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# Synchrotron-Based Proton Driver

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W. Chou

for the Proton Driver Synchrotron Study Group

October 9, 2003

Presentation to the Long Range Planning  
Proton Driver Sub-Committee Town Meeting

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Ray Tomlin  
Kamran Vaziri  
Bob Webber  
Dave Wildman  
Dan Wolff  
Don Young

# Two Simple Facts

- ◆ Every large HEP lab has an accelerator project but Fermilab:
  - CERN: LHC
  - KEK/JAERI: J-PARC (US\$1.3B)
  - DESY: X-FEL (€700M)
  - GSI: Future ion facility (€700M)
  - SLAC: LCLS (\$220M)
  - Fermilab: ?
- ◆ On the DOE HEP 20-year road map, among the 12 possible facility choices, proton driver is Fermilab's only logical choice for a secured future:
  - Two LHC upgrades: Non-U.S.
  - SNAP, proton decay: Non-accelerator
  - Super-B: Non-Fermilab
  - BTeV, (CKM): can't shoulder Fermilab's future
  - LC: Remote, insecure
  - Super- $\nu$ , off-axis  $\nu$ ,  $\nu$ -factory, part of underground lab: All point to a proton driver

# Outline

- ◆ A quick review of the proton driver “story”
- ◆ An 8-GeV proton driver synchrotron
  - Problems of the present Booster
  - Design considerations
  - Parameters, layout and lattice
  - Technical systems
- ◆ Improvement of the existing linac
  - Front end and tank 1 (10 MeV)
  - Low energy section (116 MeV)
  - High energy section (313 – 500 MeV)
- ◆ Cost estimate
- ◆ R&D plan
- ◆ Conclusions

<http://www-bd.fnal.gov/pdriver/8GEV/>

# First Document on Proton Driver

September 1997



**Fermi National Accelerator Laboratory**

FERMILAB-TM-2021

## **A Development Plan for the Fermilab Proton Source**

Edited by S.D. Holmes  
For the Proton Source Summer Study Group

*Fermi National Accelerator Laboratory  
P.O. Box 500, Batavia, Illinois 60510*

September 1997

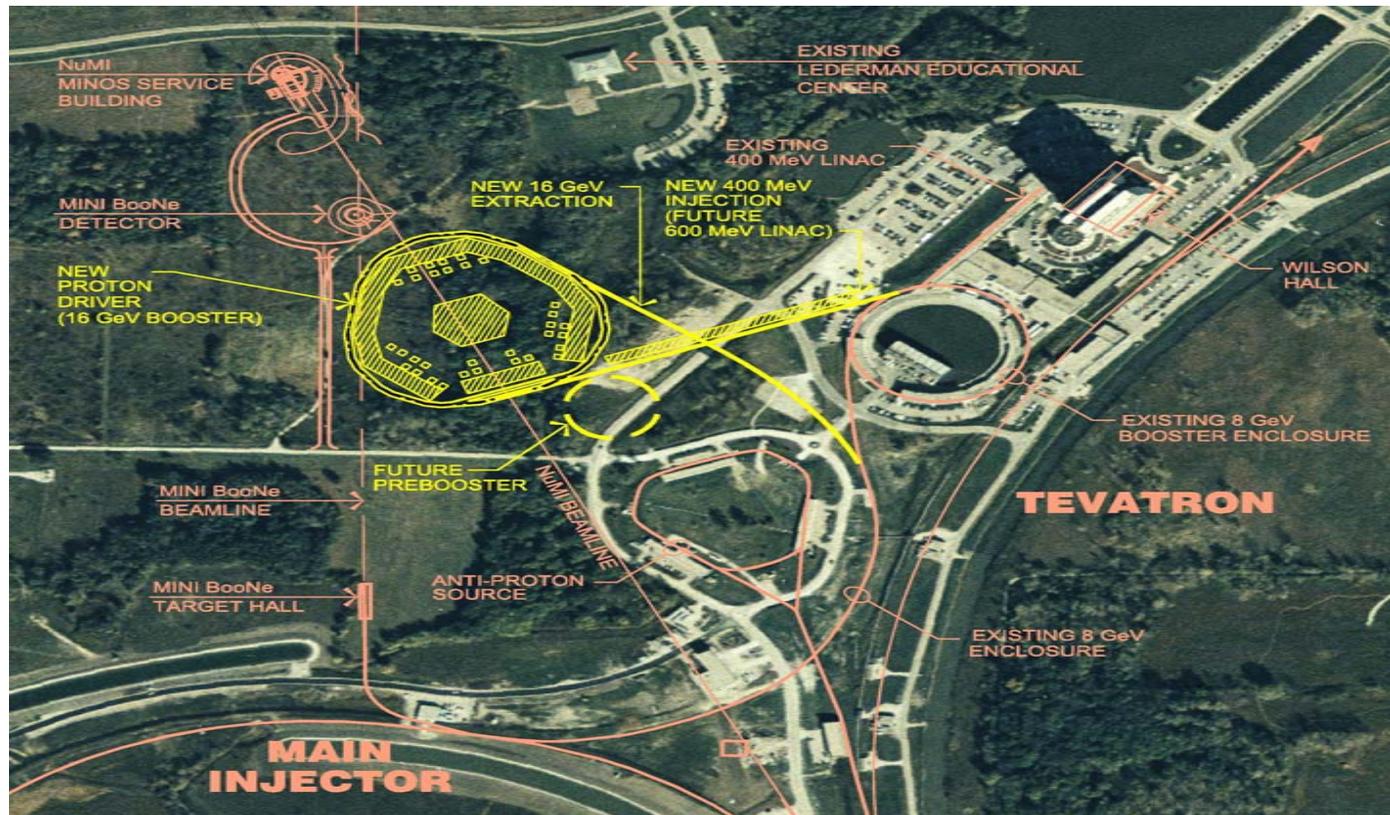
# First Meeting on Proton Driver with the Director

April 14, 1998 (w/ John Peoples)

## PROTON DRIVER

1. **Primary requirements:**
  - High intensity proton beams:  $1 \times 10^{14}$  ppp, 4 MW
  - High rep rate: 15 Hz
  - Short bunch length:  $\sigma = 1-2$  ns at extraction
2. **Design work:**
  - (a) **Documents completed:**
    - 1997 Summer Study Report
    - Two workshop reports
    - Proc. 1998 Muon Collider Collaboration Meeting
  - (b) **Document in preparation:**
    - Feasibility Study (due July 1, 1998)
  - (c) **Document to start:**
    - Conceptual Design Report (due July 2000)
3. **Machine experiments:**
  - (a) **Short bunch:**
    - Bunch rotation at the Fermilab Booster
    - Beam near transition at the AGS
  - (b) **Inductive compensation of space charge effects:**
    - Fermilab-LANL at the PSR
    - KEK at the PS
    - Fermilab-BNL at the AGS (being arranged)
4. **Planned hardware R&D:**
  - (a) Prototype high power high gradient rf cavity
  - (b) Prototype Inconel beam pipe
  - (c) Prototype short large aperture magnet
  - (d) Inductive insert
  - (e) High current ion source
  - (f) Prototype chopper

# Proton Driver Study I: 16 GeV (Fermilab-TM-2136, December 2000)



# Snowmass 2001 WG 6 Report

August 10, 2001

## Report of the Snowmass M6 Working Group on High Intensity Proton Sources\*

Conveners: W. Chou (Fermilab) and J. Wei (BNL)  
August 10, 2001

*Charge to the group:* Several present and future high-energy physics facilities are based on high intensity secondary particle beams produced by high intensity proton beams. The group is to perform a survey of the beam parameters of existing and planned multi-GeV high intensity proton sources and compare them with the requirements of high-energy physics users of secondary beams. The group should then identify areas of accelerator R&D needed to achieve the required performance. This should include simulations, engineering and possibly beam experiments. The level of effort and time scale should also be considered.

### Outline

Executive summary

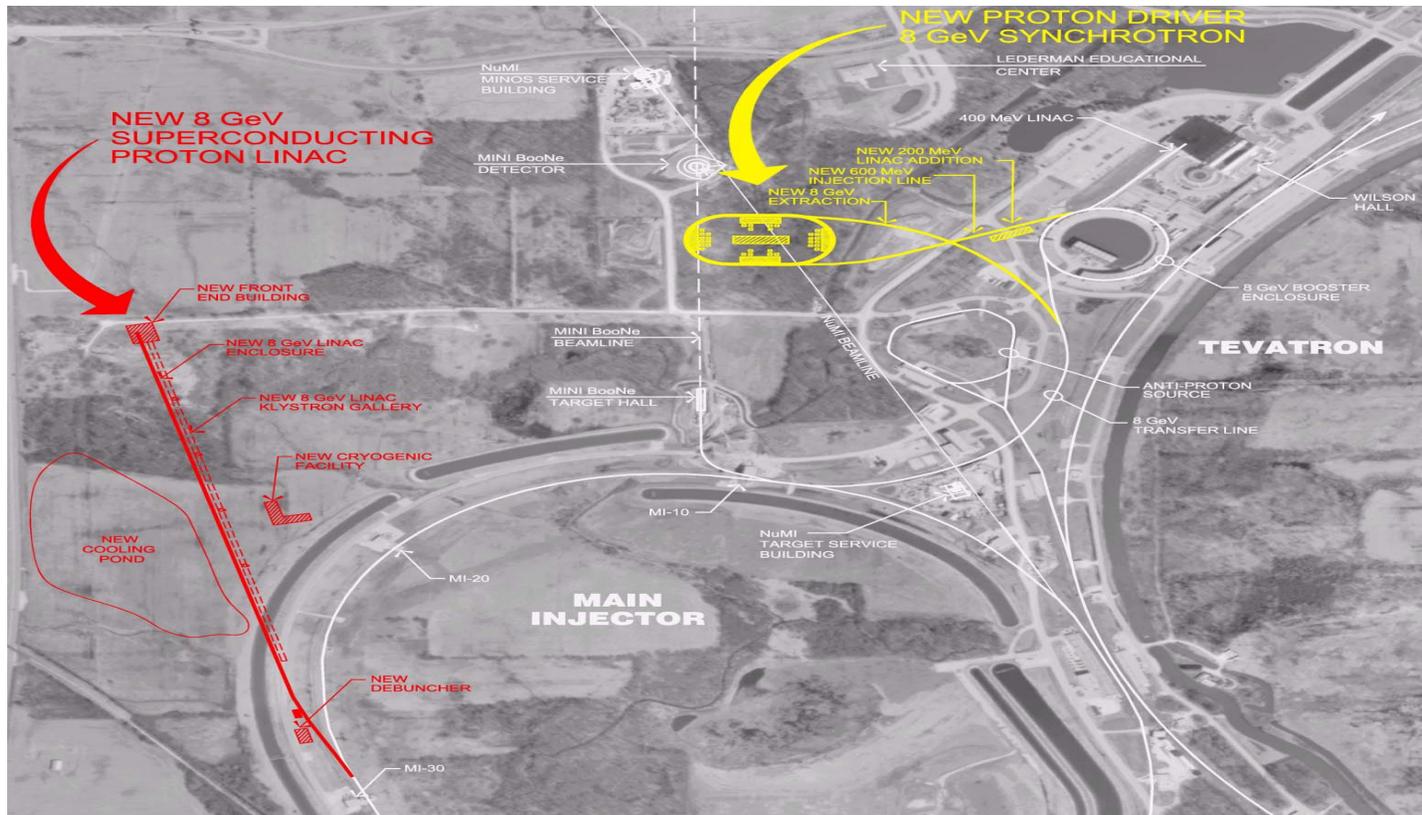
1. Introduction
2. Linac and transport lines
  - 2.1 Ion source
  - 2.2 Low-energy beam transport (LEBT) and radio frequency quadrupole (RFQ)
  - 2.3 Medium-energy beam transport (MEBT)
  - 2.4 Funneling
  - 2.5 Accelerator architecture and structures
  - 2.6 Superconducting RF linac
  - 2.7 RF control
  - 2.8 High-energy beam transport (HEBT) and ring-to-target beam transport (RTBT)
  - 2.9 Space charge effects
  - 2.10 Diagnostics

# A New Charge from the Director

January 10, 2002

- ◆ The charge requested a design report consisting of three parts:
  - An 8-GeV synchrotron based proton driver
  - An 8-GeV linac based proton driver
  - A 2-MW upgrade of the Main Injector
- ◆ The charge also requested the report be delivered to his office by May of 2002, i.e., in 5 months.

# Proton Driver Study II: 8 GeV (Fermilab-TM-2169, May 2002)



# ICFA Workshop HB2002

April 2002

**ICFA-HB2002**  
20th ICFA Advanced Beam Dynamics Workshop  
on High Intensity & High Brightness Hadron Beams

ICFA

April 8-12, 2002 • Fermilab, USA

**Workshop Co-Chairmen**  
Warren Chou (Fermilab) Yoshiharu Mori (KEK)

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Workshop supported by Fermilab and KEK  
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http://www-bd.fnal.gov/ICFA2002/

# Silence Period .....

Then it's on-again. After

- 3 charges from 2 directors
- 3 documentations
- 2 large workshops
- 3 reviews
- Countless meetings and discussions

Here is ...

# A New New Charge from the Director

Early 2003

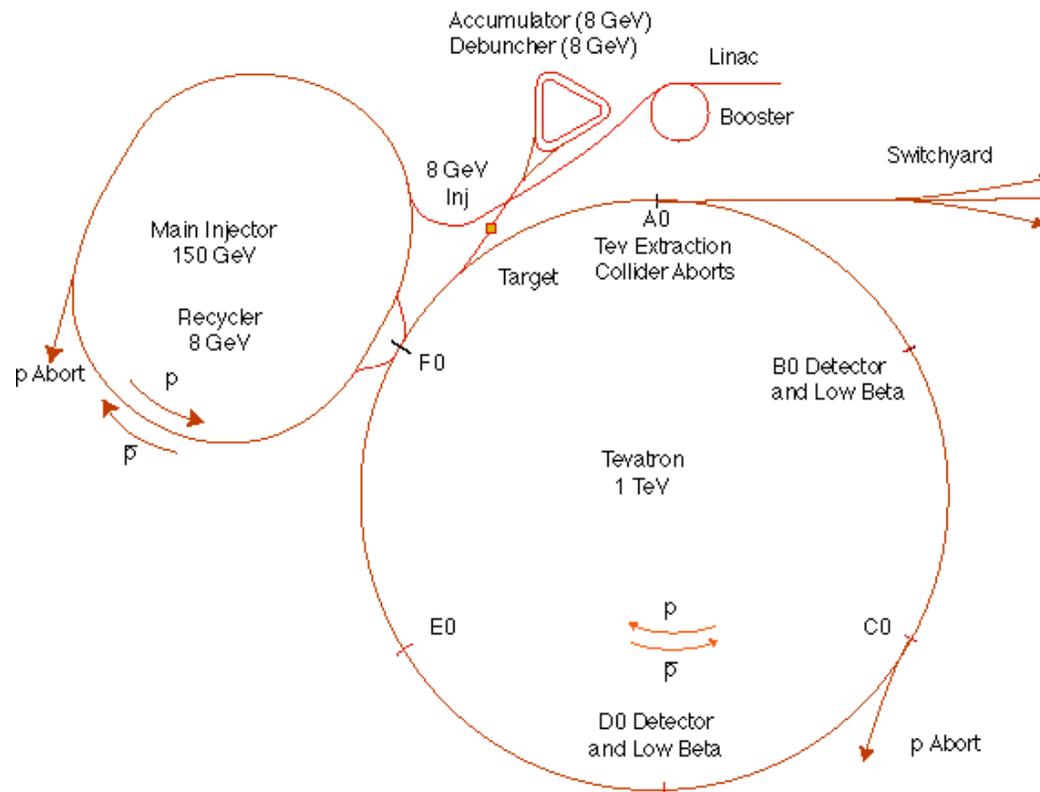
## Charge to the Fermilab Long-range Planning Committee

The first recommendation of the 2001-2 HEPAP Subpanel on Long-Range Planning for U.S. High Energy Physics was “that the United States take steps to remain a world leader in the vital and exciting field of particle physics, through a broad program of research focused on the frontiers of matter, energy, space, and time.” As the largest U.S. laboratory dedicated to High Energy Physics, Fermilab has a special responsibility to develop the research facilities needed to implement that recommendation.

The HEPAP Subpanel also recommended that the U.S. participate in the linear collider, wherever it is built in the world, and that the U.S. prepare to bid to host such a facility. Fermilab is working within the framework of the international and US steering groups to develop a global project, and to work out what it would take to host such a facility here. Finally, the HEPAP Subpanel argued persuasively that to address the range of compelling scientific issues the field needs a broad range of experimental strategies and techniques. Many of the experiments that exist as possibilities on the roadmap would be most easily done at Fermilab.

# Fermilab Accelerator Complex

Fermilab Tevatron Accelerator With Main Injector

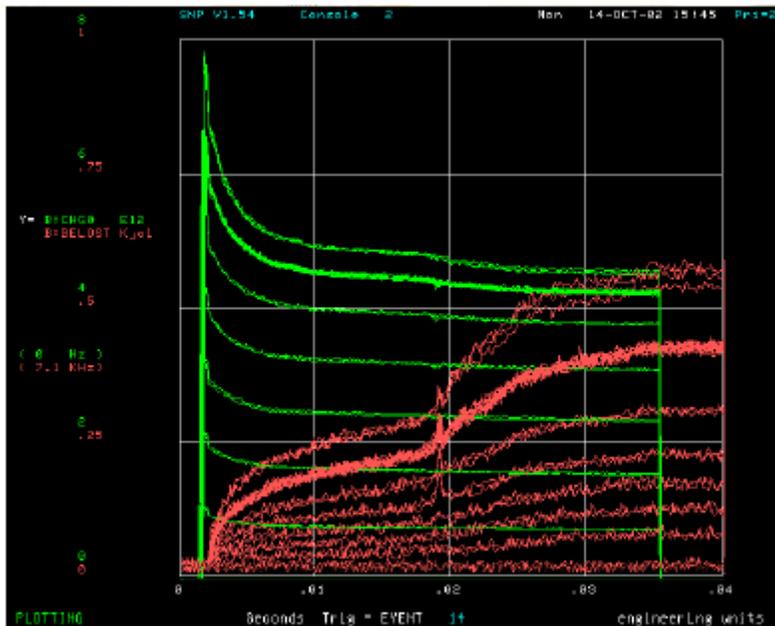


# Booster is the Bottleneck

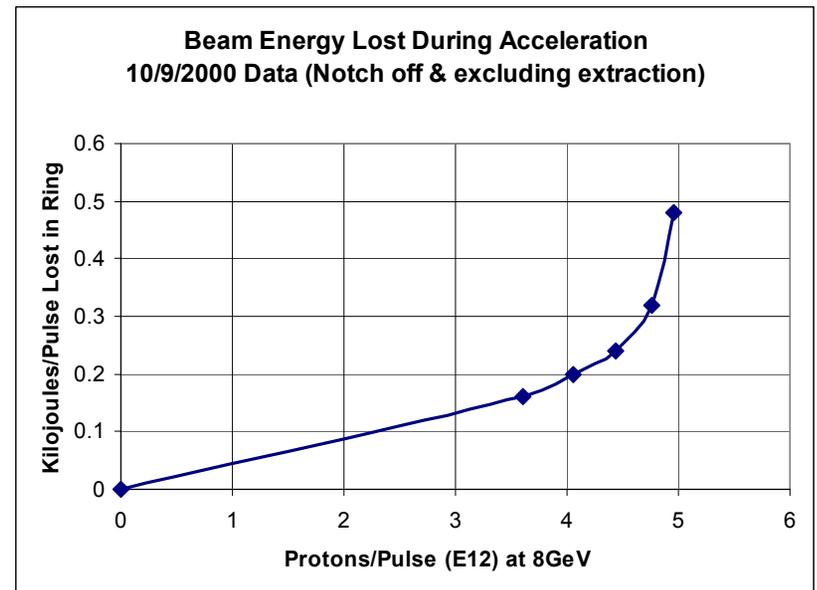
- ◆ The **Booster** is a 30 years old machine and has never been upgraded.
- ◆ The 400-MeV **Linac** can provide **25e12** particles per Booster cycle.
- ◆ The 120-GeV **Main Injector** can accept **25e12** protons per Booster cycle with modest upgrade.
- ◆ However, the 8-GeV **Booster** can only deliver **5e12** particles per cycle.

# Booster Beam Loss

(courtesy R. Webber)



For 0, 2, 4, 6, 8, 10, 12, 14 Injected Turns



# Problems of the Booster

- ◆ **Three fundamental problems:**

- Magnet aperture too small (vertical 1.6/2.2 in., horizontal good field region ~ 2.4 in.)
- Linac too close to the ring
- Tunnel not deep enough (13.5 ft.; and worse, buildings on top)

**Any change of these would mean a new machine.**

- ◆ **Other problems:**

- Transition crossing ( $\gamma_t = 5.45$ )
- Large beta- and dispersion functions (33.7/20.5 m, 3.2 m)
- Small RF cavity aperture (2-1/4 in.)
- RF cavity in dispersive region
- No RF shield inside the magnet
- Limited orbit correction capability

Some of these are being changed as part of Booster upgrade.

# 8-GeV Proton Driver Synchrotron Design Considerations

- ◆ Large magnet aperture (good field region 4 in x 6 in)
- ◆ Space reserved between the linac and ring for future linac energy upgrade
- ◆ The tunnel is twice as deep (27 ft.; no buildings on top)
- ◆ Transition free ( $\gamma_t = 13.8$ )
- ◆ Small beta- and dispersion functions (15.1/20.3 m, 2.5 m)
- ◆ RF cavity aperture 5 in.
- ◆ RF cavity in dispersion-free straight sections
- ◆ Thin metallic beam pipe reinforced by spiral ribs
- ◆ AC correctors with sufficient strength throughout the cycle
- ◆ Phase space painting during multi-turn injection
- ◆ Dual harmonic magnet power supply for 25% RF power reduction
- ◆ Two-stage collimator system for keeping uncontrolled beam loss below 1 W/m

# Scope of the Design

- ◆ A new 8-GeV rapid cycling synchrotron replacing the Booster
  - Beam intensity increased by a factor of 5
  - Beam power increased by a factor of 15
- ◆ A new linac extension of 200 MeV (to bring the linac energy to 600 MeV)
- ◆ A modest improvement of the existing H<sup>-</sup> source and 400 MeV linac
- ◆ New 600 MeV and 8 GeV transport lines
- ◆ New enclosures

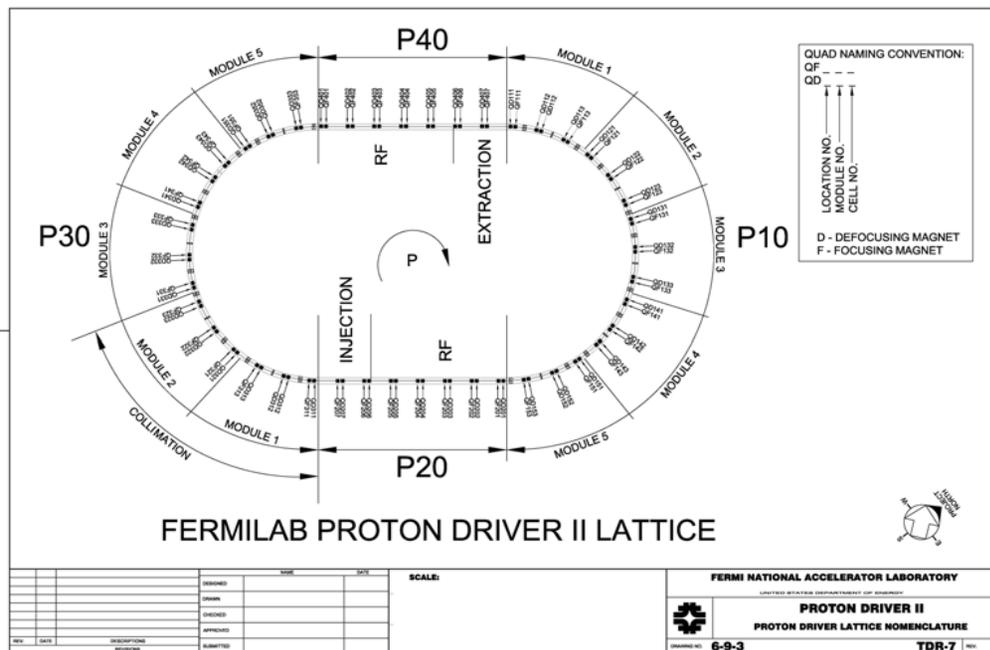
# Parameters

Parameters	Present Proton Source	Proton Driver (PD2)
<b>Linac</b> (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length ( $\mu\text{s}$ )	25	90
H <sup>-</sup> per pulse	$6.3 \times 10^{12}$	$2.8 \times 10^{13}$
Average beam current ( $\mu\text{A}$ )	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 hour	$9 \times 10^{16}$ (@ 5 Hz)	$1.35 \times 10^{18}$
Normalized transverse emittance (mm-mrad)	$15\pi$	$40\pi$
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current ( $\mu\text{A}$ )	12	60
Beam power (MW)	0.033 (@ 5 Hz)	0.5

# Notes to the Beam Power

- ◆ Such a PD would bring the MI beam power to 2 MW. So the total beam power (PD + MI) would reach 2.5 MW. This should be compared with the present MI beam power of 0.3 MW.
- ◆ Besides, the proton driver itself can be increased from 0.5 to 2 MW with a “modest” linac energy upgrade from 600 MeV to 1.9 GeV (space reserved between the linac and ring).

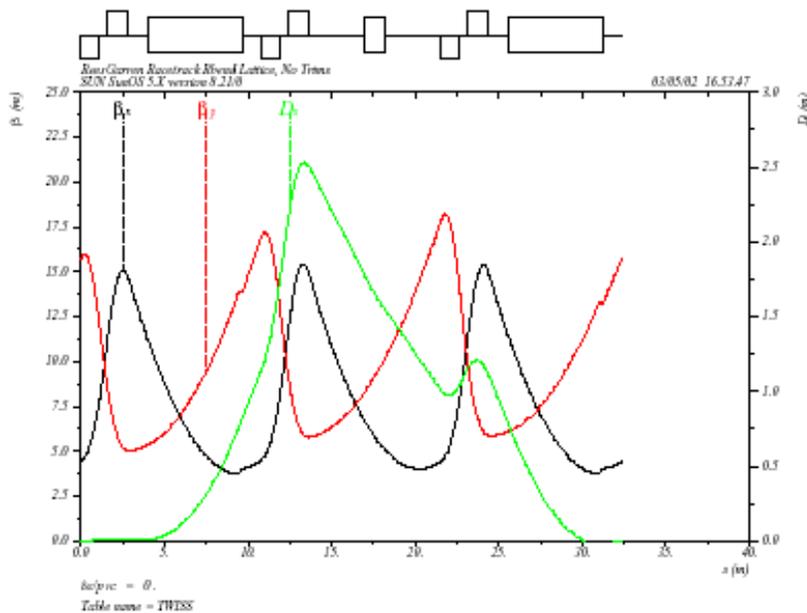
# Layout



- Racetrack shape
- 2 arcs, 2 straights
- Each arc with 5 modules
- Each module with 3 doublet cells
- Straight sections for injection, extraction and RF
- Plenty space for diagnostics in the arcs and straights

# Lattice

## Arc module

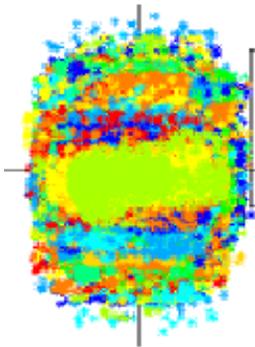


- ◆ Transition-free
- ◆ Dispersion-free straight sections
- ◆ Arc module: doublet 3-cell structure with a short dipole in the mid-cell
- ◆ Phase advance per module 0.8 and 0.6, respectively, in h- and v-plane

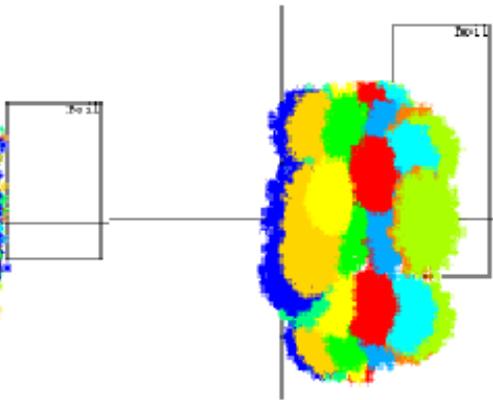
# Space Charge

## x-y plot of the multi-turn injection beam cross section

**with s.c.**



**without s.c.**



- ◆ Space charge is a main concern for low energy high intensity proton machines
- ◆ Numerical simulations by using three codes:
  - ESME (J. MacLachlan, FNAL)
  - ORBIT (J. Holmes, ORNL)
  - Track2D (C. Prior, RAL)

# RF



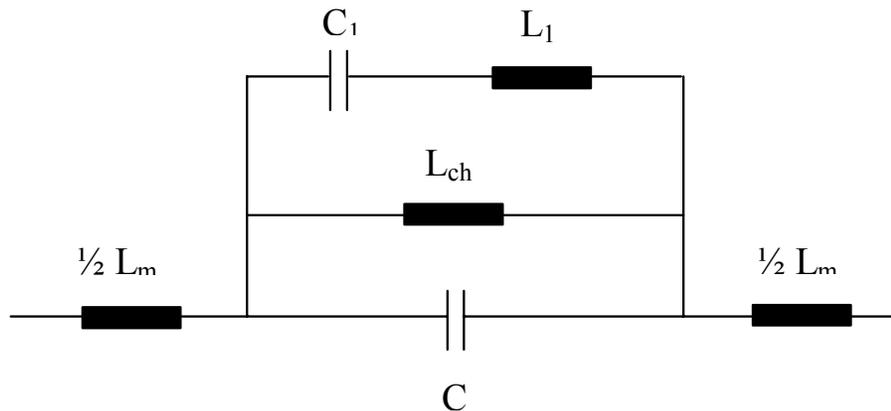
- ◆ Booster RF will be reused with modifications:
  - To increase the aperture from 2-1/4 in. to 5 in.
  - To increase the gap voltage from 55 kV to 66 kV.
- ◆ Two (out of 18) cavities have been modified and will be installed during summer shutdown.



# Dual Harmonic Power Supply

$$B(t) = B_0 - B_1 \cos(2\pi ft) + B_2 \sin(4\pi ft)$$

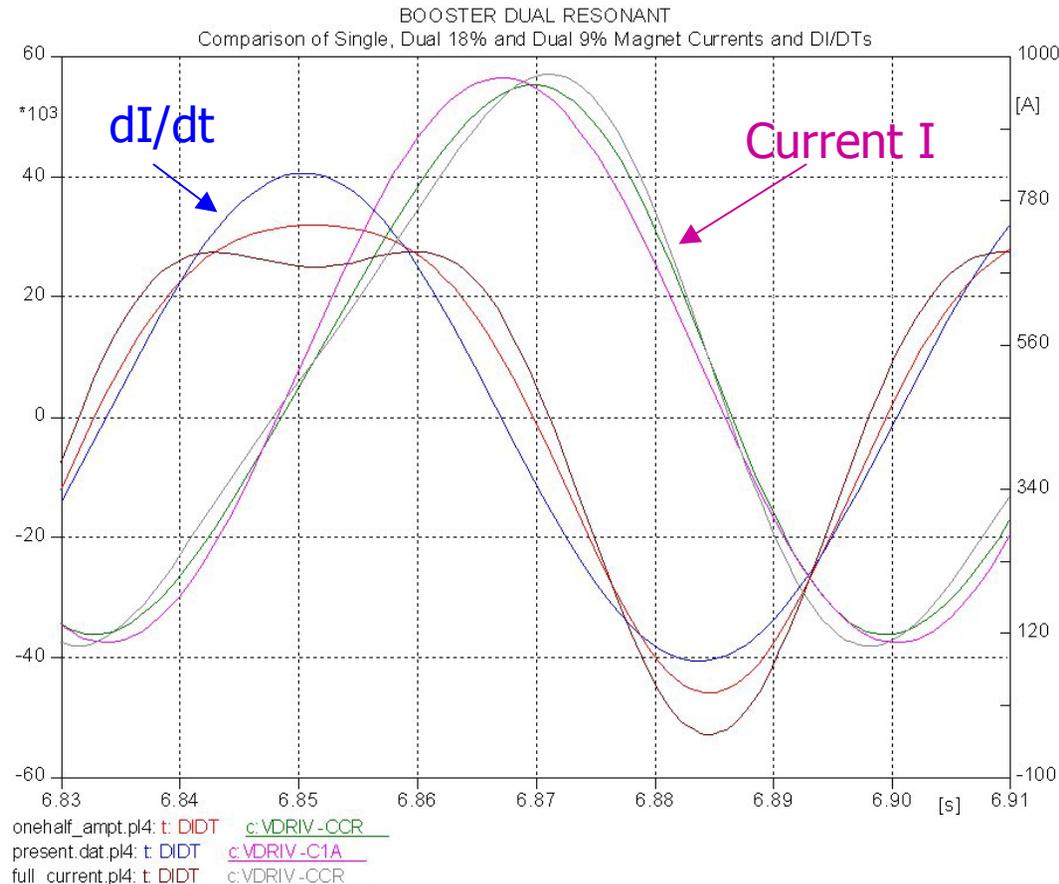
DC      15 Hz      30 Hz



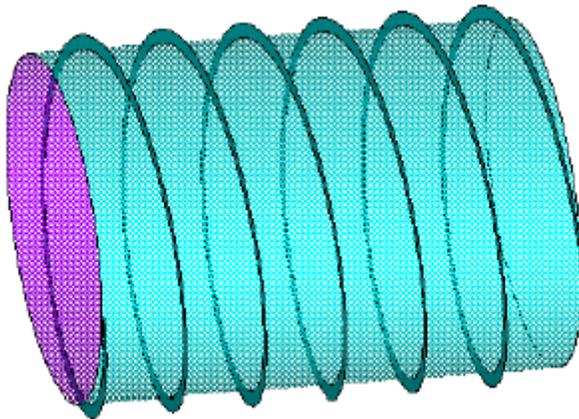
- $B_2 = 12.5\% B_1$
- Peak RF power ( $\propto dI/dt$ ) reduced by 25%
- Test at E4R using Booster power supply

# Dual Harmonic Current and $dI/dt$

(3 cases: dual 0%, 9%, 18%)



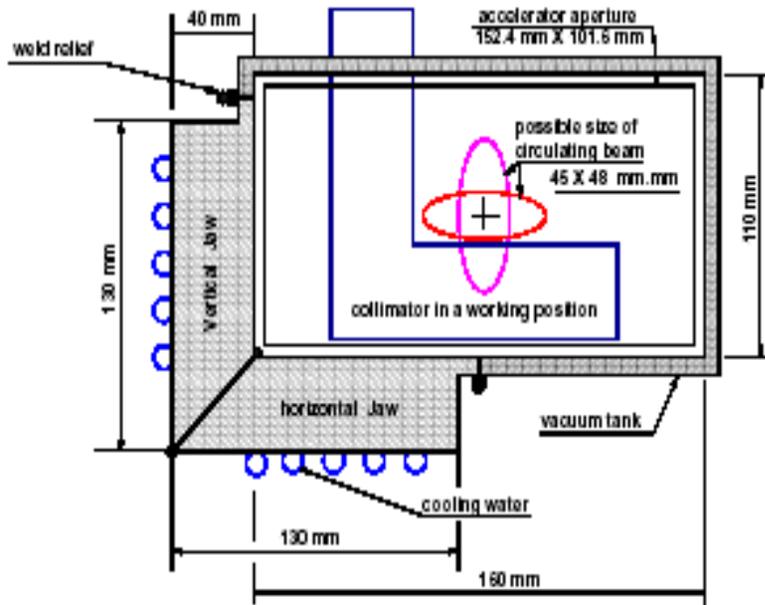
# Beam Pipe



- ◆ New design: thin metallic pipe reinforced by spiral ribs
- ◆ Aperture: 4 in x 6 in oval
- ◆ Material: Inconel 718
- ◆ Wall thickness: 8 mils (0.2 mm)
- ◆ Spiral ribs: rectangular cross-section, width 28 mils, height 18 mils, 10 layers (total height 0.18 inch)
- ◆ Welding technique: laser deposition

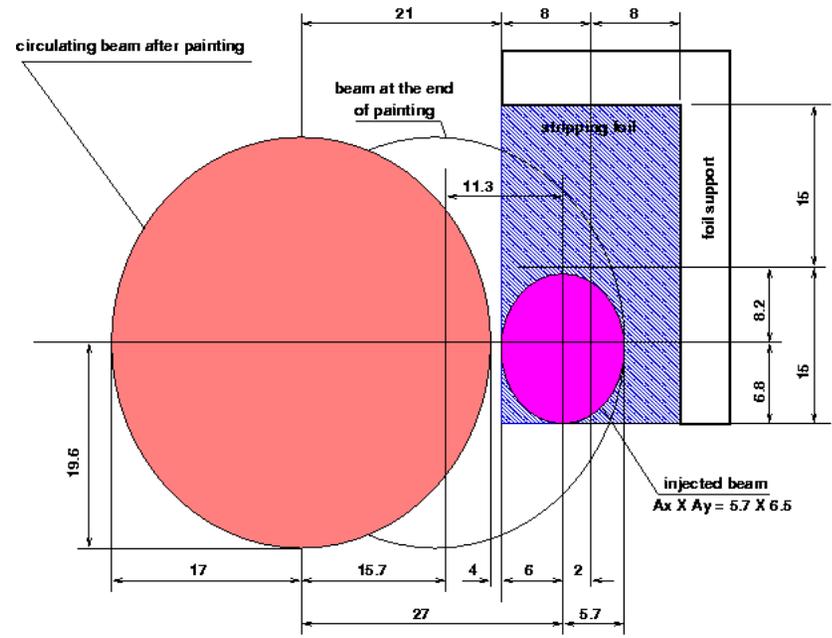
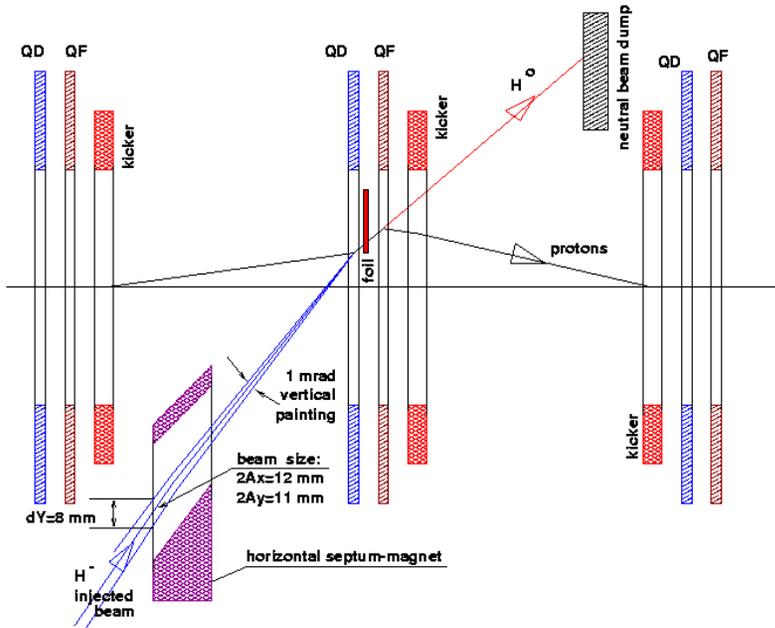
# Collimator

## Collimator cross section

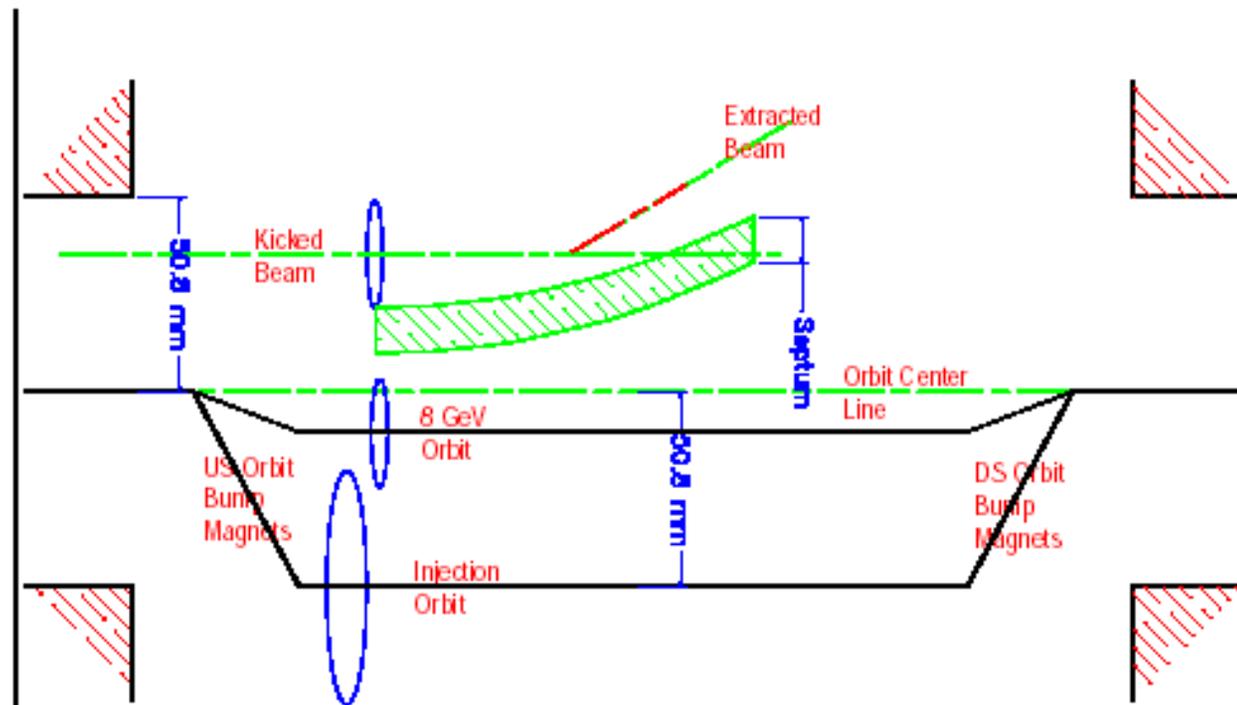


- ◆ To allow hands-on maintenance, the uncontrolled beam loss must be kept below 1 W/m
- ◆ A 2-stage collimator system will collect more than 90% of the lost particles (controlled beam loss)
- ◆ The collimator area will be “hot,” but most of the tunnel will be “cool”

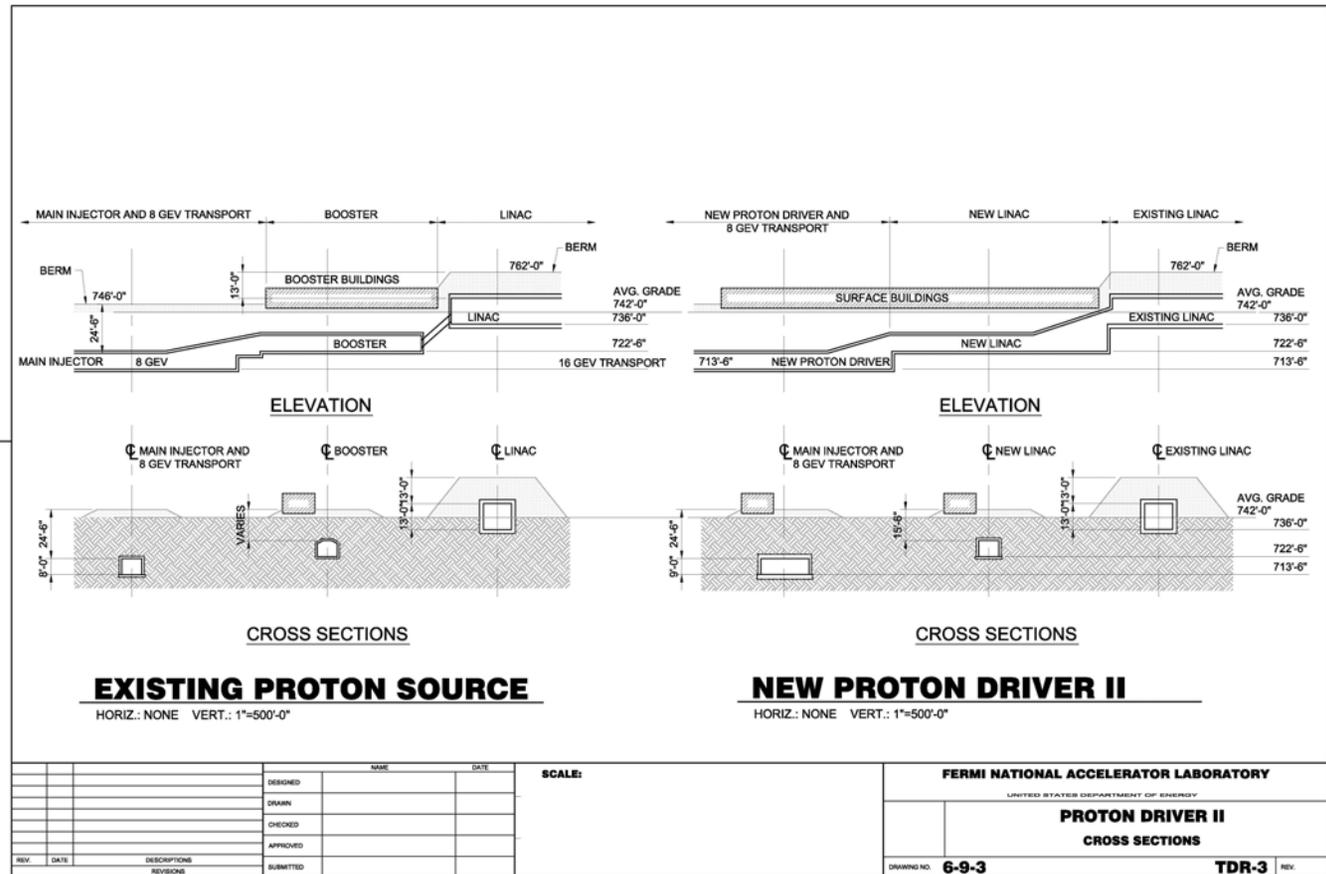
# Injection with Painting



# Extraction



# Tunnel Elevation



# Improvement of the Existing Linac

- ◆ Linac improvement:

This is the “common denominator” of the two proton driver options (linear or circular) and can go ahead regardless which option would be chosen.

- ◆ There are three choices: (choose as many as you wish)

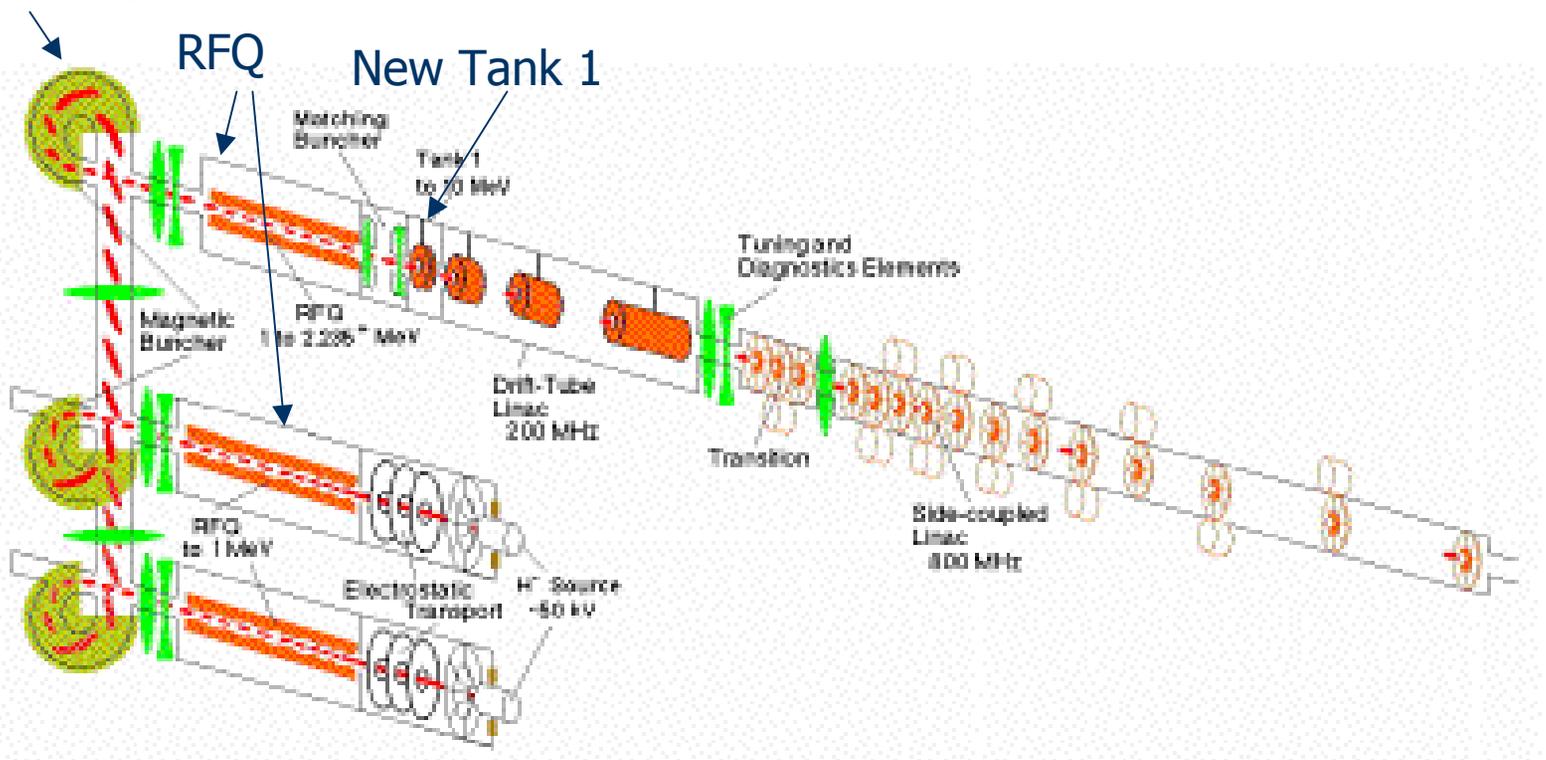
- (1) New 201 MHz front end & Tank 1 (10 MeV)

- (2) New 402 MHz low energy section (116 MeV)

- (3) New 805 MHz sc high energy section (313 - 500 MeV, replacing CCL station no. 6 and 7)

# (1) Linac New Front End & Tank 1 (10 MeV)

Alpha magnet



## (2) New 402 MHz Low Energy Section (116 MeV)

				DTL			CCL	
	RFQ	Tank 1	Tank 2	Tank 3	Tank 4	Match Section	Mod 1	Mod 2
MeV	0.035	3	13.4	32.9	51.6	70.3	70.3	93.3
MeV	3	13.4	32.9	51.6	70.3	70.3	93.3	116.5
MeV	2.965	10.4	19.5	18.7	18.7	0	23	23.2
mA	70	55	55	55	55	50	50	50
MHz	402.5	402.5	402.5	402.5	402.5	805	805	805
usec	90	90	90	90	90	90	90	90
usec	130	130	130	130	130	125	125	125
Hz	15	15	15	15	15	15	15	15
	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
MV/m		2.4 to 4.6	4.6	4.6	4.6	7.5 to 7.35	8	8
m		4.5	6	6.1	6.2	3.25	4.8	4.9
MW		1	1.75	2	2		5.4	5.4
MW		0.63	1.07	1.02	1.02		1.38	1.39
MW		2.5	3.8	4	4		8.5	8.5

## (2) New 402 MHz Low Energy Section (cont...)

The cost estimate of this 402 MHz low-energy system in 2002 dollars is as follows (in K\$):

Components, including the RFQ, RGDTL, DTL, matching section, CCL, DTL rf systems, matching section rf systems, beam diagnostics, and the control systems	24,649
Installation and commissioning	2,500
Building modifications	500
<b>TOTAL (K\$)</b>	<b>27,649</b>

## (3) New 805 MHz SC High Energy Section (313 – 500 MeV)

- ◆ Retain the existing CCL stations No. 1-5 for accelerating the beam to 313.6 MeV.
- ◆ Replace the last two CCL stations No. 6-7 by SNS-type  $\beta=0.81$  sc cavity for an energy upgrade to 500 MeV.
- ◆ The requires a “real estate” gradient of 9.5 MV/m in a 19.5 m long space, which is feasible.
  - The peak field is 35 MV/m, already achieved by the SNS
  - The fill factor is 0.63, which will require some changes in the SNS design (using quadrupole doublet, replacing SNS input coupler by TESLA type)

# Cost Estimate – Proton Driver

1	<b>Technical Systems</b>			98,986
1.1	8 GeV Synchrotron		78,997	
1.2	Linac Improvements and Upgrade		17,500	
1.3	600 MeV Transport Line		900	
1.4	8 GeV Transport Line		1,589	
2	<b>Civil Construction</b>			37,152
2.1	8 GeV Synchrotron		17,500	
2.2	Linac extension		2,500	
2.3	600 MeV Transport Line		1,800	
2.4	8 GeV Transport Line		2,200	
2.5	Site work		4,800	
2.6	Subcontractors OH&P		5,760	
2.8	Environmental controls and permits		2,592	
	<b>Total Direct Cost</b>			<b>136,138</b>
	EDIA (15%)			20,421
	Lab Project Overhead (13%)			20,353
	Contingency (30%)			53,073
	<b>Total Estimated Cost (TEC) (\$k)</b> (in FY02 dollars)			<b>229,985</b>

# Notes to the Cost Estimate

- ◆ A fair comparison between different design options (e.g., linear *vs.* circular) is the total direct cost, which is **\$136M** for the synchrotron. The TEC depends on the cost model.
- ◆ Our cost model (EDIA, overhead, contingency) is the same as that in the BNL proton driver report. The **BNL's TEC is \$390M for 1 MW** beam power, whereas **ours** is \$230M for a PD and \$36M for an MI upgrade, a total of **\$266M for 2.5 MW**.

# Cost Estimate – Linac Improvement

- ◆ New 200 MHz front end & Tank 1 (10 MeV) \$4M
- ◆ New 402 MHz low energy section (116 MeV) \$27.6M (incl. \$4M)
- ◆ New 805 MHz sc high energy section (313 – 500 MeV) (TBD)

# R&D Plan

- ◆ One important feature of the Proton driver synchrotron R&D is that **it will help improve the Booster performance.**
- ◆ It is fair to say that to large extent the three major Booster projects during this shutdown are all spin-offs of the proton driver study.
  - RF cavity modification
  - Collimators
  - Doglegs
- ◆ R&D list:
  - Space charge study
  - Inductive inserts
  - Dual harmonic power supply test in E4R
  - Magnet field measurement in E4R
  - Laser chopping
  - AC sc magnet development
  - Beam pipe prototyping

# RF Cavity Modification

(courtesy J. Reid)



- ◆ Booster RF will be reused with modifications:
  - To increase the aperture from 2-1/4 in. to 5 in.
  - To increase the gap voltage from 55 kV to 66 kV.
- ◆ Two (out of 18) cavities have been modified and will be installed during summer shutdown.

# Space Charge Study

- ◆ Code development
  - ESME (P. Lucas, J. MacLachlan)
  - ORBIT (F. Ostiguy, L. Michelotti, W. Chou)
  - Synergia (P. Spentzouris, J. Amundson)
- ◆ Weekly Booster space charge study meeting

# Inductive Insert

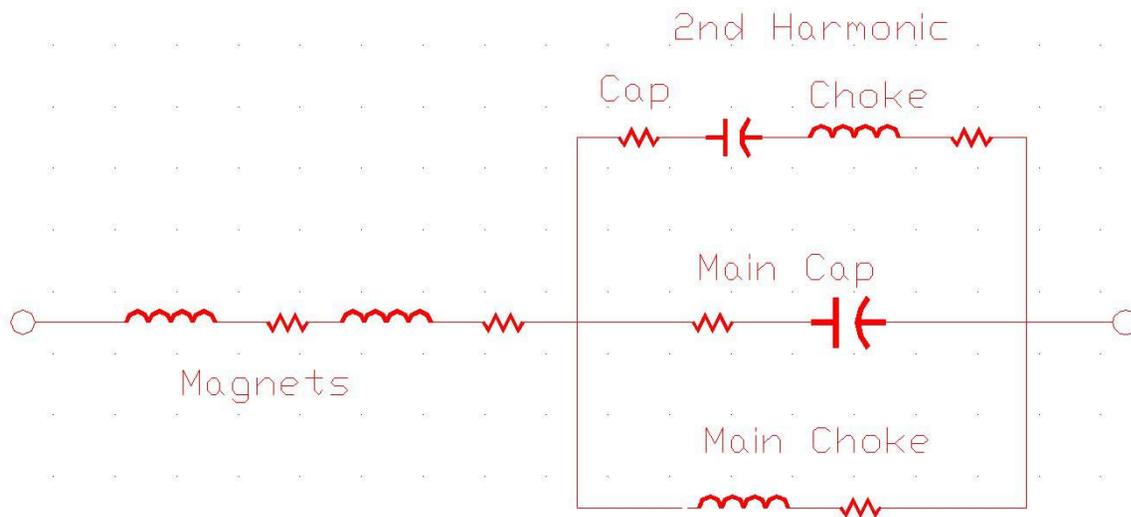
(courtesy D. Wildman and J. Lackey)



- ◆ For compensating space charge
- ◆ Test will be done in the Booster
  - Two modules have been tested, but inductance too low
  - A total of seven modules have been made and will be installed

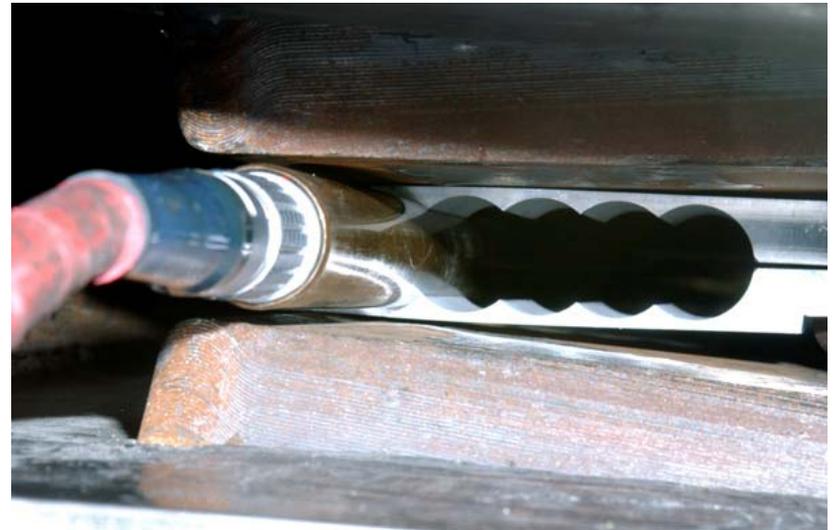
# Booster Cell With 2<sup>nd</sup> Harmonic

(courtesy D. Wolff)



# Field Measurement at E4R

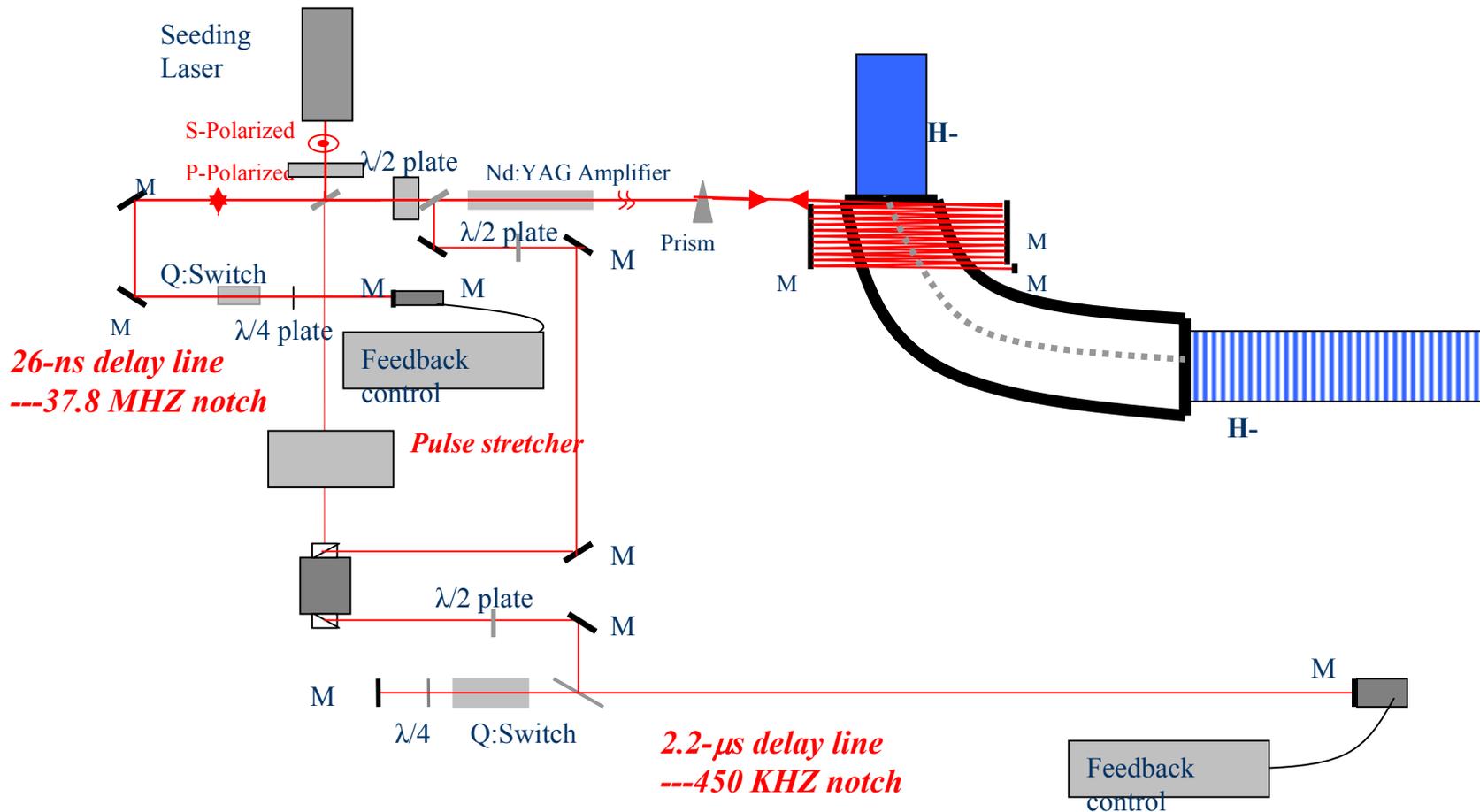
(courtesy J. DiMarco and P. Schlabach)



A mole used for field measurement

# Laser Chopping

(courtesy R. Tomlin and X. Yang)



# Superconducting Dipole Magnet (courtesy V. Kashikhin)

**Main Issue:**

**Superconducting cable and winding with low eddy current losses**

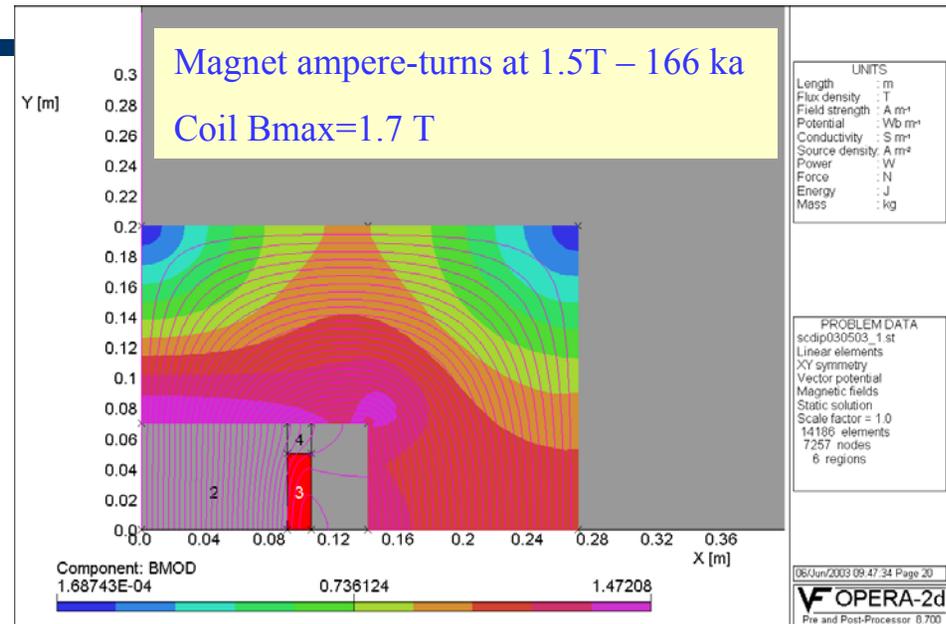
## Magnet Parameters:

Magnetic field	1.5 – 3.0 T
Frequency	15 Hz
Air gap	100 – 150 mm
Length	5.72m – 2.86 m
Superconductor	NbTi/CuNi or HTS
Iron/air core	room temperature
Cooling	LHe forced flow

Superconductor AC losses < 3.3 kW/m<sup>3</sup>  
at 15 Hz and 0.5 mm dia.

Losses for 1.5 T magnet 1.2 W/m  
for NbTi/CuNi ALSTHOM superconductor  
with 0.16  $\mu$ m filaments

Hysteresis losses can be effectively reduced by  
decreasing a filament size up to  $\sim$  0.2  $\mu$ m

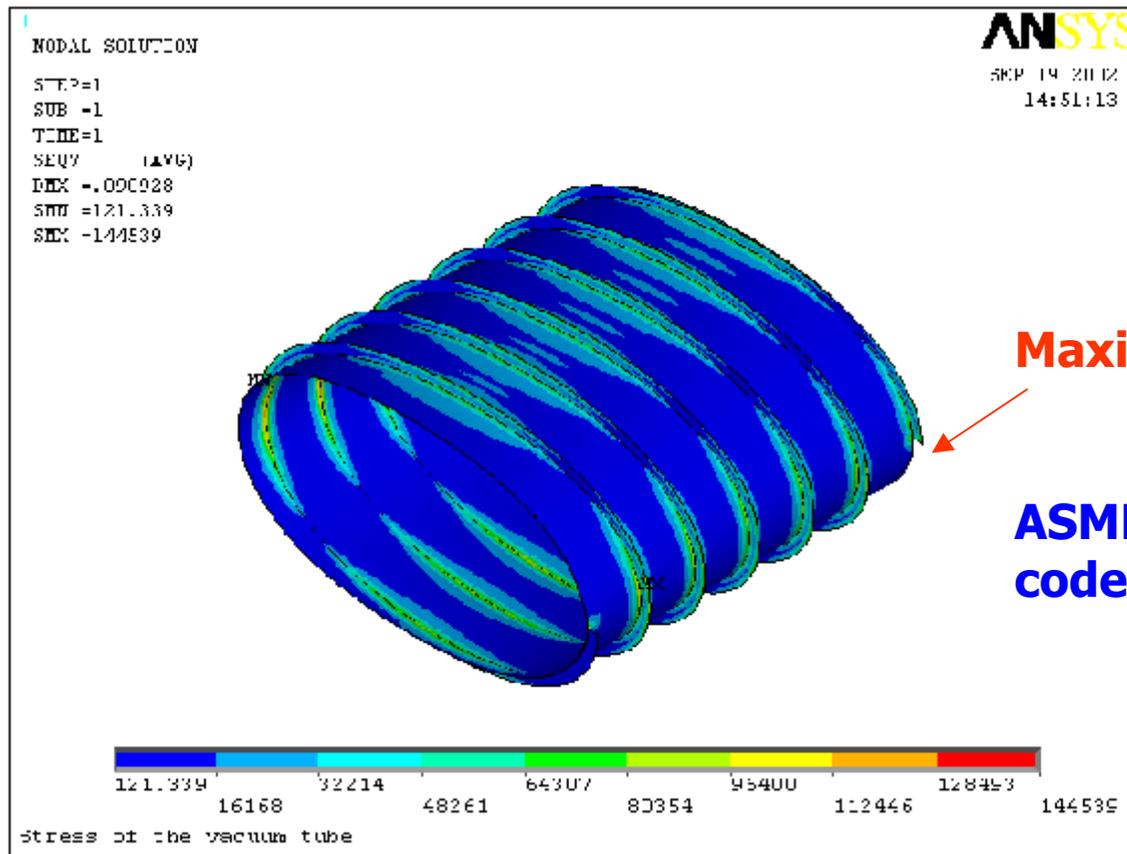


Eddy current losses effectively reduced by using high resistive CuNi matrix and small twist pitch 1.5mm for sub-wire and 6-8mm in 0.5mm wire.

Careful optimization needed between SC cable, cooling pipes/channels and construction elements to reduce heat load up to reasonable value

# Beam Pipe Stress Analysis

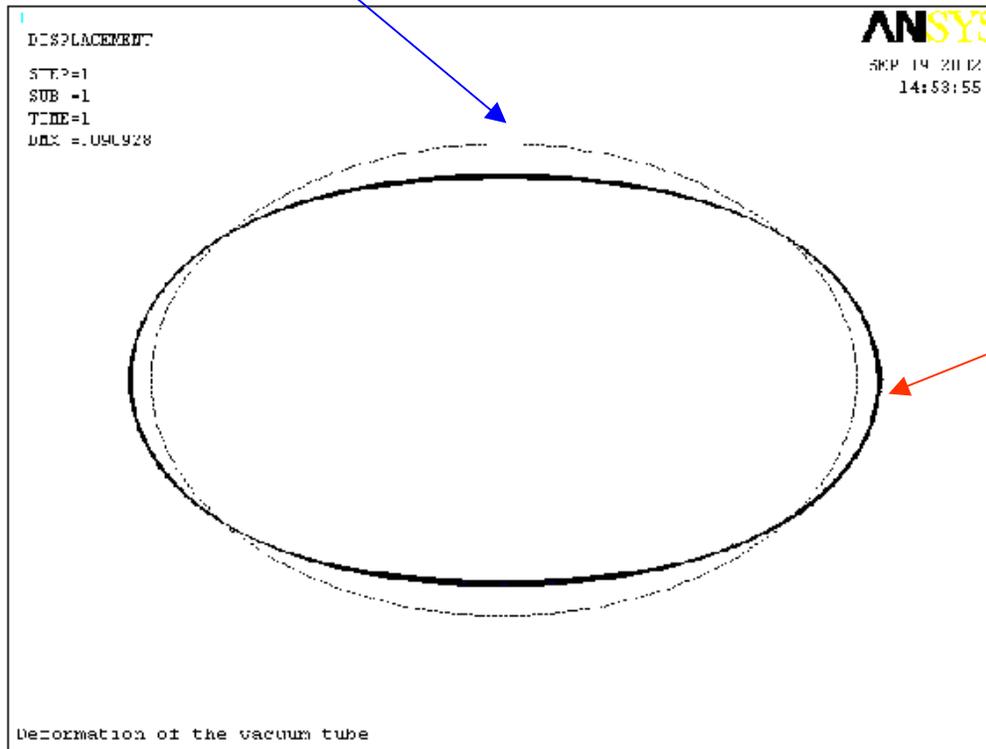
(courtesy Z. Tang and A. Chen)



# Beam Pipe Deformation Analysis

(courtesy Z. Tang and A. Chen)

**Max  $\Delta y = -0.089$  in**

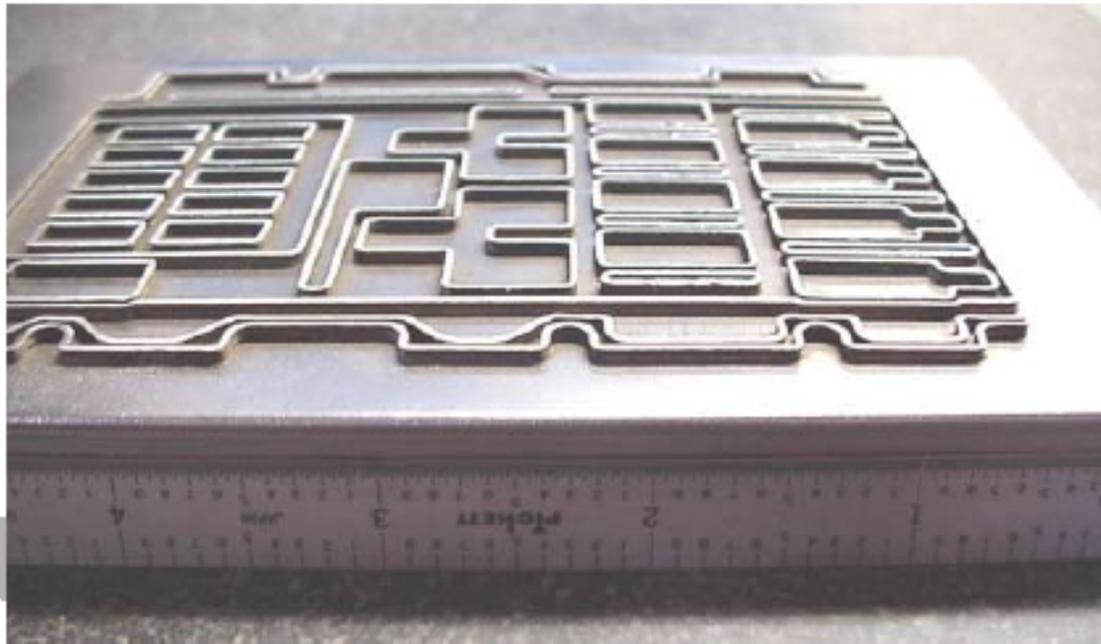


**Max  $\Delta x = 0.055$  in**

# Laser Precision Metal Deposition

(courtesy H&R Technology Inc.)

**Cutting die prior to sharpening;  
Die Base: Carbon Steel, Knife Pattern: 420 SST**



## R&D Cost Estimate (M/S Part)

◆ Laser chopping	\$38 k
◆ Dual harmonic power supply test	\$45 k
◆ Thin metallic pipe	\$60 k
◆ Inductive inserts	\$ 6 k
◆ Magnet R&D	\$60 k
◆ AC sc magnet development	\$50 k
◆ Collimation system	\$10 k (FESS)
◆ RF modification	\$0
<b>Total:</b>	<b>\$269 k</b>

# Conclusions

- ◆ With a Proton Driver, Fermilab will get two high power proton facilities – the PD itself (0.5-2 MW), and a 2-MW Main Injector
- ◆ This will put Fermilab in a solid leading position in the neutrino physics for a foreseeable future
- ◆ The construction cost is modest and can be supported by the HEP base program
- ◆ It is "*the One*" that can fit in the time window between the end of Run2 (2009) and the possible beginning of a linear collider (2015?)

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Questions?

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# Circular vs. Linear

## Synchrotron: cheaper, more secure

- Strengths
  - A lot of the work completed - Three design iterations, all documented
  - More matured technology (“*Boring is good*”)
  - Less expensive (TEC \$230M, including 15% EDIA, 13% overhead, 30% contingency)
  - Fit the existing complex better
  - Better use of Fermilab’s expertise
  - R&D helps improve the performance of existing machines
- Weaknesses
  - Less innovative (less attractive to universities)
  - Longer injection time to the MI
- Possible improvement
  - To investigate ac superconducting magnet technology

## Linac: better, more challenging

- Strengths
  - Natural connection to a TESLA type LC
  - More intense beam intensity possible
  - More versatile physics (p, e, X-FEL)
- Weaknesses
  - More expensive
  - Two critical technical issues:
    - 1 klystron driving multiple cavities
    - 8 GeV H<sup>-</sup> injection into the MI
  - Difficult to use the MiniBooNE beam line
  - 1 ms pulse too long for expt
  - To be a true “proton driver” (i.e., serving a neutrino factory), the linac needs a compressor ring.
- Possible improvement
  - To have a cost review
  - To carefully investigate these technical issues