Slow Extraction of High Intensity Protons at BNL's AGS

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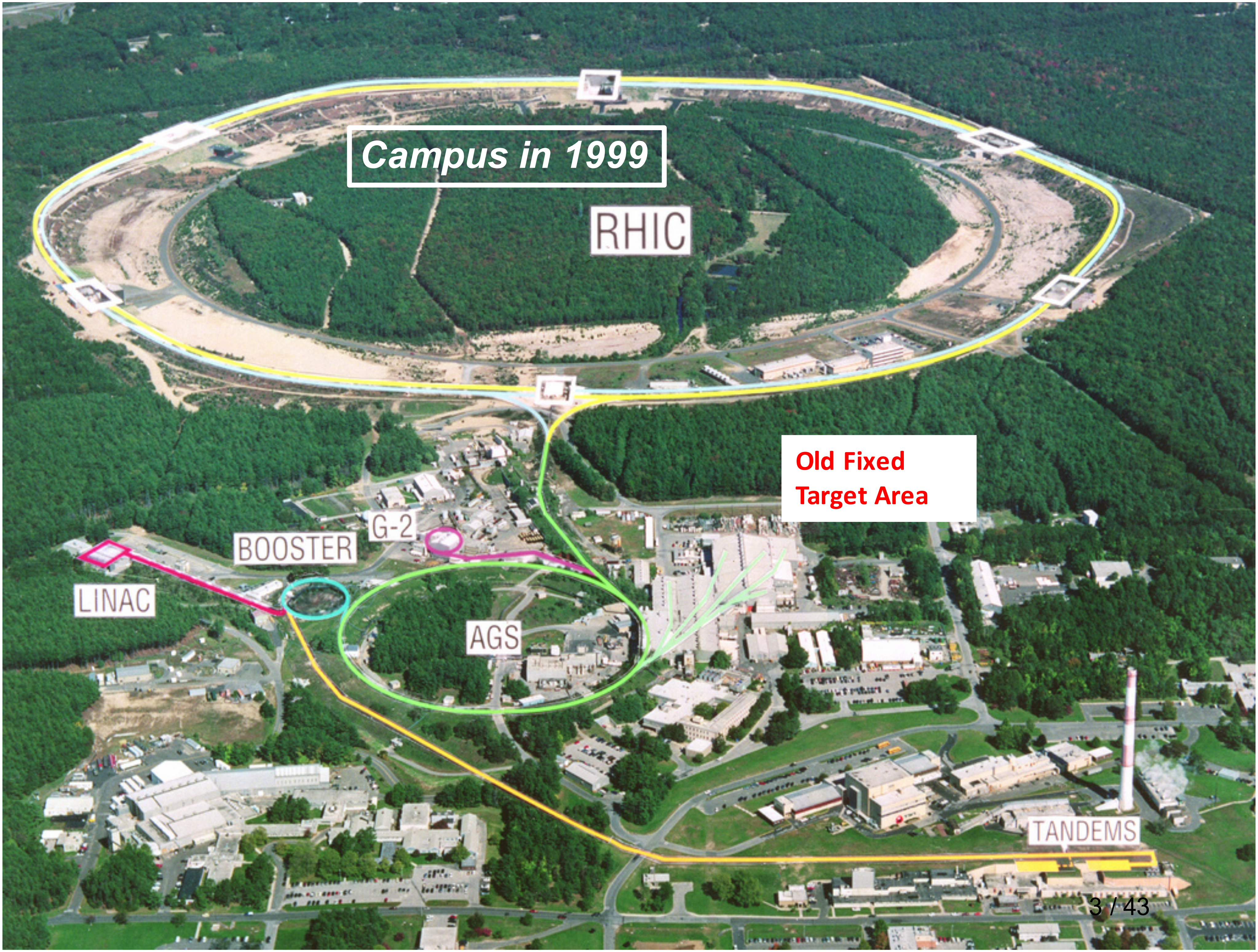
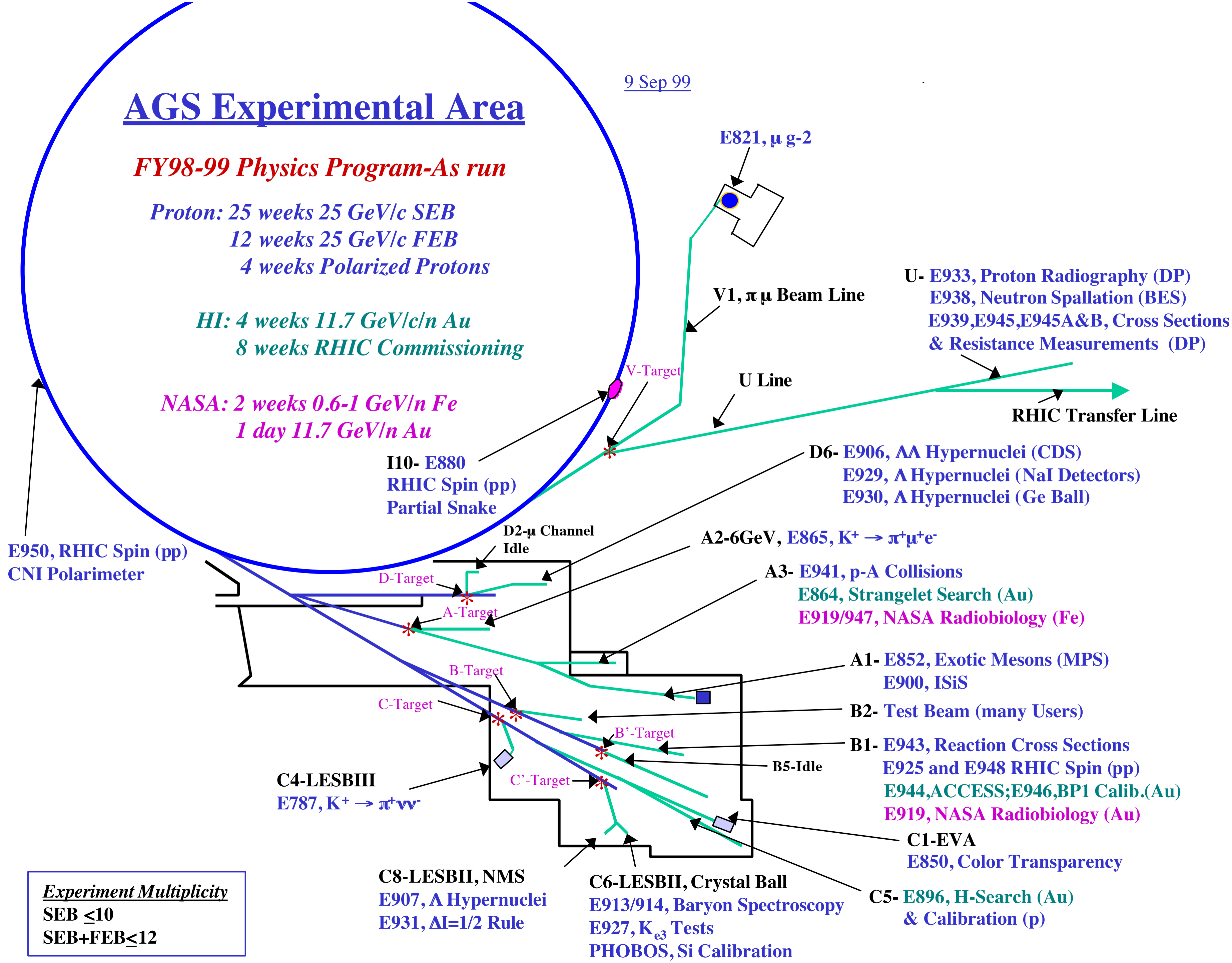
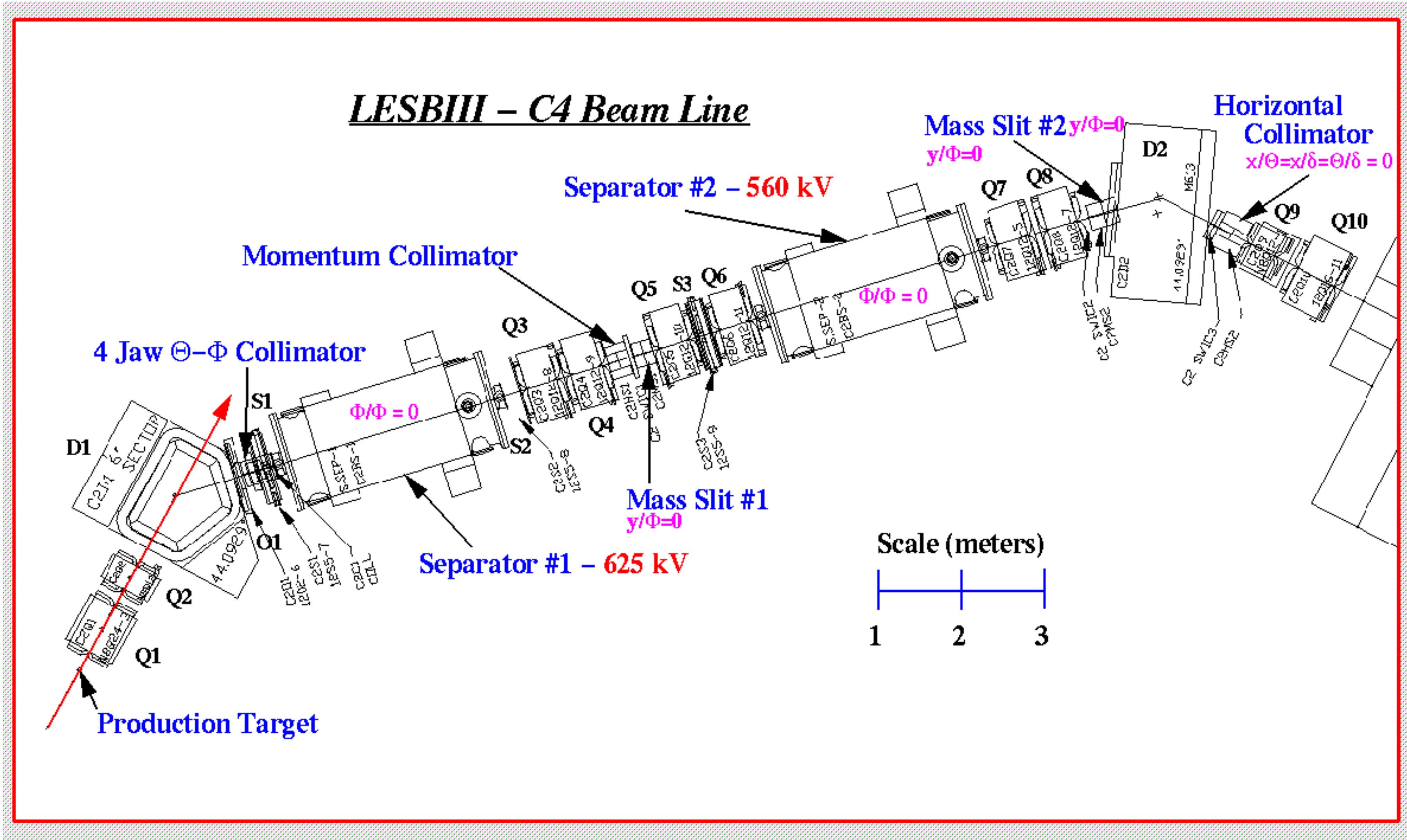
BROOKHAVEN
NATIONAL LABORATORY

Contents



Campus in 1999
RHIC
Old Fixed
Target Area
G-2
BOOSTER
LINAC
AGS
TANDEMS


AGS Experimental Area
9 Sep 99
FY98-99 Physics Program-As run
Proton: 25 weeks 25 GeV/c SEB
12 weeks 25 GeV/c FEB
4 weeks Polarized Protons
HI: 4 weeks 11.7 GeV/c/n Au
8 weeks RHIC Commissioning
NASA: 2 weeks 0.6-1 GeV/n Fe
1 day 11.7 GeV/n Au
E821, μ g-2
V1, π μ Beam Line
U- E933, Proton Radiography (DP)
E938, Neutron Spallation (BES)
E939,E945,E945A&B, Cross Sections
& Resistance Measurements (DP)
V-Target
U Line
RHIC Transfer Line
I10- E880
RHIC Spin (pp)
Partial Snake
D6- E906, ΛΛ Hypernuclei (CDS)
E929, Λ Hypernuclei (NaI Detectors)
E930, Λ Hypernuclei (Ge Ball)
E950, RHIC Spin (pp)
CNI Polarimeter
D2-μ Channel
Idle
A2-6GeV, E865, $K^+ \rightarrow \pi^+\mu^+e^-$
D-Target
A-Target
A3- E941, p-A Collisions
E864, Strangelet Search (Au)
E919/947, NASA Radiobiology (Fe)
A1- E852, Exotic Mesons (MPS)
E900, ISiS
B-Target
B2- Test Beam (many Users)
C-Target
B'-Target
B1- E943, Reaction Cross Sections
B5-Idle
E925 and E948 RHIC Spin (pp)
E944,ACCESS;E946,BP1 Calib.(Au)
E919, NASA Radiobiology (Au)
C4-LESBIII
$E787, K^+ \rightarrow \pi^+\nu\bar{\nu}$
C'-Target
C1-EVA
E850, Color Transparency
C8-LESBII, NMS
E907, Λ Hypernuclei
E931, ΔI=1/2 Rule
C6-LESBII, Crystal Ball
E913/914, Baryon Spectroscopy
E927, K_{e3} Tests
PHOBOS, Si Calibration
C5- E896, H-Search (Au)
& Calibration (p)
Experiment Multiplicity
SEB ≤10
SEB+FEB≤12



1 billion 800 MeV K^+ / 10^{13} protons with 60 - 70% Purity (π^+ / K^+ = 0.3 – 0.4)

Contents

Slow Extraction at the AGS

- March, 1968: first SE for HEP, $3Q_H$=26
  - Simple system with no ES septum
- 1972: 200 MeV LINAC (previous was 50 MeV), H+ injection to AGS
- 1979: first ES septum installed
- 1979: new multi-hall switchyard (3 lines)
- 1980's: pre-Booster era, H- injection to AGS
  - Intensities 1.0 – 1.6 x 10^{13} protons/pulse
  - Extraction momentum 25-29 GeV/c
  - Spills 1 – 2 sec., repetition periods 2.4 - 4.0 sec.
  - Extraction inefficiency 3 – 5 %
  - Began doing heavy ion experiments (NPP)
- 1990's: post-Booster era
  - Intensities 5.0 – 7.6 x 10^{13} protons/pulse
  - Extraction momentum 25.5 GeV/c (to improve uptime)
  - Similar spills and rep periods, more optimization on duty factor
  - Extraction inefficiency 2 – 3 %
  - Problem! Higher losses in switchyard beam transport (more later)
- 2002: program ends. RHIC era.

AGS Performance

Proton Beams	FY94	FY95	FY96	FY97	FY98	FY99 (G-2)	FY00 (G-2)	FY01 (G-2)	FY02
Beam Energy (GeV)	24	24	24	24	24	24	24	24	24
Peak Beam Intensity (10^{12} #p/pulse)	40	63	62	62	72	58	61	63	76
Total Integrated (10^{20} protons)	0.3	1.1	0.9	0.4	0.9	0.4	0.5	0.6	0.7
Spill Length/Cycle Time (seconds)	1.0 / 3.0	1.6 / 3.6	1.6 / 3.6	1.6 / 3.6	2.8 / 5.1				2.4 / 5.4
Duty Cycle	26 %	44 %	44 %	44 %	55 %				44 %
Spill Structure (peak-average) /average	50 %	20 %	20 %	20 %	20 %				20 %

Note: Each year also included Heavy Ion operations.
G-2 Operations used Fast Beam to the U-line (now upstream end of AtR line)
G-2 Commissioning began FY97

Booster & AGS Performance: SEB

Imposed limits to lost beam power to maintain hands-on maintenance (ALARA).

•AGS SEB operation, 5.4 s AGS cycle time, 6 Booster cycles.

Achieved 19.6 Tp/sec, Booster Late & 13.7 Tp/second, AGS Late.

Table: SEB 10 Pulse Ave. Data (best performance)

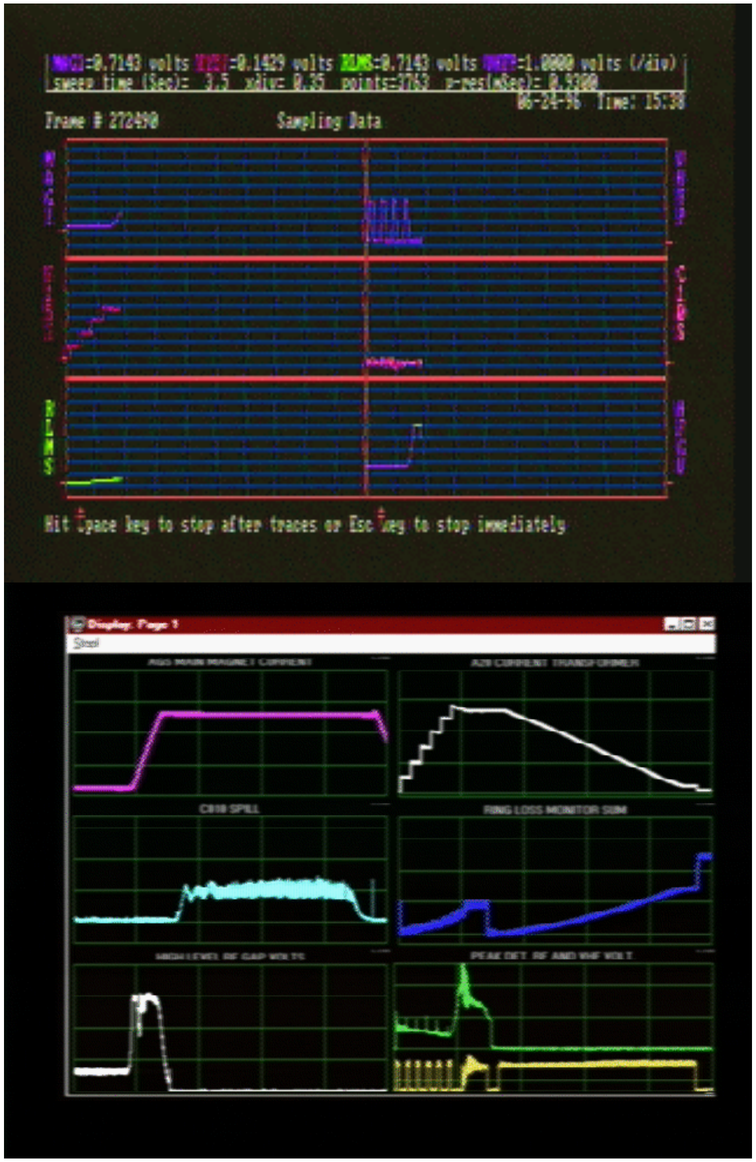
	Intensity (Tp/cycle)*	Efficiency (%)	Beam Loss (Tp/cycle)	ALARA (Tp/cycle)	Loss (kW)	Loss/m (W/m)
Linac	177	-	-	-	-	
Booster Injected	125	71	52	54	0.31	1.5
Booster Extracted	106	86	18	18	0.5	2.5
AGS Injected	78	74	28	31.5	1.62	2.0**
Transition	76	98	2	3	0.26	0.3
After Transition	73	95	3	4.5	0.63	0.8
AGS Late	73	100	0	1.5	0	0

* 1 Tp = 1×10^{12} protons

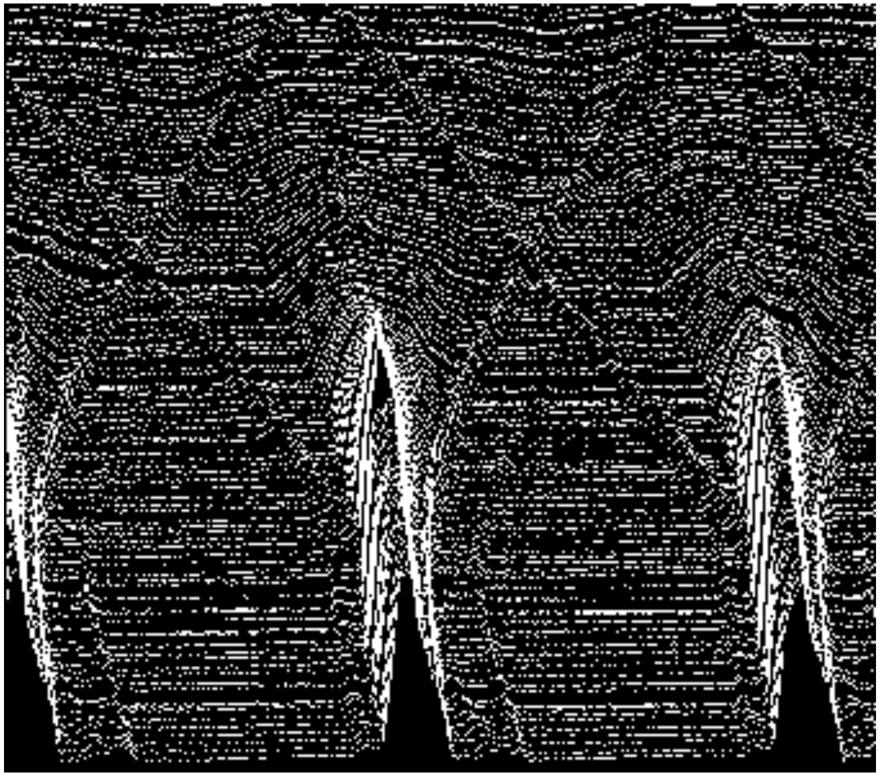
** assumed lost in AGS

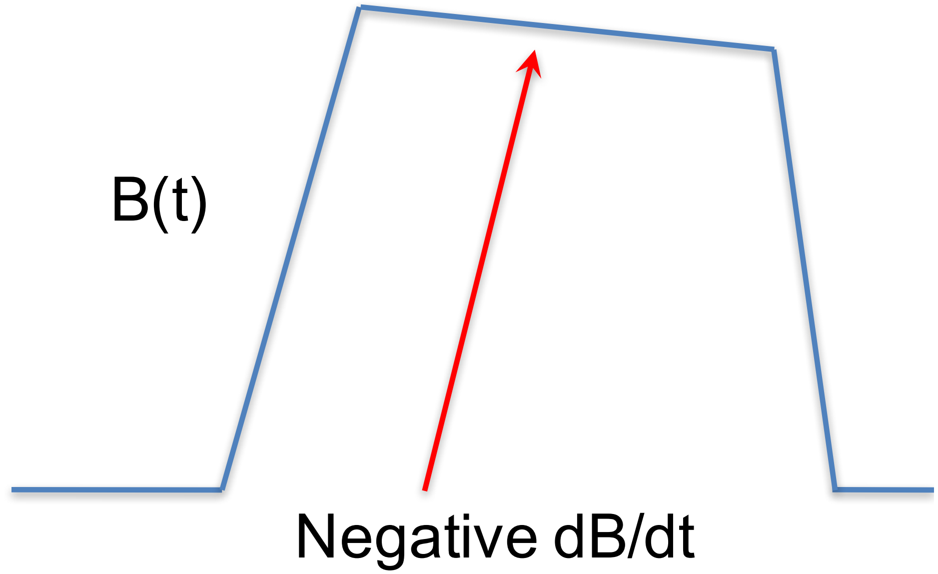
Contents

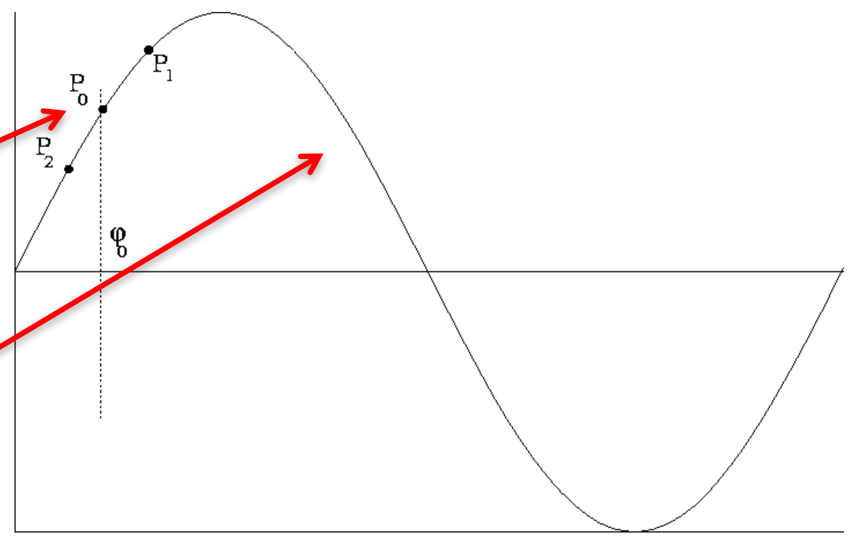
Overview of AGS Slow Extraction



Extraction Method: Chromatic SE



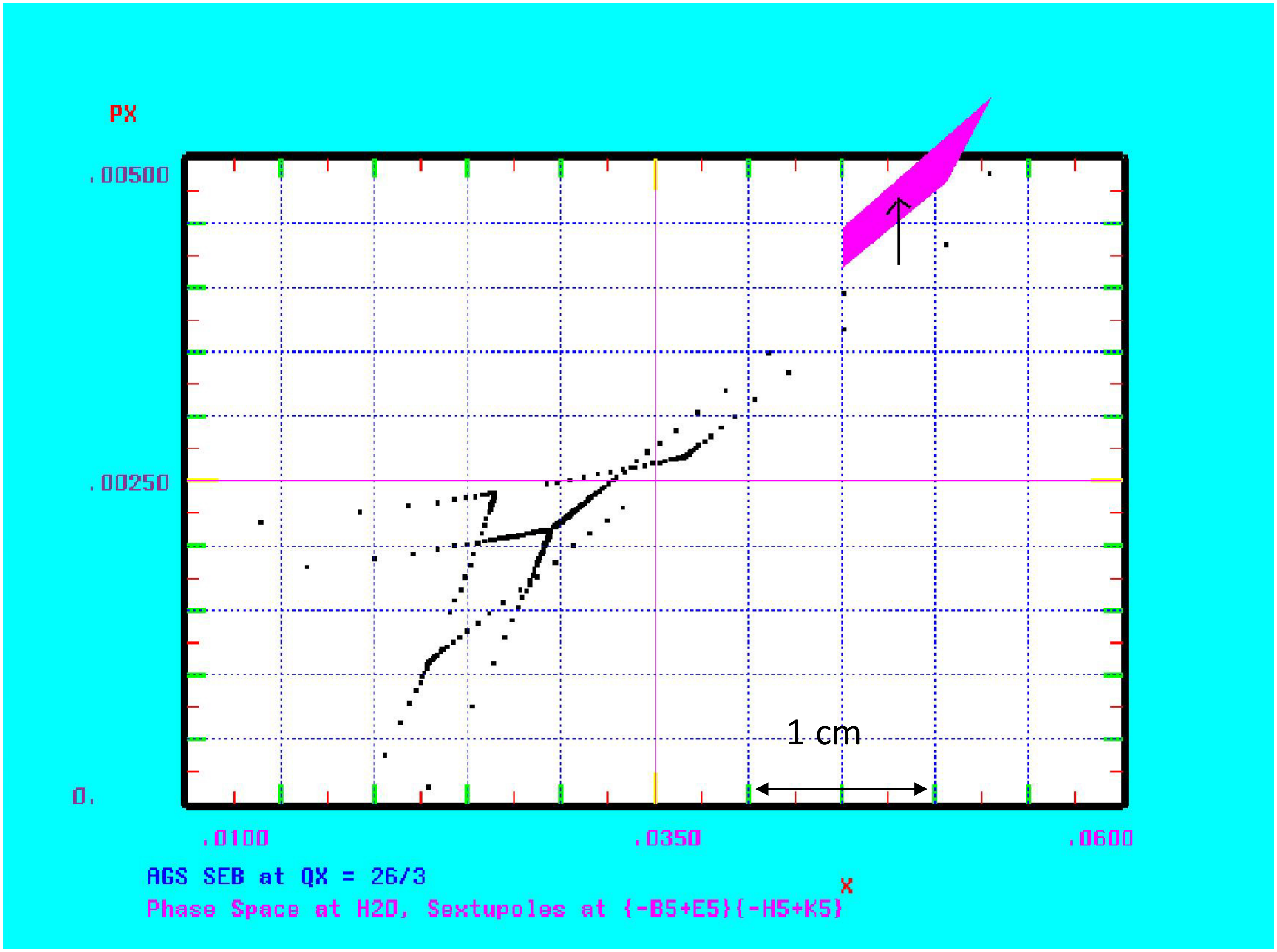




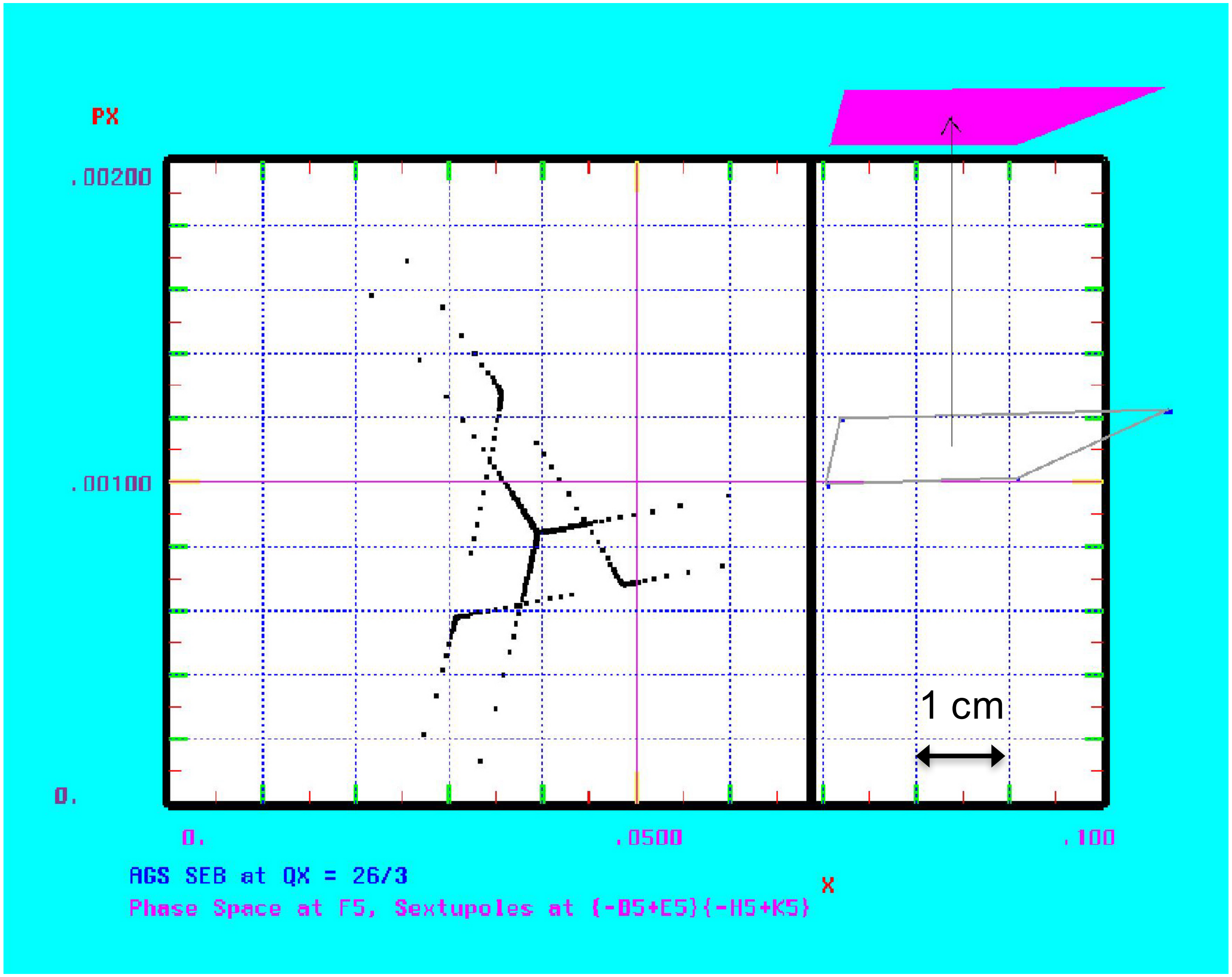
To increase dp/p, phase back
Drive dp/p to as high as 0.5%

After γ_{tr} accel. on (-) slope

Slow Extraction: ES Phase Space



Slow Extraction: Thin MS Phase Space



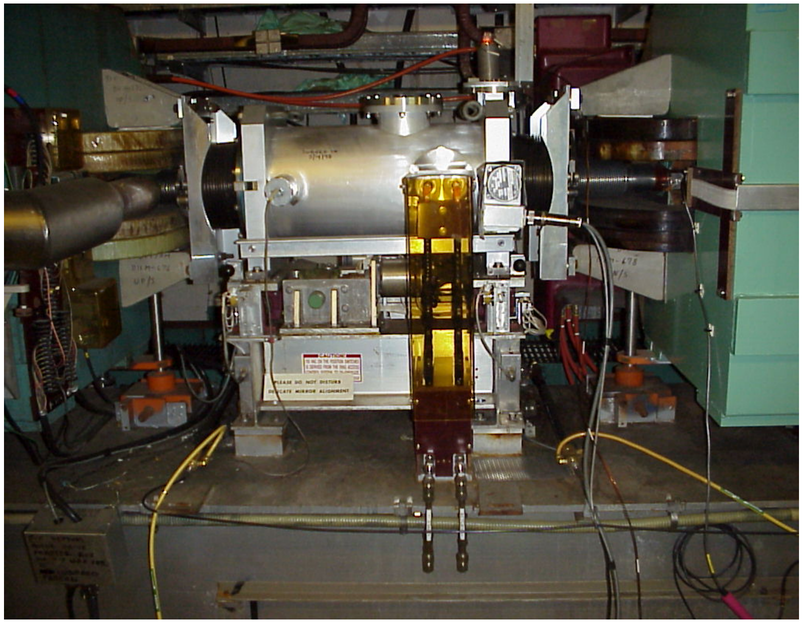
Contents

SEB Device 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 / 3.175 space WRe 1.58 wide foil	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

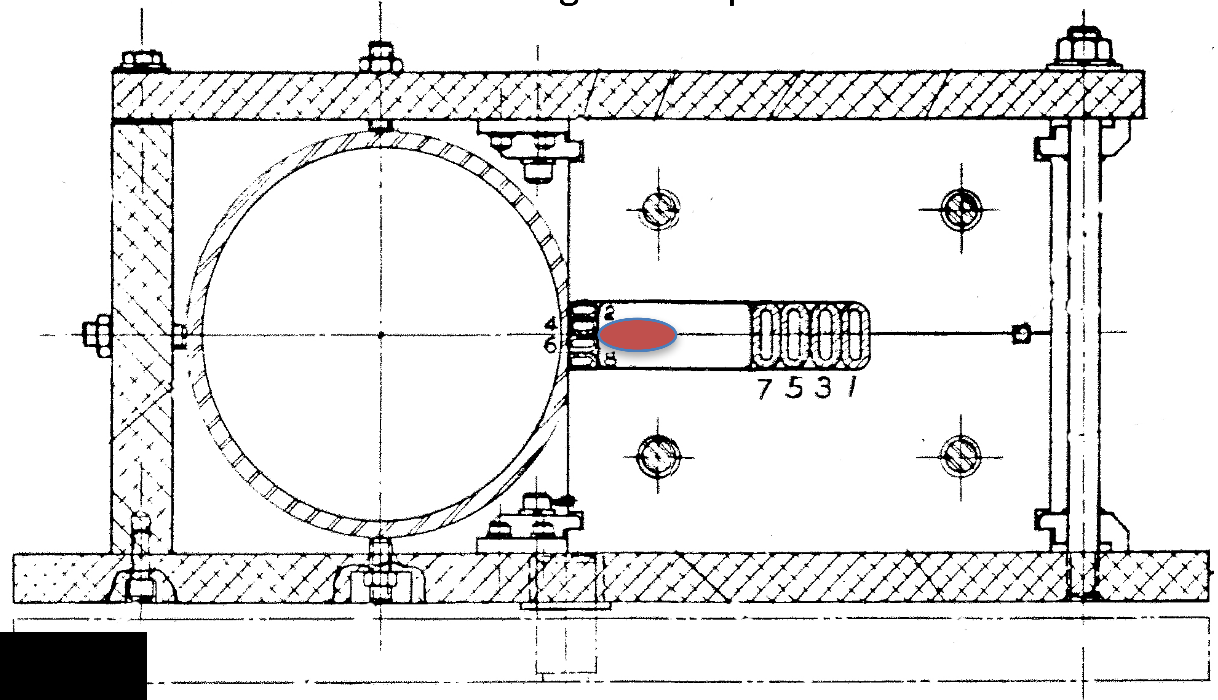
All US/DS remotely movable

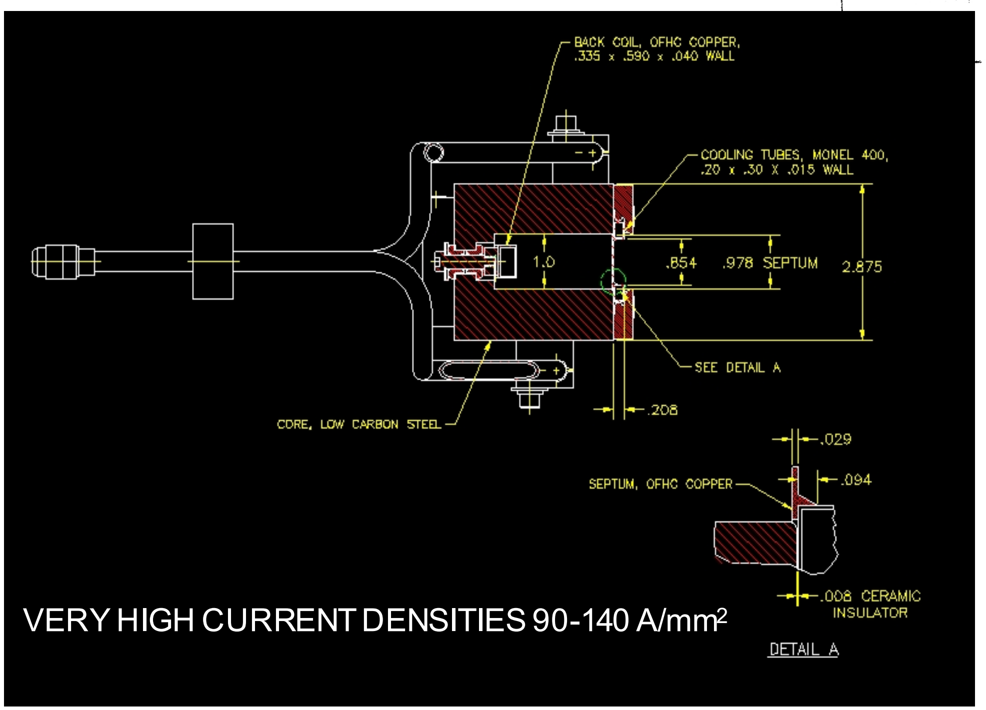
SEB Devices : Septa



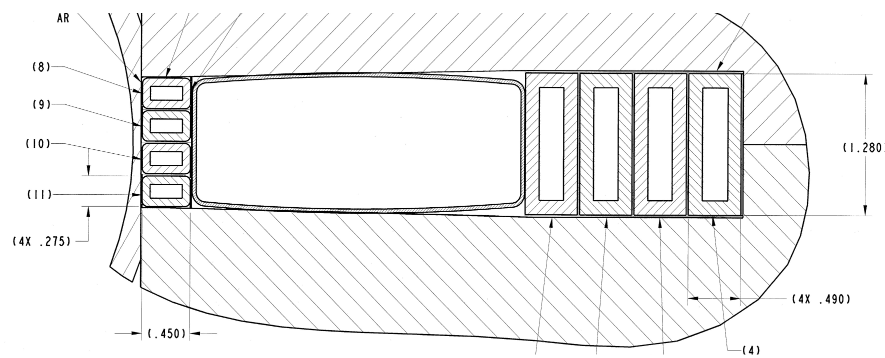
Thin Magnetic Septum in Place.

Thick Magnetic Septum





VERY HIGH CURRENT DENSITIES 90-140 A/mm²



SEB Devices : Electrostatic Septum

<u>Properties of Foil Septum</u>

Material : 75% Tungsten and 25% Rhenium

Special property: Ductile in High Temperature

Foil thickness .051 mm

Foil Width 1.5 mm

Foil Spacing 3.175 mm

Number of foils 1000

Gap = 1cm

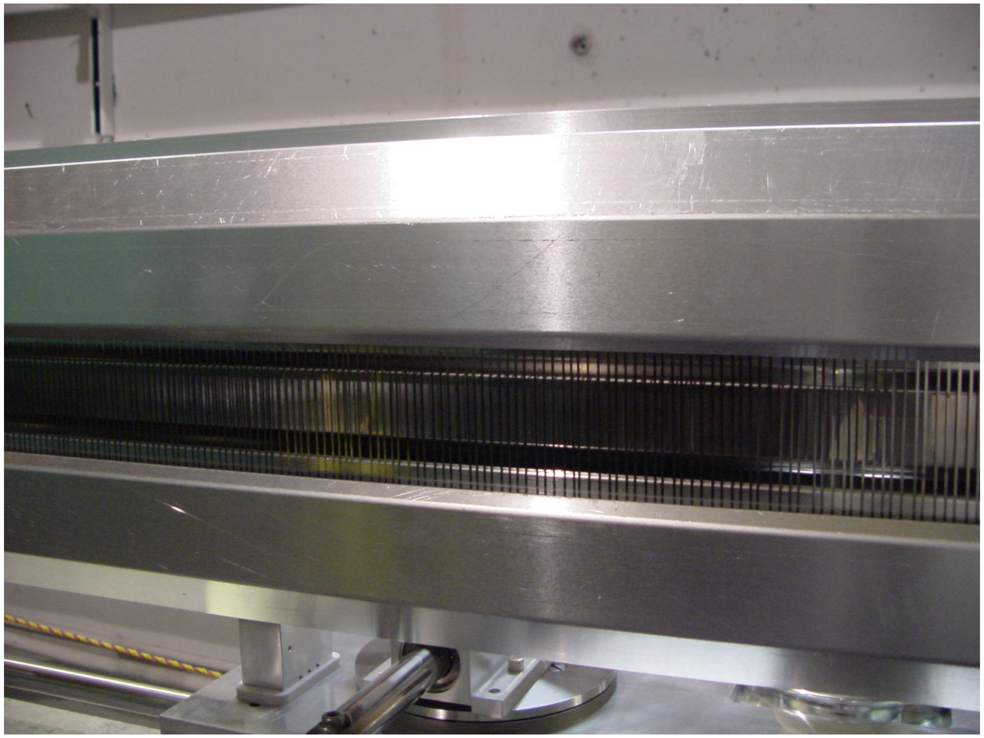
Length = 2.5 meter

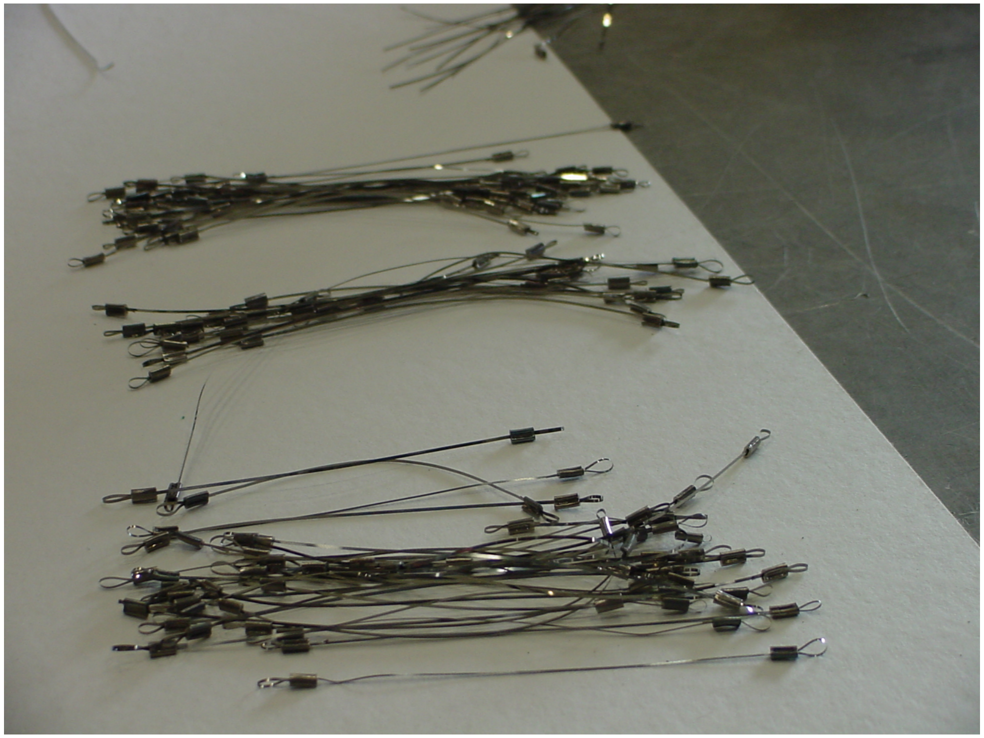
Operating voltage 56 kV

Conditioning Voltage 64 kV

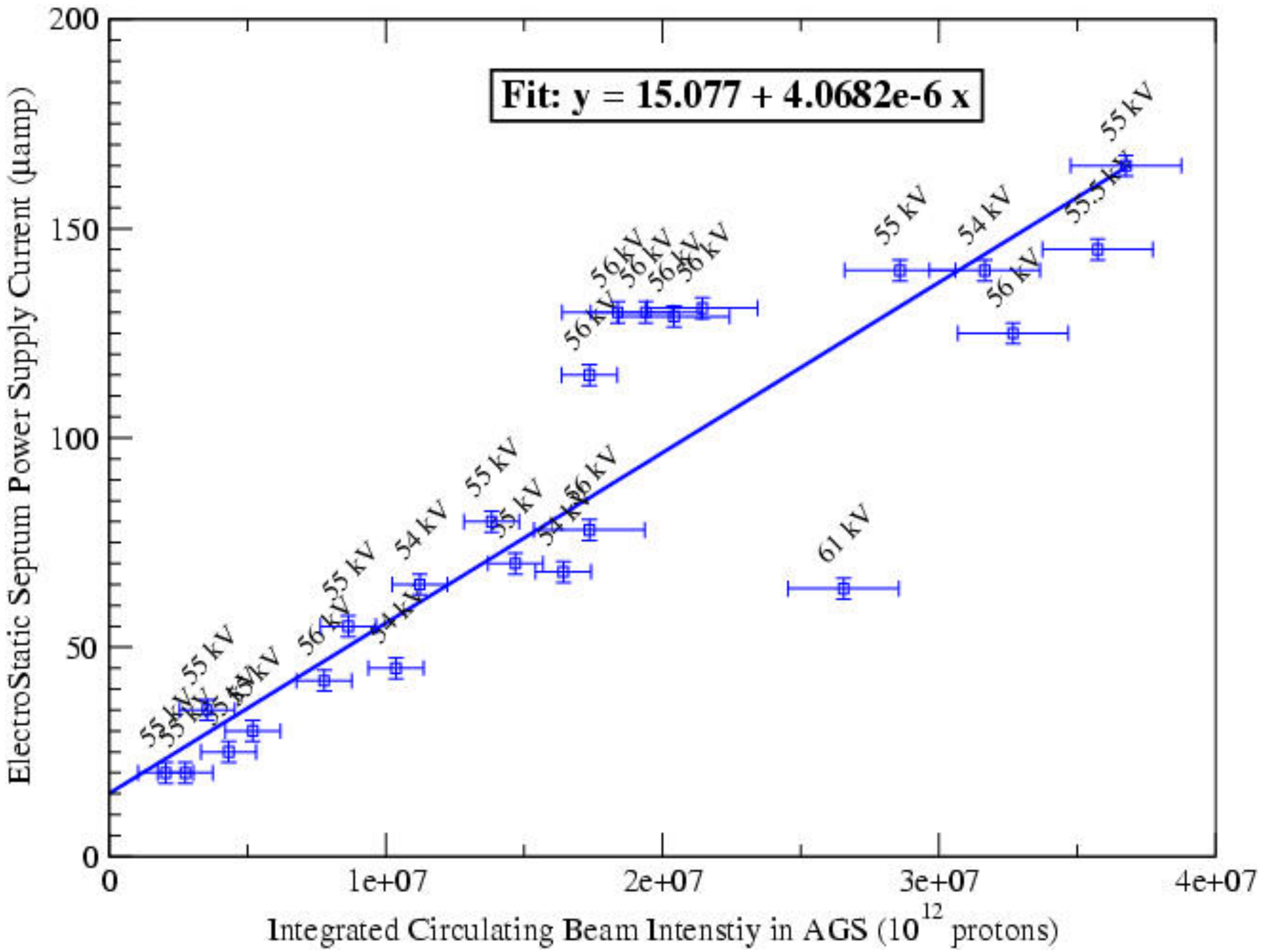
Operating Vacuum 10^{-8} Torr

Foils on Septum



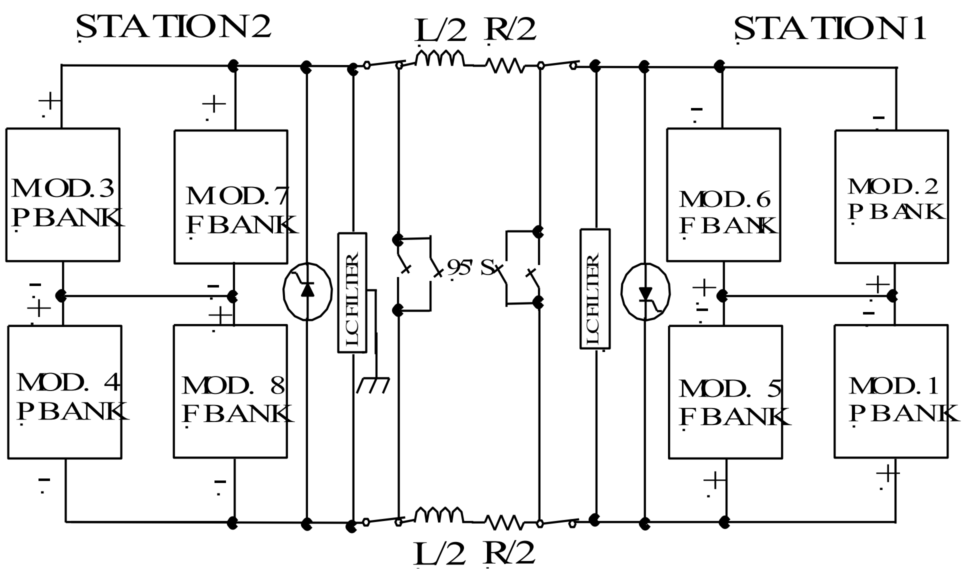


AGS High Intensity & ES Operation



Contents

AGS Magnet Power Supply Configuration.

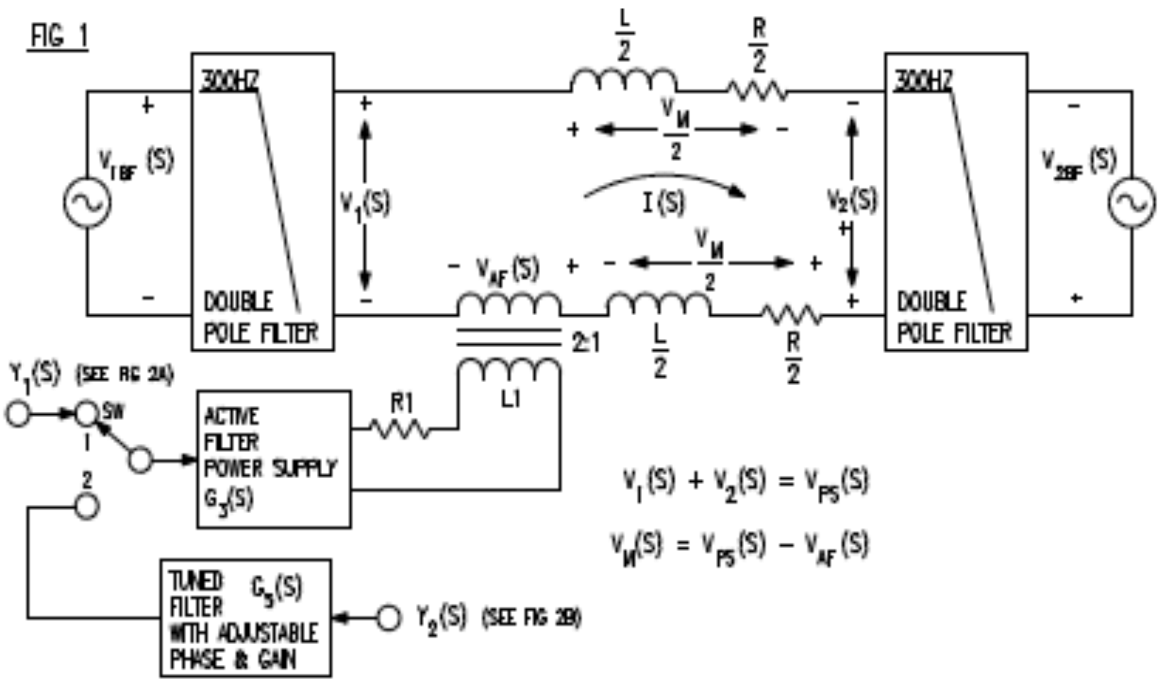


- 2 stations
- each with F-bank and P-bank power supplies in parallel.
- 24 pulse thyristor control rectifiers
- F-bank operate at ±1900 Volt maximum, and 6000 Amp, and it is used during the flat-tops of the AGS cycles.
- P-bank operates at ±9000 Volt maximum, and 6000 Amp, and it is used during ramping

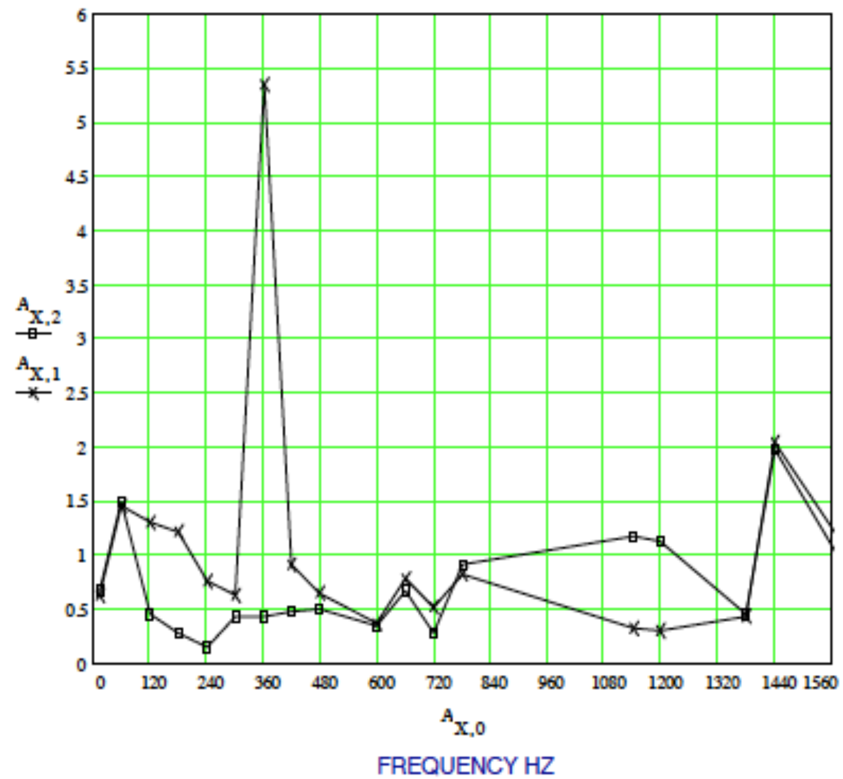
- Each PS is 12 phase
- Magnets are powered in two strings, alternating top/bottom coils on separate power supplies
- Field ripple fundamental is therefore 24 phase
- This ensures minimum ripple during the flat-tops, an essential condition for a slowly extracted beam.

Active Ripple Filter

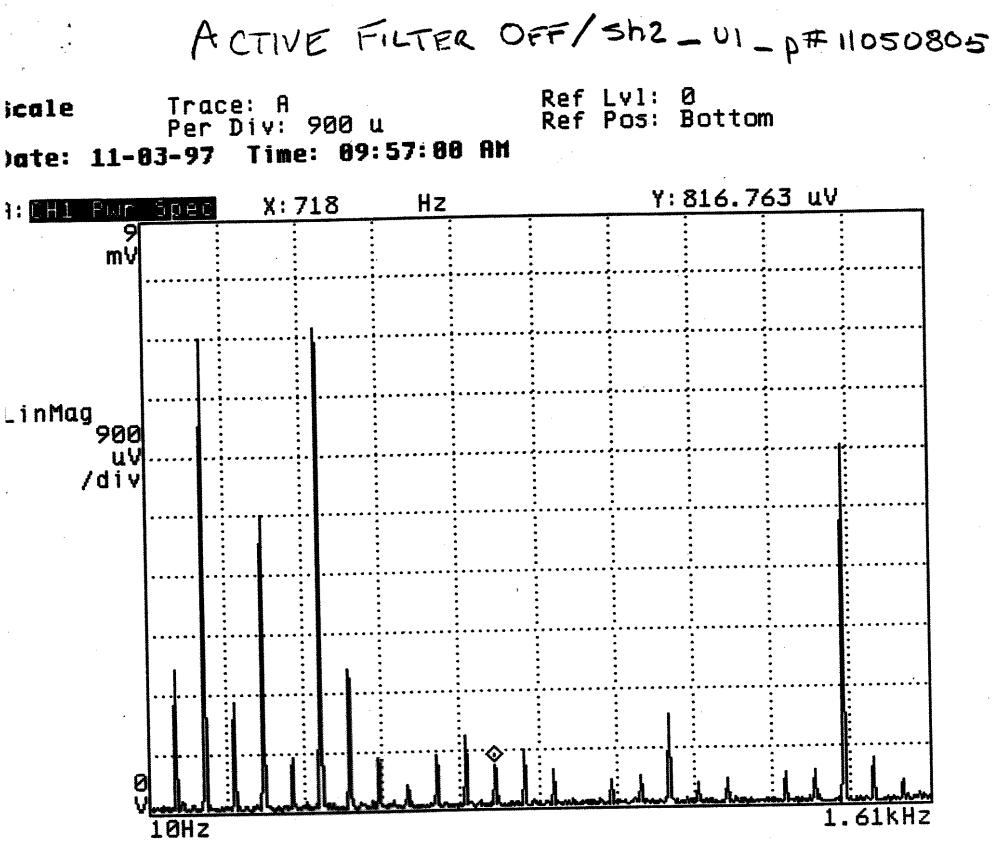
FIG 1

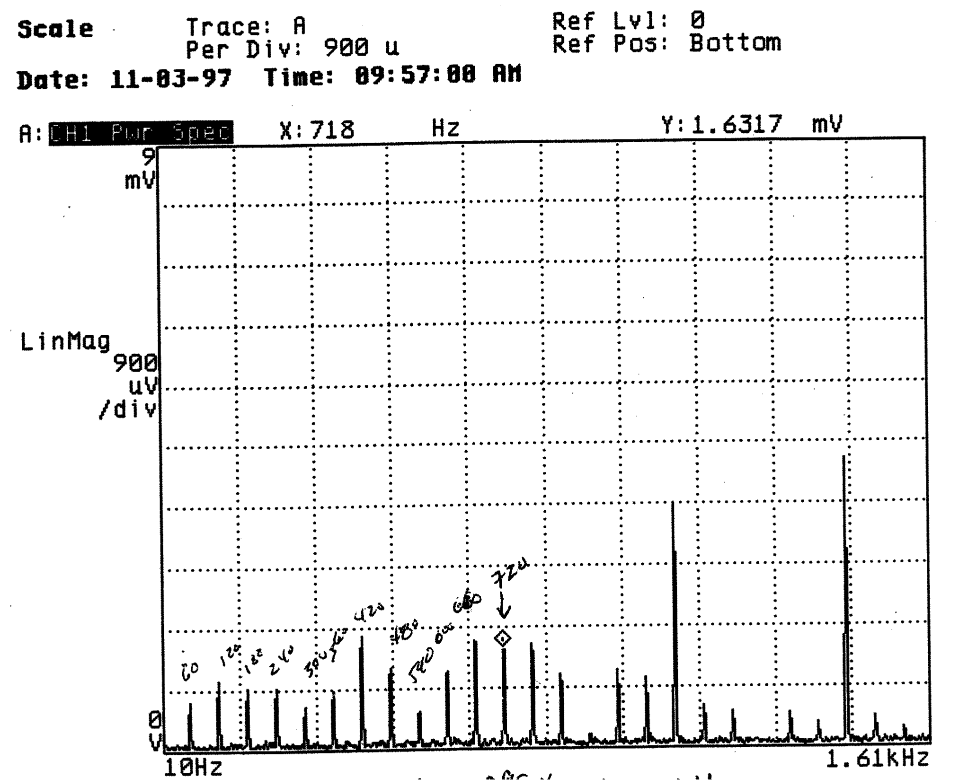


1. Ax,1 IS THE RIPPLE WITHOUT THE ACTIVE FILTER CORRECTION
2. Ax,2 IS THE RIPPLE USING THE ACTIVE FILTER CORRECTION, WITH SWITCH (SW) IN POSITION 2 (SEE FIG. 2). TUNED FILTER WAS TUNED TO CORRECT 120 HZ, 180 HZ, 240 HZ, 360 HZ, 720 HZ.



Active Filter Effect on Spill 60 Hz Harmonics





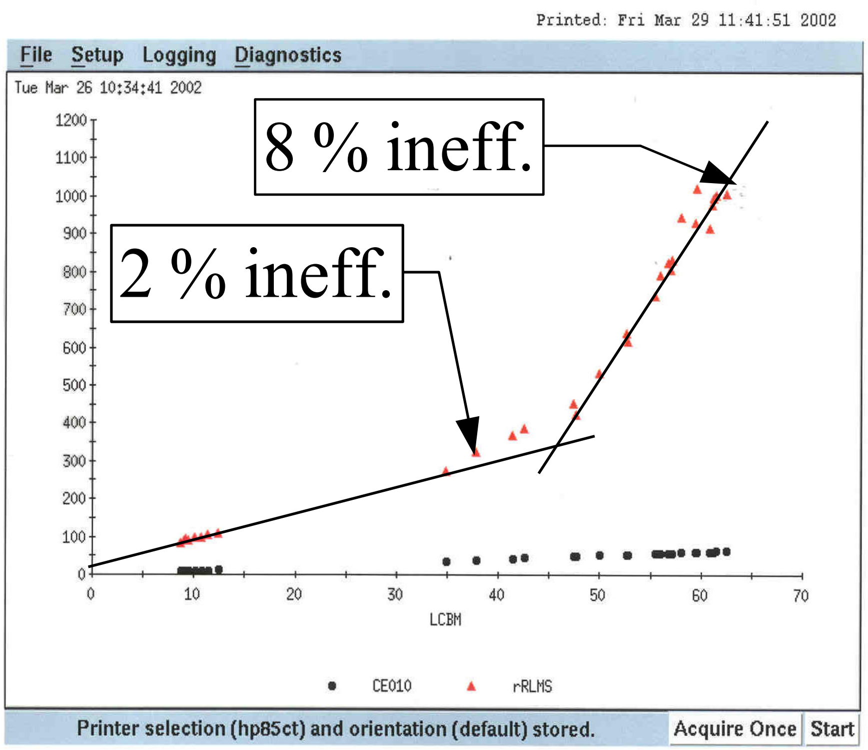
Contents

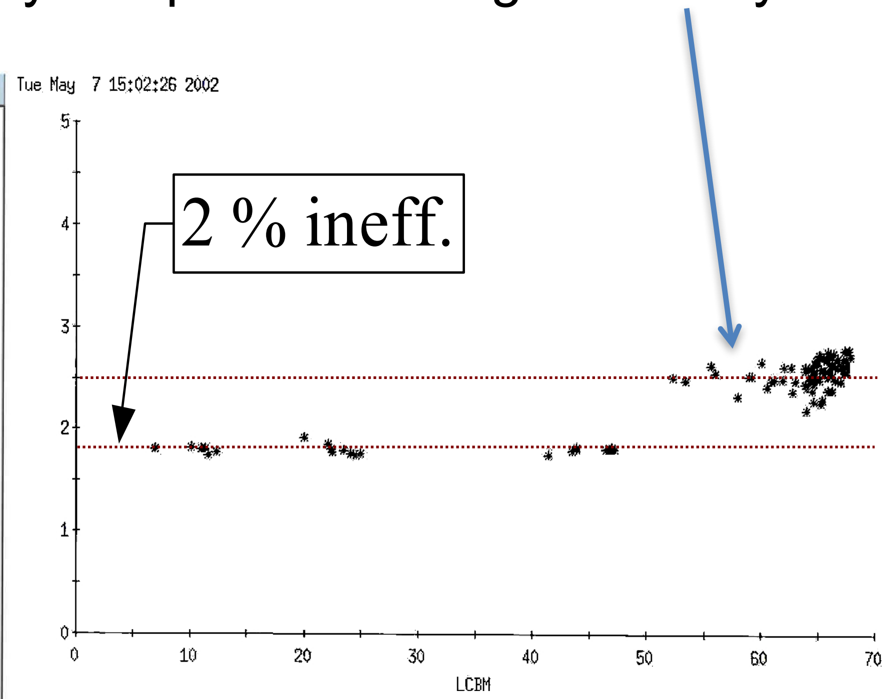
High Intensity Slow Extraction

70 TP Slow extracted beam observations.

Vertical Chromaticity is kept positive after transition.

Negative Horizontal Chromaticity is a problem at high intensity.

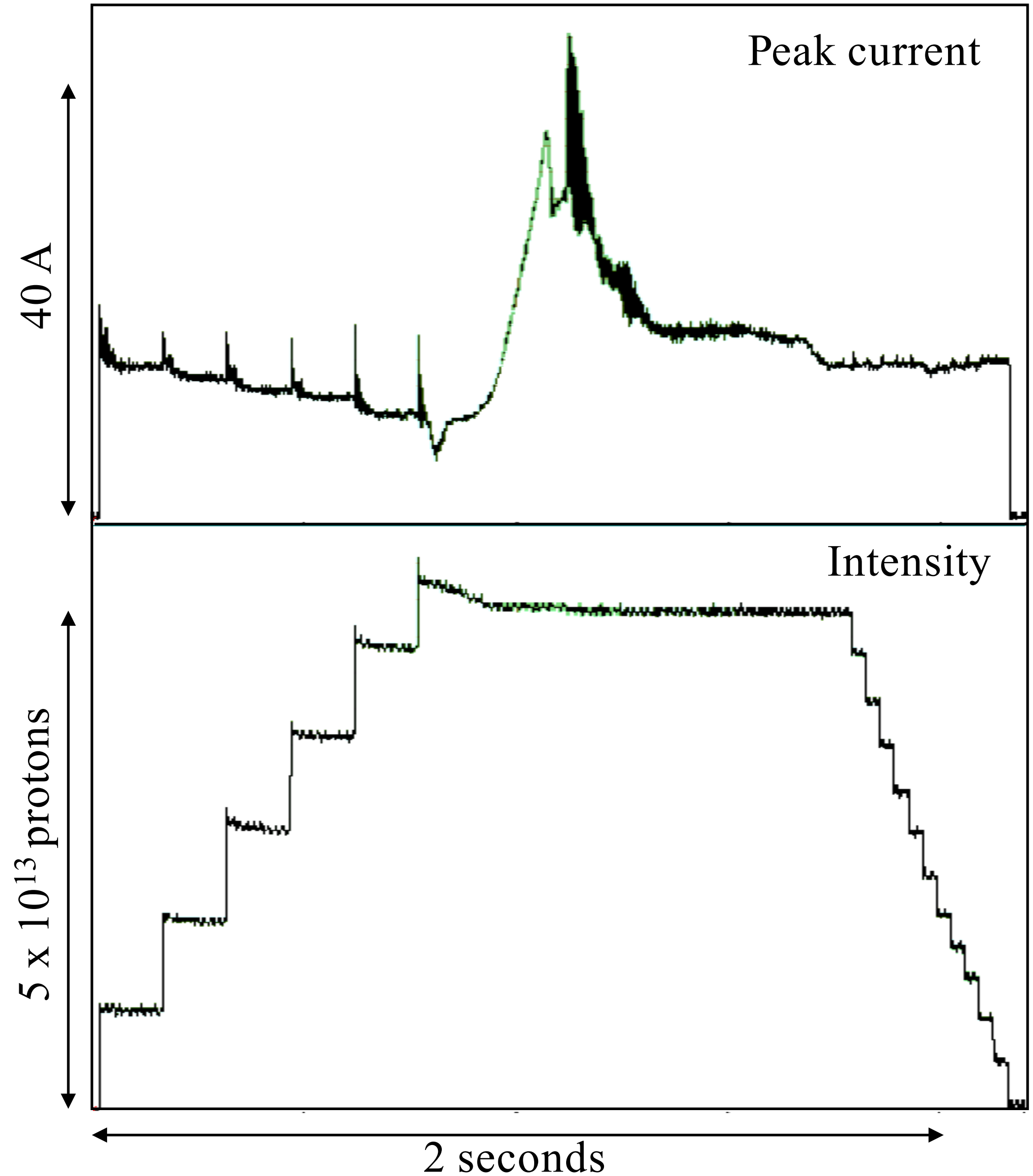




AGS performance for high intensity

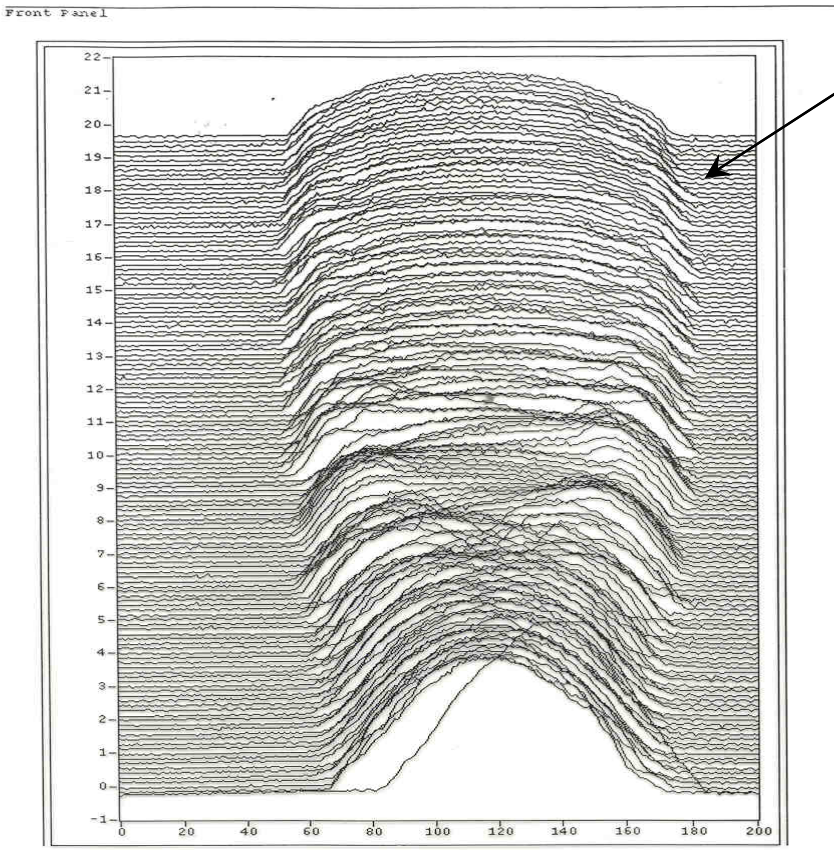
- 6 single bunch transfers from Booster
- Peak intensity reached: 76 x10^{12} ppp
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for g-2 ops: 50-60 x10^{12} ppp

- 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



Longitudinal Phase Space Dilution

Keeping peak beam current low. Trade off with larger longitudinal emittance.



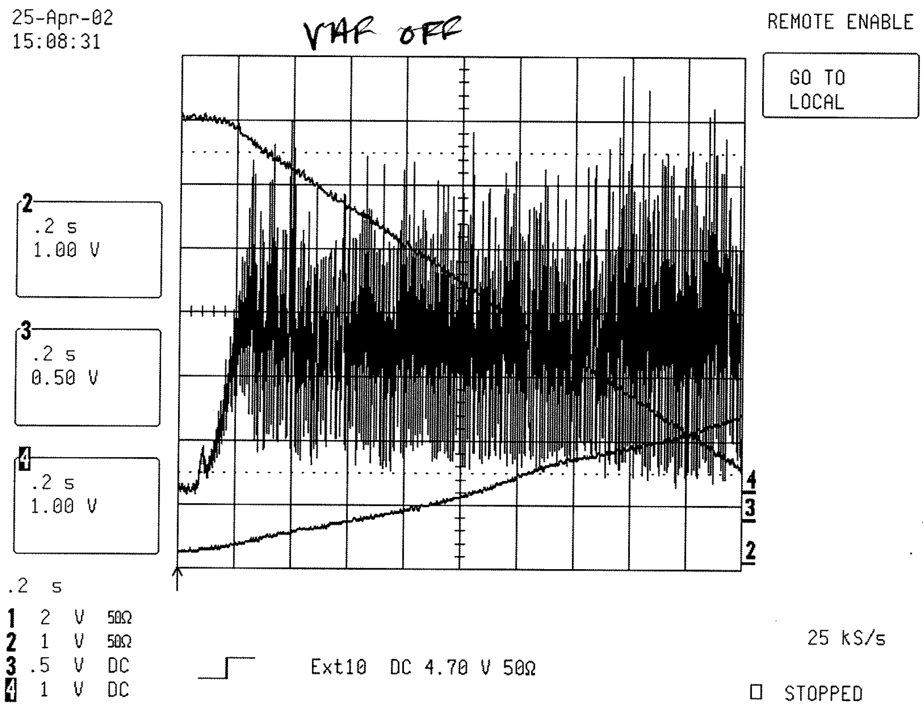
Bunch Dilution using 93.15 MHz VHF cavity

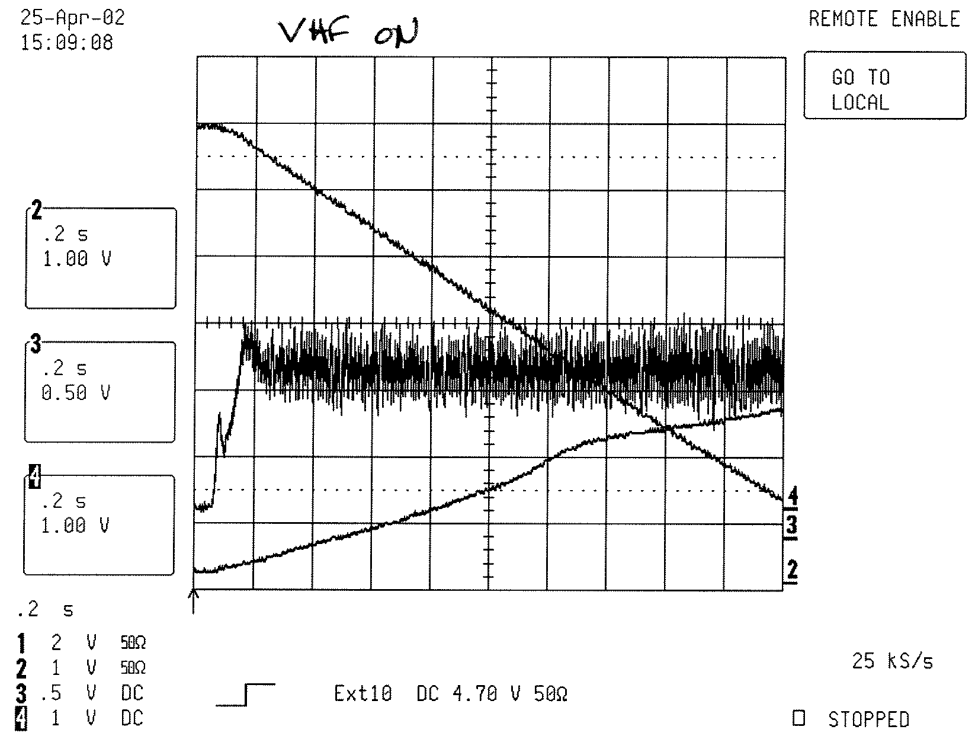
The cavity:

- a shorted quarter wave TEM mode cavity
- 30 kV of gap voltage for less than 10 kW of drive power.
- When not in operation it was switched to a low-impedance state by a PIN diode switch.
- Harmonics 268, 272
- Phase modulated between 6.7 to 7.3 kHz

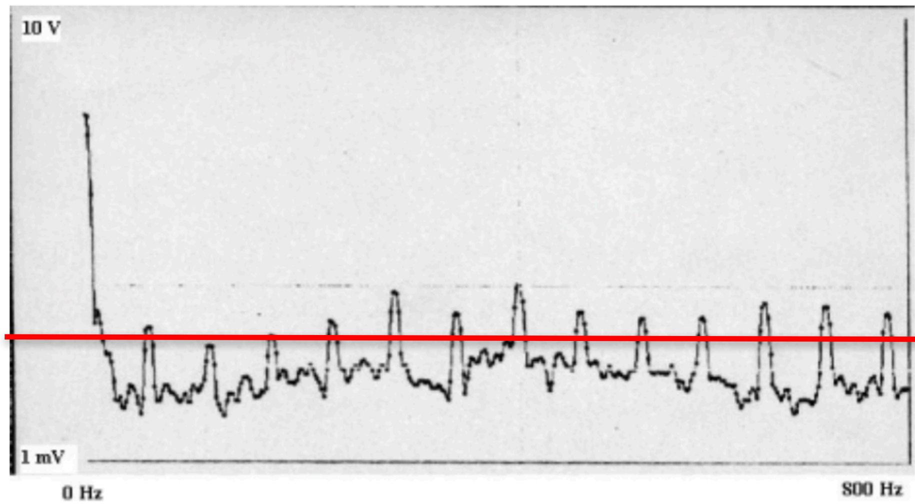
Contents

High Intensity & Spill Structure

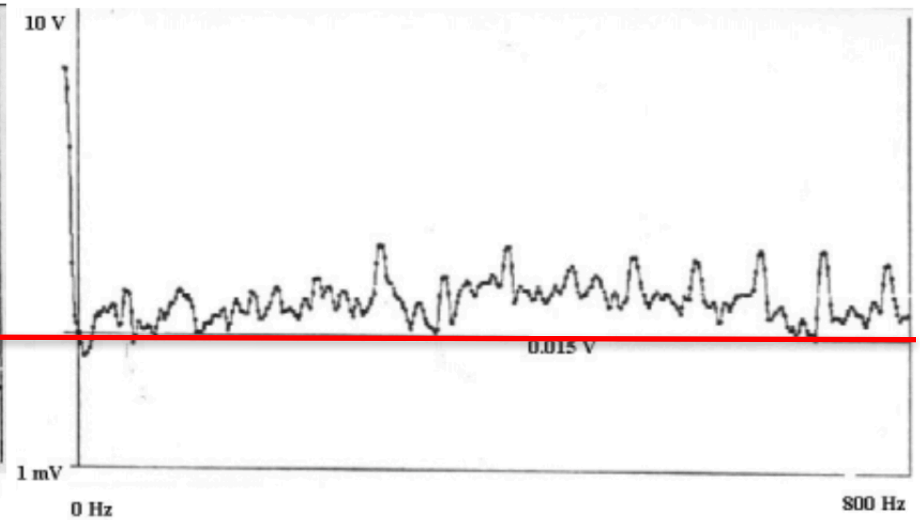




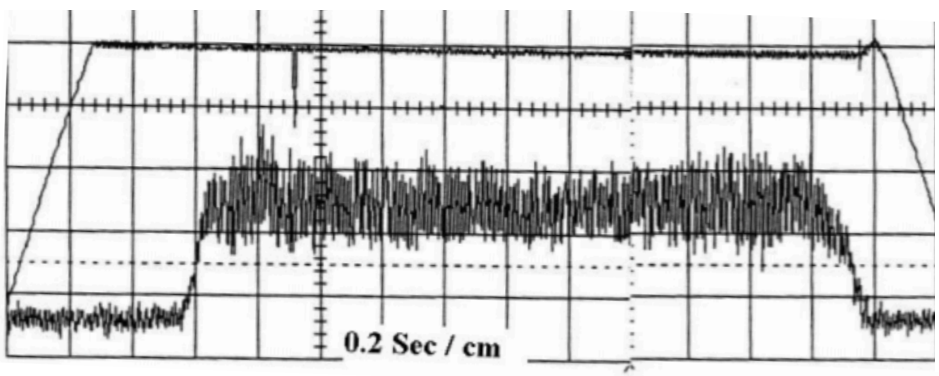
High Intensity & Spill Structure

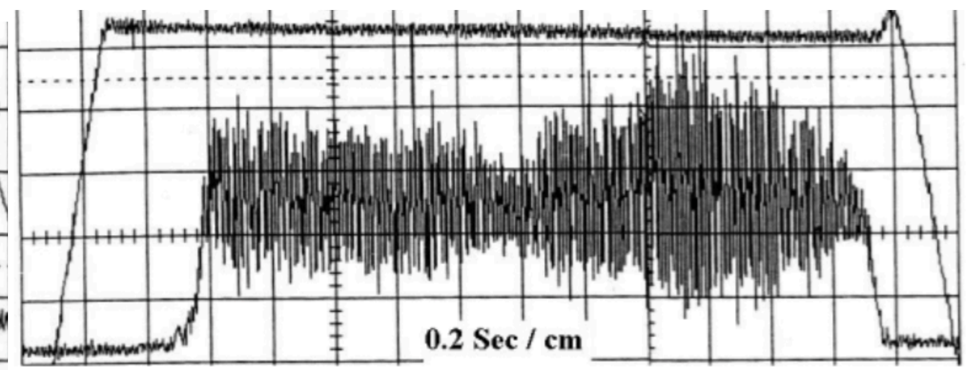


Spill – 20 TP / 2 Sec

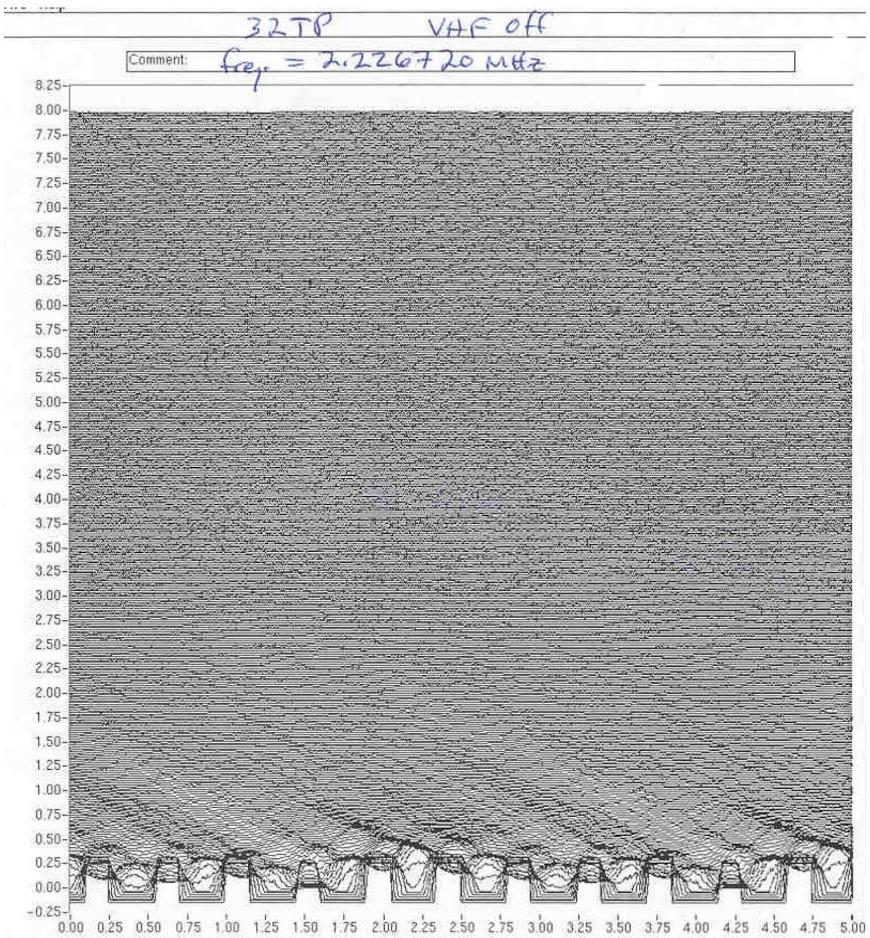


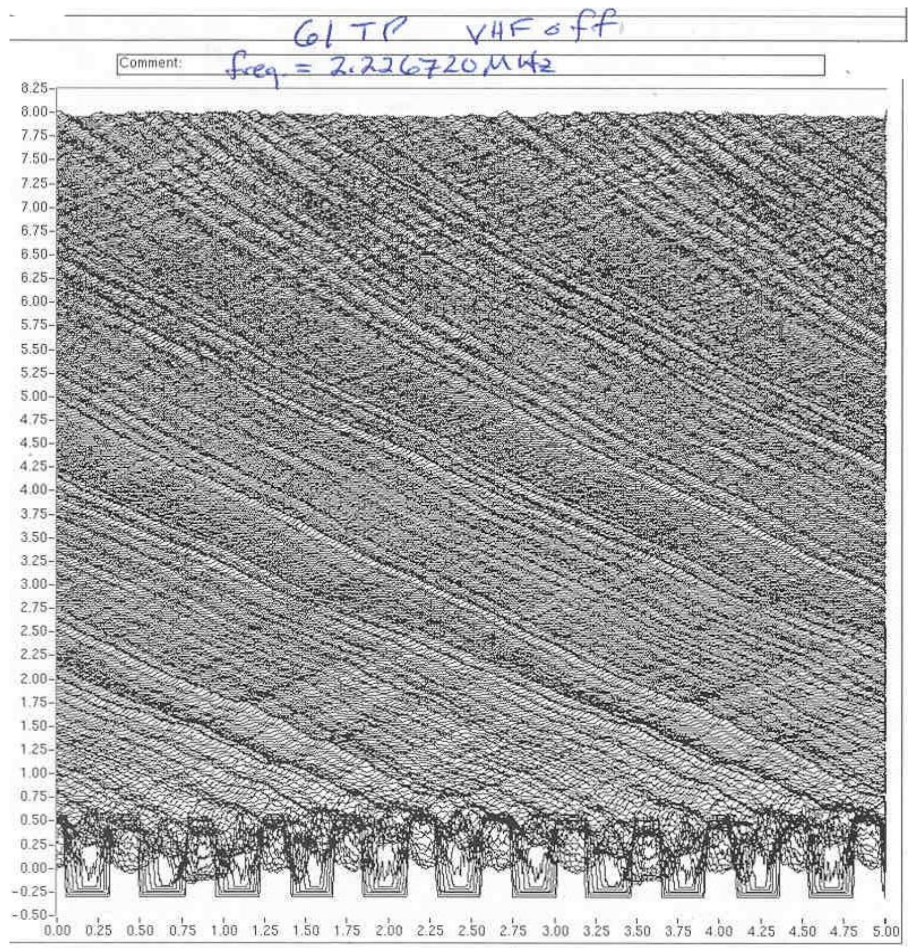
Spill – 50 TP / 2 Sec





Wall Current Monitor View





<u>Worry's/Conjectures?</u>

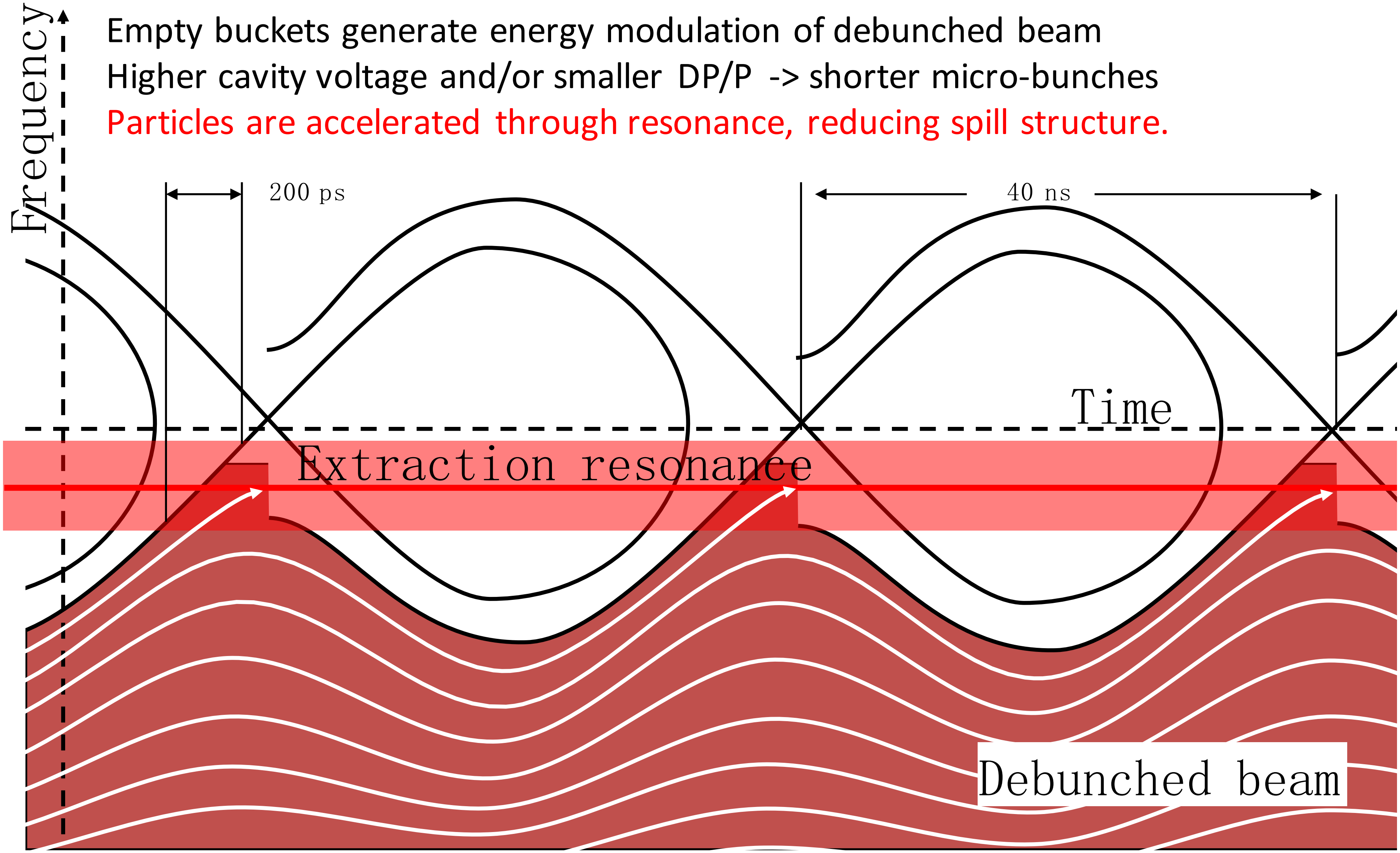
How are such solitons formed, if that is what they are?

What kind of impedance drives the phenomena?

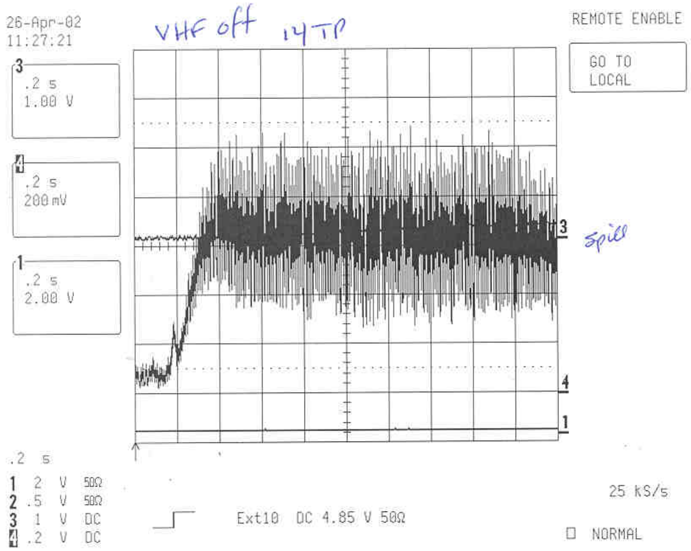
(Keil-Schnell just as/after RF voltage is dropped to zero?)

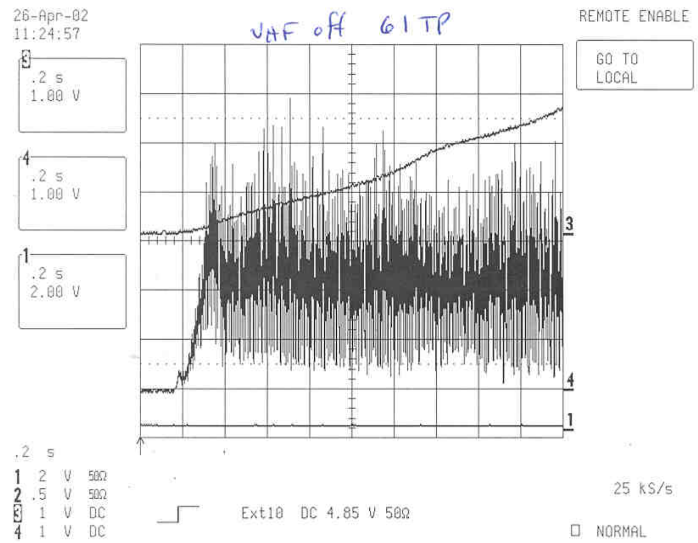
RF Phase Displacement slow extraction

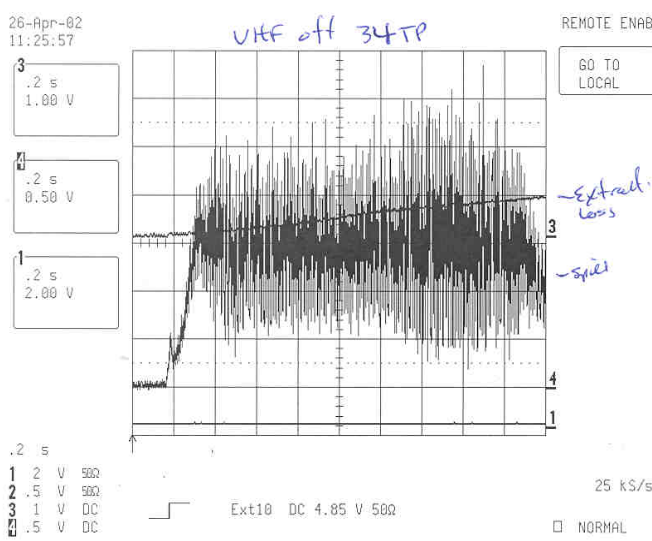
Empty buckets generate energy modulation of debunched beam
Higher cavity voltage and/or smaller DP/P -> shorter micro-bunches
Particles are accelerated through resonance, reducing spill structure.

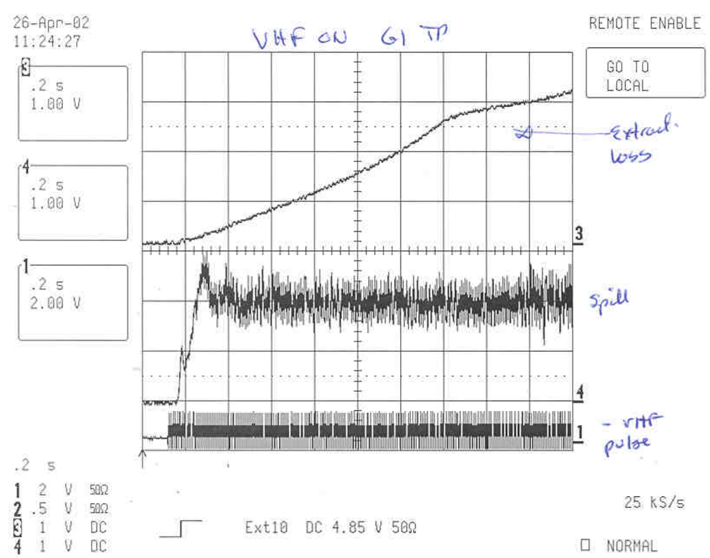


Spill and Ripple

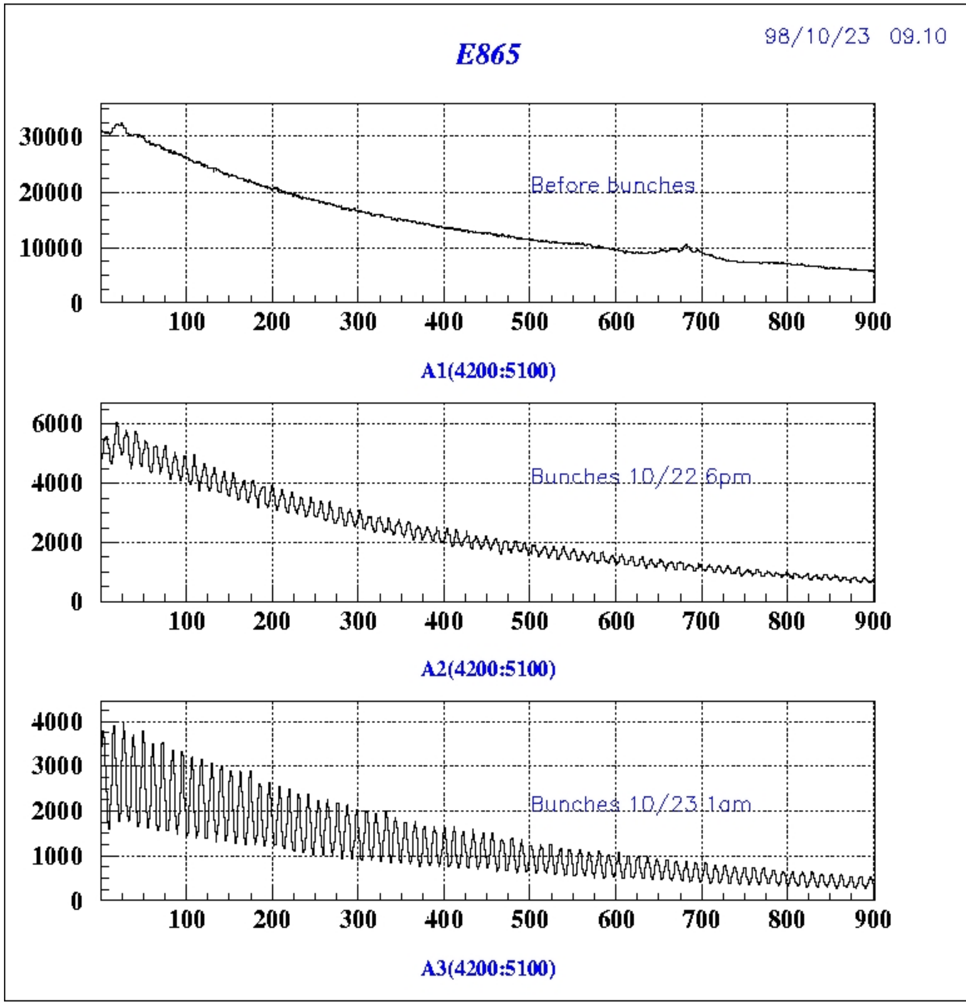


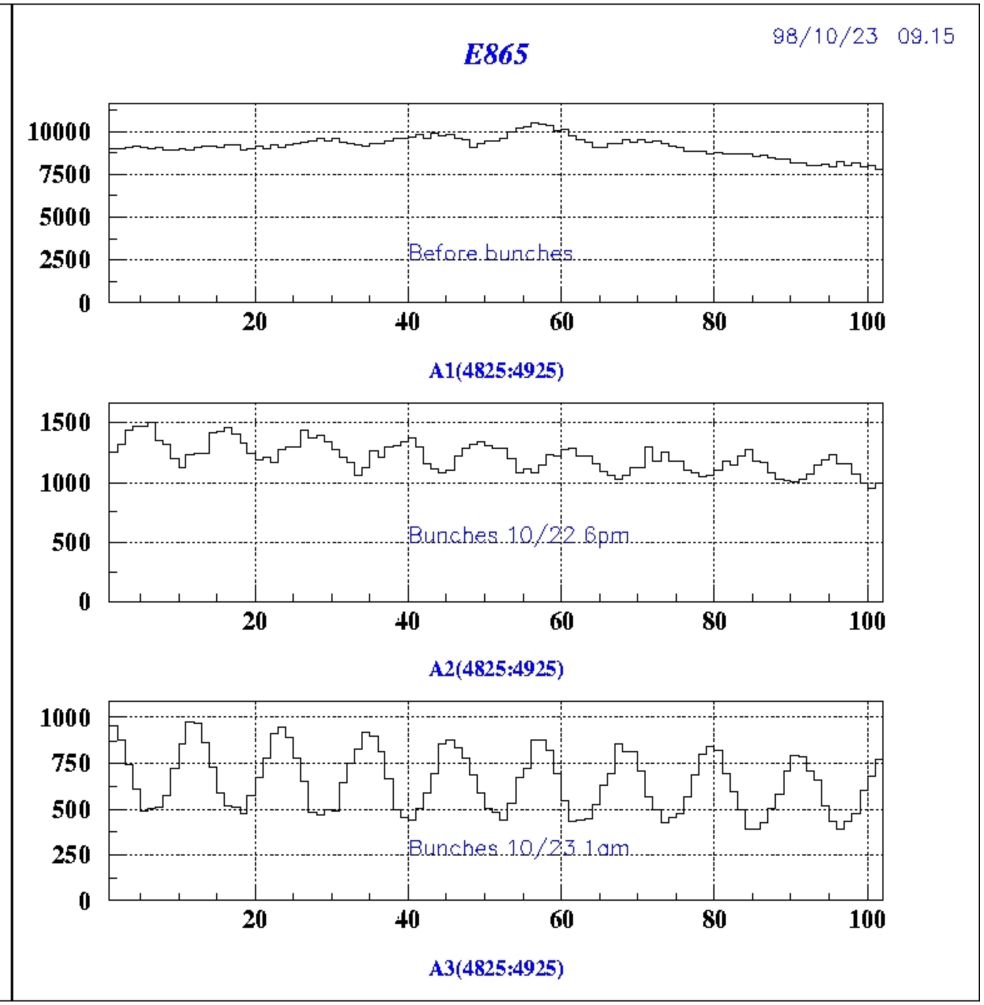






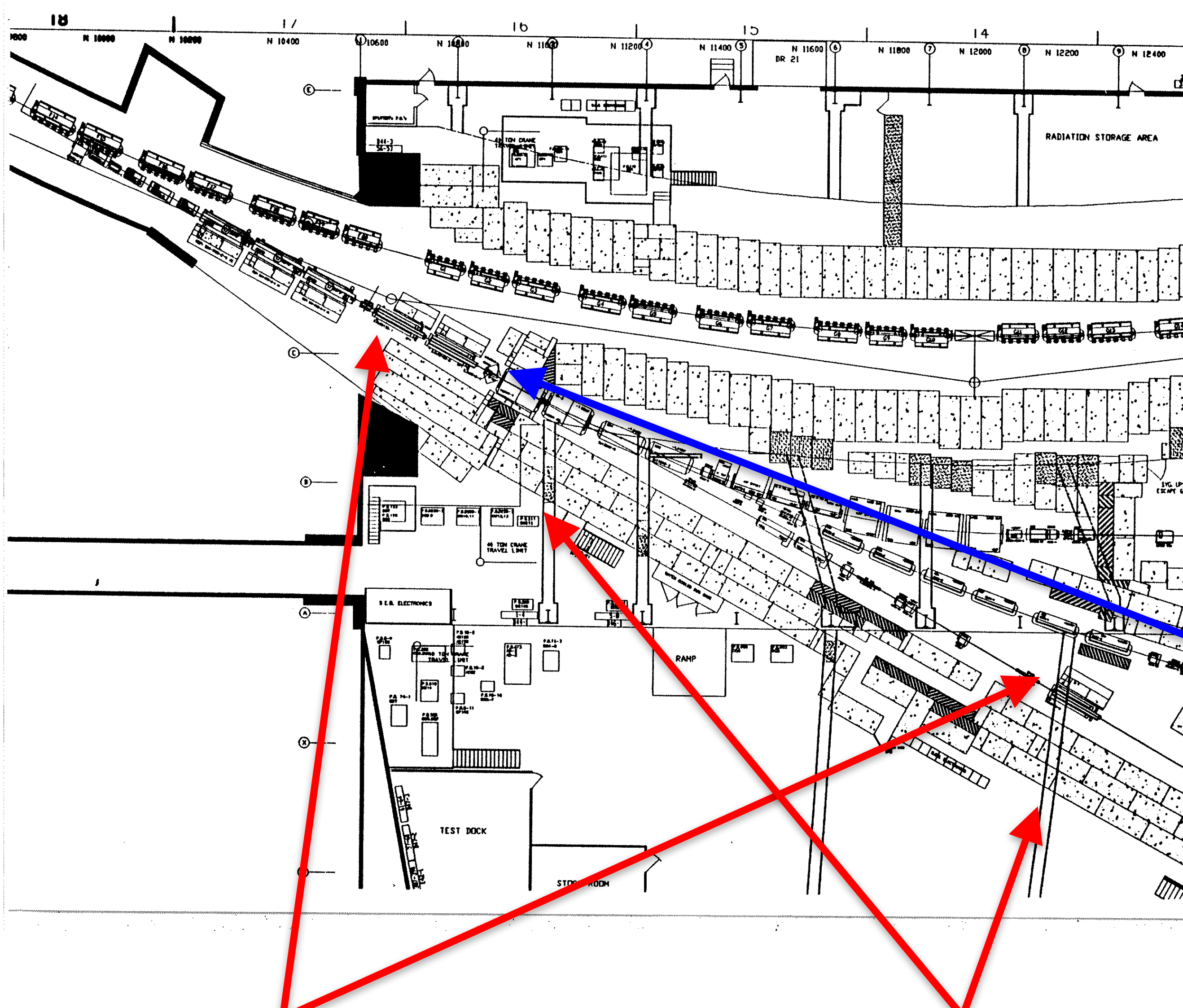
Beam Transport

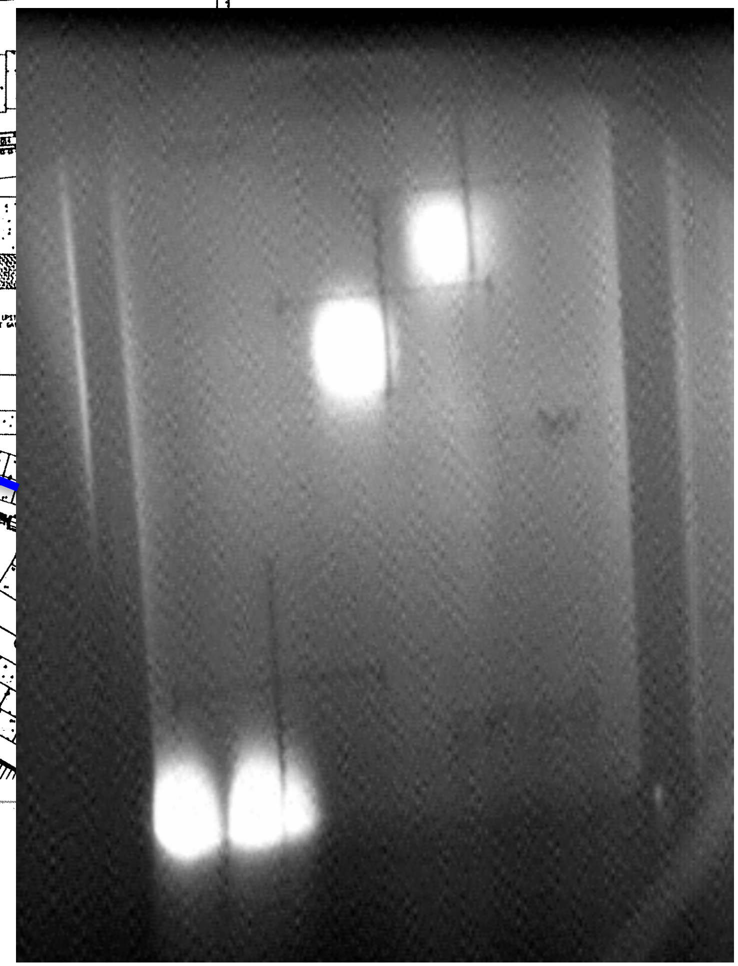




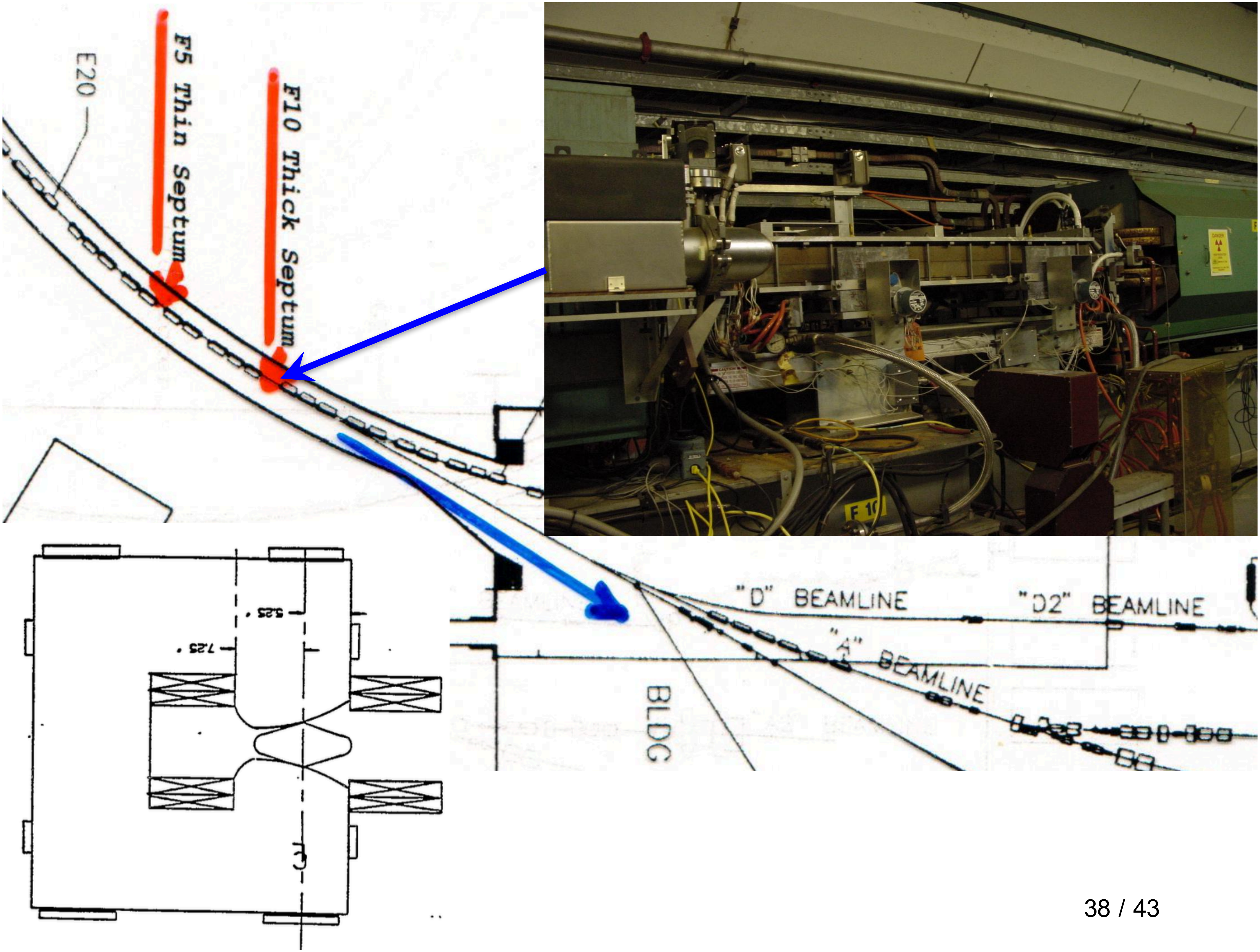
Contents

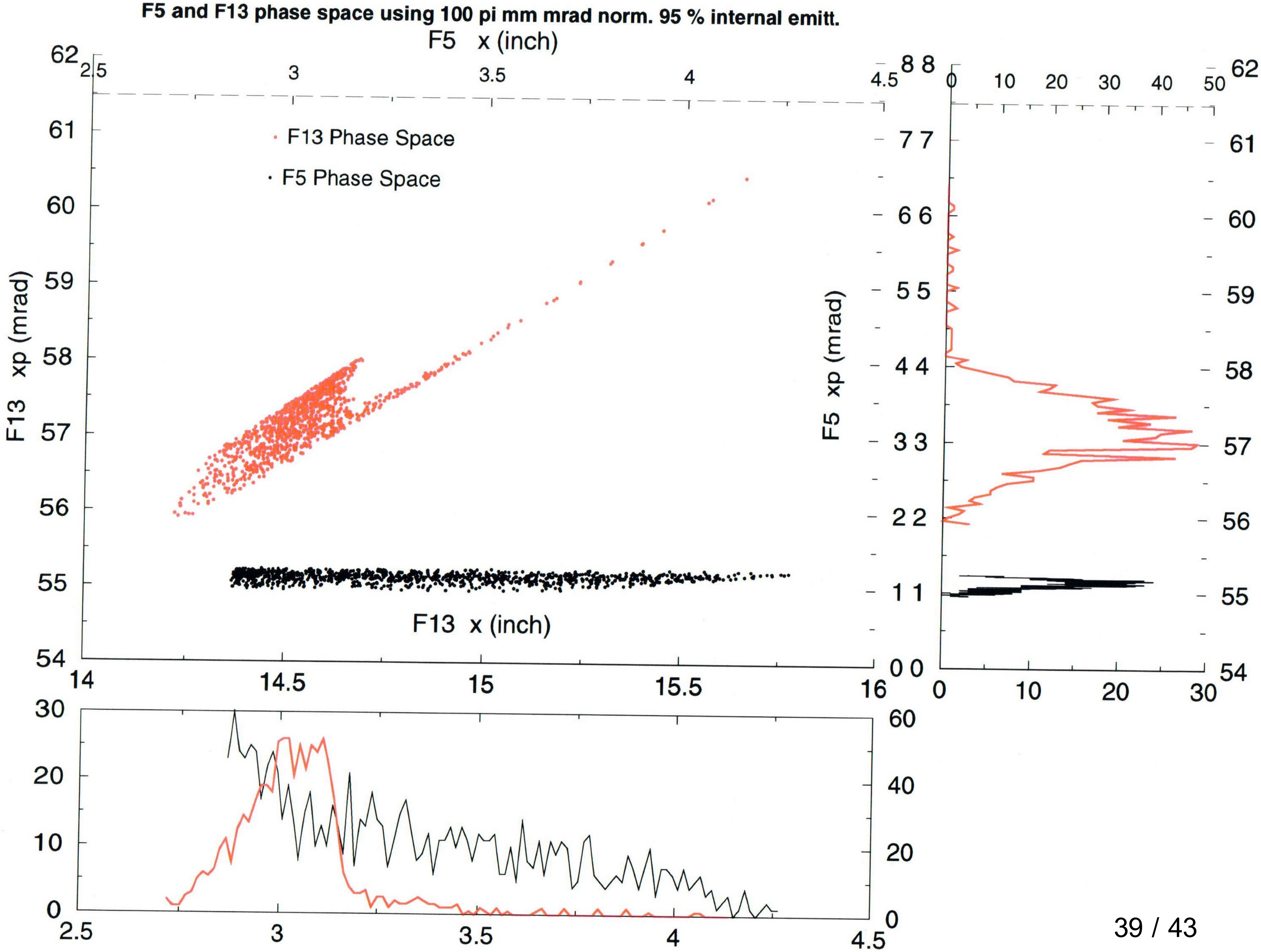
Switchyard: Two Post-Booster Problems



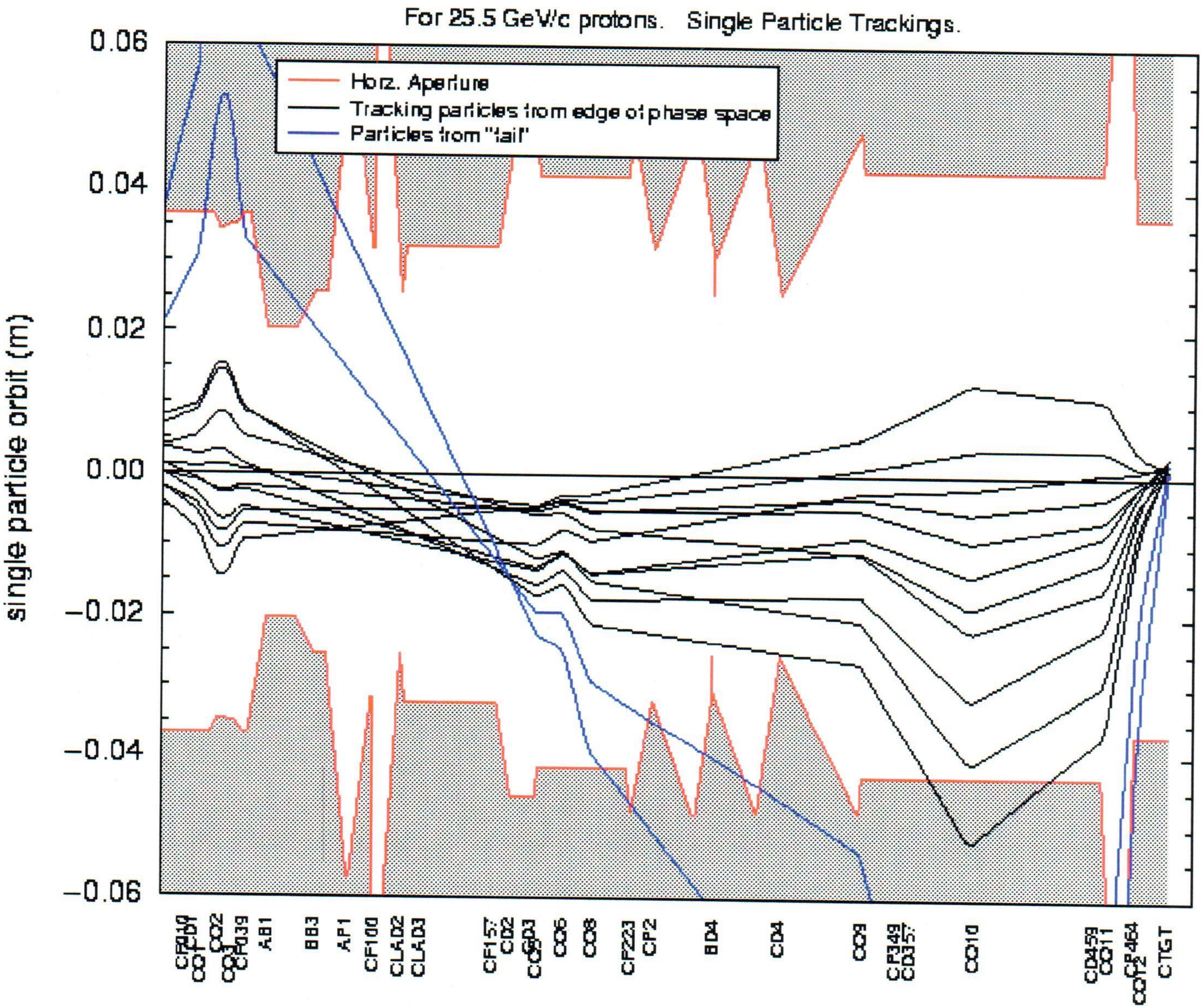


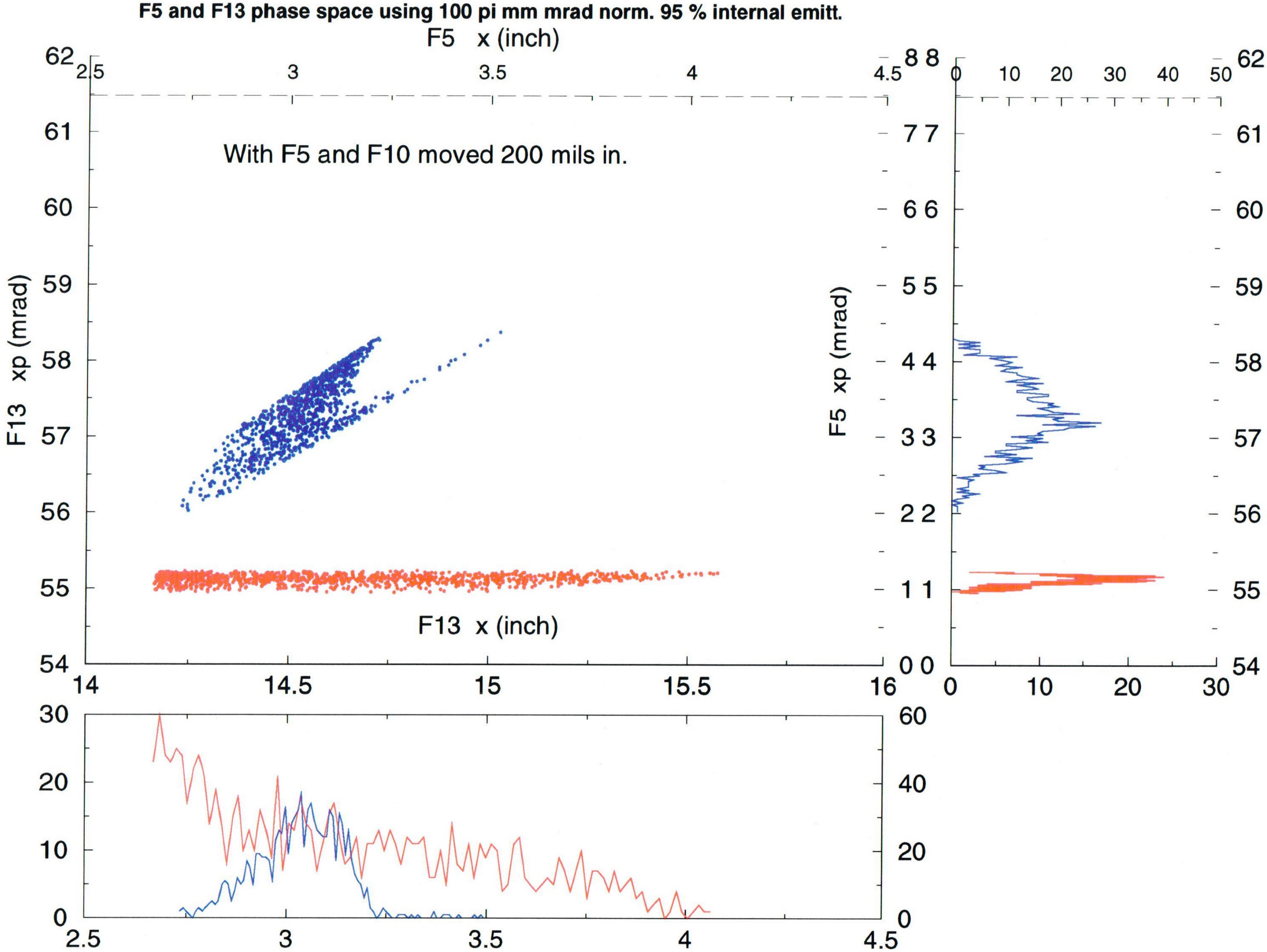
High Beam Losses & Outside Radiation Monitor Alarms/Trips


E20
F5 Thin Septum
F10 Thick Septum
F 10
"D" BEAMLINE
"D2" BEAMLINE
"A" BEAMLINE
BLDG
5.25"
7.25"


F5 and F13 phase space using 100 pi mm mrad norm. 95 % internal emitt.
F5 x (inch)
F13 Phase Space
F5 Phase Space
F13 xp (mrad)
F5 xp (mrad)
F13 x (inch)

Mad Model of C Line





F5 and F13 phase space using 100 pi mm mrad norm. 95 % internal emitt.
F5 x (inch)
With F5 and F10 moved 200 mils in.
F13 xp (mrad)
F5 xp (mrad)
F13 x (inch)

Measured emittance with High Intensity

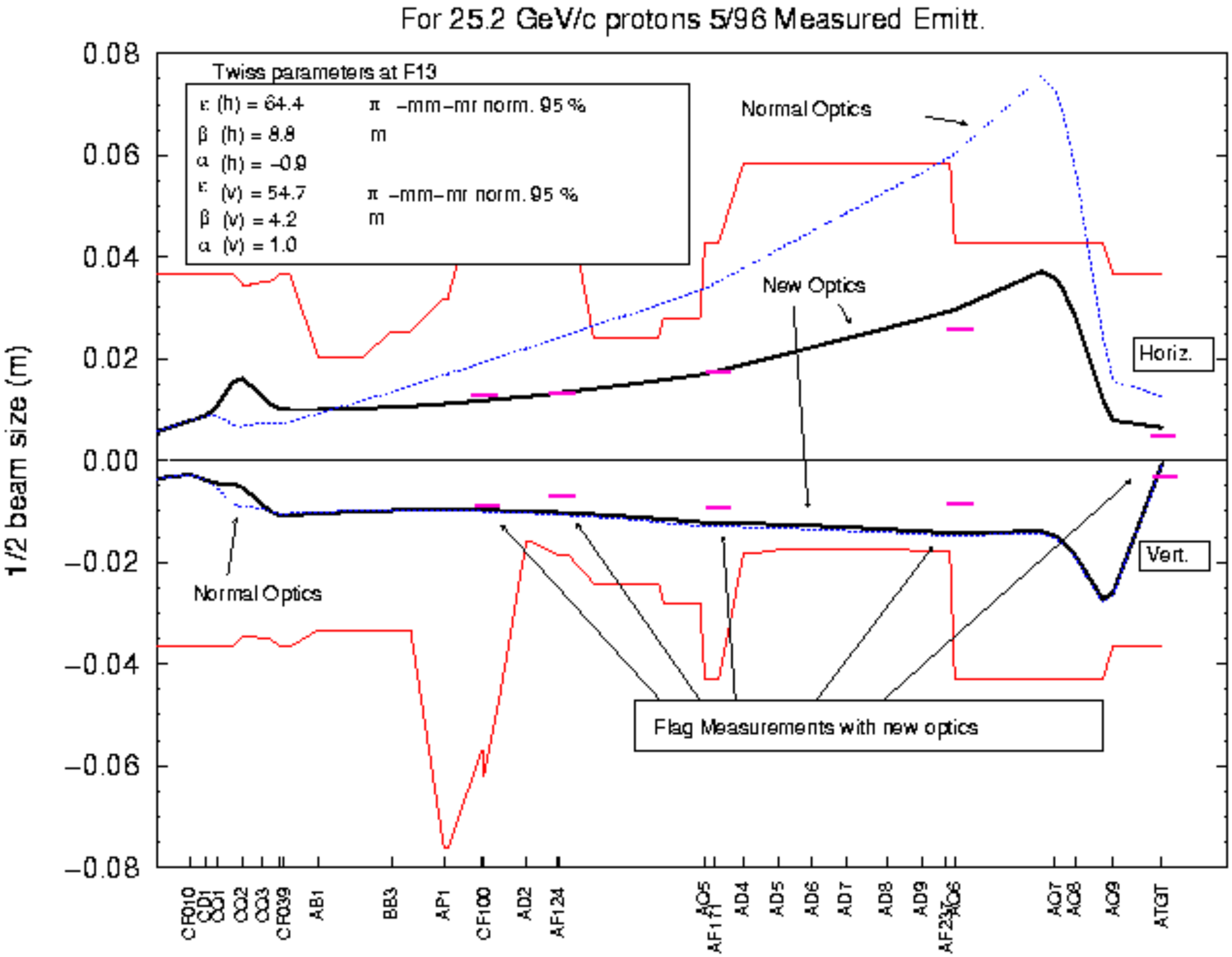
Circulating Beam Emittances

	$\varepsilon_H^{99\%,N}$ (π mm-mrad)	$\varepsilon_V^{99\%,N}$ (π mm-mrad)
Pre-Booster (1980) 200 MeV injection	49	60
Post-Booster (1997) 1.94 GeV injection	99	85

Extracted Beam Emittances

	$\varepsilon_x^{95\%,N}$	β_x [m]	α_x	$\varepsilon_y^{95\%,\ N}$	β_y [m]	α_y
1980	31.9	57.6	-6.64	38.8	3.25	0.87
1997	64.4	8.77	-0.92	54.7	4.18	1.01

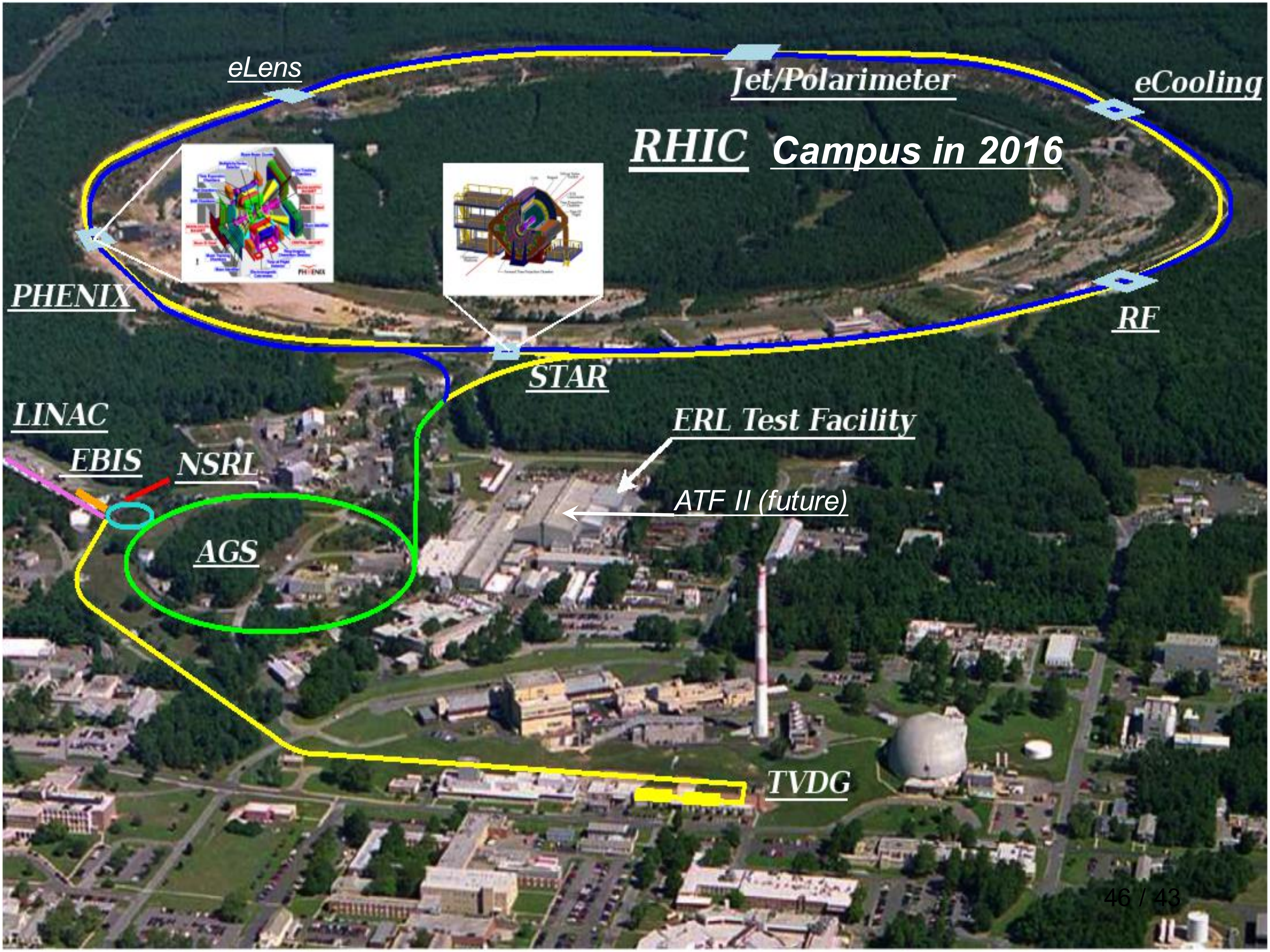
Beam Transport



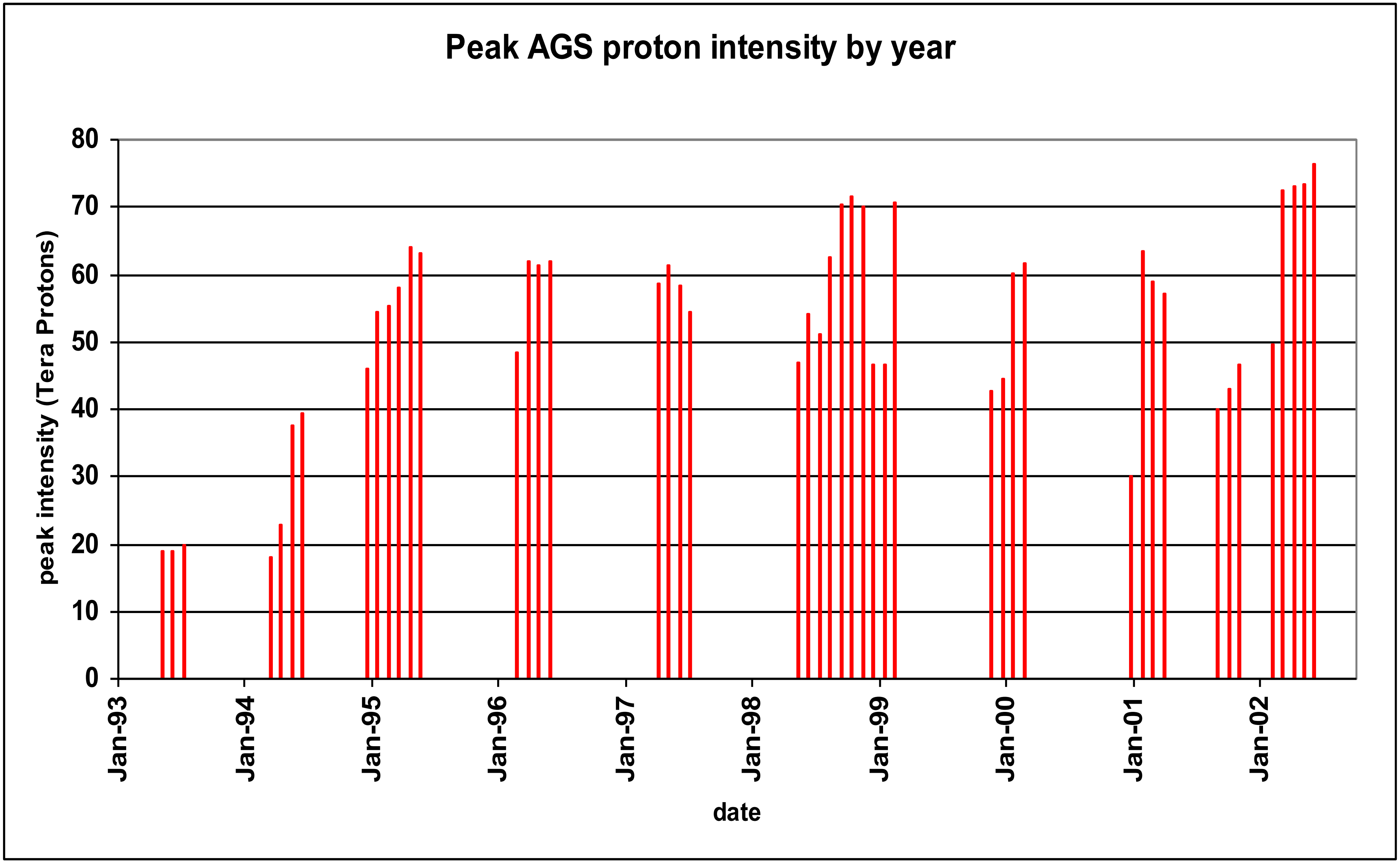
Summary

1. High Intensity History & Experience with the AGS SEB spans 35 years
2. Longitudinal Phase Space Dilution to reduce peak current
3. Collective Effects on Losses and Spill Structure
4. Positive Vertical Chromaticity was required
5. Positive Horizontal Chromaticity was needed at high intensity for further reducing inefficiency – but not implemented
6. RF Phase Displacement using a high frequency RF cavity was important for achieving low ripple, high duty factor beam spills
7. Electrostatic septum current increased over time/int. intensity
8. Tails/Halo created losses
9. Booster brought higher intensity, but also brought larger emittance beams, requiring a change in the switchyard optics.

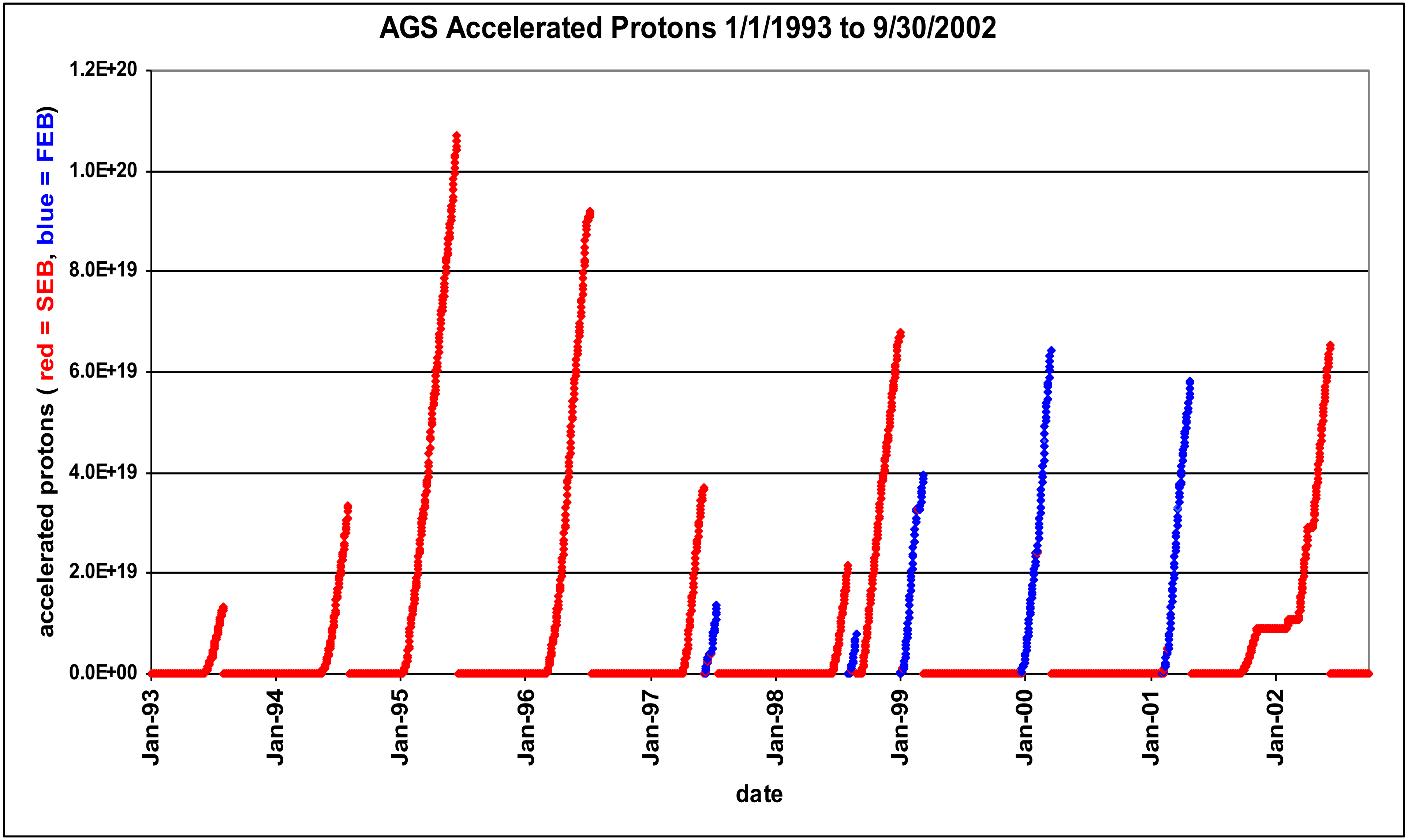
Backup Slides


eLens
Jet/Polarimeter
eCooling
RHIC
Campus in 2016
PHENIX
RF
STAR
LINAC
ERL Test Facility
EBIS
NSRL
ATF II (future)
AGS
TVDG

Peak Intensities by Year



Integrated Intensity per Run



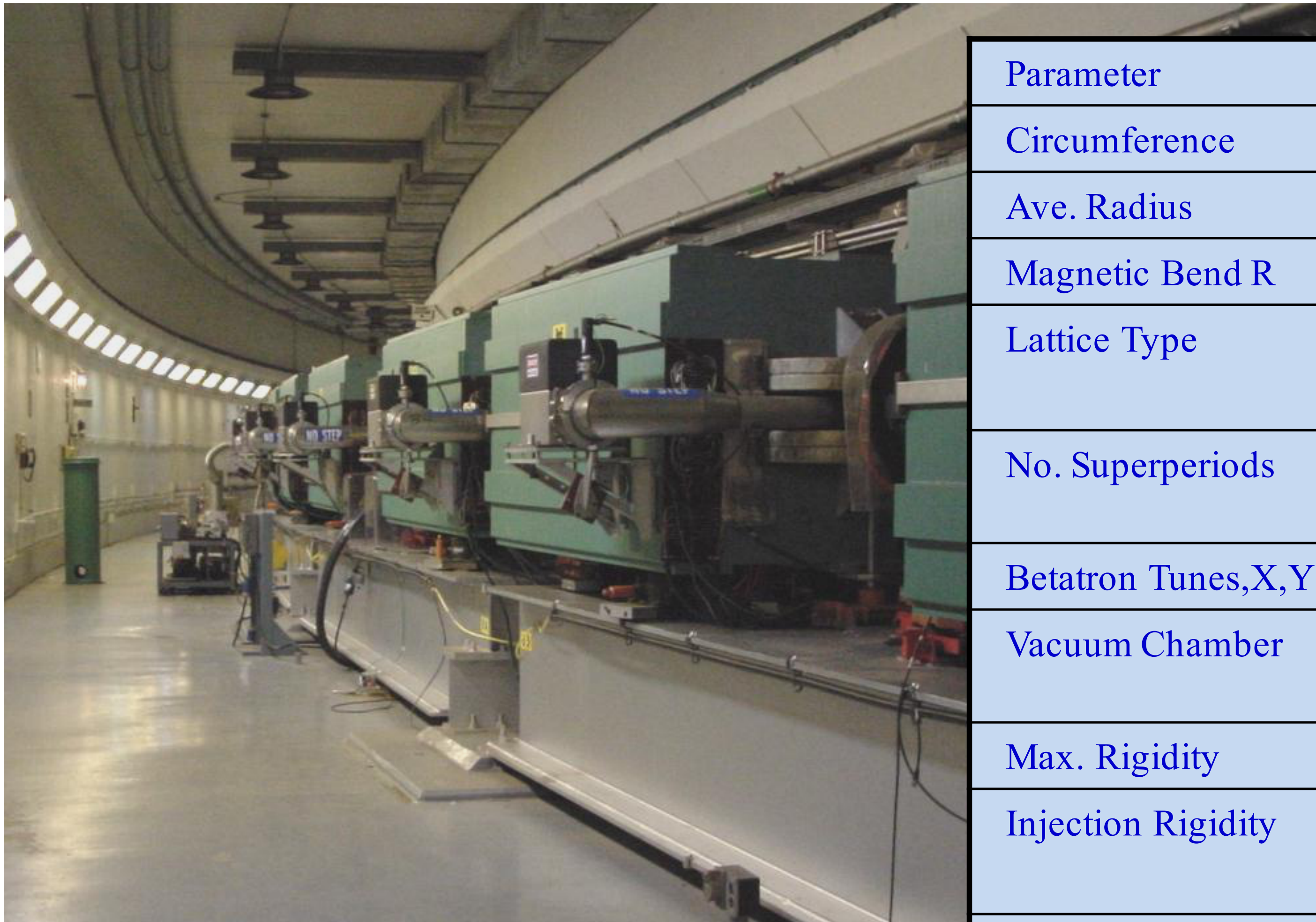
Sample of Physics program from 1998

AGS Beams, July 98

Beam	GeV/c	$\delta p/p$ (% fwhm)	Prod. Angle (deg)	$\Delta\Omega$ (msr)	Flux / 10^{13} 24 GeV/c protons on target: K^+	K^-	p	$\bar{p}$	π^+	π^-	GeV/c	Purity	Remarks
Separated Charged Particle Beams													L = 18 m – "LESBIII"
C4	≤ 0.83	4	0	12.0	4.6×10^{6}	1.5×10^{6}	1.5×10^{9}	1.0×10^{6}	6.0×10^{9}	6.0×10^{9}	0.80	$\pi^+/K^+ = 0.4$	~ 1×10^{6} stopped $K^+/10^{13}$ protons
C6,C8	≤ 0.75	5	5	10.0	1.0×10^{6}	3.3×10^{5}	3.3×10^{8}	4.6×10^{4}	2.0×10^{9}	2.0×10^{9}	0.70	$\pi^-/K^- = 5$ $\pi^+/K^+ = 1$	L = 15 m – "LESBII"
D6	≤ 1.9	6	5	1.6	5.5×10^{6}	2.3×10^{6}	3.0×10^{8}	1.1×10^{6}	4.9×10^{8}	4.1×10^{8}	1.80	$\pi^-/K^- = 0.8$ $\pi^-/\bar{p} = .07$	L = 31 m – "2GEV"
Unseparated Charged Particle Beams													
A1*	5–28	3	0	0.2	1.9×10^{6}	2.9×10^{4}	5.0×10^{9}	2.3×10^{3}	3.0×10^{7}	1.0×10^{7}	18		L = 130 m to MPS – "HEUB"
A2	< 6.5	5	3.5	0.75	5.8×10^{7}	1.9×10^{7}	6.9×10^{8}	6.3×10^{6}	1.3×10^{9}	8.8×10^{8}	6		L = 34 m – "6GEV"
A3*	1–28	4	0	0.1			6.0×10^{8}		1.0×10^{8}	4.0×10^{7}	14		Primarily HI "OR" with A1
B1*	5–28	3	0	0.05			3.0×10^{8}		3.0×10^{7}	2.0×10^{7}	14		HI/Test Beam "OR" with B5
B1’	0.5–28	8	3	.001			3.0×10^{4}		6.0×10^{4}	4.0×10^{4}	5		L = 56 m – Test Beam
B2	< 9	5	6	0.5	3.4×10^{5}	1.2×10^{5}	8.5×10^{6}	9.5×10^{4}	1.2×10^{7}	9.0×10^{7}	4		L = 40 m – Test Beam
C1	1–20	5	0	0.8	3.0×10^{7}	3.5×10^{6}	1.0×10^{9}	0.7×10^{6}	3.5×10^{8}	1.6×10^{8}	13		L = 100 m – "OR" with C5
C5*	1–28	2	0	0.15			1.0×10^{8}				13		L = 81 m – "OR" with C1
Neutral Beam													
B5	2–20		1–4.5	0.1			K^0_L flux = 1.3×10^{8} @ 3.75^0				2–20	$n/K^0_L = 20$	L = 10 m – "OR" with B1
Muon Channel													L = 12 m
D2	0.025–0.15	9 (π) 30 (μ)	135 (π)	24 (π)			μ^+ flux = 2.0×10^{6} Surface μ^+ flux = 2.0×10^{6}						Inactive, not yet commissioned
Neutrino Beam													Not Presently Available
U							ν flux = $2.0 \times 10^{10}/m^2$ (Wide Band) $\bar{\nu}$ flux = $1.4 \times 10^{10}/m^2$ (Wide Band)						FEB Flux avg. over 1.5 m R. <E> = 1.4 GeV/c^2 Wide Band
g–2 π–μ Transfer Line													
V1	< 3.0	0.6	0				π^+ flux = 1.7×10^{8} μ^+ flux = 7×10^{5}				3.0		L = 120, for injection to g–2 ring commissioned in 1996

* These 0^0 beam lines can be used for full energy polarized protons and/or heavy ion beams

AGS Parameters



Parameter	Value
Circumference	807.091 m
Ave. Radius	128.453 m
Magnetic Bend R	85.3785 m
Lattice Type	Combined Function, FODO
No. Superperiods	12 (20 magnets each)
Betatron Tunes,X,Y	8.72, 8.80
Vacuum Chamber	78 x 173 mm Dipoles
Max. Rigidity	110 Tm
Injection Rigidity	9.076 Tm (1.94 GeV protons)
Acceleration Rate (max)	2.5 T/s

Booster & AGS Performance: FEB

Imposed limits to lost beam power to maintain hands-on maintenance (ALARA).

- **AGS FEB operation, 2.77 s cycle AGS cycle time, 6 Booster cycles**

Achieved 30 Tp/sec, Booster Late & 22 Tp/sec, AGS Late

Table: FEB 10 Pulse Ave. Data (best performance, not sustainable operation)

	Intensity (Tp/cycle)	Efficiency (%)	Beam Loss (Tp/cycle)	ALARA (Tp/cycle)	Loss (kW)	Loss/m (W/m)
Linac	115	-	-	-	-	-
Booster Injected	89	77	27	27.7	0.31	1.5
Booster Extracted	83	93	6	9.2	0.33	1.6
AGS Injected	66	78	18	16.3	2.0	2.5**
Before Transition	62.3	94	3.7	1.5	0.9	1.1
After Transition	61.6	99	0.6	2.3	0.2	0.2
AGS Late	61.4	99.5	0.3	0.8	0.25	0.3

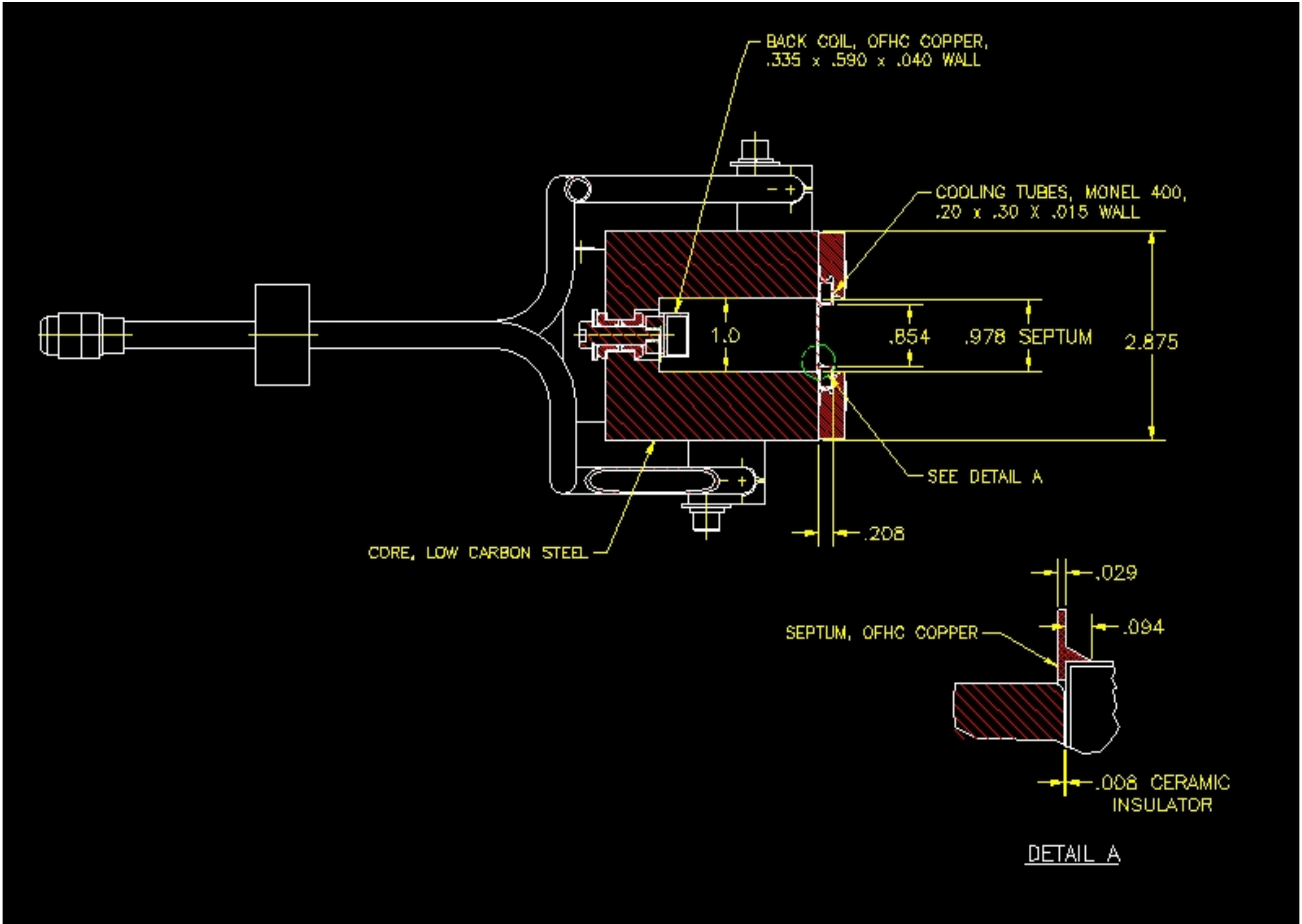
** assumed lost in AGS

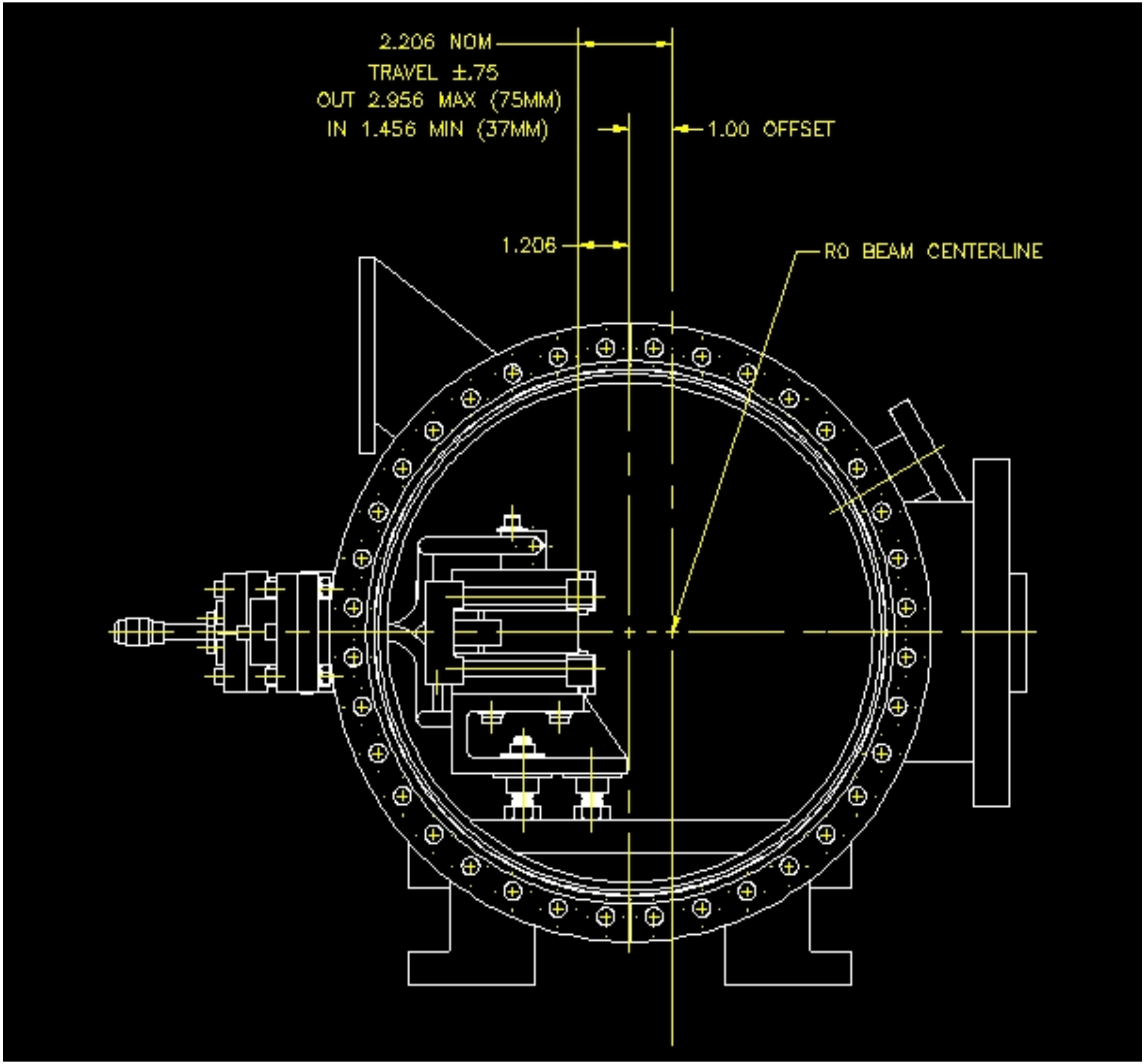
Naming Conventions & P.S. Families

- 12 Superperiods, labeled A – L; 20 magnets/superperiod
  - 12 Long magnets = 94 inches, bend ~1.6 degrees
  - 8 Short magnets = 79 inches, bend ~1.4 degrees
  - All are combined function, strong focusing
- 2 Tune control families
  - Horiz. Focusing – 1/superperiod at #17 straight sections
  - Vert. Focusing – 1/superperiod at #3 straight sections
- 2 Chromaticity control families
  - Horiz. – 1/superperiod at #13 straight sections
  - Vert. – 1/superperiod at #7 straight sections
- Skew quadrupoles – 1 string, 6 magnets every other superperiod
  - B17, D17, F17, H17, J17, L17
- Drive sextupoles – 1 string (+ - + -) = don't affect chrom.
- Orbit deformation bumps – two sets, using backleg windings
  - One for electrostatic septum
  - One for two magnet septa

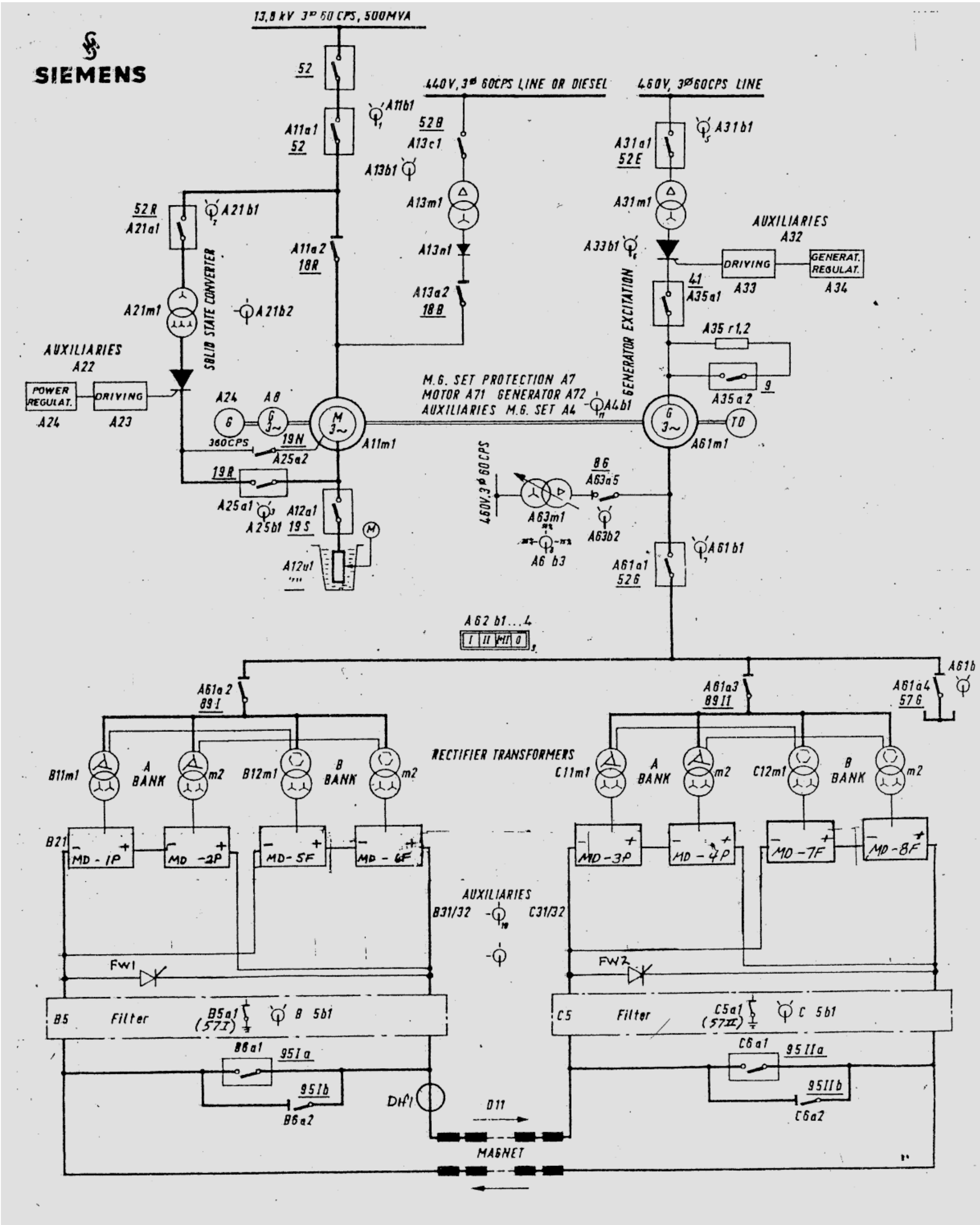
Slow Extraction Parameters

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


BACK COIL, OFHC COPPER,
.335 x .590 x .040 WALL
COOLING TUBES, MONEL 400,
.20 x .30 X .015 WALL
1.0
.854
.978 SEPTUM
2.875
SEE DETAIL A
.208
CORE, LOW CARBON STEEL
.029
.094
SEPTUM, OFHC COPPER
.008 CERAMIC
INSULATOR
DETAIL A

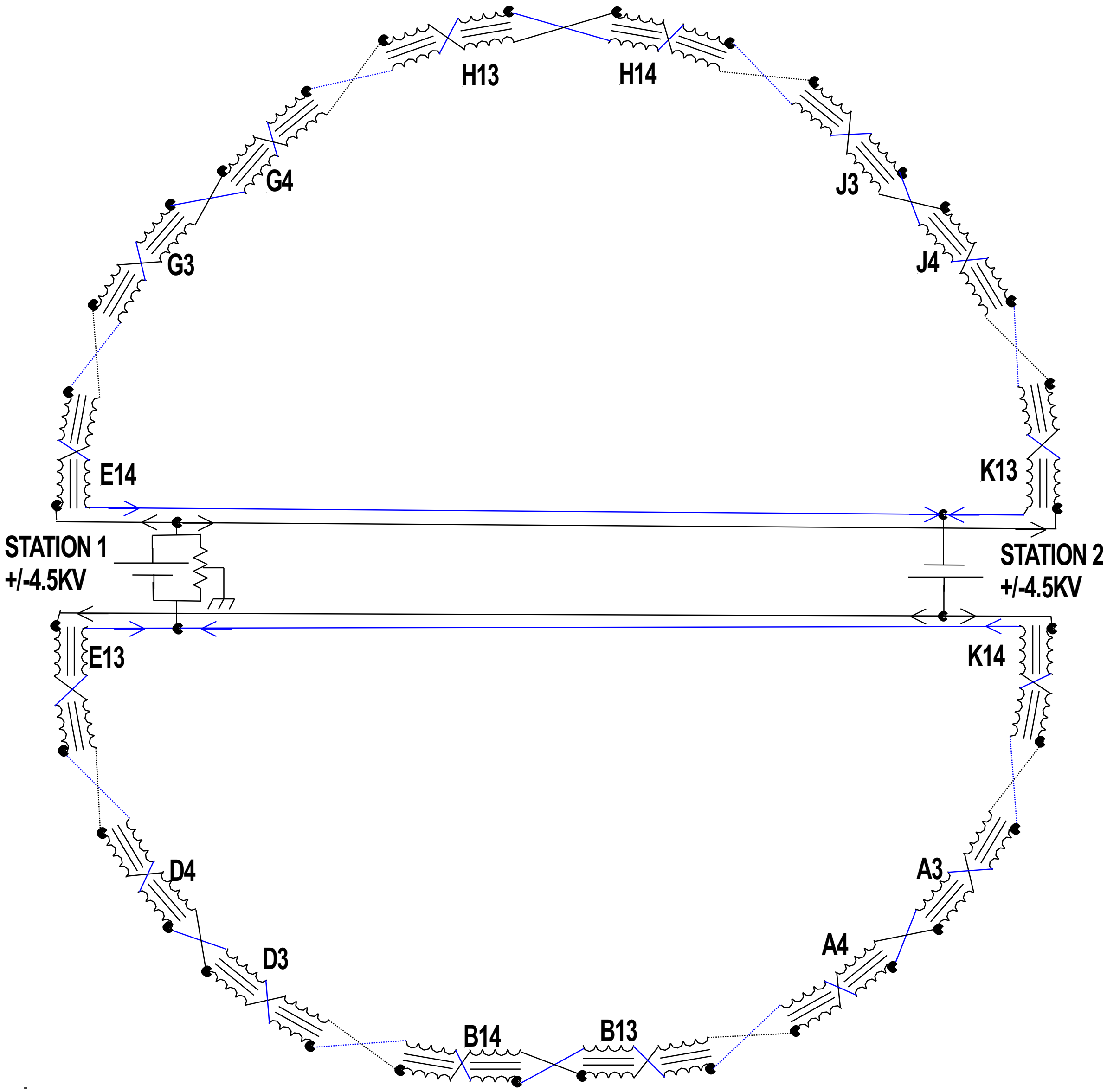

2.206 NOM
TRAVEL ±.75
OUT 2.956 MAX (75MM)
IN 1.456 MIN (37MM)
1.00 OFFSET
1.206
RO BEAM CENTERLINE

AGS MMPS BLOCK DIAGRAM



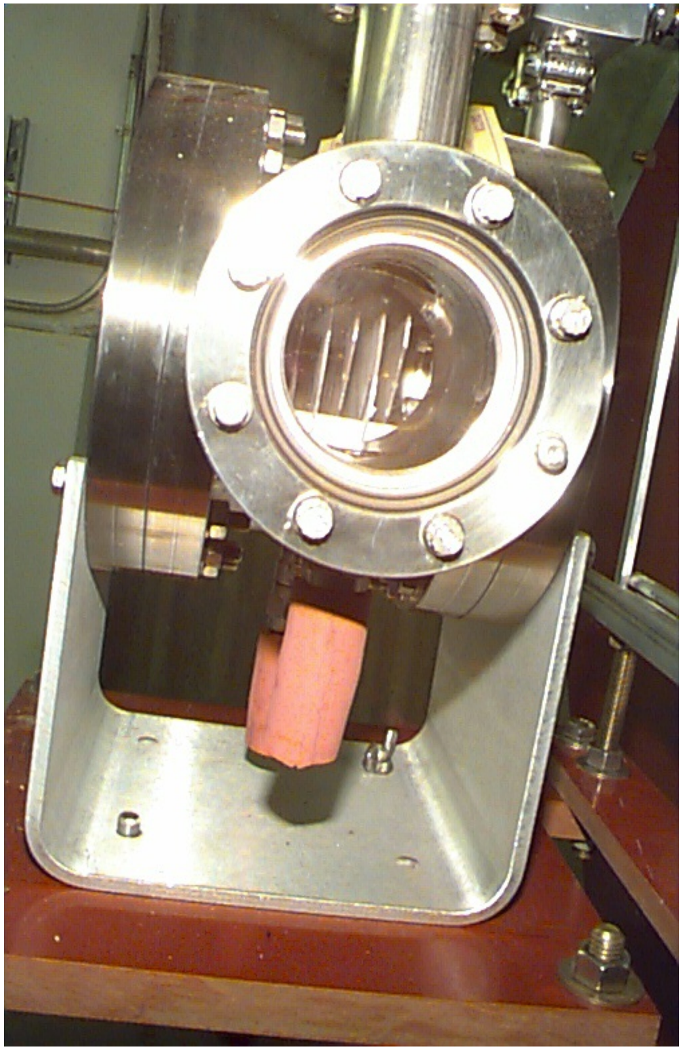
- AGS MMPS 6000 Amps, ±9000 Volts (SCR) power supply.
- Maximum AGS magnets average power 5 MW.
- Two stations of power supplies +/-4500 Volts and 6000 Amps each.
- The grounding of the power supply is done in the middle of station 1 or 2 through a resistive network.
- With this grounding configuration, the maximum magnet voltage to ground will not exceed 2500 Volts.

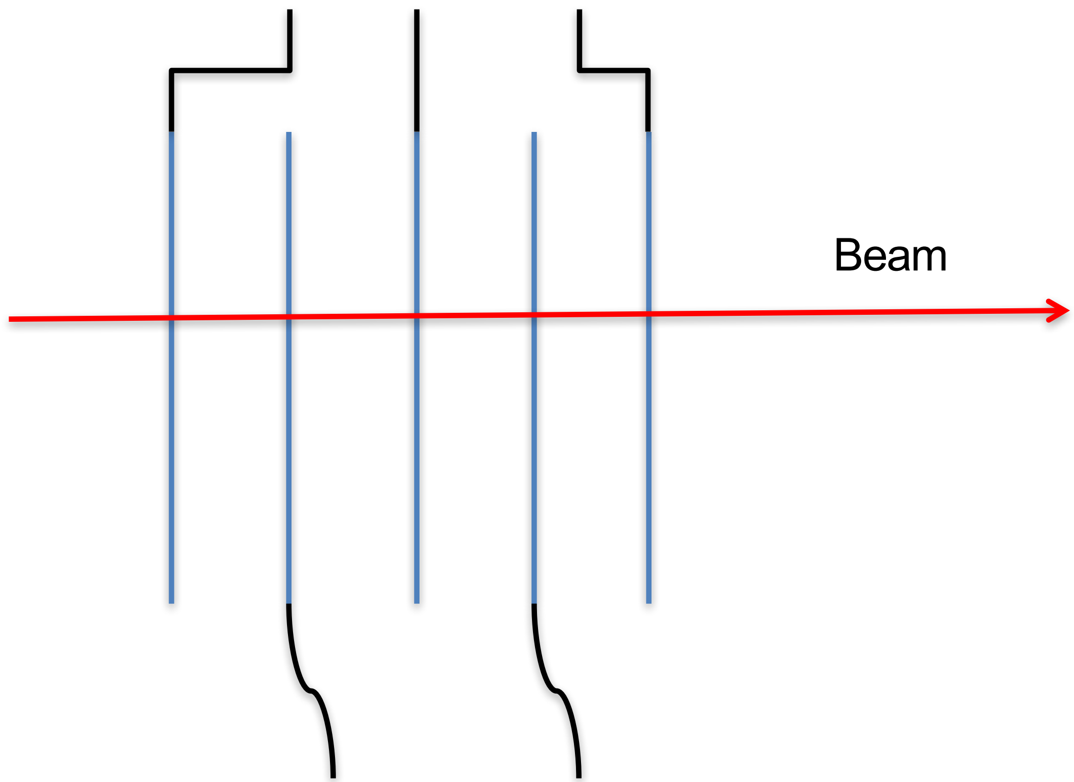
AGS Magnet Power Supply Configuration.



- The AGS ring consists of 240 magnets hooked up in series.
- The total resistance R is 0.28 ohms and the total inductance L, is 0.8 henries.
- There are 12 super-periods, A through L, of 20 magnets each.

Measuring Extracted Beam Intensity

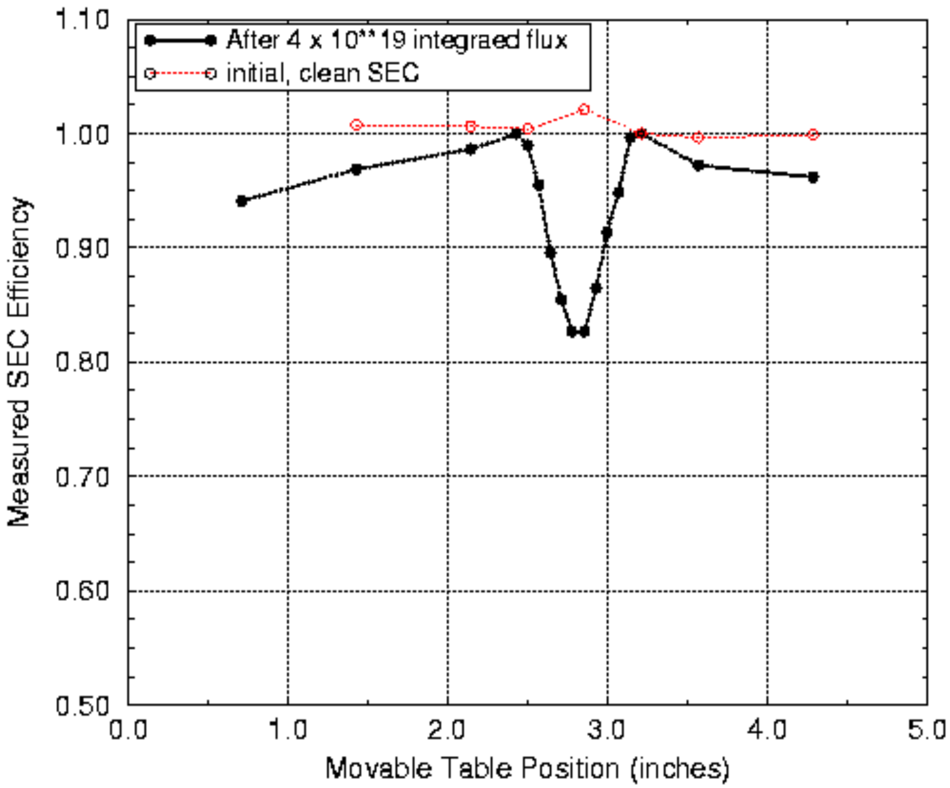


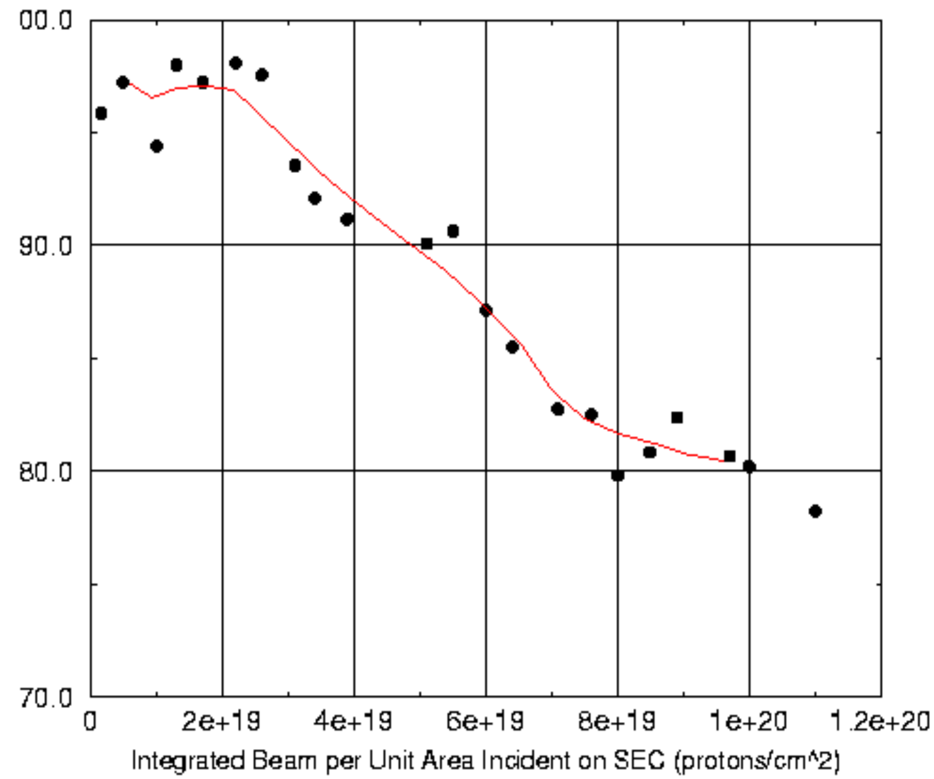


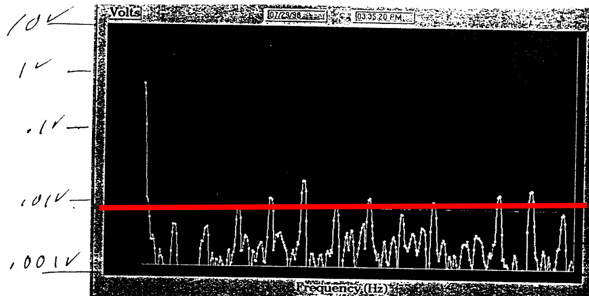
Secondary Emission Chambers

Measuring Extracted Beam Intensity

Secondary Emission degradation



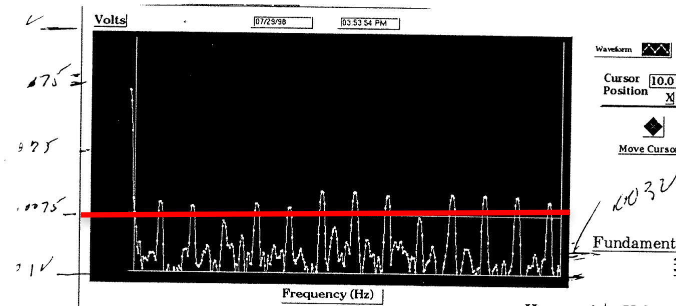




Fundamental frequency of interest: 60.00

Harmonic	Voltage	% of DC
0.00	1.309182	100.00
60.00	0.005087	0.39
120.00	0.004513	0.34
180.00	0.009863	0.75
240.00	0.014928	1.14
300.00	0.030620	2.34
360.00	0.010965	0.84
420.00	0.014613	1.12
480.00	0.008180	0.62
540.00	0.013268	1.01
600.00	0.002432	0.19
660.00	0.018707	1.43
720.00	0.022555	1.72

~~Siemens~~ Lilco 20 TP



Cursor Position: X 10.0, Y 0.009868

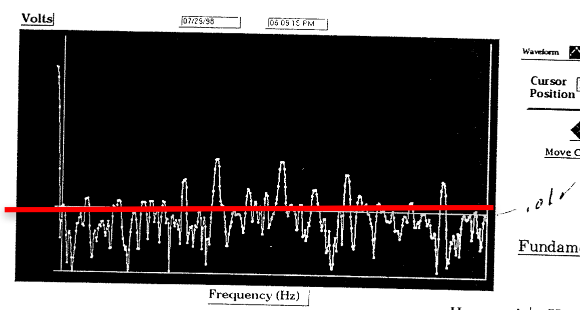
Move Cursor

Fundamental frequency of interest: 60.00

start freq(Hz): 0.0000 — freq span(Hz): 800.000 — # averages: 10

Harmonic	Voltage	% of DC
0.00	1.298674	100.00
60.00	0.015524	1.20
120.00	0.013482	1.04
180.00	0.006757	0.52
240.00	0.014859	1.14
300.00	0.012890	0.99
360.00	0.025177	1.94
420.00	0.024392	1.88
480.00	0.020785	1.60
540.00	0.008700	0.67
600.00	0.021966	1.69
660.00	0.022169	1.71
720.00	0.021038	1.62

Siemens [20] TP



Cursor Position: X 14.0, Y 0.012517

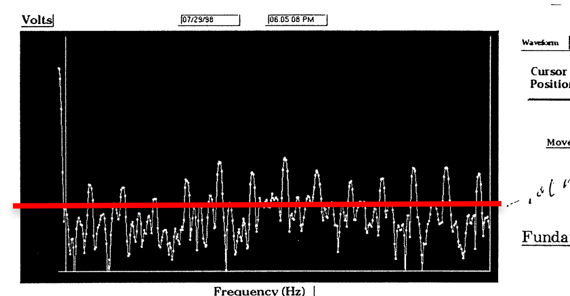
Move Cursor

Fundamental frequency of interest: 60.00

start freq(Hz): 0.0000 — freq span(Hz): 800.000 — # averages: 10

Harmonic	Voltage	% of DC
0.00	3.084963	100.00
60.00	0.017885	0.58
120.00	0.016653	0.54
180.00	0.016453	0.53
240.00	0.038194	1.24
300.00	0.089588	2.90
360.00	0.027008	0.88
420.00	0.083272	2.70
480.00	0.027432	0.89
540.00	0.052390	1.70
600.00	0.017509	0.57
660.00	0.018535	0.60
720.00	0.040621	1.32

Lilco 50 TP



Cursor Position: X 14.0, Y 0.013328

Move Cursor

Fundamental frequency of interest: 60.00

start freq(Hz): 0.0000 — freq span(Hz): 800.000 — # averages: 10

Harmonic	Voltage	% of DC
0.00	2.925836	100.00
60.00	0.029326	1.00
120.00	0.026607	0.91
180.00	0.017258	0.59
240.00	0.035379	1.21
300.00	0.072694	2.48
360.00	0.048529	1.66
420.00	0.084431	2.89
480.00	0.049006	1.67
540.00	0.032565	1.11
600.00	0.038194	1.31
660.00	0.056754	1.94
720.00	0.059463	2.03

Siemans 50 TP

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.

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

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

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

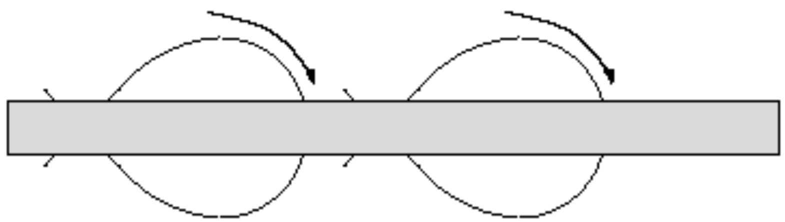
Spill and Ripple

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.

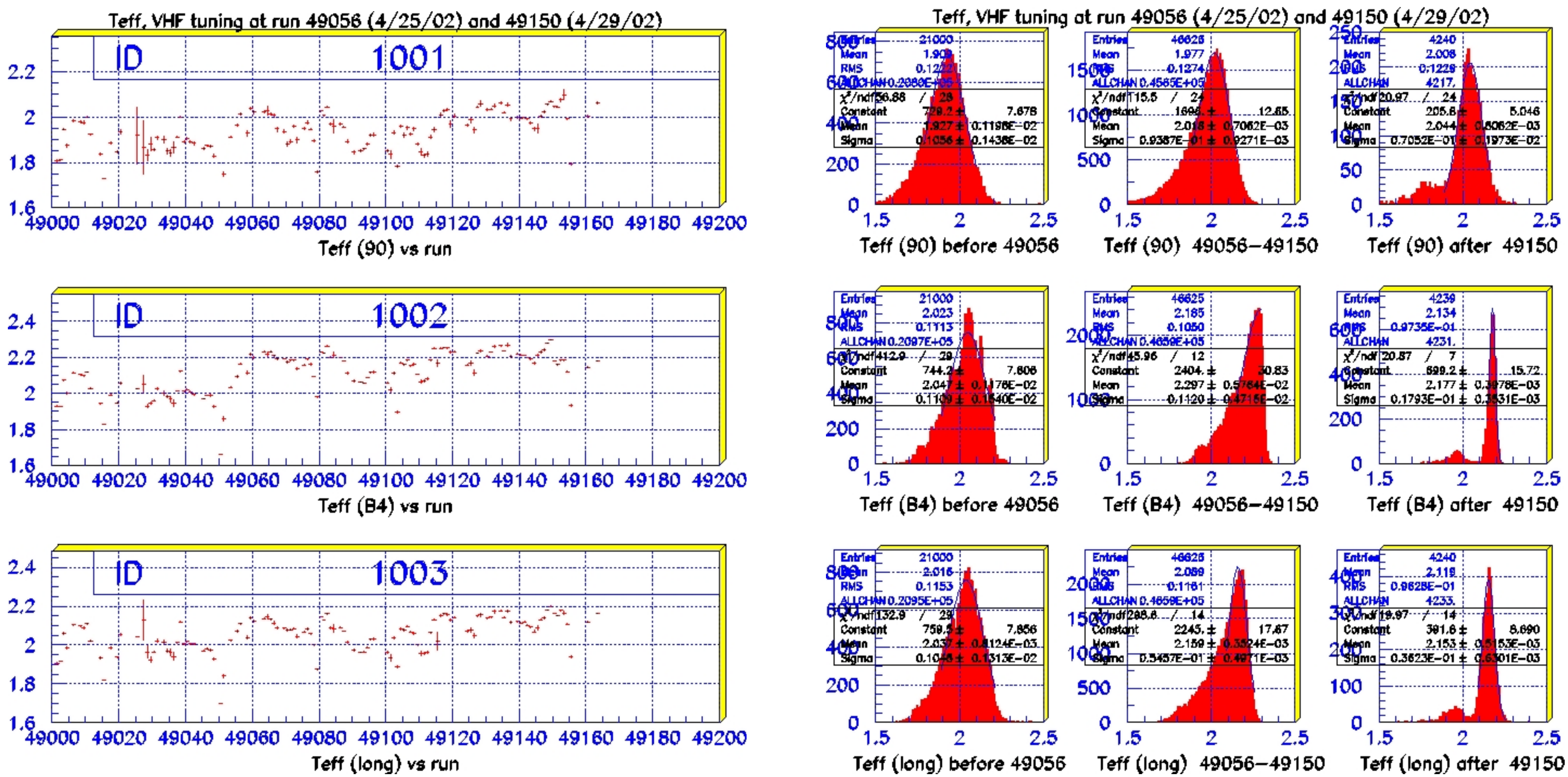
Now,

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

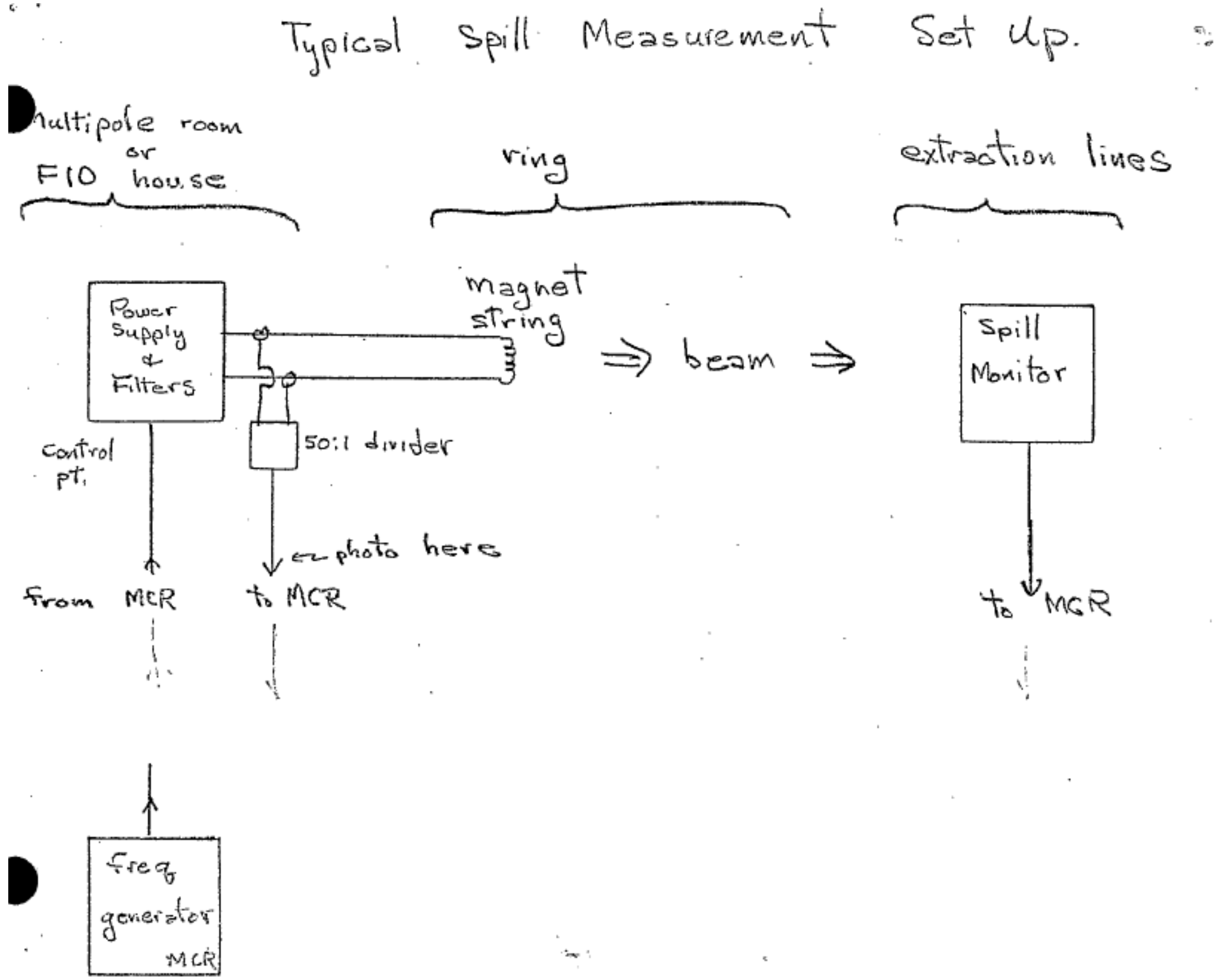
Without RF phase displacement, a 100 % modulated spill has $D_f = 0.67$. In this case,

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

Improved Effective Spill Length



Transfer Function Measurements



Transfer Function Measurements