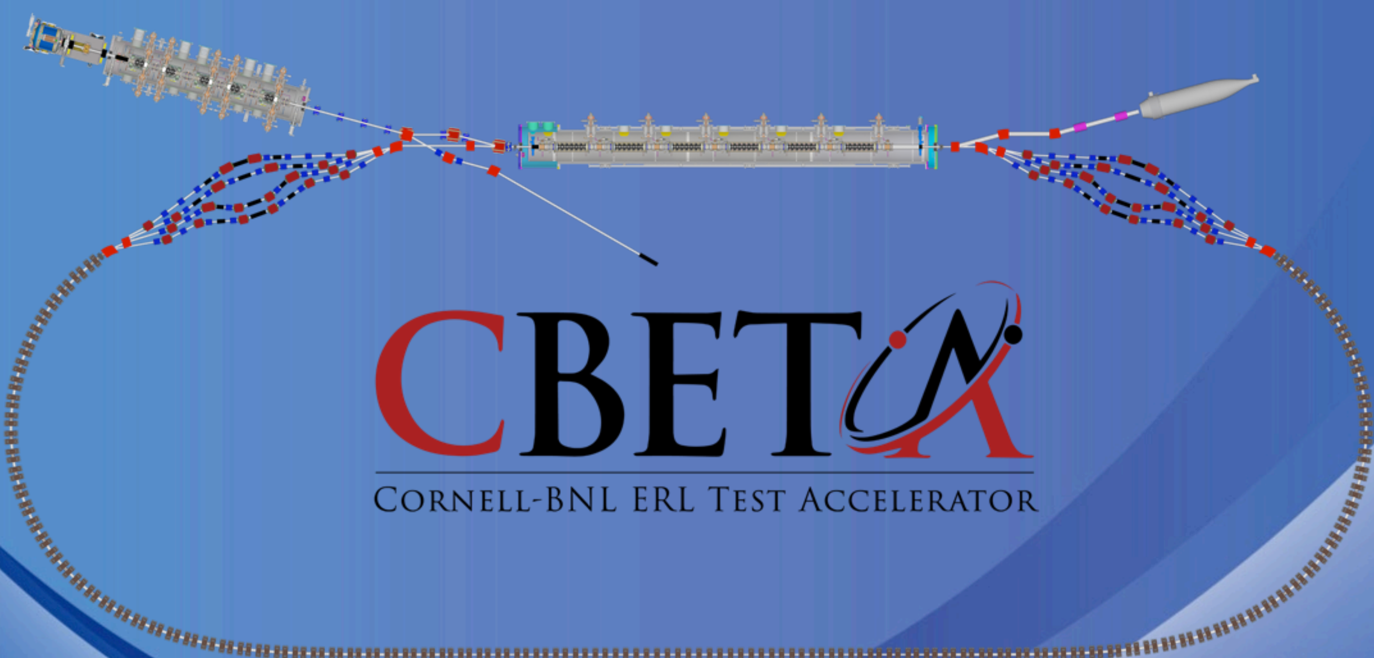
Beam Dynamics issues for multi-pass ERLs

ERL workshop 07/19/2017

Georg Hoffstaetter (Cornell)



Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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Beam dynamics specific to ERLs

ERLs provide: High currents for (a) either highly damaged beams or

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➔ All of the above, only worse!

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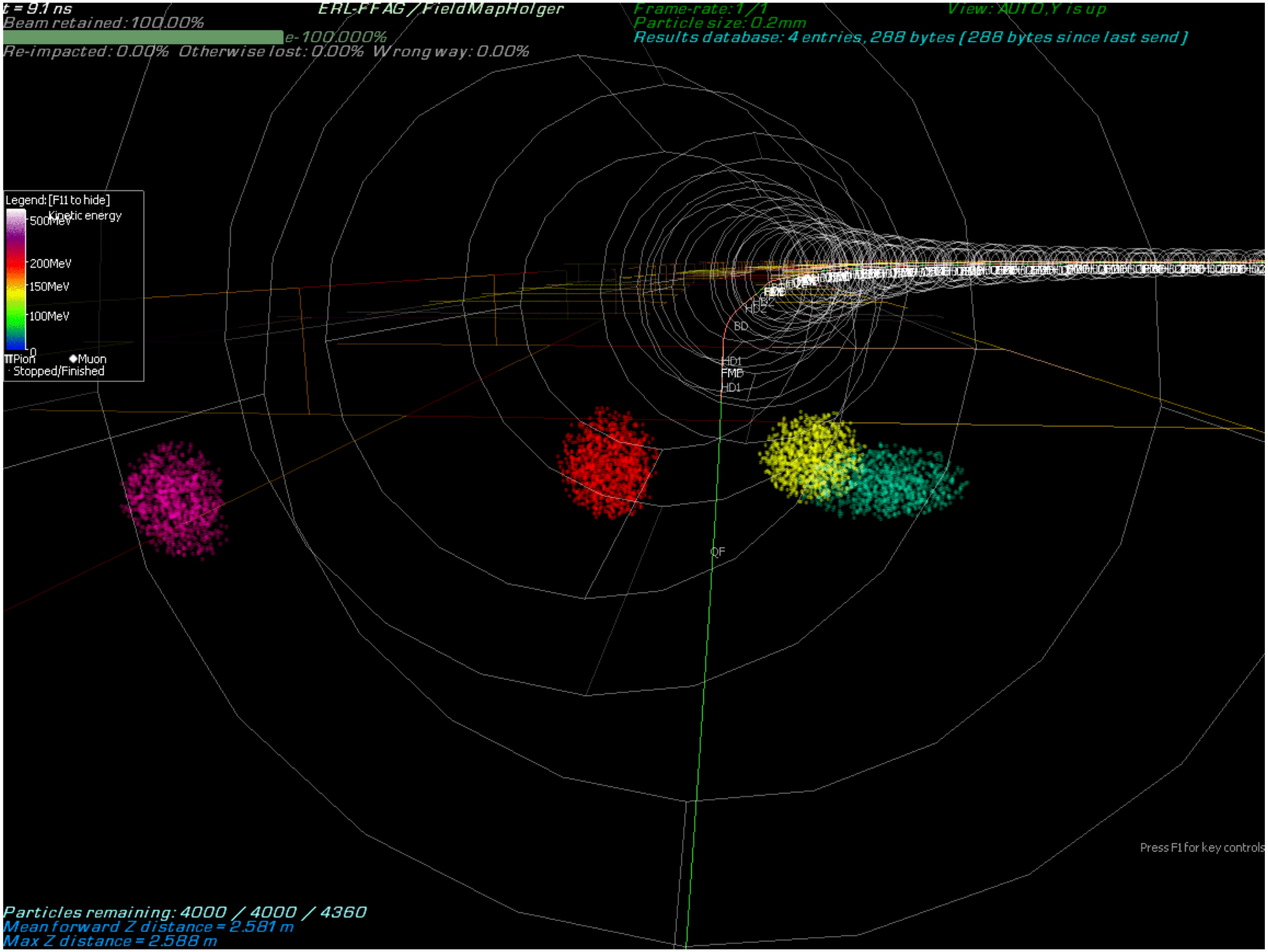
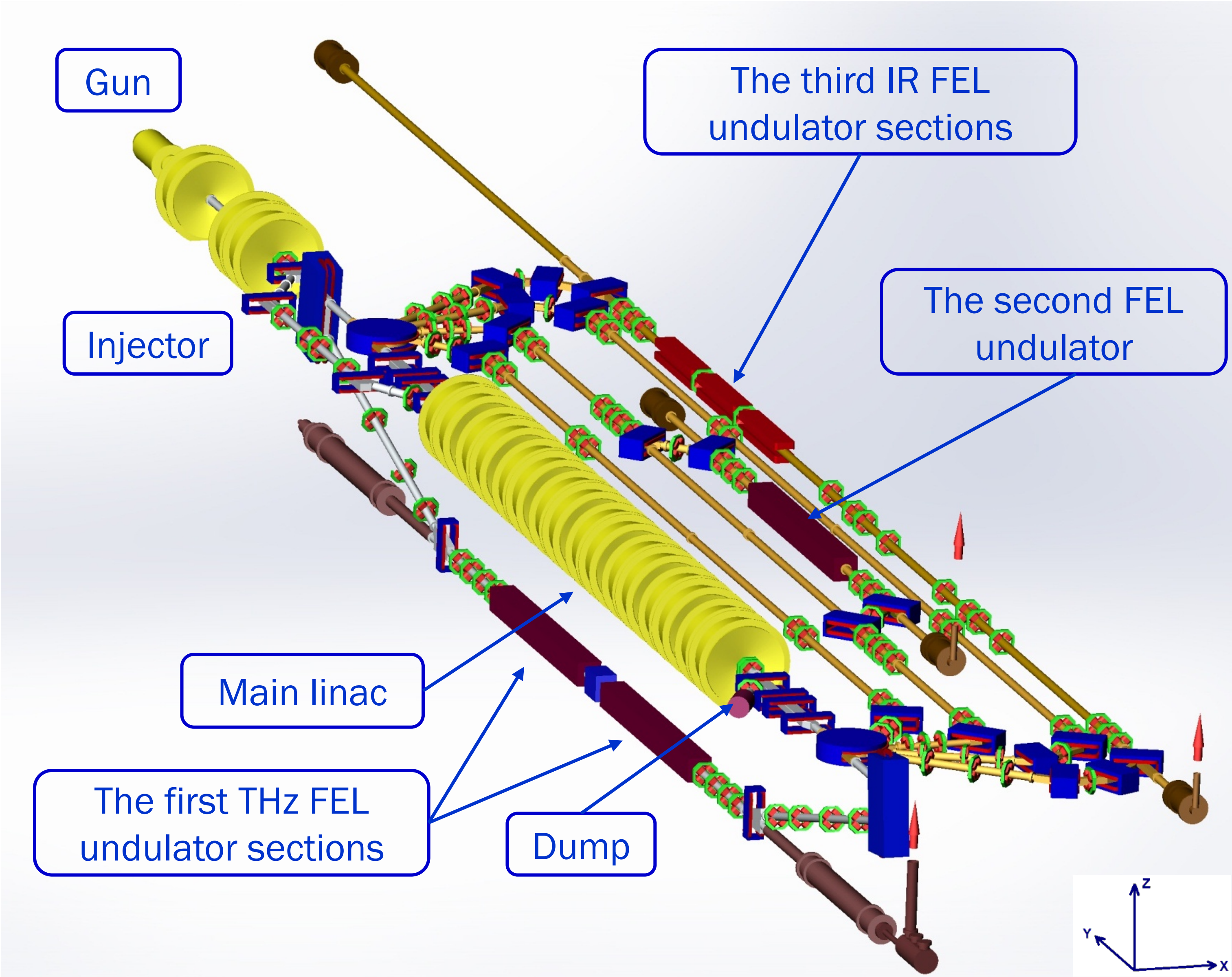
Bunche dynamics in 3D field maps

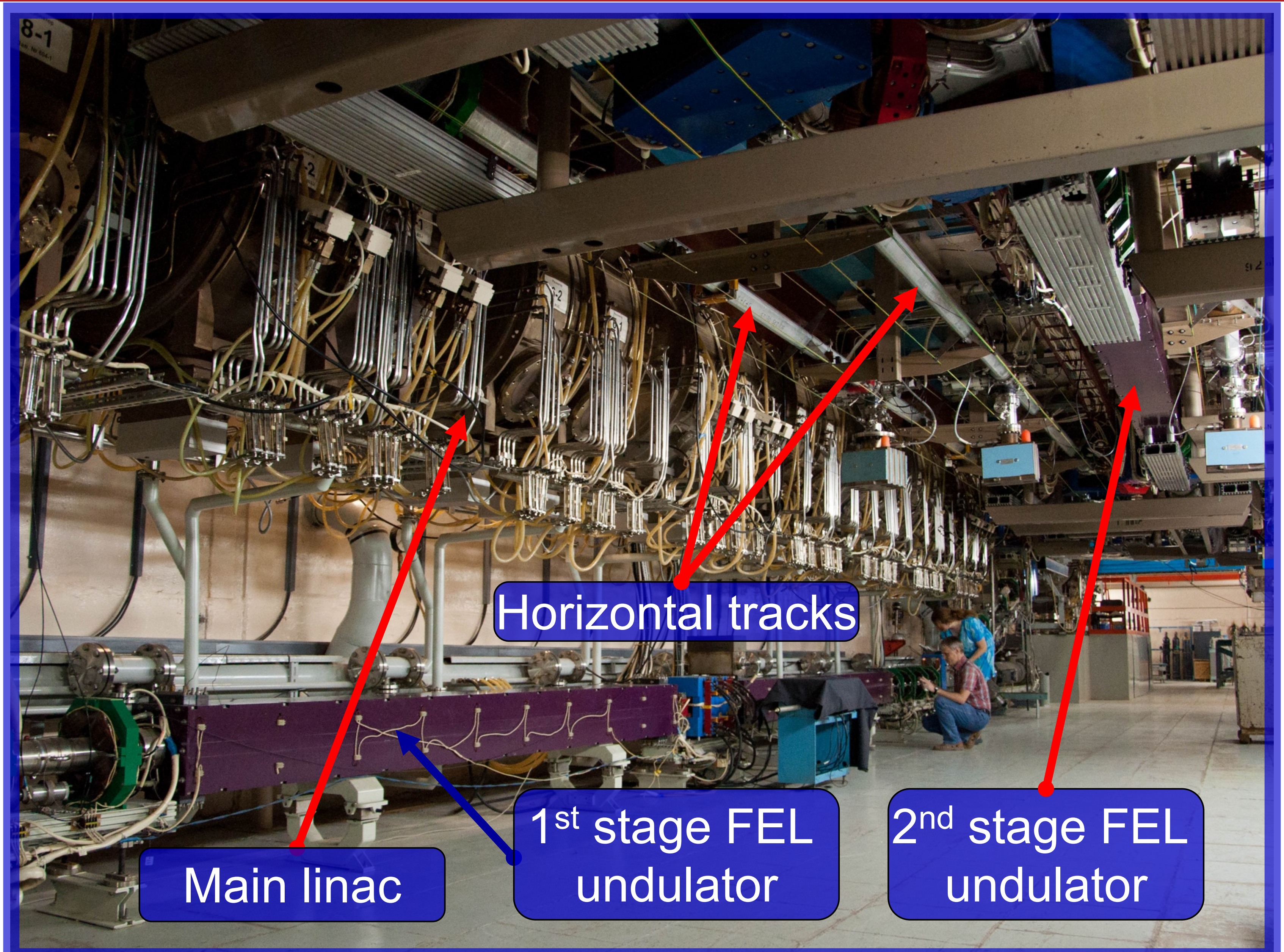


NovoFEL Accelerator Design



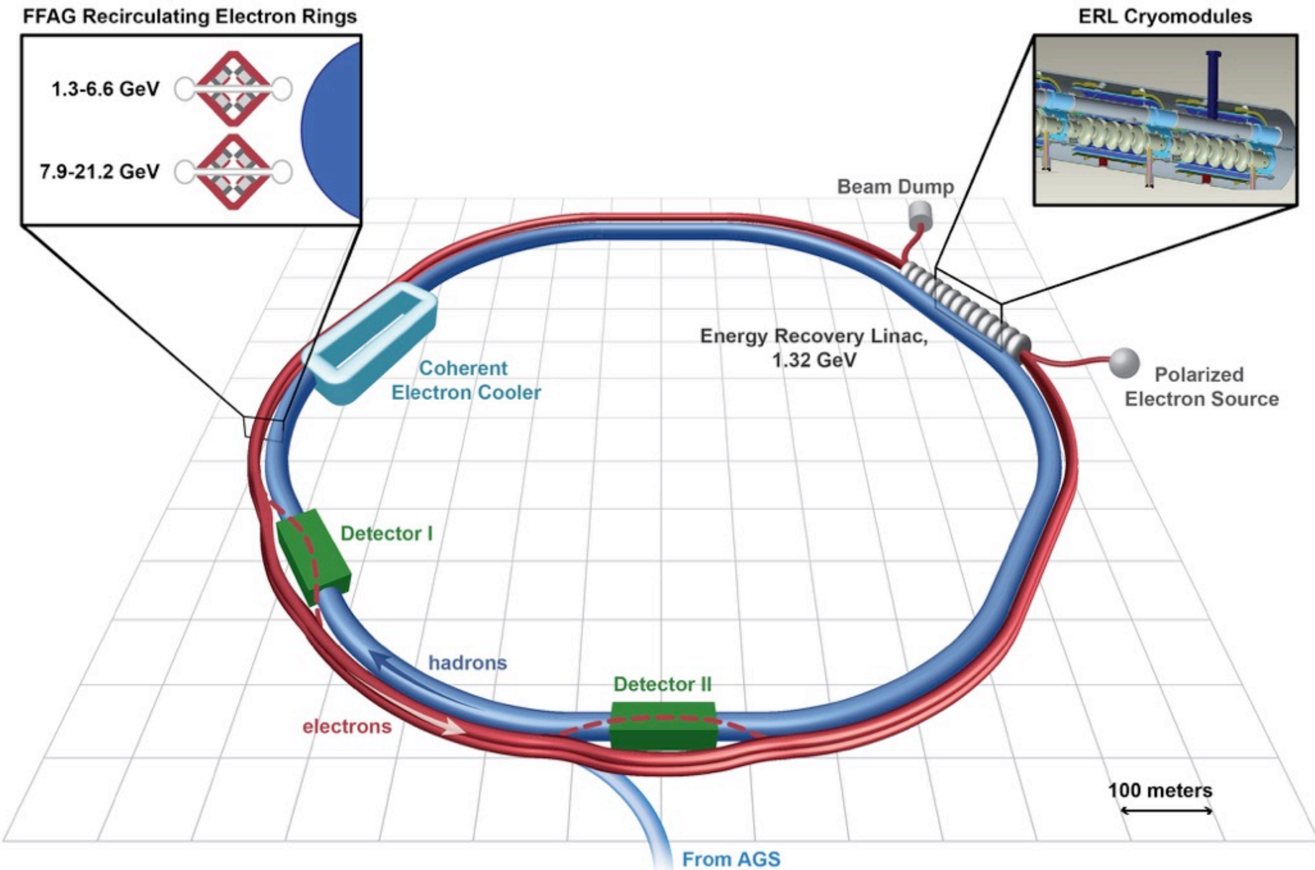
Courtesy G. Kulipanov

NovoFEL Accelerator Construction

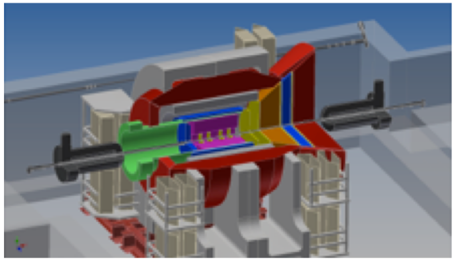


Courtesy G. Kulipanov

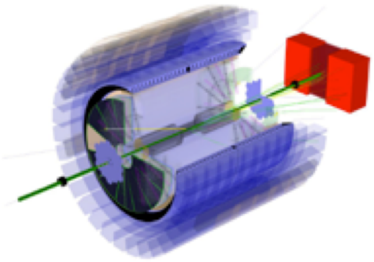
Multi-Turn ERL eRHIC (or recirculation)



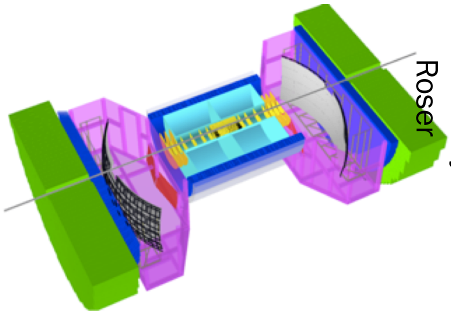
ePHENIX



eSTAR



BeAST

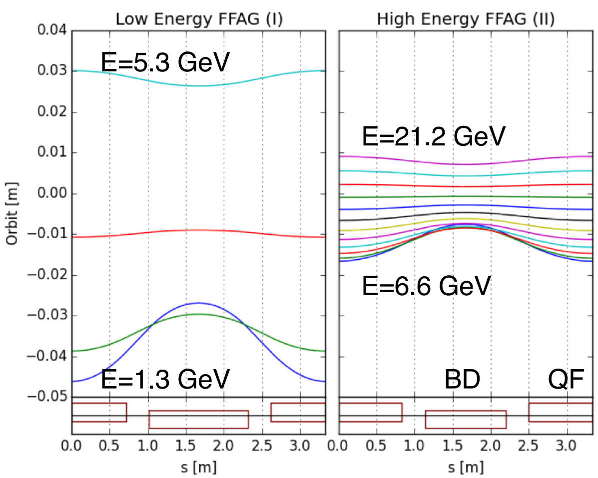


courtesy Thomas Roser

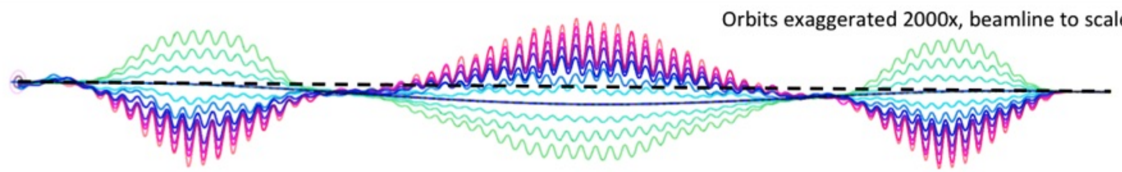
- 1.7 × 10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 127 GeV (15.9 GeV e↑on 255 GeV p↑)
- × 10 luminosity with modest improvements (coating of RHIC vacuum chamber)
- × 100 luminosity with shorter bunch spacing (ultimate capability)

Multiple-beam orbits and optics

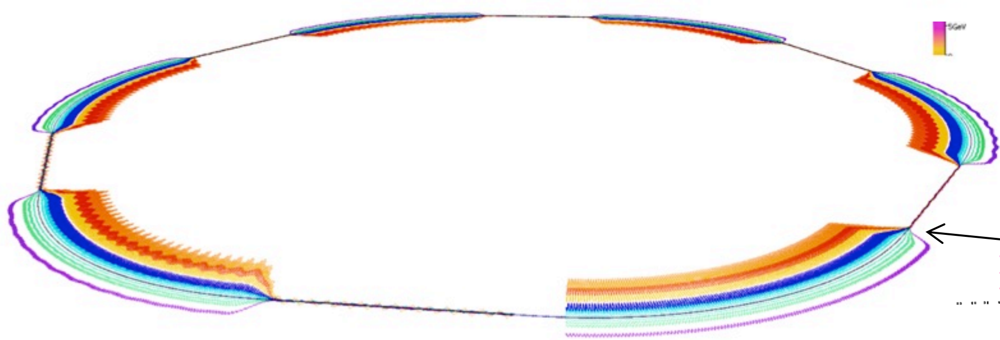
- eRHIC uses two FFAG beamlines to do multiple recirculations.
 (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



@S.Brooks, D.Trbojevic

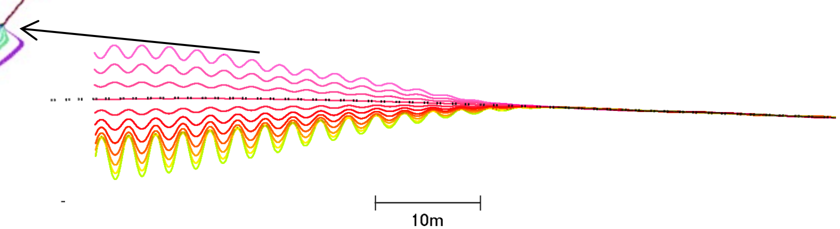


Orbits in Detector bypass section



Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

CBETA topics to support eRHIC

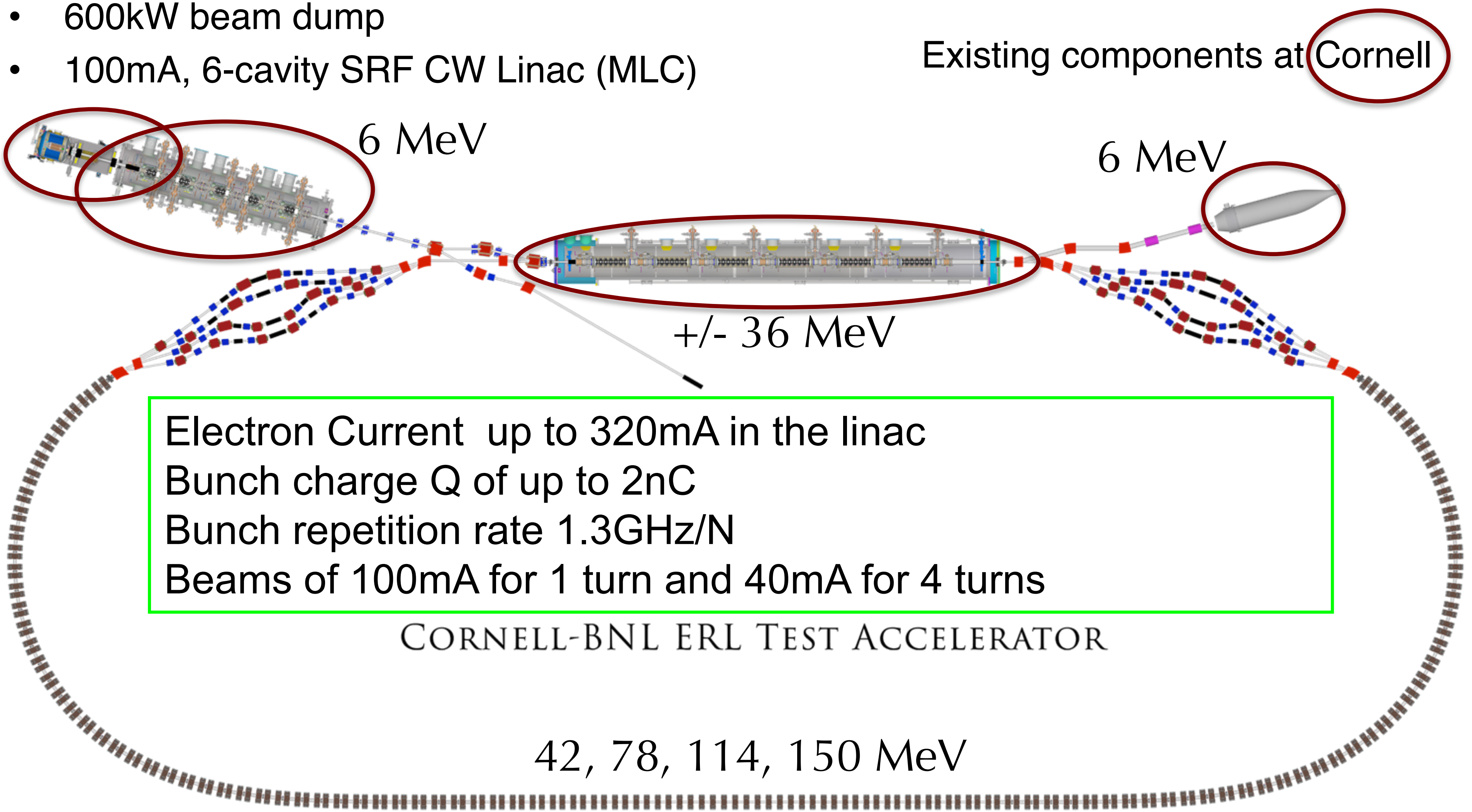
CBETA study topics important for eRHIC:

1) **FFAG** loops with a factor of 4 in momentum **aperture**.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) **Matching** and correction of multiple simultaneous **orbits**.
   d) **Matching** and correction of multiple simultaneous **optics**.
   e) **Path length control** for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) **HOM damping.**
   b) **BBU limits.**
   c) **LLRF control and microphonics.**
   d) **ERL startup from low-power beam.**

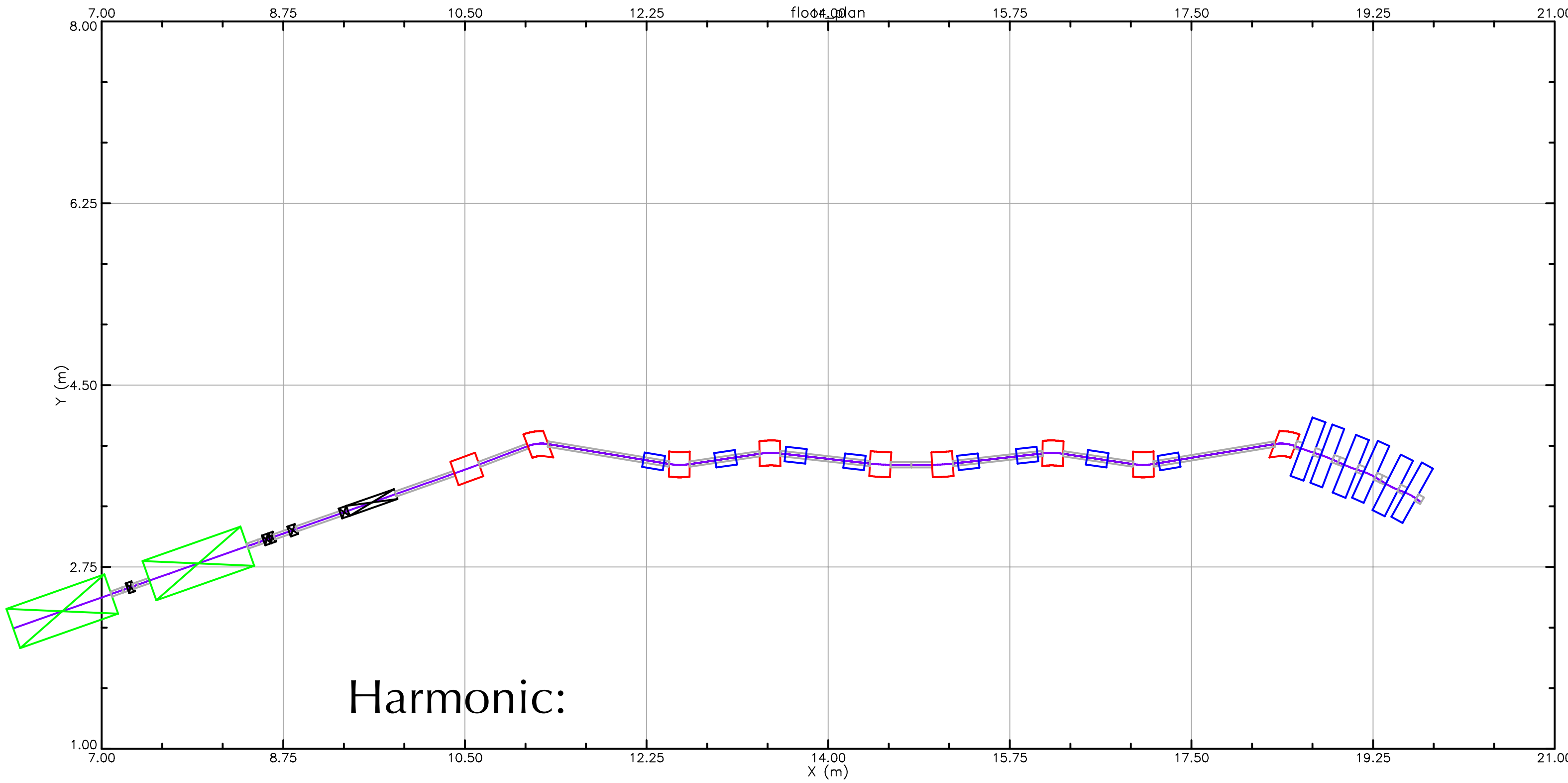
The test ERL in Cornell's hall LOE

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)



Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

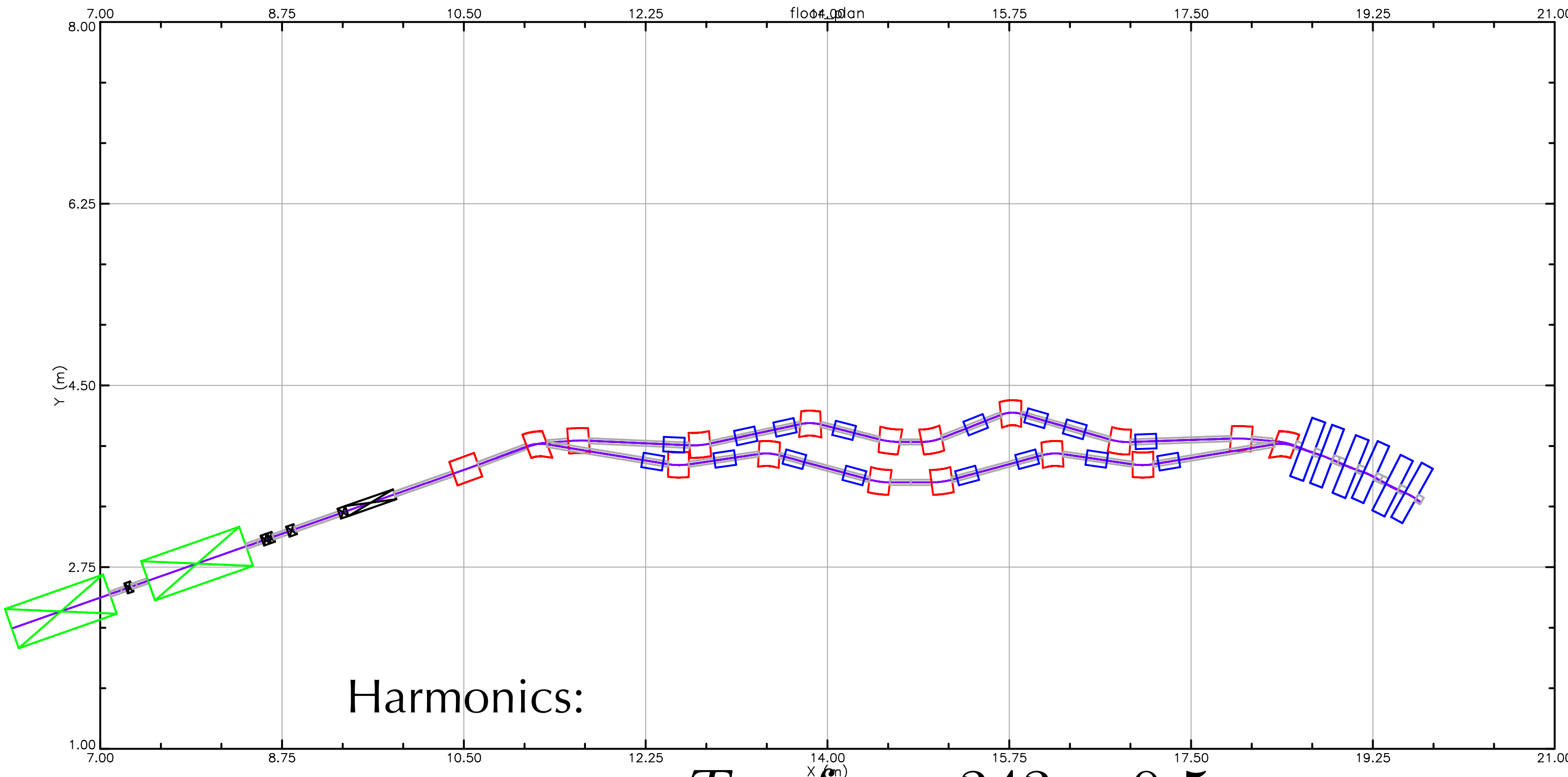
Path length: 1-pass ERL



Harmonic:

$$T_1 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

Path length: 2-pass ERL

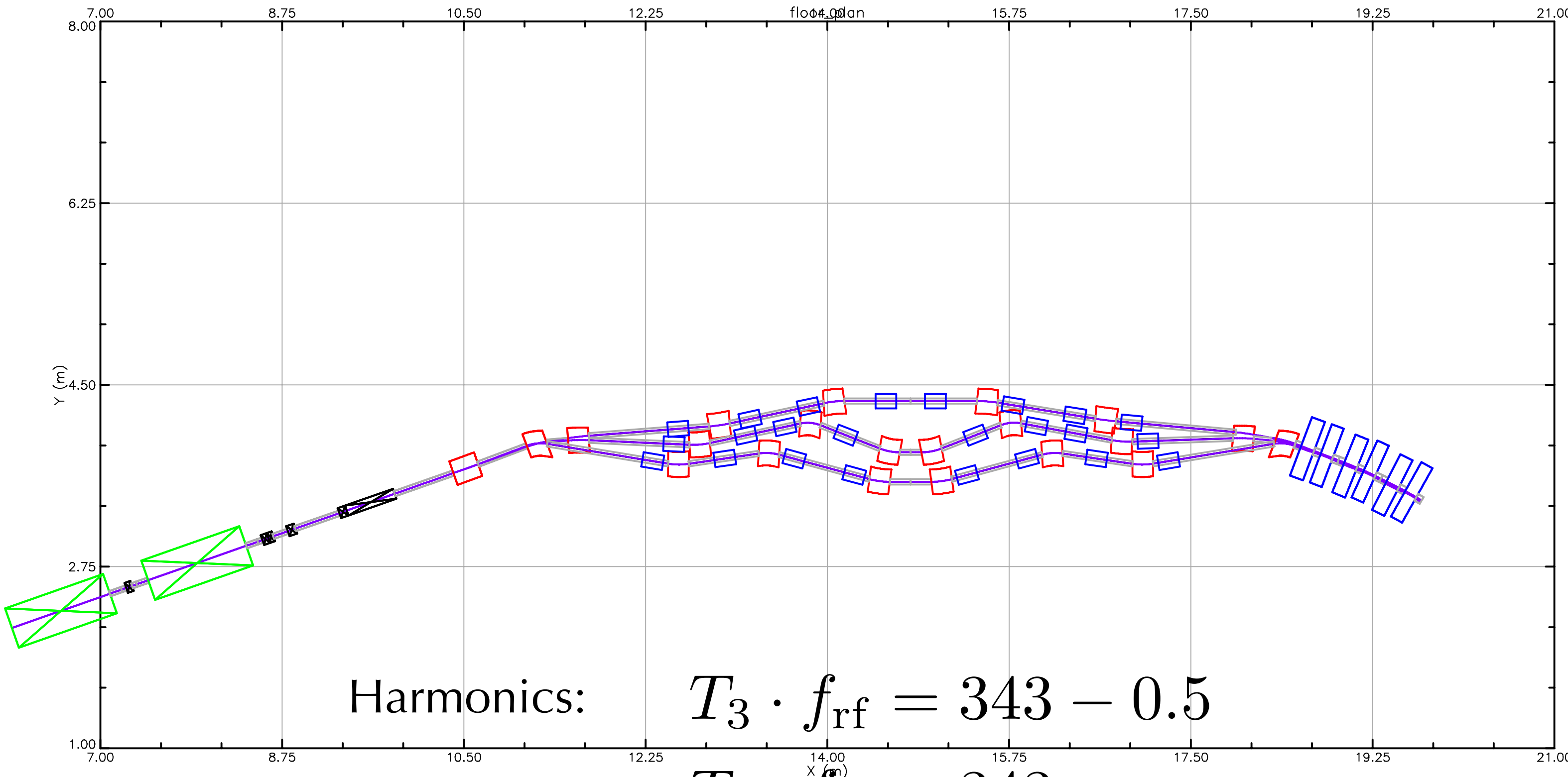


Harmonics:

$$T_2 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Path length: 3-pass ERL



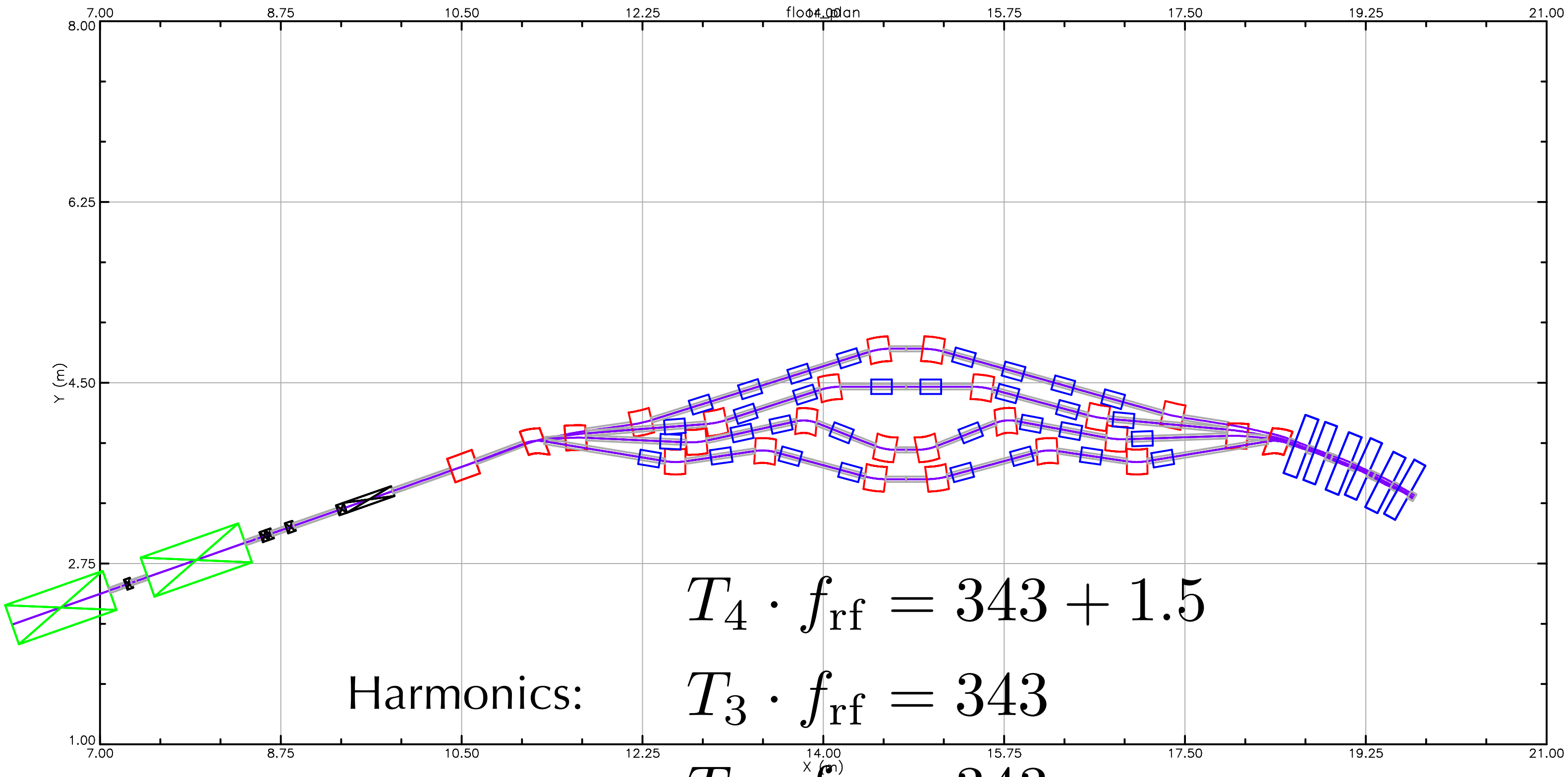
Harmonics:

$$T_3 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Path length: 4-pass ERL



Harmonics:

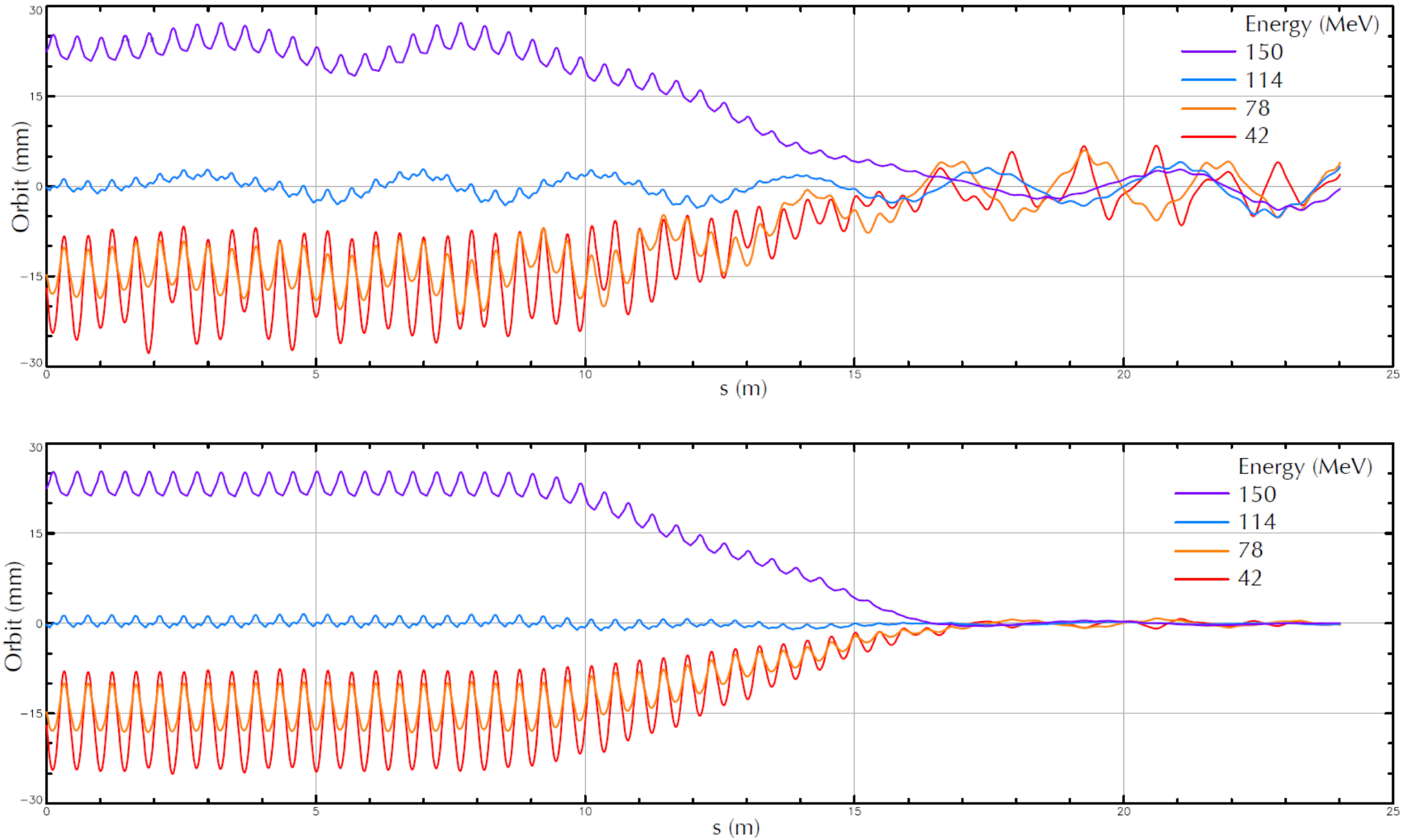
$$T_4 \cdot f_{\mathrm{rf}} = 343 + 1.5$$

$$T_3 \cdot f_{\mathrm{rf}} = 343$$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Orbit Correction of 4 Beams



Courtesy C. Mayes

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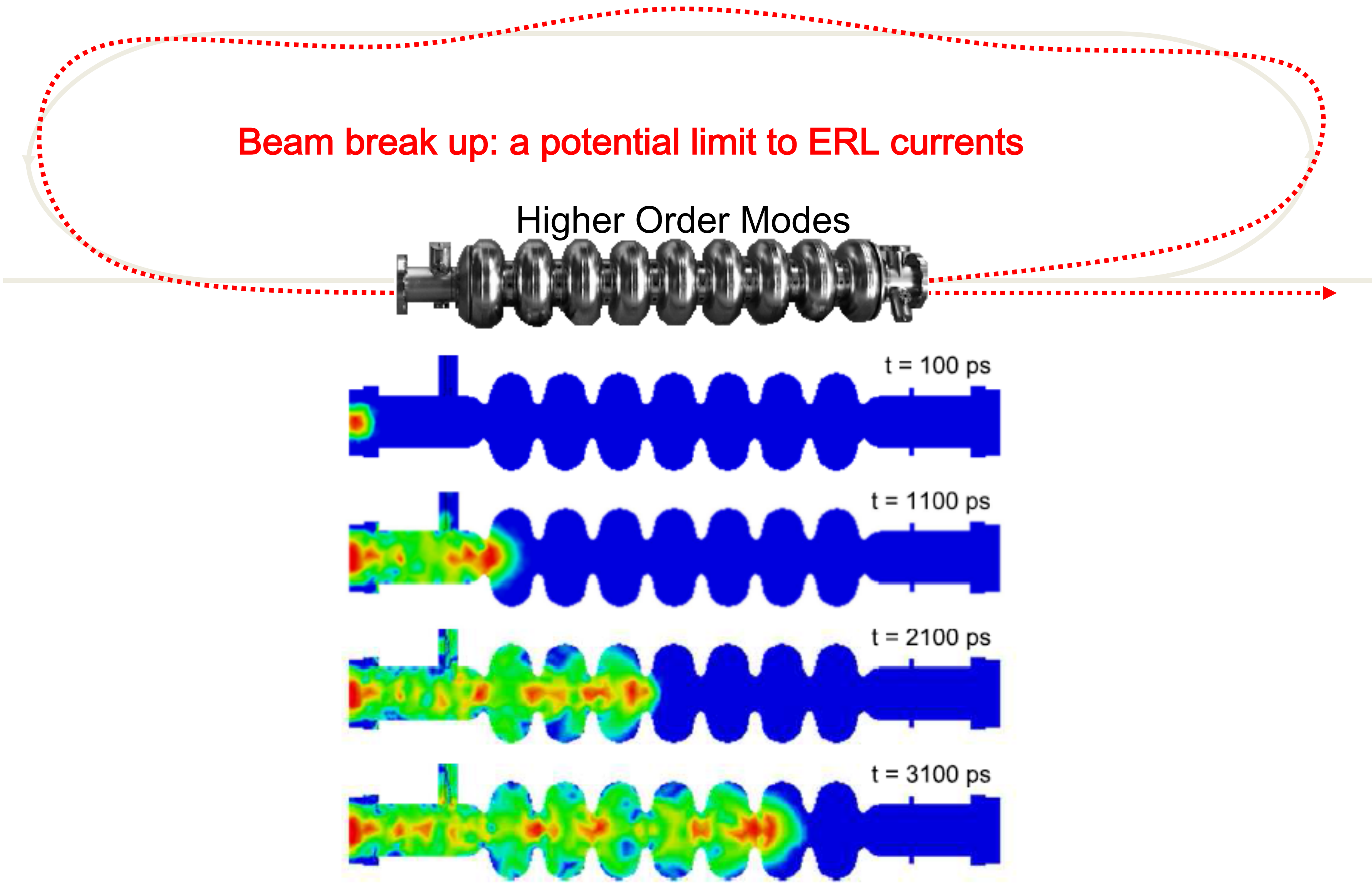
New current limit



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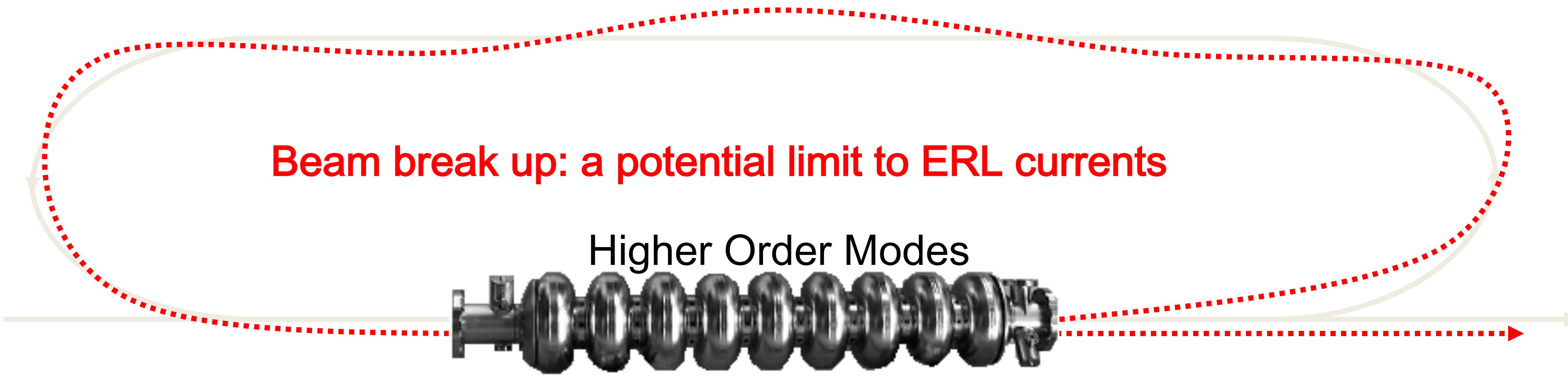

$$V_x(t) = T_{12}\,\frac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

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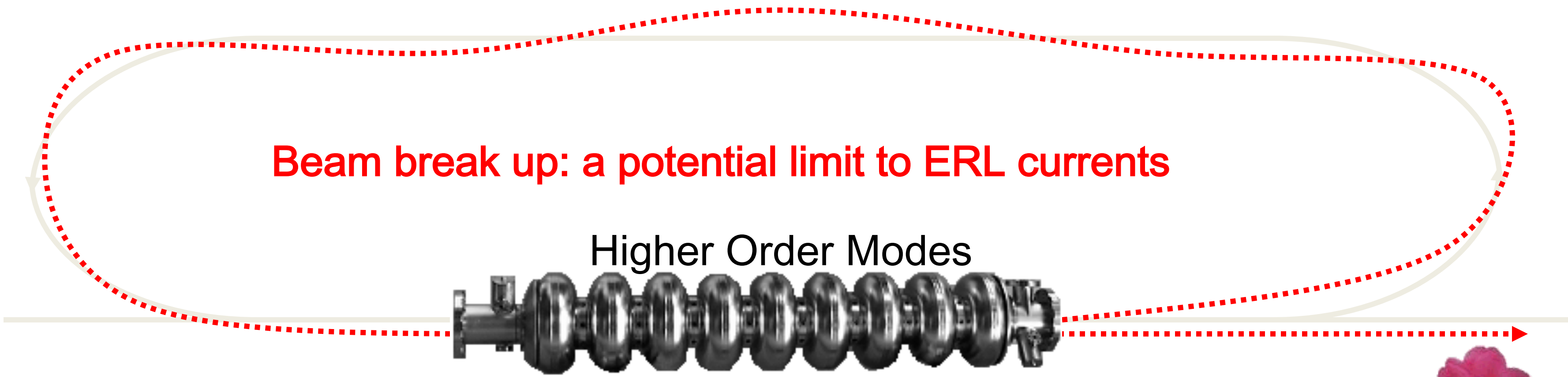

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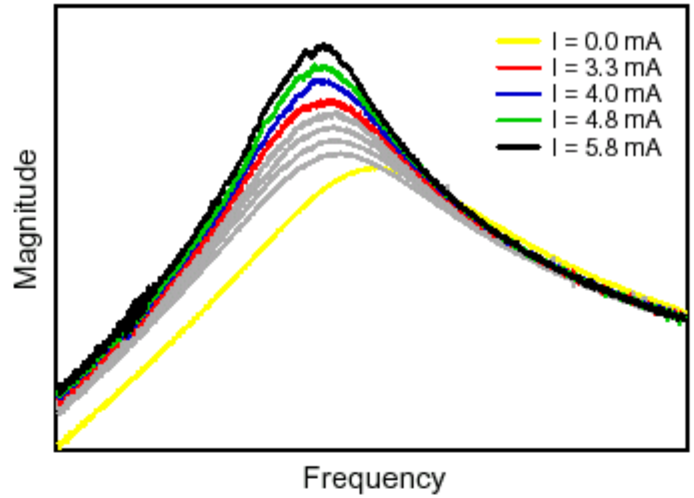
BBU measurements

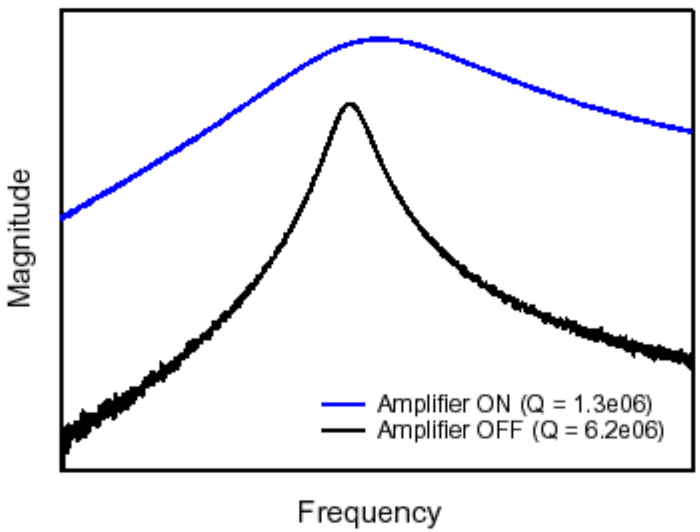
Recall… $I_{threshold} \propto \frac{1}{Q_{HOM}}$

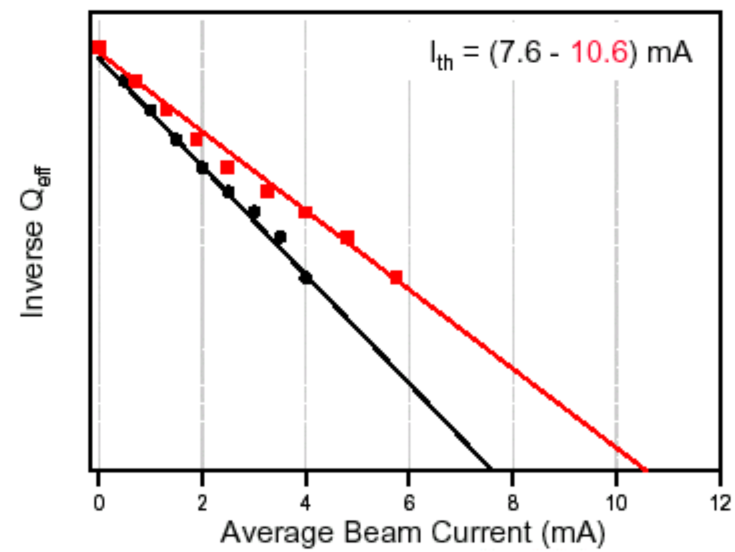
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

  (Above a factor of about 10, the system becomes sensitive to external disturbances)

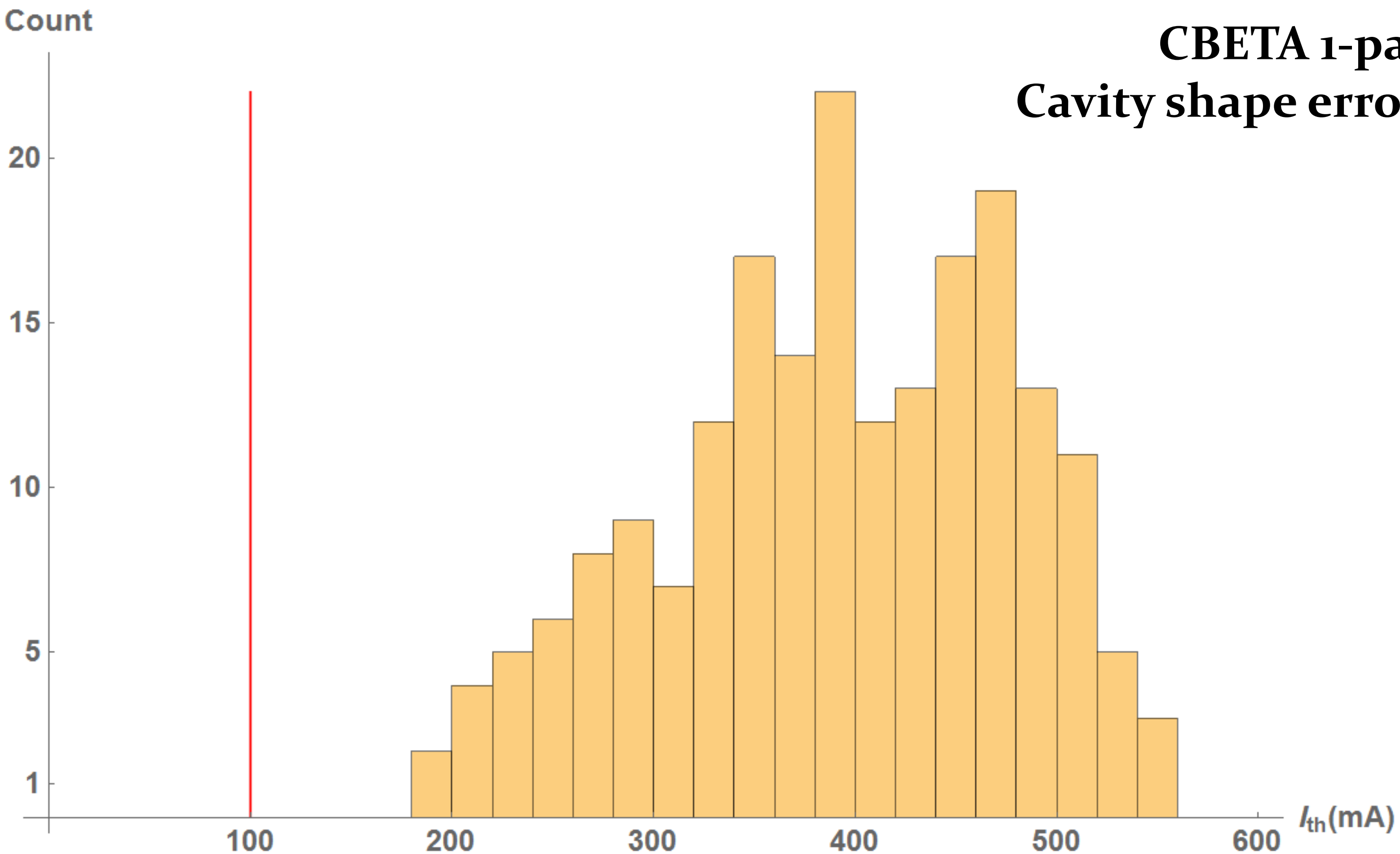
- The threshold is increased accordingly: from 2 mA to ~10 mA





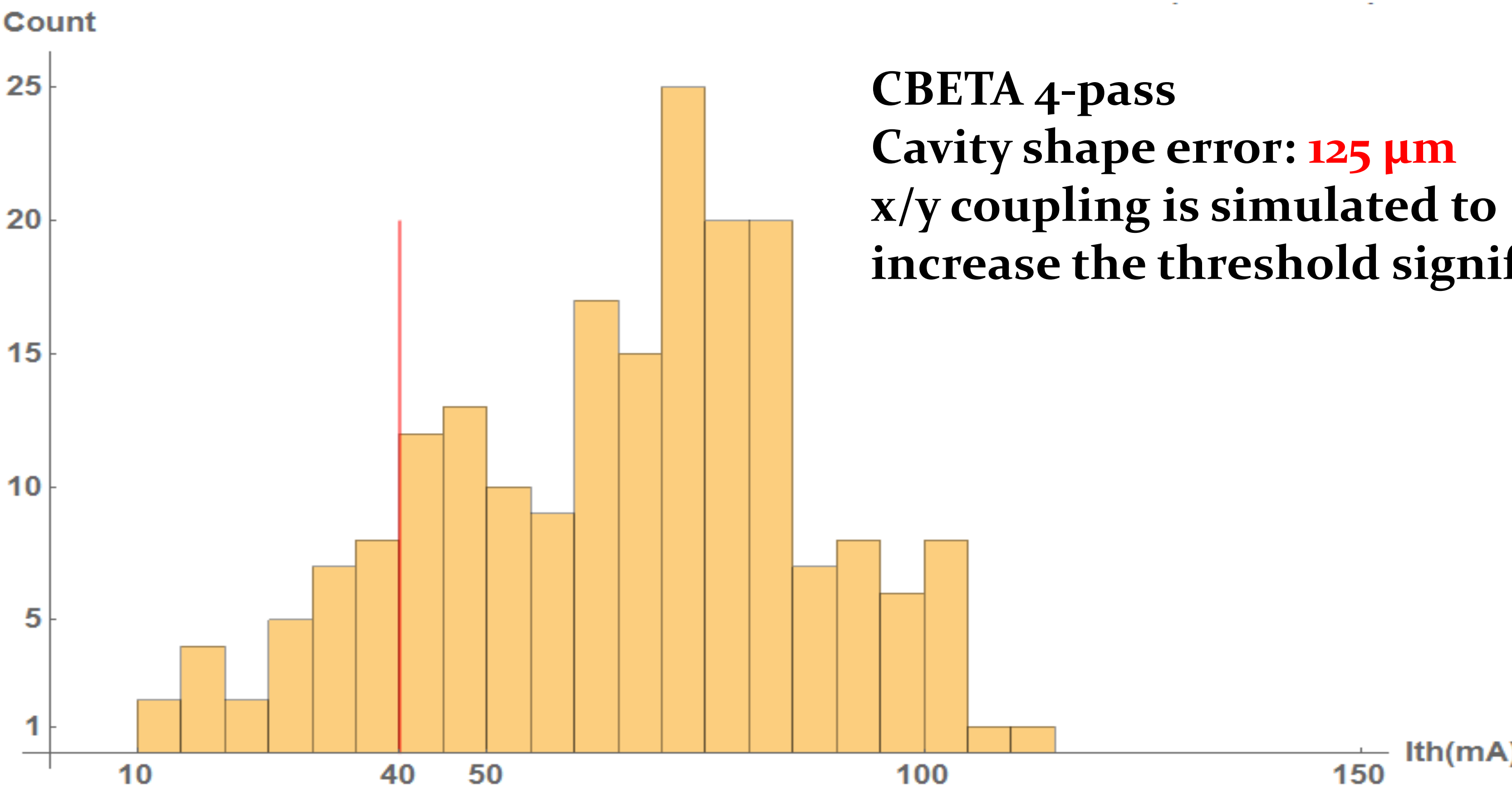


BBU for 1 pass in CBETA



100% of simulations have $I_{th} > 100$mA

BBU for 4 passes in CBETA



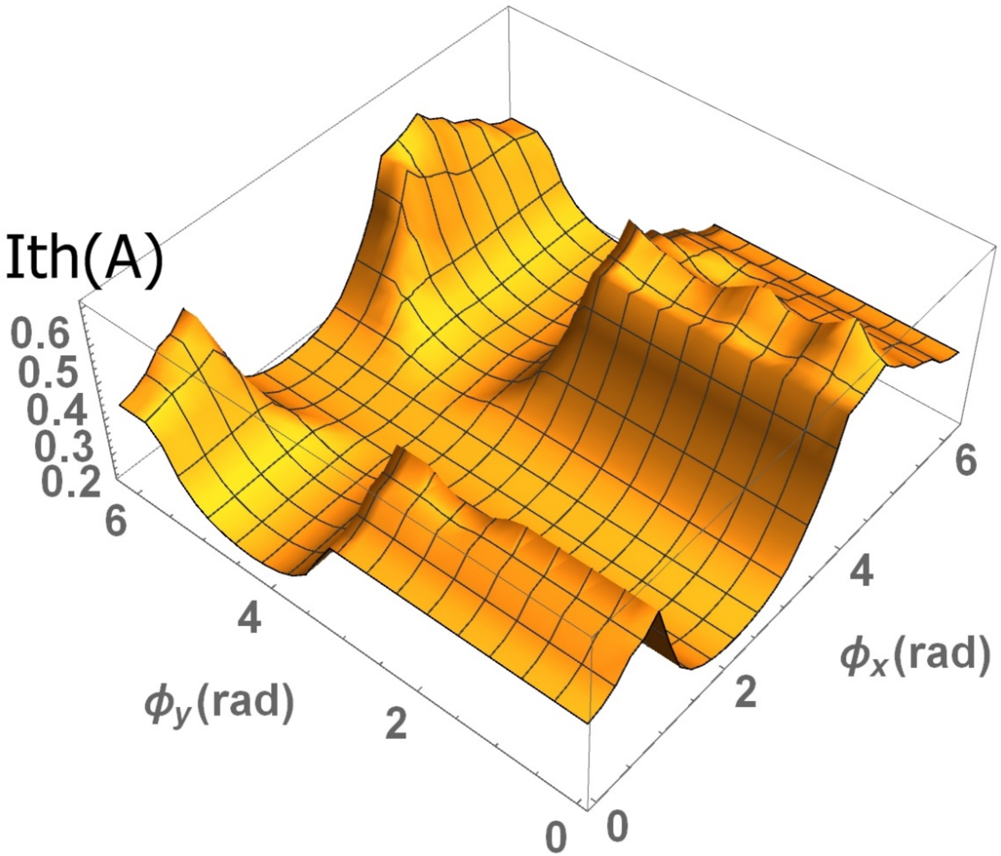
CBETA 4-pass
Cavity shape error: 125 µm
x/y coupling is simulated to increase the threshold significantly

100% of simulations have I_{th} > 100mA

86% of simulations have I_{th} > 40mA

1-pass ERL with variable phases

I_{th}

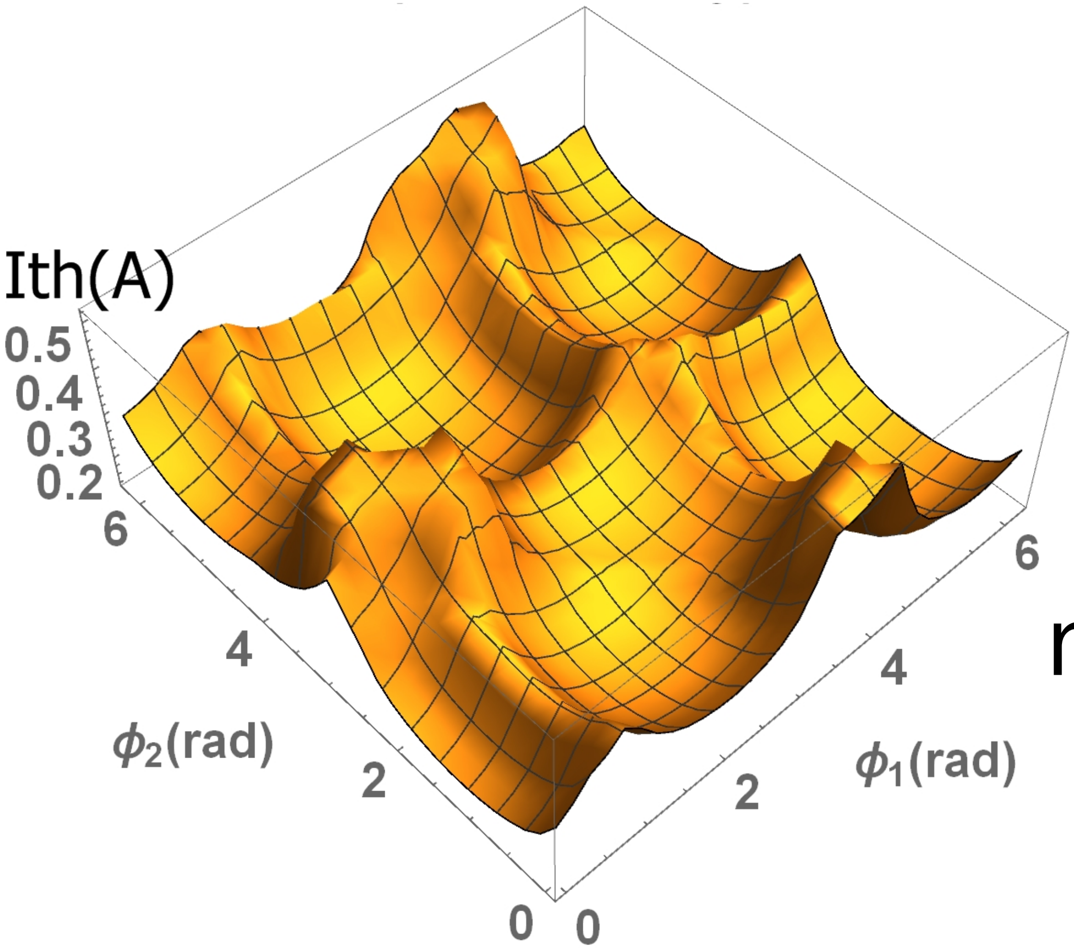


Min = 140 mA
Max = 611 mA
nominal = 342 mA

I_{th} results can improve significantly

1-pass ERL with x/y coupling

I_{th}

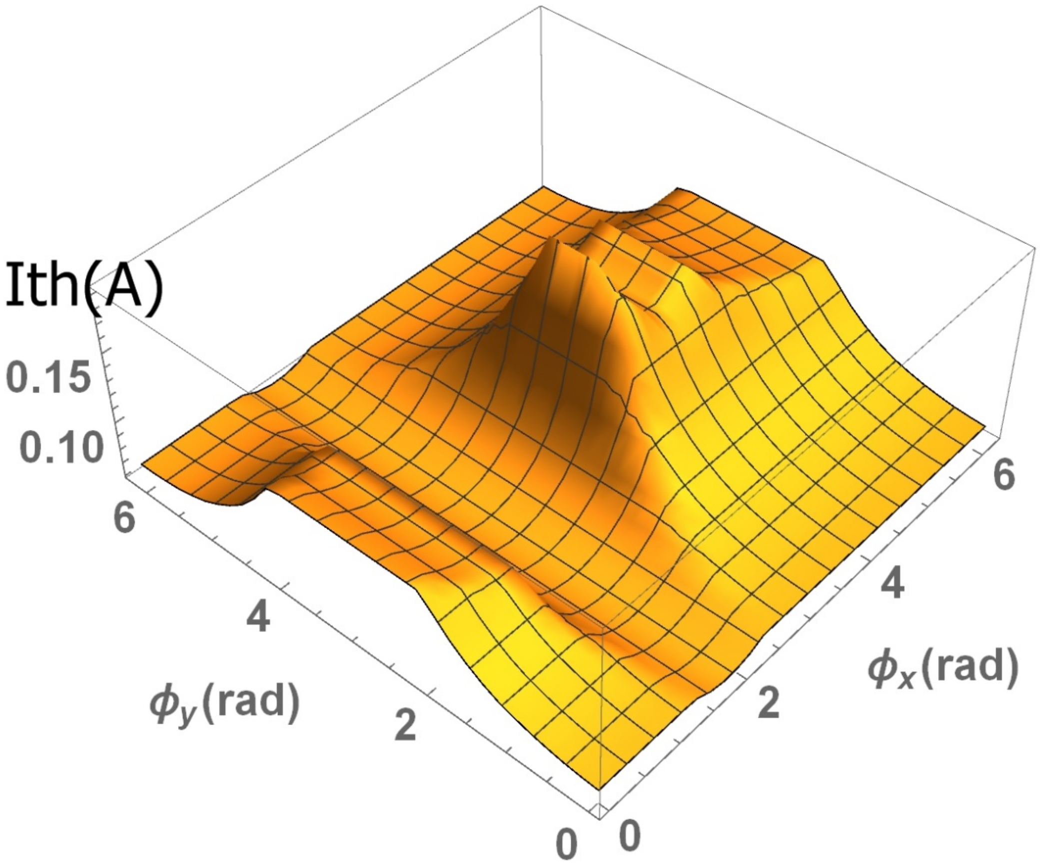


Min = 140 mA
Max = 520 mA
nominal = 342 mA

I_{th} results can improve significantly

4-path ERL with variable phases

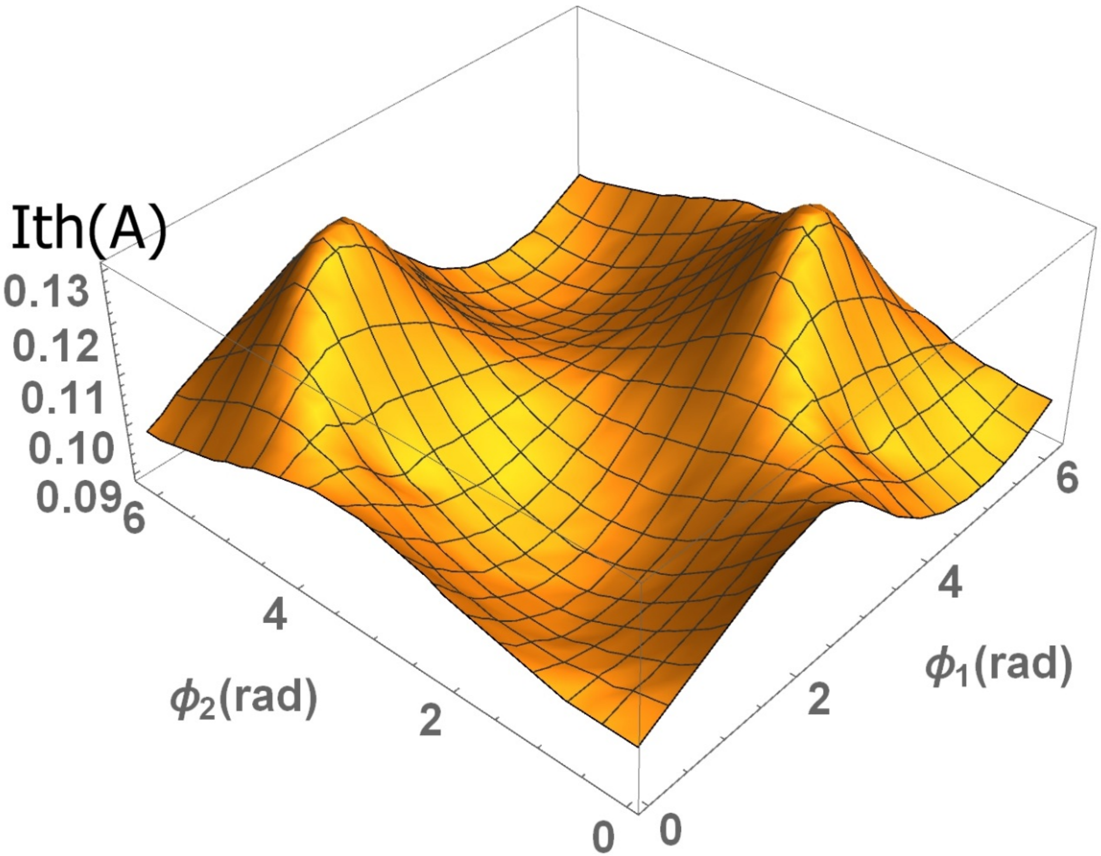
I_{th}



Min = 61 mA
Max = 193 mA
Nominal = 69 mA

I_{th} results can improve

4-path ERL with x/y coupling

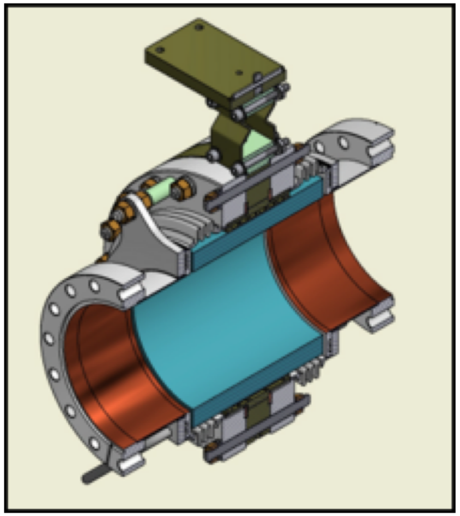


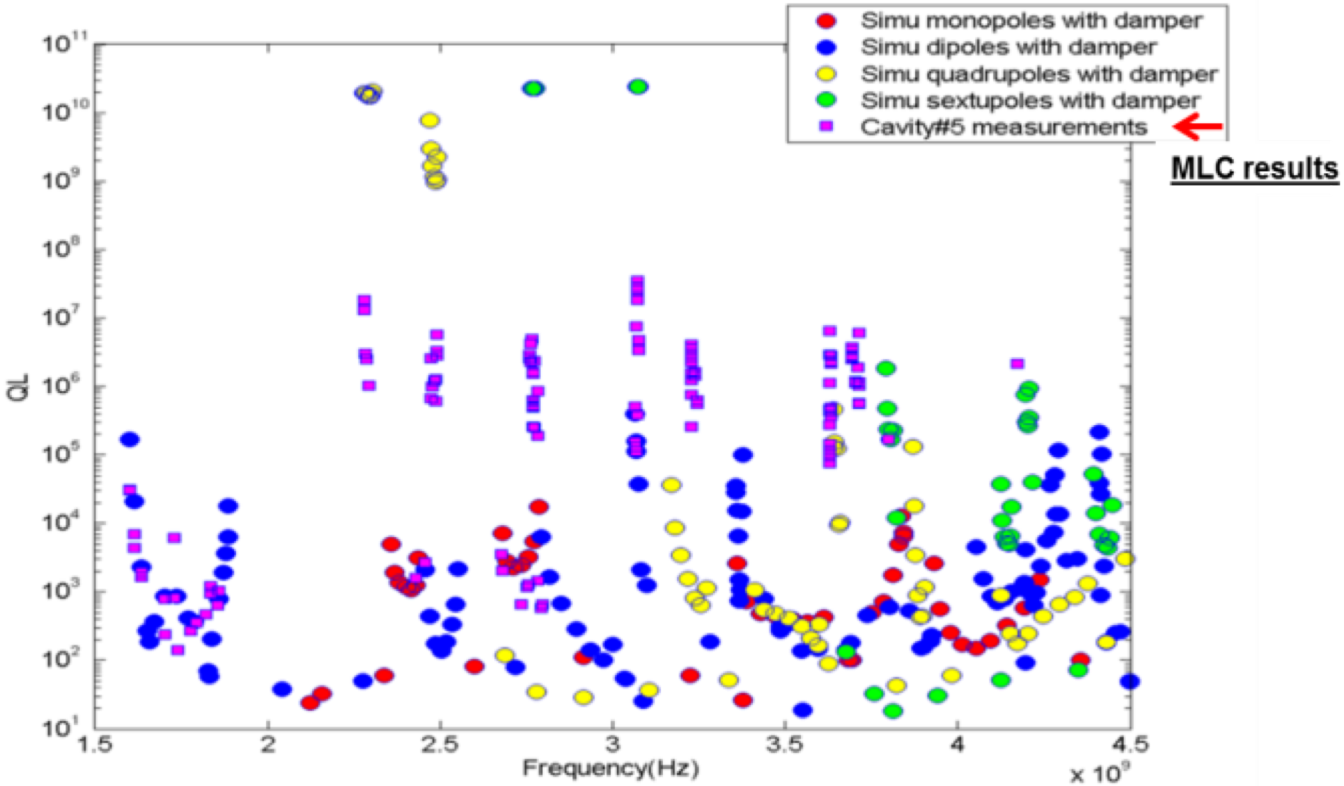
Min = 89 mA
Max = 131 mA
Nominal = 69 mA

I_{th} results can improve

Conclusion: In 1-path ERLs the benefit from coupling and phase optimization can be significant. In multi-turn ERLs this benefit is much diminished.

Current limits from HOMs





Dipole HOMs on MLC were strongly damped below Q~10^4.
Consistent with HTC and simulation results.

HTC results were:

- HOM heating: currents are limited to < 40mA in CBETA
- BBU no HOM limits BBU to below 100mA in one turn

Comments on BBU theory

The fundamental theory paper [1] solved the BBU time-delay integral equation by Laplace transform techniques.

$$V(t) = \int_{-\infty}^{t} W(t-\tau) I(\tau) V(\tau - T) d\tau$$

But with the special form of exponentially damped wake fields

$$W(t) = e^{-kt} \sin \omega t$$

One can transform to a time-delay differential equation

$$V''(t) = \omega I(t) V(t-T) - 2kV'(t) - (k^2 + \omega^2) V(t)$$

Which is now accessible to a set of theories for such equations, especially those for **Delay Differential Equations (DDEs) with periodic coefficients.**

[1] G.H. Hoffstaetter, I. Bazarov, Physical Review ST-AB, Volume 7, 54401 (May 2004)

[2] Delay-Coupled Mathieu Equations in Synchrotron Dynamics, A. Bernstein and R. Rand, Journal of Applied Nonlinear Dynamics, 5(3):337-348 (2016)

Next-order BBU

Don't forget that there is

(A) Transverse Dipole BBU that is often considered and there are good codes

(B) Longitudinal BBU

- contained in the BMAD simulation code
- It is important because they excite monopole (accelerating) modes with very large Q
- Is minimized by T56=0 for all cavity couplings
- Phase and time-of-flight tricks need to be checked against this instability.

(C) Quadrupole BBU

- Is important because the frequencies of the lowest order Quadrupole modes are below the first higher order dipole modes. Their Q can therefore be extremely large.

(D) Higher-order multipole BBU: Check out the simple scaling formulas in [1]

- Is usually benign if (C) is ok. But it can be important for similar reasons at (C).

[1] Recirculative BBU, G.H. Hoffstaetter in A. Chao, M. Tigner, Accelerator Handbook.

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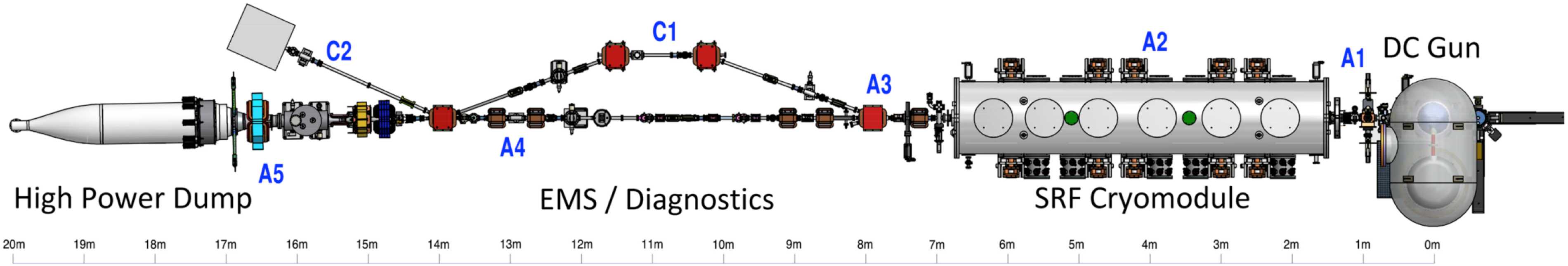
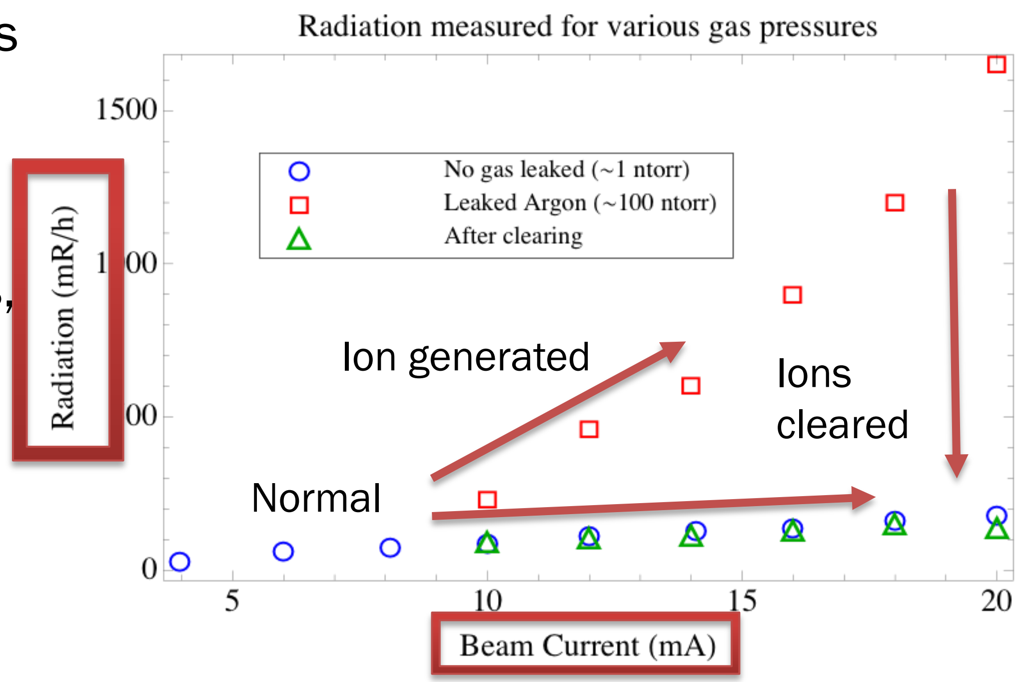
Evidence of Ion trapping in Lincas



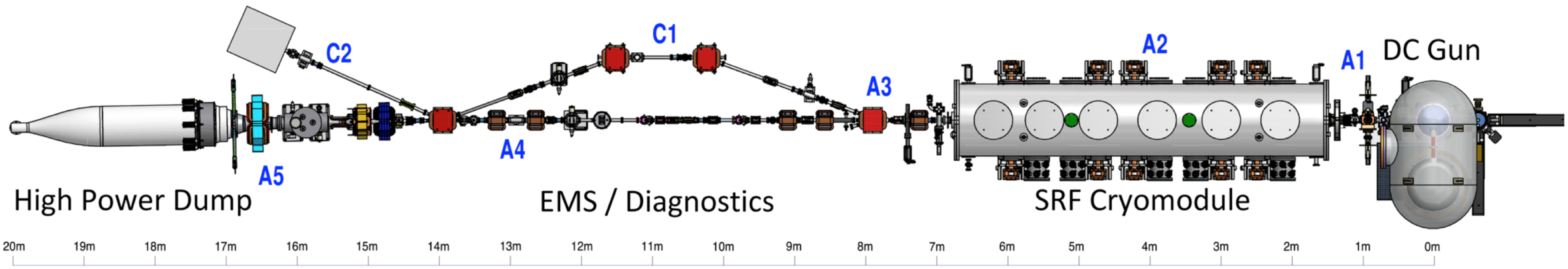
Observed ion trapping multiple times

1) During 75 mA, 5 MeV runs, ion clearing electrode reduced background radiation by > 50%
2) During low energy 350 keV runs, intermittent trips vanished after using clearing electrode



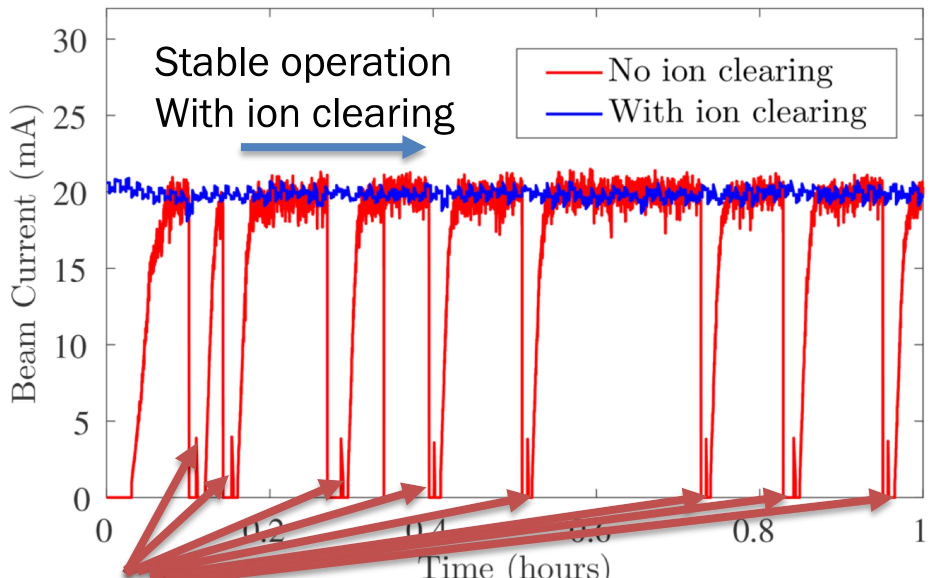
3/20/18

Evidence of Ion trapping in Lincas



Observed ion trapping multiple times

1) During 75 mA, 5 MeV runs, ion clearing electrode reduced background radiation by > 50%
2) During low energy 350 keV runs, intermittent trips vanished after using clearing electrode



Multi-turn ERLs

ERLs provide: High currents for (a) either highly damaged beams or
(b) pristine beams (small emittance, small energy spread).

If the current is not high, use a linac!
If the beam is not pristine and not highly damaged, use a ring!

What are then the beam dynamics issues specific to ERLs?

1. High current effects
   a) space charge
   b) **halo dynamics**
   c) HOM heating
   d) Intra-Beam Scattering
   e) Touschek scattering
   f) Rest Gas scattering
   g) Ion accumulation
      i) optics changes
      ii) nonlinear dynamics
      iii) scattering
2. Beam quality
   a) Emittance matching
   b) **Time of flight control of energy spread**
   c) Wakefield interactions
   d) Micro bunching instability
   e) **Coherent Synchrotron Radiation**
3. Transport of damaged beam
   a) Phase space rotation for energy spread
   b) Large 6-D phase-space-aperture optics
4. Recovery topics
   a) Energy spread growth during deceleration.
   b) Halo transverse growth during deceleration.
   c) **Recirculative Beam Breakup instabilities.**
      i) **Transverse Dipole BBU**
      ii) **Longitudinal BBU**
      iii) **Quadrupole BBU**
   d) Ion instabilities
   e) **Simultaneous control of multiple beams**

What are the Beam Dynamic Issues for Multi-Turn ERLs?

➔ All of the above, only worse!

Questions?