The Cockcroft Institute of Accelerator Science and Technology

Lancaster University

Recirculating ERL Filling Pattern Study

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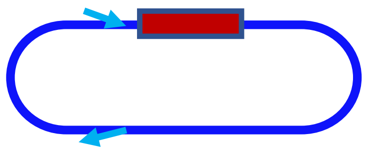
Filling Patterns

Simple 6-turn recirculating linac with 1 bunch train.

6 turns = 3 accelerations + 3 decelerations



Only 1 bunch is injected per turn to minimize voltage fluctuation by beamloading.

Filling pattern describes injection order: which bunch goes to which bucket.

Filling pattern [1 4 3 6 5 2]:

1st bucket filled in 1st turn

2nd bucket filled in 4th turn

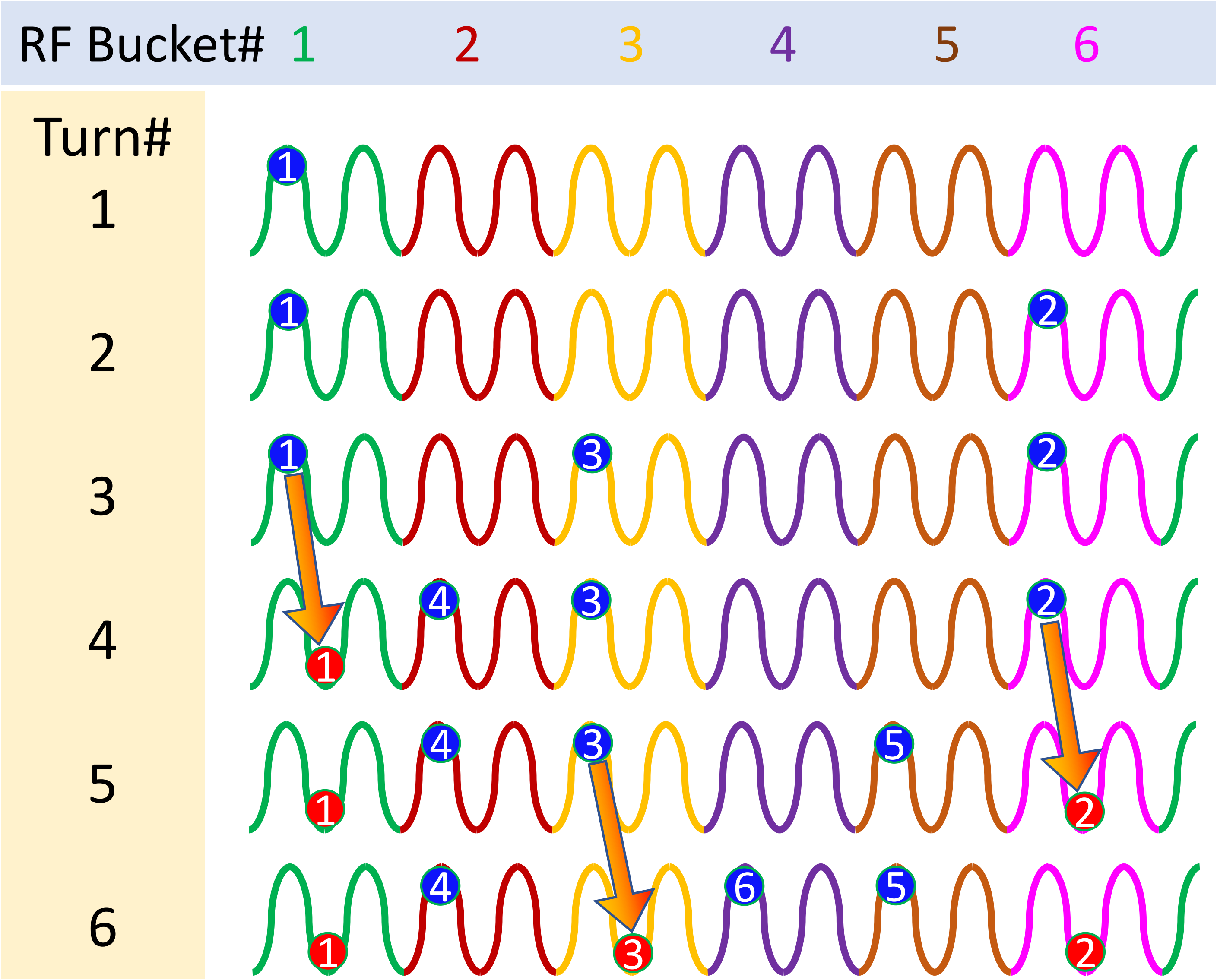
3rd bucket filled in 3rd turn

4th bucket filled in 6th turn

5th bucket filled in 5th turn

6th bucket filled in 2nd turn

Bunch phase changes by 180^{o} every 3 turns.



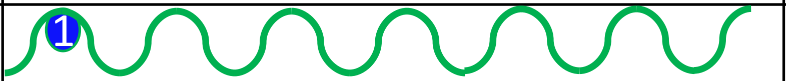
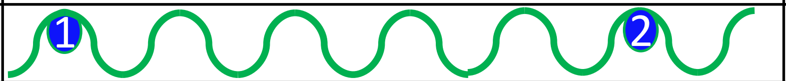
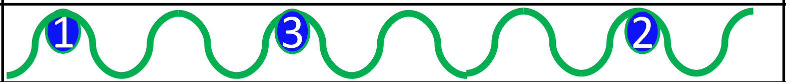
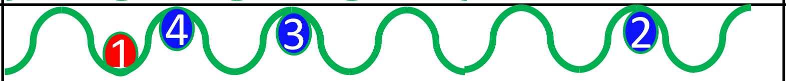
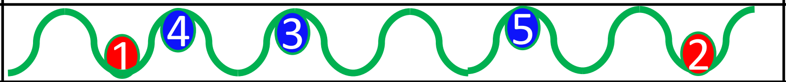
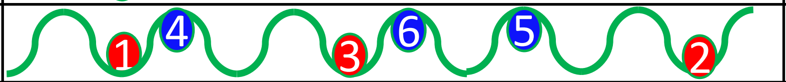
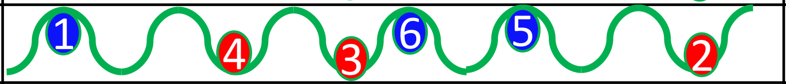
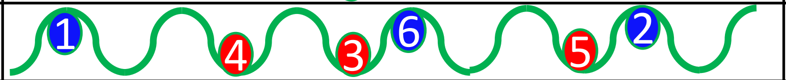
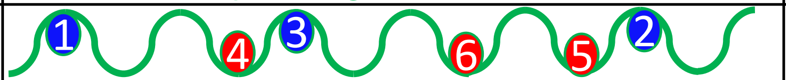
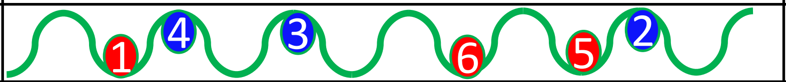
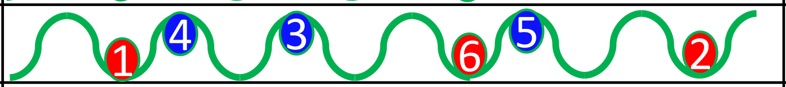
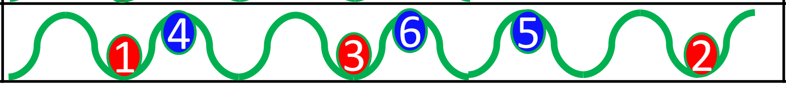
Beamloading Patterns

Fill patterns generate beamloading patterns.

Beamloading type:
Accelerating & Decelerating

Acceleration takes voltage from cavity: -1
Deceleration adds voltage to cavity: 1

Modes	Beamloading Notation	Binary Notation
Acceleration	**-1**	**0**
Deceleration	**1**	**1**

Turn	RF buckets and patterns	Beamloading Pattern
1		0
2		0 0
3		0 0 0
4		100 0
5		100 01
6		101001
7		011001
8		011010
9		010110
10		100110
11		100101
12		101001

Beamloading Pattern Periodicity

In simple recirculating linac, the beamloading pattern changes every turn.

- N-turn recirculating ERL:
  - N bunches form a train
  - Ring can be filled with many similar trains
  - Total of (N-1)! fill patterns
    - 120 patterns for 6-turn
- Beamloading patterns repeats with N-turn period.

Turn #	123456	142365	143652
1	011100	101100	011001
2	001110	011100	011010
3	000111	010101	010110
4	100011	010011	100110
5	110001	100011	100101
6	111000	101010	101001
7	011100	101100	011001
8	001110	011100	011010
9	000111	010101	010110

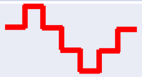
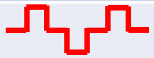
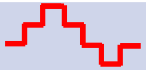
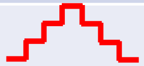
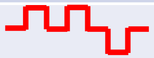
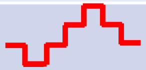
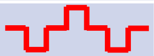
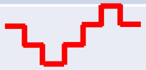
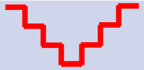
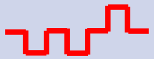
Note: N-turn = (accelerating turns) + (decelerating turns)

Fill pattern and Cavity Voltage

Fill pattern → beamloading pattern → cavity voltage change.
Different fill patterns → different cavity voltage fluctuations.

$$V_{ji} = \sum_{j=1}^{N} \boldsymbol{B_j}\,(\boldsymbol{F_i})$$

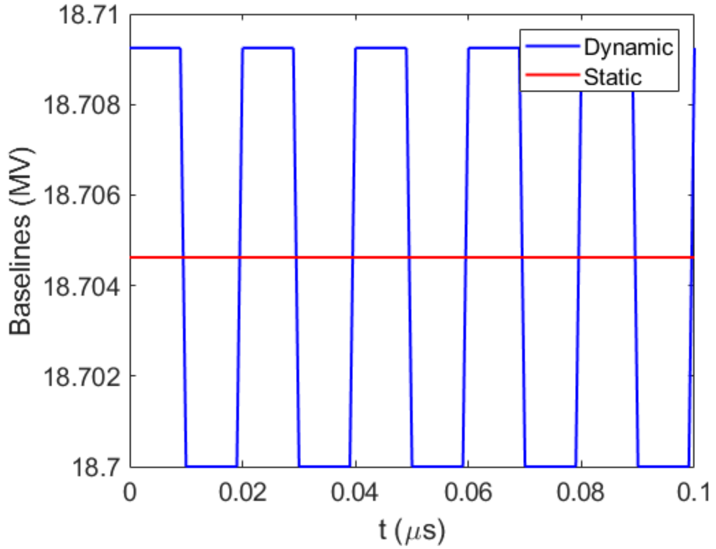
$\boldsymbol{F_i}$**:** i^{th} Fill pattern
B_j: Beam Loading Pattern in the j^{th} turn
V_j: Voltage in the j^{th} turn
N: number of bunches in a train.

	F_1: 123456			**F_{60}: 143652**		
J^{th} turn	**B_j**	**V_j**	$\overline{V}_{turn}$	**B_j**	**V_j**	$\overline{V}_{turn}$
1	100011		**-0.5**	100110		**0.17**
2	110001		**-1.5**	100101		**- 0.17**
3	111000		**-0.5**	101001		**0.17**
4	011100		**0.5**	011001		**- 0.17**
5	001110		**1.5**	011010		**0.17**
6	000111		**0.5**	010110		**-0.17**
$\sigma_{\overline{V}_{turn}}$	0.96			0.1667		
σ_V/N	1.3540/6 = 0.23			$\frac{1}{\sqrt{2}}$/6 = 0.12		

LLRF Setpoint: Static vs Dynamic

Static setpoint:
- feedback voltage setpoint is set to a constant value
- LLRF makes corrections to all voltage changes

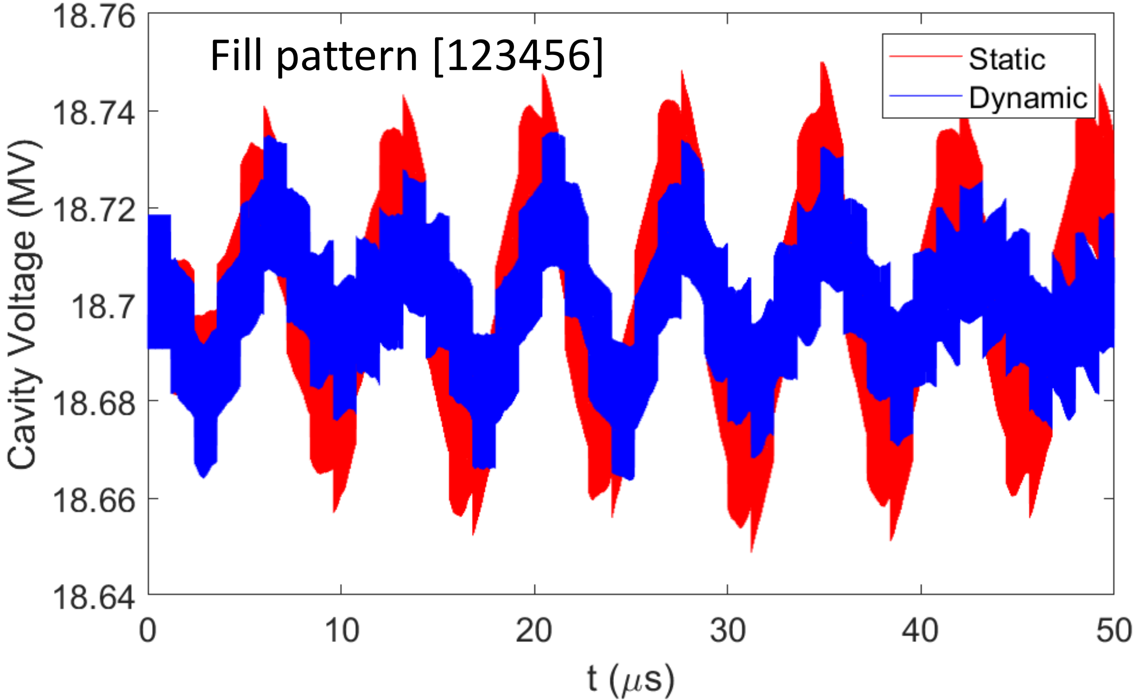
Dynamic setpoint:
- feedback voltage setpoint changes dynamically according to the expected voltage change due to the beamloading
- LLRF makes corrections to non-beamloading voltage changes only



Voltage change by beamloading is corrected by itself later, so no need for correction.

In static setpoint, LLRF system tries to fight itself during beamloading!

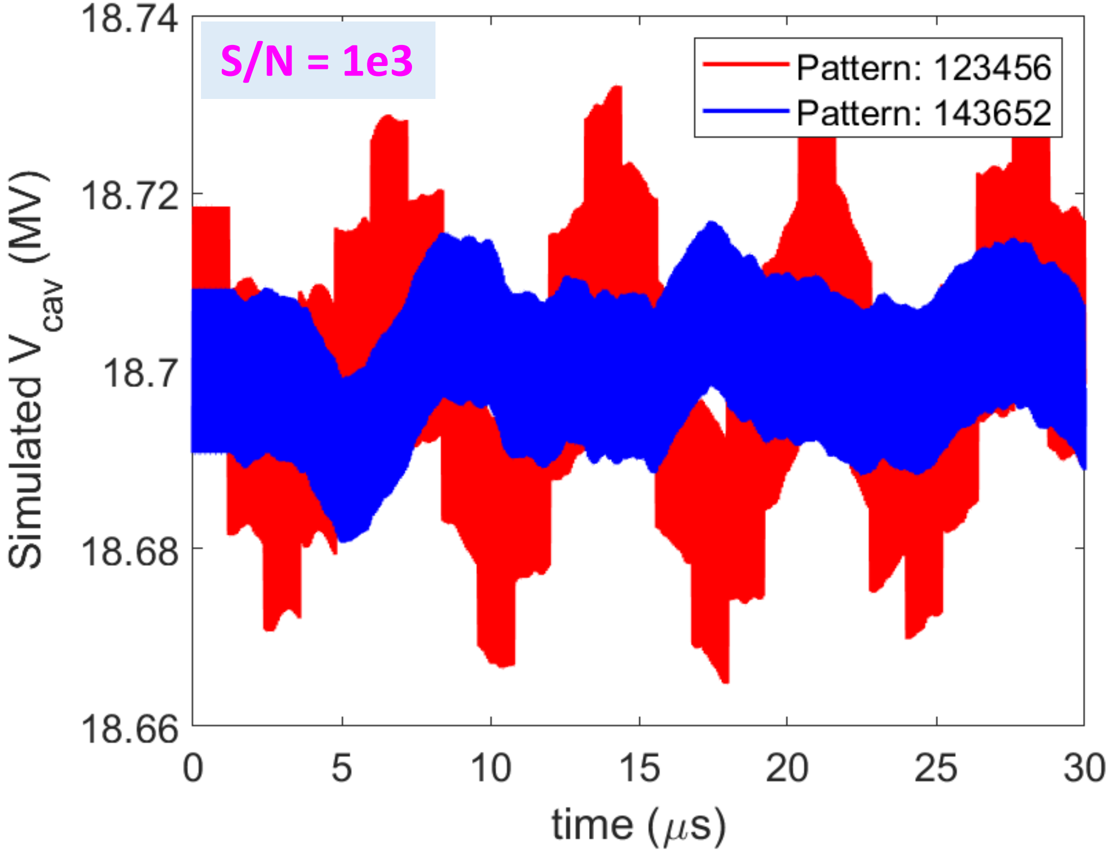
Dynamic setpoint is better.

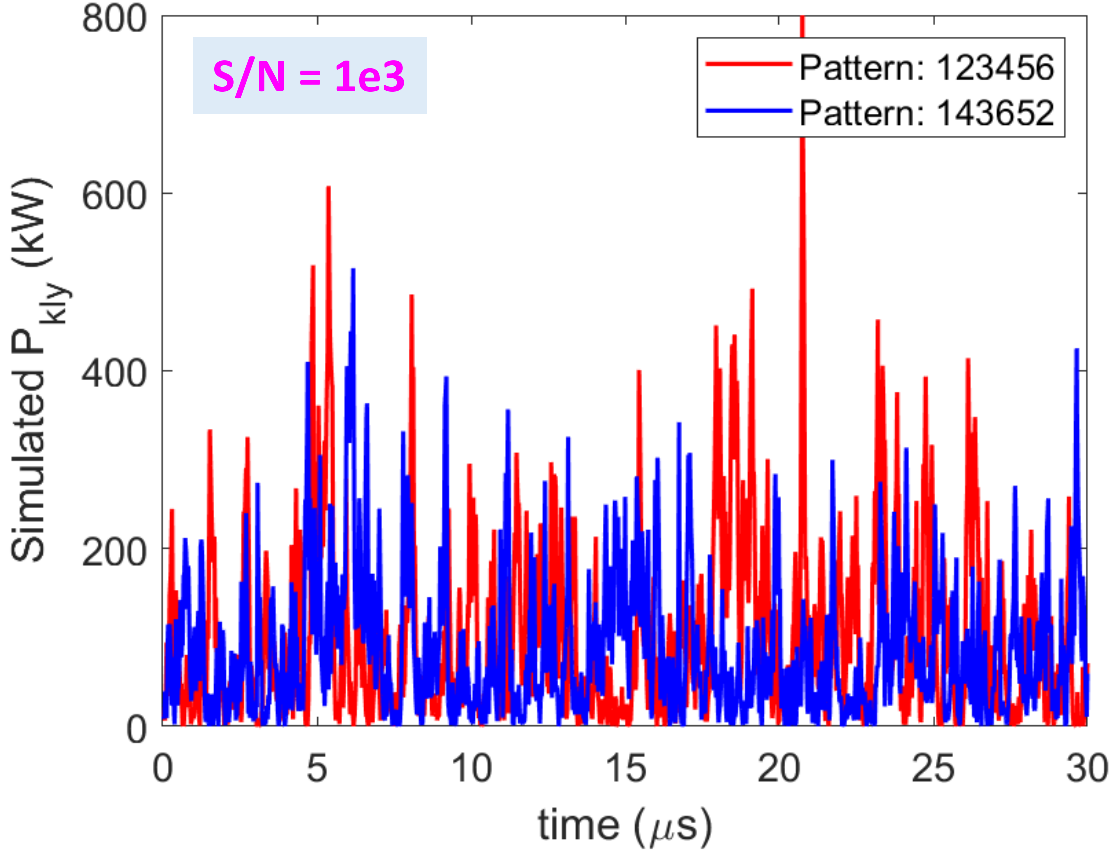


Pattern Matters for RF Stability

Fill patterns matter for RF stability.
Some patterns are better because they create less cavity voltage fluctuation and requires less power from klystron to maintain stable cavity voltage.

Beamloading simulation: beam interaction with cavity and RF system; dynamic setpoint and with noise.





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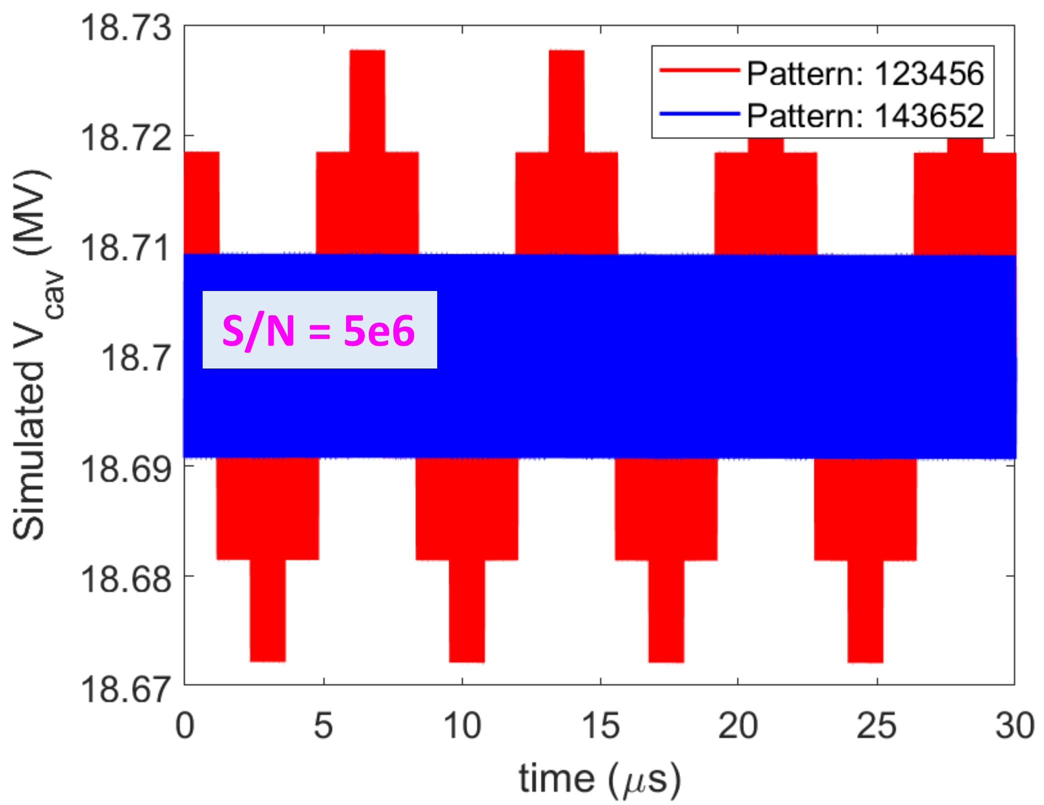
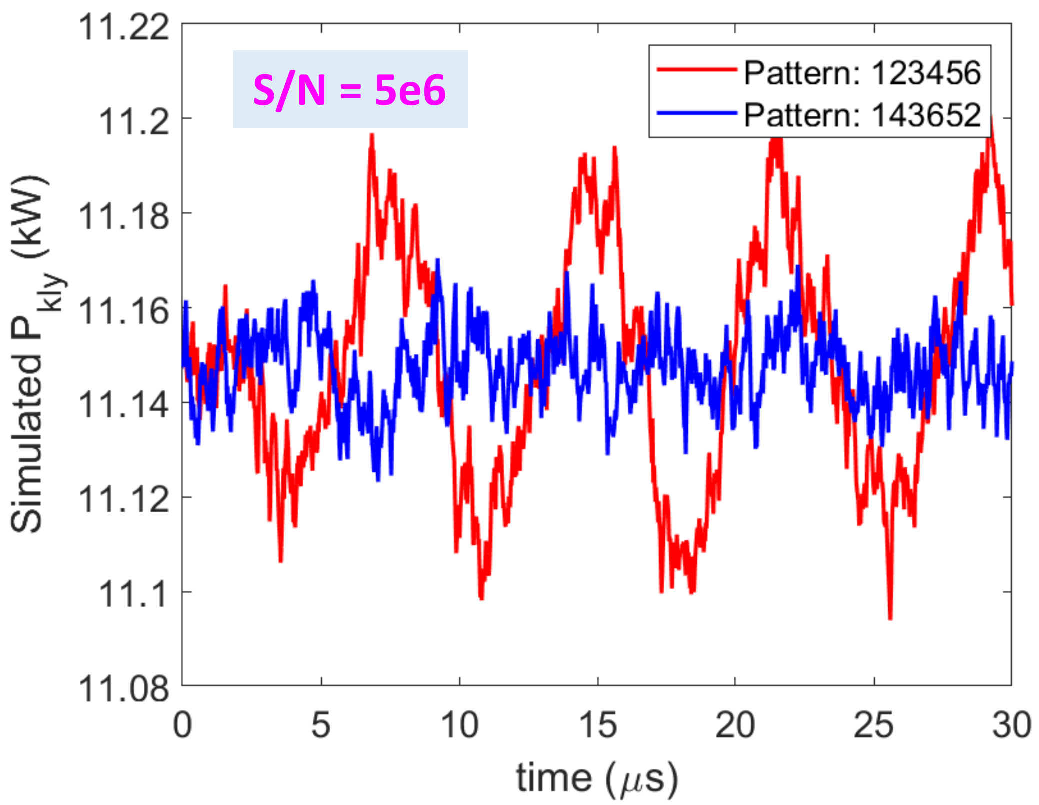
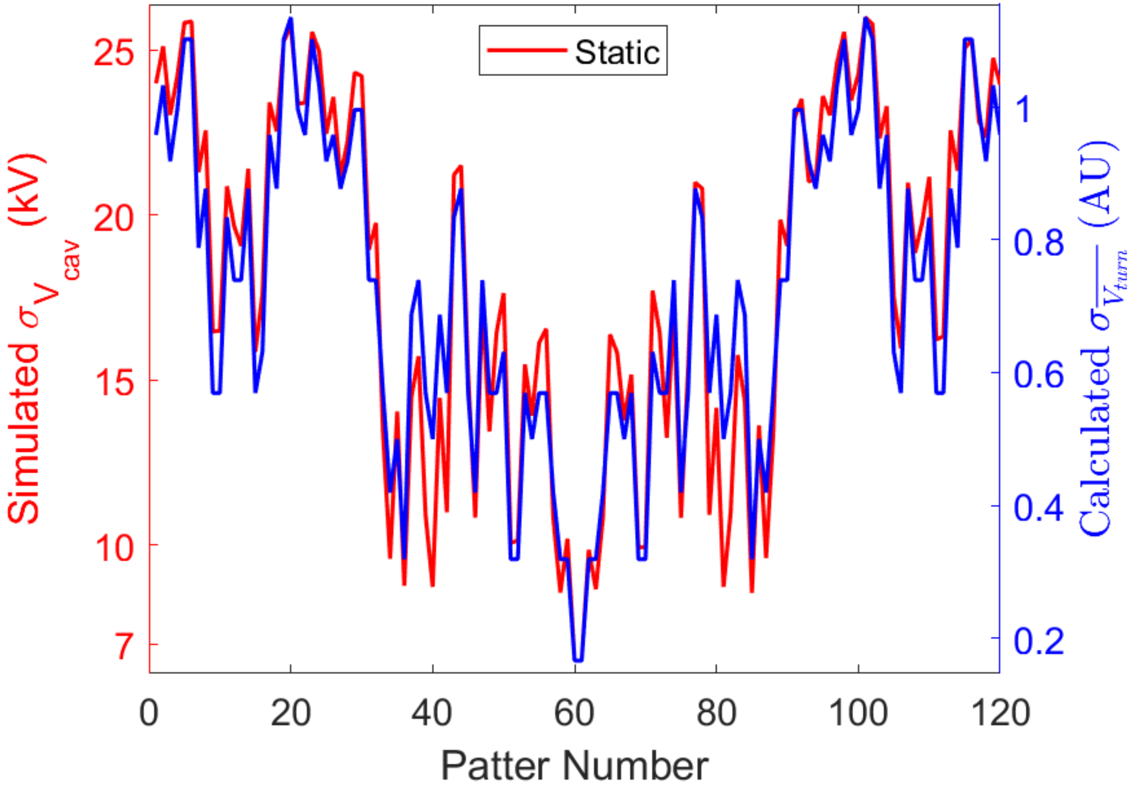
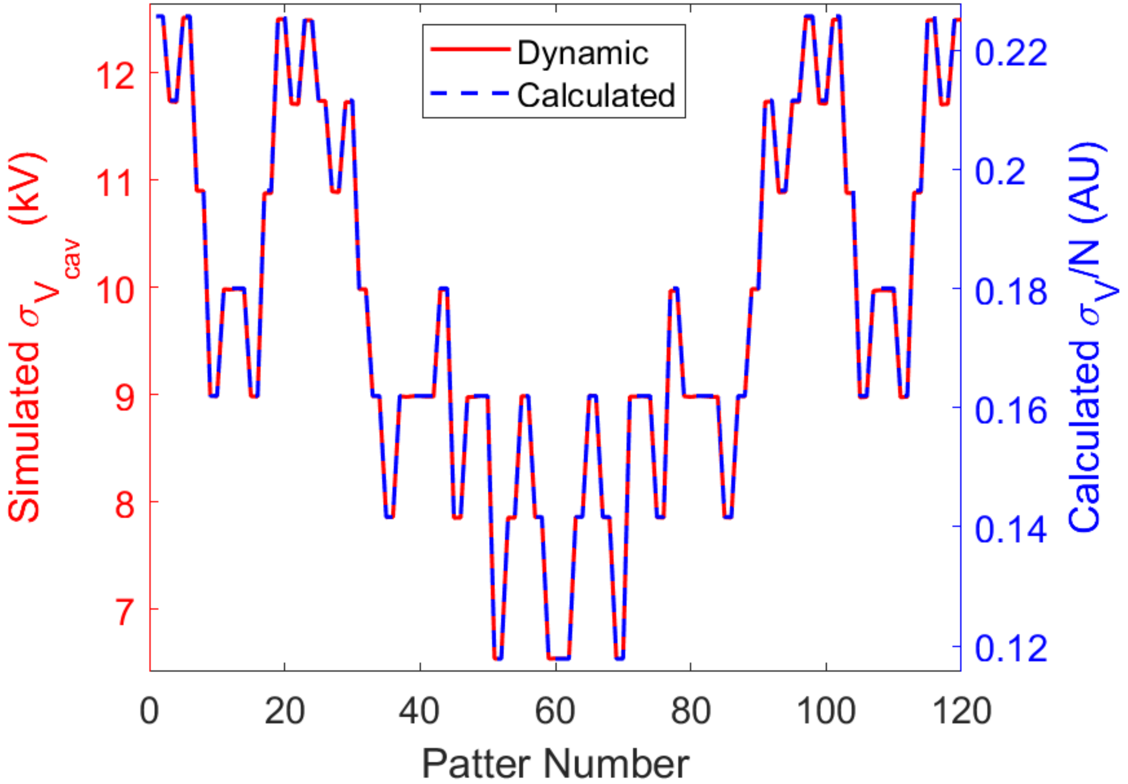




6 turn ERL Optimal Patterns

Scanned all 120 fill patterns in simulation without noise.
Found optimal patterns with least RF jitter.
Patterns #60 & #61 are optimal for both static and dynamic setpoints.
Patterns optimal for dynamic setpoint: 143652 (#60), 145236 (#61), 142536, 142563,143625, 145263, 146325, and 146352.
LLRF feedback effects optimal pattern figure of merit: static → $\sigma_{\overline{V}_{turn}}$; dynamic → $\frac{\sigma_V}{N}$.





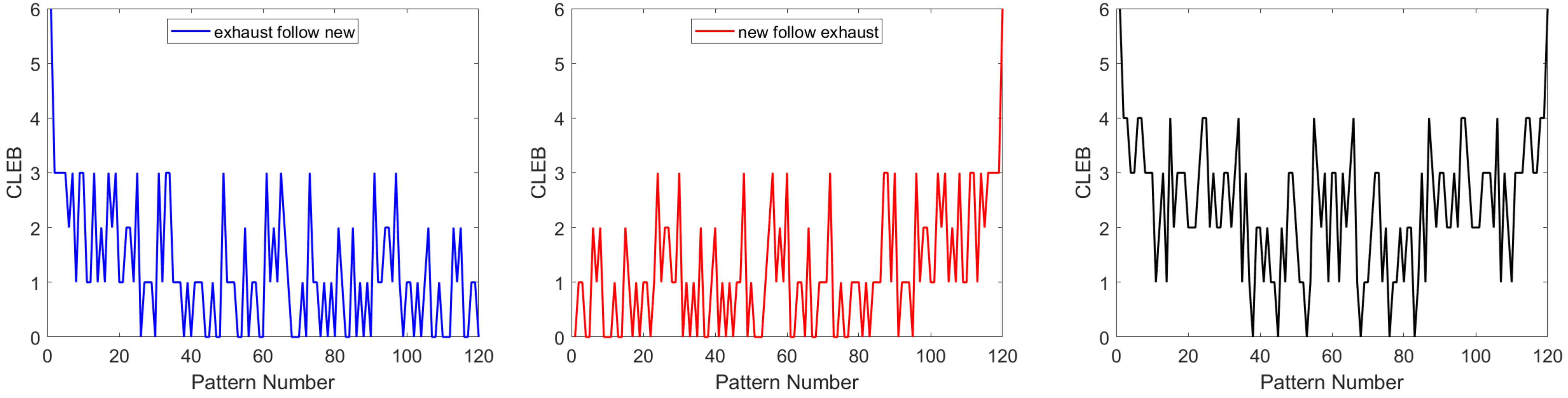
Beamloading & BBU

Low energy particles are more susceptible to multi-bunch effect: ∝ β/E.

Avoid Consecutive Low Energy Bunches (CLEB) to maximize threshold current [1].

Good CLEB: exhaust bunch follows new bunch; second bunch is dumped on this turn.

Bad CLEB: new bunch follows exhaust bunch.



[1] D. Angal-Kalinin, et al., PERLE: Powerful Energy Recovery LINAC for Experiments - Conceptual Design Report, https://arxiv.org/abs/1705.08783

Ongoing and Future Studies

- Studying the effect of:
  - different topologies
  - injection timing
  - ring circumference
  - off-crest beam loading phases

- More detailed BBU studies.

- Optimal LLRF requirements.

Conclusion

- Developed mathematical construct to analyze bunches over many turns.
- This can be applied to different scenarios like RF stability and BBU.
- Our studies show that LLRF requires dynamic setpoint and it is highly sensitive to noise.
- We welcome any comments.

THE END

Thanks for your attention!

Comments & Questions?