Fermilab Proton Driver Design

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Fermilab

$\bar{p}$ 2000 Workshop, Aug 3-5, 2000, IIT

Status Report of the Proton Driver Design Study

OUTLINE

- First technical review and the revised guidance
- Parameter set
- Machine layout
- Technical systems
  - Modification of the linac front end
  - New booster
  - (Transport lines)
- Design issues and R&D
- Schedule of the design report

First Technical Review of the Proton Driver Design

- Charge: From J. Marriner
- Committee: Chaired by P. Martin. Members are: R. Webber, D. Finley, M. Syphers, G. Krafczyk, A. Thiessen (LANL), Y. Mori (KEK), H. Schonauer (CERN).
- Dates: April 17-19, 2000
- Presentations: Total about 30.
- Review report: Issued on May 17. 2000

Revised Guidance from S. Holmes and J. Marriner

1. The first customer of the proton driver would be the Main Injector. The goal is to increase the MI beam intensity by a factor of 3-4. The proton driver would use a 53 MHz rf system for this purpose. One should also study necessary modifications of the MI.

2. If a neutrino factory would be built at Fermilab, then the proton driver should be able to serve both the MI and the neutrino factory. The beam power delivered onto the production target should be about 1 MW. The proton driver should assume a 7.5 MHz rf system. (The MI would still use a 53 MHz rf.)

3. The design study should be focused on Phase I, which includes both stages 1 and 2 above. Phase II, which would serve a muon collider and would require a 1 GeV linac and a 3 GeV pre-booster, should be treated as an appendix in the final report.

4. The present linac should be considered a major design constraint (*i.e.,* 60 mA $\times$ 90 μs, 15 Hz, 400 MeV). This would require a 16 GeV proton driver. However, if the study shows 16 GeV is difficult to achieve or is not cost effective, one should be allowed to reconsider this constraint.

5. The study should include a discussion of the likely performance and cost impacts, both at stage 1 and at stage 2, of varying the energy of the proton driver over the range 16-8 GeV. It should also identify supplemental modifications, for example to the linac energy, required to meet the goals stated in items 1 and 2. (This request is for something analogous to Appendix B in the Neutrino Factory Study.)

Required Beam Power by a ν-Factory

2×10^{20} μ/year for experiments

$\Downarrow$

1/3 useful muons $\longrightarrow 6 \times 10^{20}$ μ/year in the ring

$\Downarrow$

1/15 μ/p(16GeV) $\longrightarrow 9 \times 10^{21}$ p/year

$\Downarrow$

2×10^7 sec/year $\longrightarrow 4.5 \times 10^{14}$ p/sec

$\Downarrow$

15 Hz $\longrightarrow 3 \times 10^{13}$ p/cycle

$\Downarrow$

72 μA average current

$\Downarrow$

16 GeV $\longrightarrow$ 1.2 MW beam power

Table 1: High Beam Power Proton Machines

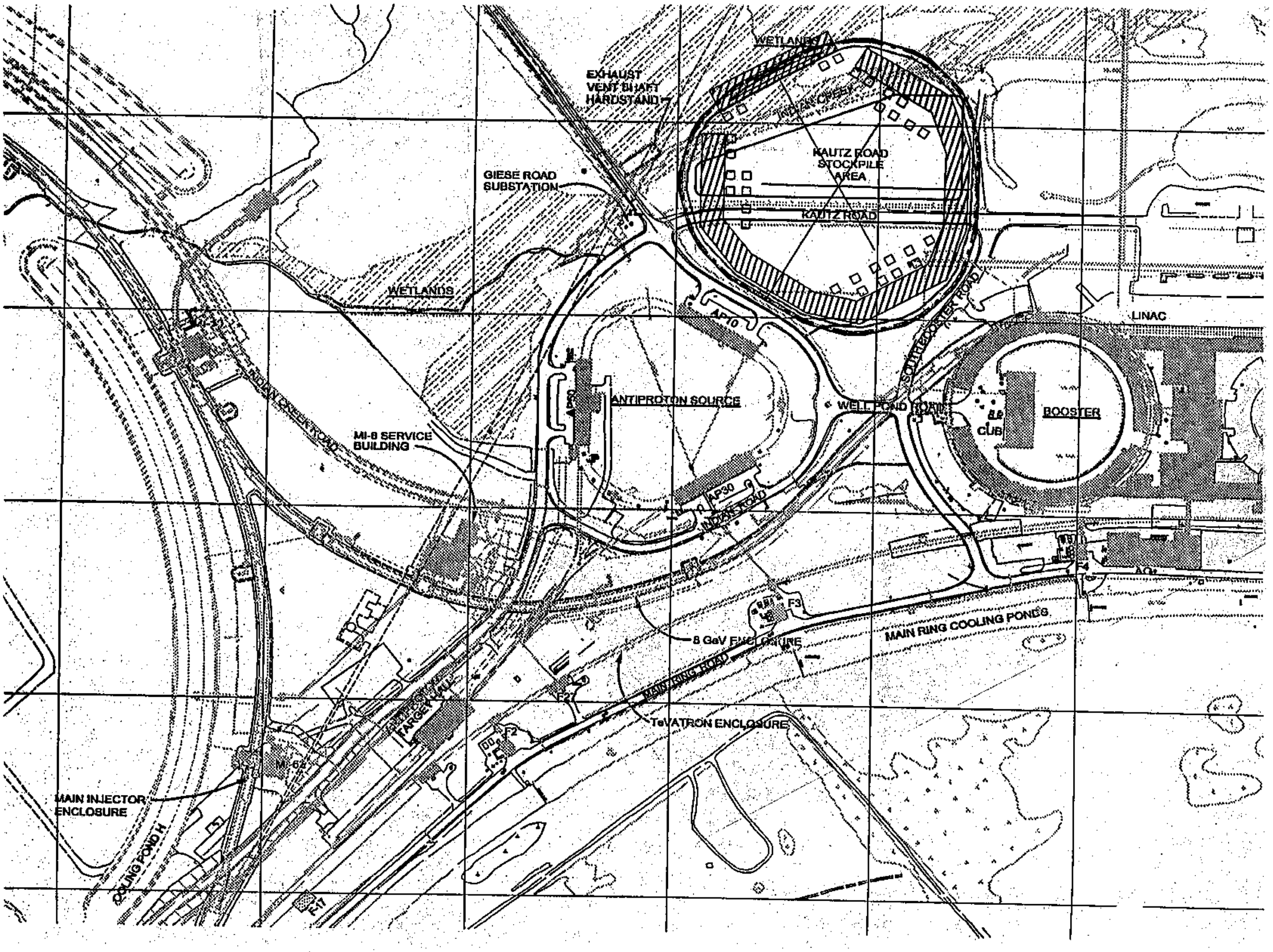
Machine	Protons per Cycle	Repetition Rate (Hz)	Protons per Second	Beam Energy (GeV)	Beam Power (kW)
Existing:					
RAL ISIS	2.5×10^{13}	50	1.25×10^{15}	0.8	160
BNL AGS	7×10^{13}	0.5	3.5×10^{13}	24	130
LANL PSR	2.5×10^{13}	20	5×10^{14}	0.8	64
Planned:					
Fermilab MiniBooNE	5×10^{12}	7.5	3.8×10^{13}	8	50
Fermilab NUMI	4×10^{13}	0.5	2×10^{13}	120	400
Proton Driver Phase I	3×10^{13}	15	4.5×10^{14}	16	1200
Proton Driver Phase II	1×10^{14}	15	1.5×10^{15}	16	4000
Europe ESS	2.34×10^{14}	50	1.2×10^{16}	1.334	2500
ORNL SNS	2×10^{14}	60	1.2×10^{16}	1	2000
Japan JHF	3.3×10^{14}	0.3	1×10^{14}	50	800

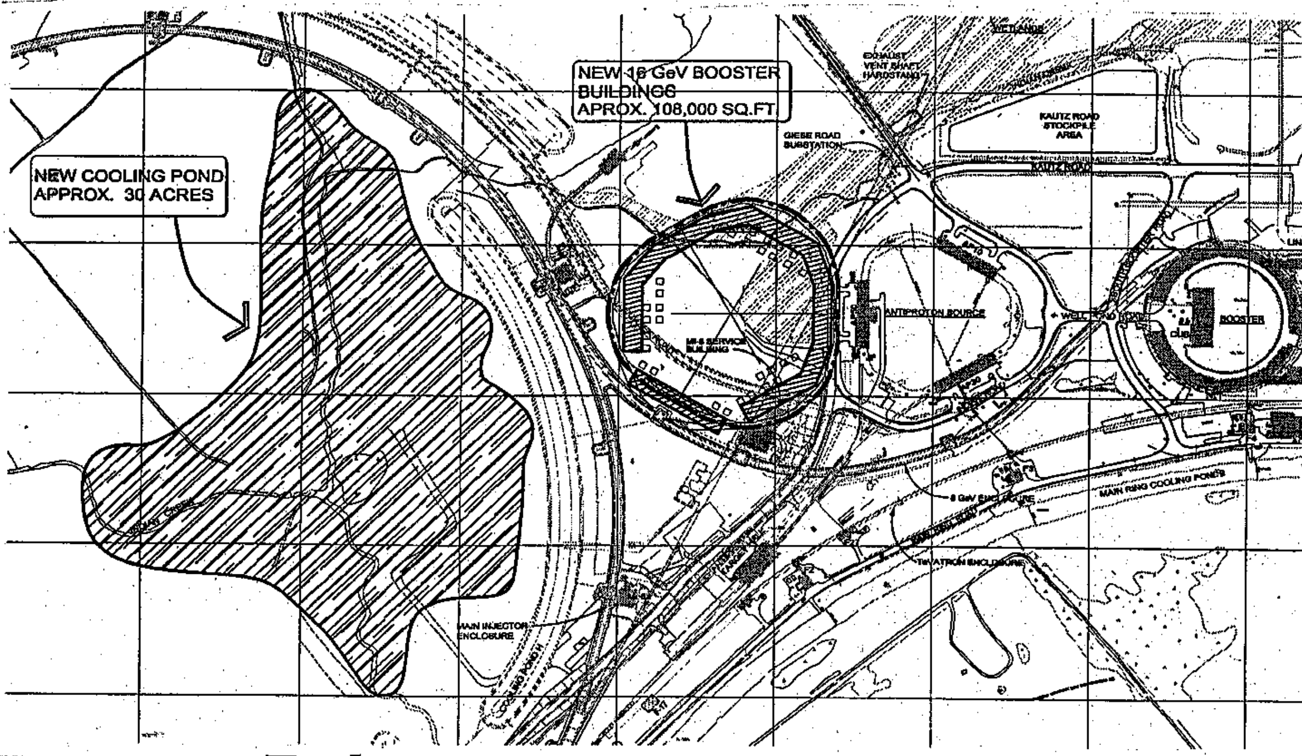
Table 2: Proton Driver Parameters of Present, Phase I and Phase II (04/06/00)

	Present	Phase I (ν-factory)	Phase II ($\mu\mu$-collider)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	3.4×10^{13}	1×10^{14}
Average beam current (μA)	15	81	240
Beam power (kW)	6	32	240
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
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	$7.5\,(1.7) \times 10^{12}$	2.5×10^{13}
Number of bunches	84	4 (18)	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	60π	200π
Longitudinal emittance (eV-s)	0.1	2 (0.5)	2
RF frequency (MHz)	53	1.7 (7.5)	7.5
Extracted bunch length σ_t (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (kW)	100	1200	4000

Table 3: Proton Driver Parameters of Present and Phase I (7/5/00)

	Present	Stage 1 (MI)	Stage 2 (MI+ν-fact)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	400
Peak current (mA)	40	60	60
Pulse length (μs)	25	90	90
H^- per pulse	6.3×10^{12}	3.4×10^{13}	3.4×10^{13}
Average beam current (μA)	15	81	81
Beam power (kW)	6	32	32
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	12	16
Protons per bunch	6×10^{10}	2.4×10^{11}	1.7×10^{12}
Number of bunches	84	126	18
Total number of protons	5×10^{12}	3×10^{13}	3×10^{13}
Normalized transverse emittance (mm-mrad)	15π	60π	60π
Longitudinal emittance (eV-s)	0.1	0.1	0.4
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	3	3
Average beam current (μA)	12	72	72
Target beam power (MW)	0.1	0.9	1.2


WETLANDS
EXHAUST
VENT SHAFT
HARDSTAND
INDIAN CREEK
KAUTZ ROAD
STOCKPILE
AREA
KAUTZ ROAD
GIESE ROAD
SUBSTATION
WETLANDS
AP10
LINAC
ANTIPROTON SOURCE
WELL POND ROAD
BOOSTER
CUB
INDIAN CREEK ROAD
MI-8 SERVICE
BUILDING
AP30
INDIAN ROAD
F3
8 GeV ENCLOSURE
MAIN RING COOLING PONDS
MAIN RING ROAD
TeVATRON ENCLOSURE
F2
MAIN INJECTOR
ENCLOSURE
COOLING POND H



Proton Driver

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

Preliminary Site Plan

PROJECT NO. 6-9-2

Technical Systems

- Modification of the linac front end:
  The goal is to get 60 mA (time average), 90 μs, 3π chopped H^- beam at 400 MeV.

  1. High intensity low emittance H^- source
  2. Low energy beam transport (LEBT)
  3. RFQ
  4. Double-α transport (MEBT)
  5. Chopper

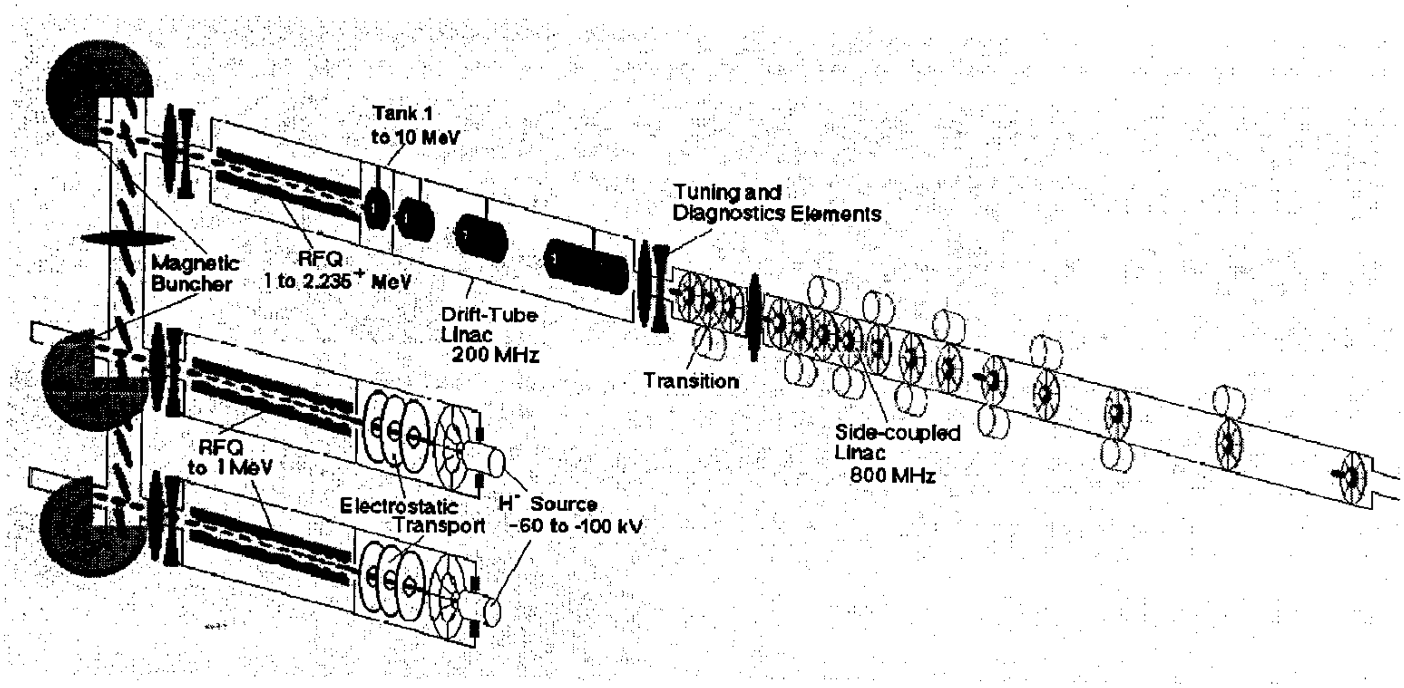
- New booster:
  This is a 15 Hz high intensity proton synchrotron. Compared with the existing synchrotrons, it has a number of new features.

  1. Lattice: FMC, no transition crossing, large dynamic aperture and large momentum acceptance.
  2. RF: Finemet cores (high accelerating gradient).
  3. Power supply: Dual harmonic resonance circuit (saving rf power by 25%).
  4. Beam pipe: Thin metallic (saving magnet aperture by 2").
  5. Injection: Painting (reducing space charge effect).
  6. Collimator: Two (or three) stages, high efficiency (99%).
  7. Shielding: Proposal for a new definition of "*worst credible accident*" (reducing earth shielding by 10 feet).

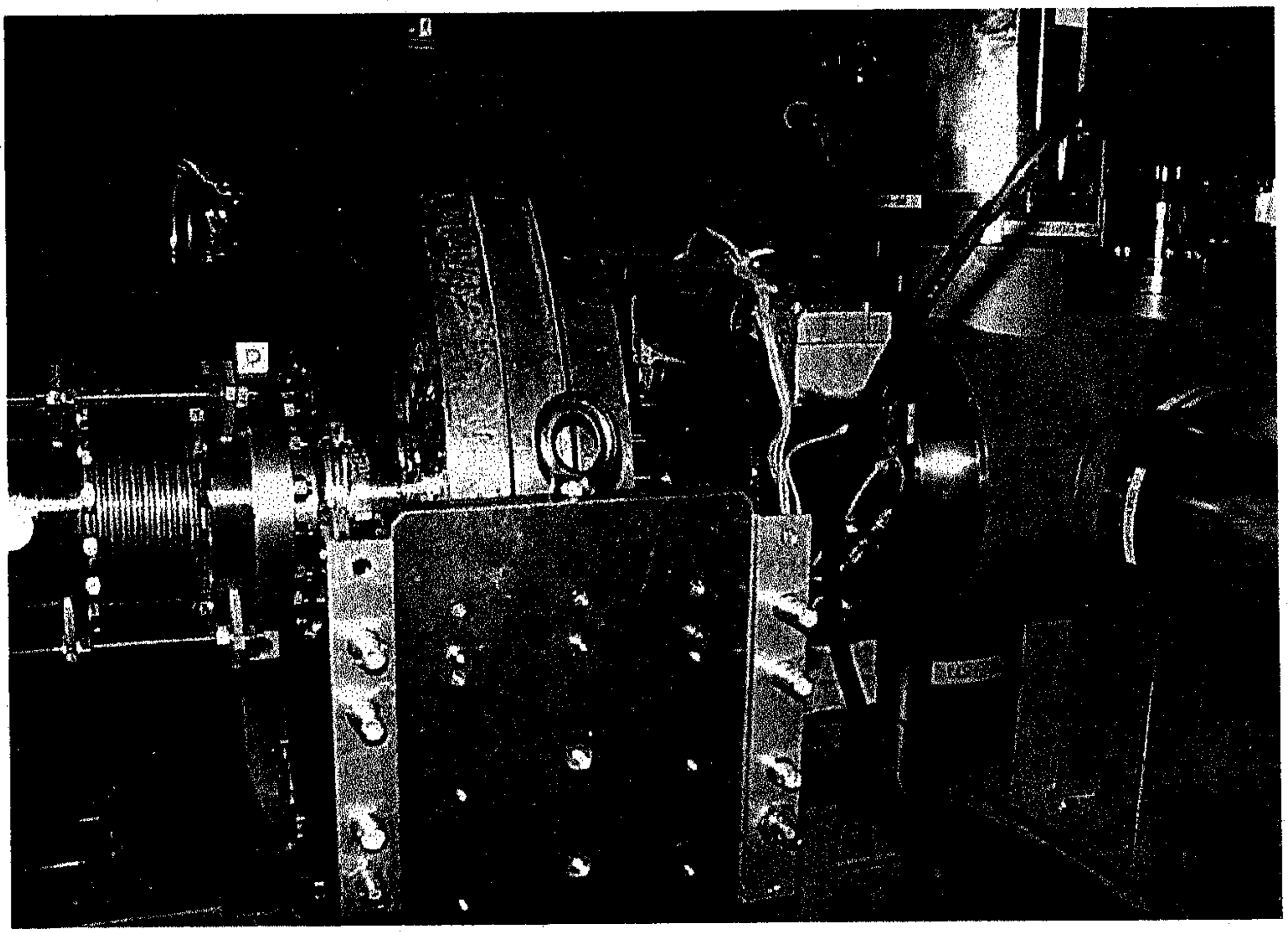
- (Transport lines)

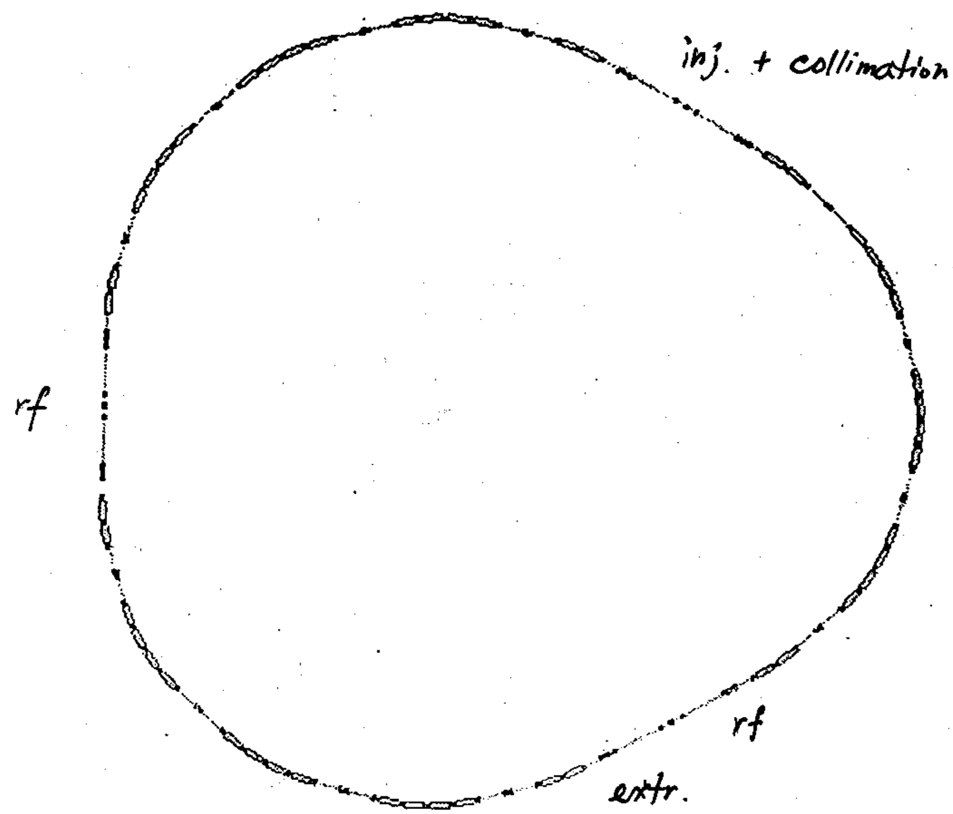
PARAMETERS FOR LOW ENERGY LINAC IMPROVEMENT

	ION SOURCE	LEBT/ CHOPPER	RFQ-1	MEBT	RFQ-2	MATCH SECTION	DTL	CCL
TYPE	H^-	ELECTRO-STATIC	VANE	"LARSON" 540°	VANE	3 QUADS 1 BUNCHER	DRIFT-TUBE	COUPLED-CAVITY
OUTPUT ENERGY (MeV)	0.05	0.05	1	1	2.23	2.23	116	400
OUTPUT CURRENT (mA)	115	115	102	102	97	93	86	86
OUTPUT CHOPPED CURRENT (mA)	115	80	72	72	68	65	60	60
EMITTANCE (πmm-mrad) (95%)	1		1.25		2.3		2.8	3
FREQUENCY (MHz)			201		201		201	805
PULSE LENGTH (μsec)	90		90		90		90	90

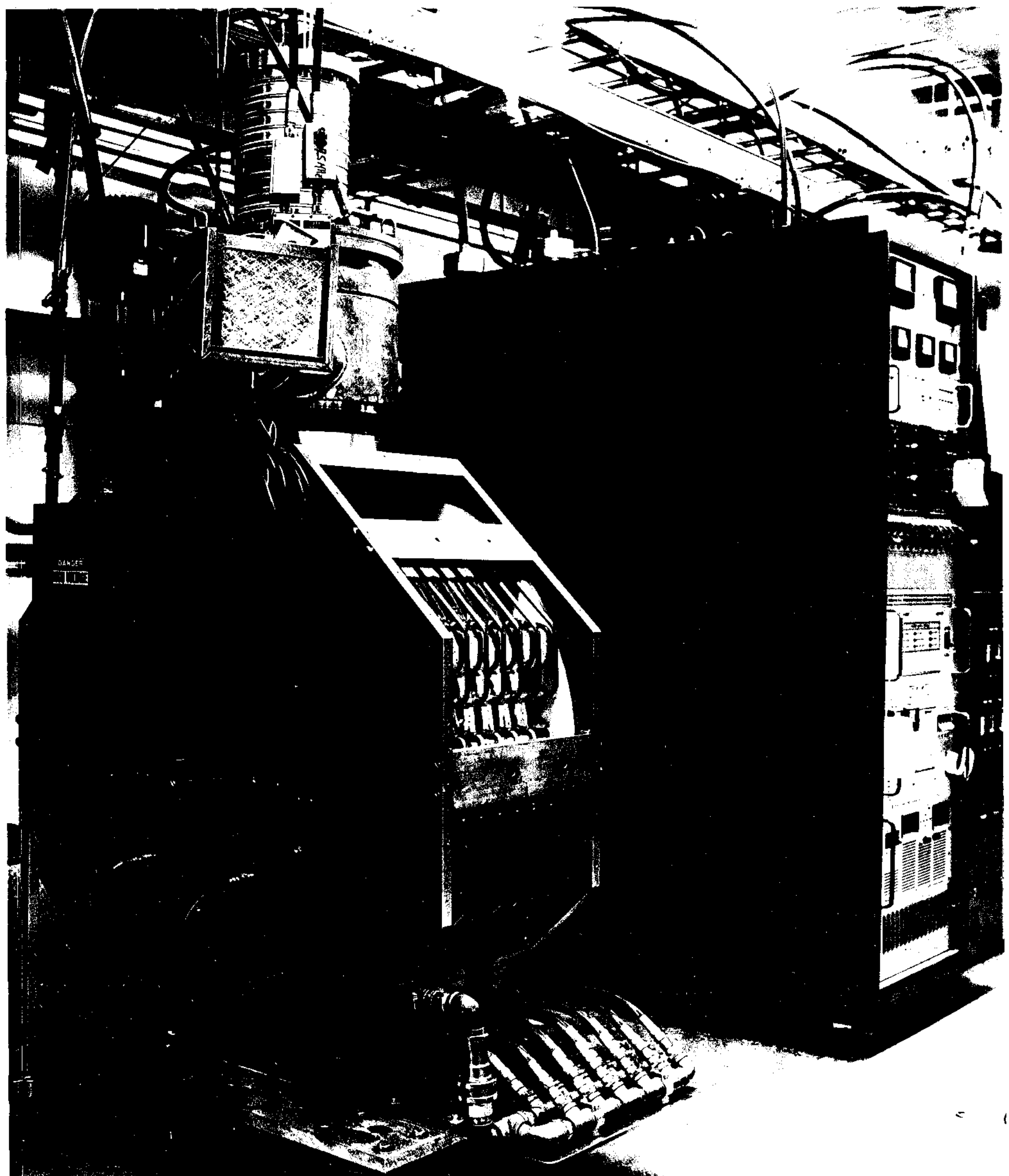

Tank 1
to 10 MeV
Tuning and
Diagnostics Elements
Magnetic
Buncher
RFQ
1 to 2.235+ MeV
Drift-Tube
Linac
200 MHz
Transition
Side-coupled
Linac
800 MHz
RFQ
to 1 MeV
Electrostatic
Transport
H- Source
-60 to -100 kV

Chopper installed on the HIMAC linac





Footprint of the proton driver showing the triangular lattice.


DANGER

F. Mills

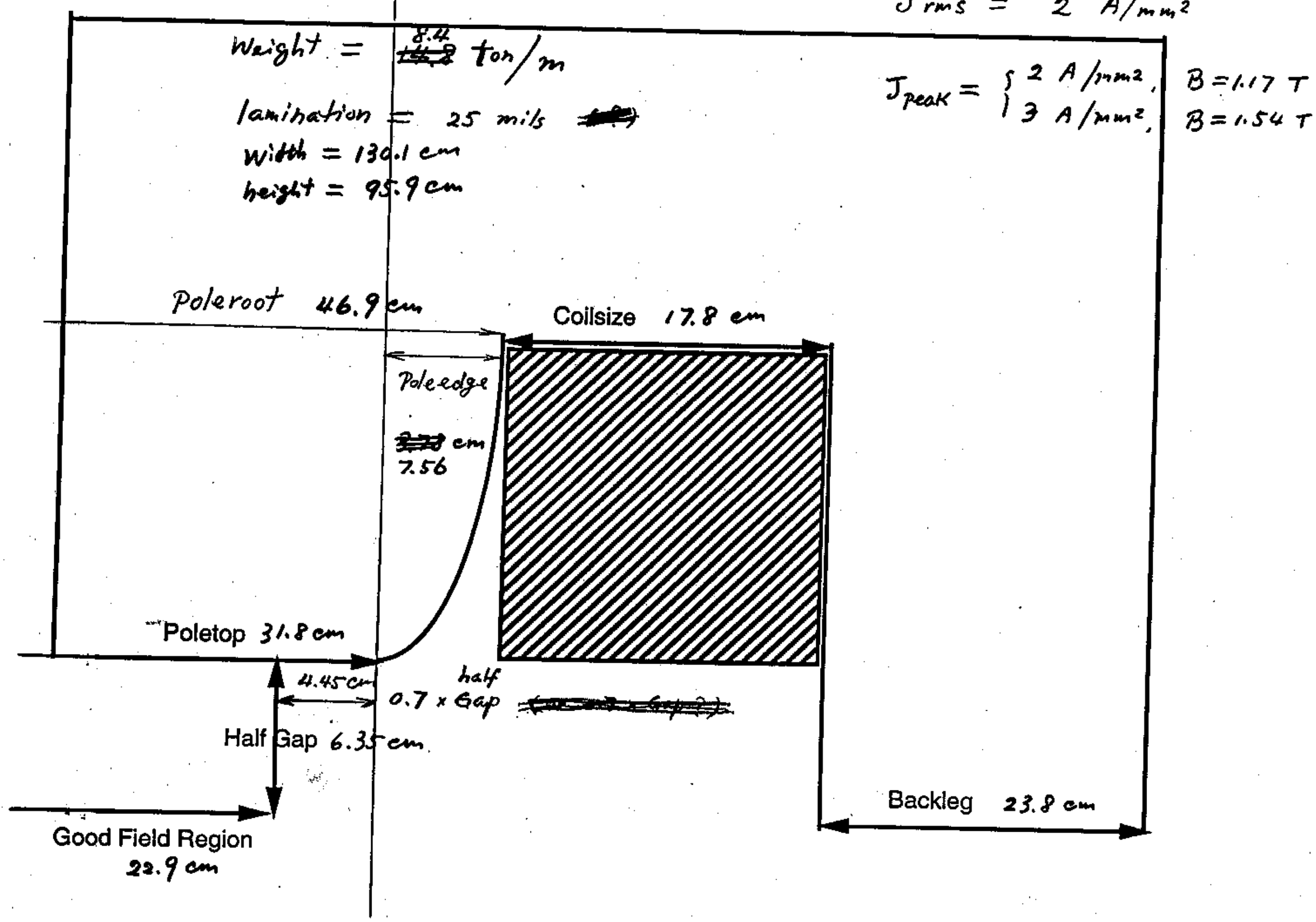
$B_{max} = 1.5$ T (16 GeV)

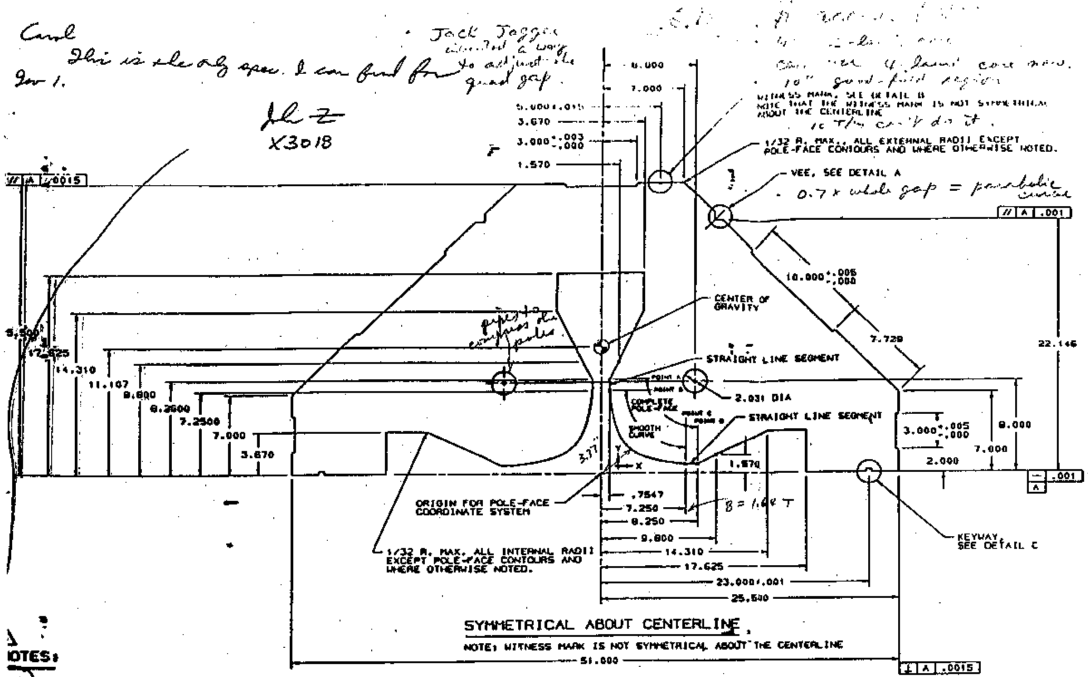
$B_{min} = 0.0846$ T (400 MeV)

$I_{peak} = 152$ KA

$I_{rms} = 127$ KA

$J_{rms} = 2$ A/mm²





NOTES:

1.0 STEEL DESCRIPTION: COMMERCIAL QUALITY 1008 COLD ROLLED DRAWING QUALITY ASTMA 619-75 CLASS 1, 16 GUAGE .0598 ± .005" (AISI STANDARD) THICKNESS. MASTER COIL CROWN SHALL BE .003" OR LESS OVER THE FULL WIDTH BEFORE SLITTING. THIS STEEL SHALL HAVE AN IRON PHOSPHATE COATING WITH WITH A COATING WEIGHT BETWEEN 36-60 MG. PER SQUARE FT.

2.0 HARDNESS: HARDNESS WILL BE MEASURED ON THE ROCKWELL B SCALE. A MINIMUM OF 30 AND A MAXIMUM OF 45 WILL BE SET AS REJECTION LEVELS.

3.0 TEST SPECIMENS: VENDOR SHALL PROVIDE FERMILAB WITH SAMPLES FOR EPSTEIN TESTS, CONSISTING OF 20 PARALLEL AND 20 TRANSVERSE STRIPS 1.180" X 12" AS SHEARED. THESE SAMPLES WILL BE LABELLED WITH THE HEAT AND COIL NUMBERS APPLIED TO EACH STOCK CARD. THESE SAMPLES WILL BE DISTRIBUTED THROUGHOUT THE HEAT.

4.0 THE LAMINATIONS, AND THE STEEL BEFORE STAMPING, MUST BE HANDLED CAREFULLY SO AS NOT TO CAUSE DAMAGE BY BENDING, OR SCRATCHING.

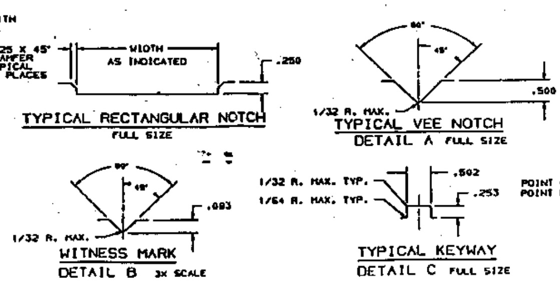
5.0 THE EDGE BURR SHALL NOT EXCEED .003

6.0 VARIATION BETWEEN PARTS SHALL NOT EXCEED ±.0005

7 PIECE PART SHALL BE FLAT WITHIN .250 (B)

8 USE TABLE TO LOCATE POINTS FOR POLE-FACE SURFACES. SURFACES SHALL BE SMOOTH CURVES WHERE INDICATED.

9.0 LAMINATION PERIMETER: 192.26 INCHES
LAMINATION AREA: 801.81 SQUARE INCHES



COORDINATES FOR 1/2 OF THE LAMINATION

X	Y
0.0000	25.5000
0.0000	17.6250
3.6700	17.6250
3.6700	14.3100
1.5700	9.8000
.7547	8.2500 (POINT A)
.7547	7.2500 (POINT B)
.7680	7.1250
.7818	7.0000
.7960	6.8750
.8108	6.7500
.8261	6.6250
.8421	6.5000
.8586	6.3750
.8778	6.2500
.8957	6.1250
.9144	6.0000
.9338	5.8750
.9541	5.7500
.9754	5.6250
.9975	5.5000
1.0207	5.3750
1.0450	5.2500
1.0705	5.1250
1.0973	5.0000
1.1254	4.8750
1.1550	4.7500
1.1862	4.6250
1.2192	4.5000
1.2540	4.3750
1.2909	4.2500
1.3300	4.1250
1.3716	4.0000
1.4158	3.8750
1.4630	3.7500
1.5135	3.6250
1.5675	3.5000
1.6256	3.3750
1.6881	3.2500
1.7556	3.1250
1.8288	3.0000
1.9083	2.8750
1.9950	2.7500
2.0900	2.6250
2.1945	2.5000
2.3100	2.3750
2.3423	2.3423
2.3750	2.3100
2.5000	2.1945
2.6250	2.0900
2.7500	1.9950
2.8750	1.9083
3.0000	1.8288
3.1250	1.7556
3.2500	1.6881
3.3750	1.6256
3.5000	1.5675
3.6250	1.5135
3.7500	1.4630
3.8750	1.4158
4.0000	1.3716
4.1250	1.3300
4.2500	1.2909
4.3750	1.2540
4.5000	1.2192
4.6250	1.1862
4.7500	1.1550
4.8750	1.1254
5.0000	1.0973
5.1250	1.0705
5.2500	1.0450
5.3750	1.0207
5.5000	.9975
5.6250	.9754
5.7500	.9541
5.8750	.9338
6.0000	.9144
6.1250	.8957
6.2500	.8778
6.3750	.8586
6.5000	.8421
6.6250	.8261
6.7500	.8108
6.8750	.7960
7.0000	.7818
7.1250	.7680
(POINT C) 7.2500	.7547
(POINT D) 8.2500	.7547
9.8000	1.5700
14.3100	3.6700
17.6250	3.6700
17.6250	0.0000
25.5000	0.0000
25.5000	7.0000
7.0000	25.5000
0.0000	25.5000

ADDITIONAL COORDINATES DESCRIBE THE REST OF THE LAMINATION, BUT NOT THE NOTCHES OR KEYWAY.

60 mils lami. (dc)

COORDINATES FOR COMPLETE POLE-FACE

TOL. ±.001

SEE NOTE 8.0

ITEM	PART NO.	DESCRIPTION OR SIZE
PARTS LIST		

UNLESS OTHERWISE SPECIFIED				
FRACTIONS ± 1/64	DECIMALS ± .002	ANGLES ± 1°	ORIGINATOR	J. HEIM
			DRAWN	J. R. BISHOP
			CHECKED	S. C. SNOWDON
			APPROVED	F. E. MILLS
			USED ON	
			MATERIAL	SEE NOTES

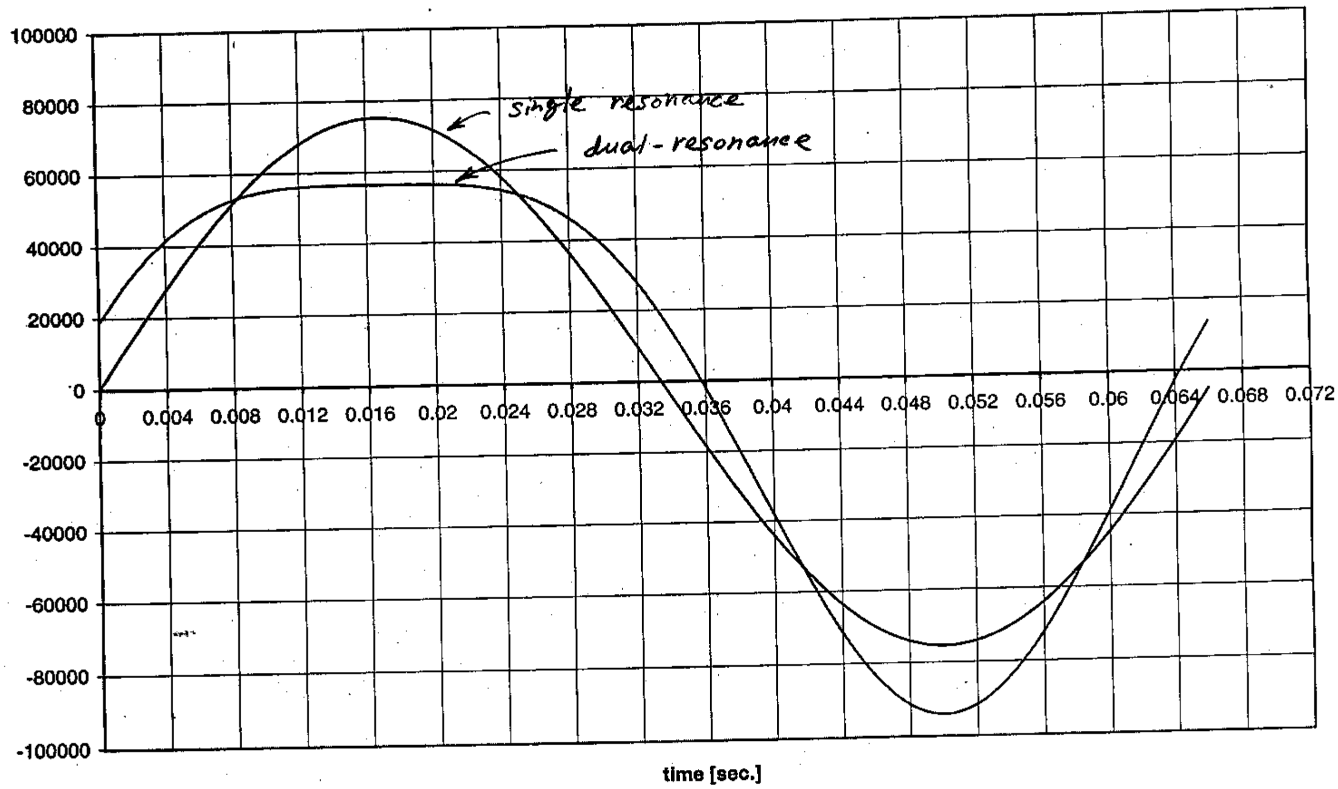
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

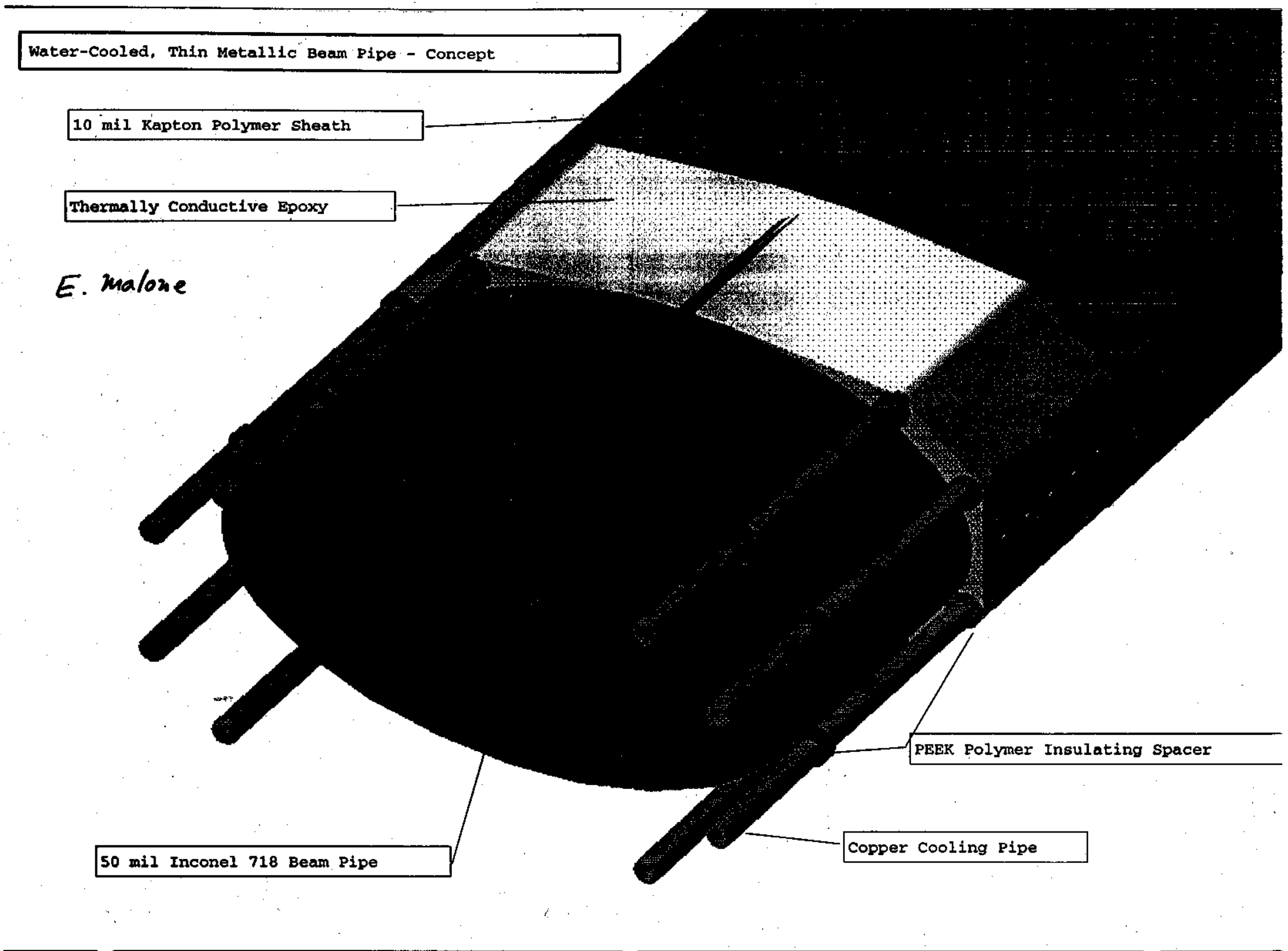
TEVATRON I
LARGE APERTURE QUAD
LAMINATION

SCALE 1/4 — DRAWING NUMBER 8020-MD-176020

10a

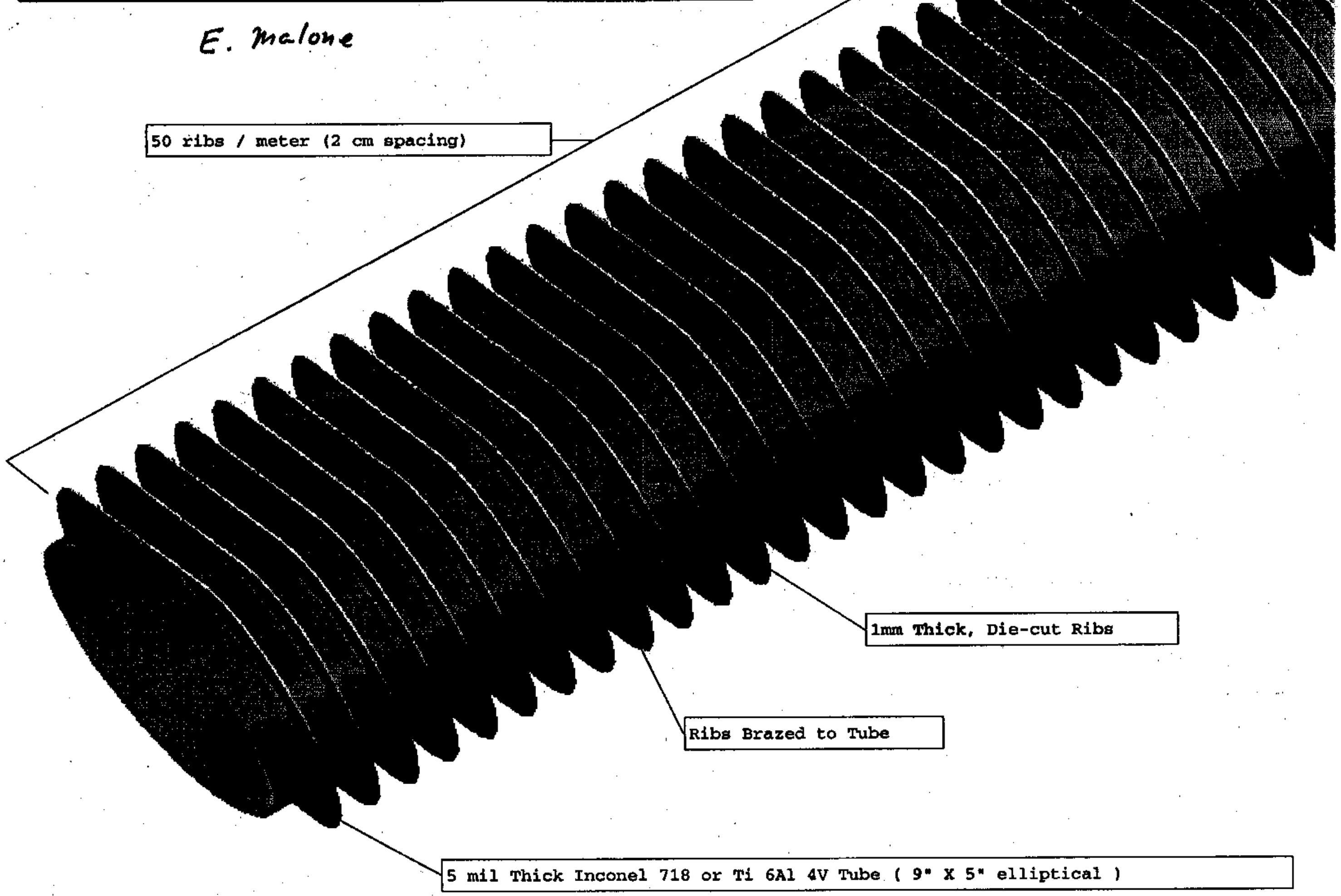
Magnet Current Derrivatives $\frac{dI}{dt} \sim \dot{B}$




Water-Cooled, Thin Metallic Beam Pipe - Concept
10 mil Kapton Polymer Sheath
Thermally Conductive Epoxy
E. Malone
PEEK Polymer Insulating Spacer
Copper Cooling Pipe
50 mil Inconel 718 Beam Pipe

Rib-reenforced, Very Thin Metallic Beam Pipe - Concept

E. Malone



Design issues

- High longitudinal brightness:
  - High N_b/ϵ_L due to:
    - * High beam power, a few bunches $\longrightarrow$ large N_b
    - * Short bunch length $\longrightarrow$ small ϵ_L
  - Minimize ϵ_L dilution:
    - * Avoid transition (lattice design)
    - * Avoid microwave instability
      - · Keep beam below transition
      - · Keep resistive wall impedance small (uniform beam pipe)
    - * Avoid coupled bunch instability (low Q cavity)
    - * Inductive insert for compensating space charge
    - * Minimize filamentation during early acceleration (rf parameters optimization)
    - * Longitudinal damper
- High intensity bunch compression:
  - Microwave instability during debunching;
  - Beamloading during debunching;
  - η-spread (or α-spread) effect:
    - * due to higher order momentum compaction factor α_1
    - * due to space charge tune spread ΔQ

Table 5: Longitudinal Brightness of Proton Machines

Machine	$E_{\max}$ (GeV)	N_{tot} (10^{12})	N_b (10^{12})	ϵ_L (eV-s)	N_b/ϵ_L $(10^{12}/\text{eV-s})$
Existing:					
CERN SPS	450	46	0.012	0.5	0.024
FNAL MR	150	20	0.03	0.2	0.15
FNAL Booster	8	4	0.05	0.1	0.5
PETRA II	40	5	0.08	0.12	0.7
KEK PS	12	3.6	0.4	0.4	1
DESY III	7.5	1.2	0.11	0.09	1.2
FNAL Main Inj	150	60	0.12	0.1	1.2
CERN PS	14	25	1.25	0.7	1.8
BNL AGS	24	63	8	4	2
LANL PSR	0.797	23	23	1.25	18
RAL ISIS	0.8	25	12.5	0.6	21
Planned:					
Proton Driver Phase I	16	30	7.5	2	3.8
Proton Driver Phase II	16	100	25	2	12.5
Japan JHF	50	200	12.5	5	2.5
AGS for RHIC	25	0.4	0.4	0.3	1.3
PS for LHC	26	14	0.9	1.0	0.9
SPS for LHC	450	24	0.1	0.5	0.2

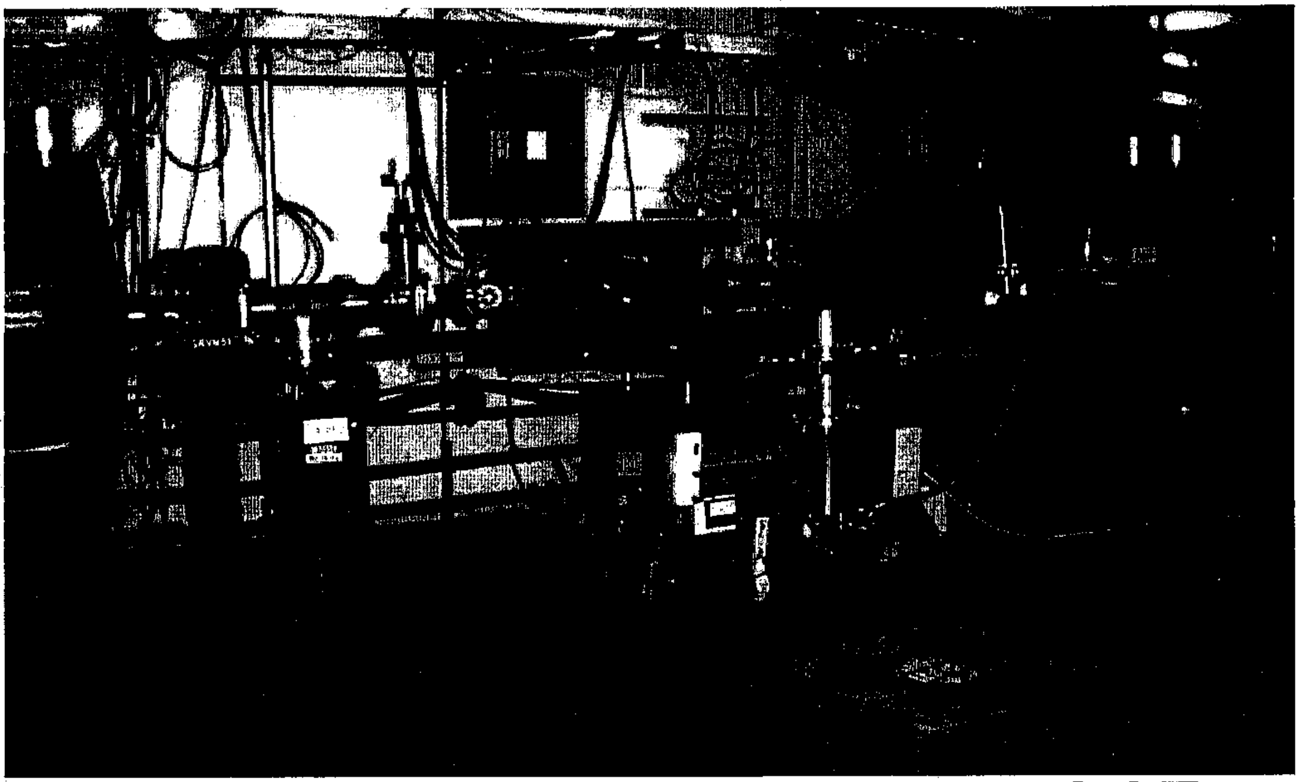
R&D program

- Hardware R&D:
  With limited resources, we have divided R&D into three categories:

  1. Critical for the proton driver, also benefitting present machines:
     (a) High gradient Finemet rf cavity (will give 132 ns bunch spacing in Run III);
     (b) Beamloading compensation (will benefit the MI);
     (c) 53 MHz booster rf cavity modification (will benefit the Booster);
     (d) High intensity low emittance H^- source (will benefit the linac);
     (e) New front end test station (will benefit the linac).
  2. Critical for the proton driver:
     (a) Thin metallic beam pipe;
     (b) RF chopper
  3. Important for the proton driver, but may have to wait:
     (a) High gradient, low frequency rf in burst mode operation;
     (b) High current RFQ;
     (c) Collimators (including bent crystal as the primary);
     (d) Tracking error correctors;
     (e) Power supply using new technology (dual-resonance, dual-frequency, IGBT, *etc.*);
     (f) Fast rise- and fall-time kicker;
     (g) Passive and active feedback systems;
     (h) Large aperture magnets (including end effects).

- Machine experiments:
  1. Beam test of Finemet cavity (Fermilab/MI, BNL/AGS)
  2. Inductive insert (LANL/PSR, ANL/IPNS)
  3. Lab "contest" on intense short bunch production:
     - Six labs: BNL, KEK, Fermilab, CERN, Indiana U. and GSI.
     - Two experiments:
       * bunch compression;
       * μ-wave instability below γ_t.
     - Three competing items:
       * Max I_{peak}
       * Max N_b/eV-s
       * Max compression ratio

Inductor in Section 5



LANSCE
Los Alamos Neutron Science Center

Schedule of the Report

- We plan to finish the design report by the end of this year.
- But we need help in several weak points: lattice corrector system, space charge, beam pipe, transport lines, distance/remote handling.
- We also need to fill several "holes" in this study: special magnets (Lambertson, kicker, bumper, septum), diagnostics, control, *etc.*