Slow extraction of high intensity protons at Brookhaven's AGS

K.A. Brown

L.Ahrens, J.W.Glenn, N.Tsoupas, K.Zeno

Collider Accelerator Department, BNL

BROOKHAVEN NATIONAL LABORATORY

ICFA 10th Mini-workshop on Show Extraction

October 15-17, 2002

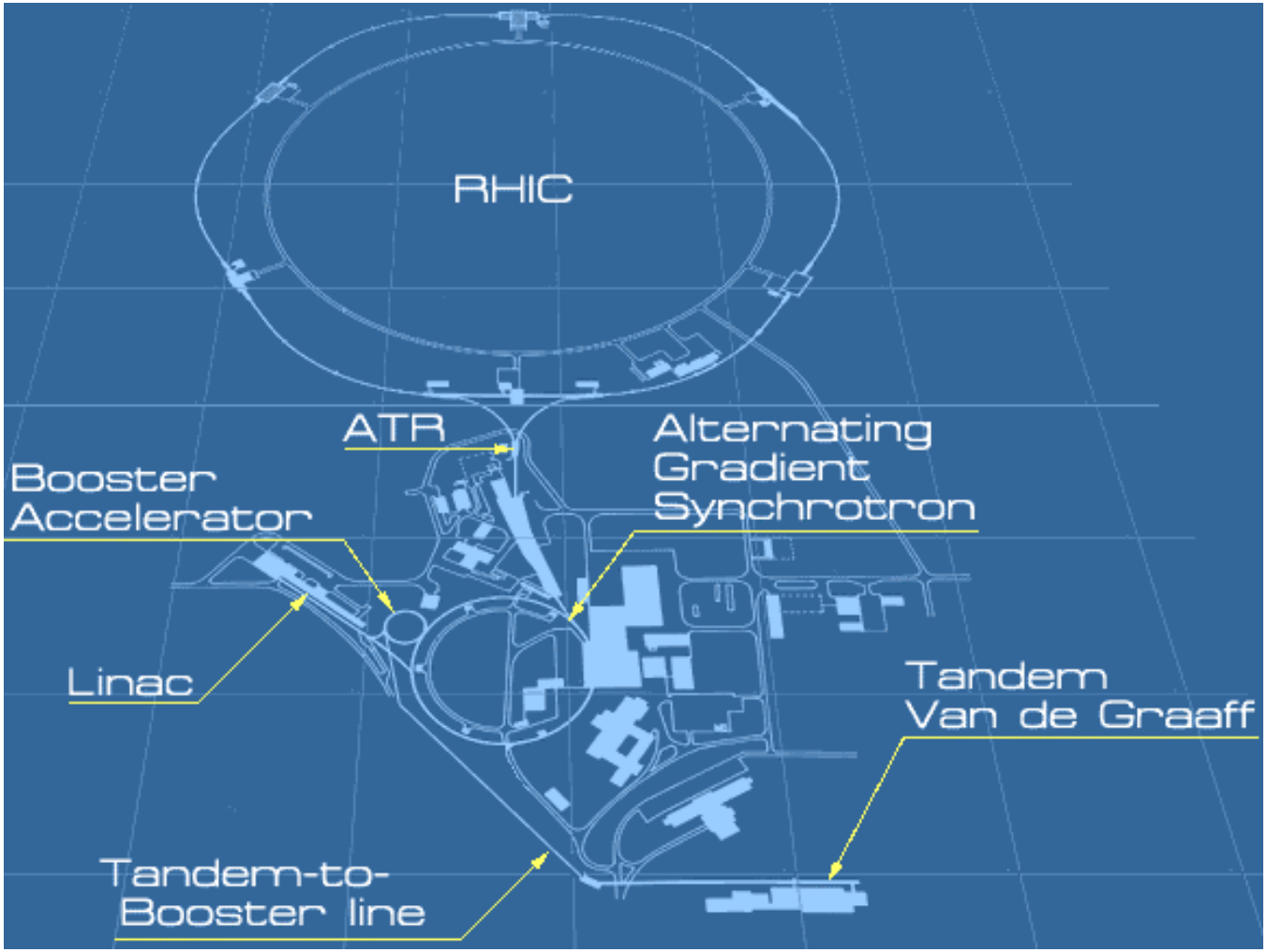
Contents

Overview of AGS Slow Extraction
AGS Parameters
SEB Devices
High Intensity Slow Extraction
Longitudinal Phase Space Dilution
Collective effects
Spill and ripple
Electrostatic Septum
Transport to target stations
Future Improvements
Summary

BROOKHAVEN NATIONAL LABORATORY

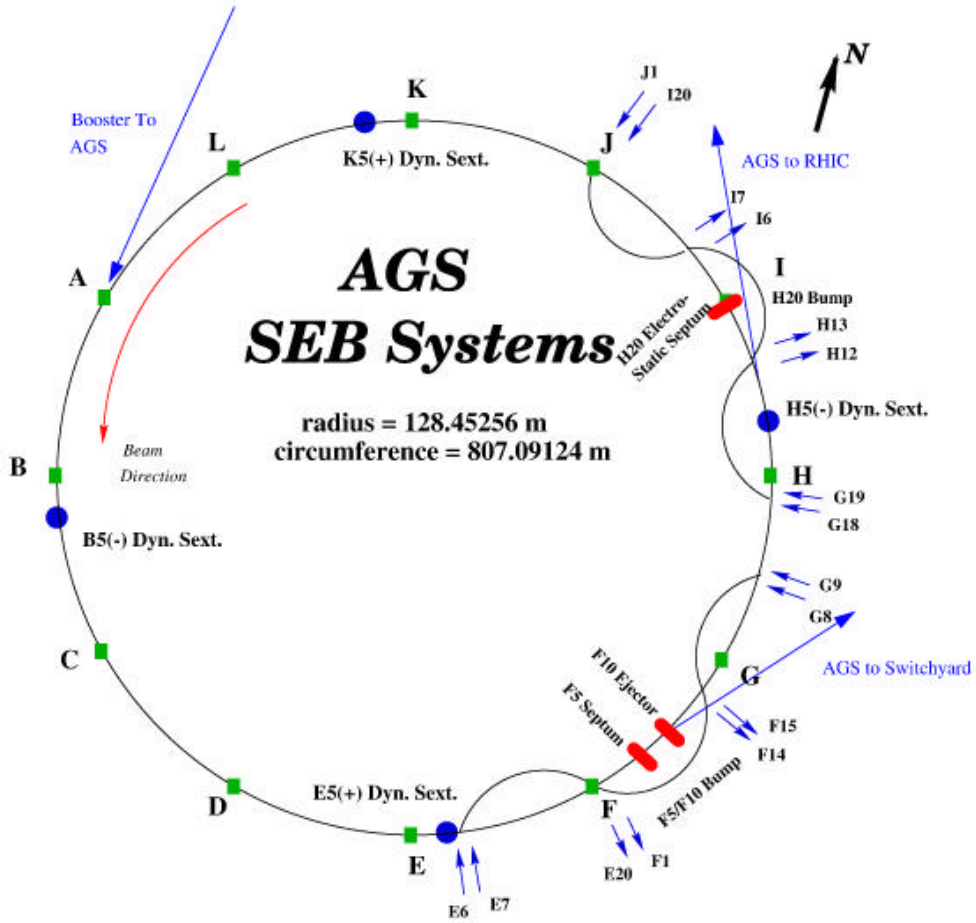
BROOKHAVEN
NATIONAL LABORATORY

Overview of AGS Slow Extraction



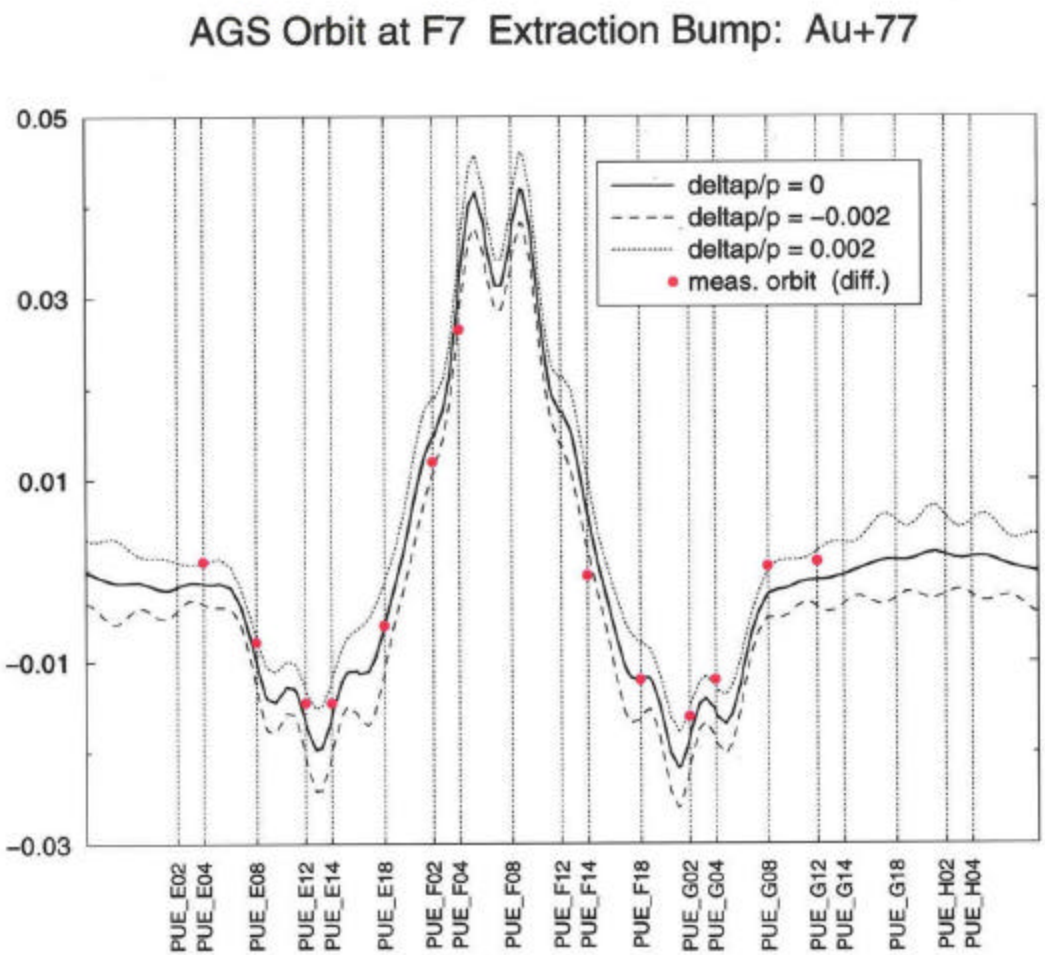
BROOKHAVEN
NATIONAL LABORATORY

Overview of AGS Slow Extraction



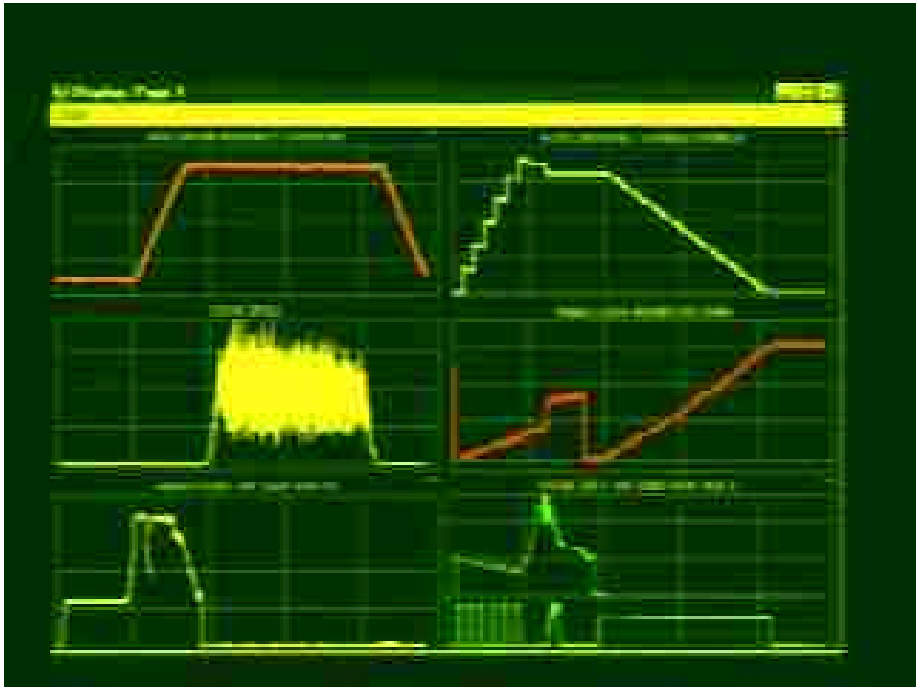
BROOKHAVEN NATIONAL LABORATORY

Overview of AGS Slow Extraction



BROOKHAVEN NATIONAL LABORATORY

Overview of AGS Slow Extraction



Summary of emittance measurements.

note: β and α are referred to F13

	$\epsilon_x^{95\%,N}$	β_x (m)	α_x	$\epsilon_y^{95\%,N}$	β_y (m)	α_y
1980 Meas.	31.9	57.61	-6.636	38.8	3.249	0.8708
1997 Meas.	64.37± 9.60	8.77 ± 1.4	−0.92± 0.2	54.71± 5.0	4.18 ± 0.4	1.01 ± 0.09

1980 measurements are pre-Booster beam.

1997 measurements are post-Booster beam.

New tune for switchyard matching section successfully implemented for high intensity proton running using 1997 measurements.

BROOKHAVEN NATIONAL LABORATORY

AGS Parameters

Parameter	Value	Units
Peak Intensity	76.0	10^{12} protons/pulse
Extraction Efficiency	97-98	%
Rep Period/Flattop Length	4-8/2-6	Seconds
Spill Lengths	1.8 – 5.8	Seconds
Working Point	8.667 / 8.78	Horiz./Vert. Tune
Chromaticity	-2.5 / 0.05	Horiz./Vert. Chrom.
Extraction Momentum	25.5	GeV/c

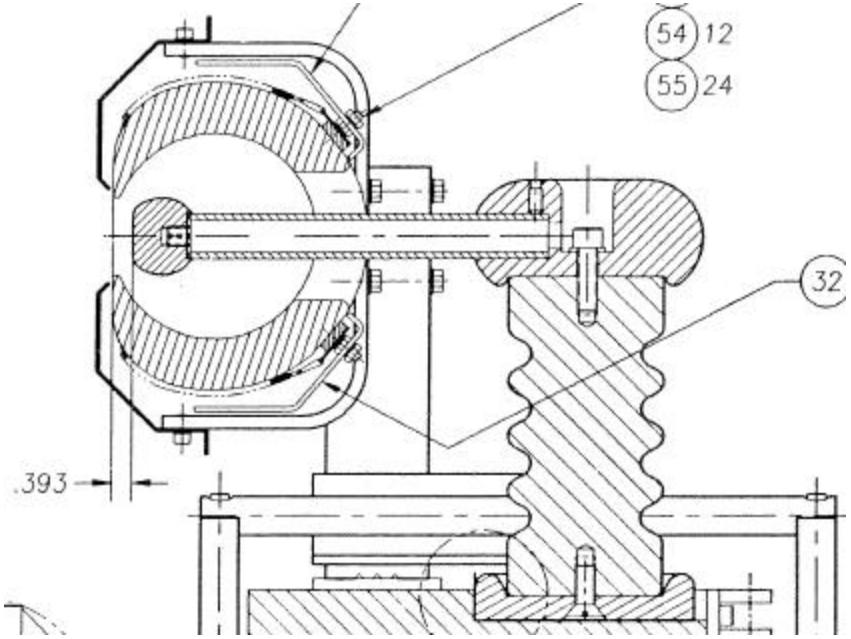
BROOKHAVEN NATIONAL LABORATORY

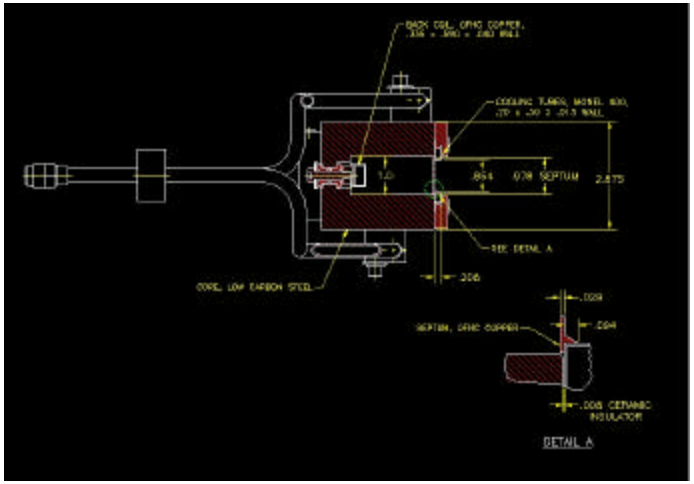
AGS Parameters

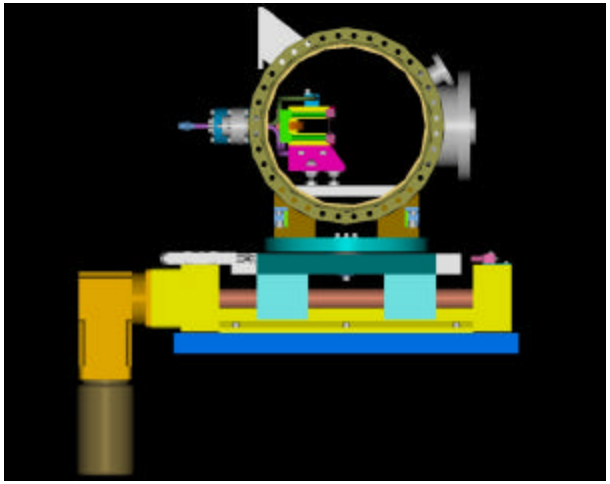
	Elect. Septum	Thin Septum	Thick Septum
β_x [m]	12.0 – 19.9	22.1	19.9 – 12.0
β_y [m]	19.9 – 12.0	10.5	12.0 – 19.9
Vert. Gap [mm]	20.0	17.8 (25.4)	19.1
Horiz. Gap [mm]	10.0	44.45	38.1
Length [m]	2.30	0.667	0.81+1.22 = 2.03
N turns		1	4
Septum w [mm]	0.051 / 2.54 space	0.76	13.5 / 15.85
Deflect. [mrad]	0.43	1.1	18.5
Field B/E	80 kV/cm	1.5 kG	9.5 kG

BROOKHAVEN NATIONAL LABORATORY

SEB Devices

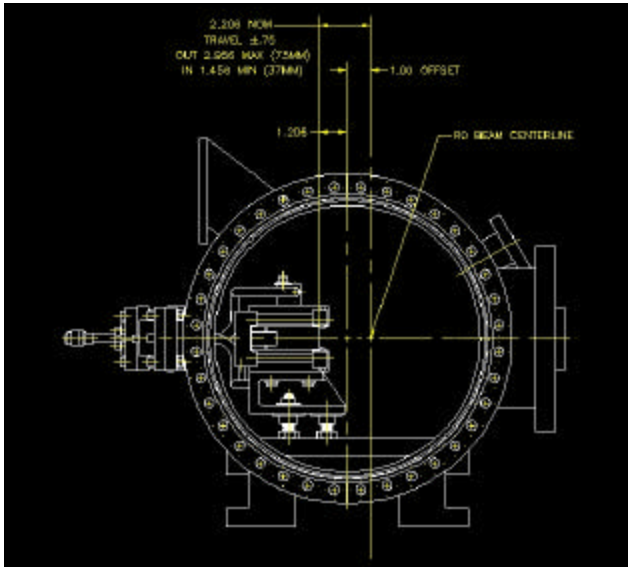


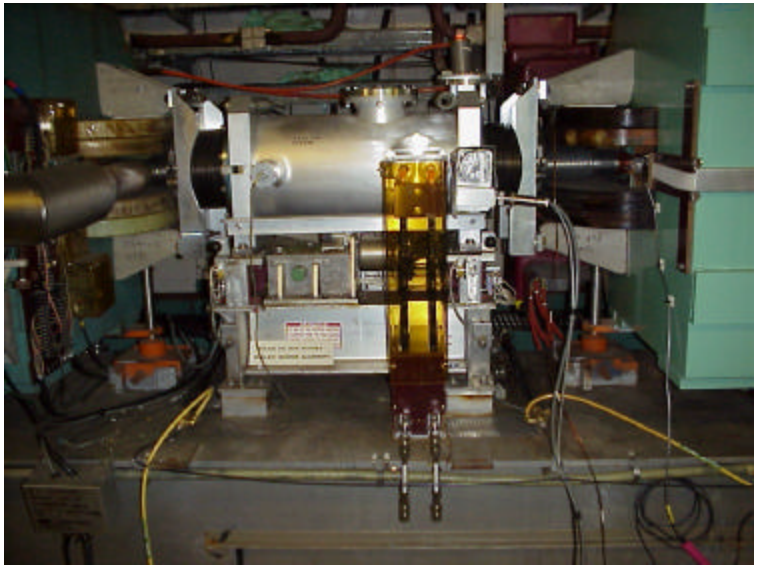


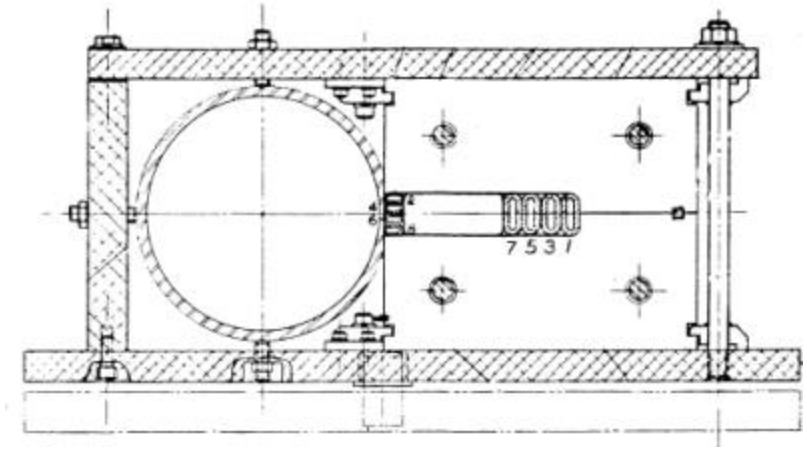


BROOKHAVEN
NATIONAL LABORATORY

SEB Devices

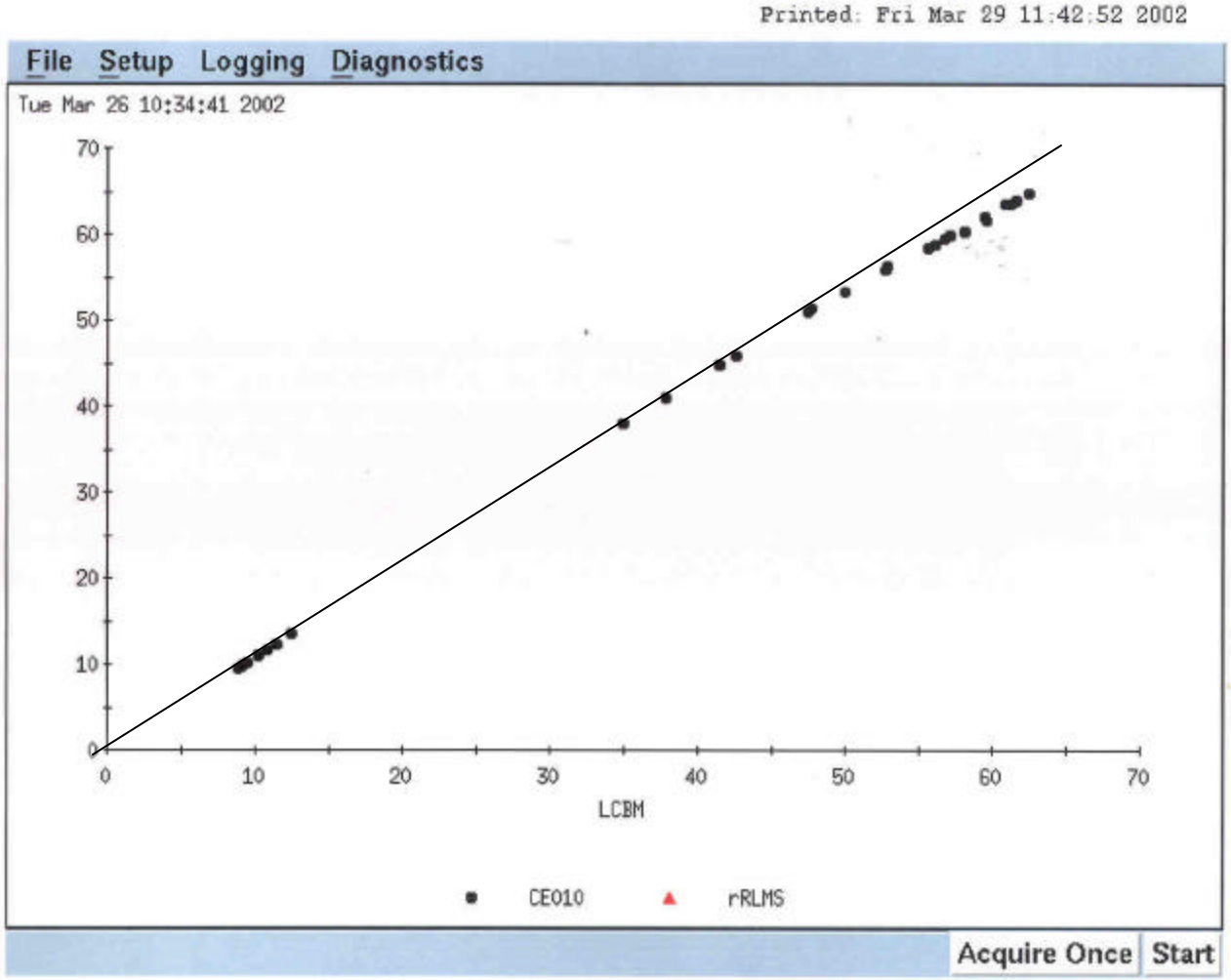






BROOKHAVEN
NATIONAL LABORATORY

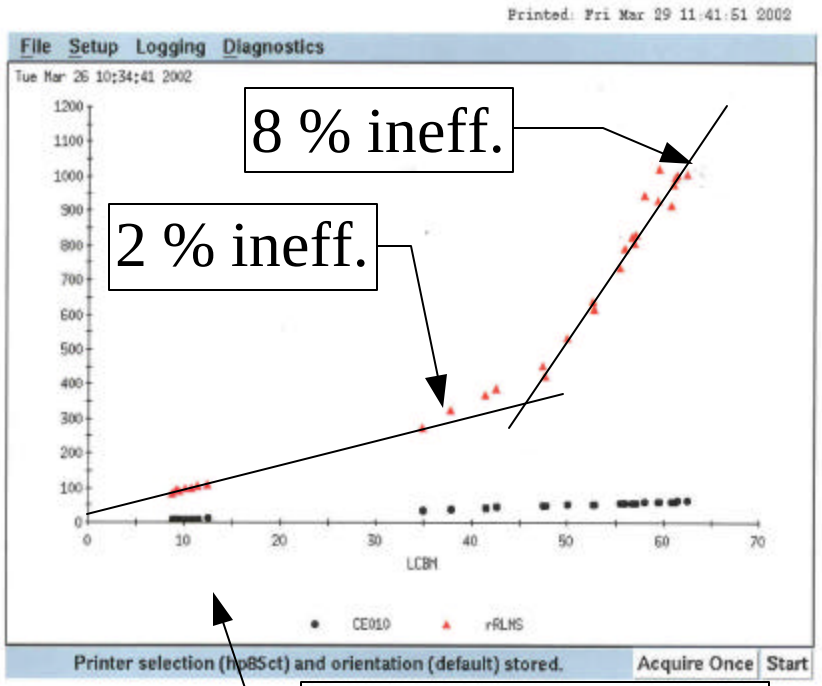
High Intensity Slow Extraction

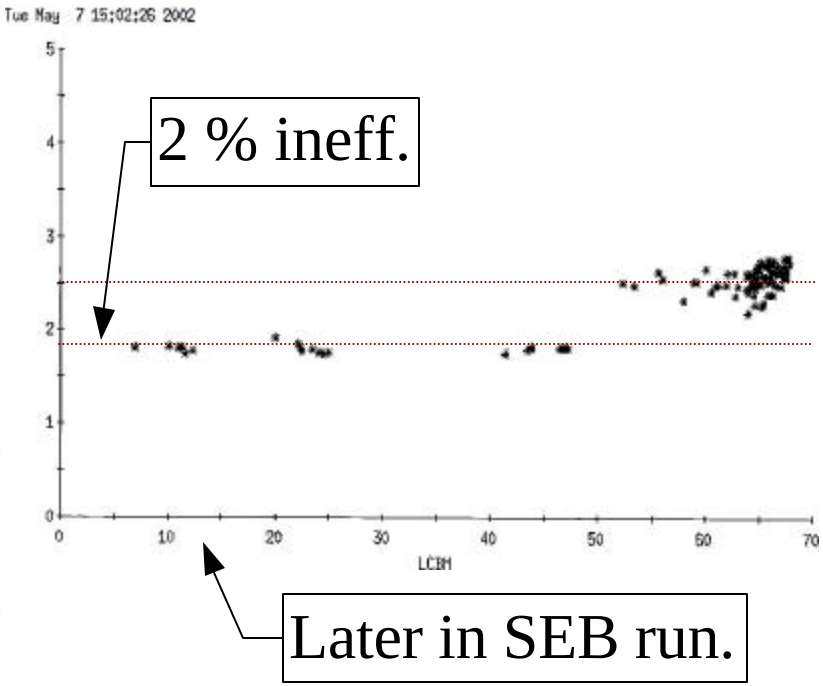


BROOKHAVEN NATIONAL LABORATORY

High Intensity Slow Extraction

- 70 TP Slow extracted beam observations. Vertical Chromaticity is kept positive after transition.

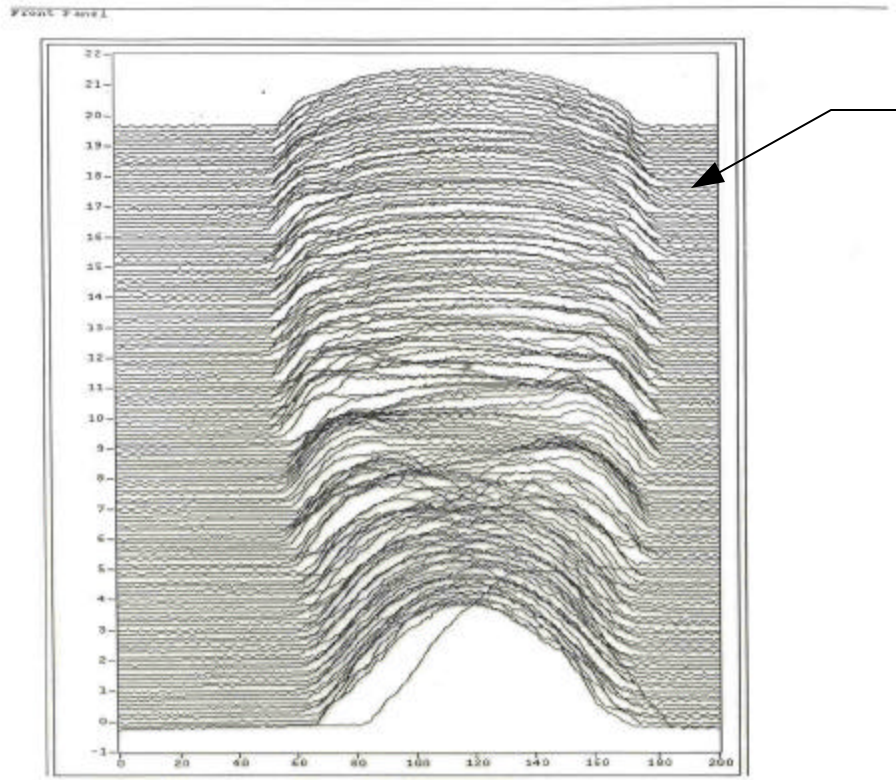




BROOKHAVEN NATIONAL LABORATORY

Longitudinal Phase Space Dilution

- A key parameter is peak beam current.

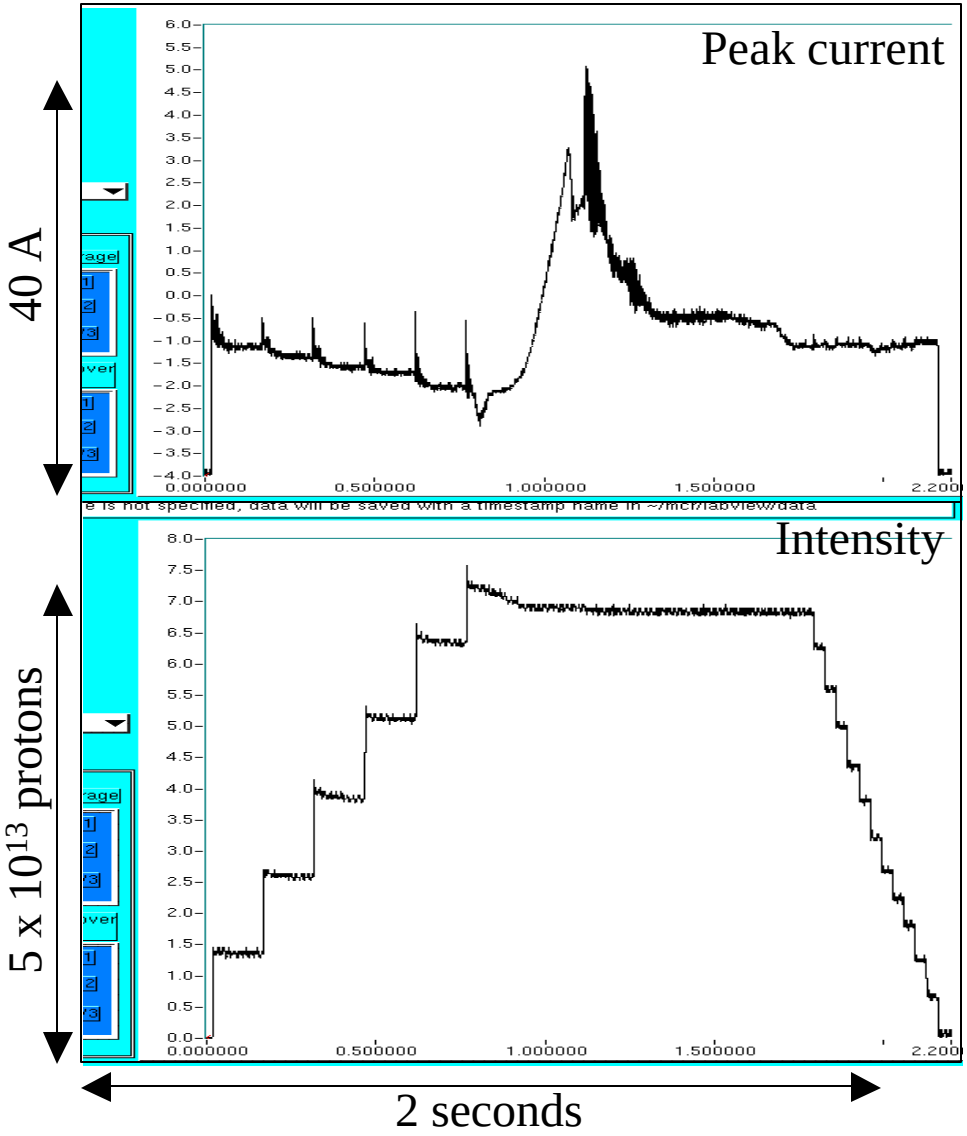


Bunch Dilution using VHF cavity

BROOKHAVEN NATIONAL LABORATORY

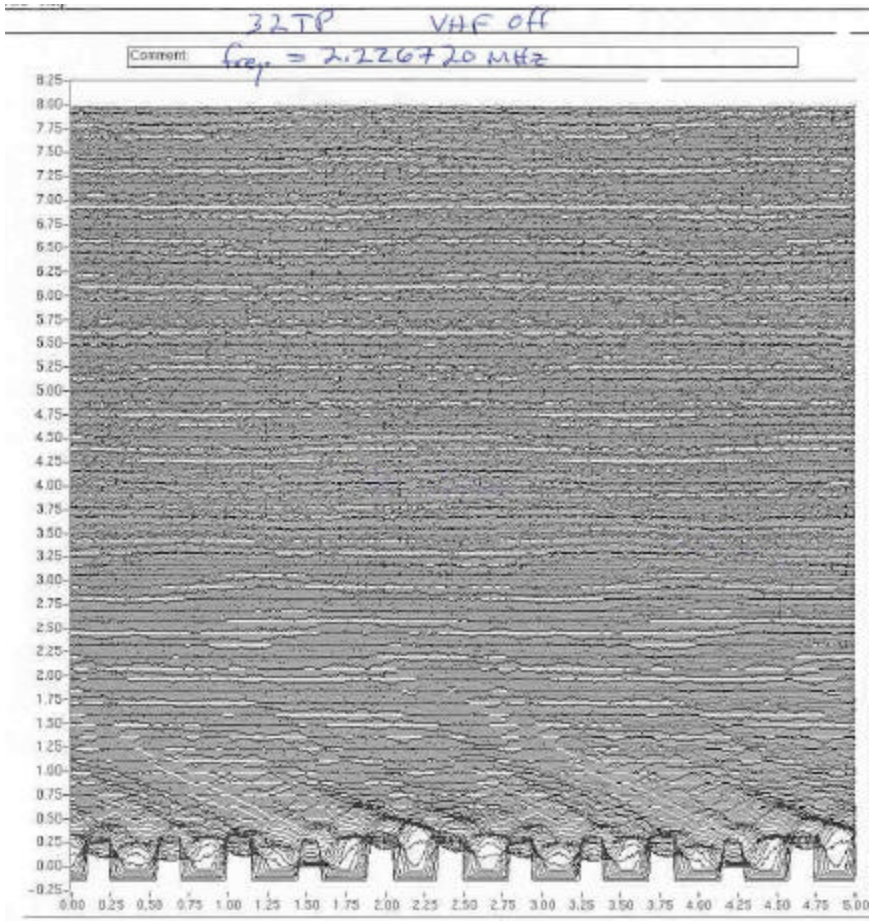
AGS performance for g-2 operation

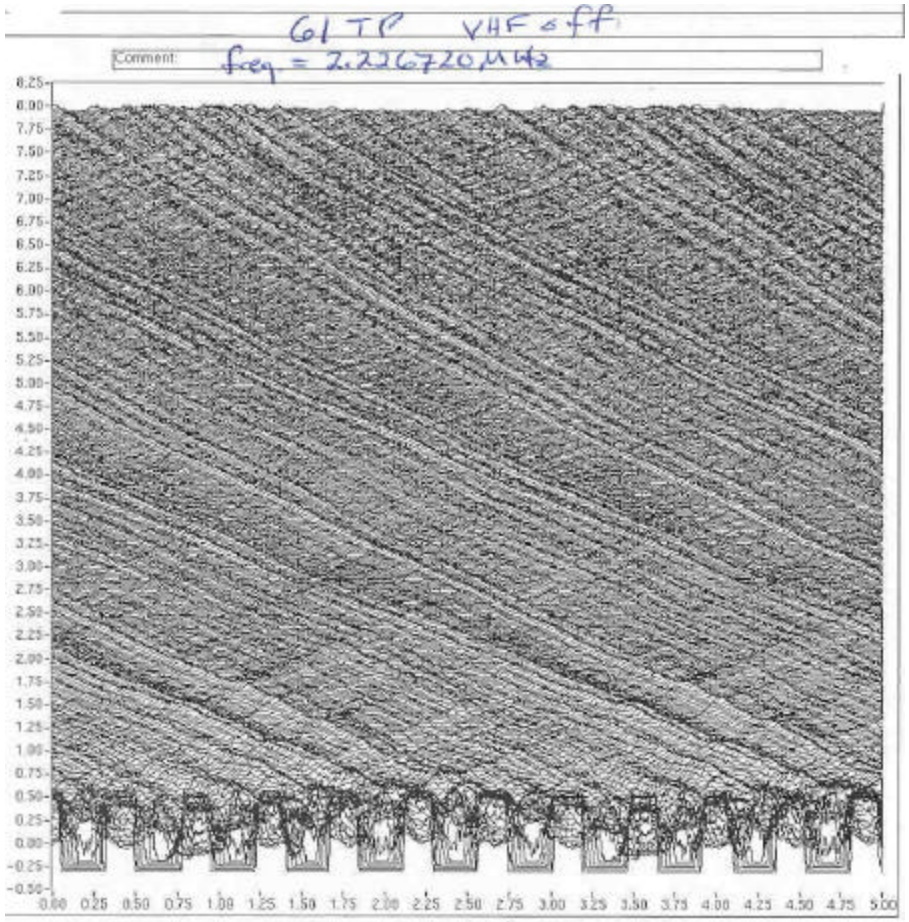
- 6 single bunch transfers from Booster
- Peak intensity reached: 72×10^{12} ppp
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for g-2 ops: $50\text{-}60 \times 10^{12}$ ppp
- Strong space charge effects during accumulation in AGS
- 2nd order transition energy jump limits available momentum aperture.
- Chromatic mismatch at transition causes emittance dilution
- Dilution needed for beam stability



BROOKHAVEN NATIONAL LABORATORY

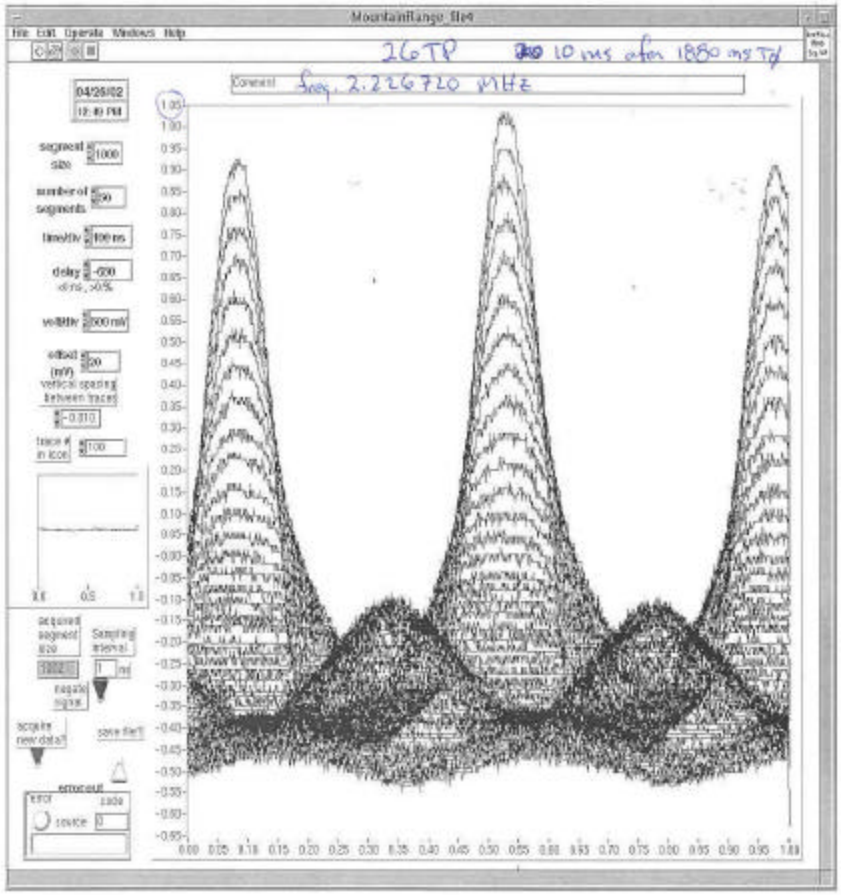
Collective Effects

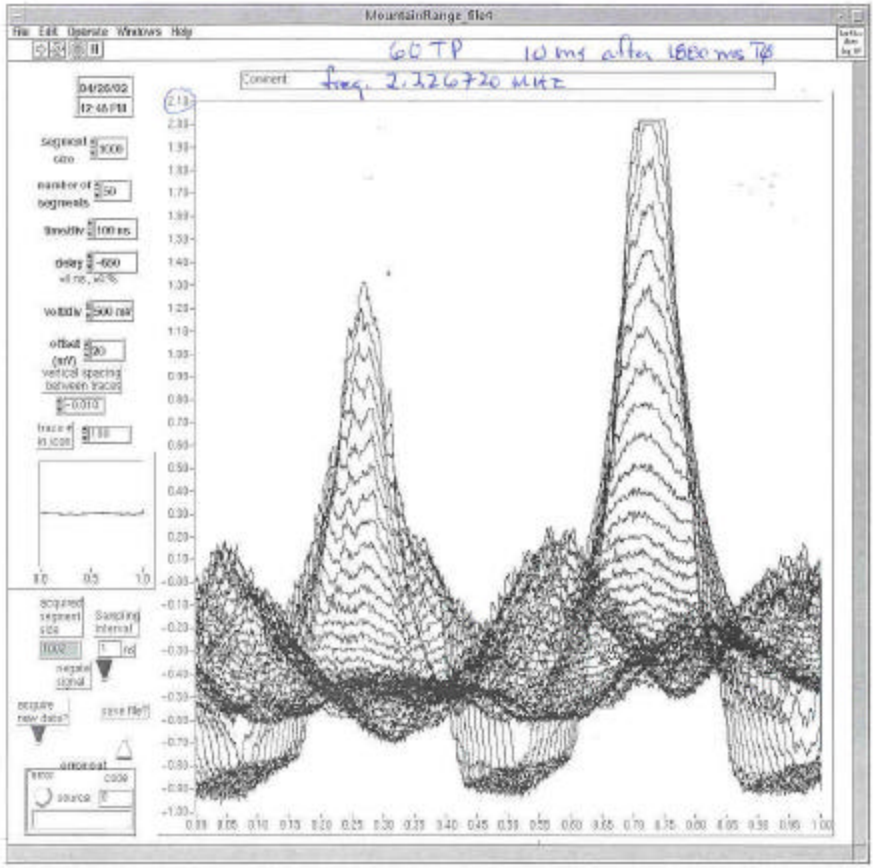




BROOKHAVEN
NATIONAL LABORATORY

Collective Effects





BROOKHAVEN
NATIONAL LABORATORY

Spill and Ripple

Time Structure Formalism

definitions:

Q = horizontal betatron tune

ξ = horizontal chromaticity = $\frac{dQ/Q}{dp/p}$

I_m = current in the Main Dipoles and Quadrupoles

N = number of particles ($\frac{dN}{dQ}$ represents the particle distribution in tune space

T = period over which particles are extracted

Low frequency duty factor:

$$D_f = \frac{[\int_T S(t)dt]^2}{T \int_T [S(t)]^2 dt} \Rightarrow (\frac{f_{av}}{f_{rms}})^2 \ \ in\ general$$

where

$$S(t) = \frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt}$$

if there is no ripple,

$$S(t) = \frac{dN}{dQ}\dot{Q}_0$$

where $\dot{Q}_0$ is the rate at which particles move into resonance.

$$\dot{Q}_0 = \frac{Q\xi}{I_m}\frac{dI_m}{dt}$$

BROOKHAVEN NATIONAL LABORATORY

Spill and Ripple

If there is ripple on the magnet power supplies;

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v)$$

where $\dot{Q}_v$ is the variations in the rate at which particles move into resonance.

$$\dot{Q}_v = \frac{Q\xi}{I_m L_m} \sum_h V_h$$

L_m is the total inductance of the main dipoles and quads and V_h is the sum of the 60 Hz harmonics amplitudes (in volts).

Reducing Time structure using RF Phase Displacement

$$S(t) = \frac{dN}{dQ}\dot{Q}_0(1 + \frac{\dot{Q}_v}{\dot{Q}_0})$$

For 1 particular frequency we can write the duty factor as

$$D_f = \frac{1}{1 + \frac{1}{2}(\frac{\dot{Q}_v}{\dot{Q}_0})^2} = \frac{1}{1 + \frac{1}{2}(\frac{\omega \delta Q}{v_0})^2}$$

where

ω = frequency

δQ = relative ampl. of that freq. in tune space

v_0 = speed that beam crosses resonance

$$v_0 = \frac{\Delta p}{p}\frac{1}{T}$$

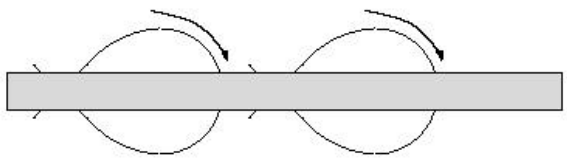
BROOKHAVEN NATIONAL LABORATORY

Spill and Ripple

D_f is increased by

1. decreasing δQ
2. increasing v_0

One way to increase v_0 is to increase $\frac{\Delta p}{p}$. To further increase it we use RF phase displacement, using a high frequency RF cavity. In this case RF buckets are centered on the resonance.



The buckets are empty and beam is forced between them.

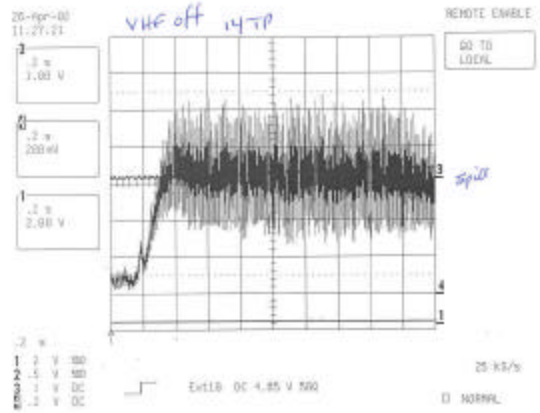
Now,

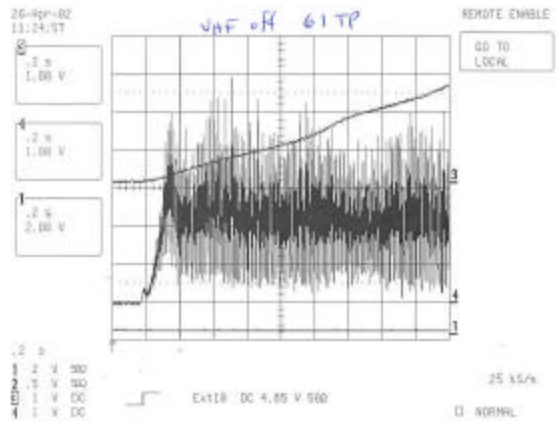
$$D_f = \frac{1}{1 + \frac{RB\rho T}{V\frac{\Delta p}{p}}(\omega\delta Q)^2}$$

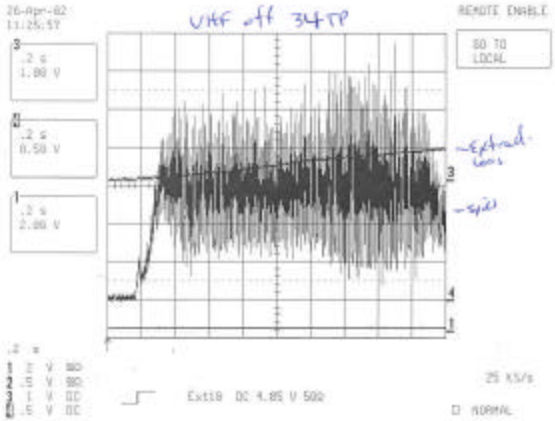
Without RF phase displacement, a 100 % modulated spill has $D_f = 0.67$. In this case,

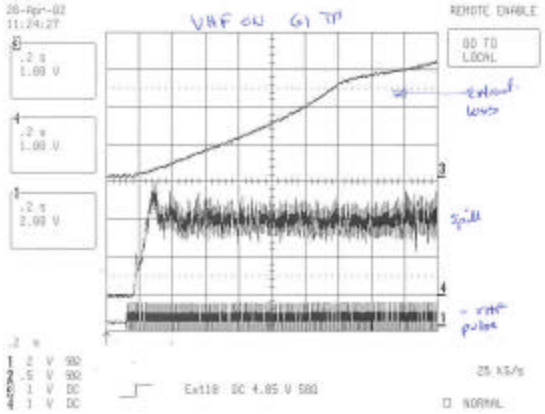
$$\omega\delta Q \geq \frac{\Delta p}{p}\frac{1}{T}$$

Spill and Ripple



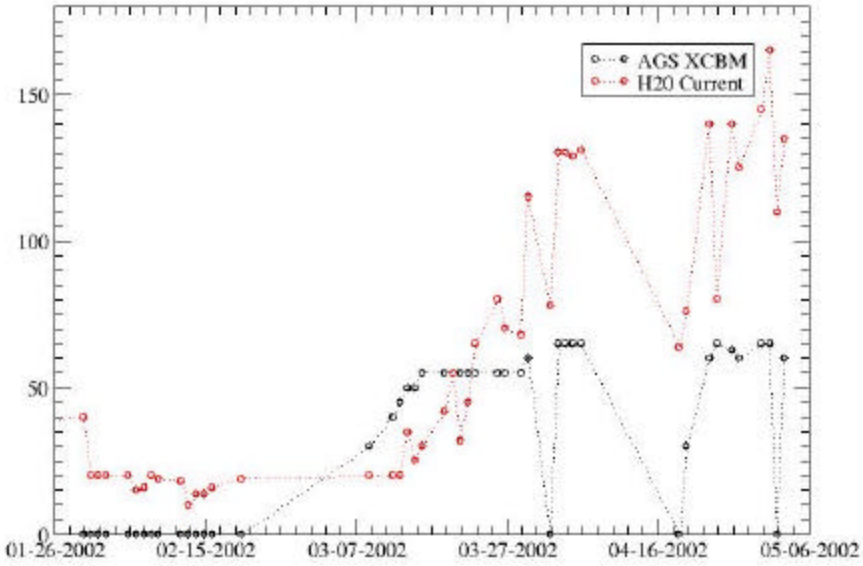


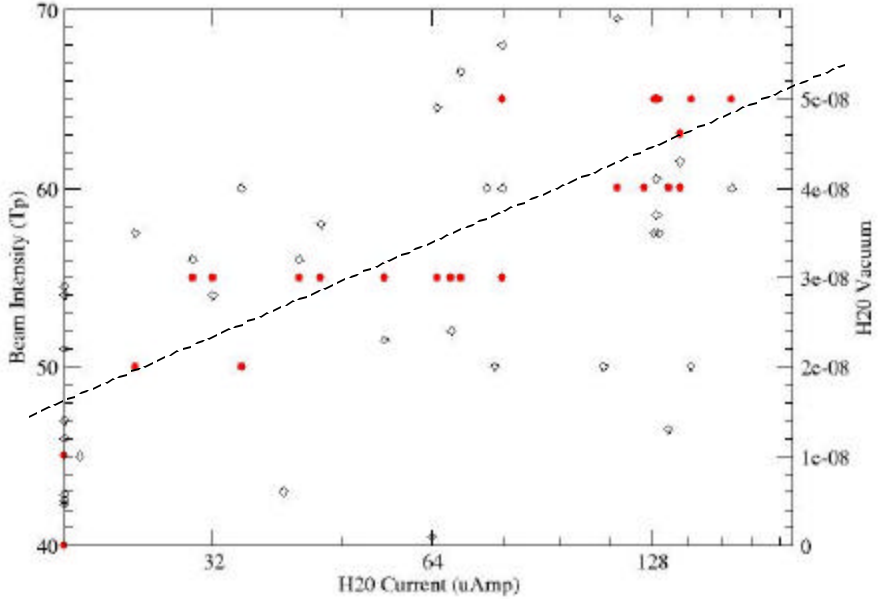




BROOKHAVEN NATIONAL LABORATORY

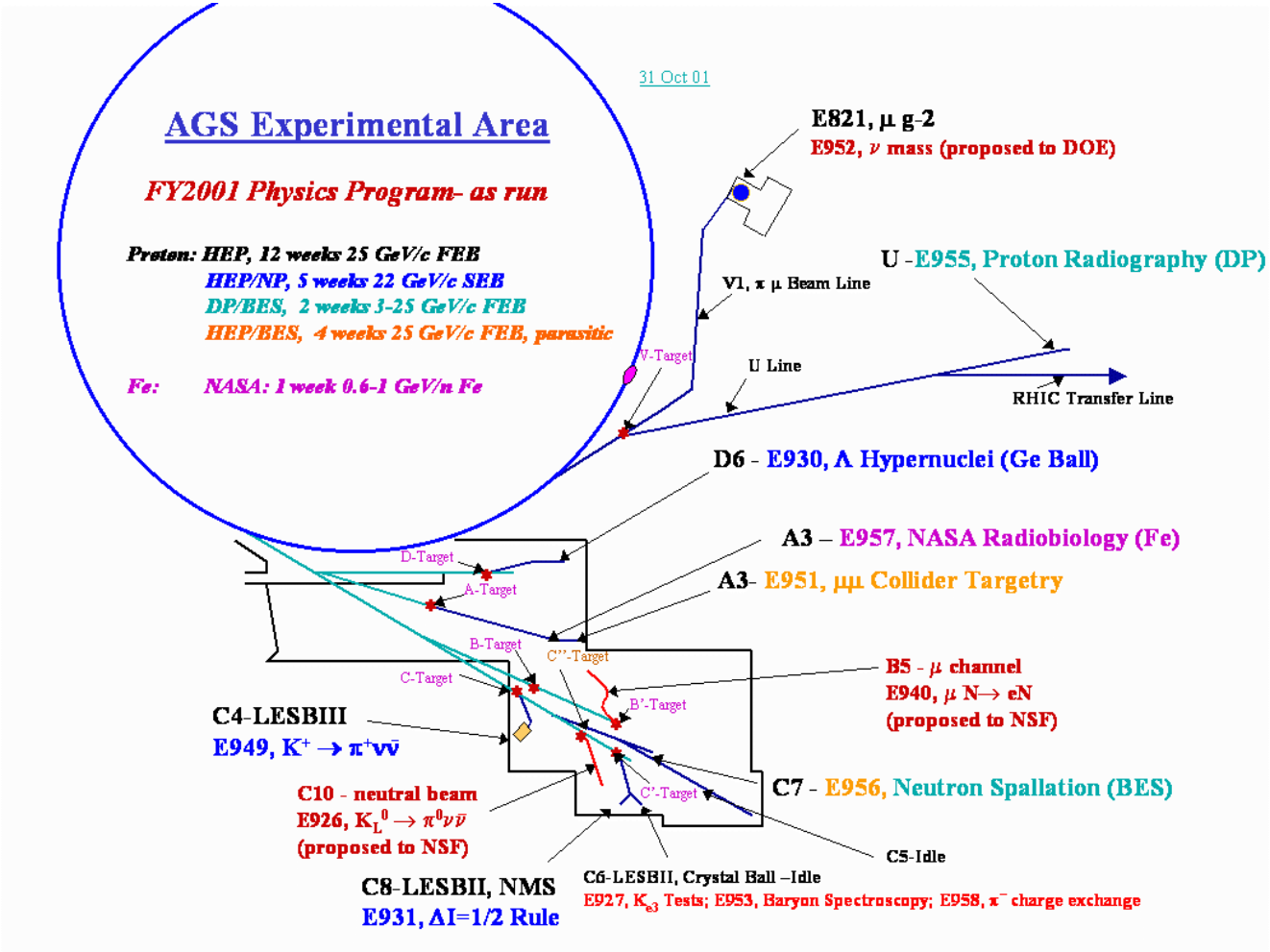
Electrostatic Septum





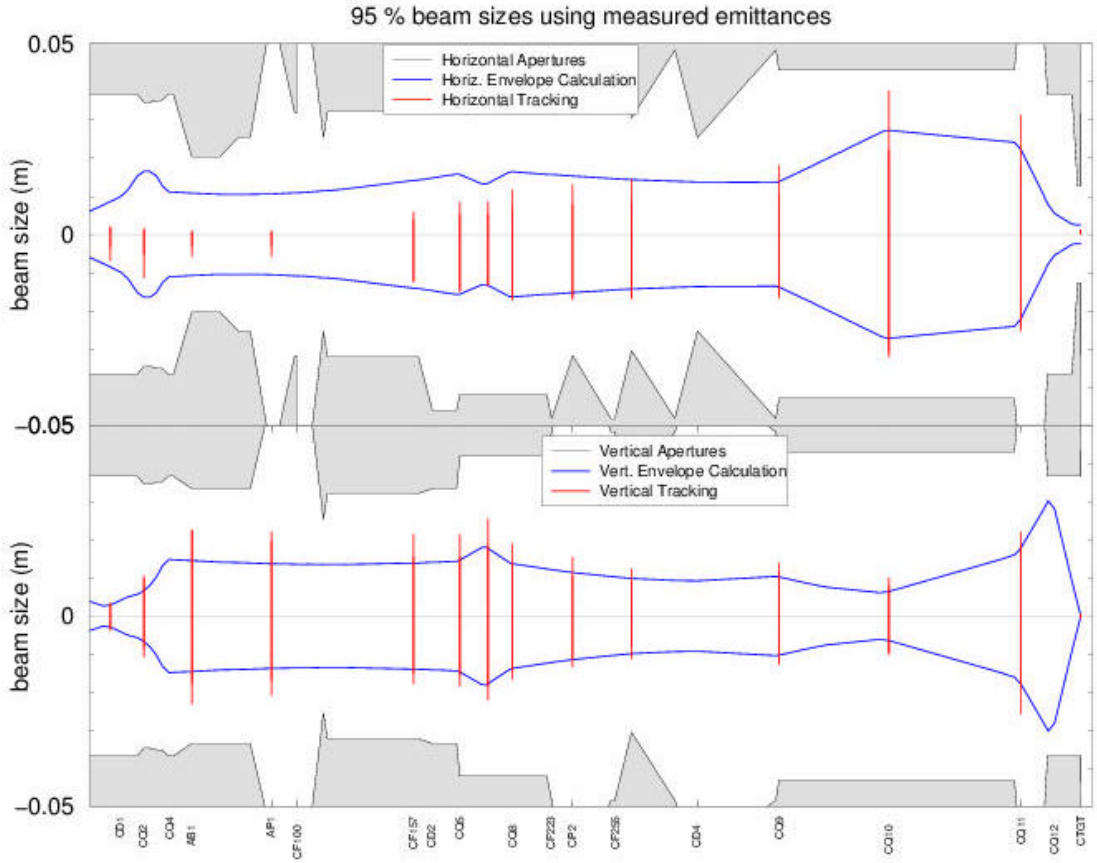
BROOKHAVEN
NATIONAL LABORATORY

Beam Transport



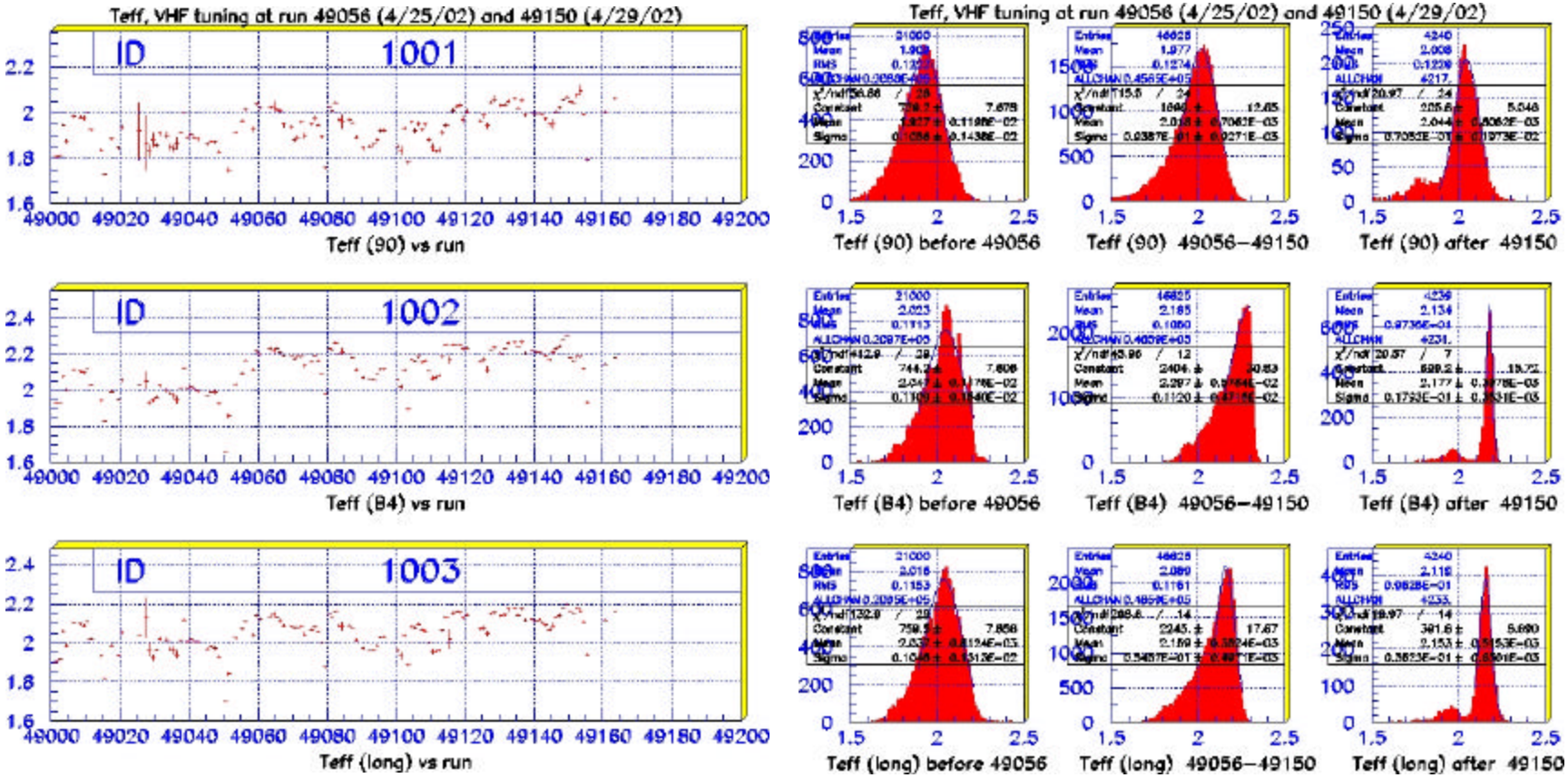
BROOKHAVEN NATIONAL LABORATORY

Beam Transport



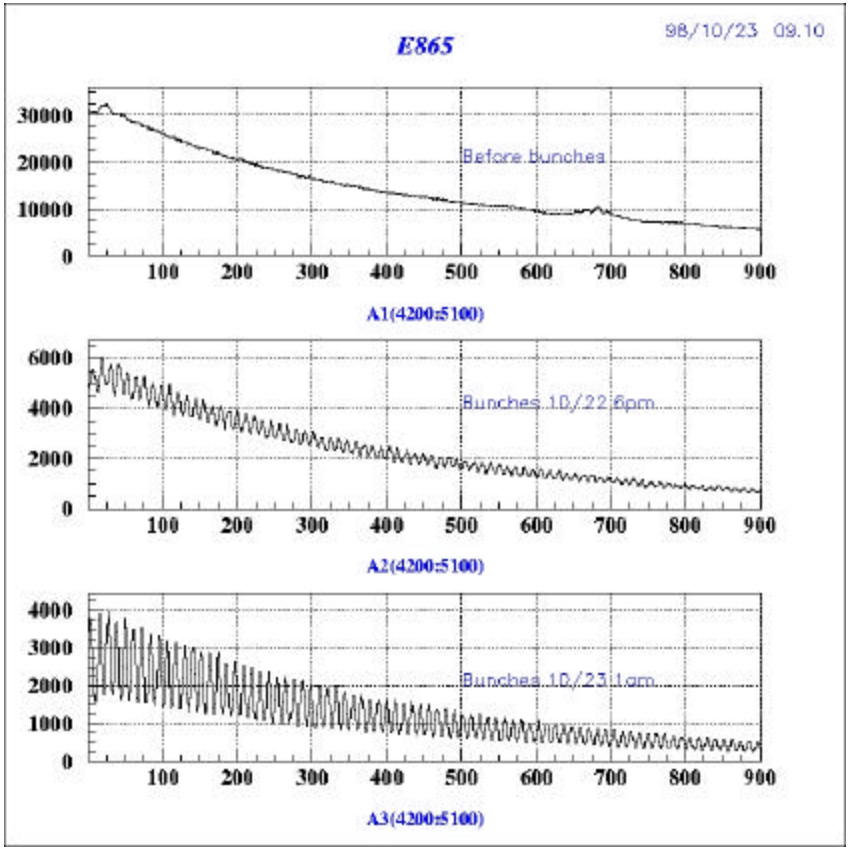
BROOKHAVEN NATIONAL LABORATORY

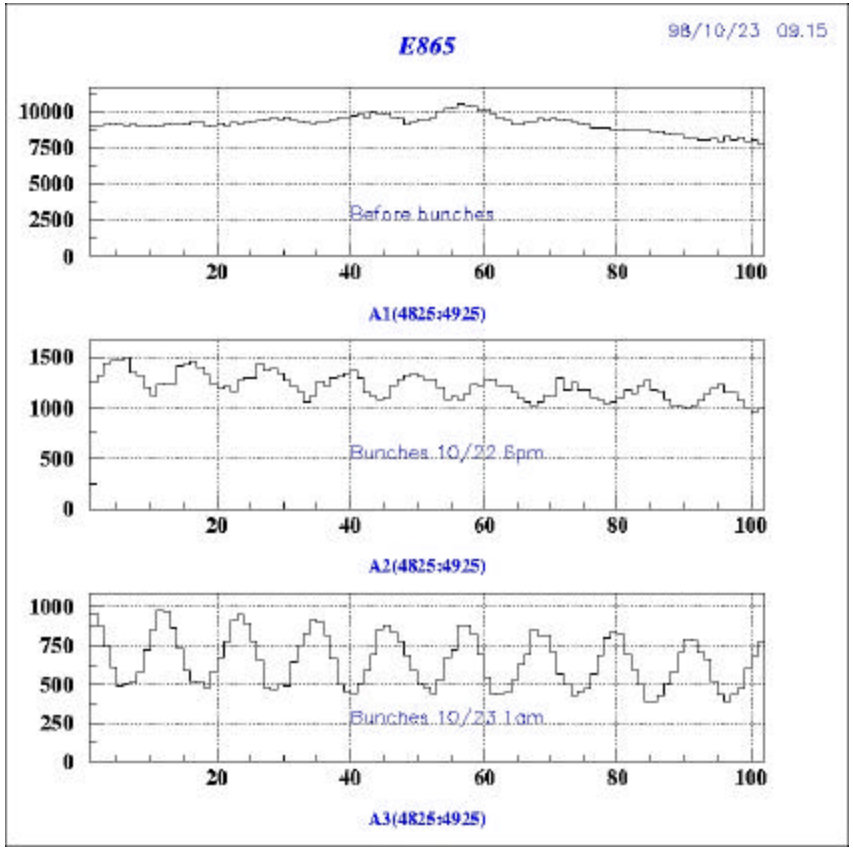
Beam Transport



BROOKHAVEN NATIONAL LABORATORY

Beam Transport

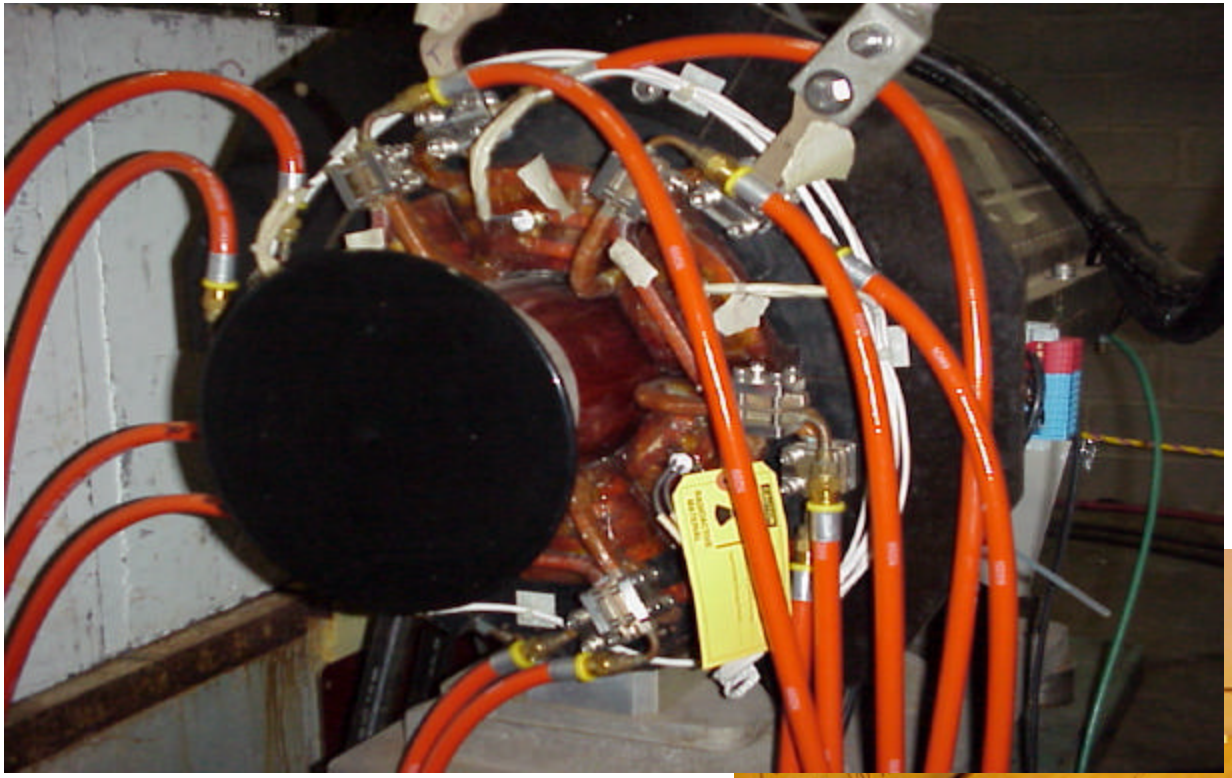




BROOKHAVEN NATIONAL LABORATORY

AGS Modifications

New Coils for AGS Sextupoles: tested to 600 amp dc



BROOKHAVEN
NATIONAL LABORATORY

AGS Modifications

HORIZONTAL SEXTUPOLE SPECIFICATION DATA SHEET

Input Voltage:	460 Vrms 3 phase, +10%, -5%, 60 Hz
DC Output Voltage:	-300 V to +300 V Continuously Adjustable
DC Output Current:	600A Continuously Adjustable
Pulse Repetition Frequency:	DC to 10 Hz
Regulation mode:	Current
Load Current Tracking:	0.01% during flat-top, 0.5% during rise/fall
Zero Current Crossover Distortion:	< 0.5%
Load Current Rise Time:	< 20 msec @ 100A
Load Current Settling Time:	< 5 msec
Output Voltage Ripple:	< 0.03%, DC to 10 kHz < 0.3%, 10 kHz to 1MHz
Electrical Load:	0.34 ohm + 40 mH

BROOKHAVEN NATIONAL LABORATORY

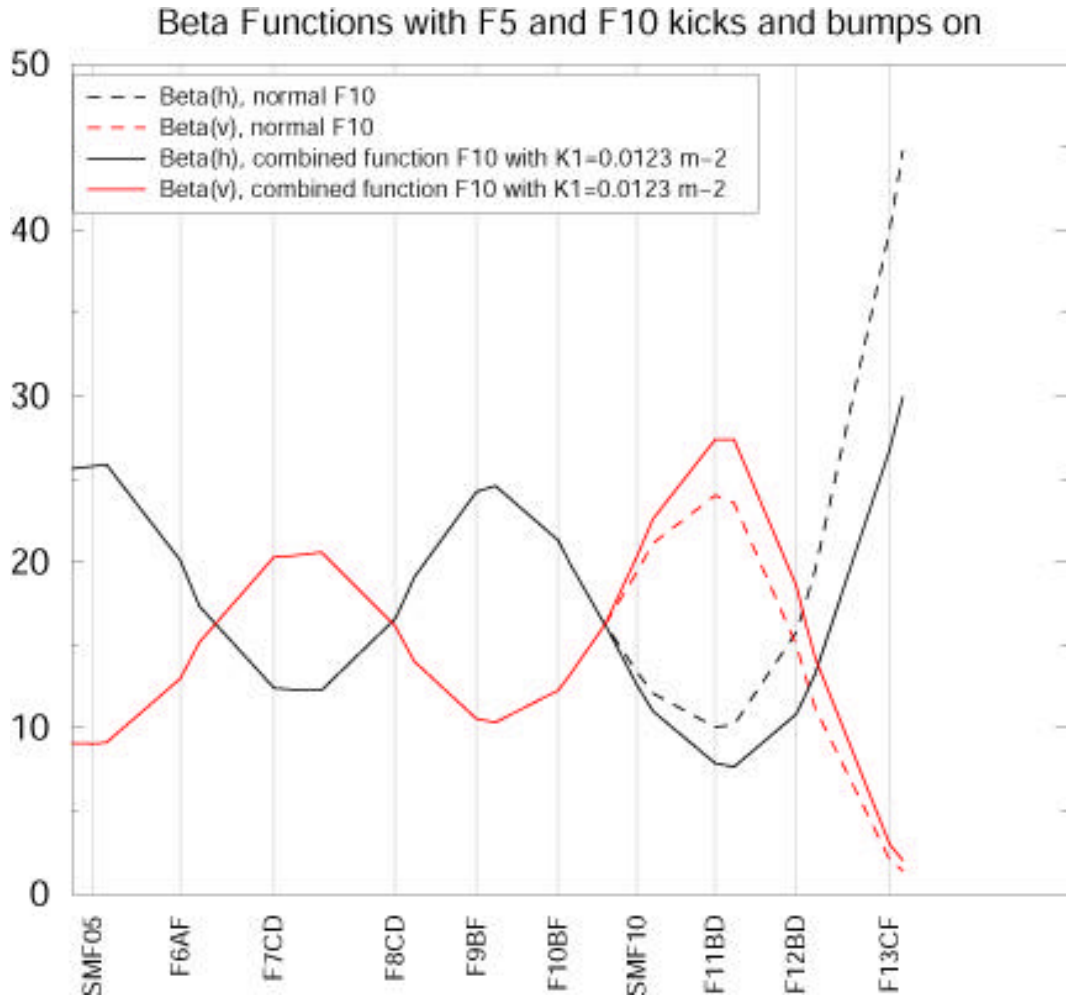
AGS Modifications

VERTICAL F7 P. S. SPECIFICATION DATA SHEET

Input Voltage:	460 Vrms 3 phase, +10%, -5%, 60 Hz
DC Output Voltage:	-40 V to +40 V Continuously Adjustable
DC Output Current:	-500A to +500A Continuously Adjustable
Pulse Repetition Frequency:	DC to 10 Hz
Regulation mode:	Current
Load Current Tracking:	+/- 0.01% during flat-top, 0.5% during rise/fall
Load Current Rise Time:	< 20 msec @250A
Load Current Settling Time:	< 5 msec
Output Voltage Ripple:	< 0.1%, DC to 10 kHz < 1%, 10 kHz to 1 MHz
Electrical Load:	0.02 ohm + 3 mH

BROOKHAVEN NATIONAL LABORATORY

AGS Modifications



BROOKHAVEN NATIONAL LABORATORY

Summary

1. High Intensity Experience at the AGS
2. Longitudinal Phase Space Dilution
3. Collective Effects on Losses and Spill Structure
4. Positive Vertical Chromaticity is Important
5. Positive Horizontal Chromaticity may be Important for further reducing inefficiency
6. RF Phase Displacement using a high frequency RF cavity is important for achieving low ripple, high duty factor beam spills
7. Current Mystery: electrostatic septum current related to intensity ?

BROOKHAVEN NATIONAL LABORATORY