Experimental Observations of a Multi-Stream in a Long Intense Beam

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Outline

1. Motivation behind this work

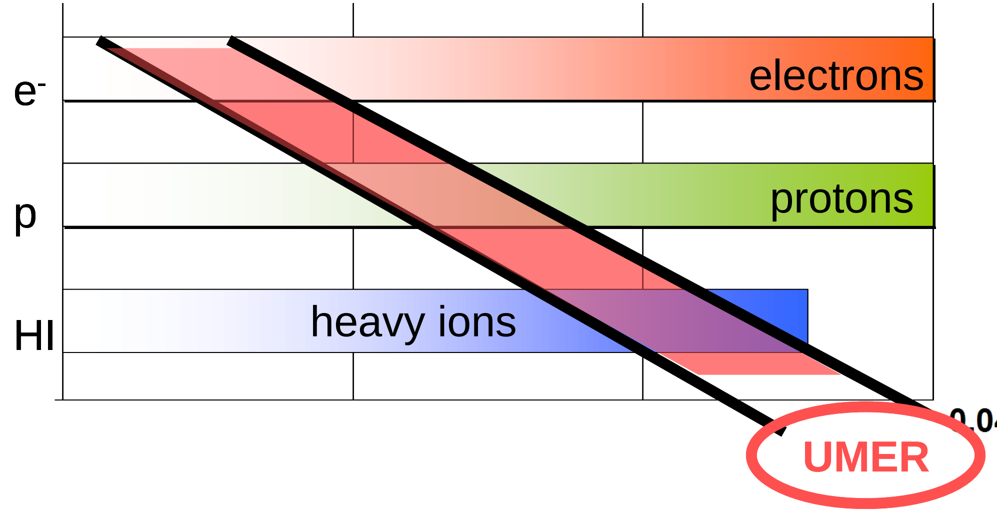
2. The University of Maryland Electron Ring (UMER), a tool to study intense beams on a small scale using low energy electrons

3. Bunch wrapping and onset condition
   - Longitudinal erosion (debunching) of long beams due to space charge
   - PIC simulations of bunch wrapping
   - Calculation of the onset
   - Comparison between theory, measurements and simulations

4. Extending to multi-bunch trains (still within the long wavelength limit)

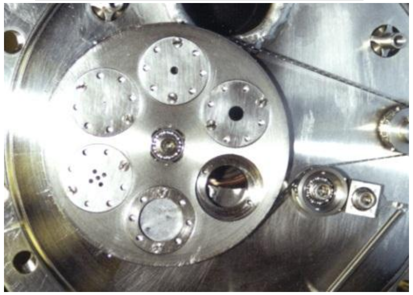
5. Conclude

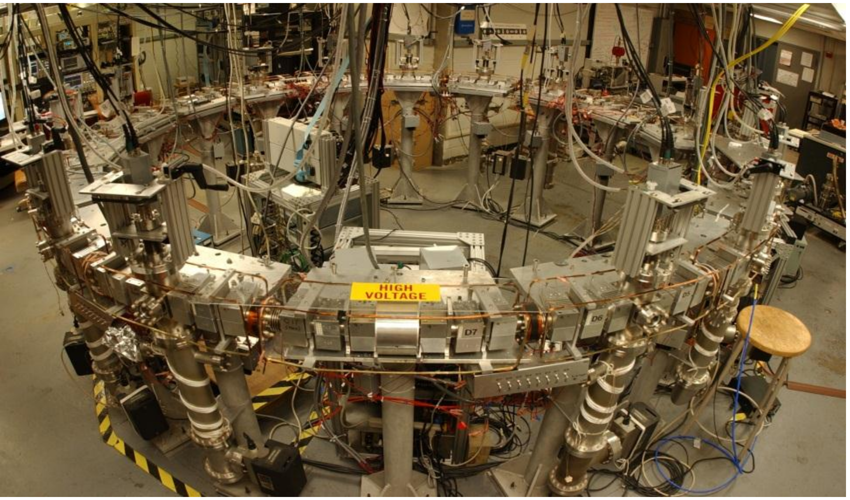
Background

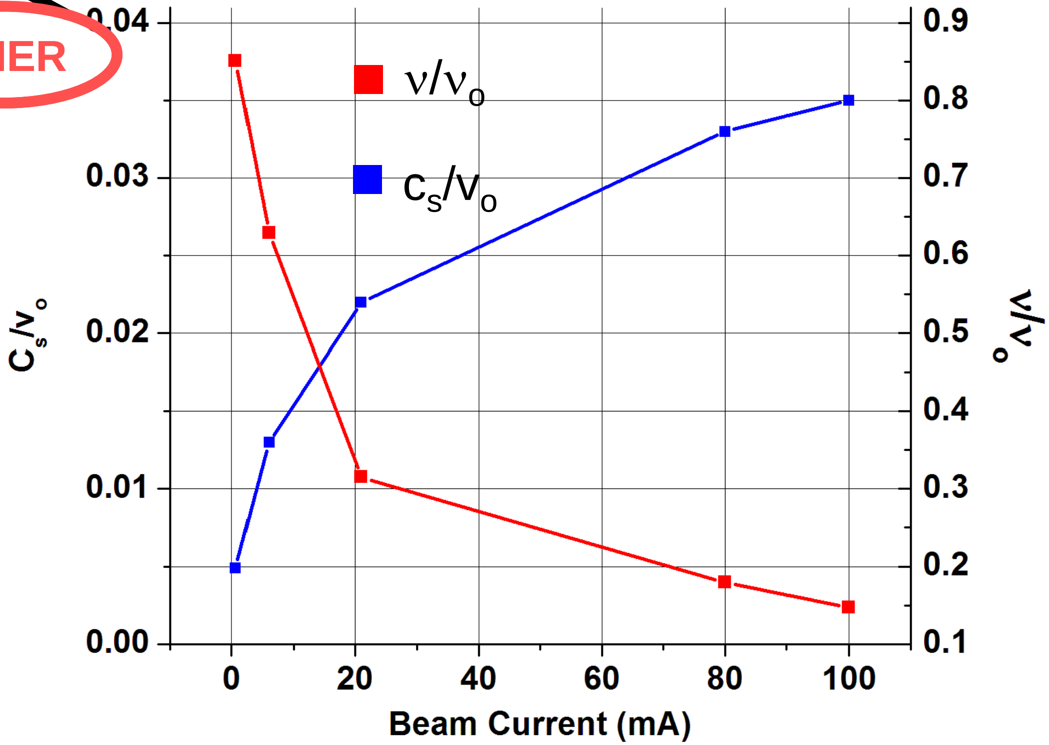


UMER spans a broad range of intensities through the use of the aperture plate

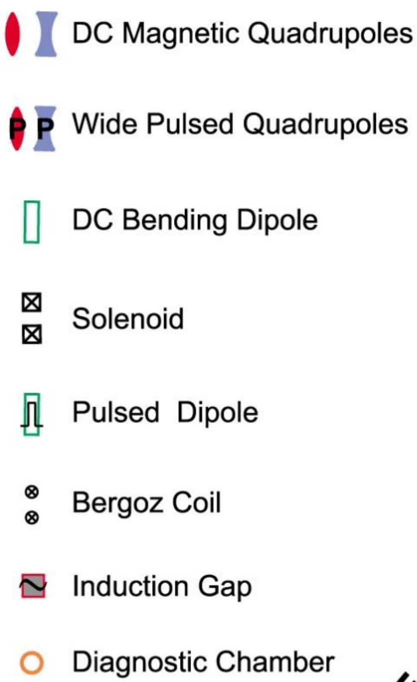
APERTURE PLATE



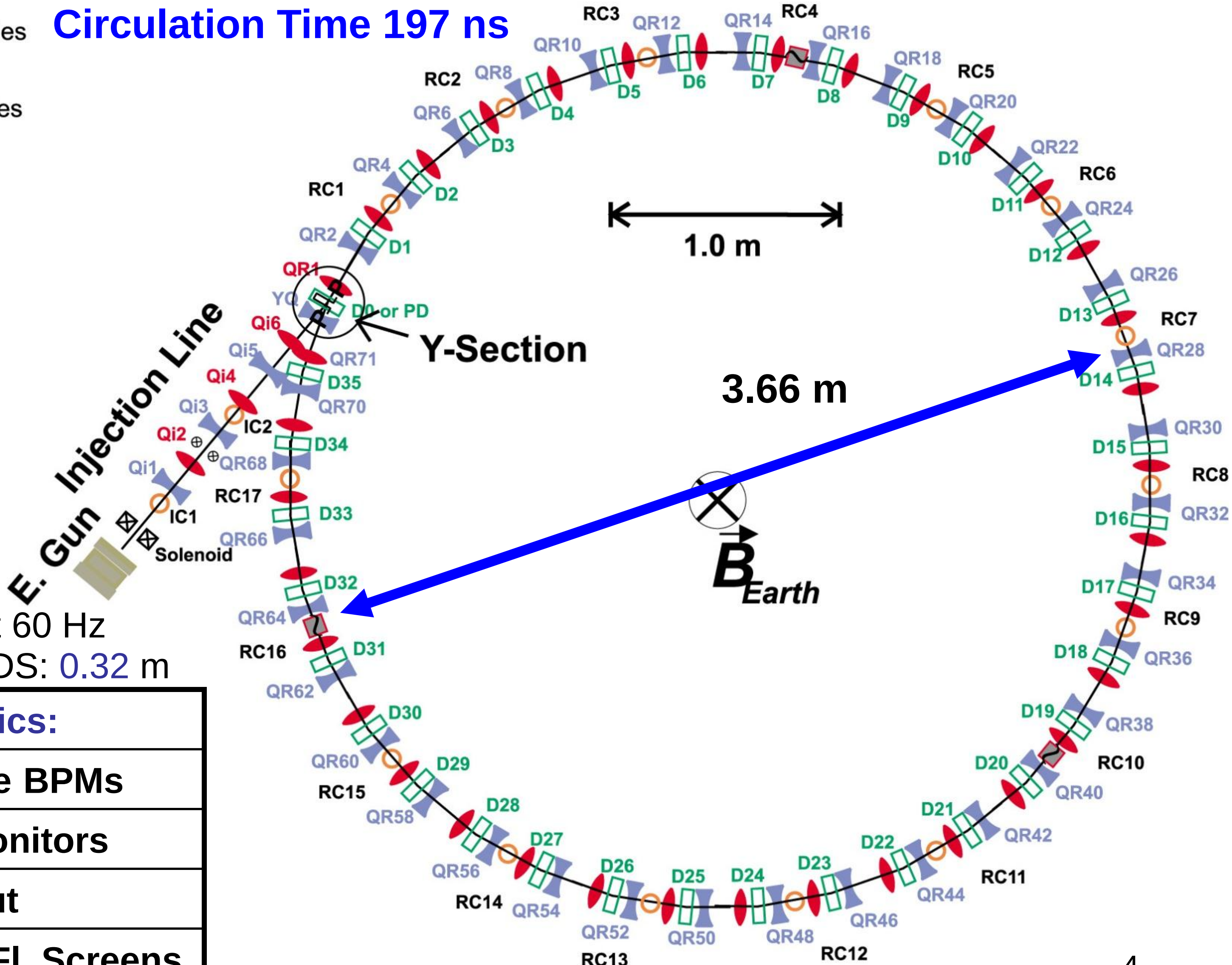




University of Maryland Electron Ring



Circulation Time 197 ns

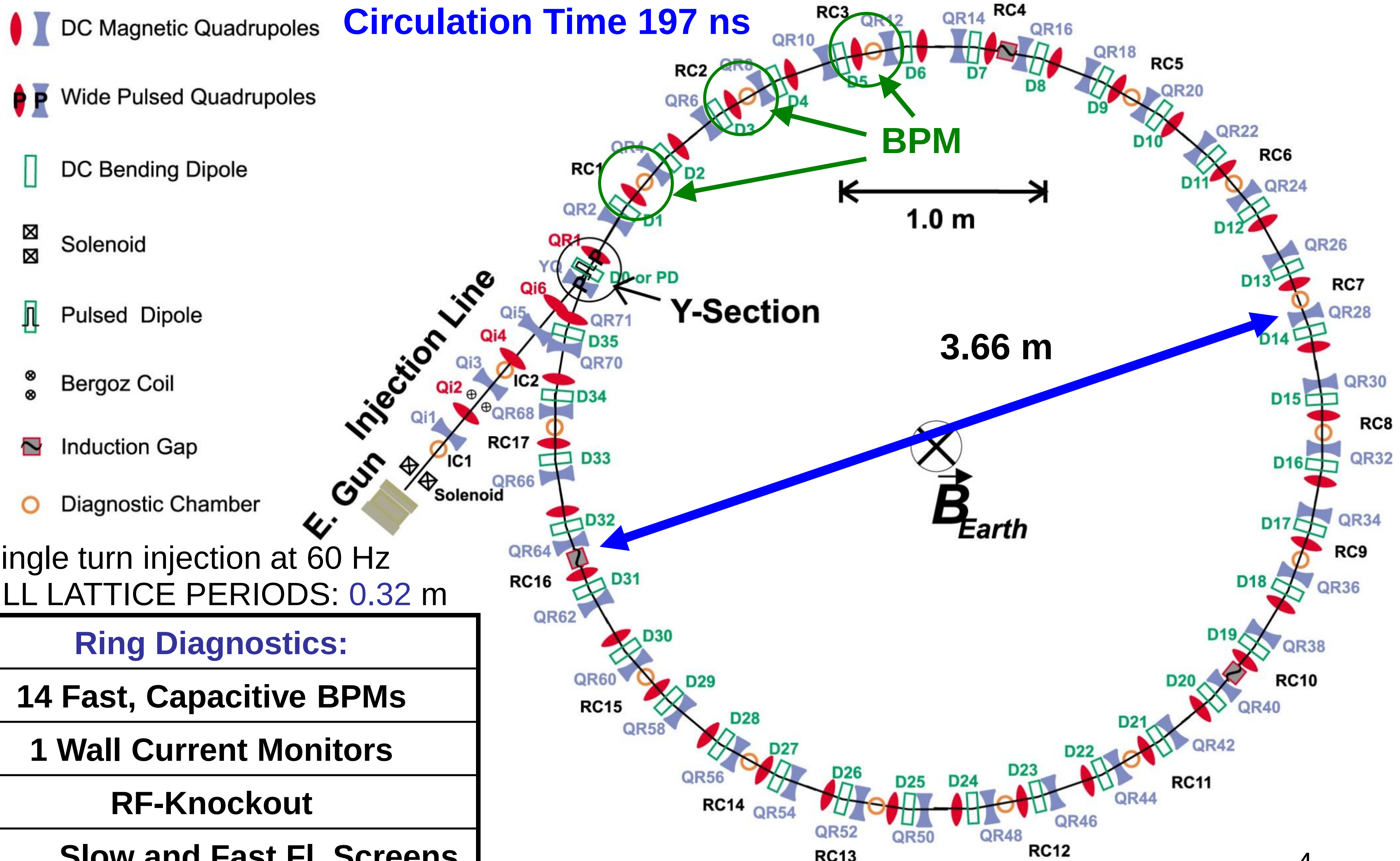


Single turn injection at 60 Hz
FULL LATTICE PERIODS: 0.32 m

Ring Diagnostics:
14 Fast, Capacitive BPMs
1 Wall Current Monitors
RF-Knockout
Slow and Fast Fl. Screens
OTR Screens

University of Maryland Electron Ring

Circulation Time 197 ns



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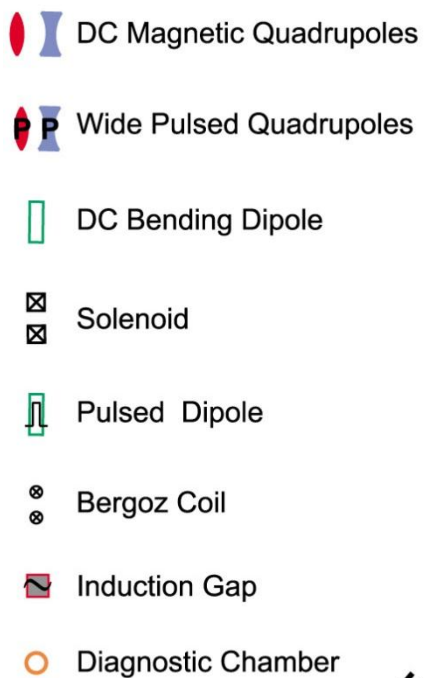

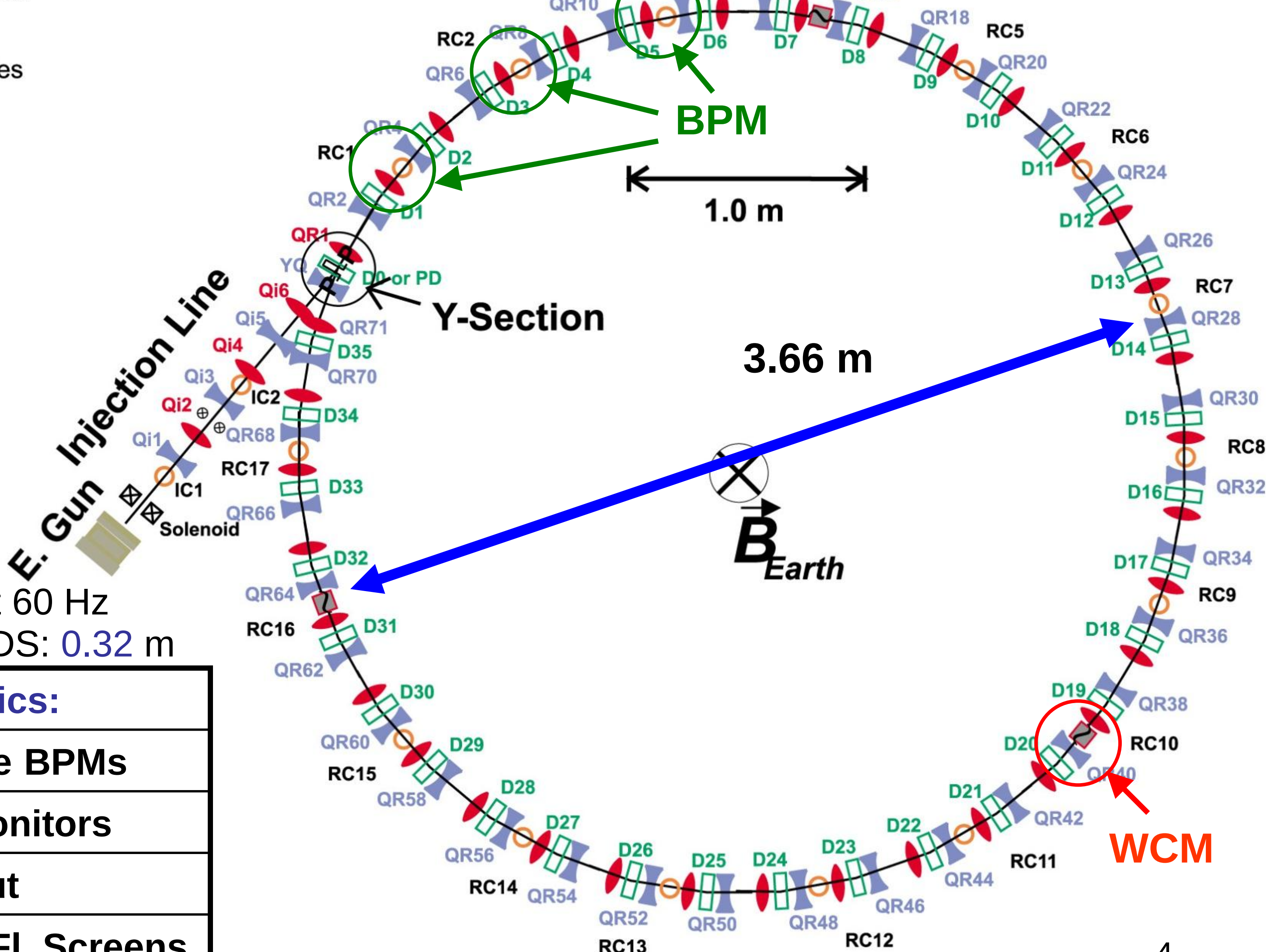

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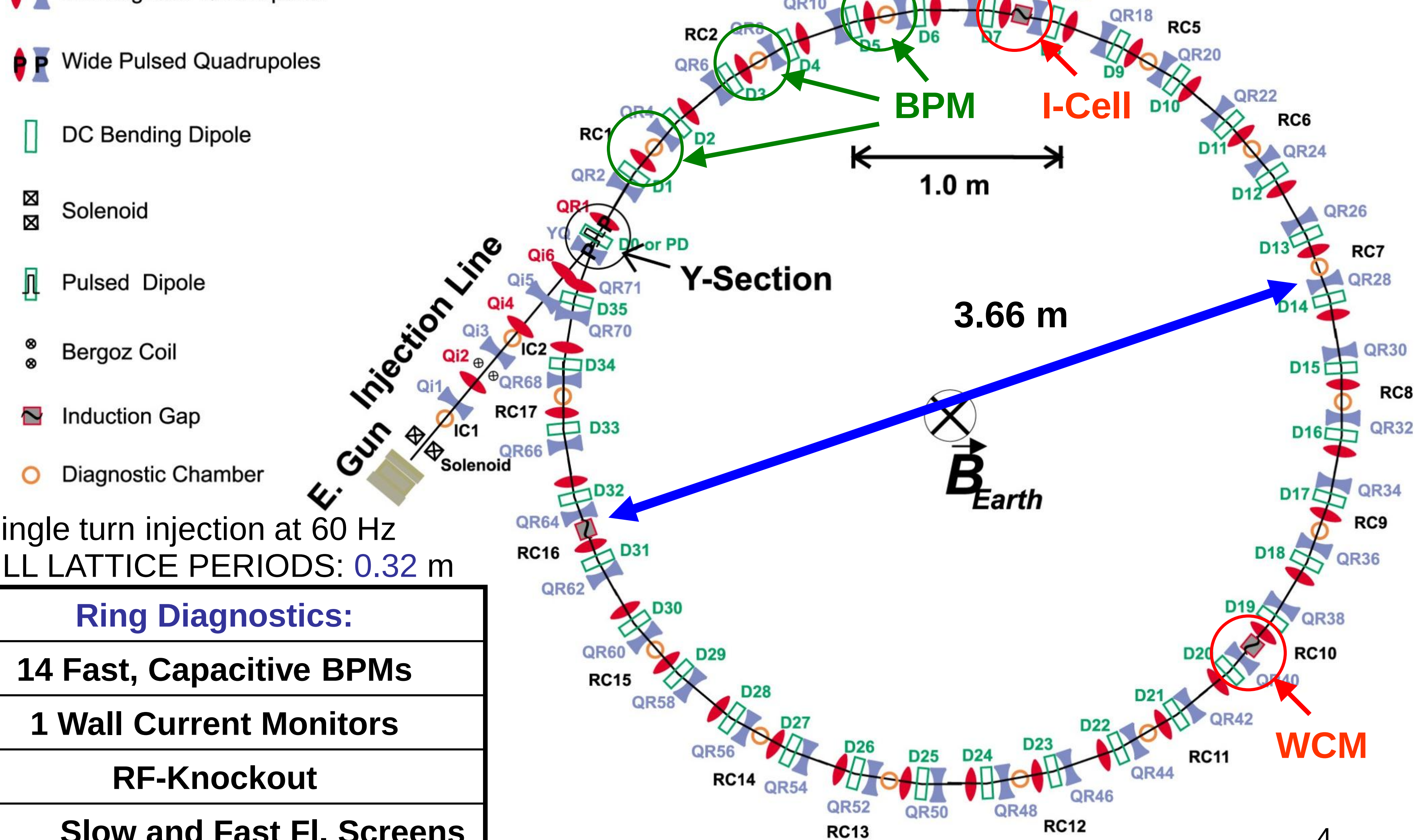

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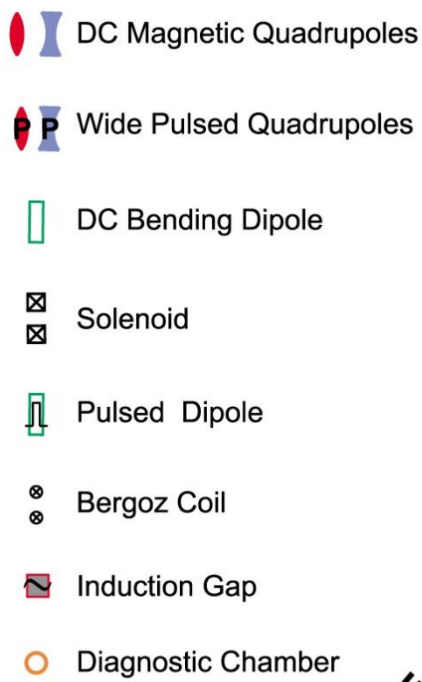

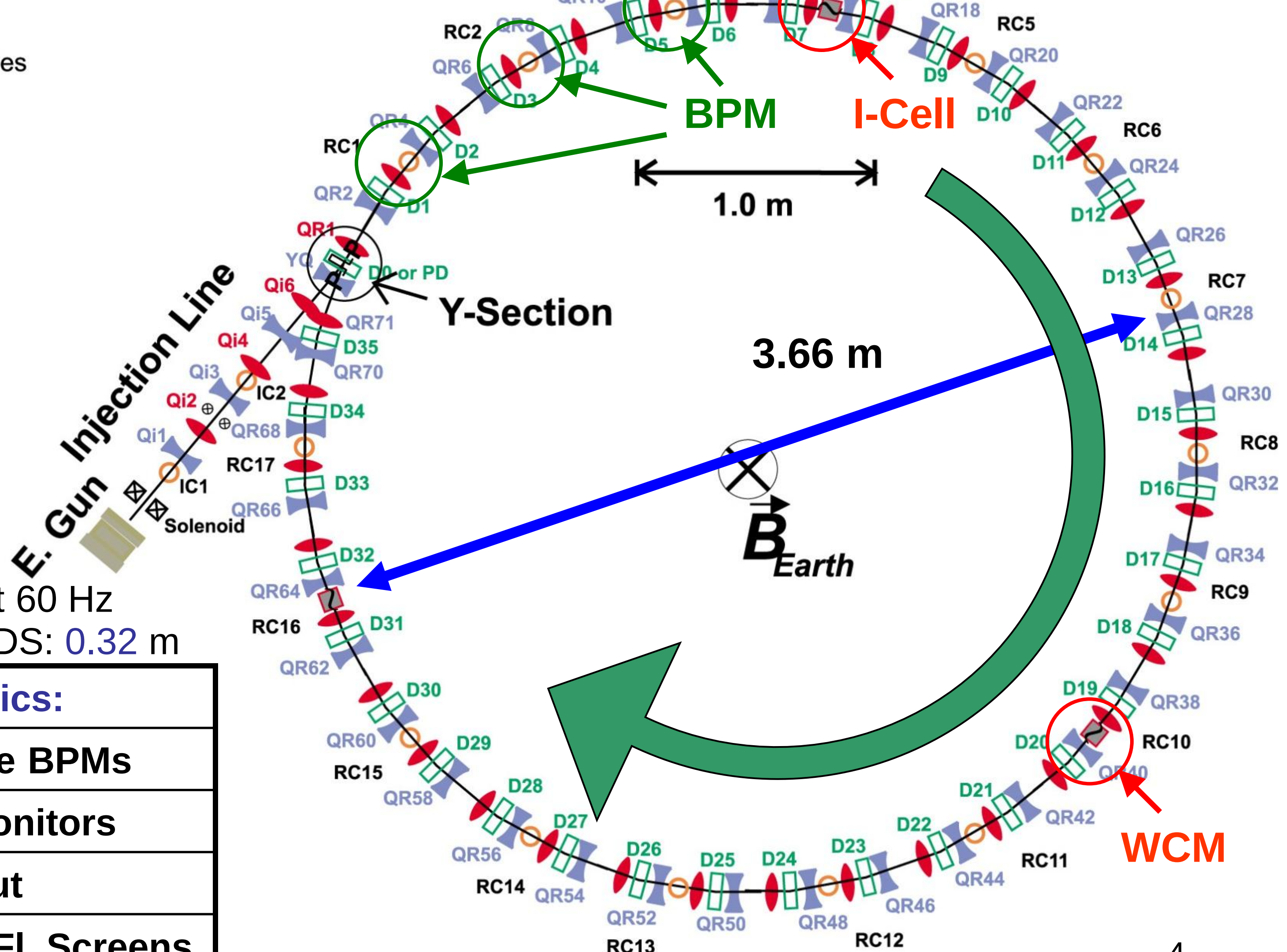

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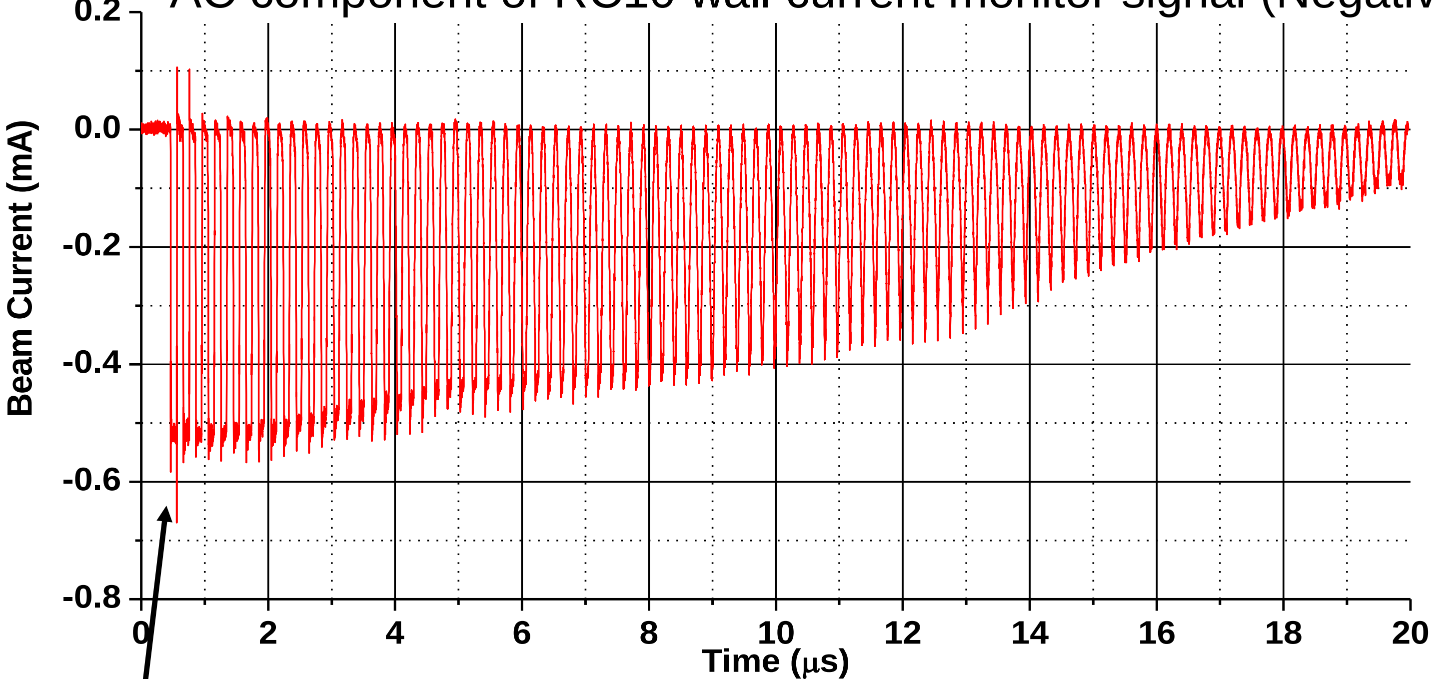
Longitudinal Bunch Erosion of Bunch Current

AC component of RC10 wall current monitor signal (Negative going signal)



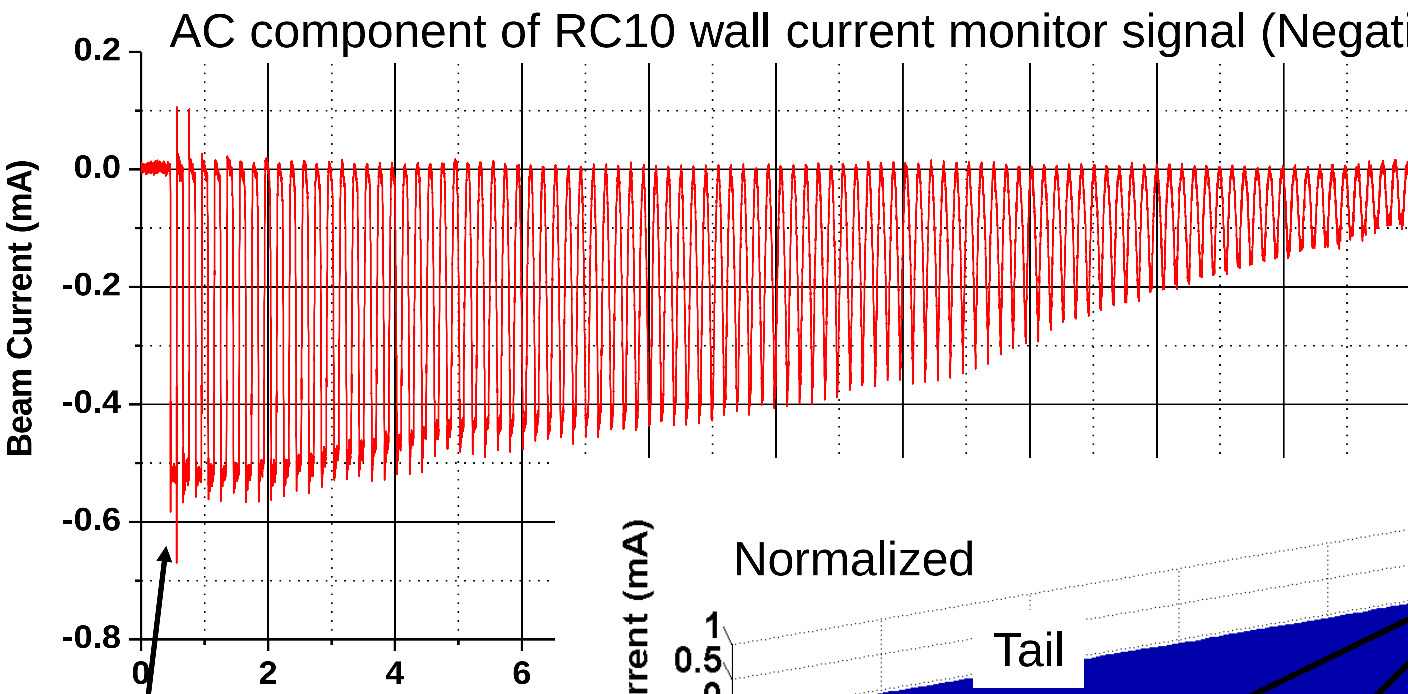
$$c_s = \sqrt{\frac{qg\lambda_o}{4\pi\varepsilon_o\gamma_o^5 m}}$$

The 0.6 mA beam

$$\frac{c_s}{v_o} = 0.0049$$

Injected Turn

Longitudinal Bunch Erosion of Bunch Current



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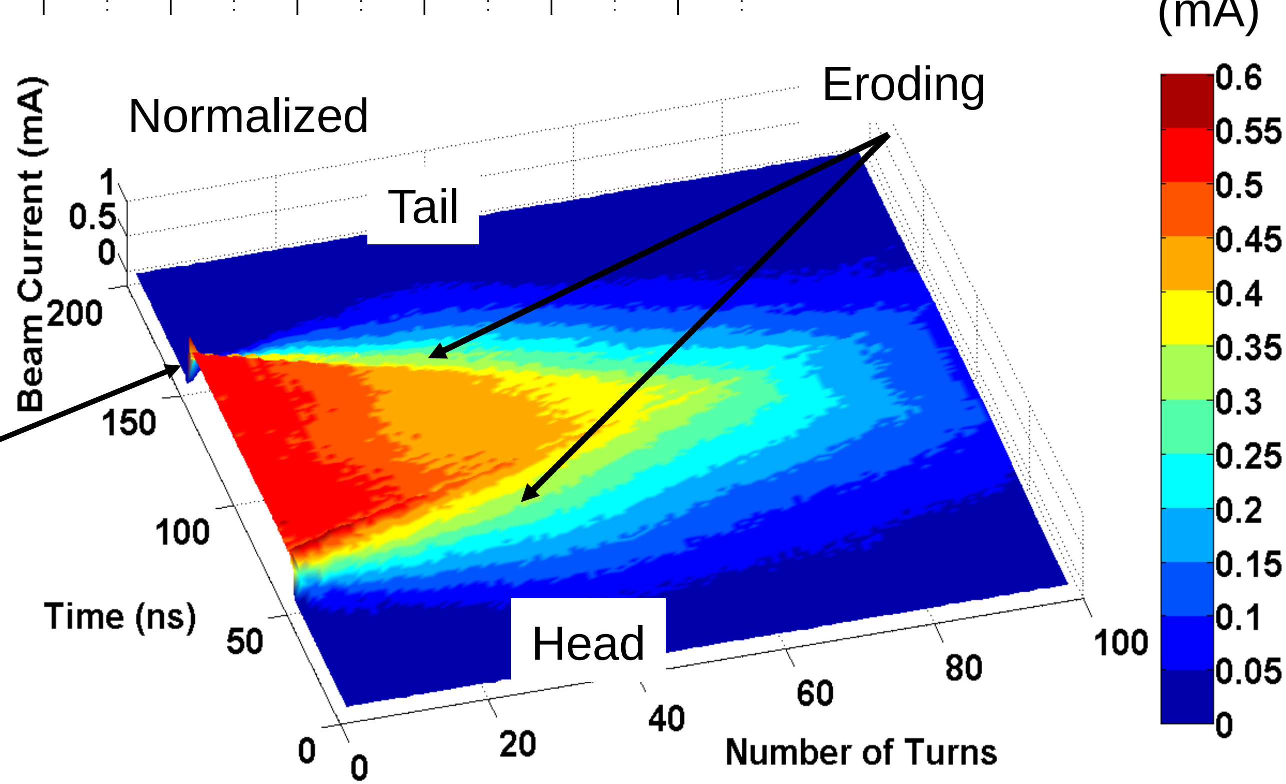
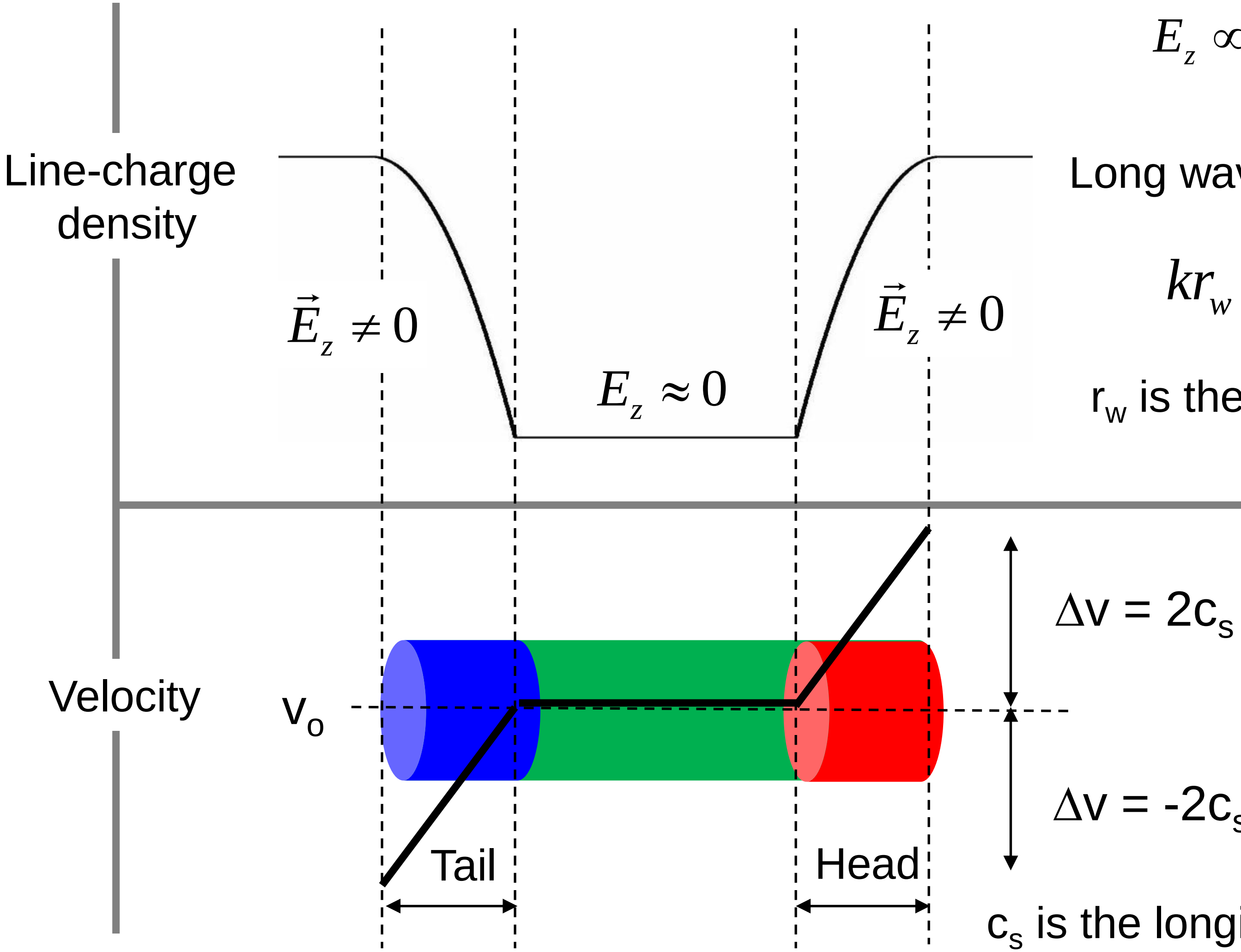


Longitudinal Space-Charge Physics

One - Dimensional

$$E_z \propto -\frac{d\lambda}{dz}$$



Long wavelength limit

$$kr_w << 1$$

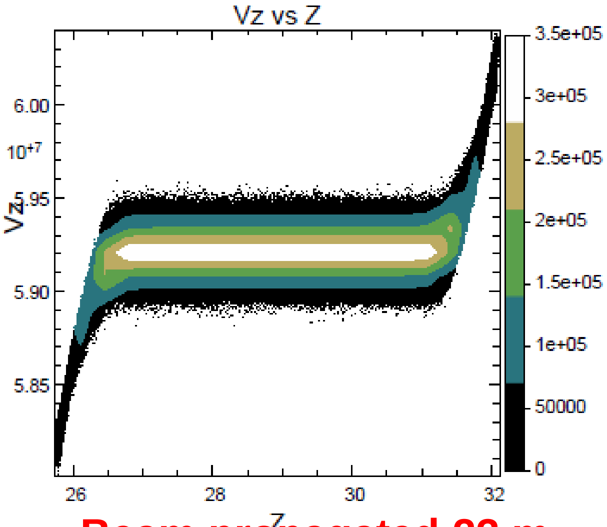
r_w is the pipe radius

$$c_s = \sqrt{\frac{qg\lambda_o}{4\pi\varepsilon_o\gamma_o^5 m}}$$

c_s is the longitudinal wave speed of a perturbation on the bunch.

-CERN 77-13, 19 July 1977,
"Theoretical Aspects of the Behavior of Beams in Accelerators and Storage Rings
-A. Faltens, E.P. Lee, and S.S. Rosenblum, Journal of Applied Physics, 61, 5219, (1987).

Inter Spacing Shrinks as the Bunch wraps



Beam propagated 23 m

$\Delta L > 0.56C$

Simulated Phase Space

ΔL = Bunch length

C = Ring circumference

Injected length
$\Delta L = 0.5C$

η = fill factor = injected pulse length / ring lap-time

6 mA beam
$\eta = 0.50$

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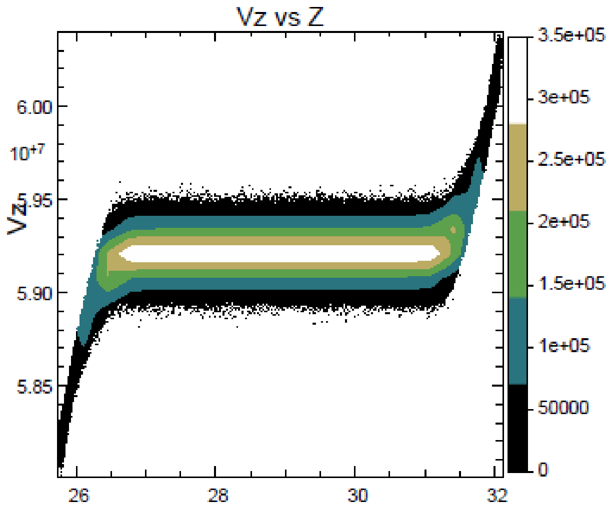

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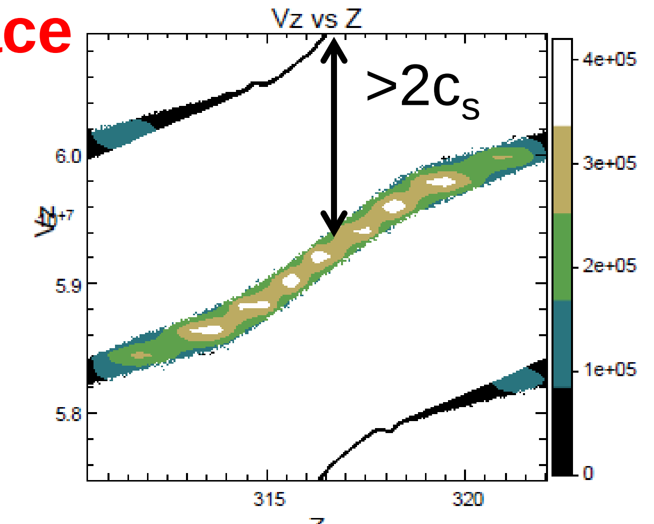


Beam propagated 310.5 m

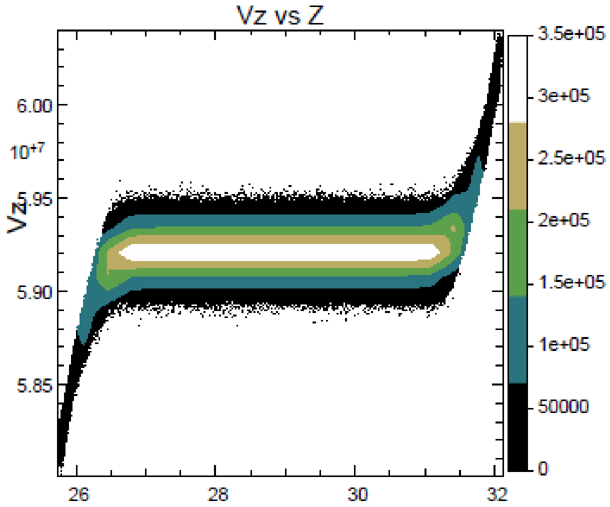
$\Delta L = 2C$

η = fill factor = injected pulse length / ring lap-time

6 mA beam

$\eta = 0.50$

Inter Spacing Shrinks as the Bunch wraps



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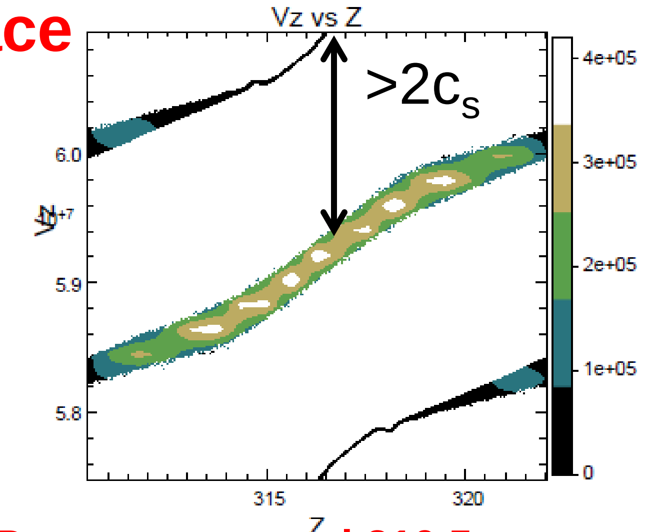

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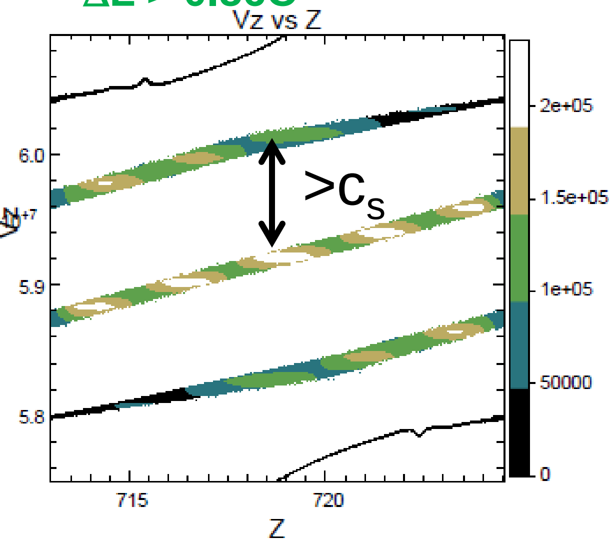


Beam propagated 713 m

$\Delta L > 4C$

η = fill factor = injected pulse length / ring lap-time

6 mA beam

$\eta = 0.50$

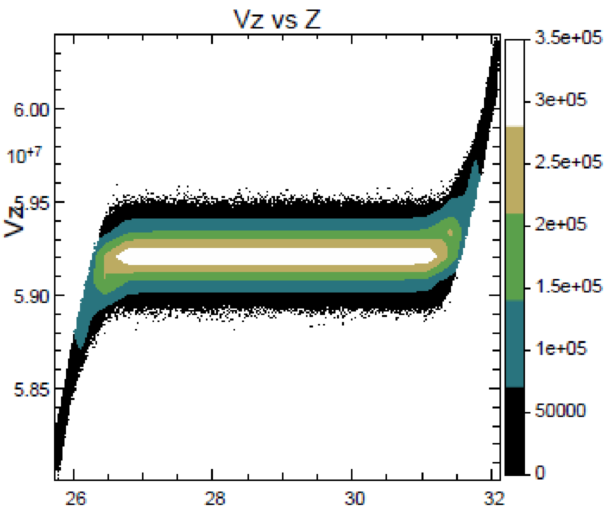
Inter Spacing Shrinks as the Bunch wraps

Simulated Phase Space

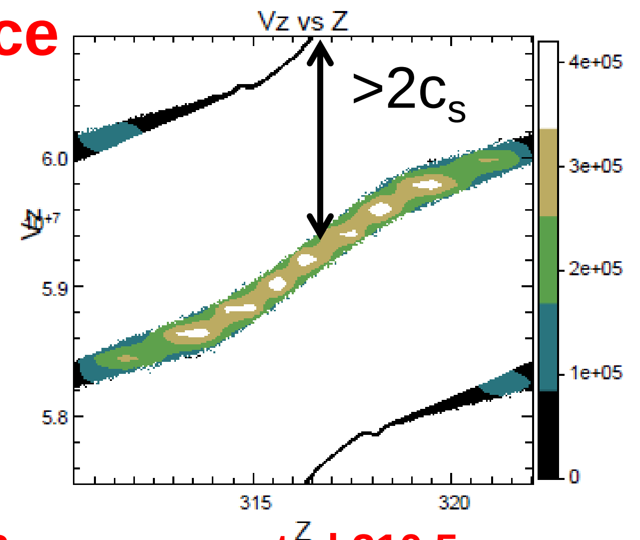
ΔL = Bunch length

C = Ring circumference

Injected length
$\Delta L = 0.5C$



Beam propagated 23 m
$\Delta L > 0.56C$



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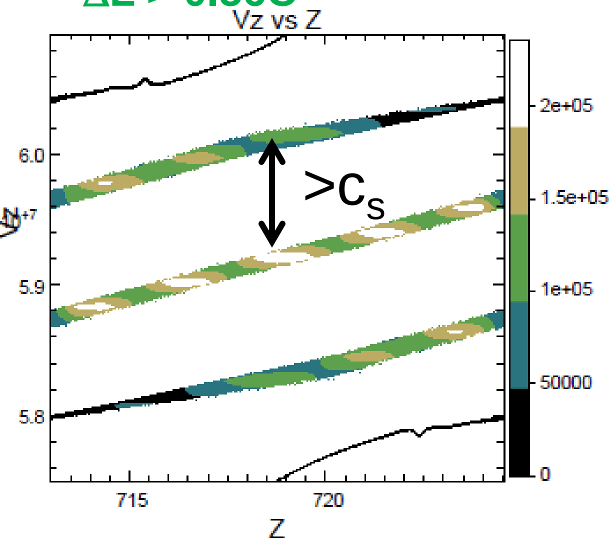

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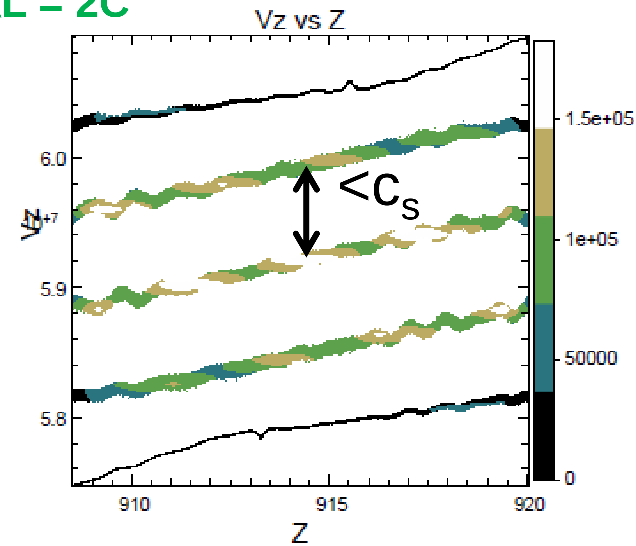
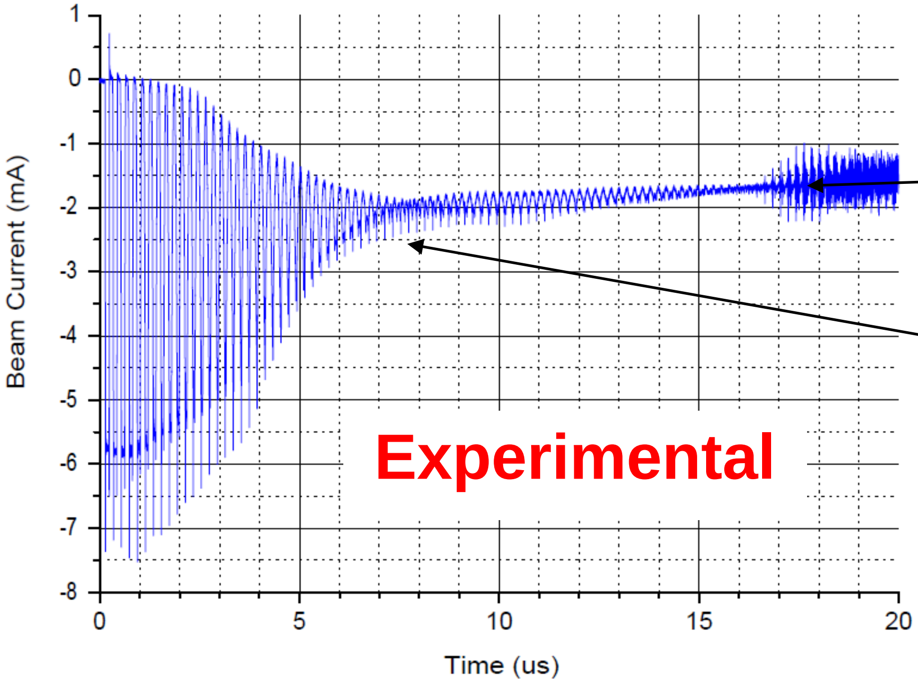


Beam propagated 908.5 m
$\Delta L = 5C$

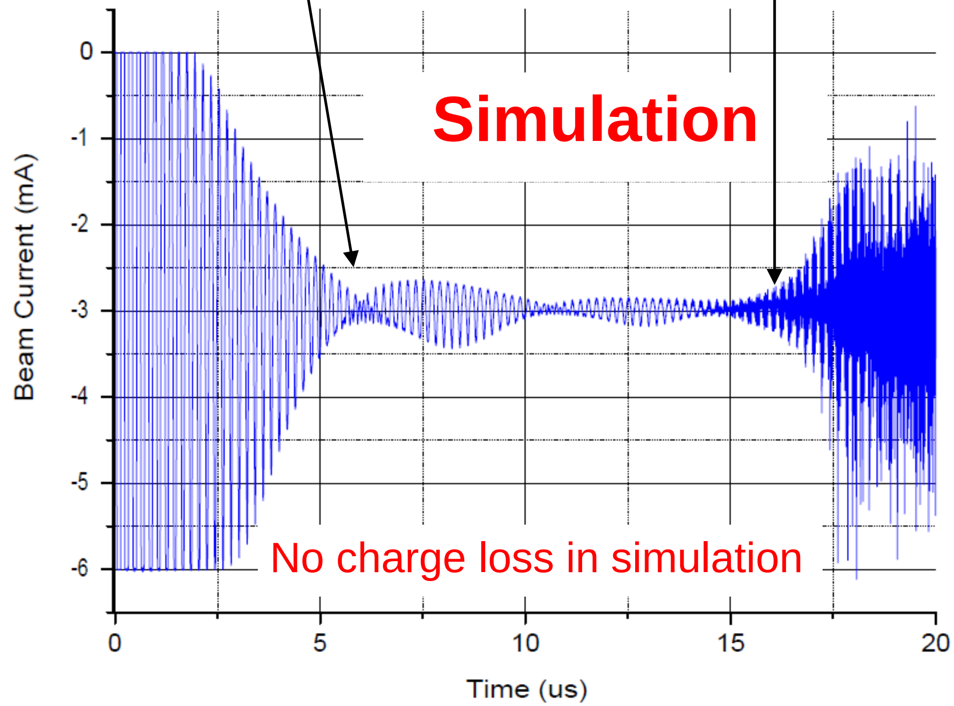
Signature of the Onset in the Current Profiles

Current Profiles from the RC 10 Wall Current Monitor



Onset

Beam becomes “DC”



6 mA beam

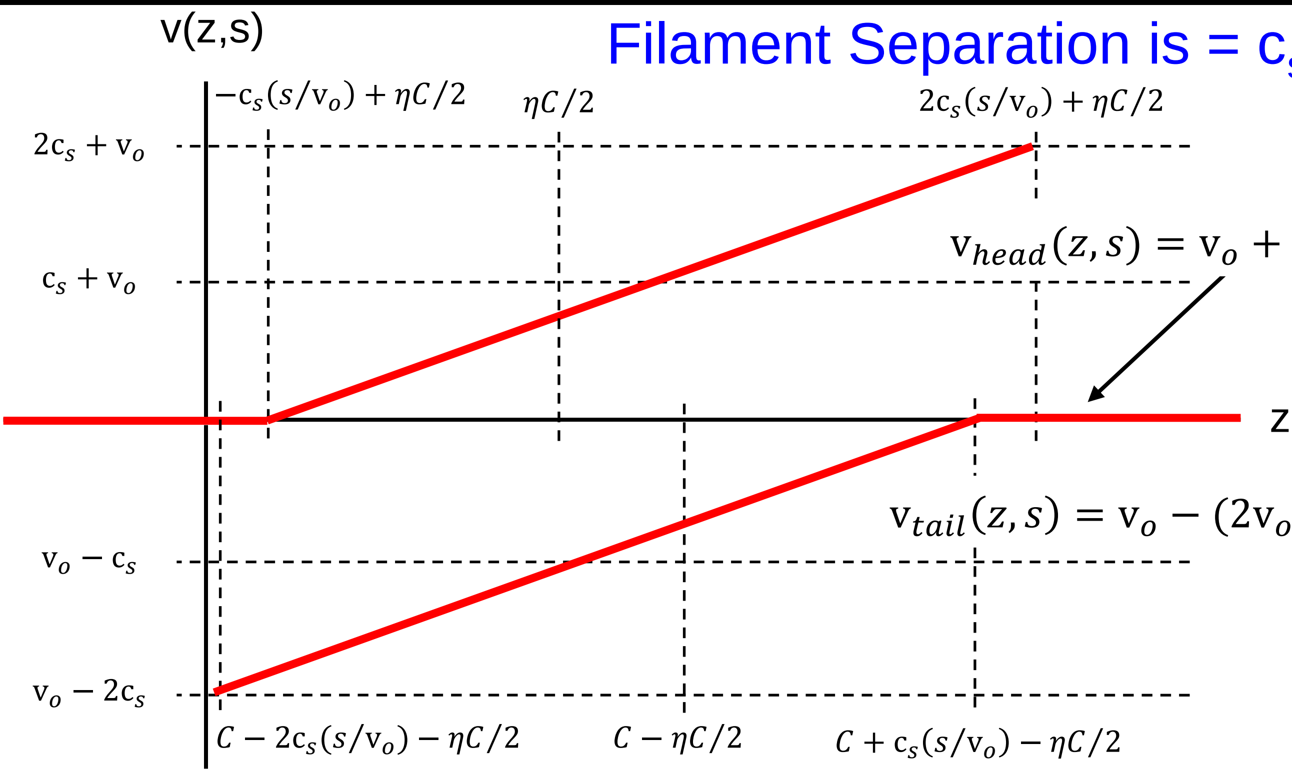
$\eta = 0.50$

$$\frac{c_s}{v_o} = 0.013$$

Condition required for the Onset

Filament Separation is = c_s

Wrapped around beam end in ring geometry



$$v_{head}(z,s) = v_o + (2v_o/3\,s)(z + c_s(s/v_o) - \eta C/2)$$

$$v_{tail}(z,s) = v_o - (2v_o/3\,s)(C - z + c_s(s/v_o) - \eta C/2)$$

$$\Delta v = v_{head}(z,s) - v_{tail}(z,s) = 4c_s/3 - (2v_o C/3\,s)|\eta - 1|$$

Assume the filament separation is a c_s

$$\Delta v = c_s = 4c_s/3 - (2v_o C/3\,s_{onset})|\eta - 1|$$

s_{onset} = Onset of instability

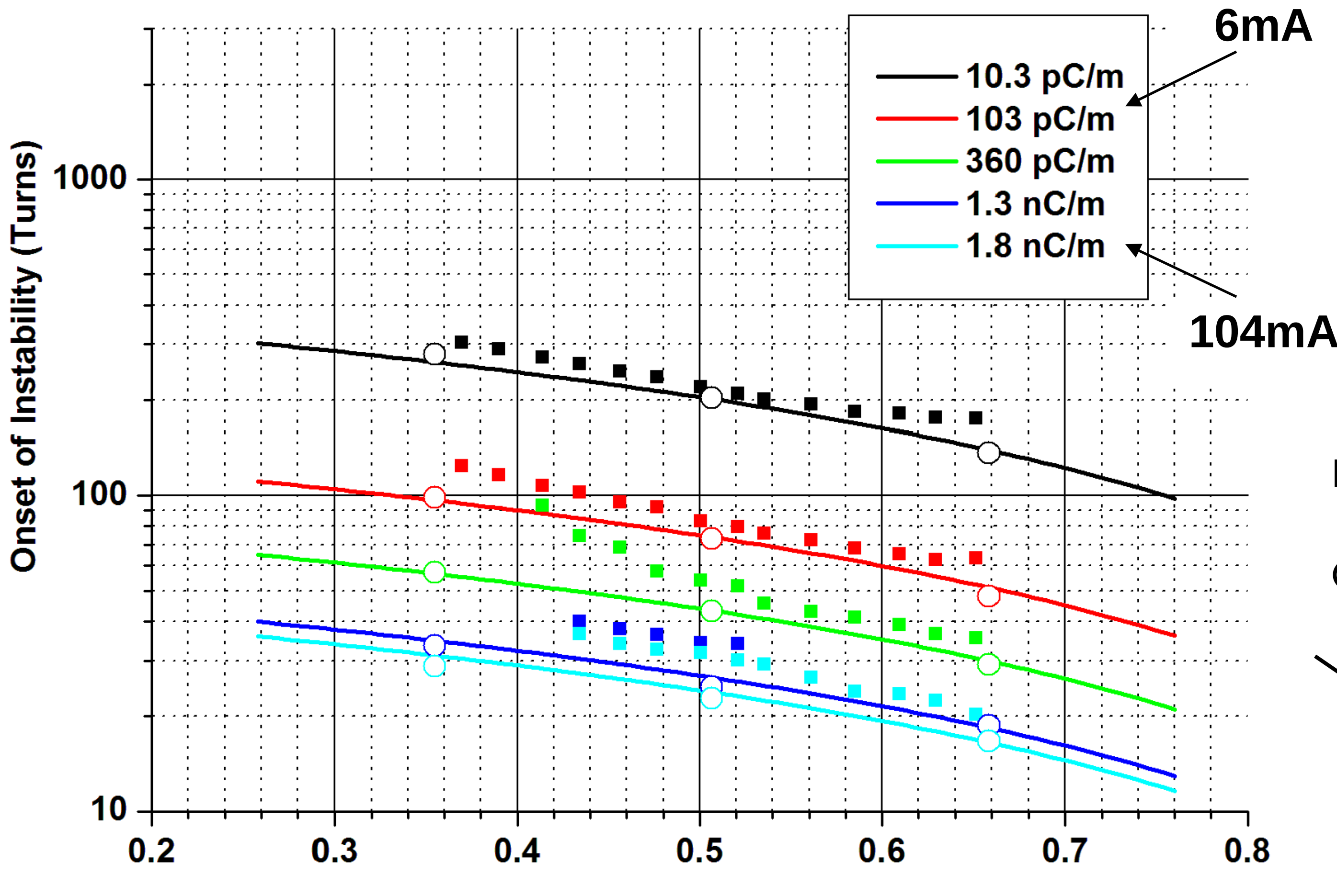
$$s_{onset} = (2v_o C/c_s)|\eta - 1|$$

Fill Factor and Current Dependence on the Onset

$$s_{onset} = \frac{2v_o C}{c_s}|\eta - 1|$$

$$turns_{onset} = \frac{s_{onset}}{C}$$

Onset of Instability



$$c_s = \left(\frac{qg\lambda_o}{4\pi\varepsilon_0\gamma_0^5 m}\right)^{1/2}$$

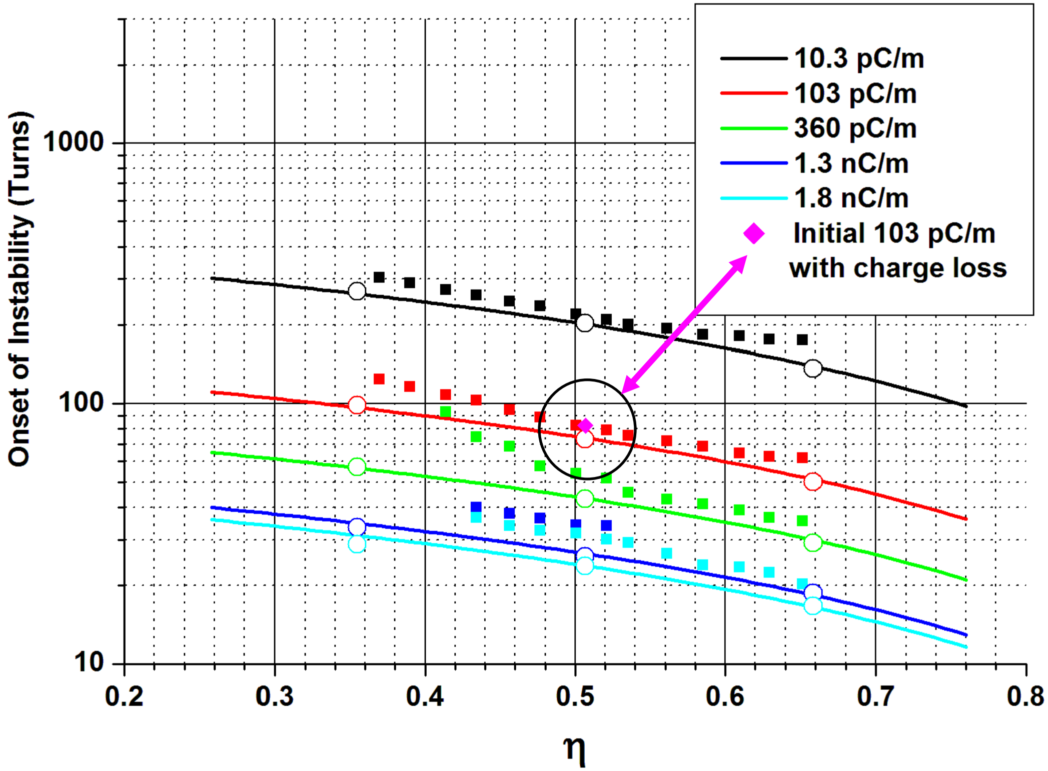
■ Experiment

○ Simulation (WARP)

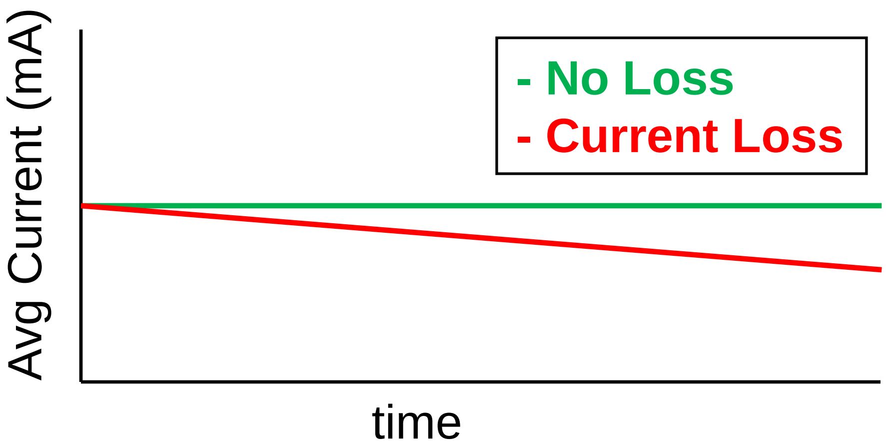
╲ Theory

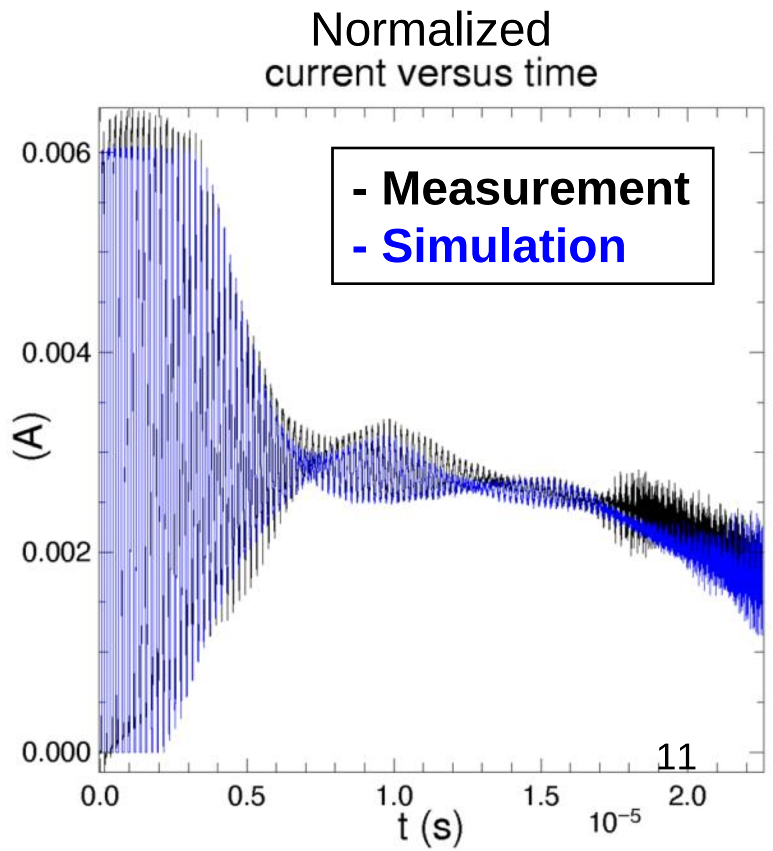
B.L. Beaudoin, R.A. Kishek, I. Haber, T.W. Koeth, submitted (2012).

Incorporating Transverse Current Loss into the Simulation Model

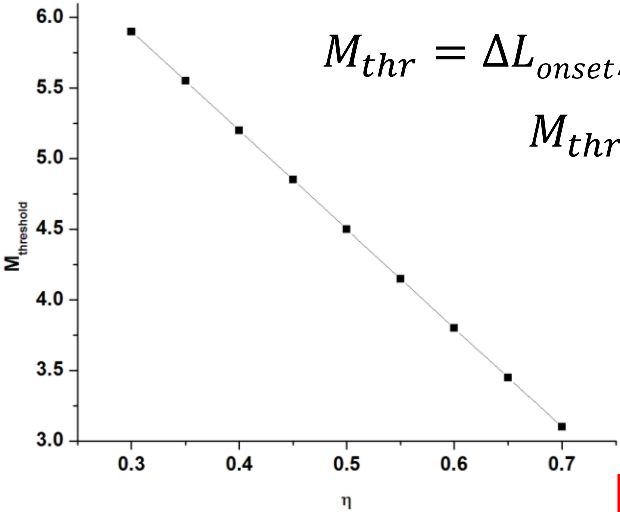


Current loss delays the longitudinal wave velocity, c_s and thus delays the onset of the instability





Fill Factor Dependence on the Number of Filamentations



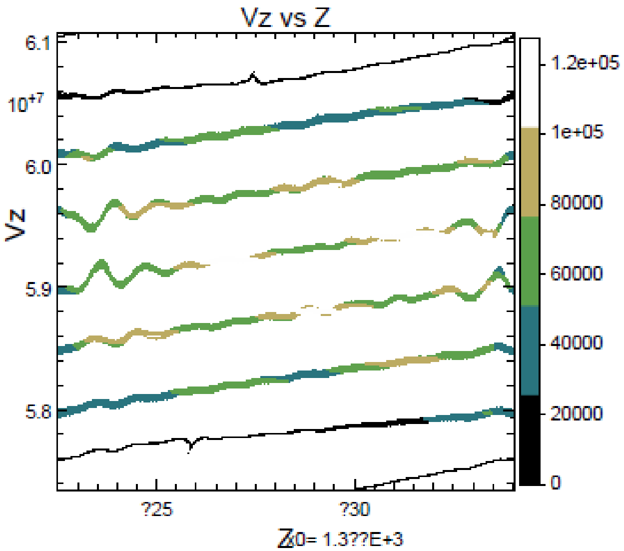
$$M_{thr} = \Delta L_{onset}/C = (8C|\eta - 1| + \eta C)/C$$

$$M_{thr} = 8|\eta - 1| + \eta$$

The growth rate of the modulations in phase space is also dependent on the fill factor

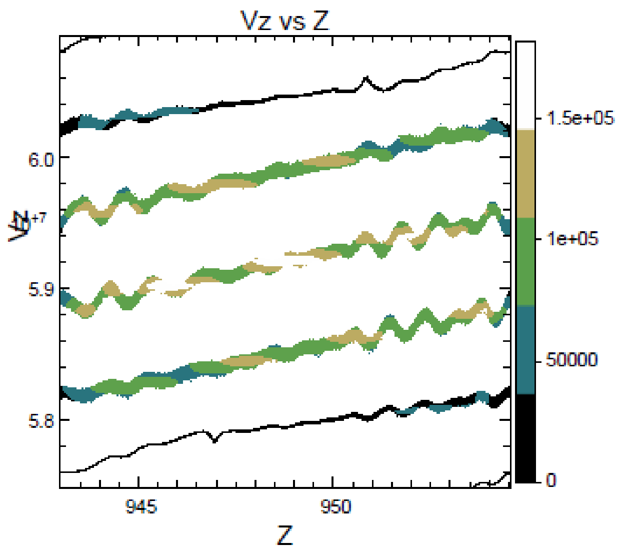
Phase Space (6 mA beam)

70 ns long bunch



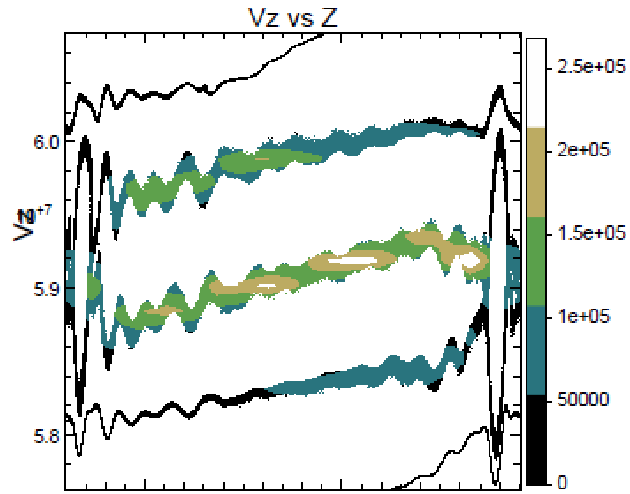
ΔL > 7C $\eta = 0.35$

100 ns long bunch



ΔL > 5C $\eta = 0.50$

130 ns long bunch



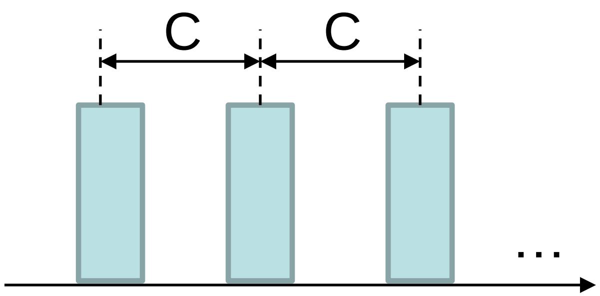
ΔL > 3.5C $\eta = 0.66$

Extending to Multi-Short-Bunch Trains

Preliminary

$$s_{onset} = \frac{2v_o C}{c_s}|\eta - 1|$$

Multi-Bunch Train



For multiple bunch trains, C is the pulse to pulse spacing

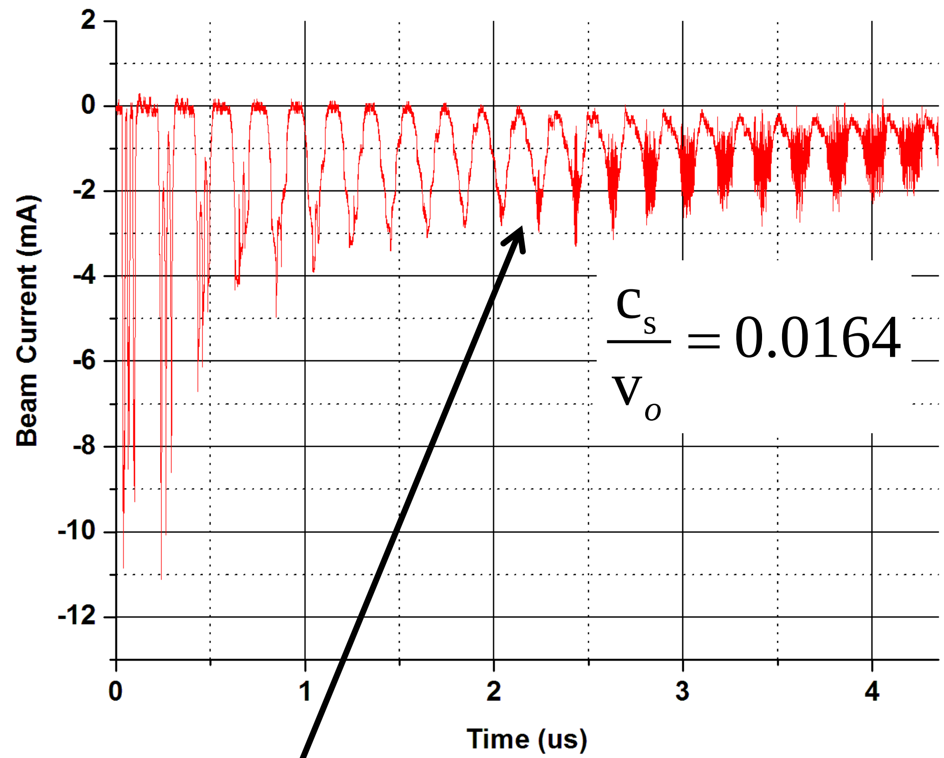
$$C = (20ns)v_o = 1.167m$$

$$\eta = \frac{12.57ns}{197.39ns} = 0.0636$$

$$s_{onset} = 131.2m$$

Experimental Observation

7.7 mA beam
3 pulse bunch train at 50 MHz



$$\frac{c_s}{v_o} = 0.0164$$

Onset of instability
s_{onset} = 132.7 m
$turns_{onset}$ = 11.5

Summary and Concluding Remarks

- Longitudinal space-charge causes the beam to wrap the machine several times.
- The onset of the instability occurs when the separation between the innermost filaments is a **longitudinal wave velocity, c_s.**
- Comparisons between theory, measurements and PIC simulations have shown good agreement.
- **Future Activities**
  - Measure growth rates and amplitudes as a function of line-charge density and fill factor
  - Continue to work on multi-bunch trains to characterize parameter space for multiple bunches.
  - Inject shorter and shorter bunches until we approach the short wavelength limit where $kr_w >> 1$

Thank you

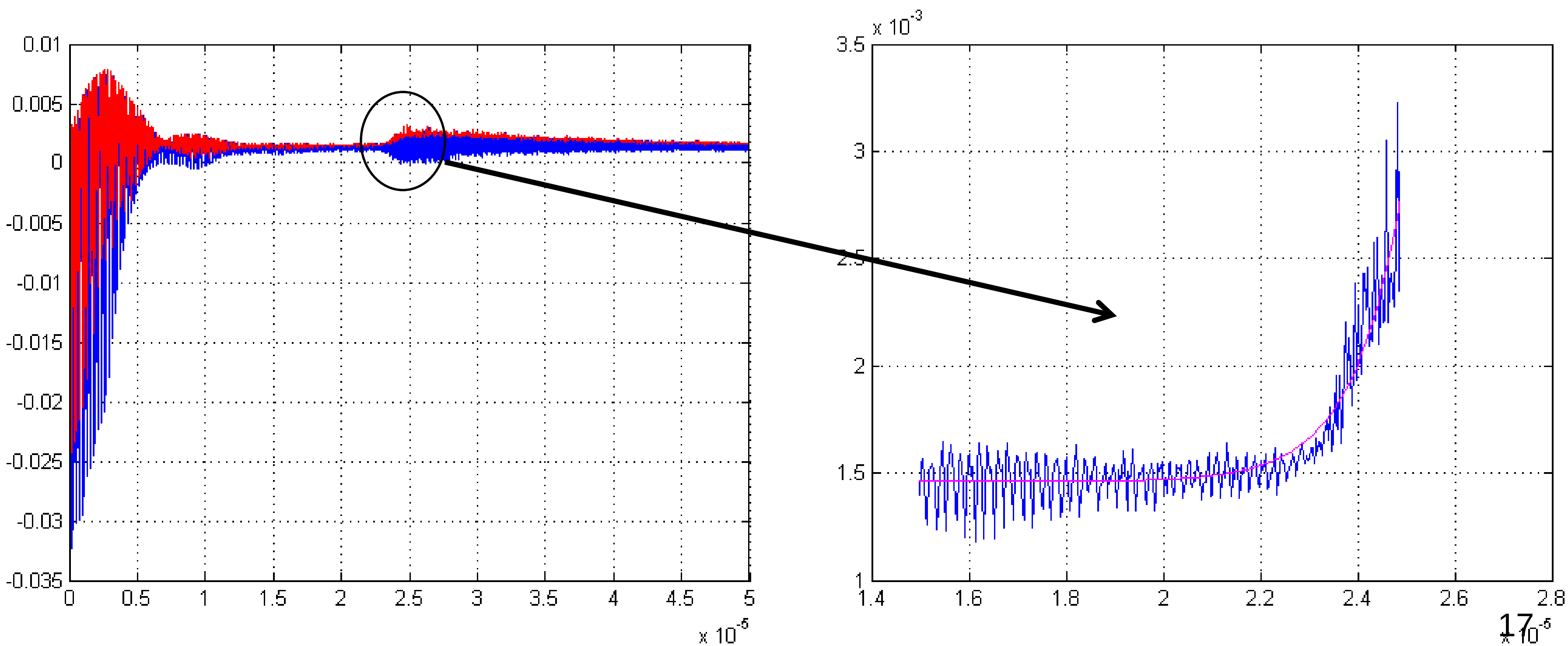
Extra Slides

Fitting to Determine the Onset

Beam current 6.0 mA

$\eta = 0.38$

To go from $exp^{-3.5}$ to exp^{0}, for this particular case, the growth is about ~3.5 μs or 17.7 turns.



Time

Time