DARHT

Electron-Beam Dynamics in the Long-Pulse, High-Current DARHT-II Linear Induction Accelerator

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Los Alamos National Laboratory

Presented at

PAC09

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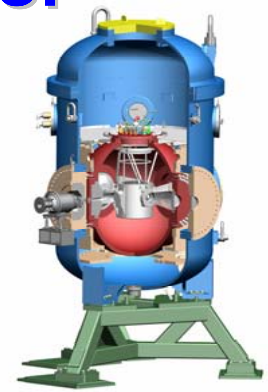
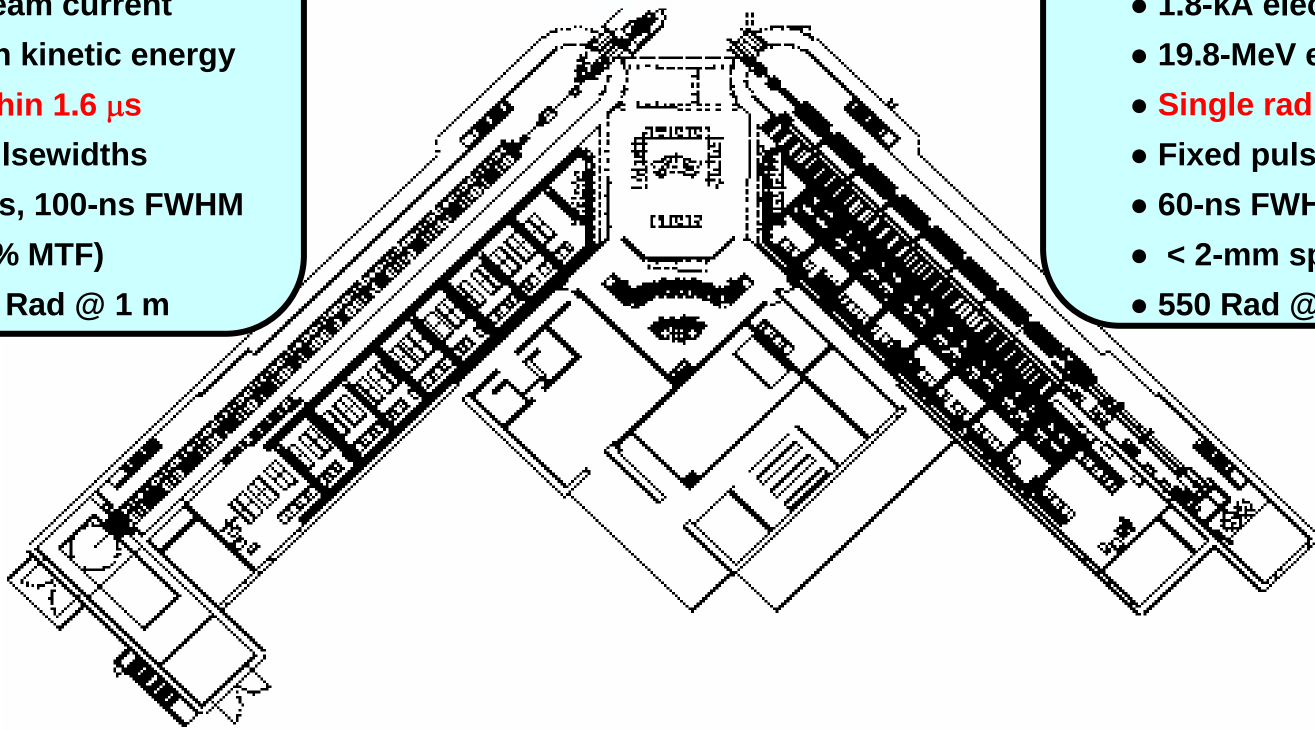
Dual-Axis Radiography for Hydrodynamic Testing

- Flash radiography of large, high-explosive driven experiments contained in vessels.
- Two accelerators provide simultaneous, orthogonal radiographs.



- Axis 2, Completed 2008
- Linear Induction Accelerator
- 2.0-kA electron-beam current
- > 17-MeV electron kinetic energy
- 4 radiographs within 1.6 μs
- Programmable pulsewidths
- 35-ns, 40-ns, 40-ns, 100-ns FWHM
- < 2 mm spots (50% MTF)
- 170, 185, 170, 445 Rad @ 1 m



- Axis 1, Completed 1999
- Linear Induction Accelerator
- 1.8-kA electron-beam current
- 19.8-MeV electron kinetic energy
- Single radiograph
- Fixed pulsewidth
- 60-ns FWHM
- < 2-mm spot (50% MTF)
- 550 Rad @ 1 m

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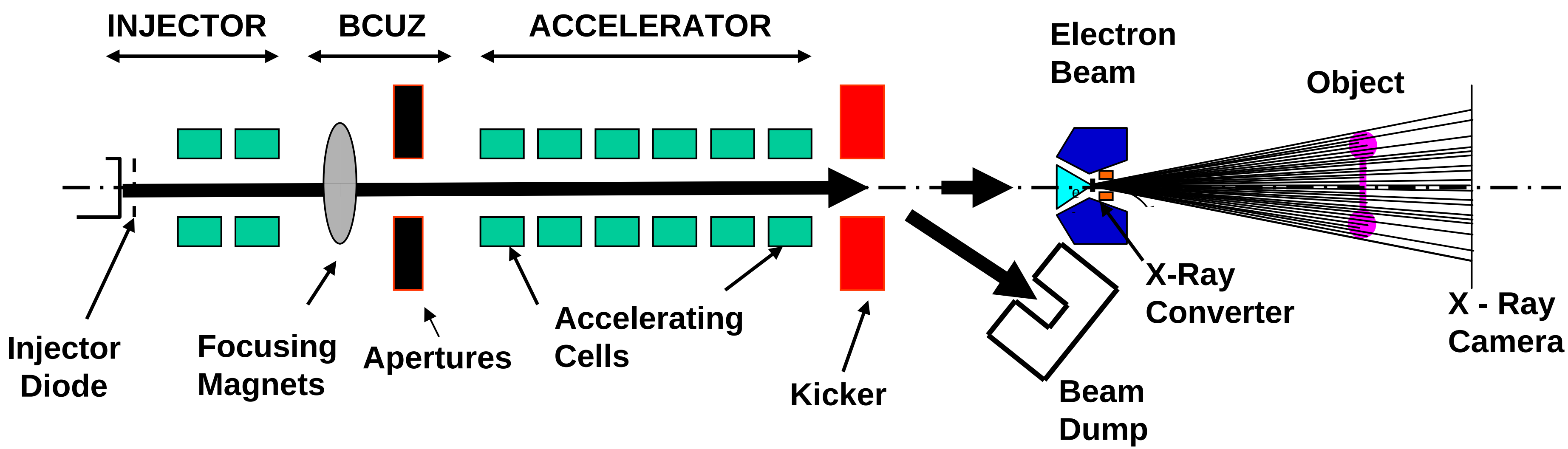
In this talk I will briefly tell you about:

- Beam Dynamics in the Axis-II Linear Induction Accelerator
  - Beam Sweep
    - < 10 mm (> beam size)
  - Beam Breakup (BBU)
    - << 1 mm (<< beam size)
  - Ion Hose instability
    - << 1 mm (<< beam size)

- Transport of kicked pulses to converter target and production of multiple radiography source spots
  - 4 spots, < 2 mm "50%MTF"

The multiple-pulse second axis is a significant advance in LIA technology.



- Commissioning completed March 2008
- Injector diode – 2.5 MeV, 2 kA, 1.6 μs
  - Marx generator powered
  - Hot dispenser cathode
- 6 Injector cells at 185 keV/cell
- 68 Accelerator cells at 216 keV/cell

- Final Beam Energy > 17 MeV
- Kicker system used to produce 4 pulses on the x-ray target:
- < 2 mm spot size (50% MTF)
- 35-ns, 40-ns, 40-ns, 100-ns pulse FWHM
- 170, 185, 170, 445 Rad @ 1 m

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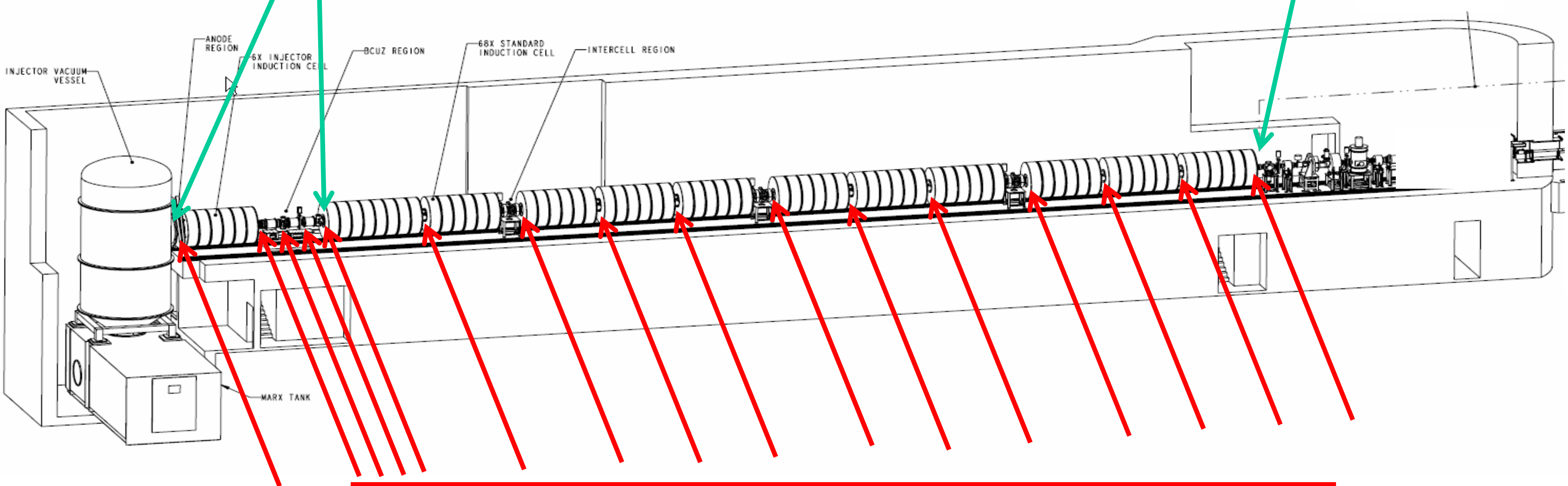
Beam position monitors (BPM) measure position and current throughout the accelerator.

2 Gs/s

High-bandwidth recording is used at entrance and exit to measure BBU

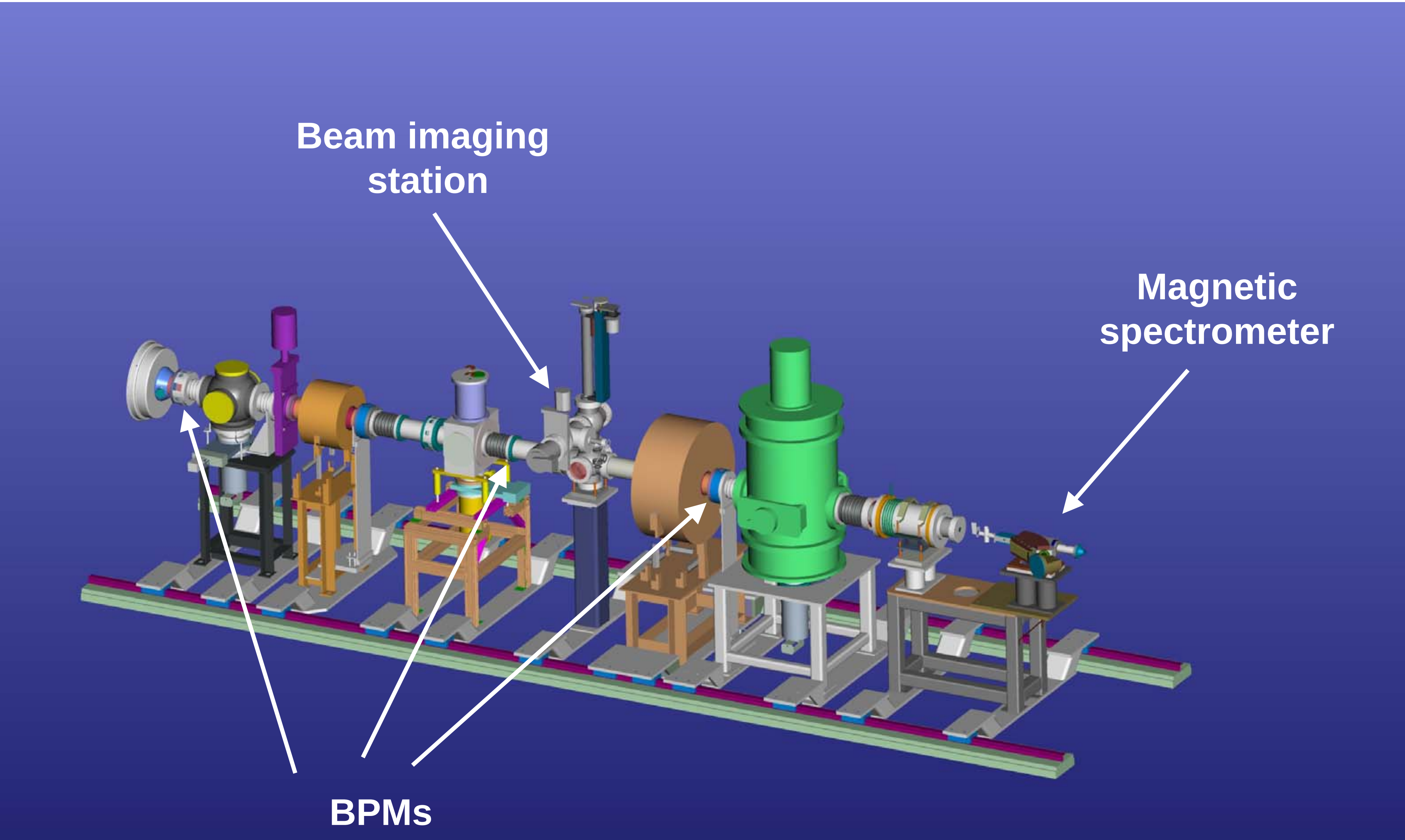
5 Gs/s



BPMs are located at the diode exit, at the entrance to every block of cells, and at the accelerator exit.

Poster: TH5RFP074, "DARHT II Accelerator Beam Position Monitor Performance Analysis," Jeff Johnson, et al. , This Conference

For commissioning, we installed diagnostics after the exit to measure the accelerated beam parameters.



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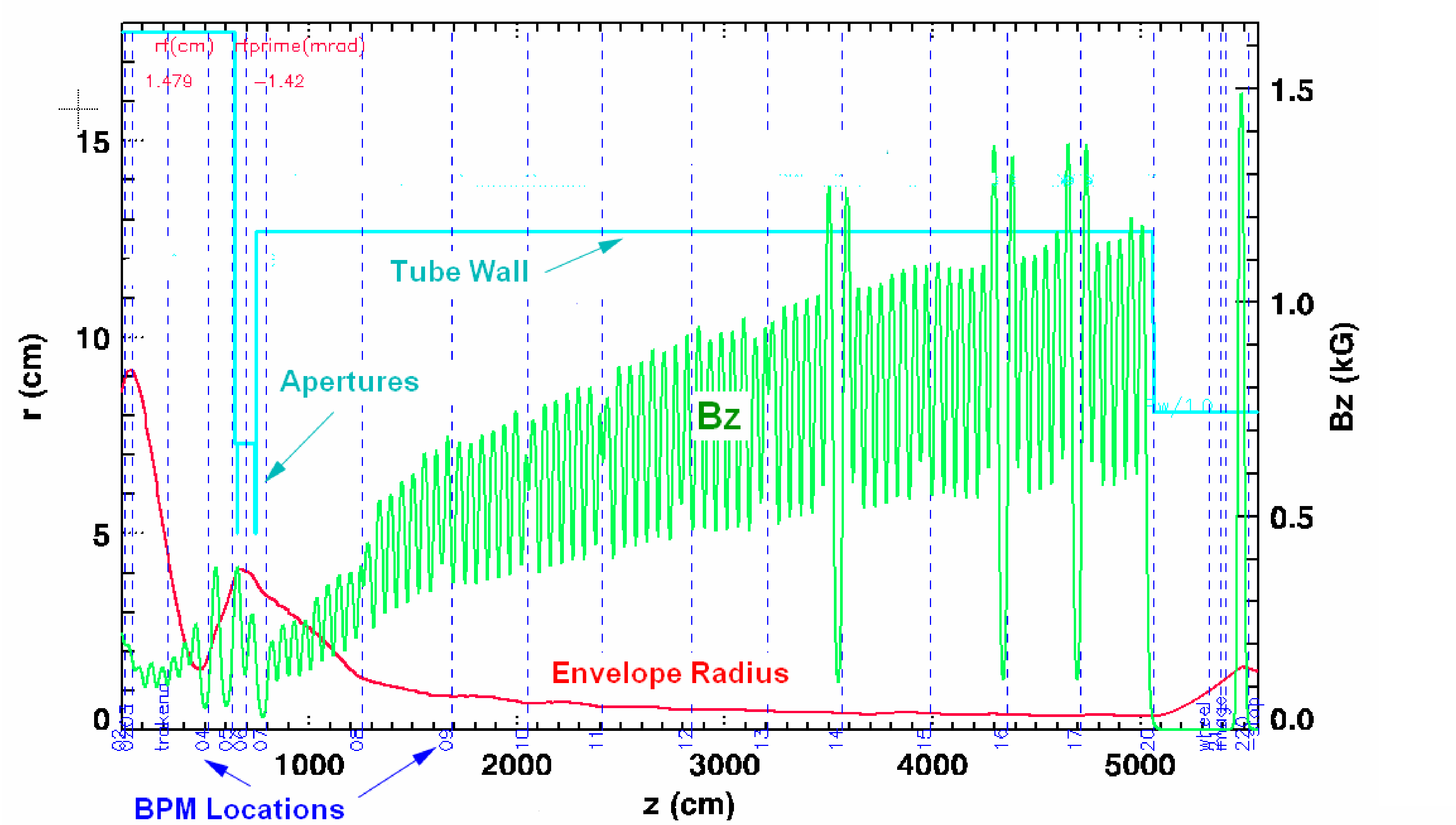
The beam is transported in a strong solenoidal focusing field with an axial variation (tune) designed using beam envelope codes.



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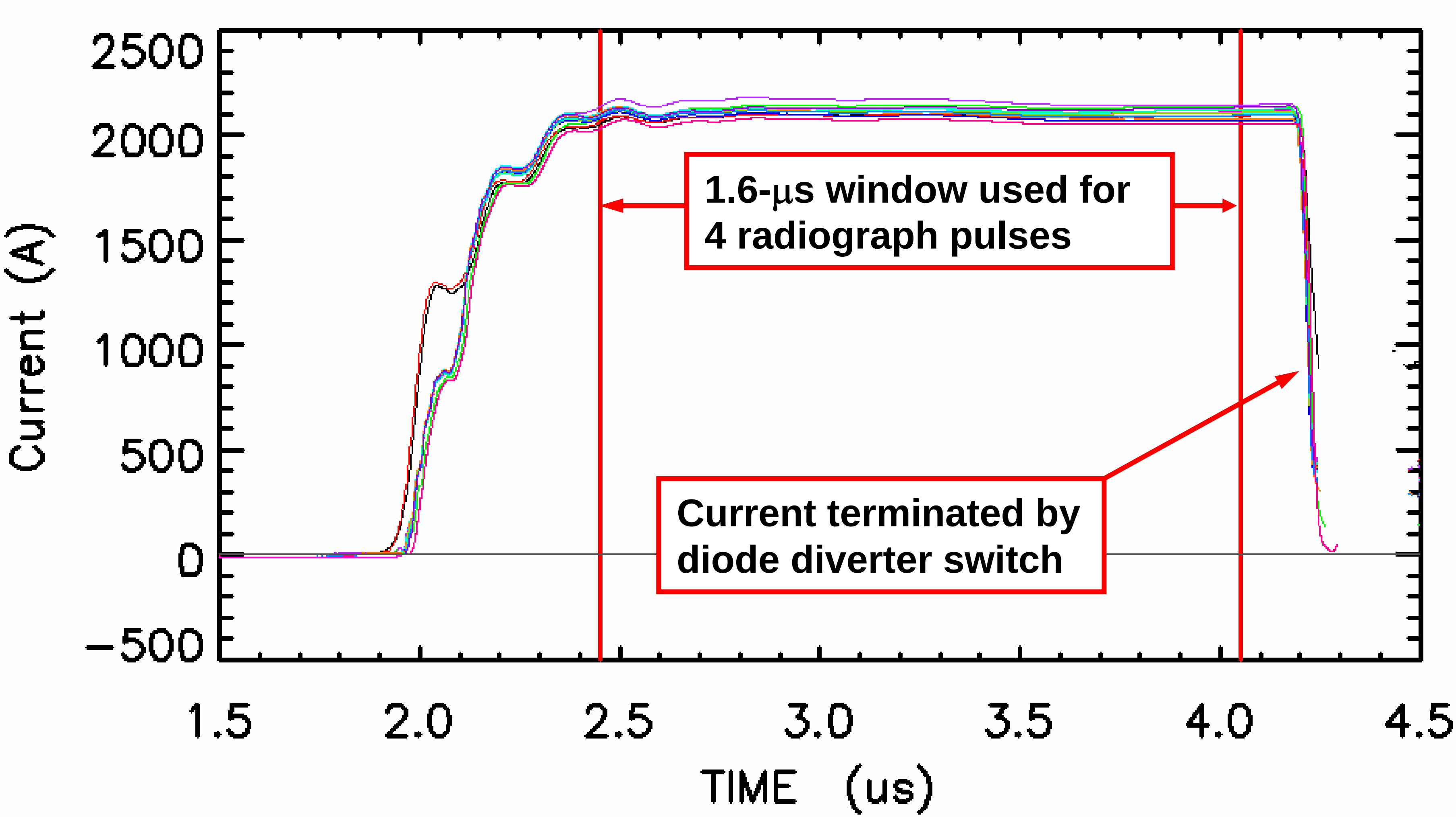
The 2-kA electron beam is transported through the accelerator without losses.



Overlay of BPM Measurements

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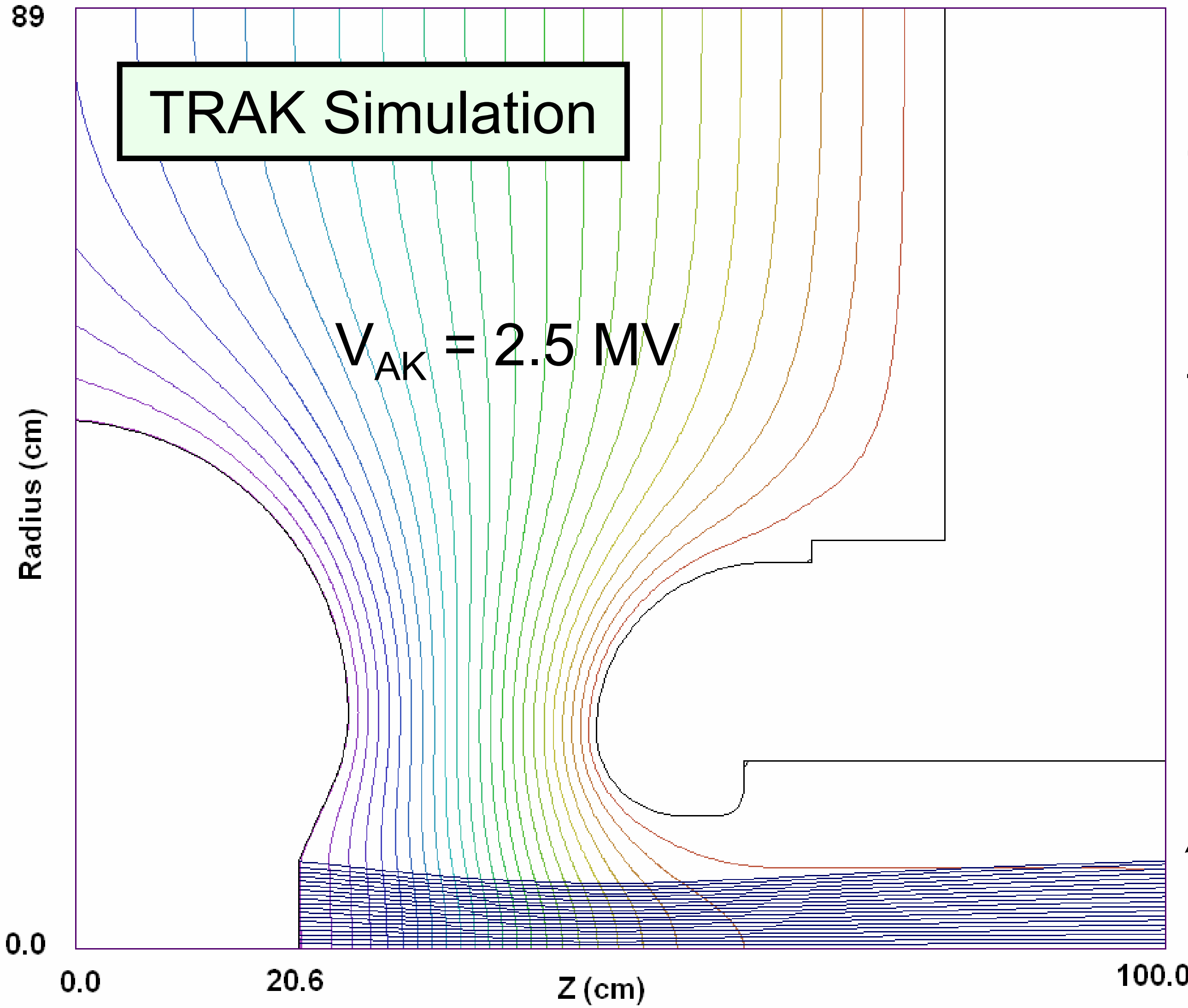
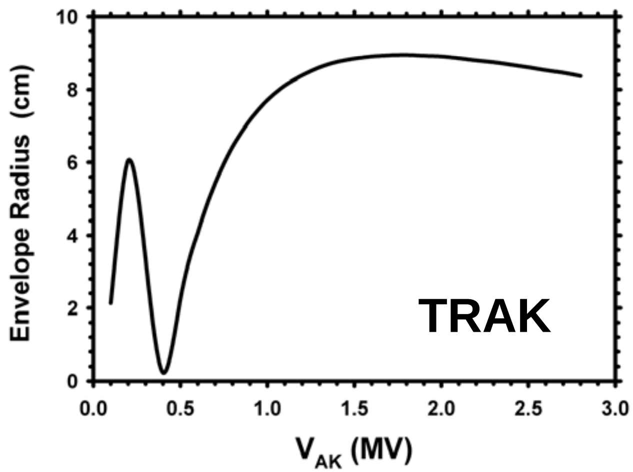
The initial conditions for the envelope equations (radius and convergence) are obtained from PIC (LSP) and gun-design (TRAK) simulations of the diode.



TRAK and LSP also provide current and emittance as functions of V_{AK}

r_0 and r_0' as functions of V_{AK}

Initial conditions as functions of diode voltage from simulations were converted to initial conditions as functions of time using measured diode waveforms.



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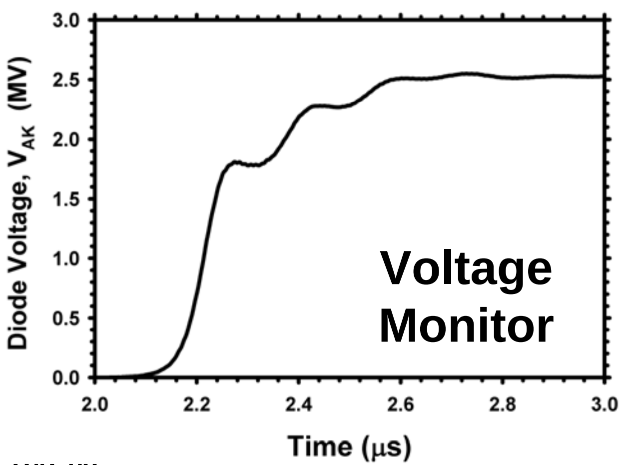

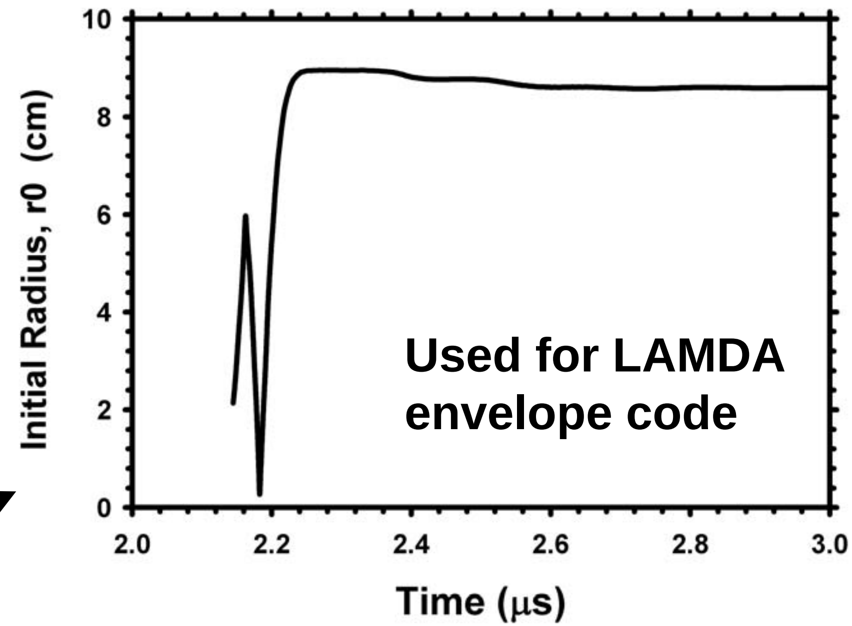

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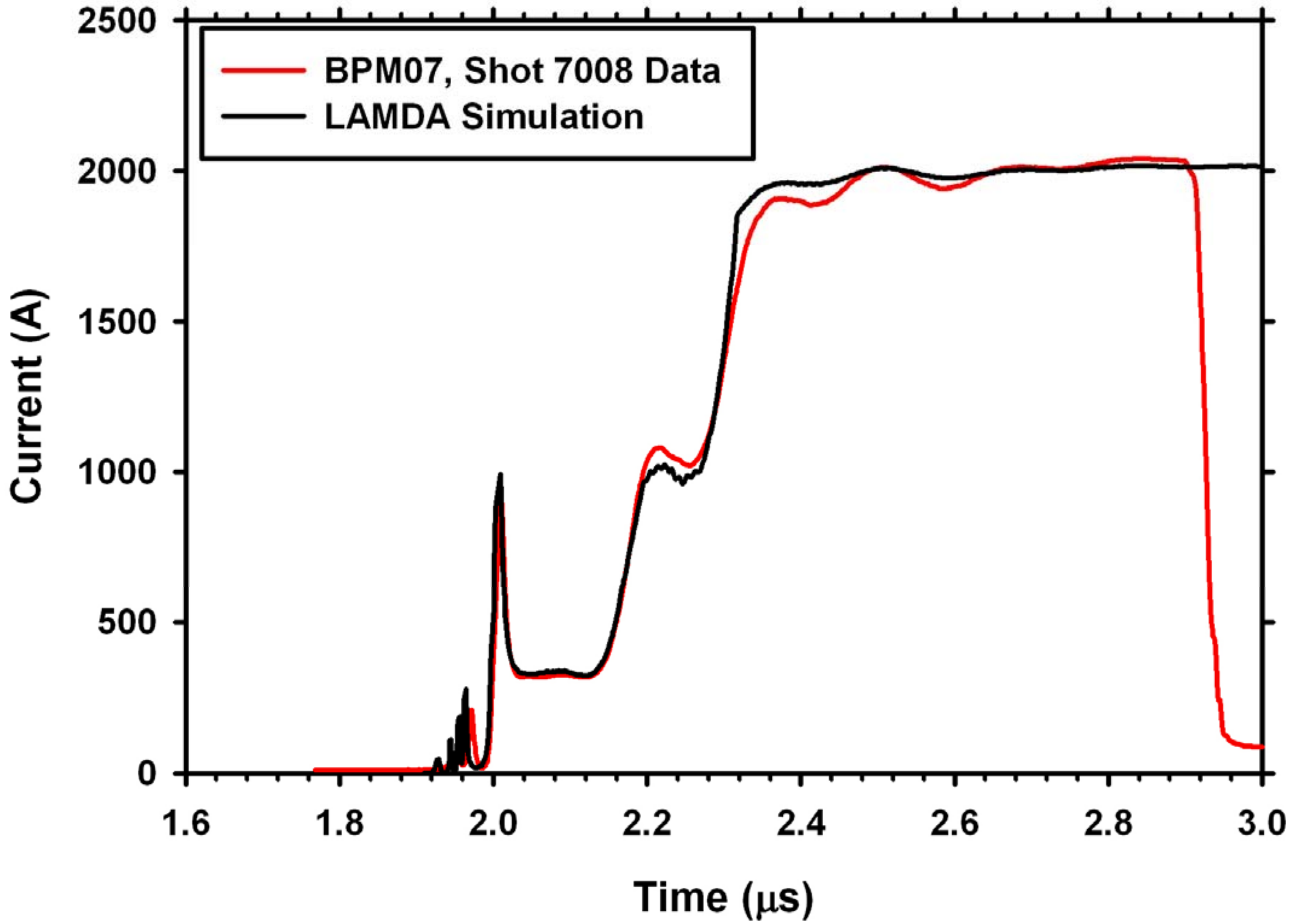
The TRAK/LSP initial conditions were validated by retuning the injector output to scrape off most of the beam head.



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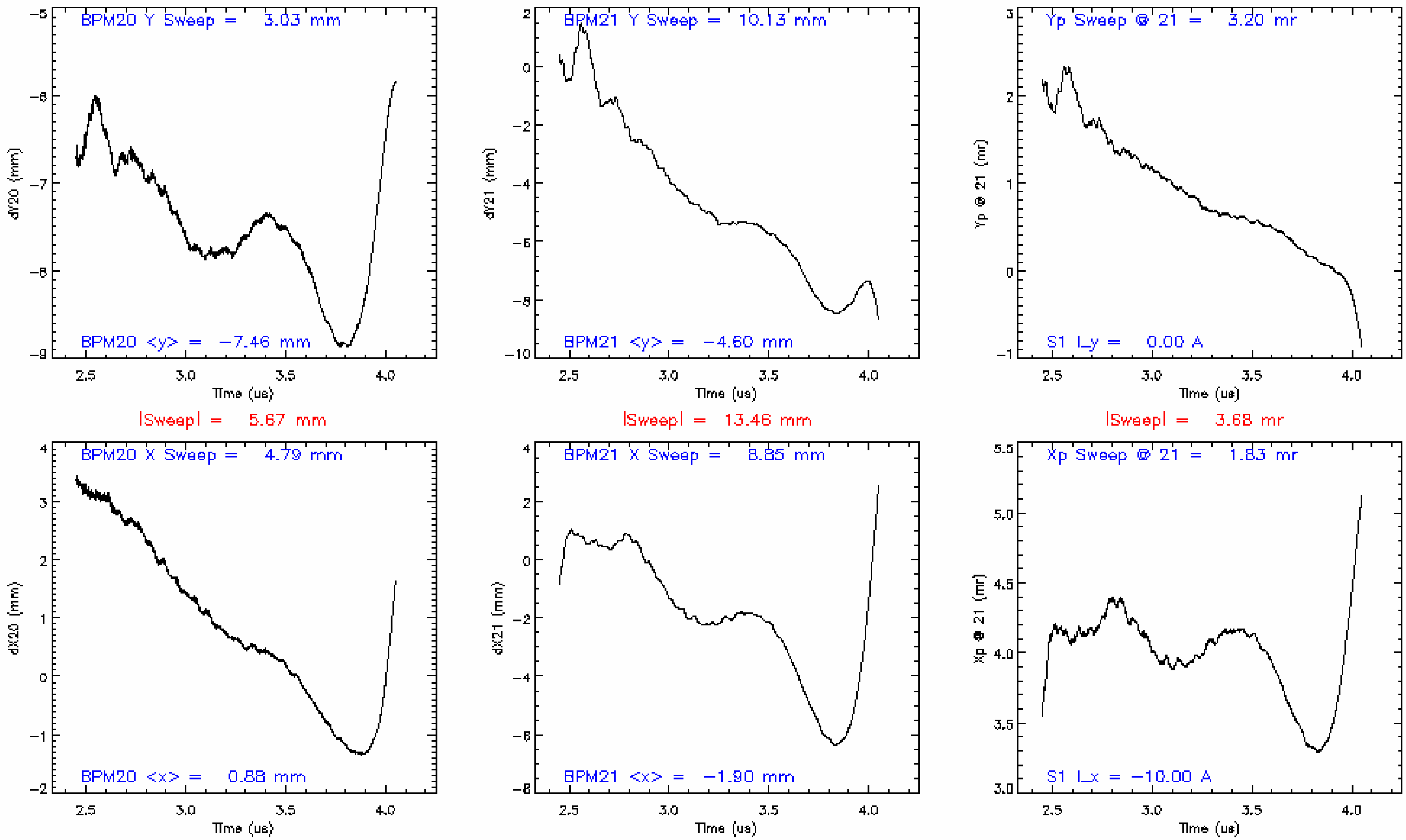
A slow, energy-dependent sweep dominated the beam motion at the LIA exit.

Exit 3-m from Exit

Y(mm) θ_y (mr)

X(mm) θ_x (mr)



← 1.6 μs →

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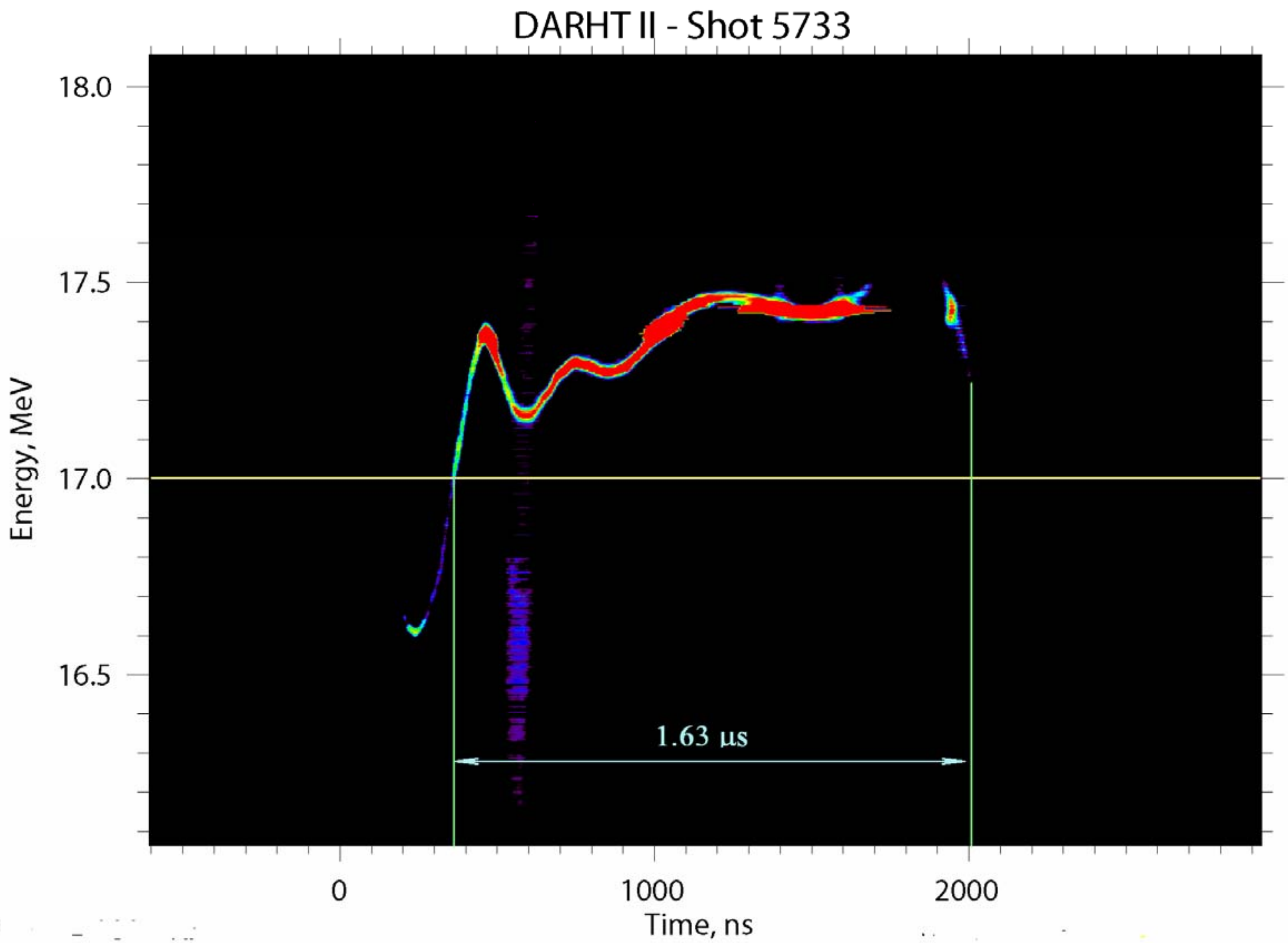
The sweep correlates with the small variation of the > 17 MeV beam energy measured with a magnetic spectrometer.



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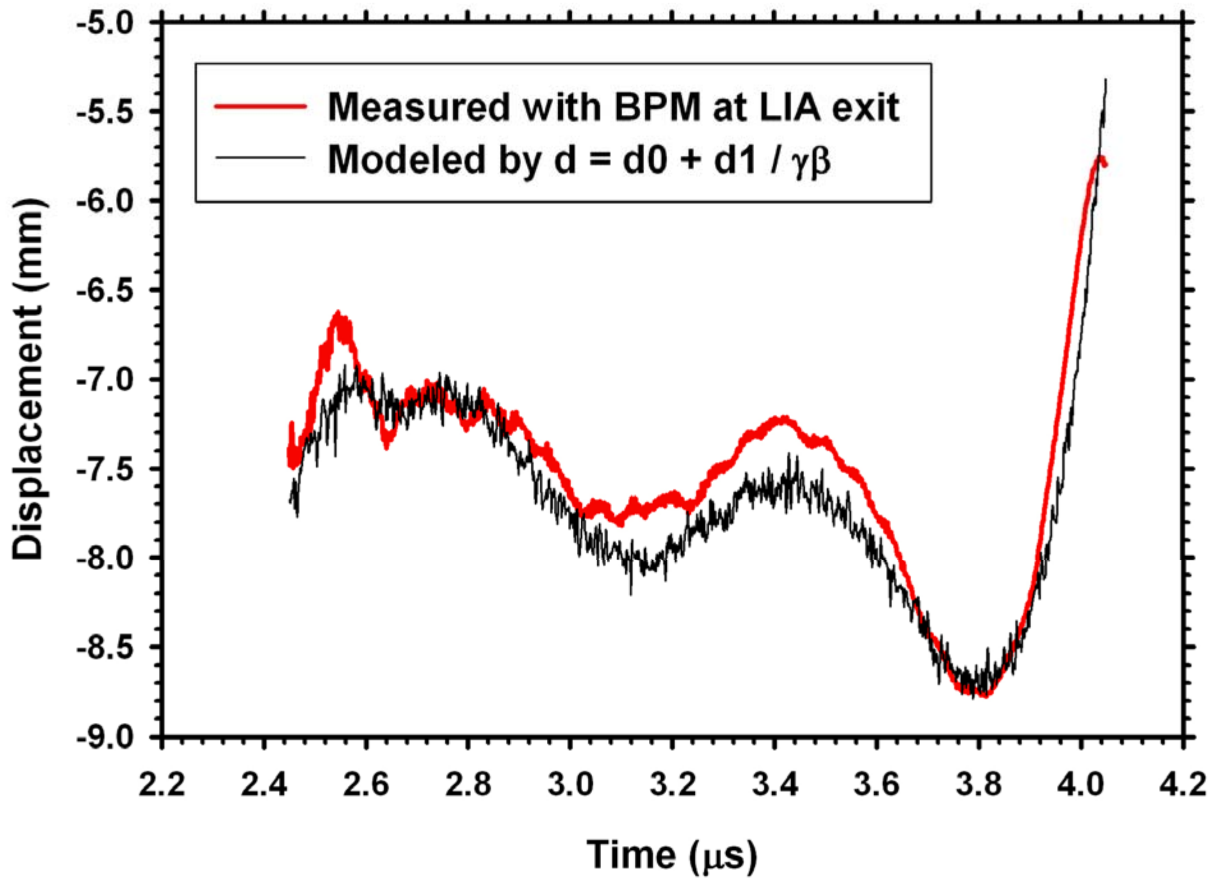
The strong energy dependence suggests that the sweep is an interaction with misalignment produced dipoles, like the corkscrew present in earlier LIAs.



This sweep is unlikely the result of the resistive-wall instability growth, which is independent of energy in a solenoidal focusing field.

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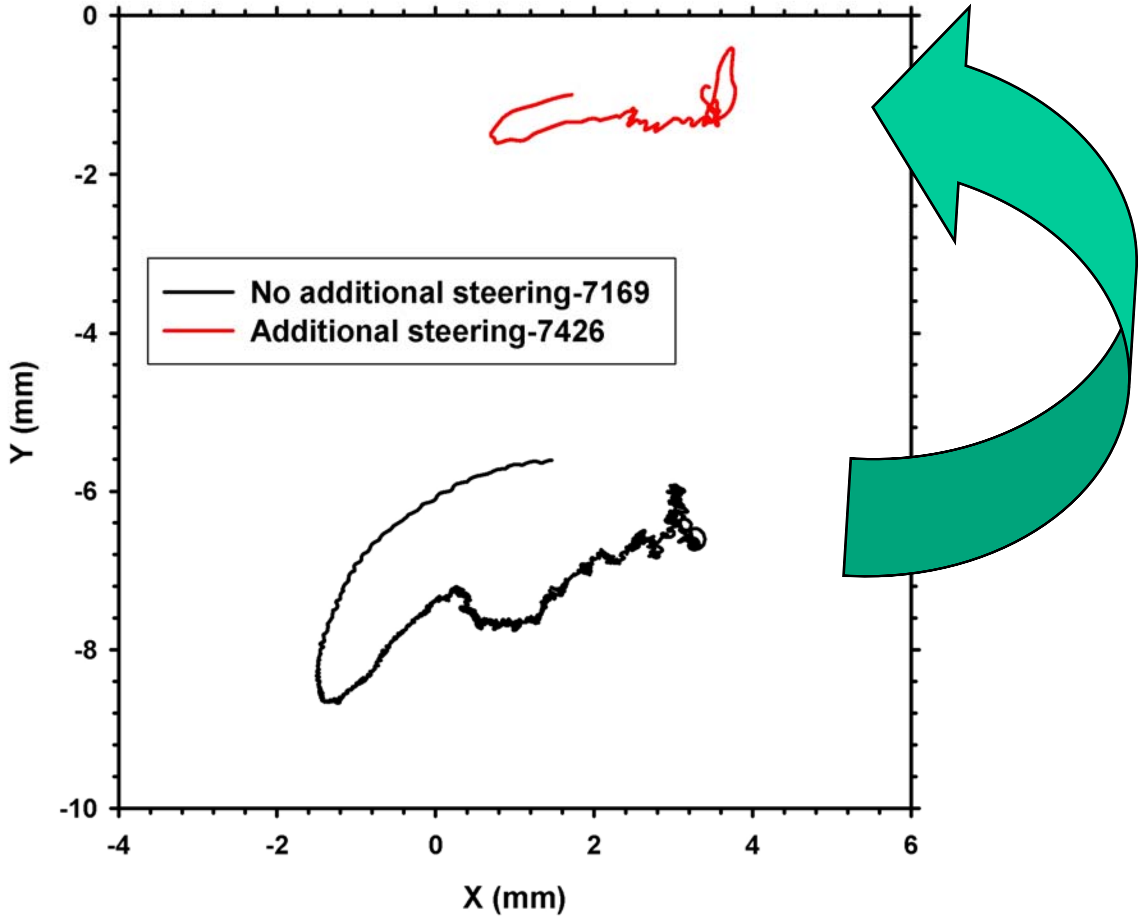
We demonstrated that we could reduce the sweep by using steering dipoles to center beam through the accelerator.



Beam centered through accelerator

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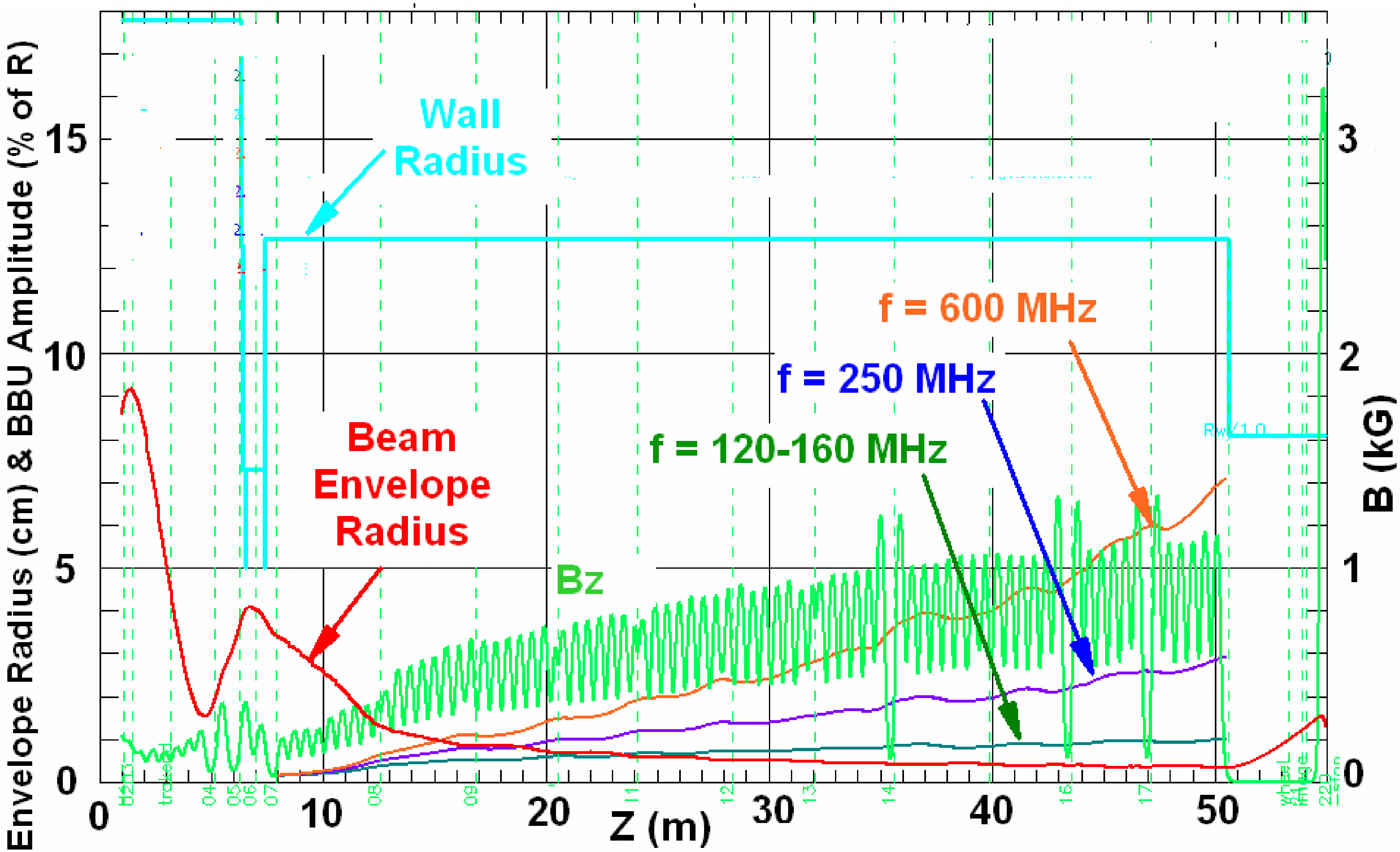
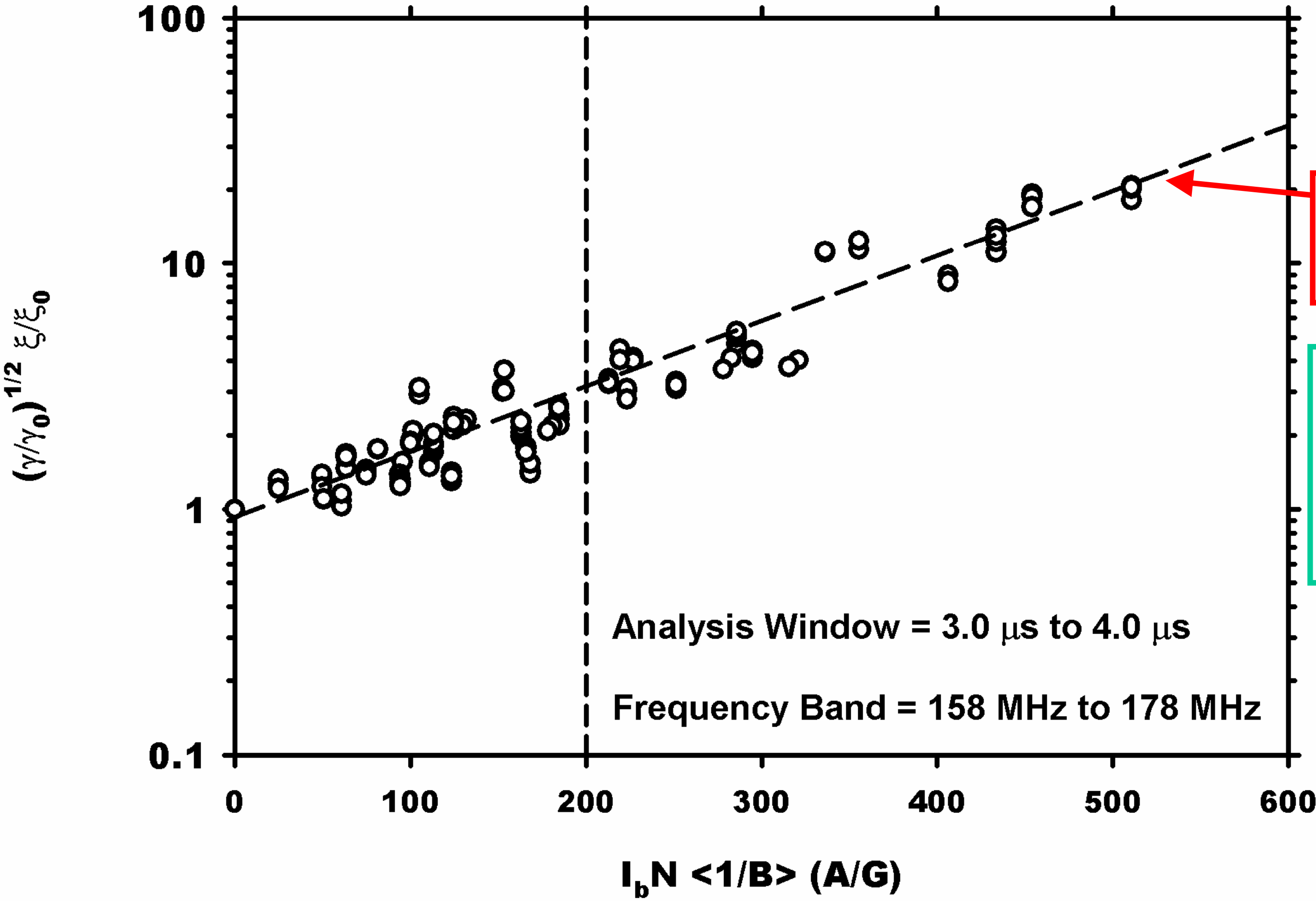
The magnetic focusing tune of the present tune is strong enough to suppress the beam-breakup (BBU) instability to less than 10% of the beam radius.



In an earlier experiment with the original cells (2005), we confirmed the theoretical scaling of BBU growth.



Best Fit to data is with $Z_\perp$ = 184 ± 6 Ω/m

Direct RF measurement of $Z_\perp$ in a cell :
157 Ω/m average over 158 – 178 MHz band

Carl Ekdahl, et al., *IEEE Trans. Plasma. Sci. Vol. 34*, 2006, pp. 460-466

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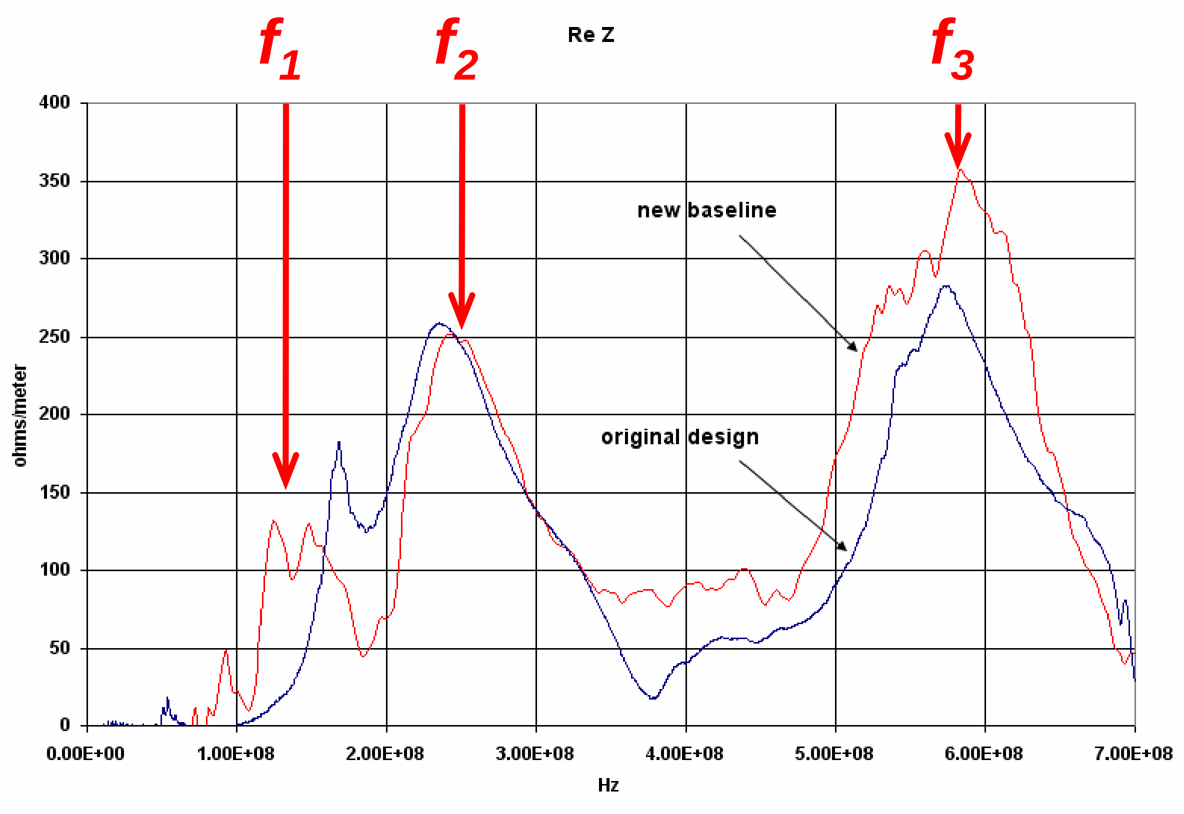
The transverse impedance of the upgraded cells is only slightly different than the legacy cells, so BBU growth was expected to be similar to previous measurements.

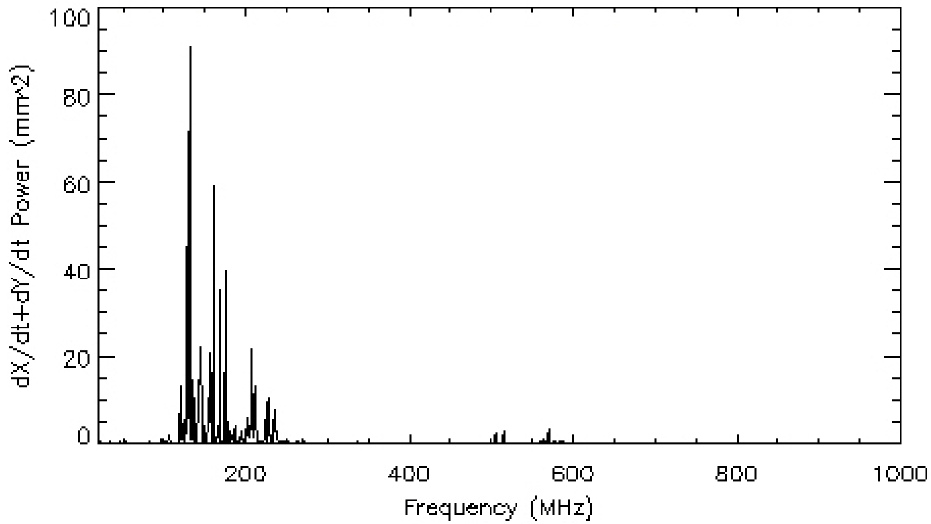
- **In the high-current, strongly-focused, accelerated-beam regime the BBU rapidly grows to a saturated amplitude:**

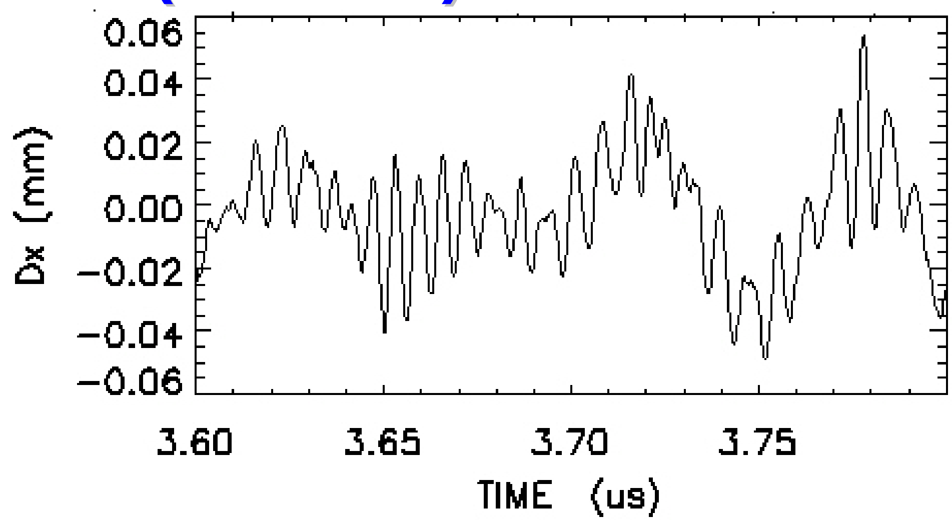
$$\xi/\xi_0 = (\gamma_0/\gamma)^{1/2} e^{\Gamma} \quad \textbf{with} \quad \Gamma = I_b N_G Z_\perp \langle 1/B_Z \rangle / 3E4$$

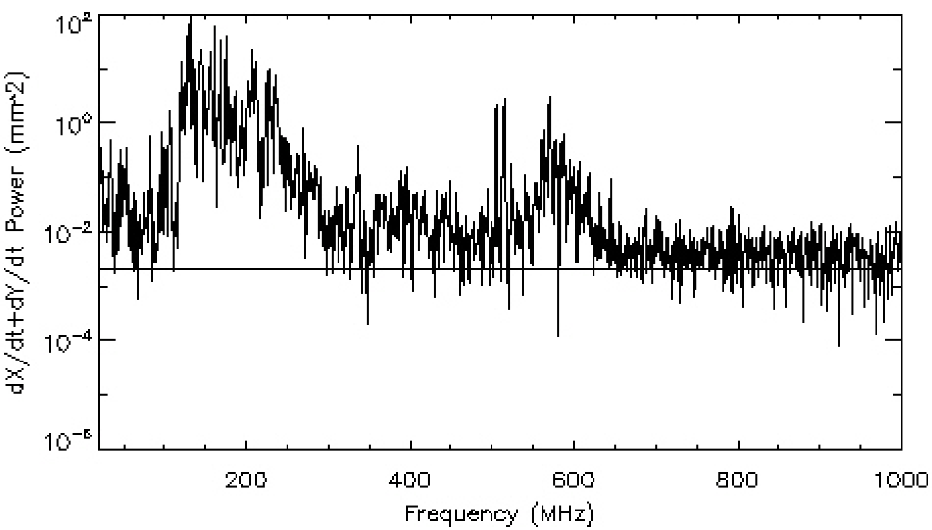
- ***The transverse impedance, $Z_\perp$, of individual cells was measured using RF techniques at LBNL in both the original and the new cells.***

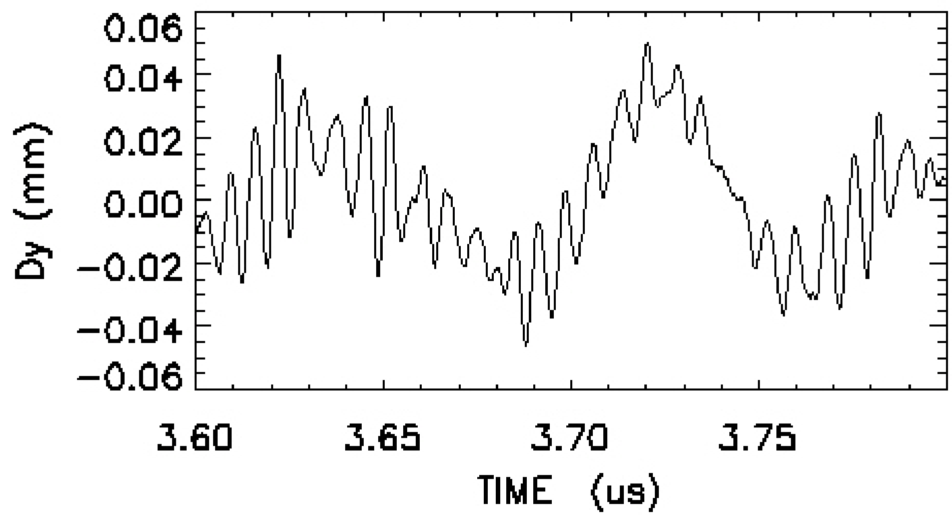


We observe BBU at all of the resonant frequencies of the cells, as well as low frequency oscillations at characteristic of ion hose. Both amplitudes are much smaller than the beam radius (r > 3-mm).









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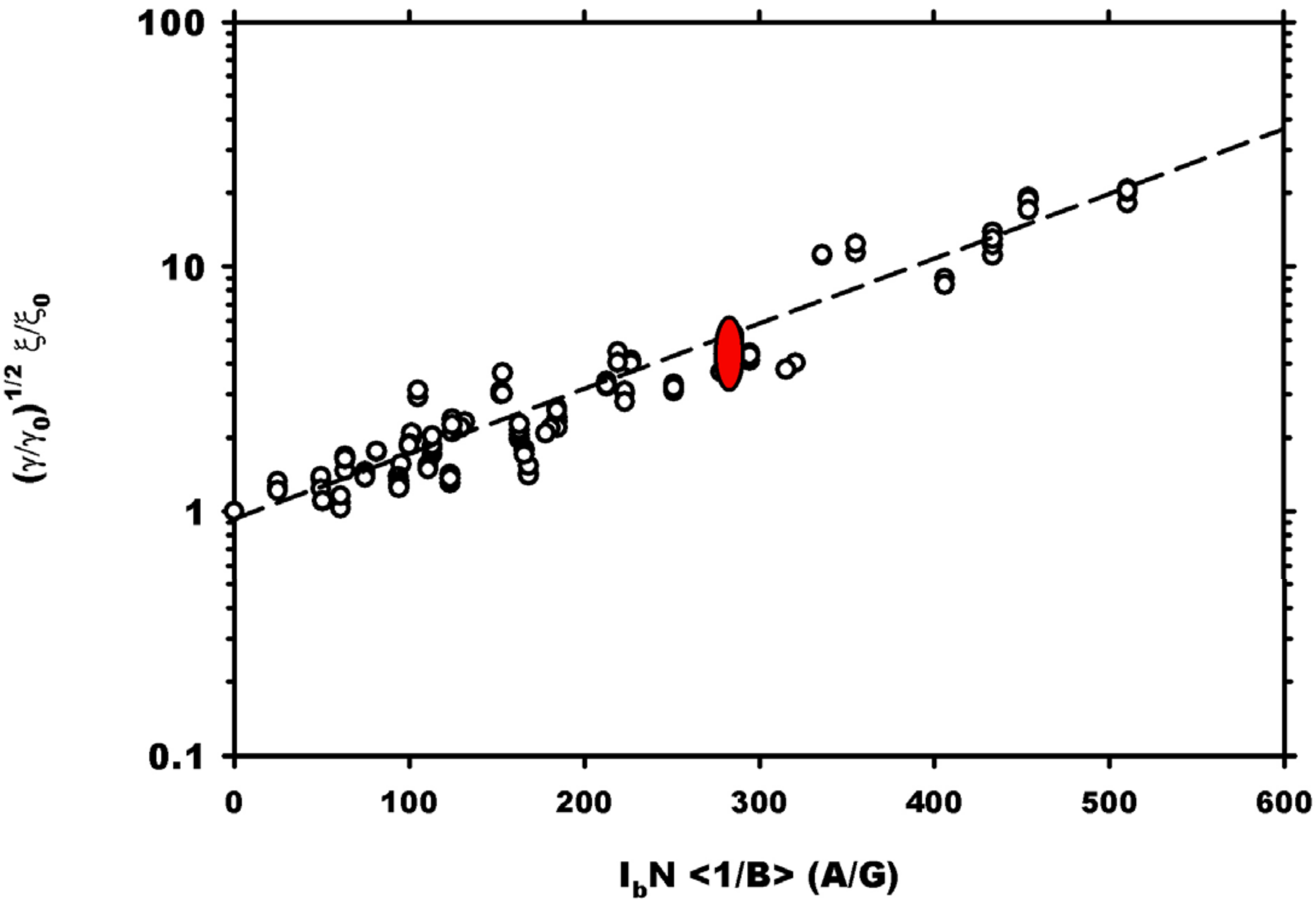
The observed BBU gain is within experimental uncertainty of previous observations.



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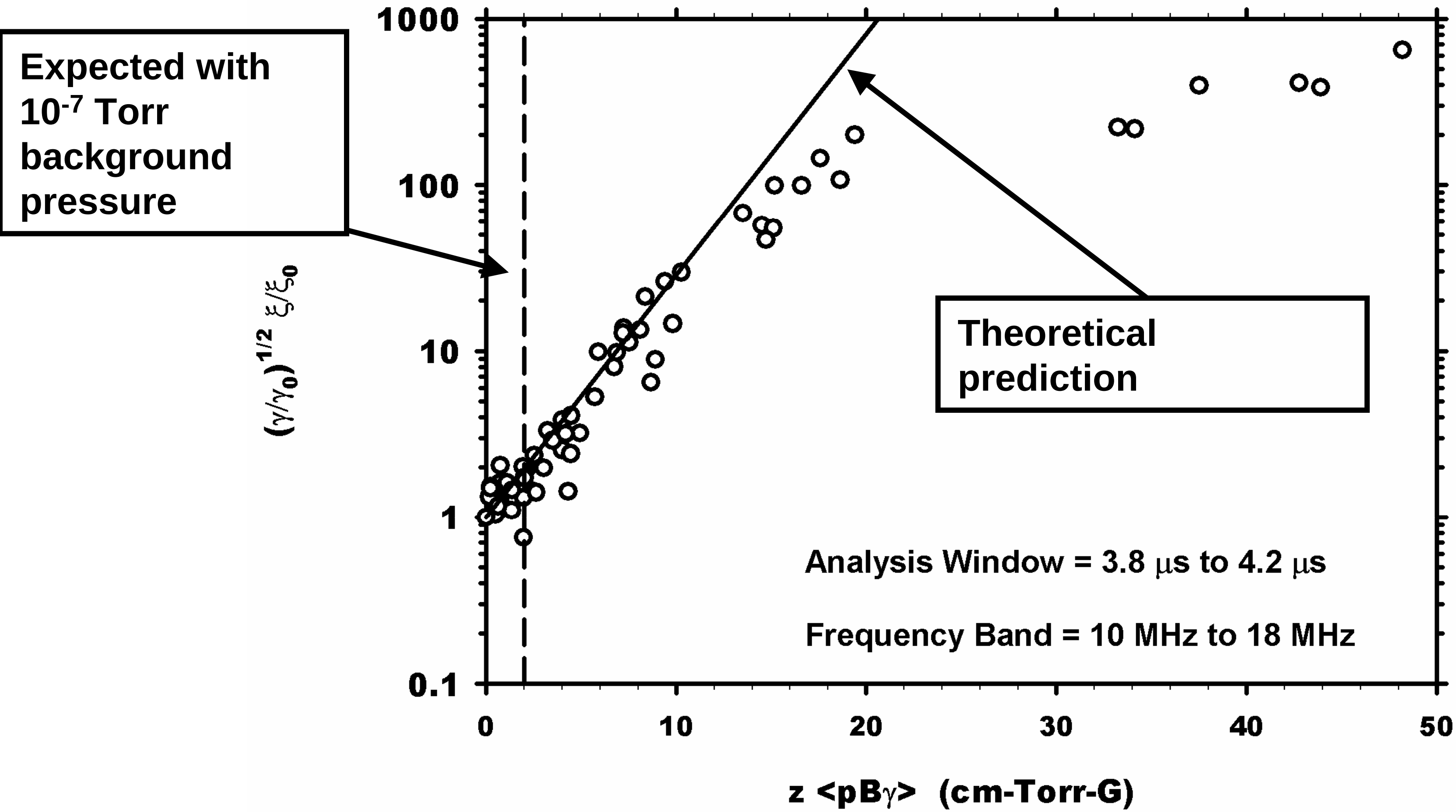
We attribute the low-frequency motion to interaction with gas liberated in the beam-head cleanup zone (BCUZ) by beam scraping on the apertures.

- The ion-hose instability is caused by the interaction of the beam with a channel of ionized gas.

- Maximum Growth Factor; $\Gamma \sim I_b \ \tau_{pulse} \ L \ \langle p/(Ba^2) \rangle$
  - (Growth saturates just like the BBU)

- Because of the strong dependence on τ_{pulse} this is only a problem for long-pulse beams like DARHT-II
- We maintain a hard vacuum to suppress the ion-hose.
- *However, gas liberated by beam scraping on apertures like those in the BCUZ can promote ion hose.*

In an our earlier (2005) stability experiments we confirmed the theoretical scaling of ion-hose growth. We observed an un-predicted further saturation at high magnetic focusing fields.



Carl Ekdahl, et al., *IEEE Trans. Plasma. Sci. Vol. 34*, 2006, pp. 460-466

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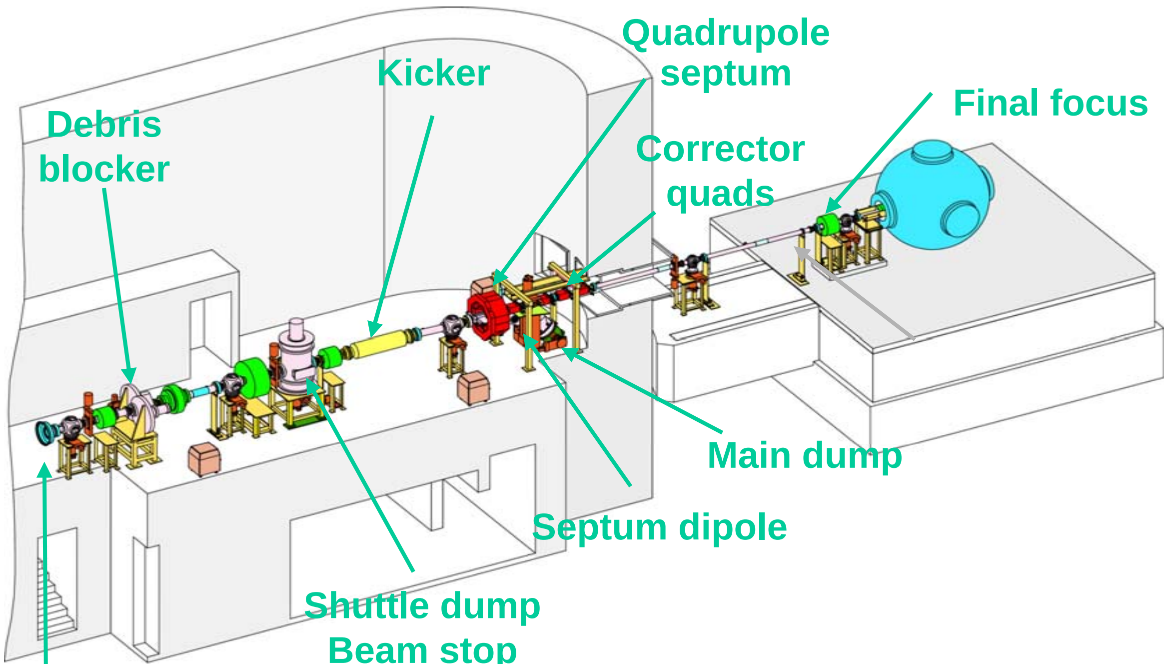
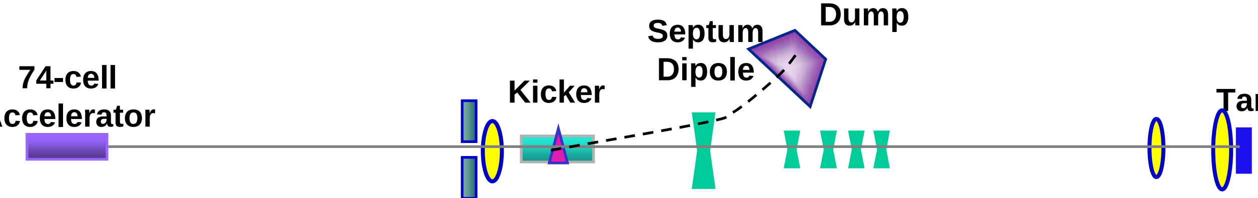
After exiting the accelerator the beam is sliced into short pulses by the kicker, and these are transported to the final focus.





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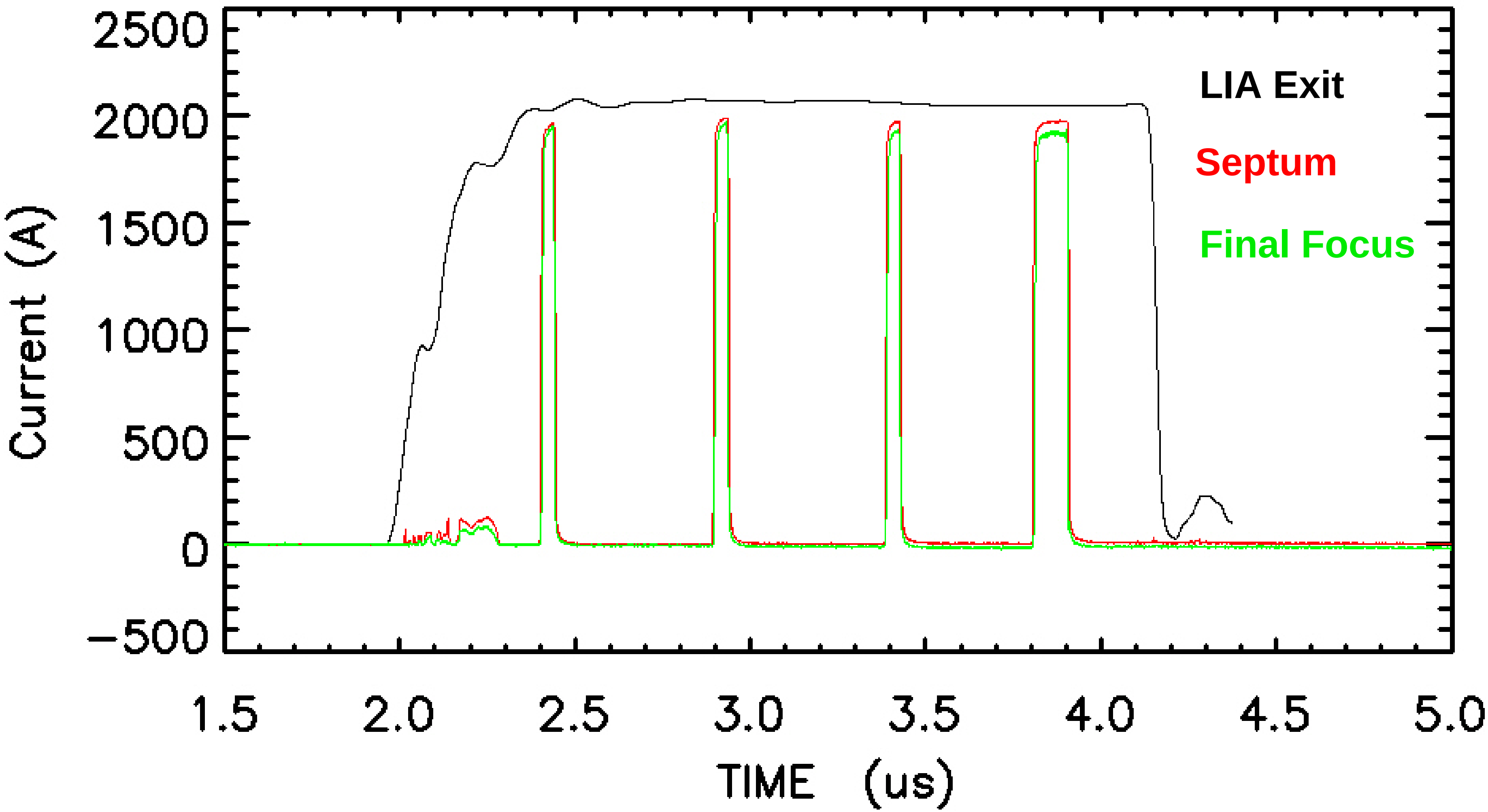
95% of the kicked-pulse current was transported to the final focus to form the 4 radiography-source spots



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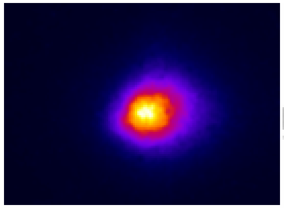
All four Axis-II radiographic source spots are equivalent to the Axis-I spot.

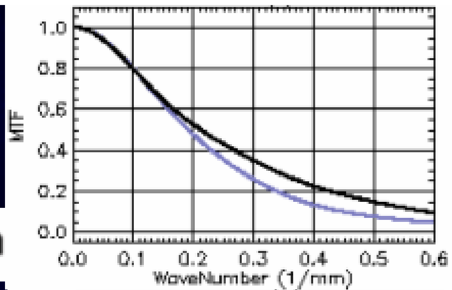
Pulse

1

170 Rad

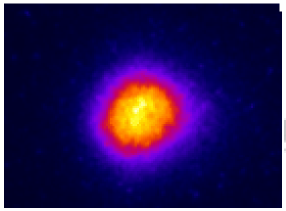


d_{LANL} = 1.50 ±0.20 mm

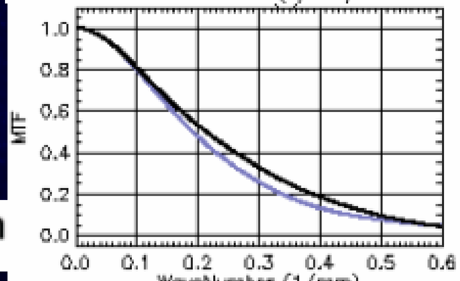


2

185 Rad

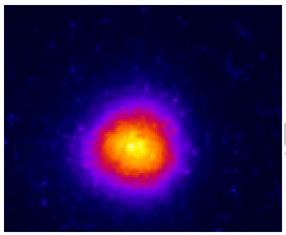


d_{LANL} = 1.78 ±0.14 mm

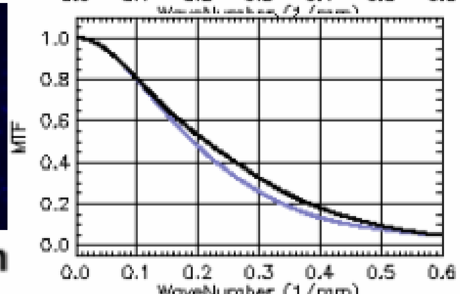


3

170 Rad

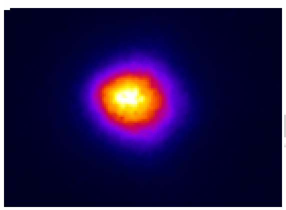


d_{LANL} = 1.89 ±0.05 mm

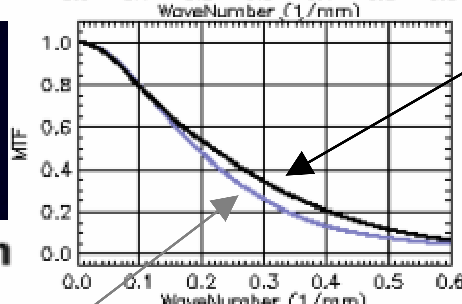


4

445 Rad

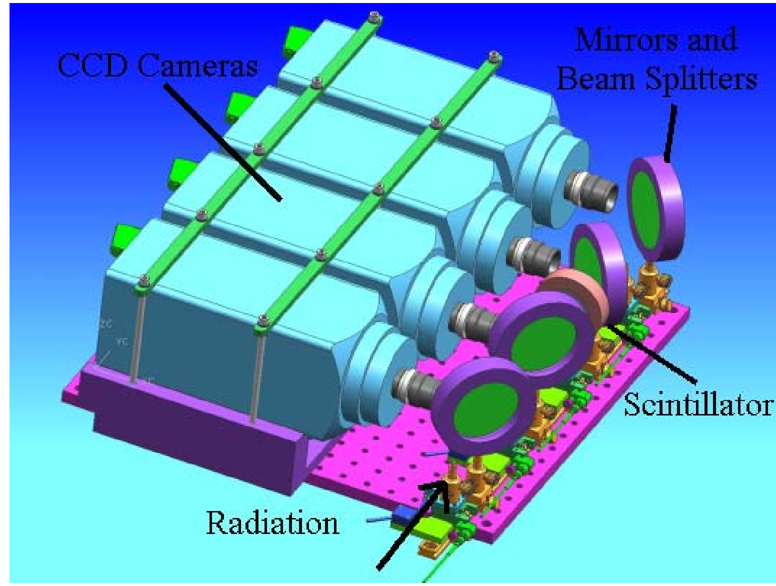


d_{LANL} = 1.63 ±0.13 mm



Axis-II

Axis-I



Pinhole images of Axis-I and Axis-II spots were measured with the same time-resolved camera system (TRSS)

d_{LANL} **= 1.85±0.1 mm on Axis-I**

Comparison of <u>M</u>odulation <u>T</u>ransfer <u>F</u>unctions

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Summary

- **DARHT-II has been operated at its full design energy (17 MeV), current (2 kA), and flat-top pulselength (1.6 μs).**

- **Beam motion from several sources is understood, acceptable, and can be further reduced if required**
  - **Sweep can be significantly reduced by additional steering**
  - **Ion hose can be reduced by minimizing beam scrape in the BCUZ**
  - **BBU is acceptable, and could be further reduced if need be by increasing the solenoidal magnetic focusing field**

- **Four kicked pulses have been successfully transported to the final focus providing excellent radiography spots.**