# Status of JLEIC Impedance Budgets

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EIC Accelerator Collaboration Meeting

Apr. 1 – Apr.3, 2019

# Acknowledgement


## JLEIC Impedance Collaboration

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RF Group: J. Guo, F. Marhauser, R. Rimmer, H. Wang, S. Wang

Engineering Group: B. Crahen, C. Hutton, R. Lassiter, T. Michalski, M. Wiseman

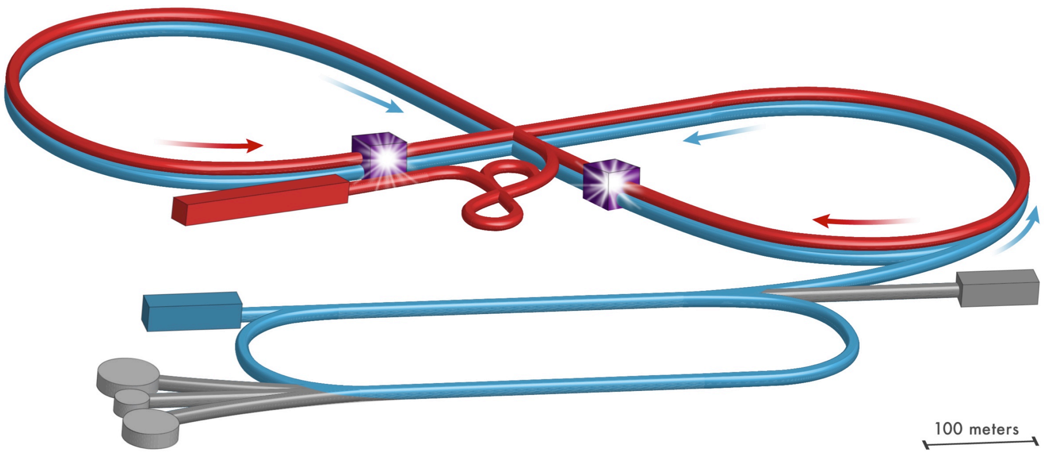
ODU: J. Delayen, H. Park, S. Sosa, S. De Silva

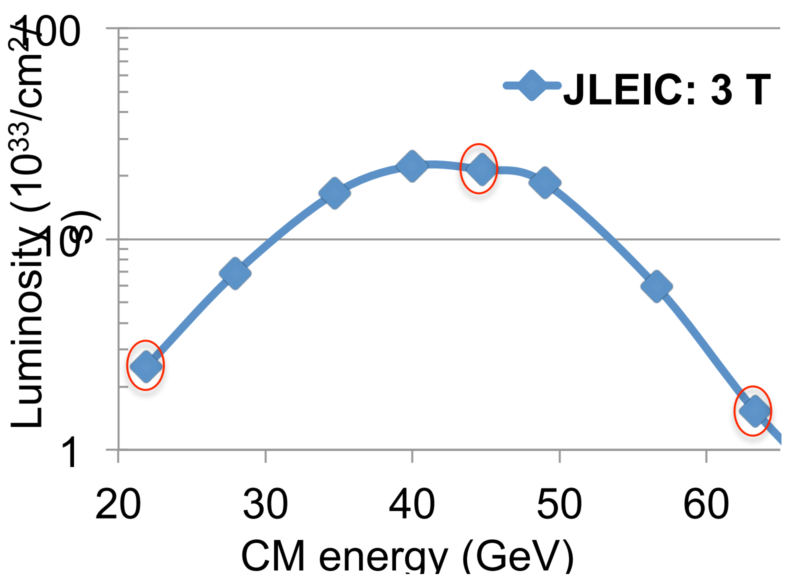
# Outline

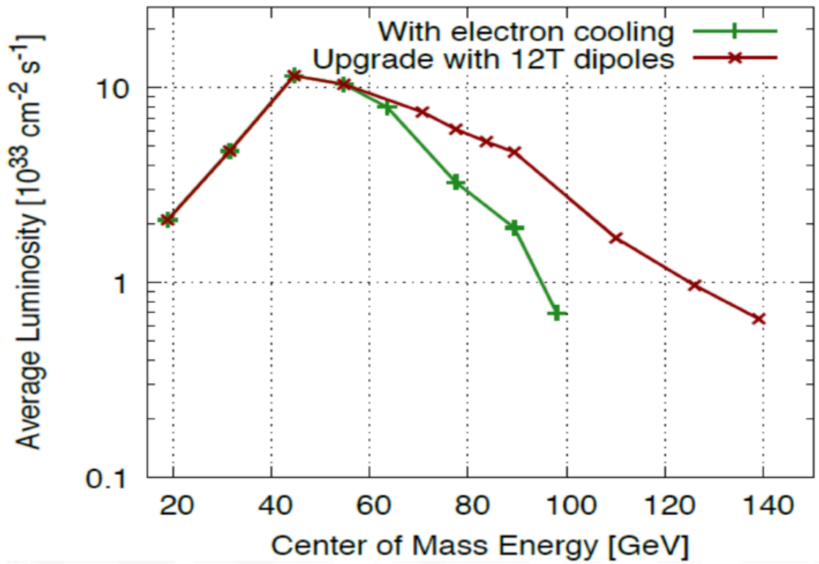
1. Introduction
2. Broadband Impedance
3. Narrowband Impedance
4. Ongoing Activities
5. Summary

# 1. Introduction

- Design goals of JLEIC
  - Luminosity: $10^{33}$~$10^{34}$ [$cm^{-2}s^{-1}$]
  - Wide range of $E_{CM}$: 30~100 [GeV]
  - Wide range of ion species
  - High polarization (~70% for $e^-$ and light ions)
- Special Features of JLEIC
  - Figure-8 rings
  - High-energy bunched beam electron cooling



# JLEIC Luminosity Concepts and Instabilities

- Luminosity concepts of JLEIC
  - Moderate single bunch charge, with low emittances and short bunch length (1.2~1.4 cm)
  - High bunch rep rate ($n_b$=3420)
  - small beta at IP (1 cm)
  - Enabled by crab cavity and high-energy bunched e-cooling for ion beam

- Goals for Vacuum Chamber Design
  - Low broadband impedances: prevent single bunch instabilities
  - Damped narrowband impedances: make coupled-bunch instabilities manageable under fast feedback system
  - Avoid excessive power loss and chamber heating

# Status of JLEIC Impedance Studies

- In this talk
  - Review the current impedance status
  - Compare machine impedances with the theoretical impedance thresholds
  - Highlight on-going activities

With limited resources, only incremental progresses were made since last collaboration meeting

# 2. Broadband Impedance in JLEIC

- Impedance budget study
  - Complete inventory of impedance-generating components
  - Engineering design and drawing of each components
  - EM field modeling for wakefield or impedance spectrum

- Current status of broadband impedance in JLEIC
  - Component counts are done (subject to modification)
  - Engineering design is in its early phase
  - Impedance are estimated using impedance budget of existing machines for reference

# Broadband Impedance Estimation: JLEIC e-Ring

- **Component Counts** (Courtesy to T. Michalski)

| Elements | e-Ring |
|---|---|
| Flanges (pairs) | 1215 |
| BPMs | 405 |
| Vacuum ports | 480 |
| Bellows | 480 |
| Vacuum Valves | 23 |
| Tapers | 6 |
| Collimators | 16 |
| DIP screen slots | 470 |
| Crab cavities | 2 |
| RF cavities | 32 |
| RF valves | 68 |
| Feedback kickers | 2 |
| IR chamber | 1 |

- **Impedance Estimation** (Courtesy to K. Deitrick)

| Broadband Impedance | Reference: PEP-II | Reference: SUPERKEKB | |
|---|---|---|---|
| $L$ [nH] | 99.2 | 28.6 | |
| $\left\|Z_{\parallel}/n\right\|$ [$\Omega$] | 0.09 | 0.02 | $\leq 0.1\ \Omega$ |
| $k_{\parallel}$ [V/pC] | 7.7 | 19 | |
| $\left\|Z_{\perp}\right\|$ [k$\Omega$/m] | 60 | 13 | $\leq 0.1\ \mathrm{M}\Omega/m$ |

- JLEIC plans to use PEP-II vacuum systems
- Effective impedance is bunch length dependent

# Electron Ring Breakdown (using PEPII elements)

| | PEP-II | | | L/L_tot |
|---|---|---|---|---|
| **Element** | L (nH) | k (V/pC) | Note | |
| Flanges (Pairs) | 0.98 | 0.06 | | |
| BPMs | 14.99 | 1.09 | | 15% |
| Vacuum ports | | | | |
| Bellows | 21.55 | 1.58 | | 22% |
| Vacuum valves | | | | |
| Tapers/Transitions | 1.80 | 0.03 | | |
| Collimators | 25.20 | 0.32 | | 25% |
| Feedback Kickers | 29.72 | 0.66 | | 30% |
| Crab Cavities | | | | |
| RF/SRF Cavities | | 3.84 | | |
| IR chamber | 5.00 | 0.12 | | |
| | | | | |
| Total | 99.24 | 7.71 | 1 cm | |
| in Ohms | 0.09 | | | |

(Courtesy to K. Deitrick)

# Broadband Impedance Estimation: JLEIC ion-Ring

- ## Component Counts (Courtesy to T. Michalski)

| Elements | p-Ring |
|---|---|
| Flanges (pairs) | 234 |
| BPMs | 214 |
| Vacuum ports | 92 |
| Bellows | 559 |
| Vacuum Valves | 14 |
| Tapers | 6 |
| Collimators | 16 |
| DIP screen slots | - |
| Crab cavities | 8 |
| RF cavities | 40 |
| RF cavity bellows | 40 |
| RF valves | 24 |
| Feedback kickers | 2 |
| Roman Pot | 2 |
| IR chamber | 1 |

- ## Impedance Estimation

(Courtesy to K. Deitrick)

| Broadband Impedance | Reference: PEP-II | |
|---|---|---|
| $L$ [nH] | 97.6 | |
| $\lvert Z_{\parallel}/n \rvert$ [Ω] | 0.08 | $\leq 0.1\ \Omega$ |
| $k_{\parallel}$ [V/pC] | 8.6 | |
| $\lvert Z_{\perp} \rvert$ [kΩ/m] | 80 | $\leq 0.1\ \mathrm{M}\Omega/m$ |

- The short bunch length (1.0cm) at collision is unprecedented for the ion beams in existing ion rings
- Bunch length varies through the whole bunch formation process

# Some Caveats

- The effective impedance is the overlap of the machine impedance spectrum with the bunch spectrum

- Even though the proton bunch rms size is comparable with that in PEPII, the bunch profile are very different

- We need to see this effect on the effective broadband impedance

Bunch Profile under Strong Electron Cooling

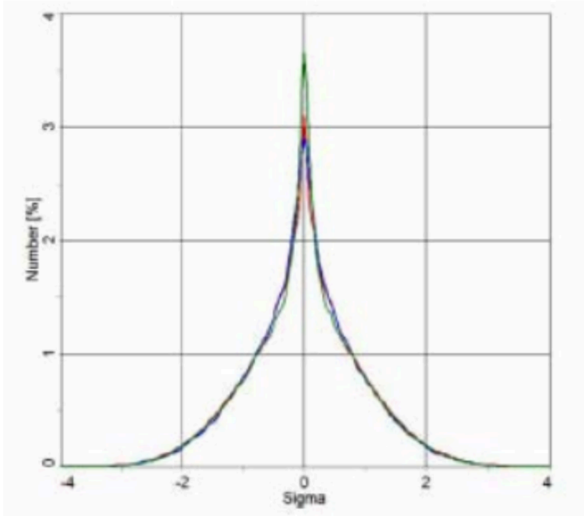



Figure 2: Horizontal (red), vertical (blue) and longitudinal (green) ion beam profiles based on assumption of Gaussian velocity distribution in all three planes.

# JLEIC Beam Parameters

| CM energy | GeV | 21.9 (low) | | 44.7 (medium) | | 63.3 (high) | |
|---|---|---|---|---|---|---|---|
| | | p | e | p | e | p | e |
| Beam energy | GeV | 40 | **3** | **100** | **5** | 100 | **10** |
| Collision frequency | MHz | **476** | | **476** | | **476** | |
| Particles per bunch | $10^{10}$ | **0.98** | **3.7** | **0.98** | **3.7** | **0.98** | **0.93** |
| Beam current | A | 0.75 | 2.8 | 0.75 | 2.8 | 0.75 | 0.71 |
| Polarization | % | 80 | 80 | 80 | 80 | 80 | 75 |
| Bunch length, RMS | cm | **3** | **1** | **1** | **1** | **1** | **1** |
| Norm. emitt., horiz./vert. | μm | **0.3/0.3** | 24/24 | **0.5/0.1** | 54/10.8 | **0.9/0.18** | 432/86.4 |
| Horizontal & vertical β* | cm | 8/8 | 13.5/13.5 | 6/1.2 | 5.1/1 | 10.5/2.1 | 4/0.8 |
| Vert. beam-beam param. | | 0.015 | 0.092 | 0.015 | 0.068 | 0.002 | 0.009 |
| Laslett tune-shift | | 0.06 | $7\times10^{-4}$ | 0.055 | $6\times10^{-4}$ | 0.056 | $7\times10^{-5}$ |
| Detector space, up/down | m | 3.6/7 | 3.2/3 | 3.6/7 | 3.2/3 | 3.6/7 | 3.2/3 |
| Hourglass(HG) reduction | | 1 | | 0.87 | | 0.86 | |
| Luminosity/IP, w/HG, $10^{33}$ | $cm^{-2}s^{-1}$ | **2.5** | | **21.4** | | **5.9** | |

Detail parameter lists for $E_{CM}$=100 GeV case will be available soon

# Machine Impedance vs. Threshold Impedance

- Longitudinal Single-Bunch Instability

$$\left|\frac{Z_{\parallel}(n)}{n}\right|_{\text{eff,th}} = \frac{2\pi|\eta|(E/e)\sigma_{\delta}^{2}}{I_{peak}}$$

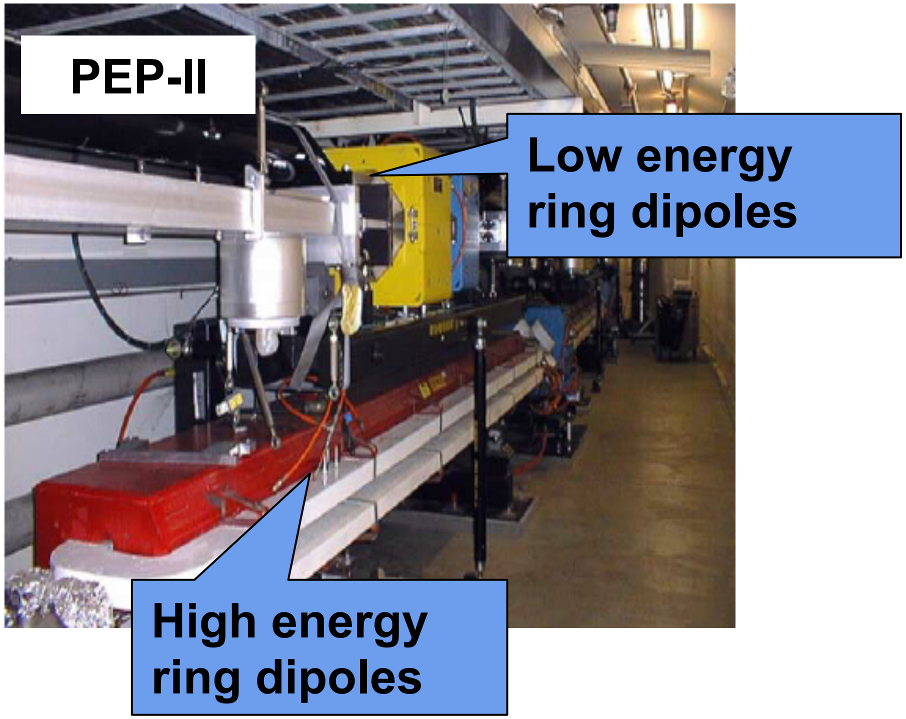
| | PEP-II (LER) | JLEIC Electron Ring | | | JLEIC p-Ring |
|---|---|---|---|---|---|
| $E$ (GeV) | 3.1 | 3 | 5 | 10 | 100 |
| $I_p$(A) | 113 | 59.0 | 62.35 | 50.6 | 15.6 |
| $\eta$ $(10^{-3})$ | 1.31 | 1.09 | 1.09 | 1.09 | 6.22 |
| $\sigma_{\delta}$ $(10^{-4})$ | 8.0 | 2.78 | 4.55 | 9.28 | 3.0 |
| $\left\|Z_{\parallel}/n\right\|^{\text{th}}$ $[\Omega]$ | 0.145 | 0.027 | 0.125 | 1.16 | 22.5 |
| | Stable | Unstable! | Marginally Stable | Stable | Stable |

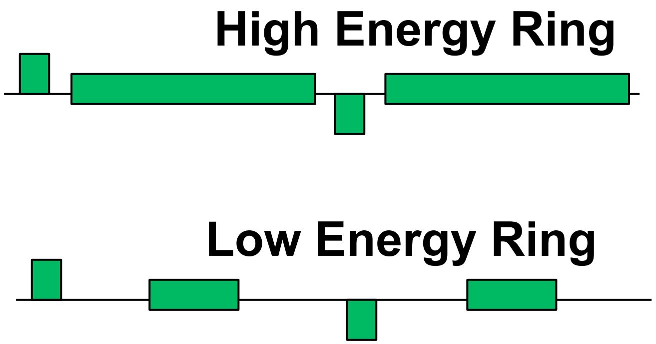
Estimated e-Ring Impedance:
$\left|Z_{\parallel}/n\right|^{\text{Ring}} \approx 0.1\ \Omega$

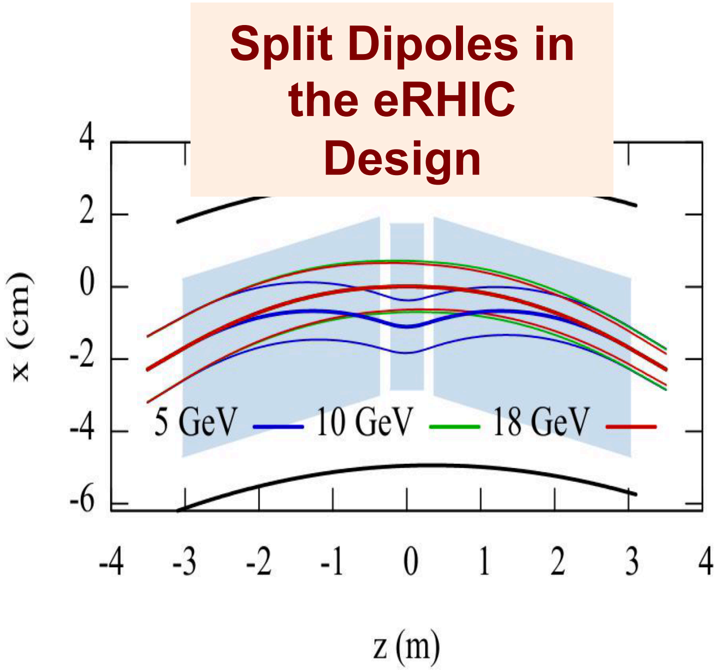
Estimated p-Ring Impedance:
$\left|Z_{\parallel}/n\right|^{\text{Ring}} \approx 0.1\ \Omega$

# Mitigation Methods

- Alternative beamline configurations at low energies




- Split dipole as proposed in the eRHIC design
- Damping wigglers
- Landau cavity

# Machine Impedance vs. Threshold Impedance

- Transverse Single-Bunch Instability

$$\left|Z_\perp(n)\right|_{\text{eff,th}} \approx \frac{16\sqrt{2}\pi}{3}\frac{(E/e)\upsilon_s}{\langle\beta_\perp\rangle I_{peak}}$$

(should include bunch lengthening effects)

| | PEP-II (LER) | JLEIC Electron Ring | | | JLEIC p-Ring |
|---|---|---|---|---|---|
| $E$ (GeV) | 3.1 | 3 | 5 | 10 | 100 |
| $I_p$(A) | 113 | 59.0 | 62.35 | 50.6 | 15.6 |
| $\nu_s$ $(10^{-2})$ | 3.7 | 0.88 | 1.46 | 2.51 | 5.3 |
| $\langle\beta_\perp\rangle$ | 20 | 13 | 13 | 13 | 64 |
| $\left|Z_\perp\right|^{\text{th}}[\text{M}\Omega/\text{m}]$ | 1.2 | 0.81 | 2.25 | 9.0 | 63 |

Stable

All Stable

Stable

Machine: e-Ring

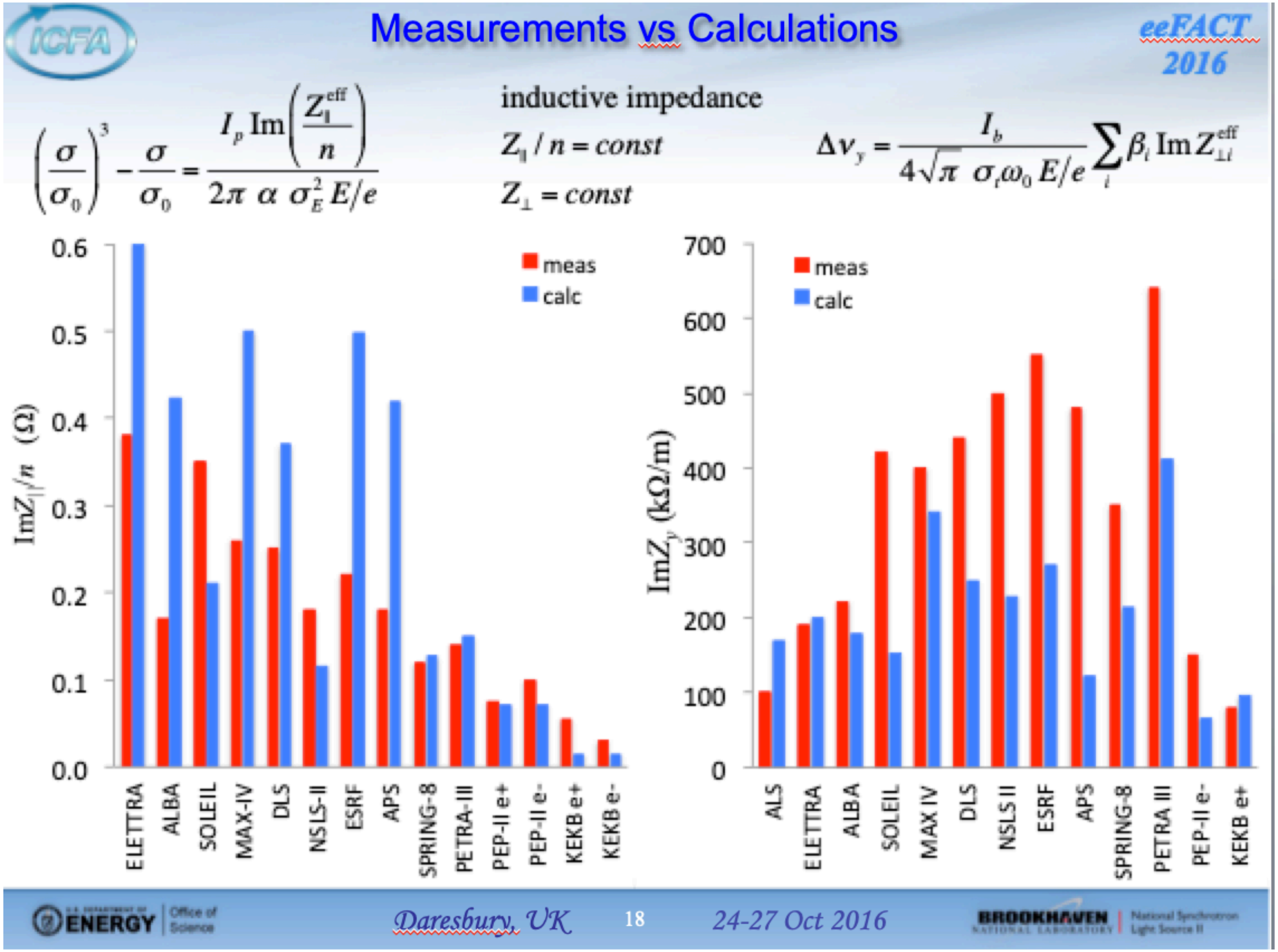
$\left|Z_\perp\right|^{\text{Ring}} \le 0.1\ \text{M}\Omega/\text{m}$

More serious effects could take place during the bunch formation process

Machine: p-Ring

$\left|Z_\perp\right|^{\text{Ring}} \le 0.1\ \text{M}\Omega/\text{m}$

# Broadband Impedance for Other Lepton Rings



# Broadband Impedance for Other Ion Rings

- RHIC (measurement)

$$\mathrm{Im}\left(Z_{\parallel}/n\right) \approx 1.5\ [\Omega]\ \text{(blue ring)}$$

$$\mathrm{Im}\left(Z_{\parallel}/n\right) \approx 5.4\ [\Omega]\ \text{(yellow ring)}$$

("Longitudianl Impedance of RHIC", M. Blaskwicz, etc)

$$\mathrm{Im}\left(Z_{x}^{eff}/n\right) \approx 13.79\ [M\Omega/m]\ \text{(blue ring)}$$

$$\mathrm{Im}\left(Z_{y}^{eff}/n\right) \approx 14.01\ [M\Omega/m]\ \text{(yellow ring)}$$

("Transverse Impedance Measurement in RHIC and the AGS",
N. Biancacci, etc)

- LHC (measurement)

$$\mathrm{Im}\left(Z_{\parallel}/n\right) = 0.08\ [\Omega]$$

("Beam Measurement of LHC Impedance…", J. F. E. Muller, etc)

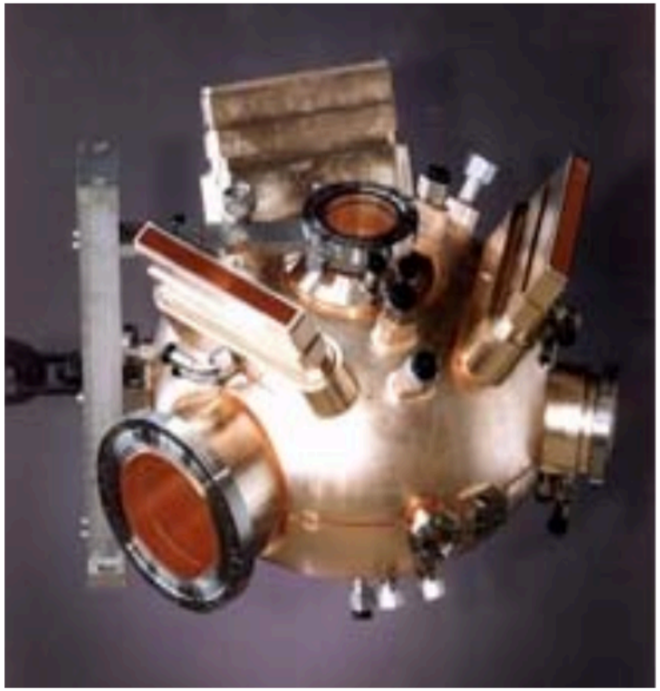
# 3. Narrowband Impedance in JLEIC

- RF Cavities
  - PEPII RF cavities
  - Ion ring cavities
  - Crab cavities

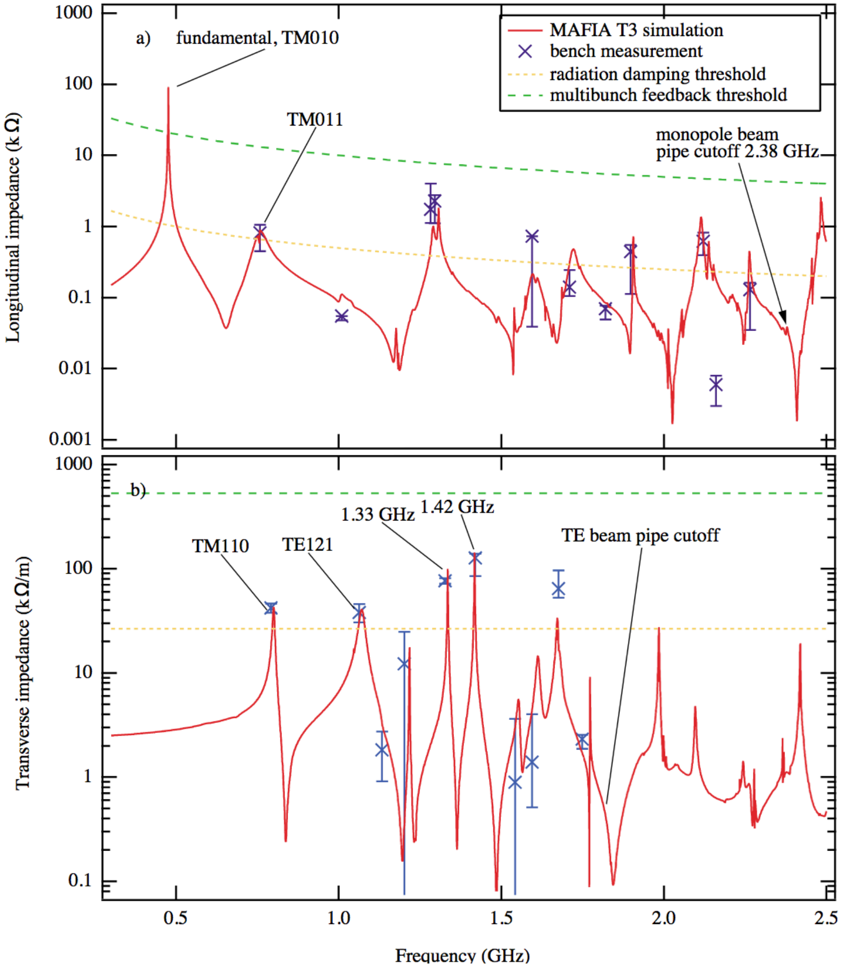
- CBI Growth Rates vs. FBS Damping Rate

# Narrowband Impedance: JLEIC e-Ring RF Cavity

- RF cavity in e-Ring (PEP-II cavities)



PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,



# Coupled Bunch Instability: JLEIC e-Ring

## Longitudinal CBI

| E [GeV] | 3 | 5 | 10 |
|---|---|---|---|
| $\tau_{a=1}$ [ms] | 2.9 | 4.0 | 72.8 |
| $\tau_{a=2}$ [ms] | 31.3 | 43.5 | 466 |
| $\tau_E$ [ms] | 187.4 | 40.5 | 5.1 |
| $V_{RF}$ [MV] | 0.40 | 2.02 | 17.87 |
| Cavity Number | 1 | 2 | 15 |

- Calculated from ZAP
- Growth times for $Z^{RF}$ +$Z^{RW}$
- Even bunch filling (assumed)
- Damping time from FBS :~ 1ms
- Crab cavity effect will be included later

## Transverse CBI

| E [GeV] | 3 | 5 | 10 |
|---|---|---|---|
| $\tau_{a=0}$ [ms] | 1.6 | 2.7 | 64 |
| $\tau_{a=1}$ [ms] | 12.8 | 19.6 | 39.8 |
| $\tau_y$ [ms] | 375 | 81 | 10.1 |
| $V_{RF}$ [MV] | 0.40 | 2.02 | 17.87 |
| Cavity Number | 1 | 2 | 15 |

(assume $\xi$=1, $\Delta\upsilon_\beta$=3e-04)

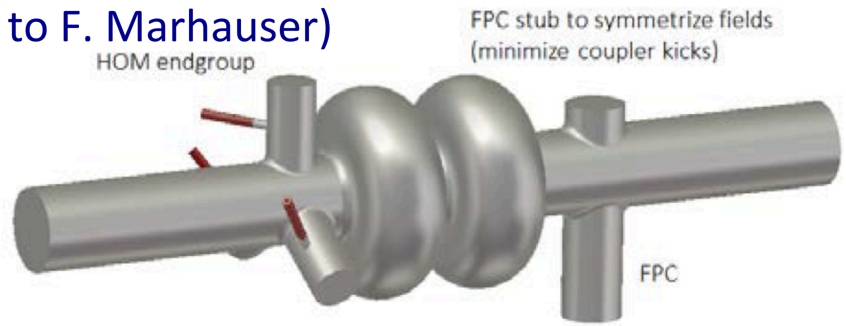
due to resistive wall impedance (Cu)

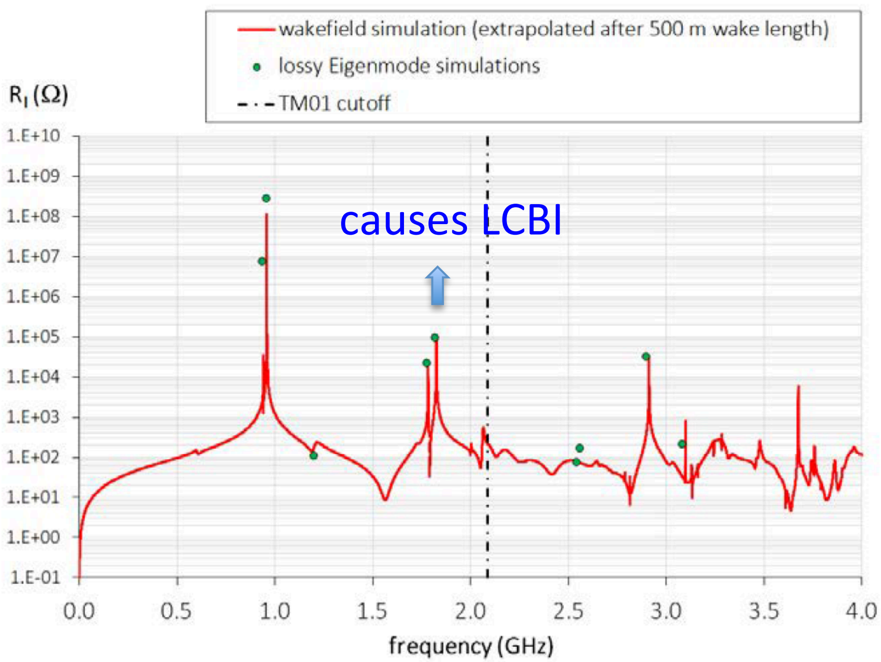
Cannot be improved by HOM damping

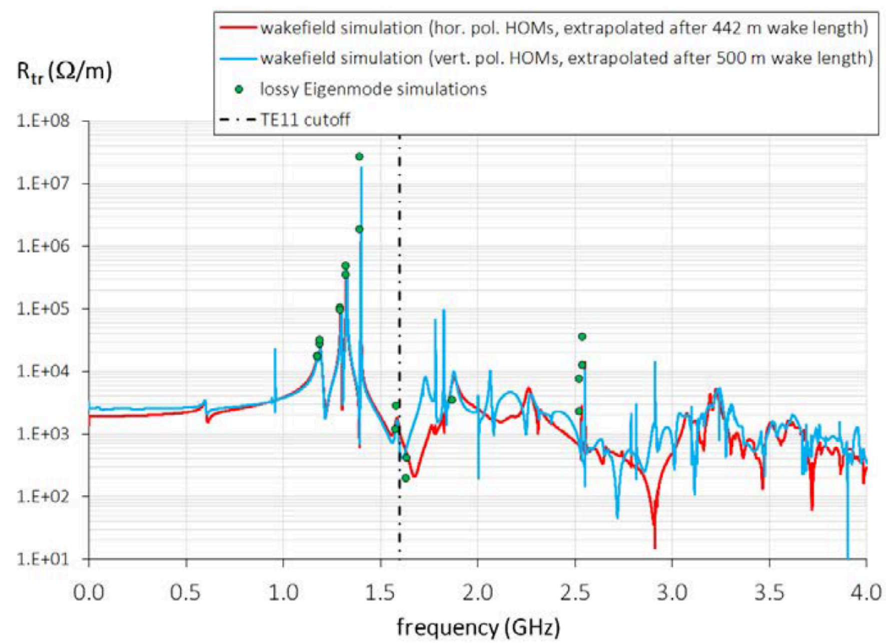
# Narrowband Impedance: Ion-Ring RF Cavity

- 956 MHz 2-cell Cavity (Courtesy to F. Marhauser)

as tradeoff between accelerating and HOM-damping efficiency



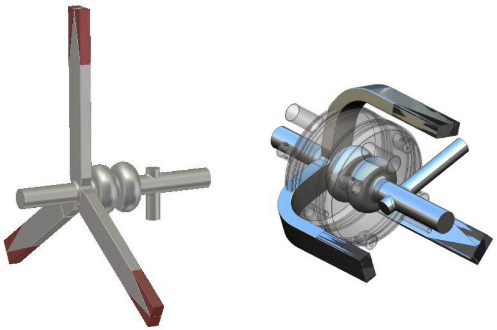



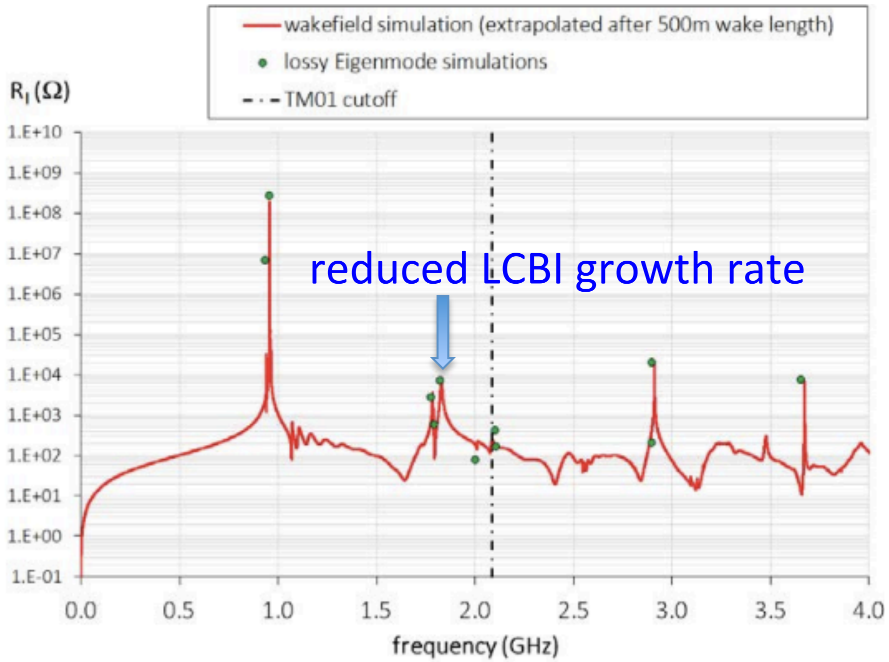
# Narrowband Impedance: Ion-Ring RF Cavity

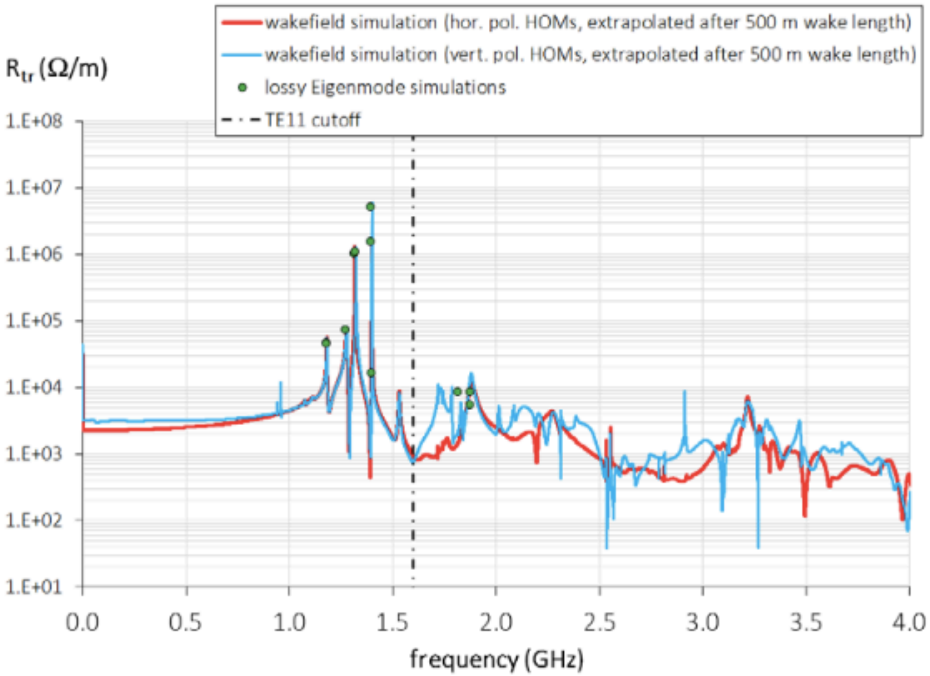
- 956 MHz 2-cell Cavity

(Courtesy to F. Marhauser)



waveguide couplers



# Coupled Bunch Instability: JLEIC p-Ring

## Longitudinal CBI

| E [GeV] | 100 |
|---|---|
| $\tau_{a=1}$ [ms] | 30.7 |
| $\tau_{a=2}$ [ms] | 6.2 |
| $V_{RF}$ [MV] | 42.6 |
| Cavity Number | 34 |

Caused By $Z^{RW}$!

- Need feedback to damp longitudinal quadrupole mode CBI
- Need to consider growth rate for a non-parabolic bunch

## Transverse CBI

| E [ GeV] | 100 |
|---|---|
| $\tau_{a=0}$ [ms] | 24.4 |
| $\tau_{a=1}$ [ms] | 805 |
| $\tau_{y}$ [min] | $>30$ |
| $V_{RF}$ [MV] | 42.6 |
| Cavity Number | 34 |

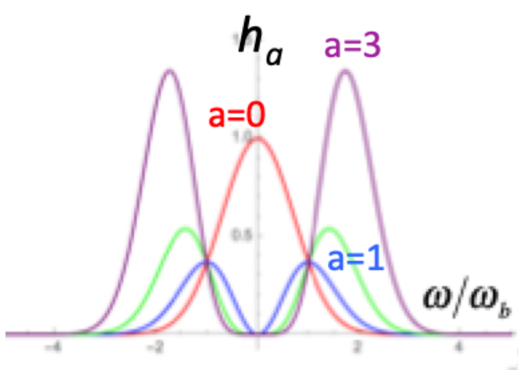
(assume $\xi$=1, $\Delta\upsilon_{\beta}$=3e-04)

# Effective Impedance

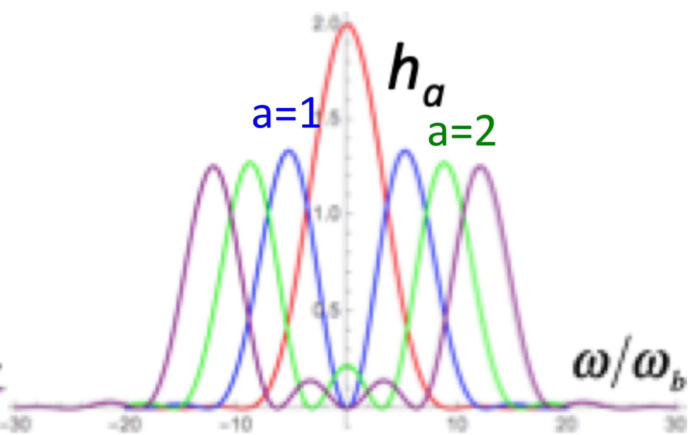
$$\left[\frac{Z_{\parallel}}{n}\right]_{\text{eff}}^{\mu,a} = \int d\omega \underbrace{\left(\frac{Z_{\parallel}(\omega)}{\omega/\omega_0}\right)}_{\substack{\text{machine}\\ \text{impedance}}} \underbrace{f_b(\omega)}_{\substack{\text{bunch}\\ \text{spectra}}},$$

$$f_b(\omega) = \underbrace{\frac{h_a(\omega)}{\sum_p h_a(\omega)}}_{\substack{\text{single-bunch}\\ \text{mode spectra}}} \underbrace{\sum_{p=-\infty}^{\infty} \delta\left(\omega - \omega_p''\right)}_{\text{Multi-bunch spectra}}$$

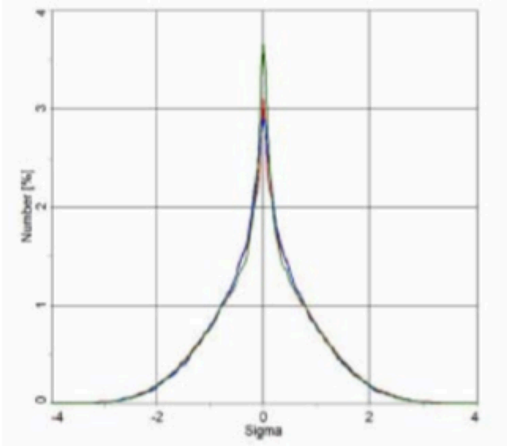
Gaussian Bunch




Parabolic Bunch

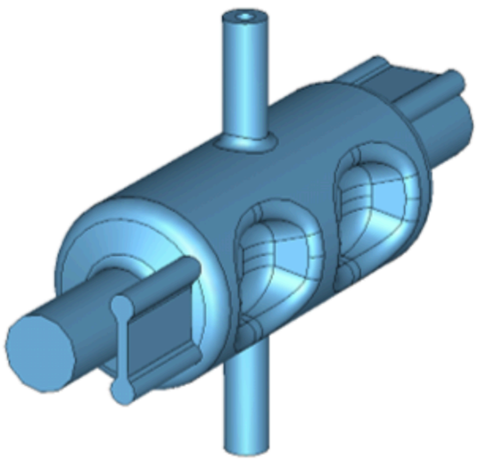


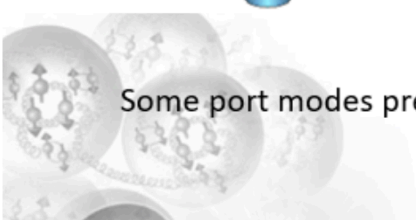

Bunch distribution under strong electron cooling



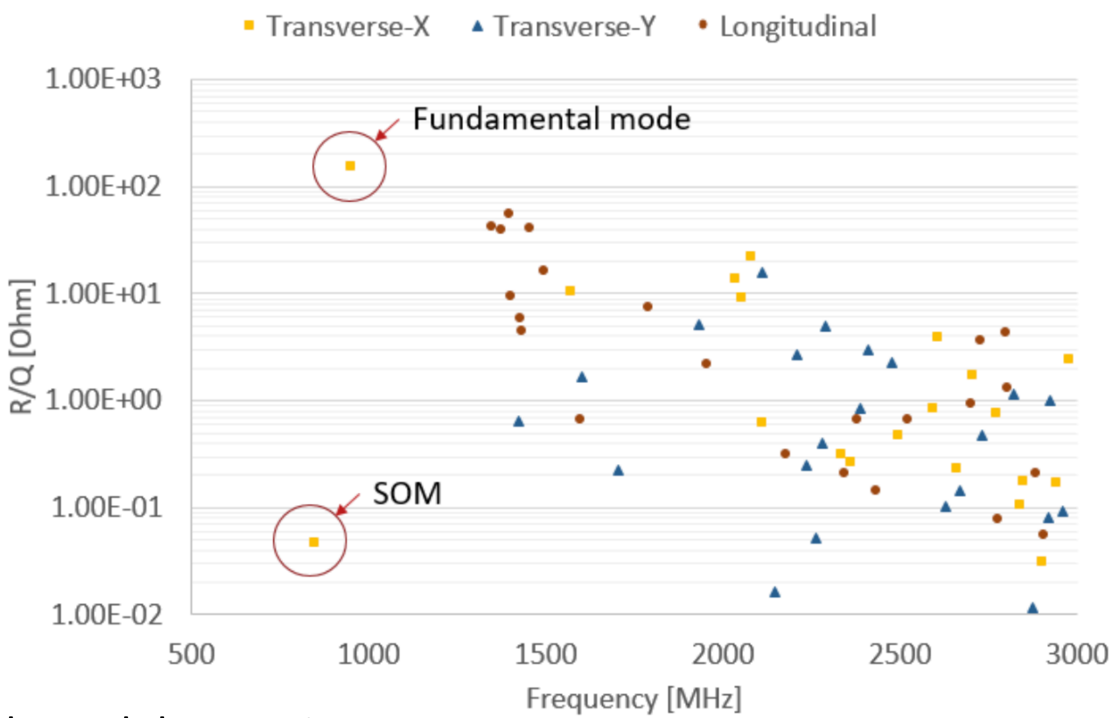
# Crab Cavities in JLEIC

Proposed number of cavities are 2 at electron ring and 12 at ion ring.





Some port modes present

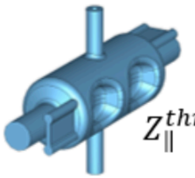



Fundamental power coupling through beam pipe.
HOM damping through coaxial electro-magnetic coupling and wave guides

Transverse X modes requires further damping through beam pipe

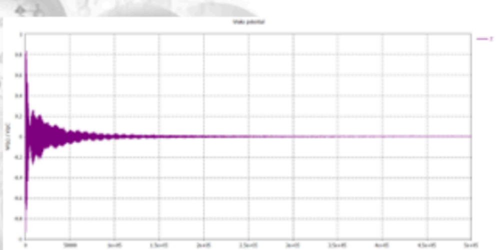
(Courtesy to HK Park)

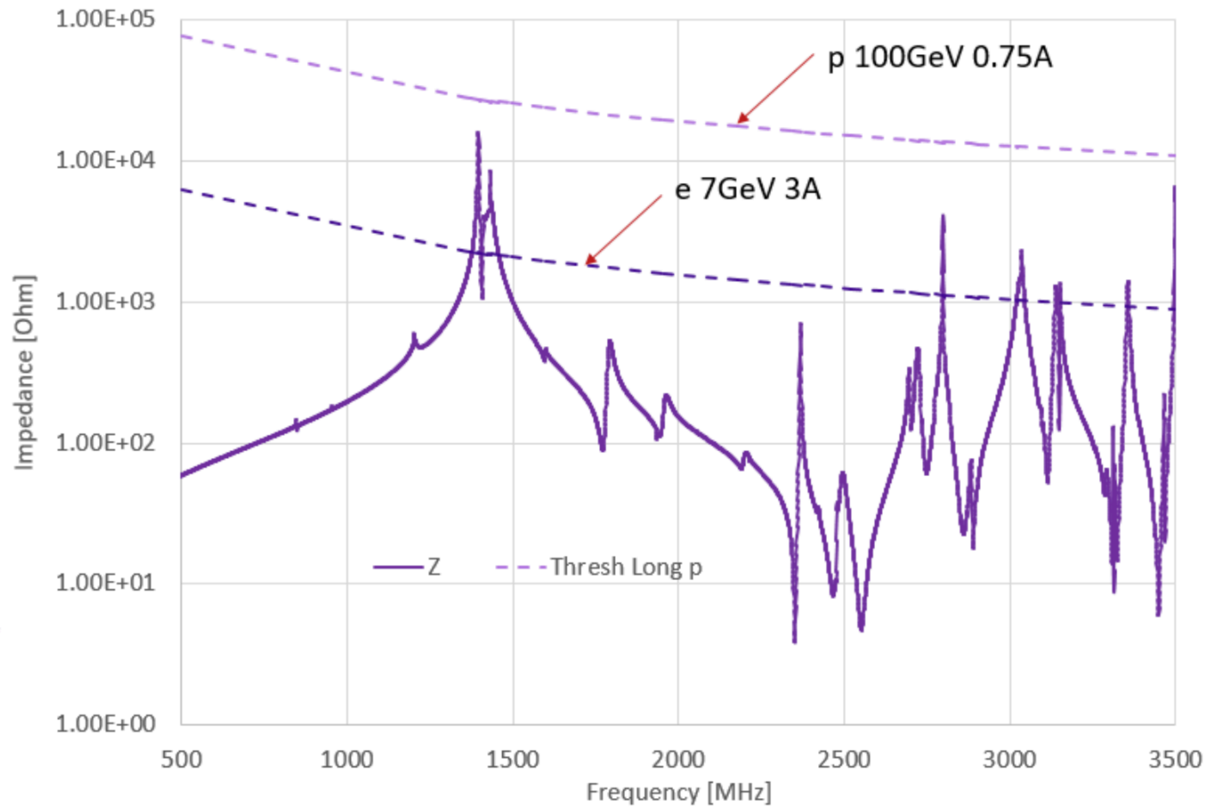
# Wakefields – Longitudinal



$$Z_{\parallel}^{thresh.} = \frac{1}{N_C} \frac{1}{f_{\parallel,HOM}} \frac{2E_b Q_s}{I_b \alpha \tau_s}$$

| | Unit | e | p |
|---|---|---|---|
| $N_C$ | - | 4 | 24 |
| $E_b$ | GeV | 7 | 100 |
| $Q_s$ | | .009 | .054 |
| $I_b$ | A | 3 | .75 |
| $\alpha$ | GeV/c | $1.09\times10^{-3}$ | $5.26\times10^{-3}$ |
| $\tau_s$ | ms | 3 | |

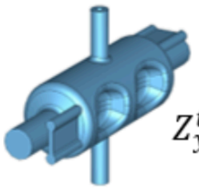






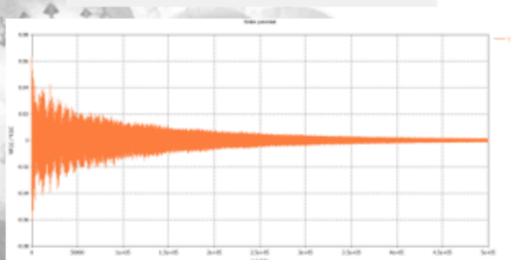

(Courtesy to HK Park)

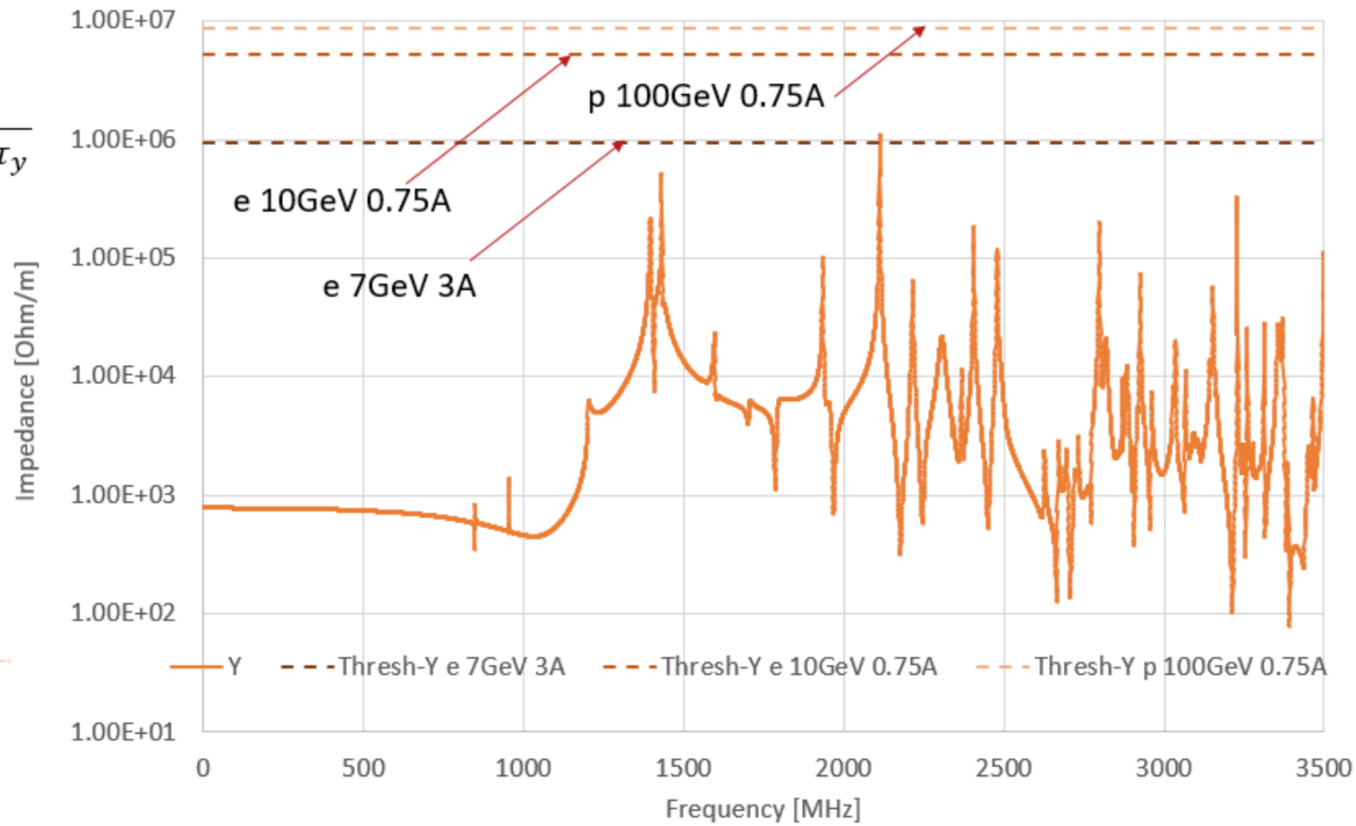
# Wakefields – Transverse Y



$$Z_y^{thresh.} = \frac{1}{N_C} \frac{2E_b}{f_{rev} I_b \beta_y \tau_y}$$

| | Unit | e | p |
|---|---|---|---|
| $N_C$ | - | 4 | 24 |
| $E_b$ | GeV | 7 | 100 |
| $I_b$ | A | 3 | .75 |
| $\beta_y$ | m | 3 | |
| $f_{rev}$ | kHz | 139 | |
| $\tau_y$ | ms | 3 | |

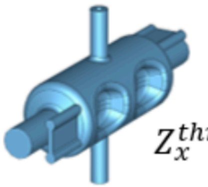






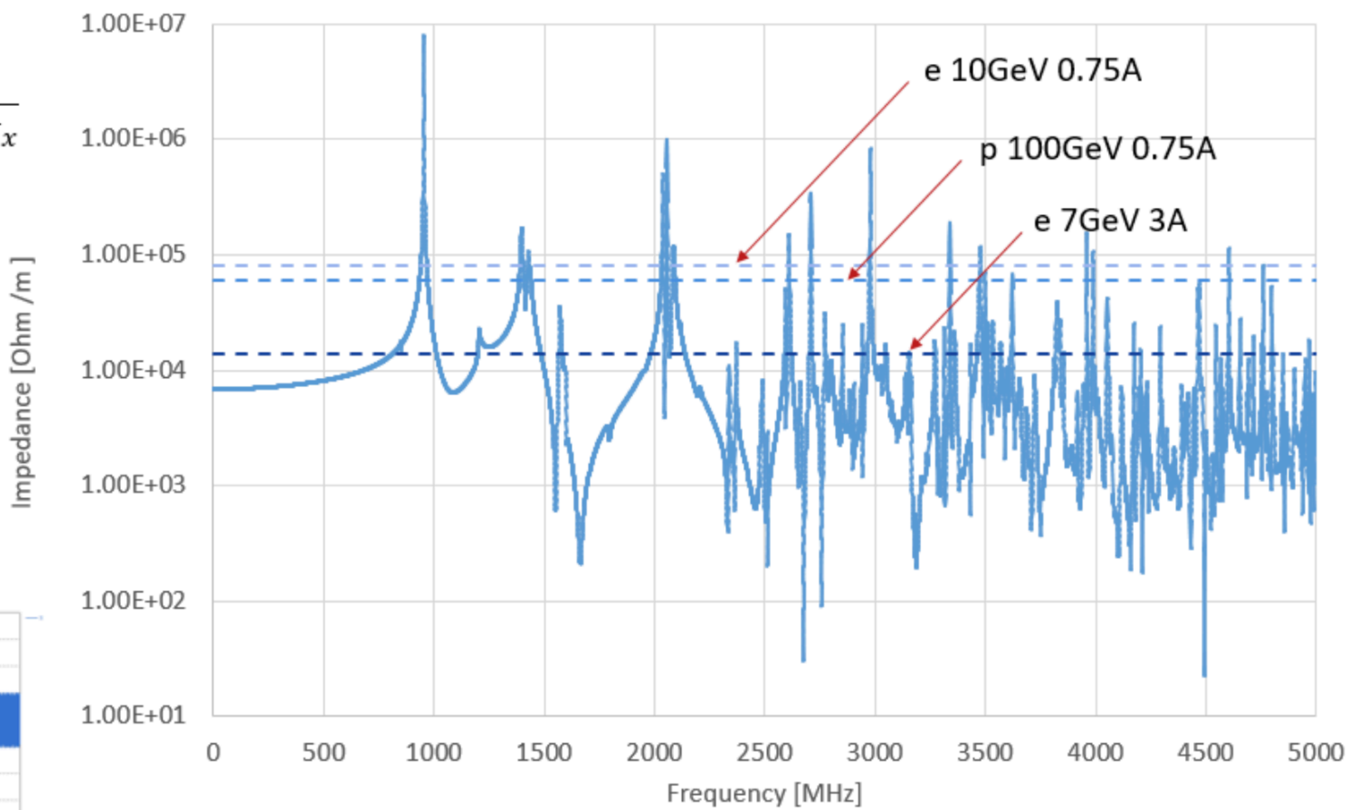

(Courtesy to HK Park)

# Wakefields – Transverse X



$$Z_x^{thresh.} = \frac{1}{N_C} \frac{2E_b}{f_{rev} I_b \beta_x \tau_x}$$

| | Unit | e | p |
|---|---|---|---|
| $N_C$ | - | 4 | 24 |
| $E_b$ | GeV | 7 | 100 |
| $I_b$ | A | 3 | .75 |
| $\beta_x$ | m | 200 | 450 |
| $f_{rev}$ | kHz | 139 | |
| $\tau_x$ | ms | 3 | |




(Courtesy to HK Park)

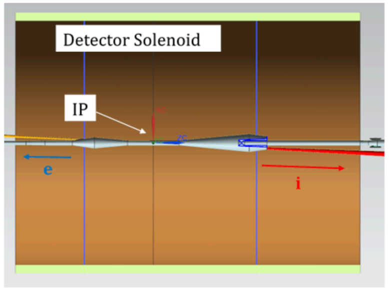
# 4. Ongoing Designs

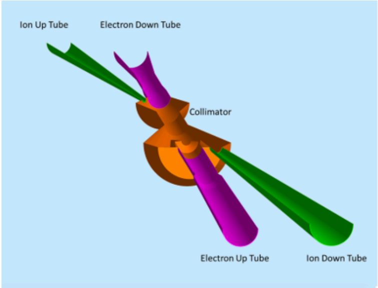
- IR Chamber
- Shielded Bellows in IR region
- Collimators
- Roman Pot

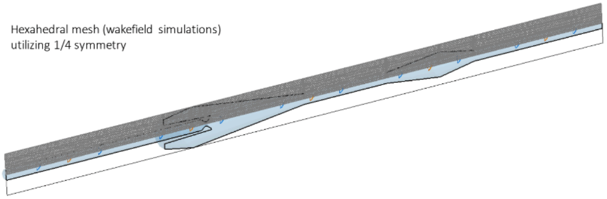
# IR Region Vacuum Chamber

## JLEIC IR Chamber CAD Model

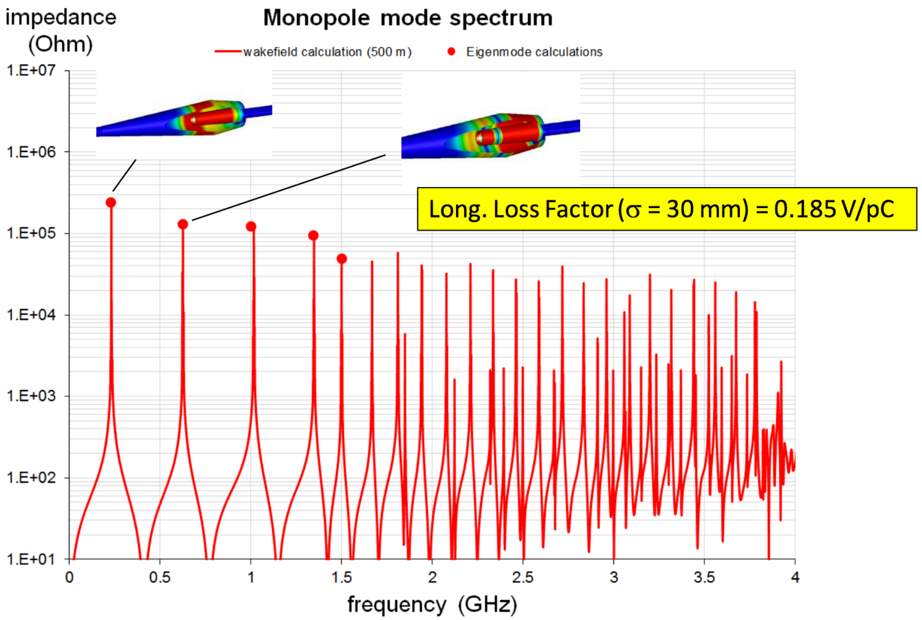
(Courtesy to F. Marhauser)



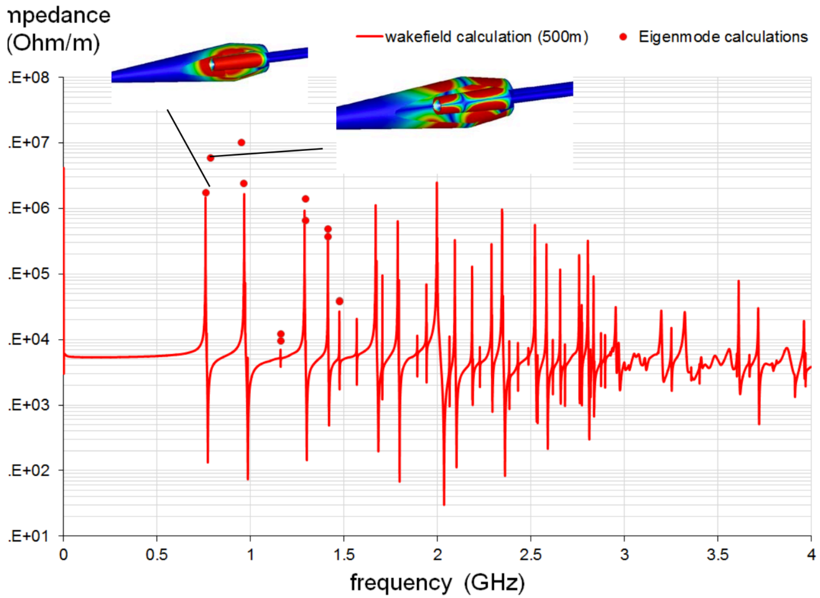




## Monopole Modes



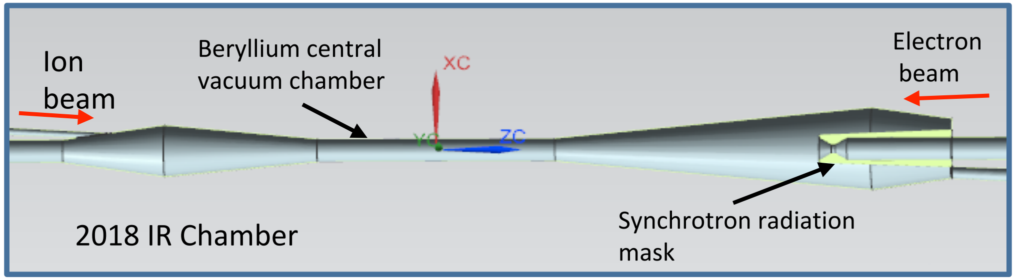

## Dipole Modes

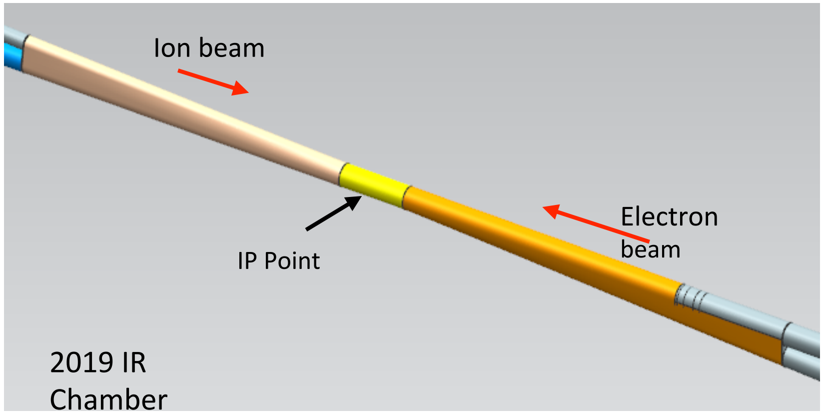


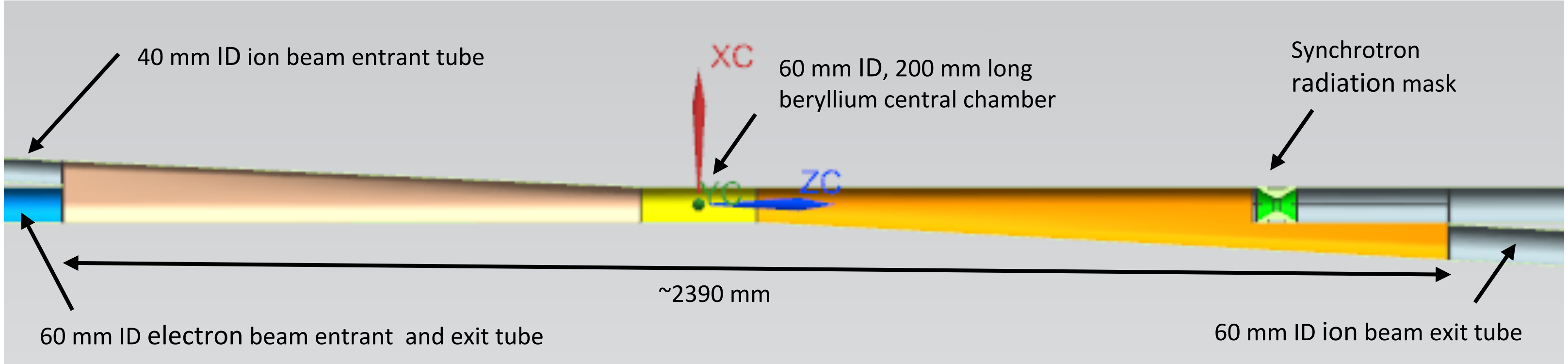
# IR Region Vacuum Chamber

(Courtesy to M. Wiseman)

- 2018 IR vacuum chamber had large beam impedance
  - Calculation by F. Marhauser
- 2019 IR vacuum chamber
  - "Cone like" transitions from beam tubes to the central beryllium IR chamber
  - Synchrotron mask unchanged (1000 mm from IP, 24 mm ID/10 mm long )
  - Design in progress and impedance calculations still to be done



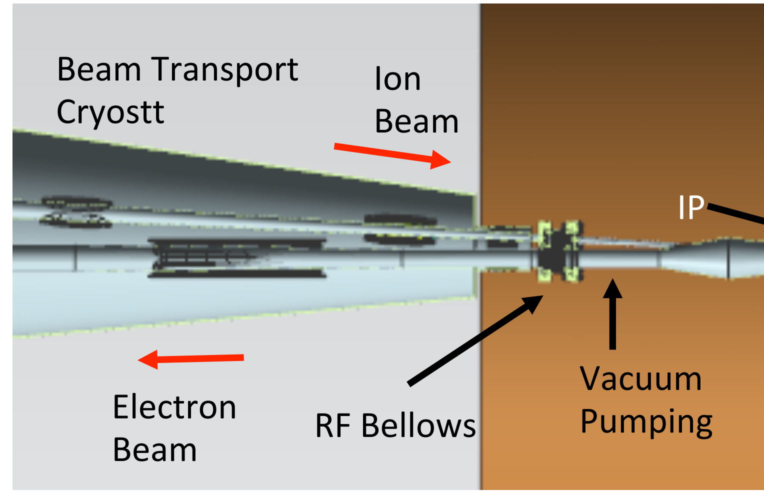



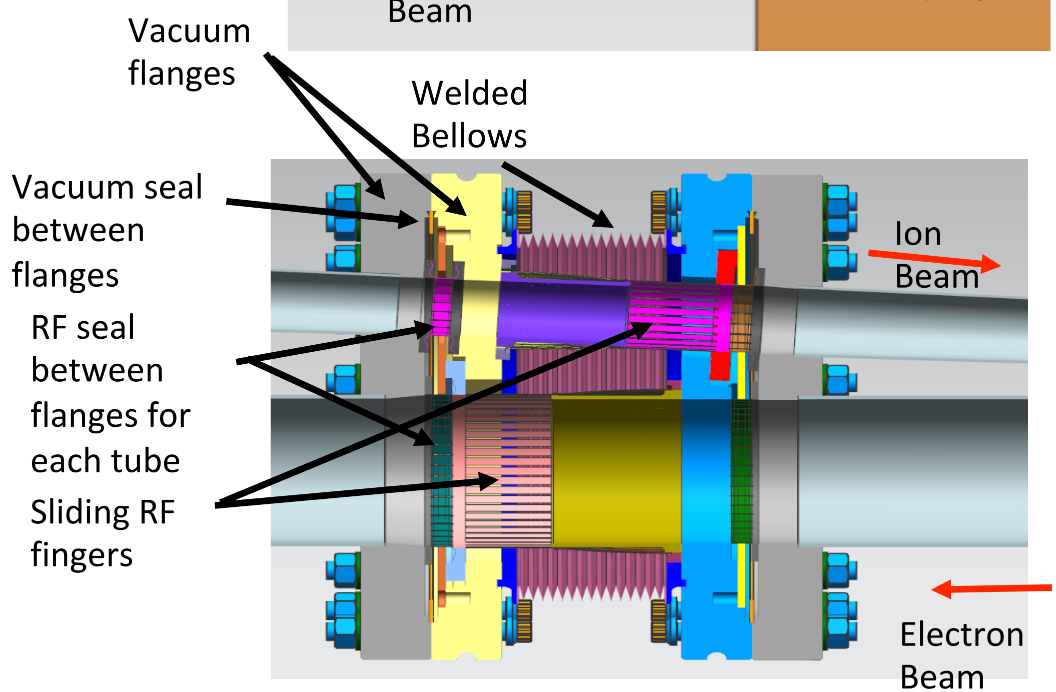



# IR Region Combined Shielded Bellows

- Bellows required between the beam transport cryostat and the IP vacuum chamber to allow for assembly and thermal contraction of the cold beam lines in the cryostat
- Close beam tubes require unique design
  - Individually shielded beam tubes
  - Single bellows around both beam tubes
  - Common vacuum and flanges
  - Based on PEP-II shielded bellows design
- New lattice moves the design shown ~40 cm further away from the IP
  - Increases the beamline separation
  - Also want to increase the ion beamline diameter
- Impedance calculations still to be done

(Courtesy to M. Wiseman)

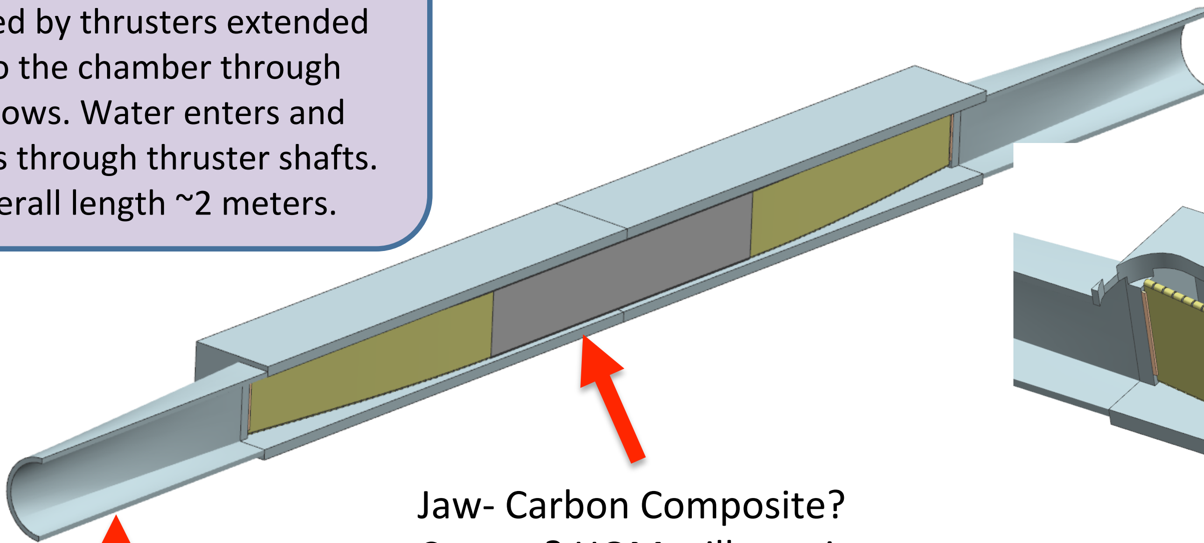


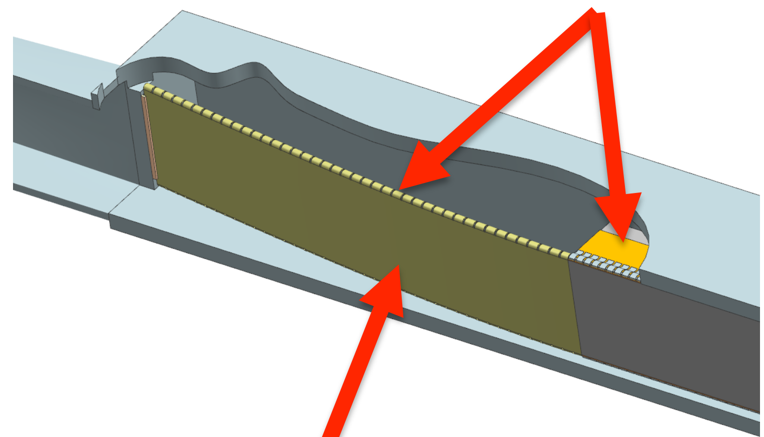
# Conceptual JLEIC Collimators

Symmetric water cooled jaws moved by thrusters extended into the chamber through bellows. Water enters and leaves through thruster shafts. Overall length ~2 meters.

(Courtesy to B. Crahen)



Flexible contacts



Jaw- Carbon Composite? Copper? HOM will require some loss mechanism.

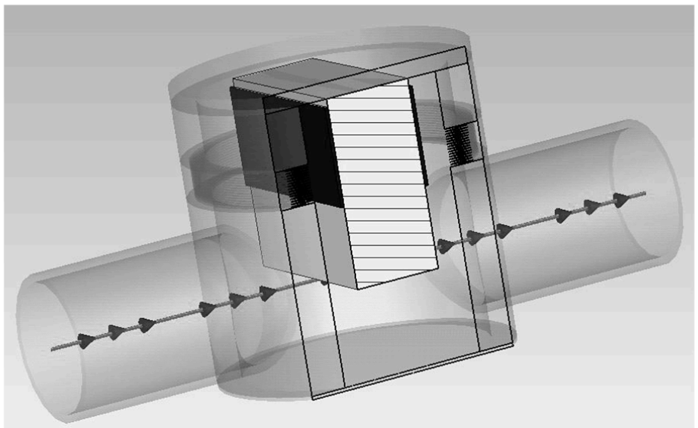
80mm round to 80 mm square transition. The square section allows use of single wide “finger”

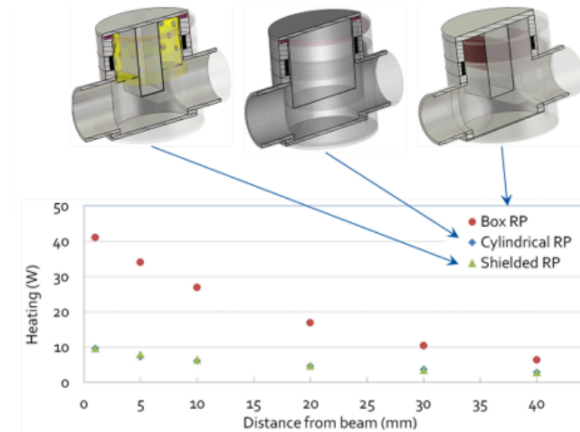
**Vacuum space model has been generated and submitted for impedance analysis**

Contact finger. Fixed to the jaw, captured sliding contact at the housing end.

# Roman Pot

The Roman Pot is an experimental technique for detection of forward protons from elastic or diffractive scattering.



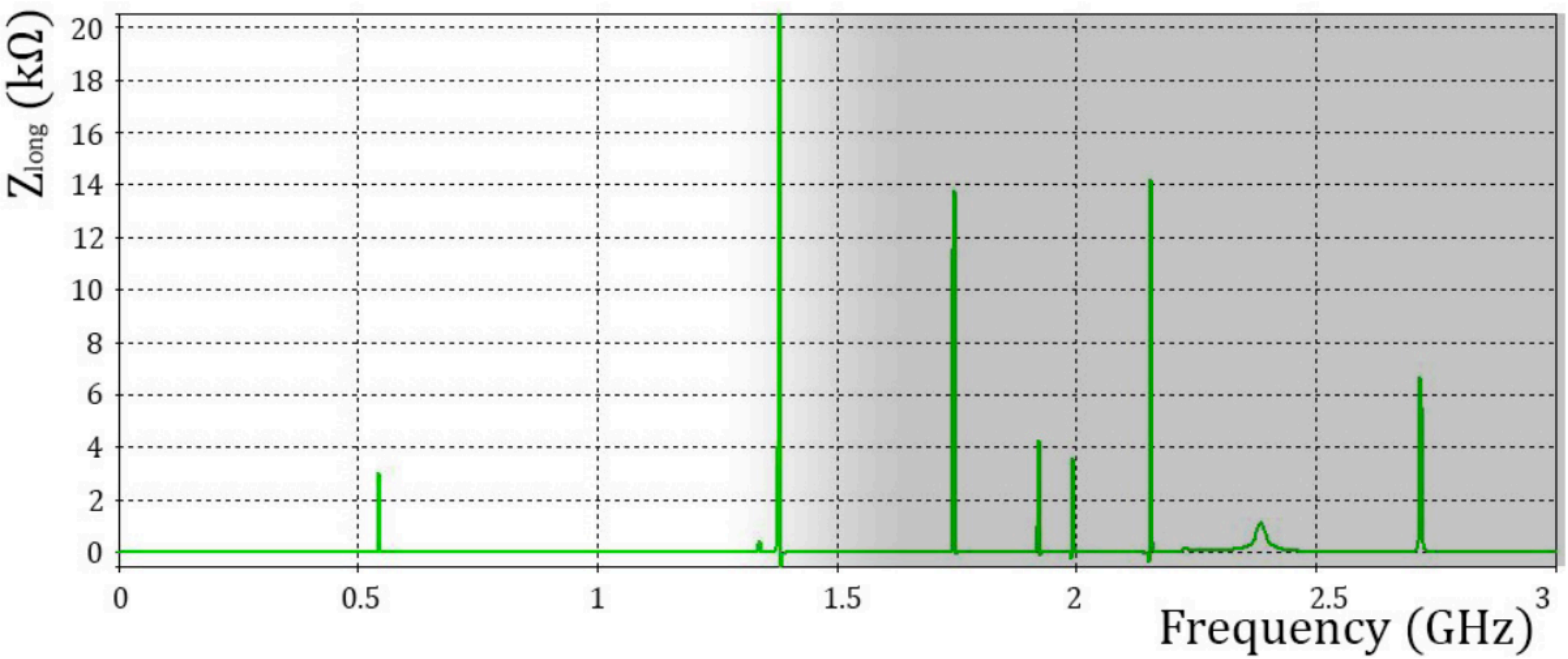



| | Distance from the beam [mm] | $\frac{\Im Z^0_{\mathrm{long}}}{n}$ [m$\Omega$] | fraction of $\left(\frac{\Im Z_{\mathrm{long}}}{n}\right)^{\mathrm{eff}}_{\mathrm{LHC}}$ (90 m$\Omega$) | $\overline{\Im Z^{\mathrm{driving}}_{\mathrm{trans}}}$ [M$\Omega$/m] | fraction of $\Im(Z_{\mathrm{x}})^{\mathrm{eff}}_{\mathrm{LHC}}$ (25 M$\Omega$/m) | Heating [W] |
|---|---|---|---|---|---|---|
| BoxRP | 1<br>40 (garage) | 1.7<br>0.41 | $<$ 1.9%<br>$<$ 0.45% | 0.15 | $<$ 0.6 % | 62<br>10 |
| LongBoxRP | 1<br>40 (garage) | 2.6<br>0.45 | $<$ 2.9%<br>$<$ 0.5% | 0.15 | $<$ 0.6 % | 241<br>39 |

Table 1: Main results of the simulation of the present box RP (BoxRP) and the rotated box RP (LongBoxRP). The effective impedances are compared with the total value estimated for the present LHC impedances.

(N. Minafra, CERN)

# Roman Pot: Narrowband Impedance




*For LHC, the dark area is beyond bunch frequency range (bunch rms length=7cm)
*For JLEIC, the dark area still contributes

(N. Minafra, CERN)

# 5. Summary of JLEIC Impedance Status

- We are at the beginning phase of impedance studies
- Broadband impedances
  - Preliminary estimations are done by referencing existing machine impedance budget
  - Comparison with instability threshold indicate weak areas
- Narrowband impedances
  - New ion ring cavities are designed
  - Growth rates for CBI are computed and compared with feedback damping rates
  - Crab cavity design and HOM results
- Engineering Designs for various components are underway

# Thank You!