Barrier RF Study at Fermilab

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Seminar Talk at the KEK PS Division

Barrier RF Study Group

Fermilab-KEK-Caltech collaboration

- Fermilab:

  D. Wildman, J. Griffin, K.Y. Ng, J. MacLachlan, W. Chou

- KEK:

  A. Takagi, Y. Mori

- Caltech:

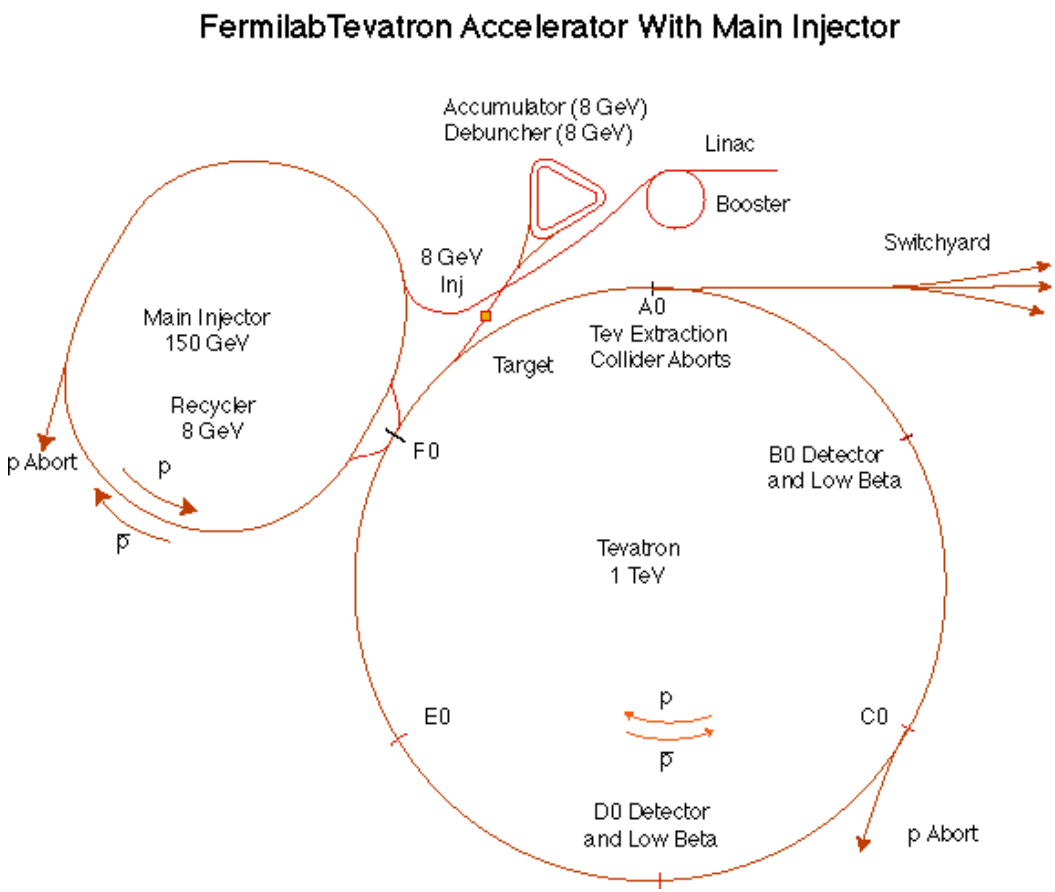
  H. Zhang, D. Michael

Outline

- Bottleneck at Fermilab
- Stacking: motivation, goals and method
- Simulations
- Hardware
- Bench test
- Summary
- *(Bonus topic: The dogleg effect)*

http://www-bd.fnal.gov/pdriver/barrier/

Fermilab Accelerator Complex



Bottleneck Phenomenon

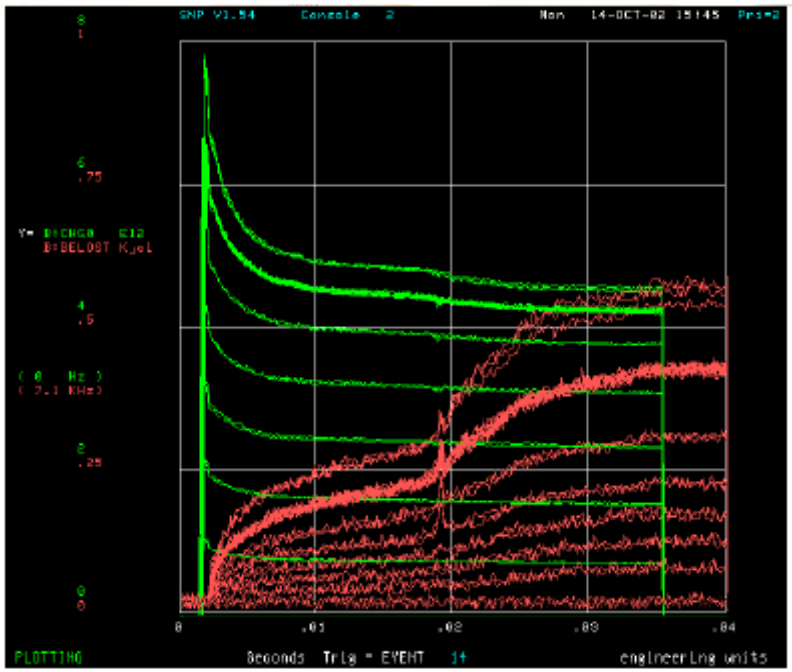
- When a lab has multiple accelerators in a chain (e.g., Fermilab, CERN, DESY, BNL, etc.), these machines are usually balanced.
- However, for historical reasons, this is not the case at Fermilab. It has a bottleneck in the chain.
- The bottleneck used to be the Main Ring.
  - When the Tevatron was built in the same tunnel of the Main Ring, the Main Ring was modified to have an overpass around the detector CDF and became a true 3-dimensional machine. This greatly reduced the machine acceptance.
- In 1999 the Main Ring was replaced by the Main Injector. This bottleneck was removed.
- However, the Fermilab accelerator chain is still not balanced. The Booster now becomes a bottleneck.

Bottleneck Phenomenon (cont…)

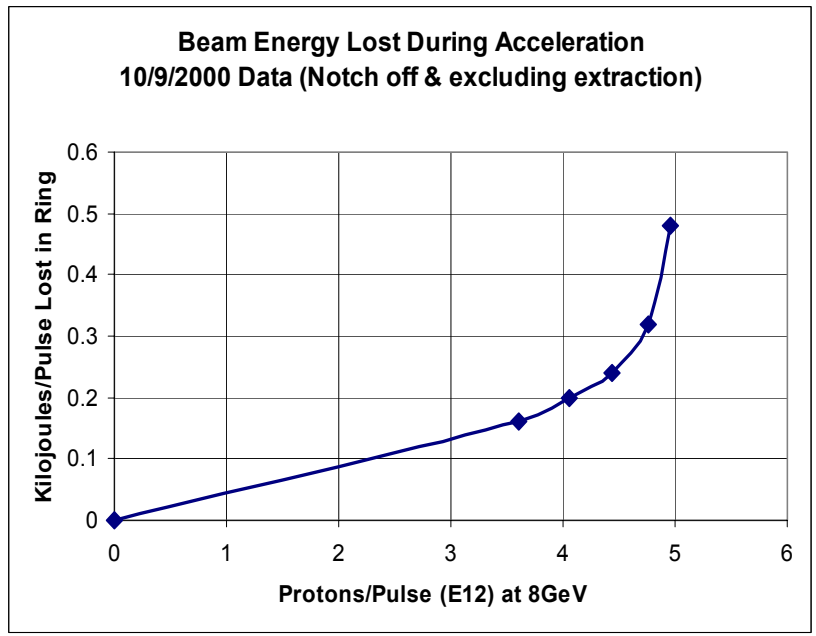
- The Booster is a 30 years old machine and has never been upgraded.
- The 400-MeV Linac can provide 25e12 particles per Booster cycle.
- The 120-GeV Main Injector can accept 25e12 protons per Booster cycle.
- However, the 8-GeV Booster can only deliver 5e12 particles per cycle.

Booster Beam Loss

(courtesy R. Webber)



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



Solution - Stacking

- A solution is to stack two Booster bunches into one Main Injector RF bucket
- This is possible because the Main Injector momentum acceptance (0.4 eV-s) is larger than the Booster beam emittance (0.1 eV-s)

Motivation

- To increase the Tevatron luminosity in Run2 by increasing the proton intensity on the pbar production target (2 x 1 Booster batch)
- To increase the neutrino flux in NuMI experiment by increasing the proton intensity on the pion production target (2 x 6 Booster batches)

Stacking Goals

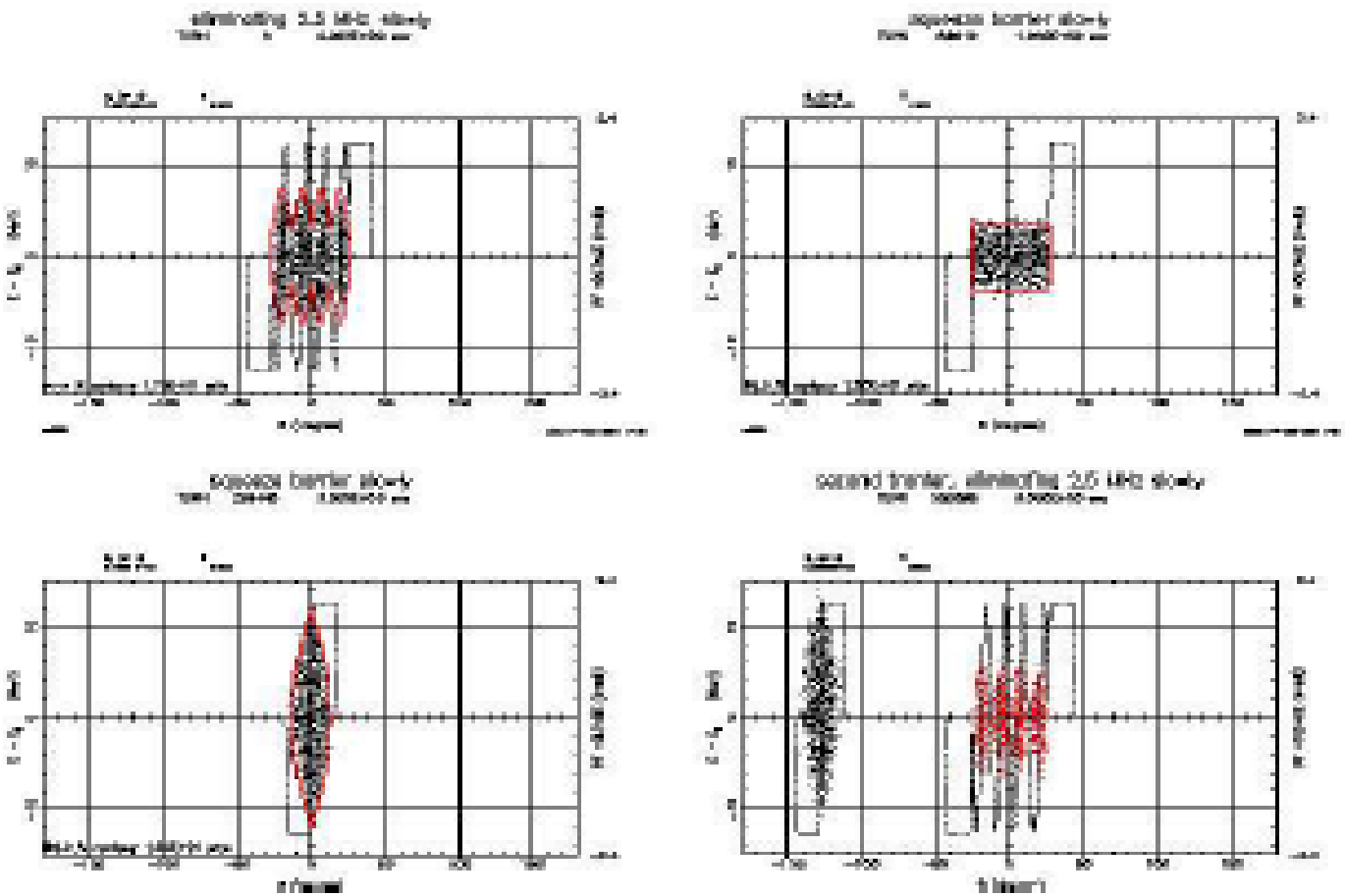
- Goal for Run2 – To increase protons per second (pps) on the pbar target by 50%
  - Present: 5e12 every 1.467 sec
  - Goal: 2 x 5e12 every 2 sec
- Goal for NuMI – To increase pps on the NuMI target by 60%
  - Baseline: 3e13 every 1.867 sec
  - Goal: 2 x 3e13 every 2.333 sec

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

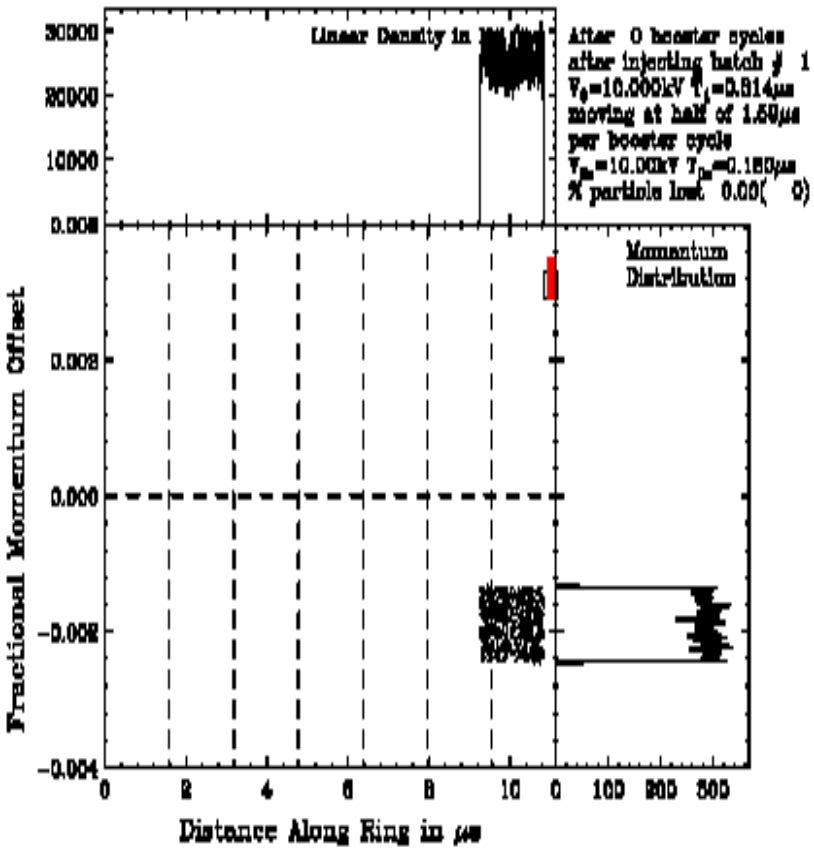
Injection On-Axis

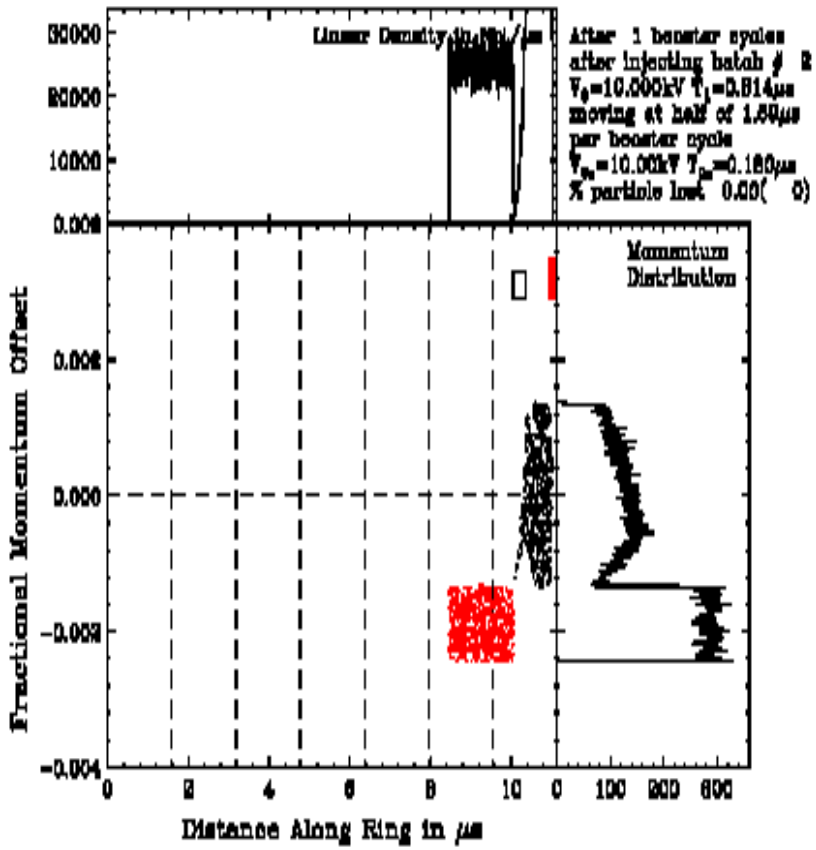
(Recycler, courtesy C. Bhat)



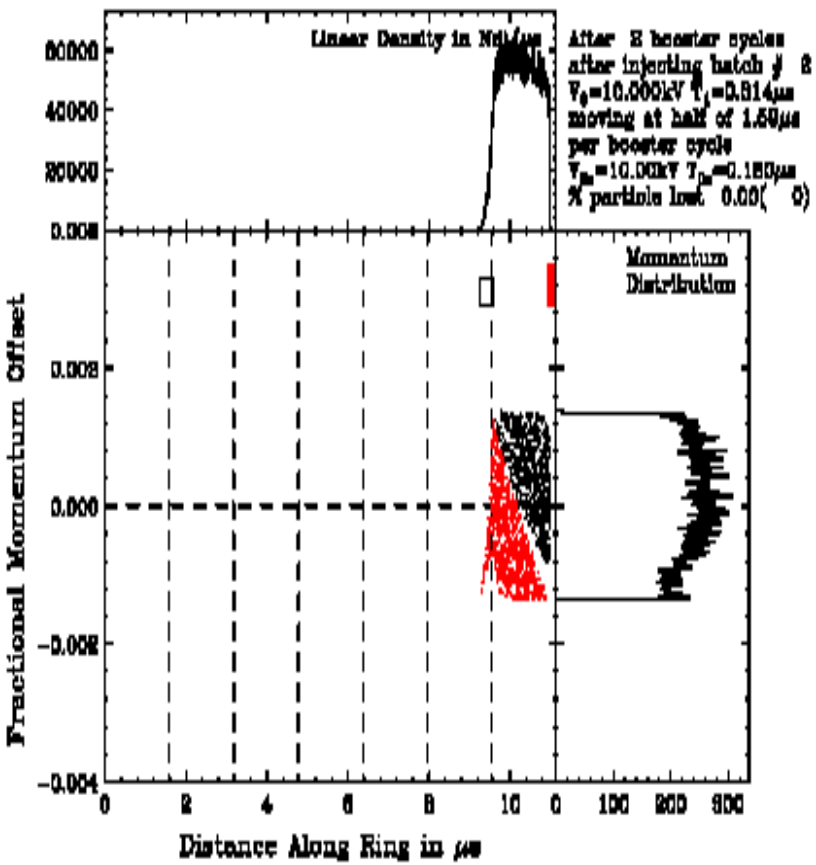
Injection Off-Axis: 2-Batch Stacking

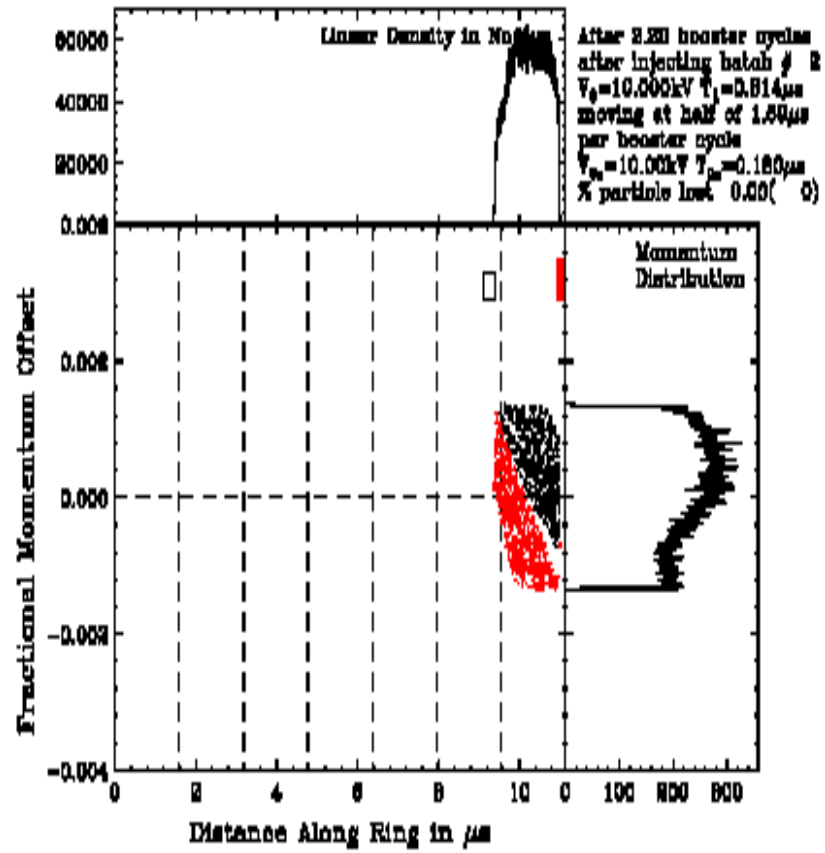
(courtesy K.Y. Ng)





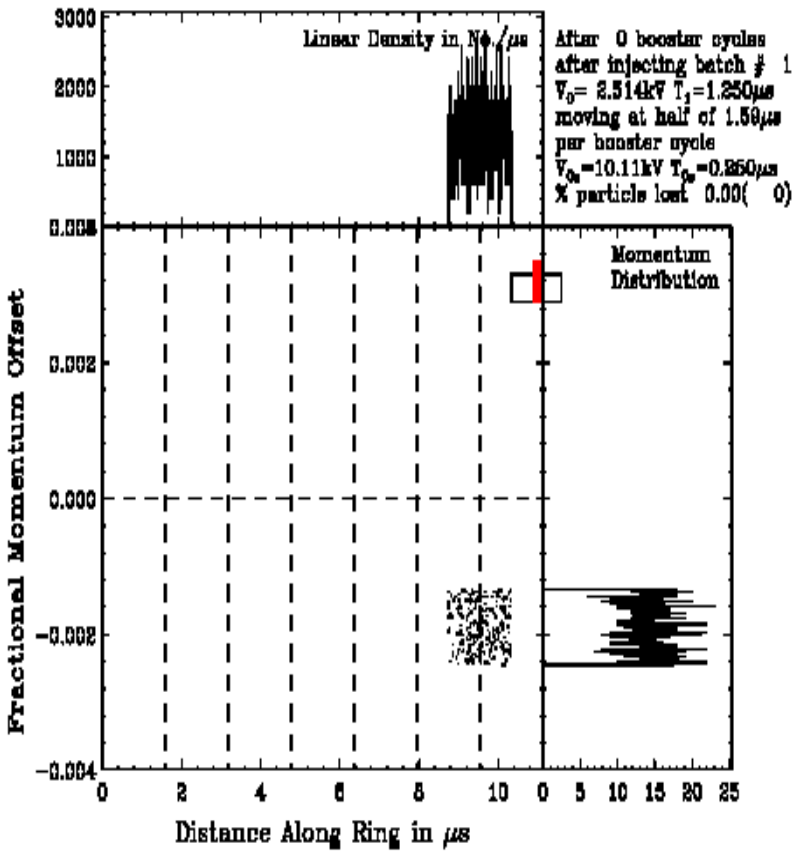
2-Batch Stacking (cont…)

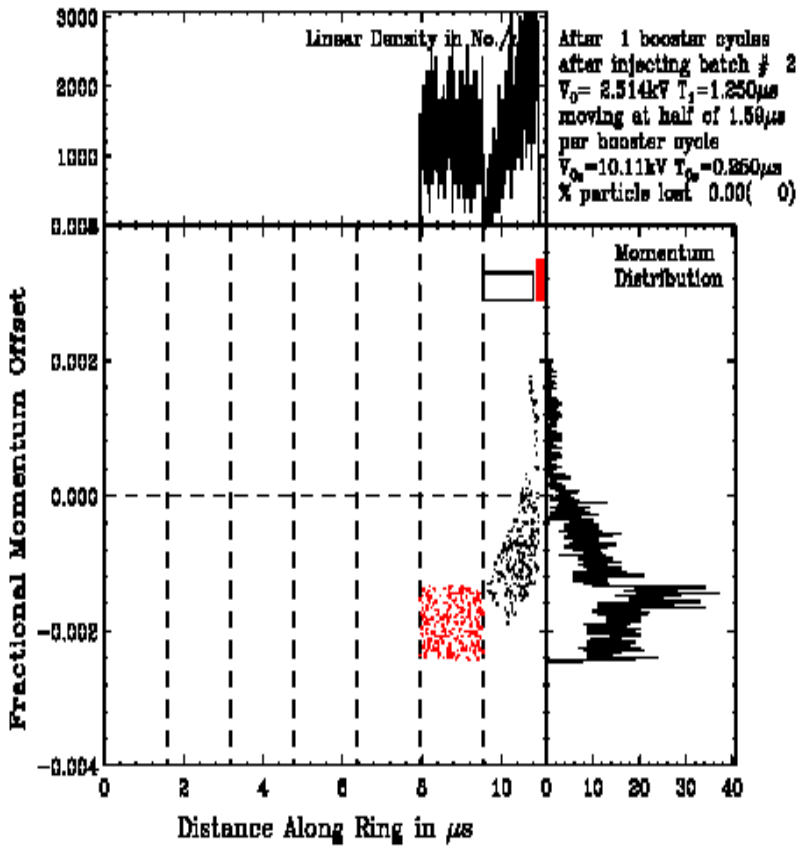




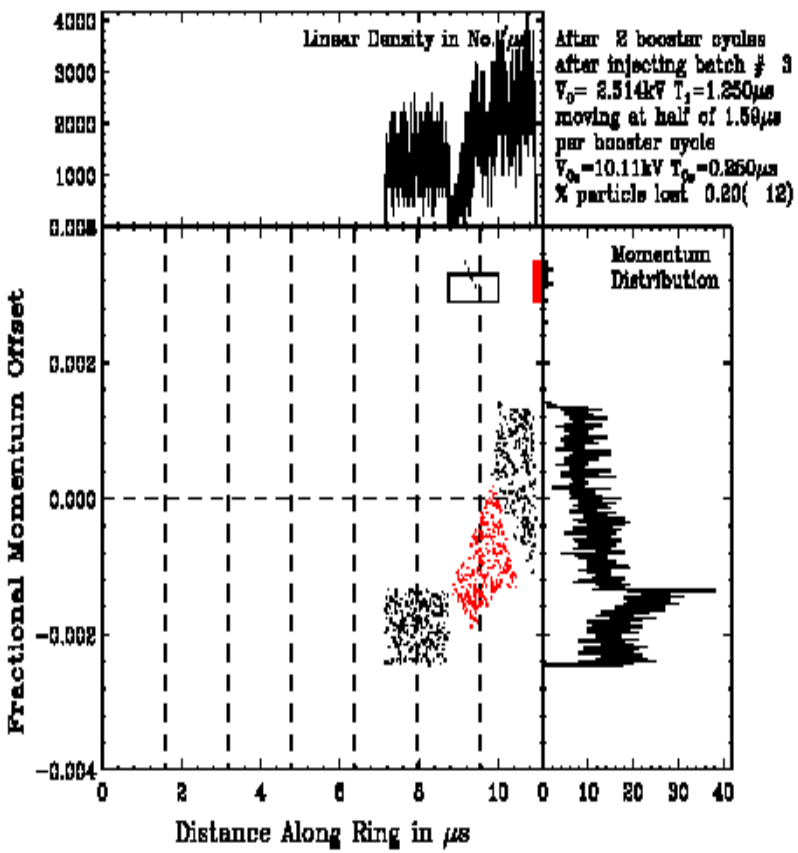
Injection Off-Axis: 12-Batch Stacking

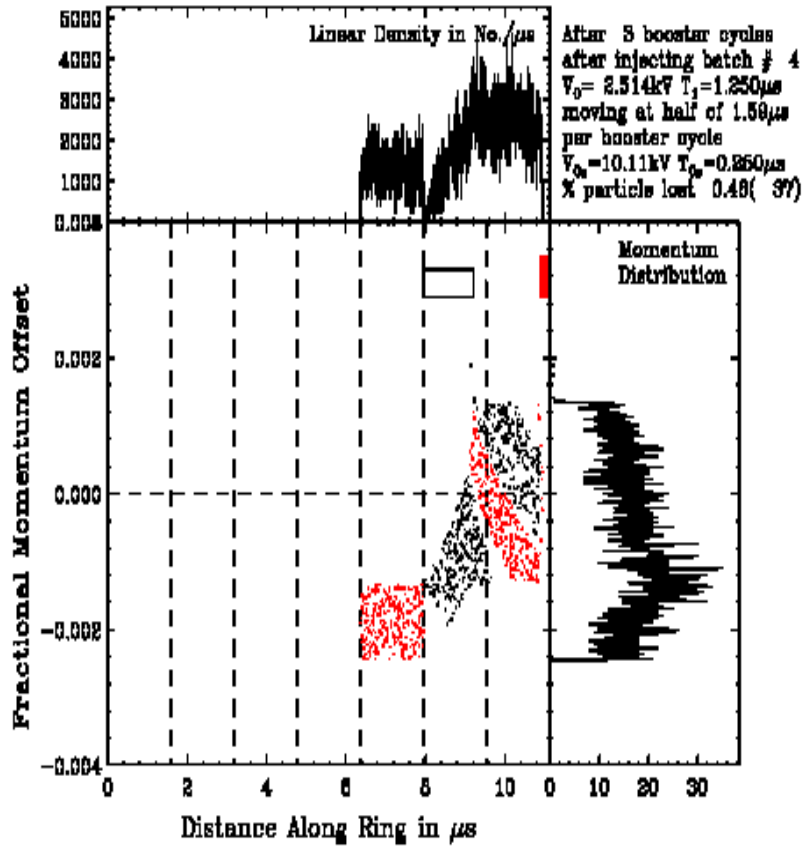
(courtesy K.Y. Ng)



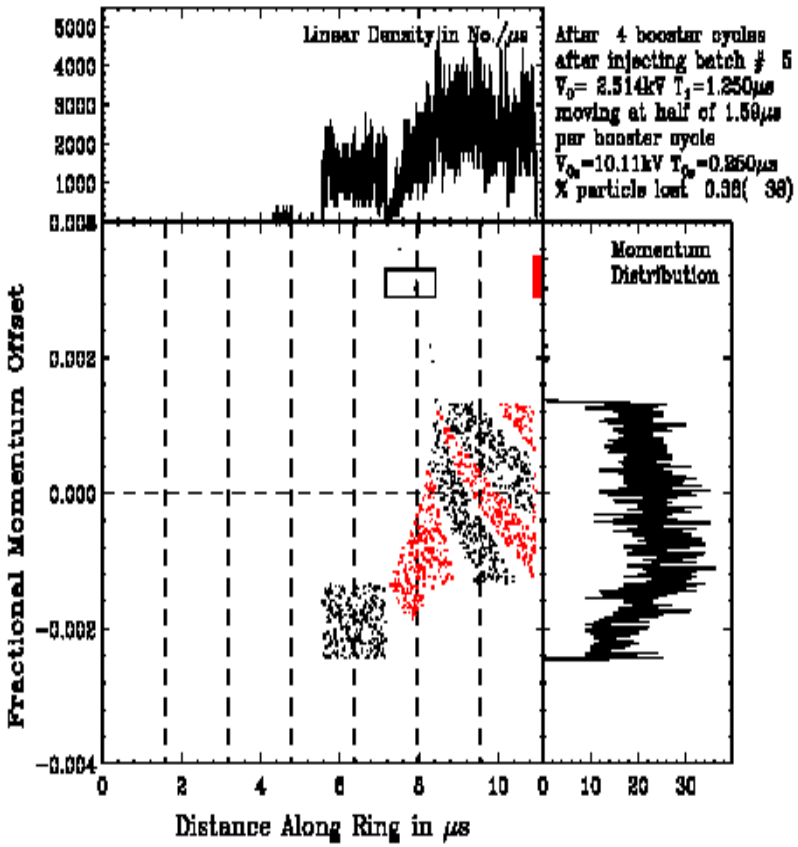


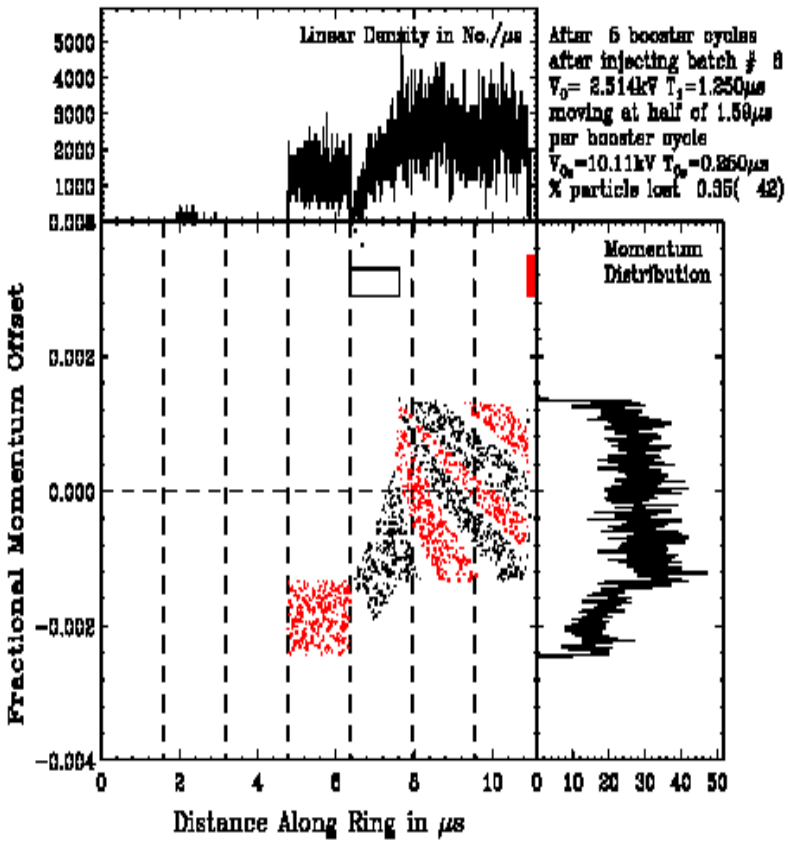
12-Batch Stacking (cont…)



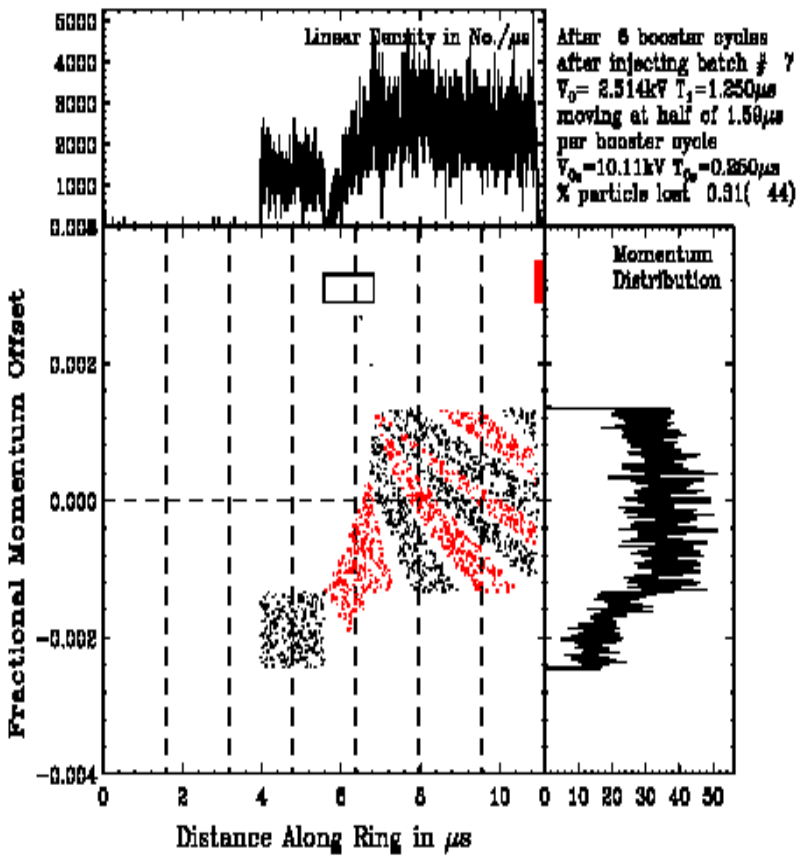


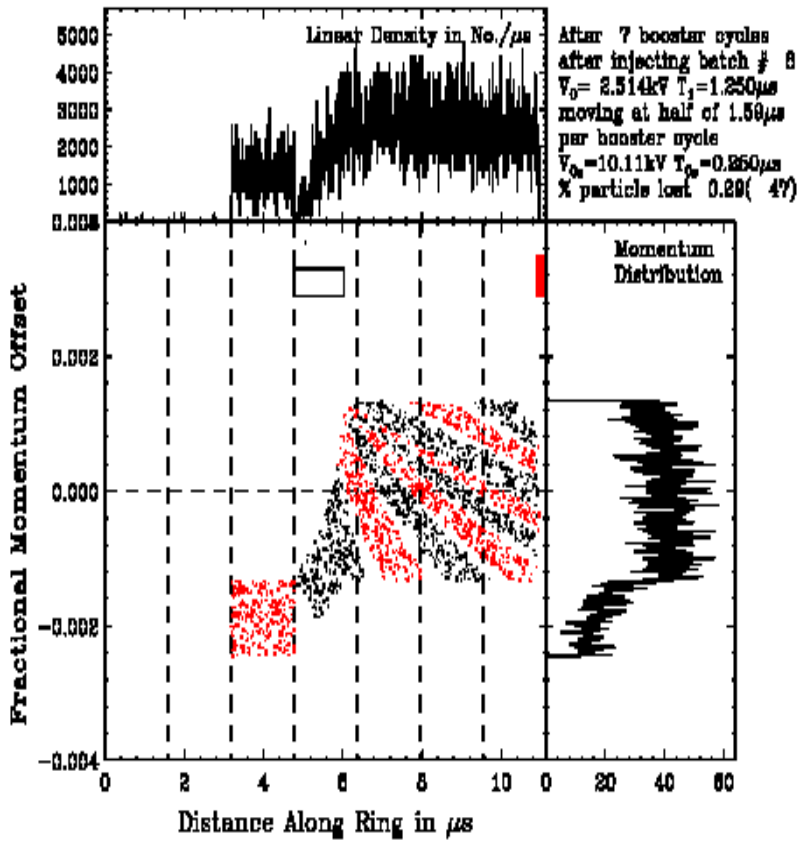
12-Batch Stacking (cont…)



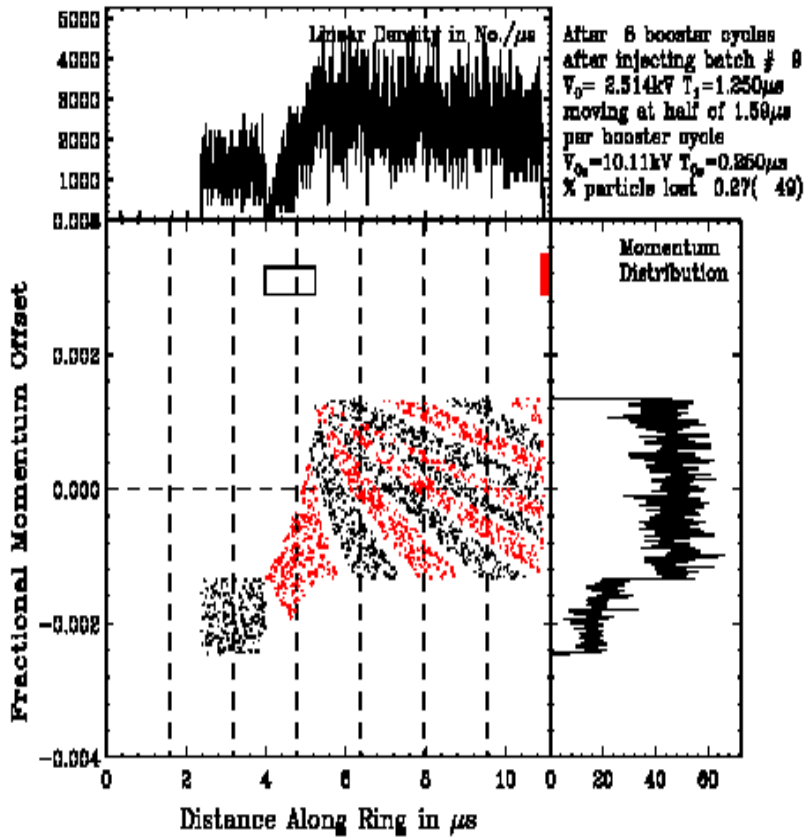


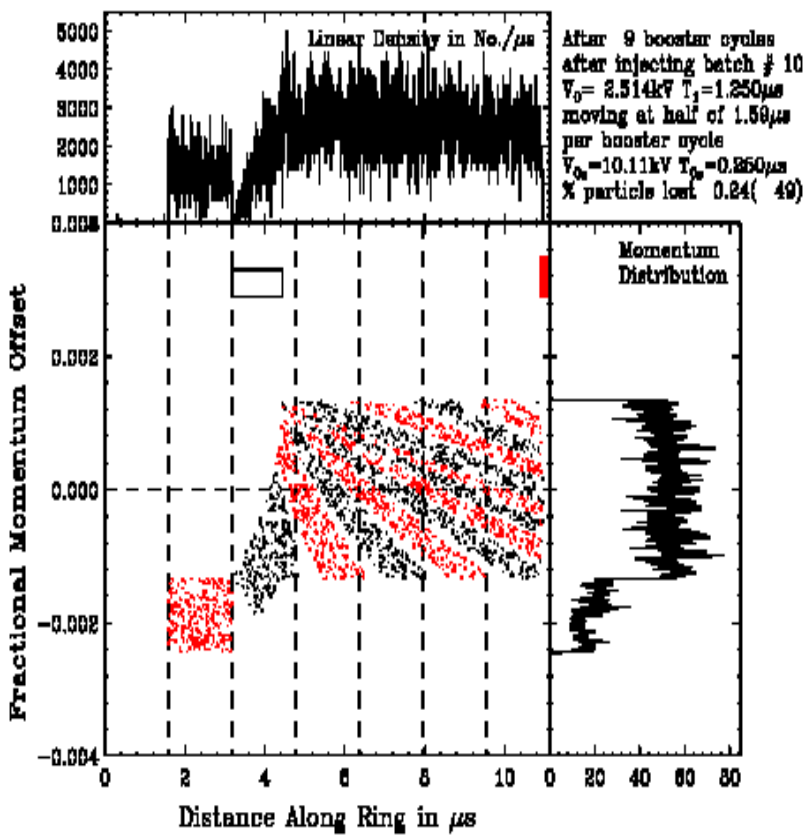
12-Batch Stacking (cont…)



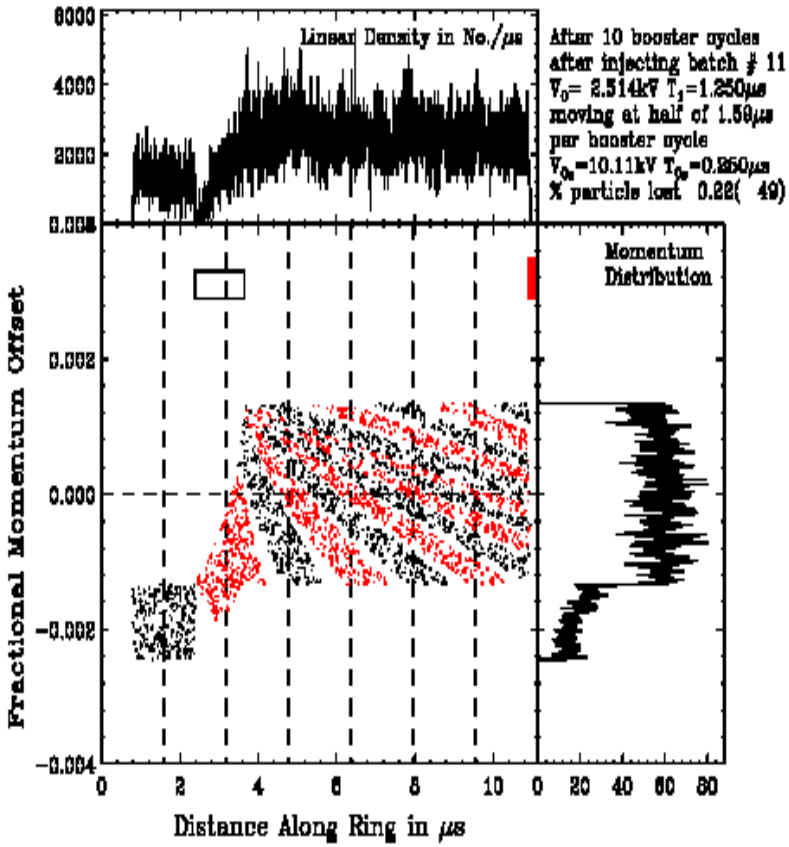


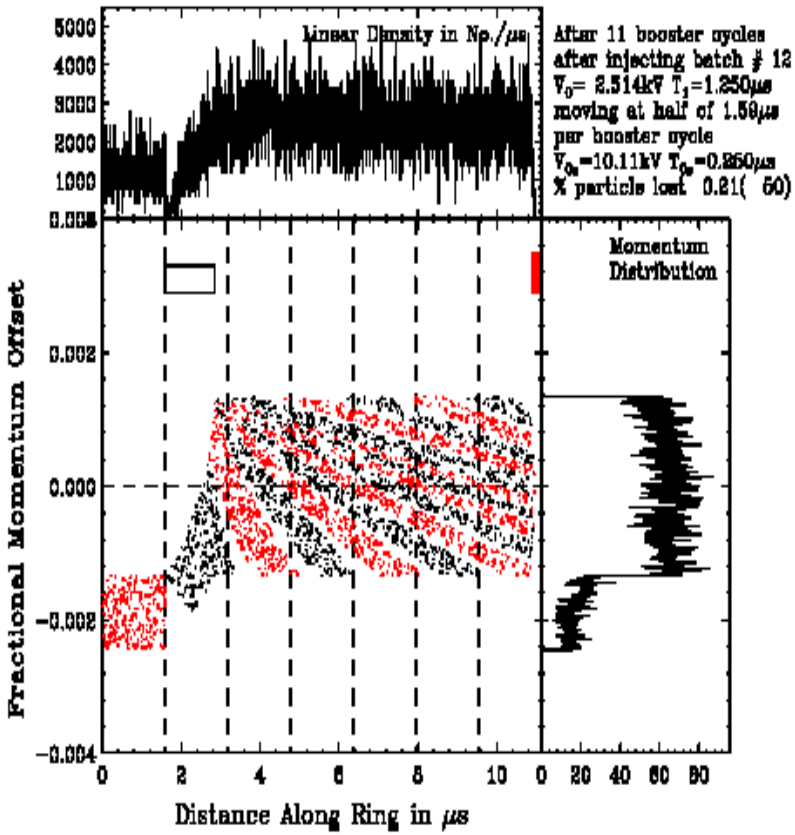
12-Batch Stacking (cont…)



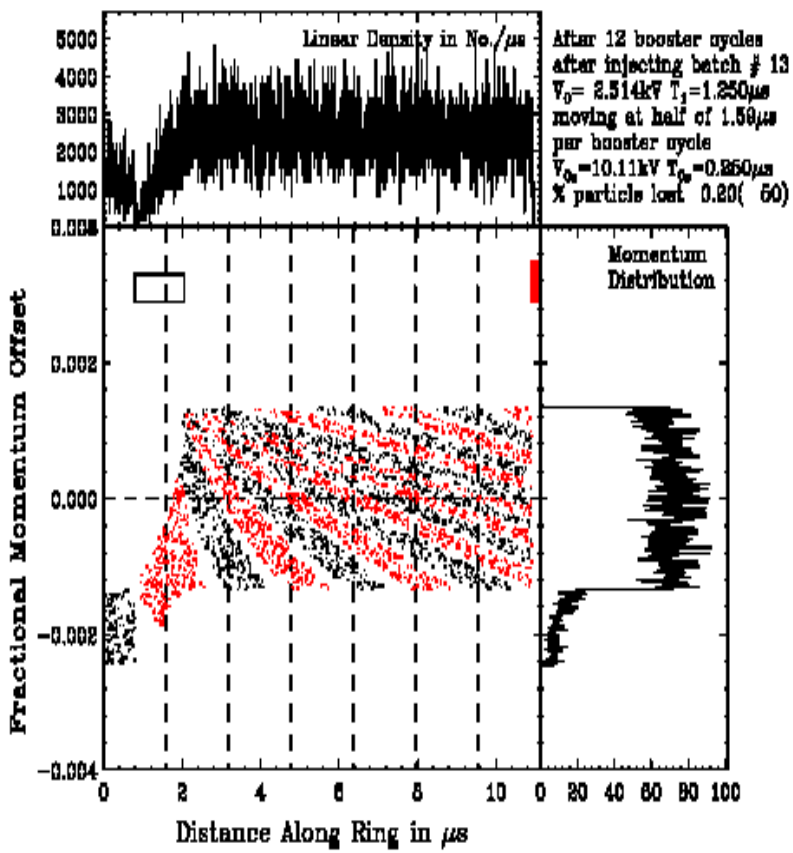


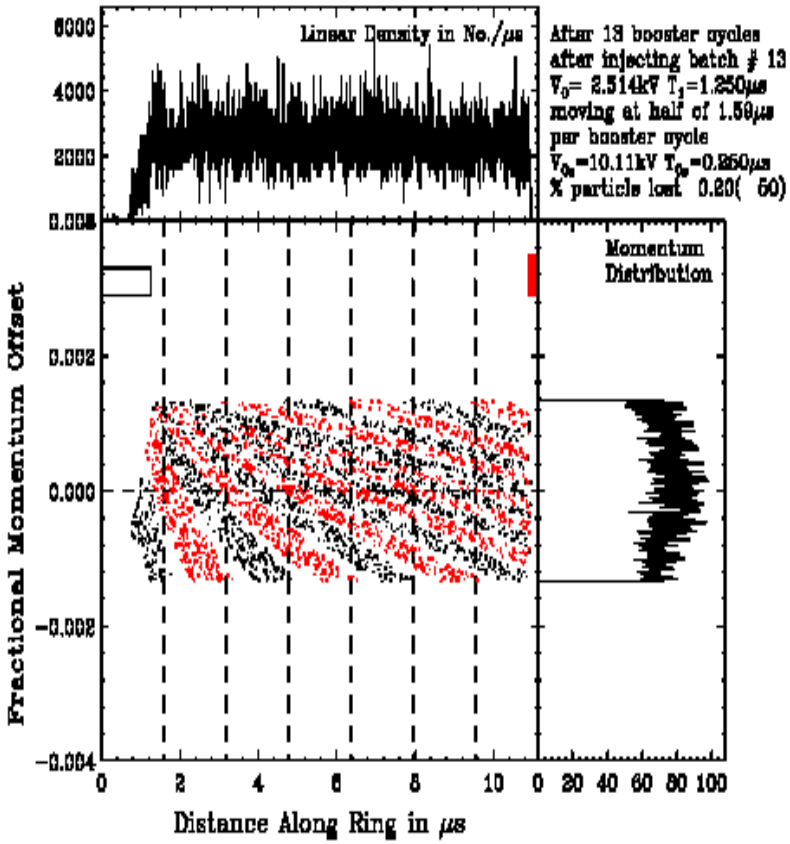
12-Batch Stacking (cont…)

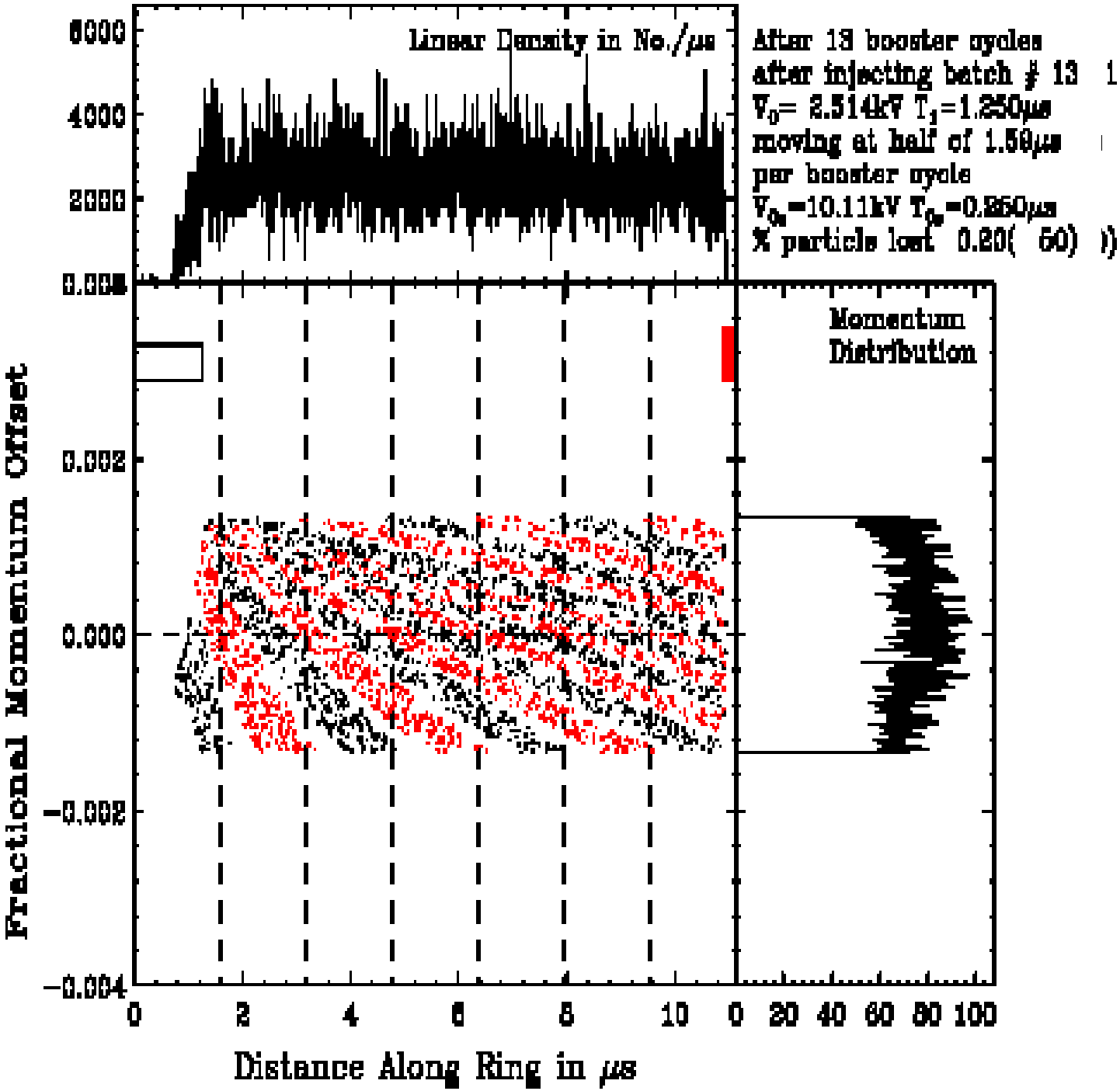




12-Batch Stacking (cont…)





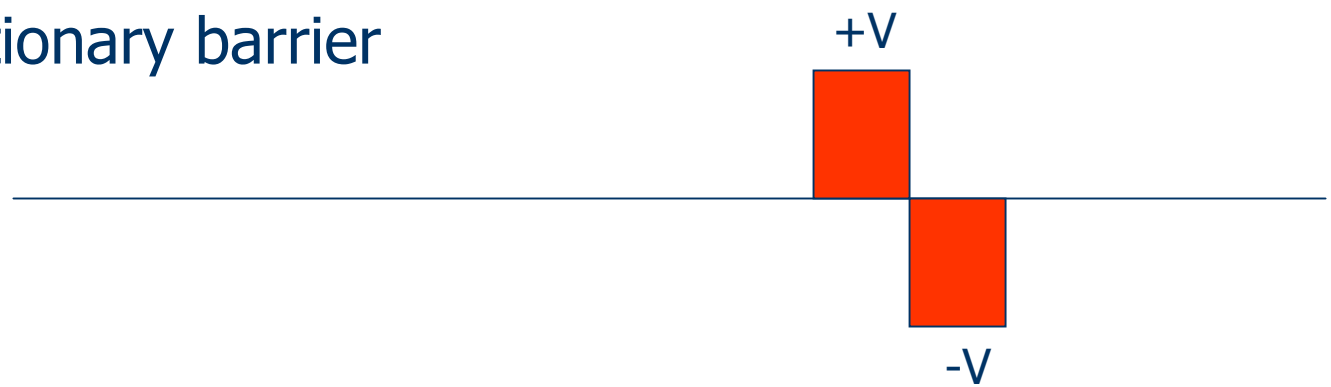

Linear Density in No./μs
After 13 booster cycles
after injecting batch # 13
V0= 2.514kV T1=1.250μs
moving at half of 1.59μs
per booster cycle
V0a=10.11kV T0a=0.250μs
% particle lost 0.20(60)
Momentum
Distribution
Fractional Momentum Offset
Distance Along Ring in μs
6000
4000
2000
0.002
0.000
−0.002
−0.004
0
2
4
6
8
10
20
40
60
80
100

Hardware

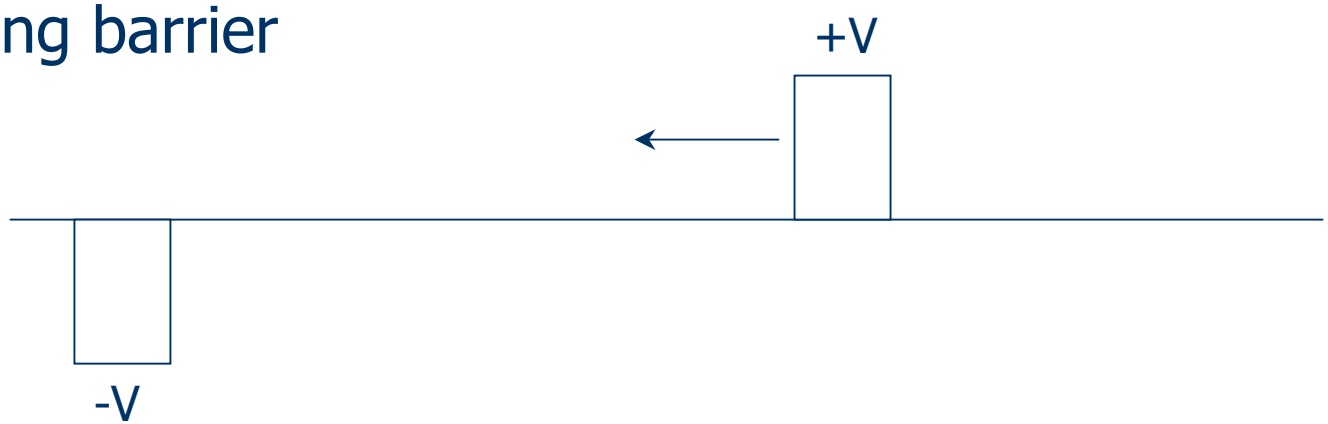
- Task: To build a $\pm$ 6 kV wideband RF system (i.e, the barrier RF)
- Cavity: Based on the design of an RF chopper built at Chiba by a KEK-Fermilab team; using Finemet cores made by Hitachi Metals
- Switch circuit: Also based on the design of the RF chopper; using high voltage solid-state switches made by Behlke Co. (Germany)

Two Types of Barrier

Stationary barrier

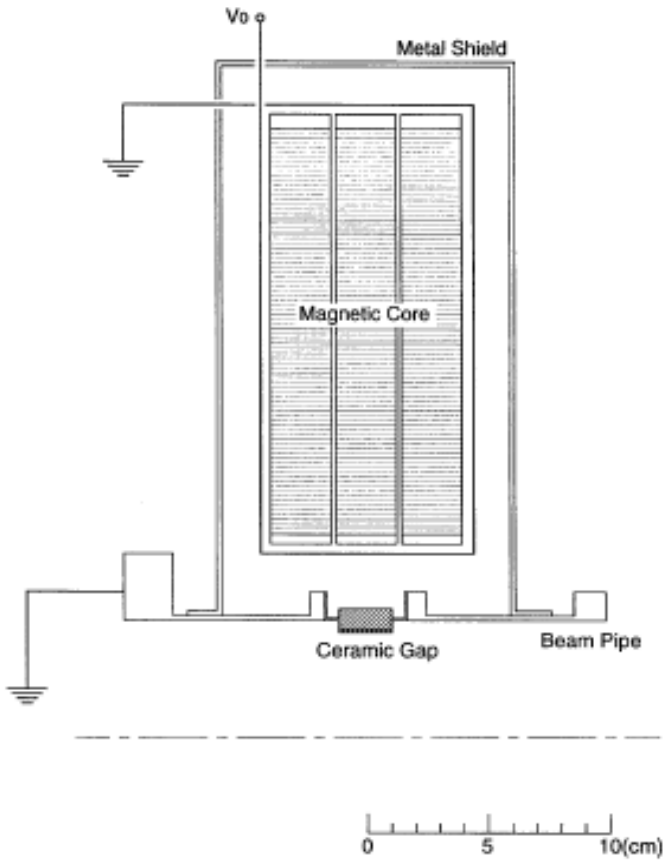


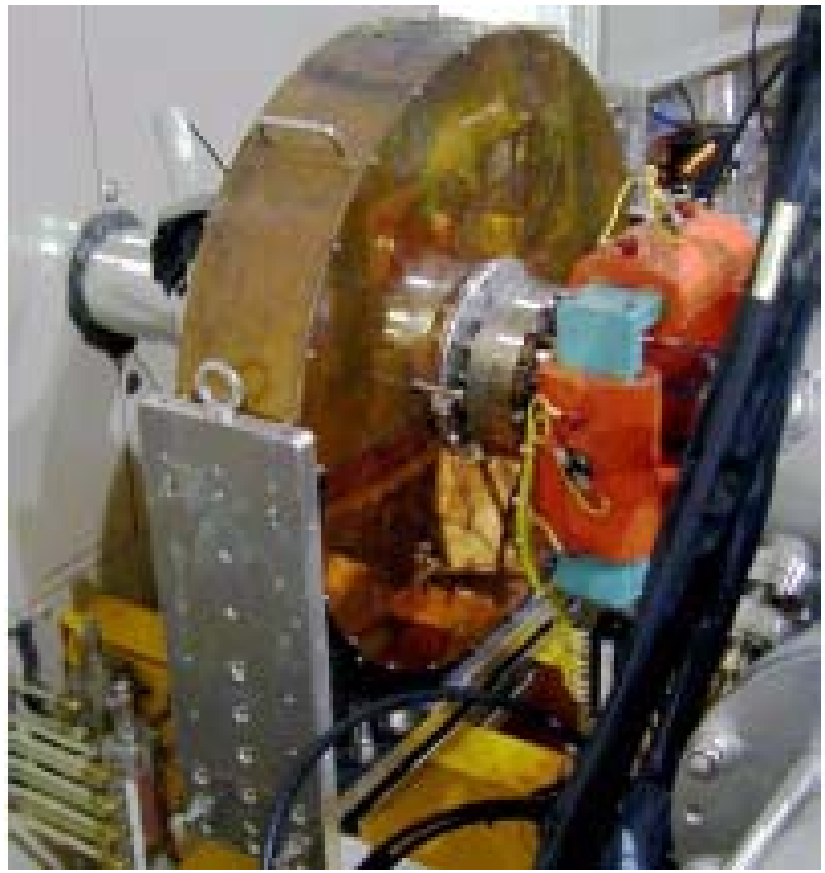
Moving barrier



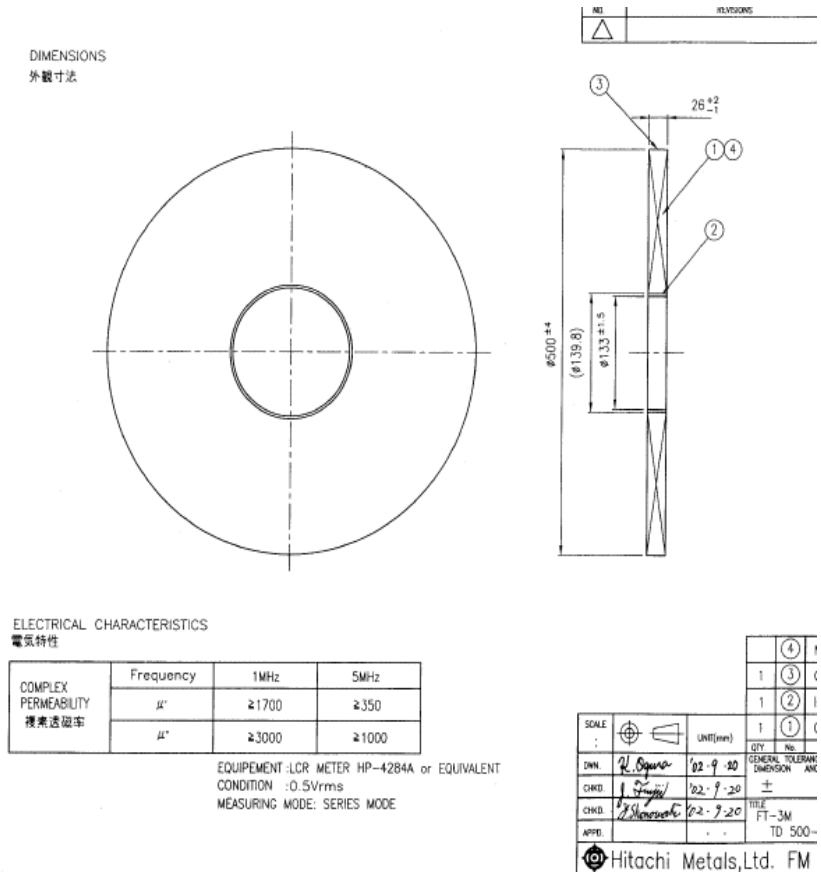
Finemet Cavity as a Chopper

(installed on the linac of HIMAC in Chiba)





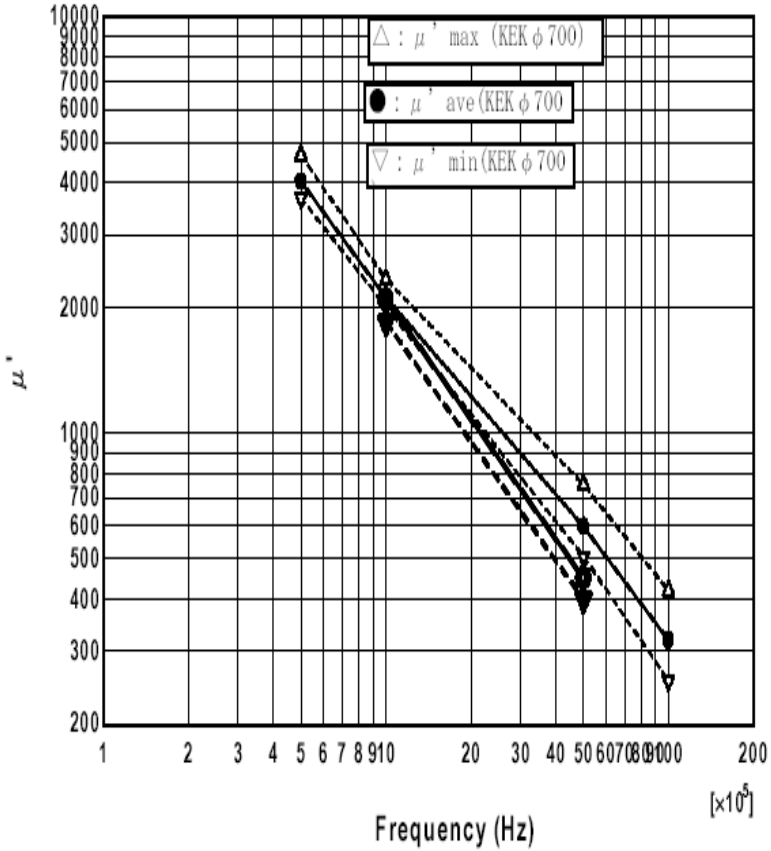
Finemet Core

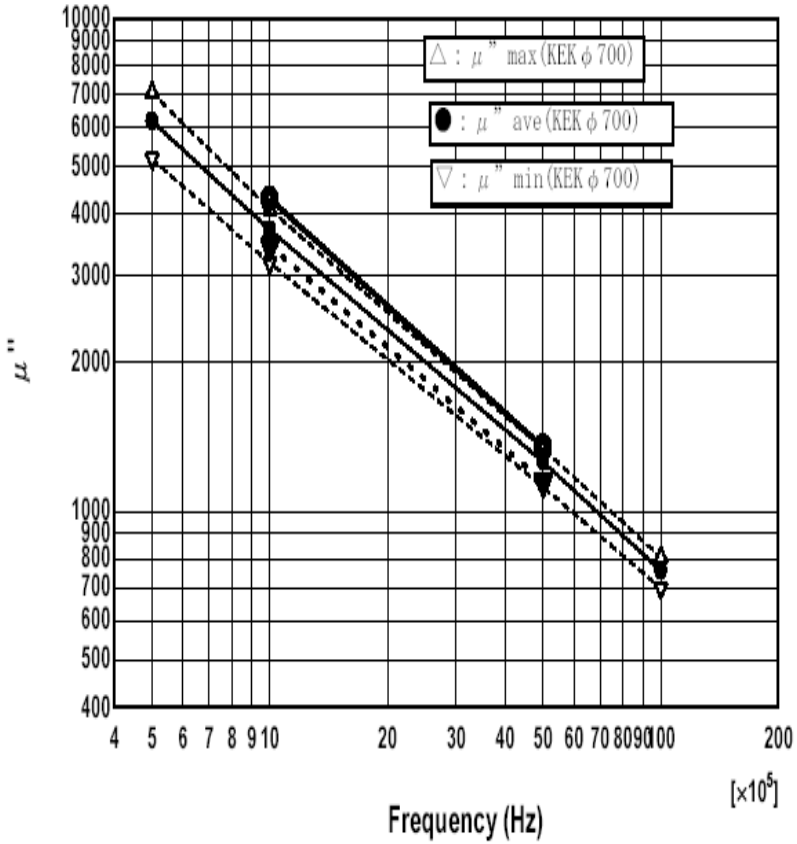


Finemet Core Specs

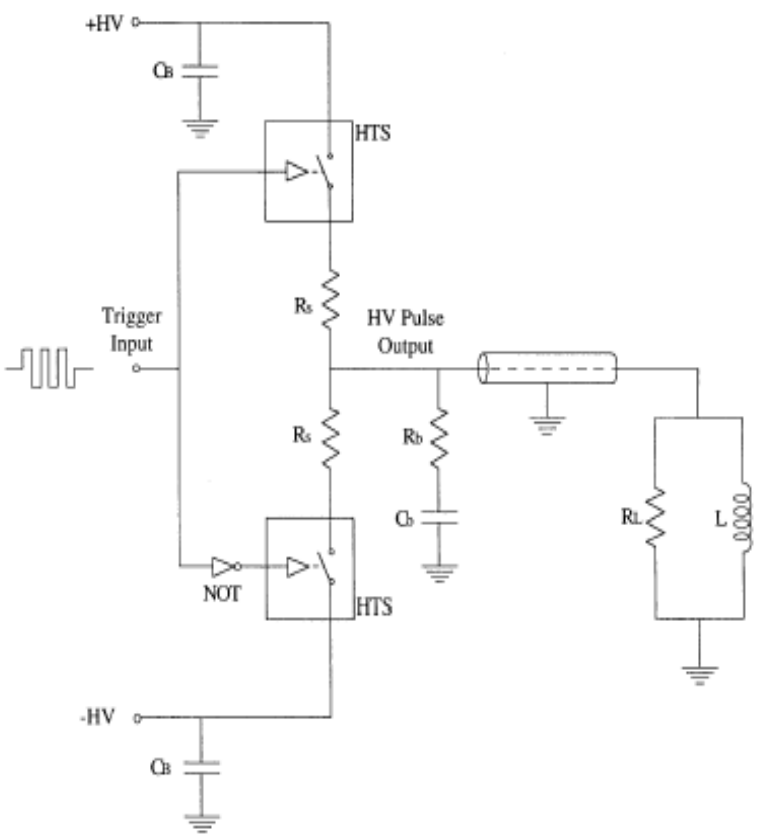
OD	500 mm
ID	139.8 mm
thickness	25 mm
Stainless steel mandrel OD	139.8 mm
Stainless steel mandrel ID	133 mm
Mandrel thickness	3.4 mm
Inductance	56 μH (per core)
Resistance	190 Ω (per core)

Finemet Core (cont…)



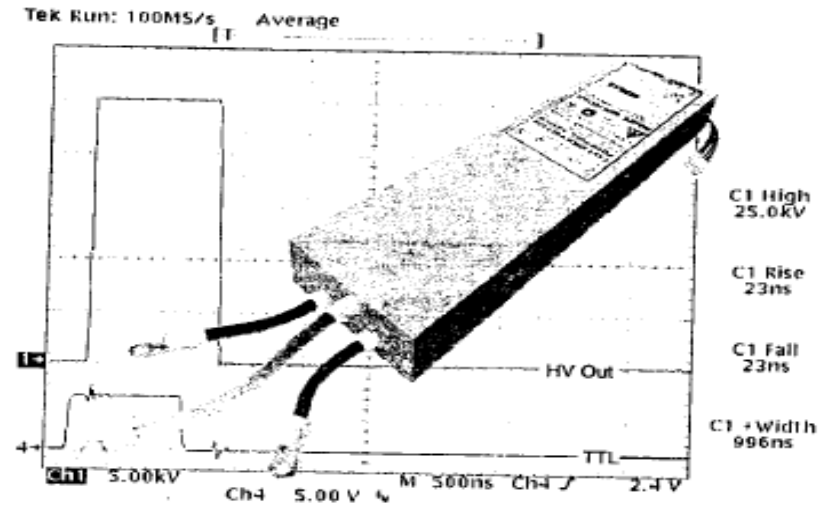


Behlke Switch



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

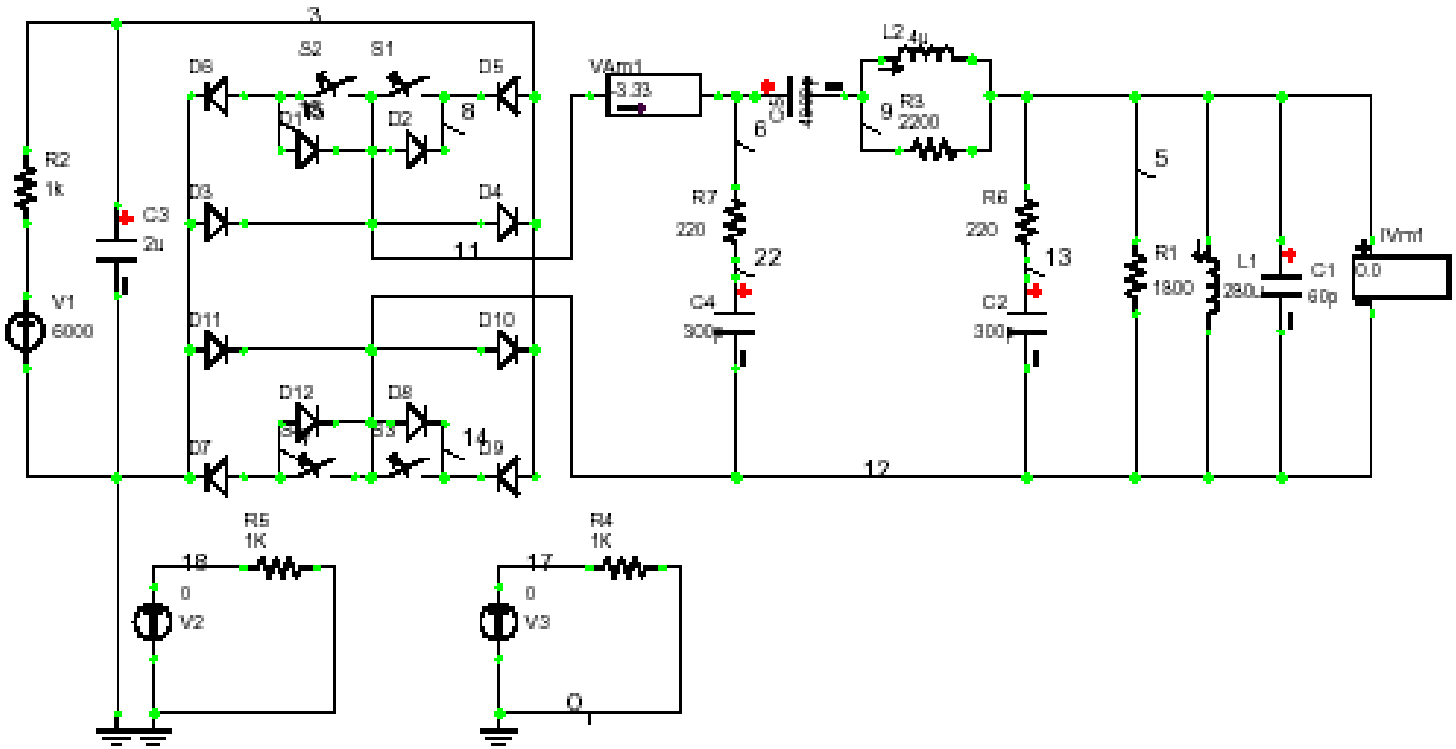
PUSH-PULL - Patented - Made in Germany **MOSFET TECHNOLOGY**

High-Voltage Fast Switch Specs

Pulse peak voltage	$\pm$ 6 kV
Pulse width	0.3 μs
Gap between a pair of pulses	0 – 11 μs
Pulse repetition rate	100 kHz
Burst length	150 ms
Burst repetition rate	0.5 Hz

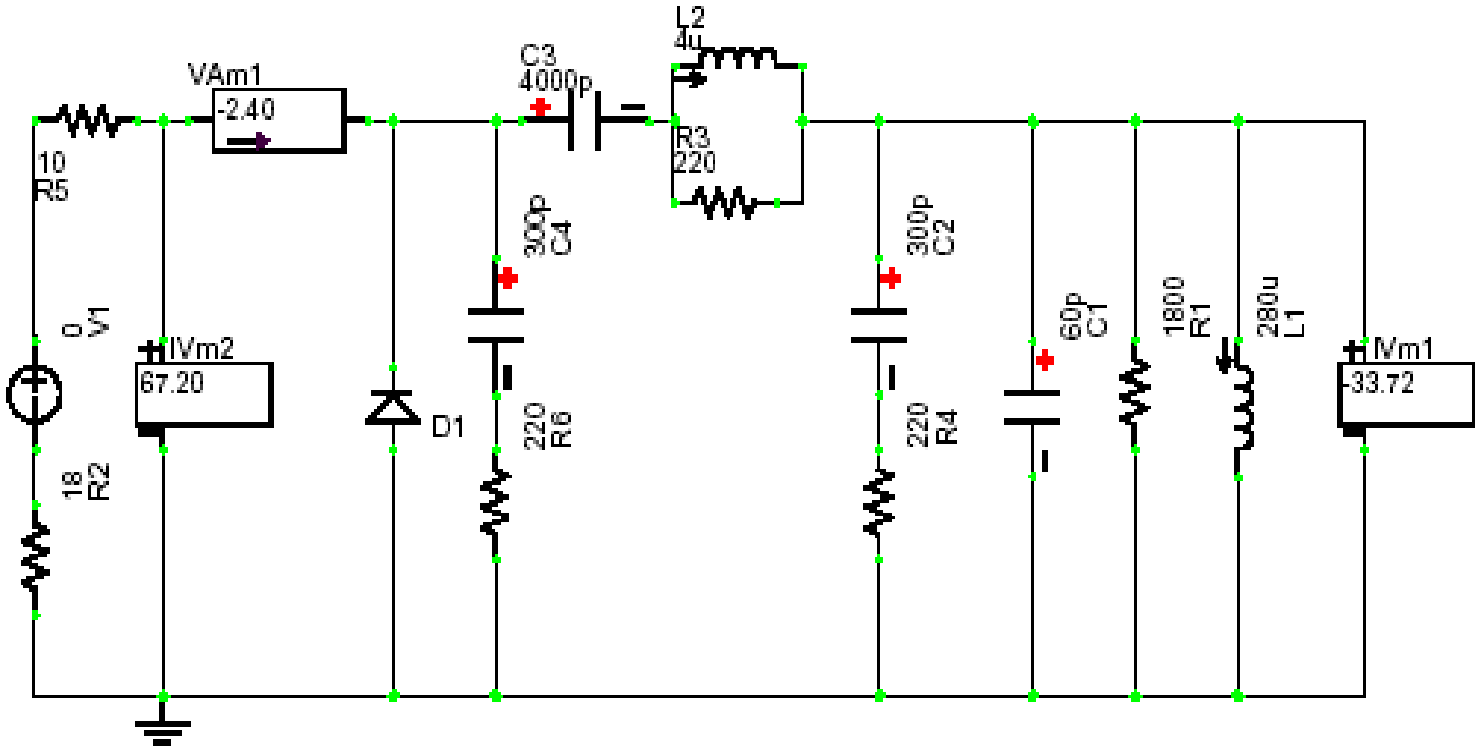
Design Circuit Diagram

Full-bridge push-pull, bipolar pulse

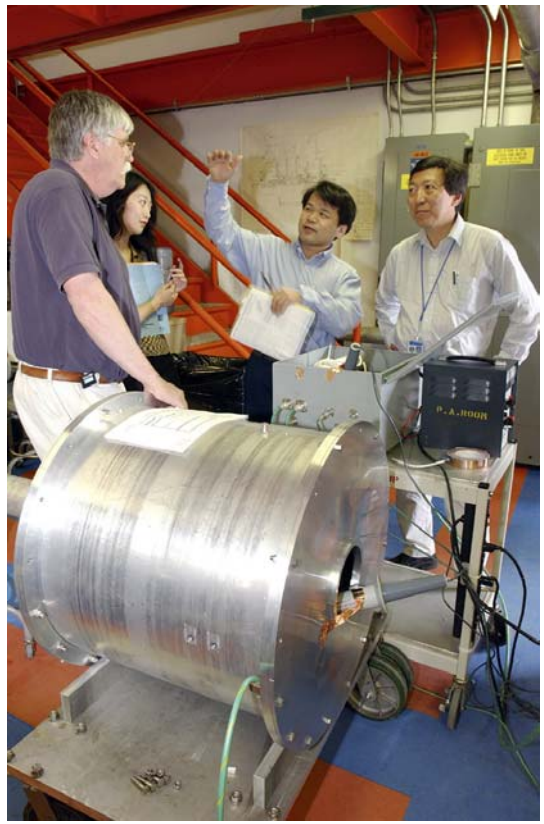


Test Circuit Diagram

One push-pull, mono polar pulse

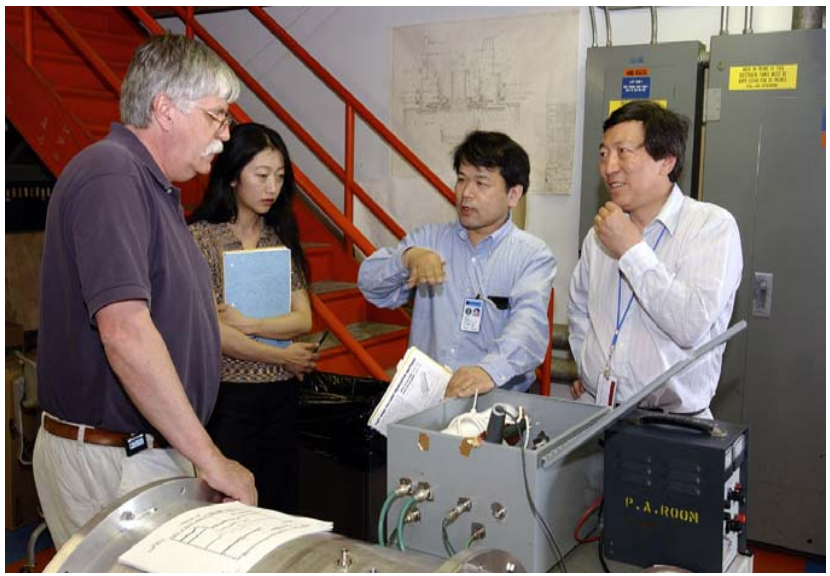


Building a Barrier RF System



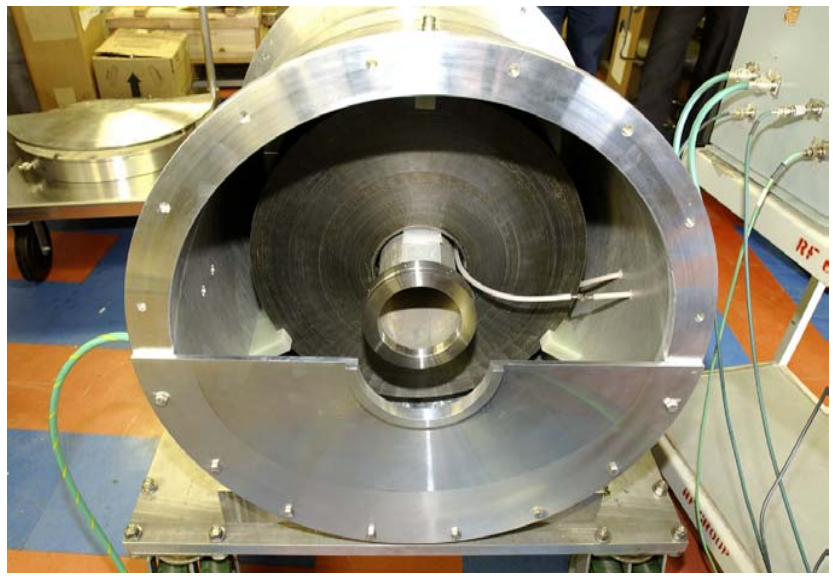
A Fermilab-KEK-Caltech team

Building a Barrier RF System (cont…)



Barrier RF power supply

Building a Barrier RF System (cont…)

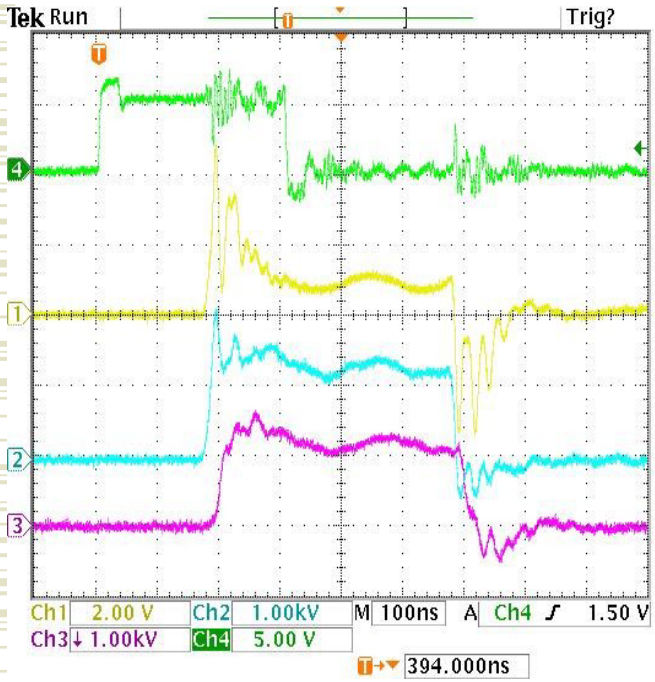


Barrier RF cavity

Testing a Barrier RF System

One barrier

Before tuning



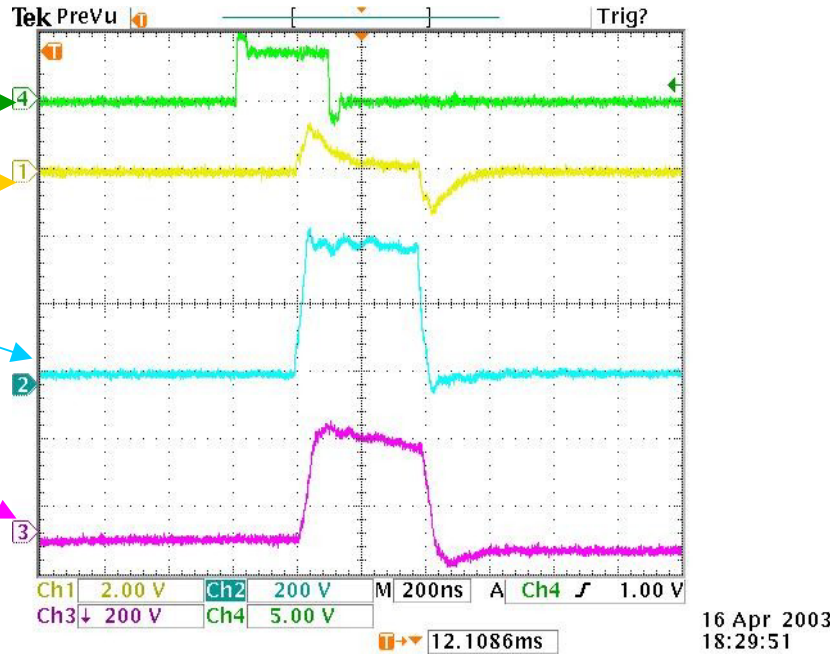
trigger

current

primary voltage

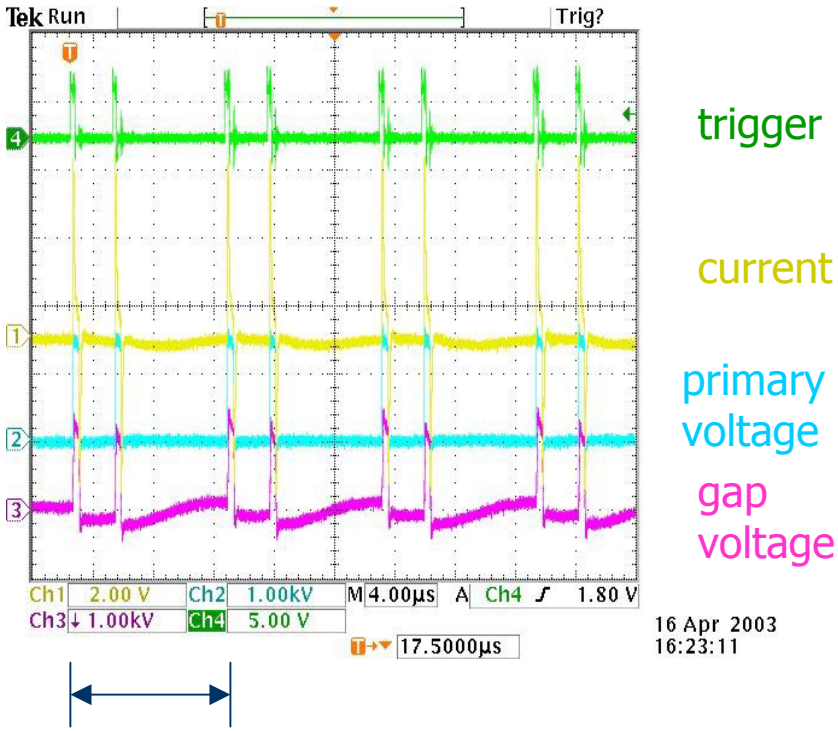
gap voltage

After tuning



Testing a Barrier RF System (cont…)

Two barriers per MI period with variable barrier spacing

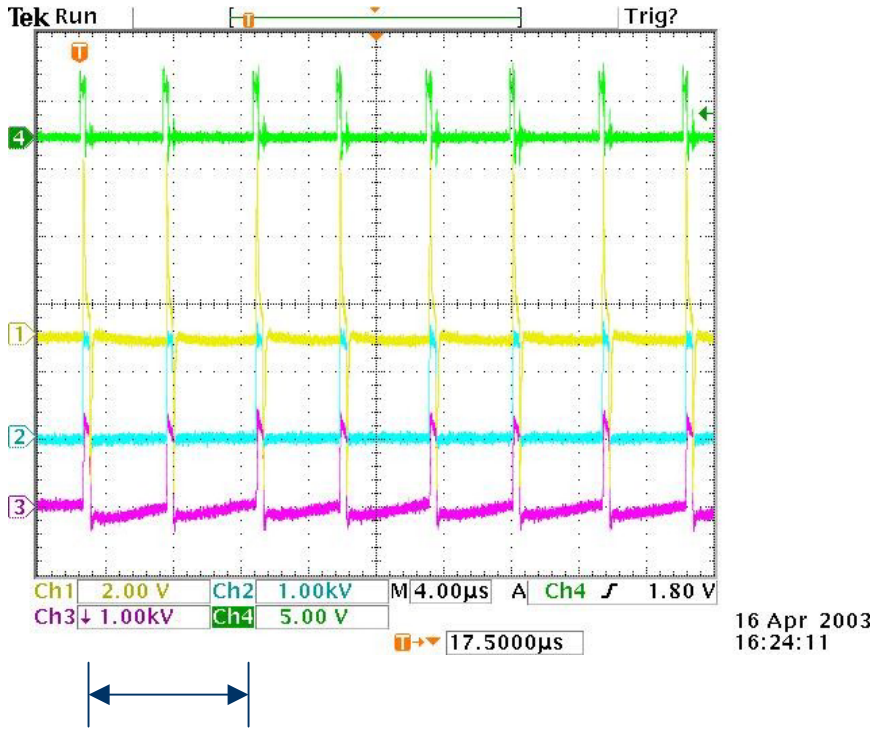


trigger

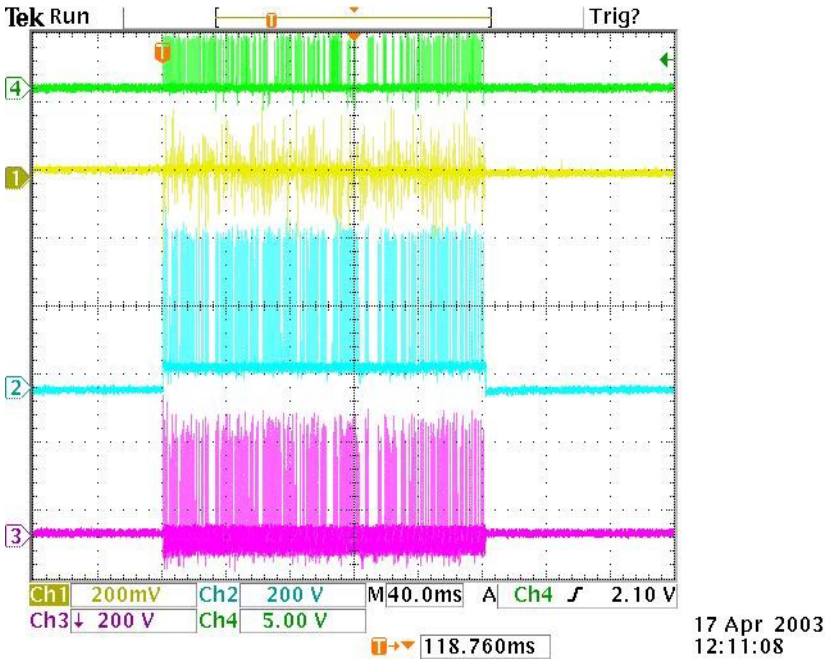
current

primary voltage

gap voltage



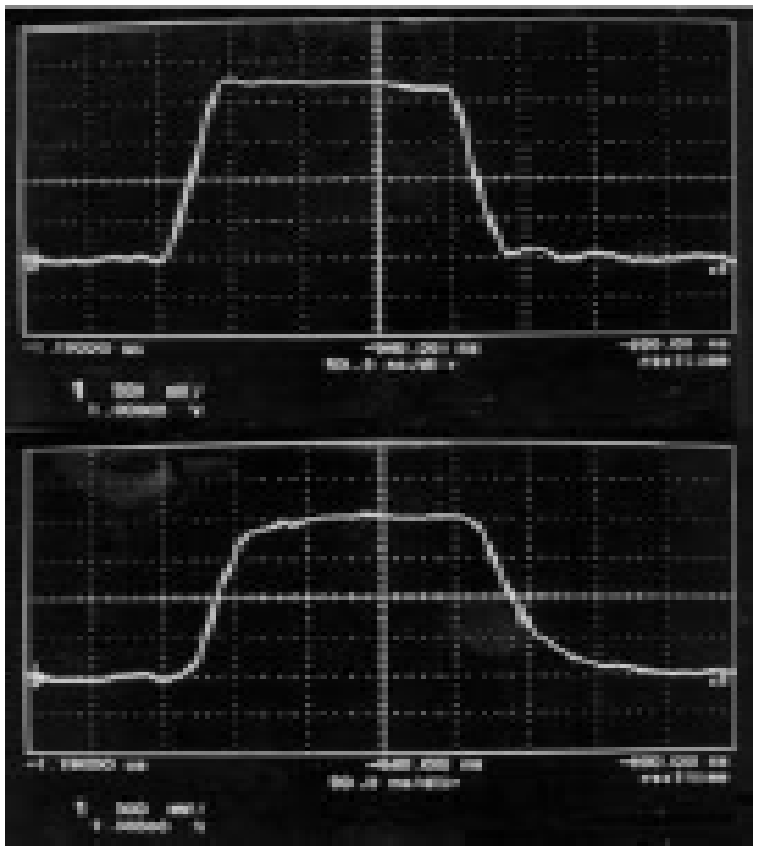
Testing a Barrier RF System (cont…)

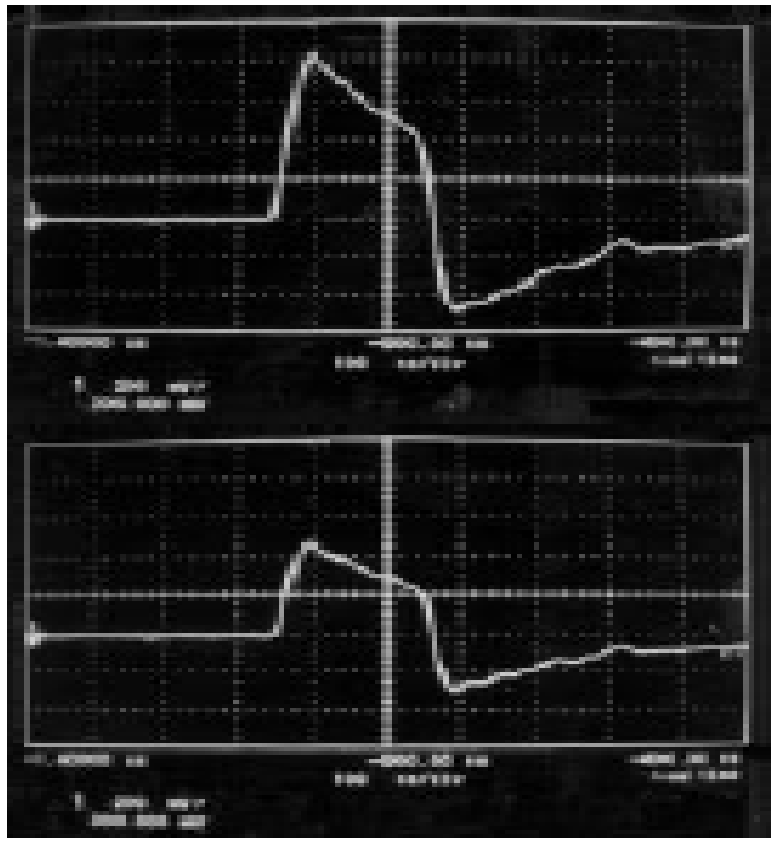


Burst length

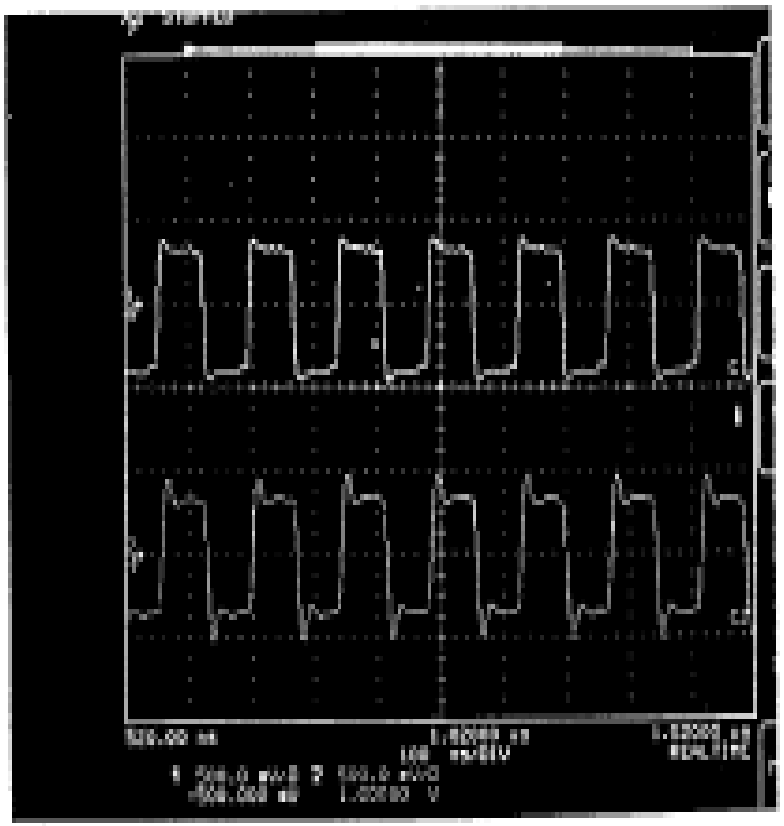
- The required burst length is 150 ms (2.2 Booster cycles); achieved 200 ms (40,000 pulses).
- The required peak voltage is 6 kV; achieved 3-4 kV.
- Will use larger switches to raise the voltage to 6 kV.

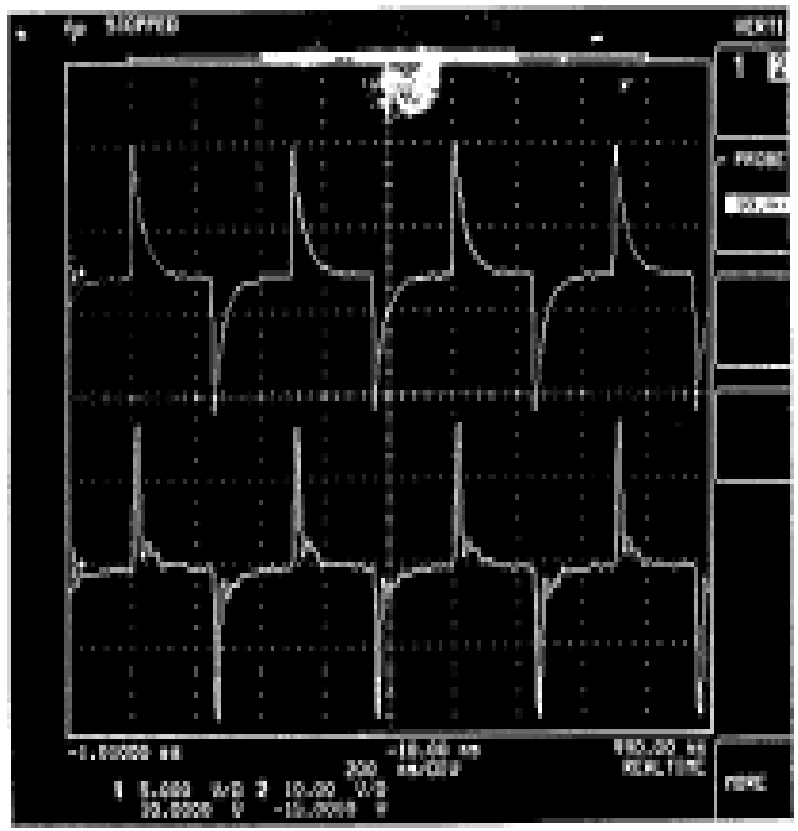
Finemet *vs.* Ferrite (4M2)





Finemet *vs.* Ferrite (4M2) (cont…)





Barrier RF Stacking *vs.* Slip Stacking

- Another method to stack beam is the slip stacking, which is also under investigation at Fermilab.
- One main problem of the slip stacking is beam loading, which makes high intensity beam stacking difficult.
- As a comparison, the barrier RF stacking has much smaller beam loading effect because of lower peak beam current. The beam is debunched during stacking.
- Also this method is new and has never been tried. By contrast, we already know how hard slip stacking is, which was invented and tested about 25 years ago at CERN.

Issues

1. Booster beam quality control

- The Booster beam must have a small $\Delta p/p$. The required ΔE is about ± 6 MeV, which is about 2-3 times smaller than the present Booster beam.
- Need better control of the Booster beam
  - Install longitudinal damper
  - RF frequency modulation for Landau damping
    - 18 cavities, 16 with h = 84, one with h = 83, another with h = 85
    - Tested in 1977, but discontinued for some unknown reason
  - Perform a bunch rotation prior to extraction

Issues (cont…)

2. Radiation hardness of MOSFET
   - To minimize the stray inductance and capacitance of the cable, the switch box must be placed near the cavity in the tunnel. The radiation damage to the switch is a concern.
   - We are using a loss monitor to measure the prompt dose at the location where the cavity will be installed.
   - Experience with radiation damage of MOSFET is being solicited.

Issues (cont…)

3. Power dissipation of the switch
   - With air speed > 4 m/s, the maximum continuous power dissipation of HTS switches is 200 W.
   - For Run2, the duty cycle is low (0.2%). The switch can run up to 6 kV or higher.
   - For NuMI, the duty cycle will be 6 times larger. Possible solutions:
     - Oil cooling
     - Multiple power supplies for a cavity

Summary

- A barrier RF system has been built and tested at Fermilab
- This system will be used for beam stacking for luminosity upgrade in the Tevatron collider program (Run2)
- It will also be used for proton beam intensity upgrade in Fermilab's neutrino programs (NuMI/MINOS, off-axis neutrino experiment, neutrino superbeam)
- It is expected to install this system in the Main Injector during the summer shut down

Bonus Topic: The Dogleg Effect

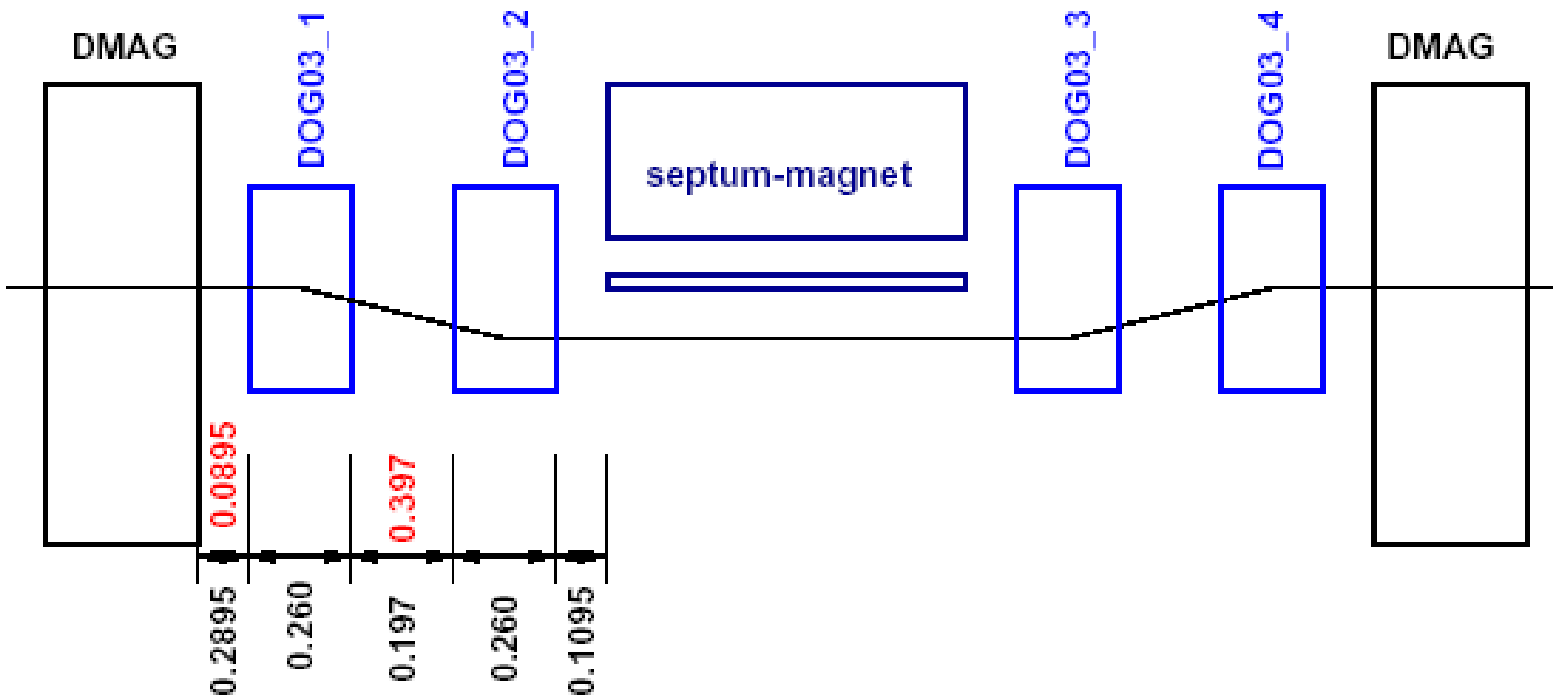
- A dogleg is a set of 4 orbit bump magnets located in the injection and/or extraction areas.
  - Injection area: to create orbit bump for H^- injection. (pulse length ~60 μs)
  - Extraction area: to increase the aperture at the septum. (dc)
- The *dogleg effect* is referred to the edge focusing of these orbit bump magnets.
- In the past 30 years, this dogleg effect was ignored in the Fermilab Booster, because it was considered to be "small perturbation." However, it is not small at all. (first pointed out by A. Drozhdin)
- The edge focusing strength is:

$$1/f = \tan\theta/\rho \cong \theta^2/L$$

θ - bending angle (60 mrad), ρ - bending radius, L – magnet length (26 cm).

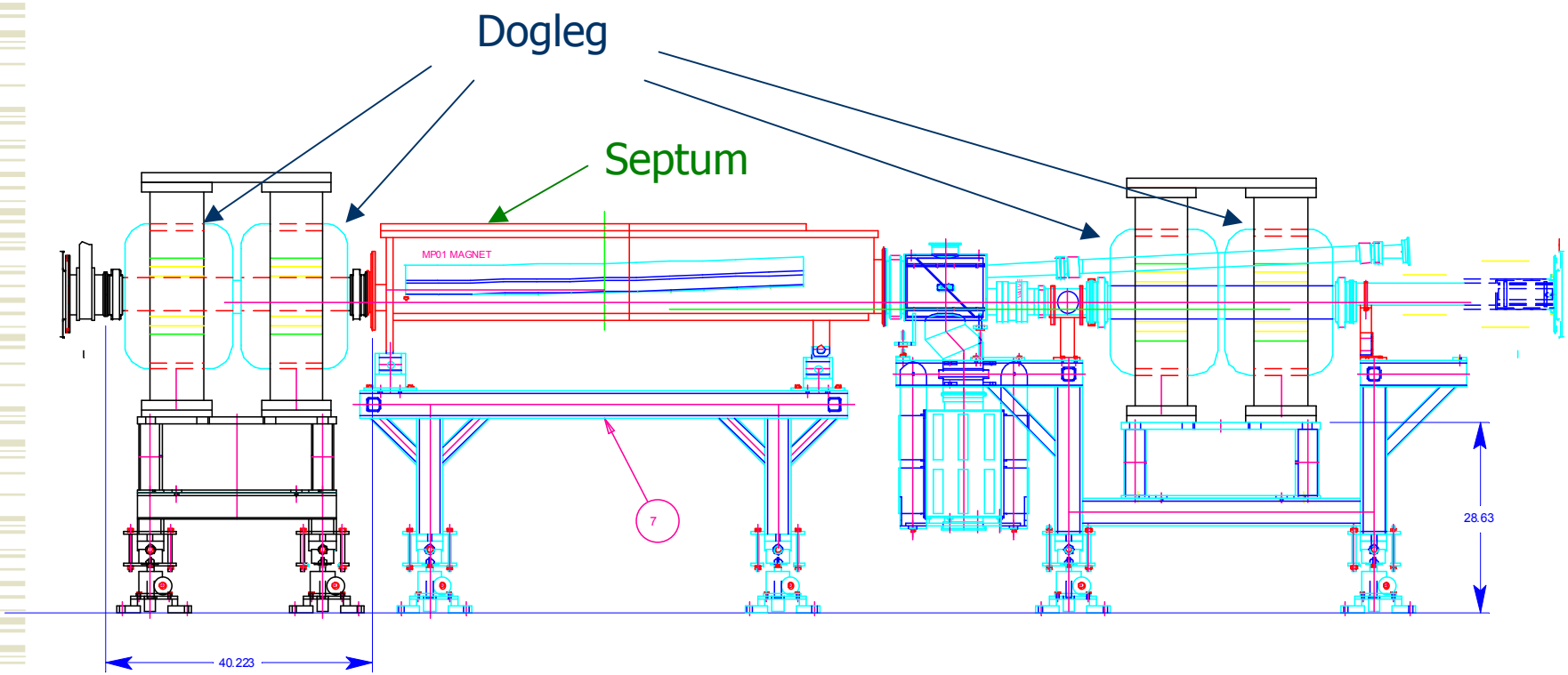
- The sum of edge focusing of the two extraction doglegs ($0.1152\ m^{-1}$) almost equals to that of one main quadrupole ($0.1567\ m^{-1}$), thus causing large perturbation to the lattice.

Dogleg Layout Sketch
(courtesy A. Drozhdin)



Dogleg Layout Drawing

(courtesy J. Lackey)



The Dogleg Effect (cont…)

- The doglegs are R-bends (horizontal or vertical) . Their edge focusing gives large perturbation in the non-deflecting plane (vertical or horizontal):

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

  $\beta(y)_{max}$: 20 m $\rightarrow$ 27 m

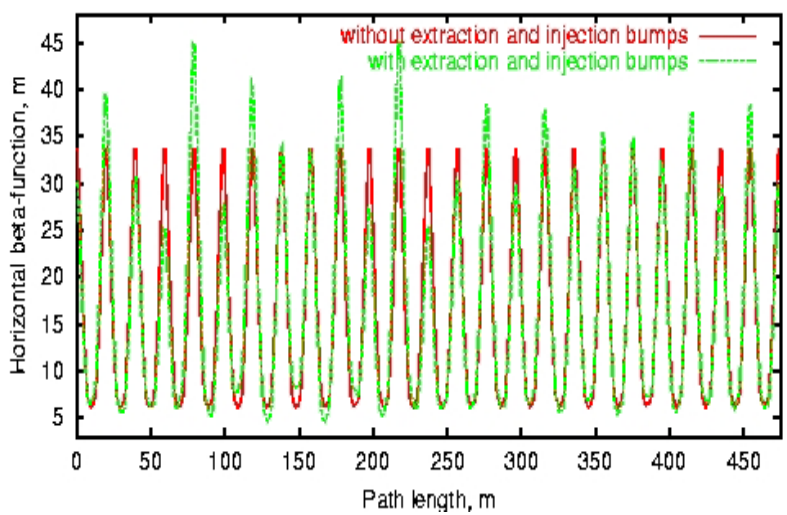
  $D(x)_{max}$: 3 m $\rightarrow$ 6 m

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

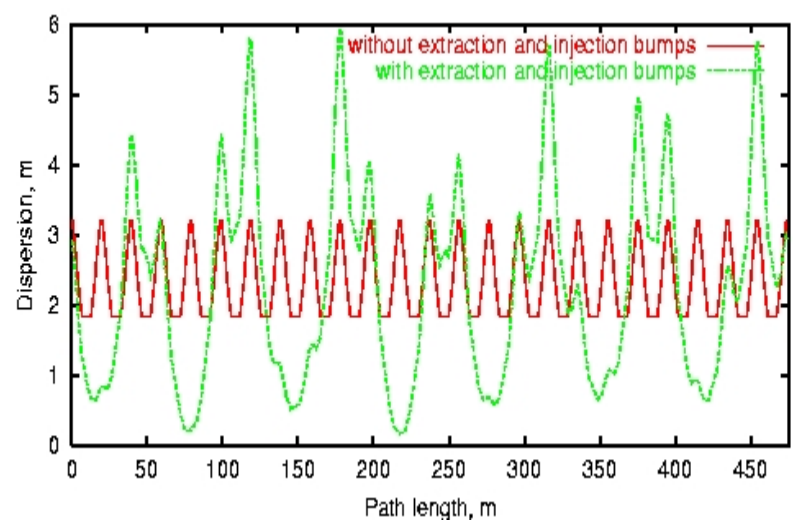
- Beam measurement agreed with the model.
- Removal of one of the two doglegs led to immediate improvement:
  - Beam loss cut to half
  - A milestone of the MiniBooNE experiment reached (5e16 protons per hour)
  - $\rightarrow$ champagne celebration

Dogleg Perturbation on Linear Lattice: MAD Simulation

(courtesy A. Drozhdin)



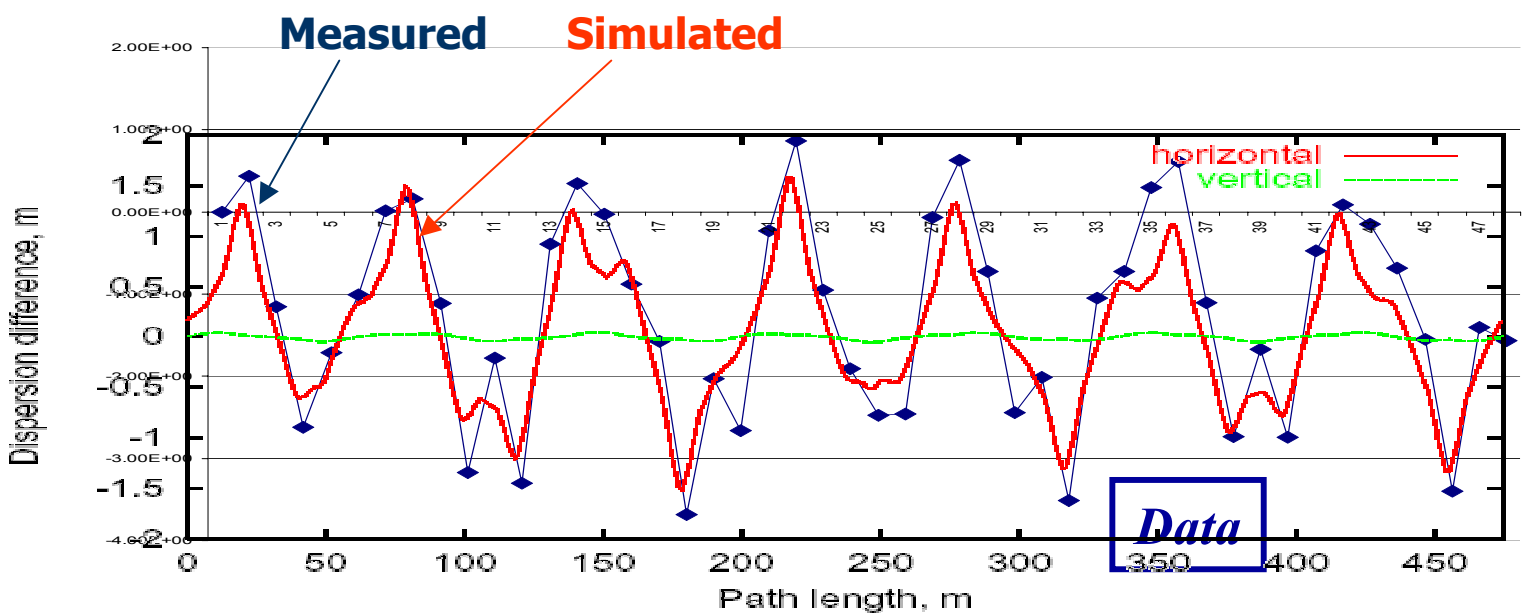
Horizontal beta-function



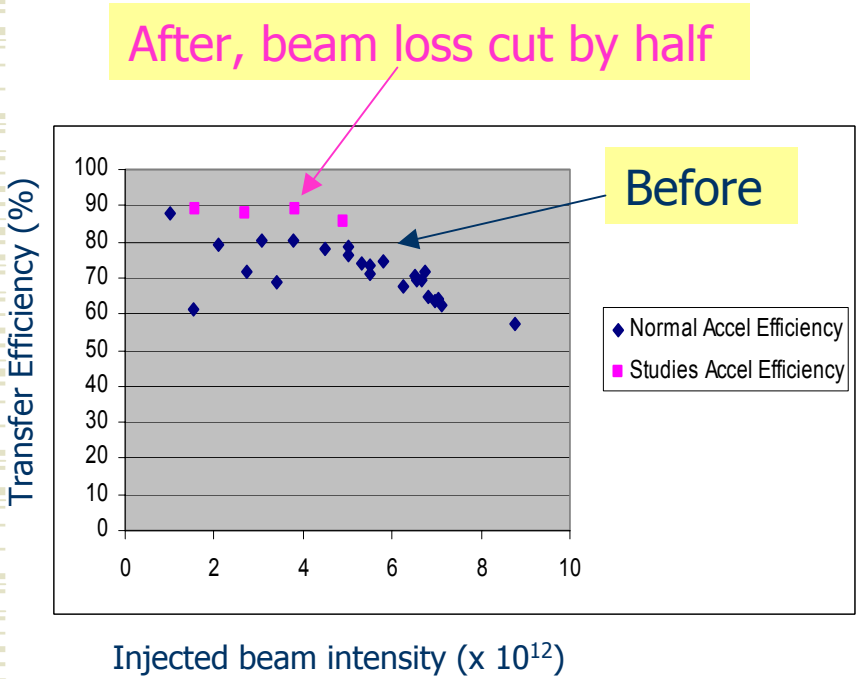
Horizontal dispersion

Dogleg Perturbation on Dispersion: Simulation *vs.* Measurement

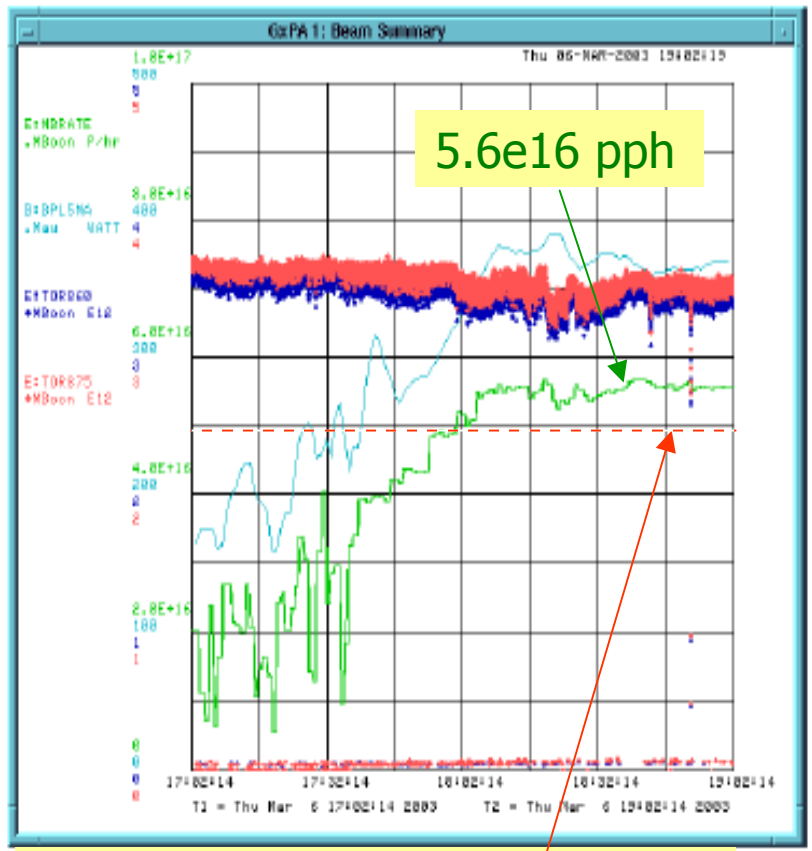
(courtesy E. McCrory)



Beam Experiment: Removing One of the Two Doglegs



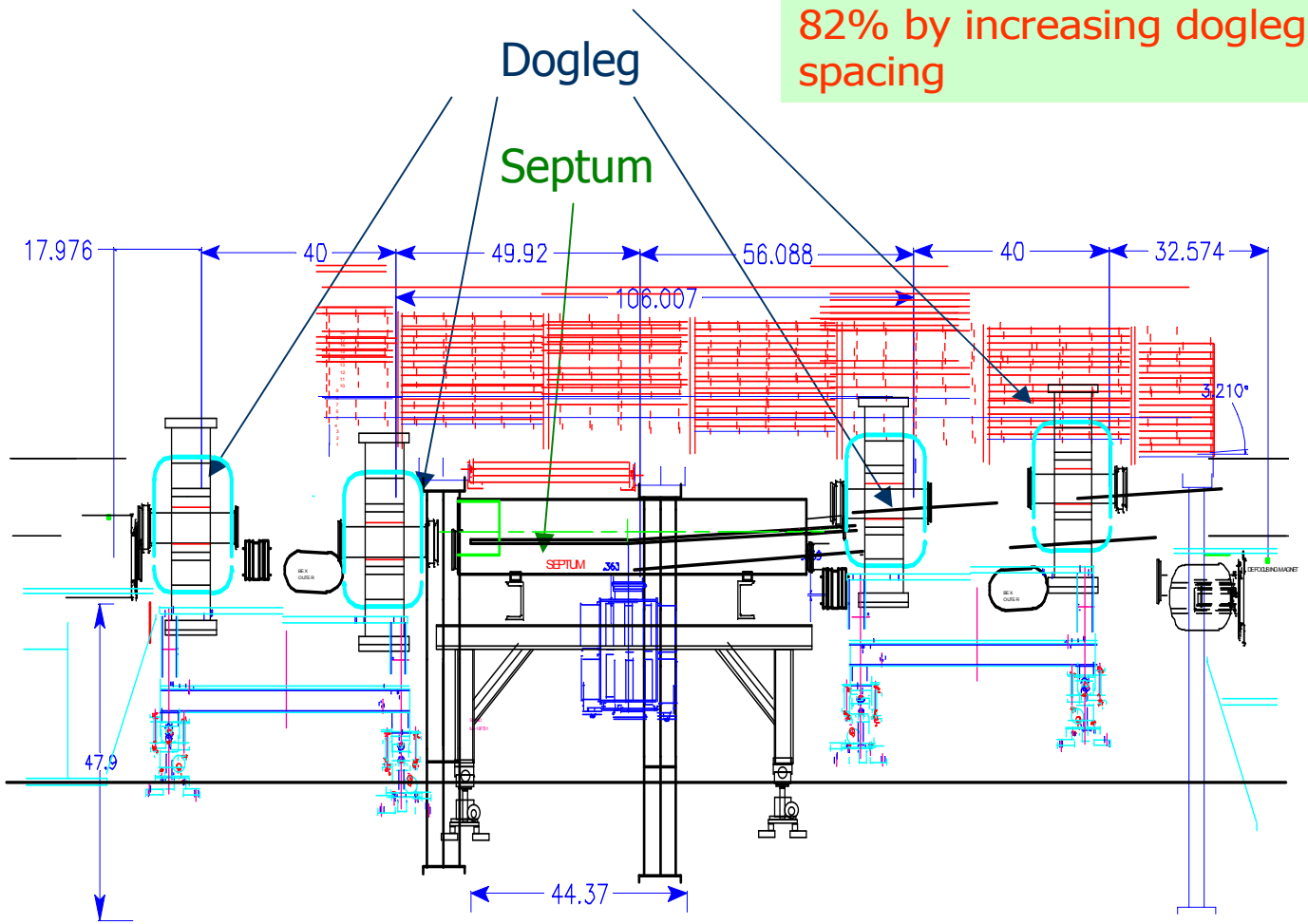
(Courtesy J. Lackey)



New Dogleg Layout

(courtesy J. Lackey)

Edge focusing reduced by 82% by increasing dogleg spacing



Application to the KEK Booster and Main Ring

- The KEK Booster is a small 500 MeV rapid cycling (20 Hz) synchrotron. It has 4 orbit bump magnets in the H^- injection area. The pulse width is about 100 μs. It also has extraction bump magnets.
- The KEK 12 GeV Main Ring is a slow ramp (2-4 sec) synchrotron. It also has extraction bump magnets.
- Because these are horizontal R-bends, the edge focusing will change the vertical lattice function.
- To estimate this effect, calculate θ^2/L for each bump magnet and add them up for each machine. Then compare the sum with the main quadrupole 1/f value.
  - If $\sum \theta^2/L << 1/f$, don't worry
  - If $\sum \theta^2/L \sim 1/f$, you need to worry

Application to the KEK Booster and Main Ring (cont…)

- Example – KEK Booster's four horizontal injection bump magnets:

θ (mrad)	140	-180	-100	140
L (m)	0.349	0.449	0.249	0.349

  total edge focusing strength: $\sum \theta^2/L = 0.2246\ \mathrm{m}^{-1}$

- KEK Booster main quadrupole strength: 1/f = $0.6987\ \mathrm{m}^{-1}$
- So the additional focusing is about 1/3 of a main quadrupole and is in the vertical plane.
- Need to run MAD or other program to check the perturbation to the lattice functions.

Questions?