Proton Driver Study II

Synchrotron Based 8-GeV Proton Driver and Main Injector Upgrades

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May 14, 2002, AAC Meeting, Fermilab

Outline

- What happened after Proton Driver Study I
- An 8-GeV synchrotron based Proton Driver
- A 2-MW Main Injector
- R&D program

Chronological Events after Proton Driver Study I

- *January 2001:* The Proton Driver Study I report was submitted to the Director's office. The Director wrote a nice "thank you" letter and asked us to wait for further actions.
- *May 2001:* AAC review. The committee endorsed several R&D items.
- *July 2001:* Snowmass Workshop. Four working groups (E1, E5, M1, M6) delivered a clear and loud message at the meeting:

"We need the Proton Driver Now!"

- *Janaury 2002:* HEP sub-panel report released. The proton driver was treated somewhat like a "Plan B" to a linear collider.
- *January 10, 2002:* The Director issued a new charge to Foster and Chou for Proton Driver study II.
- *About the same time:* BNL established a task force for a proton driver study based on its linac and AGS upgrades.
- *April 8-12, 2002:* ICFA-HB2002 workshop at Fermilab. The topic was high intensity hadron beams in general, and proton drivers in particular. 150 people came (about 30 from Fermilab and 120 from other institutions), showing strong interest in this field.
- *May 2002:* Proton Driver Study II report due. It will be published as Fermilab-TM-2169.

US DoE HEPAP Sub-Panel Report (Jan 2002)

Two scenarios in its 20-year Road Map:

- Scenario 1
  - A linear collider sited in the US
  - A neutrino physics program offshore
  - (other HEP programs)

- Scenario 2
  - A linear collider offshore
  - A neutrino physics program sited in the US (including the construction of a Proton Driver)
  - (other HEP programs)

However, we cannot forget a painful lesson nine years ago:

- In addition to a Big Project (such as a Linear Collider), the U.S. HEP community needs to plan for one or two mid-size projects.

  Imagine how much worse it would be if there were no Main Injector or PEP-II project in 1993 when the SSC was scraped. (These two projects are now the backbone of the U.S. HEP program.)

About the Proton Driver

- What is a Proton Driver?

  Proton Driver = High beam power + Short bunch length

- Nominal parameters:

  Beam power = 1-4 MW
  Bunch length = 1-3 ns (rms)

- Proton driver (and other high intensity proton source) studies around the world:

  - Fermilab
  - BNL
  - LANL (AHF)
  - CERN (SPL)
  - RAL (ISIS upgrade)
  - KEK-JAERI (JHF)
  - China (100 kW, 25 Hz RCS)
  - South Korea (KOMAC)

Table 1. Beam Parameters of Existing and Proposed Proton Sources (Snowmass 2001)

Machine	Flux (10^{13}/pulse)	Rep Rate (Hz)	Flux† (10^{20}/year)	Energy (GeV)	Power (MW)
Existing:					
RAL ISIS	2.5	50	125	0.8	0.16
BNL AGS	7	0.5	3.5	24	0.13
LANL PSR	2.5	20	50	0.8	0.064
Fermilab MiniBooNE (*)	0.5	7.5	3.8	8	0.05
Fermilab NuMI	3	0.5	1.5	120	0.3
CERN CNGS	4.8	0.17	0.8	400	0.5
Under construction:					
ORNL SNS	14	60	840	1	1.4
JHF 50 GeV	32	0.3	10	50	0.75
JHF 3 GeV	8	25	200	3	1
Proton Driver proposals:					
Fermilab Phase I	3	15	45	16	1.2
Fermilab Phase II	10	15	150	16	4
BNL Phase I	10	2.5	25	24	1
BNL Phase II	20	5	100	24	4
CERN SPL	23	50	1100	2.2	4
RAL 15 GeV (**)	6.6	25	165	15	4
RAL 5 GeV (**)	10	50	500	5	4
Other proposals:					
Europe ESS (**)	46.8	50	2340	1.334	5
Europe CONCERT	234	50	12000	1.334	25
LANL AAA	-	CW	62500	1	100
LANL AHF	3	0.04	0.03	50	0.003

† 1 year = 1 x 10^7 seconds.
(*) Including planned improvements.
(**) Based on 2-ring design.

Executive Summary (Snowmass 2001 M6 Group Report)

The US high-energy physics program needs an intense proton source (a 1-4 MW Proton Driver) by the end of this decade. This machine will serve multiple purposes: (i) a stand-alone facility that will provide neutrino superbeams and other high intensity secondary beams such as kaons, muons, neutrons, and anti-protons (cf. E1 and E5 group reports); (ii) the first stage of a neutrino factory (cf. M1 group report); (iii) a high brightness source for a VLHC (cf. M4 group report).

Based on present accelerator technology and project construction experience, it is both feasible and cost-effective to construct a 1-4 MW Proton Driver. There are two PD design studies, one at FNAL and the other at the BNL. Both are designed for 1 MW proton beams at a cost of about US$200M (excluding contingency and overhead) and upgradeable to 4 MW. An international collaboration between FNAL, BNL and KEK on high intensity proton facilities addresses a number of key design issues. The sc cavity, cryogenics, and RF controls developed for the SNS can be directly adopted to save R&D efforts, cost, and schedule. PD studies are also actively pursued at Europe and Japan.

There are no showstoppers towards the construction of such a high intensity facility. Key research and development items are listed below ({} indicates present status). Category A indicates items that are not only needed for future machines but also useful for the improvement of existing machine performance; category B indicates items crucial for future machines and/or currently underway.

1) H^- source: Development goals - current 60–70 mA {35 mA}, duty cycle 6-12% {6%}, emittance 0.2 π mm-mrad rms normalized, lifetime > 2 months {20 days}. (A)
2) LEBT chopper: To achieve rise time < 10 ns {50 ns}. (B)
3) Study of 4-rod RFQ at 400 MHz, 100 mA, 99% efficiency, HOM suppressed. (B)
4) MEBT chopper: To achieve rise time < 2 ns {10 ns}. (B)
5) Chopped beam dump: To perform material study & engineering design for dumped beam power > 10 kW. (A)
6) Funneling: To perform (i) one-leg experiment at the RAL by 2006 with goal one-leg current 57 mA; (ii) deflector cavity design for CONCERT. (all B)
7) Linac RF control: To develop (i) high performance HV modulator for long pulsed (>1ms) and CW operation; (ii) high efficiency RF sources (IOT, multi-beam klystron). (all A)
8) Linac sc RF control: Goal - to achieve control of RF phase error < 0.5° and amplitude error <0.5% {presently 1°, 1% for warm linac}. (i) To investigate the choice of RF source (number of cavity per RF source, use of high-power source); (A) (ii) to perform redundancy study for high reliability; (B) (iii) to develop high performance RF control (feedback and feedforward) during normal operation, tuning phases and off-normal operation (missing cavity), including piezo-electric fast feedforward. (A)
9) Space charge: (i) Comparison of simulation code ORBIT with machine data at FNAL Booster and BNL Booster; (ii) to perform 3D ring code bench marking including machine errors, impedance, and space charge (ORNL, BNL, SciDAC, PPPL). (all A)
10) Linac diagnostics: To develop (i) non-invasive (laser wire, ionization, fluorescent-based) beam profile measurement for H^-;(ii) on-line measurement of beam energy and energy spread using time-of-flight method; (iii) halo monitor especially in sc environment; (iv) longitudinal bunch shape monitor. (all A)
11) SC RF linac: (i) High gradients for intermediate beta (0.5 – 0.8) cavity; (A) (ii) Spoke cavity for low beta (0.17 – 0.34). (B)

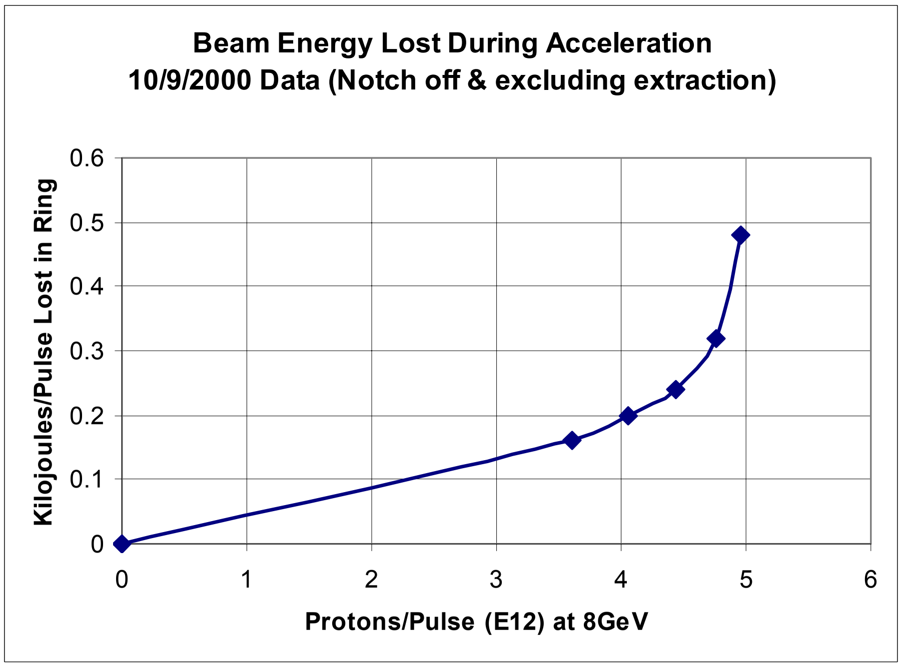
12) Transport lines: To develop (i) high efficiency collimation systems; (A) (ii) profile monitor and halo measurement; (A) (iii) energy stabilization by HEBT RF cavity using feedforward to compensate phase-jitter. (B)
13) Halo: (i) To continue LEDA experiment on linac halo and comparison with simulation; (ii) to start halo measurement in rings and comparison with simulation. (all B)
14) Ring lattice: To study higher order dependence of transition energy on momentum spread and tune spread, including space charge effects. (B)
15) Injection and extraction: (i) Development of improved foil (lifetime, efficiency, support); (A) (ii) experiment on the dependence of H^0 excited states lifetime on magnetic field and beam energy; (B) (iii) efficiency of slow extraction systems. (A)
16) Electron cloud: (i) Measurements and simulations of the electron cloud generation (comparison of the measurements at CERN and SLAC on the interaction of few eV electrons with accelerator surfaces, investigation of angular dependence of SEY, machine and beam parameter dependence); (A) (ii) determination of electron density in the beam by measuring the tune shift along the bunch train; (A) (iii) theory for bunched beam instability that reliably predicts instability thresholds and growth rates; (A) (iv) investigation of surface treatment and conditioning; (A) (v) study of fast, wide-band, active damping system at the frequency range of 50–800 MHz. (B)
17) Ring beam loss, collimation, protection: (i) Code benchmarking & validation (STRUCT, K2, ORBIT); (A) (ii) engineering design of collimator and beam dump; (A) (iii) experimental study of the efficiency of beam-in-gap cleaning; (A) (iv) bent crystal collimator experiment in the RHIC; (B) (v) collimation with resonance extraction. (B)
18) Ring diagnostics: (i) Whole area of diagnosing beam parameters during multi-turn injection; (ii) circulating beam profile monitor over large dynamic range with turn-by-turn speed; (iii) fast, accurate non-invasive tune measurement. (all A)
19) Ring RF: To develop (i) low frequency (~5 MHz), high gradient (~1 MV/m) burst mode RF systems; (B) (ii) high gradient (50-100 kV/m), low frequency (several MHz) RF system with 50-60% duty cycle; (B) (iii) high-voltage (>100 kV) barrier bucket system; (B) (iv) transient beam loading compensation systems (e.g. for low-Q MA cavity). (A)
20) Ring magnets: (i) To develop stranded conductor coil; (ii) to study voltage-to-ground electrical insulation; (iii) to study dipole/quadrupole tracking error correction. (all B)
21) Ring power supplies: To develop (i) dual-harmonic resonant power supplies; (ii) cost effective programmable power supplies. (all B)
22) Kicker: (i) Development of stacked MOSFET modulator for DARHT and AHF to achieve rise/fall time <10-20 ns; (B) (ii) impedance reduction of lumped ferrite kicker for SNS. (A)
23) Instability & impedance: (i) To establish approaches for improved estimates of thresholds of fast instabilities, both transverse and longitudinal (including space charge and electron cloud effects); (ii) to place currently-used models such as the broadband resonator and distributed impedance on a firmer theoretical basis; (iii) impedance measurement based on coherent tune shifts *vs*. beam intensity, and instability growth rate *vs*. chromaticity, including that for flat vacuum chambers; (iv) to develop new technology in feedback implementation. (all B)
24) FFAG: (i) 3-D modeling of magnetic fields and optimization of magnet profiles; (ii) wide-band RF systems; (iii) transient phase shift in high frequency RF structures; (iv) application of sc magnets. (all B)
25) Inductive inserts: (i) Experiments at the FNAL Booster & JHF3; (A) (ii) programmable inductive inserts; (B) (iii) development of inductive inserts which have large inductive impedance and very small resistive impedance; (B) (iv) theoretical analysis. (B)
26) Induction synchrotron: (i) Study of beam stability; (ii) development of high impedance, low loss magnetic cores. (all B)

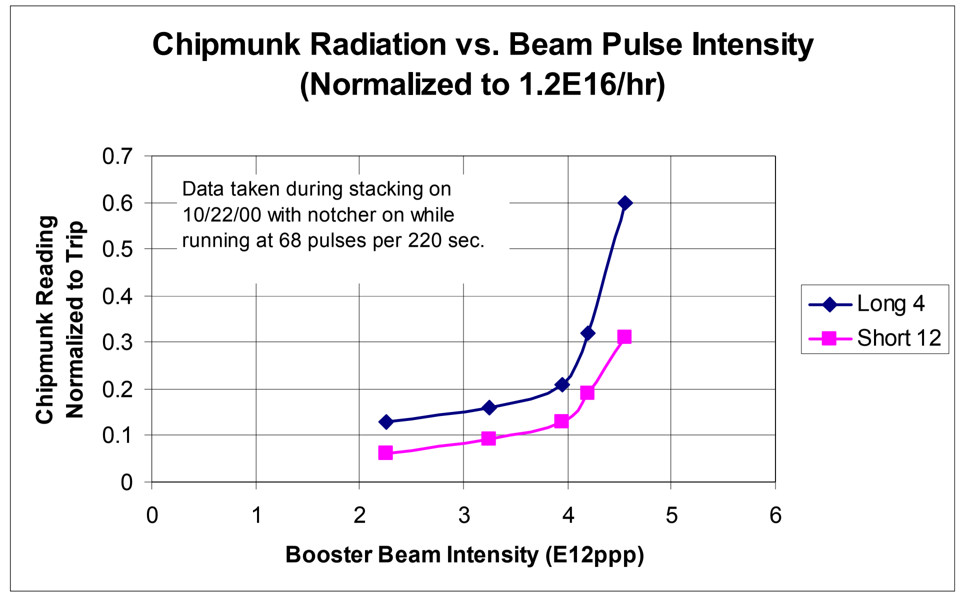
Problems of the Present Booster

1. Three fundamental problems:
    - The magnet aperture is too small
    - The linac is too close to the ring
    - The tunnel is not deep enough (and there are office buildings on top of it)

2. Other problems:
    - The lattice beta functions and dispersion are large
    - The rf cavity aperture is too small
    - The rf is in the dispersive region
    - There is transition crossing
    - There is no rf shield in the beam path
    - Orbit correction is limited

Beam Loss Intensity Sensitivity





Fermilab

FERMILAB-TM-2136
December 2000

THE PROTON DRIVER DESIGN STUDY

PD1 Parameters: Present, Phase I and Phase II

Parameters	Present	Phase I (MI, ν-Fact)	Phase II (μ-Coll)
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			$2,5 \times 10^{13}$
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200 p
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Target beam power (MW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	1.7×10^{12}	2.5×10^{13}
Number of bunches	84	18	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15 p	60 p	200 p
Longitudinal emittance (eV-s)	0.1	0.4	2
RF frequency (MHz)	53	7.5	7.5
Extracted bunch length s_t (ns)	0.2	1	1
Average beam current (μA)	12	72	240
Target beam power (MW)	0.1	1.2	4

PD1 (12/16 GeV Synchrotron) Cost Estimate (in thousand US dollars K$)

1	**Technical Systems**			**184,893**
1.1	16 GeV Synchrotron		173,551	
1.1.1	Magnets	53,982		
1.1.2	Power supplies	52,095		
1.1.3	RF	11,051		
1.1.4	Vacuum	9,222		
1.1.5	Collimators	325		
1.1.6	Injection system	1,039		
1.1.7	Extraction system	3,542		
1.1.8	Instrumentation	2,553		
1.1.9	Controls	2,214		
1.1.10	Utilities	10,615		
1.1.11	Installation	1,696		
1.1.12	ED&I	25,217		
1.2	400 MeV Transport Line		2,110	
1.2.1	Magnets	1,443		
1.2.2	Power supplies	361		
1.2.3	ED&I	307		
1.3	12/16 GeV Transport Line		3,718	
1.3.1	Magnets	2,542		
1.3.2	Power supplies	636		
1.3.3	ED&I	540		
1.4	Ion Source and Linac Improvements		5,514	
1.4.1	Negative ion source	480		
1.4.2	LEBT	225		
1.4.3	RFQ	1,850		
1.4.4	MEBT	255		
1.4.5	Chopper	100		
1.4.6	New drift tube Tank #1	1,500		
1.4.7	Instrumentation and controls	135		
1.4.8	Building modification	250		
1.4.9	ED&I	719		
2	**Civil construction**			**54,184**
2.1	16 GeV Synchrotron		25,600	
2.1.1	Enclosure	8,600		
2.1.2	Service buildings	10,200		
2.1.3	Utility support building	6,800		
2.2	400 MeV Transport Line		1,800	
2.3	12/16 GeV Transport Line		2,200	
2.4	Site work		6,300	
2.5	Subcontractors OH&P		7,180	
2.6	ED&I		7,324	
2.7	Environmental controls and permits		3,780	
3	**Project Management**			**3,000**
	TOTAL			**242,077**

Note: Items 1.1.4, 1.1.8, 1.1.9, 1.1.10 and 1.1.11 include the costs for the synchrotron as well as for the two transport lines.

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January 10, 2002

To: Bill Foster and Weiren Chou

From: Mike Witherell

SUBJECT: DESIGN STUDY OF PROTON DRIVER OPTIONS FOR THE MAIN INJECTOR

The HEPAP Subpanel report is expected to identify a modest energy, high average power, proton facility as a possible candidate for a construction project in the U.S. starting in the middle of the current decade. Fermilab represents an attractive location for such a facility and we need to identify options that could be presented to the DOE and U.S. community over the next few years if the physics is determined to warrant construction. One such option has been identified, the 8-16 GeV Proton Driver described in Fermilab-TM-2136, and another concept has recently come to light, an 8 GeV superconducting linac.

I would like the two of you to prepare a common document that would outline the two possible approaches to a Proton Driver at Fermilab and required modifications to the Main Injector to accommodate the increased intensity. In both cases I would like you to work with the following parameters:

Peak (Kinetic) Energy	8 GeV
Protons per Main Injector acceleration cycle	1.5×10^{14} (=1.9 MW @ 0.67 Hz)
Protons per second at 8 GeV	3.0×10^{14} (=380 KW)

For each option the report should include a description of the design concept and the technical components, identification of possible siting within Fermilab, and a preliminary cost estimate. In addition I would like you to provide a description and cost estimate for upgrades to the Main Injector, including its existing beamlines, and to the MiniBoone beamline required to support the performance defined above.

To the extent that you have the time and ability to do so I would like you to identify options for subsequent upgrades that could provide enhanced capabilities further into the future, including:

- Higher beam power at 8 GeV
- Higher beam power at energies up to 120 GeV, specifically through the implementation of reduced cycle time in the Main Injector
- An accumulator or compressor ring that could be used to achieve the performance required of the driver for a Neutrino Factory
- Utilization of the linac-based facility as an 8 GeV electron source

In general I would like to see each of these two options brought to a comparable state of development in this report. Because of the significant prior effort expended in the synchrotron-based proton driver, I expect that the development of the linac-based proton driver concept will require the bulk of the effort. Steve Holmes will provide Directorate guidance and support on this, including defining primary reference design parameters.

I would like to receive an interim report on progress prior to the ICFA Workshop at Fermilab on April 8-12 and a final report by May 15, 2002. Preparation of this report will require support of personnel in both the Beams and Technical Division. You should identify required resources and then work with the Divisions/Sections to secure support, consistent with their commitments to Run II . Both the Division/Section heads and Steve Holmes can help you in this task.

The identification of promising ventures utilizing hadrons and building upon Fermilab infrastructure and expertise is an important part of planning for the future of U.S. HEP. A Proton Driver could represent a strong candidate for a construction project in the intermediate term future with strong potential links to the longer-term future. Both Steve and I look forward to working closely with you and the participating divisions in defining the possibilities.

cc

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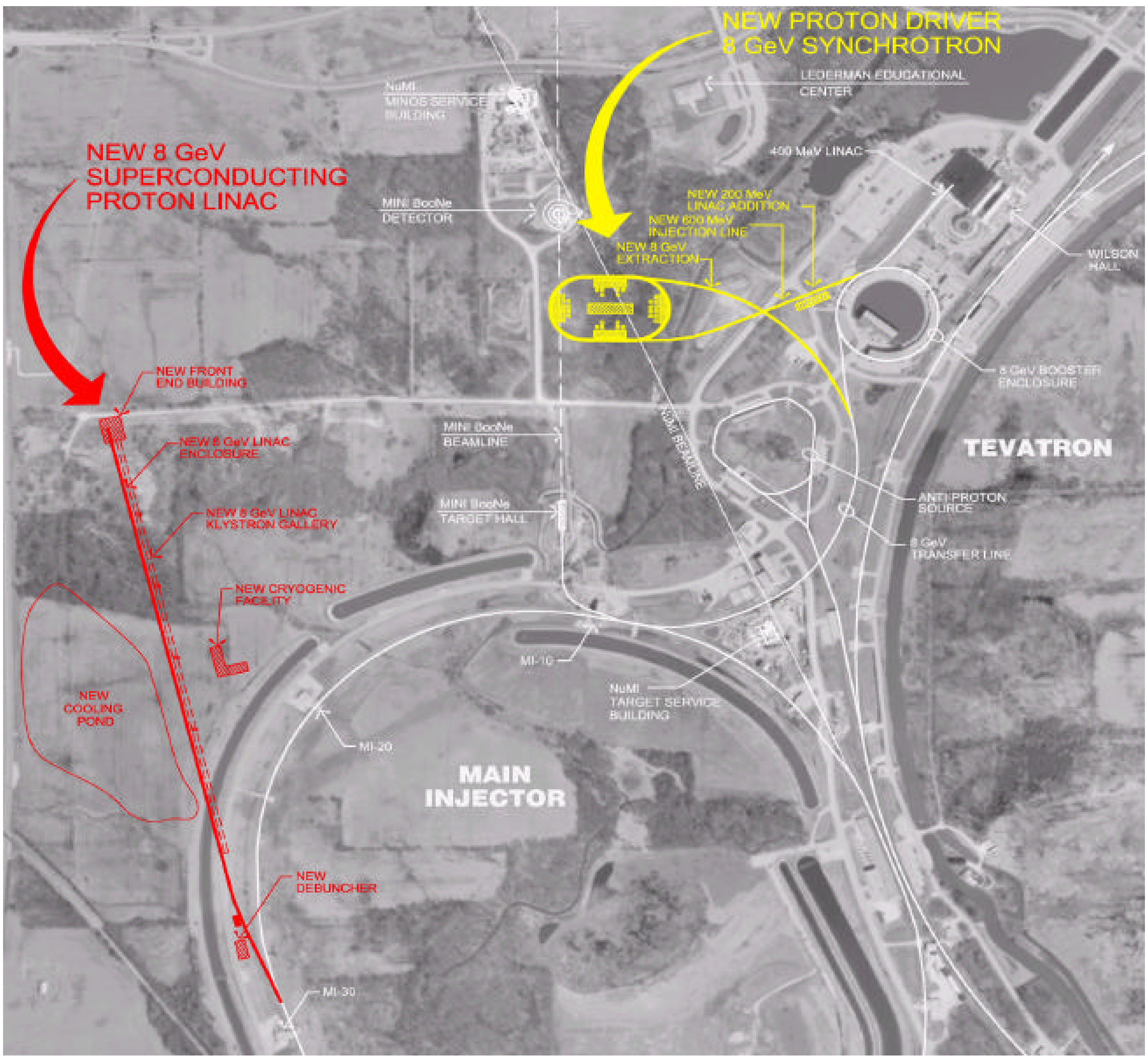
THE PROTON DRIVER STUDY II



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The Proton Driver Study II

Edited by G.W. Foster, W. Chou and E. Malamud

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May 2002

PROTON DRIVER STUDY II

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An 8-GeV Synchrotron-based Proton Driver

- Proton Driver Study II (PD2) includes an 8 GeV, 0.5 MW synchrotron, upgradeable to 2 MW. It is smaller than PD1 but also cheaper.

- Design features of the PD2 synchrotron:
  - Same size as the present Booster (474.2 m).
  - Racetrack shape in a new enclosure.
  - Transition-free lattice with zero-dispersion long straights.
  - Reuse of the existing 400 MeV linac, addition of another 200 MeV rf $\rightarrow$ Total linac energy 600 MeV.

Parameter Comparison: The Present Proton Source vs. the Proton Driver

Parameters	Present Proton Source	Proton Driver
Linac (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (µs)	25	90
H^- per pulse	6.3×10^{12}	2.8×10^{13}
Average beam current (µA)	15	67
Beam power (kW)	6	40
Booster (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	6×10^{10}	3×10^{11}
Number of bunches	84	84
Protons per cycle	5×10^{12}	2.5×10^{13}
Protons per second	7.5×10^{13}	3.75×10^{14}
Normalized transverse emittance (mm-mrad)	15p	40p
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (µA)	12	60
Beam power (MW)	0.05(*)	0.5

(*) Although originally designed for 15 Hz operations, the present Booster has never delivered beam at 15 Hz continuously. In the past it used to run at 2.5 Hz. In the MiniBooNE era, it will run at 7.5 Hz and deliver 50 kW beams.

PD2: An 8-GeV Proton Synchrotron Parameter List

Circumference (m)	474.2
Injection kinetic energy (MeV)	600
Extraction kinetic energy (GeV)	8
Protons per cycle	2.5×10^{13}
Repetition rate (Hz)	15
Protons per second	3.75×10^{14}
Average beam current (µA)	60
Target beam power (MW)	0.48
RF frequency (MHz)	53
Number of bunches	84
Protons per bunch	3×10^{11}
Peak dipole field (T)	1.5
Good field region	4 in × 6 in
Dispersion in the straight sections	0
Transition γ_t	13.8
Revolution time at injection, extraction (µs)	2.0, 1.6
Linac injection current (mA)	50
Injection time (µs)	90
Injection turns	45
Laslett tune shift at injection	0.23
Normalized transverse emittance (mm-mrad)	
Injection beam (95%)	3 π
Circulating beam (100%)	40 π
Longitudinal emittance (95%, eV-s)	
Injection beam	0.1
Circulating beam	0.2
Extraction bunch length σ_t (rms, ns)	1
Momentum acceptance	±1%
Dynamic aperture	> 120 π

Technical Challenges to Proton Driver Design

- Lattice
  - Transition-free
  - Zero-dispersion straights
  - Ample space for correctors and diagnostics
  - Low beta-functions and dispersion
  - Large dynamic aperture
  - Flexibility

- Space charge (ICFA Mini-Workshop, April 2-4, 2003, RAL, England, Chris Prior)
  - Simulations: 1D, 2D and 3D code bench marking, including higher order multipoles, machine errors and impedance.
  - Experiments, including beam halo study.
  - Possible cures (tune ramp, phase space painting, inductive inserts, transverse quadrupole damper)

- Electron cloud effects (CERN Workshop, April 15-18, 2002, Frank Zimmermann)
  - Simulations and measurements
  - A ***reliable*** theory that can predict the e-p instability threshold and growth rates

- Beam dynamics issues
  - Impedance reduction
  - Microwave instability of bunched beam below transition
  - Bunch rotation with path length dependence on ? p/p and space charge tune shift ? ?
  - Betatron tune split – How big is big enough (half-integer or integer)?

- Beam loss, collimation and remote handling
    - Beam loss calculation and bench marking
    - Collimation system: efficiency, susceptibility to parameter changes (tune, closed orbit, beginning and end of cycles)
    - Remote handling of "*hot*" components (e.g., a magnet) in the collimation area

- Ion sources
    - High current, low emittance (high brightness)
    - High duty factor

- Chopper
    - Fast rise- and fall-time
    - Short physical length
    - Waveform has flat top and flat bottom

- H^- injection
    - Foil issues (lifetime, efficiency, support)
    - Collection of unstripped H^-, H^0 and electrons

- Slow extraction (ICFA Mini-Workshop, October 14-18, 2002, BNL, Kevin Brown and Thomas Roser)
    - Efficiency at high intensity operations

- Magnet
    - Large aperture, large saggita, end effects, Sbend *vs.* Rbend
    - Eddy current loss in the coil
    - High voltage-to-ground

- Power supply
    - Resonant system *vs*. programmable system
    - Dual-harmonic resonant system
    - Cost of IGBT

- RF
  - High gradient at low frequency
  - Tunability
  - Beamloading problem

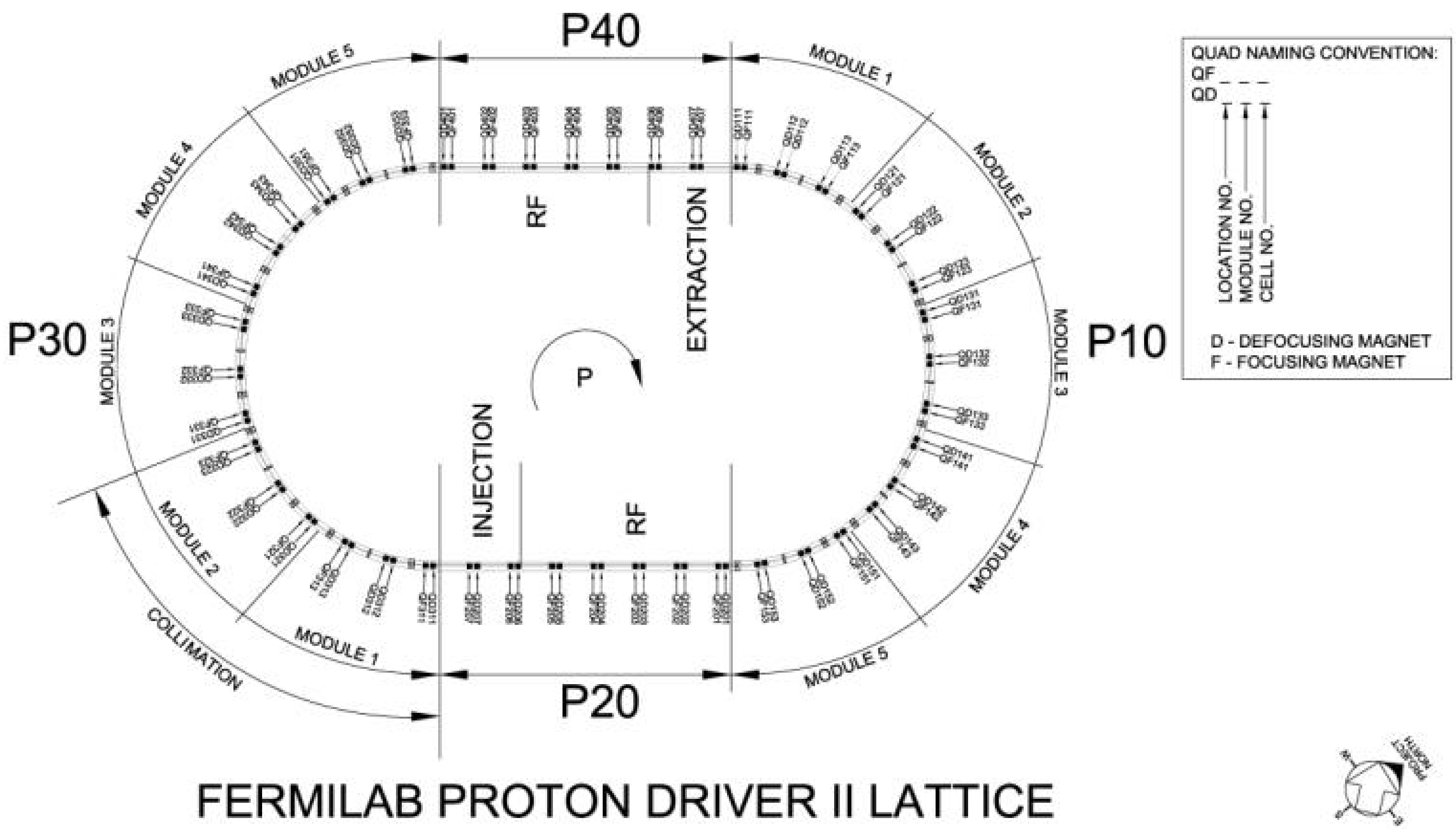
- Beam pipe
  - Ceramic (or Peek) vs. thin metal
  - Image current carrier
  - Mechanical stability

- Diagnostics (ICFA Mini-Workshop, Ocotber 21-25, 2002, ORNL, John Galambos and Tom Shea)
  - Special requirement for high intensity machines (e.g., during multi-turn injection)

- New (or revitalized) ideas
  - FFAG
  - Longitudinally separated function accelerators (superbunch acceleration)
  - Beam echo
  - Slip stacking
  - Barrier bucket rf stacking
  - Inductive inserts
  - High gradient (1 MV/m) low frequency (a few MHz) low duty cycle ($< 1\%$) rf system

Lattice Candidates for Fermilab Proton Driver

- Simple FODO
- Simple FODO with combined function magnets
- FMC with superperiod = 3
- FMC with superperiod = 2
- FMC using low-beta insertions
- Doublet with superperiod = 3
- Doublet with superperiod = 2
  - Missing dipole in mid-cell
  - Short dipole in mid-cell
    - Phase advance per module = 0.8/0.5
    - Phase advance per module = 0.8/0.6
    - Phase advance per module = 0.8/0.7
    - Phase advance per module = 0.8/0.8
    - Phase advance per module = 0.75/0.75



REV.	DATE	DESCRIPTIONS		NAME	DATE
		REVISIONS	DESIGNED		
			DRAWN		
			CHECKED		
			APPROVED		
			SUBMITTED		

SCALE:

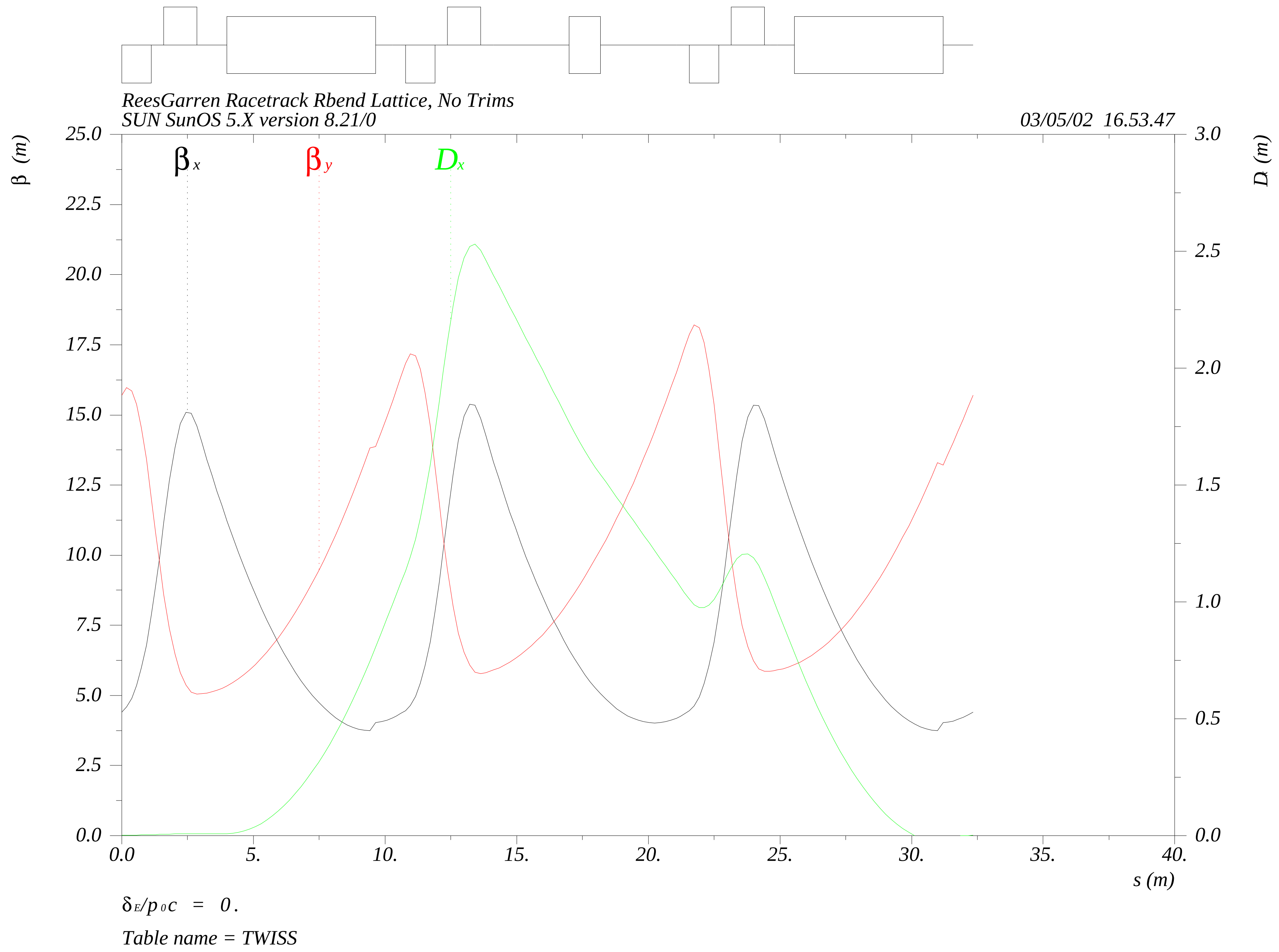
FERMI NATIONAL ACCELERATOR LABORATORY

UNITED STATES DEPARTMENT OF ENERGY

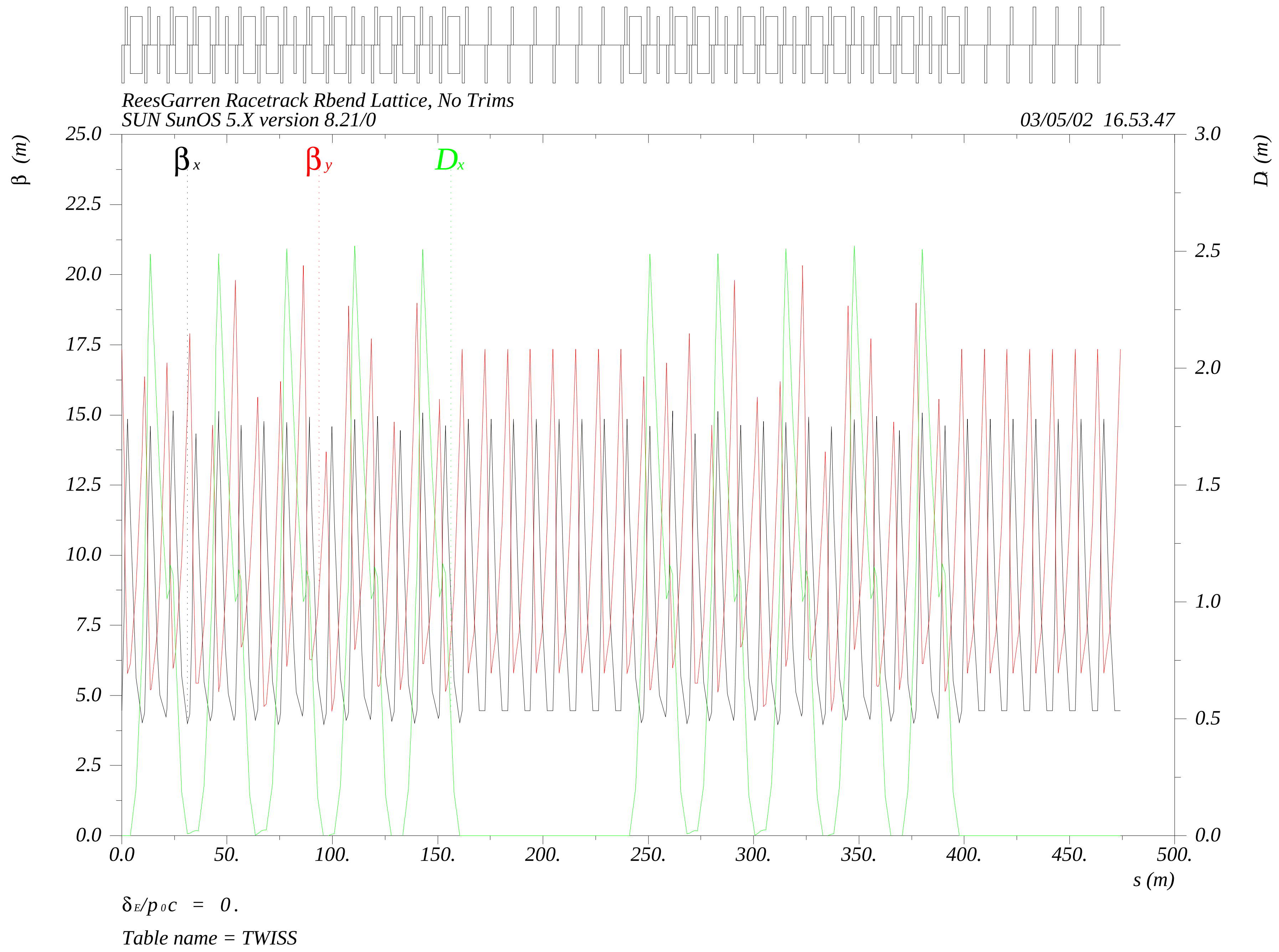
PROTON DRIVER II

PROTON DRIVER LATTICE NOMENCLATURE

DRAWING NO. **6-9-3** **TDR-7** REV.



ReesGarren Racetrack Rbend Lattice, No Trims
SUN SunOS 5.X version 8.21/0
03/05/02 16.53.47
β (m)
D (m)
βx
βy
Dx
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
5.
10.
15.
20.
25.
30.
35.
40.
s (m)
δE/p0c = 0.
Table name = TWISS


ReesGarren Racetrack Rbend Lattice, No Trims
SUN SunOS 5.X version 8.21/0
03/05/02 16.53.47
β (m)
D (m)
βx
βy
Dx
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
50.
100.
150.
200.
250.
300.
350.
400.
450.
500.
s (m)
δE/p0c = 0.
Table name = TWISS

monotonically, only slightly faster than linearly, by more than 2.5. The overall variation across $\pm$ 1% is small.

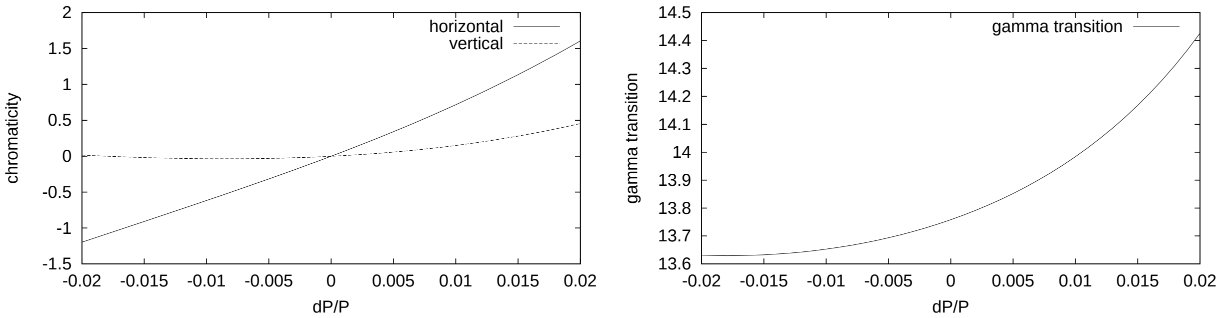


Figure 3.3.4.: Proton Driver chromaticity and γ_t.

The corresponding plot of γ_t vs. $\Delta p/p$ is the almost exponential looking curve displayed on the right in Figure 3.3.4.. Its variation is of no concern, because all of these values are larger than required.

Lattice functions, β_x, β_y, and D, take on perturbed values when $\Delta p/p \neq 0$. Their maxima are plotted, as functions of $\Delta p/p$, in Figure 3.3.5.. The variations of $\beta_{y,\mathrm{max}}$ and D_{max}

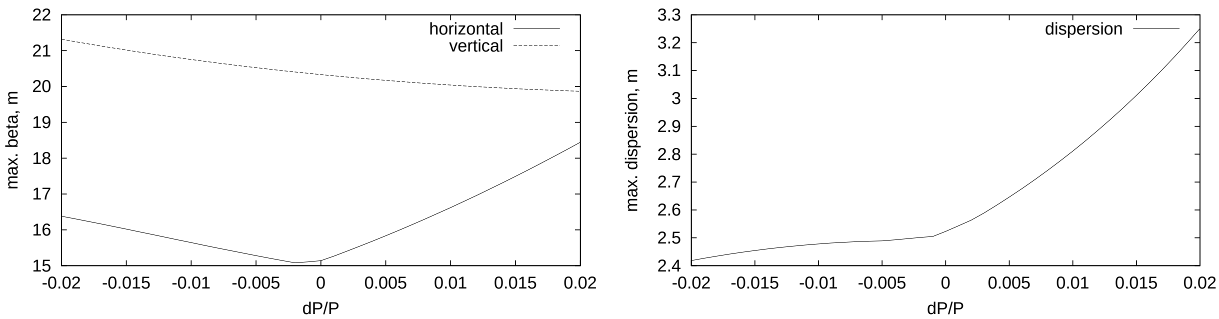


Figure 3.3.5.: Proton Driver maximum β functions and dispersion.

are monotonic, while $\beta_{x,\mathrm{max}}$ goes through a minimum near $\Delta p/p = 0$. As in the previous figures, there is larger variation for positive than negative $\Delta p/p$. Estimates of the closed orbit based on the value $D|_{\Delta p/p=0}$ should be increased by $\approx$ 12% at the momentum acceptance limit, $\Delta p/p = 1\%$.

3.3.2. Tune footprint

The sextupoles used to zero chromaticity will produce an amplitude dependent tune shift proportional to the square of their excitation. Second order perturbation theory predicts, for the PD2 base configuration,

$$\Delta\nu_x \quad = \quad 0.120\,\varepsilon_x/\pi + 0.114\,\varepsilon_y/\pi$$

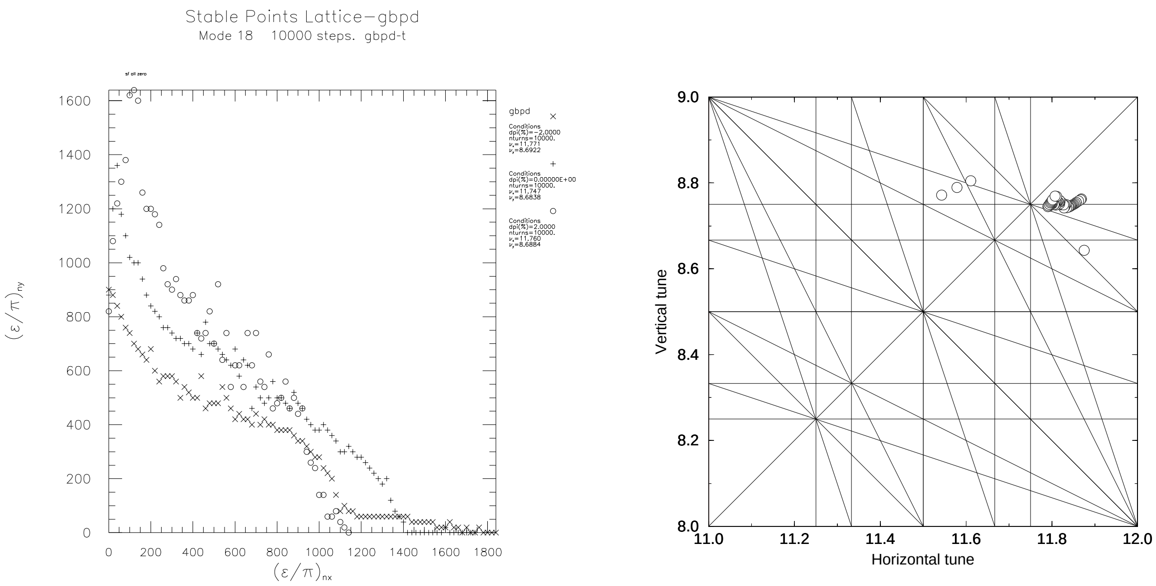


Figure 3.3.6.: Dynamic aperture: (a) Scatter plot of largest amplitude stable orbits at $\Delta p/p = 0$ and $\pm 2\%$. (b) Tunes of orbits at the boundary of the dynamic aperture.

scanned further to make certain that the stable orbits defining the dynamic aperture were not caused fortuitously by isolated stable regions (islands) in an otherwise unstable portion of phase space.

Peaks of the tune spectra were calculated for all orbits just inside the dynamic aperture. The right hand side of Figure 3.3.6. shows a scatterplot of these values superposed on the tune diagram of Figure 3.3.3.. Clearly, there is a clustering about the line $4\nu_y = 35$, which is excited at second order in the strength of sextupoles. The chromaticity sextupoles both excite this resonance and provide the necessary tune spread to put it within the reach of very large amplitude orbits, as will be discussed in Section 3.3.4.

3.3.4. Errors

We will assume the same estimates for positioning errors that were made in the PD1 Report [1, p.3-12]:

1) transverse quadrupole misalignments: $\sigma_X = \sigma_Y = 0.2$ mm.
2) dipole roll: $\sigma_\Theta = 0.2$ mrad; this will be relaxed to 0.5 mrad.
3) integrated dipole field uniformity: $|\Delta B/B| < 2 \times 10^{-4}$; this will be relaxed to 5×10^{-4}.

These estimates were based on criteria set for alignment of the Antiproton Accumulator. Those which are to be "relaxed" were considered too difficult to achieve reliably.

Machine Acceptance Comparison

Beam size:

$$L_b = \{\varepsilon_N \times \beta_{max} / \beta\gamma\}^{1/2} + D_{max} \times \Delta p/p$$

At injection (400 MeV): $\beta\gamma = 1.0$, $\Delta p/p = \pm 1\%$

Present Booster lattice:

$\varepsilon_N = 40\ \pi$ mm-mrad, $\beta(x)_{max} = 33.7$ m, $D_{max} = 3.2$ m $\rightarrow$ $L_b = 2.7$ inch

(But Booster magnet good field region < 1 inch)

New Proton Driver lattice:

$\varepsilon_N = 127\ \pi$ mm-mrad, $\beta(x)_{max} = 15.7$ m, $D_{max} = 2.4$ m $\rightarrow$ $L_b = 2.7$ inch

(Proton Driver magnet good field region = 3 inch)

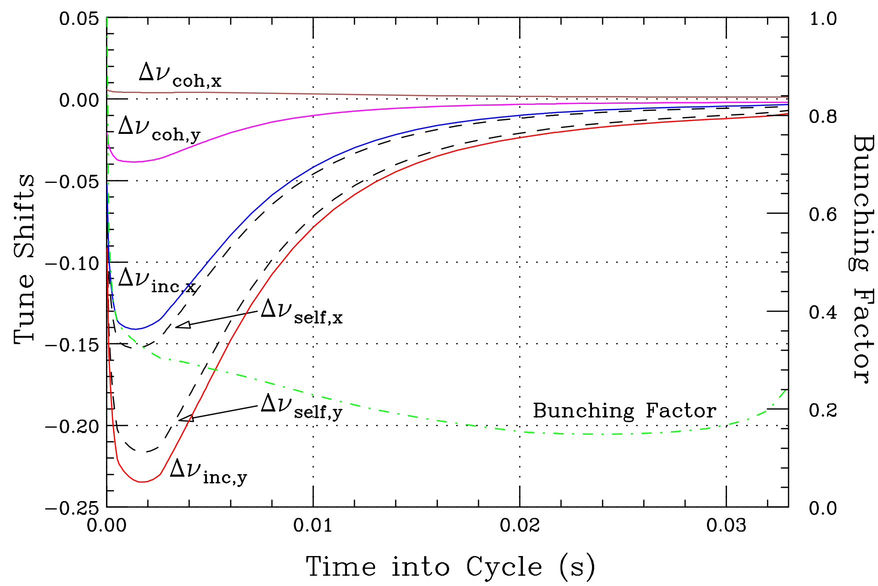


Figure 4.1.1: Coherent and incoherent betatron tune shifts of the new Fermilab booster.

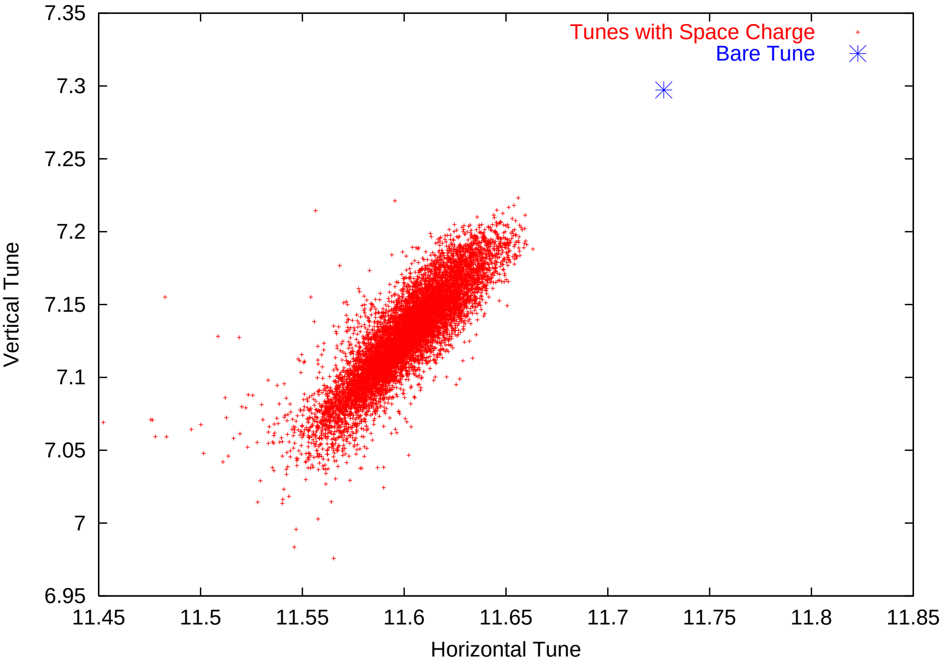
values, we can write

$$\Delta\nu_{\mathrm{incoh},x} = -0.153 + 0.013 = -0.140\,, \quad \Delta\nu_{\mathrm{incoh},y} = -0.216 - 0.018 = -0.234\,, \qquad (4.1.3)$$

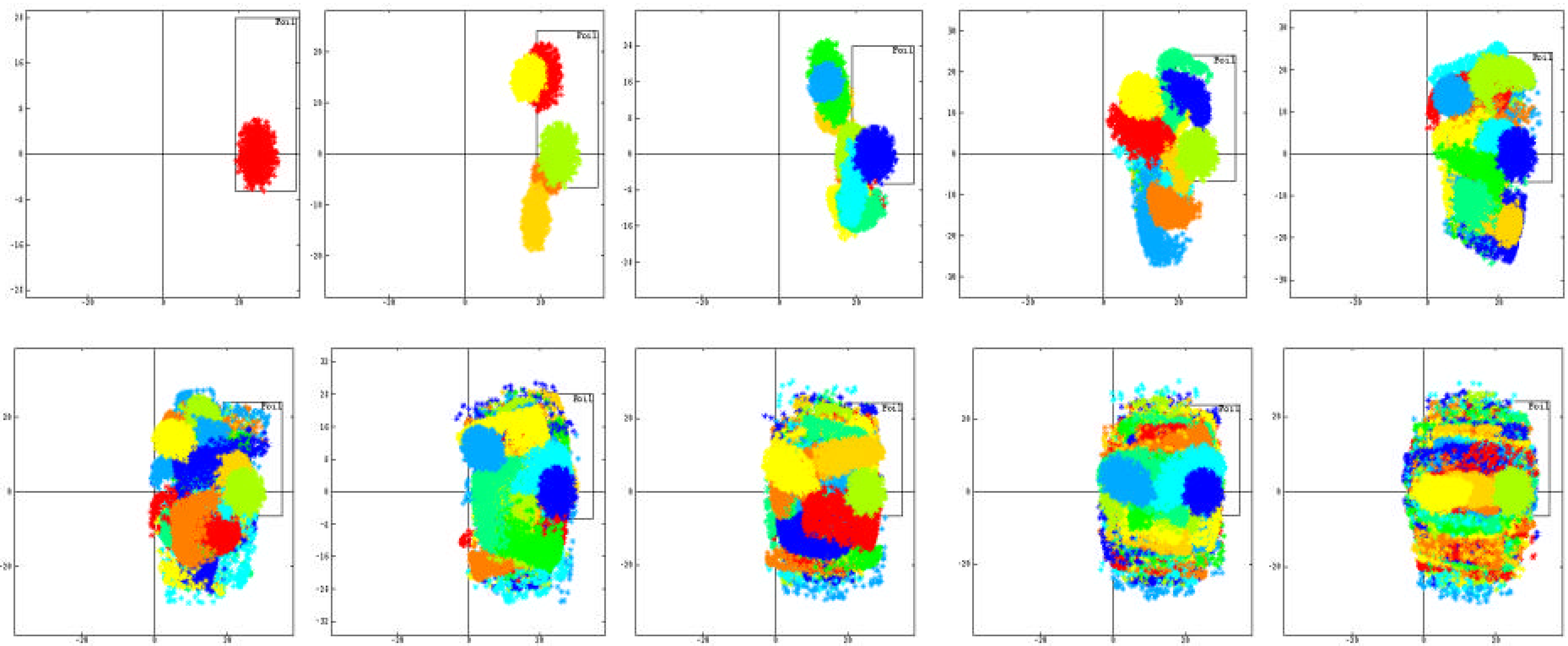
where the first terms in the middle correspond to self-force contributions and the second image contributions. It is obvious that space charge dominates the incoherent tune shifts. However, it is well-known that only the coherent tune shifts are responsible for parametric resonances [2]. Although the space charge self-force does not contribute to the dipole coherent tune shifts, it contributes to the quadrupole coherent tune shifts. The symmetric coherent quadrupole mode will be shifted by $2 \times \frac{3}{4}$ of the incoherent dipole shift, or $\nu_{\mathrm{quad}} = 2\big[\nu_{\mathrm{dipole}} - \frac{3}{4}|\Delta\nu_{\mathrm{incoh}}|\big]$. Therefore, $2\nu_y$ is shifted from 2×7.34 to 2×7.16 and $2\nu_x$ is shifted from 2×11.70 to 2×11.61. With the vertical and horizontal betatron bare tunes at $\nu_{y0} = 7.34$ and $\nu_{x0} = 11.7$, the equivalent vertical tune ν_y passes through the stopbands at 7.33, 7.25 and 7.20, while the equivalent horizontal tune ν_x passes through the stopband at 11.67.

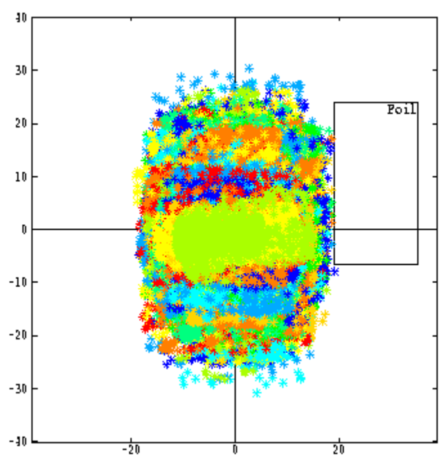
4.1.2 Space charge at Injection

The code TRACK-2D, developed in the Rutherford Laboratory in England [3], includes also transverse space-charge effects, making use of a nonlinear space-charge solver based on finite elements. The code has been applied to the parameters of the Fermilab new booster to study the evolution of particles in transverse phase space. The results are shown in Figs. 4.1.2 for the transverse plane (x, y). Reading from left to right and top to bottom, each plot shows a sequence of shots in the first 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 51 revolutions. Although these plots are on different scales, the transverse size of the injected beam can be inferred by comparison with the size



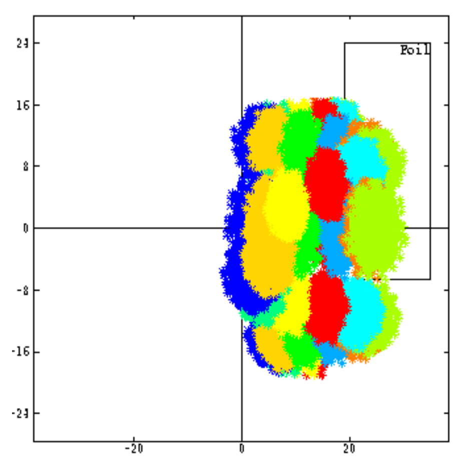
Tunes with Space Charge
Bare Tune
Vertical Tune
Horizontal Tune
7.35
7.3
7.25
7.2
7.15
7.1
7.05
7
6.95
11.45
11.5
11.55
11.6
11.65
11.7
11.75
11.8
11.85

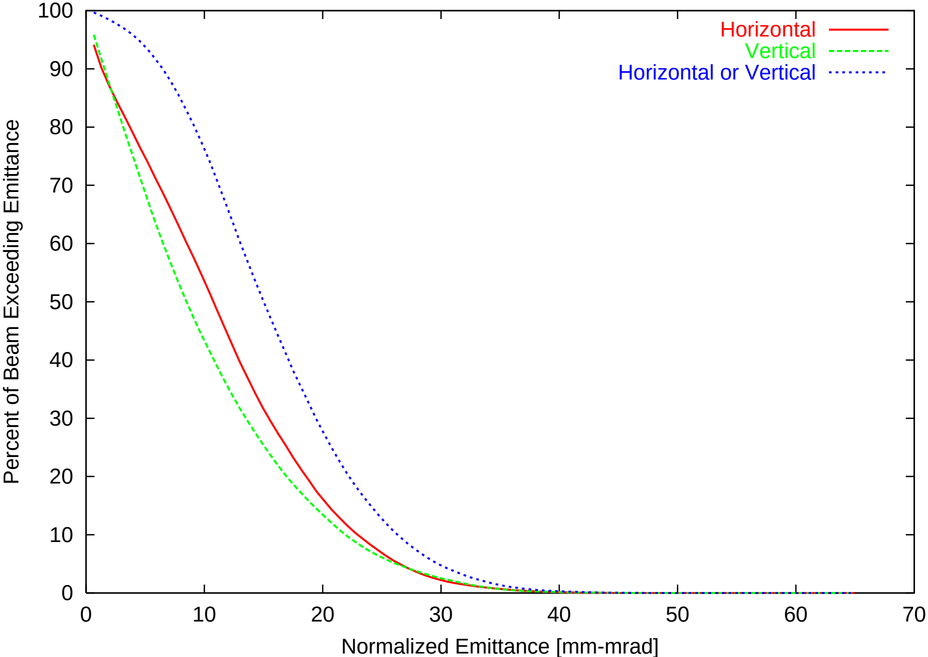




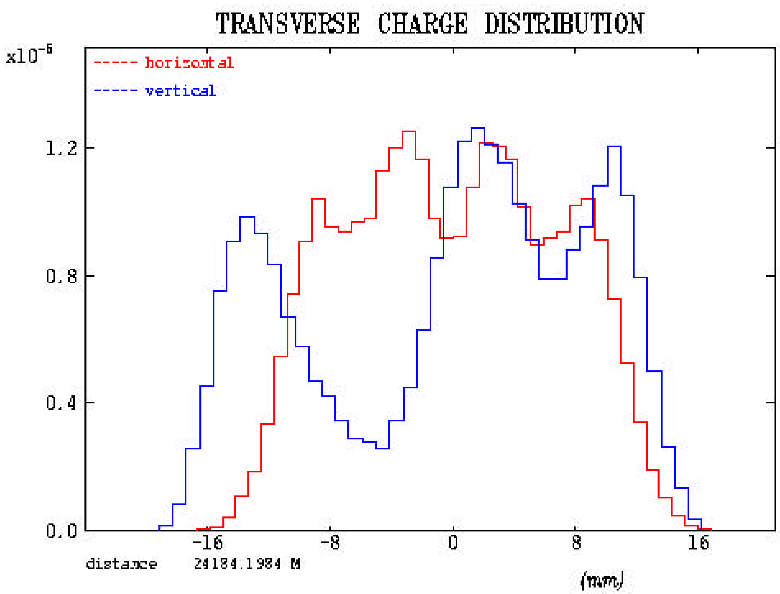
Rees Lattice:

Injected beam cross section at foil with space charge (zero space charge comparison to right)

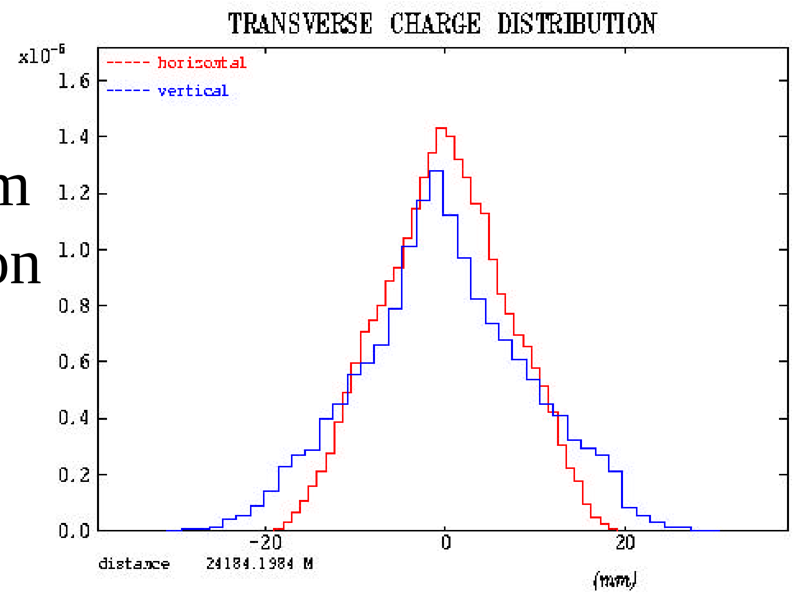




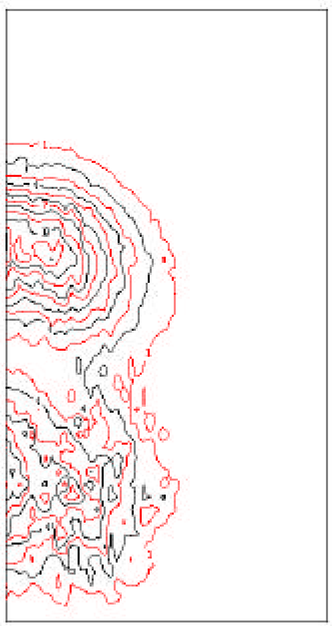
Percent of Beam Exceeding Emittance
Normalized Emittance [mm-mrad]
Horizontal
Vertical
Horizontal or Vertical
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70



Final beam distribution

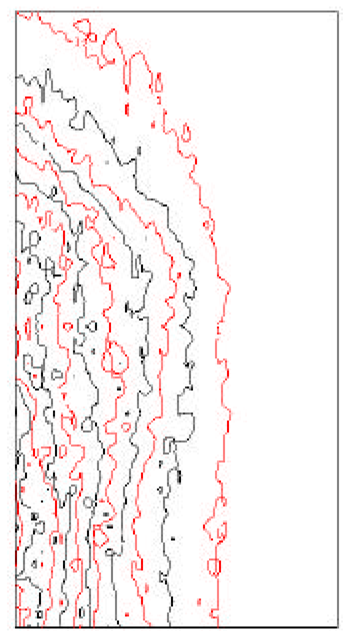


Zero space charge



Proton hits on foil

Space charge



Inductive Inserts in Booster (installed 10/01)

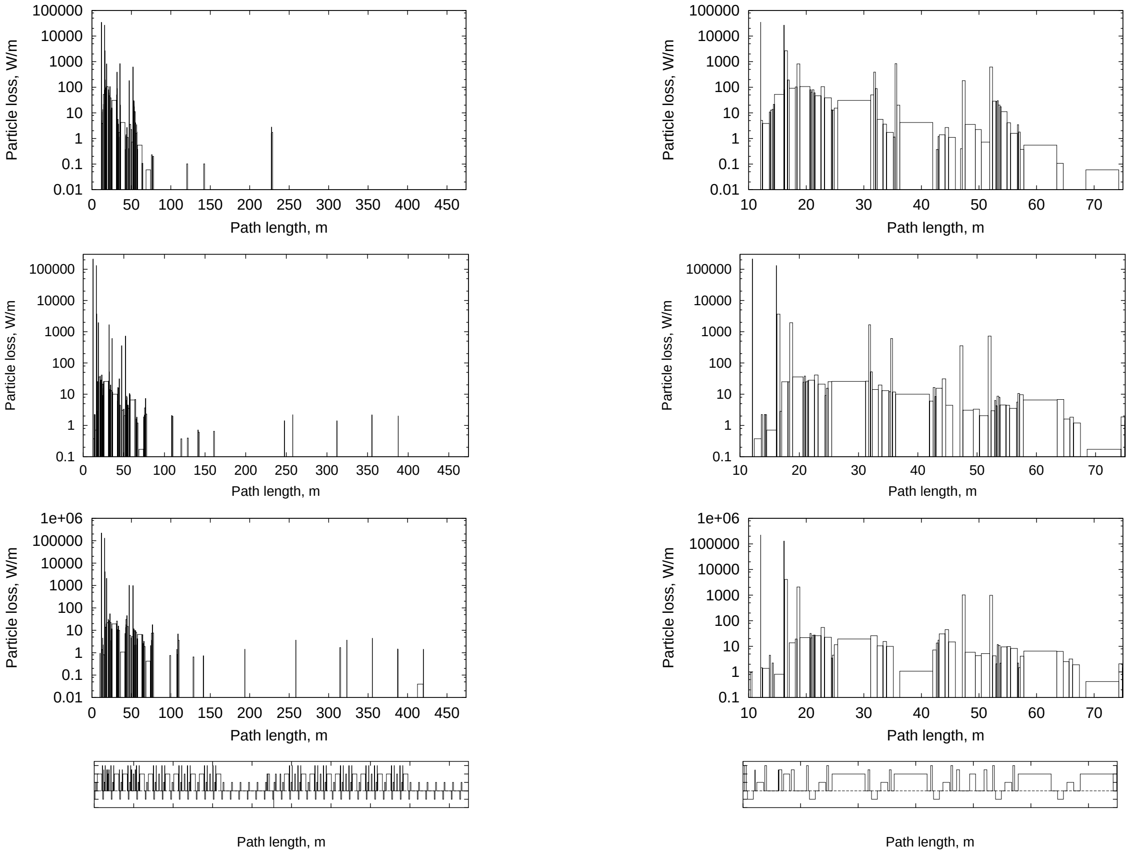


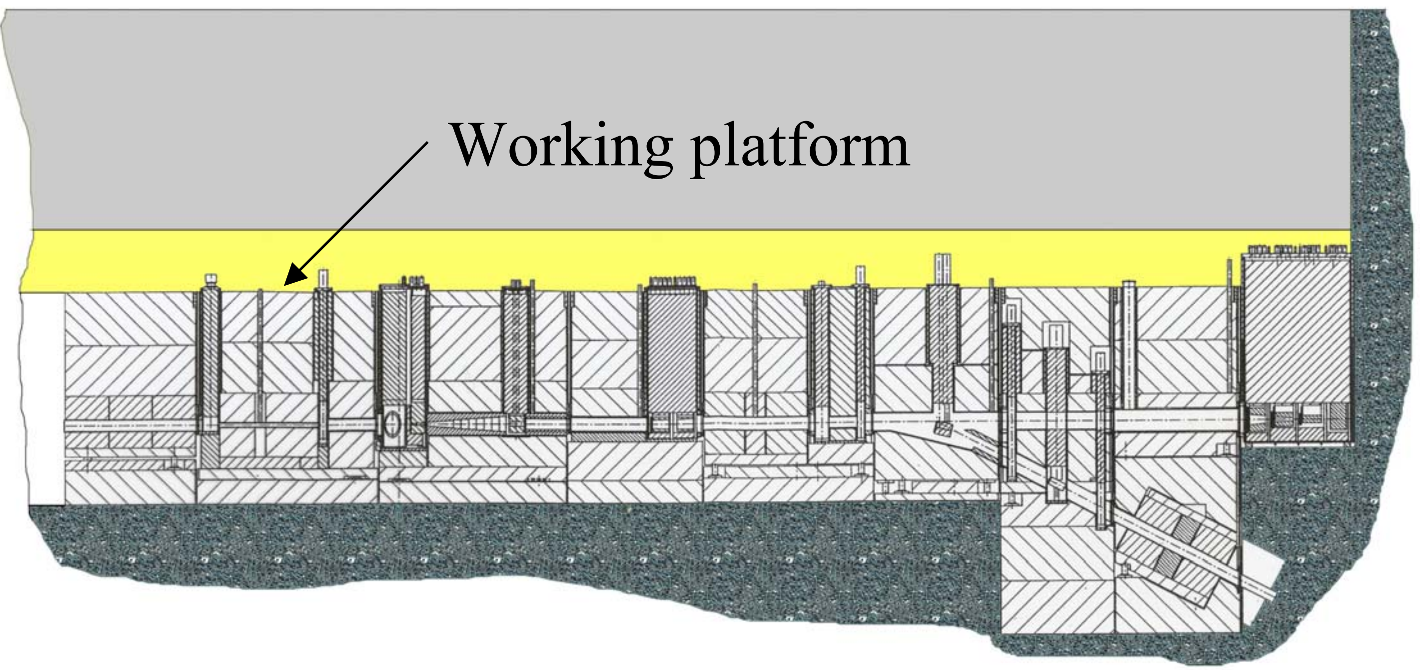
Figure 6.3. Beam loss distributions at injection (top) and at top energy with (middle) and without (bottom) supplementary collimators. Left group shows the entire machine and right group shows collimation region.

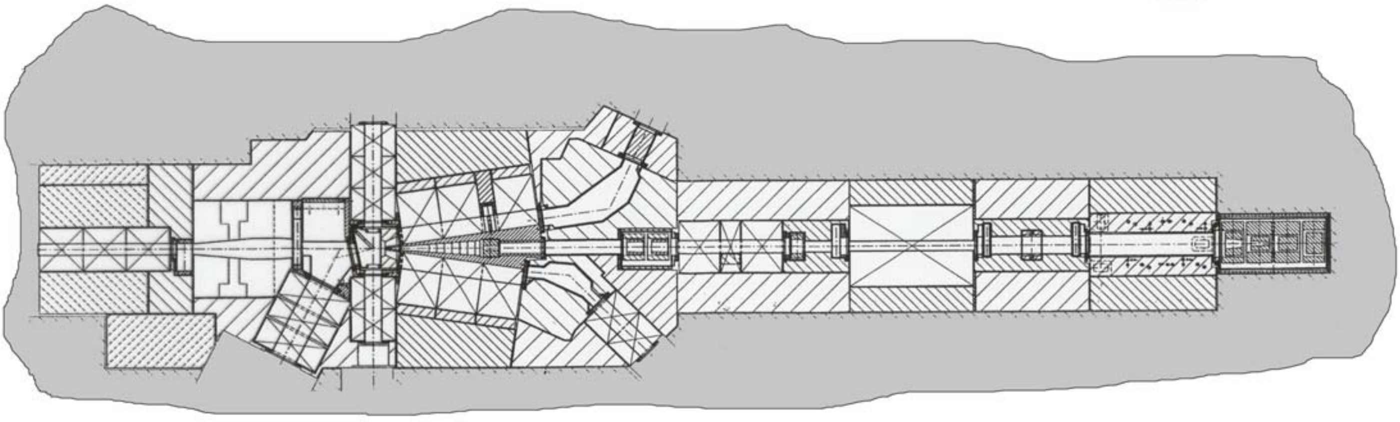
Table 6.2. Total beam losses in the 58-m collimation section (P_{coll}) and in the rest of the lattice (P_{rest}) and peak beam loss rates in the rest of the machine (p_{peak}).

Primary collimator thickness	P_{coll} (kW)	P_{rest} (kW)	p_{peak} (W/m)
E_{kin}=8 GeV without collimation			
	0.310	4.489	5900
E_{kin}=8 GeV without supplementary collimators			
t = 0.1 mm	4.768	0.035	8
t = 0.3 mm	4.753	0.048	7
t = 0.5 mm	4.749	0.051	9
t = 1.0 mm	4.742	0.058	7
t = 1.5 mm	4.743	0.057	8
E_{kin}=8 GeV with supplementary collimators			
t = 0.3 mm	4.778	0.024	2
E_{kin}=0.6 GeV with supplementary collimators			
t = 0.3 mm	3.596	0.005	0.2

Layout for 2 mA

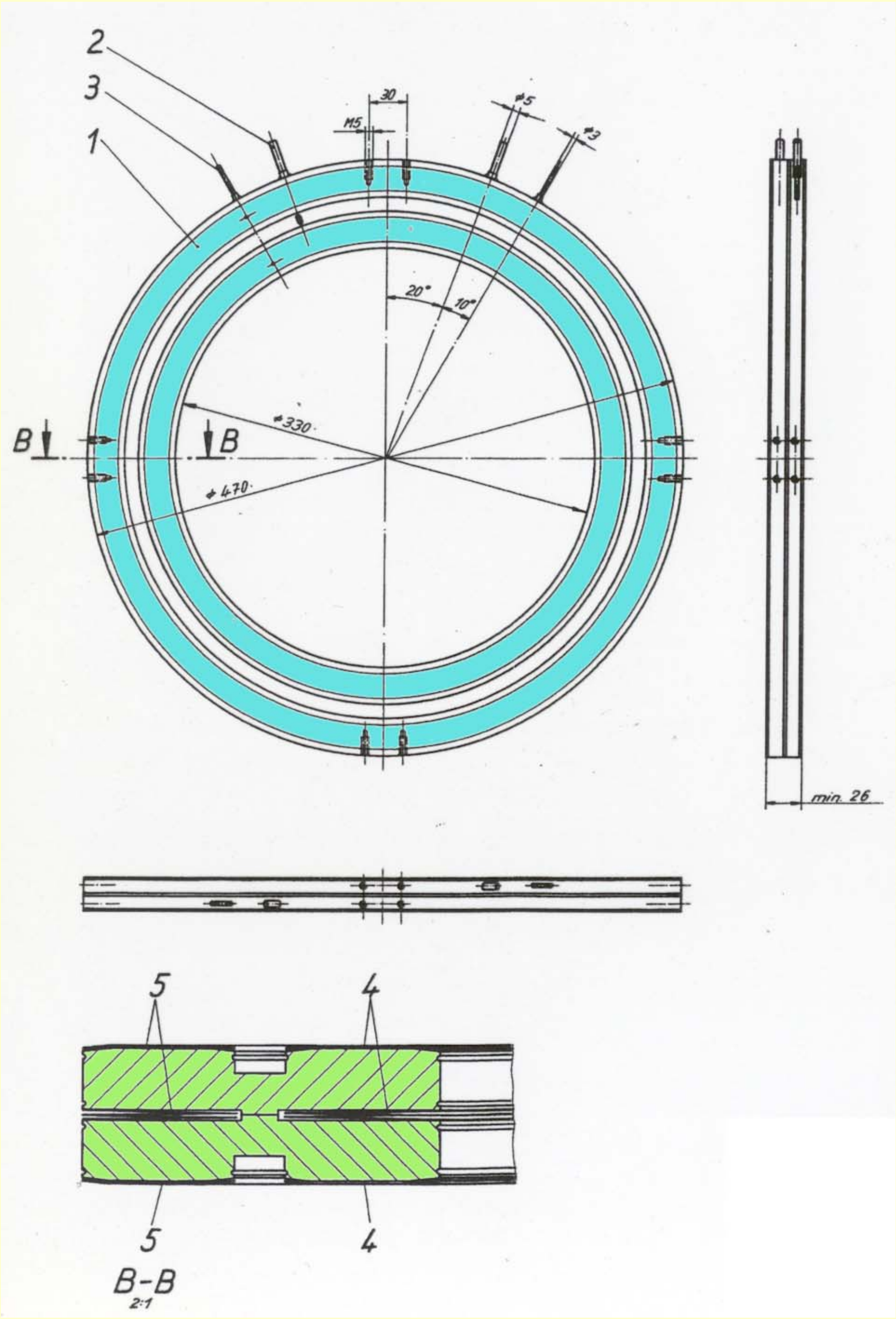
Vertical cut of the proton-channel





Horizontal cut of the proton-channel

Inflatable sealing (radiation resistent)



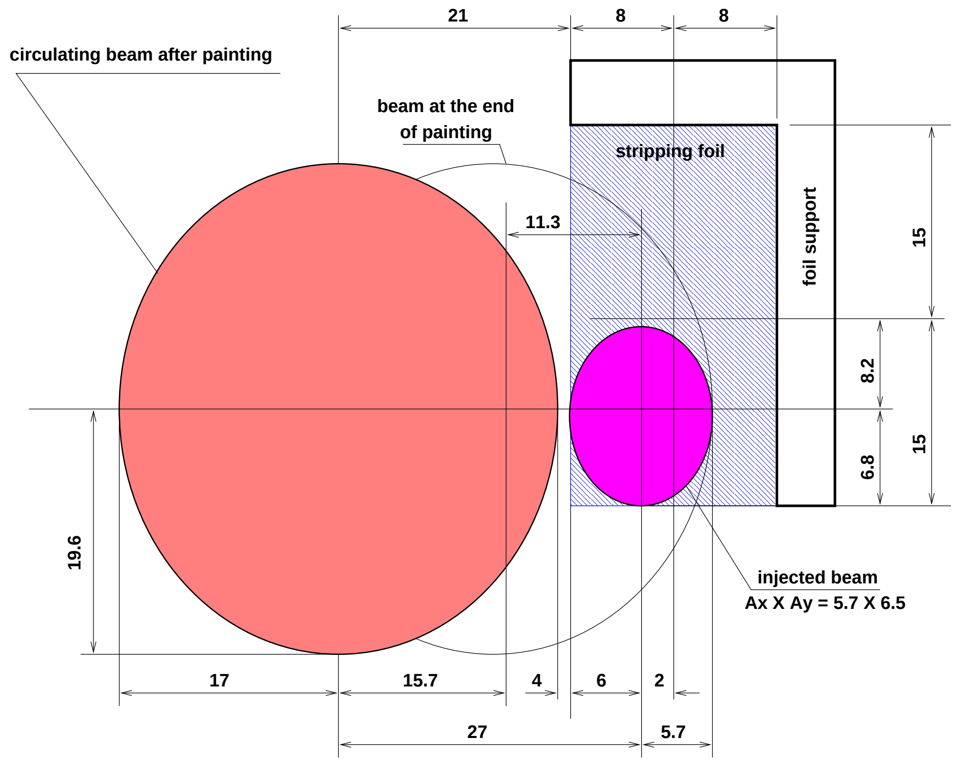


Figure 7.2. Injected and circulating beams location in the foil at painting.

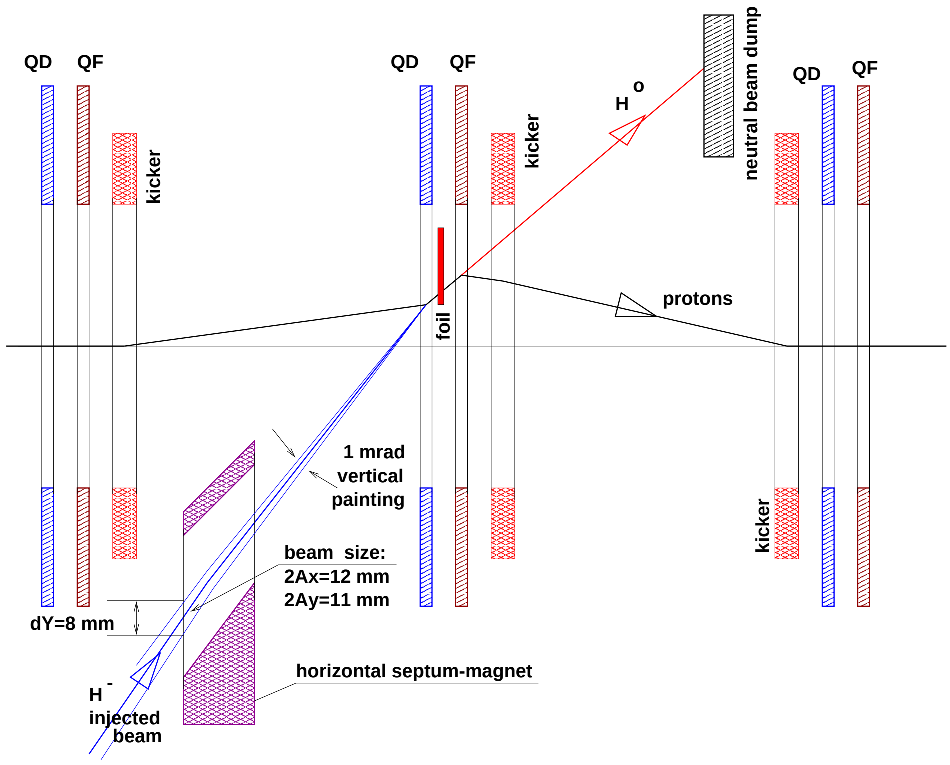
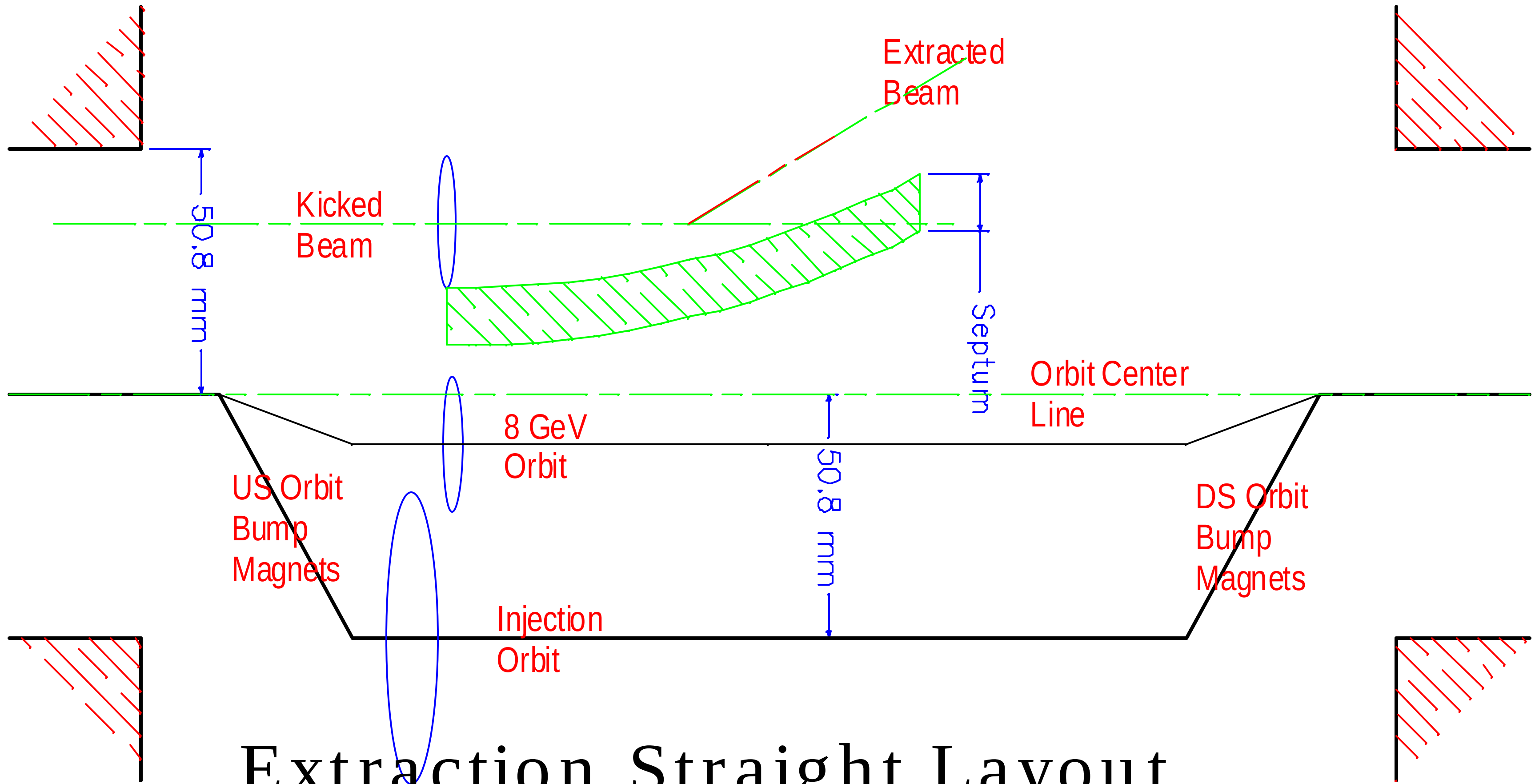


Figure 7.3. Painting injection scheme.



Extraction Straight Layout

Figure 1.1

Proton Driver Dipole Magnet Design

Magnet specification

Magnetic field	1.5 T
Good field region	
Height	101.6 mm
Width	152.4 mm
Field homogeneity	± 0.05 %
Magnet length	2.6 m
Repetition rate	15 Hz

Several issues:

- beam tube inside the magnet air gap
- ways to reduce beam pipe losses and compensate field distortions
- magnet winding made from conventional copper conductor
- eddy current losses in copper pipe with cooling channel
- voltage reduction

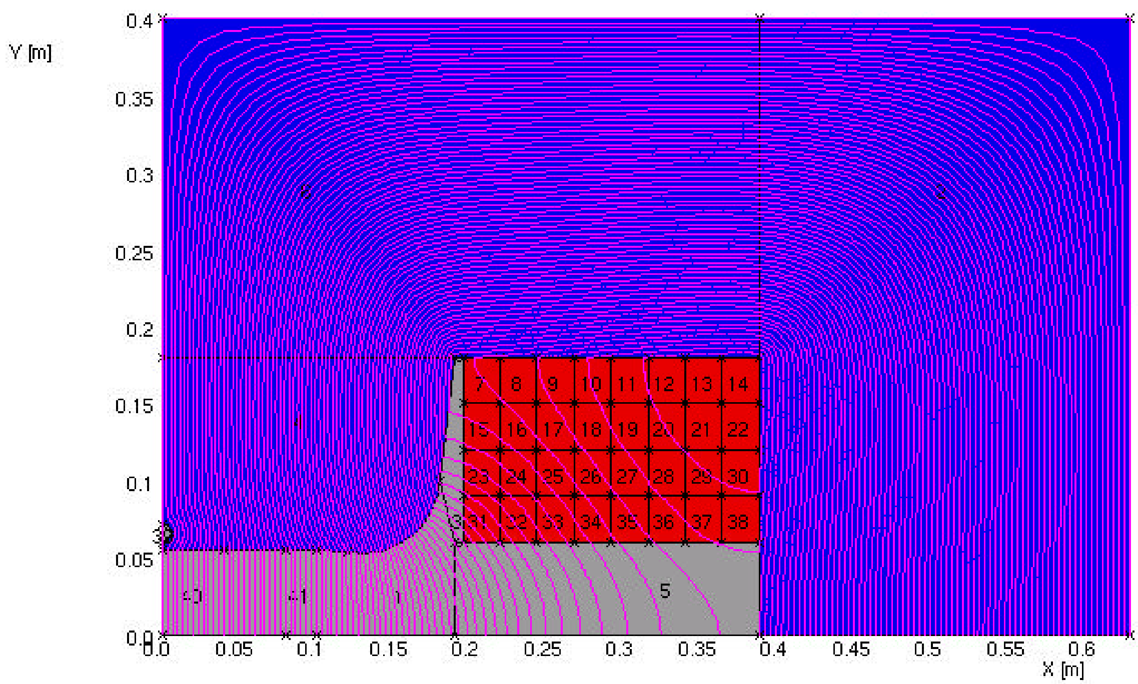


Fig. 1 Magnetic flux lines distribution in dipole magnet

Booster Magnet AC Field Measurement in E4R

Proton Driver Quadrupole

Main parameters

Gradient	**9.5626 T/m**
Pole tip radius	**88 mm**
Pole tip field	**0.84 T**
Maximum pole field	**2 T**
Aperture	**101.6 mm x 152.4 mm**
Length	**1.2 m**
Maximum current	**5170 A**
Conductor	**20mm x 20mm, 9mm dia.**
Number of turns/pole (two conductors or pancakes in parallel)	**6**
Inductance	**1.3 mH**

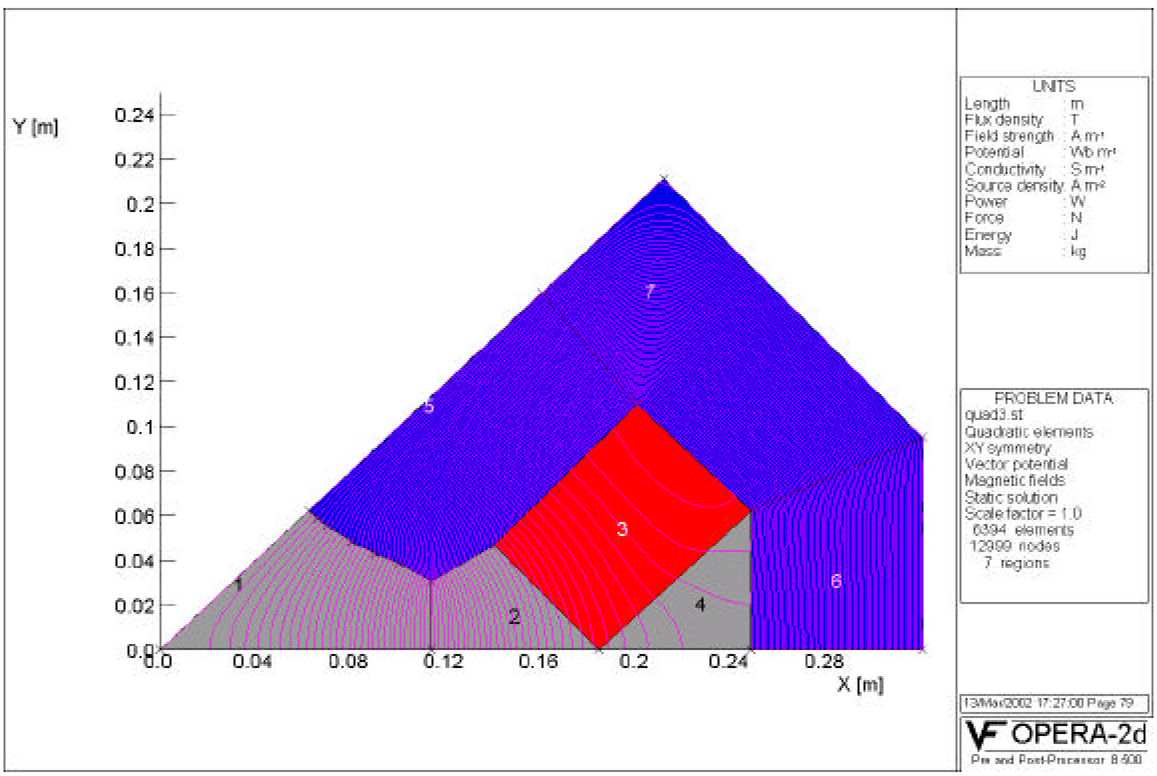
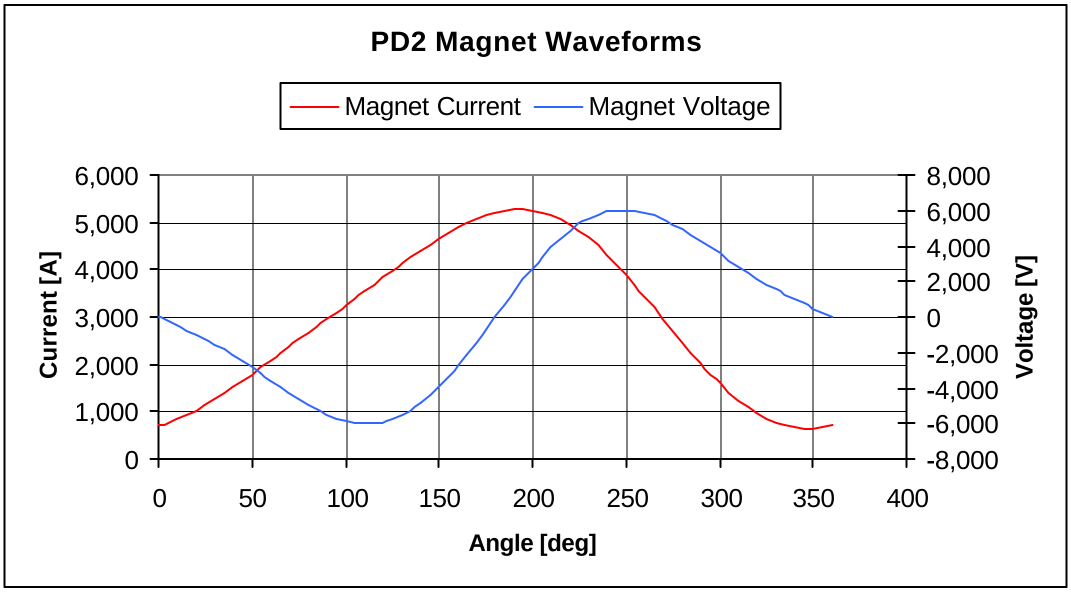


Fig.1 Flux lines

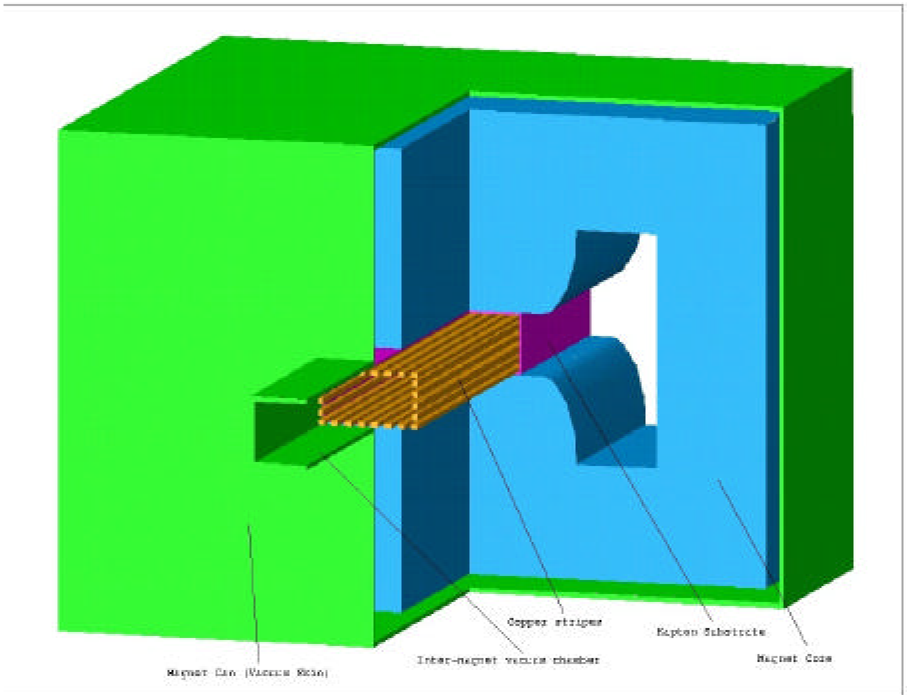
PD2 Power Supply System



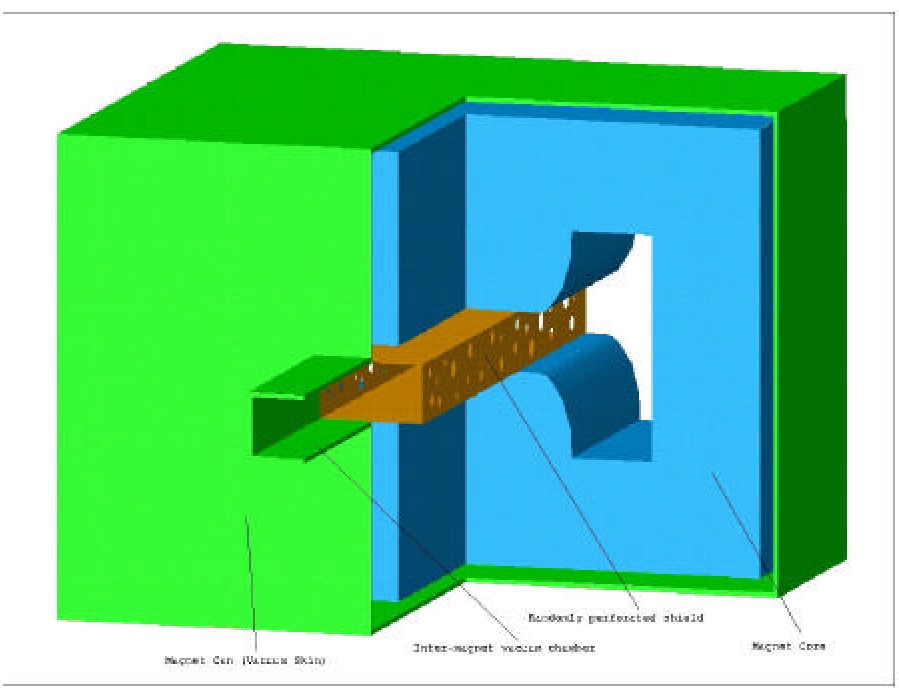
Parameter	Unit	Value
Magnet current:		
- peak	A	5,200
- dc	A	3,000
- ac, 15 Hz	A	2,200
- ac, 30 Hz	A	280
Total magnet inductance	H	0.535
Total magnet DC resistance	Ω	0.297
Magnet peak voltage to ground	V	3,050
Magnet peak stored energy	kJ	7,200
Number of resonant cells		22
Resonant cell main choke peak stored energy	kJ	318
Resonant cell aux. choke peak stored energy	kJ	72
Resonant cell main capacitor bank peak stored energy	kJ	133
Resonant cell aux. capacitor bank peak stored energy	J	107
Power supply voltage, peak	V	±2,000
Power supply current, peak	A	5,200
Number of power supplies		4

Booster RF Cavity Modification in MI-60

Stripe Line Shield



Perforated Liner Shield



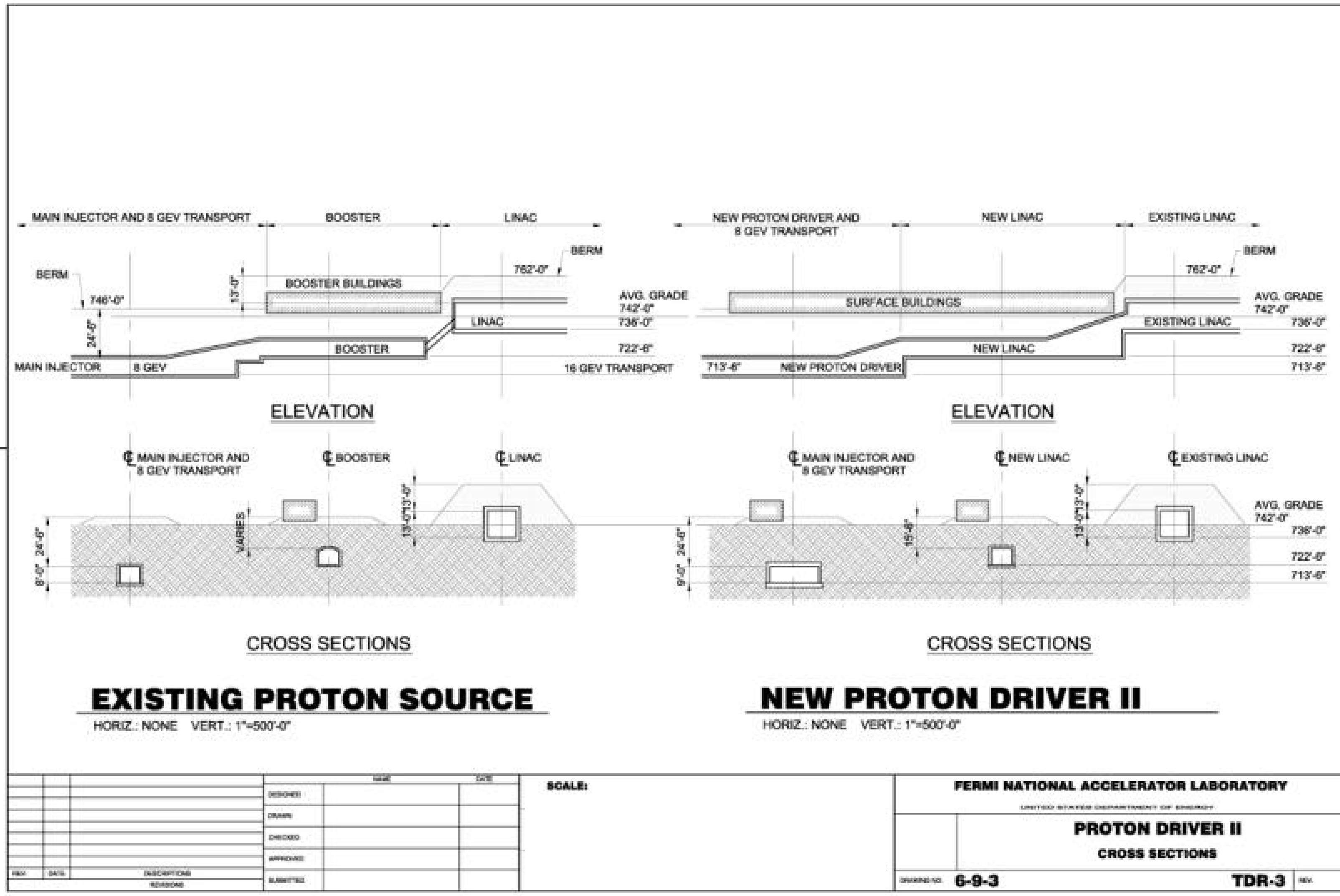
Linac Energy Upgrade (from 400 MeV to 600 MeV)

Table 8-1. Parameter Table for 600 MeV Linac and Ion Source

	Ion Source	LEBT/ Choppr	RFQ	Match Section	New Tank 1	DTL	CCL	HEBT	New CCL
Type	H^-	Electro-static	Vane	*TBD*	RGDTL	Drift-Tube	Coupled -Cavity		Coupled -Cavity
Output Energy (MeV)	0.05	0.05	2.5	2.5	10	116	401	401	601
Output Current (mA)	66	66	55	55	52	50	50	50	50
Emittance (π mm-mr, 95%)	1.0	1.2	2.0	2.6	2.8	2.8	3	3	3
Frequency (MHz)			201	201	201	201	805	805	805
Pulse Length	90	90	90	90	90	90	90	90	90

Table 8-2. Five Additional CCL Modules (#8 - #12) Parameters

Module #	Delta (KE)	KE(out)	Ave Beta	ZT**2	Lgth	E(max)	%E(k)	P(Cu)	P(cavity)	P(beam)	P(total)
7	44.4	401.5	0.70185	55.24	8.364	35.61	137%	7.6	7.6	2.22	9.79
8	40	441.5	0.72359	55.72	8.623	31.44	121%	5.9	5.9	2	7.91
9	40	481.5	0.74189	56.05	8.841	30.97	119%	5.7	5.7	2	7.73
10	40	521.5	0.75830	56.30	9.037	30.58	118%	5.6	5.6	2	7.58
11	40	561.5	0.77309	56.48	9.213	30.27	116%	5.5	5.5	2	7.46
12	40	601.5	0.78648	56.61	9.373	30.01	115%	5.4	5.4	2	7.35


MAIN INJECTOR AND 8 GEV TRANSPORT
BOOSTER
LINAC
BERM
762'-0"
BERM
746'-0"
13'-0"
BOOSTER BUILDINGS
AVG. GRADE
742'-0"
LINAC
736'-0"
24'-6"
BOOSTER
722'-6"
MAIN INJECTOR
8 GEV
16 GEV TRANSPORT
ELEVATION
MAIN INJECTOR AND
8 GEV TRANSPORT
BOOSTER
LINAC
VARIES
13'-0"
13'-0"
24'-6"
8'-0"
CROSS SECTIONS
EXISTING PROTON SOURCE
HORIZ.: NONE VERT.: 1"=500'-0"
NEW PROTON DRIVER AND
8 GEV TRANSPORT
NEW LINAC
EXISTING LINAC
BERM
762'-0"
SURFACE BUILDINGS
AVG. GRADE
742'-0"
EXISTING LINAC
736'-0"
NEW LINAC
722'-6"
713'-6"
NEW PROTON DRIVER
713'-6"
ELEVATION
MAIN INJECTOR AND
8 GEV TRANSPORT
NEW LINAC
EXISTING LINAC
15'-6"
13'-0"
13'-0"
AVG. GRADE
742'-0"
736'-0"
722'-6"
713'-6"
24'-6"
9'-0"
CROSS SECTIONS
NEW PROTON DRIVER II
HORIZ.: NONE VERT.: 1"=500'-0"
REV.
DATE
DESCRIPTIONS
REVISIONS
NAME
DATE
DESIGNED
DRAWN
CHECKED
APPROVED
SUBMITTED
SCALE:
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
PROTON DRIVER II
CROSS SECTIONS
DRAWING NO. 6-9-3
TDR-3
REV.

Main Injector Upgrade

Parameters	Present	Upgrade
Injection kinetic energy (GeV)	8	8
Extraction kinetic energy (GeV)	120	8 - 120
Protons per cycle	3×10^{13}	1.5×10^{14}
Cycle time at 120 GeV (s)	1.867	1.533
Average beam current (μA)	2.6	16
Beam power (MW)	0.3	1.9

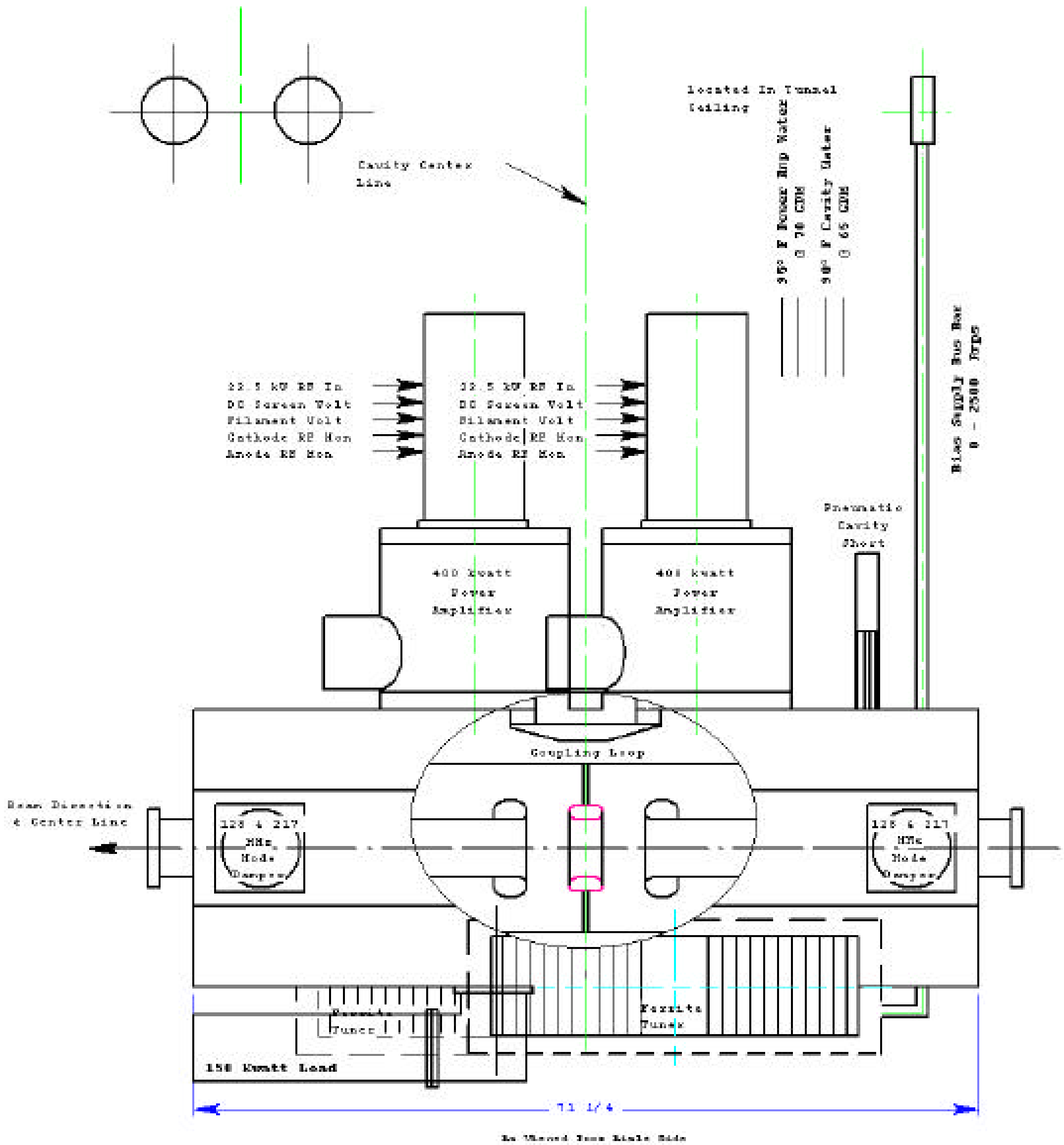
Goals:

- Intensity increased by a factor of 5
- Cycle time reduced by 20%
- Beam power increased by a factor of 6

System upgrade:

- RF: Major upgrade. Need a second power amplifier for each cavity and 2 more cavities.
- Power supply: Moderate upgrade.
- Magnet: Ok.
- Kickers: Major upgrade for larger vertical aperture.
- Cooling capacity: Ok for magnet, but need to be doubled for rf.
- Gamma-t jump system: New.
- Large aperture quad: New.
- Collimation system: New.
- Passive damper and active feedback: New or improved.
- Stop band correction: New.
- Shielding: Ok.
- Beam dump: Moderate upgrade.
- NuMI and MiniBooNE beamlines: Moderate upgrade.
- 120 GeV beamlines: Under study.
- Specific when using an 8-GeV linac:
    - H^- injection: New.
    - MiniBooNE extraction: New.

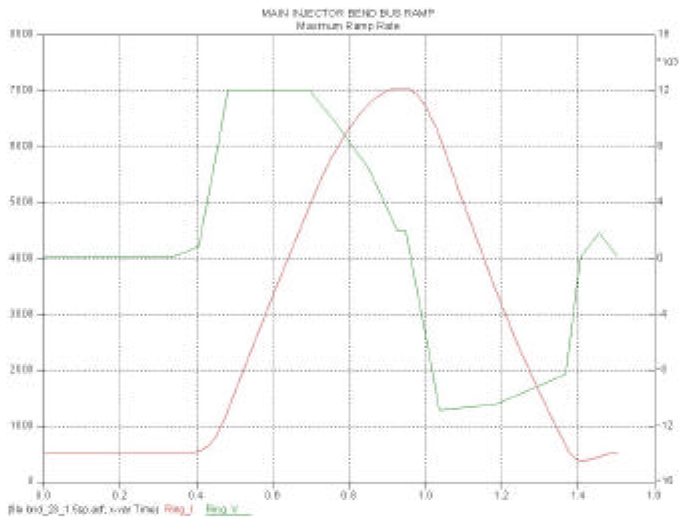
Main Injector RF Upgrade - Dual Power Amplifier



Modified Main Injector Cavity for Two Power Amplifiers

Main Injector Power Supply Upgrade

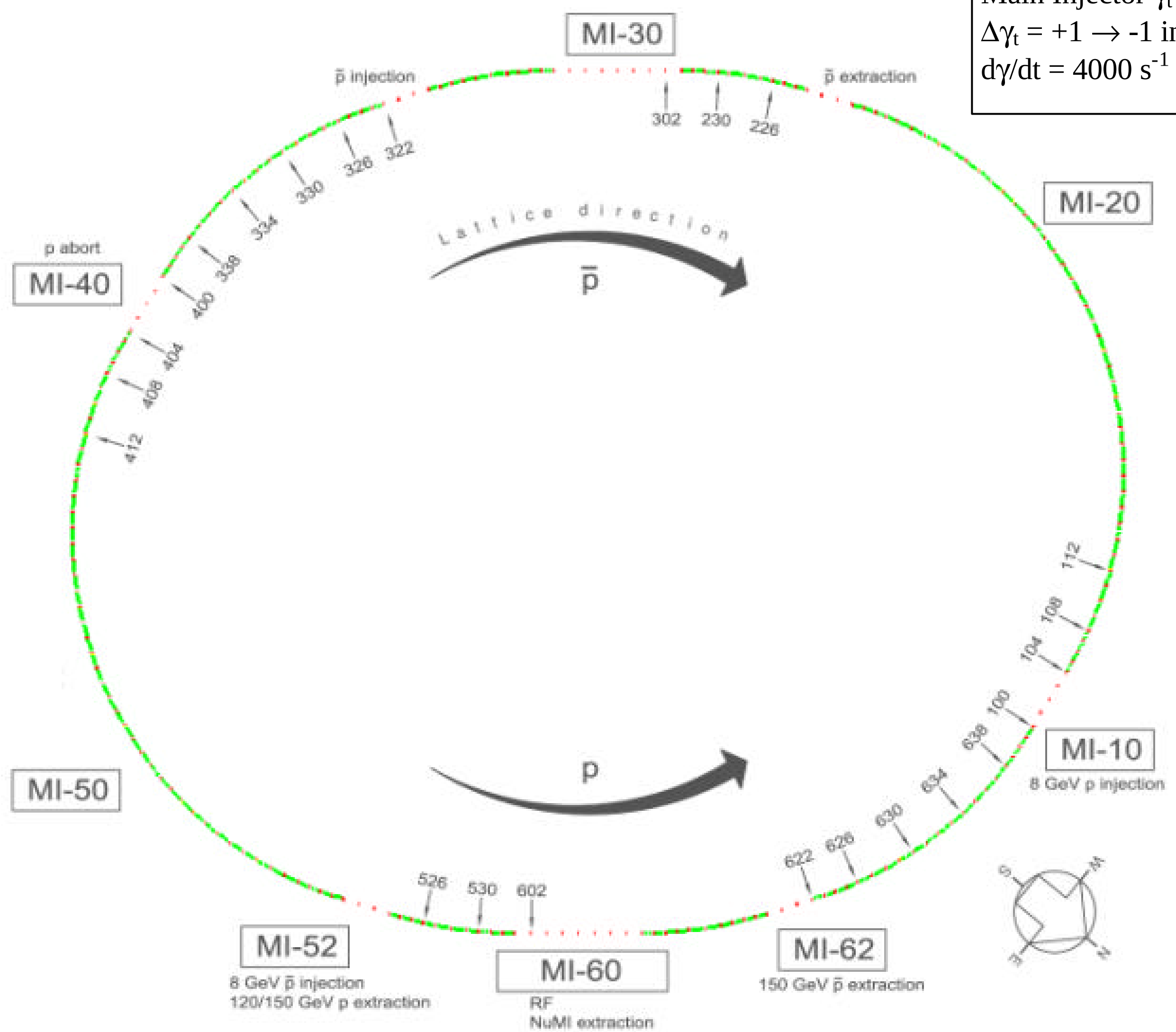
Time	Momentum	Pdot	Pddot
0.34000	8.889	0.00	0.00
0.36367	8.96	6.00	253.52
0.40521	9.5	20.00	337.04
0.48213	22	305.00	3705.00
0.69862	85	277.00	-129.33
0.84938	115	121.00	-1034.80
0.92706	119.7	0.00	-1557.55
0.94706	119.7	0.00	0.00
1.03615	105	-330.00	-3704.08
1.17901	60	-300.00	210.00
1.36747	11	-220.00	424.49
1.40656	6.7	0.00	5627.91
1.45521	7.7945	45.00	925.08
1.50385	8.889	0.00	-925.08
1.50485	8.889	0.00	0.00

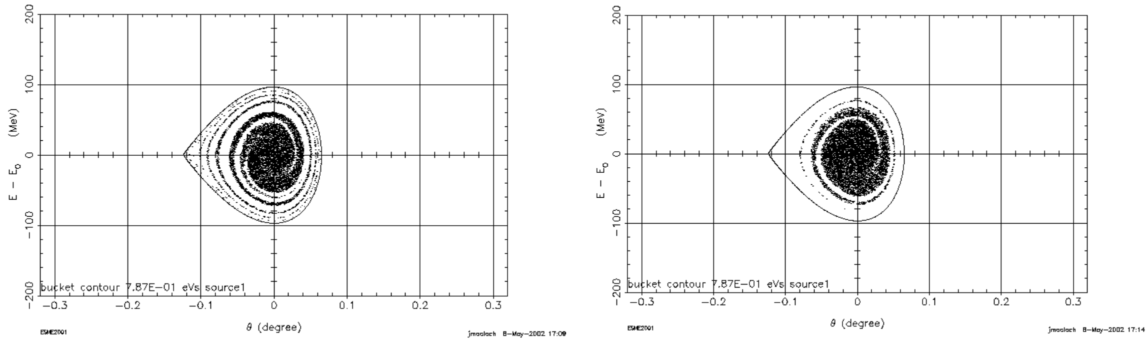


The following is a list of the changes that were made to achieve this cycle time:

1. The injection time was reduced from .5s to .34s.
2. The 22 GEV ramping segment was increased from 240 GEV/s to 305 GEV/s.
3. The 85 GEV ramping segment was increased from 230 GEV/s to 277 GEV/s.
4. The flattop time was reduced from .098s to .02s.
5. The 105 GEV invert segment was increased from -300 GEV/s to -330 GEV/s.
6. The 60 GEV invert segment was increased from -280 GEV/s to -300 GEV/s.

Main Injector γ_t-Jump System
$\Delta\gamma_t = +1 \rightarrow -1$ in 0.5 ms
$d\gamma/dt = 4000\ s^{-1}$





(a) normal transition crossing
$\varepsilon_\ell = 0.101$ eVs (rms)

(b) transition crossing with a jump of two units in γ_T
$\varepsilon_\ell = 0.077$ eVs (rms)

Figure 2.2.1. MI bunches at 42 GeV on a 300 GeV/c/s ramp. The bunches were 0.35 eVs elliptical distributions (0.069 rms) at injection.

Table 2.2.1. RMS emittance and percentage survival for 300 GeV/s MI ramps with/without γ_T-jump and with/without inductive insert to cancel imaginary impedance at transition. The effect of negative mass is *not* included.

Initial ε_ℓ [eVs]					
100%	rms	γ_T-jump	L insert	Final rms ε_ℓ	Loss %
0.30	0.060	N	Y	0.084	0.09
		Y	Y	0.066	0.00
0.35	0.069	N	N	0.101	0.74
		N	Y	0.095	0.40
		Y	N	0.077	0.00
		Y	Y	0.078	0.00
0.38	0.075	N	N	0.104	1.39
		N	Y	0.102	0.87
		Y	N	0.084	0.00
0.40	0.079	N	N	0.107	1.94
		N	Y	0.106	1.31
		Y	Y	0.089	0.00

Gamma-t Jump System 24 Pulsed Quad Location

(LS MI-10)
104 – to relocate multiwire
108 – to remove a sextupole
112 – ok

(Long arc, LS MI-22)
226 – to shorten BPM by 1" or to eliminate bellows
230 – same as 226
302 – to relocate Schottky detector

(LS MI-30, MI-32)
322 – problem : collision with MI32 pbar line from Recycler
326 – same as 108
330 – ok

334 – ok
338 – ok
400 – to move abort kicker downstream by 1 m

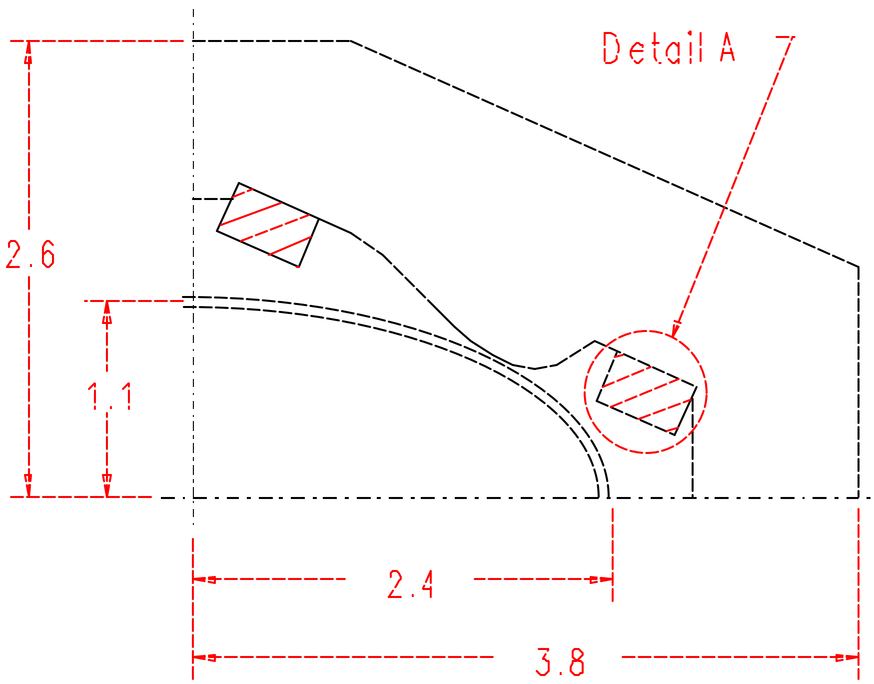
(LS MI-40)
404 – ok
408 – same as 108
412 – ok

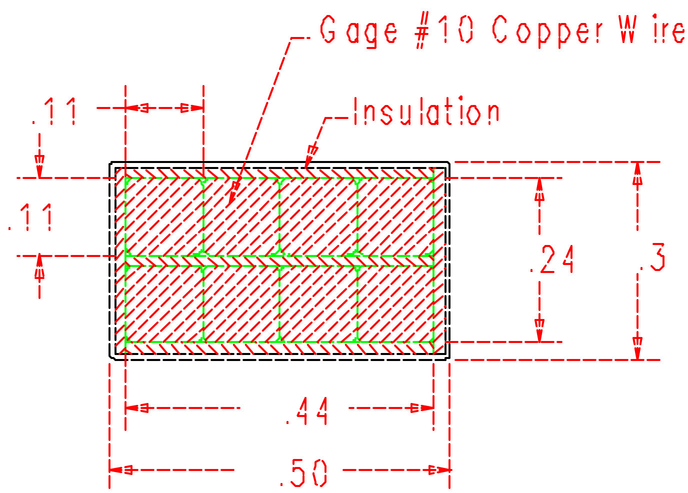
(Long arc, LS MI-52)
526 – same as 226, plus to relocate LLRF pickup
530 – same as 526
602 – to relocate Desert Air box

(LS MI-60, MI-62)
622 – to move pbar extraction kicker by 1 m
626 – same as 108
630 – to remove a trim quad

634 – ok
638 – ok
100 – to move γ_t quad downstream by 40" to avoid SQA852

Gamma-t Jump Pulsed Quadrupole



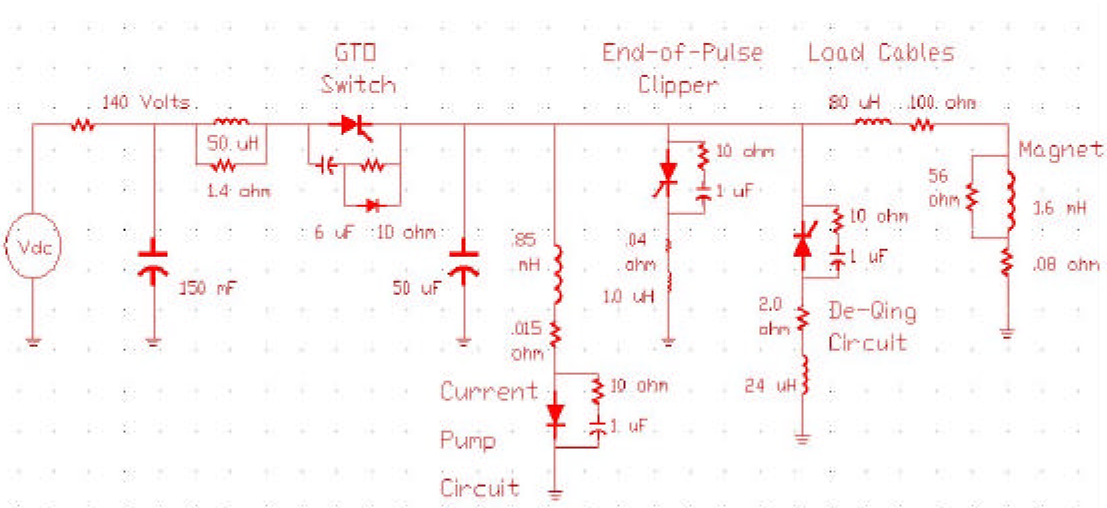


Detail A : Coil Cross-Section

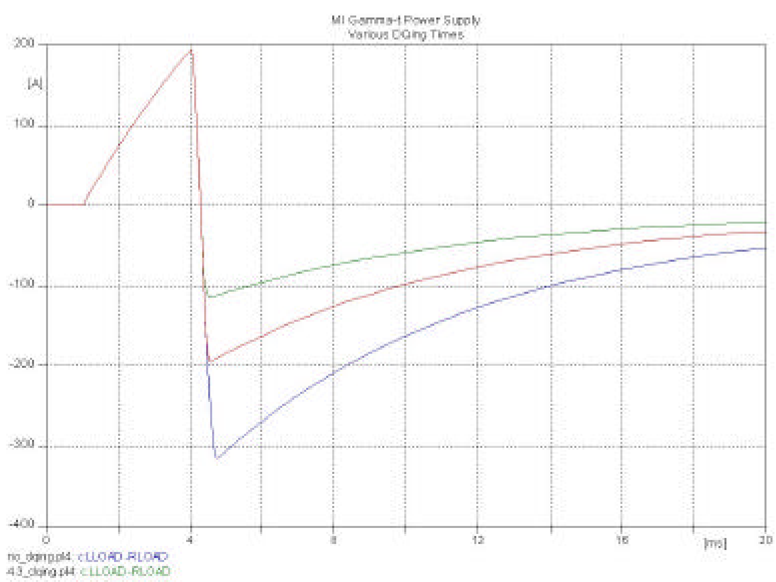
M 4:1

Gamma-t Jump Power Supply

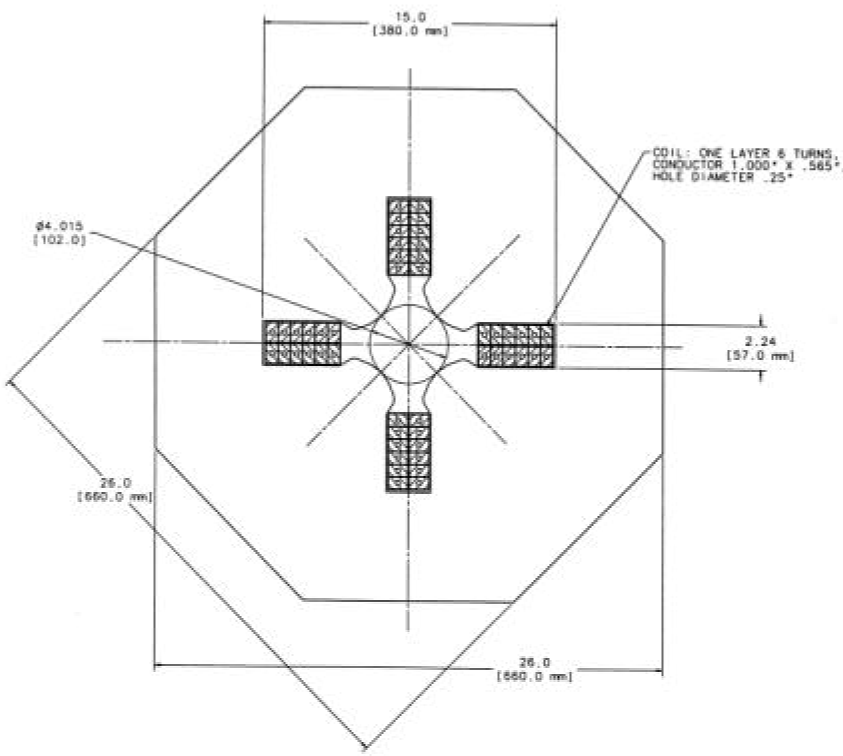
The system consists of 8 power supplies. Each power supply drives a four-magnet quadrupole string. The power Supply design is shown in the following diagram:



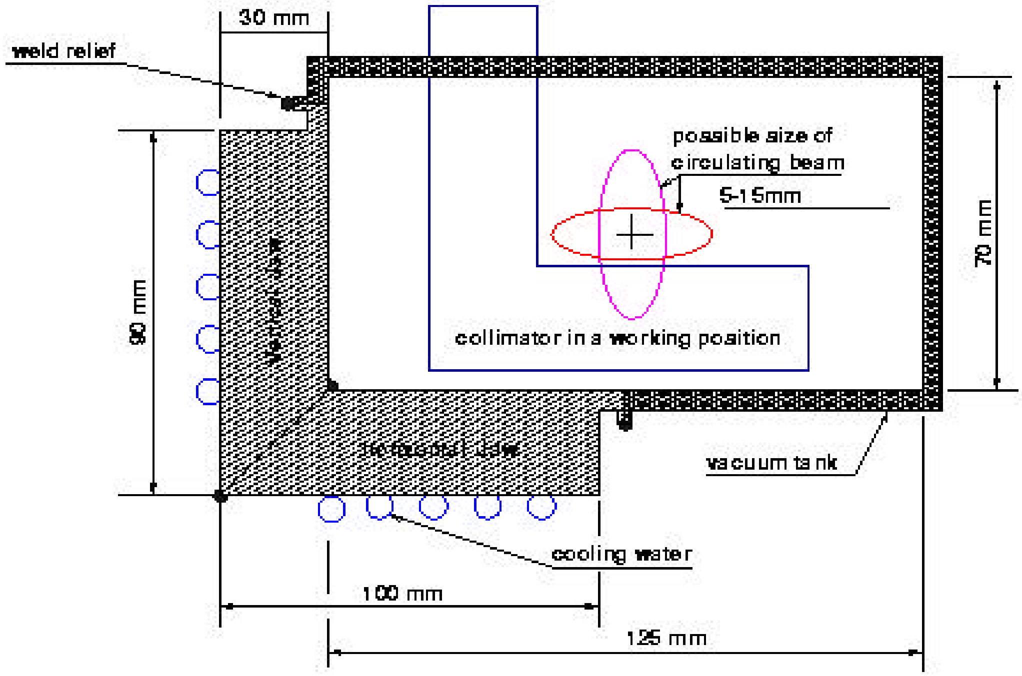
The following plot shows the various magnet current waveforms that can be produced by the power supply:

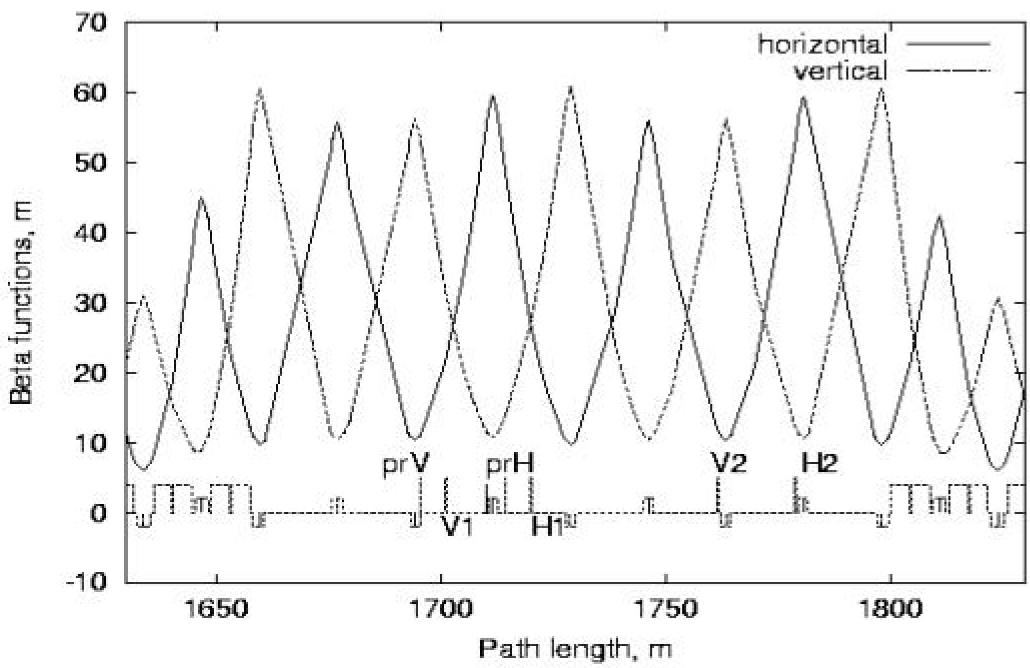


Main Injector Large Aperture (4") Quadrupole

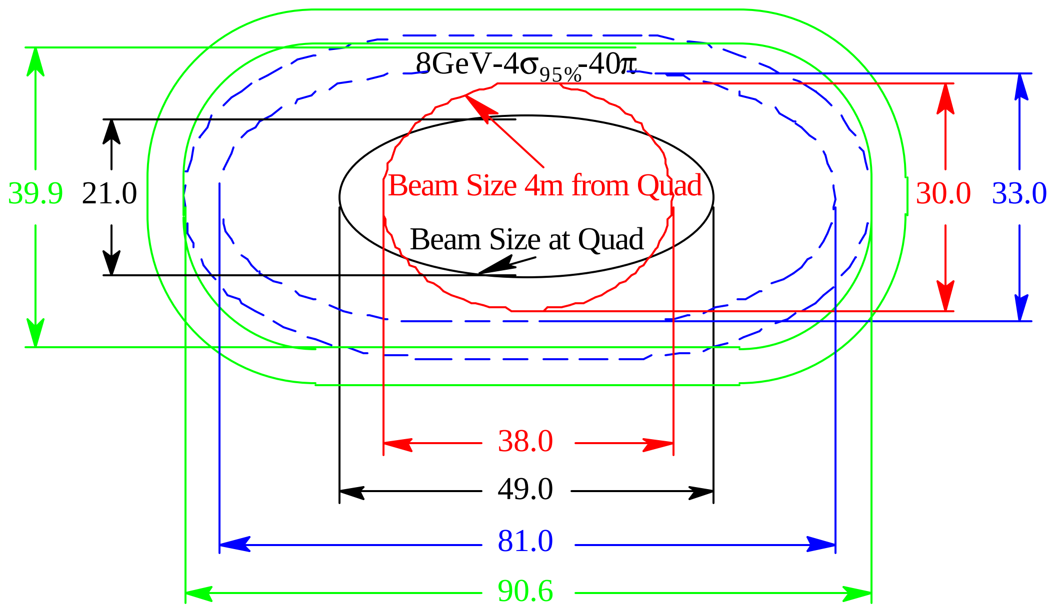


Main Injector Collimator System

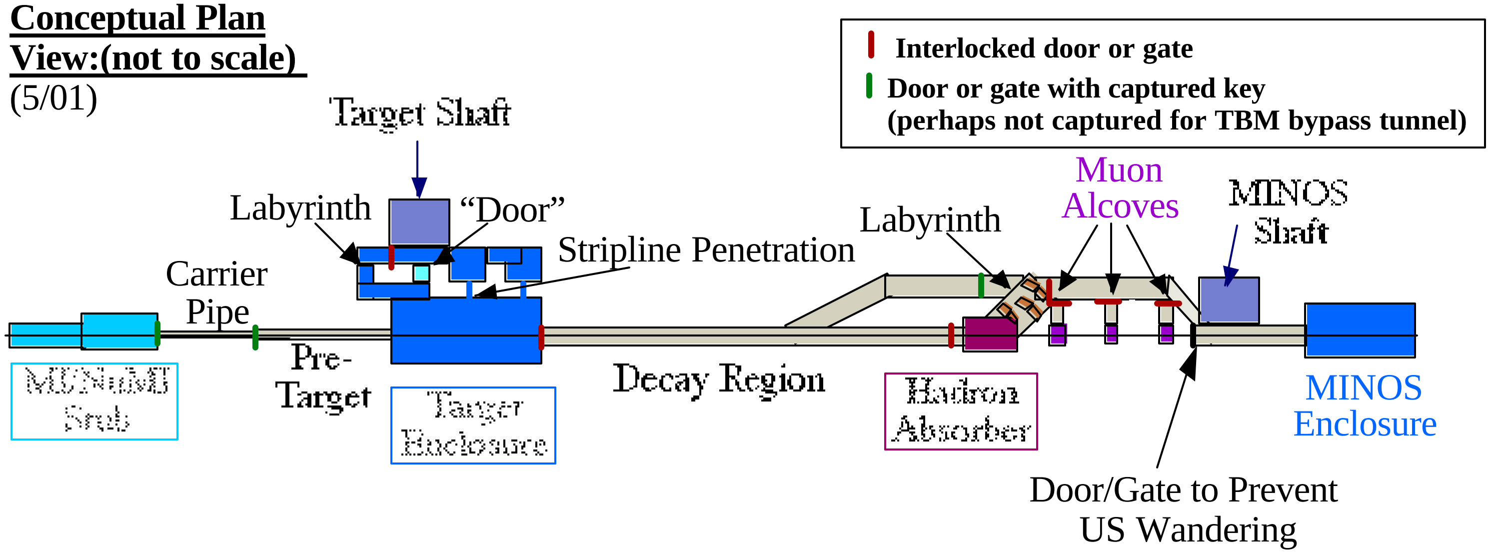




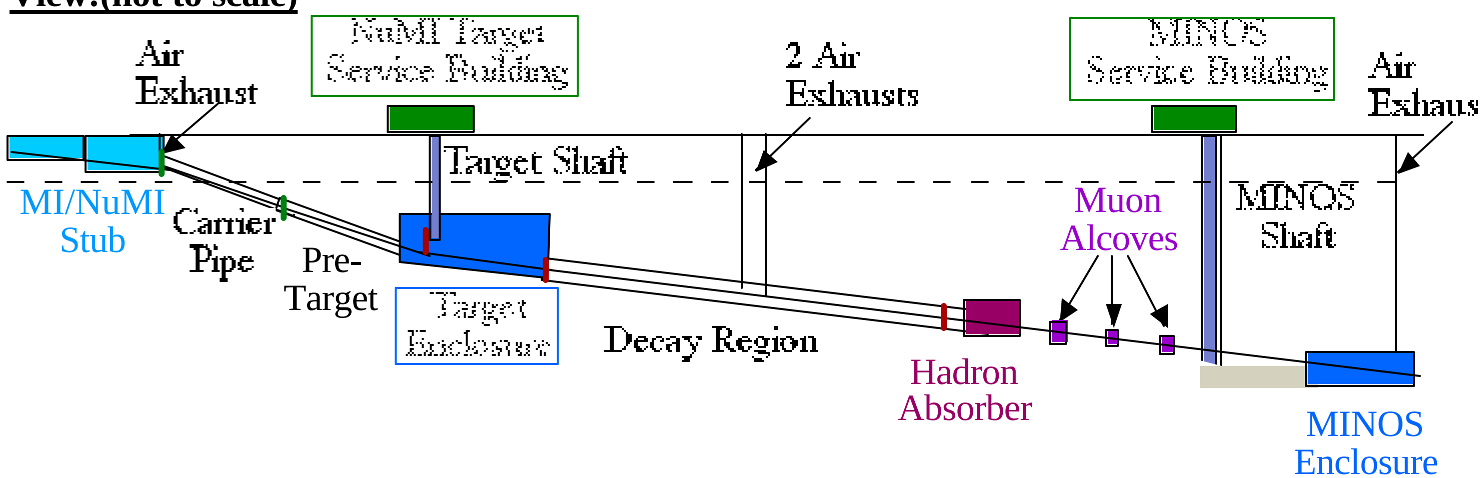
Main Injector Kicker Aperture Increase



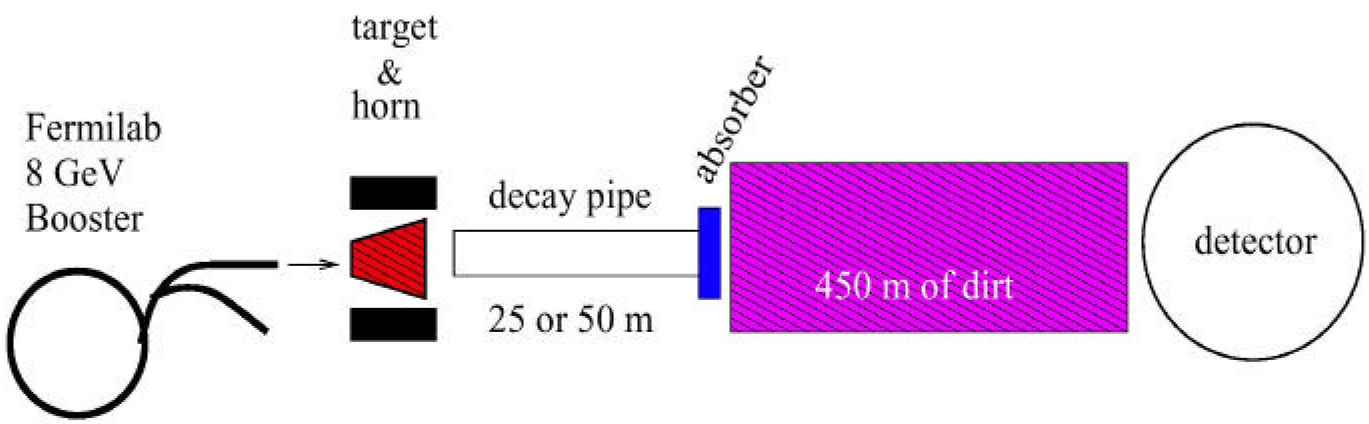
Conceptual Plan View:(not to scale)
(5/01)



Conceptual Elevation View:(not to scale)



MiniBooNE Beamline



R&D Program

Due to limited resources, we only list those R&D items that should be given higher priorities.

PD2 synchrotron:

- Booster 53 MHz rf cavity modification.
- Space charge study in the present Booster.
- Inductive insert study in the present Booster.
- Booster magnet ac field measurement in E4R.
- Dual resonance power supply test in E4R.
- Linac front-end improvement, including an RFQ.

Main Injector upgrade:

- Gamma-t jump system implementation.
- Dual power amplifier rf system test in MI-60.
- Large aperture kicker.
- Large aperture quadrupole.
- Collimators.
- Passive damper and active feedback.