Beam Timing and Cavity Phasing

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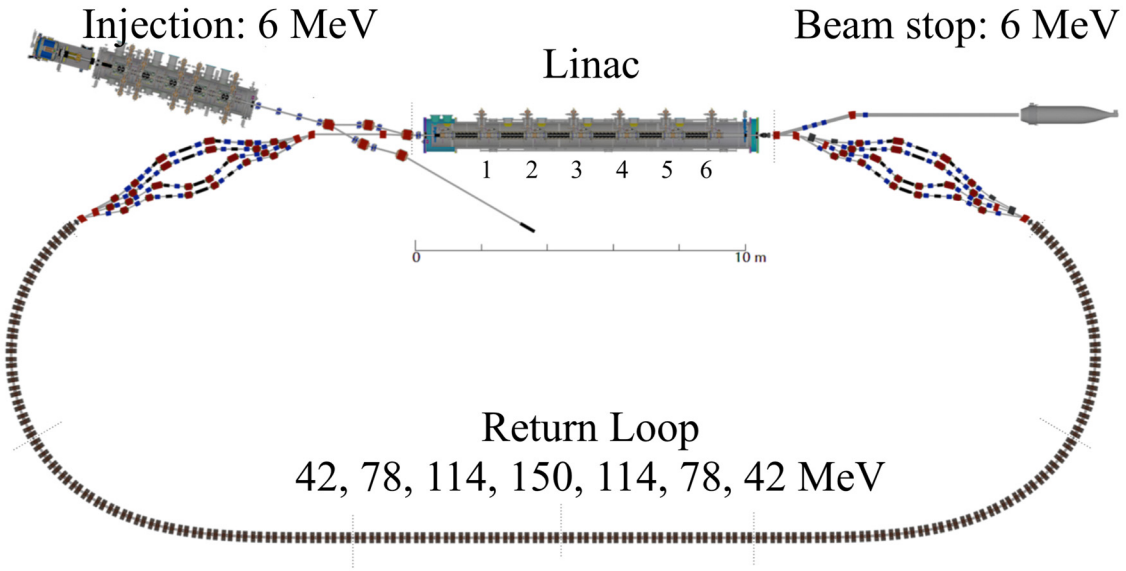
Cornell Laboratory for Accelerator Sciences and Education (CLASSE)

ERL 2019

ERL: Energy Recovery Linac

- Linac-quality beams
- Higher beam power
- Deceleration recovers energy



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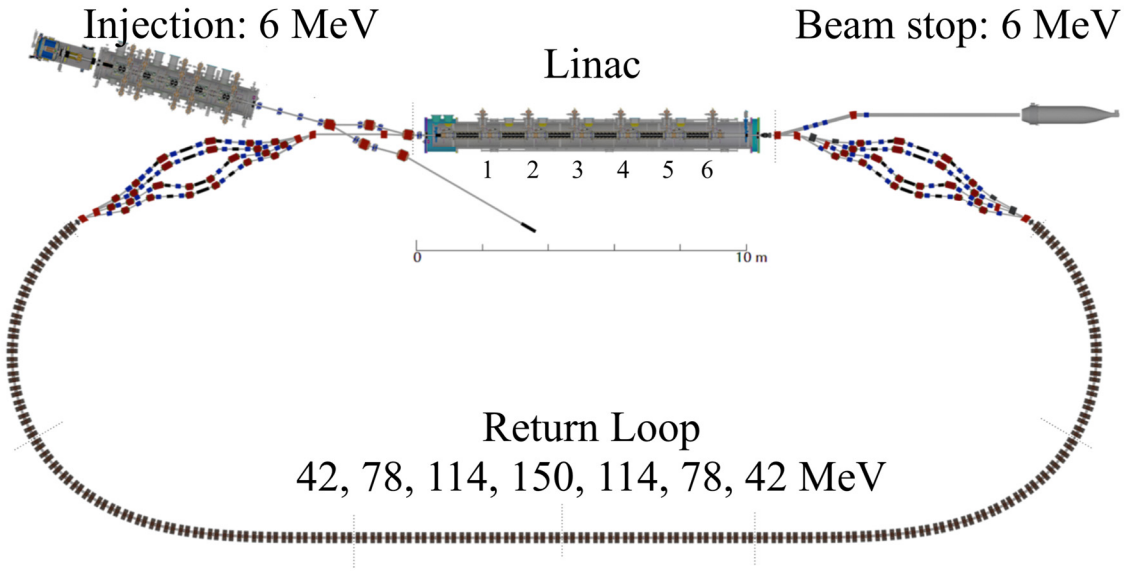
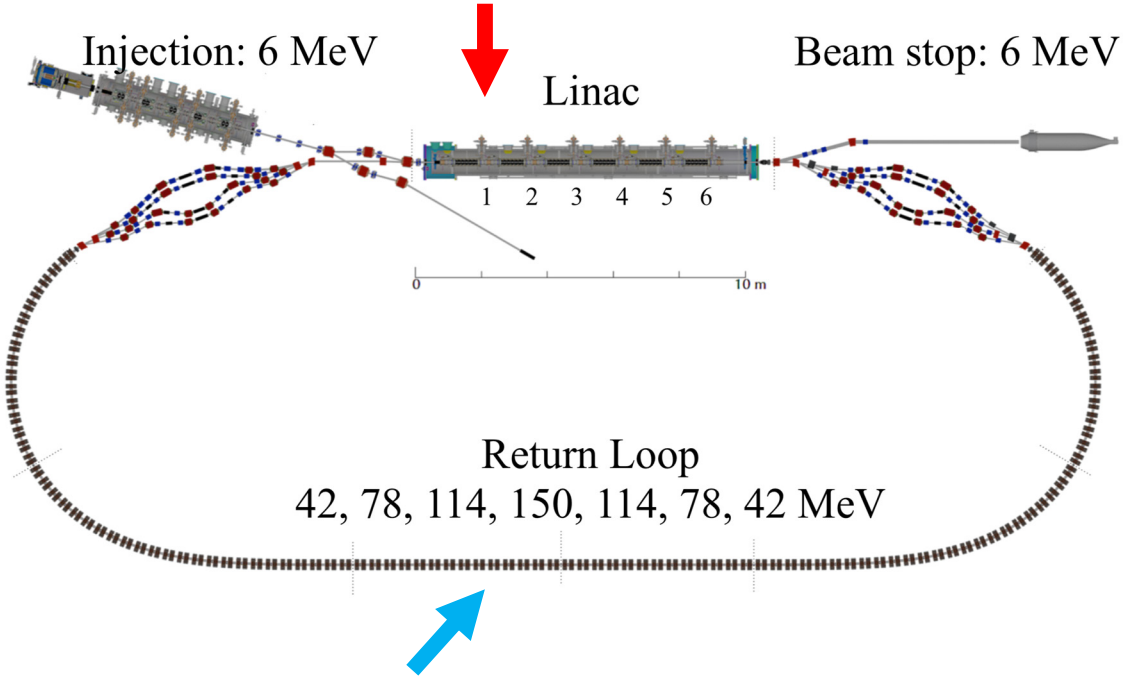
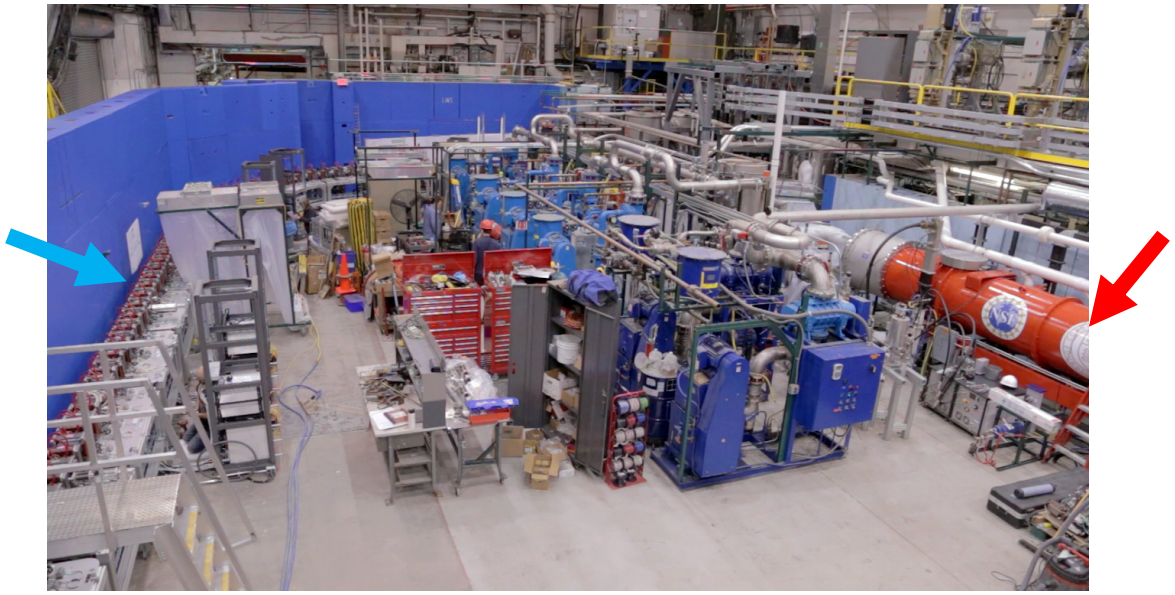


Cornell-Brookhaven ERL Test Accelerator (CBETA)

- Beam passes 8 times through a 6-cavity linac
- 4 accelerations, 4 decelerations
- Nonultrarelativistic beam





Overview

- CBETA 1-turn tests
- Multi-turn optimization*
- ERL symmetry: how can it help?*
- Symmetric CBETA model optimization*
- Longitudinal beam symmetry*

*Recently published, *Editor's Suggestion*:
Phys. Rev. Accel. Beams **22**, 091602
DOI: https://doi.org/10.1103/PhysRevAccelBeams.22.091602

ERL Requirements

- Reduce power load on cavities (0 W)

Linac: 6 cavities

Return loop: 4 independent paths

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- Achieve the correct max energy (150 MeV)
- Get equal beam energy in corresponding loops (e.g. first/last)

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Return loop: 4 independent paths

Multi-turn Challenges

If beam is assumed to always be ultra-relativistic ($v=c$) in CBETA…

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- Each cavity uses up to 46 kW per 40 mA beam

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Multi-turn Challenges

If beam is assumed to always be ultra-relativistic ($v=c$) in CBETA…

- Each cavity uses up to 46 kW per 40 mA beam
- Beam ends with double the injection energy (6 MeV → 12 MeV)

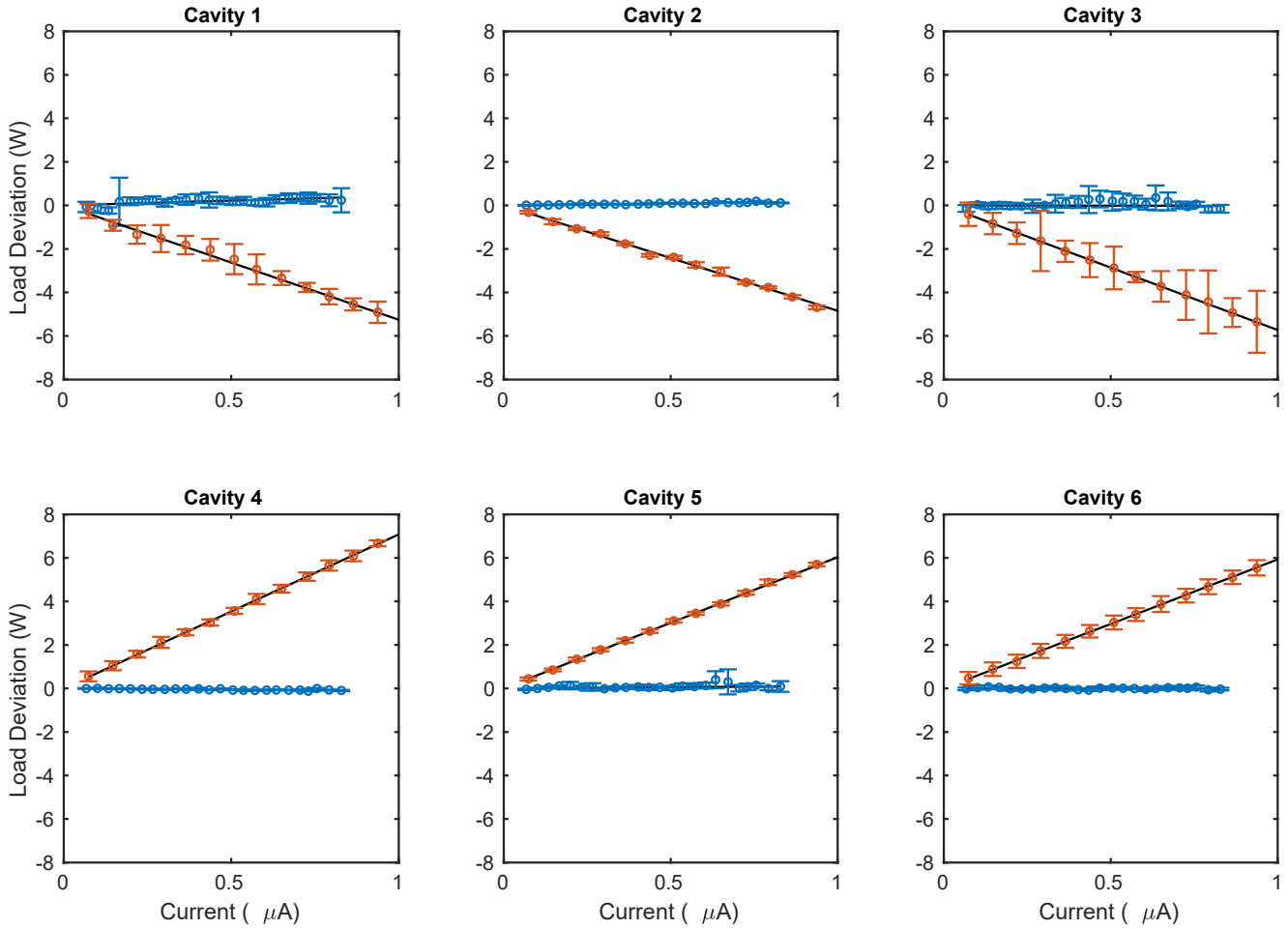
Linac: 6 cavities

Return loop: 4 independent paths

CBETA Energy Recovery

1-turn CBETA operation

- 6 → 42 → 6 MeV
- Cavity phases near on-crest
- Above 99.8% energy recovery in each cavity



CBETA 4-Turn Optimization

Objectives

- Power load: 6
- Max beam energy: 1
- Loop energies: 6

Total: 13

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- Cavity phase: 6
- Cavity voltage: 6
- Loop lengths (times): 4

Total: 16 (need ≥ 13)

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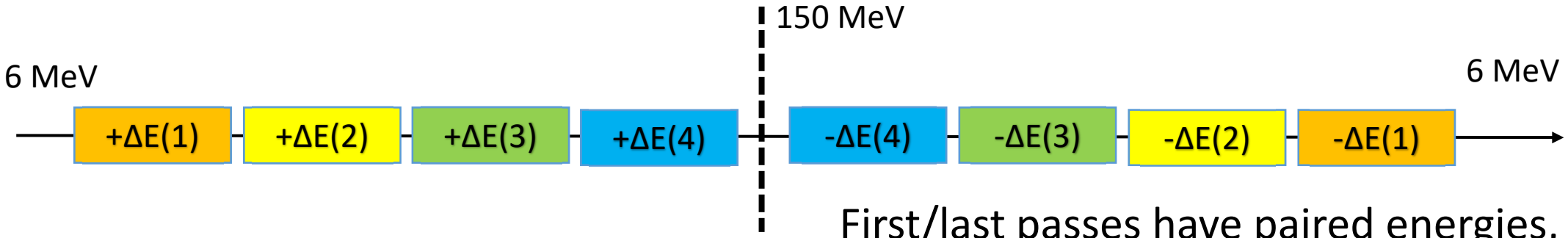
Solving requires a 13-by-13 system, at minimum.

Reduce by imposing ERL symmetry.

What is ERL symmetry?



First/last passes have paired energies,
e.g. ΔE(8) = -ΔE(1).

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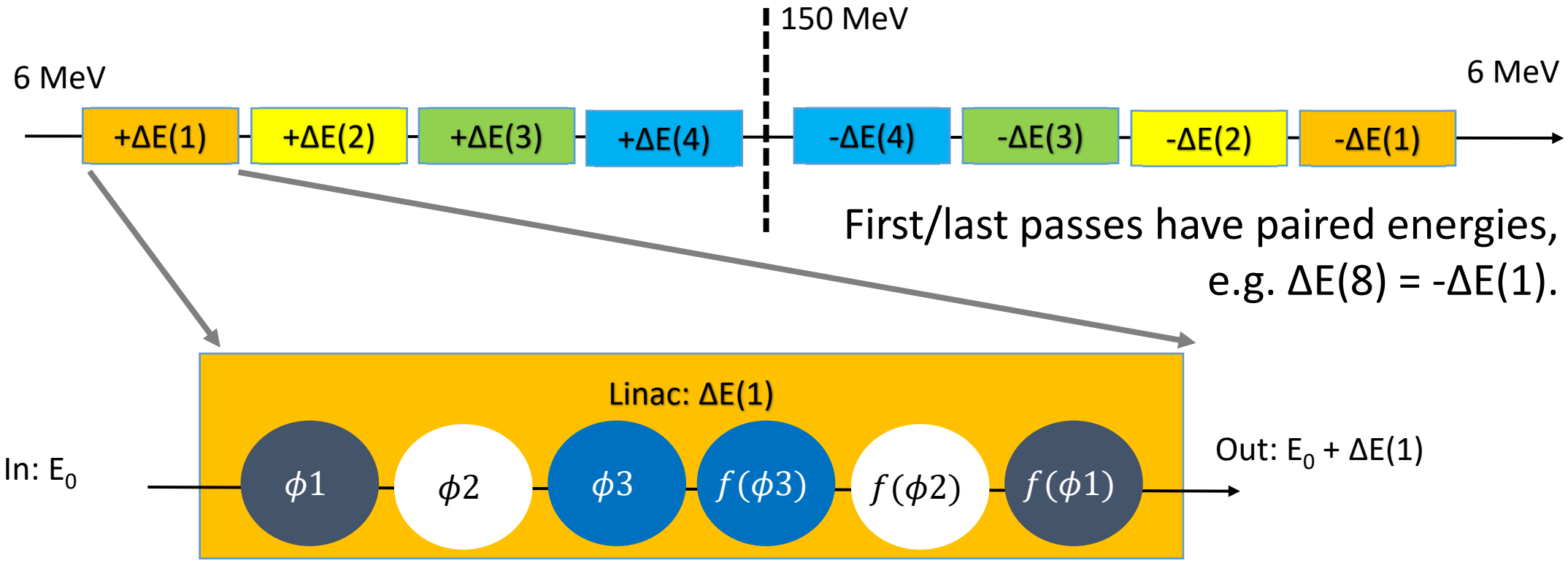

First/last cavities have paired phases, e.g. $\phi 6 = f(\phi 1)$.

Outcomes of Symmetry

- Correlate phases of cavity pairs
- Set length of central (4^{th}) loop

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Symmetric energy,
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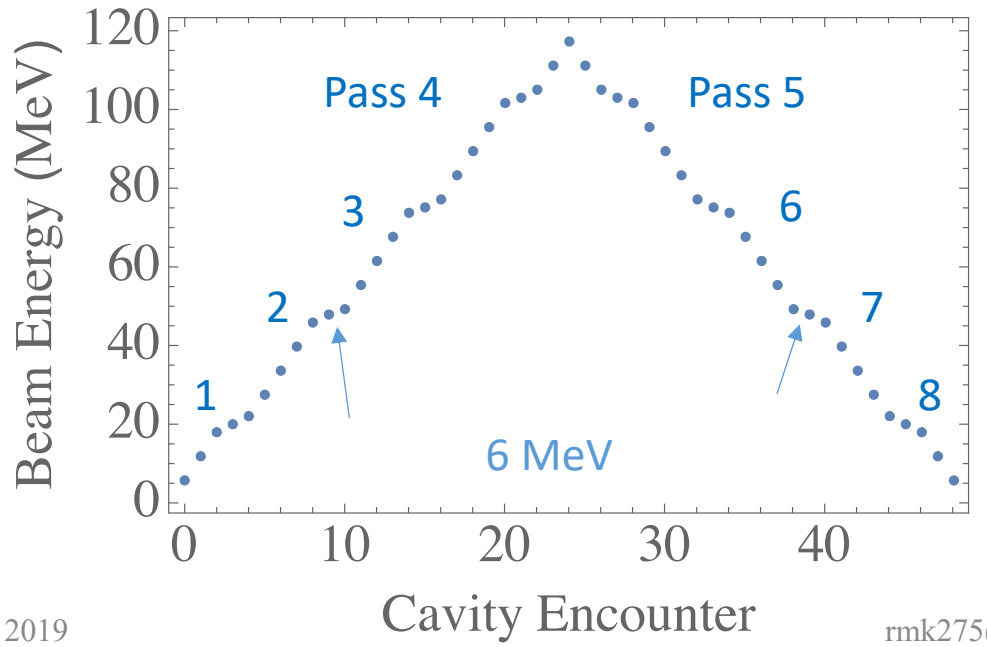

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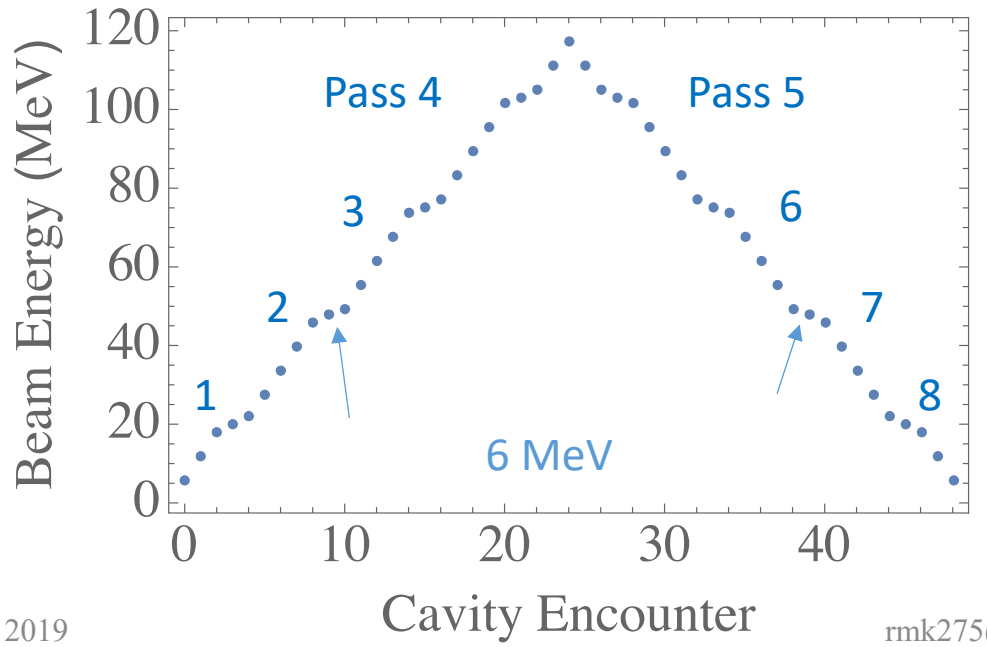

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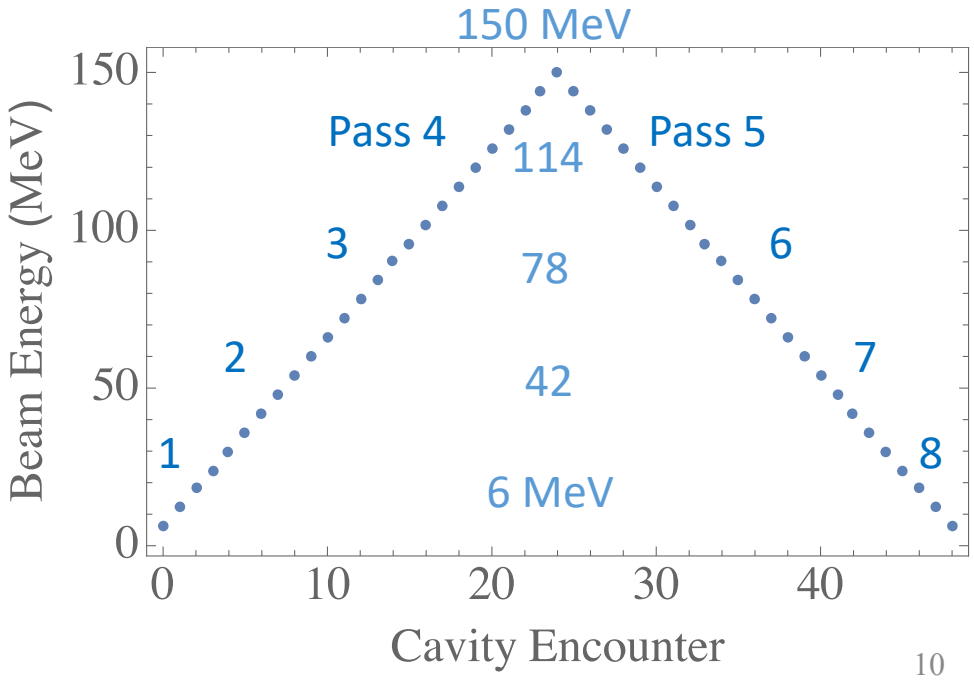

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Optimization: why symmetry?

Objective	# Targets, normal ERL	# Targets, symmetric
Load per cavity Load = 0	6	3
Max beam energy E – (150 MeV) = 0	1	1
Acc/dec loop beam energy	6	0
Total	**13**	**4**

Optimization: why symmetry?

- Degrees of Freedom
  - Phase (paired): 3
  - Voltage (paired): 3
  - Loop lengths: 4
- **Total: 10 (need ≥ 4)**

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- Opt. system shrinks
  - Old: 13-by-13
  - New: 4-by-4

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Creating Symmetry: 2 cavities

Cavity A accelerates, D decelerates

- D's electric field mirrors that of A
- Zero total load of system

Cavity phase

- $\phi_{in,D} = \phi_{out,A} + \omega \Delta t_{loop} = -\phi_{out,A}$ (Odd-cell cavities, e.g. CBETA)
- $\phi_{in,D} = \phi_{out,A} + \omega \Delta t_{loop} = \pi - \phi_{out,A}$ (Even-cell cavities)

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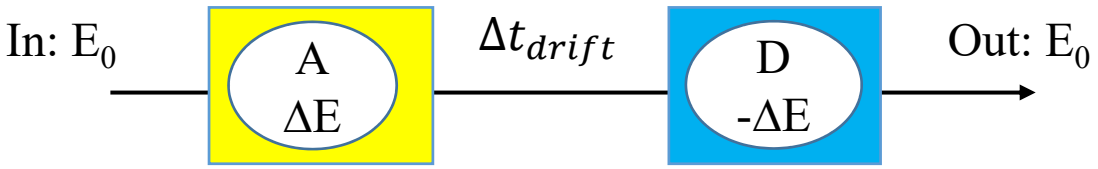

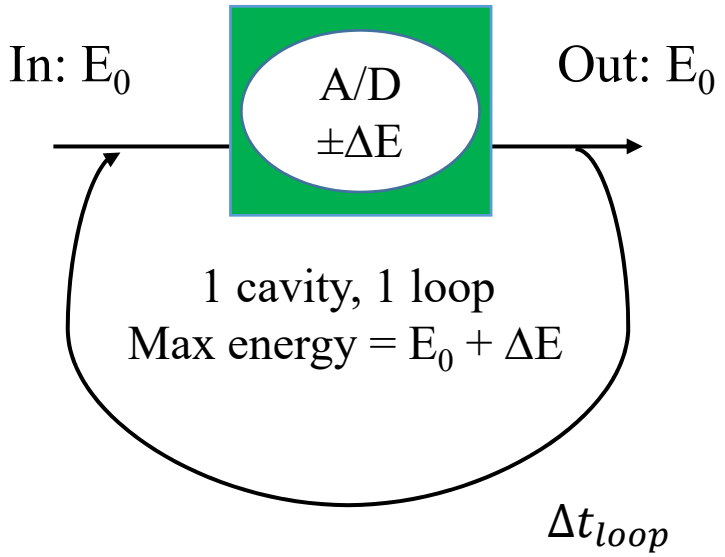

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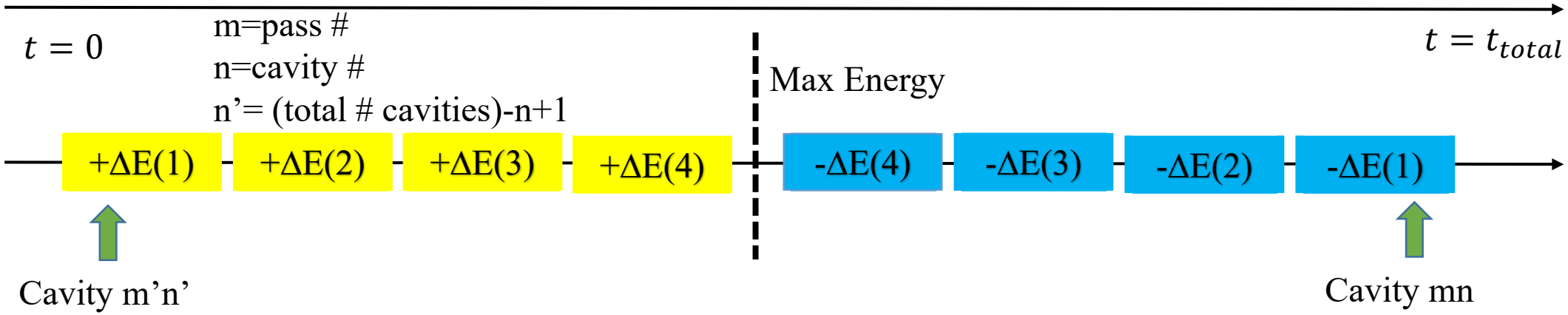
Multi-turn Symmetry



Electric fields must be mirrored in acceleration/deceleration.

- Let $\phi_{in,mn} = \phi_{0,n} + \omega t_{in,mn}$

Symmetric cavity pair: $\phi_{in,Dec} = -\phi_{out,Acc}$

$$\phi_{0,n} + \omega t_{in,mn} = -\left(\phi_{0,n'} + \omega t_{out,m'n'}\right)$$

$$\phi_{0,n} = -\phi_{0,n'} - \omega t_{\text{total}}$$

$$t_{\text{loop},M/2} = t_{\text{total}} - 2t_{\text{acceleration}}$$

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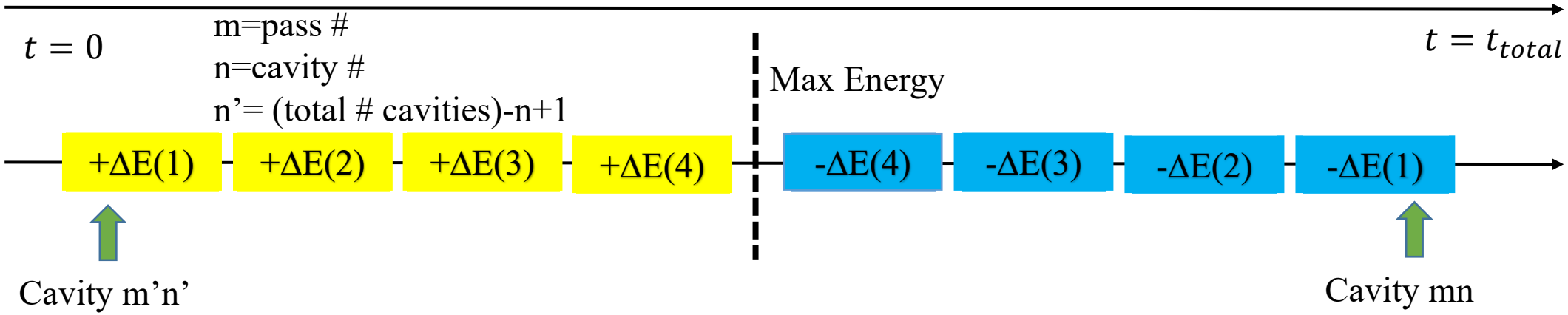

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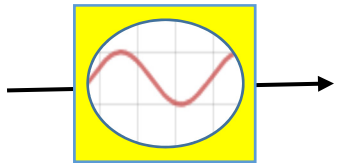

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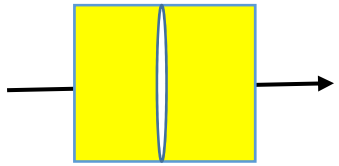

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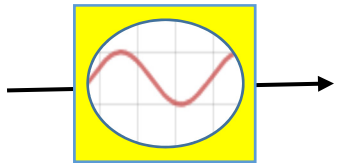

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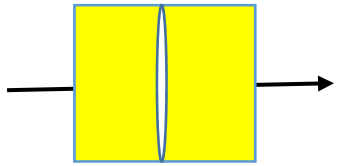
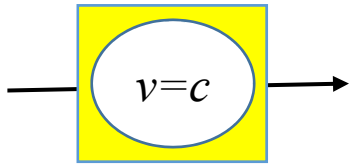


Ultra-relativistic cavities (UR)



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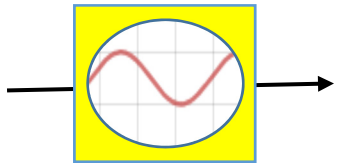

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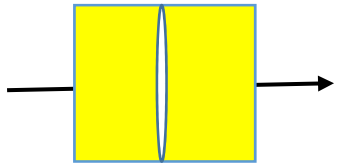

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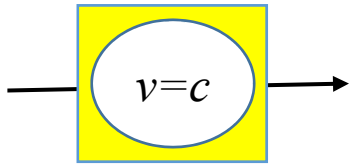
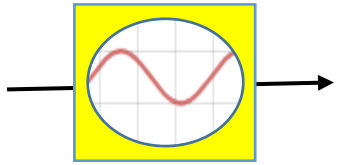


Finite Time-tracked cavities (FT)

Runge Kutta *Bmad* cavities (RK)



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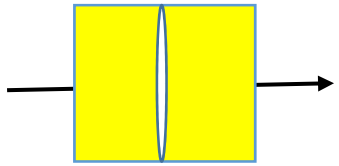

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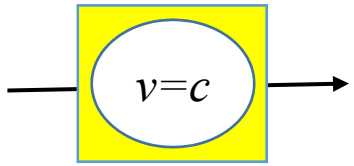

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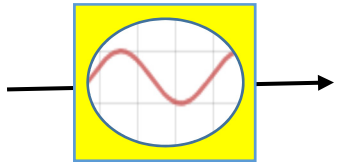
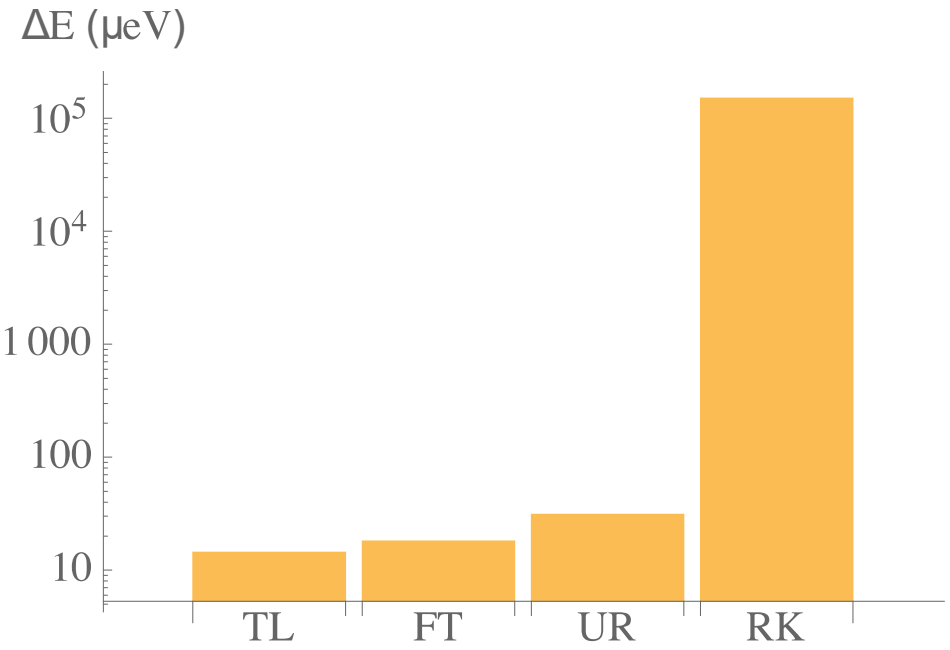


Mathematica (TL, UR, FT models) are solved with Newton's method.
Bmad (RK model) uses Levenberg-Marquardt optimization.

Optimized Models

ERL output	Objective (min)	Objective (max: RK)	Design target
Cavity load	28 pW (TL)	32 μW	0 W
Max energy (offset)	37 μeV (TL)	0.9 eV	0 eV
Loop 1 (MeV) Loop 2 Loop 3	42.00 (UR) 78.01 (UR) 114.00 (UR)	42.18 78.20 114.23	42.00 78.00 114.00

Avg. solution deviation from targets



Solutions: Error Tolerance

Find necessary control precision of optimized settings.

- All inputs modeled with "expected" fluctuations

Objective goals

- Load: 2 kW
- Max energy: ± 150 keV

ERL inputs	Tolerance (max: FT)	Tolerance (min: UR)	Expected resolution
Phase	67.0 %	51.0 %	0.100°
Voltage	67.0 %	50.7 %	600 V
Loop length	67.0 %	50.8 %	0.333 mm

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  - What about >1000 particles in a beam?

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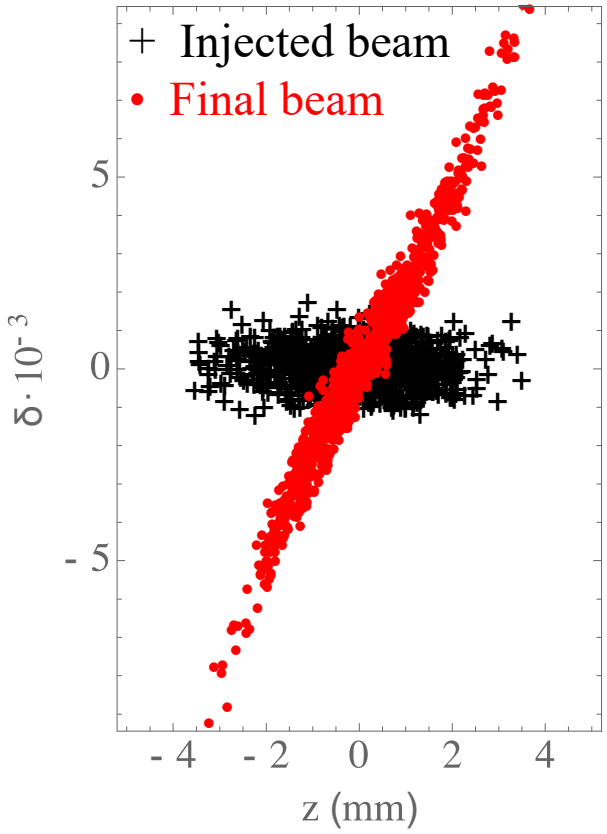
- How?
  - "Tilt" initial beam using off-crest injector phases

Beam Tilting Results

Normal input,
Model output



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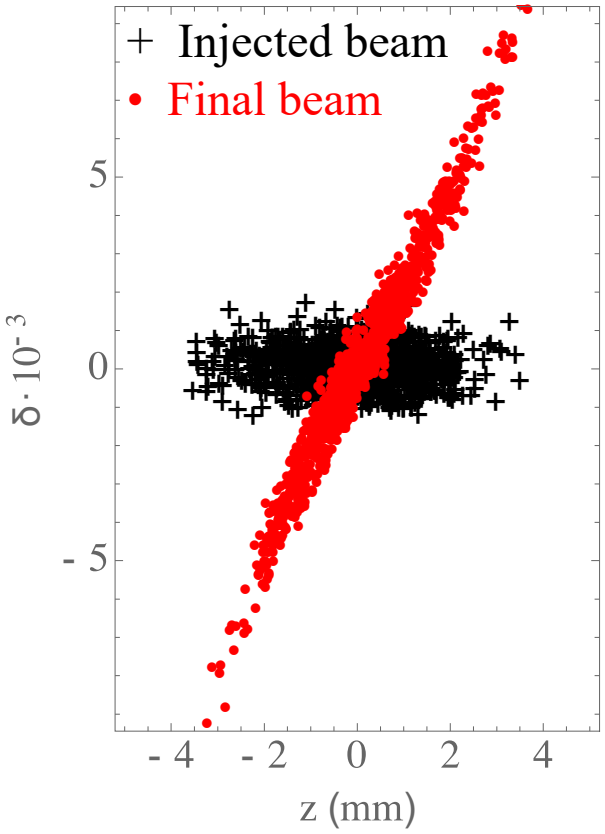
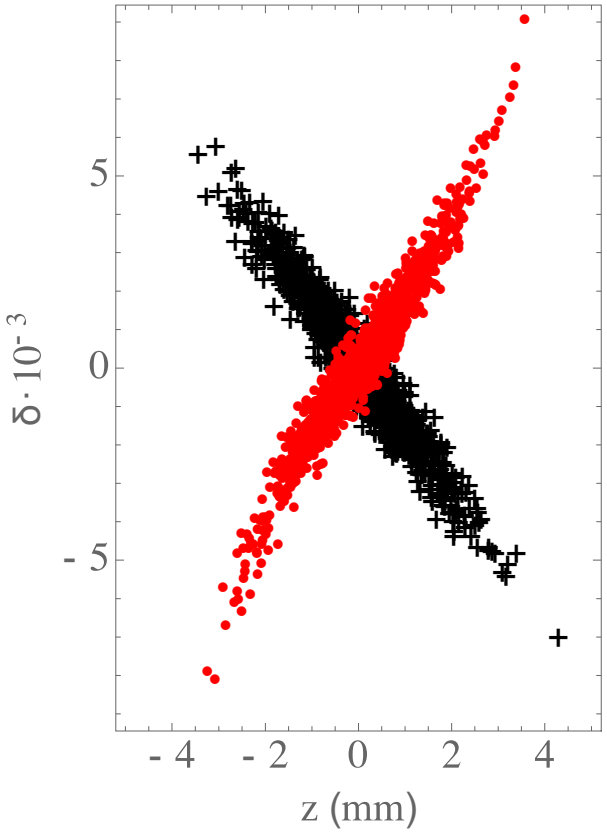


Tilted input,
Equal output spread



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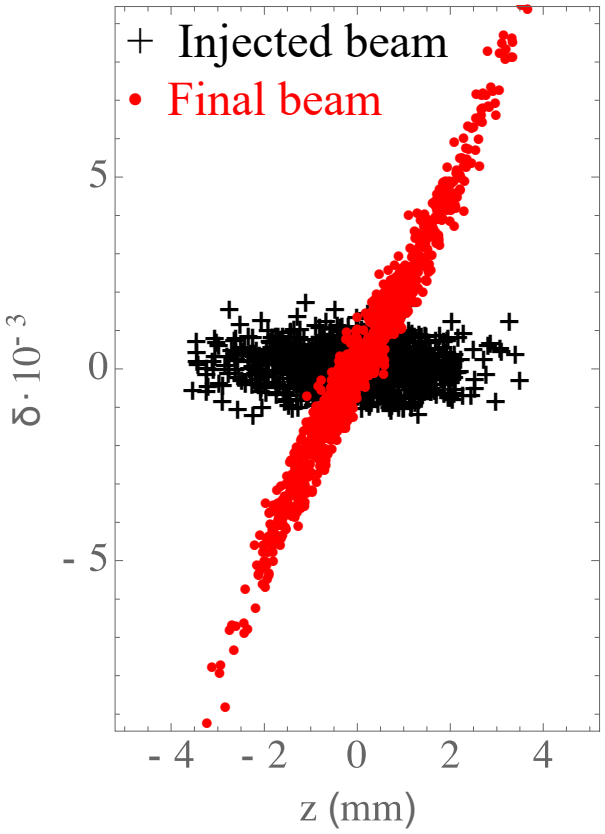

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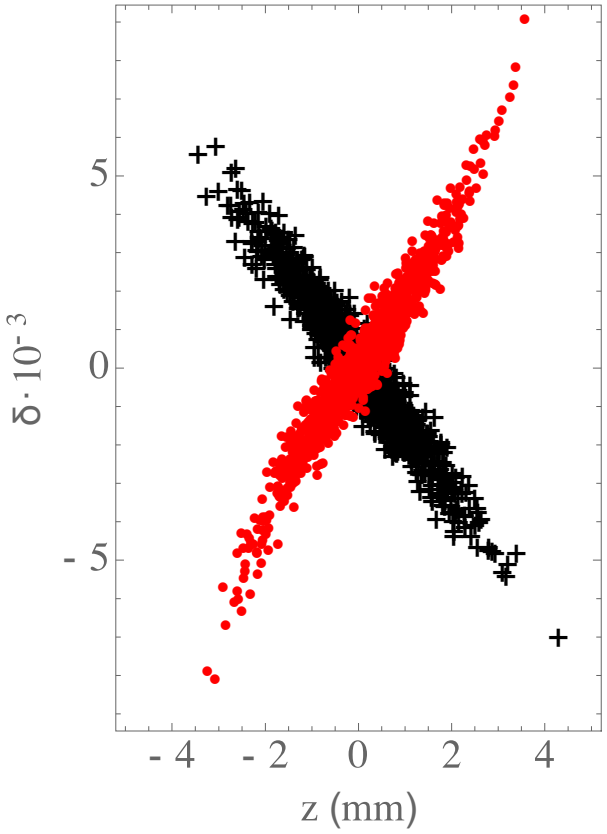

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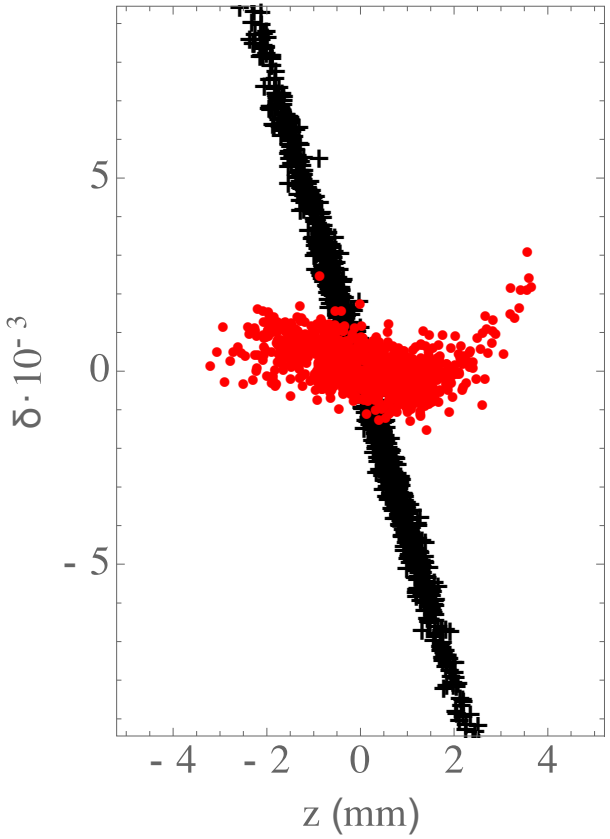

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  - Realistic solution tolerances are reasonable for CBETA
- Longitudinal beam tilting can increase symmetry in energy spread

Acknowledgements

CLASSE & Cornell University

- Dr. Georg Hoffstaetter
- Dr. David Sagan
- Dr. Christopher Meyes
- William Lou
- Nilanjan Banerjee
- Gayathrini Premawardhana

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