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AN OVERVIEW OF THE SLOW EXTRACTION AT THE AGS (The Pre-Booster Era)

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Brookhaven National Laboratory

Accelerator Division

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Subject: AN OVERVIEW OF THE SLOW EXTRACTION AT THE AGS

(The Pre-Booster Era)

Edited by

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AGS Accelerator Division

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ABSTRACT

This note gives an overall comprehensive description of the AGS slow extracted beam (SEB) system, its principle and performance in the pre-booster era, and discusses the possible improvements in extraction efficiency, spill structure and duty factor for the post-booster era.

[] Please bring any errors, updated or better data or additional information on the SEB system to our attention.

CONTENTS

§ I. INTRODUCTION

The slow extracted beam at the AGS has been available since 1968 for the High Energy Physics Program (HEP). In the SEB mode the entire debunched circulating beam is extracted to over 1 to 2 sec (spill length) for the typical repetition time of 2.4 to 4 sec (AGS cycle) by exciting a third integer resonance ($3 \cdot Qh = 26$). This relative long spill allows high energy and nuclear physics counter experiments to take data smoothly without overloading their detectors.

The present SEB system consists of an electrostatic wire septum at straight section H20 [ESH20], a thin septum magnet at F05 [SMF05], and an ejector magnet at F10 [SMF10], together with two 3/2 lamda local orbit deformations [HPBLW, FPBLW] and dynamical sextupoles [DSEXT] which excite the third-integer resonance (ref.#1,#2). The SEB system is still controlled by the PDP10 operational program AGAST.

For typically good SEB operation during the proton HEP program, the extraction efficiency and the duty factor are 95 to 97% and 40 to 50% respectively, and the extracted beam intensity is $\sim 1.6 \cdot 10^{13}$ ppp at p = 24.5 GeV/c (ref.#3).

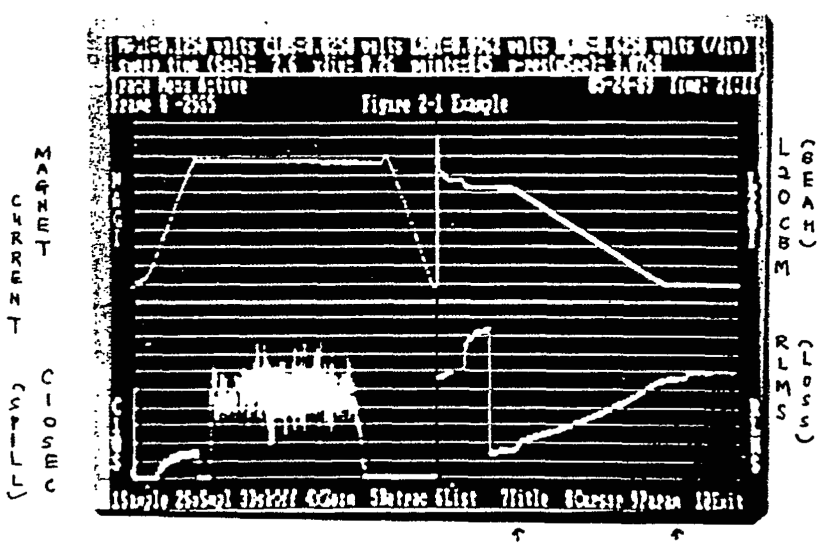
§ II. ACCELERATOR PARAMETERS

The following Table summarizes the general AGS machine and SEB parameters:

AGS		
Mean Radius	[Ro] :	128.45 m, C=2·pi·R=807.075 m
Curvature	[rho] :	85.37 m
Orbital Freq.	[frev] :	372 kHz at v=c, frev=c/C
	[trev] :	1/frev = 2.69 μs
Accelerated Particles:		Protons, 0_16, Si_28, Pol. Protons
Typical Operation Energy	:	24.5, 28.4 GeV for HEP 14 GeV p for HIP 28·(Z/A) GeV/amu for H.I.
SEB (protons)		
Typical Cycle Period	:	2.4 - 4.0 s
Extracted Intensity	:	< $1.6 \cdot 10^{13}$ ppp
Current	:	Int./(2.4·1.602·10**-19 coulomb) < 1 μA
Flattop	:	1.0 - 2.0 s
Spill Length	:	0.8 - 1.8 s
Effective S.L.	:	0.6 - 1.6 s
Eff.S.L. at target	:	0.5 - 1.5 s
Duty Factor	:	30 - 60 % (=eff.spill.length/cycle.time)
Extraction Efficiency:		95 - 97 % (overall)
Normalized Emittance	:	~50 pi mm-mrad (95%) (before extraction)

(ref.#3)

Fig.1 A TV display during the SEB run (May-1989).



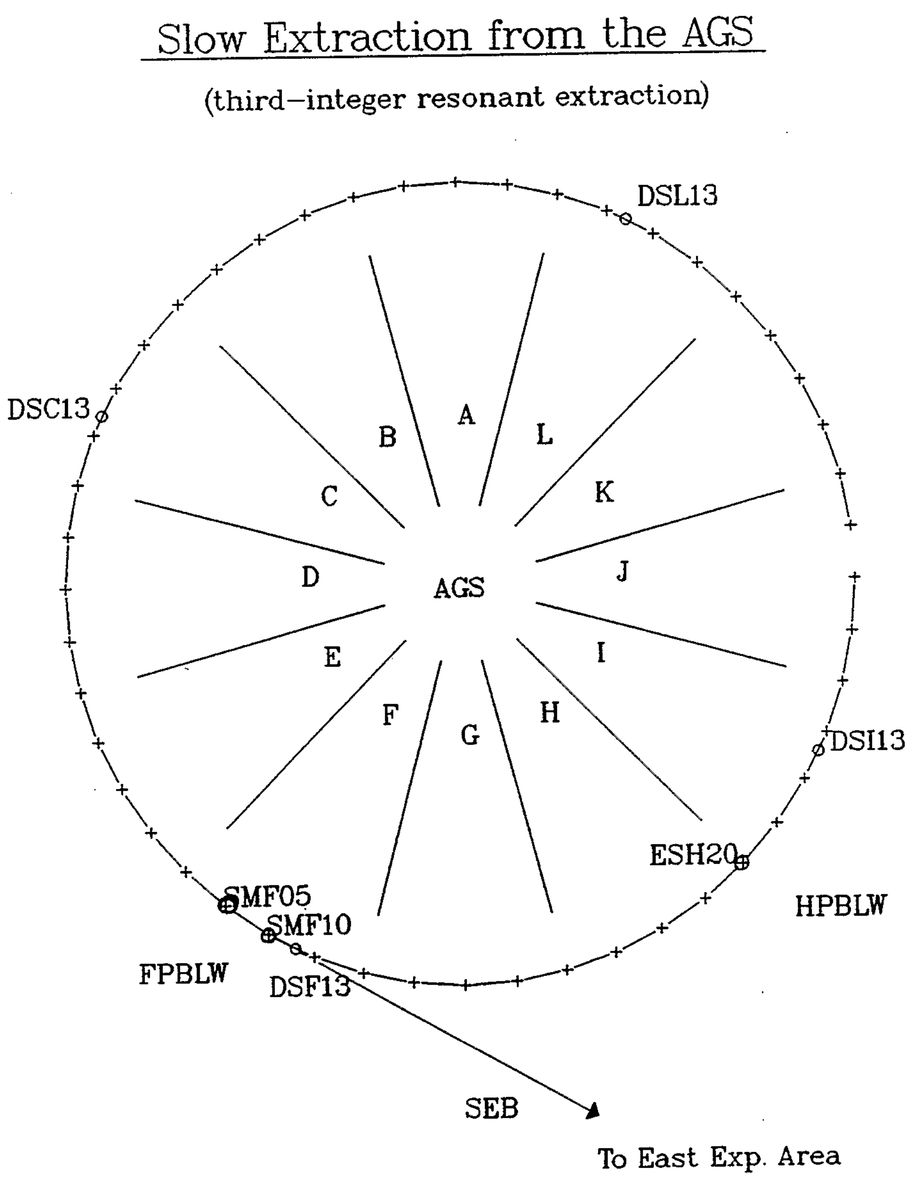
Machine Status

p	=	24.2 [GeV/c]
AGS Cycle	=	3.20 [s]
Flattop	=	1.61 [s]
CBM	=	$1.5 \cdot 10^{13}$ [ppp]
Ext. Eff.	=	95 ± 1 [%]

§ III. SEB EXTRACTION ELEMENTS

The layout of the main SEB extraction elements in the ring are schematically shown in Fig. 2 (ref.#4).

Fig. 2 The layout of the SEB extraction elements in the ring



III.A. SEB Devices [ESH20,SMF05,SMF10]

The basic parameters of the SEB extraction devices are summarized in the following Table (ref.#5,#6).

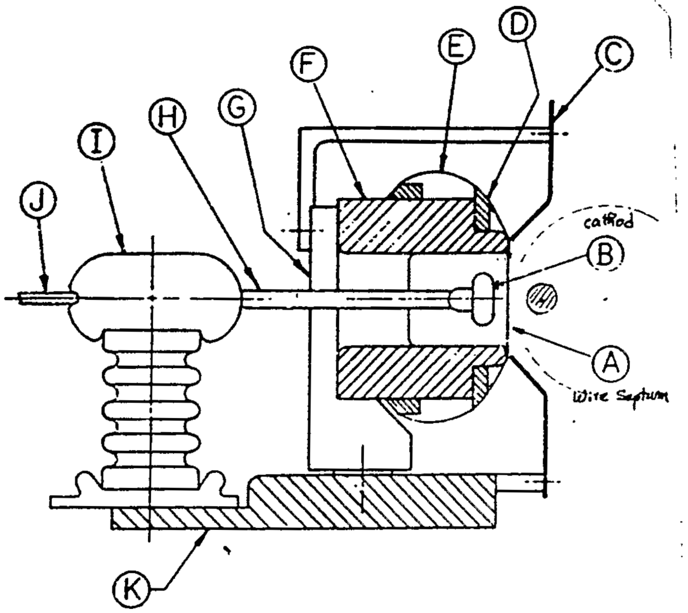
	ESH20	SMF05	SMF10 (Mark V)
Description:	electrostatic septum	septum magnet	ejector magnet
Location:	H20	F05	H10
ßv [m] =	12.0 - 19.9	22.1	19.9 - 12.0
ßh [m] =	19.9 - 12.0	10.5	12.0 - 19.9
Aperture:			
h [mm] =	>20.	17.5	25.9
W [mm] =	10.	31.75	60.0
Length:			
l [m] =	2.30	0.667	2.06
No. of Turns:			
N =		1	4
Septum :	W/Re(25%) wires	Cu	Cu
w [mm] =	0.051 (2.54 mm spacing)	0.76	15.9
Deflection :			
ø [mrad] =	0.43	1.1	18.5
Current/Voltage:			
I / V =	80 kV / 3 mA	15 V / 2.1 kA	40 V / 5.0 kA
Field:			
B / E =	80 kV/cm	1.5 kG	9.3 kG
Inductance:			
L [μH] =	---	~5.	~160.

N.B. Several models exist. Each model may have slightly different parameters. Values are design or maximum values at p= 29 GeV/c.

Fig. 3.a-c. (a) ESH20, (b)SMF05, (c) SMF10

[Key control words] (See page A4 for its meaning.)

ESH20 : H20ES, H20PI, H20SI, H20ON, H20OF, H20US, H20DS
SMF05 : F5SPS, F5ON, F5OF, F5US, F5DS
SMF10 : F10FN, F10SL, F10ID, F10ON, F10OF, F10US, F10DS, FEnf (n=1,4 & f=A,S,T)



Electrostatic septum construction. A: wire septum, 0.0051 cm diameter, 75% tungsten, 25% rhenium alloy wires, 0.127 cm spacing; B: titanium cathode (1 cm spacing from septum); C: baffle; D: soft aluminum strip to which wires are swaged; E: retractor spring, 0.041 cm diameter spring steel; F: mounting frame,

Fig. 3a. ESH20

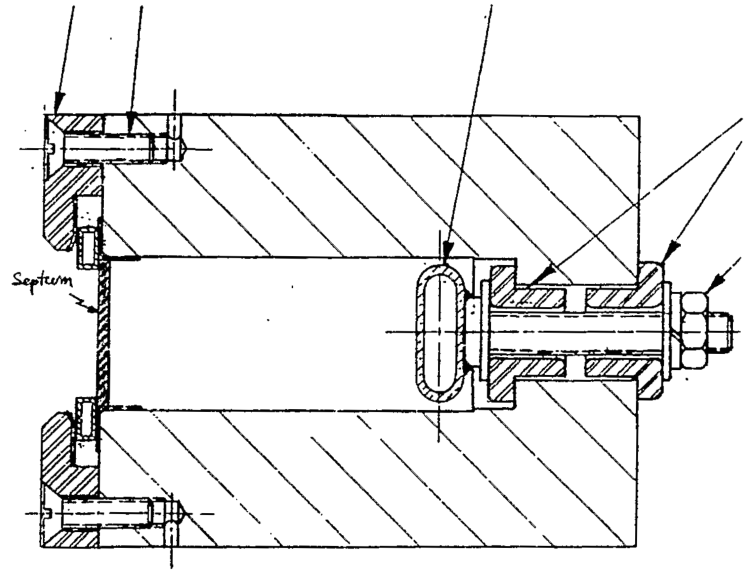


Fig. 3b. SMF05

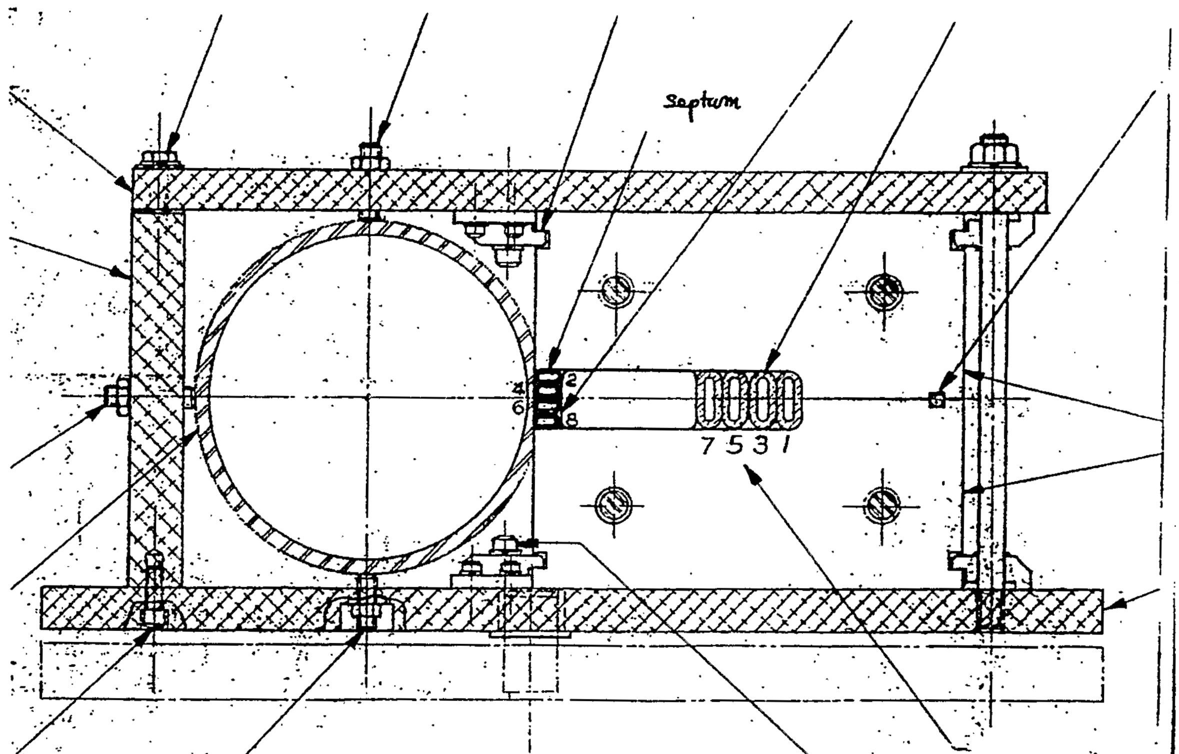


Fig. 3c. SMF10

III.B. Dynamical (or Drive) Sextupoles [DS*EXT]

A nonlinear third-integer resonance at Qh=26/3 is excited by 4 dynamical sextupoles [DSC13,DSF13,DSI13 & DSL13] with alternative polarity (- + - +) and equal strength at 90° intervals as shown in Fig.2. (ref. #7)

Magnet Type	:	6S24	
Bore Radius [a]	:	76.2	[mm] (=3'')
Turns/Pole [N]	:	12	
Length [L]	:	0.6096	[M] (=24'')
Effec. L. [Leff]	:	0.6604	[M]
Gradient [k2]	:	0.1023·I(A)	[T/M²]
DC Vmax	:	150	[V]
DC Imax	:	500	[A]
Inductance [L]	:	4	[mH]
Resistance [R]	:	40	[mO]

[Key control words]

DSEXT : DSXPS, DSXON, DSXOF

III.C. Local Backleg Winding Orbit Bumps [FPBLW,HPBLW]

There are two 3/2 lamda local orbit bumps for SEB, one for ESH20 centered around H19 [HPBLW] and another for both SMF05 and SMF10 centered around F07 [FPBLW] in order to displace the circulating beam close to ESH20 and to SMF05 & SMF10 (Fig.2). Each orbit bump is created by powering backleg winding coils on 4 pairs of the main magnets as shown in the following table. (ref.#1)

	Location (magnet type), polarity (±)			
HPBLW:	G18(F)&G19(D),	H12(D)&H13(F),	I06(F)&I07(D),	I20(D)&J01(F)
	- -	+ +	+ +	- -
FPBLW:	E06(F)&E07(D),	E20(D)&F01(F),	F14(F)&F15(D),	G08(D)&G09(F)
	- -	+ +	+ +	- -

t_rise	:	60 [ms]
Waveform	:	square pulse
Aperture	:	full
Deflection	:	1.5 [mrad]
Turns	:	5/Long_Mag, 6/Short_Mag
V/I	:	300 V / 500 A

[Key control word]

FPBLW : FPBLW, FPBON, FPBOF, FBnf (n=1,6, & f=A,S,T)
HPBLW : HPBLW, HPBON, HPBOF, HBnf (n=1,6, & f=A,S,T)

§ IV. BEAM INSTRUMENTS AND CONTROL

IV.A. Beam Loss Monitors [RLRM,RLM]

There are various radiation detector systems to monitor beam losses during the SEB process.

1. RLRM : Ring Long Radiation Monitors (120 units). Each Monitor is an extended coaxial ion chamber, 5 m long (2 main magnets).(ref.#8)

2. RLM : Ring Loss Monitor consists of 4 gas-filled coaxial cables that extends around the AGS Ring. It acts as an ionization chamber to provide a relative measurement of beam loss. (ref.#9)
   RLMAF, RLMFG, RLMGH & RLMHA
   RLMS = sum, RLME = RLM sum readout until first reading
   RLML = RLM sum readout after second reading

3. SEB Loss Monitors :

   F05ULM, F05DLM, F10ULM,F10DLM,F10LM, H20ULM,H20DLM,H20LM
   F05LM = sum , F10LM = sum, H20LM = sum

IV.B. Beam Instruments

- Current Transformer at L20 [L20CBM].
- Secondary Emission Chamber at C10 (external) [C10SEC].
- Ionization Profile Monitor [IPM] at C5 (Horz.) & E15 (Vert).
- Pick-up Electrodes [PUE] along the ring.
- Tune Meter at A10.
- Beam Catcher at E20.
- RF Frequency at constant energy (radius)
- Gauss Clock
- Wall Monitor at at F20
- SEB Flags [H20FG,F5FG,F10FG]

IV.C. SEB Spill Servo system

The SEB spill servo system is used to maintain constant energy, uniform spill and desired spill duration during extraction. The main source of intensity modulations is non-uniform dp/p distribution. The spill signal obtained from the SEC in an external beam line is compared with the reference signal generated from the circulating beam intensity, and the difference signal is fed back to the main magnet power (Siemens) supply to control the flattop slope. The servo system also provides protection for ESH20 against excess beam loss by inhibiting or aborting the beam. For details see ref.#10.

There is also a radial feed forward system which allows control of radial excursions due to changes in dB/dt (Bdot) causing phase errors, going to the flattop.

[Key control words]

SERVO: SSDLY, SSGAN, SSLNG, SSTP1, SSTP2, NSnf (n=1,4. F=A,S,T)
RFBAK: BAKGN, BAKOF, BAKON

$ V. THIRD INTEGER RESONANT EXTRACTION

V.A. Principle

Third integer resonant slow extraction is performed by controlled excitation of nonlinear third integer betatron resonance of the main ring at 3·Qh = n, which corresponds to the tune value Qh of the unperturbed ring near the center of the vacuum chamber. The factor "3" arises from the dynamical sextupole fields which excite the resonance and the integer "n" from the n-th Fourier harmonic component of the fields (n=26 for AGS and 19 for CPS).

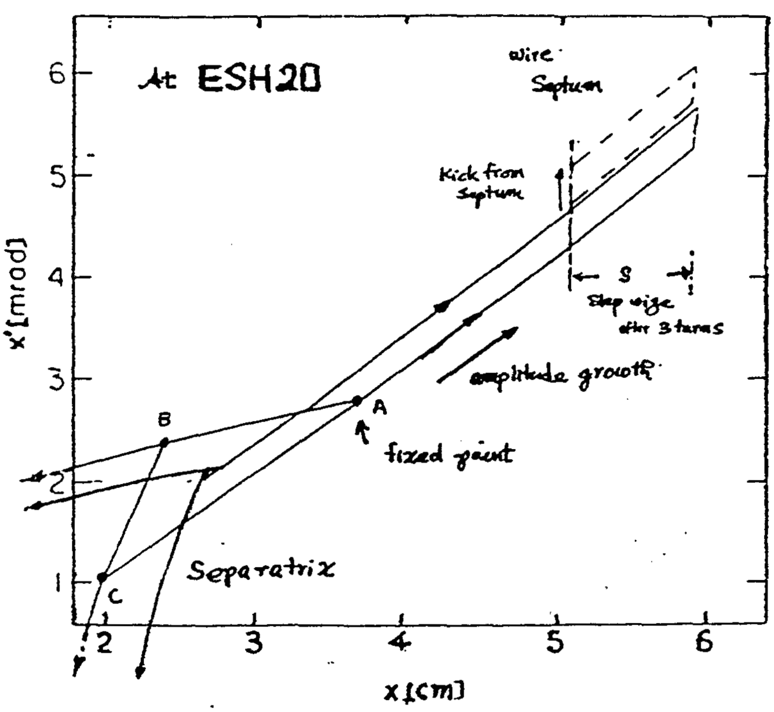
The slow extraction efficiency depends on the fraction of particles which strike the septum of the first extraction septum device (i.e., the wire septum of ESH20 for AGS) and is given by eff = 1.- f· w/s, where w is the effective wire thickness(= thickness + errors + beam divergence), s is the step size (i.e., spiral pitch, the growth of the resonant betatron amplitudes in the final few turns before extraction) and f is a factor (~1.5) to account for the horizontal beam density variation.

The step size [s] of a particle depends on its momentum, initial amplitude and its proximity to the resonant tune value. The maximum value of the step size is limited by the available aperture downstream and the circulating beam emittance.

For each momentum, there is a set of three linear separatrices which define a stable horizontal phase space area with a triangle shape. The stable triangular area can be reduced by adjusting the tune to be in the vicinity of 3·Qh = n either directly (using Quads) or indirectly (through slow beam steering or by increasing the dynamical sextupole strength. At the AGS, the quadrupole and sextupole strengths [QHORZ,DSXPS] are kept constant, and the beam is pushed slowly from its stable position to the resonance by a negative main magnet flattop slope so that different momentum particles progressively move on to the resonance. Extraction starts when the beam emittance fills the stable area for the higher end of momentum distribution. As the stable area slowly shrinks to zero for these particles, other parts of the momentum distribution are subsequently extracted.

Fig.4 Separatrix and extraction trajectory at ESH20

(ref.#2)



V.B. Extraction Process

¶ The beam is accelerated to a desired energy, flattop (e.g, p=24.5 GeV/c) After the energy get stable, the RF is turned off [SW30F] at a precise field and the beam is debunched at the end of the acceleration cycle by phase back of the RF [PHSBK] to the unstable fixed point (a ~ 180° phase jump). The bunch will shrink along one axis and stretch along the other in the øs-dE plane. In 1 ms or so the bunches will overlap each other (See Fig.11a).

¶ Extraction devices ESH20, SMF05 and SMF10 as well as high field quadrupoles are turned on before RF turn-off, and the Drive Sextupoles [DSEXT], Backleg Windings (orbit bumps) [FPBLW,HPBLW] are energized shortly after the RF turn-off.

¶ The equilibrium orbit of the beam at this time is adjusted to be located at approximately 8.0 mm inside of the resonance radius (center) and at Qh = ~8.75. The flattop slope is adjusted slightly negative so that the beam spirals slowly outward to the radius near the center corresponding to the Qh=26/3 resonance, at a rate determined by the dB/dt control (flattop voltage excitation).

¶ As the beam tune approaches Qh=26/3, the stable region (separatrix) in the horizontal phase plane shrinks for each momentum. For each momentum, there is a set of three separatrices which forms a stable triangular area. The lower the momentum, the larger the stable triangular area is.

¶ Ejection starts when the separatrix area for the highest momentum particles are equal to the phase plane area enclosed by the orbit of the particles of that momentum with the highest betatron oscillation amplitude.

¶ Slightly later, particles of a higher momentum with smaller amplitudes will be ejected simultaneously with the particles of a lower momentum with larger amplitudes. Particles outside the separatrix execute oscillations of rapidly increasing amplitude and move outward each of three asymptotes associated with the third integer resonance separatrix. For every three turns the change of the particle position (i.e., step size) increases rapidly as it approaches ESH20 in the phase space. The particle eventually jumps across the ESH20 wire septum and is kicked outward.

¶ After deflection by ESH20, the particle turns around about 2 and 3/4 orbits and then arrives at SMF05 in the proper phase for further deflection by this septum. At the distance = 24 full betatron oscillations, the angular deflection dx' at H20 will, in the linear case, produce no net spatial separation at SMF05;

$$dx(F5) = dx' \cdot \sqrt{[\beta(H20) \cdot \beta(F5)]} \cdot \sin(\mu(H20,F5) = \sim 0$$

where $\mu(H20,F5)$ = the phase advance between H20 and F5 = ~24·2·pi.

However, the non-linear effects of the sextupole moments of the drive sextupoles and of the main magnets are significant enough to produce the required displacement at SMF05. The beam kicked by SMF05 is finally extracted to the external beam line by the ejector magnet SMF10.

(ref.#1,#2)

The following data from the IPM program may help to figure out how the SEB extraction process will progress during a AGS cycle.

IPM Data from injection to extraction (t=0 to 2000 ms)		
Fig.	5a.	Momentum vs Time
	5b.	RF Gap Voltage
	5c.	Beam Intensity (L20CBM)
Fig.	6a.	Horizontal Beam Position
	6b.	Horizontal Beam Size
	6c.	Horizontal Normalized Emittance
Fig.	6d.	Vertical Beam Position
	6e.	Vertical Beam Size
	6f.	Vertical Normalized Emittance

(The data were taken in May,1989)

The Qh and Qv measured by the tune meter are shown in Fig.7 from injection to extraction.

Fig.	7a.	Measured tunes Qh and QV (t=0 to 550 ms)
	7b.	Working diagram of the machine in the Qh-Qv plane

(ref.#11)

At the higher flattop energies ($p > 29$ GeV/c) the working point in the Qh-Qv plane is outside of the Qh=Qv coupling. The measurements indicate that with the tune spread dQh, part of the beam could be affected by the coupling resonance $2\cdot Qv+Qh=26$, which is excited by the DSEXT configuration.
The extraction efficiency gets low due to a development of irregular beam spots and vertical beam size blow up. High field quadrupoles HQUADs and VQUADs are used to shift the initial tune to a point between the Qh=Qv line and the Qh=26/3 resonance line (ref.#1).

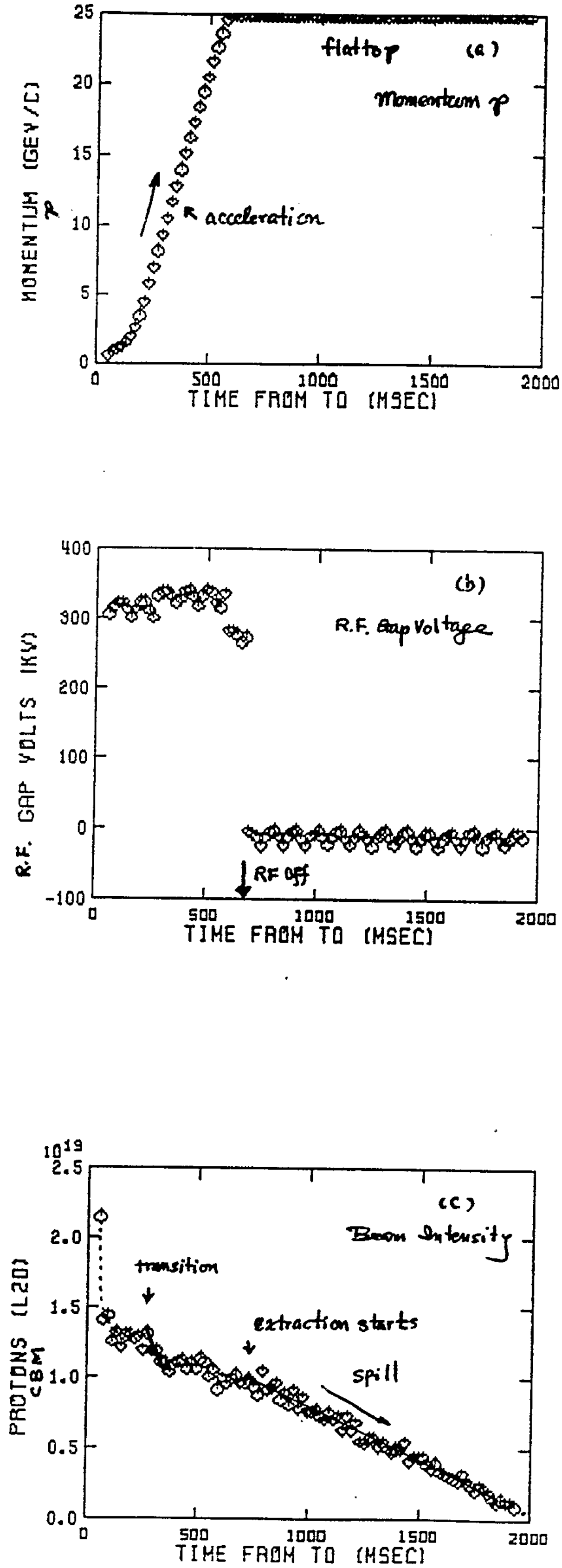

25
20
15
10
5
0
MOMENTUM (GEV/C)
p
flattop
(a)
Momentum p
acceleration
0
500
1000
1500
2000
TIME FROM T0 (MSEC)
400
300
200
100
0
-100
R.F. GAP VOLTS (KV)
(b)
R.F. Gap Voltage
RF off
0
500
1000
1500
2000
TIME FROM T0 (MSEC)
10^19
2.5
2.0
1.5
1.0
0.5
0.0
PROTONS (L20)
CBM
(c)
Beam Intensity
transition
extraction starts
spill
0
500
1000
1500
2000
TIME FROM T0 (MSEC)

Fig. 5a-c.

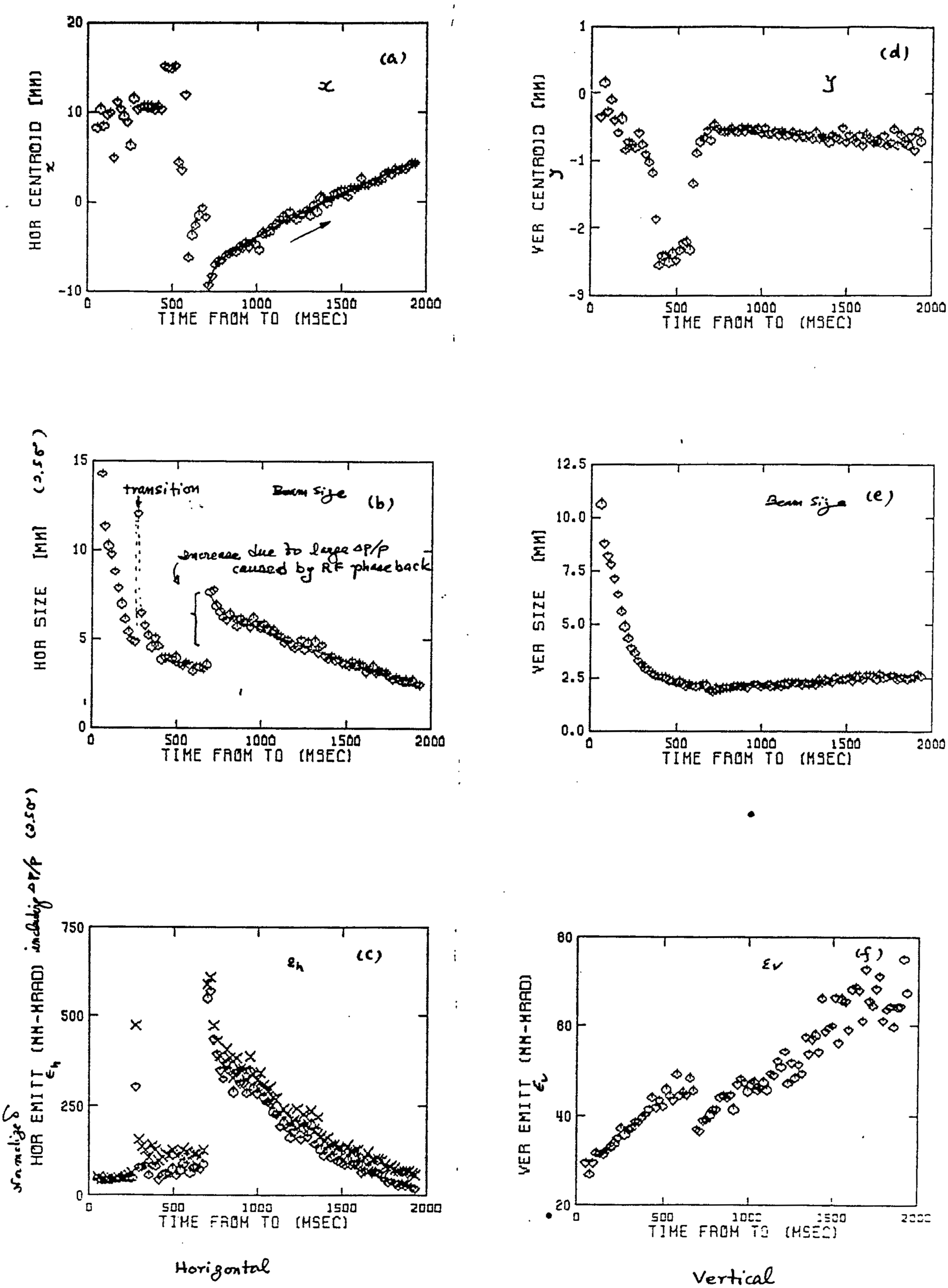
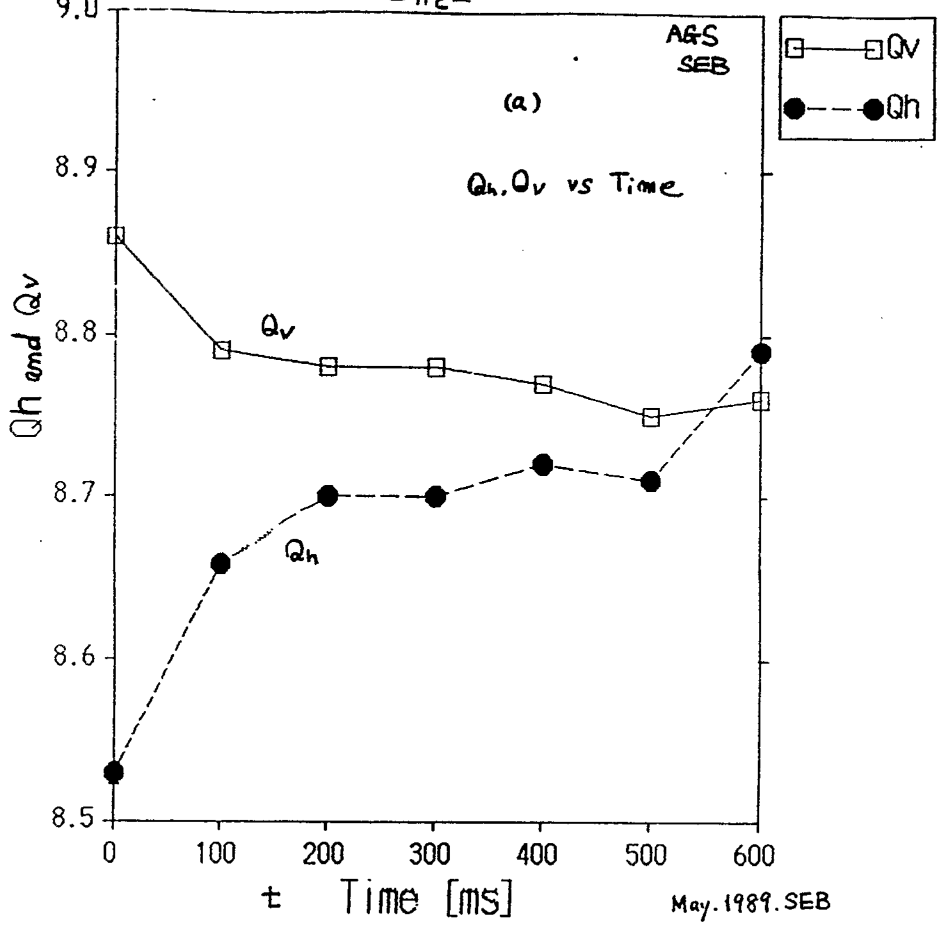

(a)
x
HOR CENTROID [MM]
TIME FROM T0 (MSEC)
(d)
y
VER CENTROID [MM]
TIME FROM T0 (MSEC)
transition
Beam size
(b)
Increase due to large Δp/p caused by RF phase back
HOR SIZE [MM] (2.56)
TIME FROM T0 (MSEC)
Beam size
(e)
VER SIZE [MM]
TIME FROM T0 (MSEC)
ε_h
(c)
Normalized HOR EMITT (MM-MRAD) including Δp/p (2.5σ)
TIME FROM T0 (MSEC)
ε_v
(f)
VER EMITT (MM-MRAD)
TIME FROM T0 (MSEC)
Horizontal
Vertical

Fig. 6 a-f



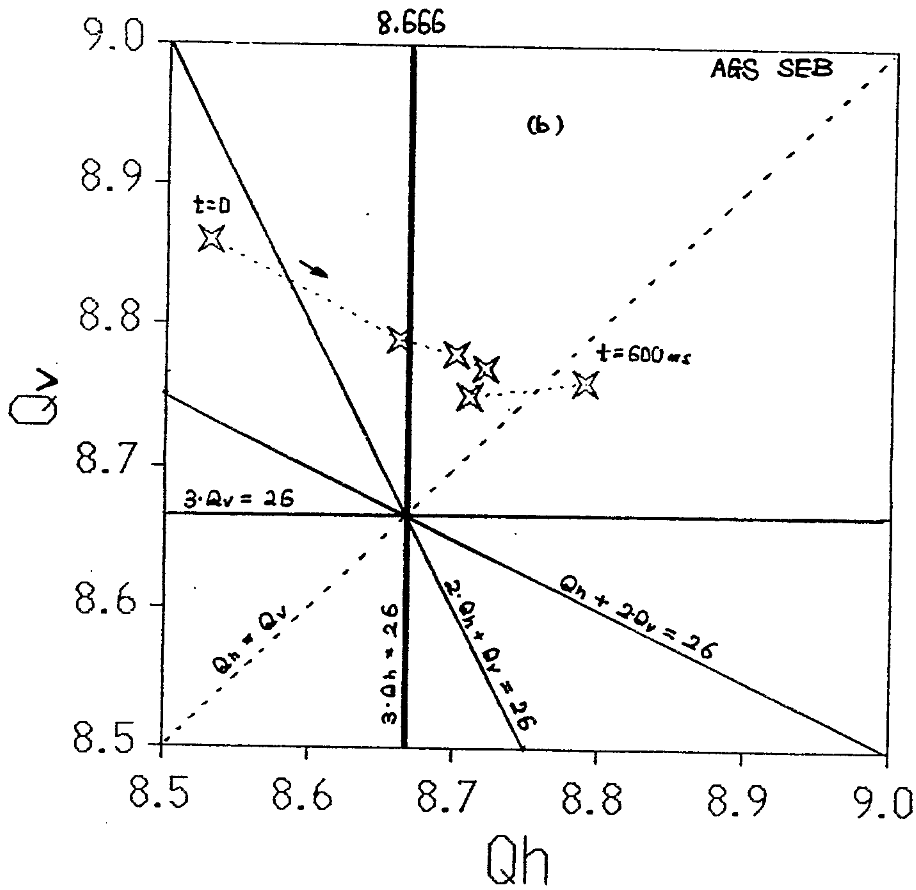


Fig. 7 (a)(b) May. 1989. SEB

V.C. Extraction Losses and Efficiency

As mentioned before, the expected extraction efficiency is given by $e = 1.- f\cdot w/s$. Substituting f=1.5, the effective wire thickness w = 90 μm (wire diameter is 50 μm), and the step size s=6 mm for the present SEB, we expect e to be ~0.975 (97.5%).

In FY1987, a series of machine studies on SEB extraction were performed to understand the third integer resonant extraction and to measure the extraction efficiency as accurately as possible for the present SEB system. The extraction efficiency at the middle of spill and for the whole extraction period was measured in order to separate the non-conventional beam loss at the beginning and the end of extraction. At the middle of spill the beam loss is solely due to the thickness of the wire septum. The non-conventional loss is due to part of the particles which are not extracted by the resonant system, which accounts for 1/3 of the the total extraction loss. For the optimal SEB setting, the extraction efficiency is 97 to 98%, and the total extraction efficiency including the the non-resonant beam components is 96 to 97%. (See ref.#12)

Fig. 9a. RLMn vs SECn varying H2ODS
9b. SECn-7 & RLMn vs H2ODS and
Ext. Eff. & Ineff. vs H2ODS.

(from ref.#12)

where RLMn=RLM/CBM and SECn=SEC/CBM.

V.D. Spill Structure

The duration of the spill is effected by the flattop slope and a momentum spread of the circulating beam. To enhance debunching of the beam the momentum spread dp/p is increased from the intrinsic value of ± 0.05 % to ± 0.25 % by a phase change of ~ 180° in the RF accelerating voltage at about 2.5 ms prior to the RF turn-off. The momentum spread dp/p = ± 0.25 % causes radial spread in equilibrium orbits,

$$\begin{aligned} dR &= alpha\cdot Ro\cdot dp/p \\ &= 0.014\cdot 128.45\cdot(\pm 0.0025)\ [m] \\ &= \pm\ 4.5\ [mm] \end{aligned}$$

where alpha = momentum compaction factor, and tune spread,

$$\begin{aligned} dQh &= Xi\cdot Qh\cdot dp/p \\ &= -3.0\cdot 8.667\cdot(\pm 0.0025) \\ &= \pm\ 0.065 \end{aligned}$$

where Xi = chromaticity, and dQh/dR = -0.014/mm. Therefore, only small fraction of the beam is affected by the resonance at any given time. The instantaneous momentum bite in the extracted beam is an order of 0.01% and dQh(resonance width)=0.0026. The rate of spill is more easily controlled as dp/p increases.

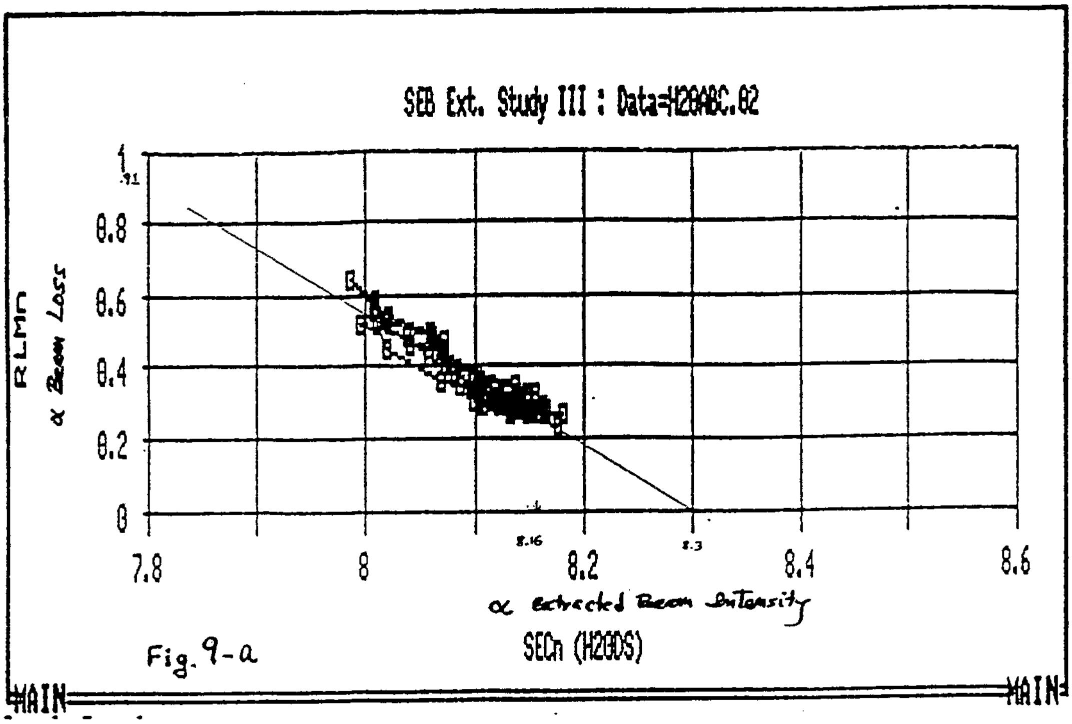

SEB Ext. Study III : Data=H20ABC.02
RLMn
α Beam Loss
α Extracted Beam Intensity
SECn (H20DS)
MAIN
MAIN

Fig. 9-a

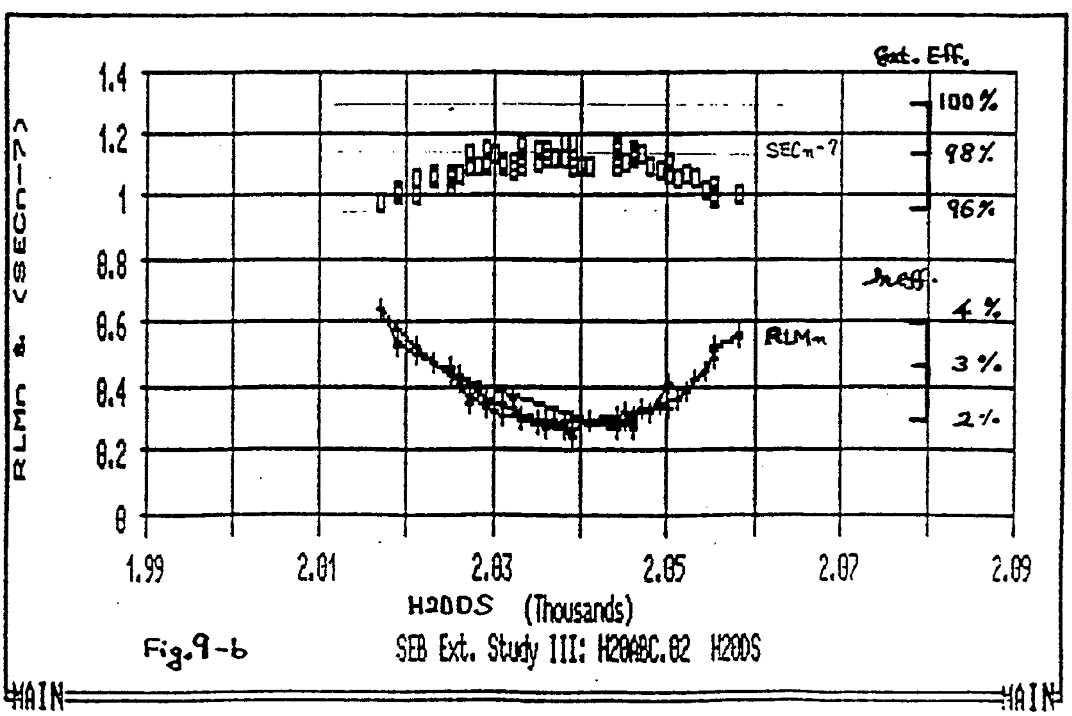

RLMn & <SECn-7>
Ext. Eff.
100%
98%
96%
SECn-7
Ineff.
4%
3%
2%
RLMn
H20DS (Thousands)
SEB Ext. Study III: H20ABC.02 H20DS
MAIN
MAIN

Fig. 9-b

As seen in Fig. 1, there are micro and macro time structures in spill which are caused by ripples in the main magnet and SEB equipment power supplies. If we define a spill duty factor (sdf) and a (overall) duty factor (DF) as

$$\text{sdf} = \frac{\text{effective spill length}}{\text{flattop}}$$

and

$$\text{DF} = \frac{\text{effective spill length}}{\text{AGS cycle time}}$$

then, the maximum achievable sdf and DF are ~0.80 and ~0.60 respectively. The effective spill length is measured based on accidental counts.

Suppose that the circulating beam is at $8.667 < Qh < 9.000$ with $dQh < 0.3$, and the variation in the main magnet current is

$$\begin{aligned} dI/I &= dB/B = dp/p \\ &= (dQh/Q)/xi \\ &= (0.3/8.75)/(-3) \\ &= -0.01 \end{aligned}$$

Substituting $I = 4000$ A, we have $dI = I \cdot 0.01 = 40$ A. For 2 sec spill, $dI/dt = 20$ A/s and $Vr = L \cdot dI/dt = 0.08 \cdot 20 = 1.6$ V for ripple voltage across magnets.

$$\begin{aligned} Vtot &= Vo\ (=IR) + Vr\ (=L \cdot dI/dt) \\ &= 4000 \cdot 0.25 + 1.6 \\ &= 1002\ [V] \end{aligned}$$

It implies that a ± 5% ripple in spill corresponds to ± 0.8 V ripple and dV/V = 0.8 /1000 = 0.08 % ripple in voltage, which is difficult to achieve.

Ripples from other P.S.s are relatively small and each contributes less than 1 % as summarized in the following table:

Device P.S.	Ripple Volts
SIEMENS	800 mV
HQUAD	50 mV
VQUAD	100 mV
HPBLWP	100 mV
FPBLWP	100 mV
HSEXT	800 mV
DSEXT	600 mV
SQUAD	10 V
SMF05	10 mV
SMF10	30 mV

(From ref.#13)

§ VI. PERFORMANCE, LIMITATIONS AND POSSIBLE IMPROVEMENTS

VI.A. Extraction Efficiency

The maximum extraction efficiency, excluding the non-conventional loss, is presently limited to 97 to 98 % due to the finite values of the effective septum thickness (w=80 μm) and the step size at ESH20 (s= 6 mm). Any further improvement in extraction efficiency is difficult and is not of much interest to SEB users. However, as the the AGS beam intensity has been steadily increasing and at least a factor of 4 increase in beam intensity is expected with the Booster, further improvement in extraction efficiency is under consideration to keep the activation of sensitive machine components as low as possible.

There are only two ways to reduce the beam loss during SEB extraction: 1) to reduce the effective wire septum thickness [w] and 2) to increase the step size [s]

1) Effective wire septum thickness [w]

The standard ESH20 has a 51 μm diameter W/Re(25%) wire septum with 2.54 mm spacing. The effective wire septum thickness [w] is estimated to be 89 μm due to alignment errors and finite beam divergence. Possibilities to reduce w are discussed in Ref.#6. Some of them are:

(a) Use low Z material wires - It may reduce the beam loss due to large angle coulomb scatterings on the wires by 20-30 %. In 1987 a hybrid Ti-alloy (Ti 6Al/4V) wire septum was tested by the extraction group. The results were encouraging, giving the extraction efficiency to ~ 98 ± 1 % and 96 to 97 % if it included the non-conventional losses. However, we cannot draw a definite conclusion due to the poor quality of the data (e.g., pulse-to-pulse variations) and some instrumental limitations.

(b) Use wires with a smaller diameter and do better alignments - It is assumed that 51 μm diameter and 25 μm alignment error are still the present achievable limits, but nowadays it may probably no longer be the case.

(c) Increase the wire spacing - It has been already increased from the original value of 1.27 mm to 2.54 mm. The non-uniformity in the field caused by the wider spacing is believed to have a negligible integrated effect.

(d) Relocate the ES - At H20 the horizontal beam divergence is large.

(e) Put a psedo-septum upstream which completely or partly shadows the ES (ref.#14).

It should be noted that factors involved in optimizing wire material, size and spacing have not yet been fully understood. Great demands have been placed on mechanical properties and soundness instead.

2) Step size [s]

Since the step size [s] is directly proportional to the dynamical sextupole strength [DSXPS], we should increase w from the present value, 6 mm to 8 mm by restoring the original design strength. Recently a simulation study on a possibly more efficient new slow extraction scheme for the AGS was done by Steinbach (ref.#15). He proposed several new schemes which may increase s to ~10 mm. One possible scheme is as follows:

(a) put ES at A20 [ESA20] so that the deflection at the ES can be used directly to create the gap between the circulating beam and the kicked beam at SMF05,
(b) put quads at A05 and at L05 to adjust phase at ESA20,
(c) reduce the chromaticity if possible,
(d) the ESA20 gap should be increased to match with the larger value of s while keeping its present field,

which can potentially reduce the extraction loss by 50 %.
(For details, see ref.#15)

VI.B. Spill Structure

Almost all recent HEP/SEB users at the AGS such as rare K-decay experiments are high statistic precision experiments which require 2000 to 6000 hours of the running time with high intensity beam and a high duty factor, i.e., long and uniform spill, which increase their physics data-taking rate and minimize accidental triggers or dead time.

Macrostructure, which has a time scale on the order of 100 ms or so, is usually minimized by tuning the servo parameters properly. Microstructure, which has $60 \cdot n$ Hz (where n= 1,2,3..) harmonics and exhibits (20 to 100) % ripple in spill as seen in Fig.10 is a major concern for experimenters. (ref.#16)

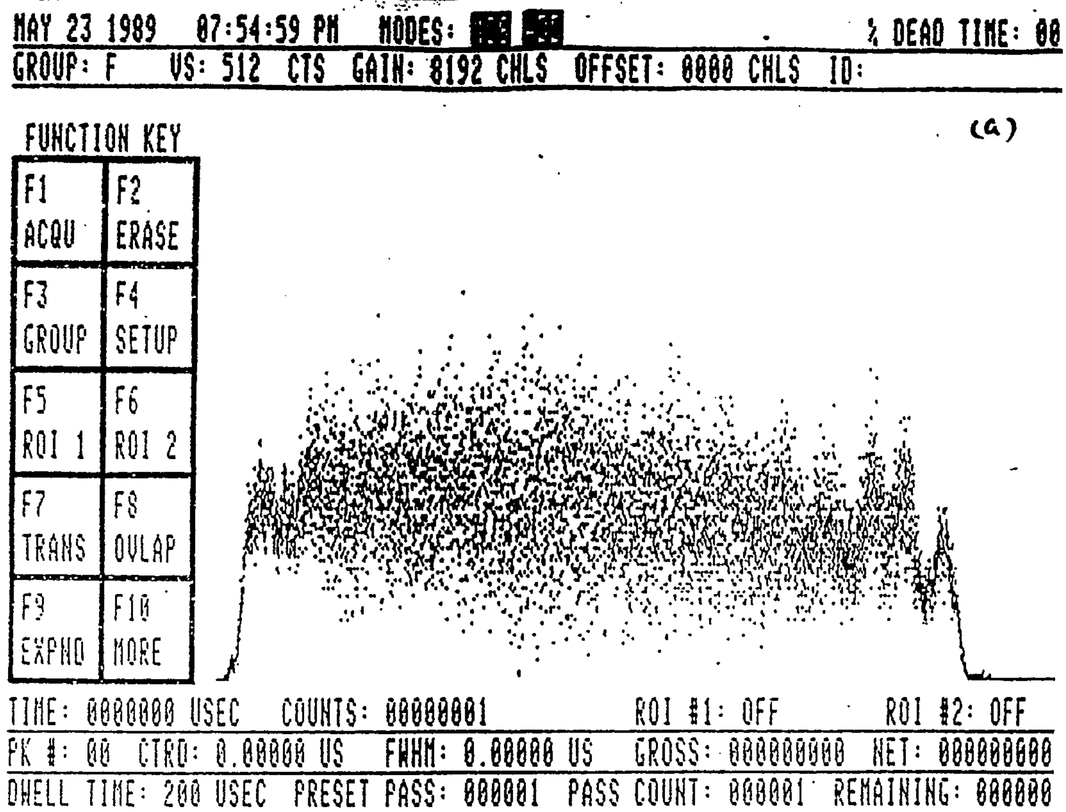
Fig.10a Beam spill in the B5 line
10b Frequency spectrum of the Spill

(ref.#11)

Besides minimizing ripple in various power supplies, we can achieve lower-rippled spill by increasing the momentum spread dp/p, at the price of increasing the non-conventional loss. This may not be acceptable for high intensity beam. However, recently Kats (ref.#17) proposed a scheme to produce more uniform rectangular dp/p distribution by reducing the RF gap voltage by a proper amount when debunching takes place as illustrated in Fig.11b. The preliminary test indicates that the uniform dp/p distribution can actually produce lower-ripple spill.

Fig.11a A phase jump.
11b A phase jump with reducing RF gap voltage.

(ref.#17)


MAY 23 1989 07:54:59 PM MODES:
% DEAD TIME: 00
GROUP: F VS: 512 CTS GAIN: 8192 CHLS OFFSET: 0000 CHLS ID:
(a)
FUNCTION KEY
F1 ACQU
F2 ERASE
F3 GROUP
F4 SETUP
F5 ROI 1
F6 ROI 2
F7 TRANS
F8 OVLAP
F9 EXPND
F10 MORE
TIME: 0000000 USEC COUNTS: 00000001 ROI #1: OFF ROI #2: OFF
PK #: 00 CTRD: 0.00000 US FWHM: 0.00000 US GROSS: 000000000 NET: 000000000
DWELL TIME: 200 USEC PRESET PASS: 000001 PASS COUNT: 000001 REMAINING: 000000

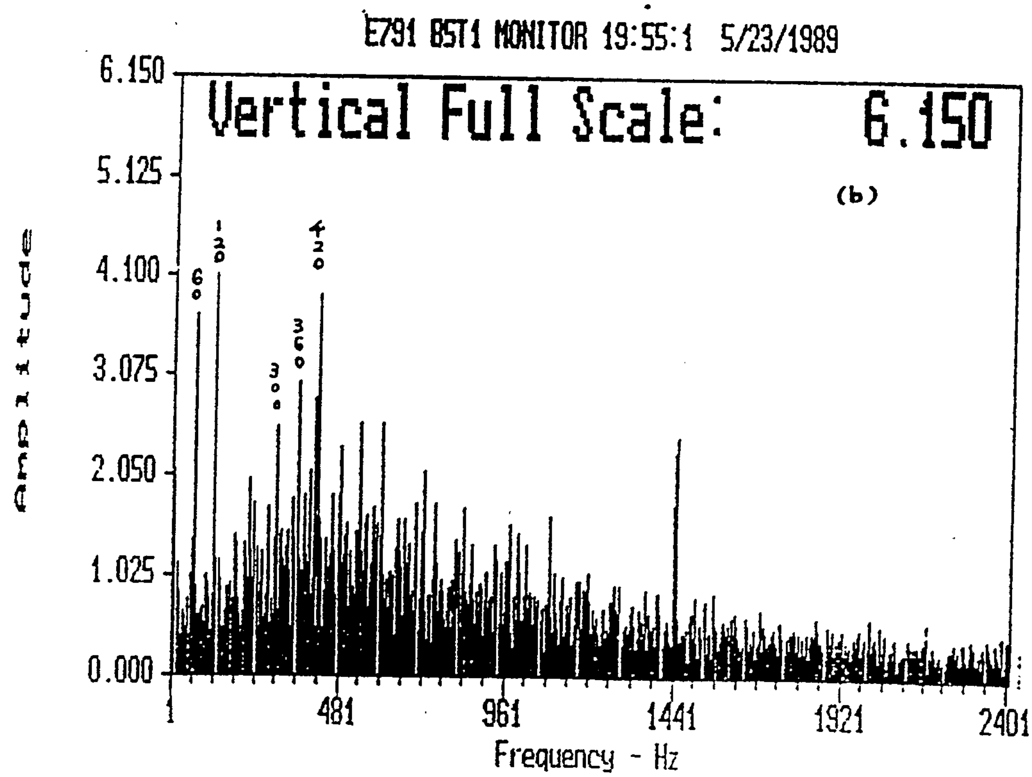
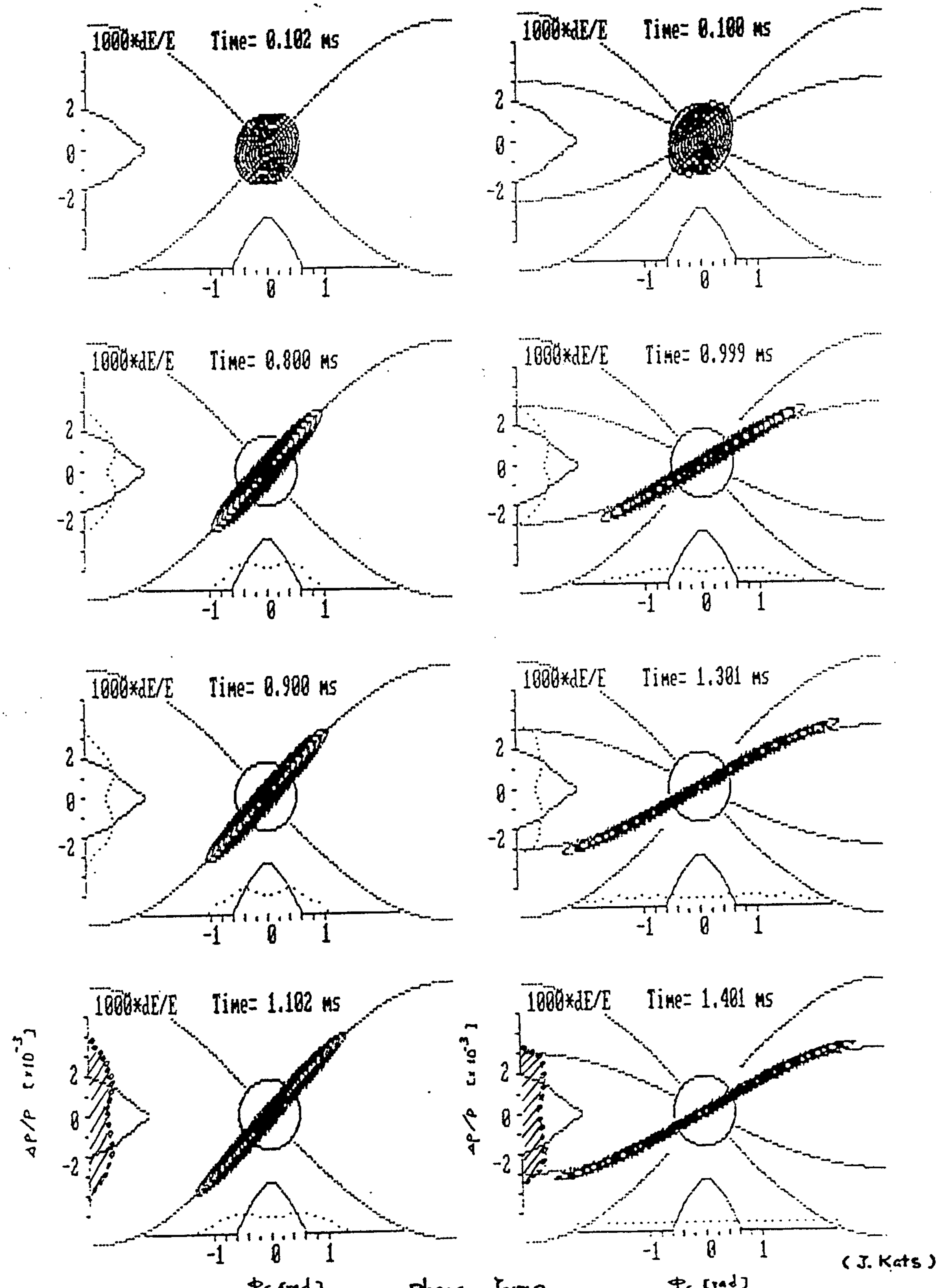

E791 BST1 MONITOR 19:55:1 5/23/1989
Vertical Full Scale: 6.150
(b)
6.150
5.125
4.100
3.075
2.050
1.025
0.000
Amplitude
60
120
300
360
420
1
481
961
1441
1921
2401
Frequency - Hz

Fig. 10



(J. Kats)

Phase Jump

Fig. 11a

Fig. 11b

V.C. Reliability

SEB has operated successfully and has improved by the AGS staff several times to satisfy the SEB users since it came into operation in 1968.
In a typical recent fiscal year, we operated the AGS for the proton HEP program (SEB) for ~2500 hours and have ~750 hours machine failures of which ~50 hours are usually attributed to ring SEB equipment failures.

We usually observe 6 to 12 wires popped up in the upstream end of the ESH20 after every major SEB run (15 - 20 week operation) including various AGS Studies which usually dump the beam inside the machine. This is not a serious problem since even losing all wires at the first foot or so does not adversely affect the ESH20 performance. However, once every two to three years one of wires breaks and touches the cathode rather than pops up, causing a short, which requires replacement of the septum with a spare. It costs at least 12 - 36 hours of machine downtime and more if the spare is not ready. (In FY1989 it happened twice!)

Since a few percent of beam loss is an intrinsic characteristic of slow resonant extraction due to the septum thickness, we expect that ring SEB failure increases proportionally as the beam intensity increases unless the mechanica performance of the septum improves and/or the beam loss at the septum reduces substantially.

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APPENDIX

§ A. History

1955	: AGS construction began.
13-Apr-1956	: Linac accelerated proton to 50 MeV.
17-May-1960	: Beam first introduced to ring.
29-Jul-1960	: Reached design energy of 30 GeV.
Aug-1964	: Multi-turn injection.
3-Dec-1964	: Beam intensity reached $1.0 \cdot 10^{12}$ ppp.
FY1967	: AGS improvement program started.
Mar-1968	: Slow extracted beam (SEB) mode
Nov-1970	: 200 MeV Linac
Nov-1973	: New fast extracted beam (FEB) mode
1978	: New SEB Switchyard
1979	: Electrostatic Wire Septum [ESH20] for SEB
1980	: New FEB system [FKH05 & SMH10]
Nov-1982	: H- injection.
Jan-1983	: Single bunch extraction (SBE) with FEB [FKE05]
Dec-1983	: CBM=$1.62 \cdot 10^{13}$ ppp (SEB)
Feb-1984	: RFQ I
Nov-1986	: Tandem-HITL-AGS for HIP
Oct-1988	: RFQ II
May-1989	: SBE with SEB

§ B. Operational Tips

Most of the tips described here are extracted from ref.#13, a talk given by Glenn at the AGS 1988 Training Program.

1) To minimize loses during the spill:

First, it is not trivial to minimize beam losses during the spill since the loss readouts include early and late losses, non-conventional losses.

When the SEB parameters are tuning , [H20US] and [FPBLW] currents should be kept on fixed values.

(a) Adjust [H20DS] to minimize [H20LM]. Care should be taken to account for backlash of ~5 mills for all drives.
(b) Adjust [HPBLW] to minimize [F5LM].
(c) Adjust both [F10US] and [F10DS] to minimize [F10LM].
(d) Check the spill length and a tail spike [CE10SEC].
(e) Repeat untill a satisfactory result is obtained.

2) To adjust beam energy:

Energy is defined at RF-off [SW30F] by field and radius of the first useful part of the high energy tail on the beam. Changing one of the following devices will change the beam energy and can be corrected by another:

[TFH3G],[TFH4G],[TFHCE] : constant energy controls

[RF7A] : radius control, assuming [RS7T] is early enough and [RS7S] is big enough)

[PHBAK],[PHSBK] : phase back on trigger and phase shift, move the radius as the beam debunches.

(N.B., [PFXFR] should only affect when the spill starts, not energy.)

3) To tune the good spill:

Want as large dp/p as possible. Want as low losses as possible. We need a trade-off.

(a) Check for P.S.s with large ripples and fix it.
(b) Adjusting phaseback, transition, radius, Boussard, RF amplitude may help.
(c) Radius, phaseback and Boussard affect beam energy - may have to adjust [TFH4G].
(d) Check if the spill starts too early -> [PFXFR]
(e) Check if the spill ends too late -> [SESLF] to correct Siemens drifts.

(The "non-resonant" beam will scatter out of the AGS with 30 % efficiency Some goes to D, the rest is lost. Moving the loss to the another section does not help. Catch it on the E20 catcher.)

4) To adjust the spill length:

(a) Spill servo gain zero. Adjust [SESLF] and Varniers (Stations I & II together) for long spill or 0.4 % sweep on Clyde.
The function generator may help "smooth" the spill a bit.
(b) Turn on [SSGAN] and adjust the spill length with [SSLNG].
(c) There are drifts in Siemens, adjustments have to be done every shift.

If [CE10] or CBM signal into the spill servo is not of an appropriate amplitude (1-5 V), the [SSGAN] and [SSLNG] may be useless. Use [SESLF] to adjust if [SSLNG] goes to 0 / 4000.

5) To reduce ripple in Siemens

(a) See that Station II ripples are resonable (< 2mV on HP Analyser for 60 to 300 Hz) Adjust if necessary.
(b) Adjust Station I, 60 to 300 Hz sin and cos to reduce the CE10 300 Hz ripple.
(c) Adjust Station I and II 360 Hz to reduce the CE10 360 Hz ripple.
(d) Adjust Station I & II Verniers to reduce 720 Hz on CE10.
(Add to I & subtract from II or vice versa.)

(ref.#13)

§ C. Dictionary of Key Control Words

DSXPS	Dynamical Sextupole [DSEXT] Power Supply (PS)
DSXON/OF	DSEXT PS on/off trigger (time)
FPBLW	FPBLW (for SMF05 and SMF10)
FPBON/OF	FPBLW PS on/off trigger
FPnf	FPBLW function generator (n=1,4 & f=A*mplitude, S*lope, T*ime)
HPBLW	HPBLW (for ESH20)
HPBON/OF	HPBLW PS on/off trigger
HPnf	HPBLW function generator
F5SPS	SMF05 PS
F5ON/OF	SMF05 on/off trigger
F5US/DS	SMF05 upstream/downstream position control
F10EJ	SMF10 current signal
F10FN	SMF10 fine current adjust
F10SL	SMF10 current slope adjust
F10ID	SMF10 PS inductrol control
F10ON/OF	SMF10 on/off trigger
F10US/DS	SMF10 upstream/downstream position control
FEnf	SMF10 function generator
H20ES	ESH20 voltage control
H20PI	ESH20 PS current readback
H20SI	ESH20 current
H20ON/OF	ESH20 on/off trigger
H20US/DS	ESH20 upstream/downstream position control
SSDLY	Start time of Spill Servo reference signal
SSGAN	Spill Servo dynamic voltage gain control
SSLNG	Spill length voltage level control
SSTP1	H20LM trip level #1 control (before extraction) for SS
SSTP2	H20LM trip level #2 control (during extraction) for SS
NSnf	Spill Servo function generator
BAKGN	Backleg function generator gain
BAKON/OF	Backleg function generator on trigger/offset

__________ q.e.d. __________