NGLS and Project X HOM calculations

(for coupler needs)

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Motivation

- Why do we need to analyze HOM in SRF linacs?
  - Charged beam bunches interact with accelerating structures by radiation of EM fields
    - Radiated EM field can be considered as superposition of excited eigenmodes of SRF cavities. These modes (other than fundamental accelerating mode) are conventionally called HOMs
  - Uncontrolled deposition of radiated EM energy in SRF cavities leads to excessive heat load and increased cost of building and operation of linac
    - Compare to 120 W/CM total expected heat load in NGLS at 17 MV/m
    - In PX HE 650 MHz section expected heat load is up to 200 W/CM
  - Radiated EM fields act back on the beam
    - Deterioration of beam quality
      - Need very high quality beam for X-ray laser applications
      - Transverse position stability less than 5%
    - Instabilities of beam in worst cases

Analysis and *control* of HOM are important for linac design

Outline

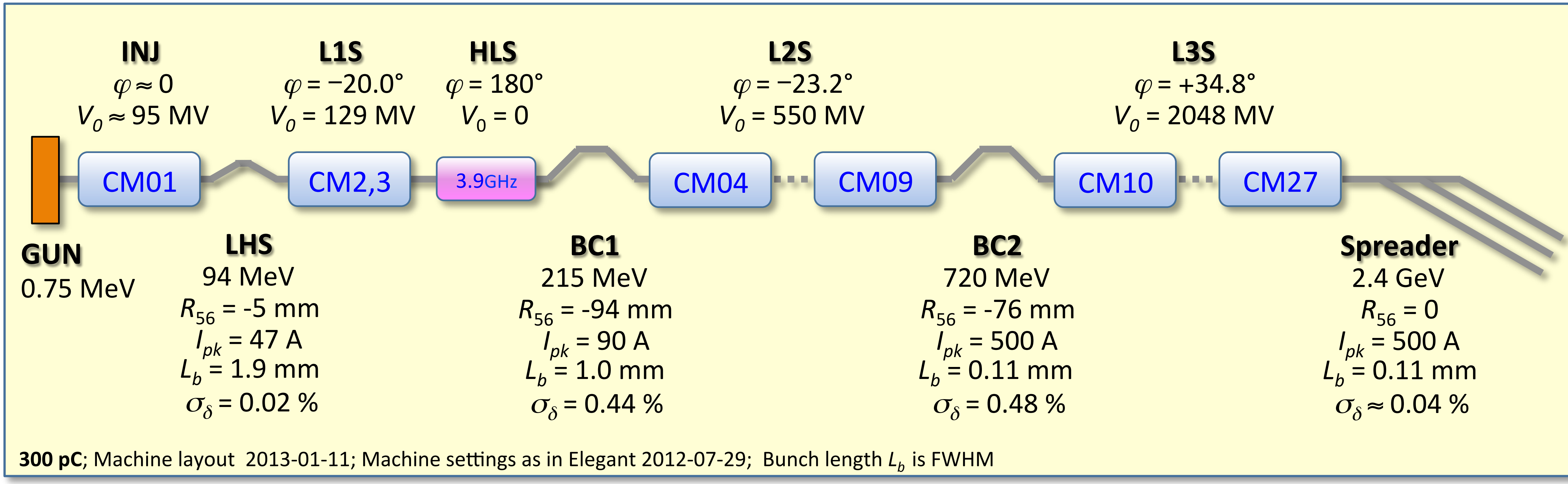
- NGLS and Project X linacs
- Incoherent losses and loss factor
- Resonance excitation of HOM
  - Monopole HOMs
    - cryogenic losses
    - very high frequency HOMs
  - Dipole HOMs
    - beam breakup
- Conclusion

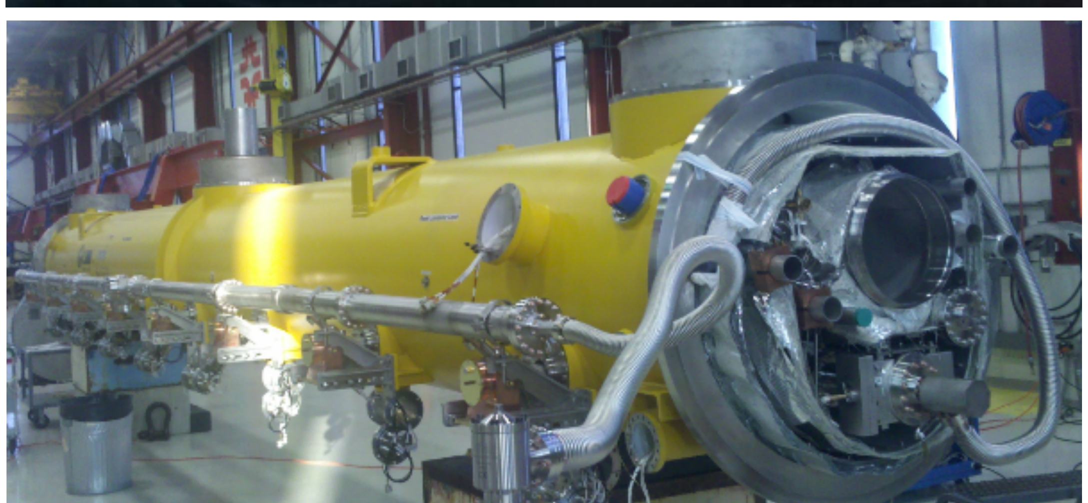
We take rather *conservative* approach for estimation of HOM effects

NGLS linac

- ILC style CM operating in CW

See more details on NGLS CM in J. Corlett talk on Friday

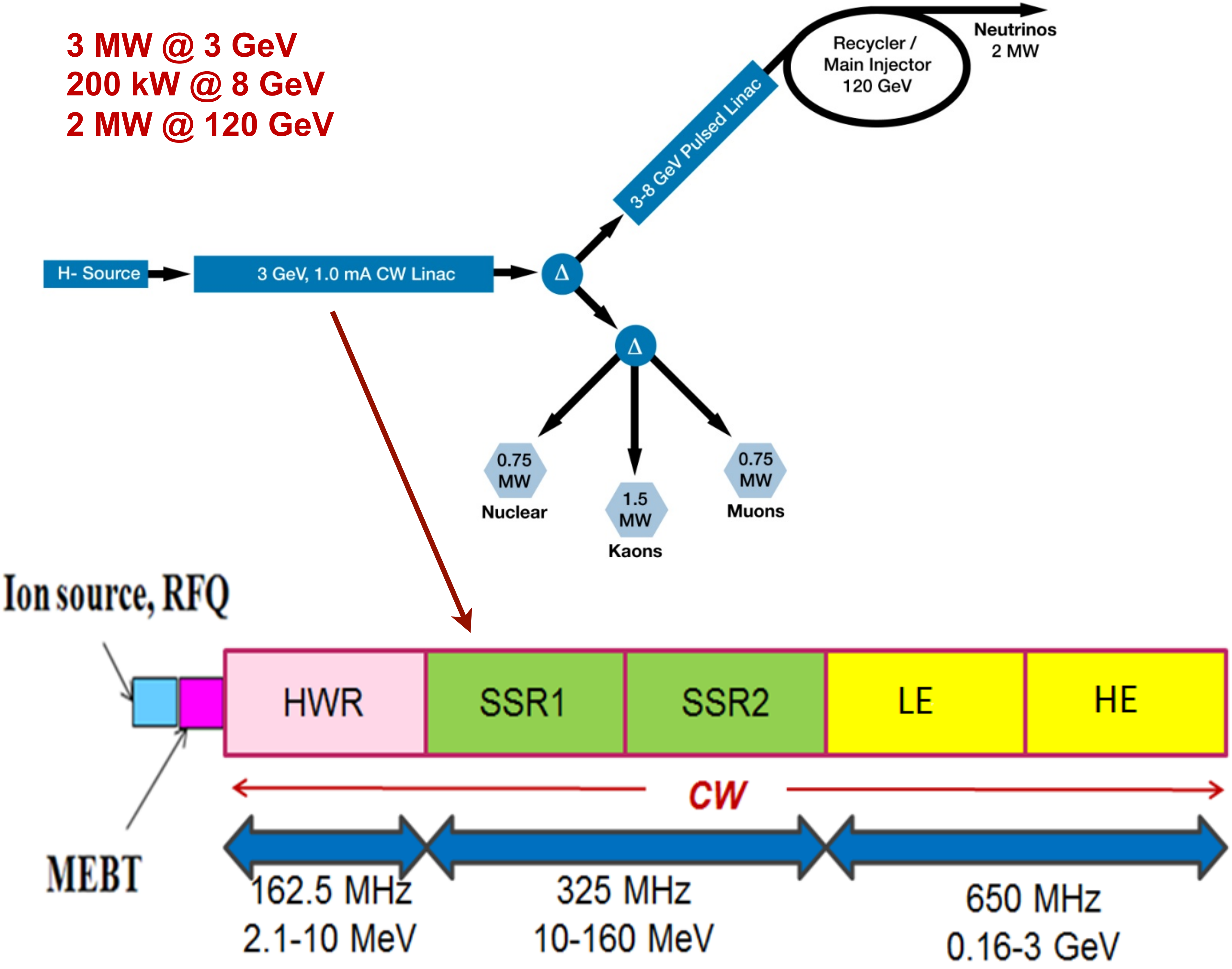




Energy, GeV	2.4
Operation mode	CW
Average current, mA	0.3
Bunch repetition rate, MHz	1
Bunch charge, nC	0.3
Bunch length, um	50
Norm. trans. emittance, um	0.6
Relative rms electron energy stability, %	< 0.01
Relative rms peak current stability, %	< 5
Bunch arrival time stability, fs	< 20
Transverse position stability, %	< 5

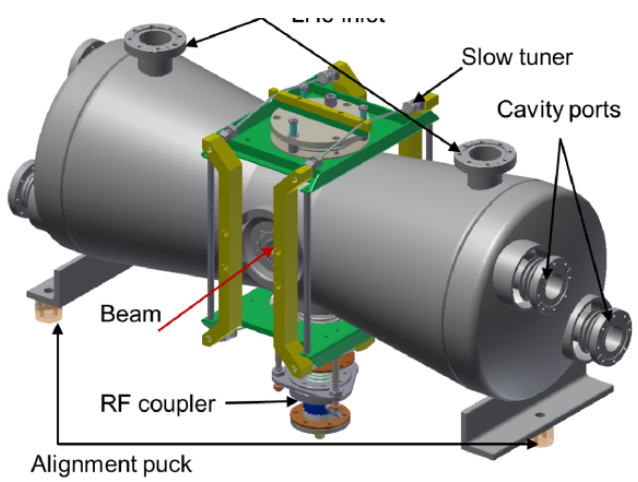
Project X linac

- Layout and technology map

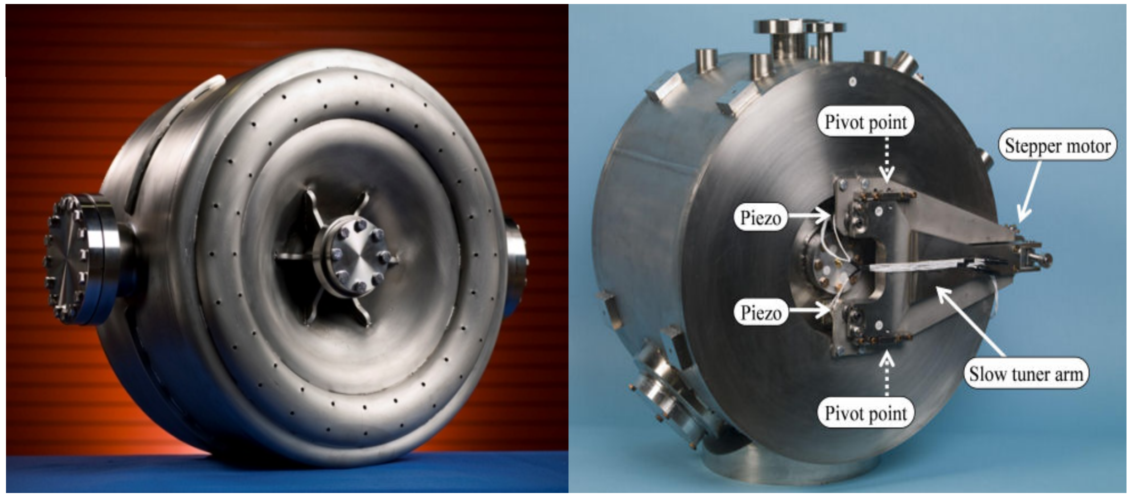


Project X technology

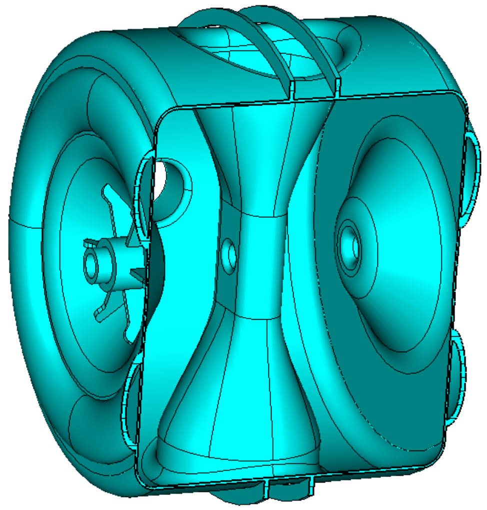
- HWR, SSR1&2, 650 MHz & 1.3 MHz elliptical cavities



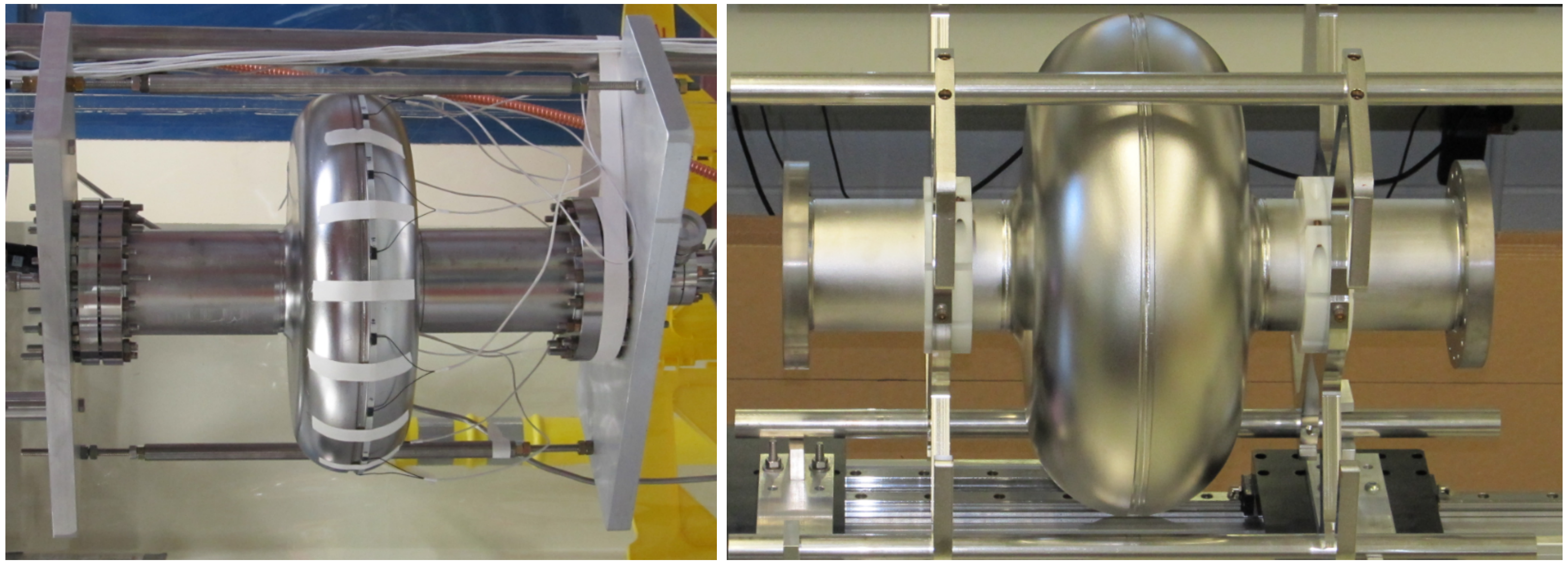
HWR, 162.5 MHz
(ANL)



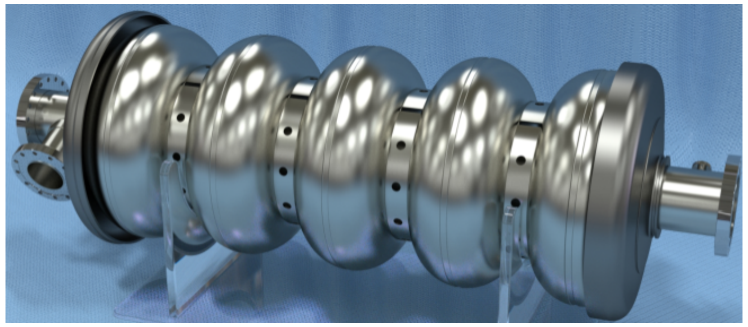
SSR1, 325 MHz
(FNAL)



SSR2, 325 MHz
(FNAL)



Single-cell models:
LE 650 MHz (JLAB) HE 650 MHz (FNAL)



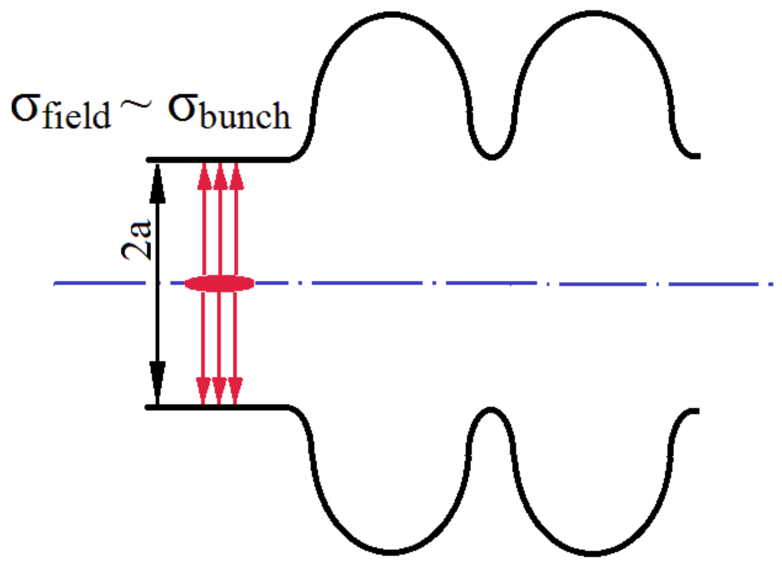
5-cell model, HE650

See more details on Project X cavities in T. Khabiboulline talk later today

Relativistic (NGLS) *VS* non-relativistic (Project X) beam

- EM losses in cavity strongly depend on the size of the field distribution of beam bunch

NGLS



$\gamma >> 1$

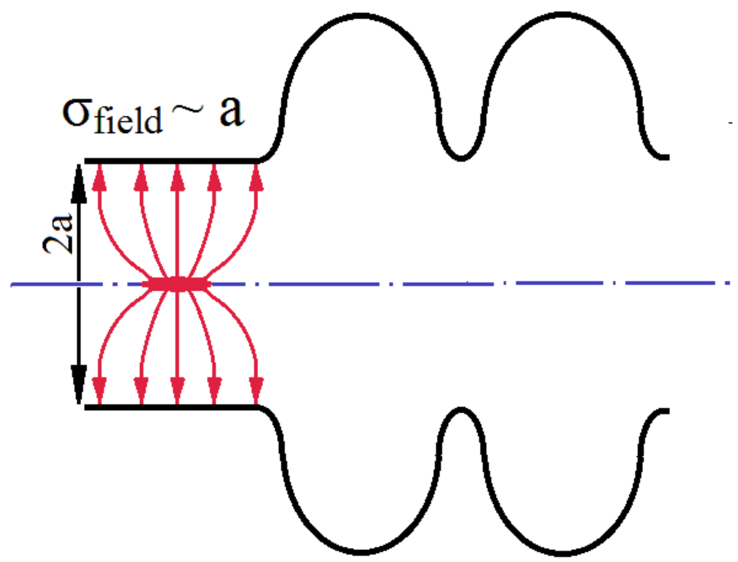
HE electron linacs

$f_{max} \sim c/\sigma_{field} \sim c/\sigma_{bunch}$

for σ_{bunch} = 50 um

$f_{max} \sim$ 6 THz

Project X



$\gamma \sim 1$

Proton linacs

$f_{max} \sim c/\sigma_{field} \sim c/a$

for a = 50 mm

$f_{max} \sim$ 6 GHz

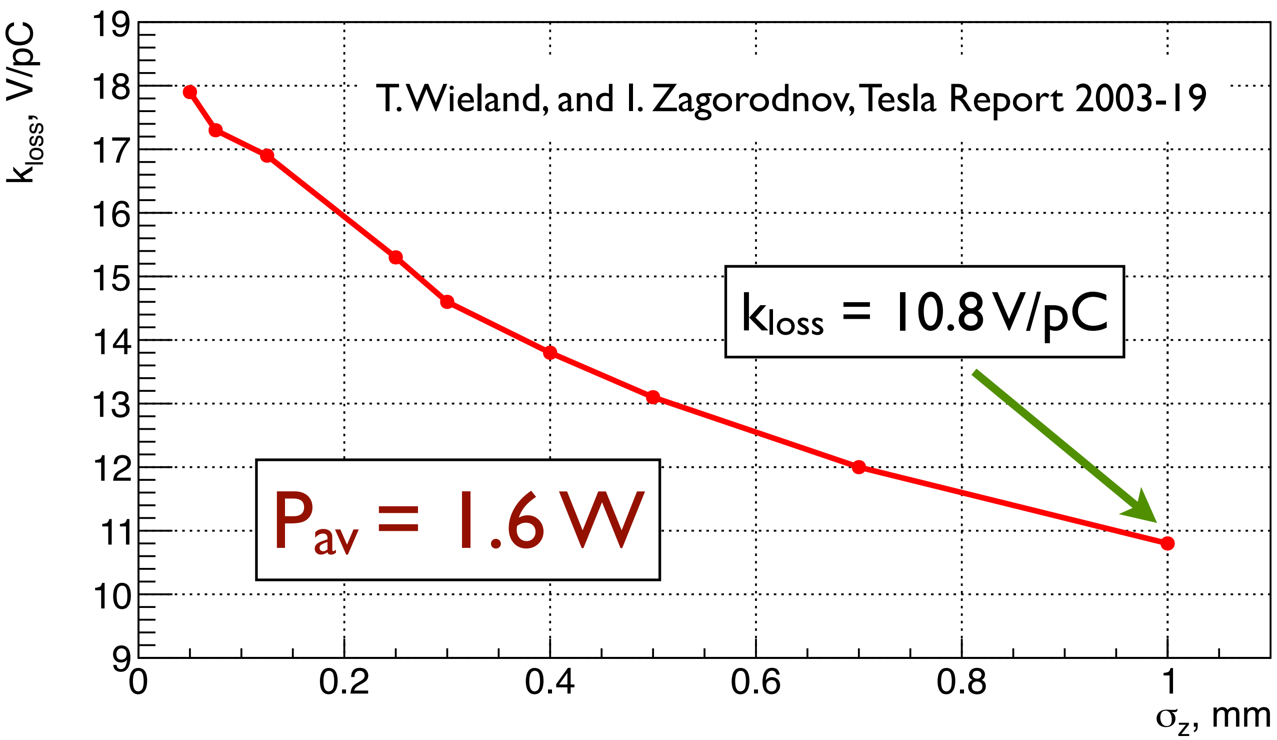
EM losses depend strongly on the size of the bunch field distribution σ_{field}

Incoherent losses

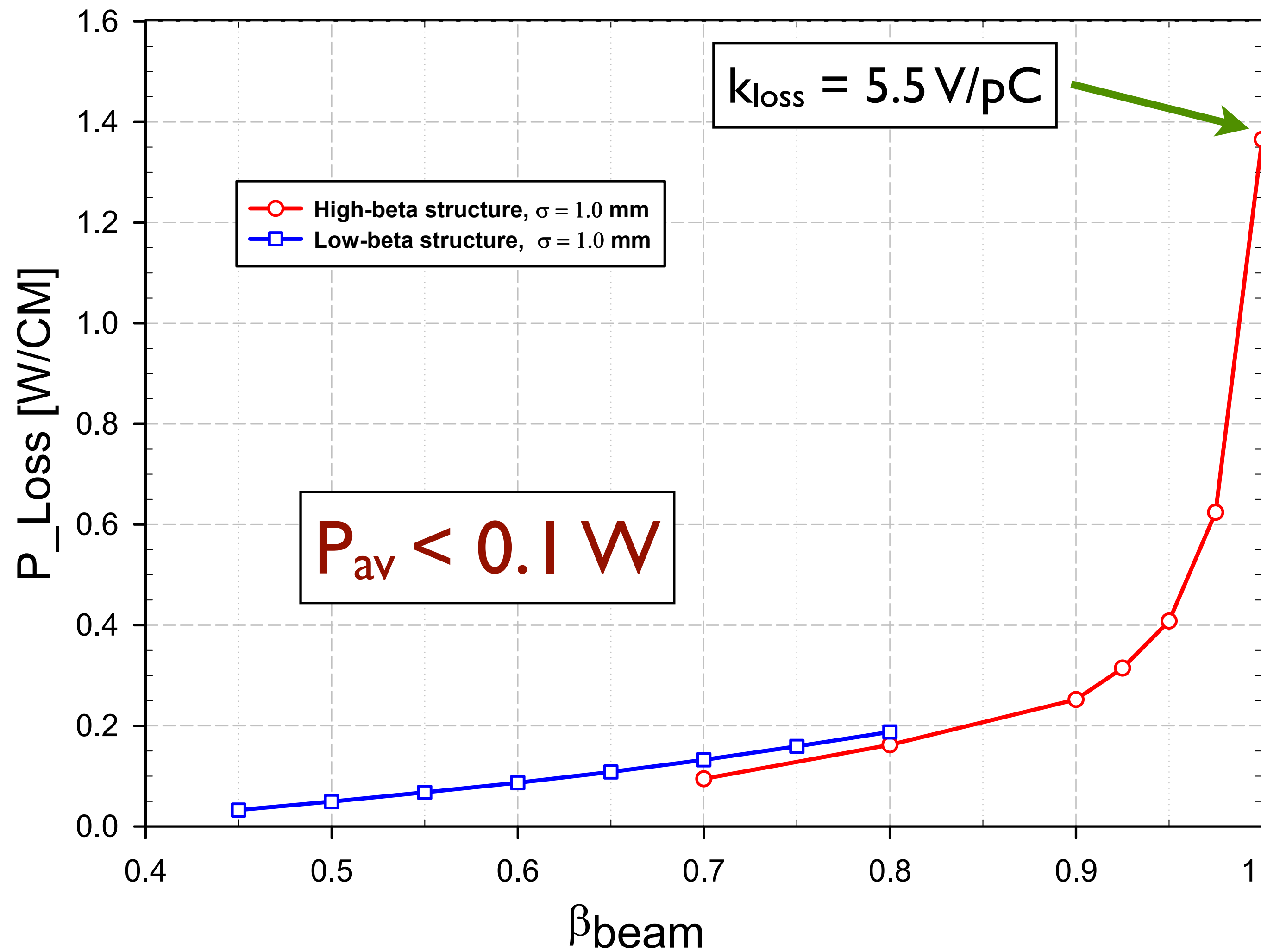
- Energy lost by a single bunch is independent of other beam bunches and characterized by loss factor, normalized to bunch charge: k_{loss}
- Average HOM power loss:

$$P_{av} = k_{loss} q_b I_{av}$$

NGLS



Project X



Compare to the loss factor of fundamental mode only: $k_{loss} = \omega(R/Q)/4 \approx$ 2 V/pC (NGLS); $\approx$ 0.7 V/pC (PX)
90 % of EM energy is lost in HOM

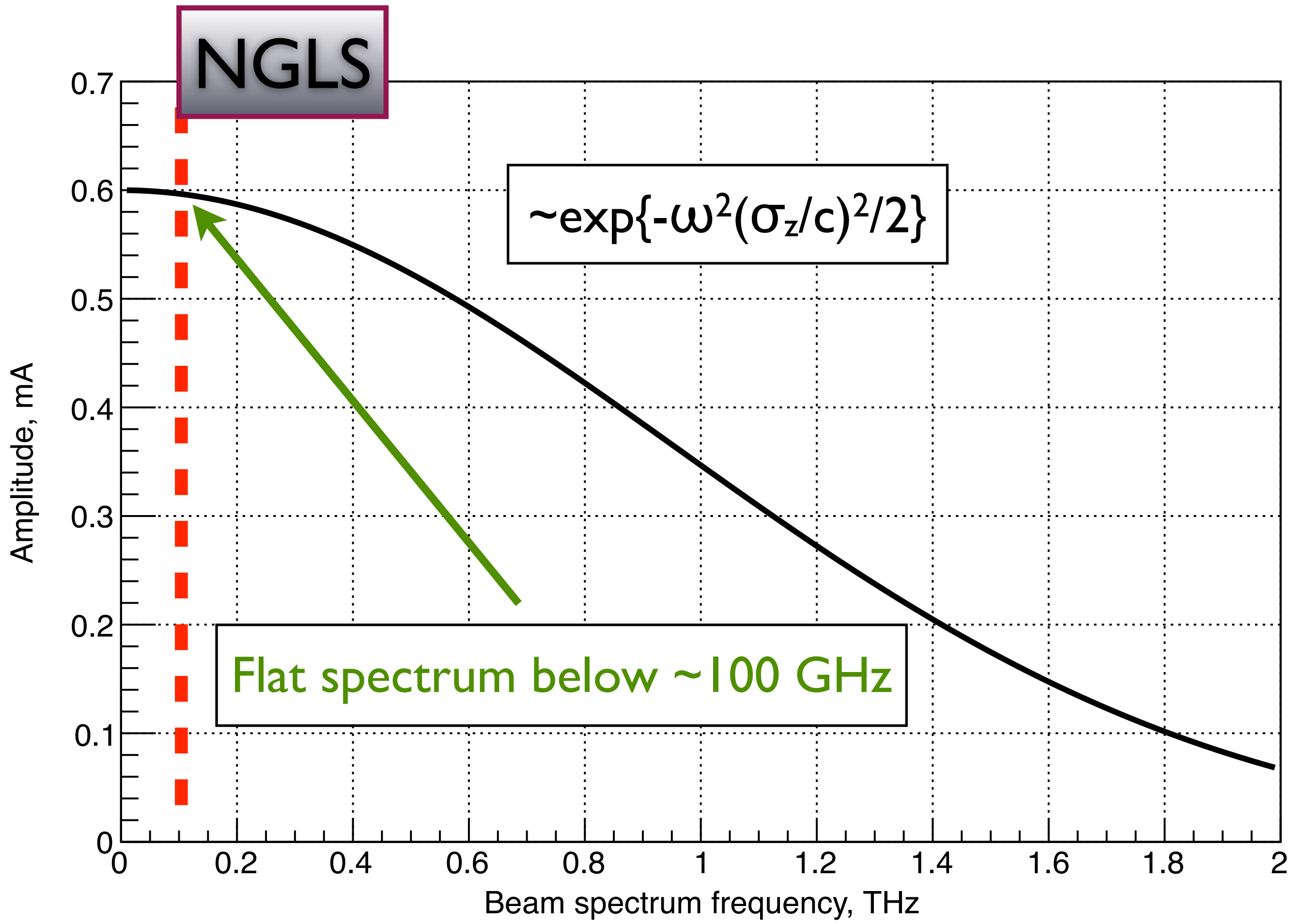
Incoherent losses are not a problem for 0.3 nC 50 um bunches in NGLS and even less problematic for Project X linac

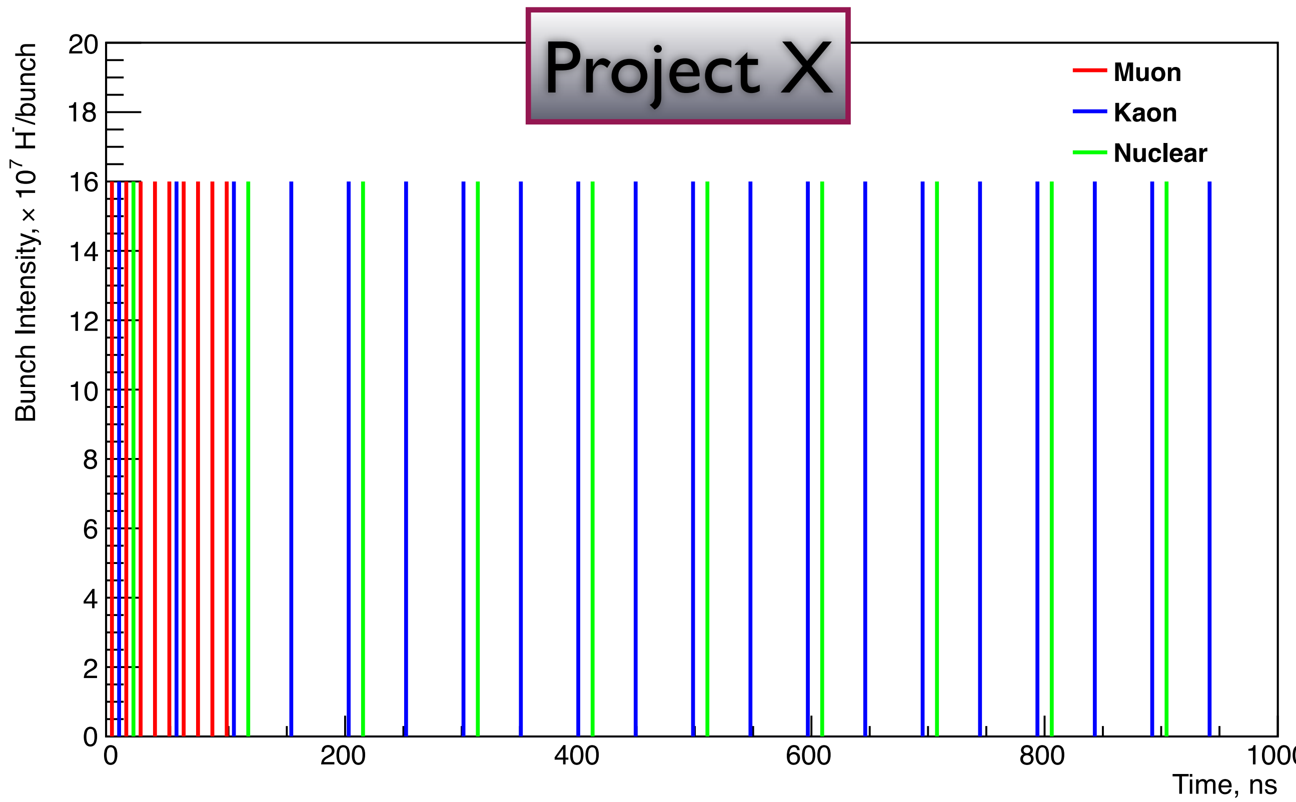
Resonant excitation of HOMs

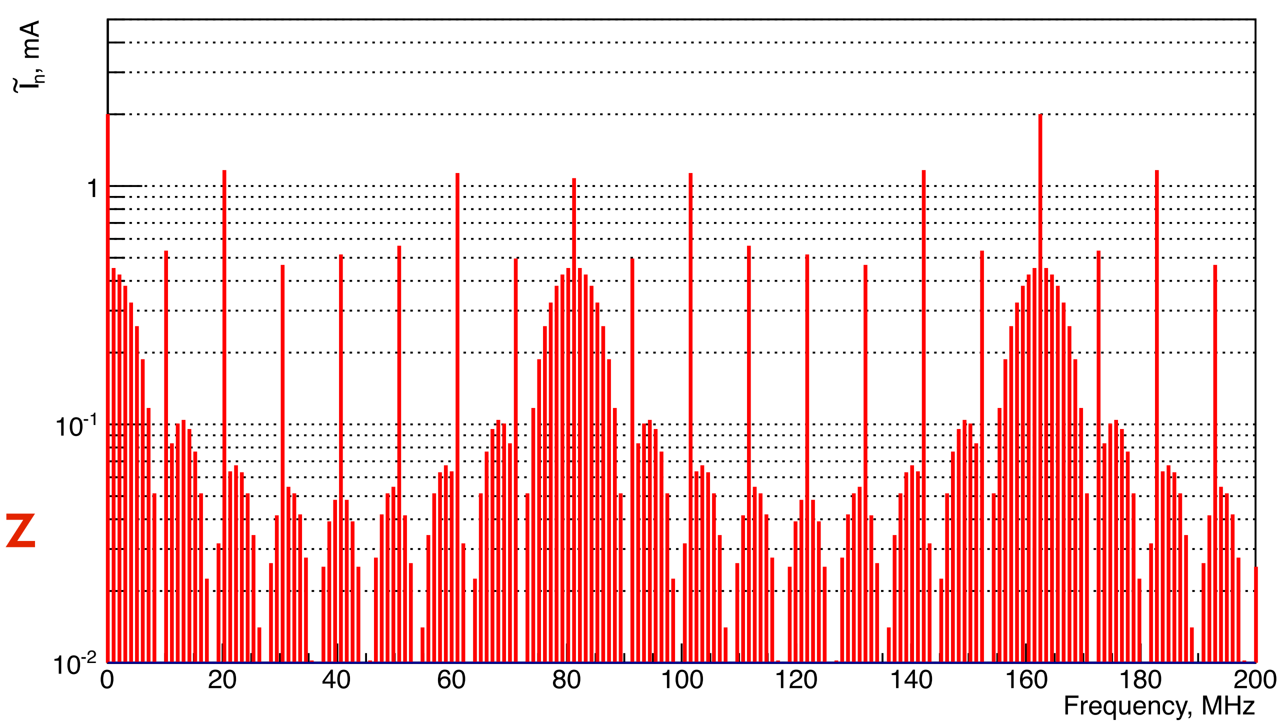
- CW bunched beam passing through SRF cavity may coherently excite HOMs with high *Q*-factor
  - When exactly in resonance effect may be significantly higher compared to incoherent losses
  - In periodic structure of multiple SRF cavities in linac conditions may be realized when HOMs with frequency above beam pipe cut-off (2.94 GHz for ILC cavities) will be effectively trapped inside cavities
- Amplitude of excited HOMs depends on beam current, beam spectrum and cavity HOM spectrum
- We estimate effects of coherent HOM excitation on cryogenic losses and transverse beam dynamics
- We use simplified models and report here rather conservative estimations

Beam spectrum

- NGLS beam structure is uniform (1 MHz bunches)
- Project X has very complicated beam structure (162.5 MHz bunches w/ sub-structure)
- We assume idealized beam spectrum:
  - no time/charge jitter







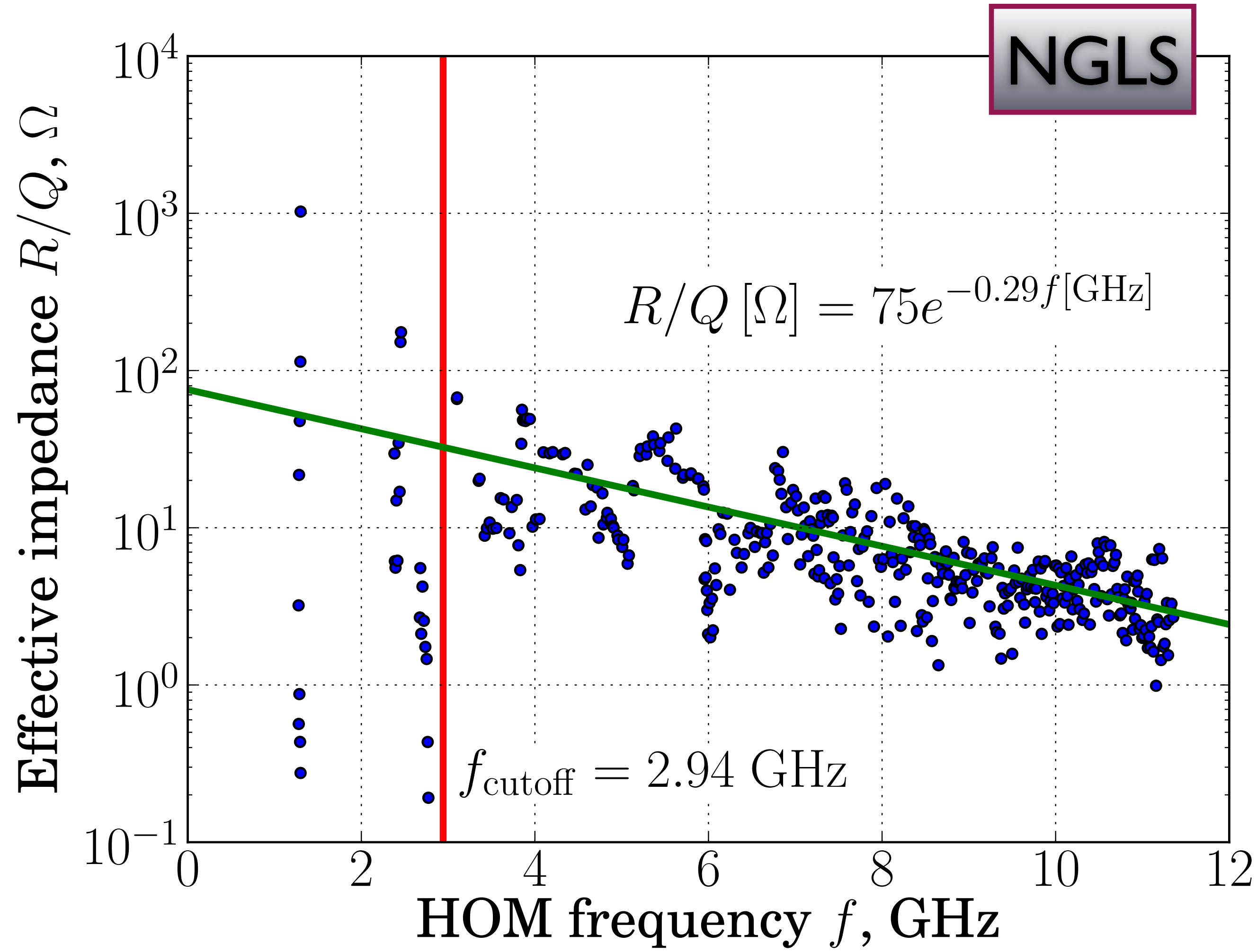
NGLS beam spectrum extends to few 100 GHz

Project X spectrum ~10 GHz

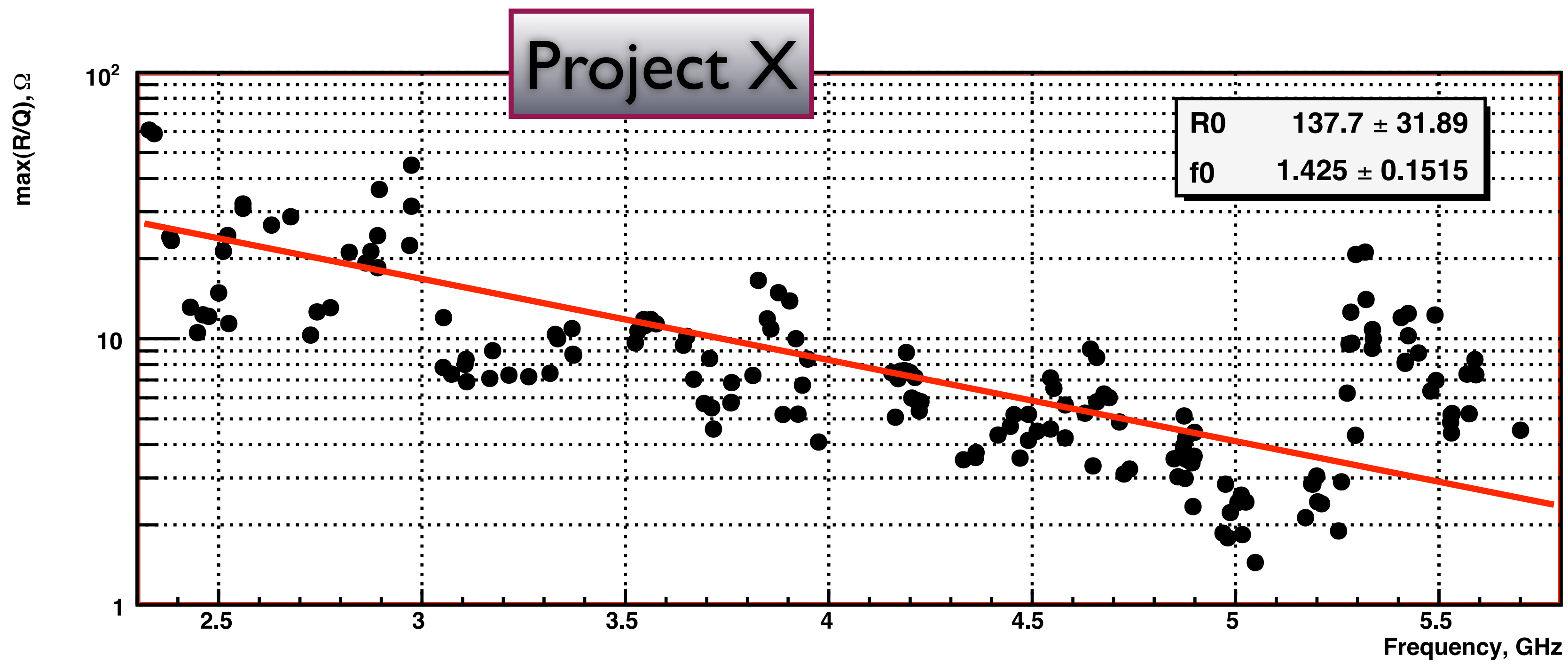
Cavity spectrum

- (R/Q) of propagating modes depends on the distance between cavities
  - RF simulation is run for different distances between cavities and maximum value of (R/Q) is selected for calculation of HOM effects
- Fit to exponential function:

$$(R/Q) = R_0 \exp(-f/f_0)$$

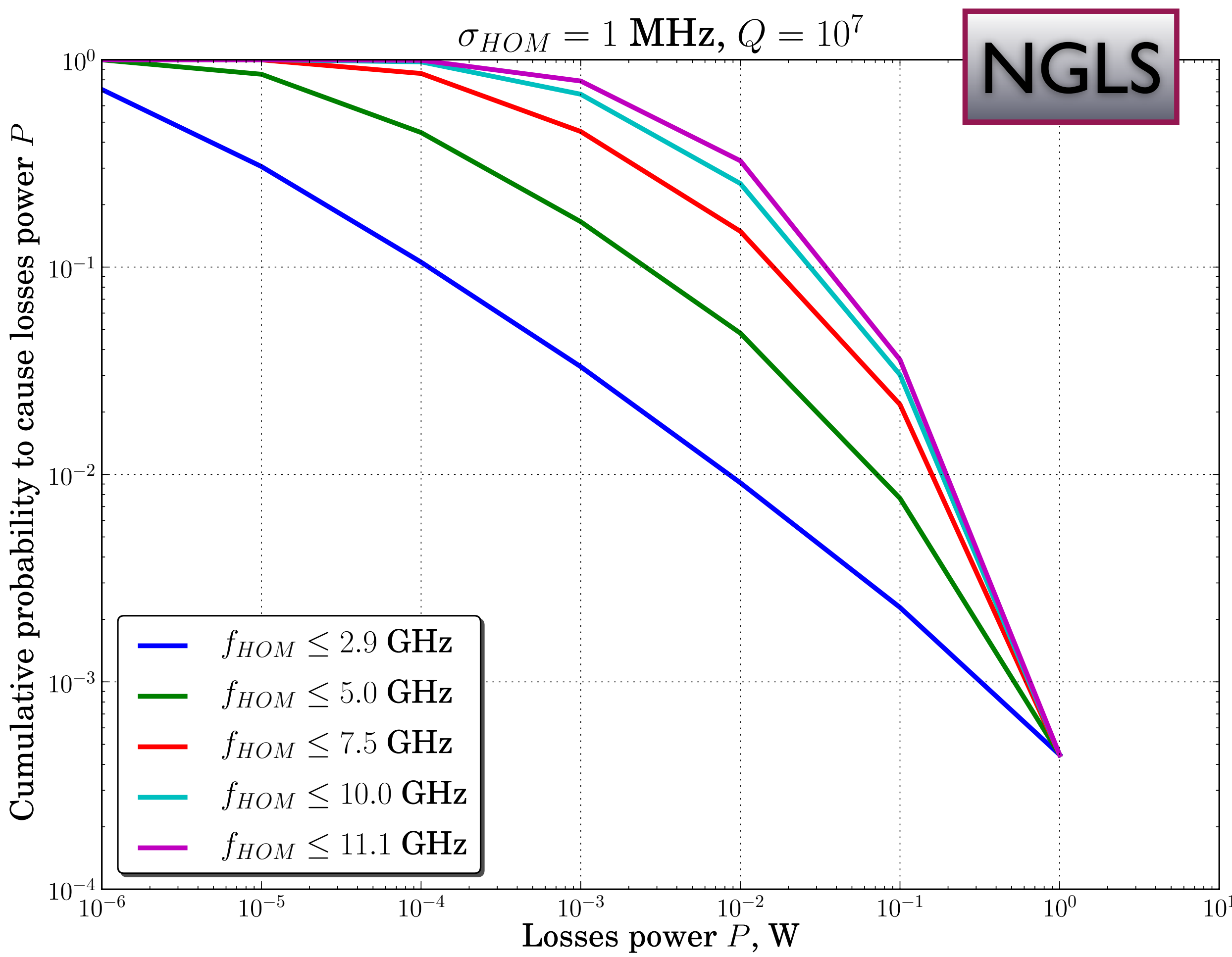


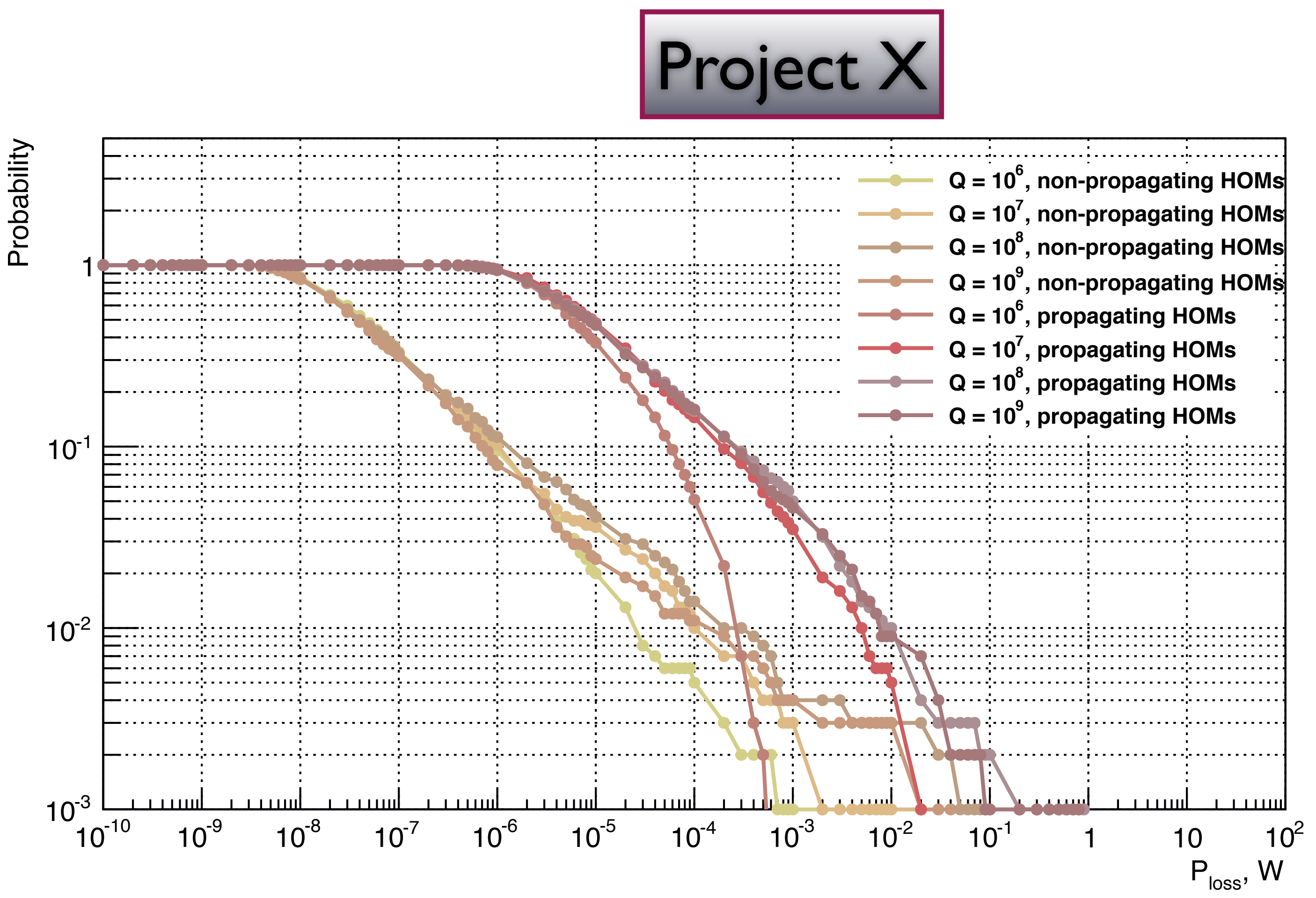
- Assume random variations of HOM frequencies from cavity to cavity along linac (due to manufacturing tolerances)
  - $\sigma_f \approx$ 1-2 MHz
  - Cornell model: $\sigma_f \approx 10.9 \times 10^{-4} (f_{HOM} - f_0)$
  - SNS model: $\sigma_f \approx (9.6 \times 10^{-4} - 13.4 \times 10^{-4})(f_{HOM} - f_0)$
  - Collect data on HOM frequency spread in TESLA cavities at Fermilab



Distribution of power loss

- Gaussian distribution of HOM frequency from cavity to cavity





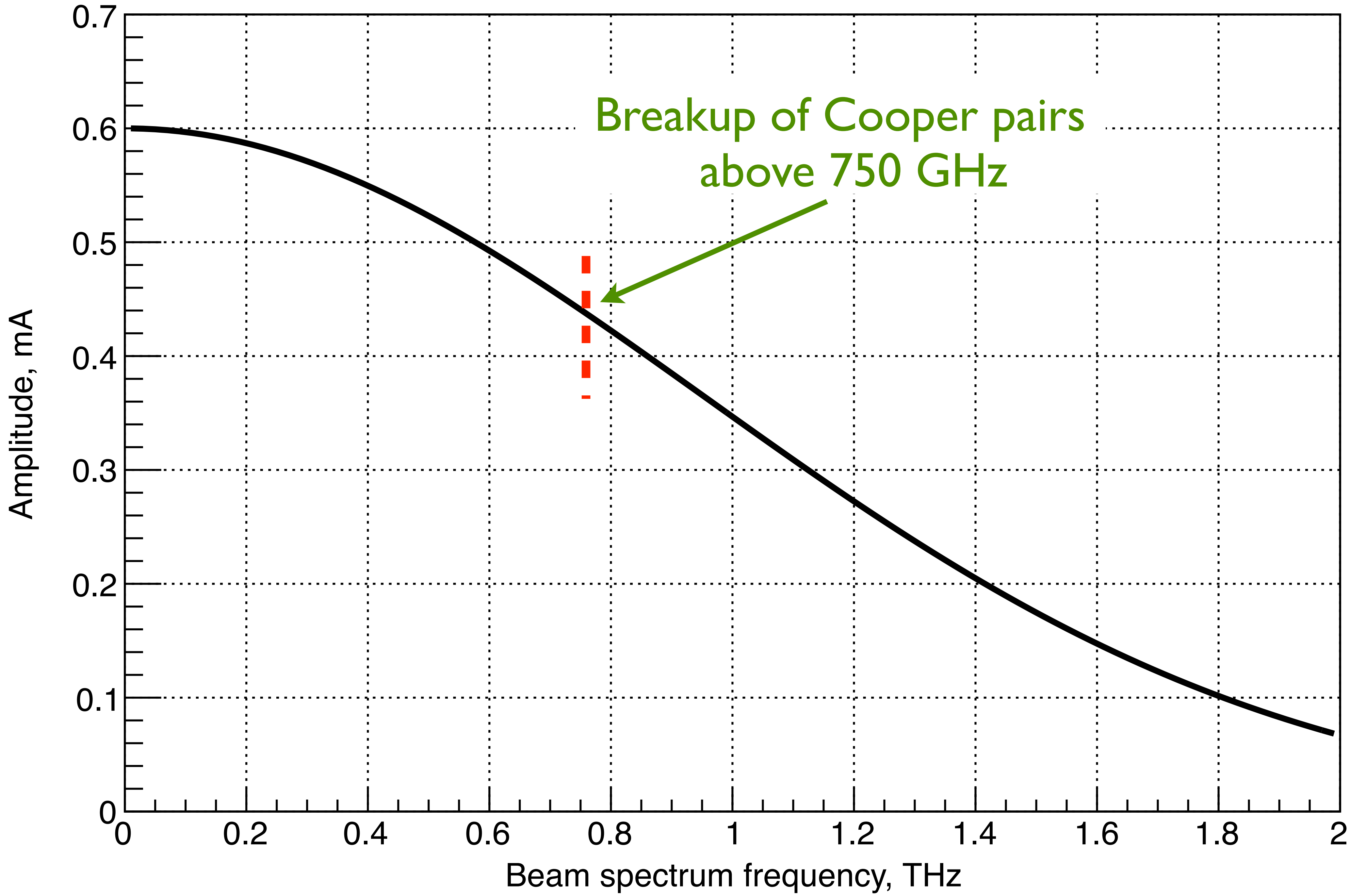
- Probability of large power loss due to resonance excitation of HOM is small:
  - NGLS: For HOMs with frequency below 11 GHz and $Q_L < 10^7$ probability is less than 10^{-3} for losses above 1 W
  - PX: For HOMs with frequency below 6 GHz and $Q_L < 10^9$ probability is less than 10^{-3} for losses above 1 W

Cryogenic losses due to coherent excitation of monopole HOM are small

Very high frequency HOMs

NGLS

- Breakup of Cooper pairs in Nb above 750 GHz
  - NC ⇒ extra heating of cavity surface ⇒ drop of cavity Q_0



Very high frequency HOMs

- Diffraction model is used to estimate power loss in high frequency HOM
  - Energy lost in diffracted field in single cell:

$$\Delta E_{1cell} = \frac{q_b^2}{4\pi\epsilon_0 a}\sqrt{\frac{L_{cell}}{2\sigma_z}}$$

  - $\Delta E_{1cell} \approx$ 0.7 μJ for 0.3 nC 50 μm bunches
  - $\Delta E_{9cell} \approx 6\Delta E_{1cell}$ and $\Delta E_{9cell} \approx \Delta E_{1cell}$ in a long string (>2 CM) of cavities due to field disturbance (see P. Hulsmann, *et al*, SRF 1997)
- Average power loss into very high frequency HOM is $P_{loss} = f_b \Delta E_{9cell} \approx$ 0.7 W/cavity
- Fraction of energy lost above 750 GHz (energy gap of Cooper pairs):

$$r = \int_{\omega_g}^{1} \frac{1}{\sqrt{\omega}} e^{\ \sigma_t^2\omega^2} d\omega \Big/ \int_{0}^{1} \frac{1}{\sqrt{\omega}} e^{\ \sigma_t^2\omega^2} d\omega \approx 0.2$$

- This corresponds to average power loss less than 0.2 Watt/cavity
- Due to initial scattering on iris and subsequent multiple scattering high frequency radiation exits cavity at large angles and effectively absorbed in HOM absorbers

Power loss into very high frequency HOM should not be a problem in NGLS CW linac

Dipole HOMs and BBU

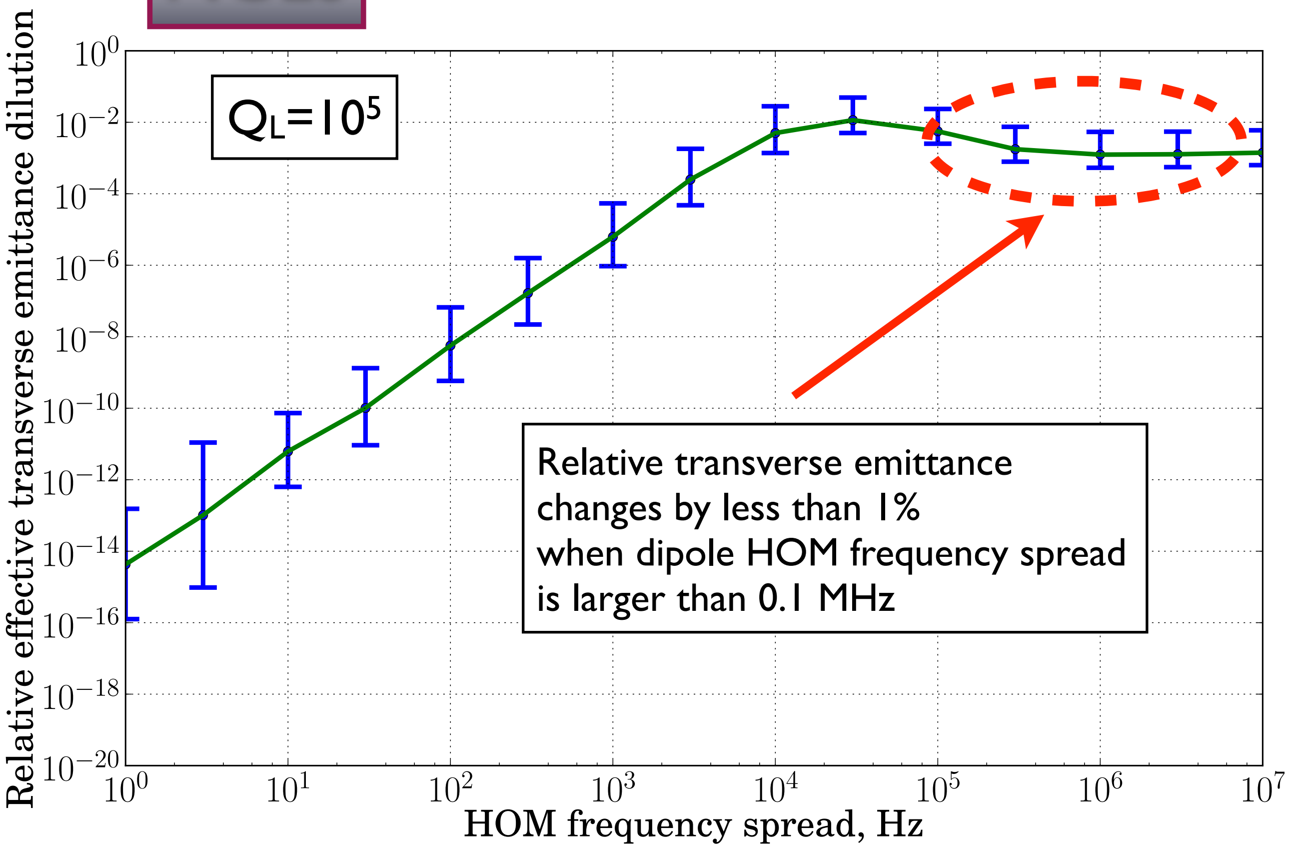
- Simplified model to estimate HOM effects on transverse dynamics
  - Random misalignment of cavities ±0.5 mm
  - Deflecting gradient at the passage of n^{th} bunch through a cavity:

$$U_n = U_{n-1} e^{-T/\tau} e^{j\omega_{HOM} T} - \frac{j}{2} c q_b (R/Q)^{(1)} (x - x_{cav})$$

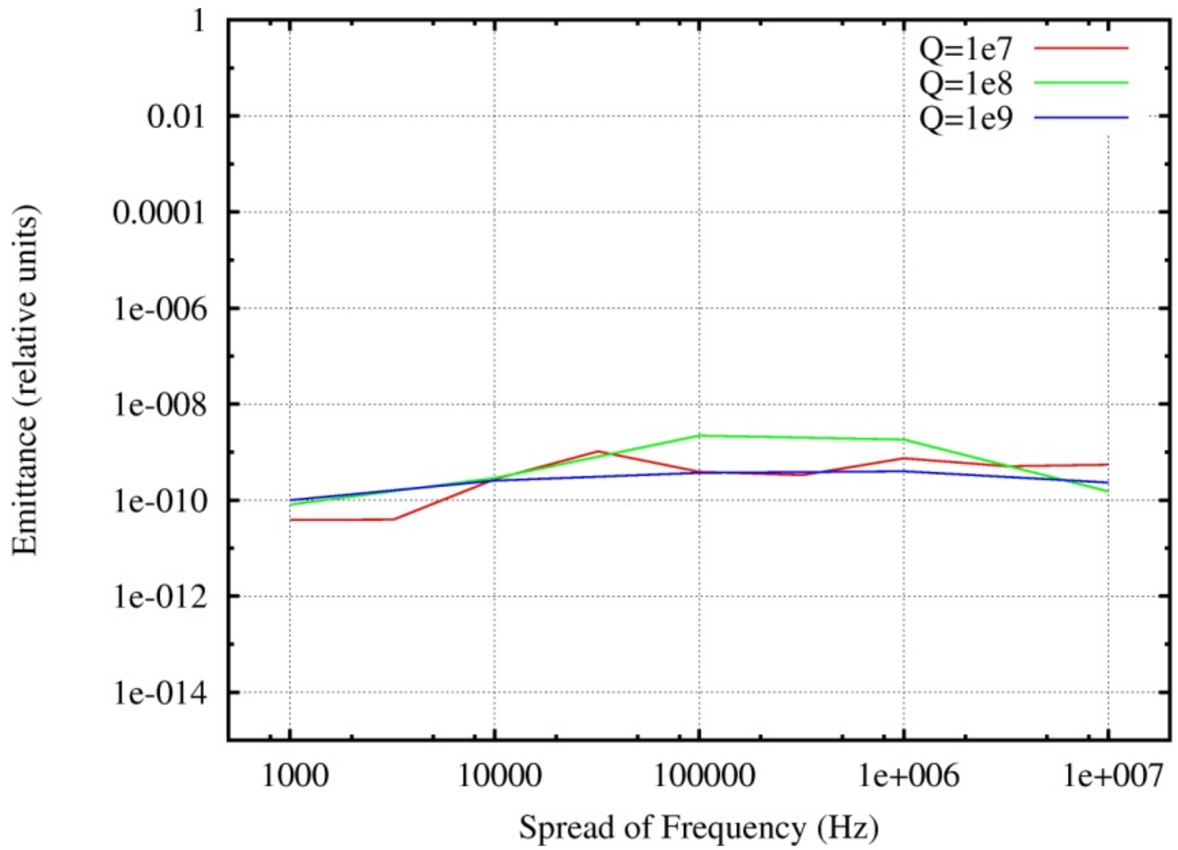
  - Bunch transverse kick:

$$\Delta x' = Re(U)/pc$$

NGLS



Project X



Resonance excitation of dipole HOMs seems not to be an issue for transverse beam dynamic

Conclusion

- Considered HOM effects in NGLS and Project X CW SRF linacs
  - Incoherent losses
  - Coherent excitation of HOMs
    - Cryogenic load
    - Transverse and longitudinal beam dynamics
    - Very high frequency HOMs
- Small effects
- No need for HOM couplers
- Topic for discussion:
  - Program for experimental study of HOM effects at existing (or soon to be operational) CW SRF linacs
    - SNS, Cornell ERL, ...

Backup slides

Power loss calculation

- 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 code for mode p
  - ω_p is the mode frequency
  - W_p is the mode stored energy normalized by LANS to 1 mJ
  - Q_p and $(R/Q)_p$ are the mode (loaded) quality factor and impedance
  - I_p and ω_n are the amplitude and frequency of beam harmonic

Power loss calculation

- Total power loss in the cavity walls is calculated as sum of losses by individual beam harmonics
  - in expression for $|H_n|^2$ cross-terms $H_{pn}H^*_{qn}$ have extremely small contribution and can be neglected

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

- Where the wall resistance (H. Padamsee, J. Knobloch, and T. Hays, *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