

# Impact of the Beam Loading Patterns on the ERL Stabilities

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# Energy Recovery Linac (ERL)

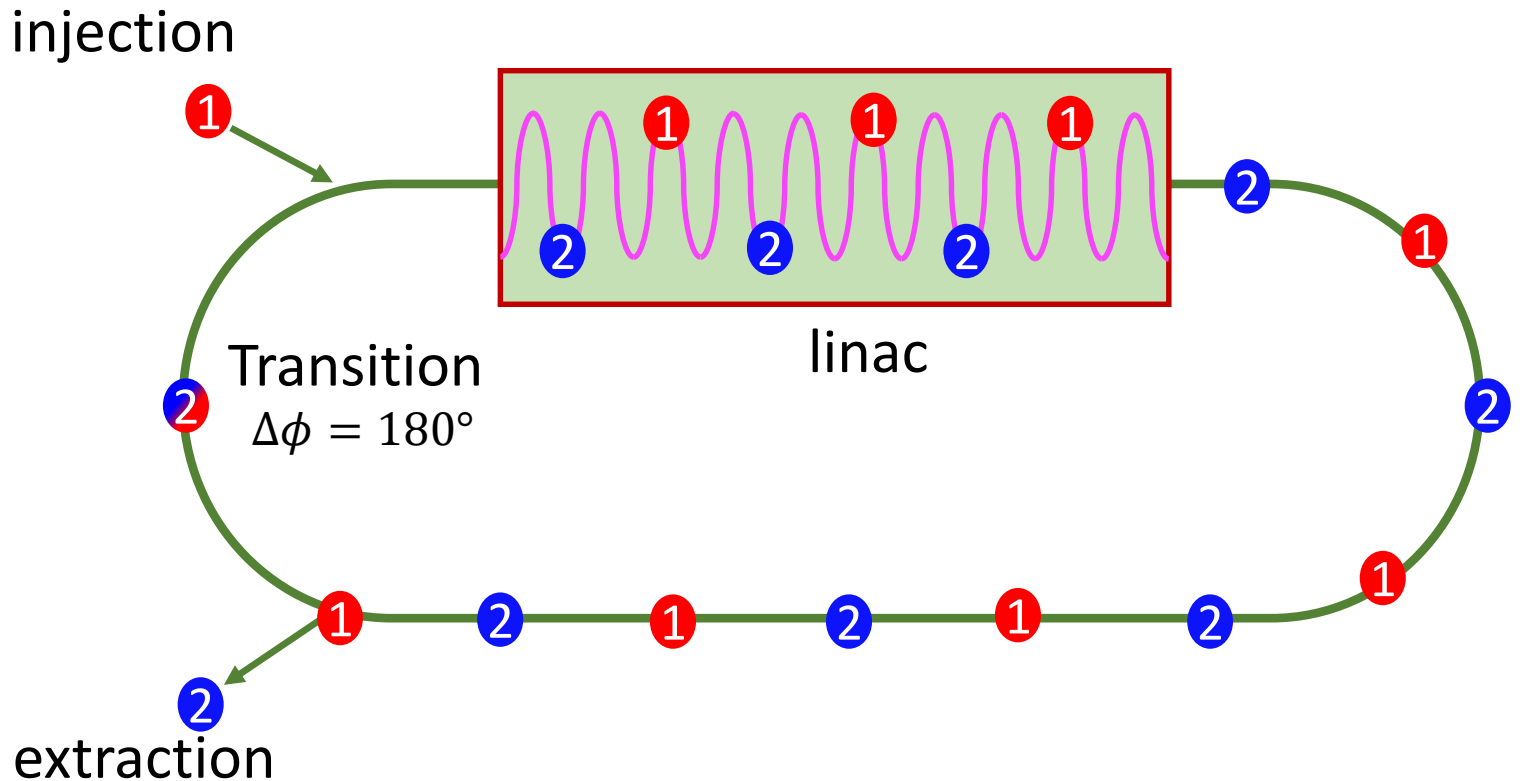
- Recovers the KE of the beam
- By decelerating the beam

**Acceleration:**  $E_{\text{cavity}} \rightarrow \text{KE}_{\text{beam}}$

**Deceleration:**  $\text{KE}_{\text{beam}} \rightarrow E_{\text{cavity}}$

**Accelerating bunch:** ●

**Decelerating bunch:** ●

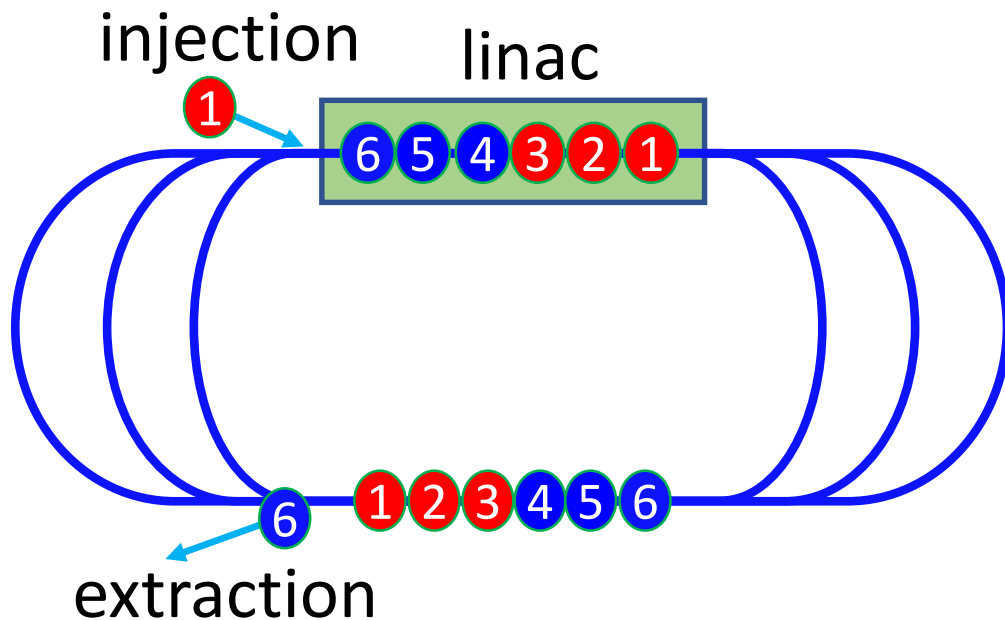


# Beam loading pattern

- The order bunches pass through the cavity.

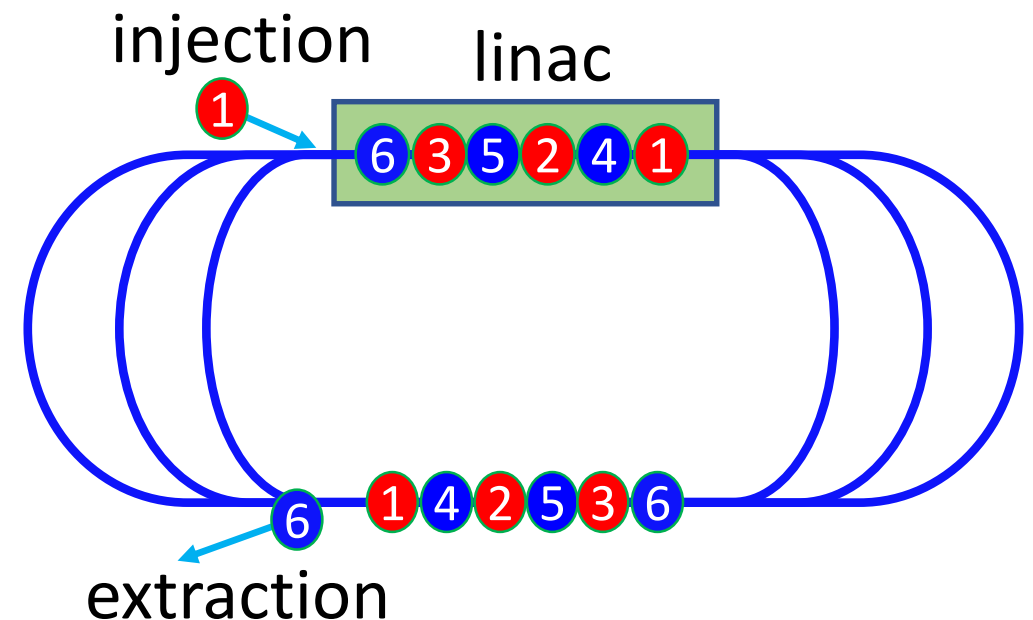
Pattern {1,2,3,4,5,6}

1 2 3 4 5 6



Pattern {1,4,2,5,3,6}

1 4 2 5 3 6



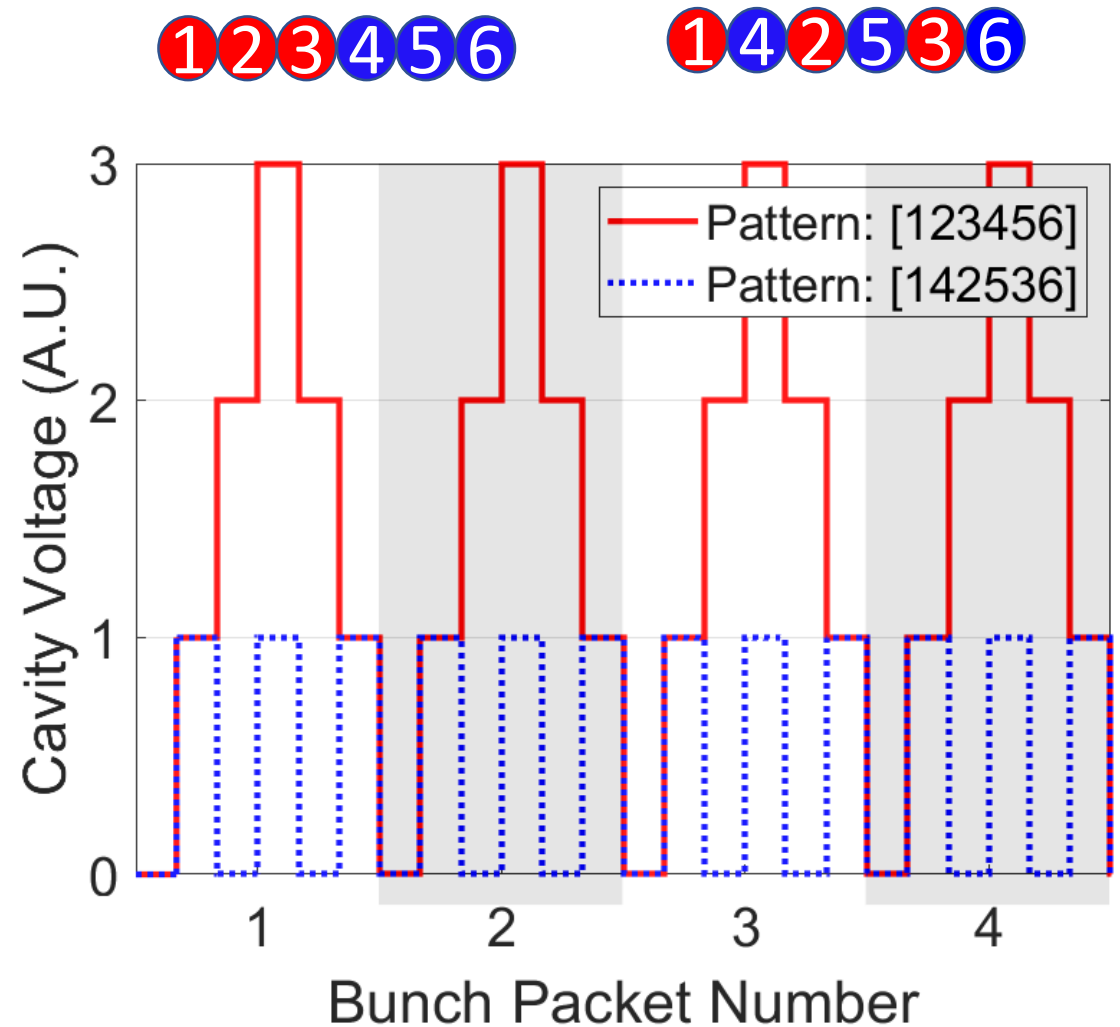
# Cavity voltage

$$\delta V_{cav} = -\frac{q_{\text{bunch}}}{2} \omega \left( \frac{R}{Q} \right) \cos(\phi)$$

$\phi$ : bunch phase

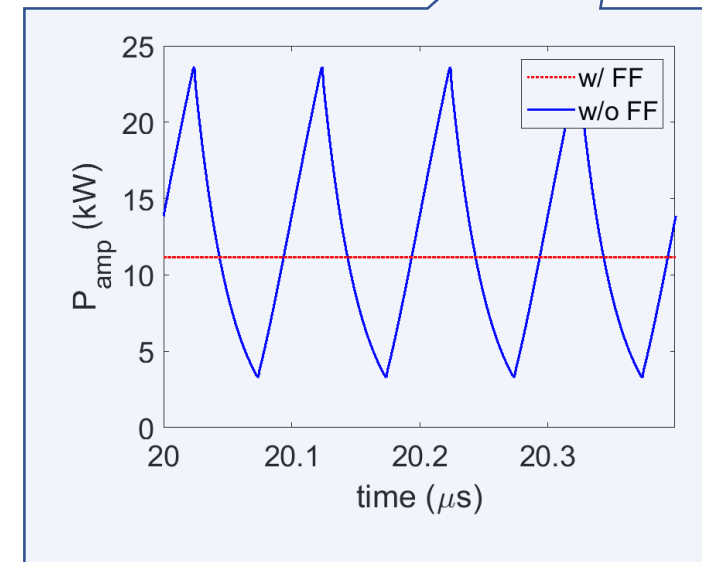
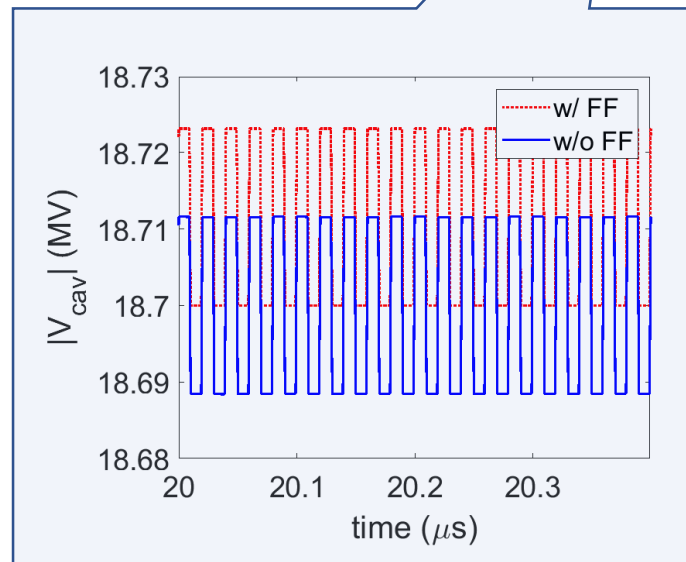
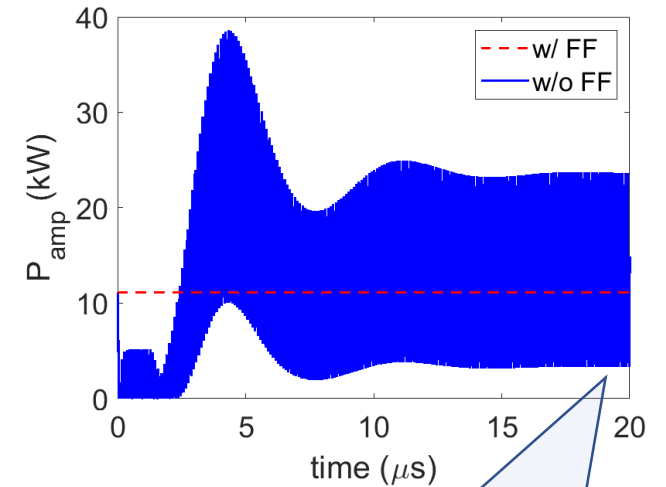
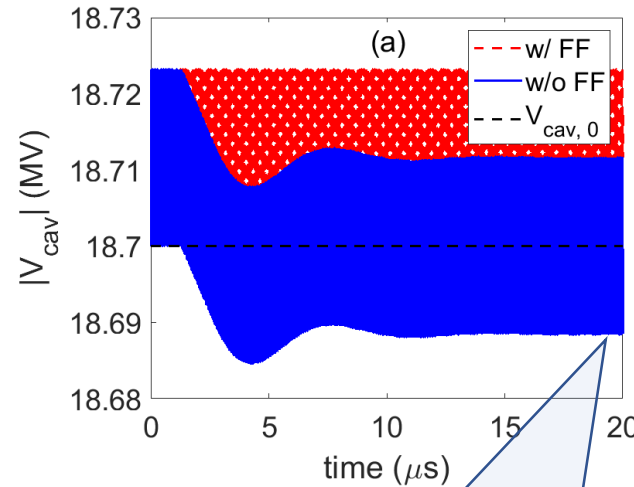
Accelerating bunch:  $\phi = 0^\circ$

Decelerating bunch:  $\phi = 180^\circ$



# LLRF Feed forward

- ERL net beam loading = zero
- A feed forward to LLRF can prevent bunch-to-bunch correction.
- Without feed forward, the LLRF can trigger amplifier and cause unnecessary fluctuation.
- Feed forward stabilizes  $V_{\text{cav}}$  and  $P_{\text{amp}}$ .



# Pattern dependance

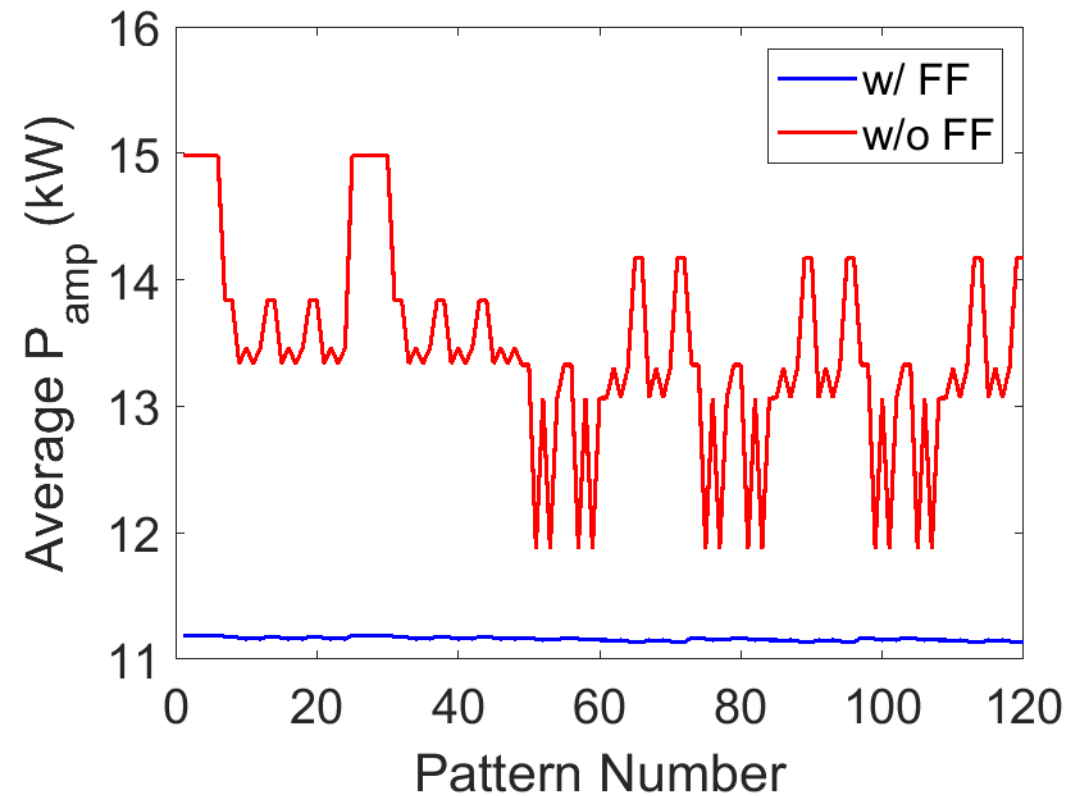
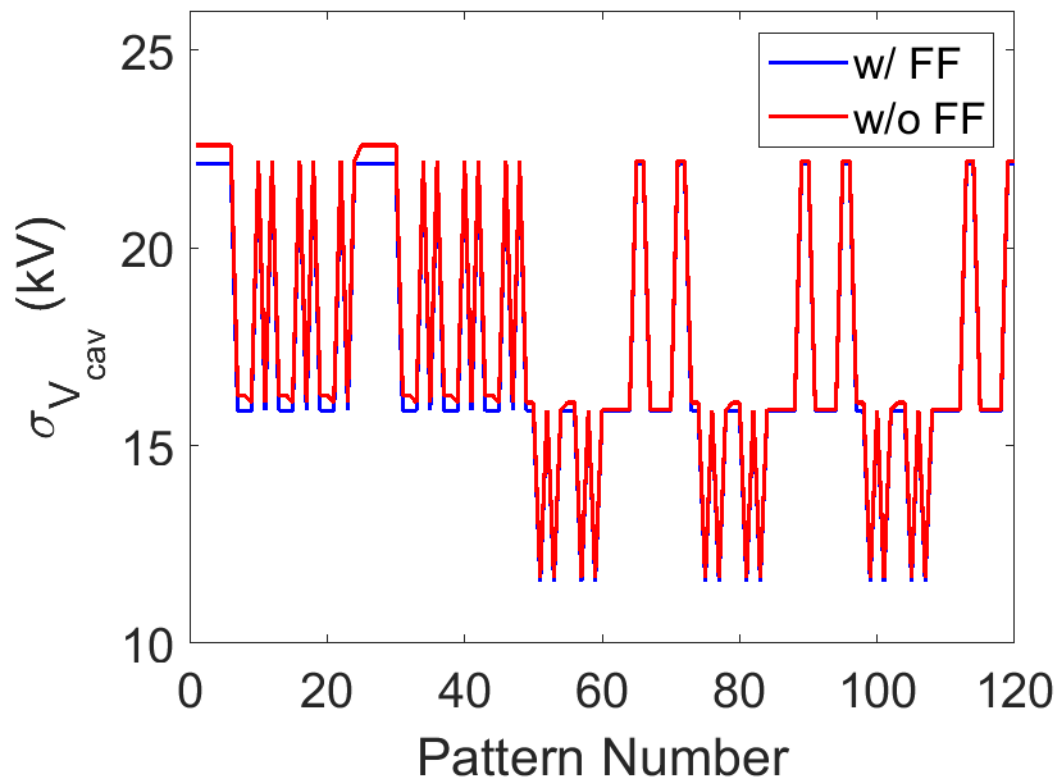
- $V_{\text{cav}}$  and  $P_{\text{amp}}$  are pattern dependent
- Some patterns are stabler than others

Pattern #1: {1,2,3,4,5,6}

Pattern #2: {1,2,3,4,6,5}

...

Pattern #120: {1,6,5,4,2,1}



# Beam Breakup (BBU) instabilities

1. Offset  $x$  causes HOM:

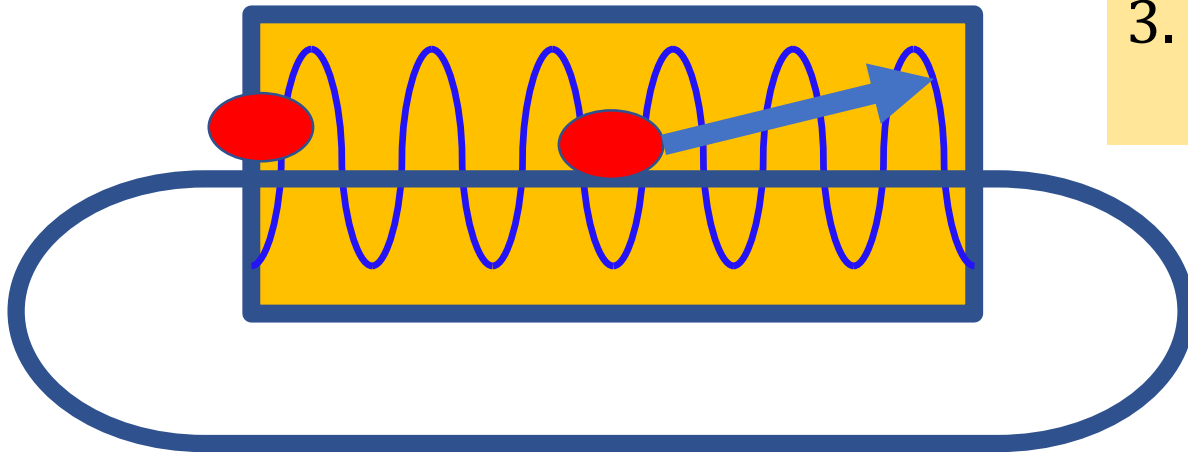
$$V_{HOM,R} = \frac{\omega_{HOM}^2}{2c} q_b \left( \frac{R}{Q} \right)_{HOM} x_n$$

2. VHOM kicks the beam:

$$x'_n = \frac{V_I}{V_{beam}}$$

3. Kick translates to offset

$$x_{n+1} = x_n + R_{12} x'_n$$

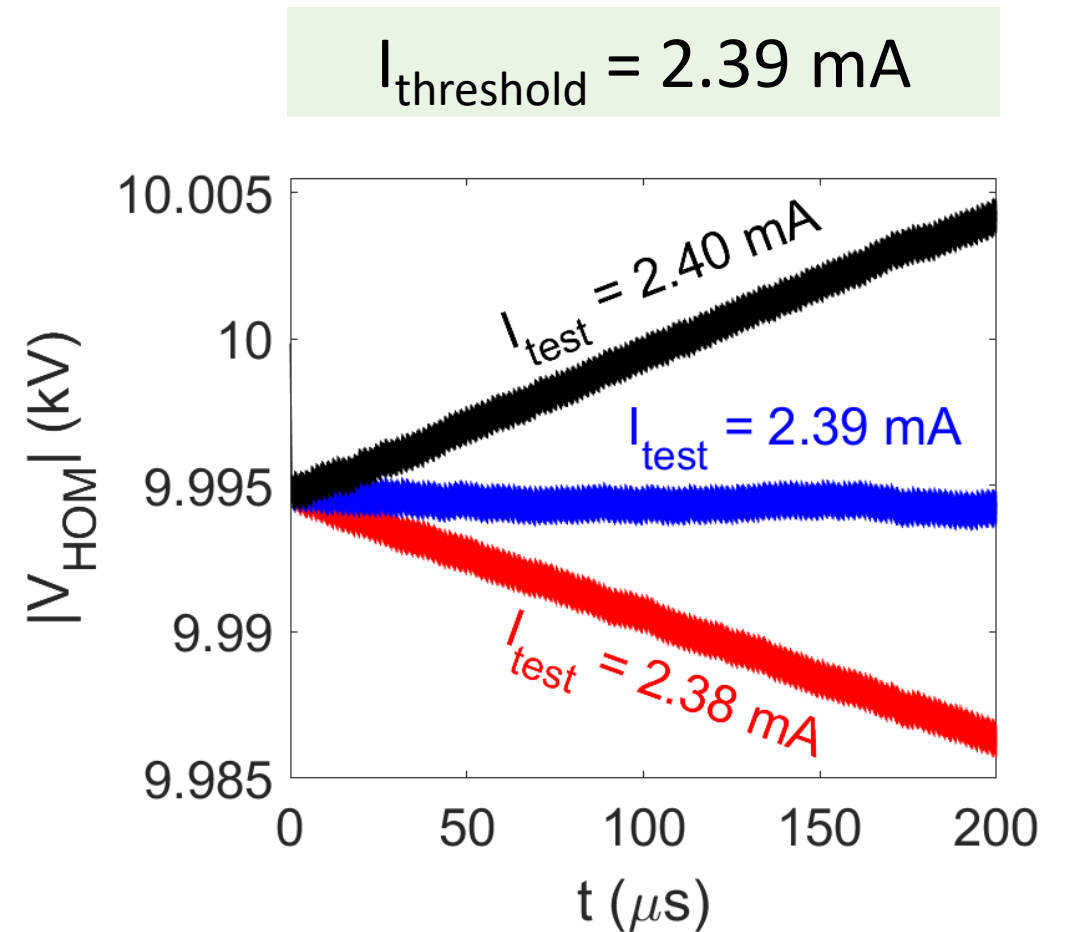


# BBU simulation

Our code can calculate the threshold current under different beam loading patterns

Benchmarked against the experimental results of the Ref. [1].

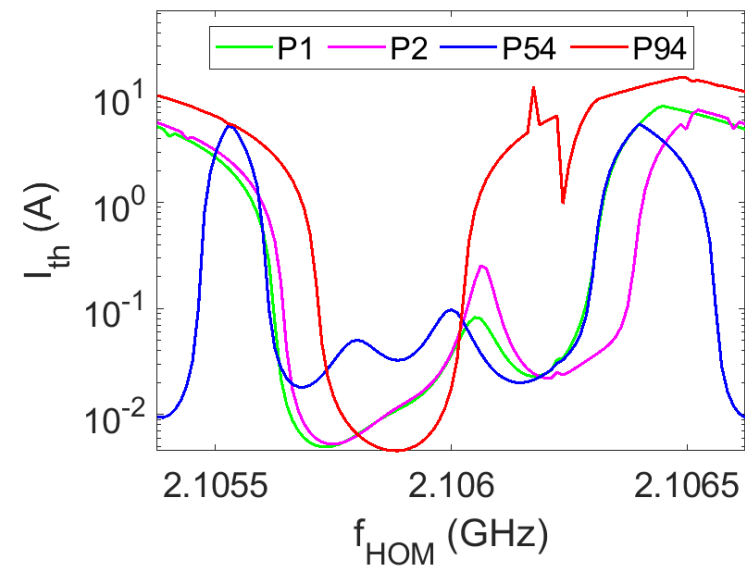
[1] Christopher D. Tennant, "STUDIES OF ENERGY RECOVERY LINACS AT JEFFERSON LABORATORY", Dissertation, (2006).



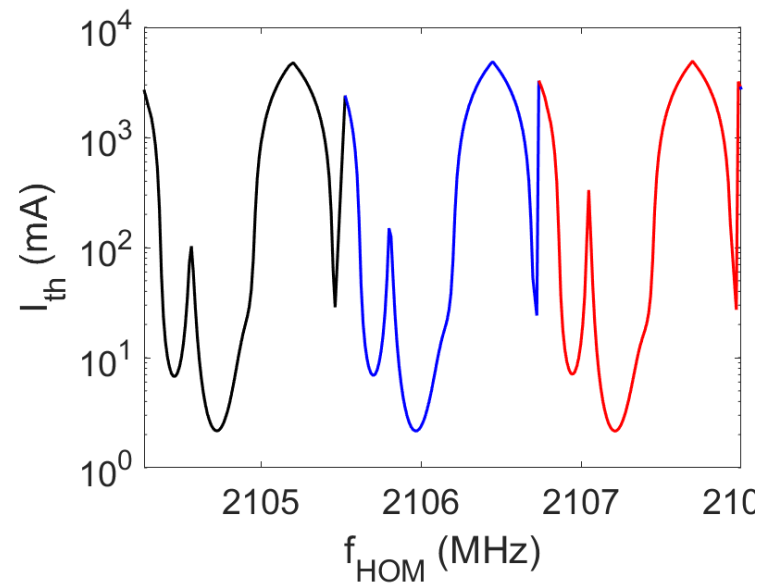


# BBU pattern dependance

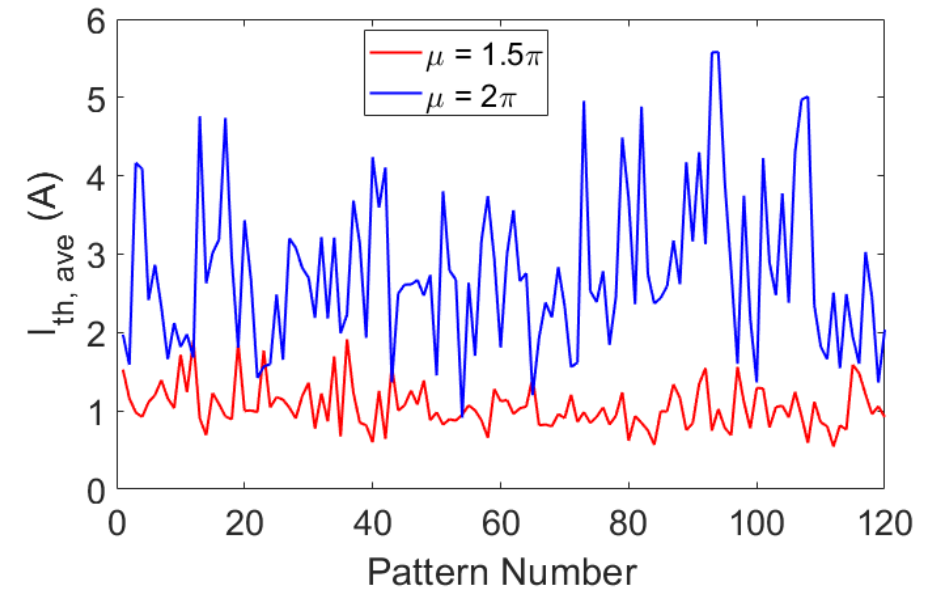
Significant difference between patterns



Periodic



$I_{th}$  is higher when  $\mu$  is integer of  $\pi$ .



# Conclusion

- Developed mathematical construct to analyze ERL bunches over many turns.
- This can be applied to different scenarios like RF stability and BBU.
- ERL LLRF requires feed forward for stability.
- ERL cavity voltage, amplifier power, and BBU are beam loading pattern dependent.
- ERL stability in these 3 areas can be improved significantly by optimizing the beam loading pattern.

The End

Thank you for your attention