Increasing Proton Intensity at Fermilab

Doug Michael, Caltech

Interaction Meeting on Linear Collider and Neutrino Physics

Delhi

Nov. 12, 2003

Overview

- A quick view of proton needs
- The current Fermilab accelerator complex
  - Features
  - Limitations
- Improvements in the existing accelerators
- A new proton driver
  - Synchrotron option
  - Super-conducting LINAC
- What is Fermilab going to do?

Why is this guy from Caltech talking about Fermilab accelerators?

- High energy neutrino experiments need as many protons as they can get.
- Long baseline experiments (MINOS for example) need as many protons as they can get. This need has become more keen in the last few years as we have learned that Δm^2_{atm} is relatively small.
- We must view the accelerator as a fundamental part of these experiments. We are trying to develop this sociology.
- Precision neutrino measurements of the future, depend on very significant improvements in proton intensity from any existing high energy machines.

Caveat

- What I will present and discuss here is not an official plan. That is why I (rather than a Fermilab Official) am giving this talk.
- It is all under discussion as part of a possible plan.
- I think that over the next 1-2 years much of this direction will be determined.

A List of Neutrino Physics Issues and Questions

- Demonstrate with precision the energy dependence of the oscillations.
  - Just the basic expected energy dependence or perhaps something a bit more subtle?
- Precise measurements of the oscillation parameters:
  - Delta m**2 to a few percent
  - What is the sign of Δm**2? This can only be determined via matter effects in long baseline experiments and only then if θ_{13} is big enough.
  - Sin**2 2θ_{23} to 1% or better
    - How close is this number to 1? Is it "fundamental"?
    - Important to remove ambiguity in θ_{13} measurement.
  - What is the value of θ_{13}? Is it "naturally" big like the other parameters or anomalously small. Is there some heirarchy here trying to teach us something about the fundamental physics involved?
- Is there CP violation in neutrino oscillations? How might this relate to CP violation that may be responsible for leptogenesis?
- What about the possibility of subtle CPT violation? Why shouldn't this be a perfectly good source of matter/anti-matter asymmetry? Could neutrino oscillations be a natural place to first observe such a violation? What quantitative limits might be of interest?
- Are there any light, sterile neutrinos and if so what are the oscillation parameters associated with them? If LSND is correct it increasingly appears that there must be at least one. Oscillation phenomenology will be very complex in this case.

Timescales and Protons

Experiment	Start	Protons/year	MW
MINOS	2005	2-5 x 10^{20}	0.2-0.5
Off Axis	2008-9	4-8 x 10^{20}	0.4-0.8
Off Axis/ new proton driver	2011-12	1-2 x 10^{21}	1-2

Other neutrino experiments?

Ongoing needs for pbar production, needs for slow extraction fixed target program. Needs for new physics programs…

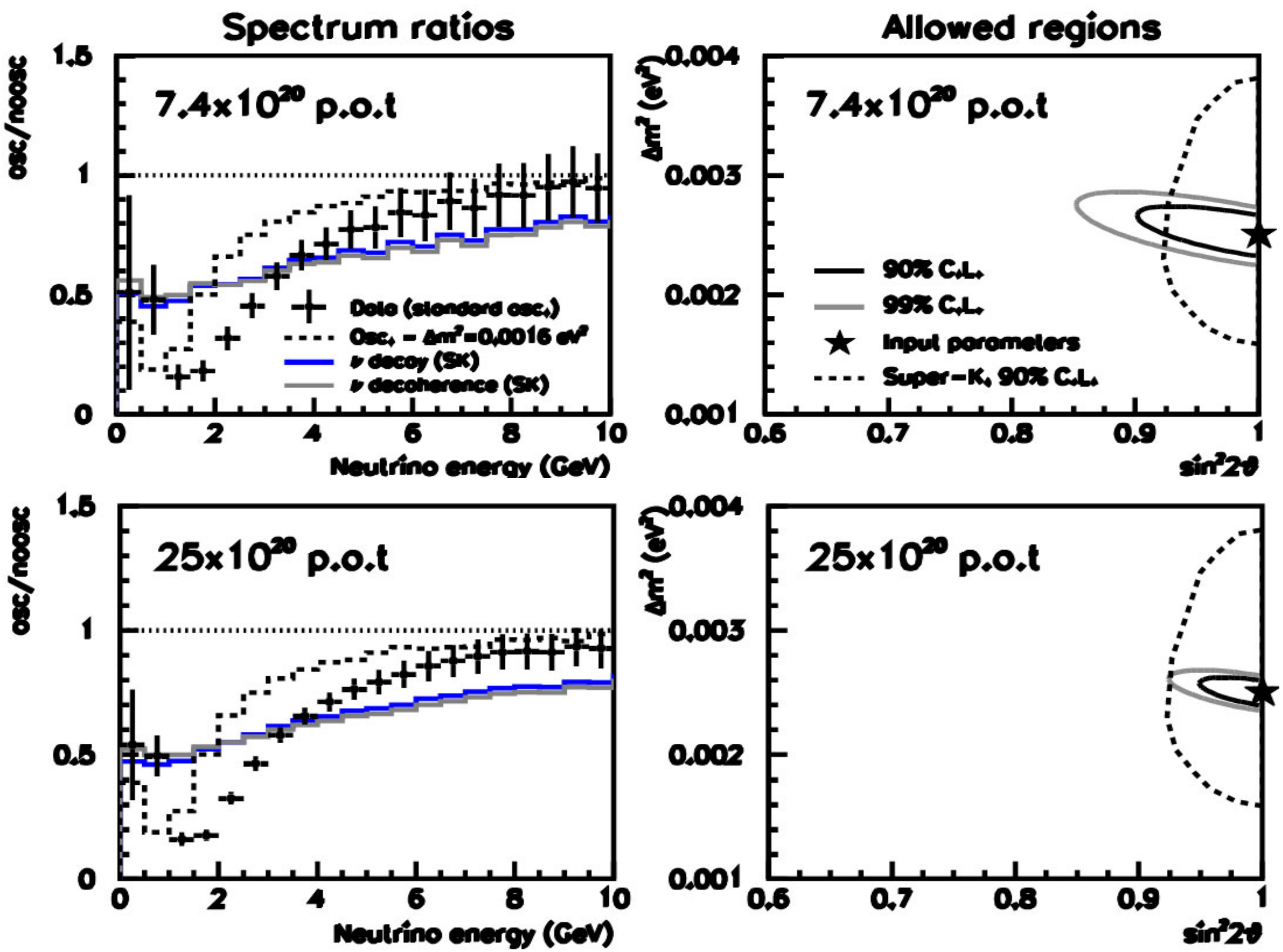
Each of these steps offers collaboration opportunities

A LINAC proton driver is the connection between neutrino physics and linear collider offering physics at the same time as developing the technology.

MINOS Running Plan

- Draft Fermilab Long-Range Plan:
  - NuMI beam commissioning starting in Dec. 2004.
  - 4 years of physics running for MINOS starting in April 2005.
  - Goal for protons on target in first year = 2.5×10^{20}
  - Plans are being developed for increased proton intensity.
- New MINOS Running Request (May 2003)
  - MINOS has submitted a request to Fermilab for 5 years of running with a total of 25×10^{20} protons on target in that time.
  - MINOS has provided updated physics sensitivity curves based on 7.4, 16 and 25 $\times 10^{20}$ total protons on target. (Original MINOS physics sensitivity was based on 7.4×10^{20} pot.)
  - There are several options for providing this number of protons.
- The performance of MINOS has always depended on the NuMI beamline being far more intense than any other.

Measurement of Oscillations in MINOS

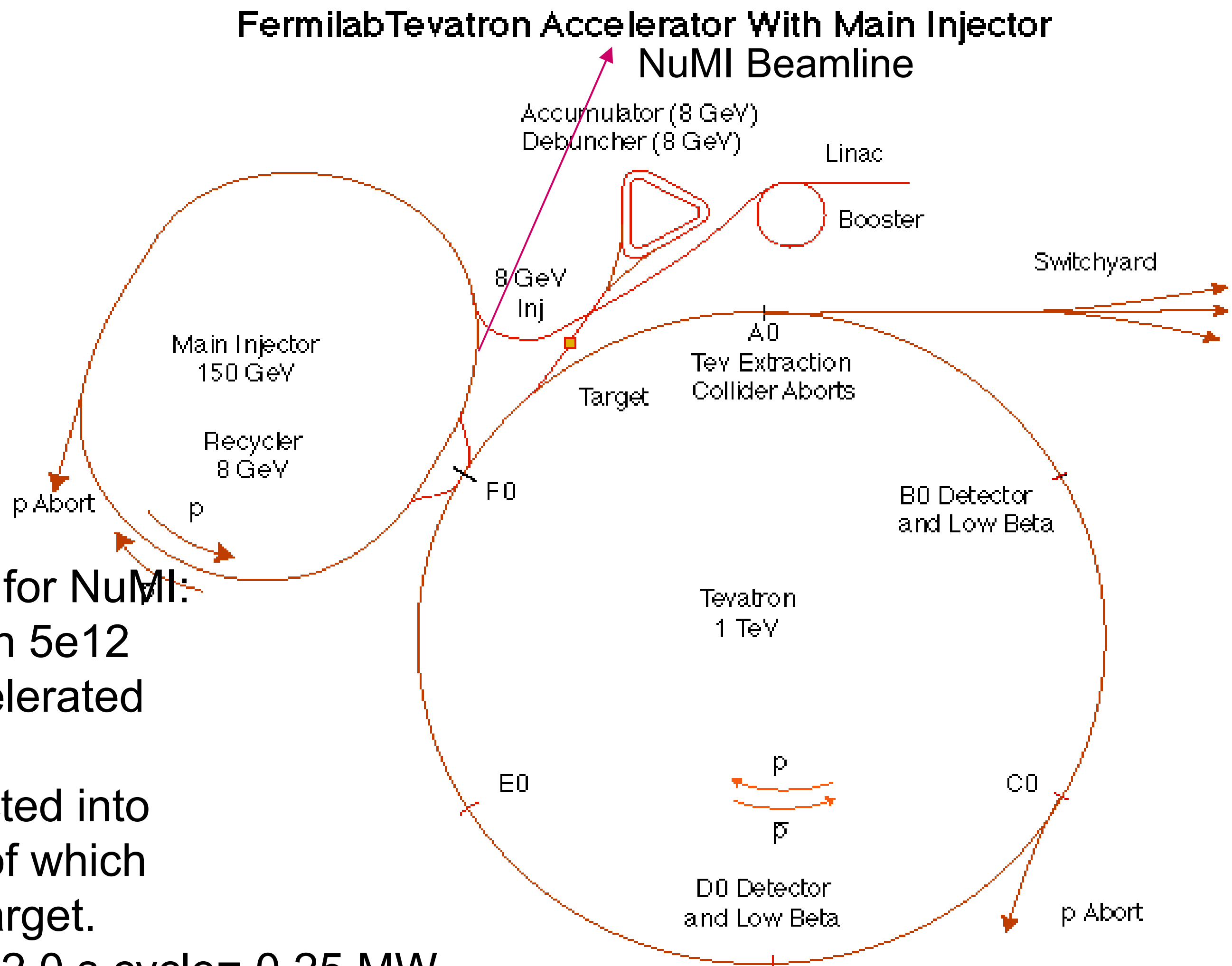


For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$

Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

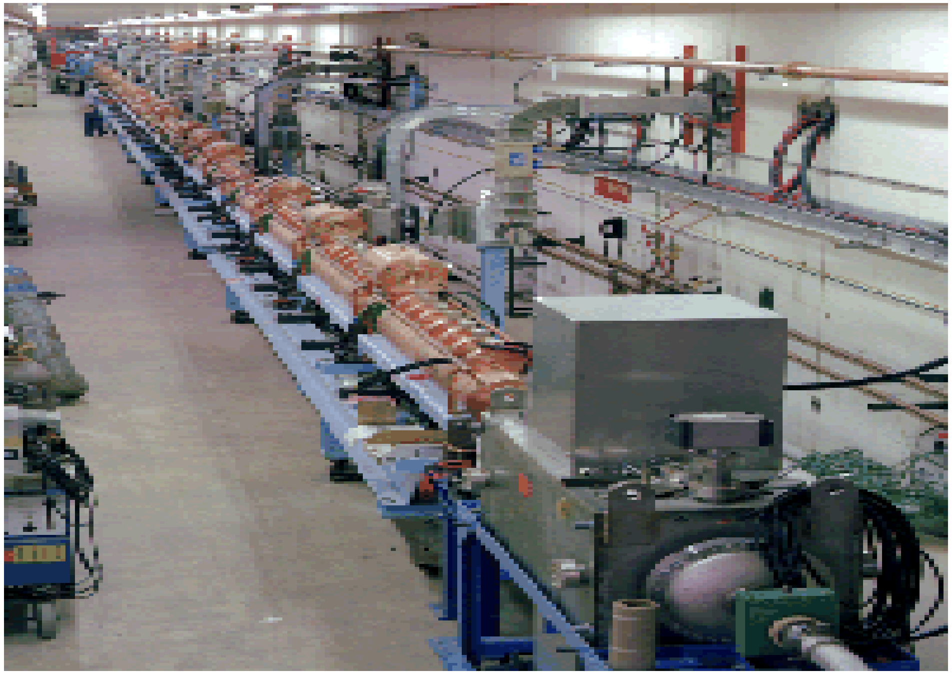
MINOS 90% and 99% CL allowed oscillation parameter space.

The Fermilab Accelerator Complex



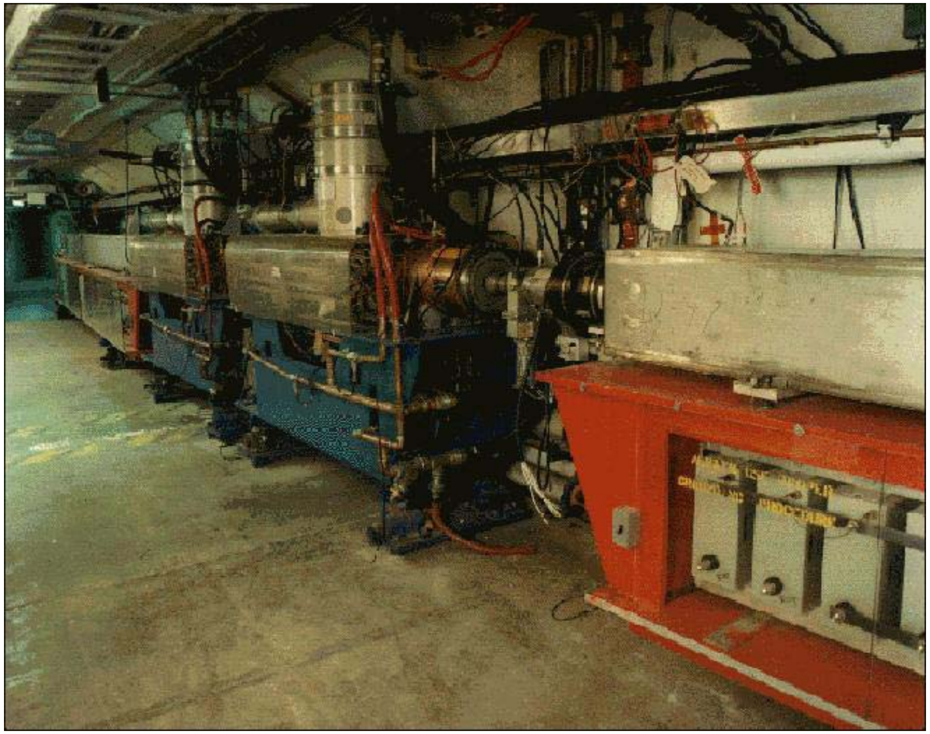
- Current nominal plan for NuMI:
  - Booster filled with 5e12 protons and accelerated to 8 GeV.
  - Six batches injected into Main Injector, 5 of which go to the NuMI target.
  - 2.5e13 protons / 2.0 s cycle= 0.25 MW
  - 2.3e20 protons/ year

The Proton LINAC



- Accelerates beam to 400 MeV for injection to the Booster.
- Typical operating ability ~45mA of which only a fraction is used.
- One can keep filling the Booster with more and more LINAC beam, the problem is keeping it in the Booster once it is there.
- Higher energy would help for the next stage but is relatively expensive.

The 8 GeV Booster



- 8 GeV Synchrotron with 15 Hz resonant magnet ramps. Slower possible. Faster not possible!
- Currently accelerates ~4-5e12 protons per cycle. Limited by proton losses (~7e12 injected)
  - One cycle every 2.3+ s for pbar production with 4.5-5e12 protons per cycle.
  - ~2-3 Hz cycles for Mini-BooNE but at lower proton intensity (~4e12) to stay within proton loss budget.
- For NuMI/MiniBooNE, the Booster must:
  - Increase typical acceleration cycle rate from ~2 Hz capability to ~7-12 Hz
  - Increase protons per cycle from typical 4.5e12 to 5-6e12. (Hopefully!)
  - Increase protons per year from ~3e19 (pre-Mini-BooNE) to ~1.5e21… radiation and activation issues.
  - Decrease longitudinal emittance from ~0.15 eVs to ~ 0.07-0.1 eVs for some types of MI stacking.

Problems of the Booster

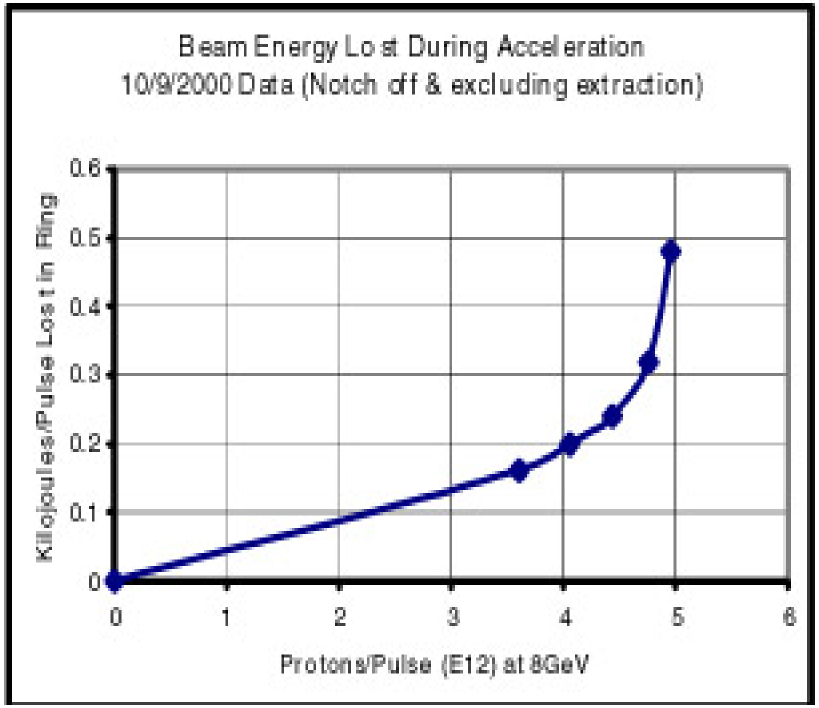
- Three fundamental problems:
  - Magnet aperture too small (vertical 1.6/2.2 in., horizontal goodfield region ~ 2.4 in.)
  - Linac too close to the ring
  - Tunnel not deep enough (13.5 ft.; and worse, buildings on top)
  - Cycle time is too slow

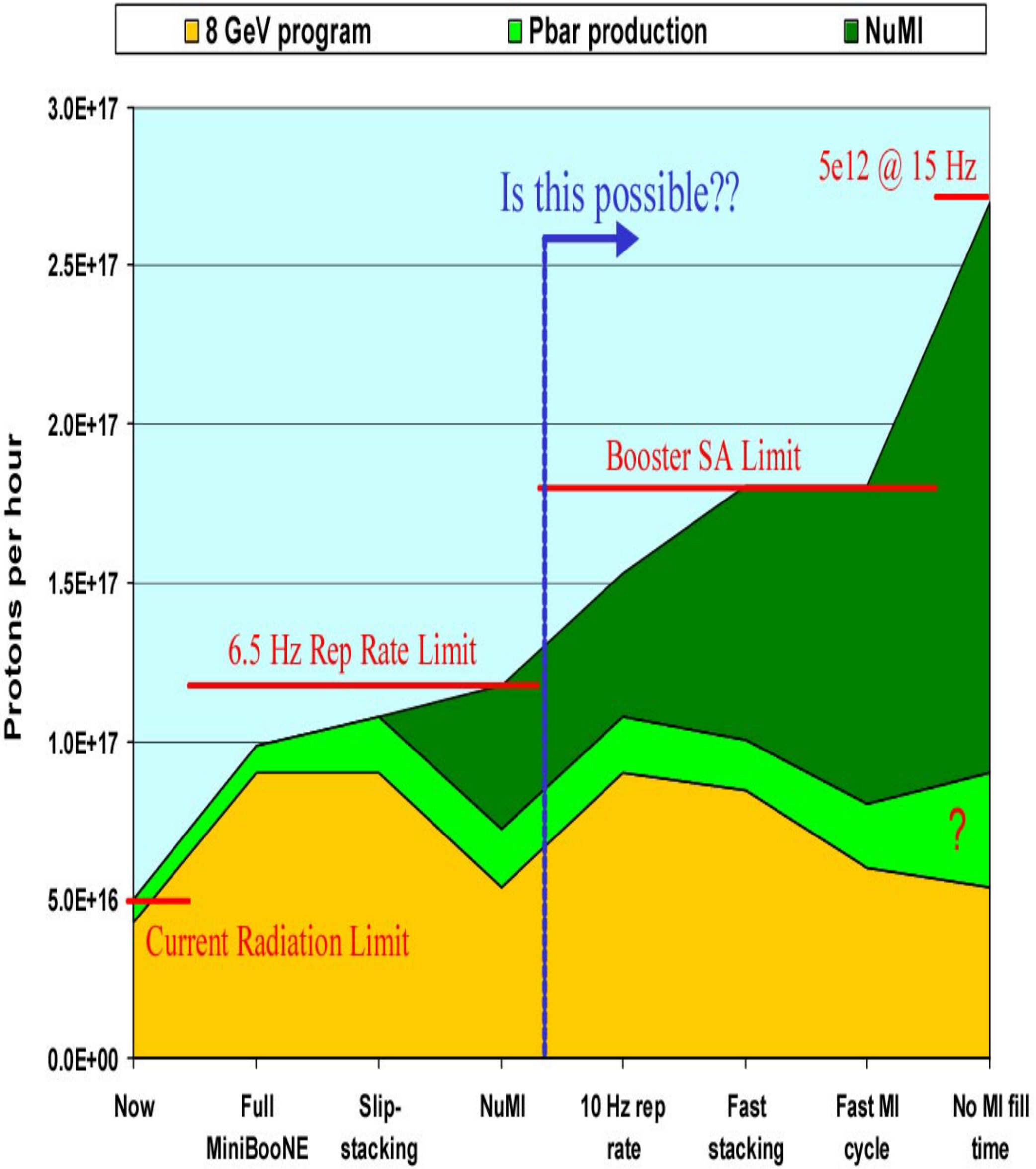
  Any change of these would mean a new machine.

- Other problems:
  - Transition crossing (γt= 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.
  Fixing everything starts to look like building a new machine.

Proton Losses in the Booster





- Proton losses in the Booster are non-linear.
- The Booster can't get too hot.
- The Booster period is 67 ms.
- The combination of these limits the protons it can deliver.

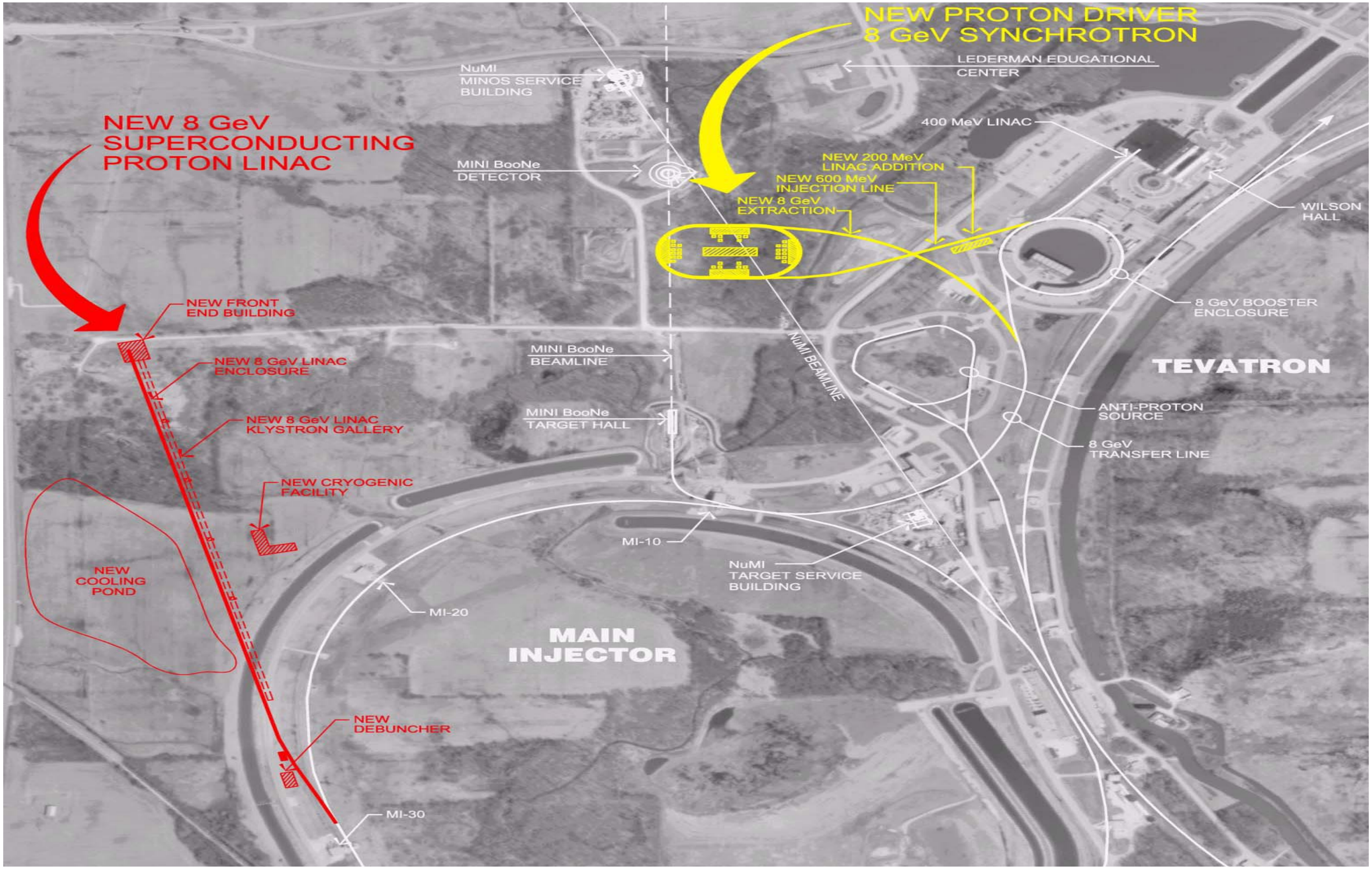
The Main Injector

- 150 GeV synchrotron run at 120 GeV (or lower) for NuMI.
- Circumference = 7x Booster: Room for 6 Booster batches. Five batches are available for other uses, NuMI being the primary user for the short-term. Slow extraction experiments (E907, test-beams, CKM…) will simply “take cycles”.
- Minimum cycle time at 120 GeV = 1.5 s. Cycle time for multi-batch NuMI operation = 1.9 s due to multiple Booster cycles for filling.
- Nominal design for 2.5e13 protons per cycle. With only small modifications can probably handle up to 5-6e13. The main issue is how to get them there.
- To go higher than ~6e13 protons per cycle, or faster than 1.5 s MI cycle time with >2.5e13 protons, additional RF power will be needed as well as additional systems to maintain stability.

Existing Complex Improvements

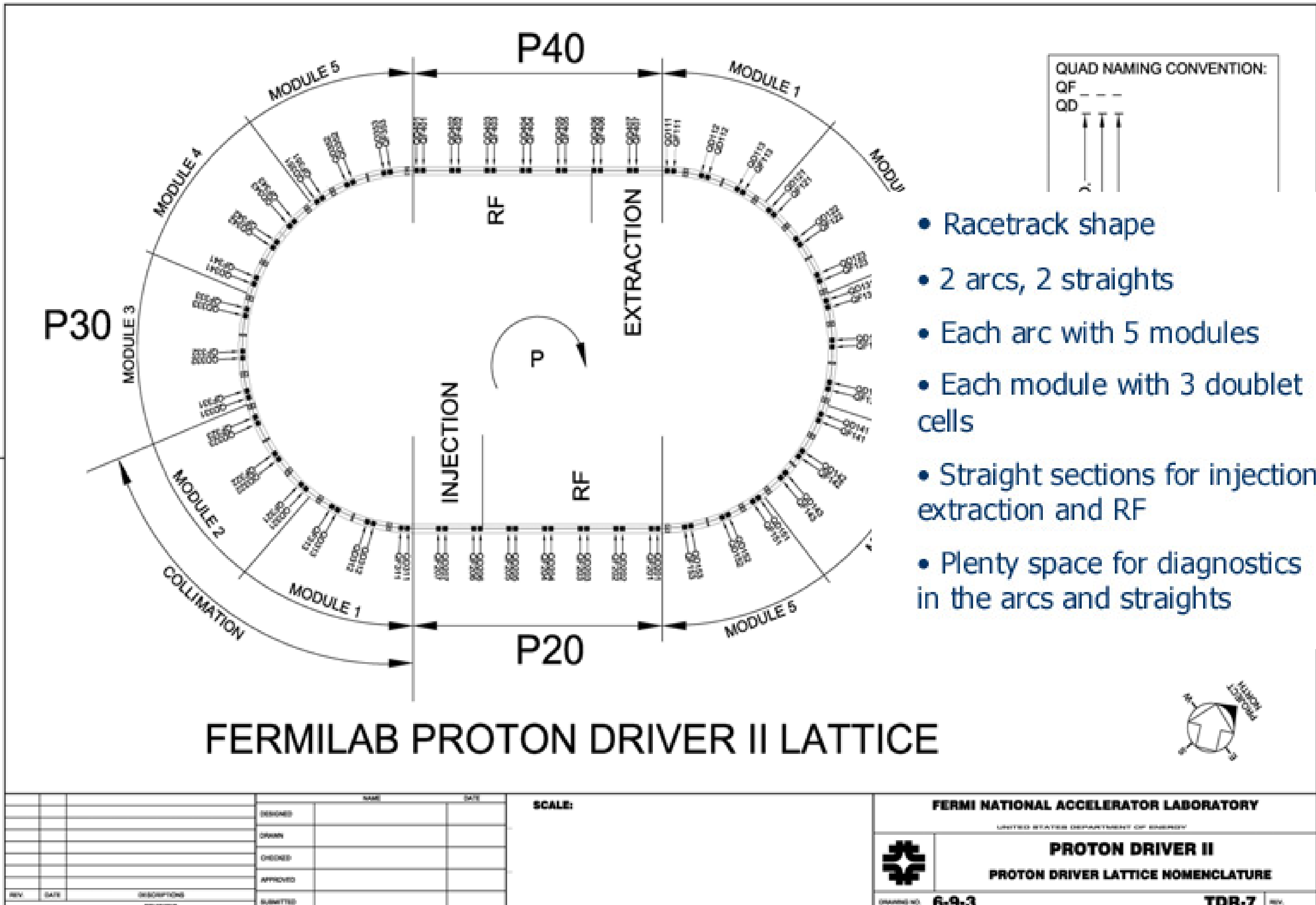
- Improve Booster per-cycle intensity
  - Reduce proton losses through machine tuning
  - Reduce impact of proton losses through collimation and selected hardware upgrades
  - Maximum 50% intensity increases possible without “rebuilding” machine.
- Increase protons per MI cycle by stacking of Booster batches
  - Slip stacking, Barrier stacking, etc.
  - Effectiveness limited to <50% increase in MI proton power by Booster cycle time. Unless…
- Hide Booster cycle time from MI cycle time
  - Use the recycler as a proton stacker
  - Requires second stage pbar cooling to go elsewhere
  - Improvements depend on other issues, such as pbar cycle time, MI cycle time and stacking
- Decrease MI cycle time
  - A “clean” factor of 2 is possible by increasing magnet and RF power and RF voltage by a factor of 2.
  - The improvements here will essentially all be very useful once a new proton driver is available.
- Something like a factor of 4 is possible… But can the Booster handle it????

A New Proton Driver (8 GeV)



Also includes upgrades to Main Injector for current and cycle

8 GeV Synchrotron Option



- 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

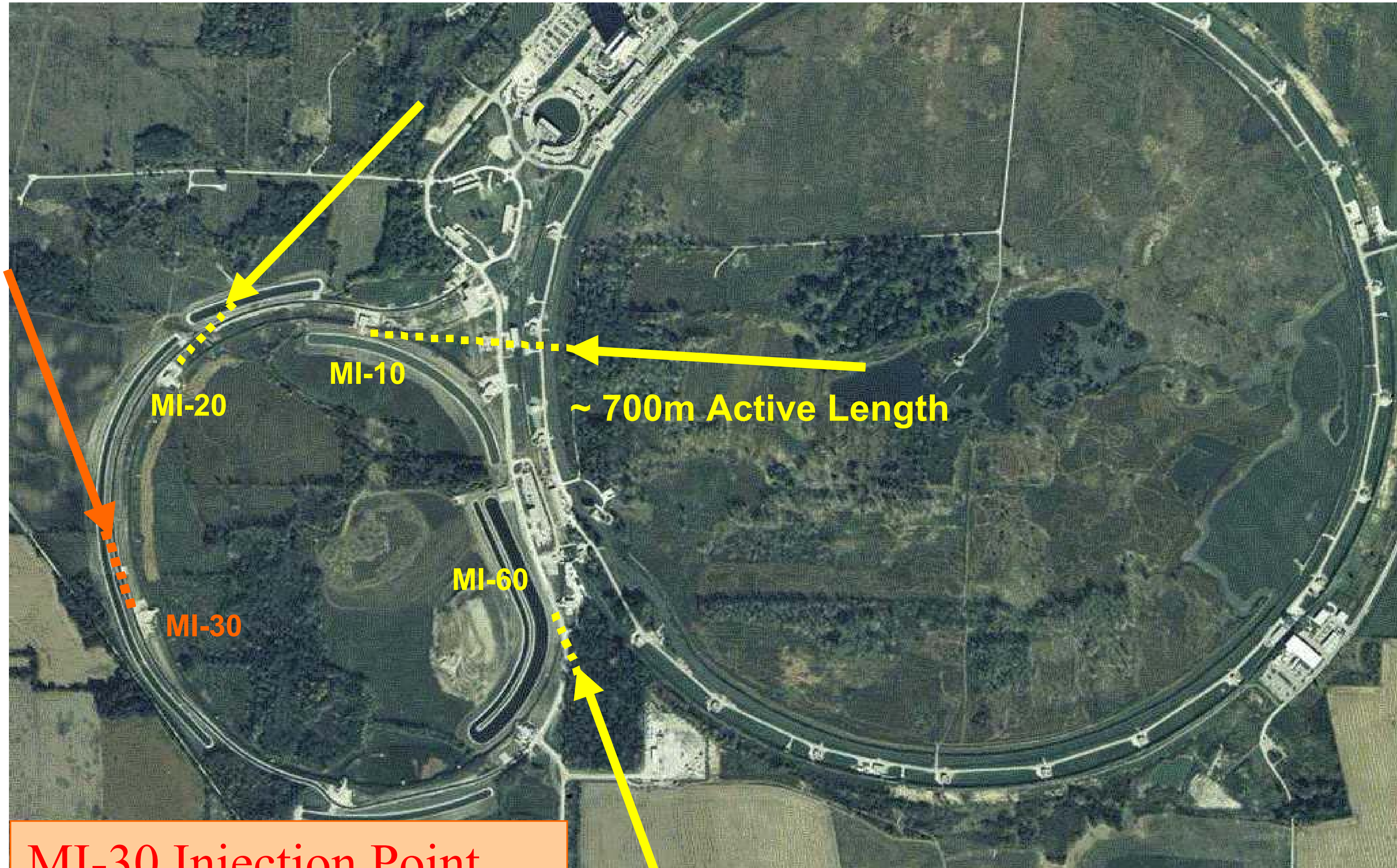
8 GeV Synchrotron Scope

- 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-source and 400 MeV linac
- New 600 MeV and 8 GeV transport lines
- New enclosures
- 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.
- 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).

Cost of 8 GeV Synchrotron

1	Technical Systems			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	Civil Construction			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	
	Total Direct Cost			136,138
	EDIA (15%)			20,421
	Lab Project Overhead (13%)			20,353
	Contingency (30%)			53,073
	Total Estimated Cost (TEC) ($k)			229,985
	(in FY02 dollars)			

8 GeV Superconducting Linac



MI-30 Injection Point
Chosen for Design Study

Several locations possible

8 GeV Superconducting Linac

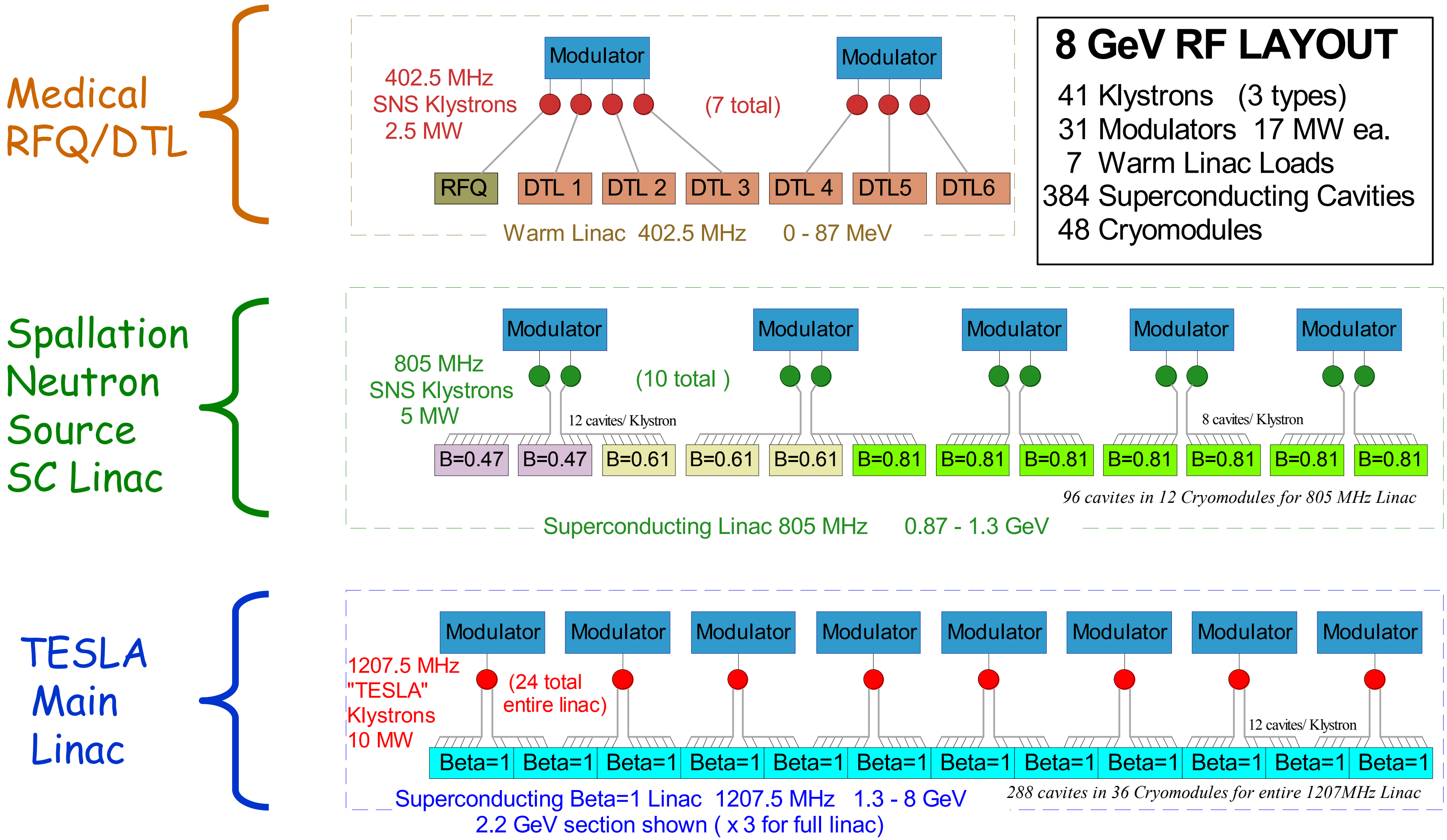
- New idea (Bill Foster) incorporating concepts from both SNS and TESLA.
  - Copy SNS Linac design up to 1.3 GeV
  - Use "TESLA" Cryomodules from 1.3 - 8 GeV
  - H^- Injection at 8 GeV in Main Injector

==> "Super-Beams" in Fermilab Main Injector:

- 2 MW Beam power at BOTH 8 GeV and 120 GeV
- Small emittances ==> Small losses in Main Injector
- Minimum (1.5 sec) cycle time (1.0 s possible?)
- MI Beam Power Independent of Beam Energy

==> *(flexible neutrino program)*

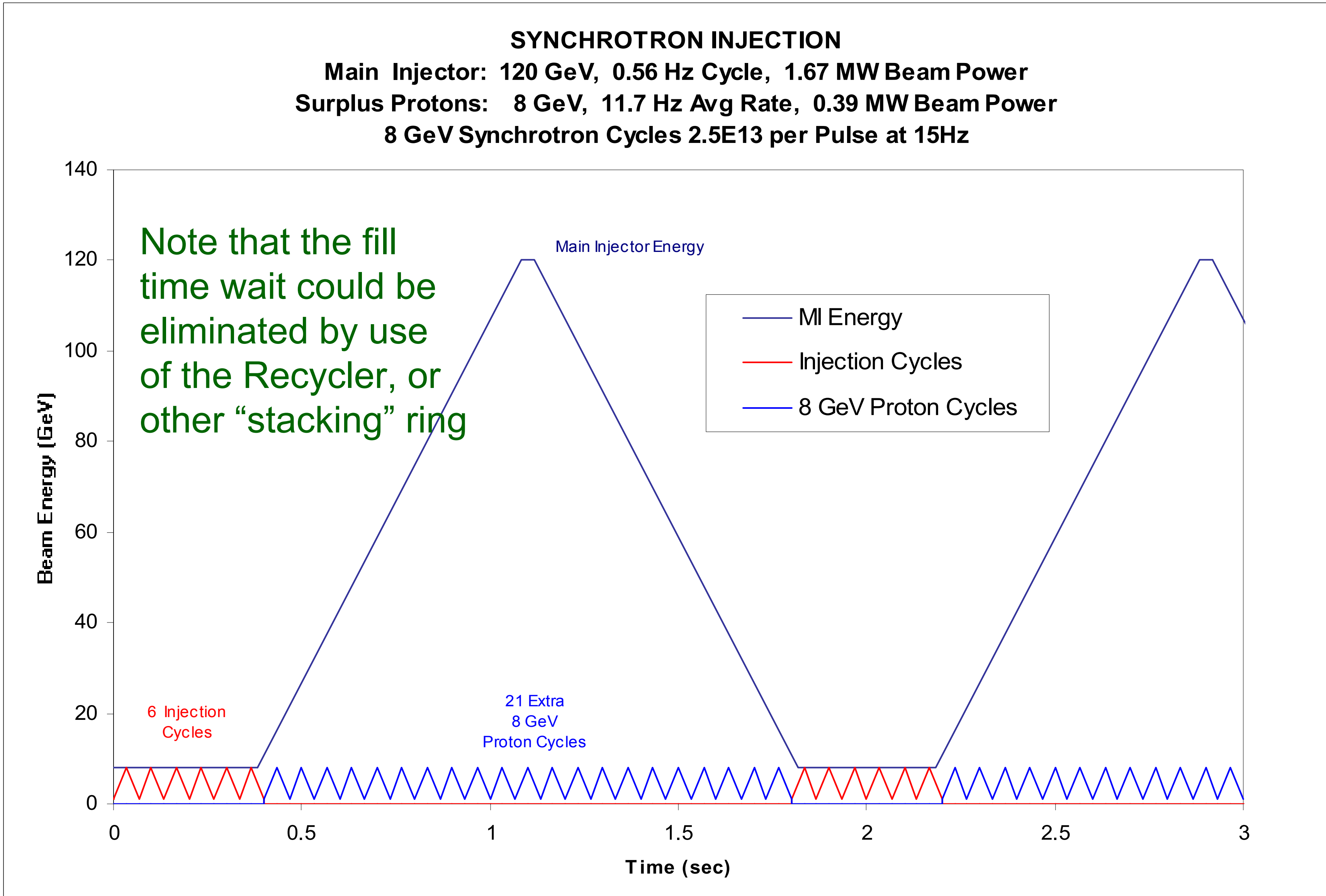
8 GeV Superconducting Linac Conceptual Layout



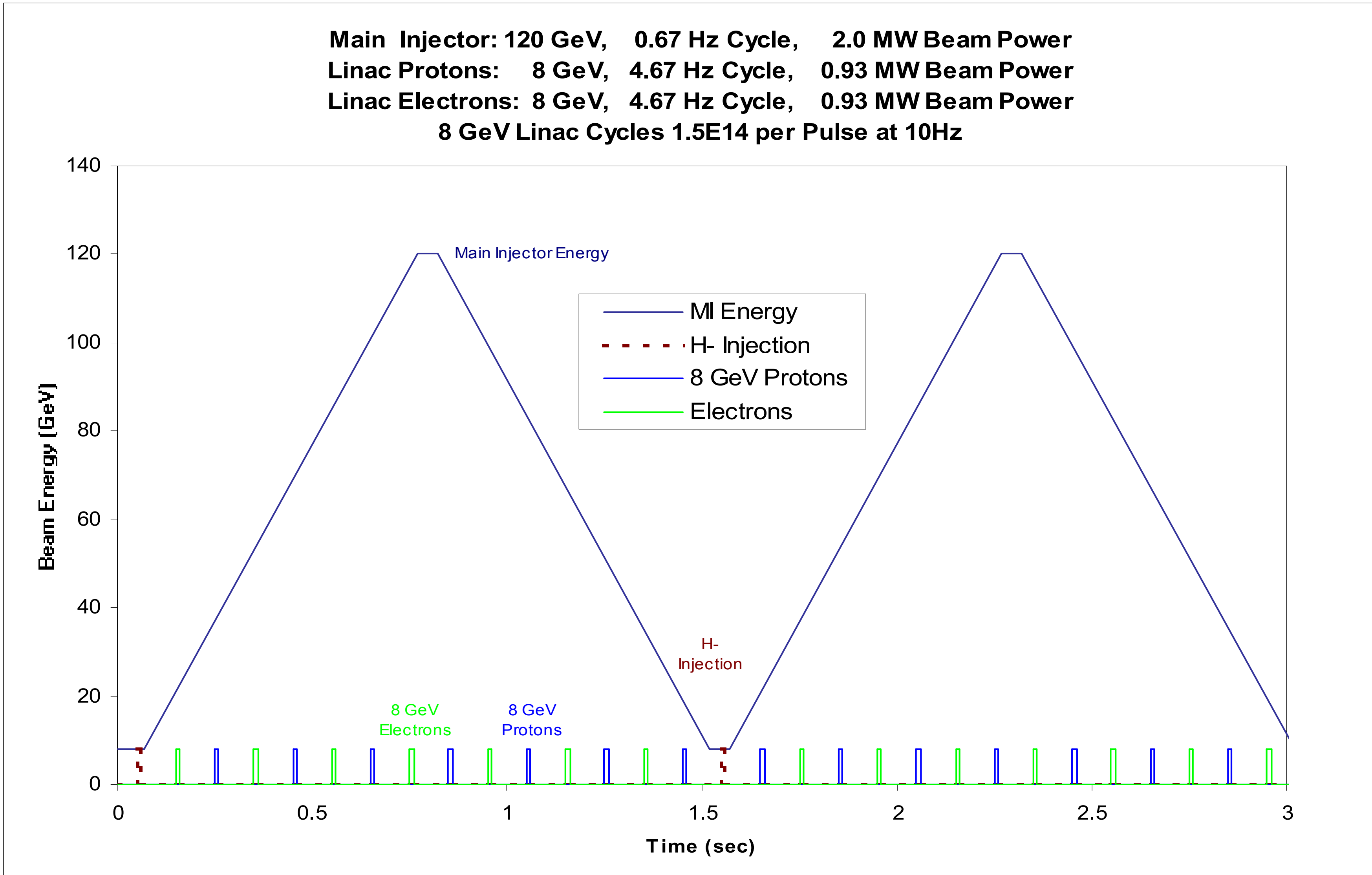
Injector Linac Parameters

- Beam Energy = **<u>8 GeV</u>**
  - Same as existing Booster
  - Anywhere from 5~15 GeV would be OK
- Beam Pulse: **<u>25mA x 1msec</u>**
  - Same as SNS (==> Beam Physics Studied)
  - Fills Main Injector at 5x Design Intensity (2 MW)
- Rep Rate: **<u>10 Hz</u>**   (MI now uses only 0.6 Hz)
  - Same as TESLA (==> Multi-Beam Klystrons)
  - 2 MW stand-alone beam power for other uses

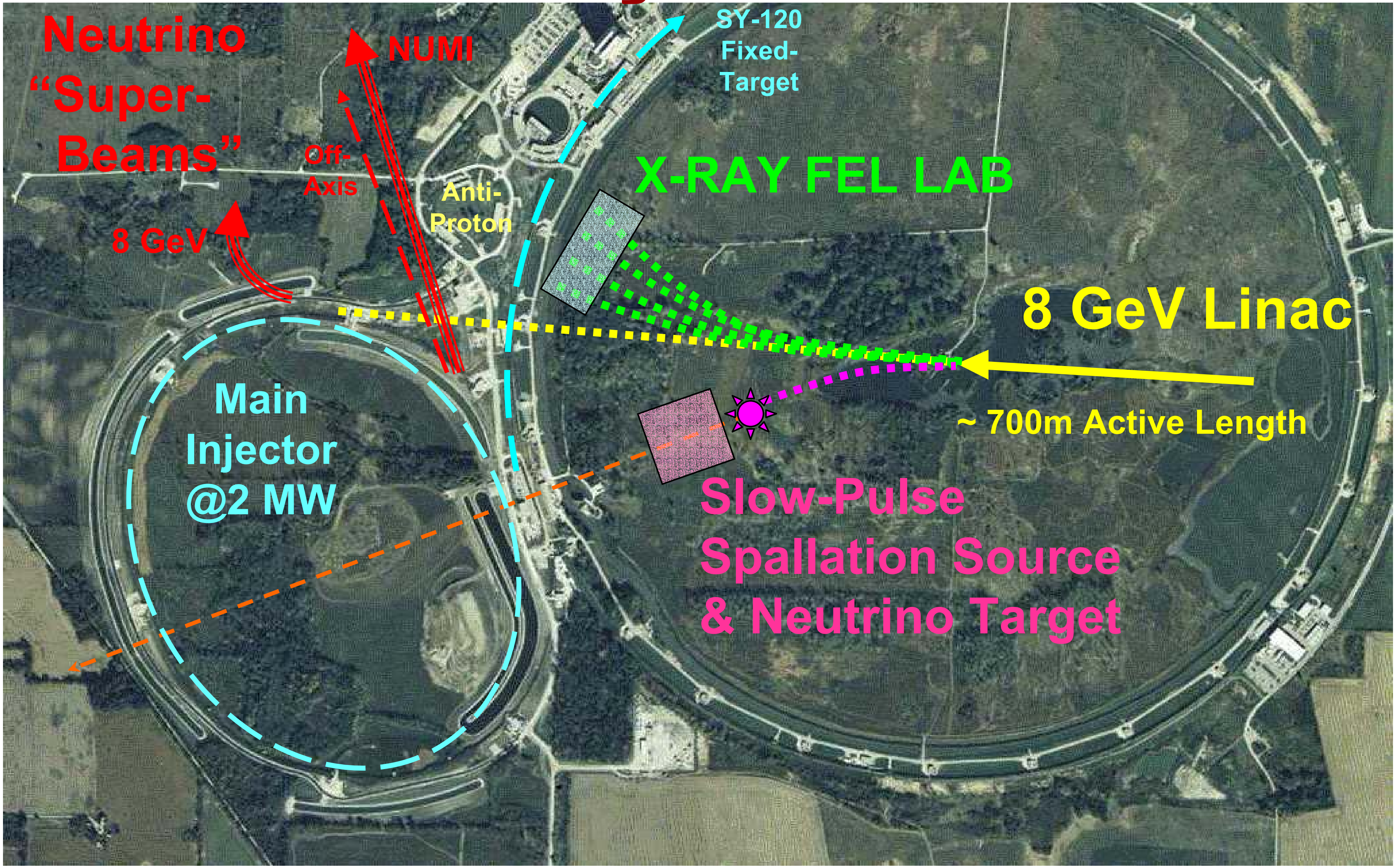
120 GeV Main Injector Cycle with 8 GeV Synchrotron



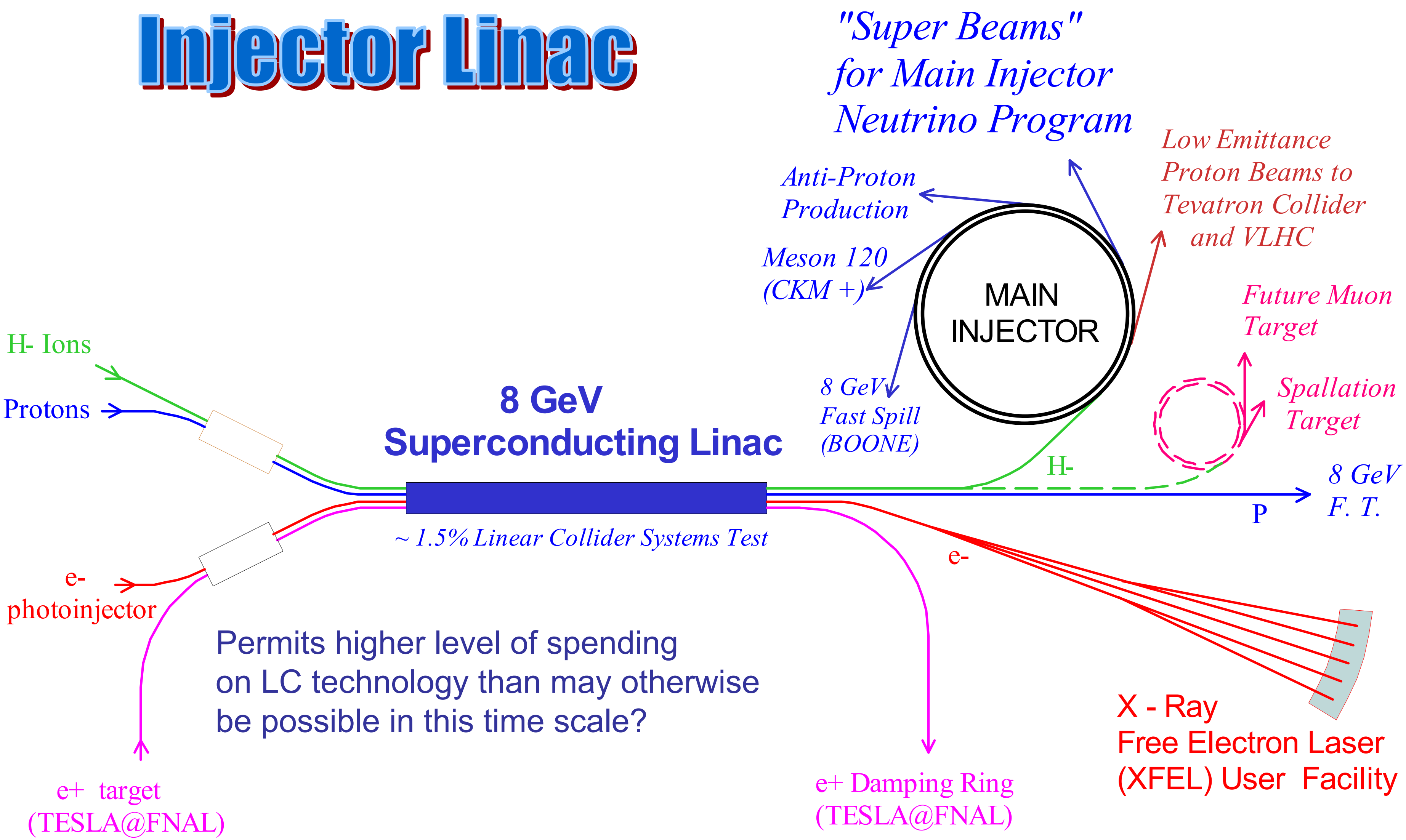
120 GeV Main Injector Cycle with 8 GeV Linac, e-



8 GeV Superconducting Linac With X-Ray FEL and 8 GeV

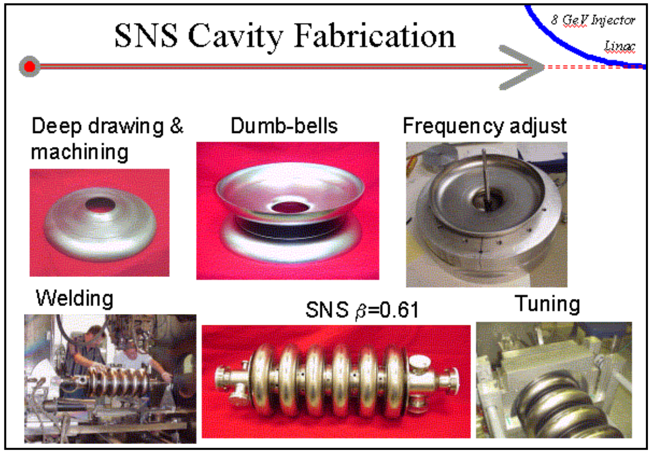


Multi-Mission 8 GeV Injector Linac



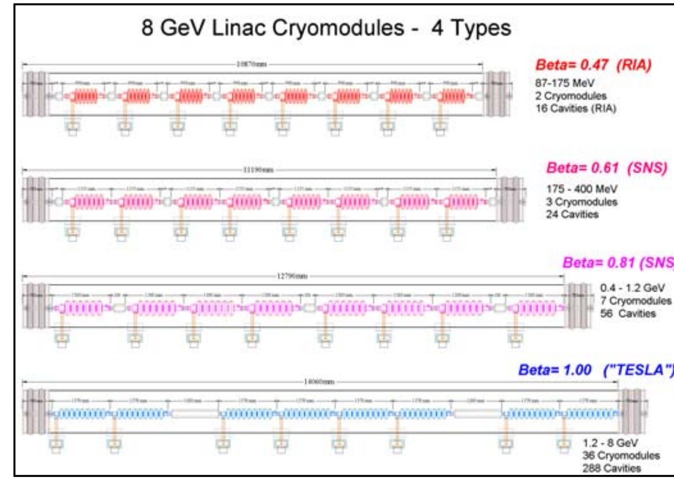
Permits higher level of spending on LC technology than may otherwise be possible in this time scale?

TECHNICAL SUBSYSTEM DESIGNS EXIST AND WORK

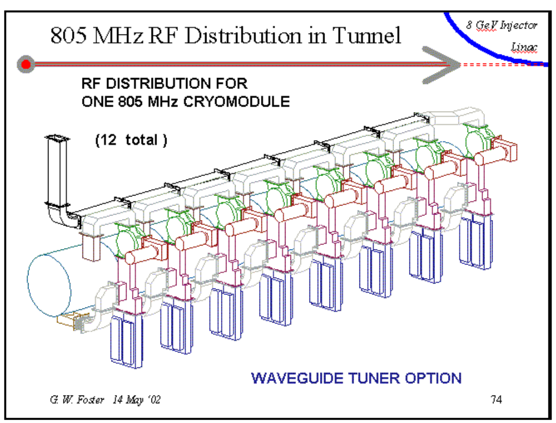


SNS Cavites

FNAL/TTF Modulators

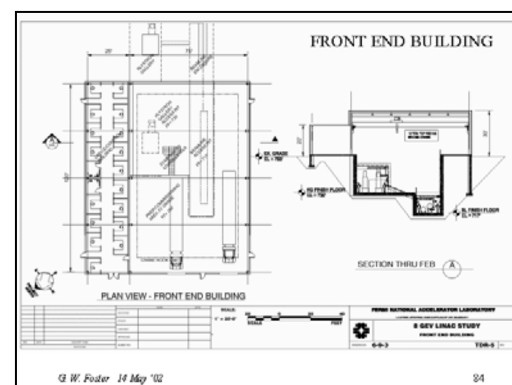


"TTF Style" Cryomodules



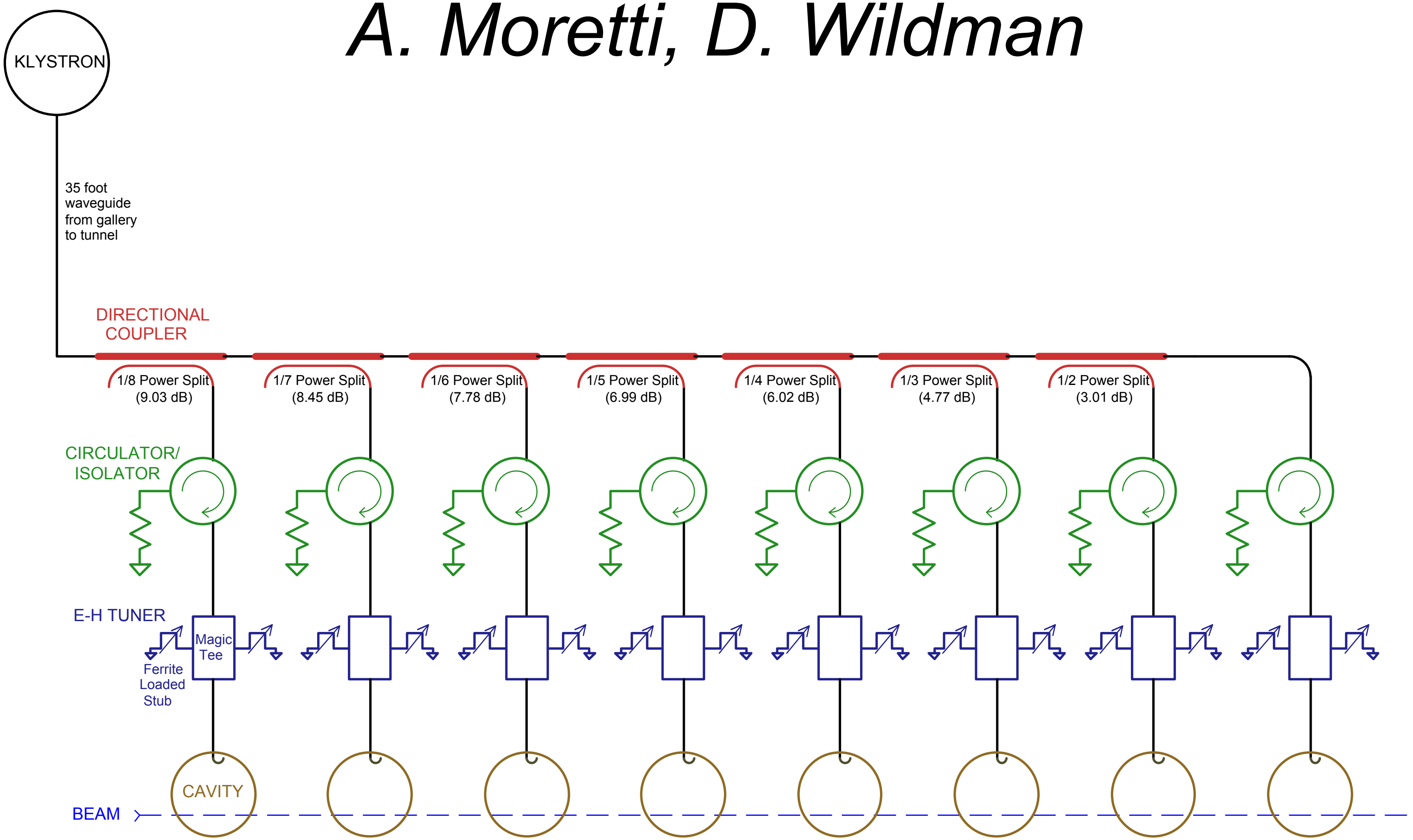
RF Distribution

Civil Const. Based on FMI



RF Fan-out for 8 GeV Linac

A. Moretti, D. Wildman

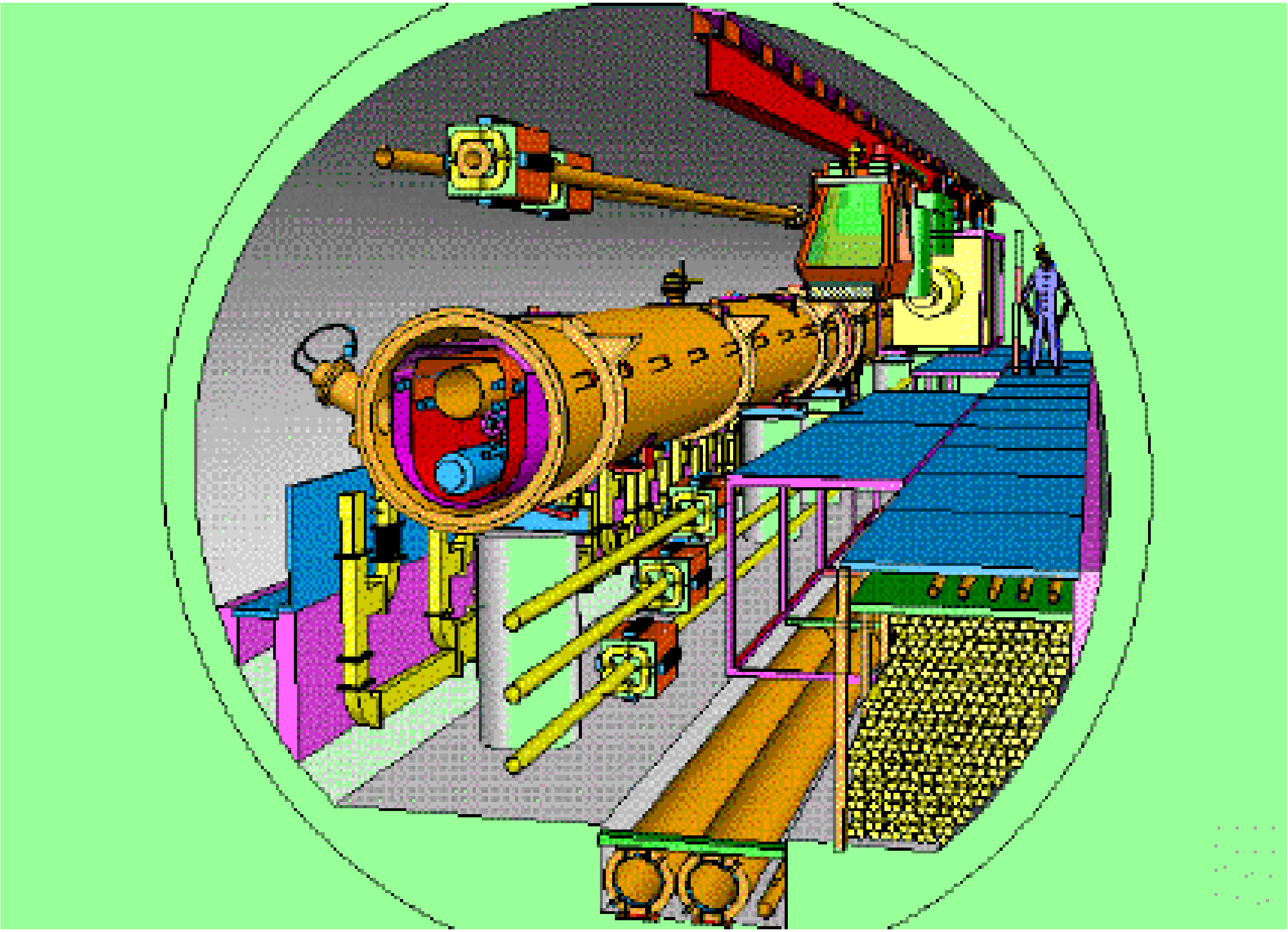


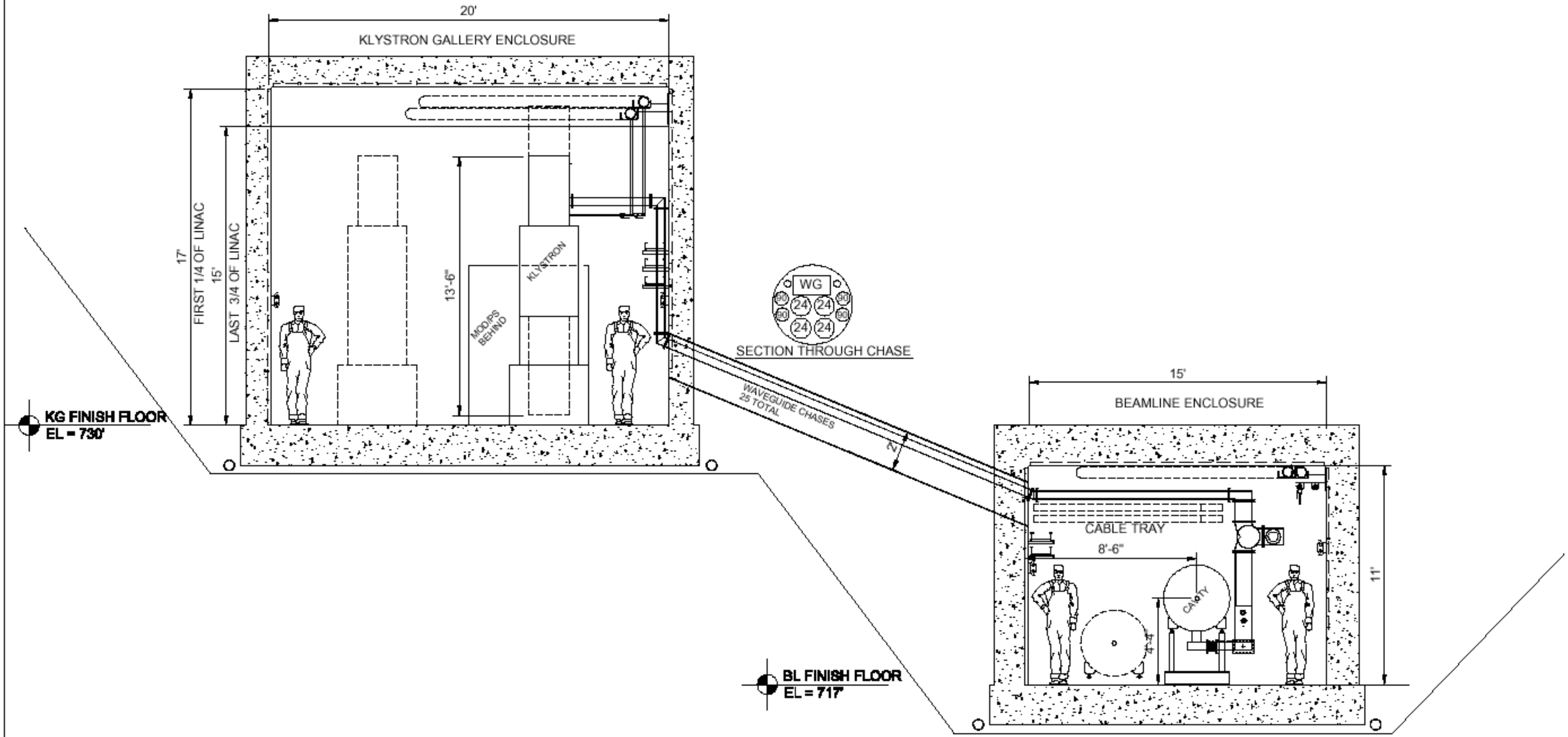
Fast Ferrite Phase Shifter R&D

- Provides fast, flexible drive to individual cavities of a proton linac, when one is using a TESLA-style RF fanout. *(1 klystron feeds 36 cavities)*
- Also needed if Linac alternates between e and P.
- This R&D was started by SNS but dropped due to lack of time. They went to one-klystron-per-cavity which cost them a lot of money (~$20M / GeV).

Making this technology work is key to the financial feasibility of the 8 GeV Linac.

TESLA Tunnel & Klystrons





TYPICAL SECTION THROUGH LINAC

SHOWING 805 MHz KLYSTRON AND CAVITY

REV.	DATE	DESCRIPTIONS
		REVISIONS

	NAME	DATE
DESIGNED		
DRAWN		
CHECKED		
APPROVED		
SUBMITTED		

SCALE: 1" = 5'-0"

5 0 5 10
SCALE FEET

FERMI NATIONAL ACCELERATOR LABORATORY

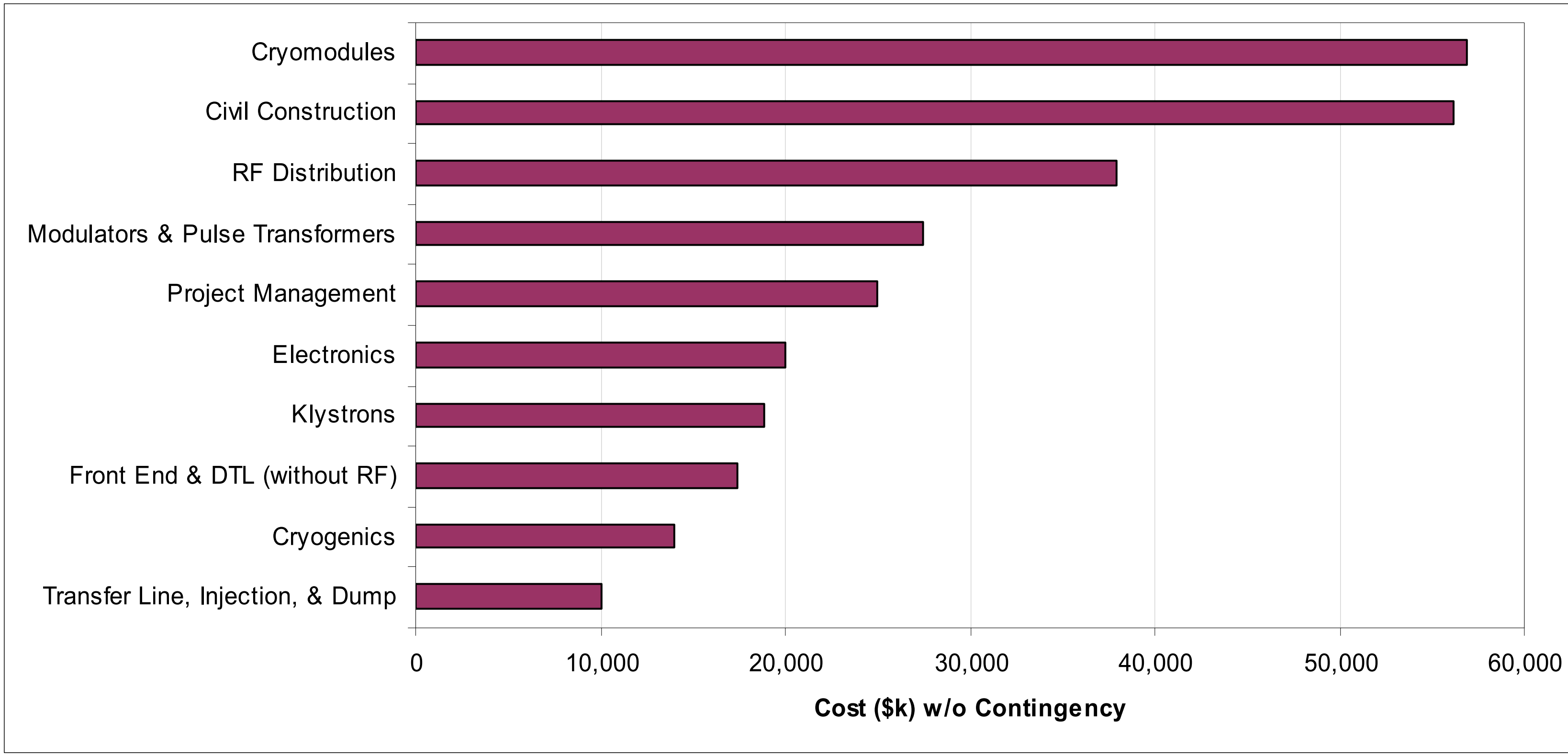
UNITED STATES DEPARTMENT OF ENERGY

8 GEV LINAC STUDY

CROSS SECTIONS

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

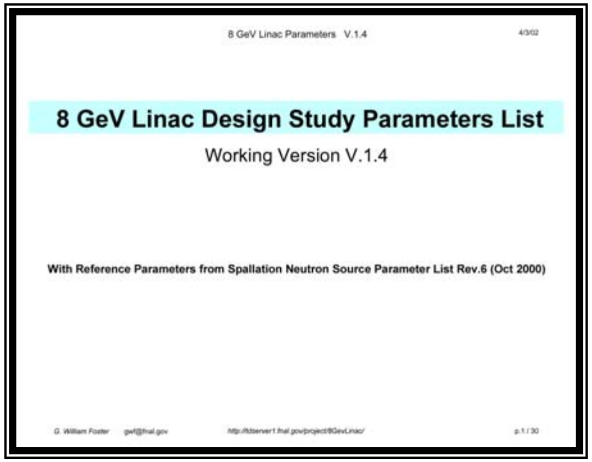
8 GeV LINAC Cost Estimate



$ 284 M + 30% Tax = $ 369 M

Above is Foster's number. I'd personally include more "tax".

More Design Details


8 GeV Linac Parameters V.1.4 4/3/02

8 GeV Linac Design Study Parameters List

Working Version V.1.4

With Reference Parameters from Spallation Neutron Source Parameter List Rev.6 (Oct 2000)

G. William Foster gwf@fnal.gov http://tdserver1.fnal.gov/project/8GevLinac/ p.1 / 30

- Longer technical talk
- 30 Page Parameter List (v1.8)
- Cost Estimate Spread Sheet w/ BoE

http://tdserver1.fnal.gov/project/8GeVlinac

- Short Paper (Linac 2002) :

http://tdserver1.fnal.gov/project/8GeVlinac/Linac_2002

Fermilab Long Range Planning Committee

- Commissioned by Director in January, 2003.
- The point (not exactly the charge):
  - Define a physics program for Fermilab in the next decade and in the context of development and perhaps implementation of a Linear Collider.
- Recommendations and a report are being completed now. A relatively broad consensus appears to be developing.
- The proto-recommendations I show here are only from a part of the committee and not yet “fully considered”. I show them because I expect they will survive the process in approximately this form.

Proto-Recommendation 1

The physics of neutrino oscillations is compelling. The Fermilab Main Injector, NUMI beam line, and the MINOS detector are unique Fermilab assets that can be brought to bear on these questions but new long baseline neutrino experiments are needed to understand the underlying physics. These experiments require an intense proton source. Such a source would also support a broad range of other physics programs. The intensity requirements of these experiments are beyond those achievable with feasible upgrades to Fermilab's aging Linac and Booster complex.

> **We recommend that Fermilab adopt as its next accelerator construction project the creation of a 1-2 MW proton source (aka Proton Driver). We envision this project to be a coordinated combination of upgrades to existing machines and new construction. We believe this recommendation to be valid in any plausible linear collider scenario.**

Proto-Recommendation 2

A new proton synchrotron or superconducting linac fed by a new copper linac and combined with changes to the Main Injector can provide the required proton source. There are many technical overlaps between the development and construction of a superconducting linac based Proton Driver and a cold technology Linear Collider. The use of SCRF in a Proton Driver also opens up a variety of other possible SCRF applications and technical collaborations at Fermilab.

We recommend that Fermilab adopt a superconducting 8 GeV linear accelerator as the preferred option to replace the existing Linac-Booster system.

Proto-Recommendation 3

Providing a new proton source in a timely fashion requires an urgent commitment of resources. We believe that commitment of the necessary resources at this time can be consistent with existing laboratory commitments to Run II and to other projects.

We recommend that Fermilab create a group charged to submit to DOE documentation sufficient to achieve a statement of mission need (CD-0). The group will elaborate the physics case, produce a Technical Design Report, prepare project management documentation including cost and schedule estimates, and prepare a plan for the required R&D.

Conclusions

- Increasing the proton intensity is a central interest for the Fermilab neutrino experiments.
- Increasing proton intensity is starting to look like a (the?) central part of the Fermilab effort in the next decade.
- There are many opportunities, both short and long term to collaborate on these activities.
- Contributions on proton intensity can be considered as collaborative effort on short and long term Fermilab neutrino experiments. We invite specific discussions in this direction.
- The specific plan of a super-conducting LINAC offers an opportunity for physics output while building towards the Linear Collider technology.