Recent Progress in Booster Study

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Fermilab
June 12, 2003

Presentation to the MINOS Collaboration Meeting
June 12-13, 2003, Fermilab

Booster Study Group

- Beams Division
  - Beam Physics Department
  - Proton Source Department
  - Operations Department
  - External Beams Department
  - Mechanical Support Department
  - Electrical Support Department
- Technical Division
- Computer Division

Weekly Thursday meeting at 1:30 pm in the Huddle

Web site: http://www-bd.fnal.gov/pdriver/booster/

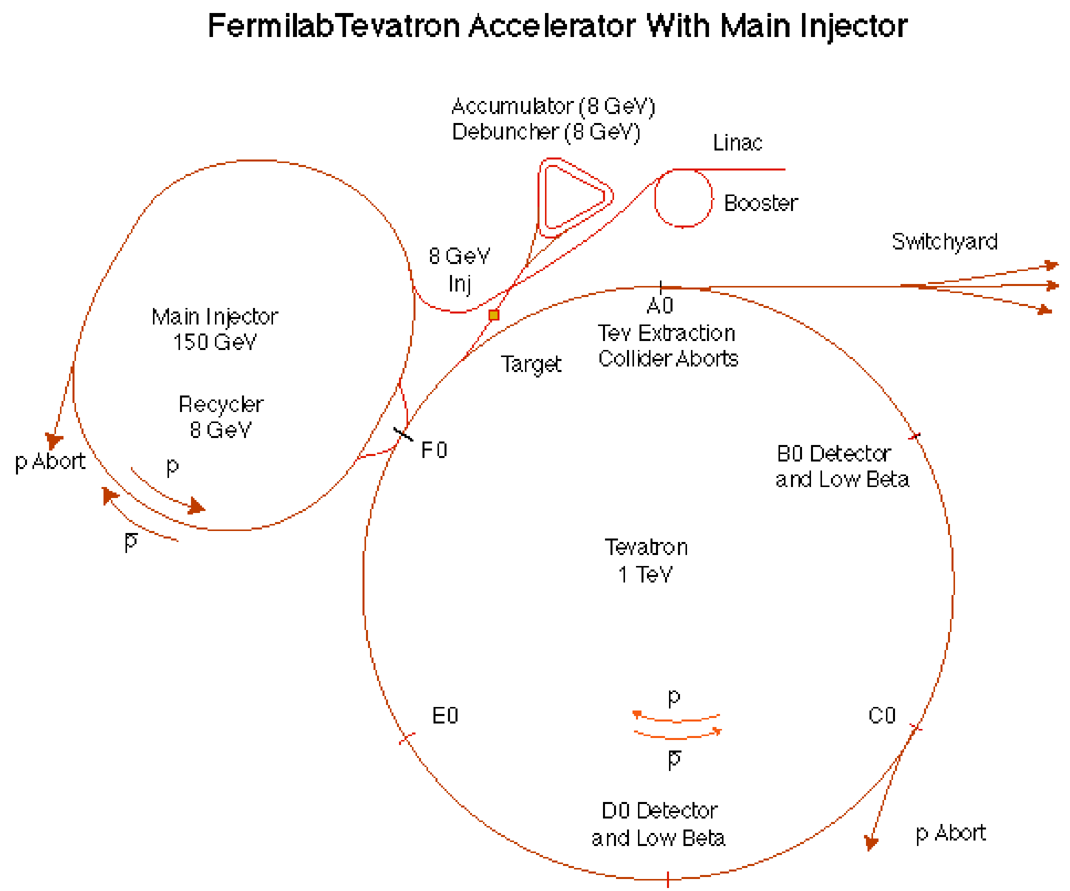
Study Goals

- To establish a realistic and useful Booster model
  - Inherited a bare FODO lattice model
  - Now it includes the correction package (steering magnets and trim quads), sextupoles, octupoles, gamma-t jump quads, injection orbit bump, doglegs, septa, BEX magnet, etc.
- To understand the beam loss and emittance blowup mechanism, and the roles of space charge and other associated effects
- To carry out both simulations and measurements
- To investigate possible measures for performance improvement

Outline of the Talk

- Booster – the bottleneck
- The dogleg effect
- Space charge study
- The first 3 milliseconds in the Booster
- Chromaticity modeling
- Power supply experiments at E4R

Fermilab Accelerator Complex

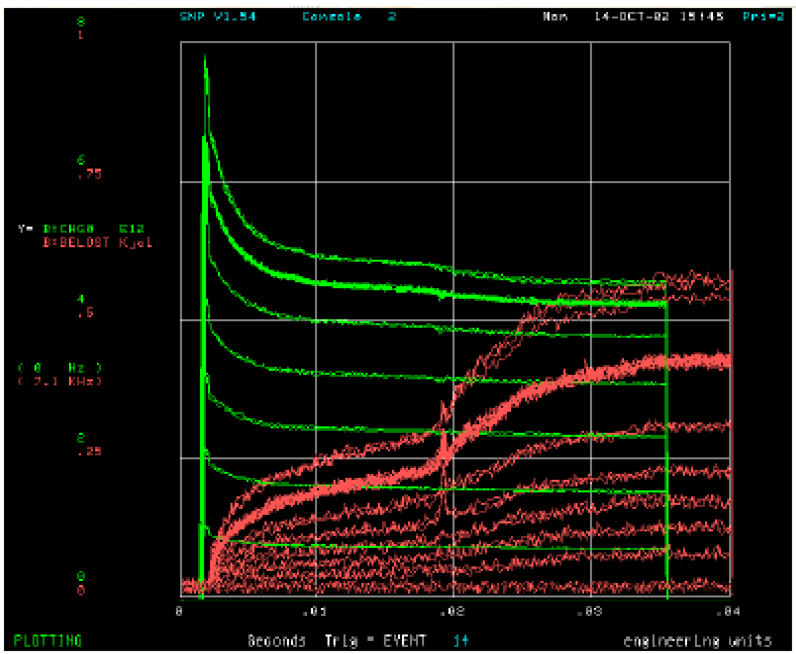


Booster – the Bottleneck

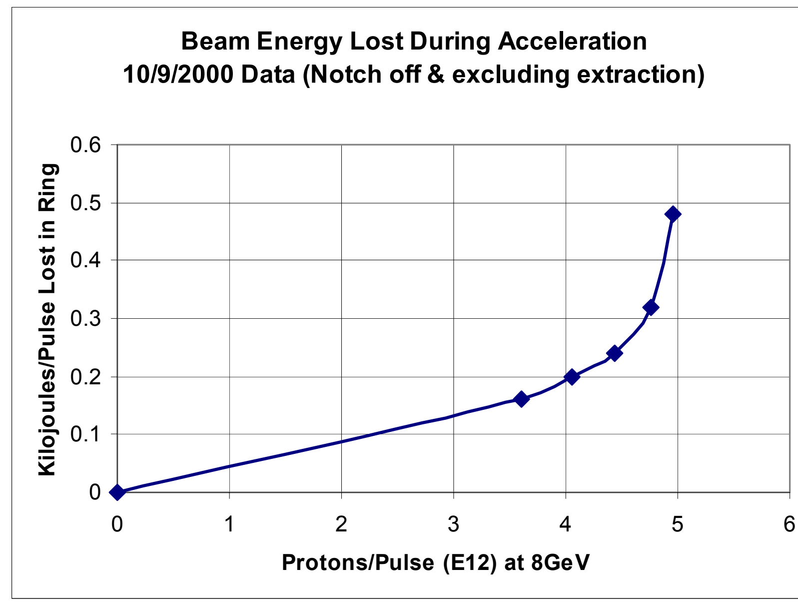
- The Booster is a 30 years old machine and has never been upgraded.
- The 400-MeV Linac can provide 25e12 particles per Booster cycle.
- The 120-GeV Main Injector can accept 25e12 protons per Booster cycle.
- However, the 8-GeV Booster can only deliver 5e12 particles per cycle.

Booster Beam Loss

(courtesy R. Webber)



For 0, 2, 4, 6, 8, 10, 12, 14 Injected Turns



How Do Particles Get Lost?

- The Booster cycle is 33.3 ms
- The first 3 ms – big loss (30%): ⇐ **This talk**
  - The dogleg effect – reducing machine acceptance
  - Space charge – diluting beam emittance
- Transition crossing: several percent loss
- After transition - coupled bunch instability: a few percent loss

The Dogleg Effect

- The doglegs are installed to increase the aperture at the extraction septum at injection when the beam has the largest size.
- These are vertical bends. Their edge focusing greatly perturbs the lattice function:

  $\beta(x)_{max}$: 33m $\rightarrow$ 47m

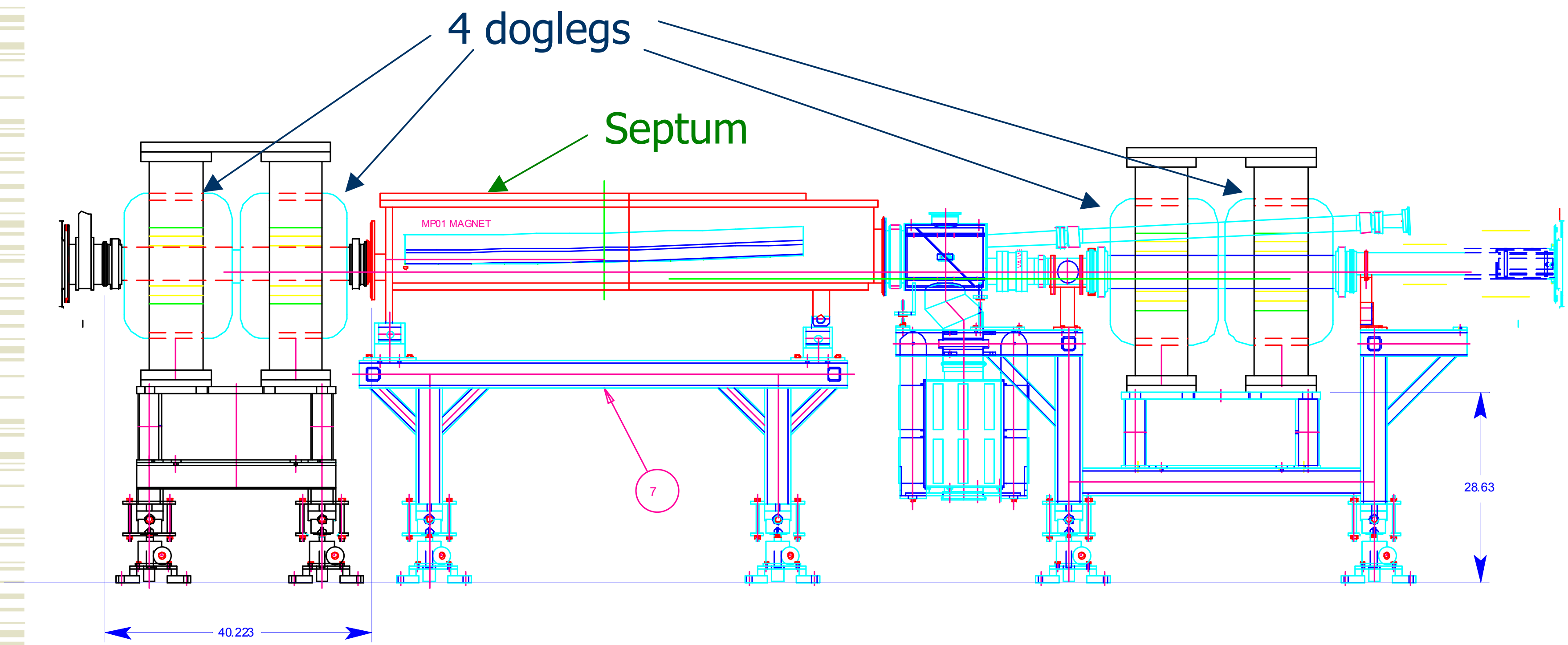
  $D(x)_{max}$: 3.2m $\rightarrow$ 6m

  acceptance: $16\pi \rightarrow 8\pi$, reduced by 50%

- Beam measurement agreed with the model.
- Removal of one of the two doglegs led to immediate improvement:
  - Beam loss cut to half
  - A milestone of the MiniBooNE experiment reached (5e16 protons per hour)
  - $\rightarrow$ champagne celebration

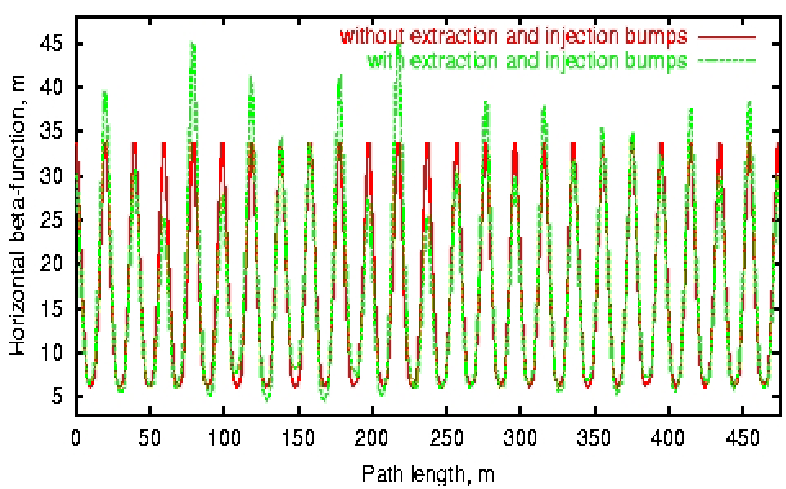
Dogleg Layout

(courtesy J. Lackey)

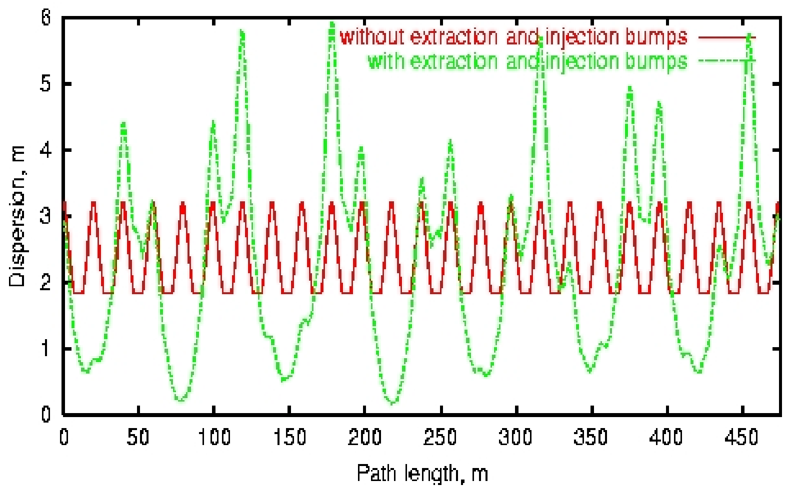


Dogleg Perturbation on Linear Lattice: MAD Simulation

(courtesy A. Drozhdin)



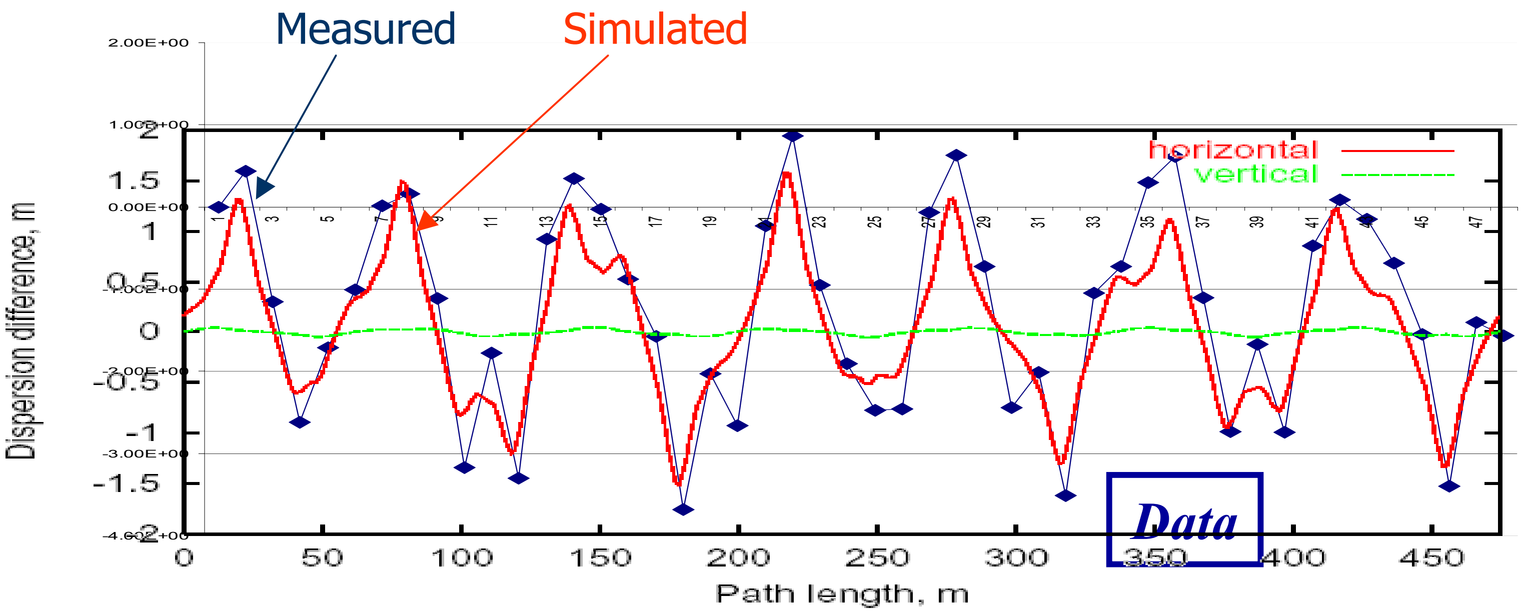
Horizontal beta-function



Horizontal dispersion

Dogleg Perturbation on Dispersion: Simulation *vs.* Measurement

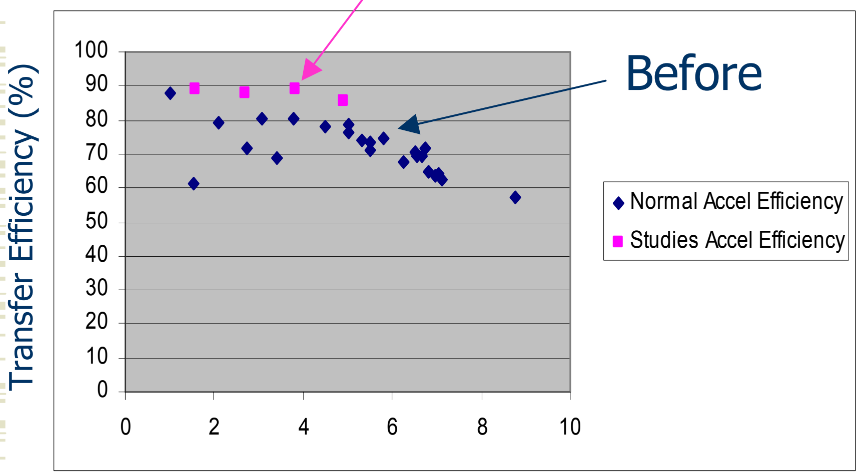
(courtesy E. McCrory)



Beam Experiment: Removing One of the Two Doglegs

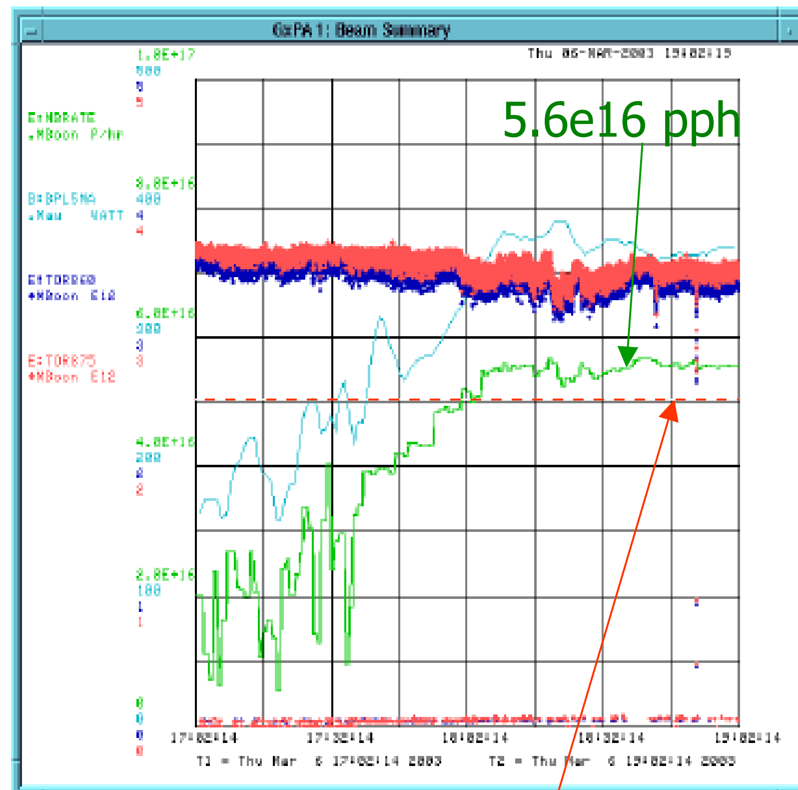
After, beam loss cut by half

Before



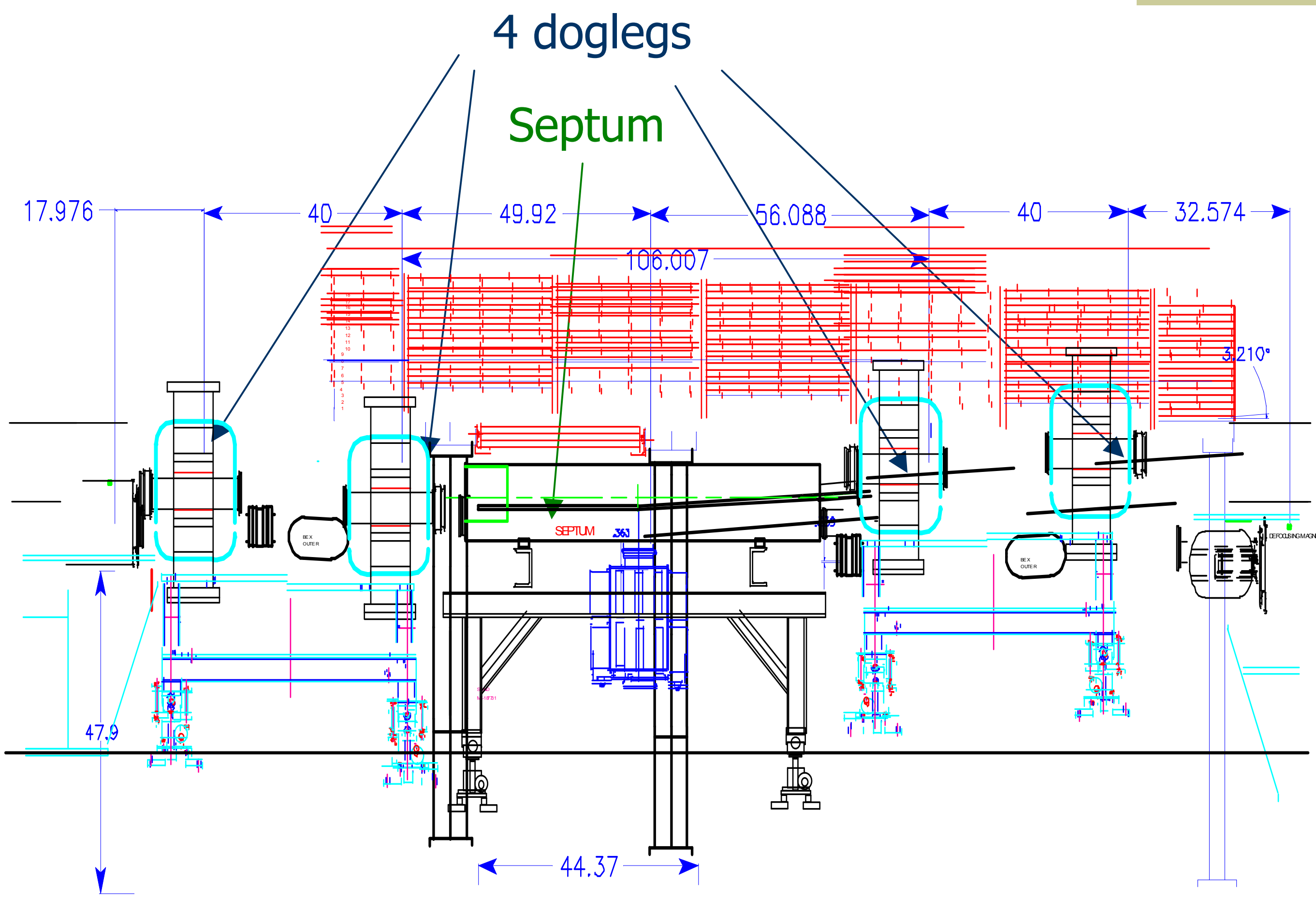
Injected beam intensity (x 10^{12})

(Courtesy J. Lackey)



MiniBooNE milestone: 5e16 pph

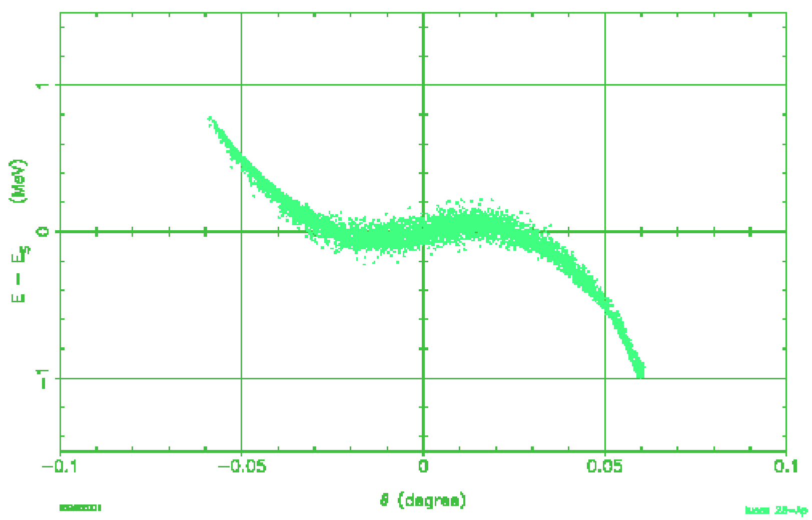
New Dogleg Layout
(courtesy J. Lackey)



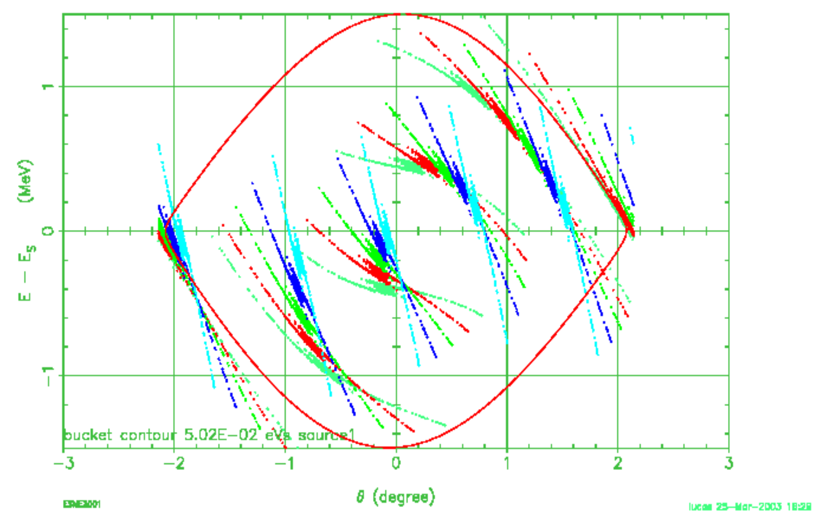
Space Charge Study

- Simulation codes
  - ESME (P. Lucas, J. MacLachlan)
  - ORBIT (F. Ostiguy, W. Chou)
  - Synergia (P. Spentzouris, J. Amundson)
- Tune footprint
- Emittance blowup during and after the injection
- Beam measurement

Linac 805 MHz Microbunches
(ESME, courtesy P. Lucas)

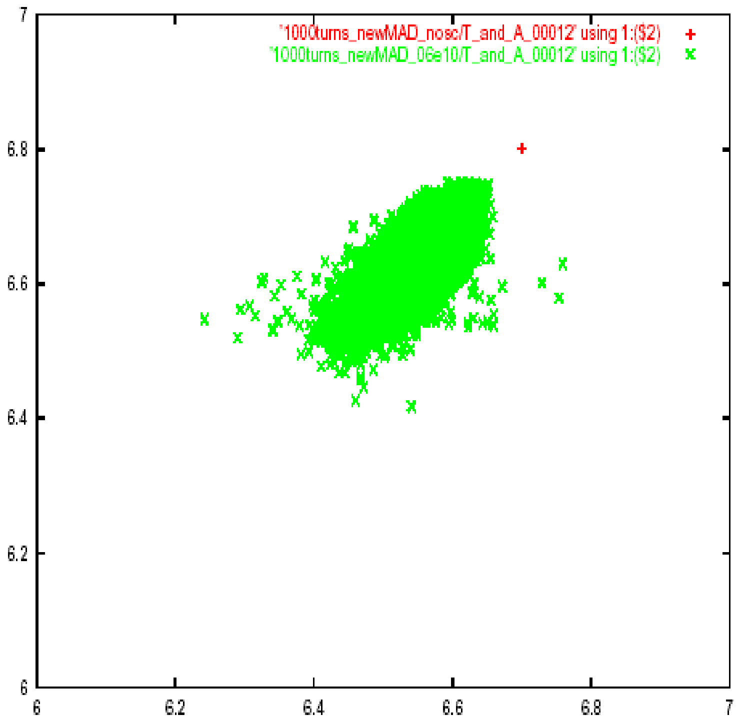


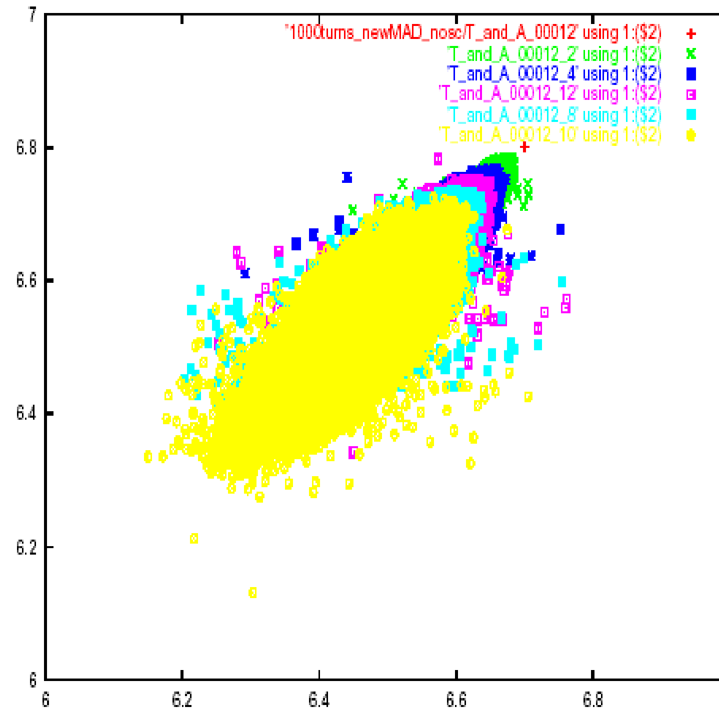
One microbunch with $\Delta p/p = \pm 0.13\%$



Multiturn injection

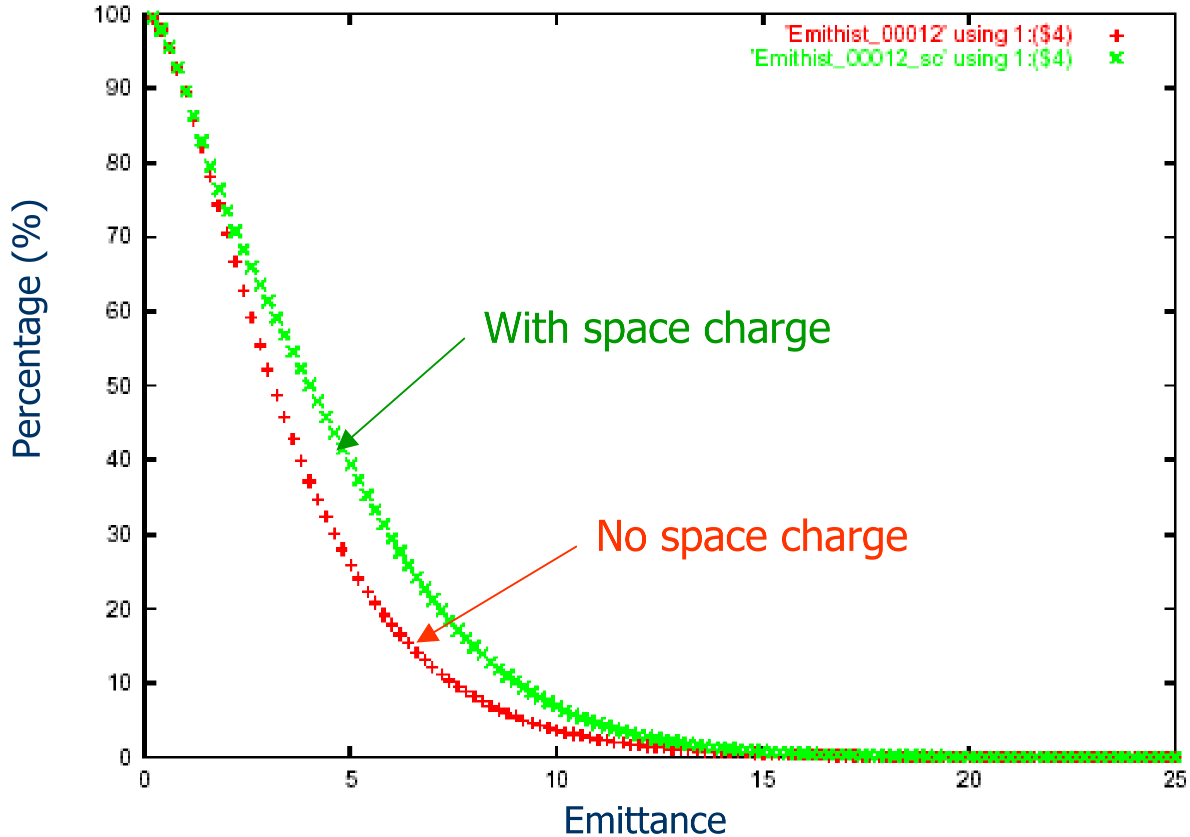
Tune Footprint
(ORBIT, varying beam intensity)





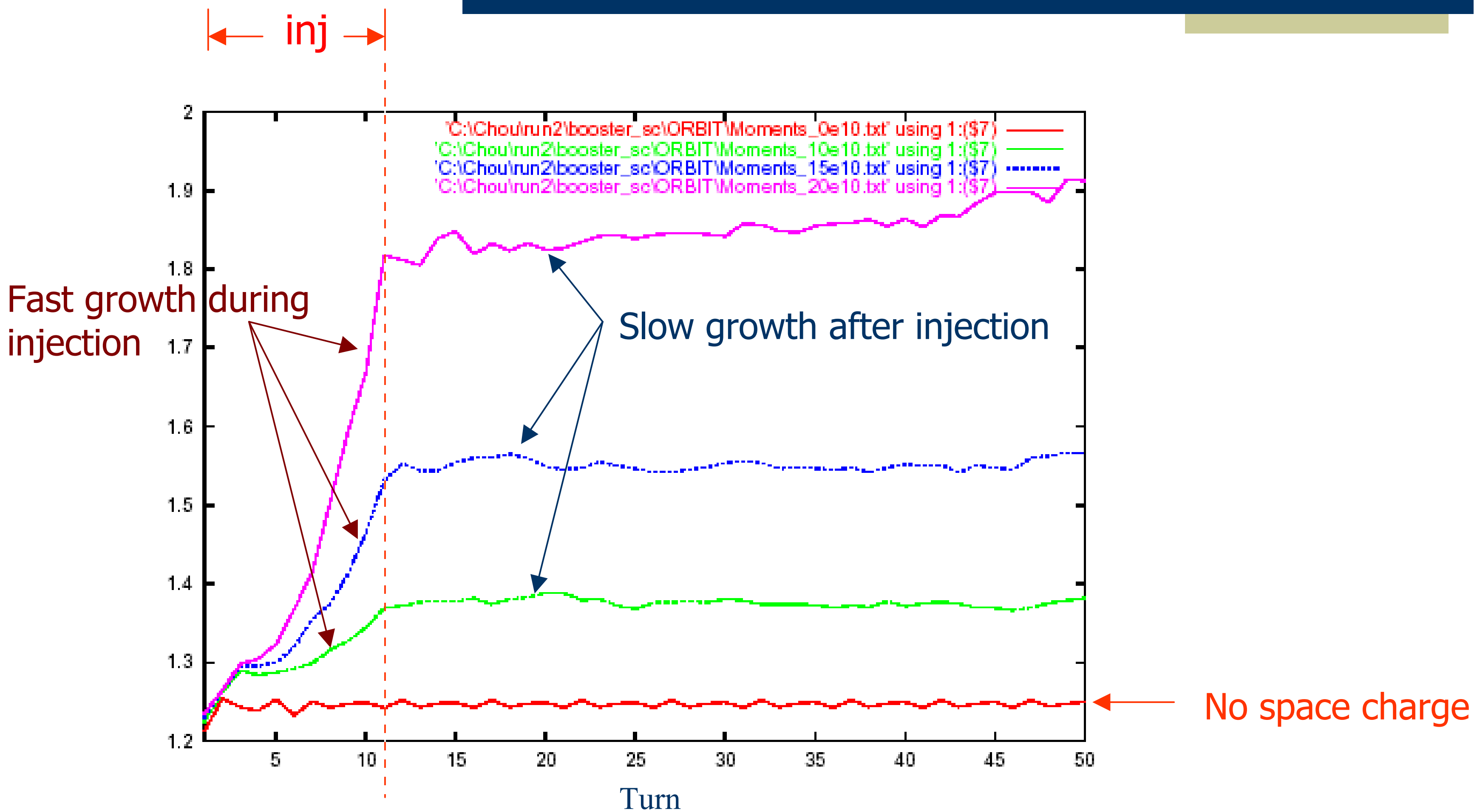
Laslett tuneshift: $\Delta\nu \approx -\mathbf{0.3}$

Emittance Histogram
(ORBIT)



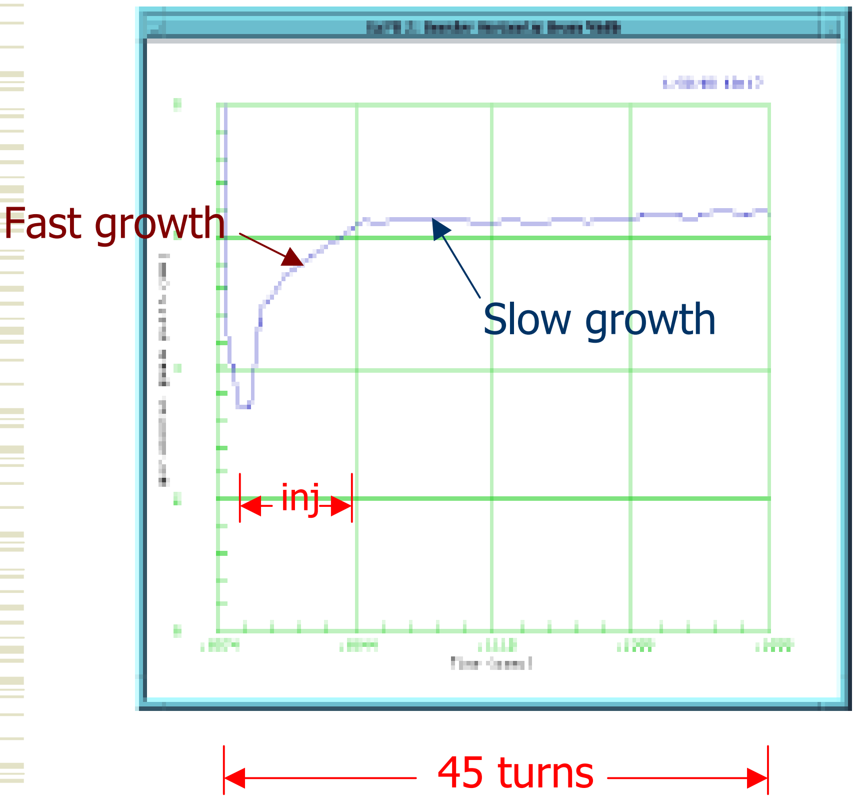
Emittance Growth

(ORBIT, 11-turn injection, varying beam intensity)

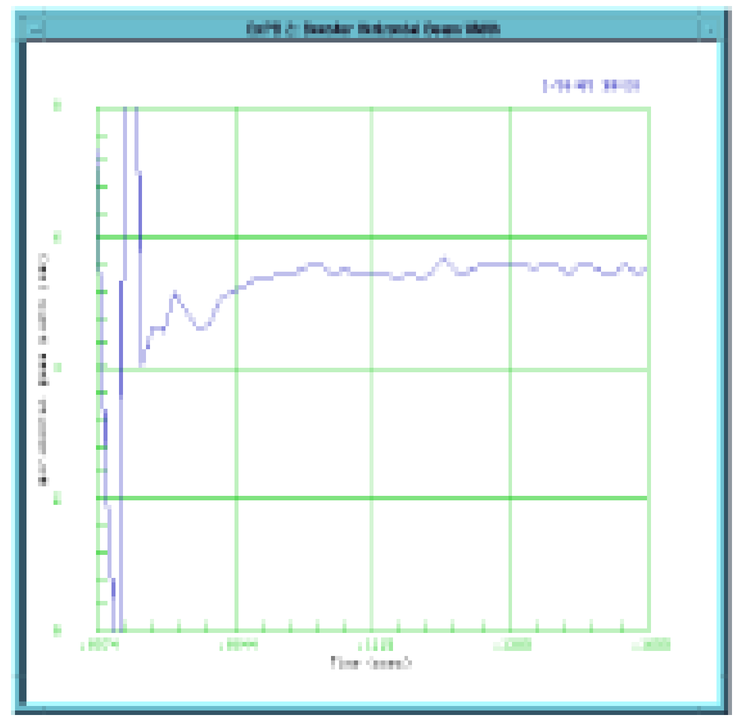


IPM (ion profile monitor) Measurement
(raw data)

40 mA, 10-turn injection

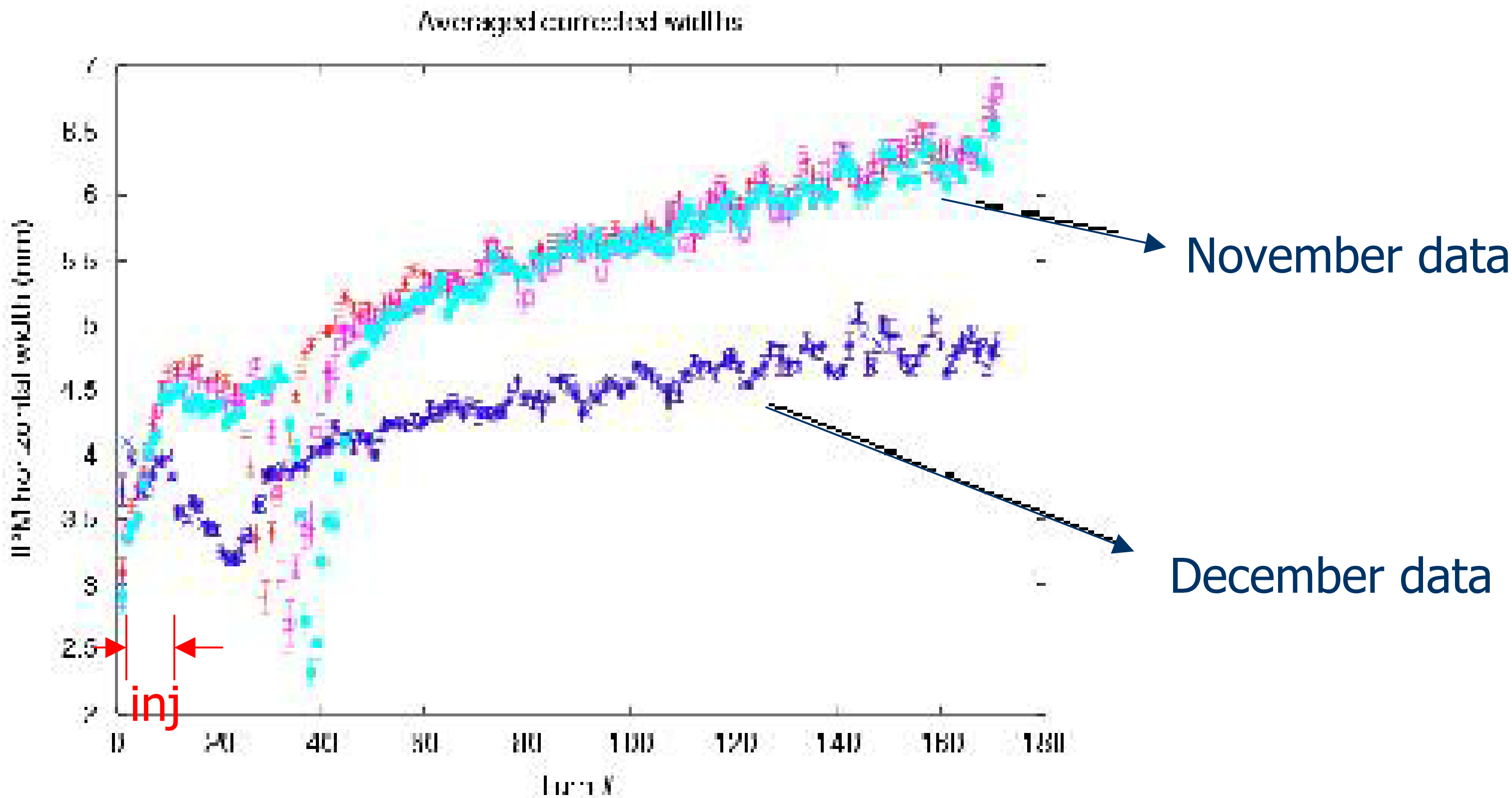


20 mA, 10-turn injection



IPM Measurement

(processed data, courtesy P. Spentzouris)



First 3 milliseconds in the Booster

- Logitudinal loss
  - The measured Booster longitudinal acceptance is small: ±0.15-0.2%
  - The measured linac beam momentum spread is about ±0.13%
  - When the beam is bunched, the momentum spread increases to ±0.3%
  - This exceeds the acceptance and results in loss
- Transverse loss
  - The transverse acceptance is:

$$A = \{\beta_{max} \times \varepsilon_N/\beta\gamma\}^{-1/2} + D_{max} \times \Delta p/p + \text{c.o.d.}$$

  - The magnet good field region is about ±1.2 inch
  - For regular β_{max} and $D_{max,}$ the maximum allowable ε_N is about 16π
  - But the doglegs blow up the lattice function and reduce ε_N to about 8π
  - The incoming linac beam is 7π
  - Space charge dilutes the emittance during the multiturn injection, resulting in loss.

First 3 milliseconds in the Booster (cont…)

When beam energy goes up, the situation improves rapidly:

- Longitudinal:
  - $\Delta E/E \downarrow$
  - $1/\beta^2 \downarrow$
  - $\Delta p/p = (1/\beta^2) \times \Delta E/E \downarrow\downarrow$
- Transverse:
  - Dogleg focusing strength: $1/f = \theta^2/L \propto 1/p^2 \downarrow\downarrow$
  - Beam size due to adiabatic damping: $\varepsilon = \varepsilon_N/\beta\gamma \downarrow$
  - Space charge effect $\propto 1/\beta\gamma^2 \downarrow\downarrow$

In the middle and late stage of the cycle, other schemes will contribute to the beam loss (e.g., transition crossing, coupled bunch instability), but which is beyond this topic.

Chromaticity Modeling

$$\xi = \xi(\text{lat}) + \xi(\text{dogleg}) + \xi(\text{mag sext}) + \xi(\text{chrom sext})$$

- Goal:

  To have a spreadsheet relating the sextupole current to the machine chromaticity throughout the cycle

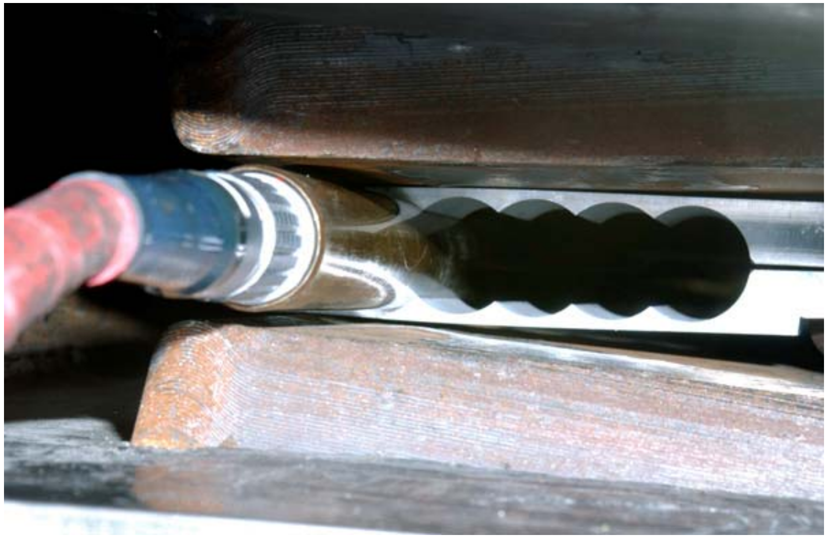
- The task is complicated by two factors:
  - The dogleg effect, which perturbs the local lattice function and has an energy dependence (calculable)
  - The main magnets have large sextupole component, which comes from both the body part and the end packs (need measurement)

Chromaticity Calculation

	$\xi(x)$	$\xi(y)$
Bare lattice (Lat)	-9.16679	-7.03638
Lat + dogleg	-9.57427	-7.01265
Lat + body sext	-23.55770	11.65977
Lat + body sext + dogleg	-23.40371	11.00271
Lat + body sext + chrom sext + dogleg	0.04399	-0.18496
Lat + body sext + chrom sext (no dogleg)	3.67119	-11.11968

The doglegs' direct contribution to the chromaticity is small. But their impact on the chromaticity is significant because of the big change of local β and D at the chromaticity sextupoles.

Field Measurement at E4R



A mole used for dc field measurement

Main Magnet Sextupole Component

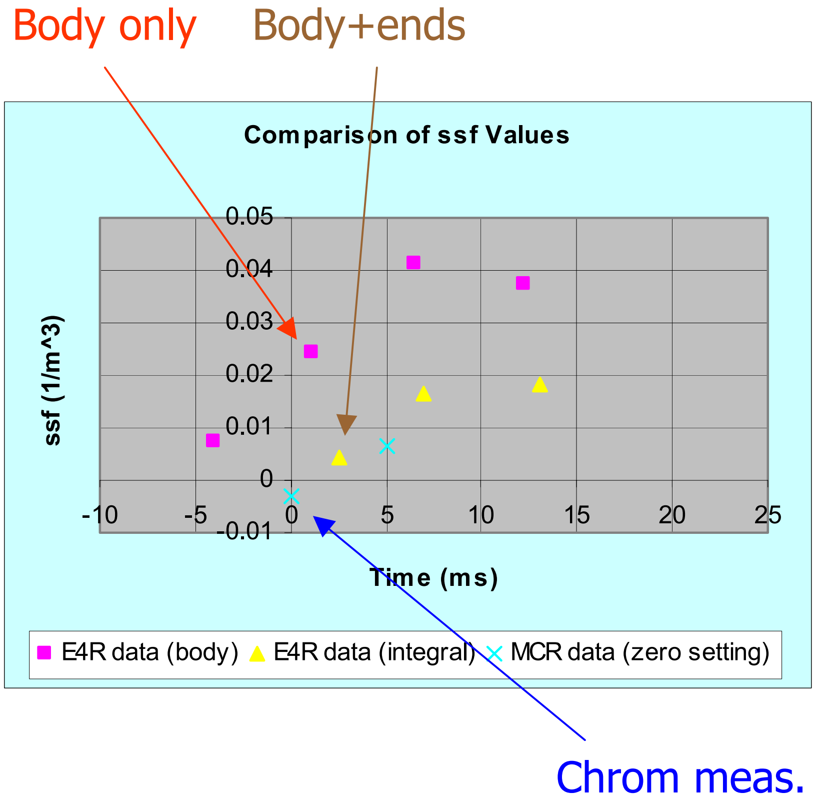
- Two independent measurements:
  - Field measurement at the E4R
  - Chromaticity measurement at the Main Control Room
- The two teams did not talk to each other on purpose (a blind check)
- The results are found to be in good agreement at 400 MeV
- Work in progress for ac measurement

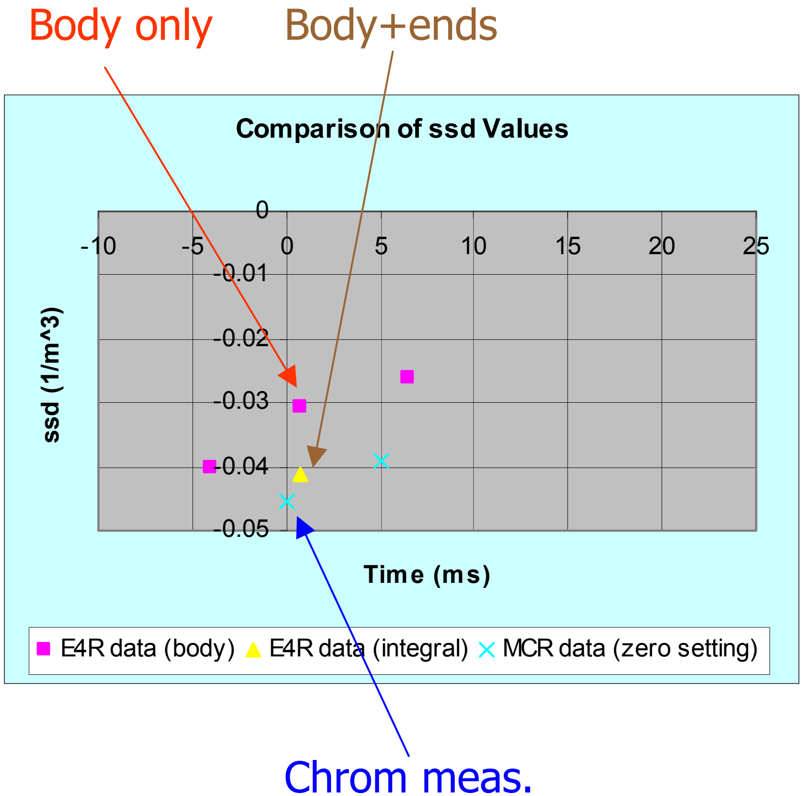
Magnet type	Body only	Body + Ends field measurement	Body + Ends chromaticity measurement
F	0.026	0.004	-0.003
D	-0.021	-0.0413	-0.0454

Main Magnet Sextupole Measurements (cont…)

F magnet

D magnet

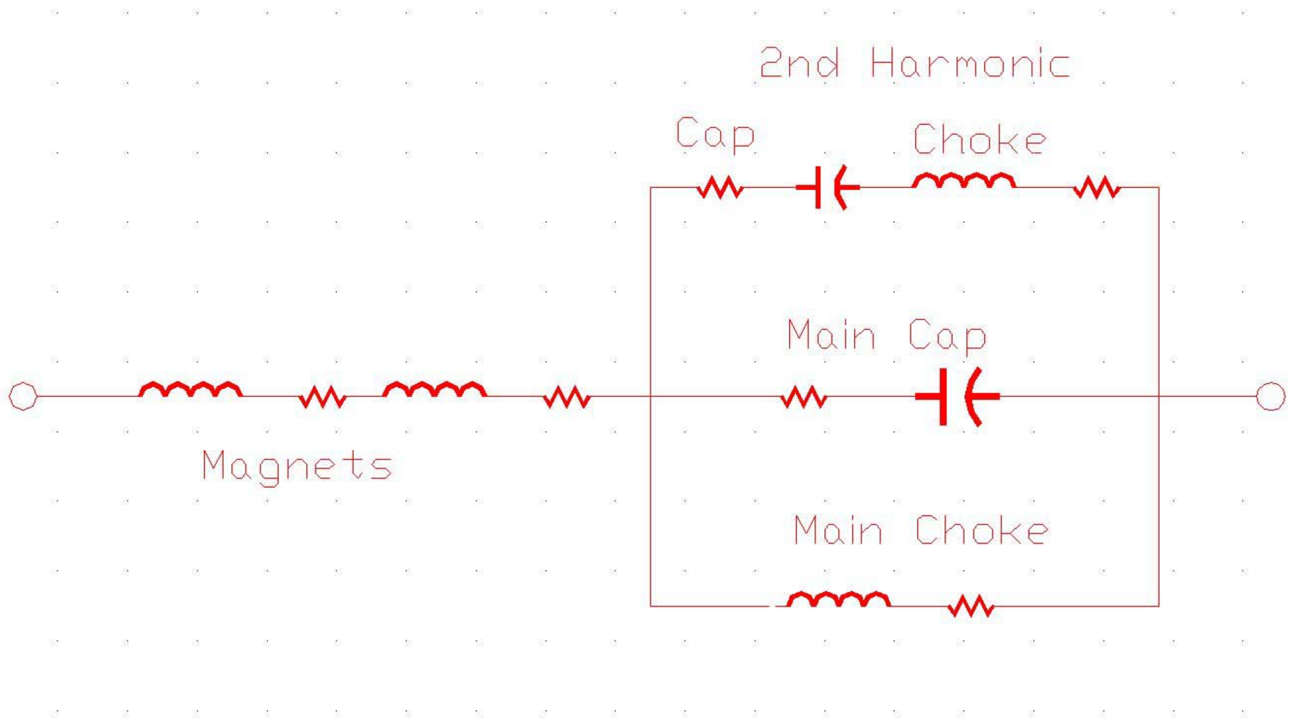




Power Supply Experiments at E4R

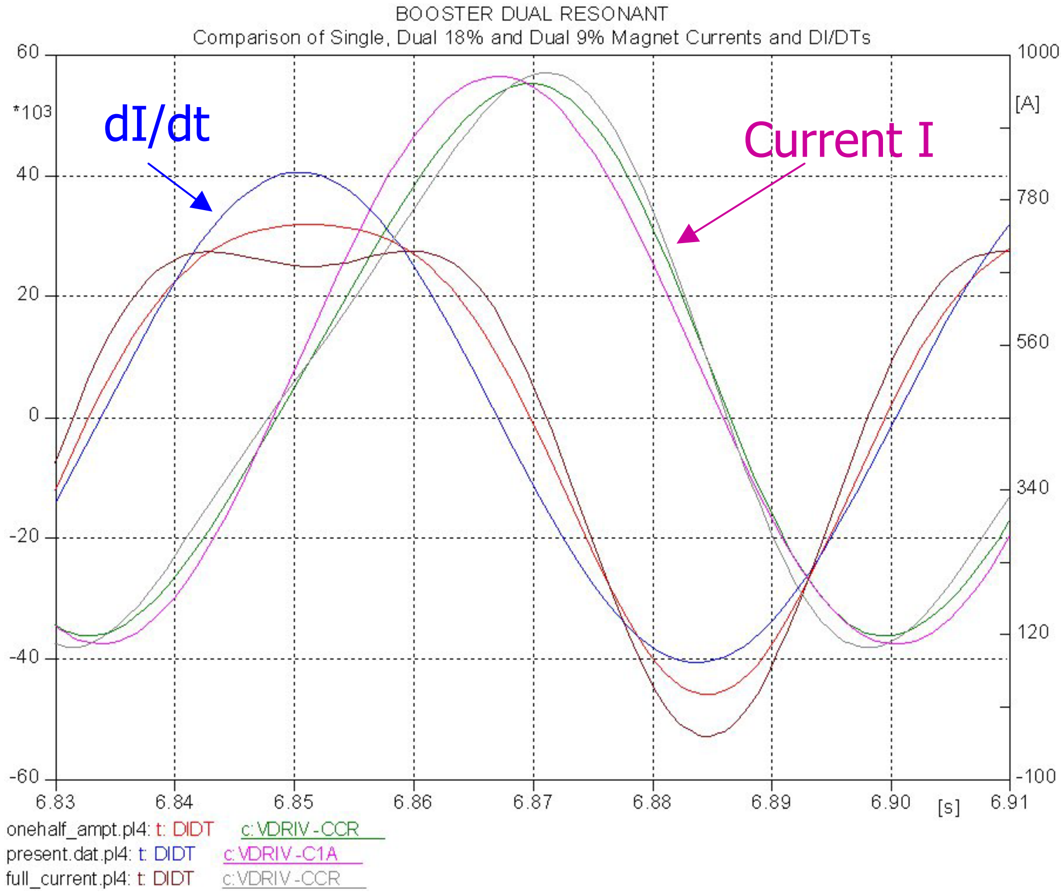
- Motivation: To make the existing RF system capable to accelerate more particles
- Experiment 1: Reduce the repetition rate from 15 Hz to 12 Hz
- Experiment 2: Dual harmonic resonant (15 Hz + 12.5% 30 Hz)
  - Purpose: To reduce the peak RF power by 25%

Booster Cell with 2nd Harmonic
(courtesy D. Wolff)



Dual Harmonic Current and dI/dt

(3 cases: dual 0%, 9%, 18%; courtesy D. Wolff)



Summary

- Thanks to many people's commitment and a collaboration among several departments and divisions, the Booster study is making good progress. The discovery and correction of the dogleg effect is an example.
- This study is making the Booster a better machine.

Questions?