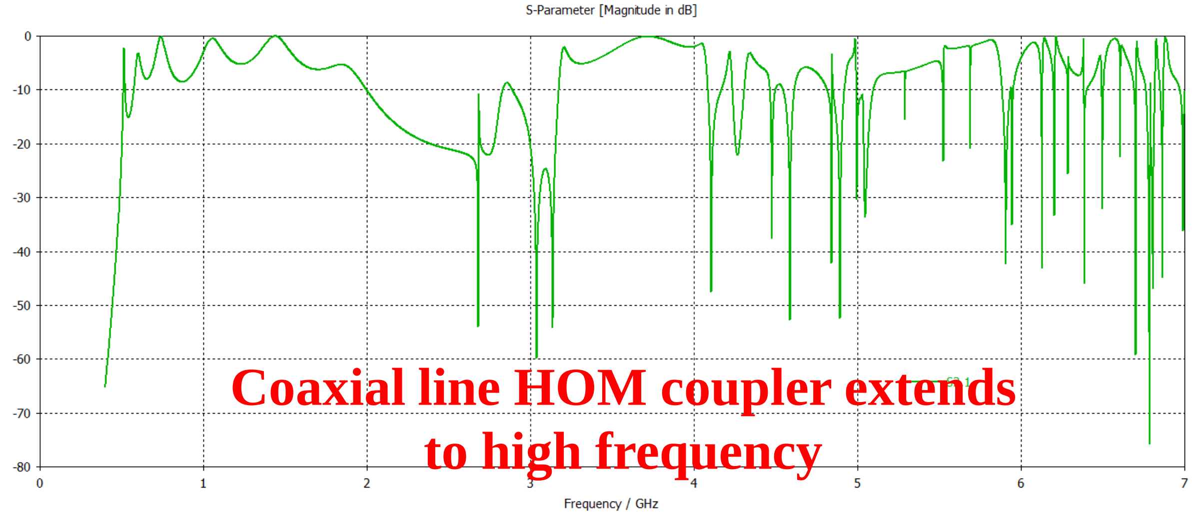
3 rectangular waveguide HOM damper on the beamline taper for high frequency HOMs: ~2.2 kW up to ~30 GHz

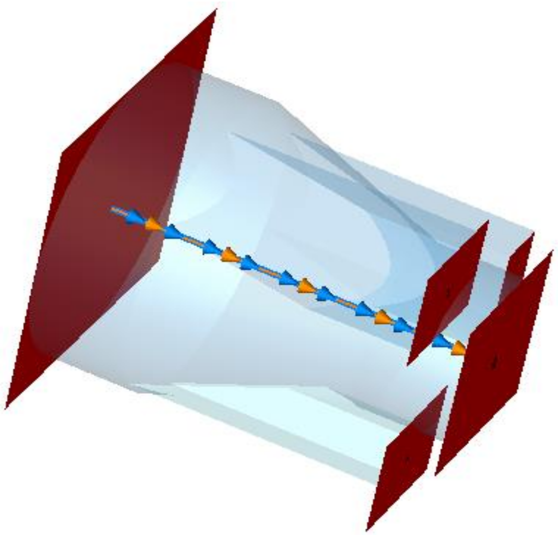


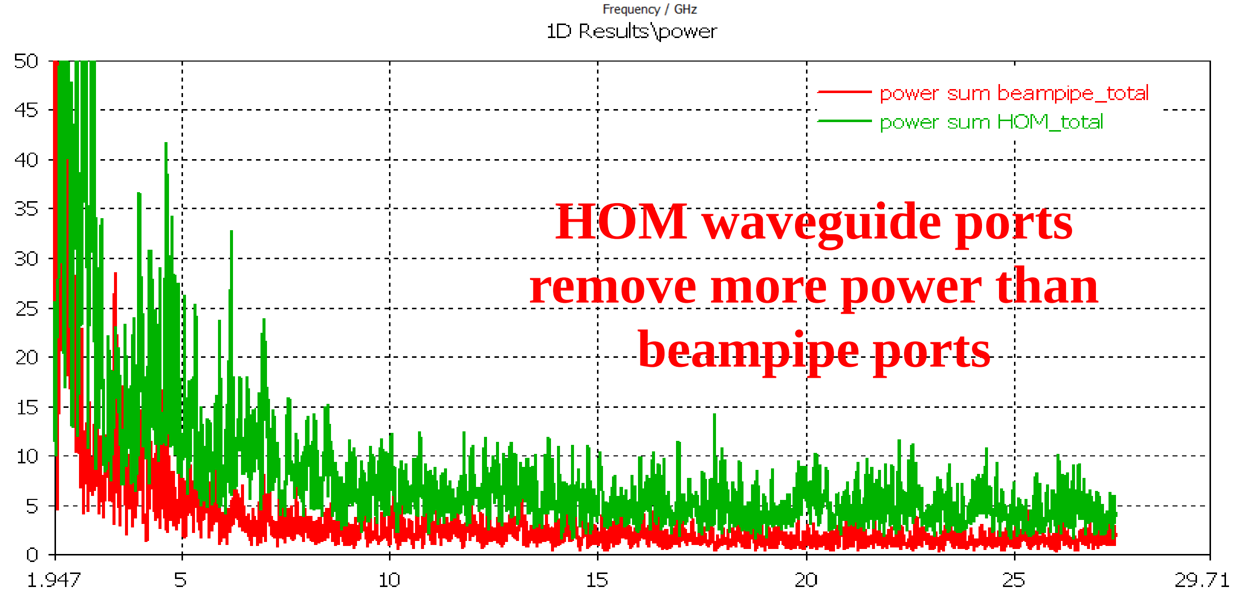
A preliminary simulation shows promise of this approach

PRELIMINARY RESULTS OF HOM DAMPING









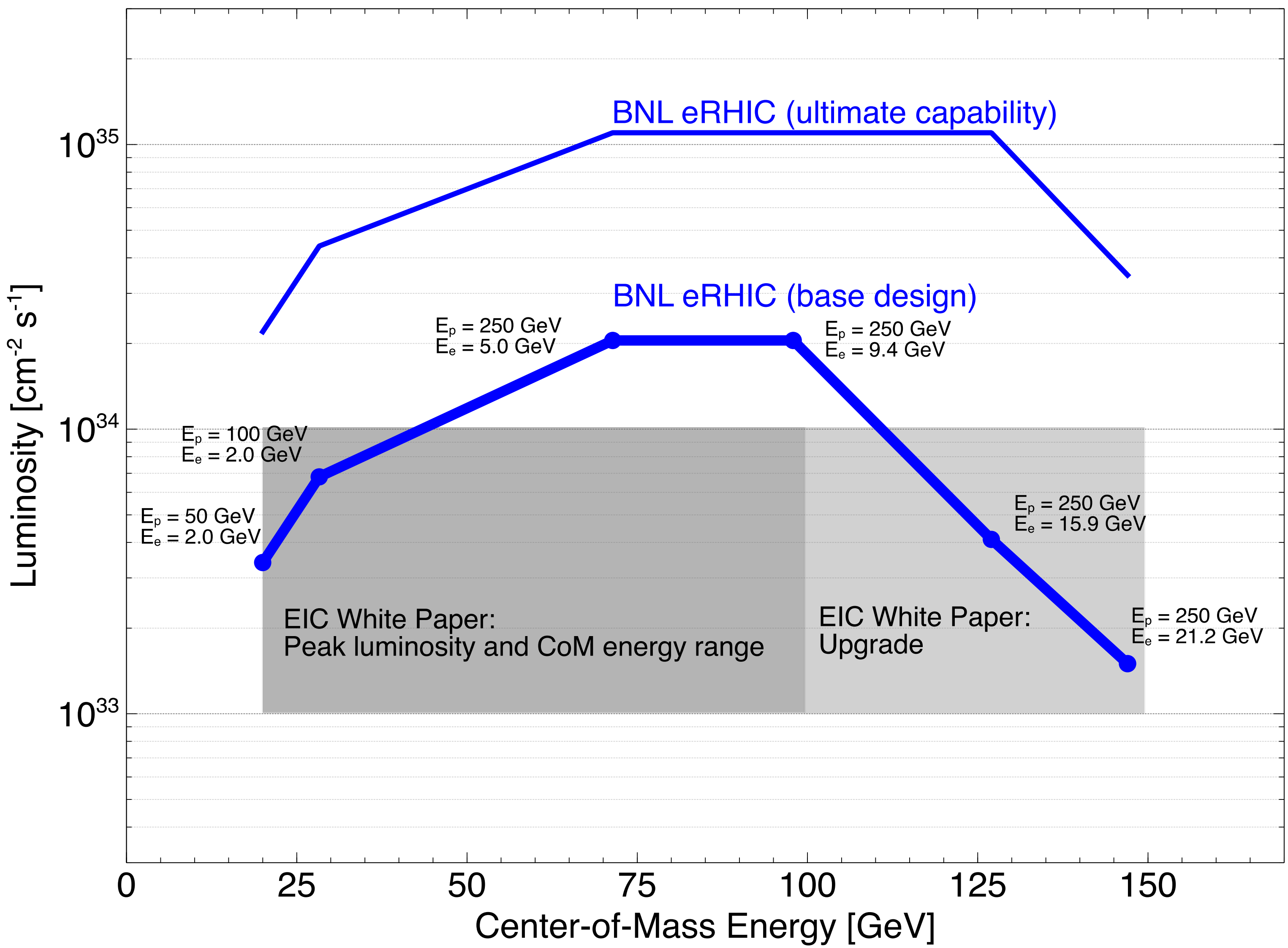
➢**Combination of these two types of HOM couplers promise to damp the full spectrum up to 30 GHz. This is work in progress.**

Summary

- The eRHIC ERL frequency choice is 422 MHz
- We have done extensive simulations of the cavity – electromagnetic, mechanical and beam-breakup.
- We are designing the HOM damping system to cover the complete spectrum of HOM up to 30 GHz.
- We will build a 3-cell solid niobium cavity to study the SRF performance of the cavity.
- We will also build a 5-cell (full scale) copper cavity to study the HOM modes and damping schemes.
- We are considering beam tests of the cavity.
- This work has a high priority in our Collider-Accelerator Department.

Special thanks to Wencan Xu for material for this presentation and to the SRF Group, headed by Sergey Belomestnykh.

Thank you for your attention!



BNL eRHIC (ultimate capability)
BNL eRHIC (base design)
10^{35}
10^{34}
10^{33}
Luminosity [cm^{-2} s^{-1}]
E_p = 250 GeV
E_e = 5.0 GeV
E_p = 250 GeV
E_e = 9.4 GeV
E_p = 100 GeV
E_e = 2.0 GeV
E_p = 50 GeV
E_e = 2.0 GeV
E_p = 250 GeV
E_e = 15.9 GeV
E_p = 250 GeV
E_e = 21.2 GeV
EIC White Paper:
Peak luminosity and CoM energy range
EIC White Paper:
Upgrade
0
25
50
75
100
125
150
Center-of-Mass Energy [GeV]