PROTON DRIVER

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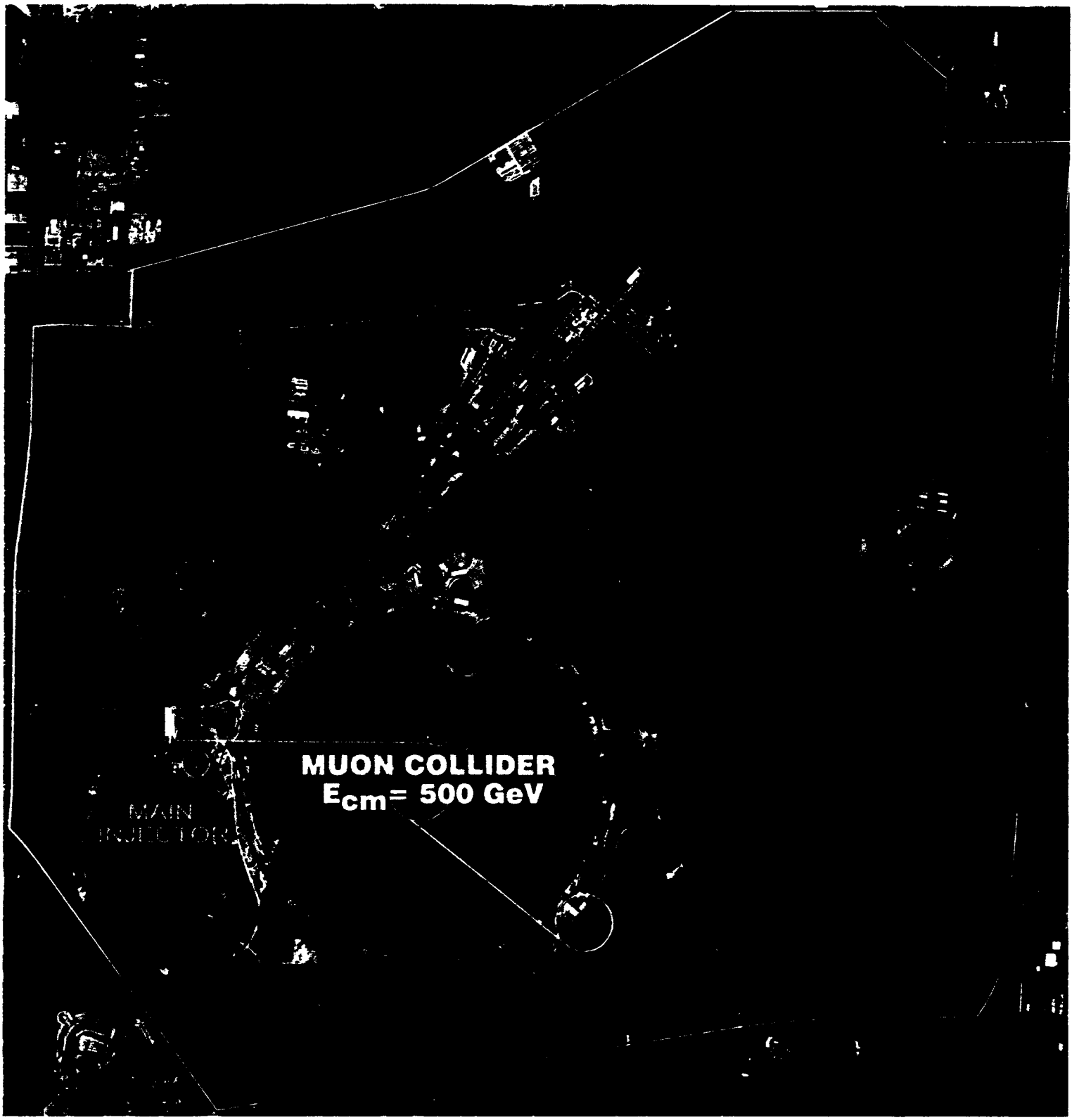
June 28, 1999 at the BNL Instability Workshop

Outline

1. Goal and plan
2. Staged implementation
3. Beam physics issues
   (a) Longitudinal dynamics
   (b) Injection
   (c) Beam instability and space charge
   (d) Lattice
   (e) Tolerable beam loss, collimation and shielding
4. Technical systems design
   (a) RF
   (b) Magnet
   (c) Power supply
   (d) Vacuum pipe
   (e) H^- source and linac
   (f) Wall power
5. Collaborations


MUON COLLIDER
E_{cm}= 500 GeV
MAIN
INJECTOR

	BNL AGS	FNAL Present Booster	FNAL New Booster Phase I	FNAL New Booster Phase II	RAL ISIS	ORNL SNS
Protons per pulse	8×10^{13}	5×10^{12}	2.5×10^{13}	1×10^{14}	2.5×10^{13}	2×10^{14}
Rep rate (Hz)	0.5	15	15	15	50	60
Protons per sec.	4×10^{13}	7.5×10^{13}	3.8×10^{14}	1.5×10^{15}	1.25×10^{15}	1.2×10^{16}
Proton energy	30 GeV	8 GeV	16 GeV	16 GeV	0.8 GeV	1 GeV
Beam power	200 KW	100 KW	1 MW	4 MW	160 KW	2 MW
	↓ "minor" upgrade	↓ "modest" upgrade				Budget: $1.36 B !
Neutrino source needs	1 MW	1 MW				

Department	Name	Time fraction (%)	Work
Proton source	C. Schmidt	20	H (Hardware)
	M. Popovic	40	H
	A. Moretti	20	H
	J. Lackey	30	H
	L. Allen	10	H
	R. Tomlin	10	H
Beam physics	F. Ostiguy	40	C (Calculations)
	B. Ng	30	C
	W. Chou	70	C
	C. Ankenbrandt	70	C
	W. Wan	20	C
	A. Drozhdin	20	C
	N. Mokhov	20	C
	O. Krivosheev	20	C
	J. Johnstone	30	C
	E. McCrory	10	C
Muon Collider	C. Johnstone	40	C
	N. Holtkamp	10	C
MI	I. Kourbanis	20	C
	D. Johnson	20	C
	C. Bhat	10	C
	S. Assadi	20	C
Tevatron	D. McGinnis	10	H
	J. Steimel	20	H
	(V. Wu)	-	C
RF	D. Wildman	40	H
	Z. Qian	40	H
ME	T. Anderson	30	H
EE	H. Pfeffer	30	H
	D. Wolff	30	H
	S. Fang	30	H
	C. Jach	30	H
	G. Krafczyk	30	H
Consultants	D. Ritson	25	C
	J. Griffin	25	C
	F. Mills	20	C
	D. Young	20	C
~~Non BD~~	~~(TBA)~~	~~100~~	~~H~~

TOTAL: ~~10~~ 9 FTE equivalent plus technicians (= same % for each H)

1. Goal and plan:

- Possible steps to realize a muon collider:
  (a) Phase I proton driver and a muon storage ring for a neutrino source.
  (b) Phase II proton driver and a 100 GeV muon collider for a Higgs Factory.
  (c) A 3-4 TeV muon collider.
- Primary requirements of a proton driver:
  (a) High intensity and high beam power: 1×10^{14} protons per cycle at 15 Hz, 16 GeV, 4 MW.
  (Compared to the present Fermilab booster: 20 times more in intensity, 40 times more in beam power.)
  (b) Short bunch length: σ = 1-2 ns at exit. → unique feature of the proton driver
- Our goal:
  To complete a Proton Driver Technical Design Report (TDR) by October 2000.
- Plan:
  - A Proton Driver TDR Team has been formed since November 1999. There are about 30 part-time physicists and engineers for a total of 9 FTE.
  - There are 5 working groups:
    * RF and beamloading;
    * Collective effects; (K-Y. Ng)
    * Magnet, power supply and vacuum;
    * Lattice, injection/extraction, collimation and beamline;
    * H^- source and linac.

    Each group has a weekly meeting. The discussions are summarized in activity reports.
- In FY99, the focus is on the design of key technical components, including several hardware R&D and prototyping (rf cavities, beam pipe and a modulator).

2. Staged implementation:

- The main requirements of the proton driver are:
  - 1×10^{14} protons per cycle (20 $\times$ that of the present Booster) at 15 Hz
  - 16 GeV (2 $\times$ that of the present Booster)
  - 4 MW (40 $\times$ that of the present Booster)
  - σ = 1-2 ns at exit
- These requirements will be met in 2 stages.
  - Phase I – To build a new 16 GeV booster in a new tunnel. The present 400 MeV linac will still be used as the injector. This new machine will deliver 2.5×10^{13} protons per cycle at 15 Hz. ($5 \times I$ and $2 \times E$ than the present Booster)
  - Phase II – The addition of a new linac and a new pre-booster for another factor of 4 increase in beam intensity.
- Justifications of Phase I:

  (a) To remove a bottleneck:
    - Present linac can deliver 2.5×10^{13} H^- per cycle. (45 mA $\times$ 90 μs)
    - With modest upgrade, the new Main Injector can take 2.5×10^{13} from a booster batch for 6 batches.
    - The bottleneck is the present Booster, which can only deliver 5×10^{12} protons.

  (b) Benefits to existing and planned Fermilab programs:
    - To meet the requirement of a future neutrino source.
    - To enhance the fixed target program (NUMI, KAMI, MiniBooNE, *etc.*)
    - To provide a possible path for the Tevatron collider experiment beyond Run II.

Table 1: Evolution of the proton source parameters in the scenario described in the text. Phase 1 of the proton driver assumes a new 16 GeV Booster that uses the present 400 MeV linac as its injector. In Phase 2 a new 1 GeV linac and a 3 GeV Pre-booster are added. Parameters of the present linac and booster are also listed for comparison.

	Present	Phase 1	Phase 2
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	45	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	2.5×10^{13}	1×10^{14}
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	3×10^{11}	2.5×10^{13}
Number of bunches	84	84	4
Total number of protons	5×10^{12}	2.5×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	50π	200π
Longitudinal emittance (eV-s)	0.1	0.1	2
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	0.2	1
Target beam power (MW)	0.1	1	4

3. Beam physics issues

(a) Longitudinal dynamics (high phase space density)

(b) Injection (painting; foil physics)

(c) Beam instability and space charge

(d) Lattice (no transition; large momentum acceptance)

(e) Tolerable beam loss, collimation and shielding

(f) Ripple effects during injection (see power supply study)

To give short bunch at exit:

$$l_b \sim \frac{\varepsilon_L}{\Delta p}$$

- Preserve a small ε_L
  - no-transition lattice
  - careful control of α_1 (and α_2)
  - inductive compensation
- Large $\frac{\Delta p}{p}$ acceptance in the lattice
- Bunch rotation before exit

(a) Longitudinal dynamics — emittance preservation: @ 2 eV-s, $\sigma_z = 1$ ns, $\Delta p/p = \pm 2.5\%$
@ 5 eV-s, $\sigma_z = 2.5$ ns, $\Delta p/p = \pm 2.5\%$

Table 1. Proton Synchrotrons Performance

longi. phase space density

Machine	E_{max} (GeV)	N_{tot} (10^{12})	N_b (10^{12})	A_b (eV-s)	ϵ^H_{rms} (μm)	ϵ^V_{rms} (μm)	N_b/A_b (10^{12}/eV-s)	N_b/ϵ_{rms} ($10^{12}/\mu$m)	$N_b/(A_b\epsilon^H_{rms}\epsilon^V_{rms})$ (10^{10}/eV-s/μm^2)
Existing:									
BNL AGS	24	63	8	4	10	10	2	0.8	2
CERN PS	14	25	1.25	0.7	12.5	10	1.8	0.11	1.4
CERN SPS	450	46	0.012	0.5	10	7	0.024	0.0014	0.03
KEK PS	12	3.6	0.4	2	5	15	0.2	0.04	0.27
FNAL Booster	8	4	0.05	0.1	3	3	0.5	0.02	5.6
FNAL MR	150	20	0.03	0.2	2	2	0.15	0.02	3.8
DESY III	7.5	1.2	0.11	0.09	5	3	1.2	0.03	8.1
PETRA II	40	5	0.08	0.12	8.7	6.2	0.7	0.01	1.2
PSR (dc)	0.797	23	23	1.25	6.5	13.4	18	2.3	21
ISIS (γ ratio: 1.7)	0.8	25	12.5	0.6	47	47	21	0.27	0.94
Planned:									
AGS for RHIC	25	0.4	0.4	0.3	1.5	1.5	1.3	0.3	59
PS for LHC	26	14	0.9	1.0	2.8	2.8	0.9	0.3	11
SPS for LHC	450	24	0.1	0.5	3.5	3.5	0.2	0.03	1.6
FNAL Main Inj	150	60	0.12	0.1	2	2	1.2	0.06	30
KEK JHP	50	200	12.5	5	55	55	2.5	0.2	0.08
$\mu\mu$ Proton Dr	16	100	25	2	35	35	12.5	0.71	1.0

(γ ratio: 4.3)

Proton Driver

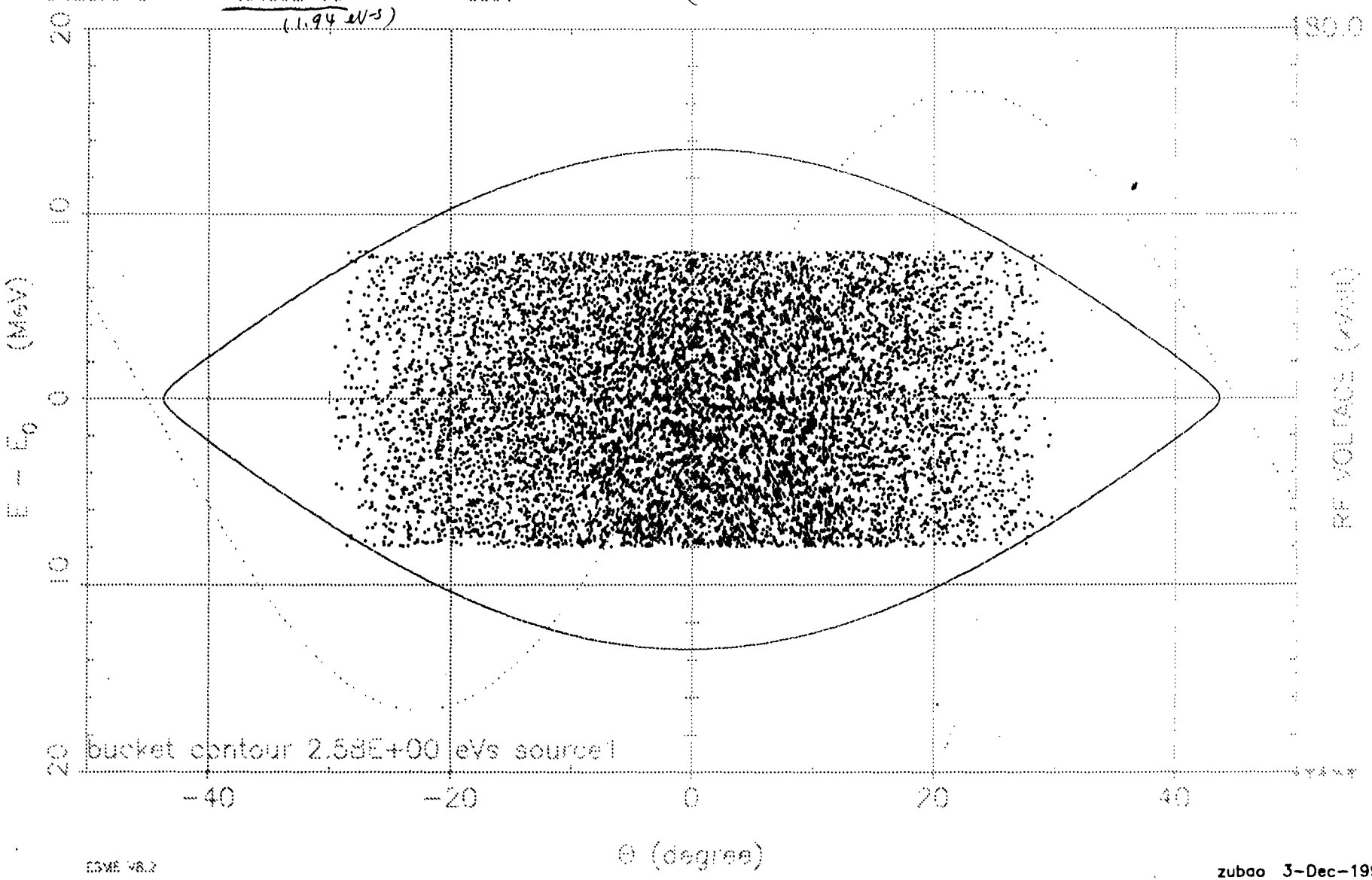
1000 MEV CAPTURE Dp/p = +.30/−.30pc Q=2.5e13

TURN 0 0.000E+00 sec

H_B (MeV)	S_B (eV s)	E_0 (MeV)	h	V (MV)	φ (deg)
1.3487E+01	2.5768E+00	1.9332E+03	1	1.500E−01	0.000E+00
ω_0 (turn^{-1})	pdot (MeV s^{-1})	η			
3.5362E−03	−1.0558E+03	−1.0434E−01			
τ (s)	S_b (eV s)	N			
6.0287E−07	1.9430E+00	10000			

(1.94 eV-s)

(@ inj into the 1st ring



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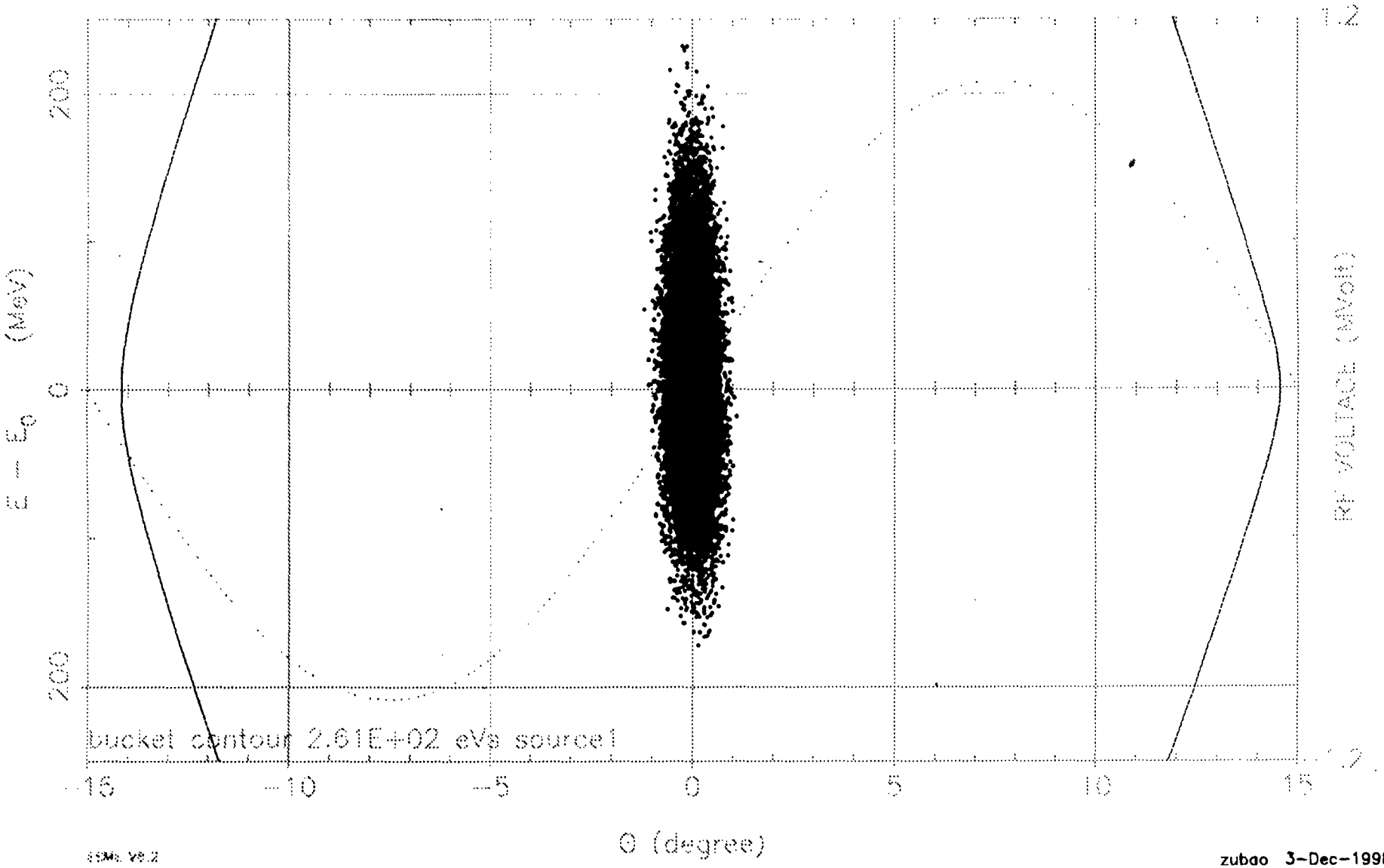
D After

TURN 79750 6.637E−02 sec

H_0 (MeV)	S_0 (eV s)	E_0 (MeV)	h	V (MV)	φ (deg)
7.8301E+02	2.8073E+02	1.8938E+04 (16 GeV)	1>	1.000E+00	0.000E−00
ν_s (turn^{-1})	pdot (MeV s^{-1})	η			
4.0755E−04	0.0000E+00	−1.4586E−03			
τ (s)	S_0 (eV s)	N			
1.5842E−06	2.1249E+00	3997			



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(b) Injection :

<i> Phase space painting : H plane : fast orbit bump
V plane : steering magnet

<ii> Foil physics : heating
emittance dilution (multiple scattering)

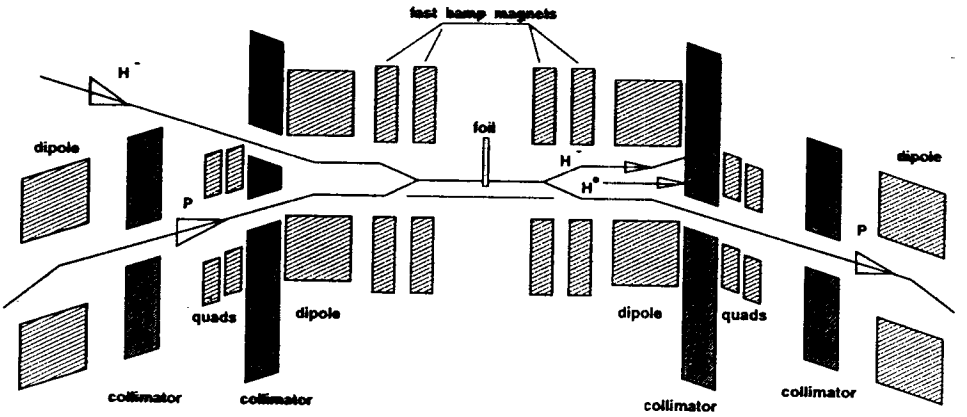


Figure 2: Collimators location in the injection region.

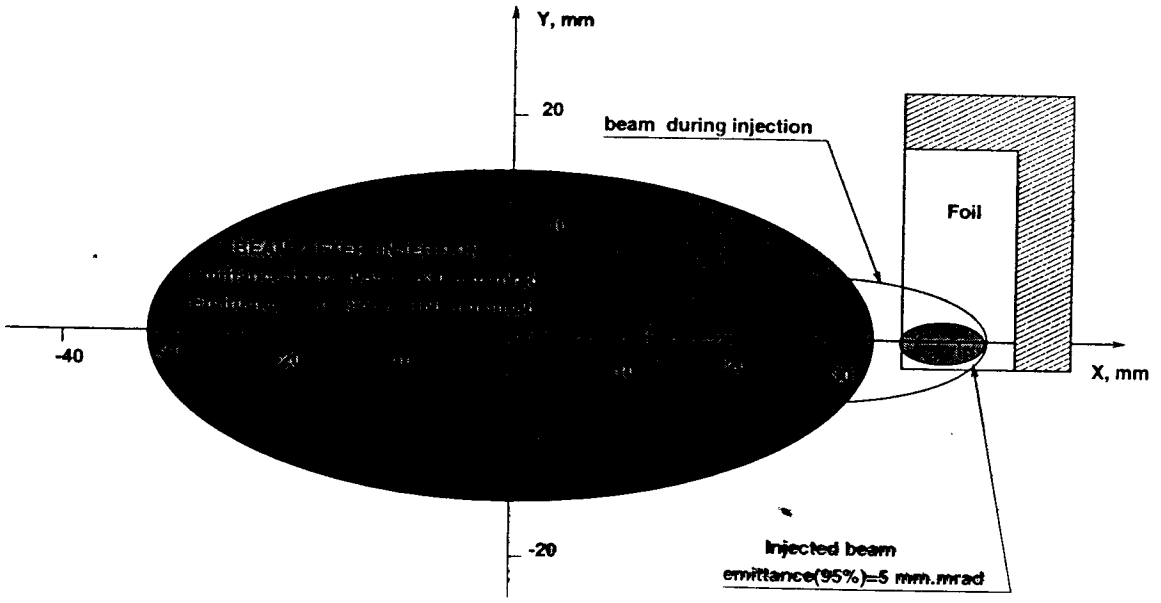


Figure 3: Cross section view at the injection point.

A. Drozhdin

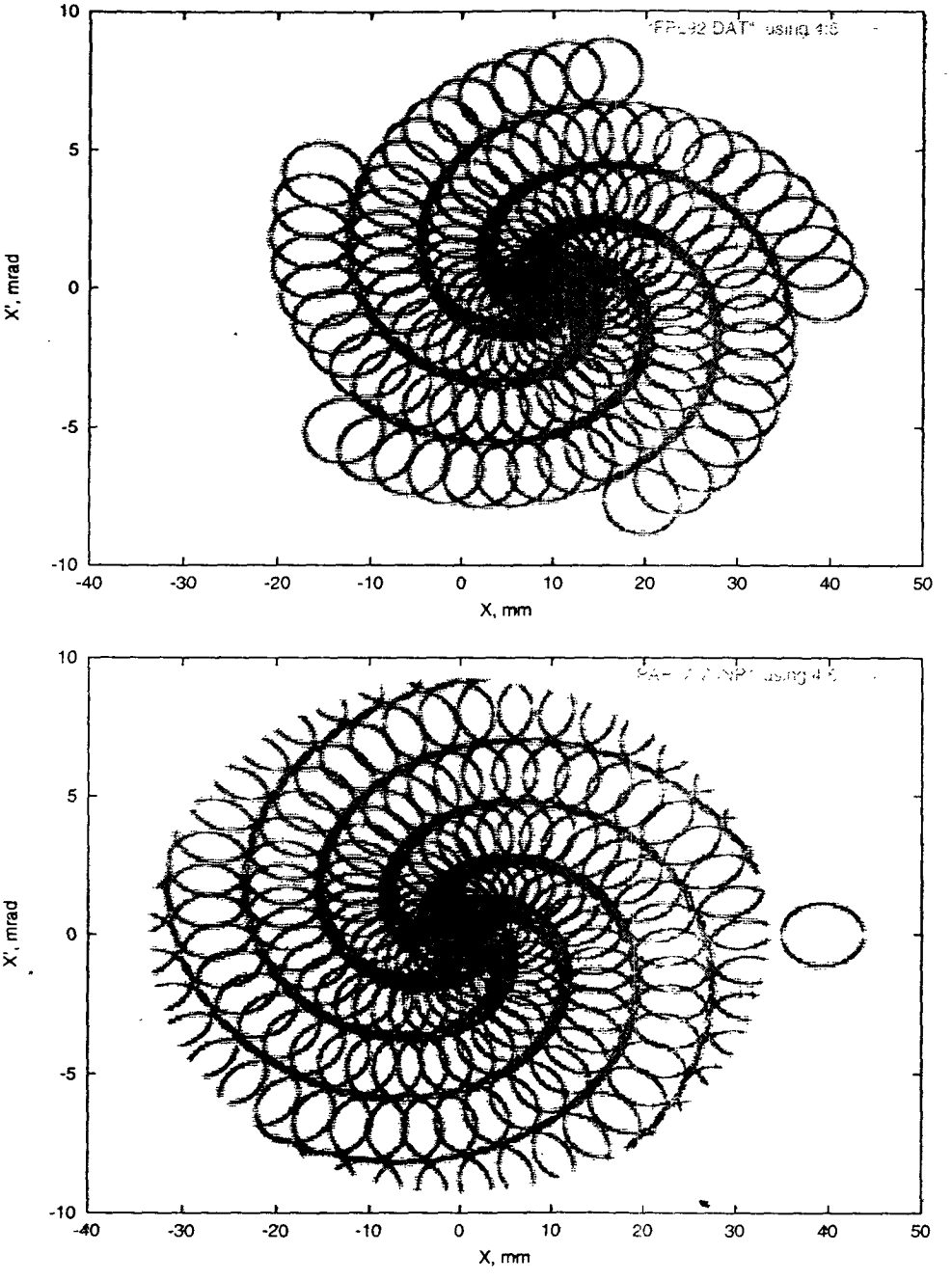


Figure 7: Beam population at the foil location at 150-th (top) and 200-th (bottom) turn from the beginning of beam painting.

A. Drozhdin

Optimal Painting

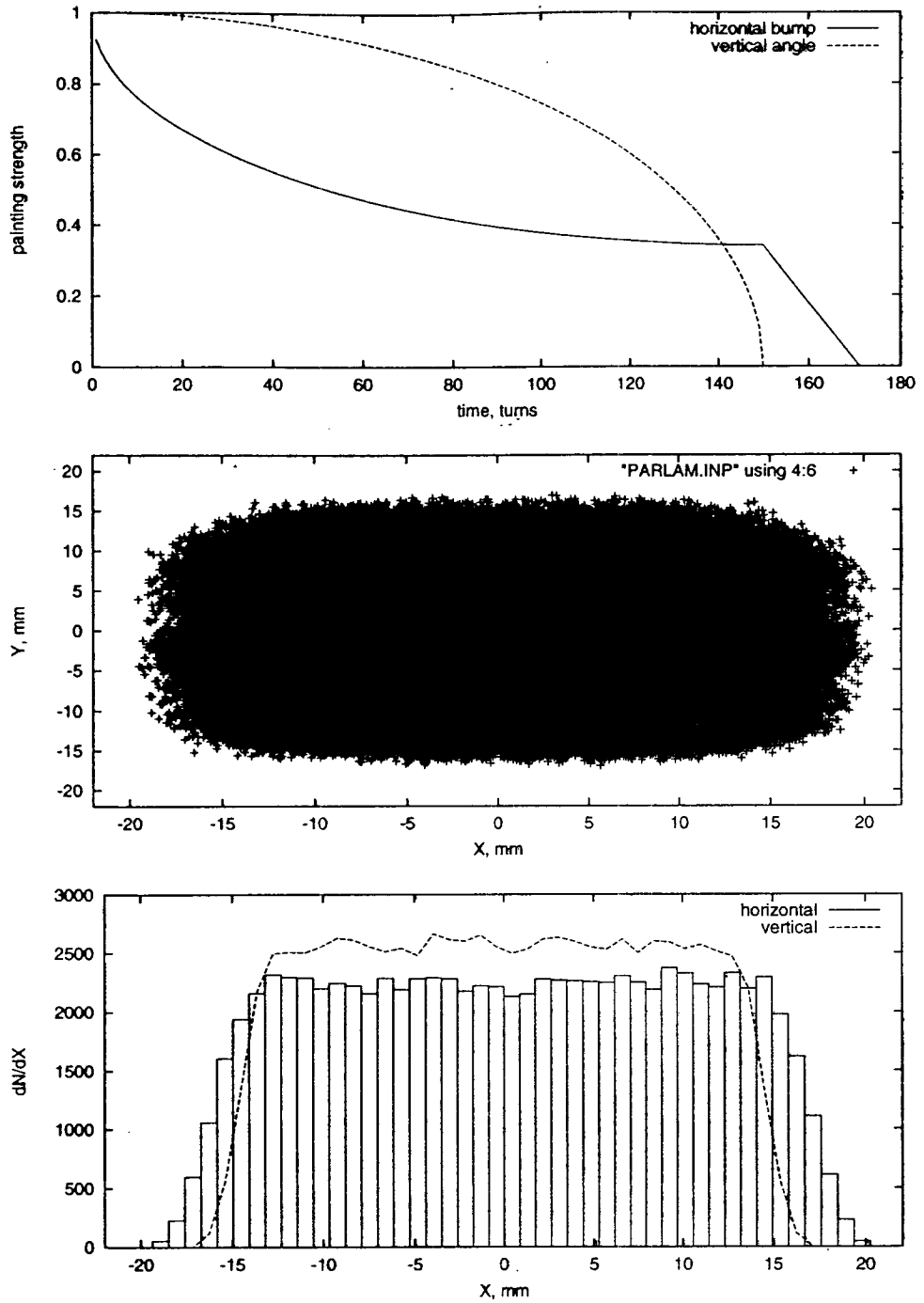


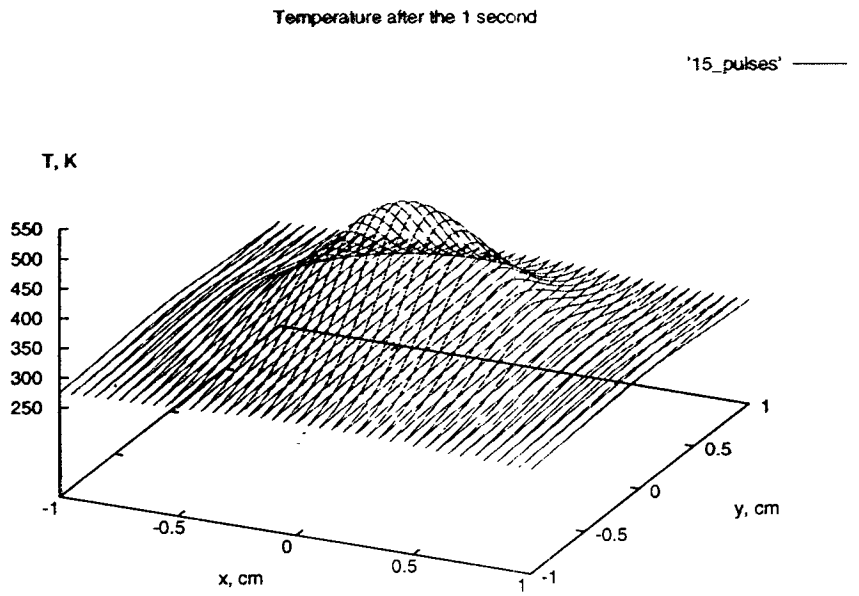
Figure 20: Horizontal bump-magnet strength and vertical angle of the beam at injection in the foil for optimal painting (top). Horizontal phase plane (middle) and particle density distribution in the foil (bottom) at 170-th turn from the beginning of beam painting ($\sigma_{dP/P=0.0004}$) for optimal painting. Bump amplitude is 25.2 mm, raise time is equal to 150 turns. Number of hits upon the stripping foil is 291035/74998=3.88

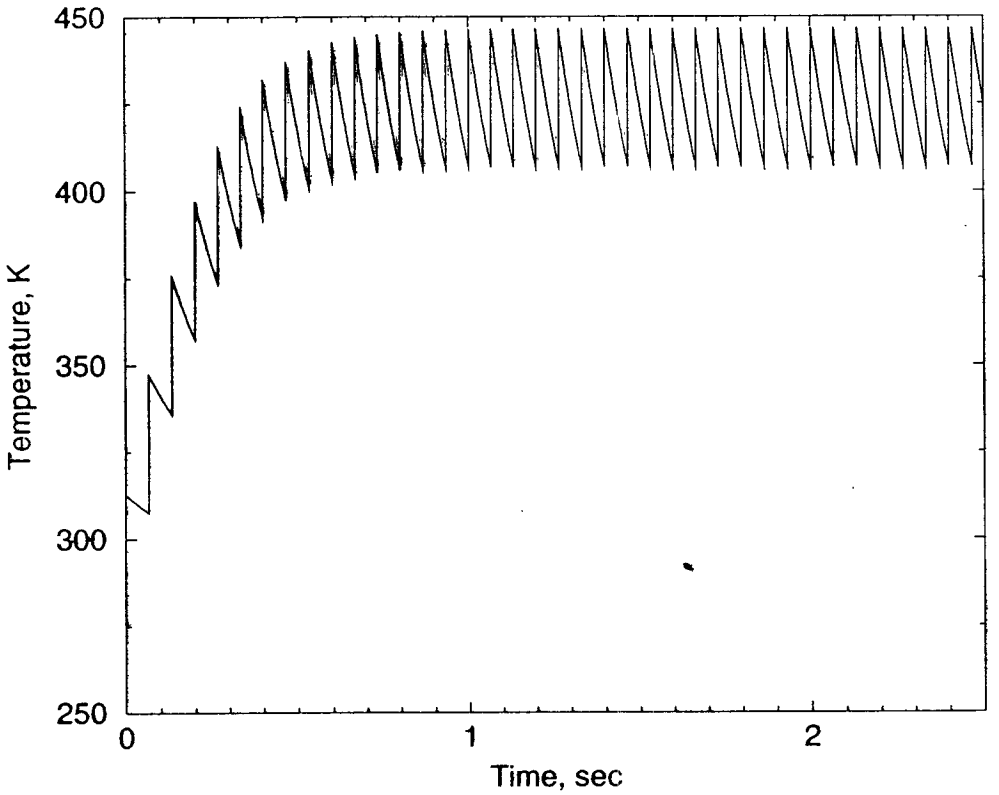
$\Delta y' = 1$ [illegible]

$\varepsilon = 2$ [illegible]

<ii> Foil Physics / temperature rise / emittance dilution

O. Krivosheev





(c) Collective effects:

(i) "Conventional": (sort of know-how)

- Impedance budget
- Resistive wall
- Slow head-tail
- Coupled bunch
- *etc.*

(ii) Non-conventional: (need to be understood)

- Longitudinal microwave instability below transition (Is it ever seen?)
- Fast head-tail (transverse mode-coupling) in the presence of strong space charge
- Inductive compensation of space charge effects (PSR, KEK-PS expts.)
- Space charge induced coherent modes (GSI, KEK studies)
- Synchro-betatron resonance due to dispersion in rf section

$$kQ_\beta \pm mQ_s = n$$

  $k = 1$ has been studied by T. Suzuki and others. How about $k = 2, 3$?
- Effects of large α_1 and α_2 during bunch rotation and ramping

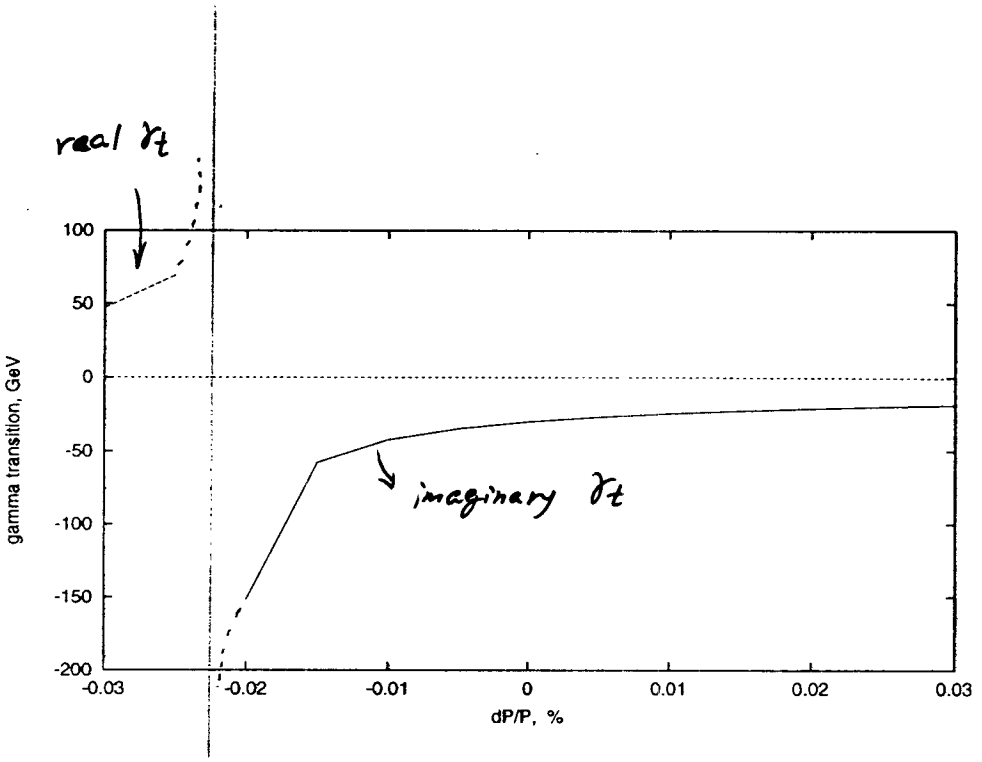
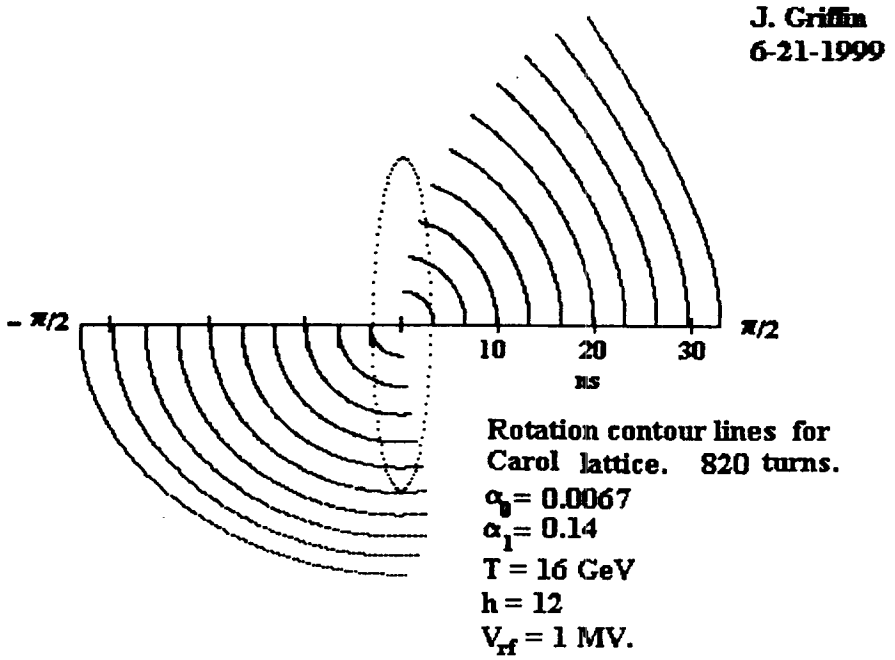
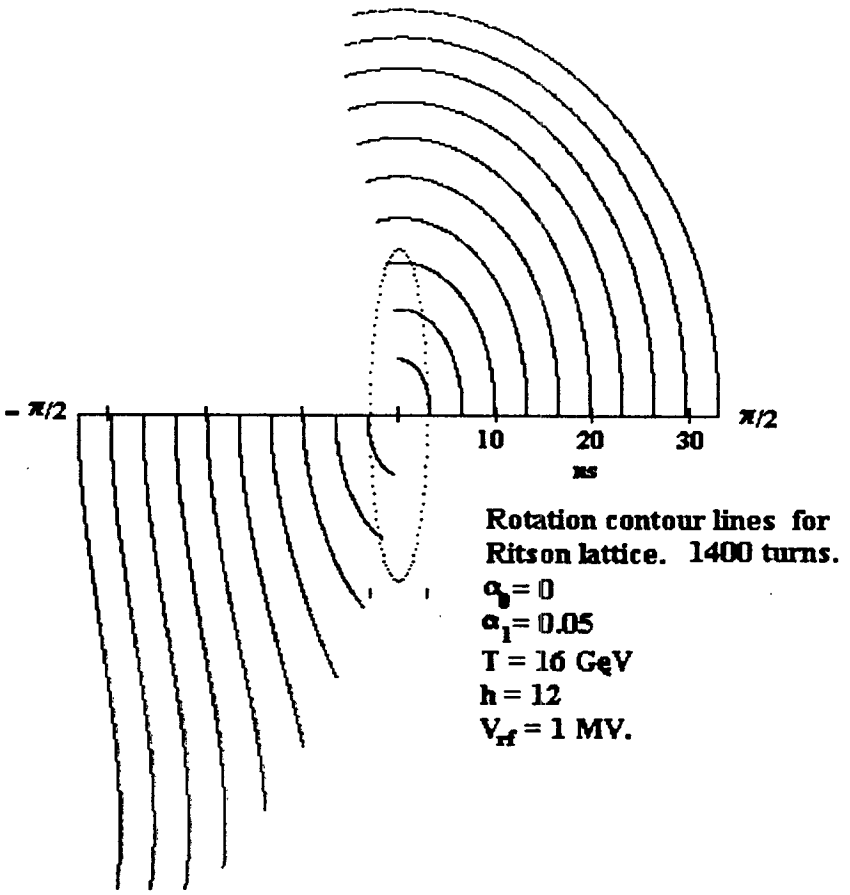


Figure 3: Ritson's 16 GeV Proton Driver lattice transition energy.

Effects of α_1 (and α_2) during bunch rotation:





(d) Lattice :

<i> Requirements :

- zero dispersion straight sections ;
- high (or imaginary) γ_t :
  - This excludes FODO due to the scaling

$$\gamma_t \sim \sqrt{R}$$

$$E \sim R$$

  - considering variations of the FMC (flexible momentum compaction)
- large momentum acceptance :

@ inj : $\pm 1\%$

@ extr : $\pm 2.5\%$ (difficult)

<ii> Ring size consideration:

$$E_{max} \sim B_{max} \cdot C$$

16 GeV 1.3 T 474 m (?)

(can not co-exist)

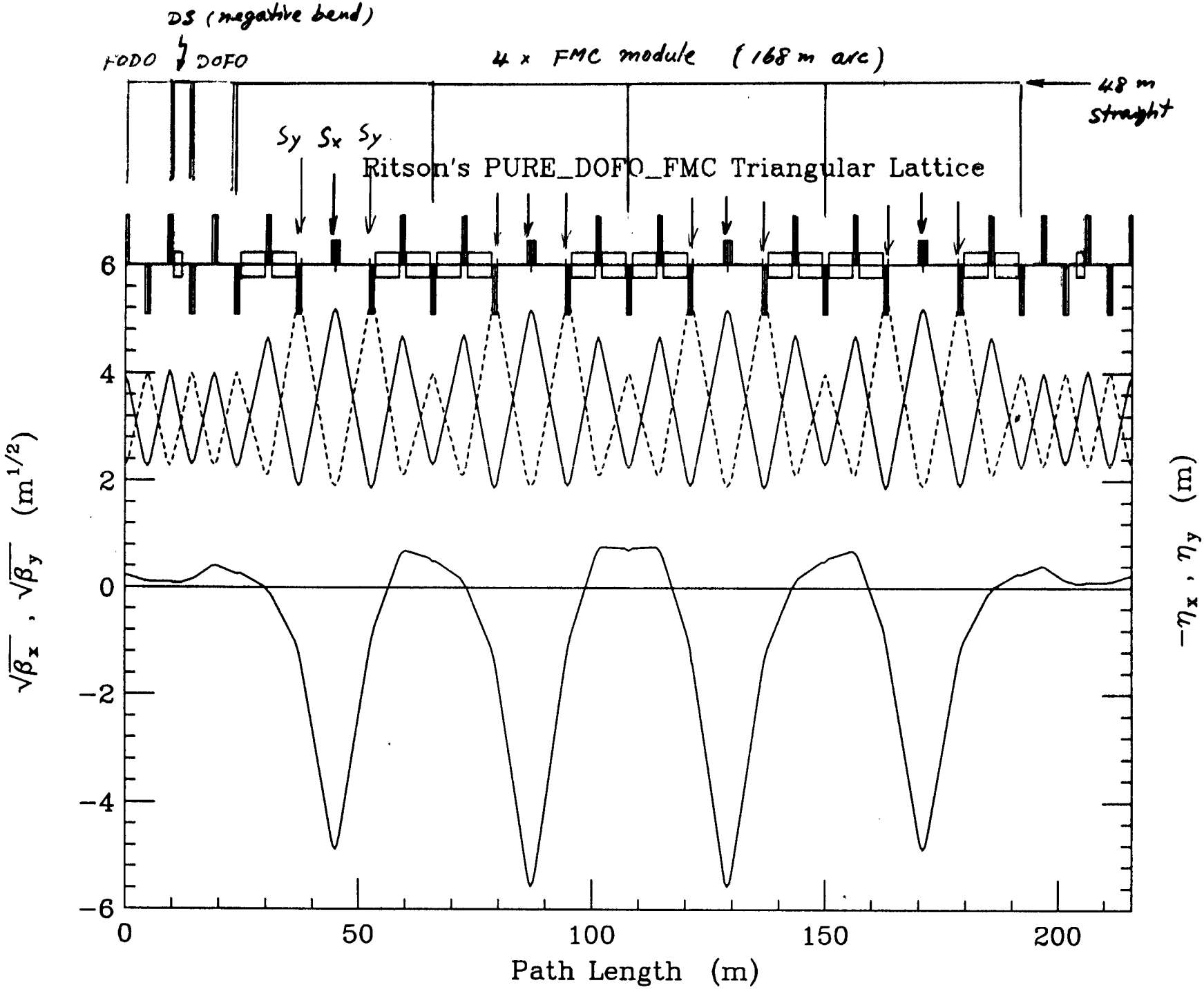
<iii> Candidates :

△ • Doublet (C. Johnstone)

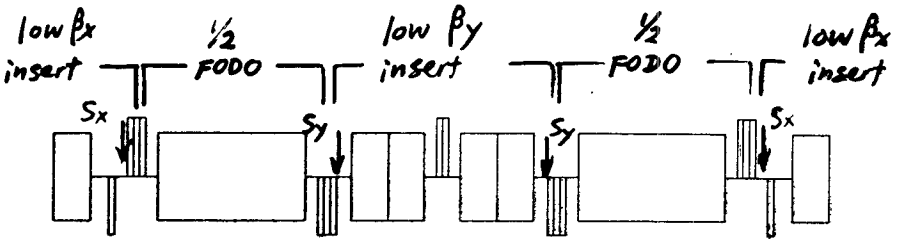
△ • DOFO with missing dipole (D. Ritson)

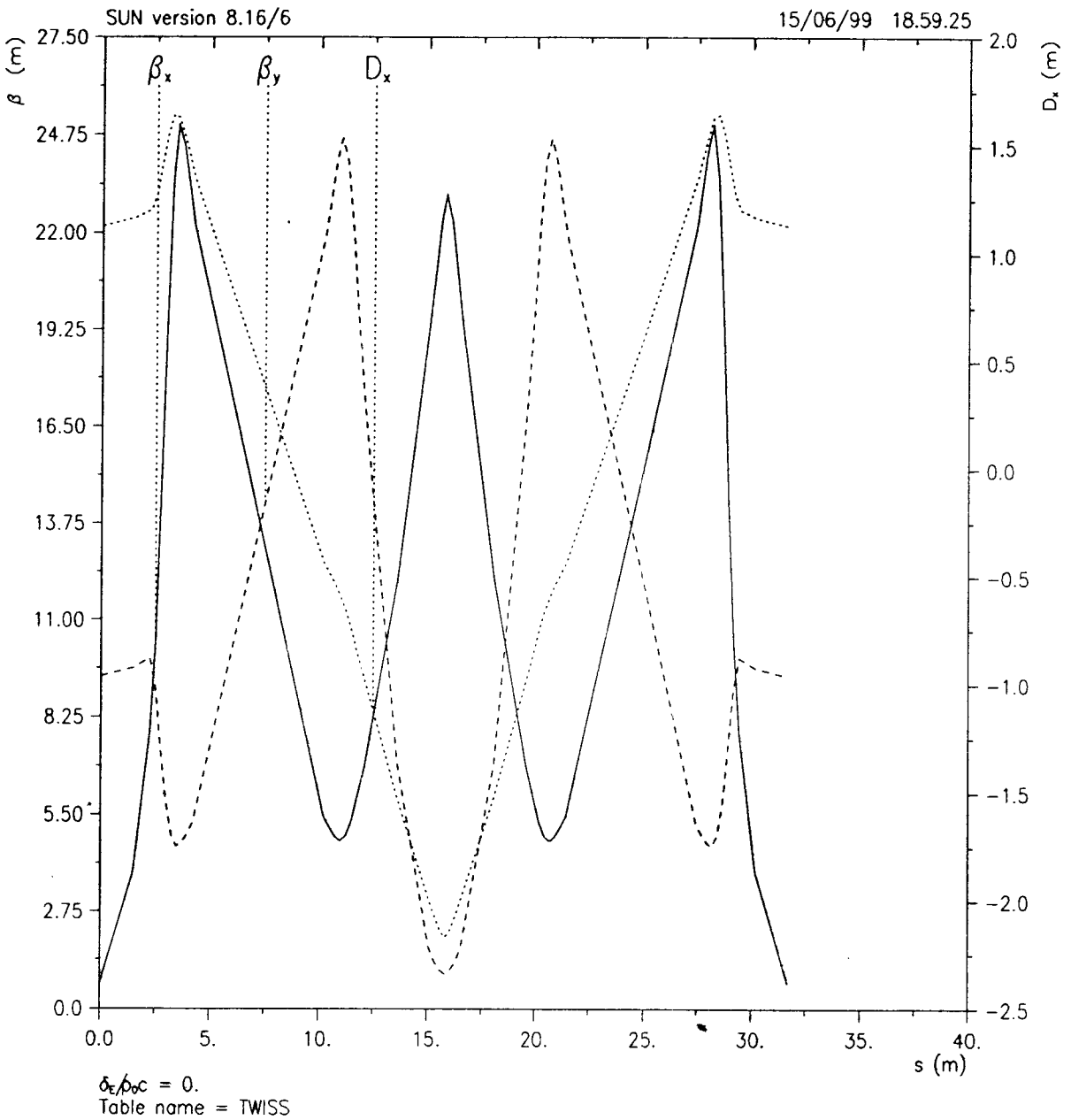
• FODO with missing dipole (D. Trbojevic)

• Combined function magnets lattice (L. Teng)


DS (negative bend)
FODO
DOFO
4 x FMC module (168 m arc)
48 m straight
Sy Sx Sy
Ritson's PURE_DOFO_FMC Triangular Lattice
6
4
2
0
−2
−4
−6
$\sqrt{\beta_x}$, $\sqrt{\beta_y}$ (m$^{1/2}$)
$-\eta_x$, η_y (m)
0
50
100
150
200
Path Length (m)

C. Johnstone


low β_x insert
½ FODO
low β_y insert
½ FODO
low β_x insert
S_x
S_y
S_y
S_x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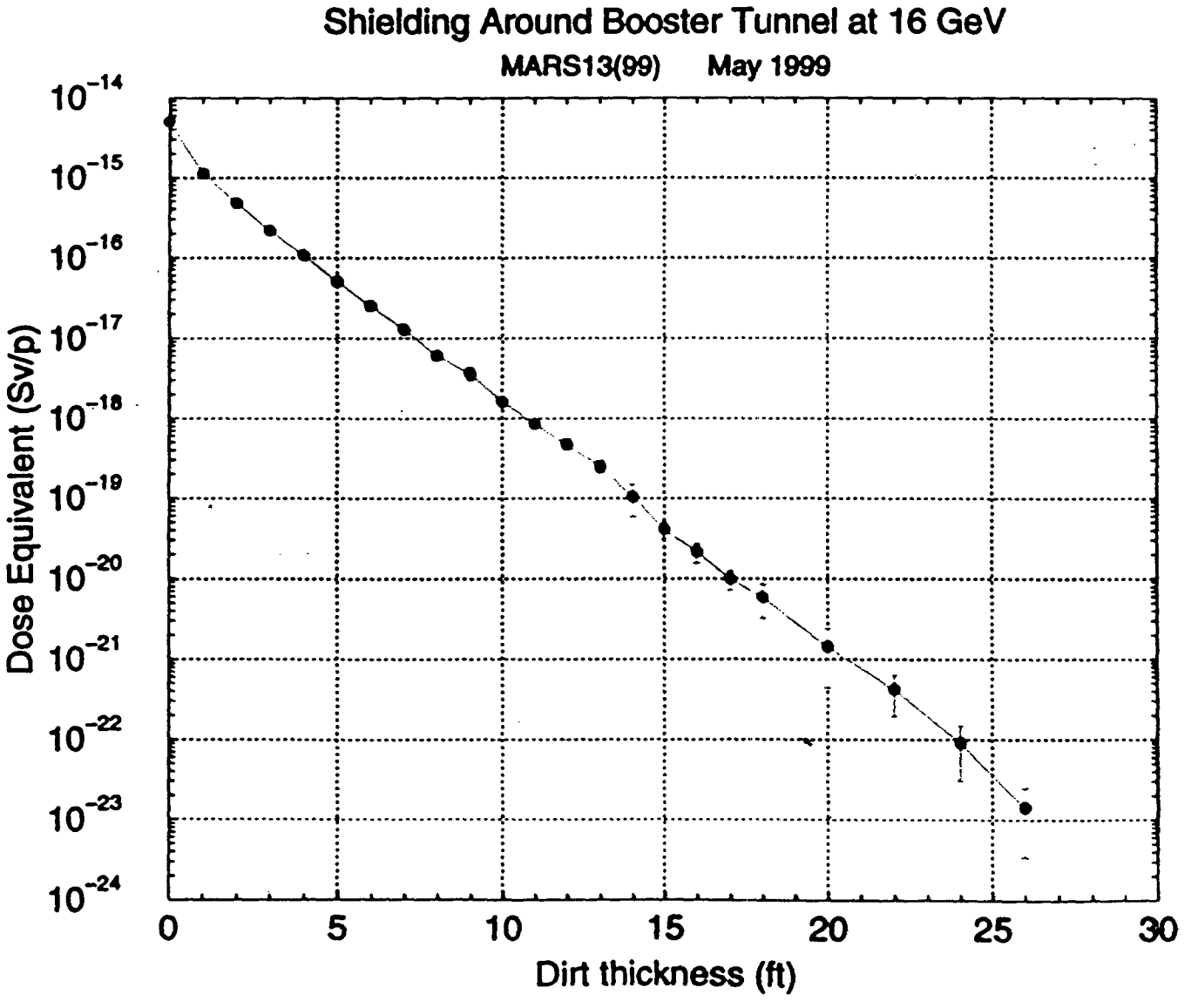
β (m)
D_x (m)
β_x
β_y
D_x
27.50
24.75
22.00
19.25
16.50
13.75
11.00
8.25
5.50
2.75
0.0
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0.0
5.
10.
15.
20.
25.
30.
35.
40.
s (m)
δ_E/p_0c = 0.
Table name = TWISS

DOSE RATES

- Peak accumulated dose in the Prebooster magnet coils at 3 GeV is 1.82 $\frac{Mrad}{y}$, i.e. one can tolerate about 26 W/m.
- Residual dose rate at the Prebooster magnet coils at 3 GeV (at contact after 30 day irradiation and 1 day cooling) is 3.7 $\frac{mrem}{hr}$, i. e. one can tolerate about 13 W/m.
- Accidental beam loss defined as a local loss of a full beam over one hour ($10^{14} \times 15\ Hz \times 3600\ sec$) requires shielding—as per Fermilab policy—to reduce dose to 1 mrem = 1.85×10^{-24} Sv/p (see plots). At 16 GeV this is 29 feet of dirt.

Maxima for the 3 GeV prebooster: 27.3 $\frac{pCi}{ml \cdot y}$ for ^{3}H and 0.456 $\frac{pCi}{ml \cdot y}$ for ^{22}Na. It is fine with a 40 cm concrete wall for each isotope separately, but cumulative effect requires the tolerable loss limit to be $0.6 \cdot 10^{10}$ p/(m·s) which is equivalent to about 3 W/m.

O. Krivosheev



A. Drozhdin

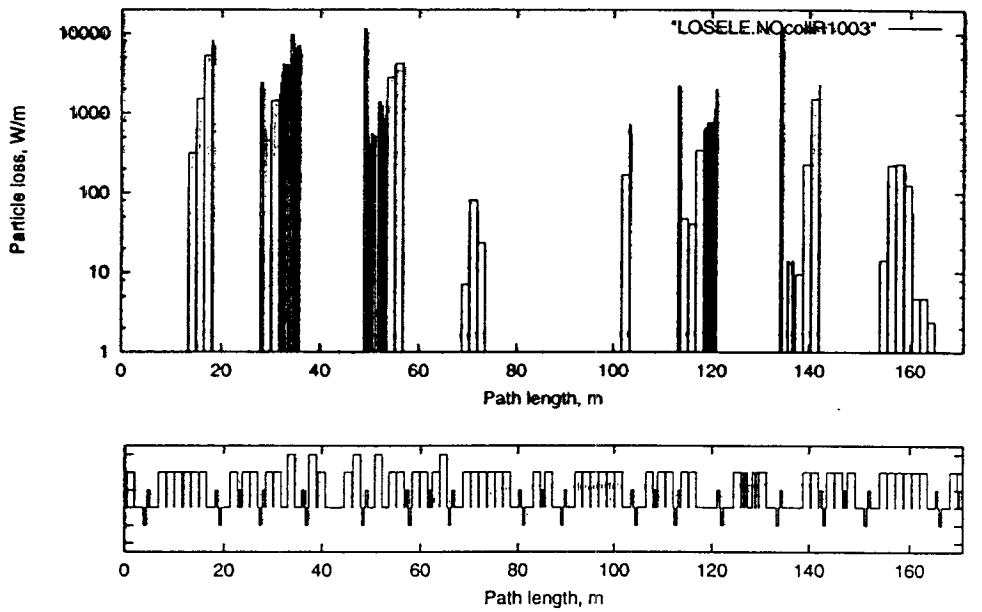


Figure 5: Beam loss at slow growth of beam size without collimators. Kinetic energy of beam particles is equal to 3 GeV.

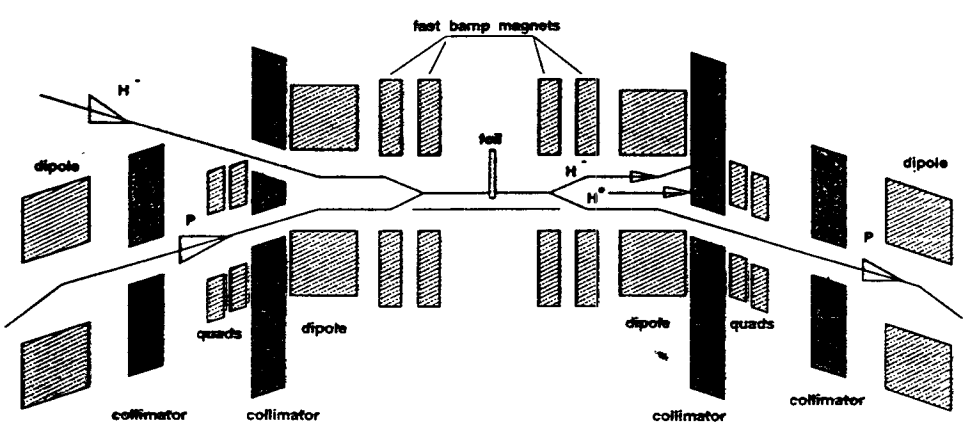


Figure 6: Collimators location in the injection region.

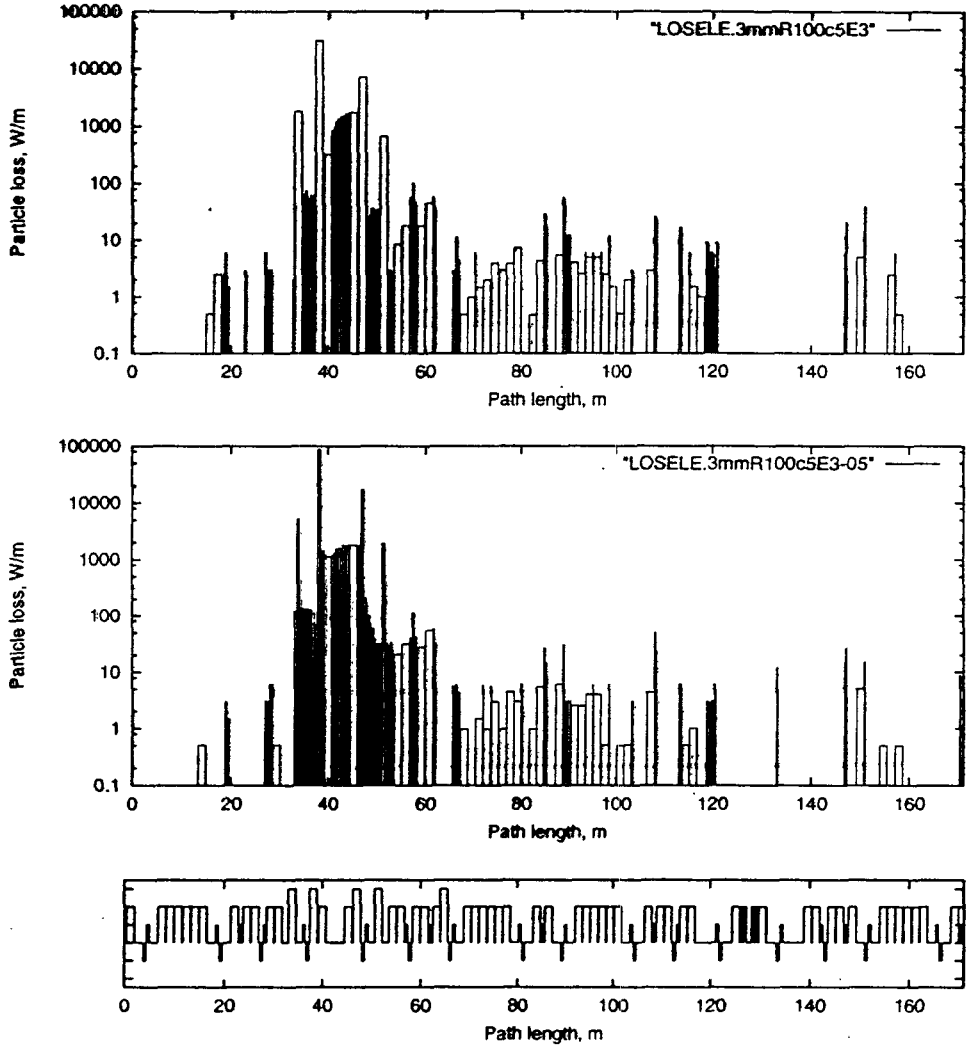


Figure 17: Beam loss with $3mm$ long primary graphite collimator. Second collimator offset is equal to $0.5mm$. 1-st, 3-d and 4-th collimators offset is $5mm$. Top - collimators length is $1.5m$. Bottom - collimators length is $0.5m$.

4. Technical systems design

(a) RF { 7.5 MHz, 53 MHz }

(b) Magnet — large aperture

(c) Power supply { single resonance, dual-resonance, dual-freq. }

(d) Vacuum pipe — Inconel

(e) H^- source and linac

(f) Wall power

D. Wildman

Status of 7.5 MHz RF Cavity

Engineering drawings 90% complete

Copper cooling plates being machined by outside vendor

Remainder of machining done at Fermilab shops

25% of parts already completed

All machined parts completed by August 2nd

Cavity complete by Sept. 1st

Design modification of Main Injector 200 kW power amplifier for 7.5 MHz operation is now in progress

Construction of amplifier to begin after Oct 1st

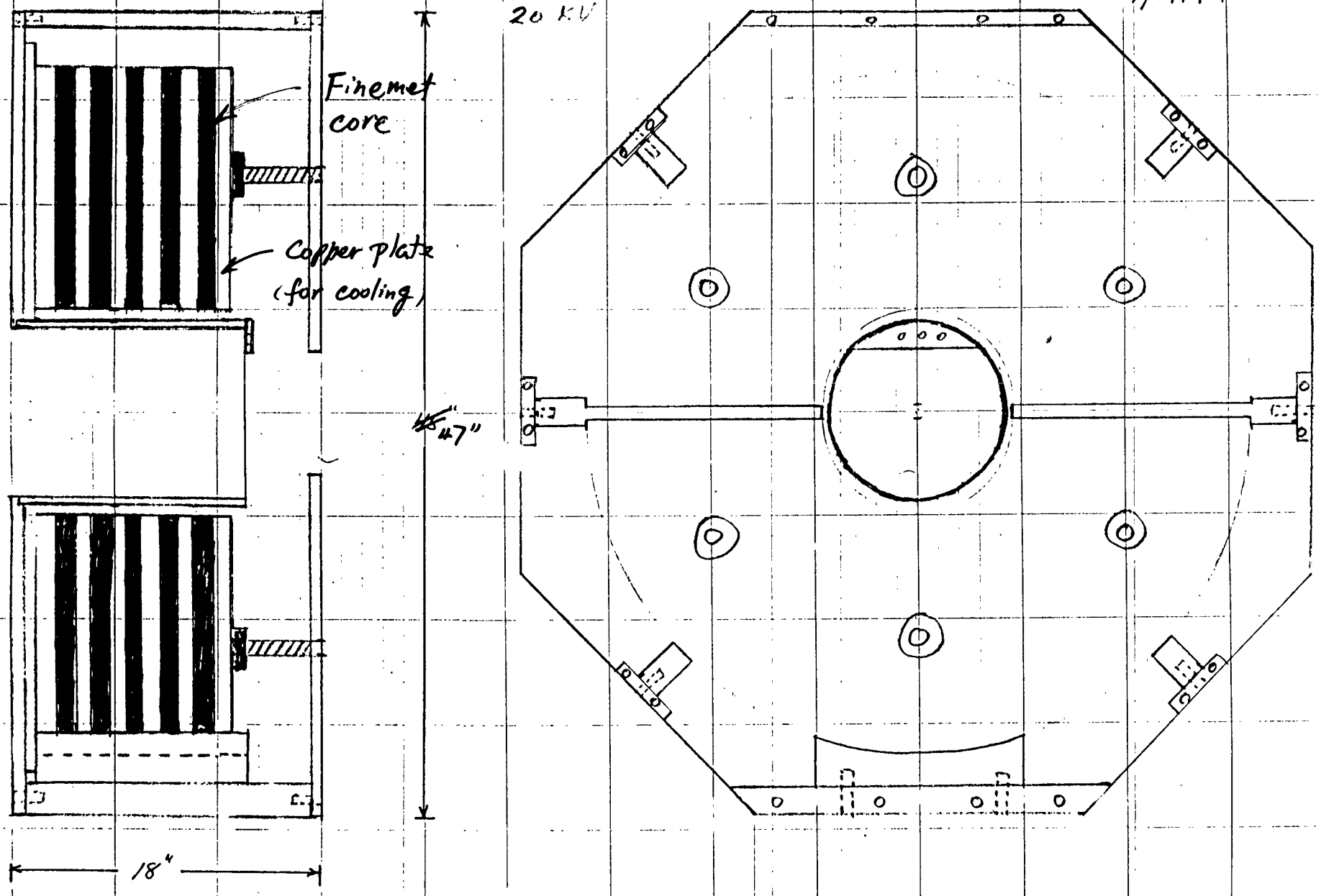
99-4674

(a) RF:

<i> 7.5 MHz system: Prototype Finemet cavity

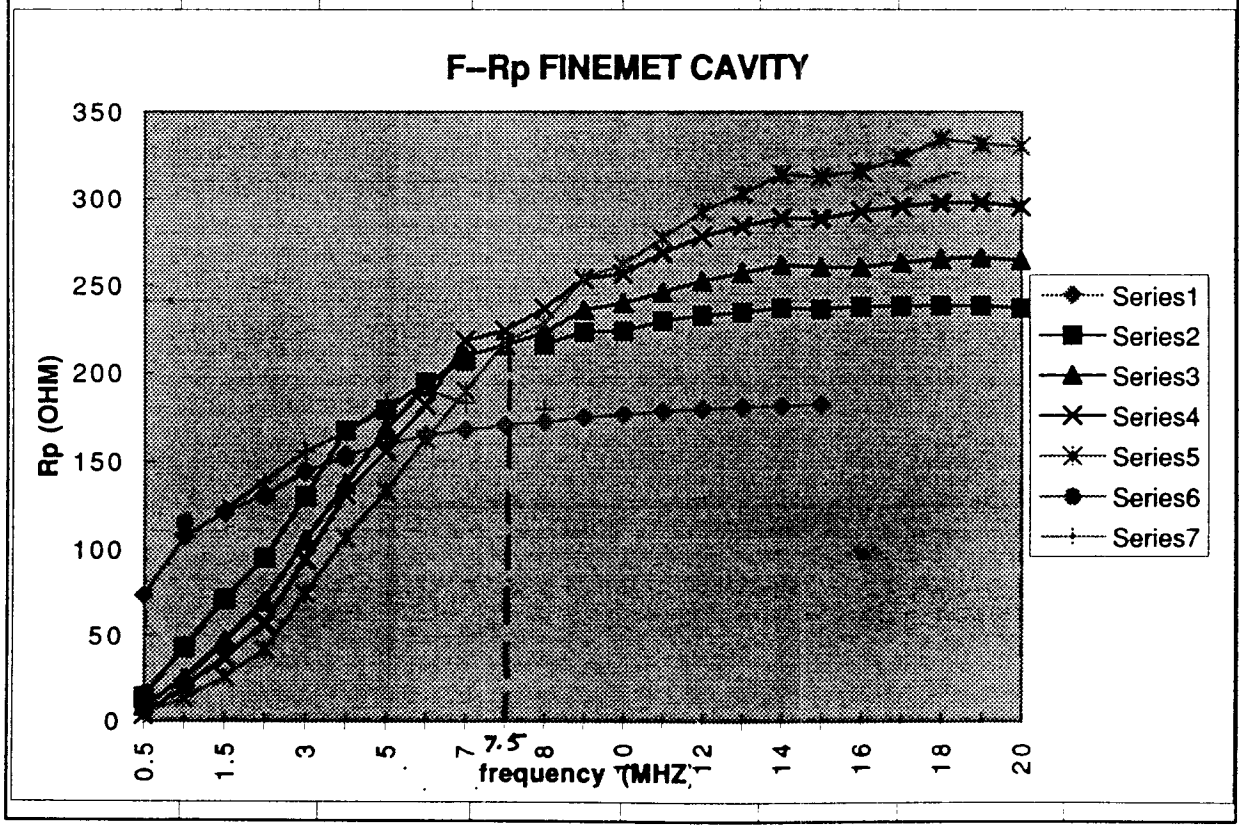
20 kV

D. Wildman
4/19/99



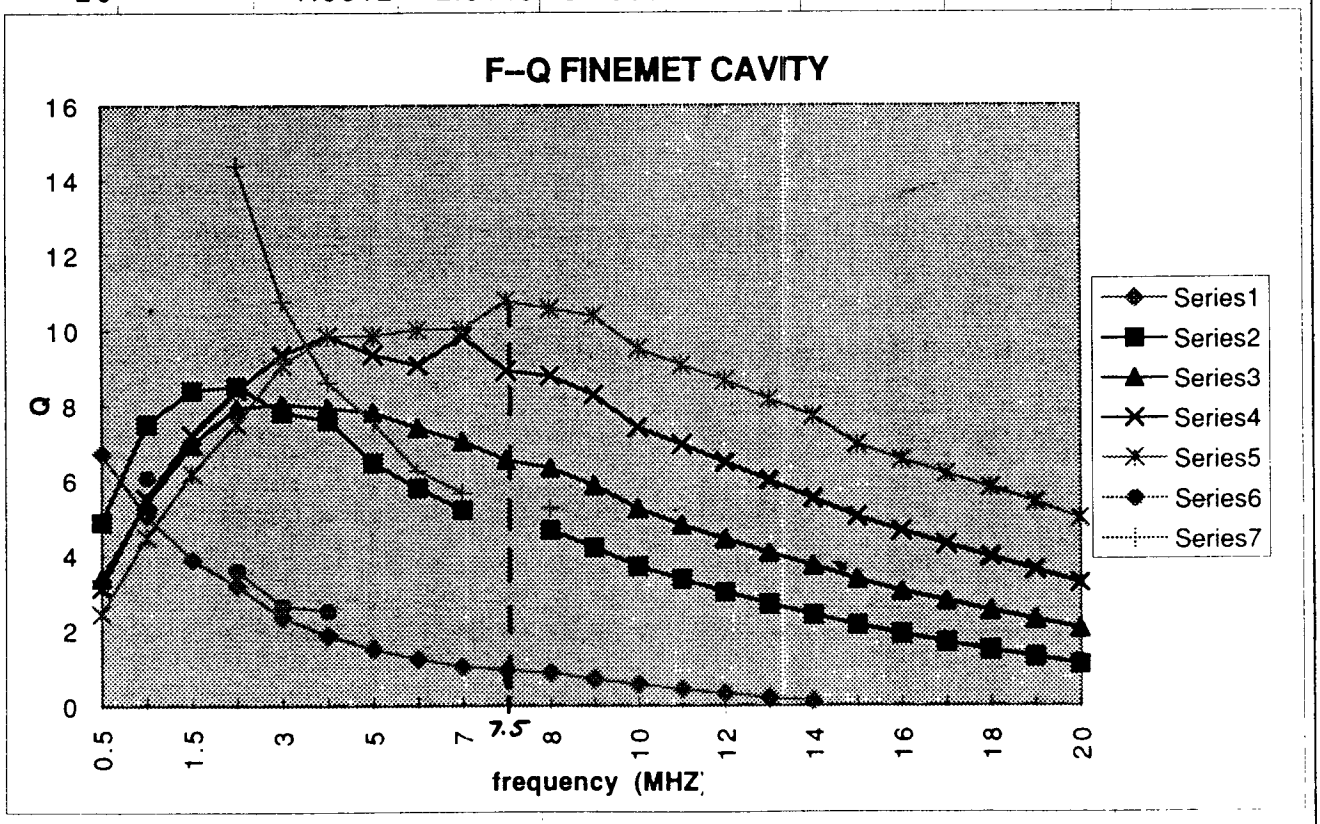
L. Qian
(4/27/99)

freg. (MHZ)	0 mm	15 mm	25mm	46 mm	75mm	KEK 0 mm	KEK 15 mm
0.5	72.8	14.27	8.03	3.17	3.94		
1	107.09	42.49	24.58	19.07	12.79	114.96	
1.5	121.02	70.61	46.13	36.67	25.71		123
2	131.03	94.67	69.26	56.42	41.06	129.93	138.27
3	143.68	129.7	104.85	93.63	73.63	144.45	155.22
4	153.48	167.2	136.92	131.02	106.28	151.45	166.16
5	159.21	179.1	168.42	155.74	132.7		182.91
6	164.74	194.47	192.56	181.62	162.4		190.44
7	167.45	206.73	209.9	218.32	189.59		182.59
7.5	170.09		215.52	224.28	217.6		
8	172.04	216.11	223.1	236.74	228.46		179.39
9	174.49	223.52	236.22	253.88	254.57		
10	176.26	223.88	240.15	256.74	262.13		
11	177.79	229.68	245.97	268.5	277.03		
12	179.13	232.58	252.31	277.8	292.33		
13	180.23	234.47	257.26	284.16	302.78		
14	181.03	237.32	261.42	288.59	313.67		
15	181.6	236.57	260.65	288.34	312.7		
16		237.93	260.42	292.44	316.01		
17		238.32	263.14	295.16	323.36		
18		238.8	265.23	297.57	334.29		
19		238.5	265.83	297.86	331.44		
20		237.23	264.71	295.22	330.37		



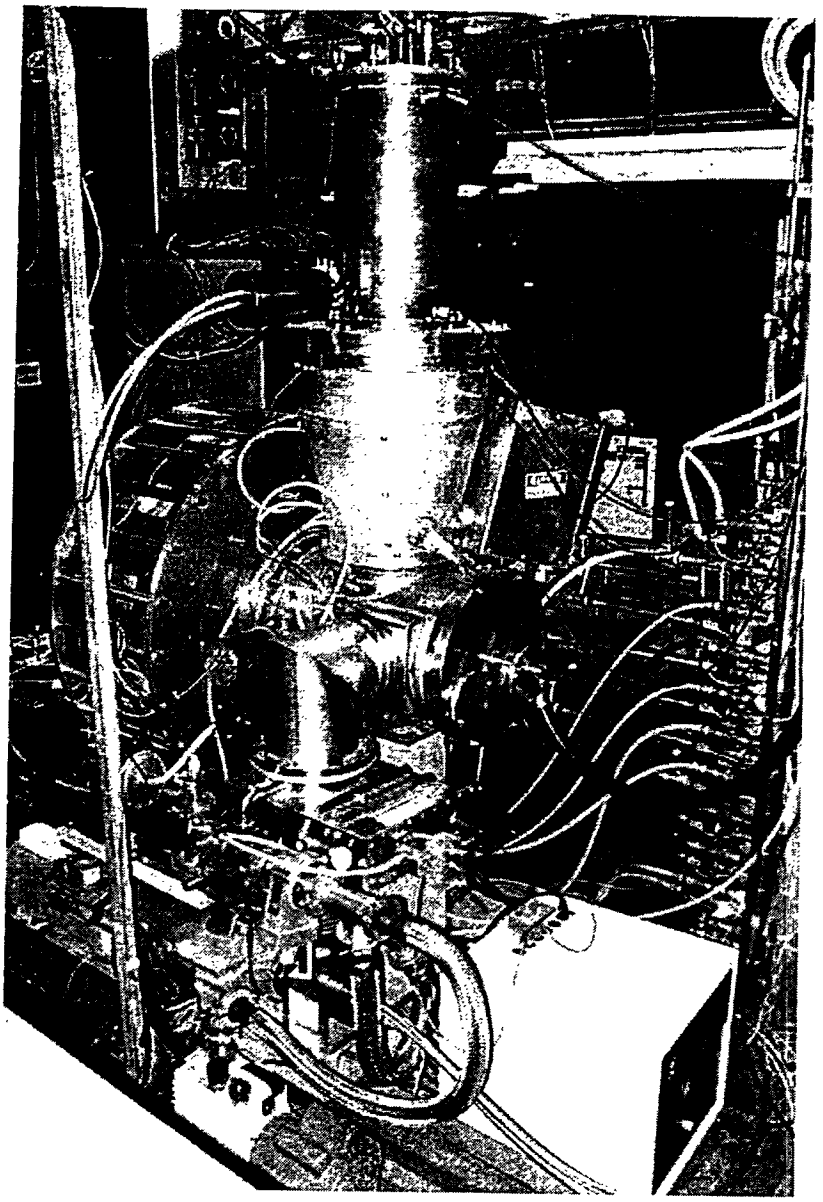
Z. Qian

F(MHZ)	0 mm	15 mm	25mm	46 mm	75mm	KEK 0 mm	KEK 15 mm
0.5	6.6911	4.8716	3.3759	3.1146	2.426		
1	5.0504	7.4947	5.3955	5.5026	4.474	6.0667	
1.5	3.8667	8.3863	6.9395	7.2066	6.174		
2	3.1716	8.5126	7.9158	8.3836	7.495	3.58	14.378
3	2.3332	7.8062	8.0285	9.3572	9.058	2.631	10.774
4	1.8495	7.5958	7.9158	9.8448	9.845	2.501	8.6067
5	1.4882	6.4596	7.8062	9.3572	9.845		7.539
6	1.2305	5.7894	7.3961	9.0579	10.019		6.228
7	1.0176	5.1929	7.0264	9.8572	10.019		5.6678
7.5	0.9228		6.535	8.9152	10.78		
8	0.8421	4.6646	6.3137	8.7769	10.58		5.255
9	0.6873	4.1976	5.85	8.2636	10.39		
10	0.543	3.6806	5.2422	7.3962	9.514		
11	0.4204	3.3332	4.7867	6.9395	9.058		
12	0.3057	2.9887	4.4015	6.4596	8.643		
13	0.198	2.6746	4.0408	5.9758	8.144		
14	0.0963	2.4023	3.7062	5.5026	7.7		
15		2.1155	3.3332	5.0045	6.94		
16		1.8807	3.0061	4.6252	6.535		
17		1.6577	2.7475	4.2635	6.174		
18		1.4496	2.5002	3.9232	5.789		
19		1.2527	2.257	3.5816	5.396		
20		1.0612	2.0145	3.2305	4.959		



(ii) 53 MHz rf system:

option I — to modify Kaon factory booster cavity;



- higher accelerating gradient;
- higher shunt impedance.

F. Mills

B_{max} = 1.5 T (16 GeV)

B_{min} = 0.0846 T (400 MeV)

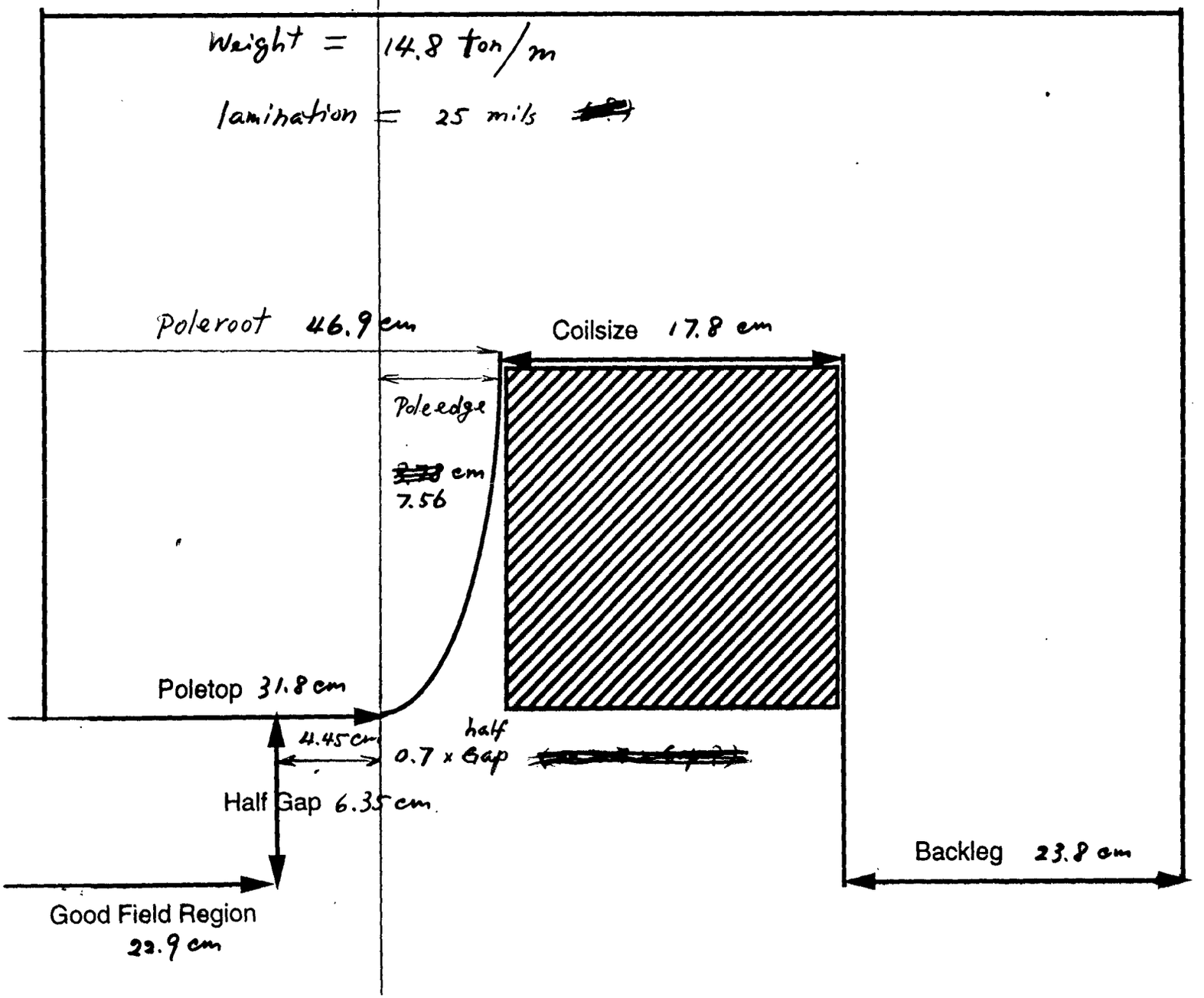
I_{peak} = 152 KA

I_{rms} = 127 KA

J_{rms} = 2 A/mm²

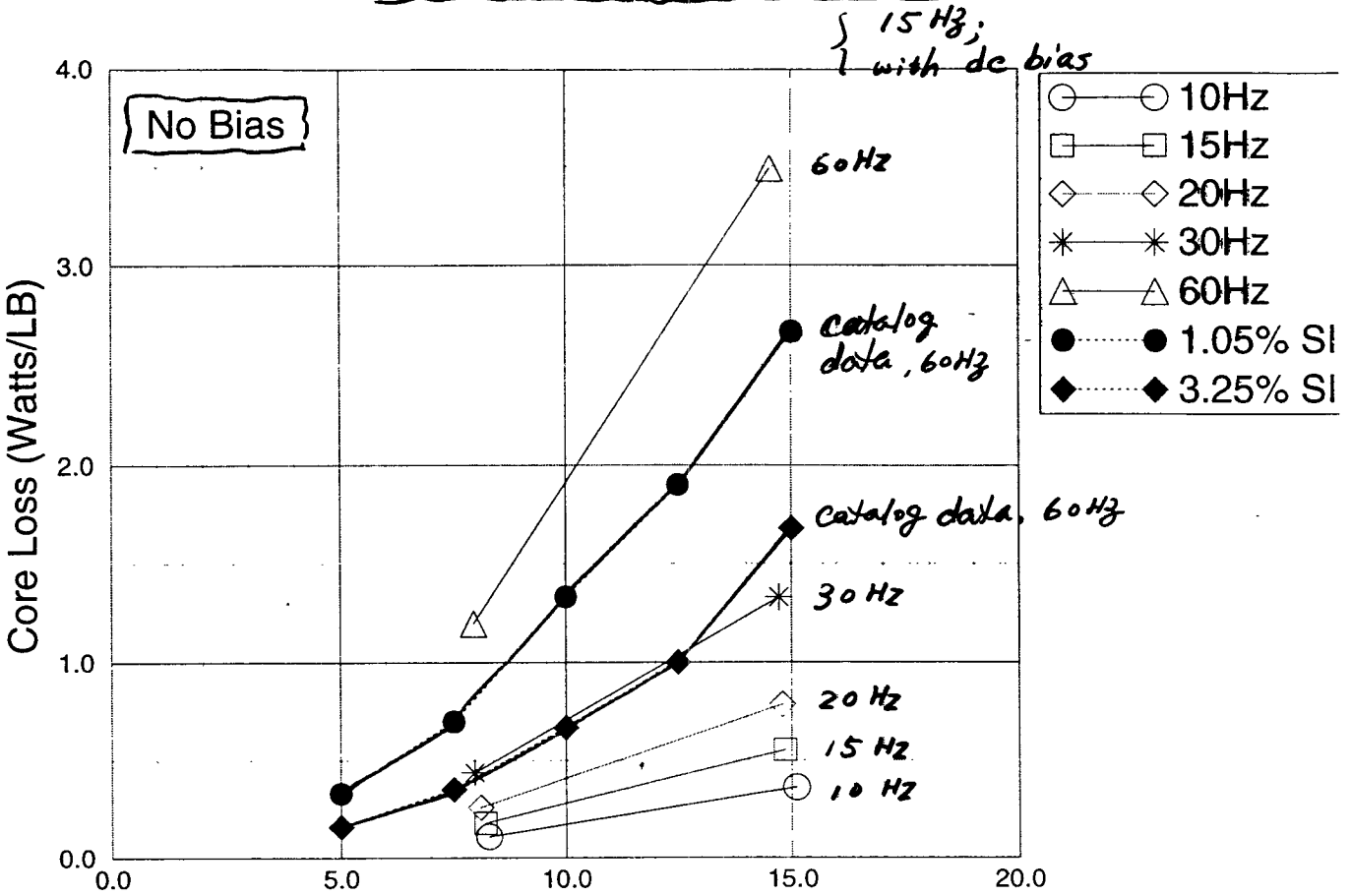
Weight = 14.8 ton/m

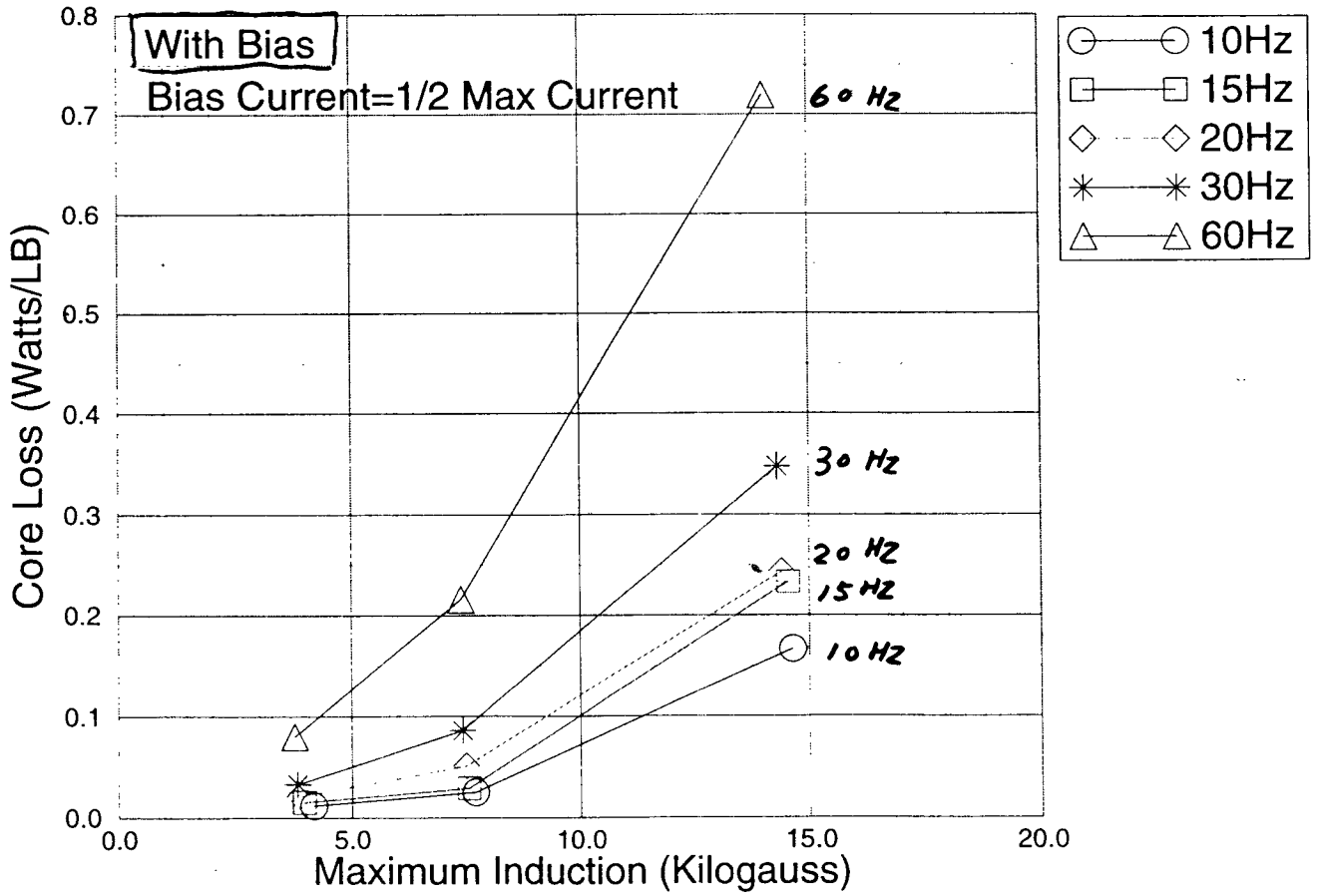
lamination = 25 mils



S. Fang

14-mil Nonoriented Silicon Steel Core Loss Measurement (4/29/99)





(C) Power supply :

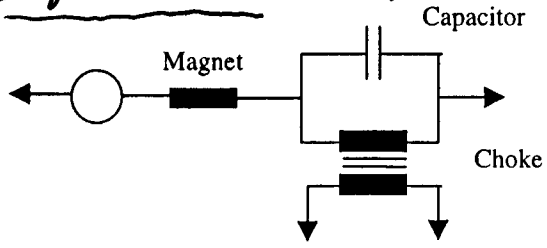
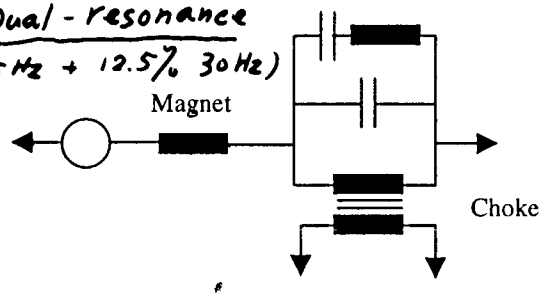
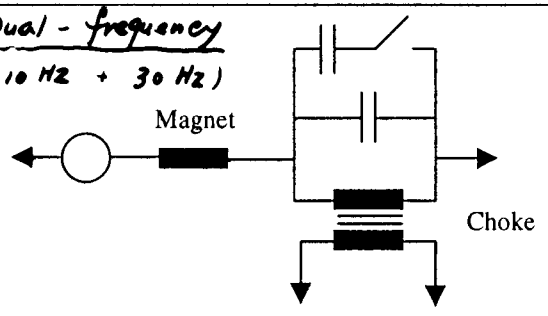
C. Jach

(5/13/99)

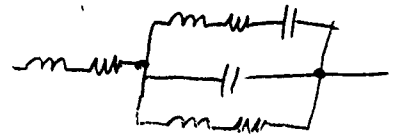
<i> Programmable p.s. is excluded : - too expensive;
- no practical solution for energy storage.

<ii> Three resonant p.s. :

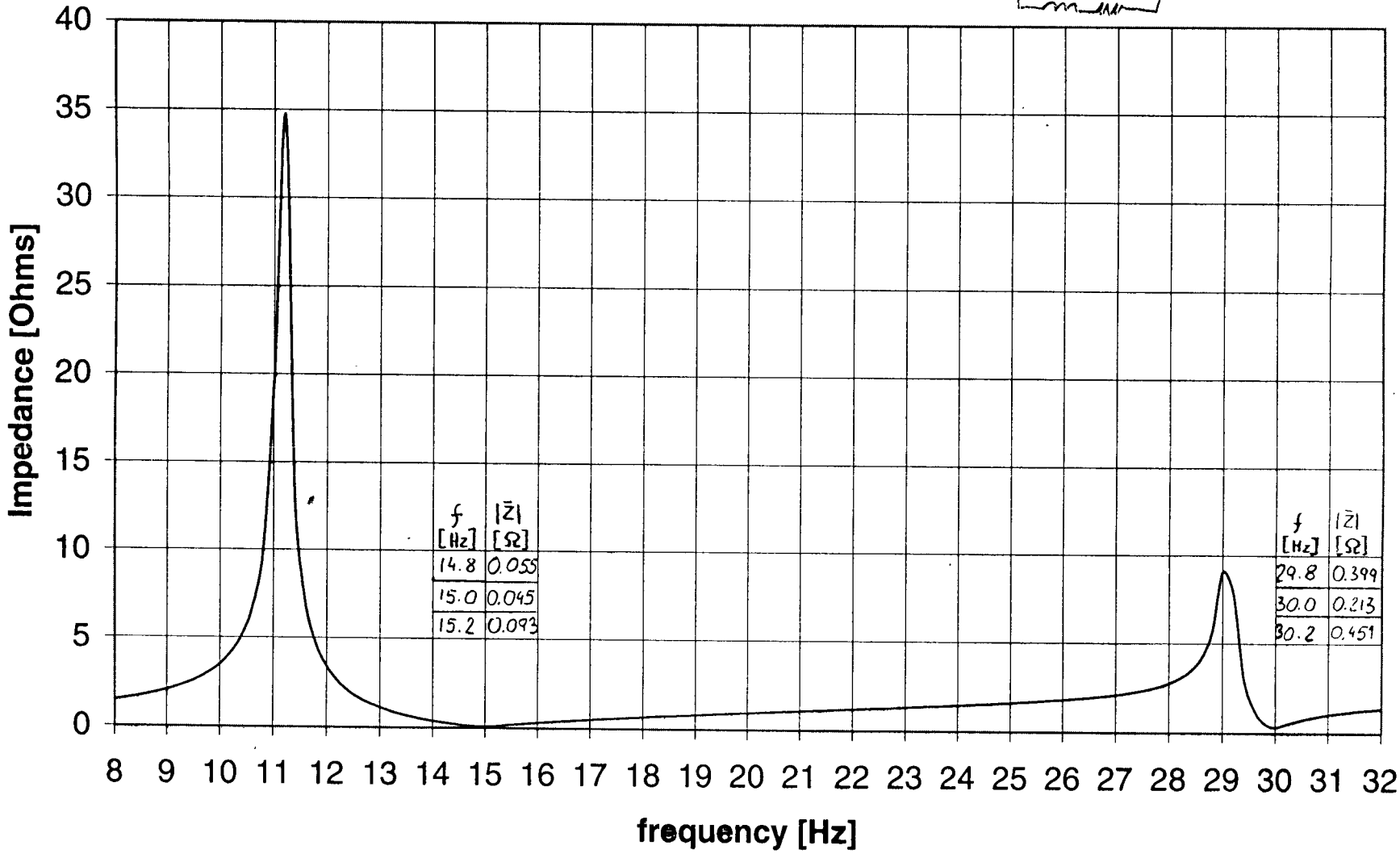
Booster Dipole Power Supply Summary

Circuit	Cost (hardware only)	Remarks
Single resonance (15 Hz)  	Caps, Chokes, PS's - 13.9 M$ Infrastructure - 5.1 M$ Contingency (25%) - 4.8 M$ **Total Dipole PS - 23.8 M$**	• Least complicated, well understood, many existing systems including Fermi Booster
Dual - resonance (15 Hz + 12.5% 30 Hz)  	Caps, Chokes, PS's - 17.8 M$ Infrastructure - 5.1 M$ Contingency (25%) - 5.7 M$ **Total Dipole PS - 28.6 M$**	• Never built before • Cost estimate assumes 12.5% of 30 Hz • Reliable • Could be built without test stand
Dual - frequency (10 Hz + 30 Hz)  	Caps, Chokes, PS's - 13.9 M$ Switches - 1.5 M$ Infrastructure - 5.1 M$ Contingency (40%) - 8.2 M$ **Total Dipole PS - 28.7 M$**	• Never built before • Requires test stand, possibly multi-cell (not in estimate) • Unknown reliability • Unknown effect of switching transient on beam especially during injection.

LC Trap with losses



(for Parameters see previous page)

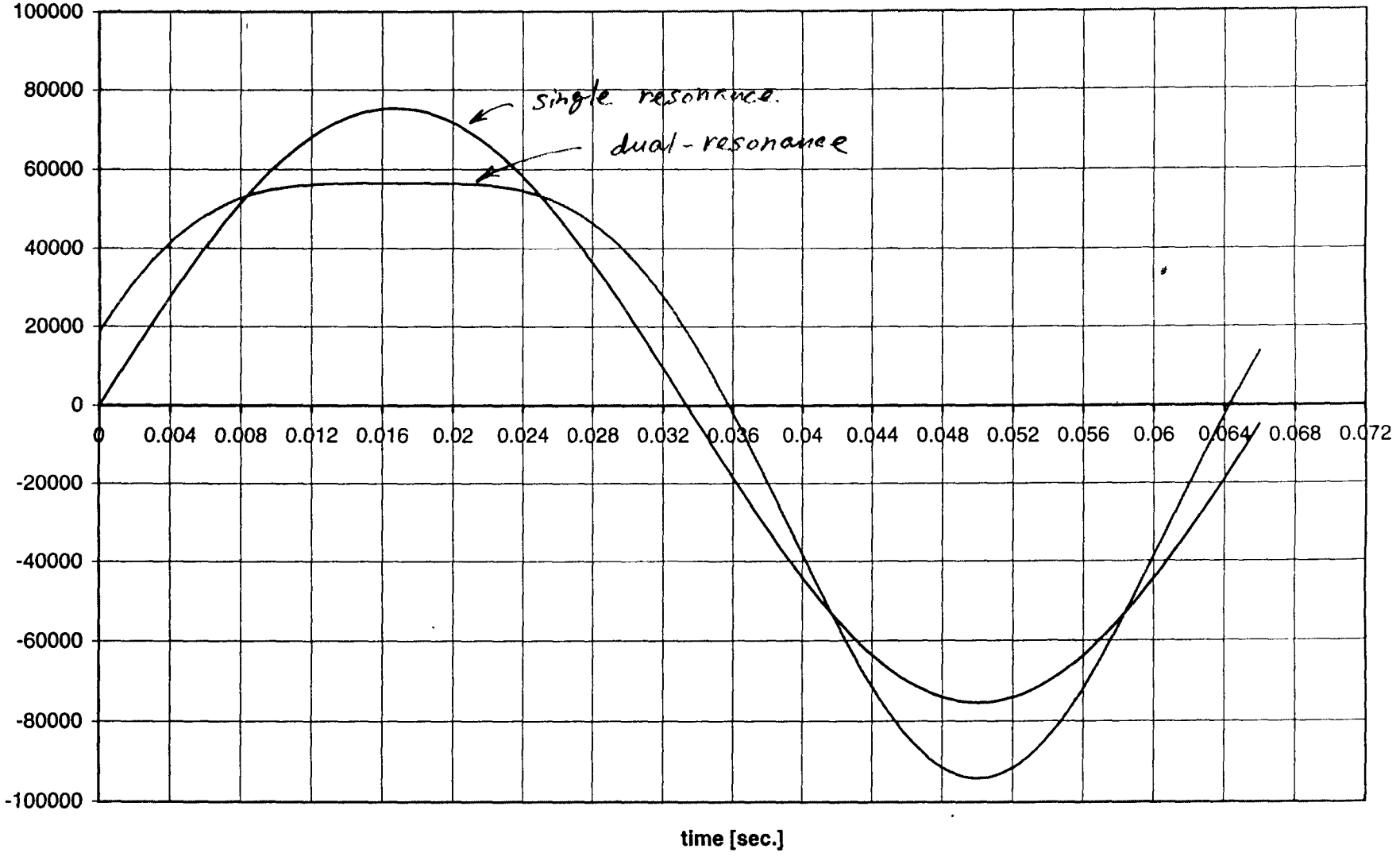


f [Hz]	|Z| [Ω]
14.8	0.055
15.0	0.045
15.2	0.093

f [Hz]	|Z| [Ω]
29.8	0.399
30.0	0.213
30.2	0.451

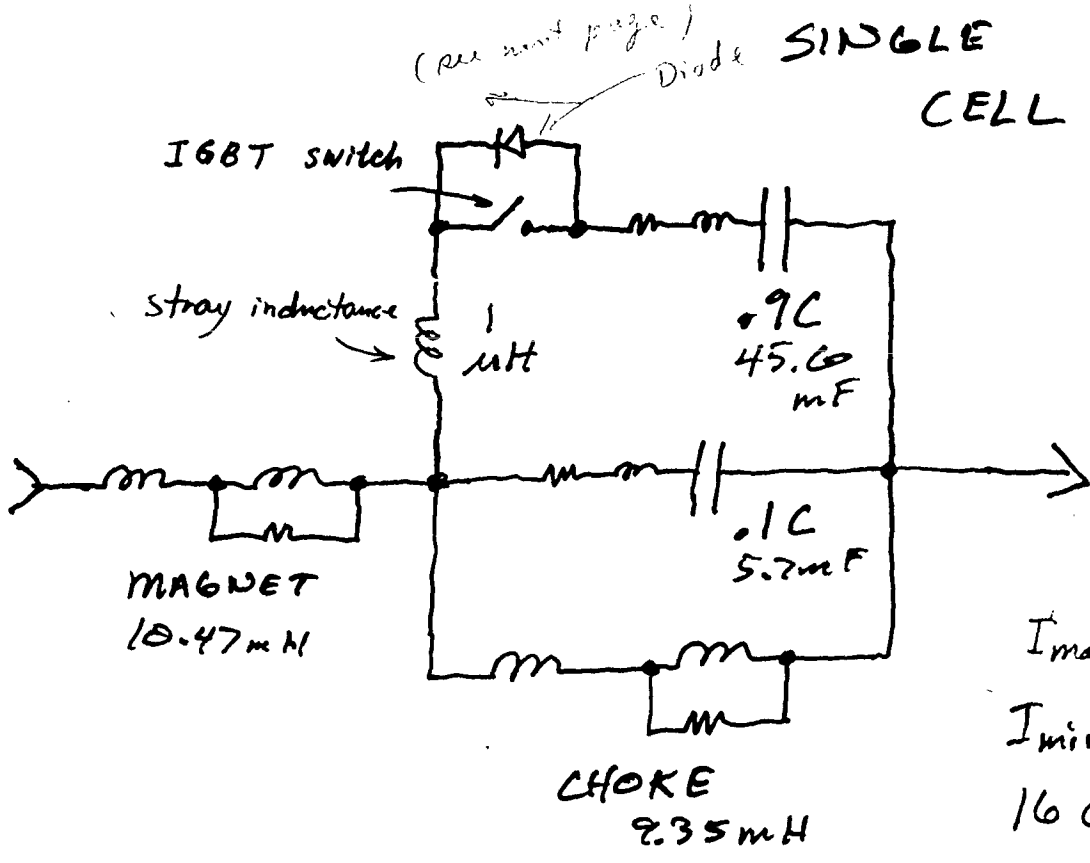
10a

Magnet Current Derrivatives $\frac{dI}{dt} \sim \dot{B}$



D. Wolff

(4/8/99)



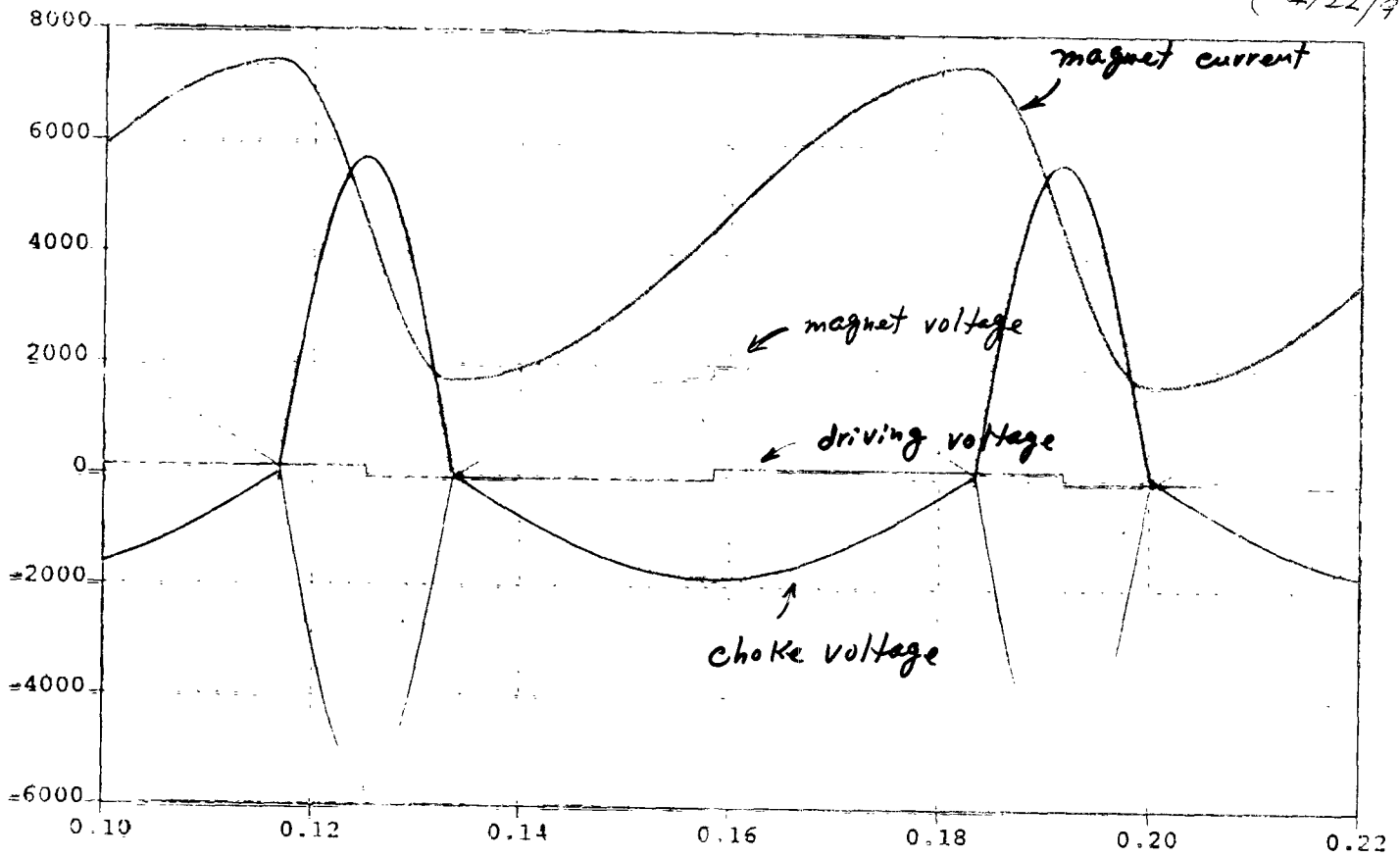
$I_{max} = 7500$ A

$I_{min} = 1695$ A

16 cell system

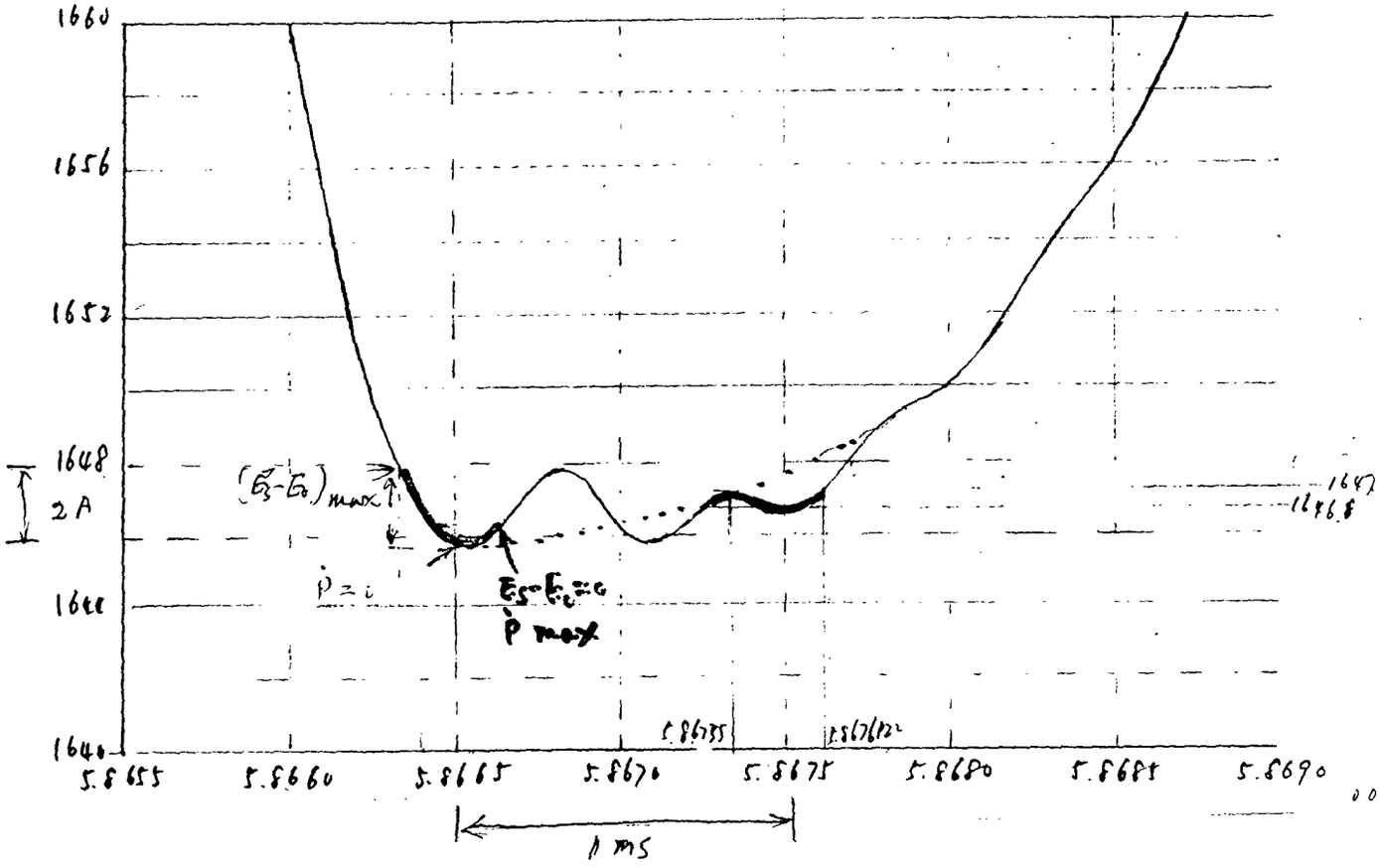
DUAL FREQUENCY

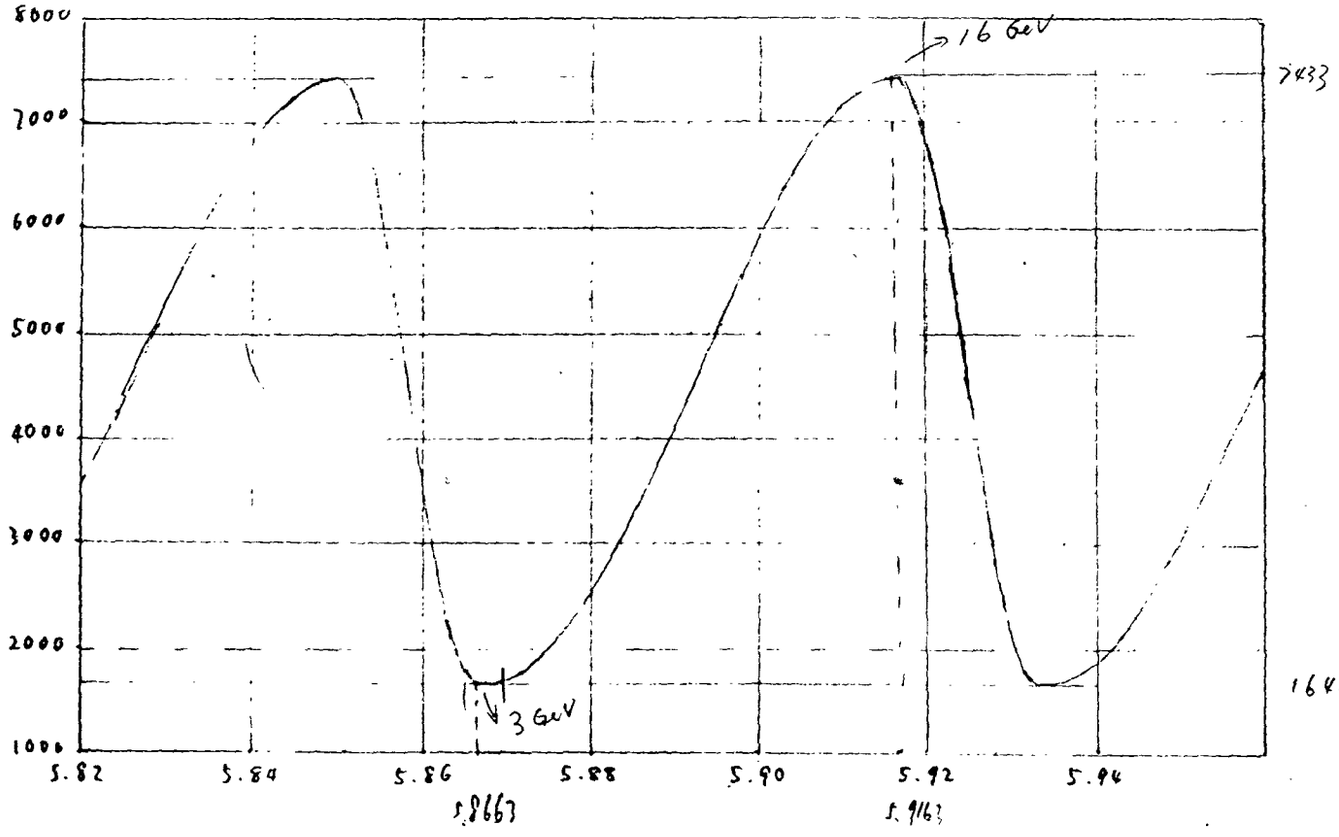
D. Wolff
(4/22/94)



(file DUAL FRQ.PL4; x=var t) v:C1D -C1G C:VDRIV -C1A

7



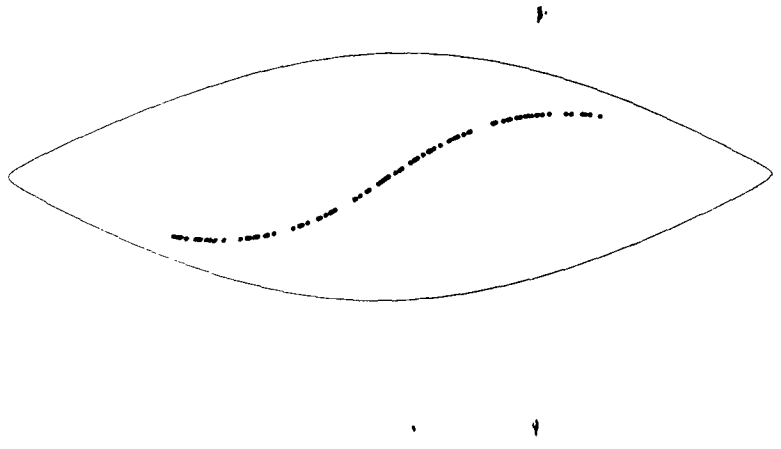


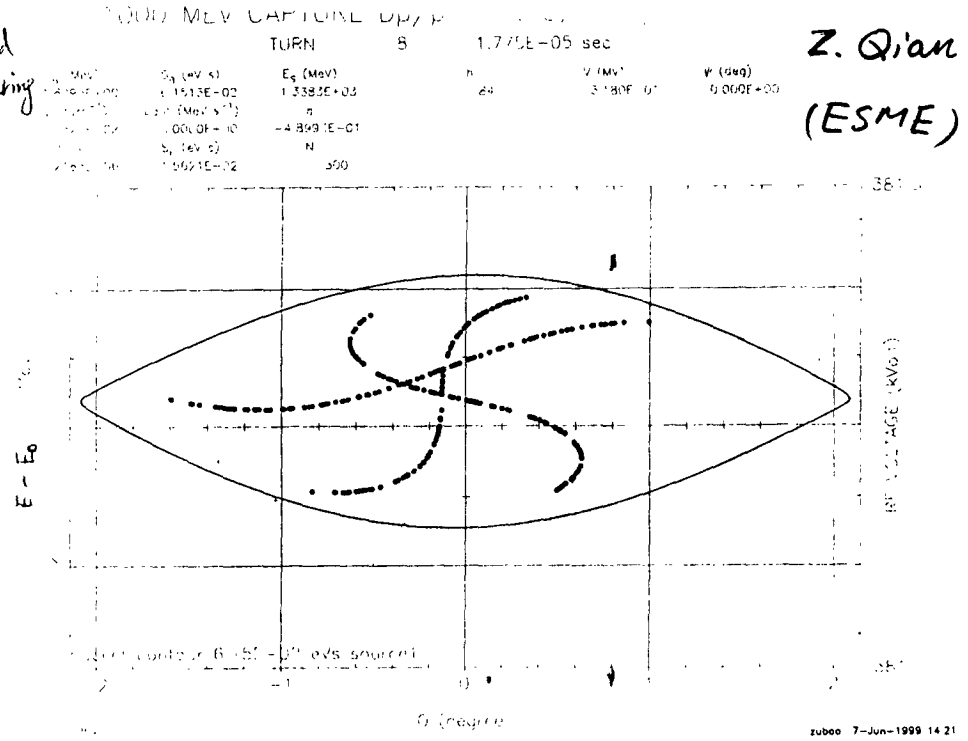
7433 − 1646 = 5787

3

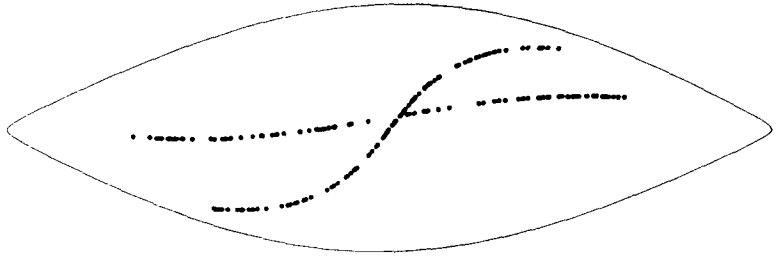
when B field decrease During injection

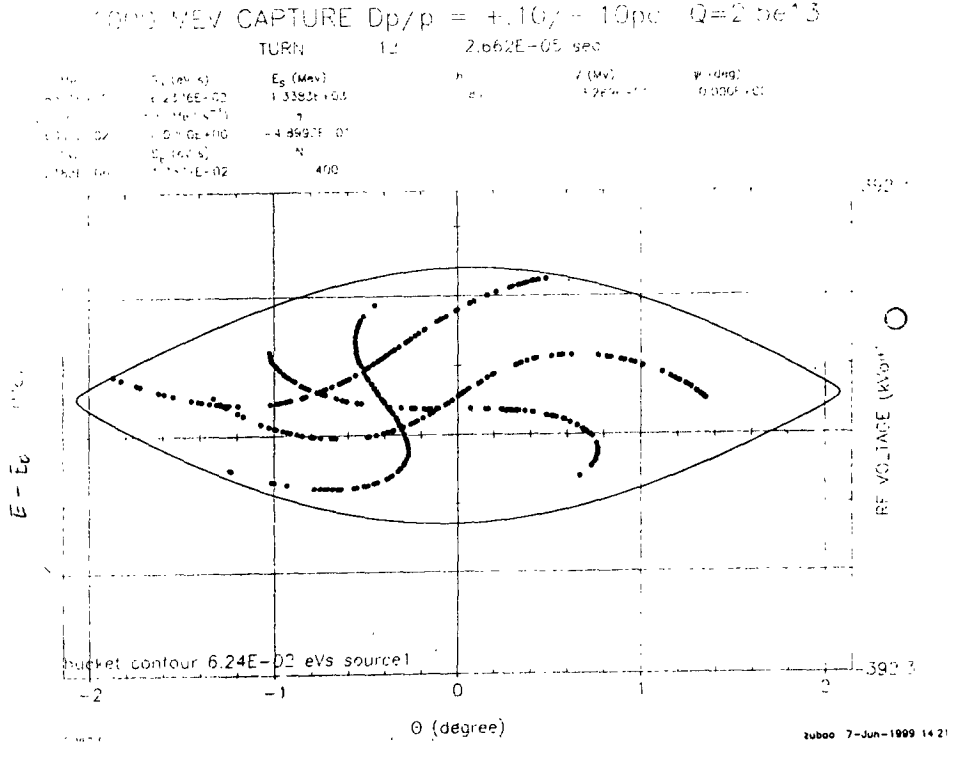
Z. Qian (ESME)



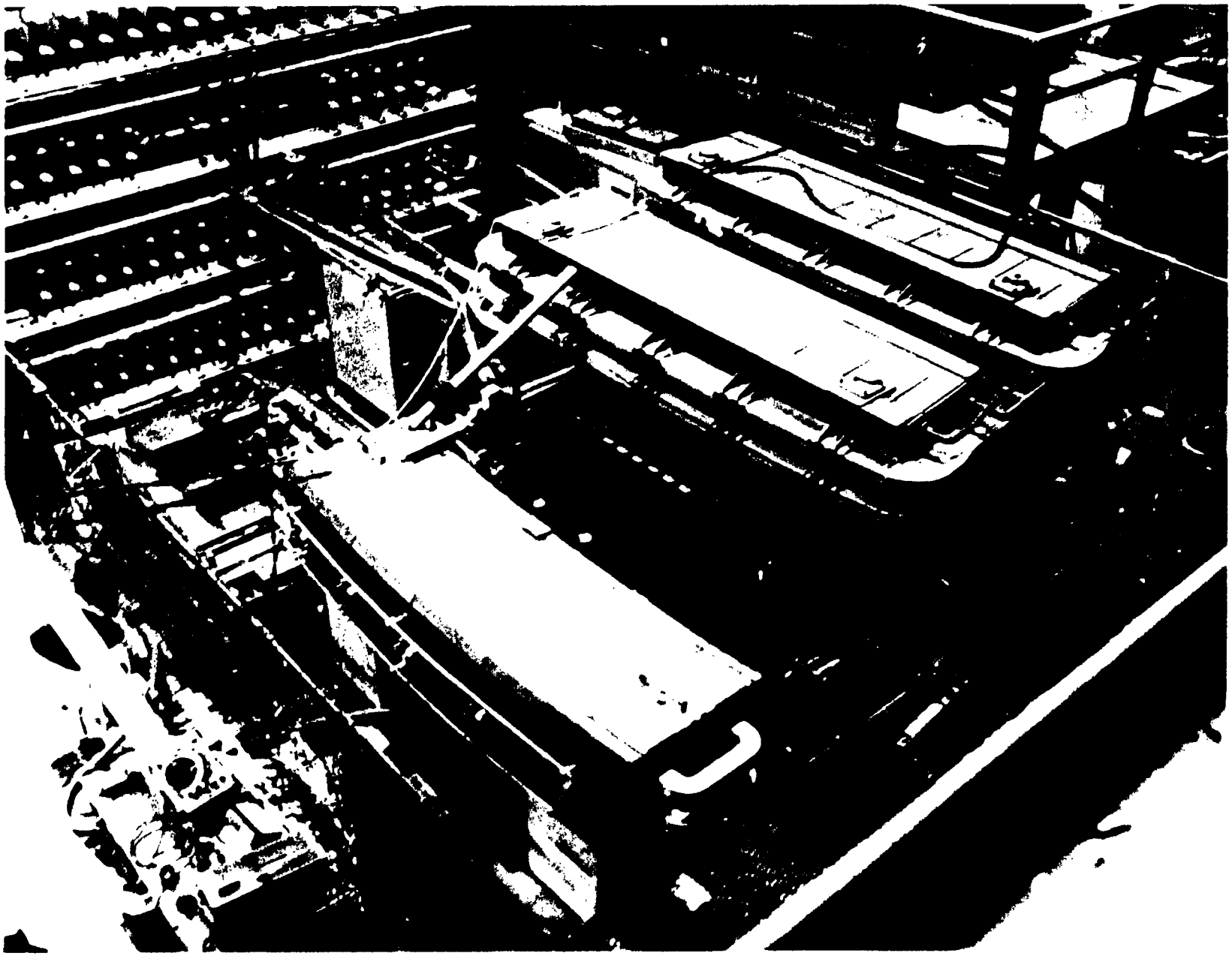


4





Triumf dual-frequency power supply test station (K. Reinger)



UP SUPERIEURE OBEN あと

(d) Beam pipe

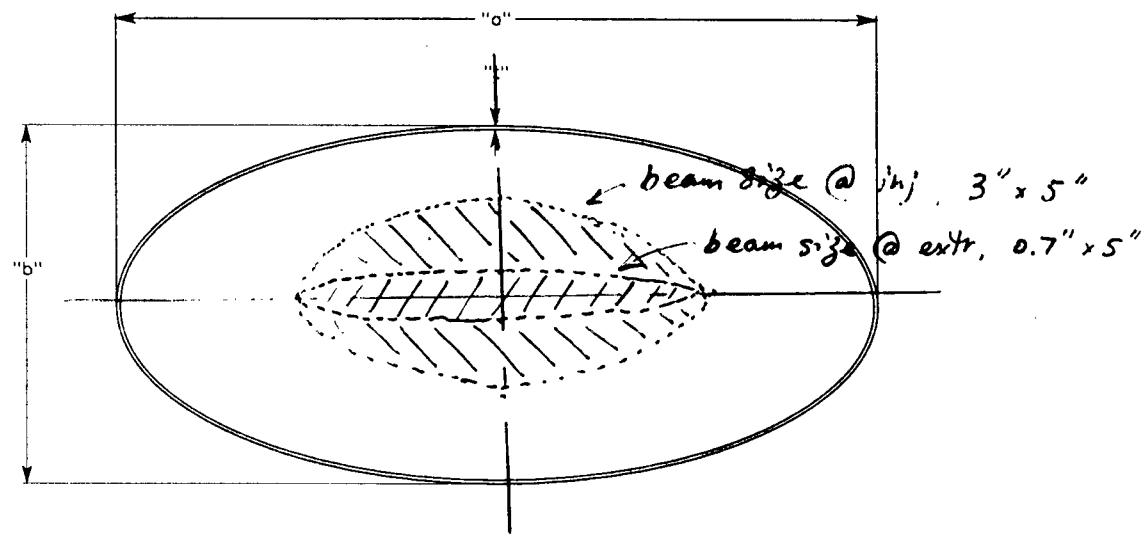
T. Anderson

Tube Stresses

Vacuum Stresses and Deflections for 5 x 10 Proton Driver Beam Tube

Inconel pipe, 5" x 9" x 0.05"

Pressure (p) =	-14.700 psi
Wall Thickness (t) =	0.050 in.
Major Axis (a) =	8.339 in.
Minor Axis (b) =	5.992 in.
Ratio b/a =	0.719
Geometry Const. (K2) =	0.140
Geometry Const. (C1) =	0.036
Geometry Const. (C2) =	-0.024
Material =	Inconel 718
Modulus of Elasticity =	2.84E+07 psi
Poisson's Ratio =	0.288
Flexural Rigidity of Material (D) =	322.590 in.-lb.
Yield Strength (Sy) =	150 - 220 ksi
Ultimate Strength (Su) =	180 - 230 ksi
Max Stress =	87 ksi
Delta "b" =	-0.992 in.
Delta "a" =	0.661 in.
Minumum Yield Strength Needed (Sy') =	145 ksi
Final Shape:	
a' =	9.000 in.
b' =	5.000 in.



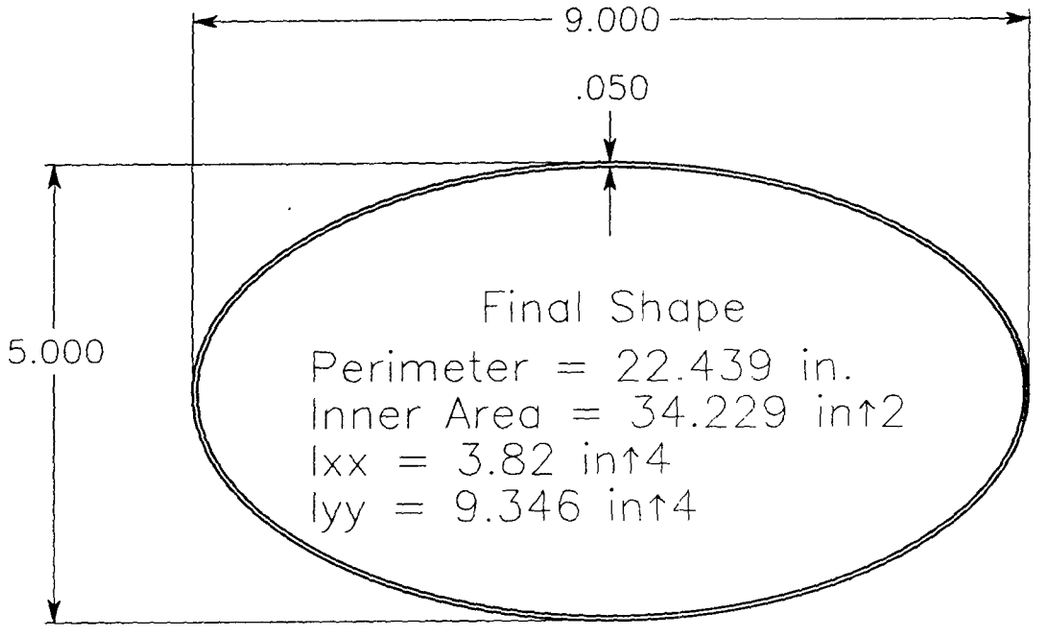
Problems :
- large deflection under vacuum
- eddy current heating
- eddy current error field

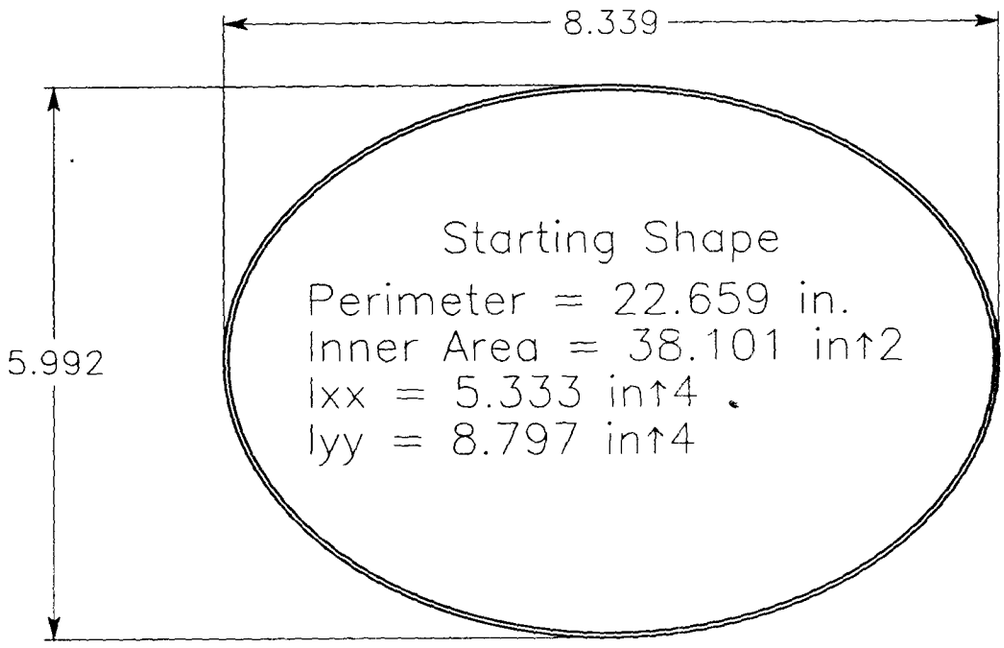
- fall-back solution : ceramic pipe + rf gap (as at ISIS)

  problem — need additional $1\frac{1}{2}$" ~ 2" vertical aperture

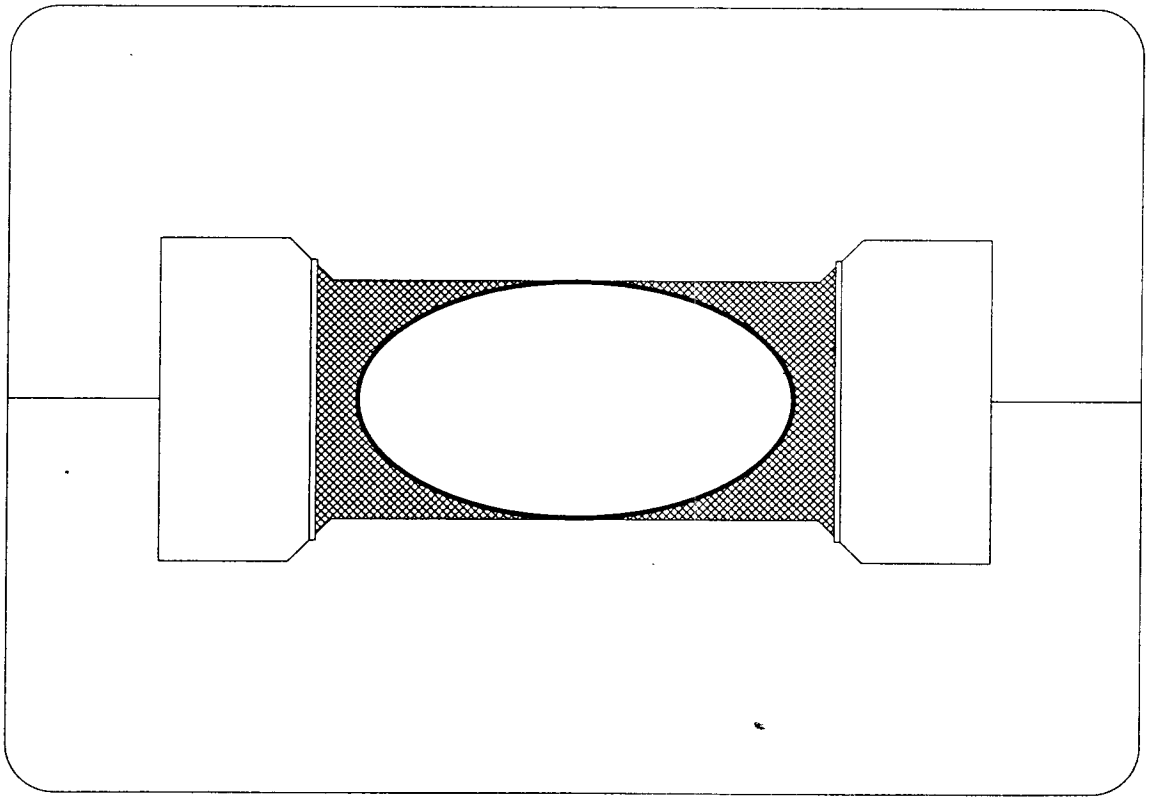
T. Anderson

Proton Driver Beam Tube Section





T. Anderson
(6/17/99)



masterbond: electrical resistivity:

$\rho = 10^{13} \sim 10^{14}$ $\Omega \cdot cm$

thermal conductivity

$10 \sim 25$ BTU-in/hr/ft^2/F°

(Inconel: 77)

/adms/home/v21_1/ms_emalone/magnet_thermal.mf1

E. Malone

RESULTS: 1- B.C. 1,LOAD 1,TEMPERATURE_1

TEMPERATURE - MAG MIN: 6.85E+02 MAX: 1.09E+03

VALUE OPTION:ACTUAL

F. Ostiguy
(6/24/99)

MULTIPOLES DUE TO EDDY CURRENTS

Assumptions:

(1) Elliptical beam pipe
(2) thickness >> skin depth
(3) Induced magnetic field << Main field

Magnetic gap	13	cm
Beam pipe wall thickness	1.25	mm
Beam pipe conductivity	0.8e6	mho m**-1
Beam pipe major radius (width):	11.34	cm
Beam pipe minor radius (height):	6.35	cm
dB/dt	780	kG/s
B	13	kG

NORMALIZED MULTIPOLES * 10**4 AT 2.54 cm

No Image Currents

Pole	normal	skew
2	-36.00365	0.00000
4	0.00000	0.00000
6	0.45323	0.00000
8	0.00000	0.00000
10	-0.00911	0.00000
12	0.00000	0.00000
14	0.00021	0.00000
16	0.00000	0.00000
18	0.00000	0.00000

Including Image Currents

Pole	normal	skew
2	-92.76814	0.00000
4	0.00000	0.00000
6	2.61130	0.00000
8	0.00000	0.00000
10	-0.14606	0.00000
12	0.00000	0.00000
14	0.00103	0.00000
16	0.00000	0.00000
18	-0.00002	0.00000

(e) H^- source and linac:

<i> Intensity requirement:

- Phase I — 45 mA × 90 μs through 400 MeV: Present linac is ok.
- Phase II — 30,000 mA-μs from H^- source; 16,000 mA-μs through 1 GeV. needs lots of work.

<ii> Two experiments:

- high current proton expt. (done)
- long pulse klystron expt.

<iii> Development of new H^- source and RFQ to be started.

<iv> chopper development — New type, using Finemet, in collaboration with the KEK; will be tested at the HIMAC.

(f) Wall power:

<i> RF:

Each 20 KV cavity:

power to cavity:

$R_{sh} = 1\ K\Omega \qquad P = 200\ KW$

power to beam:

$I_{dc} = 10\ A \qquad P = 200\ KW$

400 KW

50 cavities for 1 MV: 20 MW

50% duty factor: 10 MW

<ii> magnet power supply:

Estimate 1:

ac loss + dc loss + pipe loss ~ 30 KW/m

total magnets ~ 300 m 10 MW

Estimate 2:

Present booster. 1.3 MW

new booster x 6 ~ 7

(larger magnet, higher B, higher I)

Booster total ~ 20 MW

+ pre-booster + linac → Total ~ 30 MW

Efficiency: $\frac{\text{Beam power}}{\text{Wall power}} = \frac{4\ MW}{30\ MW} \sim 13\%$

5. Collaborations:

- Proposals from BNL-Fermilab and LBNL-Fermilab
- US-Japan accord:
  - High gradient rf cavity development. Fermilab is fabricating a Finemet cavity using the cores provided by Japan.
  - RF chopper development. It will be built at KEK and tested at HIMAC.
  - Beam halo and collimation study.
  - Barrier cavity development. (KEK and BNL)
- Machine experiments:
  - High intensity bunch rotation experiment at the AGS (Jan 1999). (Roser, Brennan)
  - Inductive insert experiment at the PSR (summer 1999). (Macek)
- ICFA mini-workshops on high intensity proton machines:
  - Sept 13-15, 1999 at Fermilab, on *beam halo and collimation*; the organizers are N. Mokhov and W. Chou.
  - March 6-8, 2000 at CERN, on *longitudinal emittance control and measurement*; the organizers are T. Linnecar, E. Shaposhnikova, R. Cappi and R. Garoby.
  - (Mid-February, 2000 ?) at LANL, on *2-stream beam instability*; the organizers are R. Macek, A. Thiessen and K. Harkay.

(Pending ICFA approval)

- ICFA "full" workshop on *high intensity high brightness hadron beams*: September or October 2000 at Fermilab.
- ICFA Beam Dynamics Newsletter: August 1999 issue will be a *special issue* on high intensity high brightness hadron beams.

PROPOSAL FOR PROTON DRIVER STUDIES IN FY99

Summary

Title: Muon Collider Proton Driver R&D

Topics: 1. Inductive insert experiment at the AGS
2. High gradient rf cavity development

Collaborating labs and contacts: Fermilab (D. Neuffer and W. Chou), BNL (T. Roser)

Budget proposal: 200,000 dollars in FY99.

Description of the Work

1. Proposal to study passive compensation for longitudinal space charge effects in the BNL AGS by insertion of ferrite inductors:

   In the development of a muon colliding beam facility the proposed source for muons is a fast cycling proton synchrotron capable of delivering two or four bunches per cycle with total beam intensity 10^{14} protons per cycle. This proton source is also useful for low energy intense muon beam and neutrino beam experiments (which the KEK is interested). The extracted bunches are required to be very short, with $\sigma \sim 1$ ns. As the bunches are shortened prior to extraction (by whatever technique), the momentum spread and horizontal beam size will be determined by the longitudinal emittance of each bunch. In order to achieve the required performance without demanding very large momentum aperture it will be imperative to minimize the growth of the beam longitudinal emittance during injection and acceleration. Space charge forces in the very intense injected beam at low momentum will be potentially harmful in this context.

   We propose here to study a technique for controlling the space charge effect in a proton driver synchrotron (below transition), through the intentional introduction of controllable inductance into the vacuum chamber of the Brookhaven National Laboratory Alternate Gradient Synchrotron (AGS). This concept has been described by A. Sessler and V. Vaccaro in 1968 [1]. Here we assume that the effective space charge in the AGS is about -j50 Ω [2]. The existing inductive components of ring impedance (about j10 Ω) reduce the space charge impedance, leaving about -j40 Ω requiring compensation. Complete cancellation of the space charge effect at injection would require insertion of about 19 μH inductance for the AGS revolution frequency of $\omega_0 = 2.2 \times 10^6$.

   At Fermilab there is a large supply of Ni-Zn ferrite cores, 8" O.D., 5" I.D., and 1" thick. (Circular inner aperture 127 mm.) The cores have nominal $\mu_r \sim 50$ up to about 45 MHz. A "waveguide inductance" composed of such cores would have inductance 4.7 μH/m. Full compensation of the AGS space charge effect would require insertion of four meters of such cores. The cores can be fit into stainless steel chambers with vacuum flanges at each end. Two

PROPOSAL FOR ION SOURCE STUDIES FOR THE PROTON DRIVER

Summary

Title: H^- Ion Source R&D for the Proton Driver

Collaborating labs and contacts: LBNL (K. Leung) and Fermilab (W. Chou).

Duration: January 1999 - December 1999

Budget: $60,000

Description of the Work

In the development of a muon colliding beam facility and/or a muon storage ring, the proposed source for muons is a fast cycling proton synchrotron (the proton driver) capable of delivering two or four bunches per cycle with total beam intensity 10^{14} protons per cycle. This proton driver is also useful for low energy intense muon beam and neutrino beam experiments, in which the KEK and CERN have shown interest. In order to stack 10^{14} protons in the proton driver, a powerful H^- source is required. This source will provide an intense H^- beam that will be transported, bunched, chopped and accelerated in a linac system and, then, will be injected to and stripped and stacked in the prton driver. Assuming that the transport efficiency is 80% and one-third of the beam will be chopped, the required intensity of the H^- beam from the source is 30,000 mA-μs. To achieve this goal, one may consider two possible scenarios: (a) a pulse current of 150 mA and a pulse length of 200 μs, or (b) 75 mA and 400 μs. At a repetition rate of 15 Hz, the duty factor for (a) and (b) will be 0.3% and 0.6%, respectively. At this moment, scenario (a) is considered to be the preferred one, because a long injection time will lead to bunch tilting due to synchrotron oscillation, which makes longitudinal painting difficult.

The ion source group at the LBNL has a long history of designing and building various types of ion sources with good beam quality. Its ion sources are used by many institutions over the world. It has the needed expertise, machine shop and measurement facility. One of its test stations can be made available for the purpose of testing the ion source of the proton driver.

We propose to start an H^- source R&D program for the proton driver at the LBNL. It will be staged as follows:

1. Modify the SSC H^- prototype source for Cs and H_2 operation.

2. Set up the LBNL 2 MHz RF generator for 200 μs or 400 μs pulse lengths at a repetition rate of 15 Hz.

3. Produce H^- beam current of 75 mA at 400 μs pulse and 150 mA at 200 μs pulse.

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研究課題名	（英文）High Intensity Proton Facility R&D	研究場所	☐ BNL ☐ FNAL ☐ SLAC ☐ LBNL
	（和文）大強度陽子加速器の開発		

研究計画概要	研究期間	平成 年度 ～ 平成 年度

本研究はBNL、FNAL、LBNL及びKEKの四研究所において陽子加速器の大強度化を目指す共同研究である。加速器科学の種々の展開において高エネルギーで大強度の陽子加速器の開発は極めて重要な課題の一つである。BNLのAGSは現在世界最高ビーム強度を誇り、FNALでは現在建設中のMain Injector並びにそのための新ブースター等により飛躍的なビーム強度の増大を目指しており、またLBNLでは世界最大輝度の体積生成型負水素イオン源を実現している。一方KEKでは大型ハドロン計画（JHF）によりビーム強度を現在の世界的レベルの１０倍近く増大させる加速器の建設を目指している。本研究では以下に述べるように、このような大強度陽子加速器を実現するために必要で重要ないくつかのテーマを選び共同研究を行う。

〈研究事項〉

1. 障壁バケツ用高周波空胴の開発
   陽子シンクロトロンビーム入射時に大きな問題となる空間電荷効果を低減して、より多くのビームをスタッキングするための方法として“障壁バケツ”法がある。本研究ではこのために必要な空胴２台（KEK、BNLそれぞれにおいて１台ずつ）開発しBNLのAGSにおいてビーム実験を行う。
2. 高加速勾配高周波空胴の開発とビーム負荷補償の研究
   新金属磁性体を用いた７.５－８MHz高加速勾配高周波空胴をFNAL、Main Injectorの３倍ハーモニック空胴及びKEK-PSの２倍ハーモニック用として開発し、それぞれビーム強度増大を図る。またそれを用いて大ビーム電流負荷に対する補償システム研究開発を行う。
3. 空間電荷効果の誘導性インピーダンスによる抑制
   大強度陽子ビーム加速において問題となるLongintudinal方向の空間電荷効果を外部からの誘導性インピーダンスにより抑制する研究を行う。
4. ビーム・コリメーション系等ビーム損失に伴う諸問題の研究開発
   陽子ビームの大強度化は多くそのビーム損失に伴う諸問題によって制限されることが多い。ここではそれに関する研究開発を行い、大強度化を目指す。
5. RFチョッパーの開発
   大強度陽子加速器において問題となる入射ビーム高速チョッピングを実現するための、金属磁性体を用いたRFチョッピングの開発を行う。

平成１１年度所要経費

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BEAM HALO AND SCRAPING

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