Power Loss in Project X SSR1 Cavities due to Resonance Excitation of Monopole HOMs

A. Sukhanov, M. Hassan, I. Gonin, V. Yakovlev

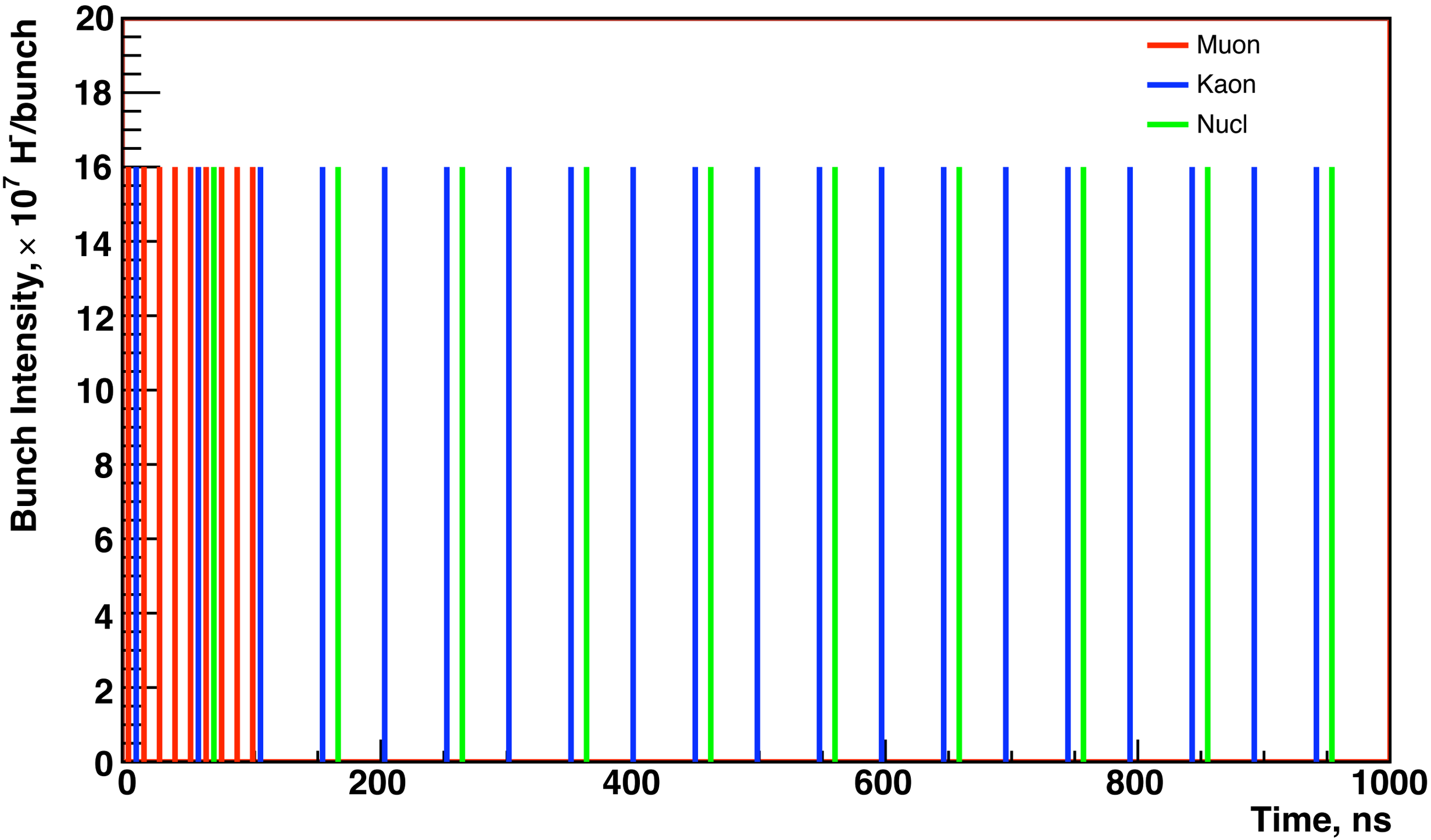
Fermilab TD SRF Department

Overview of HOM Power Loss Calculation

- Beam structure corresponds to the "standard" 3 GeV program with three components ("muon", "kaon" and "nuclear")
- 38 monopole high order modes w/ frequency < 2.2 GHz
- Since geometry of SSR1 cavities is complicated, integrals of the surface magnetic field $|H|^2$ are calculated using geometry factors rather than by direct integration
- Contribution from off-diagonal terms $H_i H_j^*$ is neglected
  - We know from our analysis of 650 MHz HOMs that this contribution is <<1%
  - In SSR1 cavities off-diagonal term are ~10-30%
- Assume 1 MHz spread in HOM frequencies
  - Confirmed by direct measurements of HOM spectra in SSR1 cavities (Timergali/ Mohamed)
- Calculate power loss as a function of beam velocity

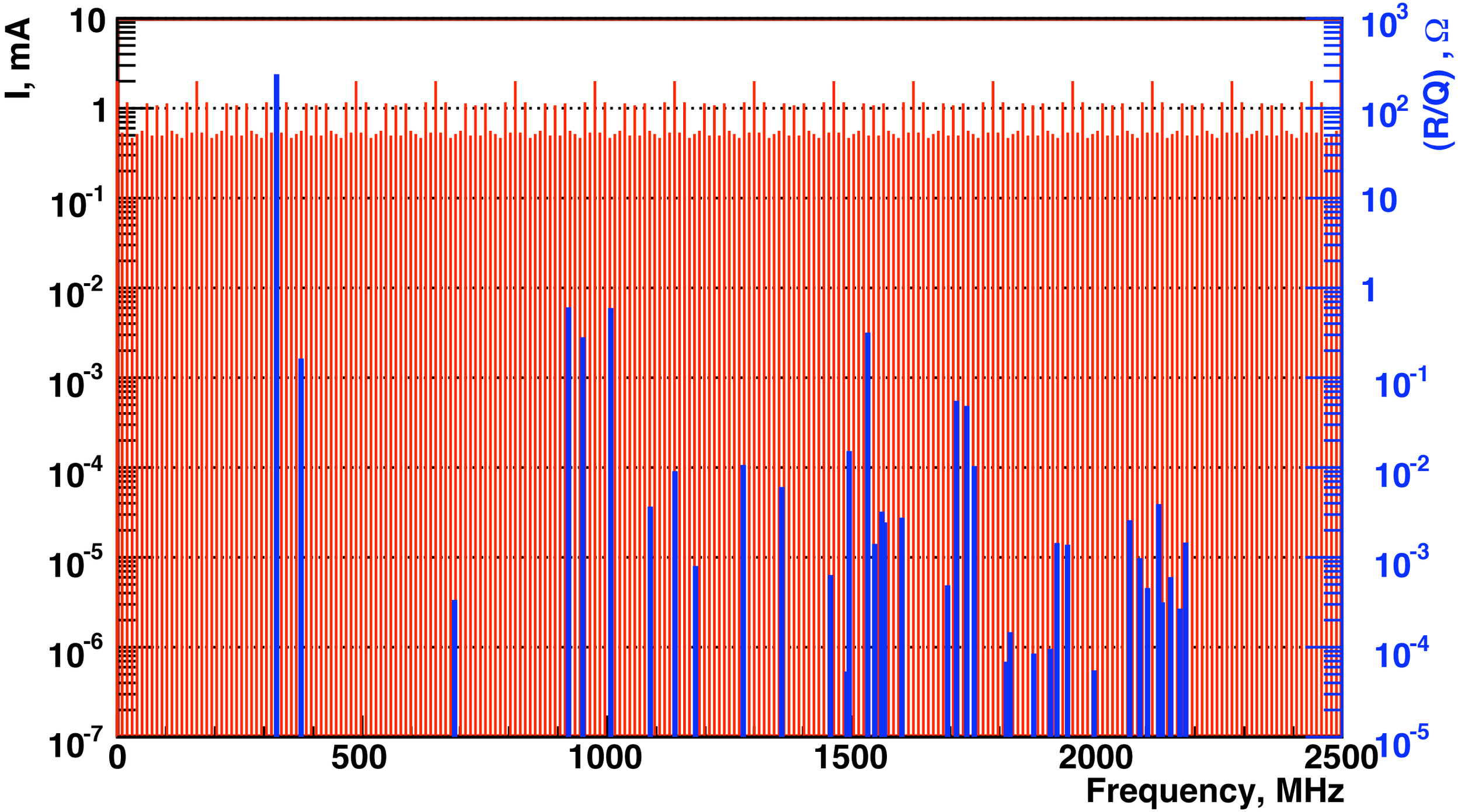
Beam Structure

- Project X beam structure for 3 GeV program



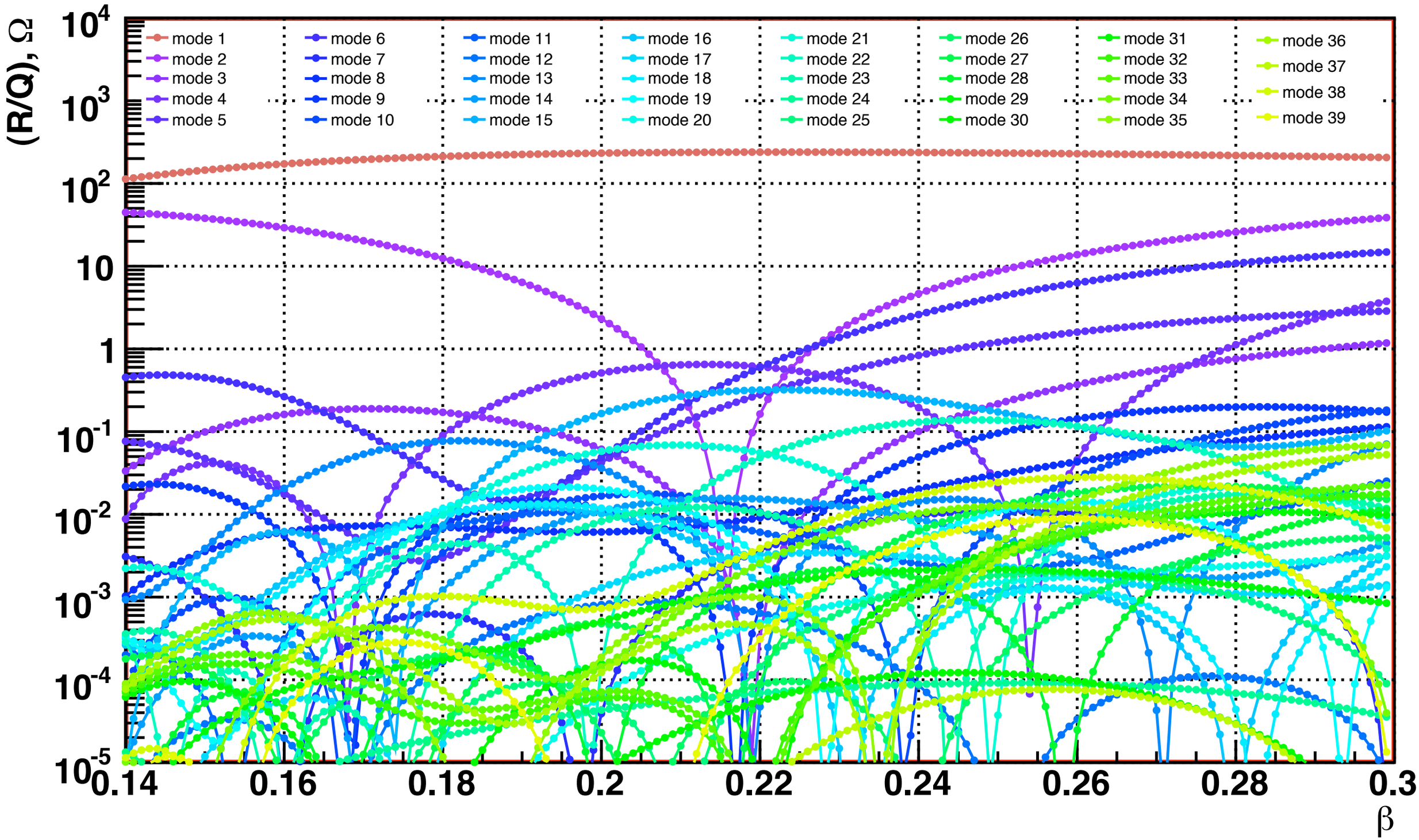
Beam and HOM Spectra

- Idealized beam (red) and monopole HOM (blue) spectra
  - Only harmonics of 10 MHz are shown in beam spectrum



Cavity Impedance *vs* Beam Velocity

- (R/Q) as a function of beam velocity



Details of Power Loss Calculations I

- Magnetic field on the surface of cavity induced by the n^{th} component of the beam spectrum is equal to the sum of all exited modes:

$$H_n = \sum_p H_{pn}(z), \text{ where } H_{pn} = \frac{-i\omega_p^2}{\omega_n^2 - \omega_p^2 - i\frac{\omega_n\omega_p}{Q_p}} \frac{I_n}{2} \sqrt{\frac{(R/Q)_p}{\omega_p W_p}} H_p^{sim}(z)$$

- Here:
  - $H_p^{sim}(z)$ is the field calculated by RF simulation for mode p
  - ω_p is the mode frequency
  - W_p is the mode stored energy
  - Q_p and $(R/Q)_p$ are the mode quality factor and impedance
  - I_n and ω_n are the amplitude and frequency of beam harmonic

Details of Power Loss Calculations II

- Total losses in the cavity walls are calculated as sum of losses by individual beam harmonics:

$$P = \sum_n \frac{1}{2} R_n \oint |H_n|^2 dS$$

- Where the wall resistance (H. Padamsee *et al*, *RF Superconductivity for Accelerators*)

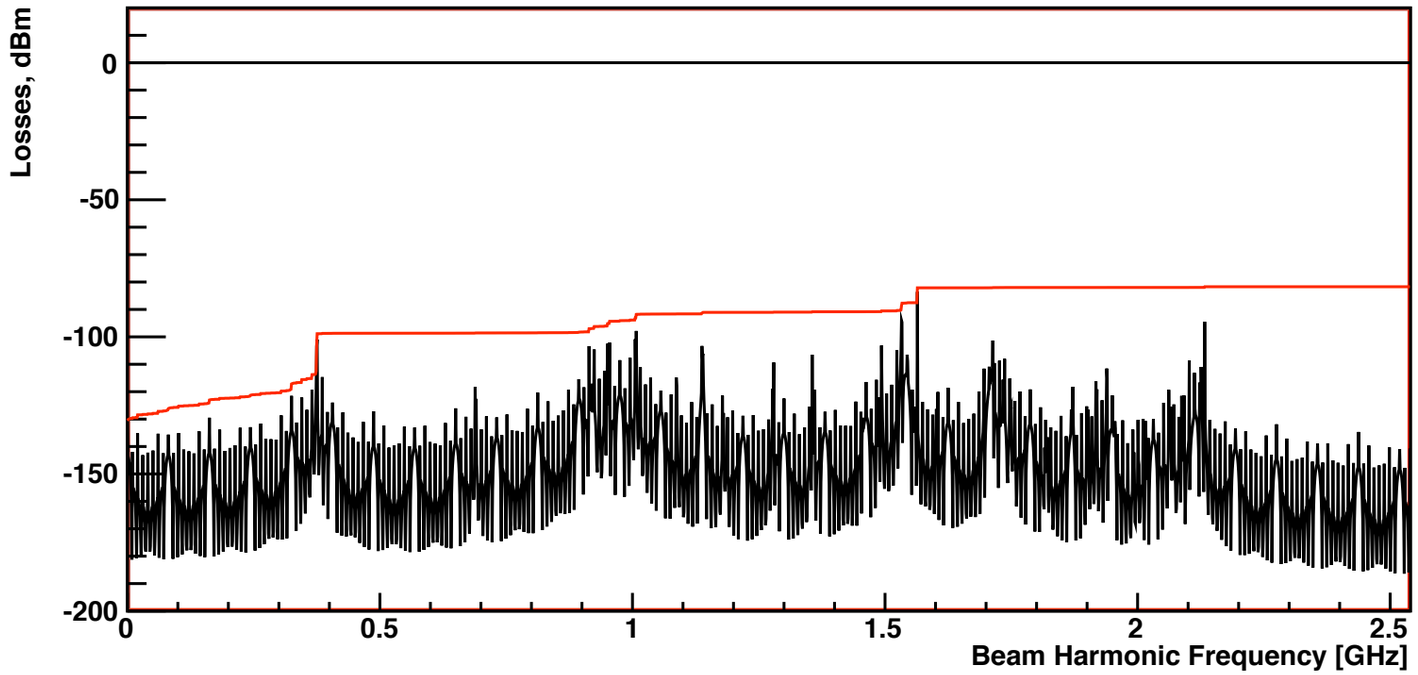
$$R_n = R_{\text{res}} + R_{\text{BCS}}, \text{ where } R_{\text{res}} = 10\text{n}\Omega,$$

$$R_{\text{BCS}}[\Omega] = 2 \cdot 10^{-4} \frac{1}{T[\text{K}]} \left(\frac{f_n[\text{GHz}]}{1.5} \right)^2 \exp\left(-\frac{17.67}{T[\text{K}]} \right)$$

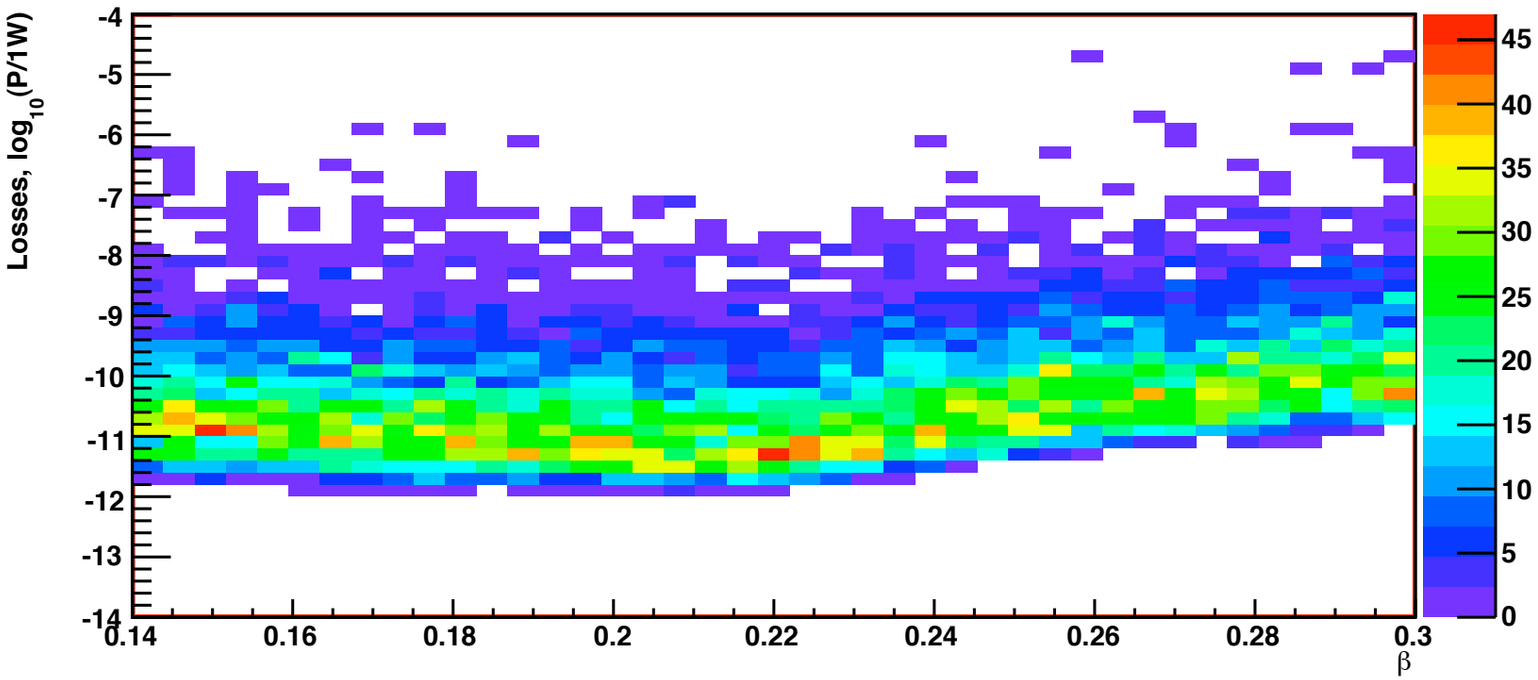
- Here:
  - f_n is beam harmonic linear frequency
  - T = 2K

HOM Power Loss Calculation

- Example of loss calculation



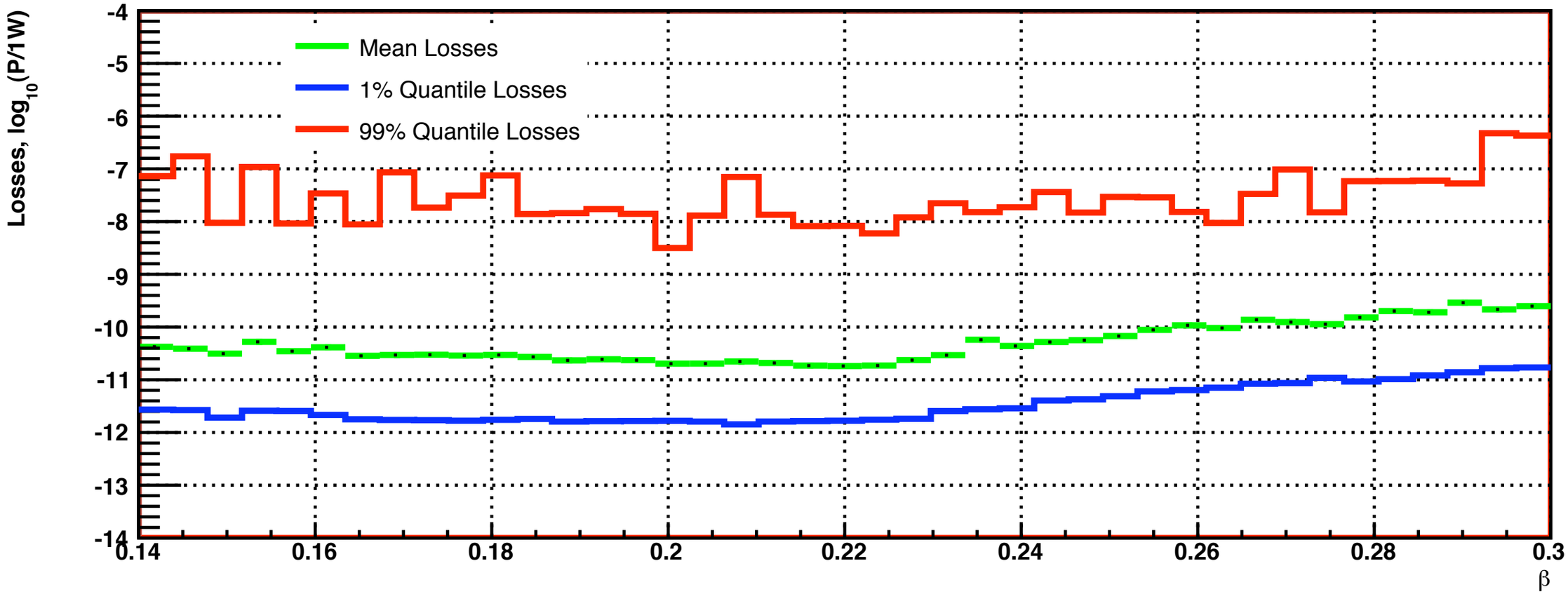
- HOM frequencies are sampled from Gaussian distribution with sigma = 1 MHz
- Black lines show contribution from individual beam lines
- Red line shows total power loss



- Power loss distribution as a function of beam velocity for 10^4 cavities with varying HOM frequencies

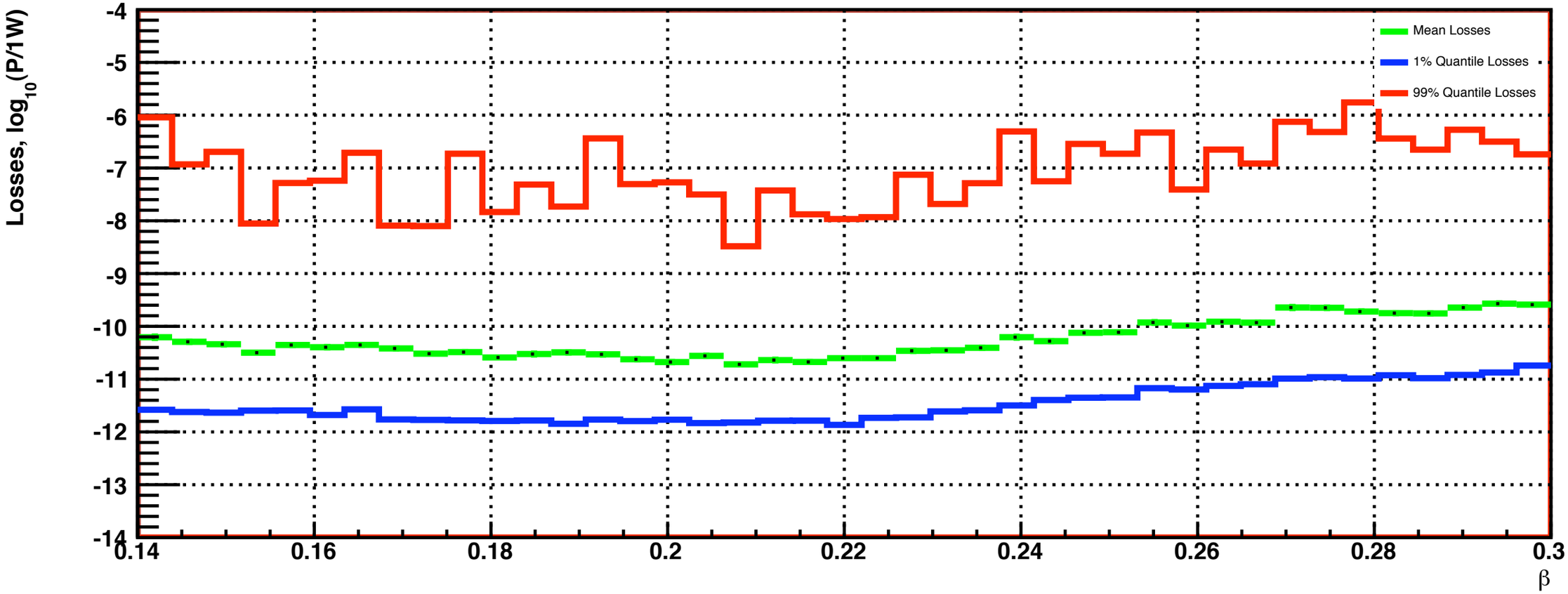
HOM Power Loss Results

- Q_L = 1e6; mean losses ~10e-10 W; 99% quantile losses < 10e-6 W



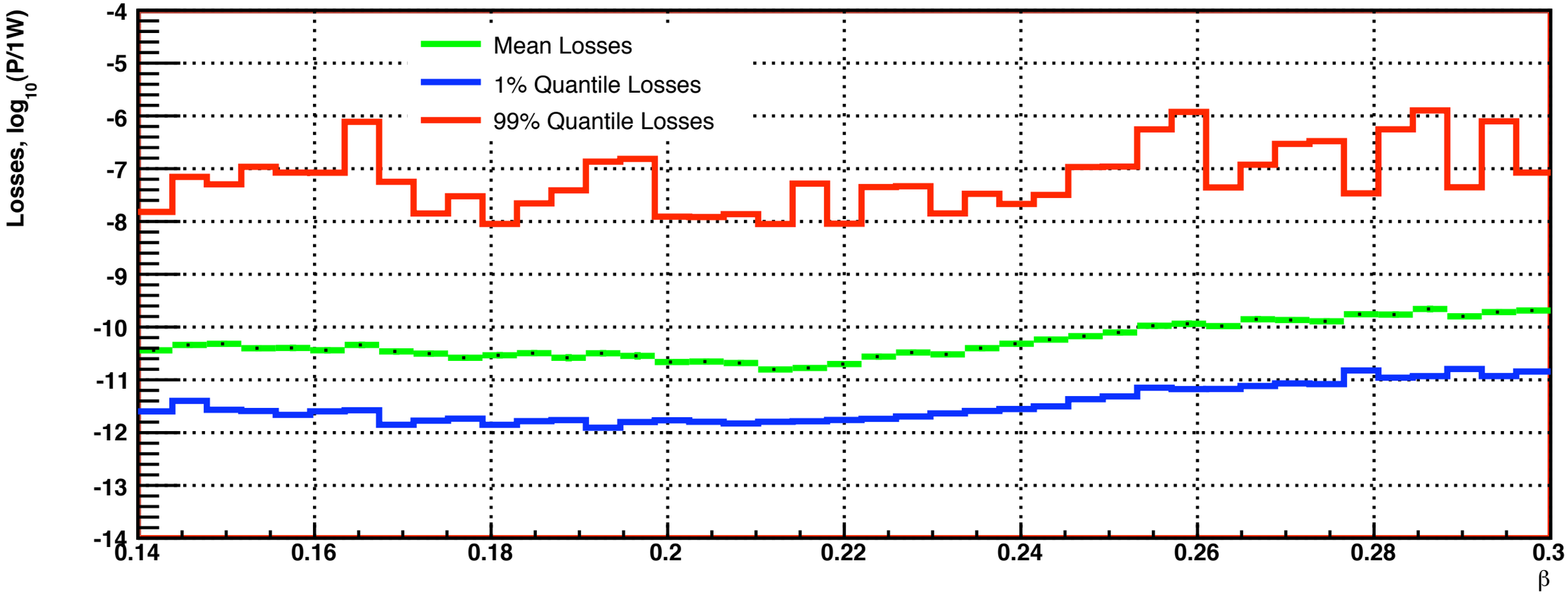
HOM Power Loss Results

- Q_L = 1e7; mean losses ~10e-10 W; 99% quantile losses < 10e-6 W



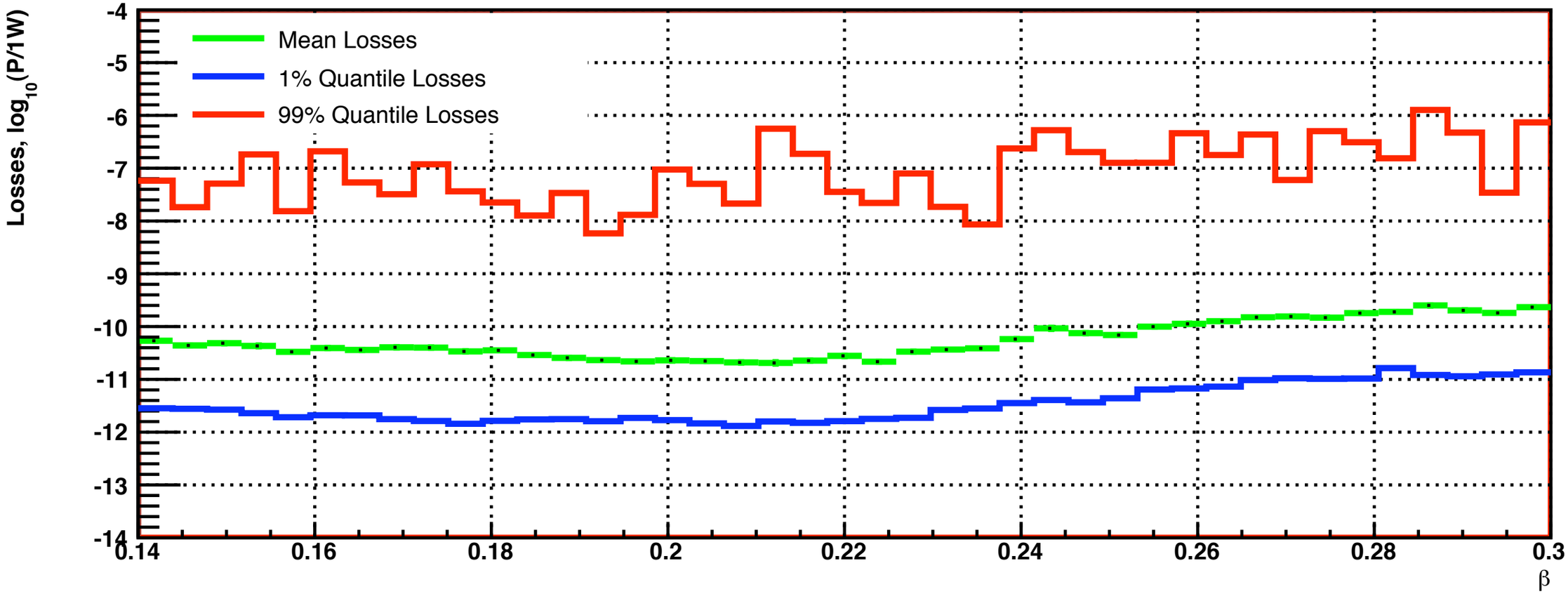
HOM Power Loss Results

- Q_L = 1e8; mean losses ~10e-10 W; 99% quantile losses < 10e-6 W



HOM Power Loss Results

- Q_L = 1e9; mean losses ~10e-10 W; 99% quantile losses < 10e-6 W



Conclusion

- Power loss due resonance excitation of non-propagating monopole HOMs in Project X SSR1 cavities has been analyzed
- Results of analysis show that HOM losses and corresponding cryogenic heat load are extremely small in the range of Q_L from 1e6 to 1e9
  - mean power loss is less than 1 nW
  - 99% quantile loss is less than 1 uW
- Will need to include off-diagonal terms into power loss calculations
  - Expect increase of power loss by ~30%