Summary Talk (11/9/97)

Accelerator Working Group (U(1)$_{EM}$ Working Group)

R. NOBLE (presenter)

Primarily concentrated on a few critical issues in proton driver design for a Fermilab source with 10^{14} protons per pulse at 15 Hz rep rate. Baseline was the Summer Study strawman design of 16 GeV synchrotron complex (TM-2021, August 1997).

- RF system design.
- Control of longitudinal space-charge effects.
- Bunching of proton beams to few nsec.
- Instability issues.

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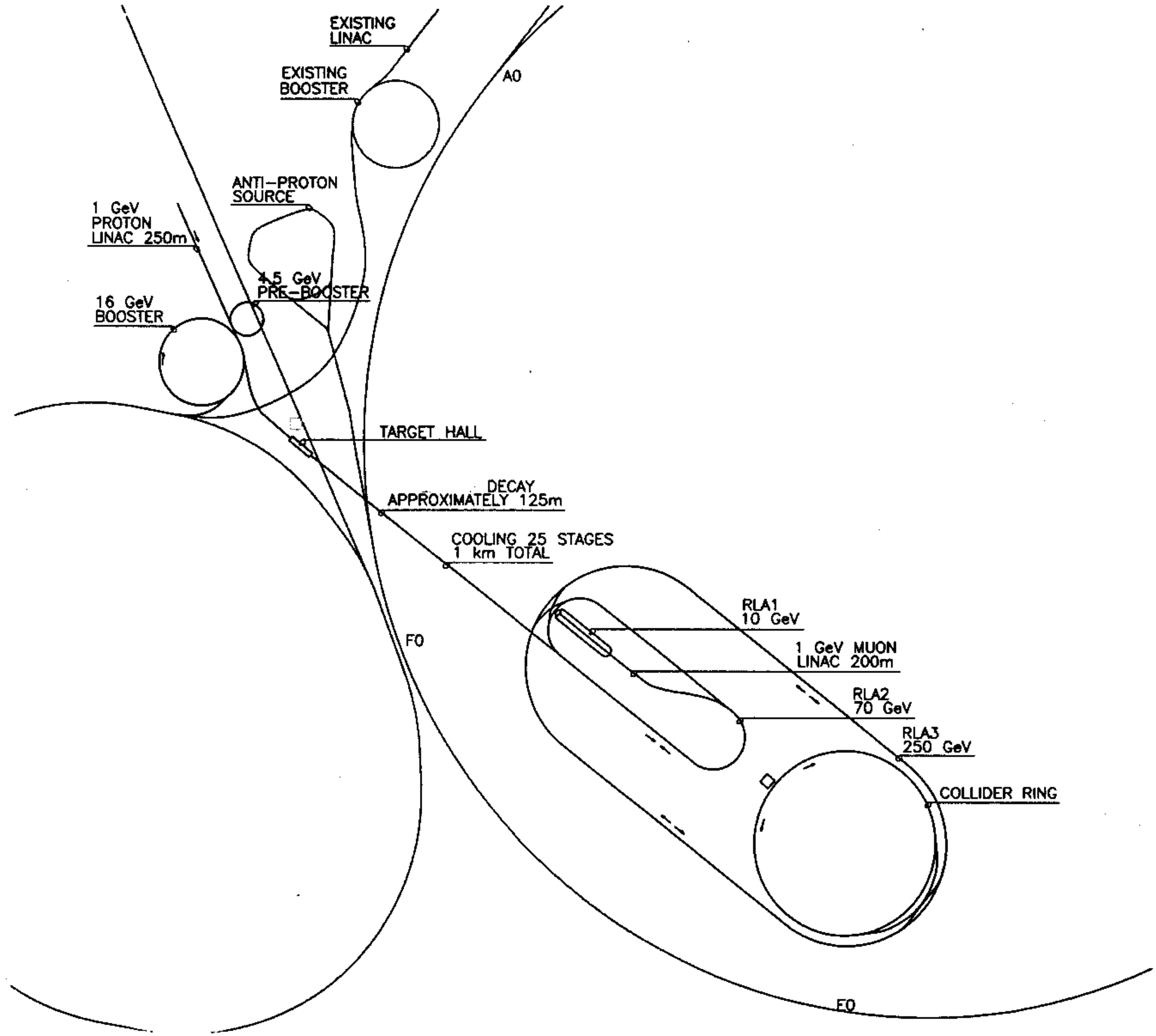

EXISTING LINAC
EXISTING BOOSTER
A0
ANTI-PROTON SOURCE
1 GeV PROTON LINAC 250m
4.5 GeV PRE-BOOSTER
16 GeV BOOSTER
TARGET HALL
DECAY APPROXIMATELY 125m
COOLING 25 STAGES 1 km TOTAL
F0
RLA1 10 GeV
1 GeV MUON LINAC 200m
RLA2 70 GeV
RLA3 250 GeV
COLLIDER RING
E0

DRAFT

Fermilab Muon Collider: A Feasibility Study

November 6, 1997

Options:	Narrow σ_p	Wide σ_p	Med-Energy	Top Factory	High-Energy
Beam Energy	50 GeV	50 GeV	100 GeV	175 GeV	250 GeV
σ_p/p	3×10^{-5}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}
γ_{beam}	473	473	946	1656	2366
$n_b(\mu)$/beam	1	1	2	2	2
Proton kin. energy	16 GeV	16 GeV	16 GeV	16 GeV	16 GeV
N_p/bunch on target	5×10^{13}	5×10^{13}	2.5×10^{13}	2.5×10^{13}	2.5×10^{13}
f_{rep}(Hz)	15	15	15	15	15
Proton power	3.85 MW	3.85 MW	3.85 MW	3.85 MW	3.85 MW
Target	Ga(liq)	Ga(liq)	Ga(liq)	Ga(liq)	Ga(liq)
λ_I	24 cm	24 cm	24 cm	24 cm	24 cm
ℓ_{targ}/λ_I	1.5	1.5	1.5	1.5	1.5
Target power	350 kW	350 kW	350 kW	350 kW	350 kW
B_{sol}(capture)	20 T	20 T	20 T	20 T	20 T
r_{sol}(inner)	7.5 cm	7.5 cm	7.5 cm	7.5 cm	7.5 cm
$p_{t,max}$(pion)	225 MeV/c	225 MeV/c	225 MeV/c	225 MeV/c	225 MeV/c
$\eta_{\pi p}$ (simul.)	0.65	0.65	0.65	0.65	0.65
$\eta_{\mu\pi}$ (simul.)	0.3	0.3	0.3	0.3	0.3
η_{cool} (goal)	0.5	0.5	0.5	0.5	0.5
η_{accel} (simul.)	0.85	0.85	0.85	0.85	0.85
$\eta_{transfer}$ (est.)	0.77	0.77	0.77	0.74	0.74
N_μ/N_p	0.064	0.064	0.064	0.061	0.061
N_μ/bunch	3.2×10^{12}	3.2×10^{12}	1.6×10^{12}	1.52×10^{12}	1.52×10^{12}
6-d $\epsilon^{cool}_{n,rms}$ (eV-m^3)	0.0125	0.0125	0.0125	0.0125	0.0125
Emitt. Dilution	1.55	1.55	1.55	1.8	1.8
6-d $\epsilon^{coll}_{n,rms}$ (eV-m^3)	0.0194	0.0194	0.0194	0.0224	0.0224
$\epsilon_{n,rms}$(mm-mrad)	315	90	73	64	57
$\Delta\nu_{bb}$(< 0.05 req.)	0.011	0.039	0.024	0.026	0.029
Collider Circ.	380 m	380 m	700 m	864 m	1000 m
B_{avg}	2.76 T	2.76 T	3 T	4.25 T	5.24 T
Turns/lifetime	820	820	891	1263	1559
f_{rev}(Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3×10^5
β^*	13 cm	4 cm	3 cm	2.6 cm	2.3 cm
σ_z	13 cm	4 cm	3 cm	2.6 cm	2.3 cm
η_A(hour-glass)	0.76	0.76	0.76	0.76	0.76
σ_r^*	294 μm	87 μm	48 μm	32 μm	24 μm
σ_θ at IP	2.3 mrad	2.2 mrad	1.6 mrad	1.2 mrad	1 mrad
ℓ^* to IP	4.5 m	4.5 m	4.5 m	4.75 m	5 m
σ_r at 1st quad	10 mm	9.8 mm	7.2 mm	5.8 mm	5 mm
L_{peak}(cm^{-2} s^{-1})	5.6×10^{32}	6.4×10^{33}	5.6×10^{33}	9.6×10^{33}	1.5×10^{34}
L_{avg}(cm^{-2} s^{-1})	4.4×10^{30}	5.0×10^{31}	8.8×10^{31}	2.6×10^{32}	5.9×10^{32}

Table 1: Draft parameter list for 100, 200, 350 and 500 GeV CM muon colliders.

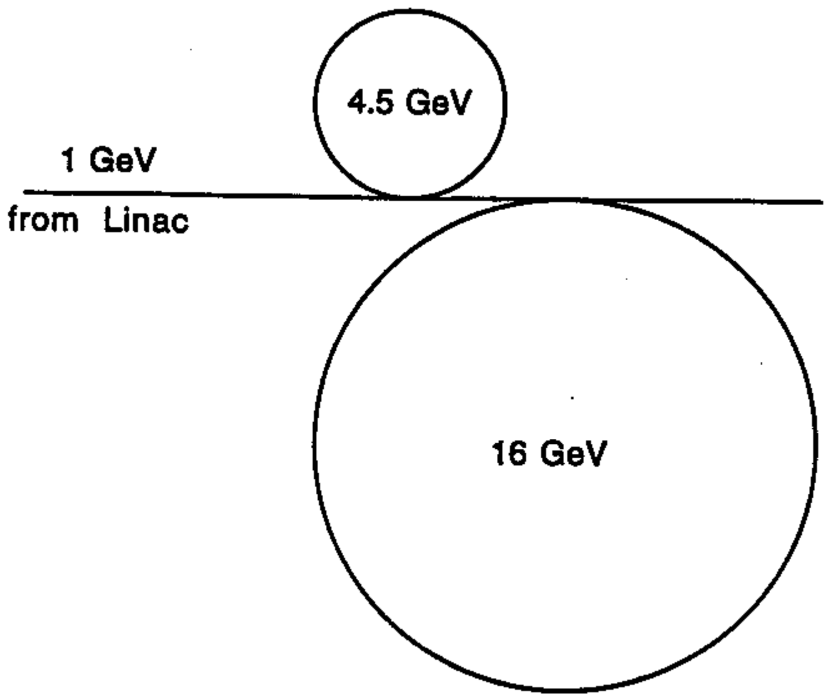


Fig. 1. Proton Source Configuration

Table II.1: Parameter list for a Proton Source capable of supporting muon production requirements for a First Muon Collider

	Linac	Pre-Booster	Booster	
Injection Energy (Kinetic)	---	1.0	4.5	GeV
Extraction Energy (Kinetic)	1.0	4.5	16.0	GeV
Circumference	---	180.65	474.20	m
Current	65	---	---	mA
Pulse Length	328	---	---	μsec
Protons/bunch	---	5×10^{13}	5×10^{13}	
Bunches	---	2	2	
Total Protons	1×10^{14}	1×10^{14}	1×10^{14}	
Repetition rate	15	15	15	Hz
Transverse Beam Emittance (95%, normalized)	7π	200π	240π	mm-mr
Bunching Factor	---	0.25	0.25×2/21	
Space-charge tune shift (injection)	---	0.39	0.39	
Longitudinal Emittance (95%, per bunch)	---	1.8	2.0	eV-sec
RF Voltage		0.148	1.23	MV
RF Frequency (injection)	805	2.90	13.08	MHz
RF Frequency (extraction)	805	3.27	13.26	MHz
Harmonic number	---	2	21	
Transition Gamma	---	7	25	
Synchrotron Frequency (at extraction)	---	473	378	Hz
Bunch Length (injection, 95% half-width))		83	21	nsec
Bunch length (extraction, 95% half-width)		21	2.3	nsec
Momentum spread (Injection , 95% half-width)	---	0.1	0.5	%
Momentum spread (Extraction , 95% half-width)	0.1	0.5	1.2	%

The transfer energy of 4.5 GeV between the two rings is chosen to equalize the space-charge tune shift in the two rings. In the tune shift formula, there are two factors of γ. Roughly speaking, one factor of γ is used to make up for the larger circumference of the second ring; the other factor of γ is used to compensate for the shorter bunch length resulting from the bunch rotation. Both effects reduce the bunching factor in the second ring.

The design of the required 1-GeV linac is discussed elsewhere; here only a brief overview is given. H^- injection is used. It is assumed that the injected beam will be chopped and injected

Assorted Comments on the 16 GeV Strawman Design:

- 16 GeV is max. energy if circumference is desired to be equal to 8 GeV Booster (475 m) and max. dipole field is 1.3 T. This circumference is an operational convenience for pbar collection in Debuncher/Accum. and feeding MI.
- Going to higher energy probably requires a third ring, say up to 25 GeV, which would get one above γ_t in MI. 15 Hz rep. rate hard to maintain.
- Collected pions/proton in solenoid channel roughly goes like $\sqrt{KE_p}$, so this is not a strong reason to increase energy. Lower proton energies will require more N_p/bunch and $\Delta p/p$ will be higher at extraction when bunches are short (1 nsec).
- To reduce losses at injection into Pre-booster, the 1 GeV linac beam should be chopped.
- Lattice designs should include special absorber components to localize beam loss as is done in neutron spallation source rings.
- Flexible momentum compaction (FMC) lattice with $\gamma < \gamma_t$ is preferred to reduce chance of microwave instability. Tracking simulations needed to determine sensitivity of beam dynamics to errors in FMC.

RF System Design for Proton Synchrotrons
- not well addressed in Summer Study
- good progress made during workshop on high-level design concept.

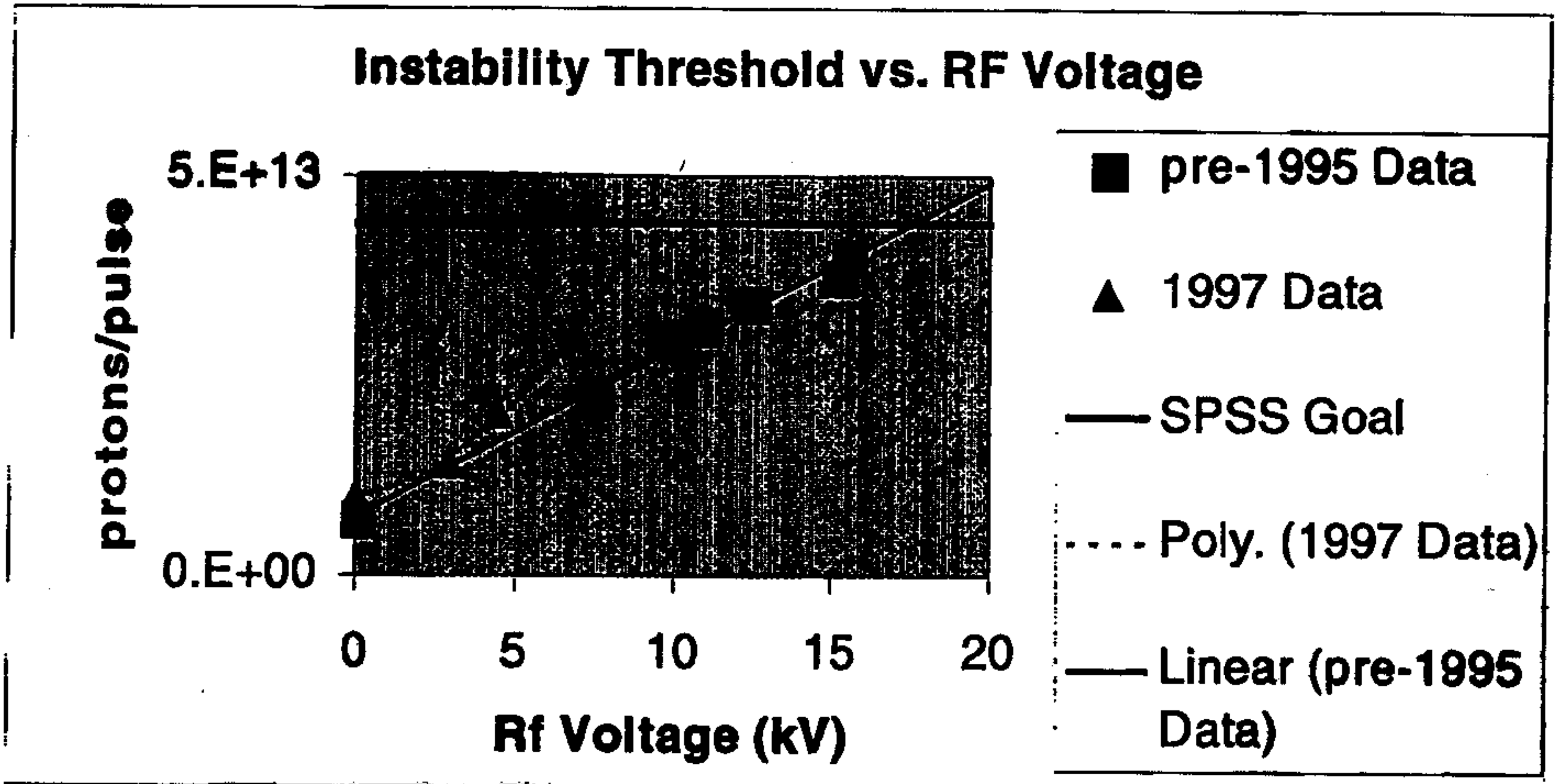
At these kinetic energies, bunch populations of 5×10^{13} protons produce space-charge potential well distortion of rf bucket and large transient beam loading ($V = Q_b / C_{cav}$).

Fixes for Potential-Well Distortion:
- increase rf voltage
* - add passive inductor to cancel capacitive space-charge induced voltage.
- raise $\beta \gamma^2$

Fixes for Transient Beam Loading:
* - fast feedback and/or feedforward
- lower harmonic number of ring
- lower R/Q of cavity (increase gap capacitance)

Note: Experiments done independently at KEK and Los Alamos PSR (FNAL-LANL) this summer suggest inductors do cancel space-charge forces very effectively. At PSR, rf voltage needed for beam stability could be reduced by 30% in a non-optimized, simple inductor array ($2000).

Instability Threshold Improvement from 1997 PSR Beam Development



- 1997 Results are Preliminary (Obtained 8/4/97), Include Space Charge Compensating Inductor plus Optimization of all Important PSR Parameters

Figure 3 shows the deformation of the rf wave due to the parabolic line charge bunch. The circles represent the effective rf wave V_e from which the final bucket area is calculated. The effective synchronous phase angle φ_e is 28 deg and the voltage V_e is 64.8 kV, slightly less than the originally required voltage. The effective rf voltage wave, even for this relatively long bunch, appears to be sufficiently close to the the actual focusing voltage so that bucket area calculations based on the sinusiod can be used.

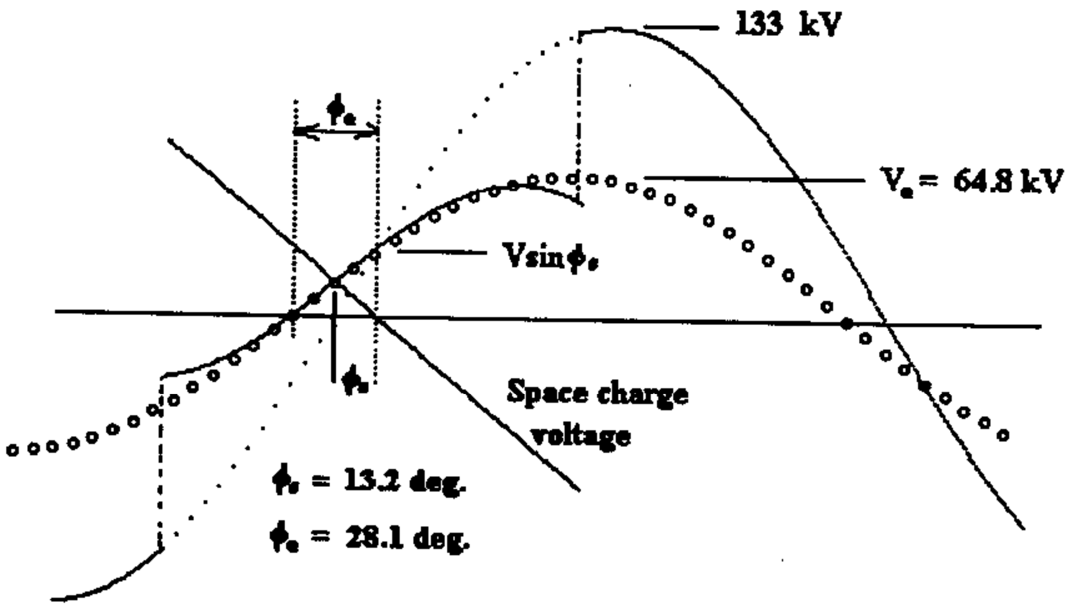
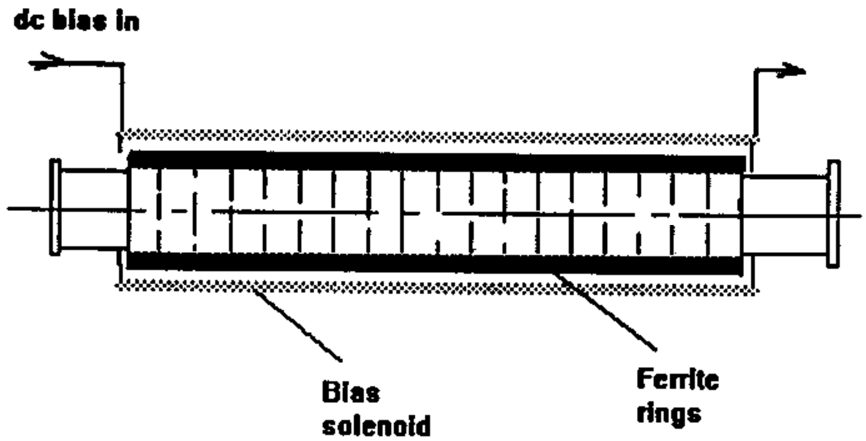


Figure 3. The solid curve is a 133 kV rf wave with longitudinal focusing reduced by space charge effects. The circled curve represents a 64.8 kV sinusoid used to calculate the effective bucket area produced by the solid curve over the bunch length.

4.-8

J. Griffin



The space charge induced voltage per turn seen by a particle within a bunch is proportional to the spacial (or time) derivative of the bunch line charge distribution λ(s) or λ(t).

$$V_s \approx -e\beta c\bar{R}\frac{\partial\lambda(s)}{\partial s}\left[\frac{g_o Z_o}{2\beta\gamma^2} - \Omega_o L\right]$$

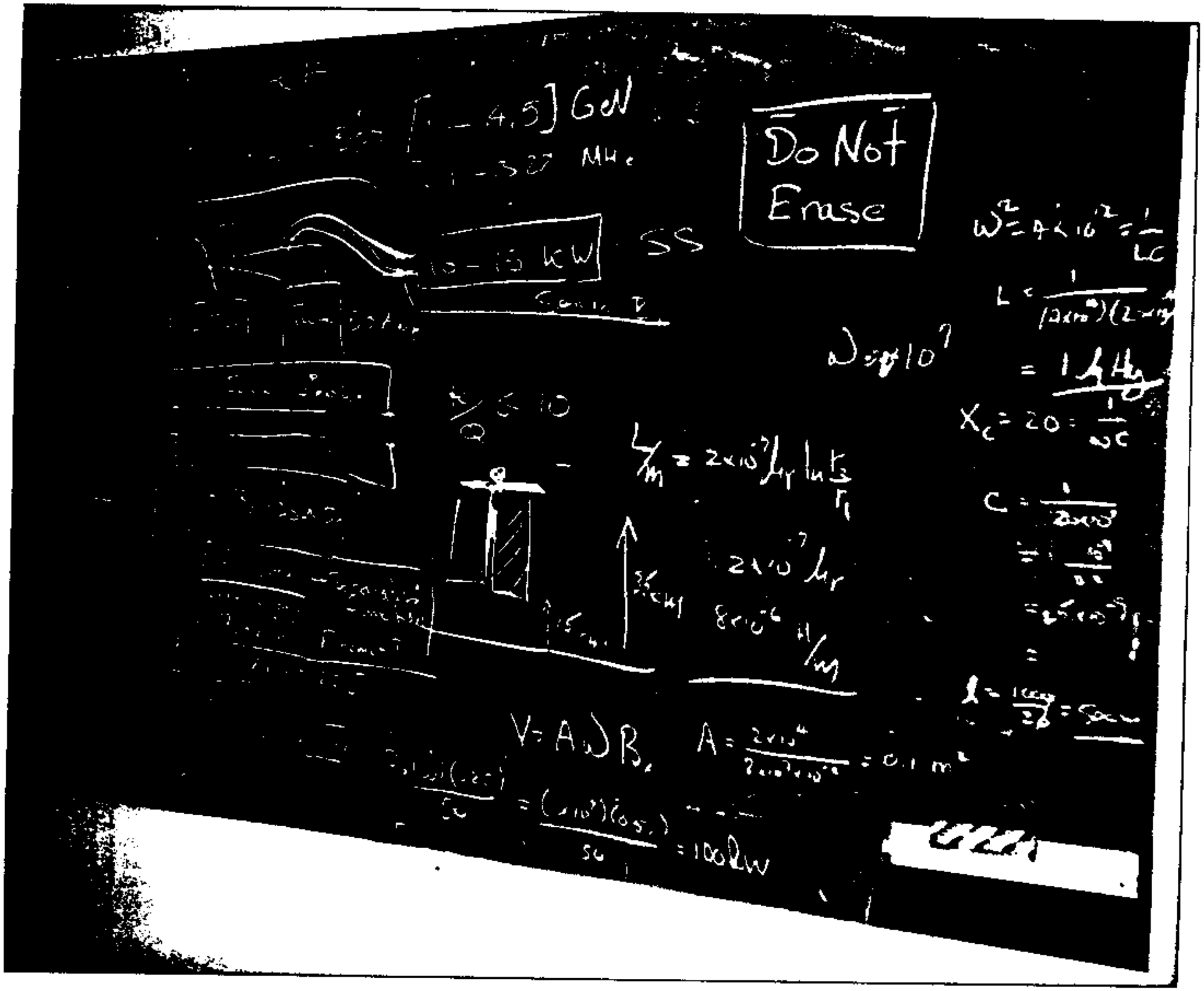
or

$$V_s \approx 2I_{dc}\frac{d}{dt}\sum_{m=1}^{\infty}F_n(m\omega_{rf})\cos(m\omega_{rf}t)\left[\frac{g_o Z_o}{2\beta\gamma^2\Omega_o} - L(\omega)\right] + I_b(\omega)\,\Re Z_{w}.$$

$\Omega_o L$ is the inductive reactance of the ring at the rotation frequency.

$F_n(m\omega)$ is the Fourier transform of the line charge distribution normalized to unity at $\omega = 0$.

$L(\omega)$ implies that the inductance introduced by ferrite for passive space charge compensation will probably not be constant over the frequency range of the beam Fourier components needed for complete compensation.



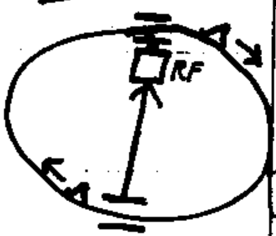
Real Work at a Workshop!

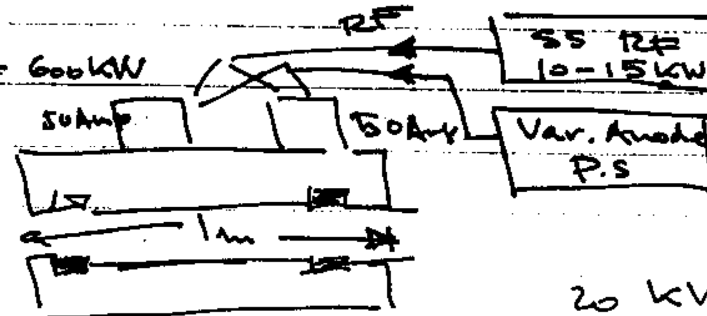
RF System Design

M. Popovic
Q. Kerns
D. Wildman
J. Griffin
I. Kourbanis
A. Moretti

Summary. (M. Popovic) 1

RF System for 4.5 GeV p ring





in Gallery.

[2.9 – 3.27 MHz] Broad Band Cavity 20 kV RF/gap

80 Amp Beam Peak Power

Tube can bring 4 times

$R/Q \sim 20$ $R/Q \sim X_c \sim \frac{1}{\omega C}$

at 2.9 MHz $\Longrightarrow$ $C = 2.75 \times 10^{-9}$

$\omega L = 20$

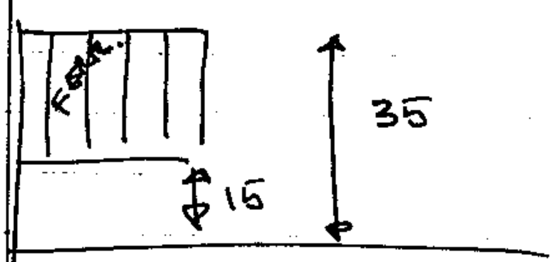
$L = 1.09 \times 10^{-6}$

Store energy.

$\overline{W} = \frac{1}{4} C V^2 = \frac{2.75}{4} \times 10^{-9} \times 4 \times 10^{8} = 0.275$ Joul.

$L/m = 2 \times 10^{-7} \mu_r \ln \frac{r_2}{r_1}$ $\Rightarrow$ $L/m = 2 \times 10^{-7} \mu_r\ 8.4 \times 10^{-}$

$L/m = 1.69 \times 10^{-7} \mu_r$



for $\mu_r = 40$

$L/m = 6.8 \times 10^{-6}$ H/m

Power Loss in ferrite (cavity)

$P_{loss} = 100$ kW

D. Wildman 7/31/97

New Booster RF System
(16 GeV ring)

The new Booster RF system will have two h=21 cavities in each of the 14 short straight sections. Each cavity will be a double gap, slow wave structure consisting of two quarter wave resonators. The cavities will be use ferrite tuners to cover the 13.077 MHz to 13.256 MHz frequency range and provide detuning to compensate for the steady state beam loading. To minimize the transient beam loading, the R/Q of the cavity will be lowered to 20 . The Q will also be lowered to 200 giving a cavity shunt impedance of 4 k. Using these design values, each cavity will produce a peak accelerating RF voltage (Vrf) of 50 kV with 312 kW of RF input.

At the maximum acceleration rate and design current, with no fast feedback, the power amplifier must deliver a total output power of approximately 620kW with half of this going directly to the beam and the other half being dissipated in the cavity plus power amplifier. Two different tetrodes are possible candidates for the final stage of the power amplifier. Both the Eimac 8973 and the Thomson TH518 have rated anode dissipations of 1MW and are capable of delivering more than 1MW of output power. These tetrodes also have sufficient current output to provide fast transient beam loading compensation to help cancel the 13kV/bunch per cavity induced voltage for a single passage of a 5E13 proton bunch. The above design is conservative in that it does not rely on any fast feedback systems to stabilize the beam.

The total cost of the RF system is driven by the requirement of providing a peak power of 8.6MW to the beam. The entire cost of the RF system should be in the range of $25M -$30M.

ESME Longitudinal Beam Simulations (Kourbanis + Qian)

- 5×10^{13} p / bunch simulated from injection (1 GeV) to extraction (16 GeV) with space-charge forces, no inductors for compensation.

- Demonstrated $\sigma_t = 1.3$ nsec, $\Delta p/p = \pm 1.2\%$ at 16 GeV extraction. Longitudinal emittance grows to 2.5 eV sec (from < 1 eVsec) due apparently to space-charge induced mismatch.

- Some initial simulations begun that include inductors for space-charge compensation. Emittance growth is greatly suppressed, and beam is maintained in the linear part of the rf bucket.

- If inductor is sufficiently broad-band so it remains effective as bunch shortens, bunches with 5×10^{13} protons could be reduced to less than 1 nsec rms. Yttrium-garnate ferrite, for example, is useful to GHz frequencies.

- Need to do more complete ESME simulations including more realistic frequency-dependent cavity properties and explore feed forward / feedback scenarios.

PROTON DRIVER SIMULATIONS WITH ESME

IOANIS KOURBANIS

11/7/97

A set of ESME simulations was performed for the two proton driver rings specifed in the Proton Source summer study report. A single proton bunch containing 5×10^{13} particles was tracked through the Pre-booster and then through the Booster ring. Only space charge was considered in this set of simulations.

A. H=2 PRE-BOOSTER RING

The Pre-Booster ring is a 15 Hz synchrotron with circumference 180.6 m injection momentum 1.938 GeV/c and extraction momentum 5.356 GeV/c. The harmonic number is 2 the gamma-t is 7 and the total beam intensity is 1×10^{14} particles.

In the simulations we assumed a multiturn injection (300 turns or) of a chopped linac beam ($\pm120^{\circ}$) with a 1.5 MeV momentum spread (FW).

In the simulation the space charge was turned on linearly from zero to the full value corresponding to 5×10^{13} ppb during the 300 turn injection. The voltage at injection was ramped linearly from 5 - 25 KV to compensate for the space charge.

The high voltage curve used for the momentum ramp took into account the potential well distortion due to space charge and was calculated using the iterative process developed by J. E. Griffin.

The bucket area assumed was 3 eV-sec (Total bucket Area 6 eV-sec). The beam emittance from an initial 0.5 eV-sec grows to 1.8 eV-sec at extraction. Most of the emittance blowup occurs during the 300 turn injection and capture phase.

The voltage at extraction was kept at about 90 KV in order to achieve a distribution narrow enough to fit into the buckets of the booster ring. The final bunch length is 42 nsec (95% FW) and the momentum spread is 44 MeV (95% FW).

B. H=21 BOOSTER RING

The Booster Ring is a 15 Hz synchrotron which operates from injection momenta 5.356 GeV/c to extraction momentum of 16.938 GeV/c.
The circumference of the Ring is 474.2 m . We assume a gamma-t of 25.
The rf system of the Booster Rings will operate at harmonic number 21 with two buckets occupied. The voltage at injection is chosen to be 580 KV and the voltage curve required to generate two 4 eV-sec buckets is calculated as before.
In this case there is no much difference between no space charge and space charge because of the higher energies.
To reduce the final bunch length a bunch rotation was performed at the end of the ramp. The rf voltage was reduced from 800-200 KV, the bunch was left to rotate for a quarter of a syn. period and then the voltage was raised again to 800 KV. After a quarter of aperiod at 800 KV the bunch length was reduced a factor of 2 as expected.
The longitudinal emittance grows from about 1.8 eV-sec to about 2.5 eV-sec and a 3% particle loss was observed.
The final bunch length is 5.2 nsec (95% FW) and the momentum spread is 406 MeV (95% FW).

PREBOOSTER RING (3 MHz RF) $\gamma_t = 7$ ③

INJECTION

FIRST TURN 1 GeV KE

chopped linac beam

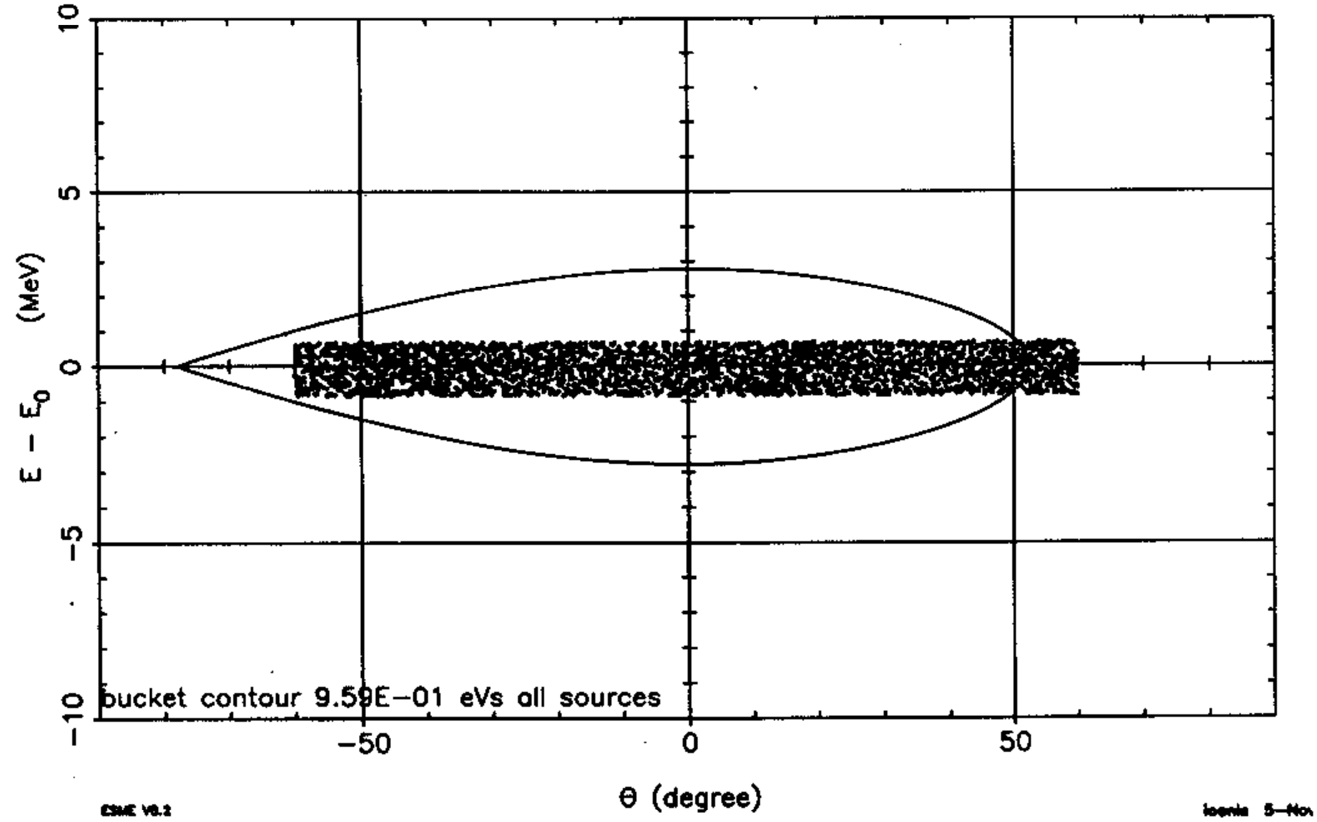
1 BUNCH WITH FRAC=2

200 nsec on
100 nsec off

TURN 0 0.000E+00 sec

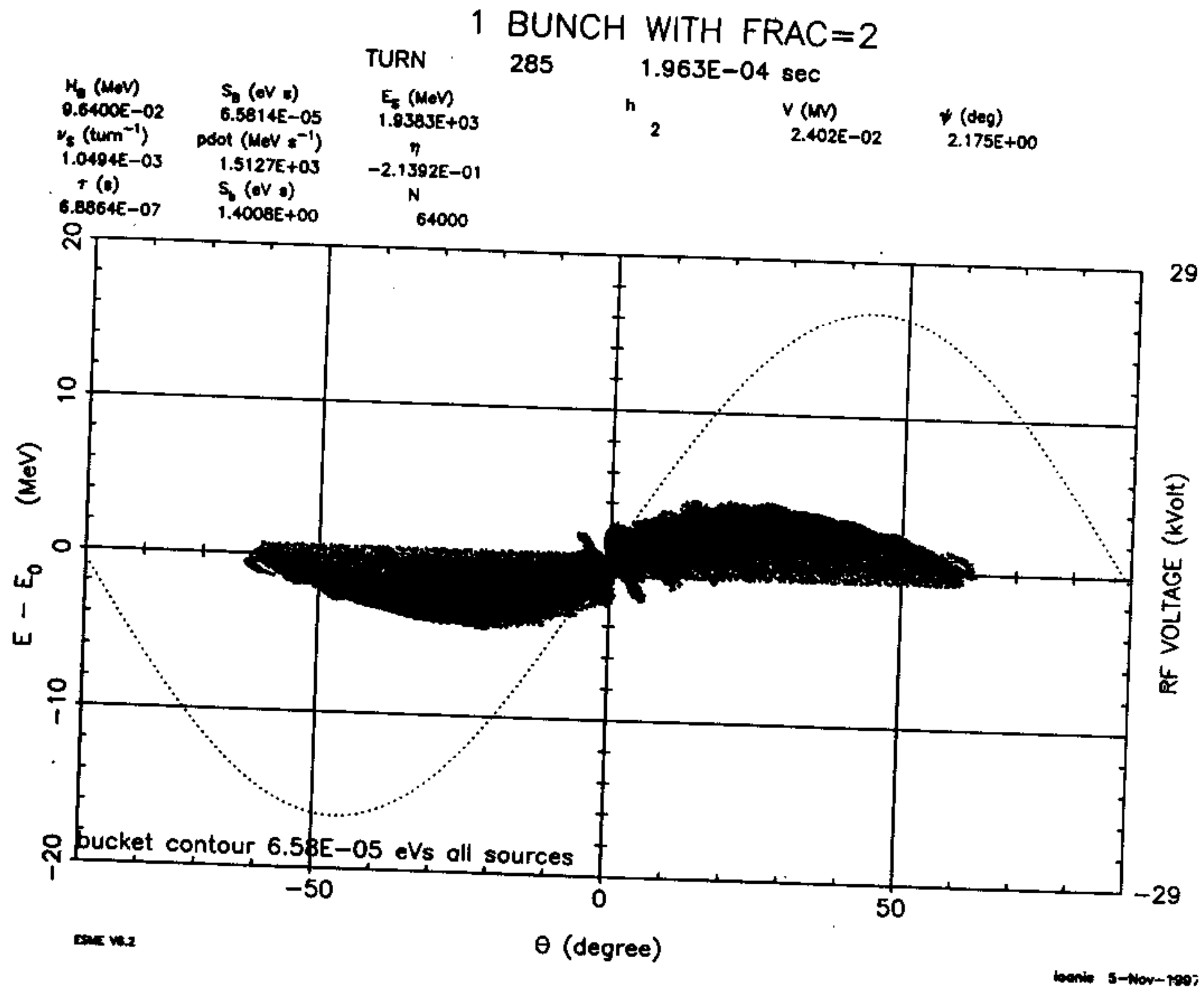
H_B (MeV)	S_B (eV s)	E_s (MeV)	h	V (MV)	ψ (deg)
2.7857E+00	9.5853E-01	1.9383E+03	2	5.000E-03	-1.166E+01
ν_s (turn^{-1})	pdot (MeV s^{-1})	η			
4.7398E-04	-1.6775E+03	-2.1391E-01			
τ (s)	S_b (eV s)	N			
6.8863E-07	5.4788E-01	4000			

±0.75 MeV



PRE BOOSTER RING

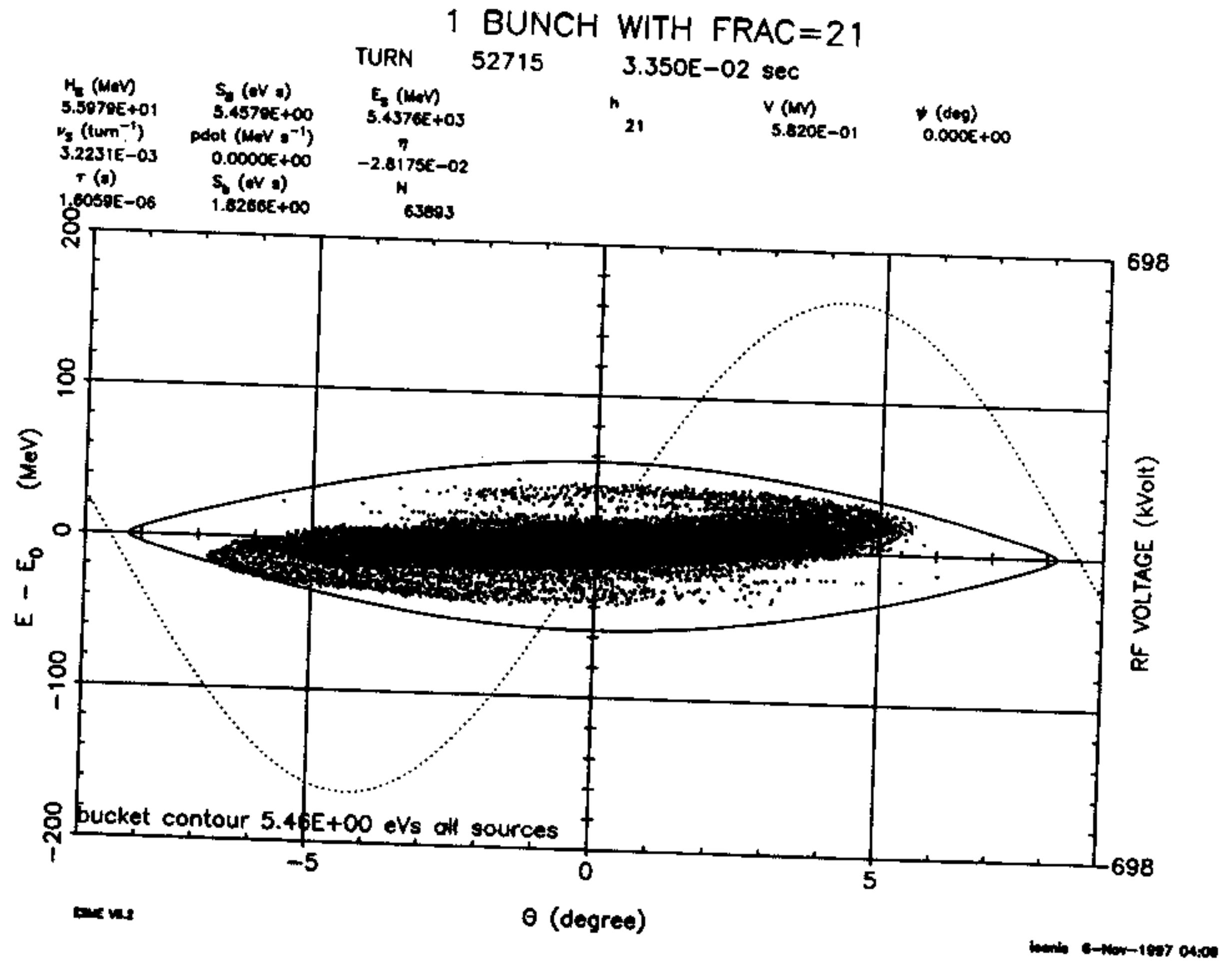
END OF INJECTION 4.5 GeV

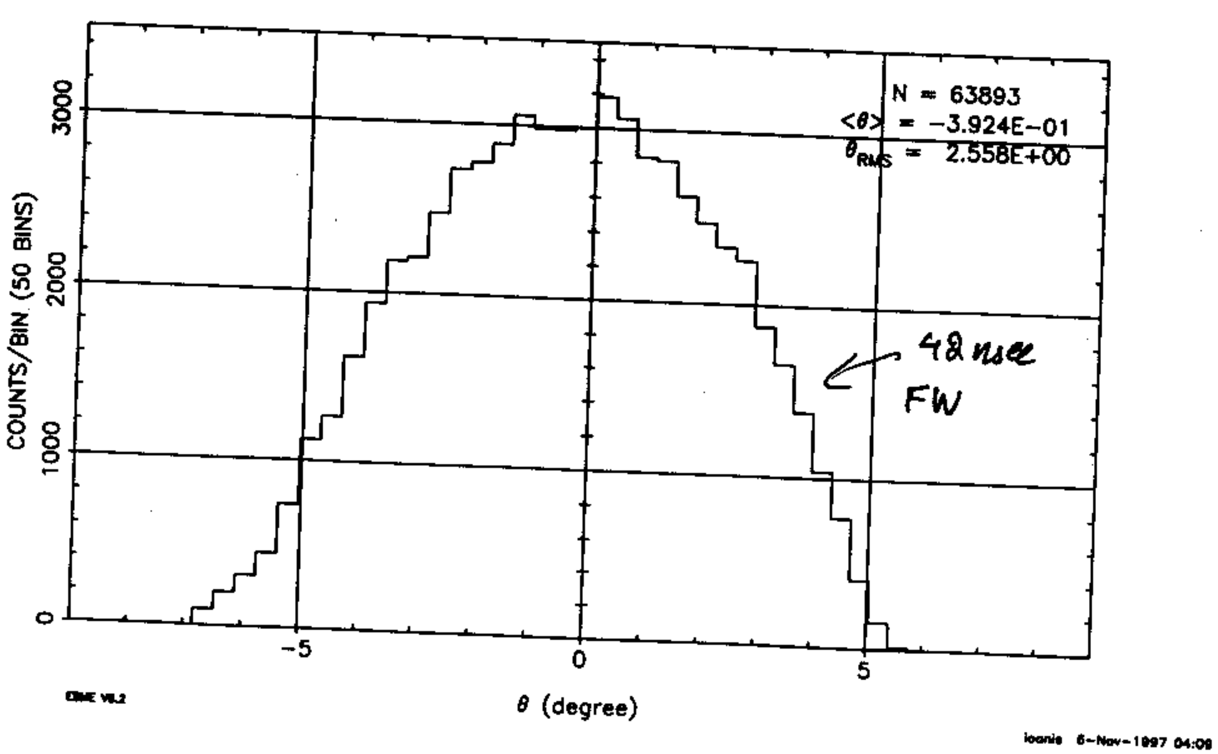


BOOSTER RING (13 MHz) $\gamma_t = 25$

INJECTION

(5)





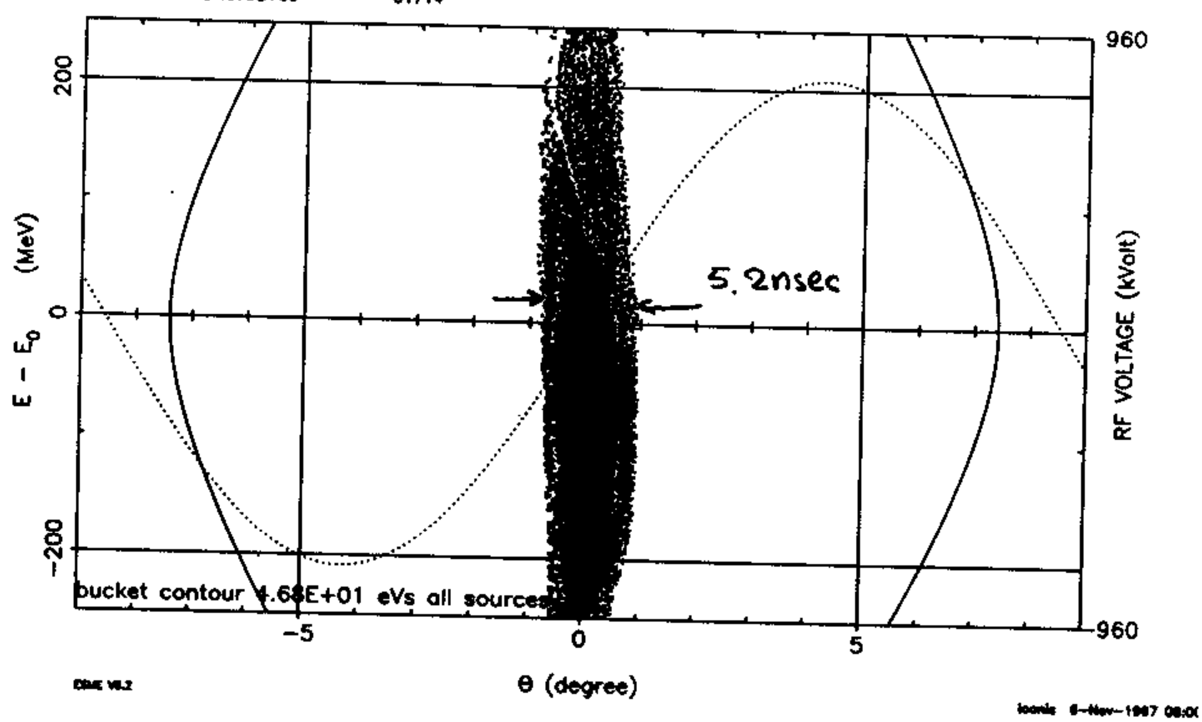
BOOSTER RING EXTRACTION (AFTER BUNCH ROTATION)

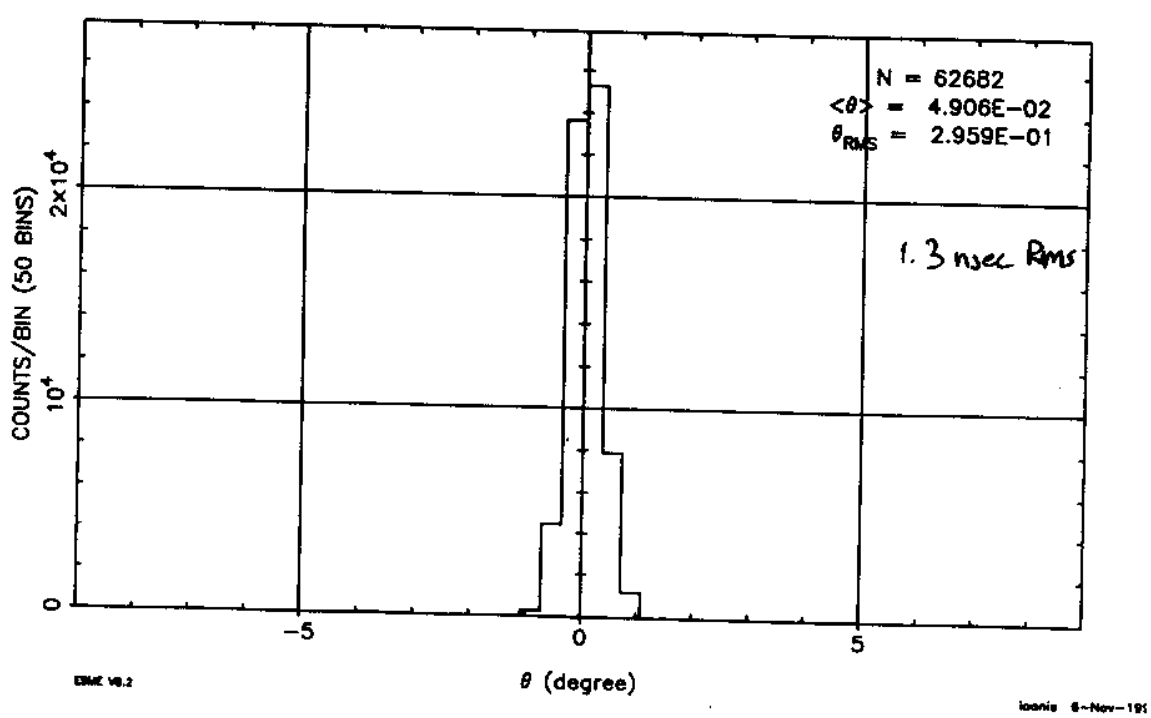
16 GeV

1 BUNCH WITH FRAC=21

TURN 74531 6.820E-02 sec

H_B (MeV)	S_B (eV s)	E_s (MeV)	h	V (MV)	ϕ (deg)
5.1361E+02	4.6805E+01	1.6938E+04	21	6.000E-01	0.000E+00
ν_s (turn^{-1})	pdot (MeV s^{-1})	η			
4.8222E-04	0.0000E+00	-1.4685E-03			
τ (s)	S_b (eV s)	N			
1.5842E-06	2.4379E+00	61714			





BOOSTER RING

EXTRACTION

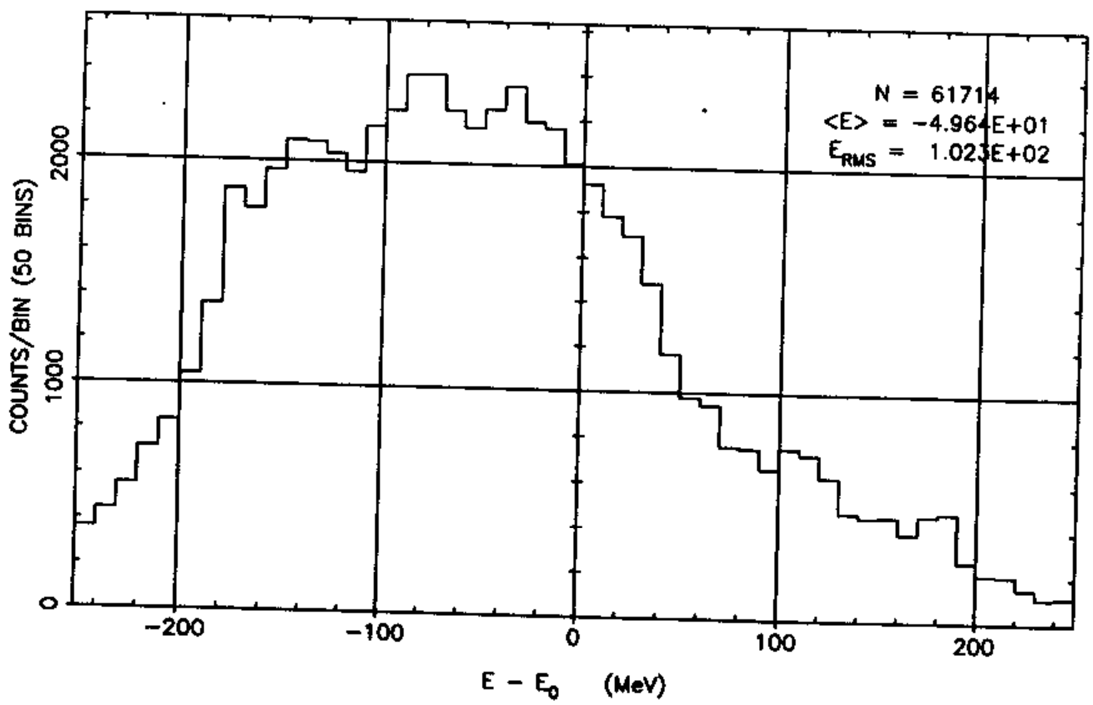
AFTER BUNCH ROTATION

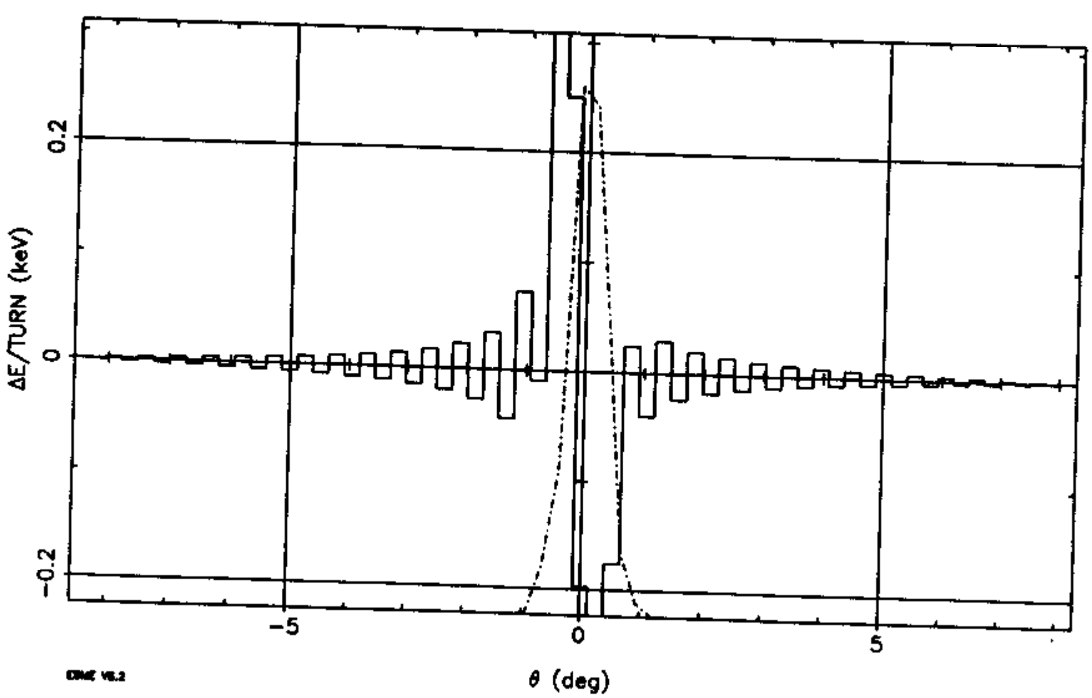
1 BUNCH WITH FRAC=21

TURN 74531

6.820E-02 SEC

$\frac{\Delta p}{p} = \pm 1.2\%$

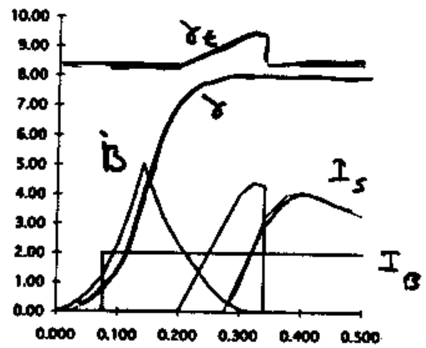




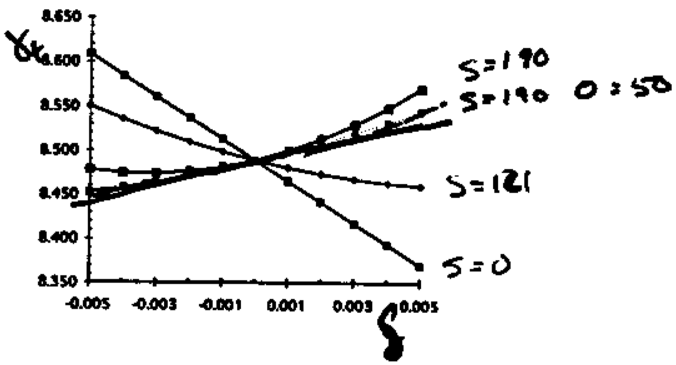
J. Norem talk

AGS Bunching Expt. (E932)

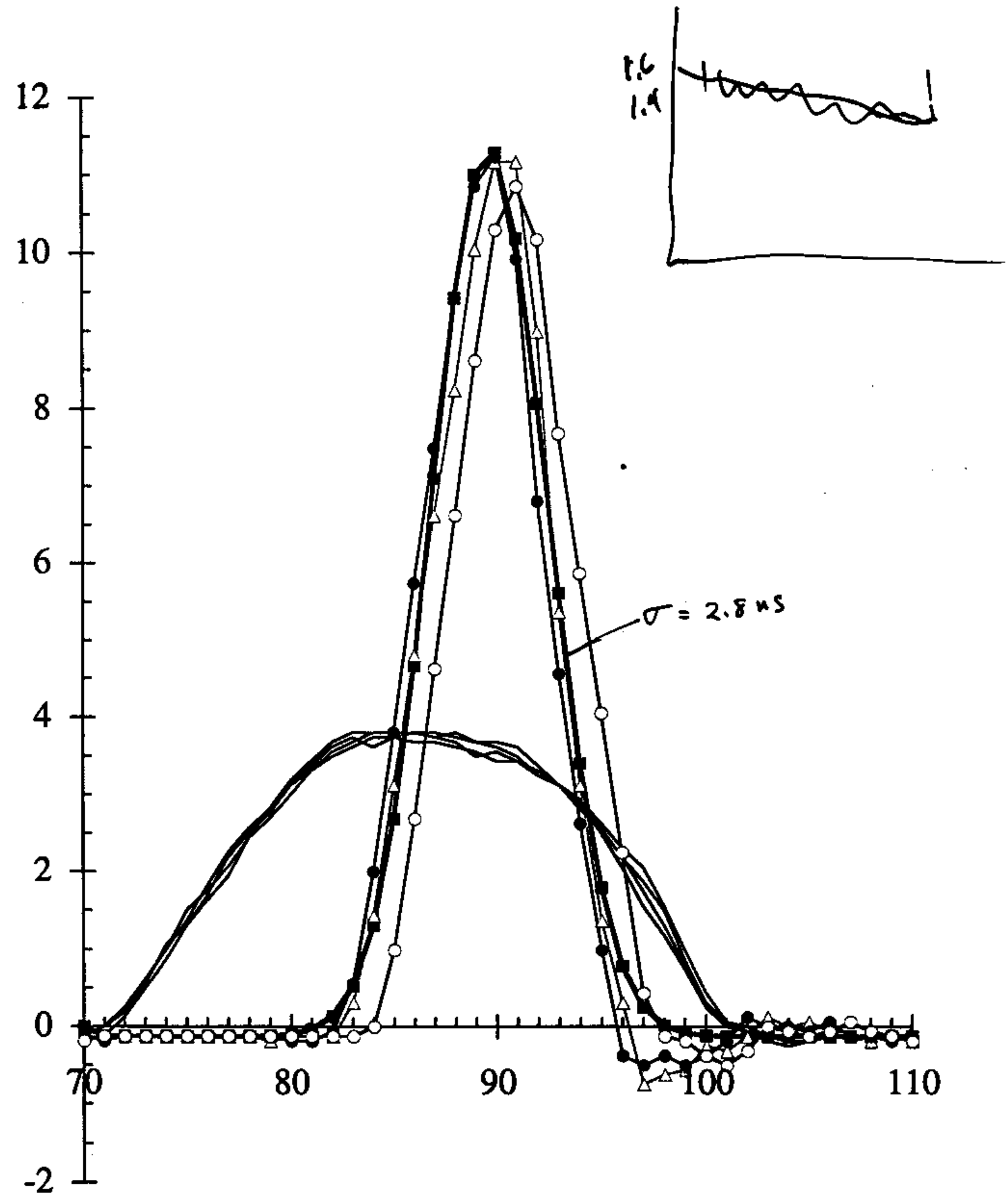
t	Bdot	3.10 gamma	tr_jump	gamma_t	sextupole	beam
0.000	0.00	0.00	0.00	8.40		
0.025	0.20	0.06	0.00	8.40		
0.050	0.60	0.26	0.00	8.40		
0.075	1.20	0.65	0.00	8.40		0
0.075	1.20	0.65	0.00	8.40		2
0.100	2.30	1.39	0.00	8.40		2
0.120	3.50	2.52	0.00	8.40		2
0.140	5.00	4.13	0.00	8.40		2
0.175	3.20	6.29	0.00	8.40		2
0.200	2.30	7.03	0.00	8.40		2
0.225	1.60	7.54	1.00	8.65		2
0.250	0.90	7.83	2.00	8.90		2
0.275	0.40	7.96	3.00	9.15	0.00	2
0.300	0.10	8.00	4.00	9.40	1.20	2
0.322	0.00	8.00	4.40	9.50	2.20	2
0.340	0.00	8.00	4.30	9.48	3.20	2
0.340	0.00	8.00	0.00	8.40	3.20	2
0.375	0.00	8.00	0.00	8.40	4.00	2
0.400	0.00	8.00	0.00	8.40	4.10	2
0.500	0.00	8.00	0.00	8.40	3.30	2



dp/p	beam	natural	s=121	1=190	O=50
-0.005	8.447	8.608	8.550	8.478	8.453
-0.004	8.455	8.584	8.535	8.475	8.459
-0.003	8.464	8.560	8.522	8.474	8.465
-0.002	8.472	8.537	8.510	8.476	8.472
-0.001	8.481	8.513	8.499	8.481	8.480
0.000	8.489	8.489	8.489	8.489	8.489
0.001	8.498	8.465	8.481	8.500	8.499
0.002	8.506	8.441	8.474	8.513	8.509
0.003	8.515	8.418	8.468	8.529	8.520
0.004	8.523	8.394	8.463	8.548	8.532
0.005	8.531	8.370	8.460	8.570	8.545



E93209 Chart 1



Instabilities and Space-Charge Effects in Proton Driver

K.Y. Ng

(November 8, 1997)

Injection	First Ring	Second Ring
Kinetic Energy (GeV)	1.0	4.5
Gamma	2.0658	5.7960
Beta	0.8750	0.9850
Cycle rate (Hz)	15	15
Circumference, C (m)	180.649	474.203
Rf harmonic, h	2	21
Number of bunches M	2	2
No. per bunch, N_b	5.0×10^{13}	5.0×10^{13}
Bucket Bunching factor, B	0.25	0.25
Transition γ_t	7	25
95% normalized emittance, ϵ_{N95} (π-m)	200×10^{-6}	240×10^{-6}
Laslett tune shift	−0.393	−0.388
Revolution frequency f_0 (MHz)	1.452	0.623
Average current per bunch I_b (amp)	11.63	4.99
Peak current (amp)	93.06	419.04
Bunch area, A (eV-s)	1.0	1.0
Half bunch length $\hat{\tau}$ (ns)	64.56	14.34
$\hat{\ell}$ (m)	16.94	4.24
Half momentum spread $\hat{\delta}$	3.222×10^{-3}	4.208×10^{-3}
Average beta function $\langle\beta\rangle$ (m)	25	25
Average dispersion $\langle D\rangle$ (m)	1.8	1.8
Average beam radius a (cm)	5.29	3.33
Beam pipe radius b (cm)	8.0	5.0
Sp Ch imp. $\left.\frac{Z_0^{\parallel}}{n}\right\|_{\text{spch}} = i\frac{Z_0}{2\gamma^2\beta}\left(1+2\ln\frac{b}{a}\right)$ (Ohm)	$i92.1$	$i10.3$
Keil Schnell: $\left\|\frac{Z_0^{\parallel}}{n}\right\| = F_{\parallel}\frac{E\|\eta\|}{e\beta^2 I_{\text{pk}}}\left(\frac{\Delta E}{E}\right)^2_{\text{FWHM}}$ (Ohm)	75.3	12.6

VI CONCLUSION

- Space charge is the main factor affecting the stability be the beams.
- The rings appear to be safe from microwave instabilities, both longitudinal and transverse, especially because they are below transition.

  However, near extraction, both rings are too close to transition, $|\eta|$'s become too small, and may not be enough to damp the instabilities. Hopefully, these moments are short and blowup will be small.

  Can also raise γ_t's during rampings and lower them when bunch-shortening rotations are required near extraction. Use FMC lattices.
- Space-charge distortion of rf focusing force is large for first ring but not for second ring.

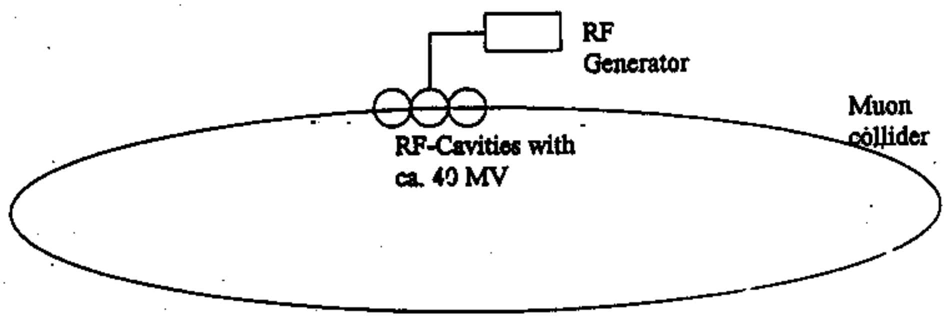
  To minimize rf system and avoid bunch-area increase due to space-charge mismatch bucket, ferrite compensation is recommended for the first ring.
- The real resistive loss due to ferrite has been computed using a self-consistent model.

R. Rossmanith
Workshop on muon colliders, Fermilab, Nov. 97

ENERGY MEASUREMENT WITH POLARIZED MUONS

(First thoughts)

a.) Horizontal or vertical spin.



A modest RF system sharpens the resonance to 10^{-6} in the same way the cavities in LEP sharpen the resonance by at least a factor of 10 by introducing energy (synchrotron) oscillations

b.) Other way: go back to microtron. Momentum compaction factor of microtron is 1:

$$\frac{\Delta s}{s} = \frac{\Delta \gamma}{\gamma}$$

example 1 km circumference: 10^{-3} is 1 m

Is in principle possible, but reduces luminosity: bunch length becomes too long.

In principle possible, but luminosity is too low

All statements are true for ~~longitudinal~~ horizontal and ~~transverse~~ vertical spin

R&D Recommendations

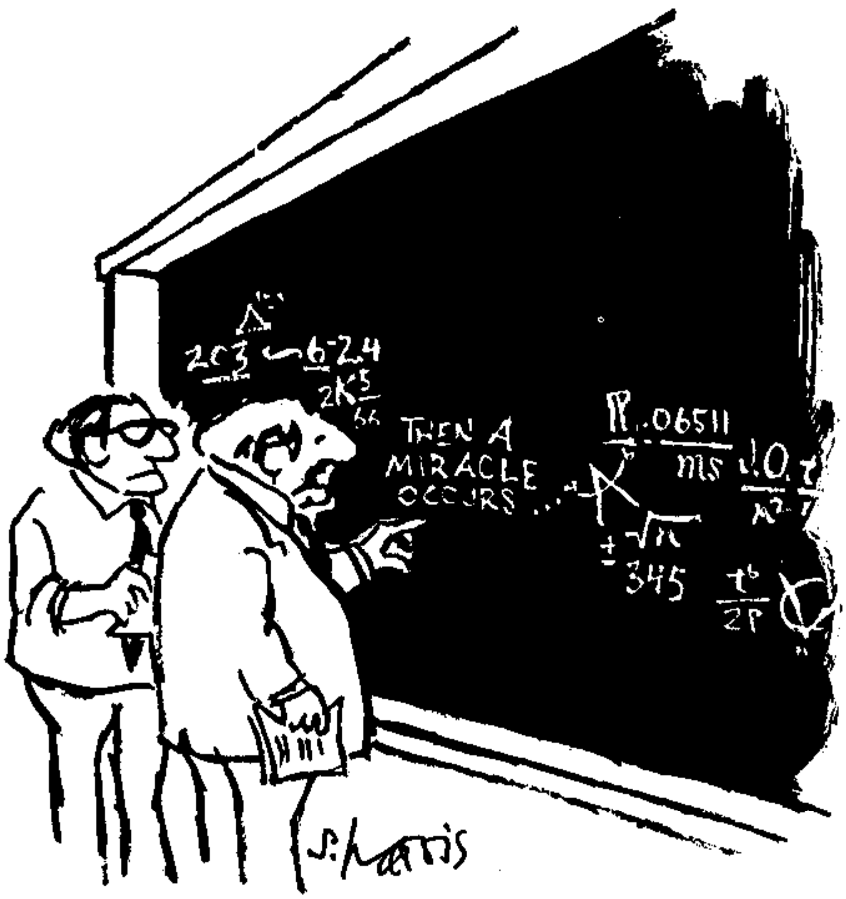
1. Further experimental investigation of inductive inserts at PSR or AGS. KEK intends adding more inductor to PS main ring this year.

2. Continue proton bunching experiments to achieve $\sigma_t \sim 1$ nsec (AGS ?).

3. Start synchrotron RF program:
   a) Broadband solid-state 15 kW driver for feedforward compensation of transient beam loading.
   b) Ceramic gaps in tunable cavities.
   c) Dual driver system (2 amplifiers driving double-gap cavity).
   d) Simulate feedforward/feedback systems to allow designs to proceed.

This initial RF experimental program is estimated to be for 2 years with 2 FTE's and $1M.

Innovative work continues on the High-Intensity Proton Source...



"I think you should be more explicit here in step two."