Several Topics in Recent Accelerator Studies

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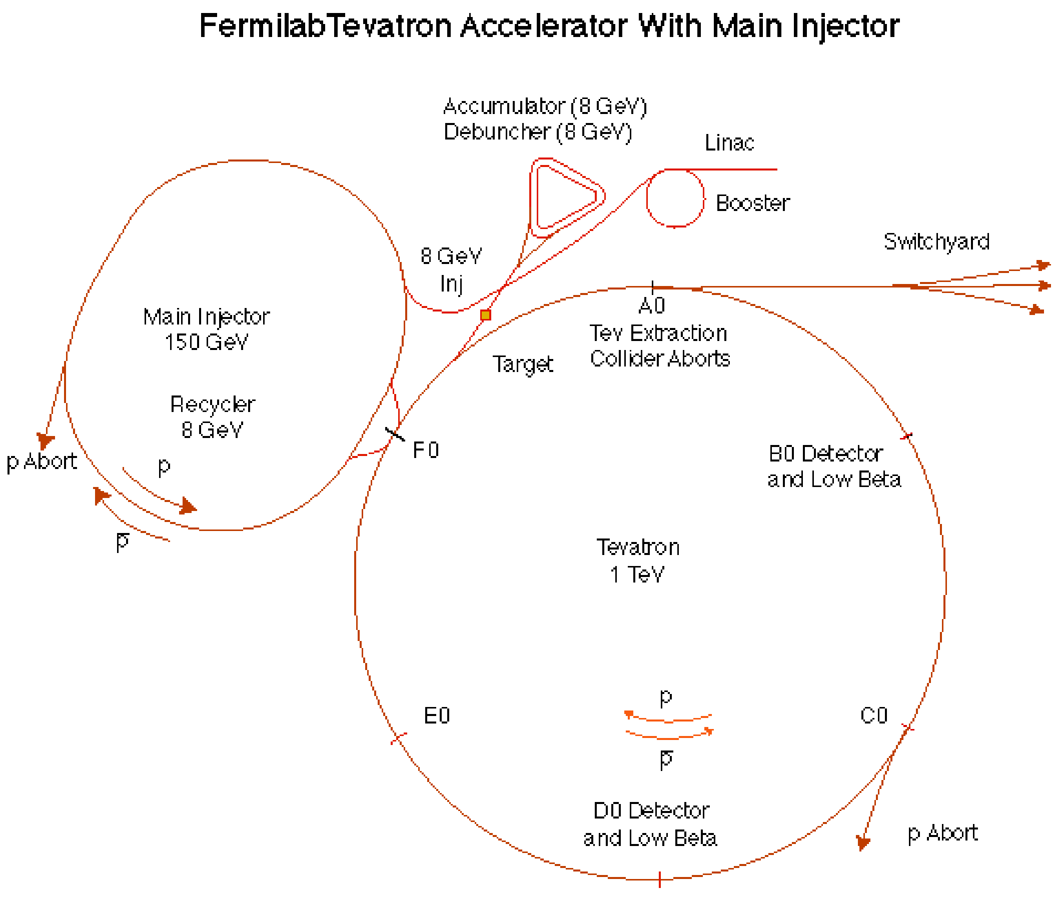
Outline

(1) Booster modeling

(2) Space charge

(3) Barrier RF stacking

Fermilab Accelerator Complex

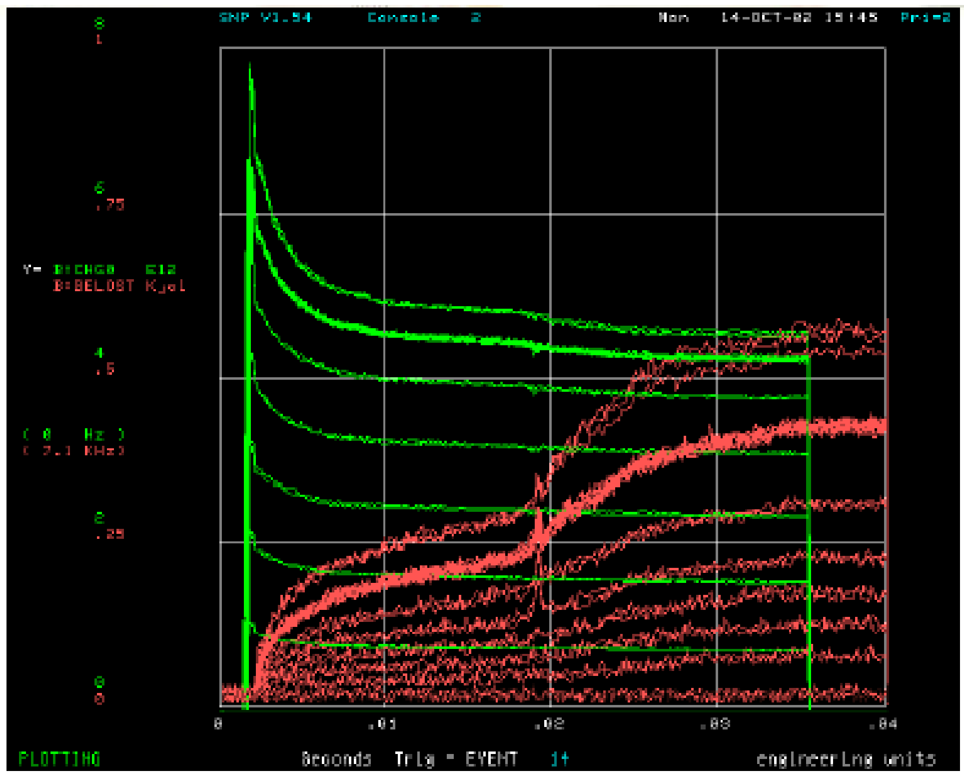


(1) Booster Modeling

- The dogleg effect (Sasha's talk)
- The first 3 milliseconds
- Chromaticity modeling
- Model improvement
- Booster power supply experiments at E4R

Booster Beam Loss

(courtesy R. Webber)



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

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

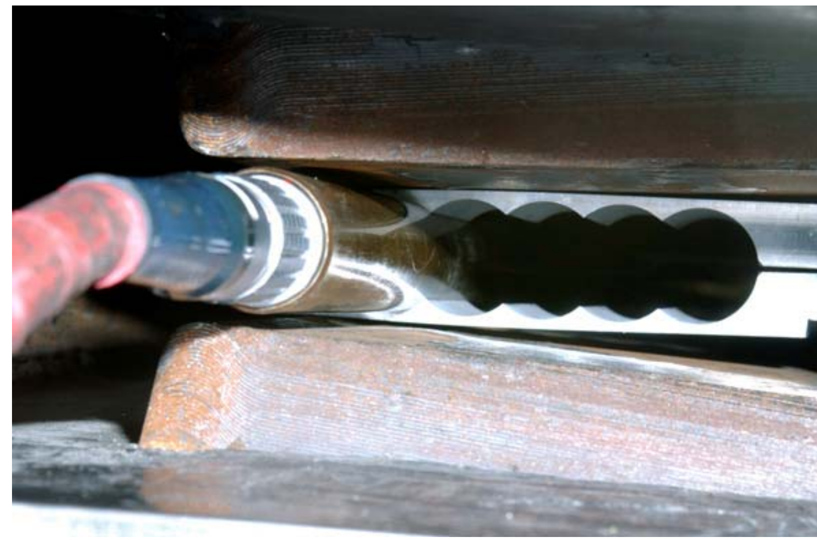
- The task is complicated by two factors:
  - The dogleg effect, which perturbs the local lattice function and has an energy dependence (calculable)
  - The main magnets have large sextupole component, which comes from both the body part and the end packs (need measurement)

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

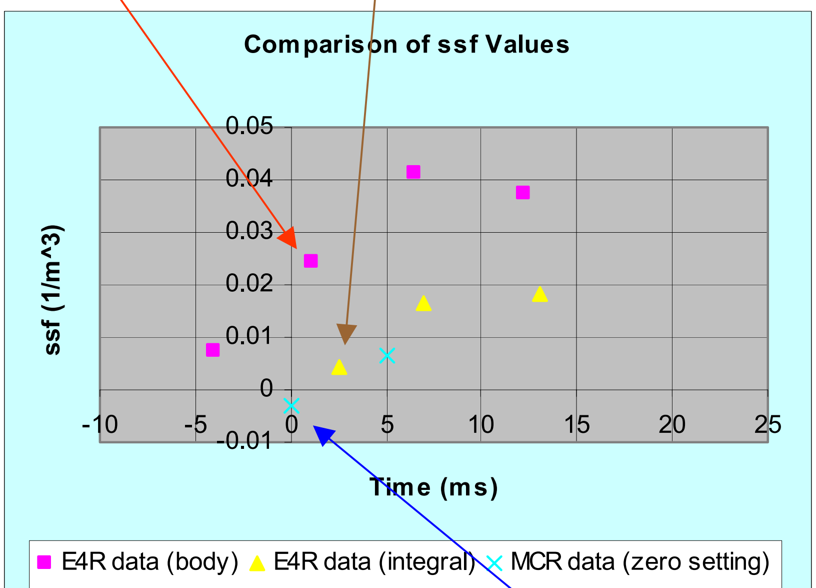
- Two independent measurements:
  - Field measurement at the E4R
  - Chromaticity measurement at the Main Control Room
- The two teams did not talk to each other on purpose (a blind check)
- The results are found to be in good agreement at 400 MeV
- Work in progress for ac measurement

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

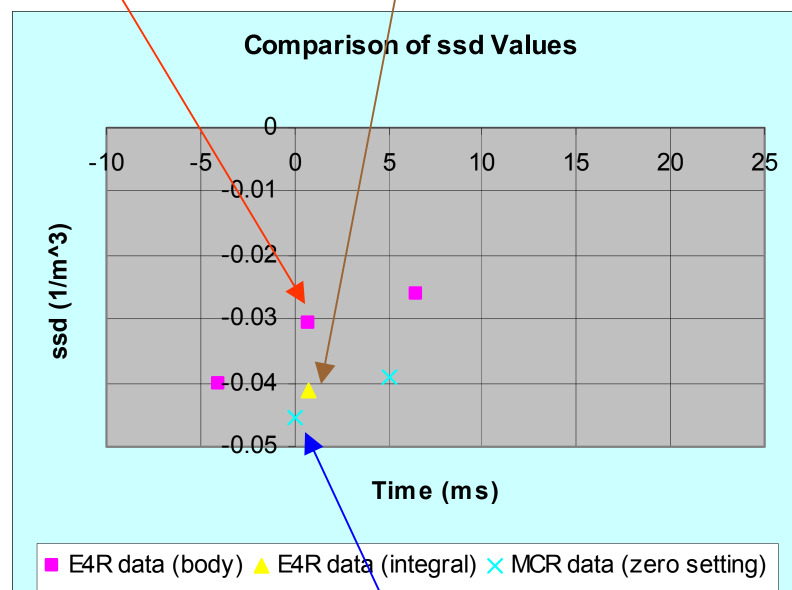
Body only Body+ends



Chrom meas.

D magnet

Body only Body+ends



Chrom meas.

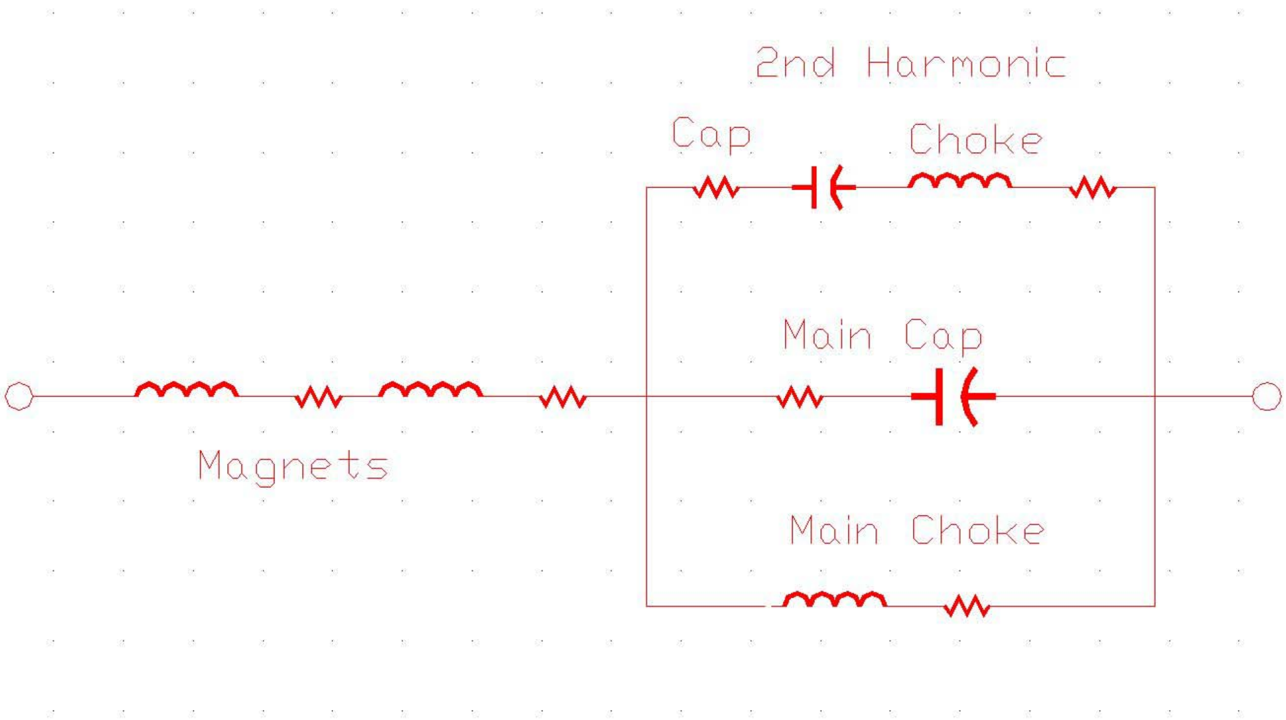
Model Improvement

- Trim quads
  - 24 H, 24 V
  - Weak, about 2% of the main quad strength
  - But perturbations on beta function and tune are big
  - MAD output does not seem to match the observation
- Steering magnets
  - Not in the model yet
- Alignment errors
  - Model uses old data, needs updated ones
- Aperture scanning
  - Need to be re-done

Power Supply Experiments at E4R

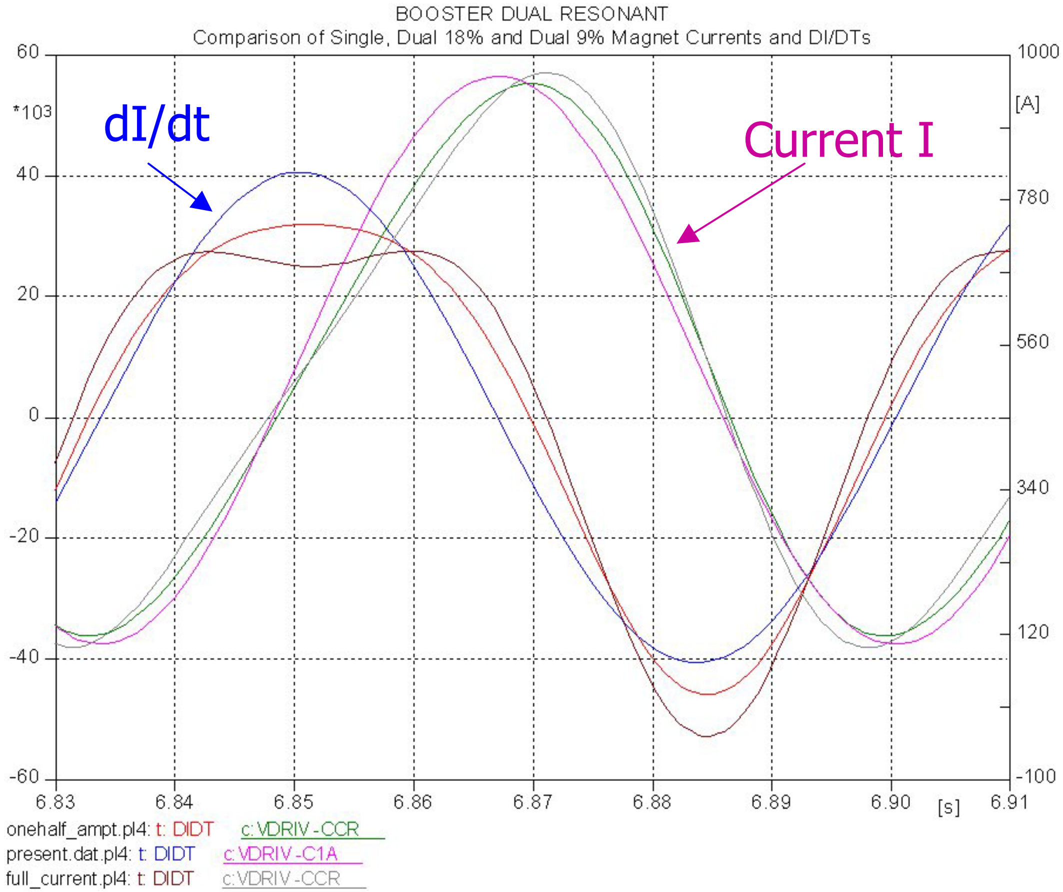
- Motivation: To make the existing RF system capable to accelerate more particles
- Experiment 1: Reduce the repetition rate from 15 Hz to 12 Hz
- Experiment 2: Dual harmonic resonant (15 Hz + 12.5% 30 Hz)
  - Purpose: To reduce the peak RF power by 25%

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



Dual Harmonic Current and dI/dt

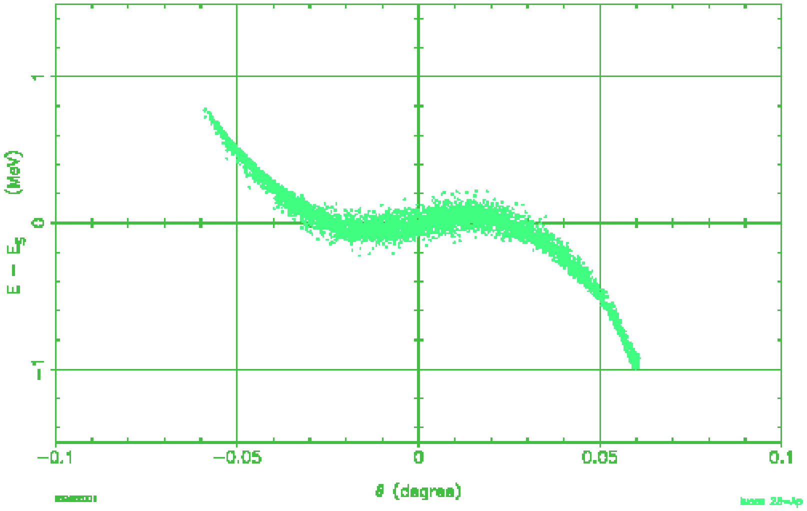
(3 cases: dual 0%, 9%, 18%; courtesy D. Wolff)



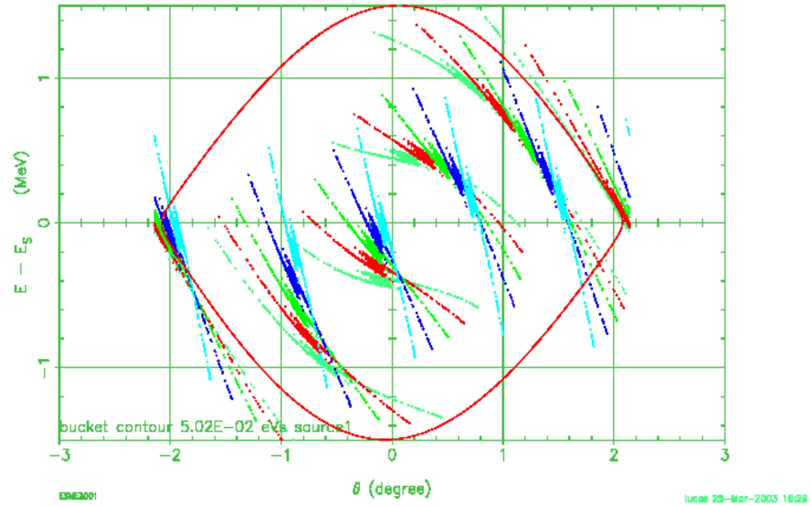
(2) Space Charge

- 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
- IPM (Ion Profile Monitor) measurement
- Code benchmarking

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

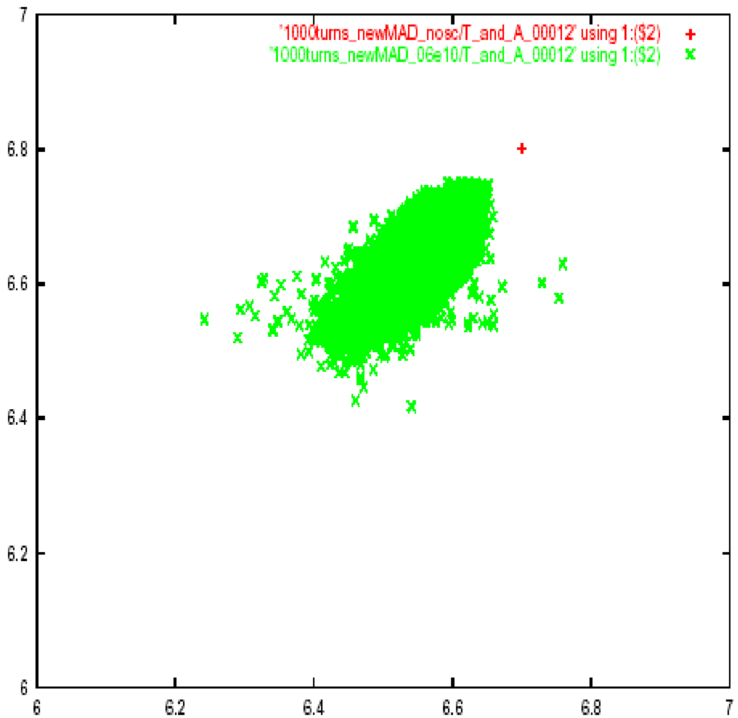


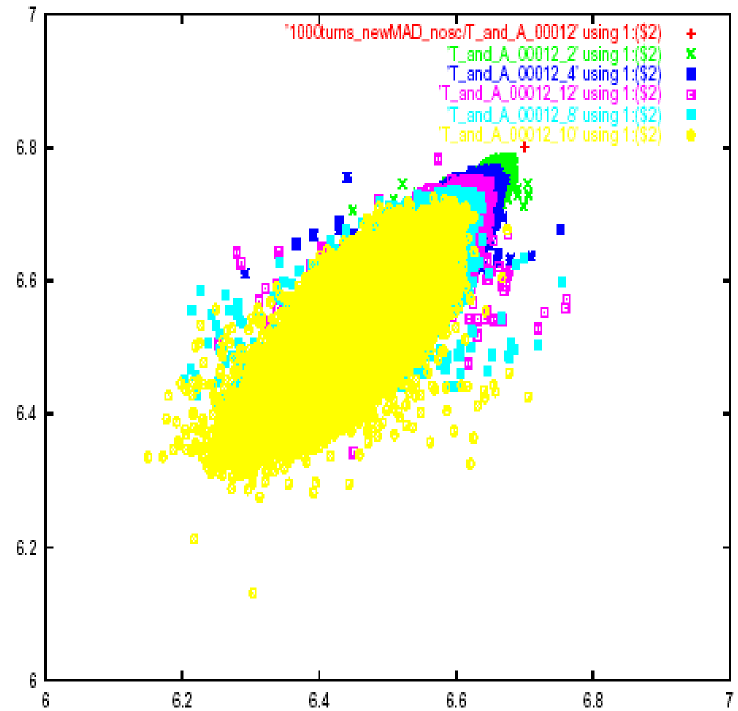
One microbunch with Δp/p = ±0.13%



Multiturn injection

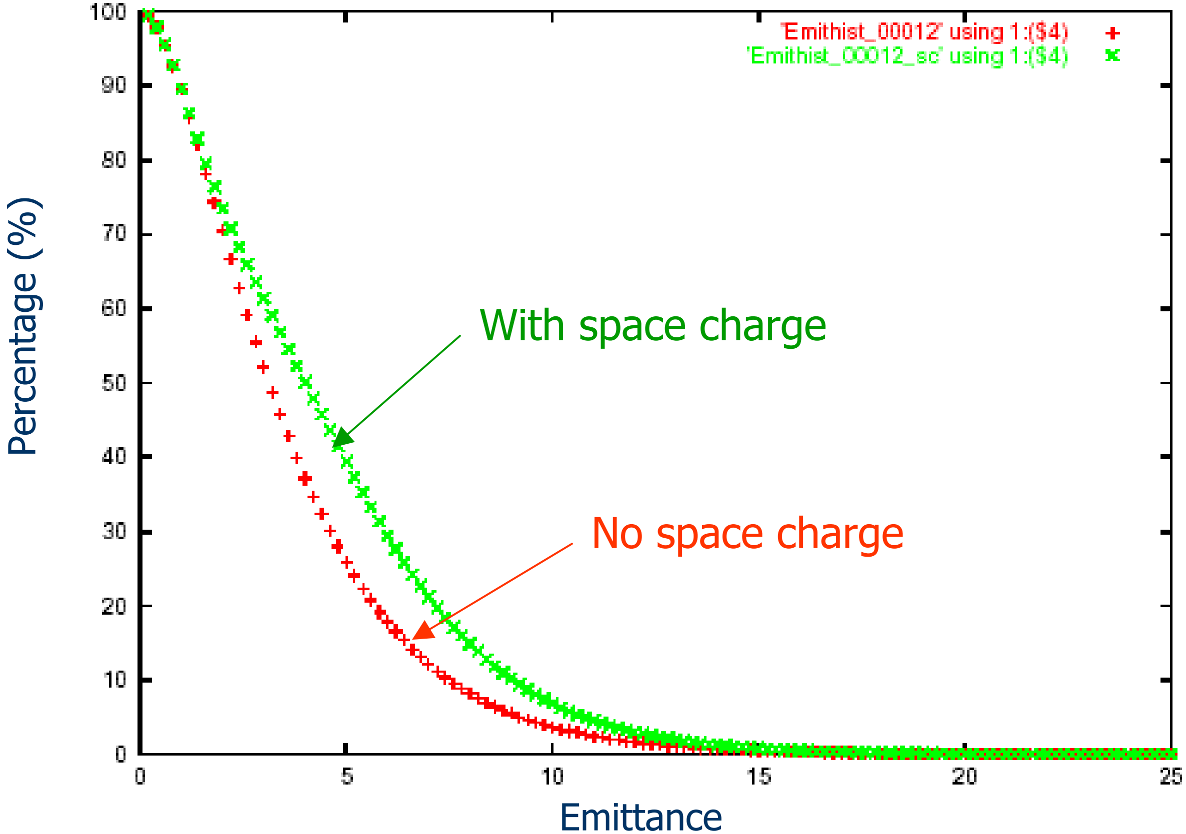
Tune Footprint
(ORBIT, varying beam intensity)





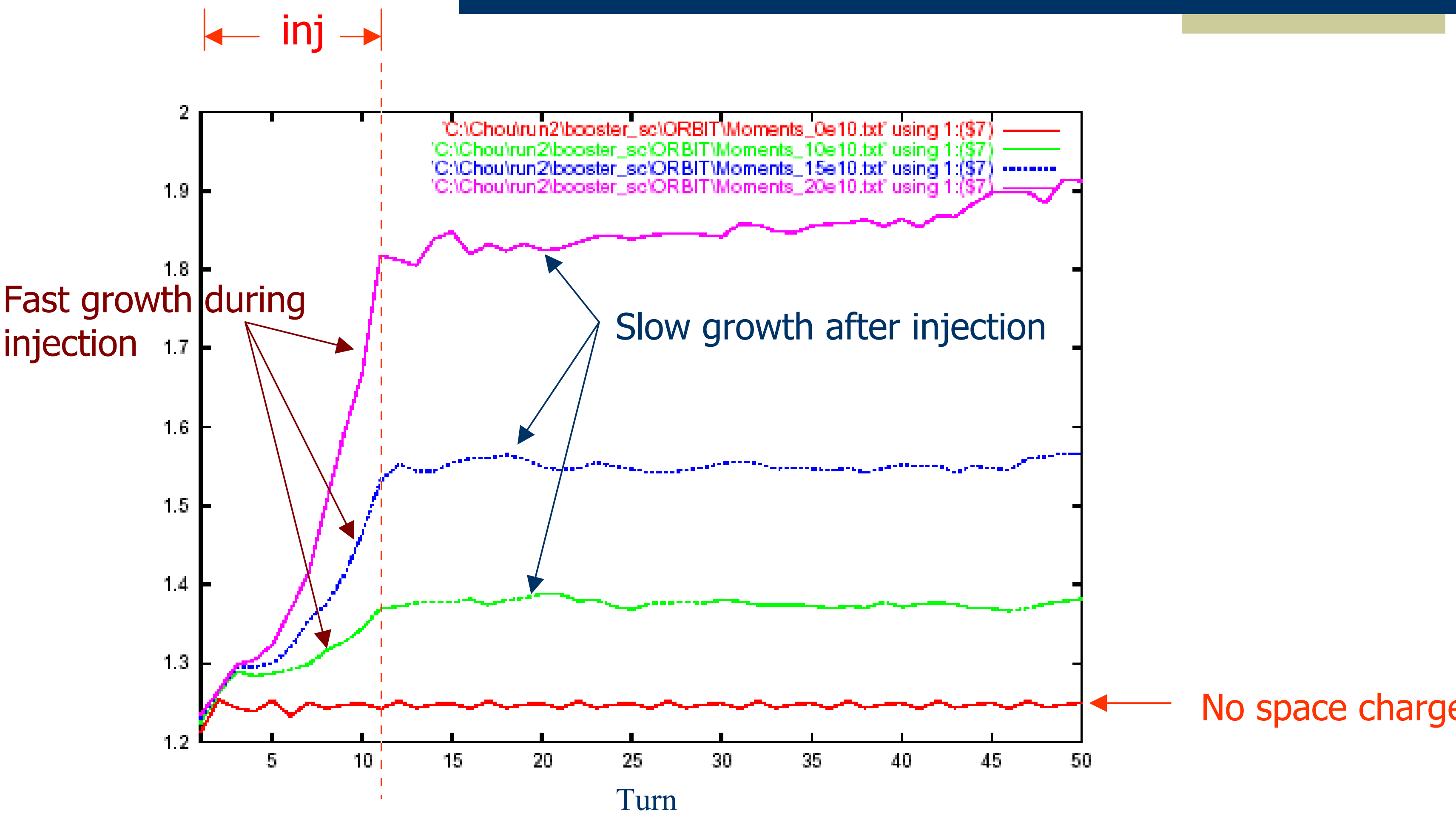
Laslett tuneshift: $\Delta\nu \approx -\mathbf{0.3}$

Emittance Histogram
(ORBIT)



Emittance Growth

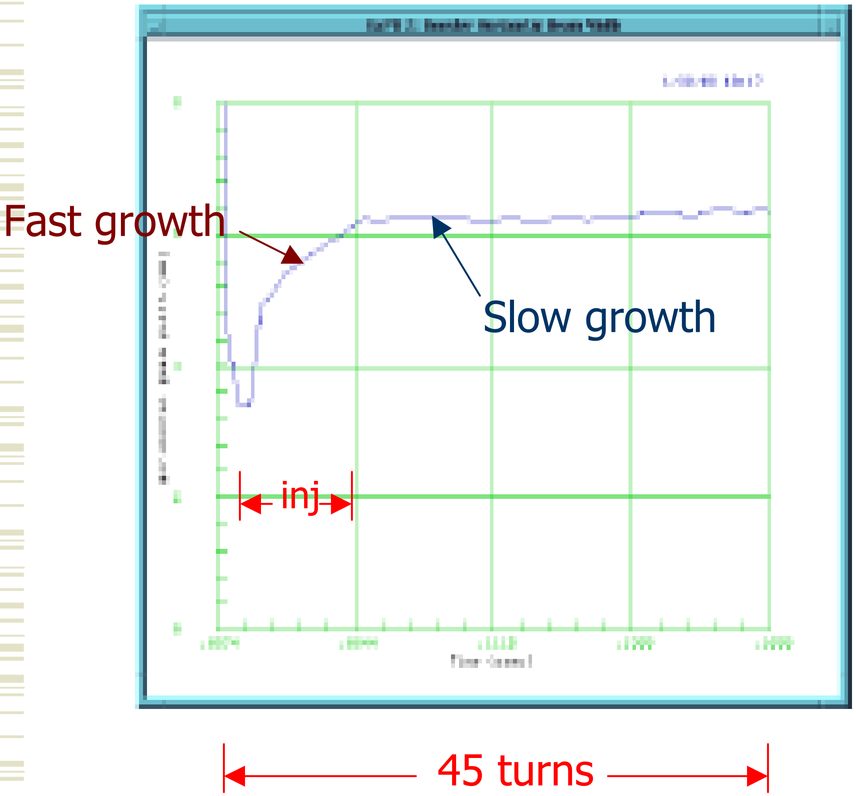
(ORBIT, 11-turn injection, varying beam intensity)



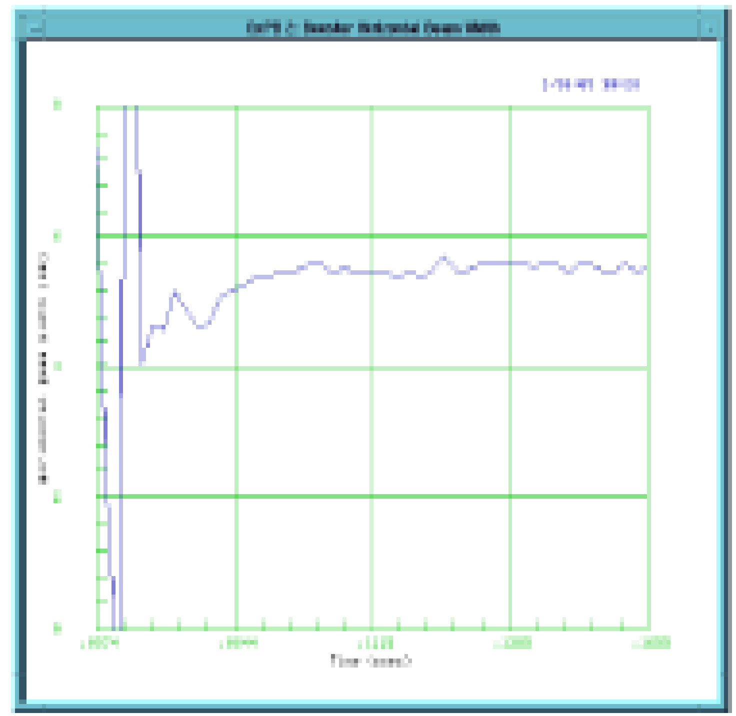
IPM Measurement

(raw data)

40 mA, 10-turn injection

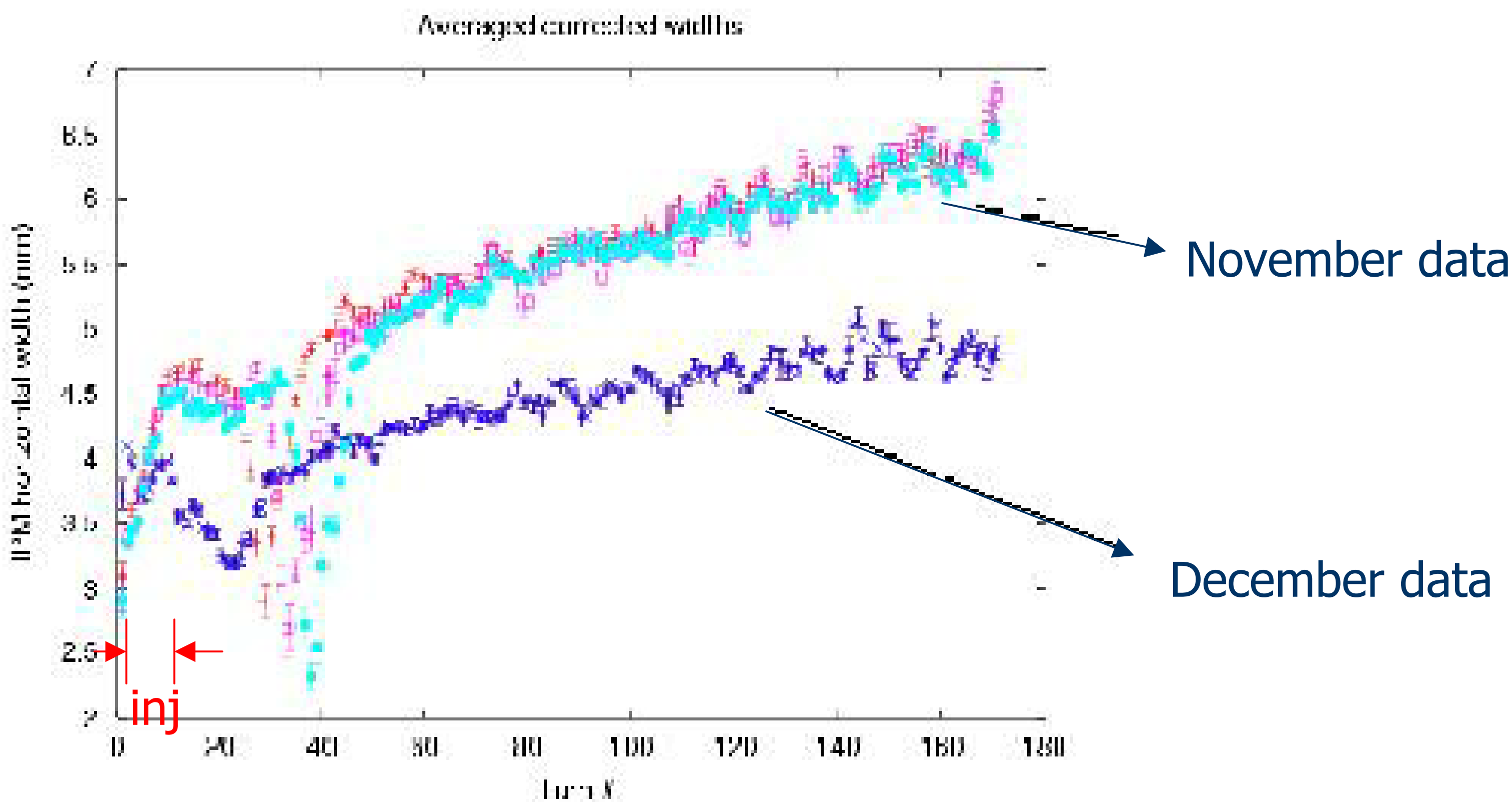


20 mA, 10-turn injection



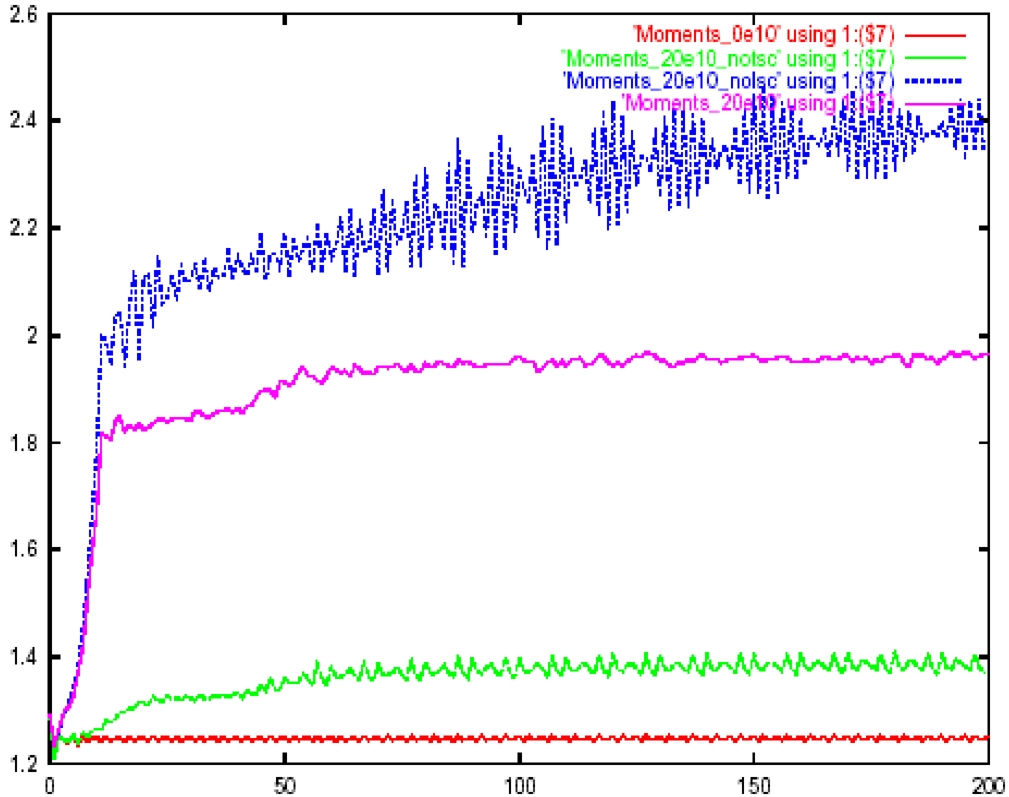
IPM Measurement

(processed data, courtesy P. Spentzouris)



Emittance Growth during Injection

(varying space charge effects)



Turn

Transverse sc only

Transverse + Longitudinal

Longitudinal sc only

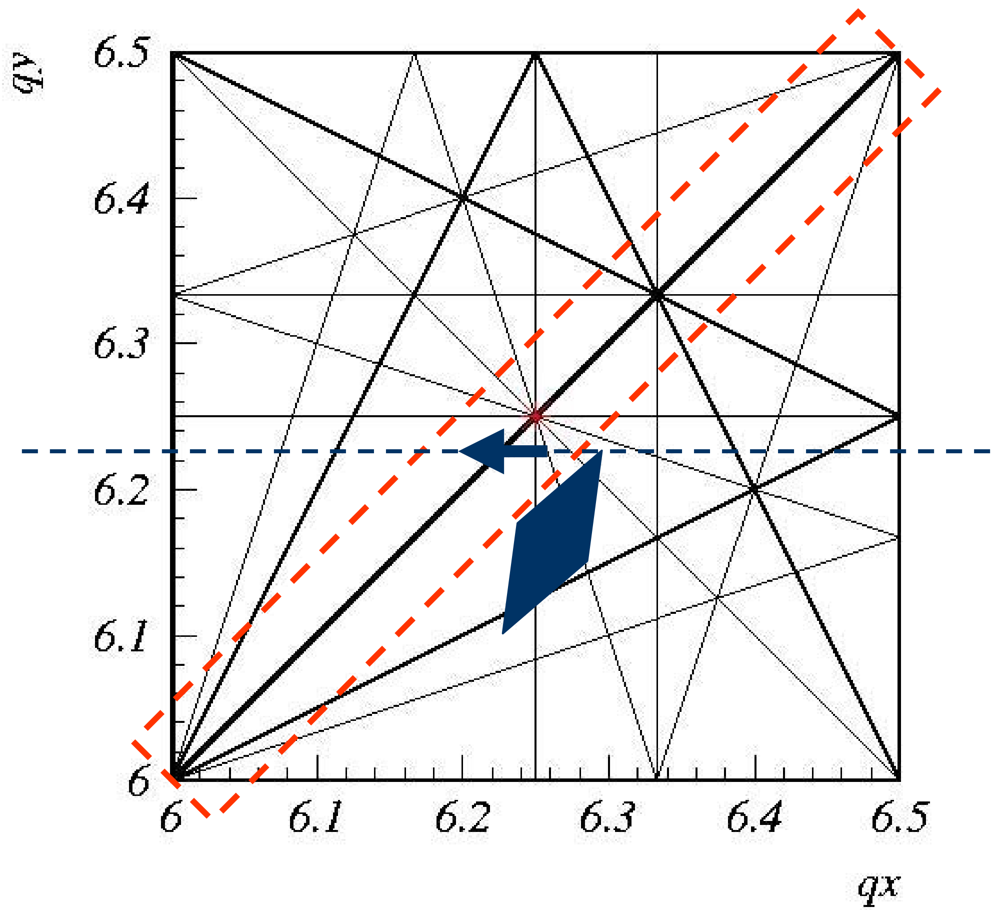
No space charge

Space Charge Code Benchmarking

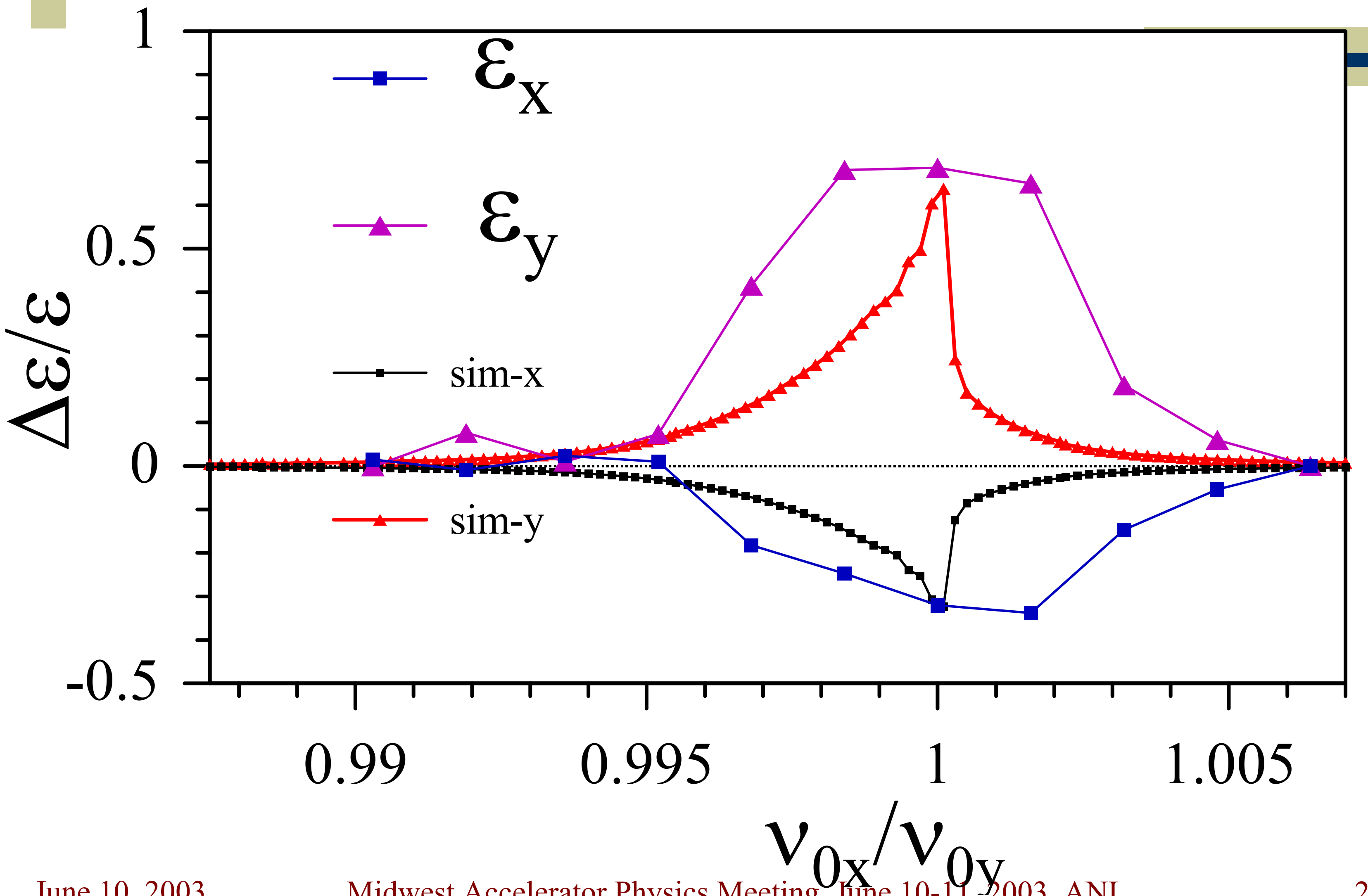
(12th ICFA Mini-Workshop, April 2-4, 2003, Oxford, England)

- Data: CERN PS experiment on Montague resonance ($2\nu_x - 2\nu_y = 0$)
- Participants in this benchmarking:
  - F. Jones (Accsim)
  - A. Luccio (Orbit)
  - J. Holmes, S. Cousineau (Orbit)
  - A. Adelmann (GenTrackE)
  - H. Qin (Best)
  - I. Hofmann (Micromap)
  - W. Chou, F. Ostiguy, P. Lucas (Orbit)
  - J. Qiang, R. Ryne (IMPACT, ML/I)
  - D. Johnson, F. Neri (Simpsons)

tune diagram
(betatron periods per turn without space charge)



Comparison with simulation (Gaussian/coasting beam)
- observed broader than in simulation



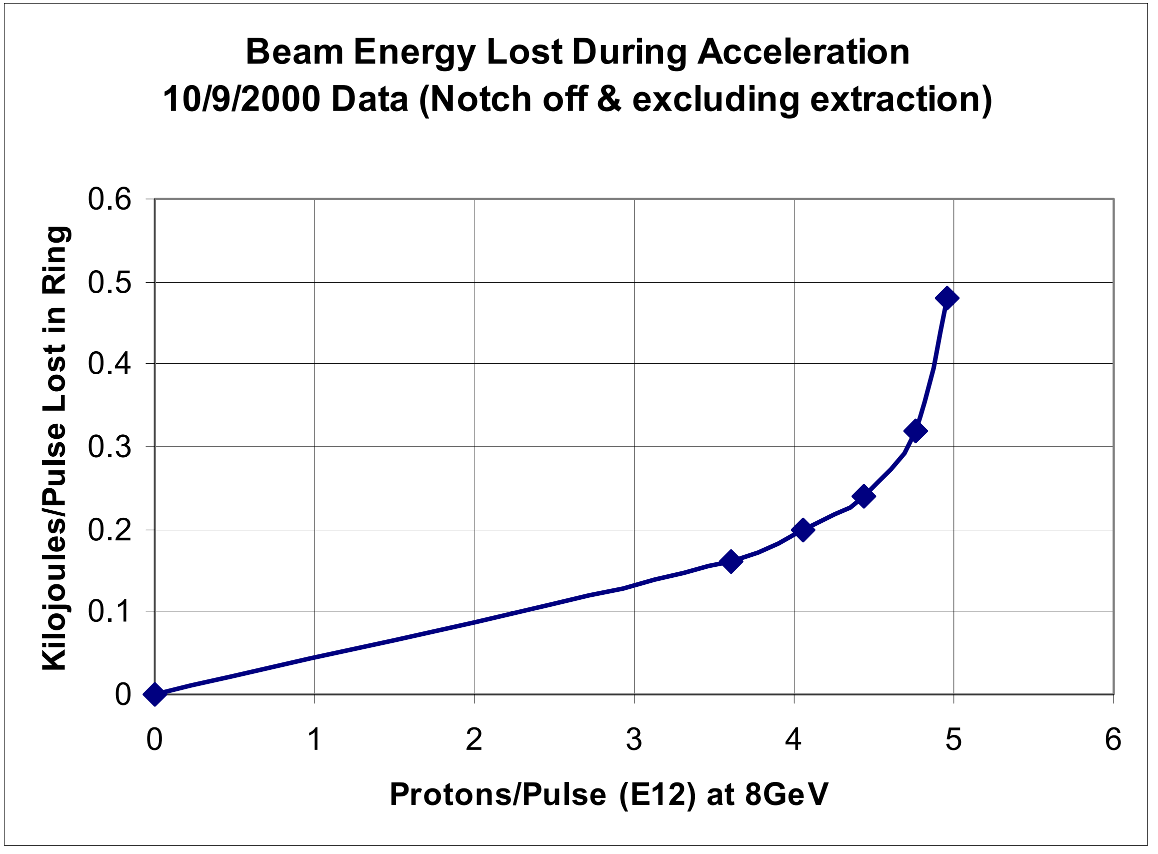
(3) Barrier RF Stacking

- Motivation:

  To overcome the Booster bottleneck problem and double the proton intensity on the production target.

- Method:
  - To stack two Booster bunches into one MI bucket by using a barrier RF system.
  - This is possible because the Main Injector momentum acceptance (0.4 eV-s) is larger than the Booster bunch emittance (0.1 eV-s)
- Ng's simulation
- Barrier RF system and bench test

Booster Energy Loss
(courtesy R. Webber)



Stacking Goals

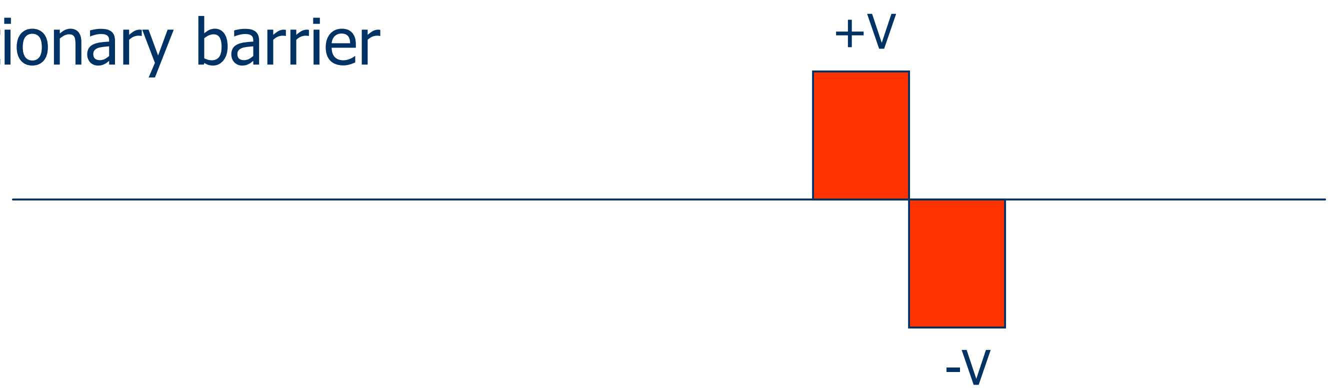
- Goal for Run2 – To increase protons per second (pps) on the pbar target by 50%
  - Baseline: 5e12 every 1.467 sec
  - Goal: 2 x 5e12 every 2 sec
- Goal for NuMI – To increase pps on the NuMI target by 60%
  - Baseline: 3e13 every 1.867 sec
  - Goal: 2 x 3e13 every 2.333 sec

Method

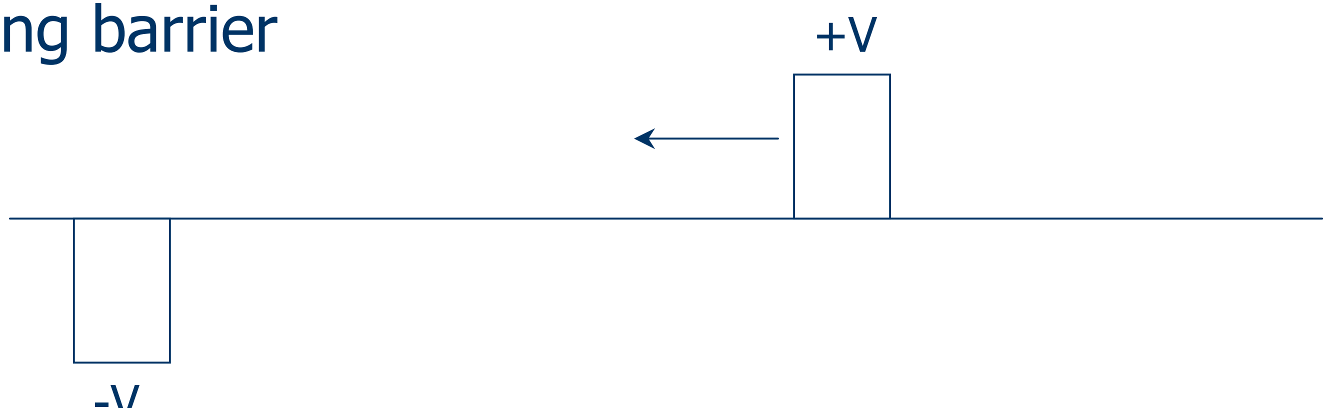
- A straightforward way is to inject two Booster batches into the MI, confine them by RF barrier buckets, then move the barrier to compress the beam.
- But the compression must be slow (adiabatic) in order to avoid emittance growth. This would lengthen the injection process and thus reduce protons per second (pps)
- A better way (first proposed by J. Griffin) is to inject Booster batches off-axis so that the injection can be continuous

Two Types of Barrier

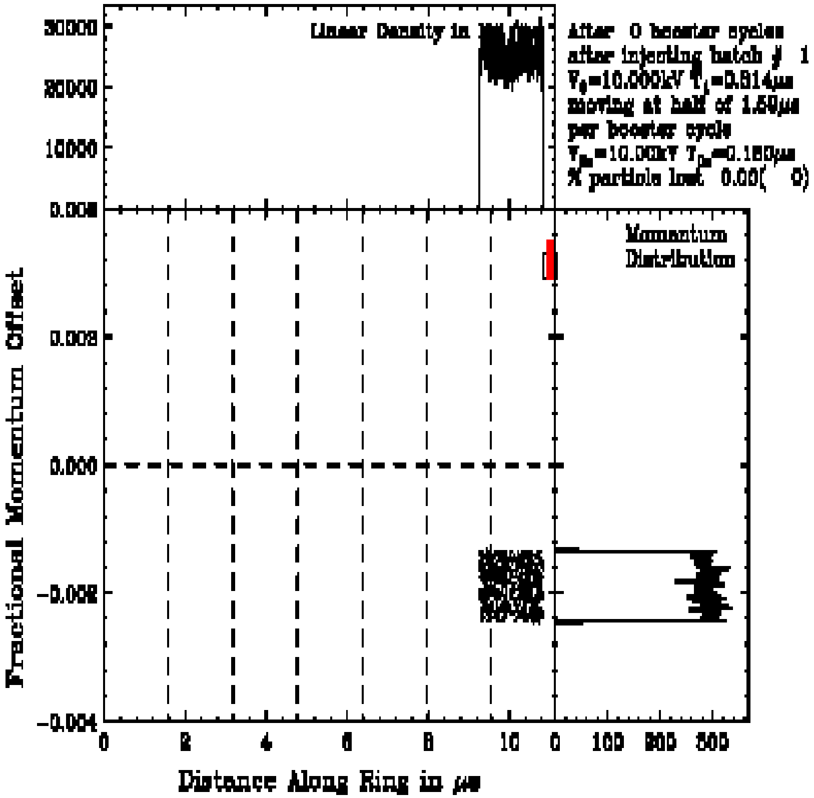
Stationary barrier

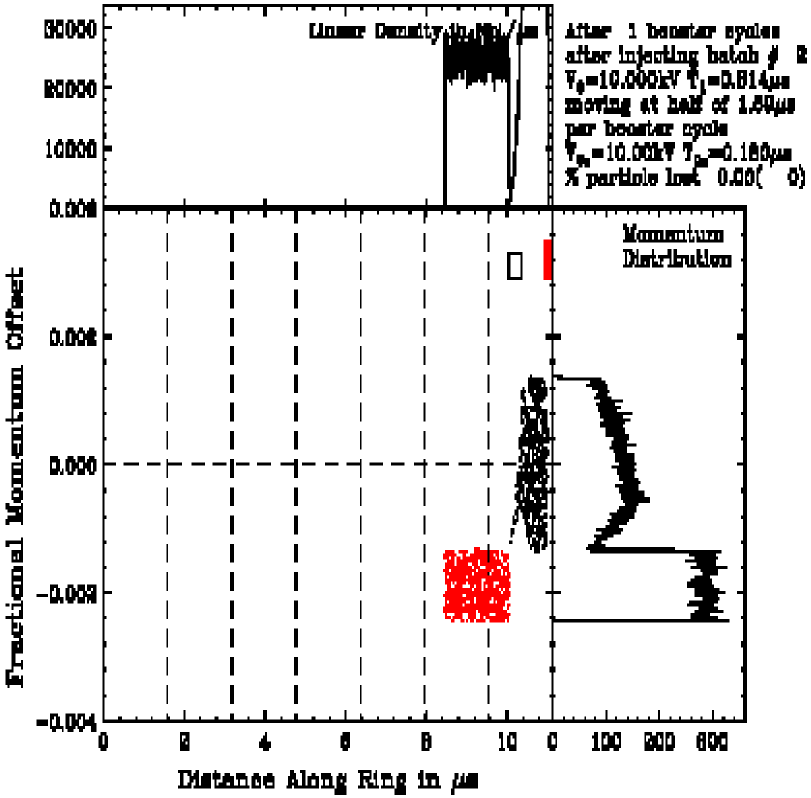


Moving barrier

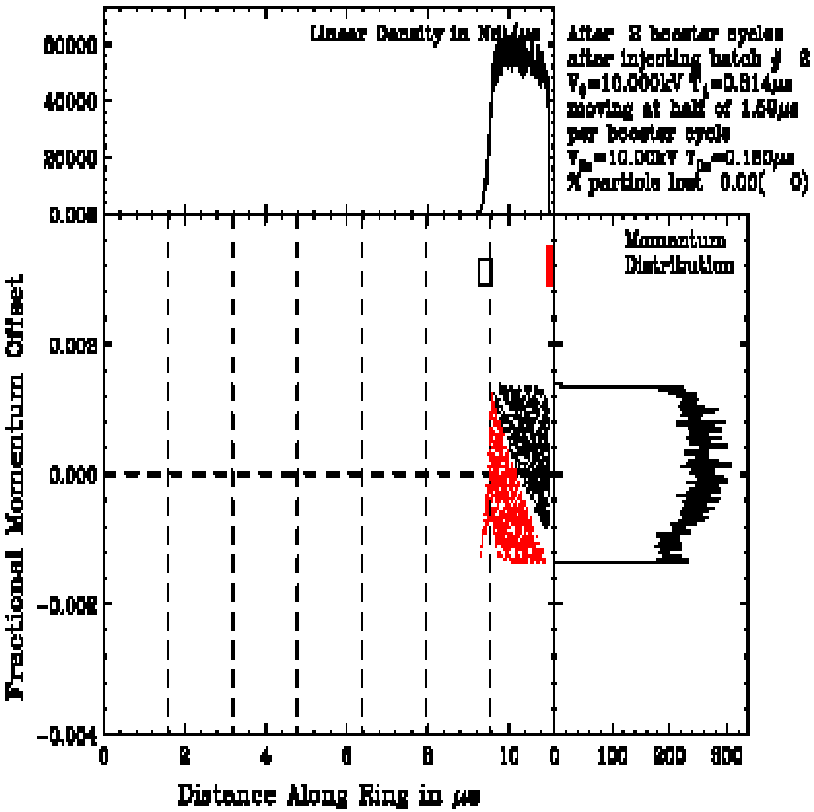


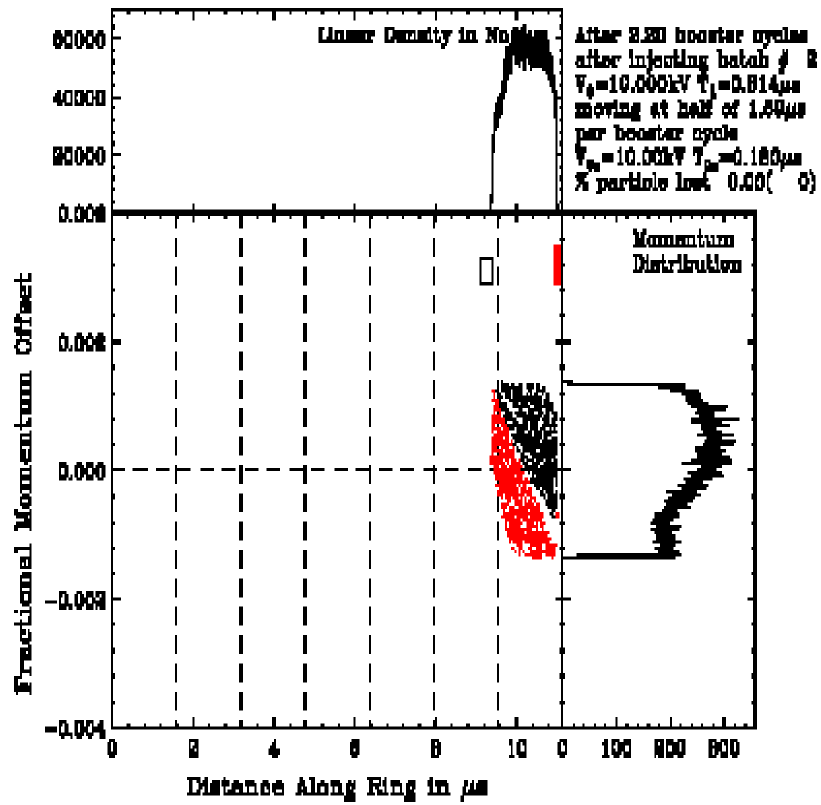
Injection Beam Off-Axis
(courtesy K.Y. Ng)



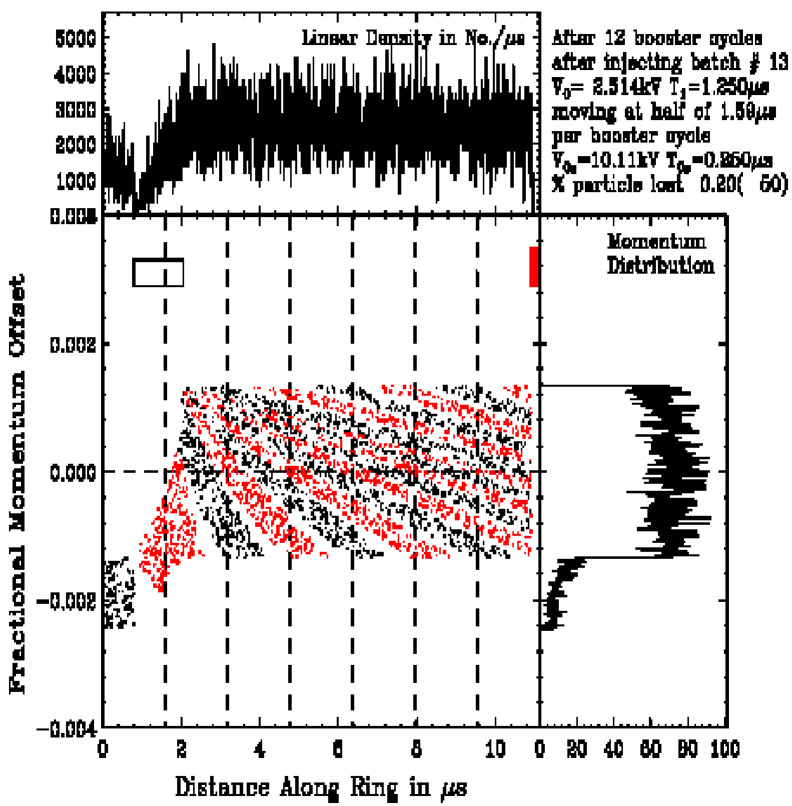


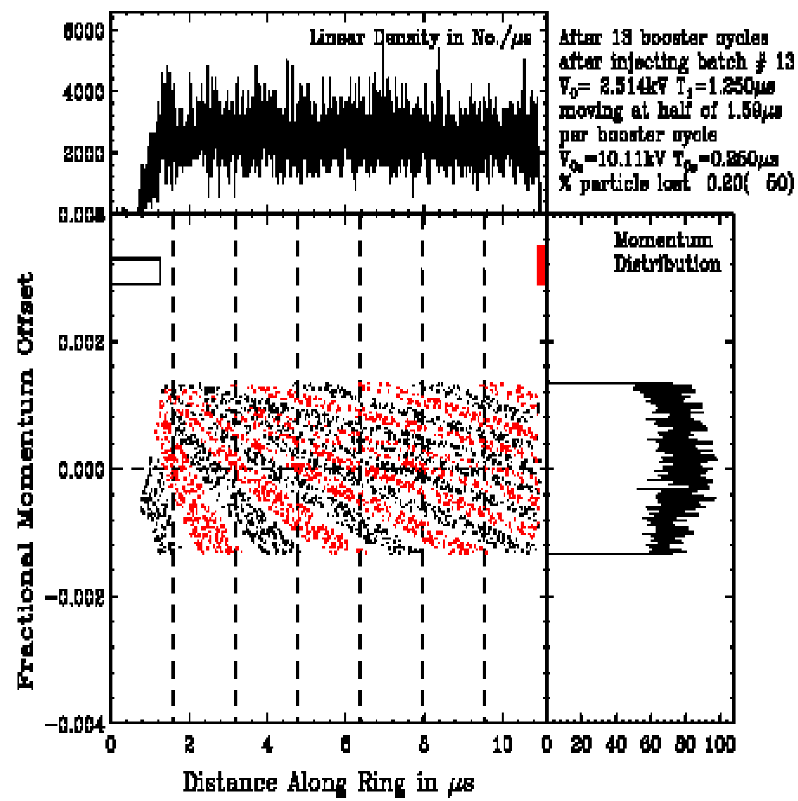
2-Batch Stacking
(Run2)



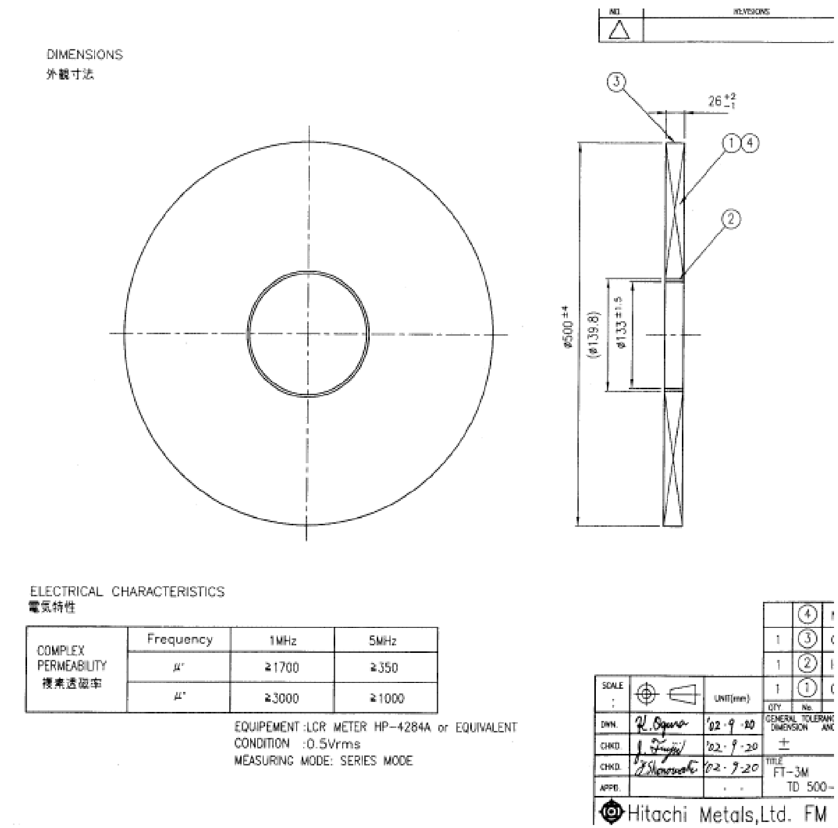


12-Batch Stacking
(NuMI)

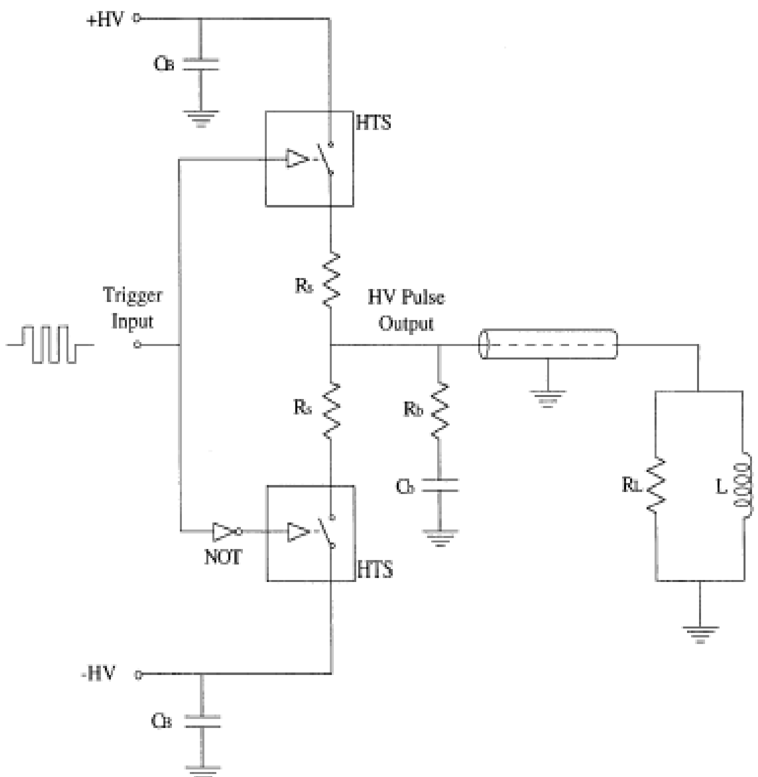




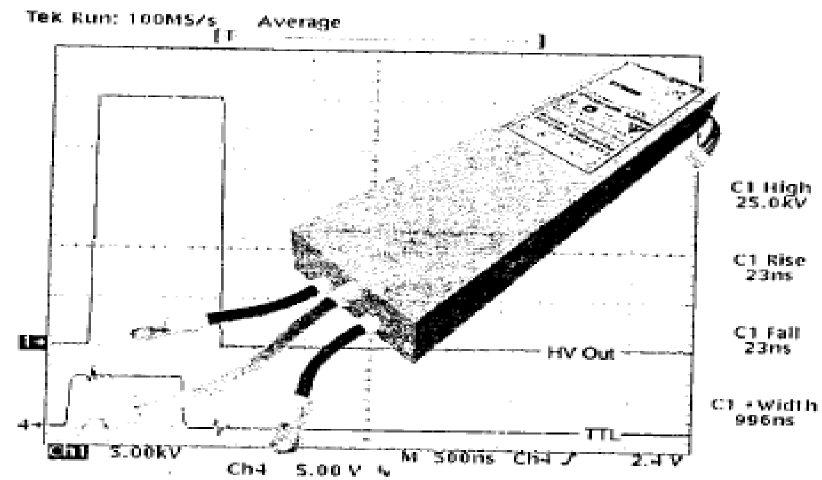
Finemet Core



High Voltage Fast Switch



HTS 161-06-GSM 2x16kV / 60A
HTS 301-03-GSM 2x30kV / 30A



- Fast transition times, rise time and fall time ~20 ns
- Variable pulse width from 200 ns to infinity
- No pulse droop and very low ripple on the pulse top
- No working resistor power, small buffer capacitors

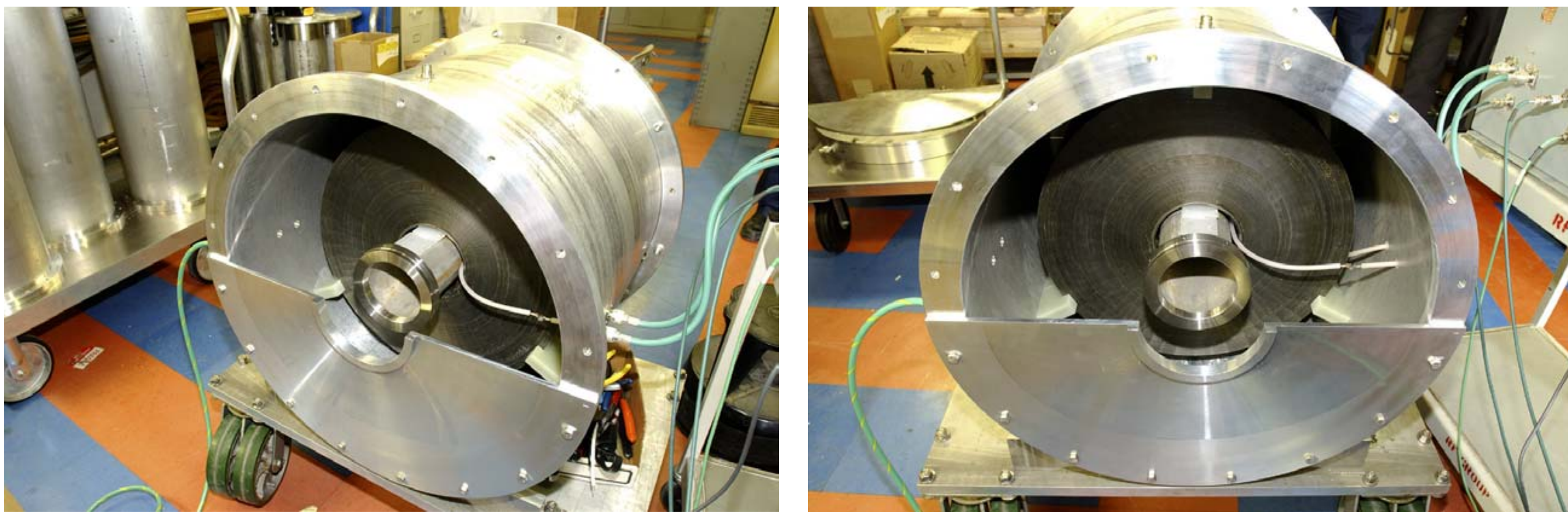
PUSH-PULL - Patented - Made in Germany **MOSFET TECHNOLOGY**

Building a Barrier RF System

A Fermilab-KEK-Caltech team

Barrier RF power supply

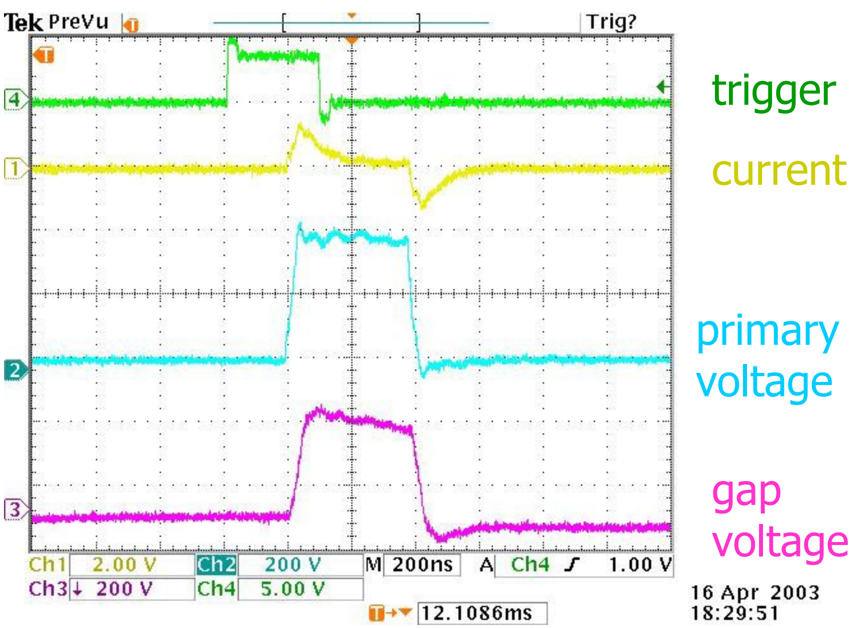
Building a Barrier RF System
(cont…)



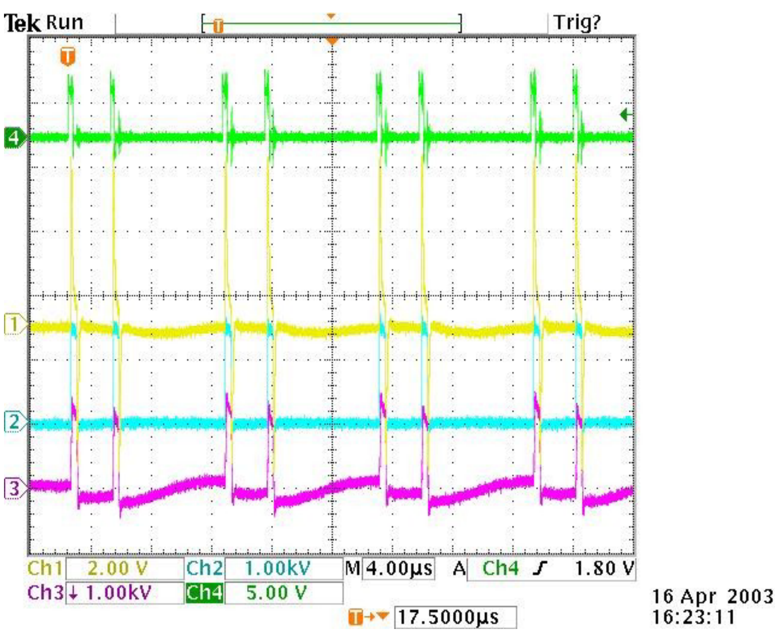
Barrier RF cavity

Testing a Barrier RF System

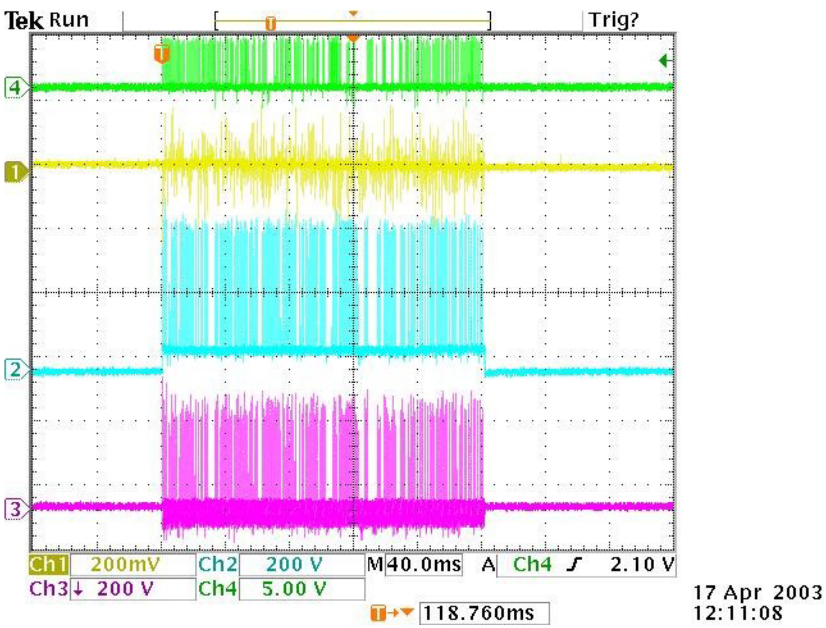
One barrier



Two barriers per MI period



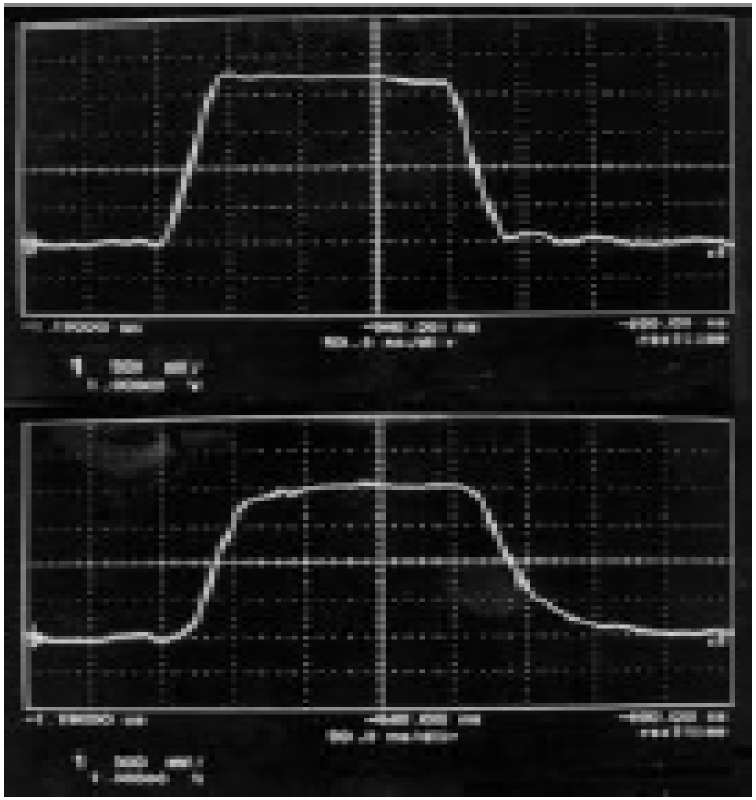
Testing a Barrier RF System (cont…)

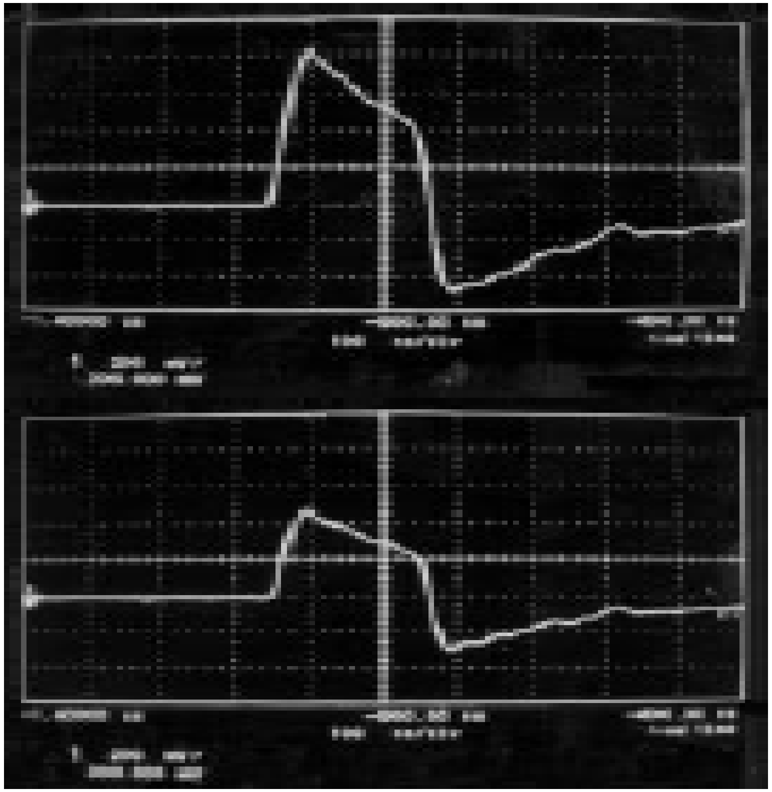


Burst length

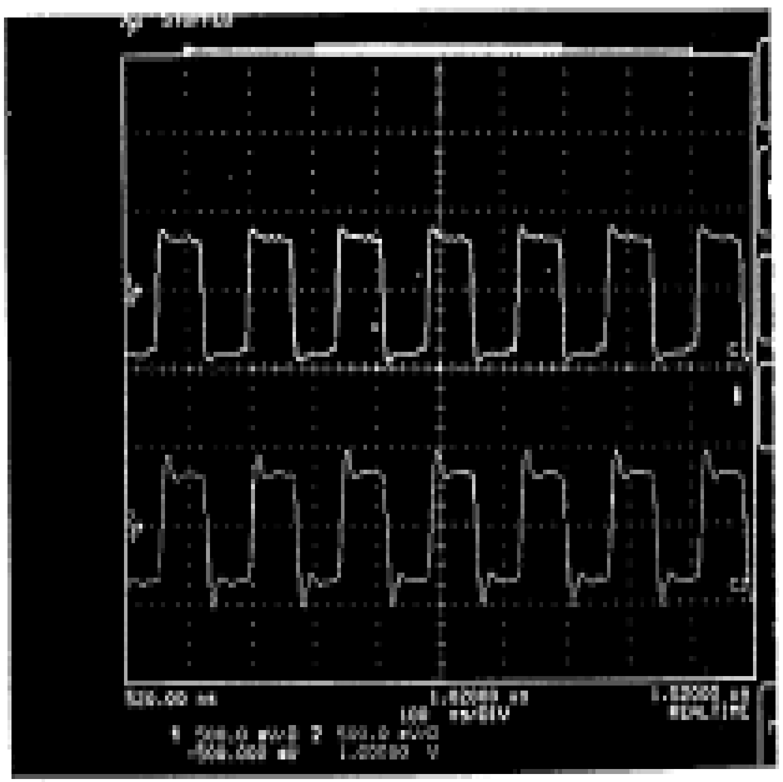
- The required burst length is 150 ms (2.2 Booster cycles); achieved 200 ms.
- The required peak voltage is 6 kV; achieved 4 kV.
- Waiting for two larger switches to raise the voltage to 6 kV.

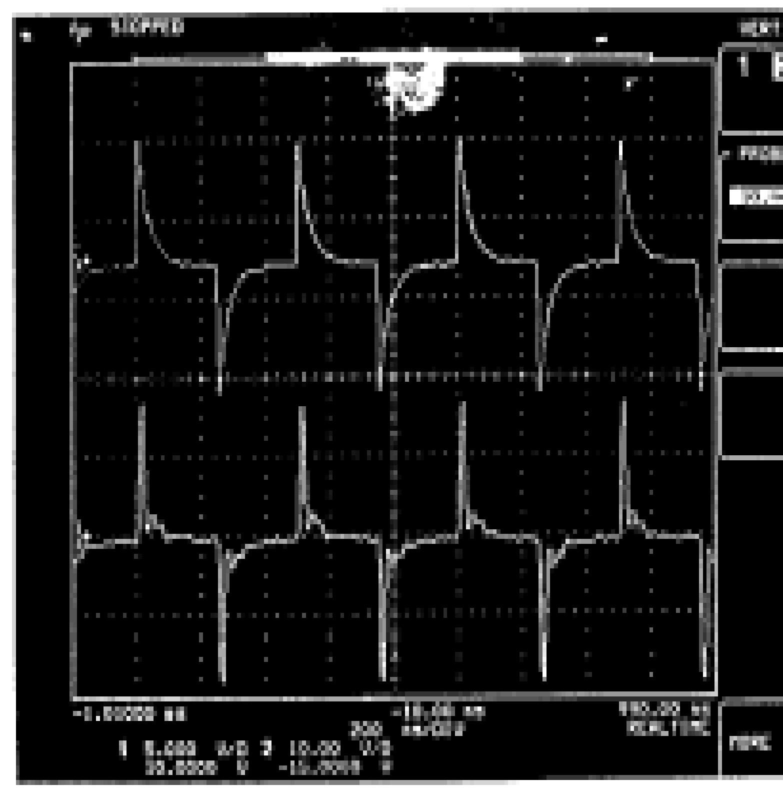
Finemet *vs.* Ferrite (4M2)





Finemet *vs.* Ferrite (4M2)
(cont…)





Barrier RF Stacking *vs.* Slip Stacking

- One main advantage of barrier RF stacking is smaller beam loading effect thanks to lower peak beam current
- Another "advantage" is that we didn't know much about this method and have never tried. (By contrast, we already know how hard slip stacking is.)

Key Issue

- Booster beam must have a small $\Delta E/E$ to start with (required ΔE about ± 6 MeV)
- This means one has to control the instability of the Booster beam:
  - longitudinal damper (D. Wildman)
  - RF frequency modulation for Landau damping (TBA)
  - bunch rotation prior to extraction (K. Koba)

Questions?