

# Synchrotron Based Proton Drivers

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April 8, 2002, ICFA-HB2002 Workshop, Fermilab

## Outline

- Survey of high intensity proton sources
- Proton driver studies around the world
- Proton driver studies in the US – Snowmass 2001
- Proton driver studies at Fermilab
- Technical challenges
- Concluding remarks

## About the Proton Driver (PD)

- 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

- CERN

- RAL

- KEK-JAERI

- China (100 kW, 25 Hz RCS)

- South Korea (KOMAC)

## Synchrotron based PD vs. Linac based PD

Synchrotrons have a number of advantages:

- For the same investment, synchrotrons can give higher beam energy.
- For the same beam power, synchrotrons need lower beam current.
- Because the injection linac has lower beam power, the stripping foil is easier. Also, larger beam loss at injection can be tolerated.
- To provide very short bunches, linac based PD would need a compressor (CERN approach).

However,

- AC machines (i.e., synchrotrons) are more difficult to build and operate than DC machines (i.e., accumulators).
- In particular, the hardware is challenging, including large aperture magnets, rapid cycling power supplies, field tracking during the cycle, eddy current in the coils as well as in the beam pipe, high power tunable rf system, etc.

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

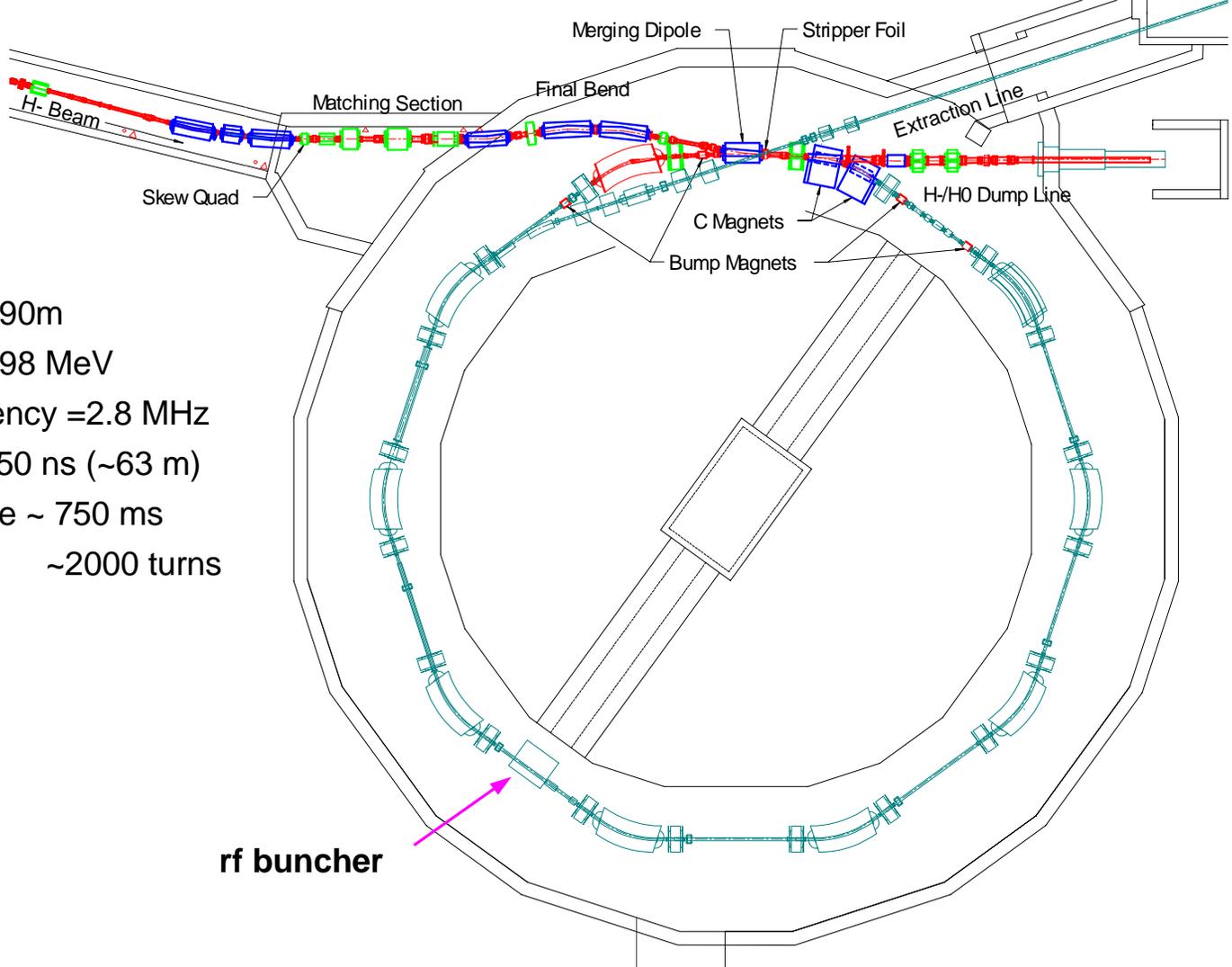
Machine	Flux ( $10^{13}$ /pulse)	Rep Rate (Hz)	Flux <sup>†</sup> ( $10^{20}$ /year)	Energy (GeV)	Power (MW)
<b>Existing:</b>					
RAL ISIS	2.5	50	125	0.8	0.16
BNL AGS	7	0.5	3.5	24	0.13
LANL PSR	2.5	20	50	0.8	0.064
Fermilab MiniBooNE (*)	0.5	7.5	3.8	8	0.05
Fermilab NuMI	3	0.5	1.5	120	0.3
CERN CNGS	4.8	0.17	0.8	400	0.5
<b>Under construction:</b>					
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
<b>Proton Driver proposals:</b>					
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
<b>Other proposals:</b>					
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

<sup>†</sup> 1 year =  $1 \times 10^7$  seconds.

(\*) Including planned improvements.

(\*\*) Based on 2-ring design.

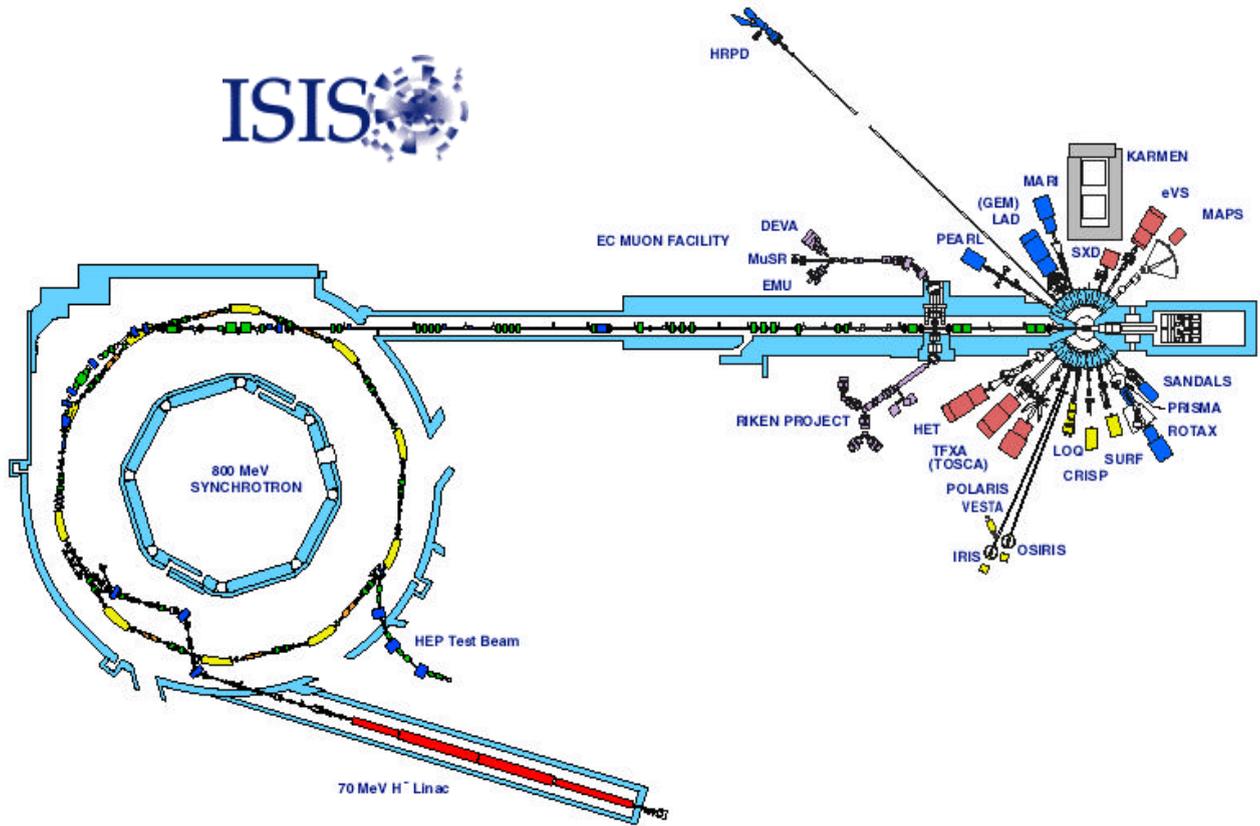
# PSR Layout



Circumference = 90m  
Beam energy = 798 MeV  
Revolution frequency = 2.8 MHz  
Bunch length ~ 250 ns (~63 m)  
Accumulation time ~ 750 ms  
~2000 turns

rf buncher

# ISIS



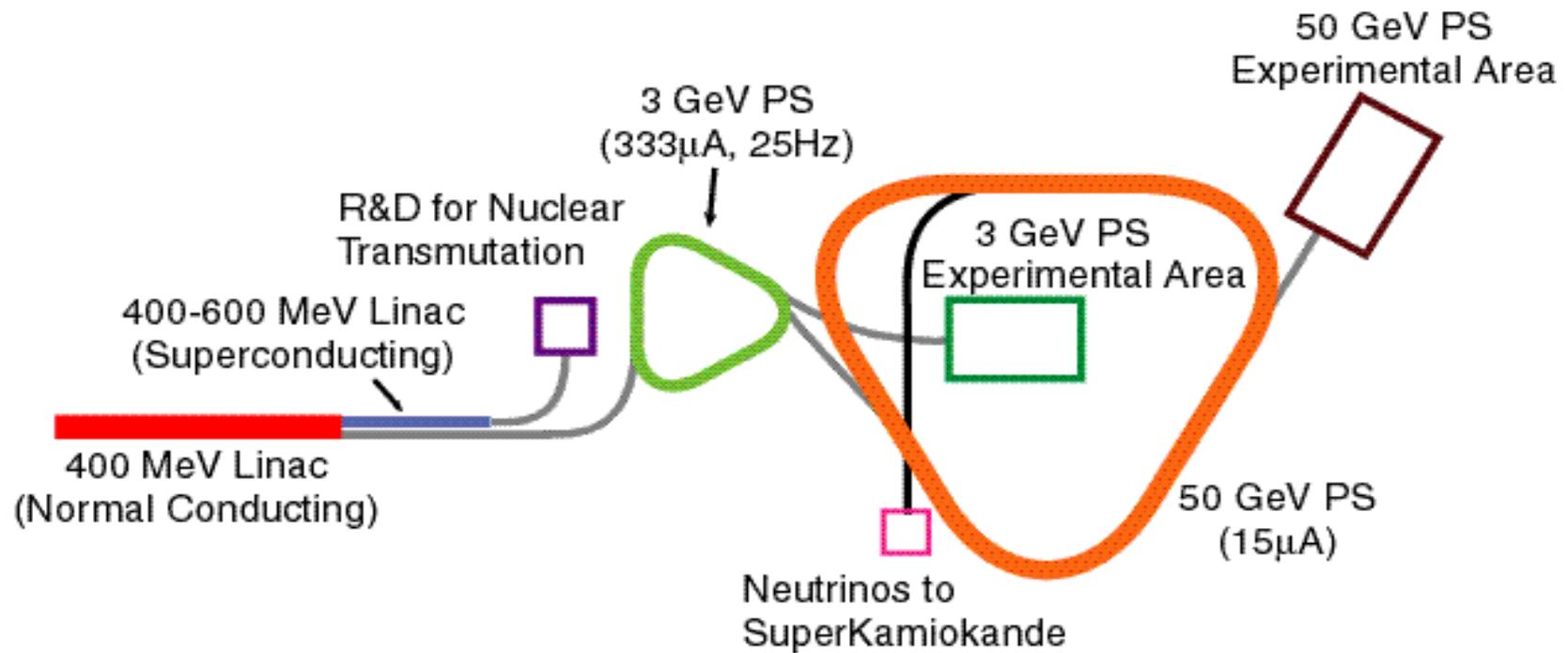
# Spallation Neutron Source



- 60 Hz repetition rate,  $2 \times 10^{14}$  per pulse, 2 MW proton facility
- In its 3<sup>rd</sup> year of a 7-year construction cycle
- H- Source, RFQ, DTL, CCL, SRF linac, Accumulator ring



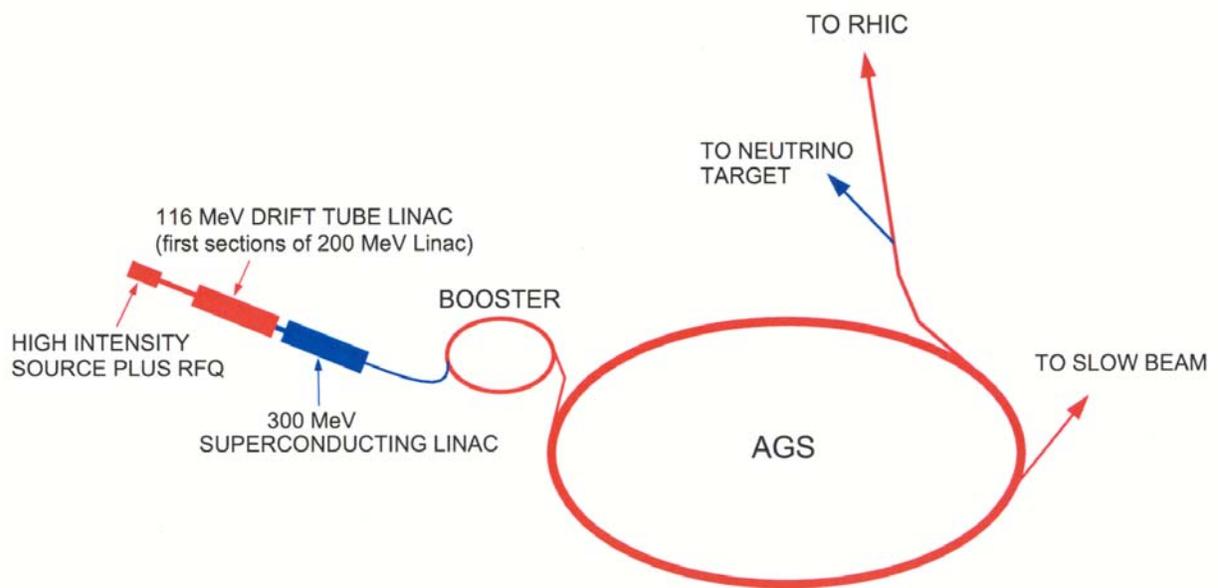
# Configuration of the Accelerator Complex



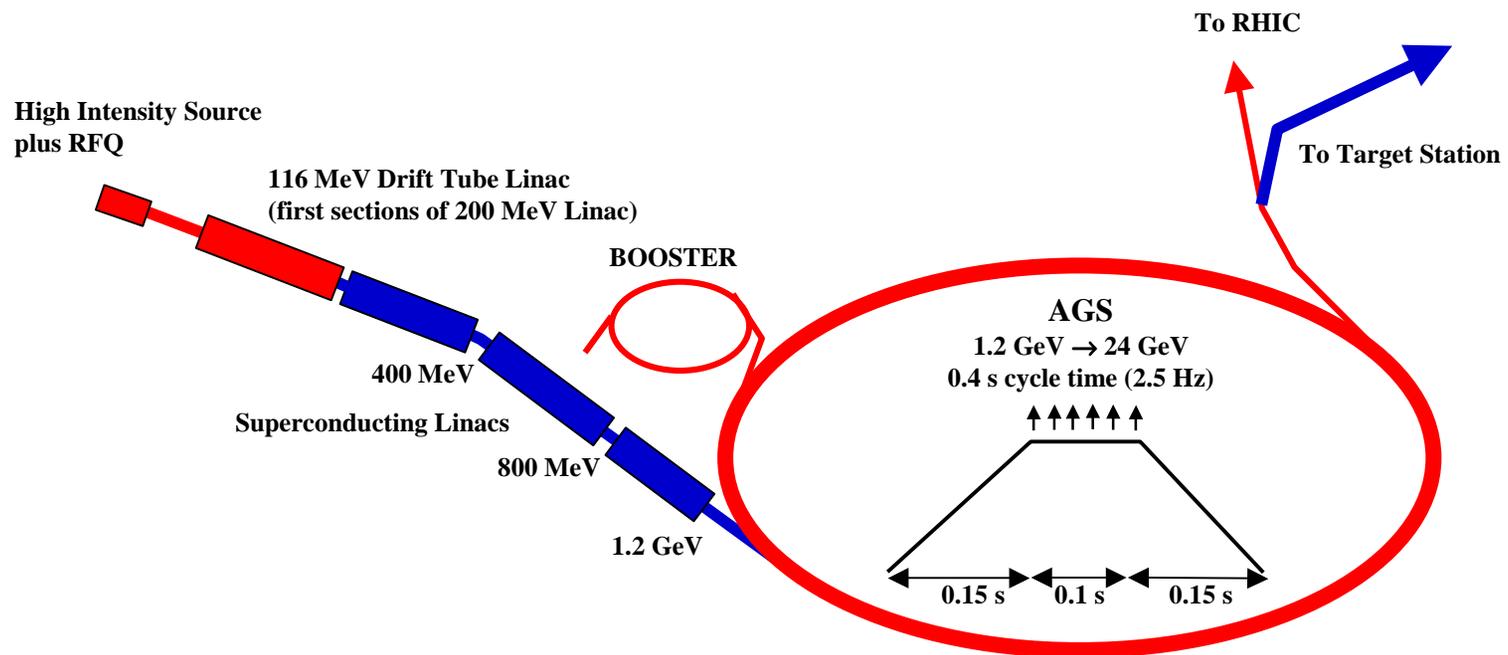
# THE PROTON DRIVER DESIGN STUDY



# AGS with SCL Addition

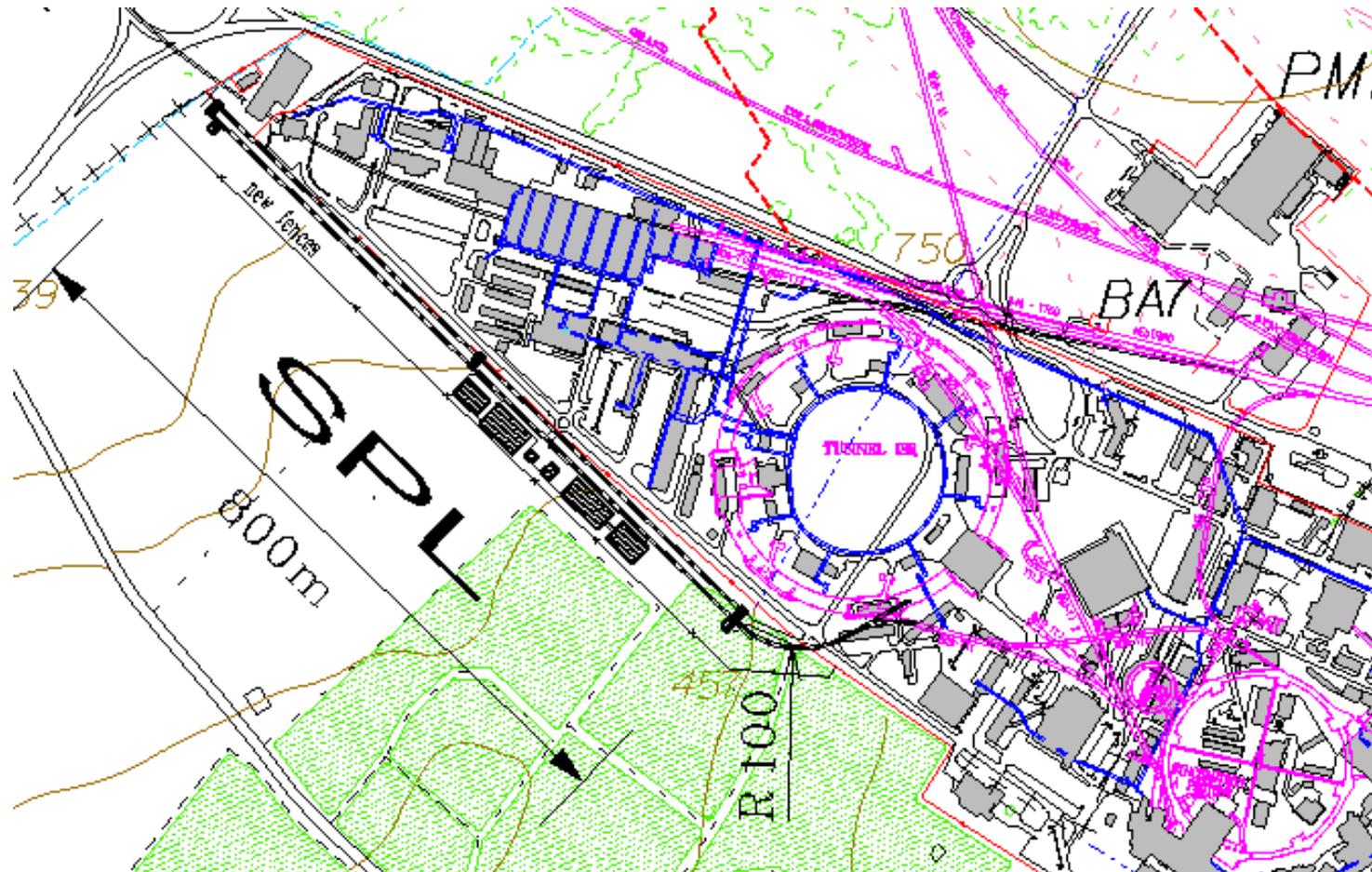


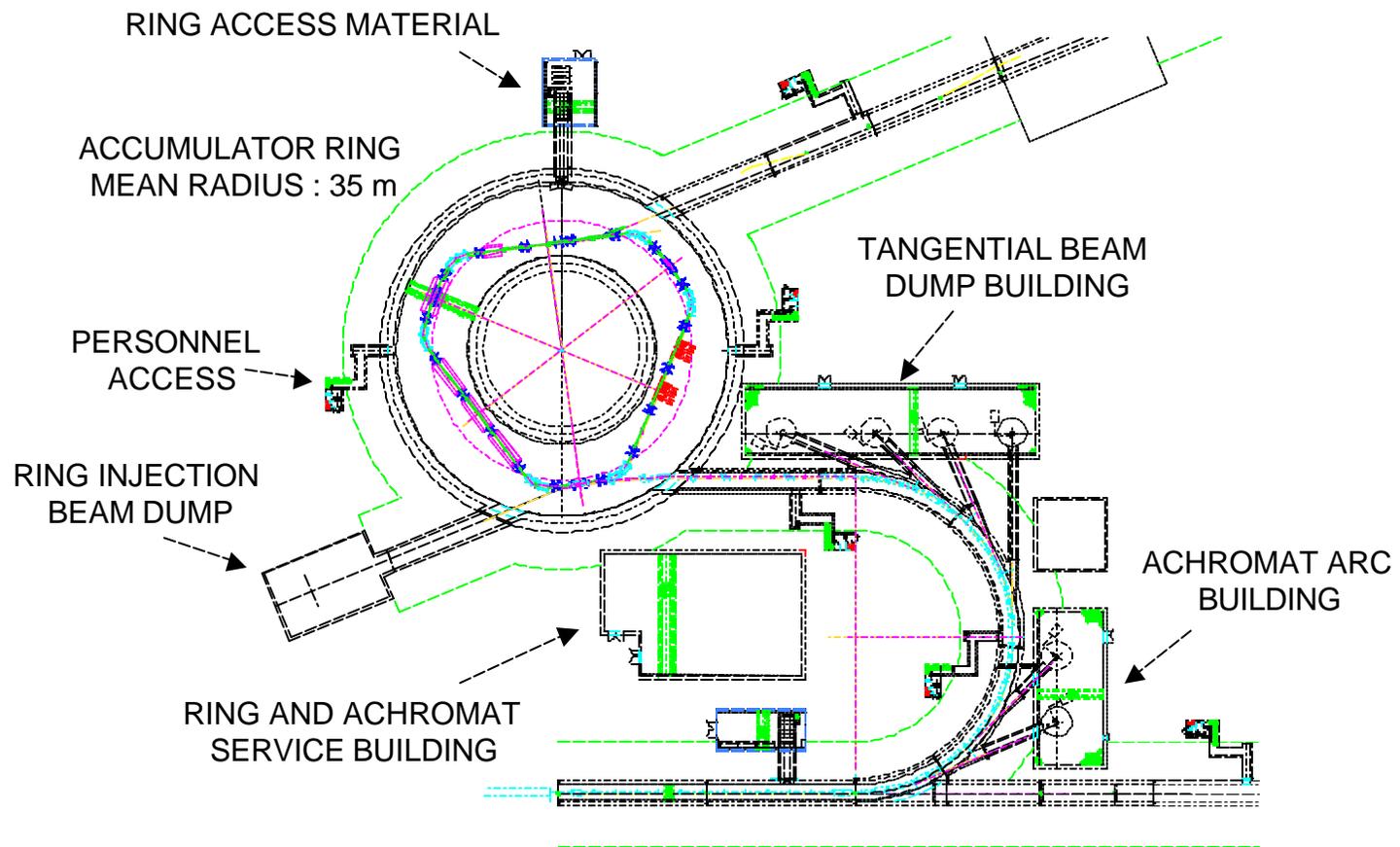
# AGS proton driver layout



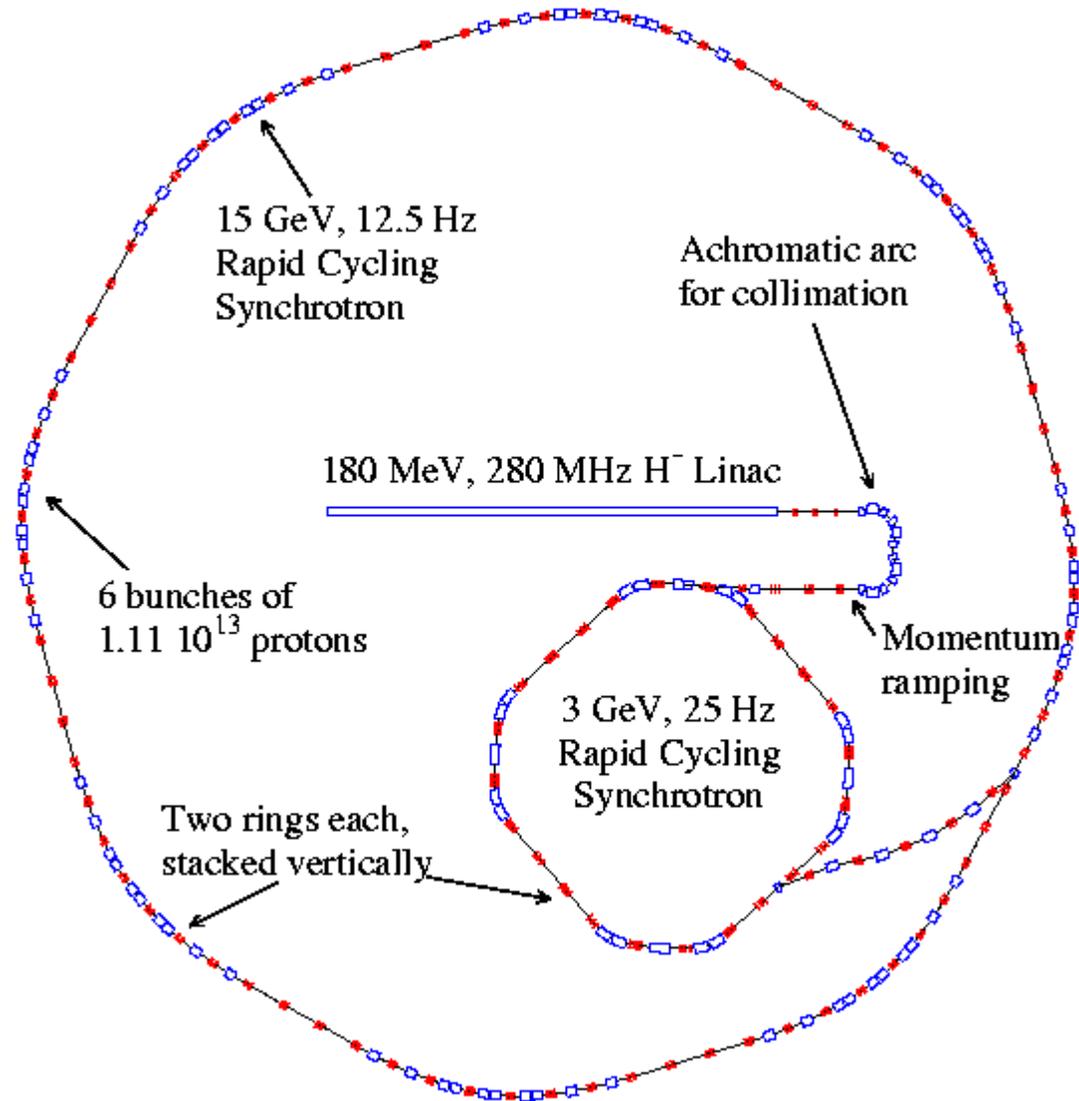


# Layout on the CERN site

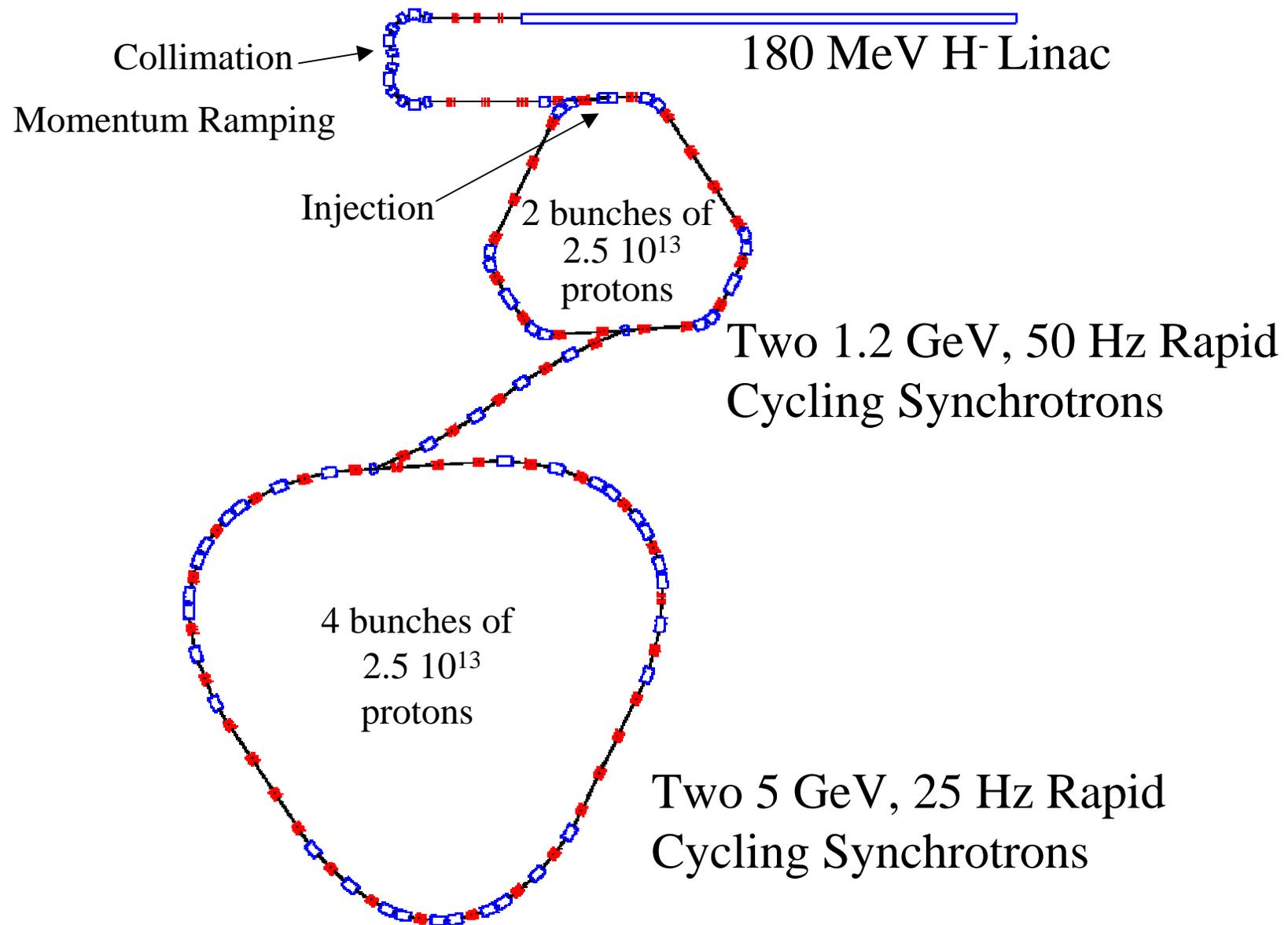




# 15 GeV, 25 Hz Proton Driver

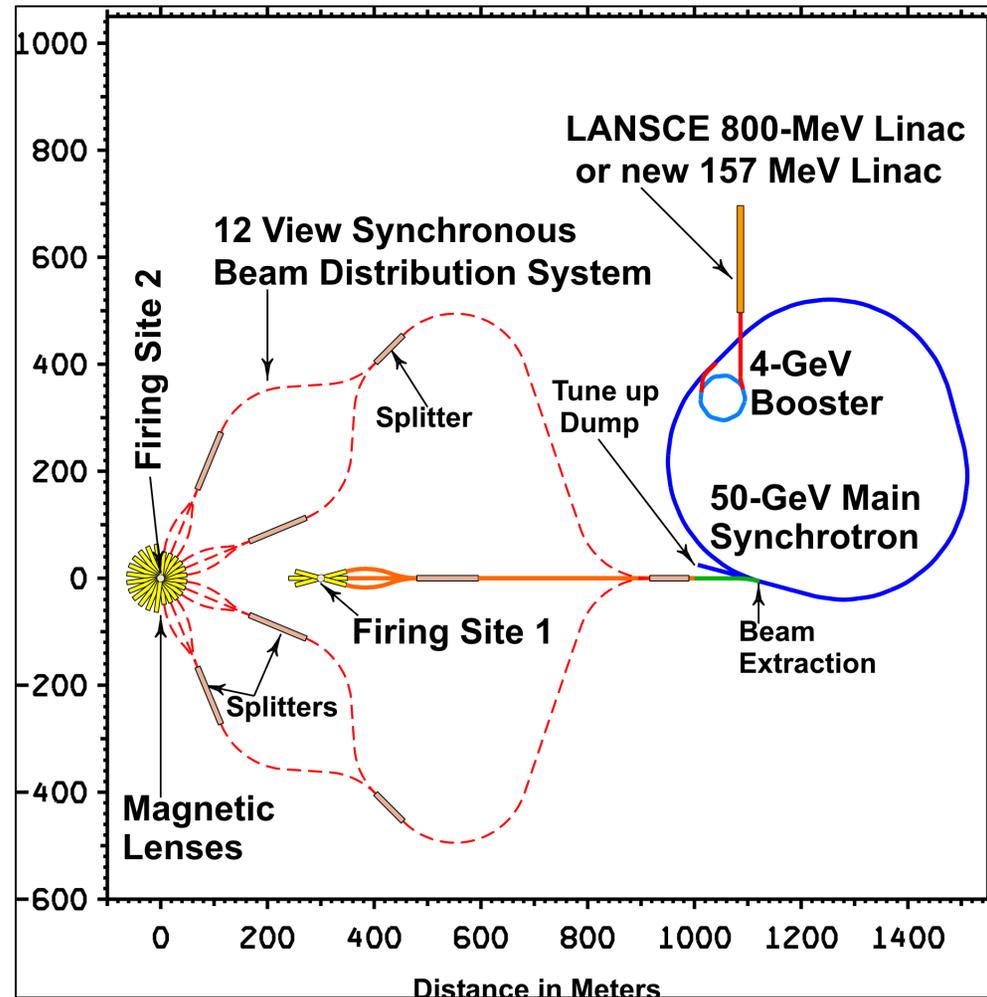


# 5 GeV, 50 Hz Proton Driver



# AHF Project Cartoon

- **Linac**
  - Existing 800 MeV H<sup>-</sup> Linac
  - or New 157 MeV H<sup>-</sup> Linac
- **Booster**
  - 4 GeV
  - 5 Hz
  - h=1
  - $3 \times 10^{12}$  protons per pulse
- **Main Ring**
  - 50 GeV
  - 30 second cycle time
  - h=29
  - $6 \times 10^{13}$  protons per pulse
- **Firing Site 1**
  - 1-3 beams
- **Firing Site 2 (Future)**
  - 12 beams



## A Message from Snowmass 2001

- ❖ The US HEP community had a 3-week workshop last summer at Snowmass to discuss the future of high-energy physics in this country. A total of about 1,200 physicists attended that workshop.
- ❖ There was a coherent effort at the Snowmass to promote the construction of a **Proton Driver** in this country.
  - E1 Group (muon and neutrino physics) and E5 Group (fixed target):

**We need the Proton Driver Now!**

- M1 Group (muon based systems):

**Proton Driver is the 1st stage of a neutrino factory.**

- M6 Group (high intensity proton sources):
  - **The Proton Driver design is ready and waiting.**
  - **The price is affordable.**  
(Can be supported by the DOE baseline HEP budget)

## M6 Working Group Participants

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## Executive Summary

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<sup>-</sup> source: Development goals - current 60–70 mA {35 mA}, duty cycle 6-12% {6%}, emittance  $0.2 \pi$  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 <  $0.5^\circ$  and amplitude error < 0.5% {presently  $1^\circ$ , 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<sup>-</sup>; (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) dualharmonic 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)

## 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)



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	$1.5 \times 10^{14}$ (=1.9 MW @ 0.67 Hz)
Protons per second at 8 GeV	$3.0 \times 10^{14}$ (=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.

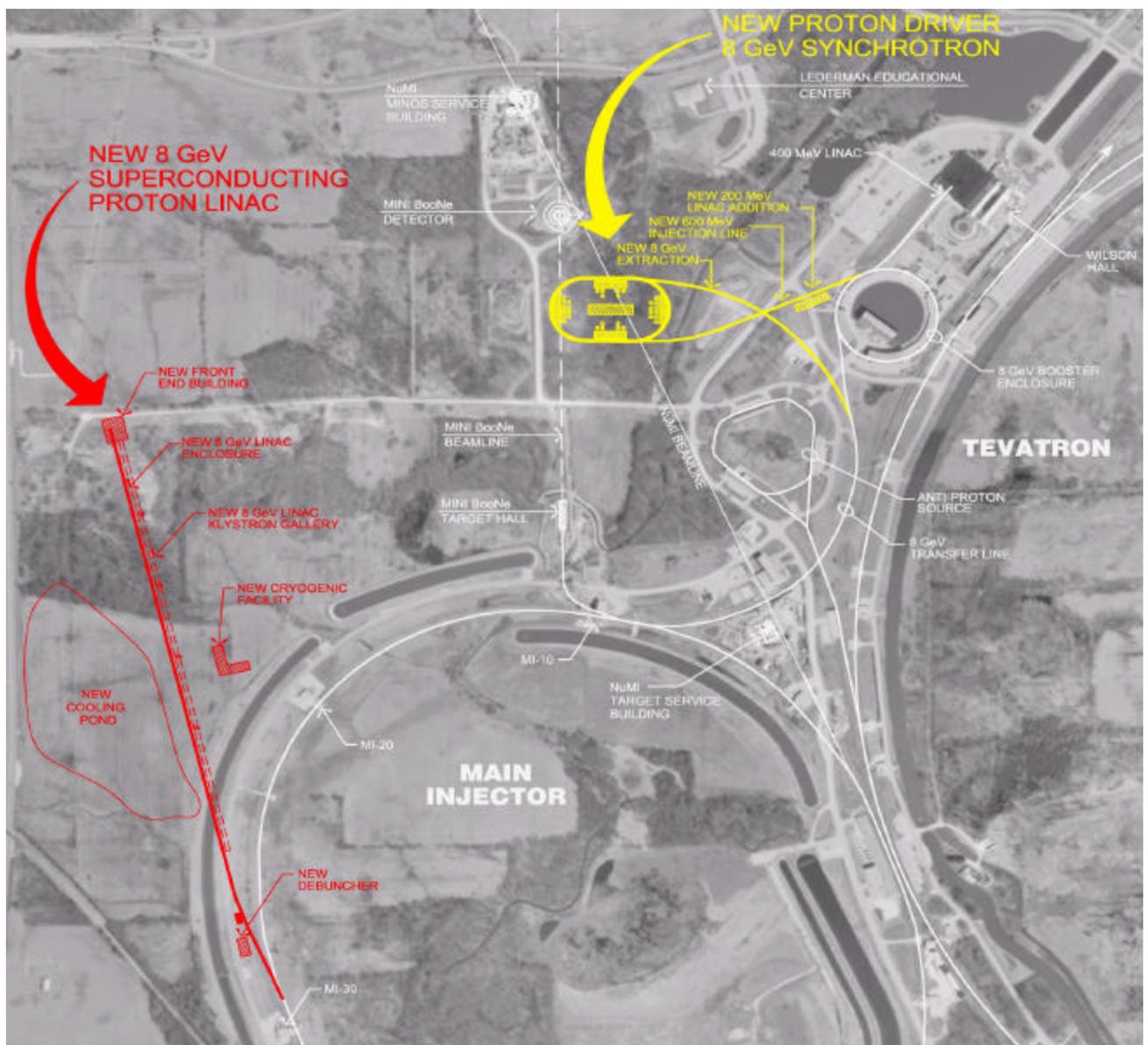
I would like to receive an interim report on progress prior to the ICFA Workshop at Fermilab on April 8-12 and a final report by May 15, 2002. Preparation of this report will require support of personnel in both the Beams and Technical Division. You should identify required resources and then work with 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





FERMILAB-TM-2169

# The Proton Driver Study II

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

for the

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May 2002

## 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 → Total linac energy 600 MeV.

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

Parameters	Present Proton Source	Proton Driver
<b>Linac</b> (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (μs)	25	90
H <sup>+</sup> per pulse	$6.3 \times 10^{12}$	$2.8 \times 10^{13}$
Average beam current (μA)	15	67
Beam power (kW)	6	40
<b>Booster</b> (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	$6 \times 10^{10}$	$3 \times 10^{11}$
Number of bunches	84	84
Protons per cycle	$5 \times 10^{12}$	$2.5 \times 10^{13}$
Protons per second	$7.5 \times 10^{13}$	$3.75 \times 10^{14}$
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

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

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## Technical Challenges

- 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 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  $\nu$  p/p and space charge tune shift ? ?
  - Betatron tune split – How big is big enough (half-integer or integer)?

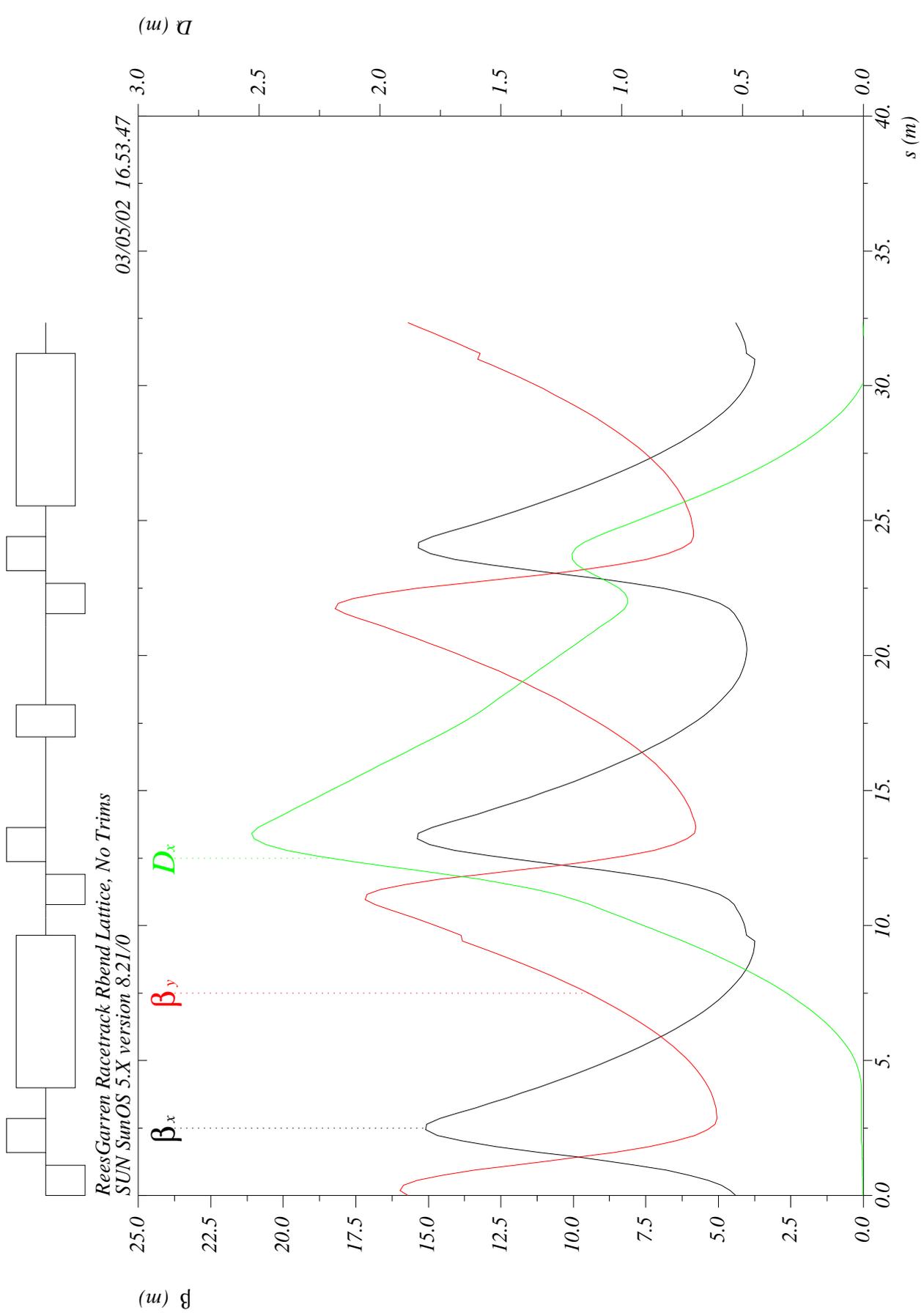
- **Beam loss, collimation and remote handling**
  - Beam loss calculation and bench marking
  - Collimation system: efficiency, susceptibility to parameter changes (tune, closed orbit, beginning and end of cycles)
  - Remote handling of “*hot*” components (e.g., a magnet) in the collimation area
- **Ion 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<sup>-</sup> injection**
  - Foil issues (lifetime, efficiency, support)
  - Collection of unstripped H<sup>-</sup>, H<sup>0</sup> and electrons
- **Slow extraction (ICFA Mini-Workshop, October 14-18, 2002, BNL, Kevin Brown)**
  - Efficiency at high intensity operations
- **Magnet**
  - Large aperture, large sagitta, end effects, S-bend vs. R-bend
  - 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, October 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 (impedance tuner)
  - High gradient (1 MV/m) low frequency (a few MHz) low duty cycle (< 1%) rf system

## Lattice Candidates for Fermilab Proton Driver

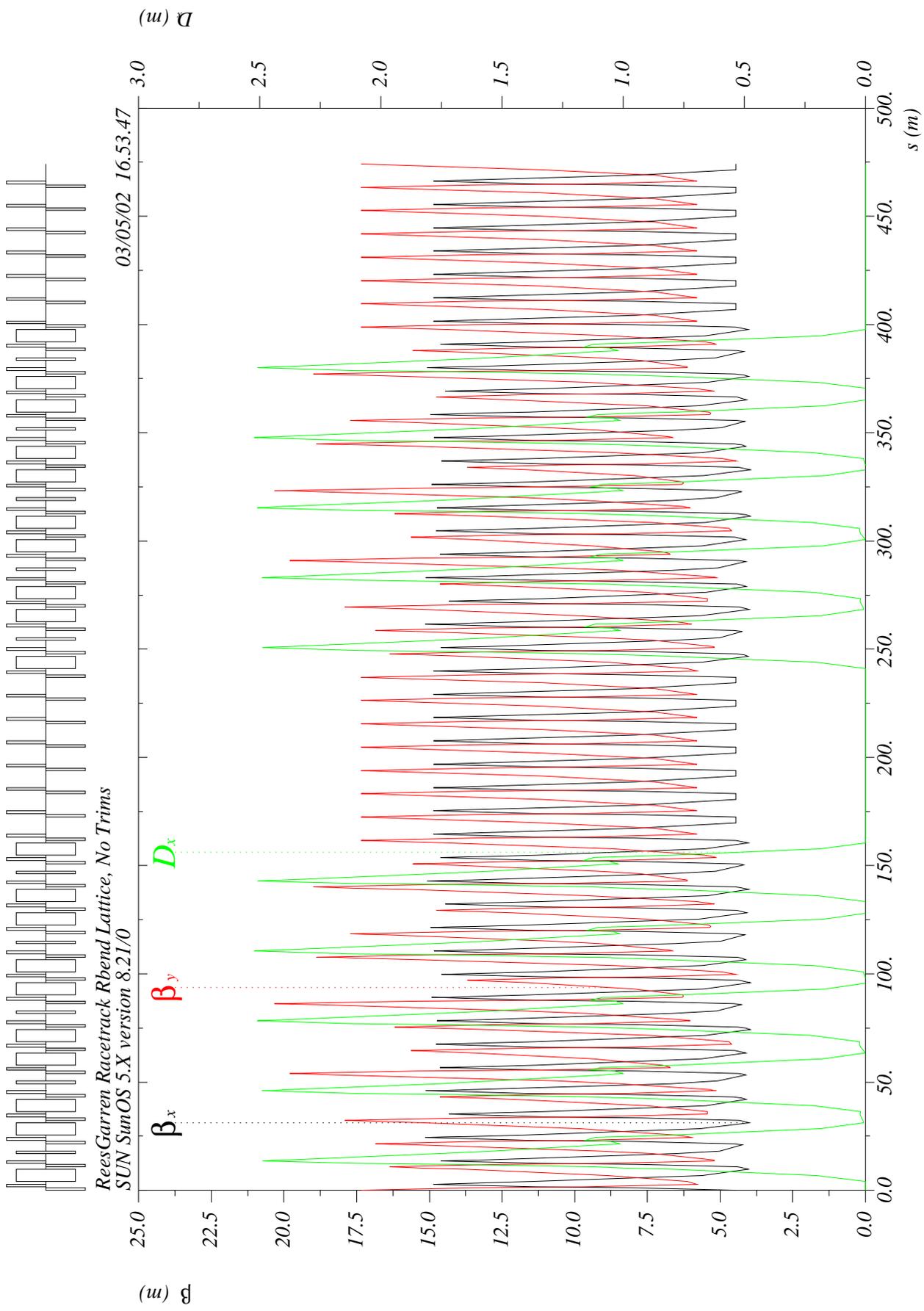
- Simple FODO
- Simple FODO with combined function magnets
- FMC with superperiod = 3
- FMC with superperiod = 2
- FMC using low-beta insertions
- Doublet with superperiod = 3
- Doublet with superperiod = 2
  - Missing dipole in mid-cell
  - Short dipole in mid-cell
    - Phase advance per module = 0.8/0.5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





$\delta_E/p_{oc} = 0.$

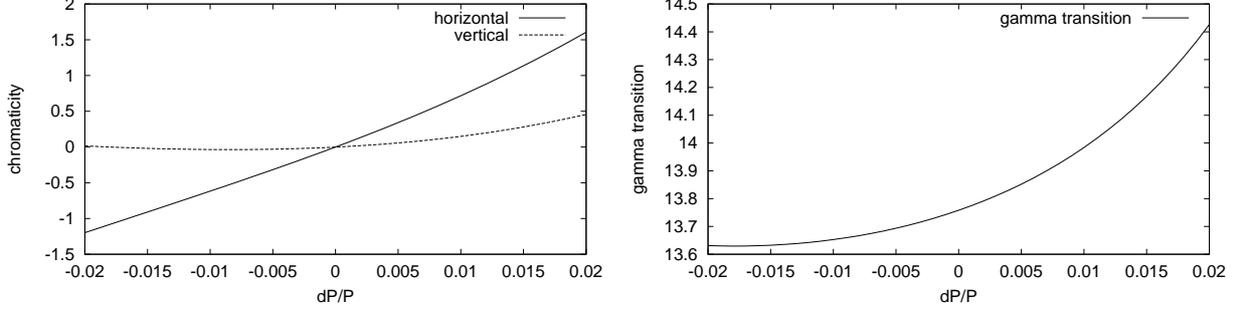
Table name = TWISS



$\delta_E/p_{oc} = 0.$

Table name = TWISS

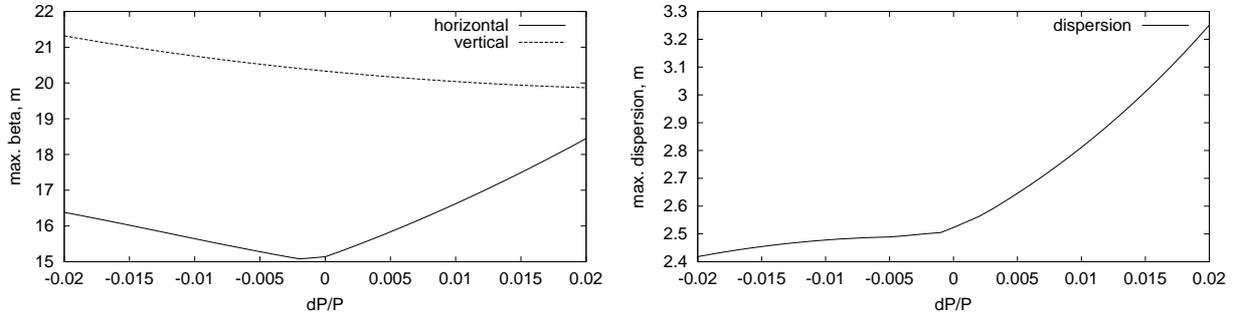
monotonically, only slightly faster than linearly, by more than 2.5. The overall variation across  $\pm 1\%$  is small.



**Figure 3.3.4.:** Proton Driver chromaticity and  $\gamma_t$ .

The corresponding plot of  $\gamma_t$  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,  $\beta_x$ ,  $\beta_y$ , 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  $\beta_{y,\max}$  and  $D_{\max}$



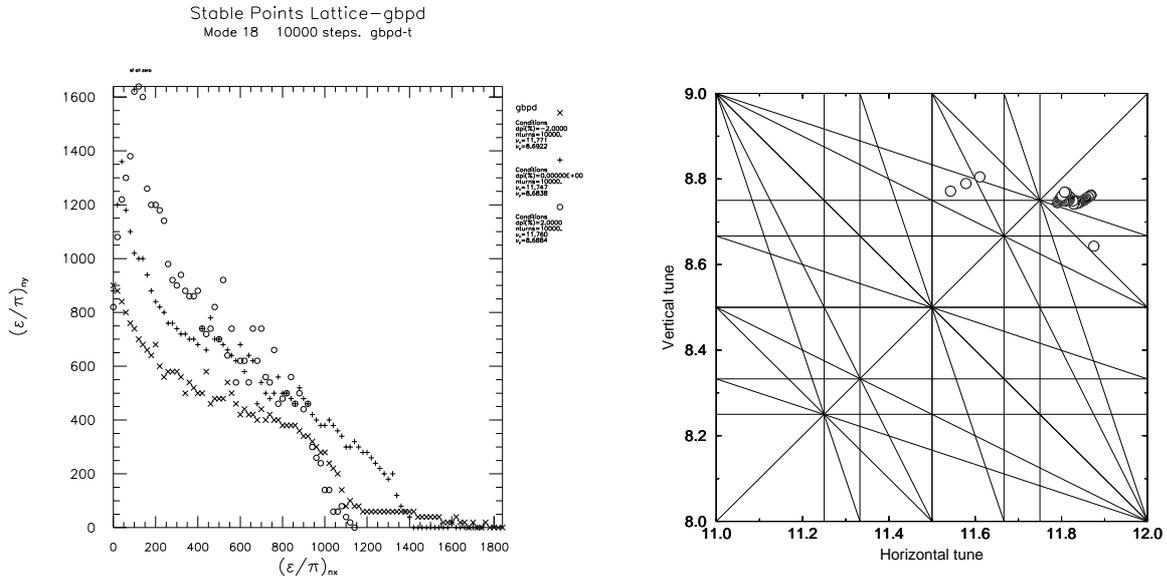
**Figure 3.3.5.:** Proton Driver maximum  $\beta$  functions and dispersion.

are monotonic, while  $\beta_{x,\max}$  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,

$$\Delta\nu_x = 0.120 \epsilon_x/\pi + 0.114 \epsilon_y/\pi$$



**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  $5 \times 10^{-4}$ .

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:

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

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

*Present Booster lattice:*

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

(But Booster magnet good field region < 1 inch)

*New Proton Driver lattice:*

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

(Proton Driver magnet good field region = 3 inch)

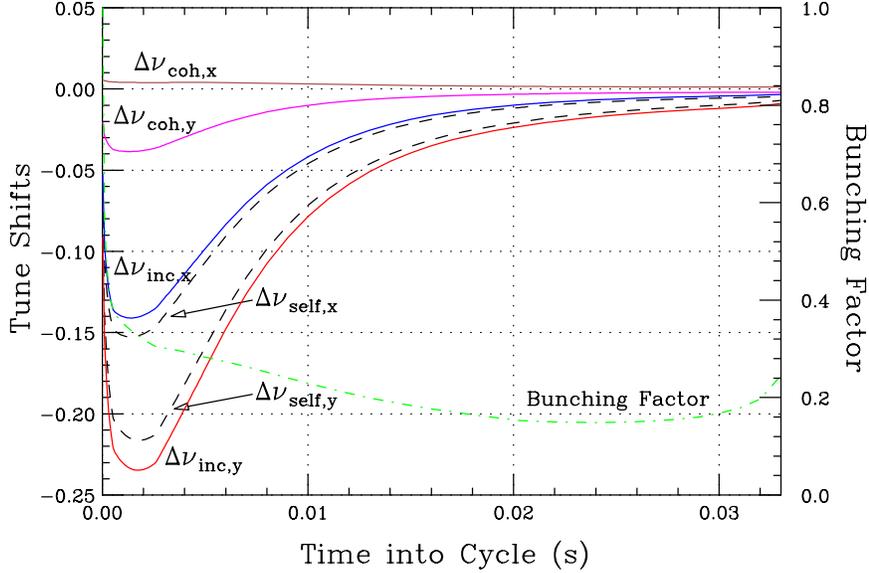


Figure 4.1.1: Coherent and incoherent betatron tune shifts of the new Fermilab booster.

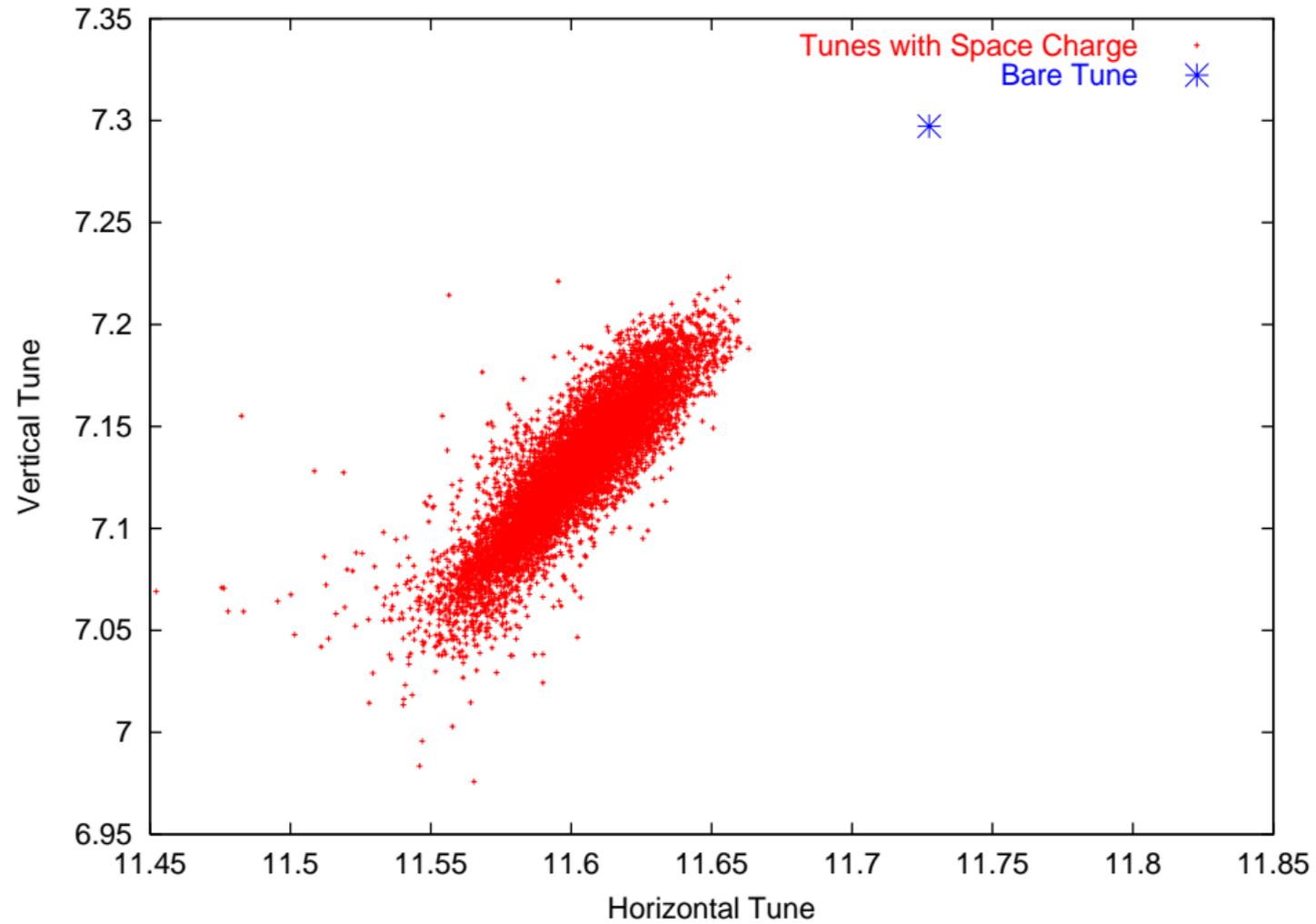
values, we can write

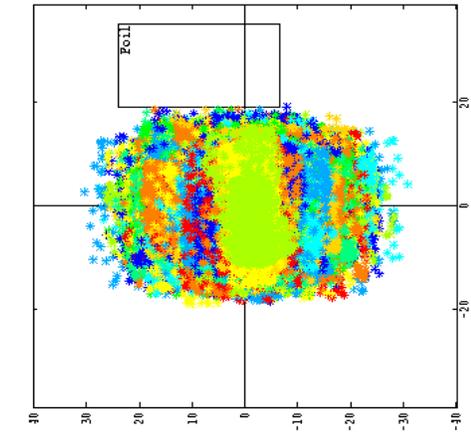
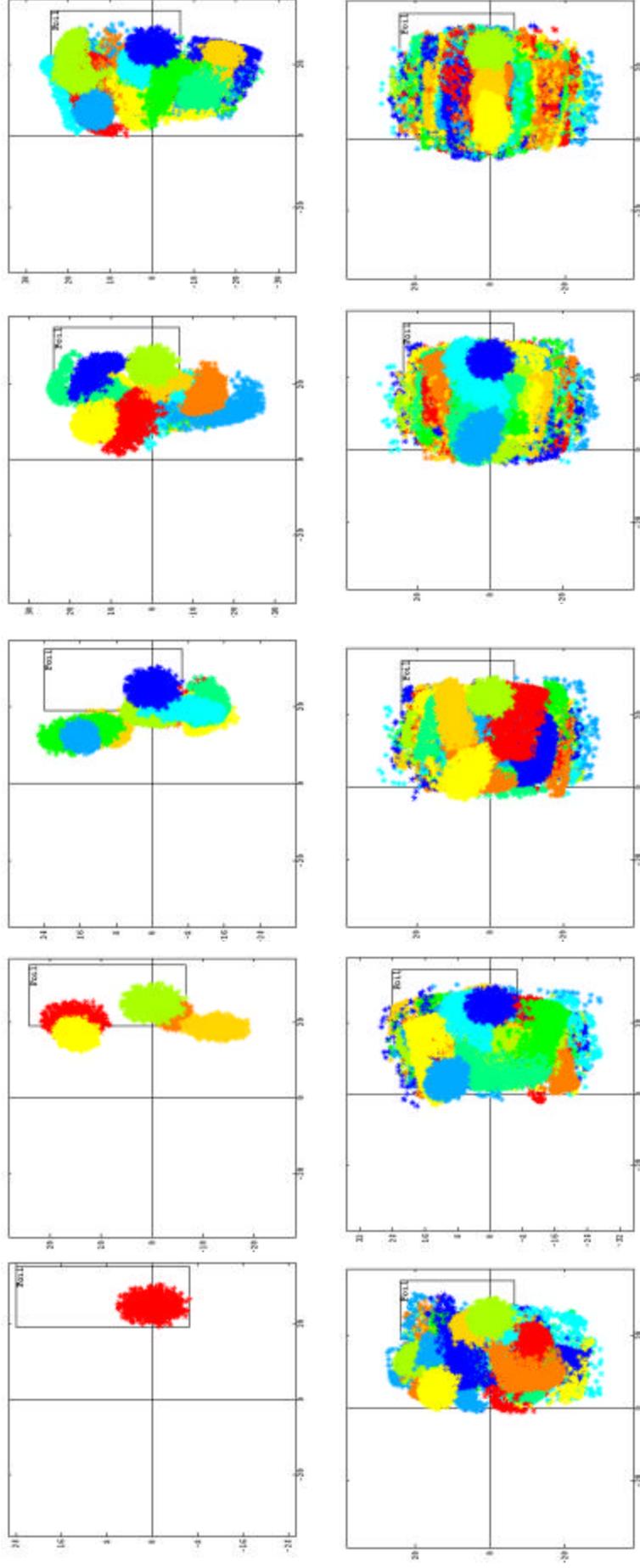
$$\Delta\nu_{\text{incoh},x} = -0.153 + 0.013 = -0.140, \quad \Delta\nu_{\text{incoh},y} = -0.216 - 0.018 = -0.234, \quad (4.1.3)$$

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  $\nu_{\text{quad}} = 2[\nu_{\text{dipole}} - \frac{3}{4}|\Delta\nu_{\text{incoh}}|]$ . Therefore,  $2\nu_y$  is shifted from  $2 \times 7.34$  to  $2 \times 7.16$  and  $2\nu_x$  is shifted from  $2 \times 11.70$  to  $2 \times 11.61$ . With the vertical and horizontal betatron bare tunes at  $\nu_{y0} = 7.34$  and  $\nu_{x0} = 11.7$ , the equivalent vertical tune  $\nu_y$  passes through the stopbands at 7.33, 7.25 and 7.20, while the equivalent horizontal tune  $\nu_x$  passes through the stopband at 11.67.

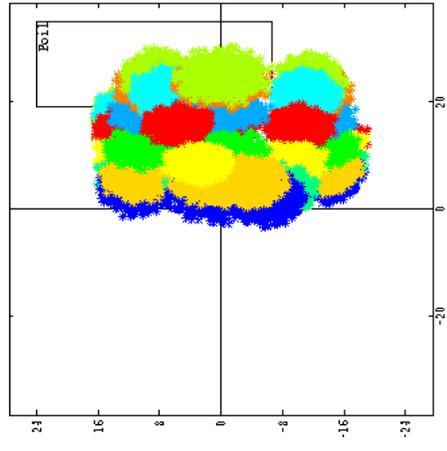
#### 4.1.2 Space charge at Injection

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

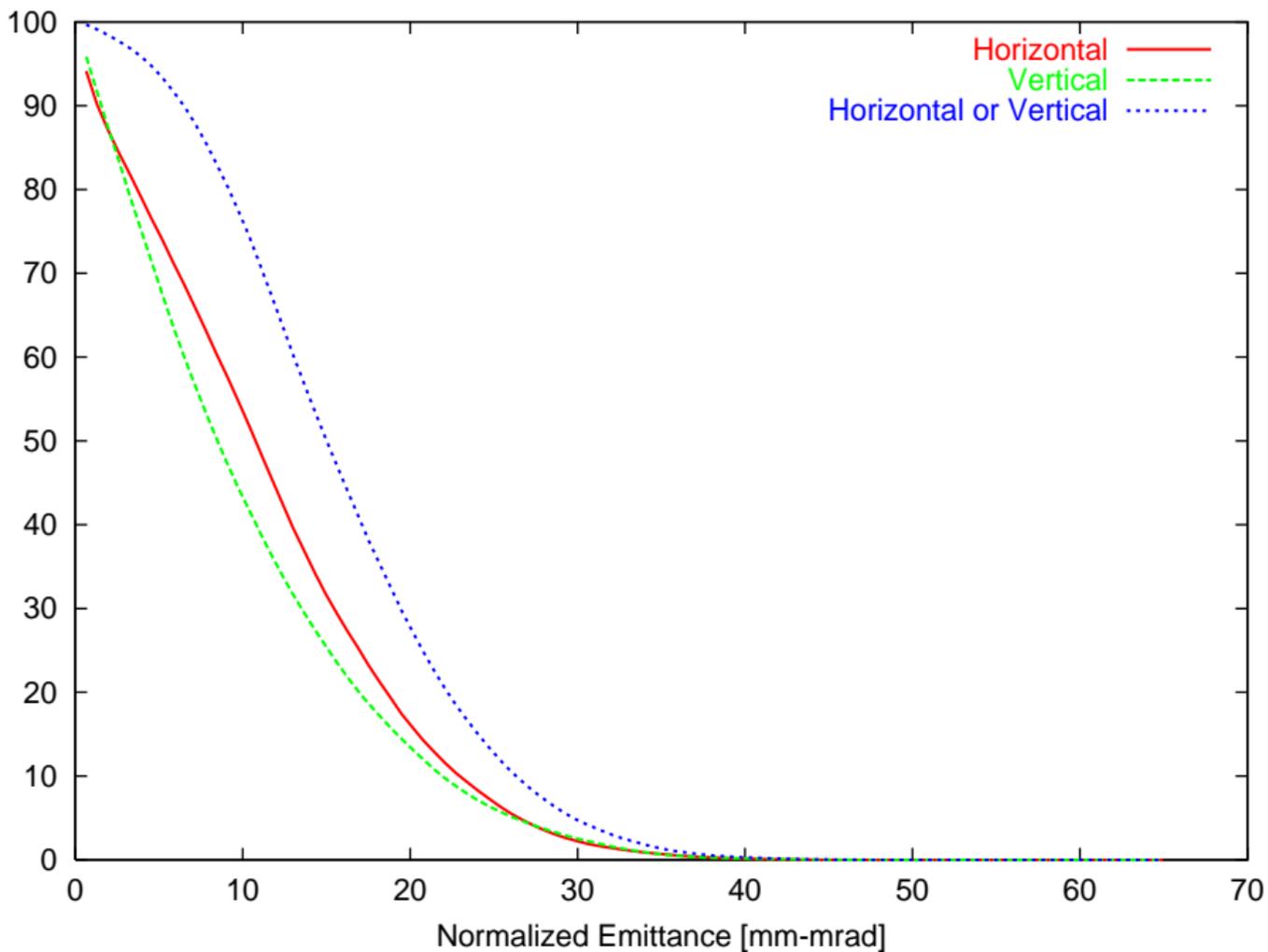


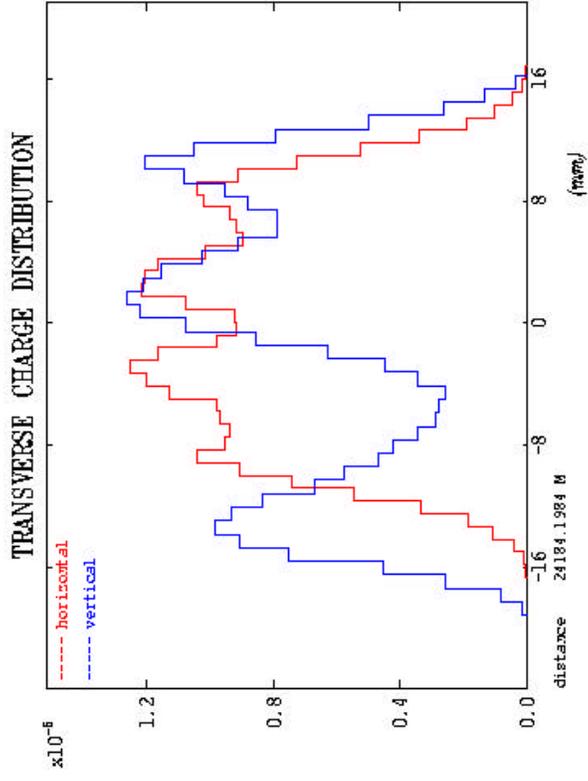


Rees Lattice:  
 Injected beam cross  
 section at foil with space  
 charge (zero space charge  
 comparison to right)

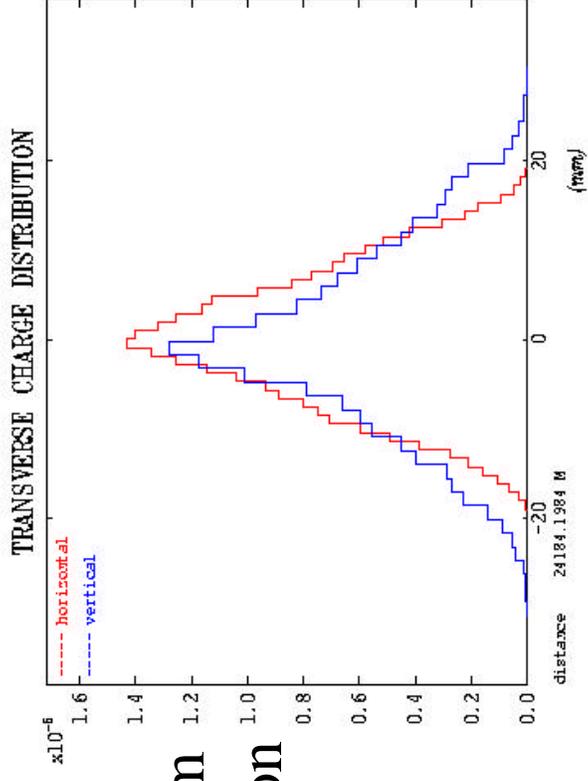


Percent of Beam Exceeding Emittance

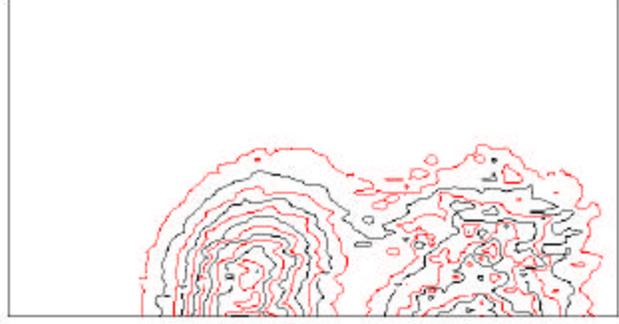




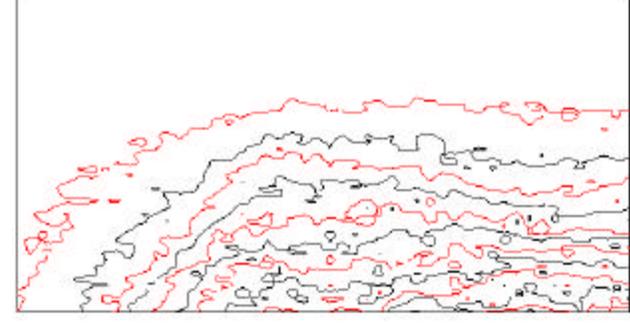
Final beam  
distribution



Space charge



Proton hits  
on foil

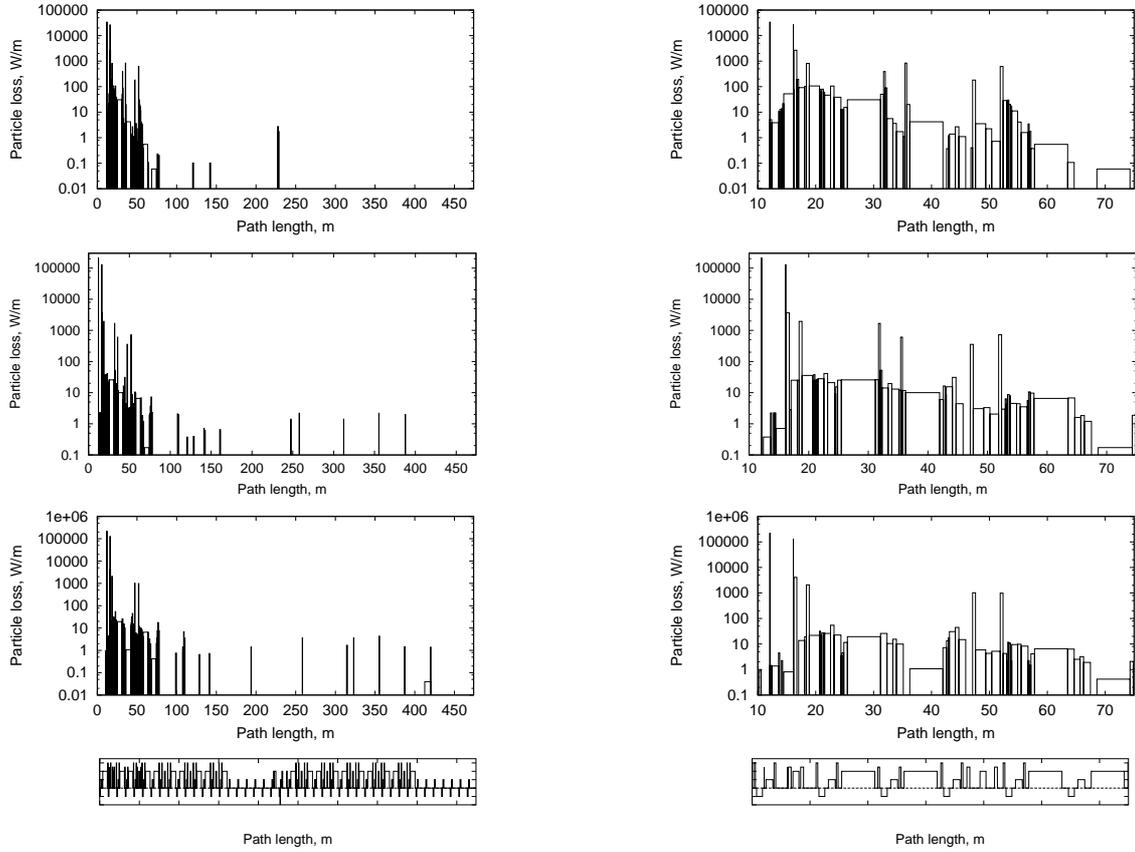




*Proton Source Department*

# Inductive Inserts in Booster (installed 10/01)





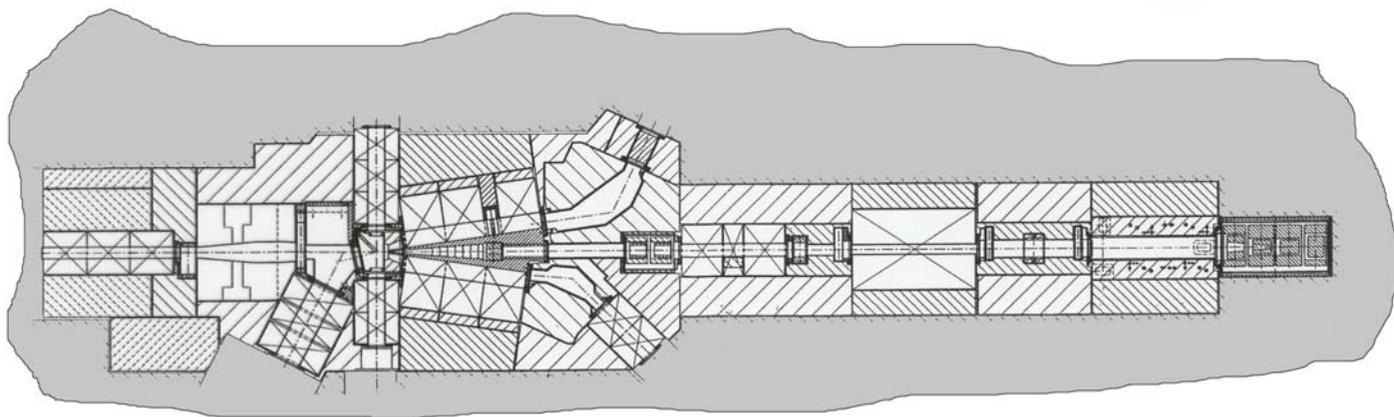
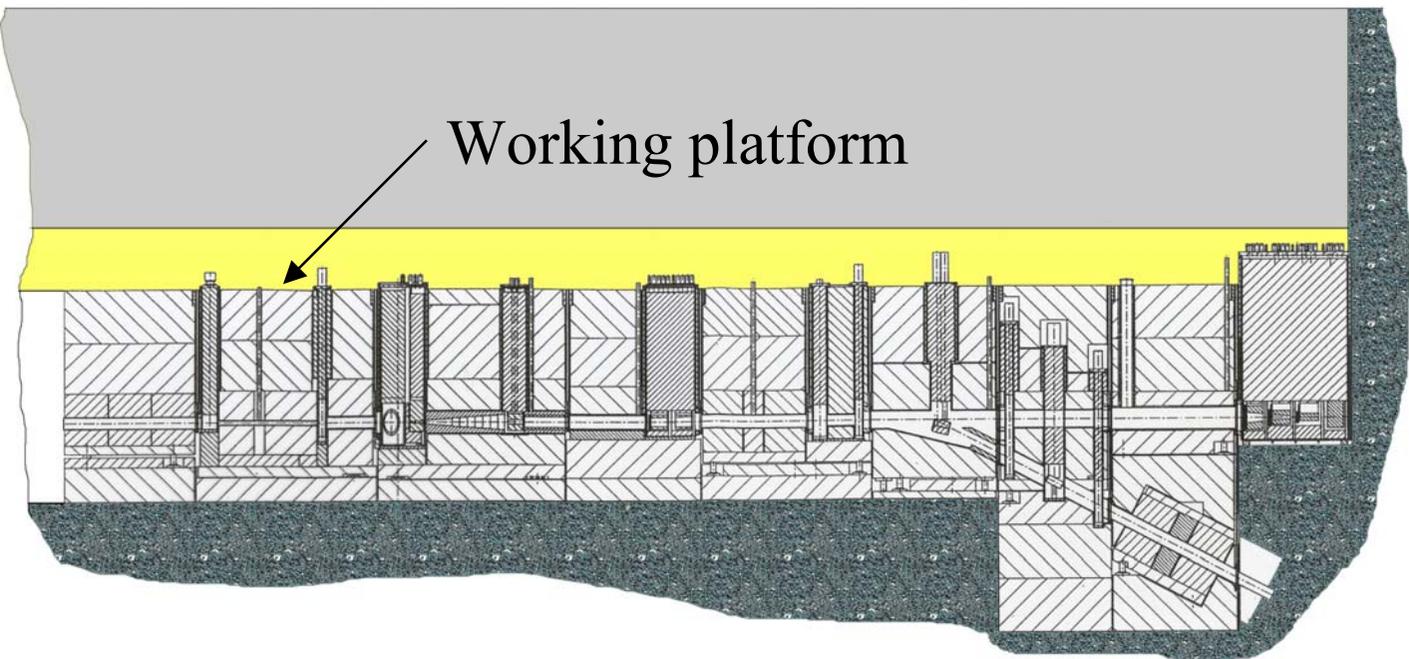
**Figure 6.3.** Beam loss distributions at injection (top) and at top energy with (middle) and without (bottom) supplementary collimators. Left group shows the entire machine and right group shows collimation region.

**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

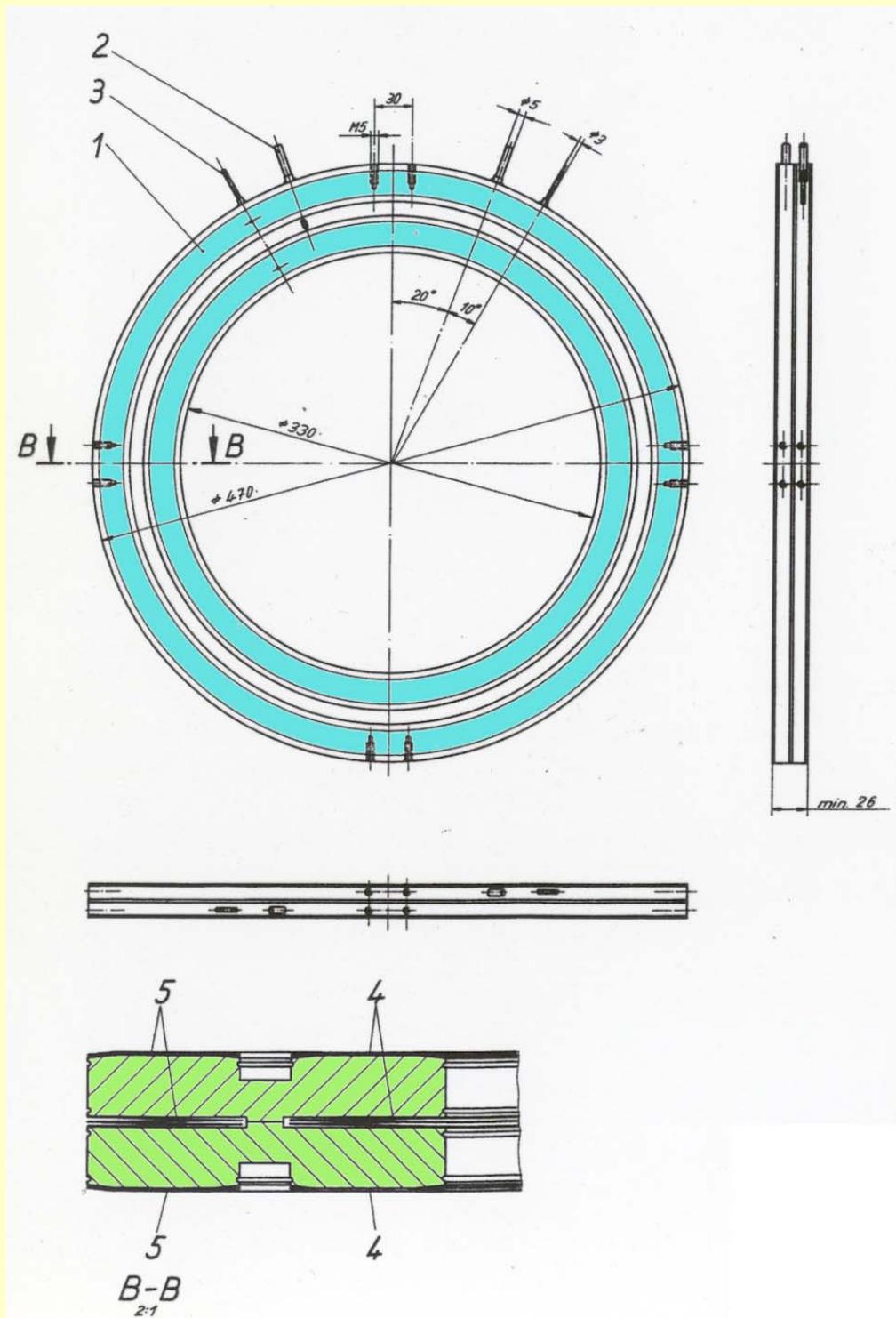
# Layout for 2 mA

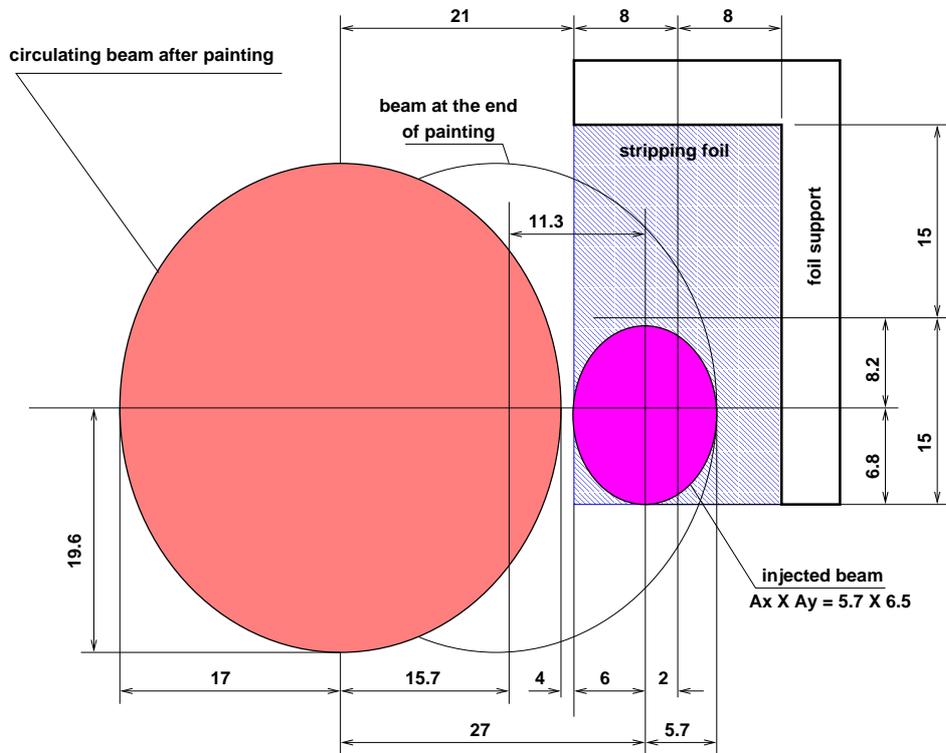
Vertical cut of the proton-channel



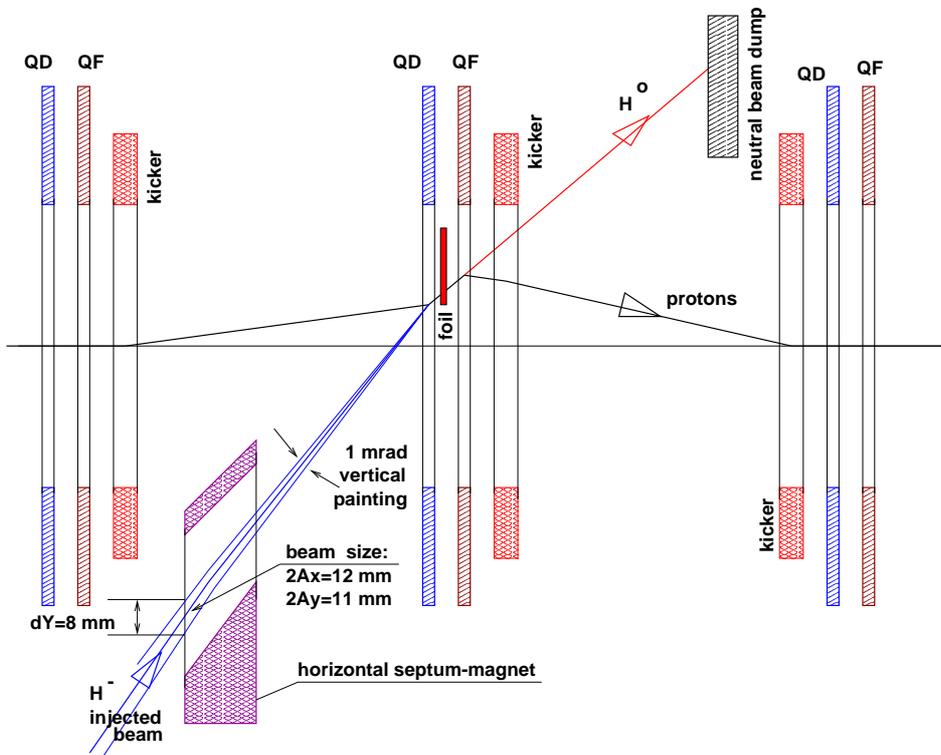
Horizontal cut of the proton-channel

# Inflatable sealing (radiation resistant)

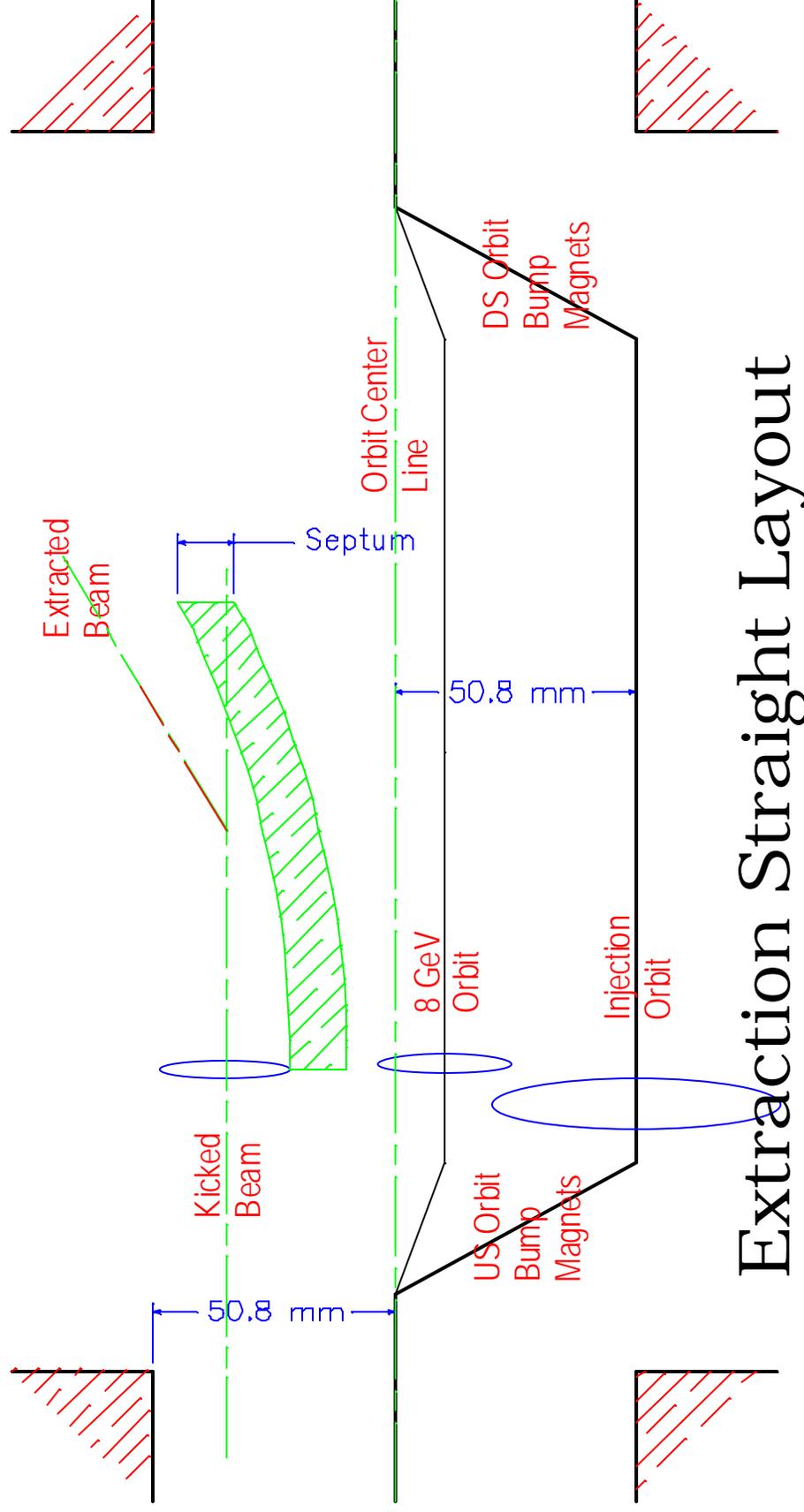




**Figure 7.2.** Injected and circulating beams location in the foil at painting.



**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	$\pm 0.05\%$
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

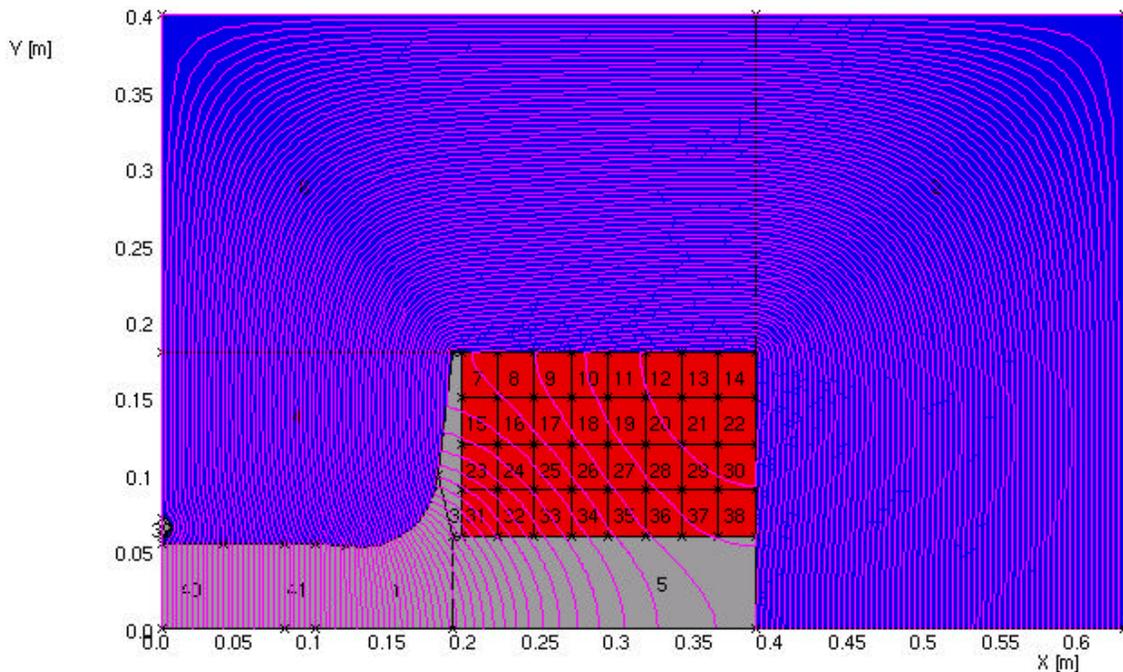


Fig. 1 Magnetic flux lines distribution in dipole magnet

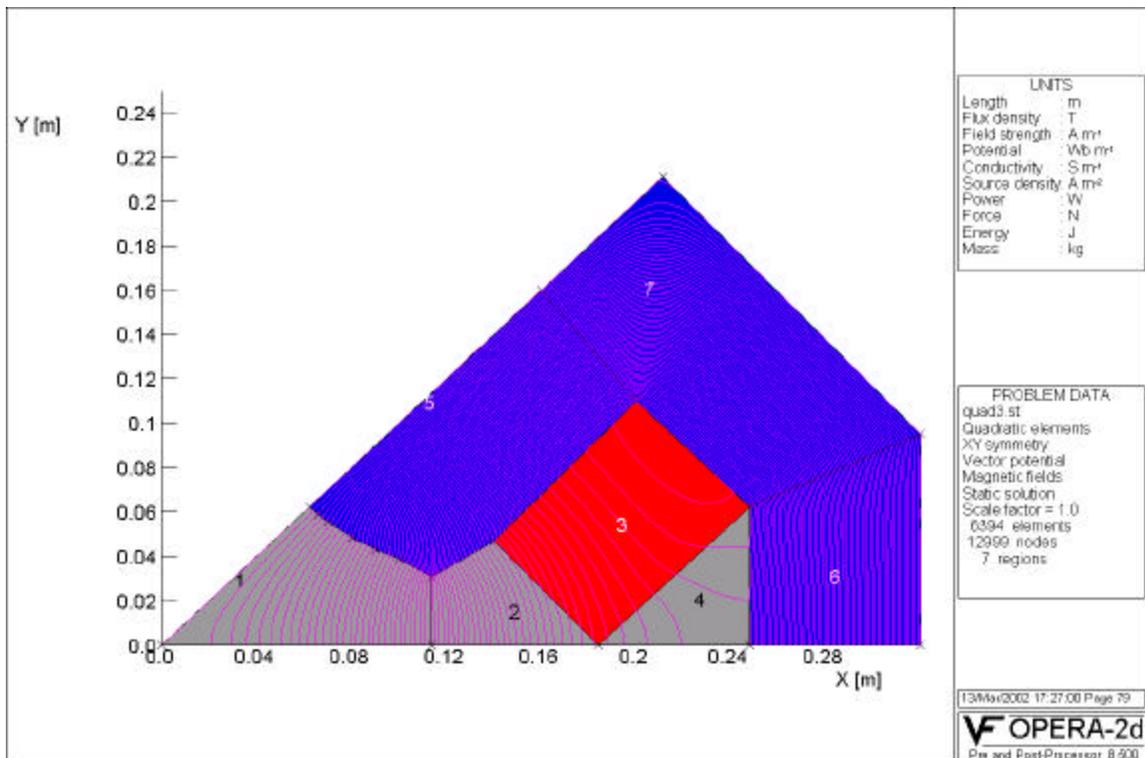
## Booster Magnet AC Field Measurement in E4R



## Proton Driver Quadrupole

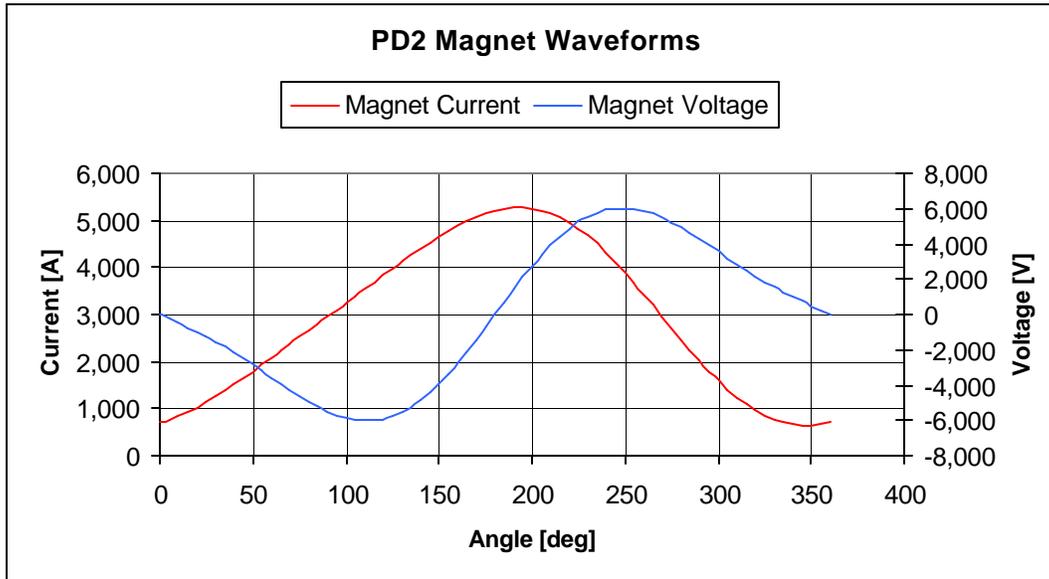
### Main parameters

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



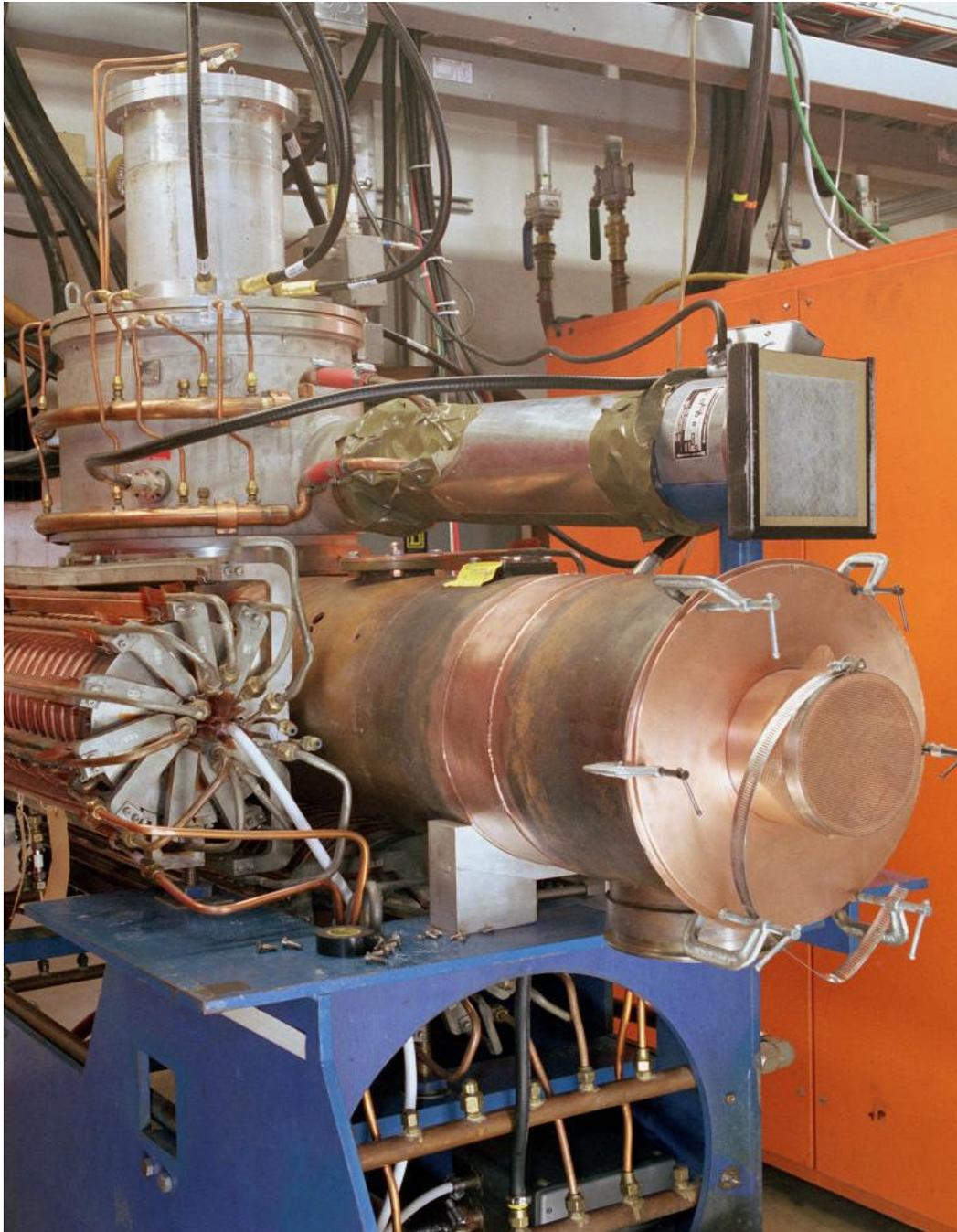
**Fig.1 Flux lines**

## 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	$\Omega$	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	$\pm 2,000$
Power supply current, peak	A	5,200
Number of power supplies		4

## Booster RF Cavity Modification in MI-60







## Concluding Remarks

- A historical lesson – 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. (Today these two projects are the backbone of the U.S. HEP program.)

- The Proton Driver is a strong contender for such a mid-size project.
  - The physics case is strong.
  - The cost is affordable (less than 1/10 of a big project).
  - We know how to build it.
- The world can afford more than one Proton Driver. (It may even be necessary to have more than one driver.)