Proton Driver Project Development Plans

G. W. Foster

Fermilab DoE Annual Program Review

Outline

- **Proton Driver Charge**
- **Issues for Synchrotron & Linac**
- **Work plan & Time Line, Planned organization**
- **Technology Options and Critical-Path Decisions**
- **Discussion of staging & cost-reduction options**
- **Collaboration Possibilities – Labs, Industry, (…LC?)**

Proton Driver Charge Letter

To: Bill Foster and Steve Geer

From: Michael Witherell

Subject: Next Steps on the Proton Driver

I would like you to assemble and lead a team to achieve the goals recommended by the Fermilab Long Range Planning Committee relative to the Proton Driver, with an emphasis on the superconducting linac as suggested by that committee. For the purpose of this assignment I will define the Proton Driver project as a complete replacement of our current 400 MeV linac and 8 GeV Booster, accompanied by Main Injector upgrades, sufficient to enable the delivery of at least 0.5 MW of average beam power at 8 GeV, and 2.0 MW of beam power at 120 GeV. I am hopeful that the assignment described above can be completed by the end of 2004.

In particular I would like you to initiate and coordinate efforts in the following areas:

- Preparation of documentation sufficient to establish mission need for the Proton Driver as defined by the Department of Energy CD-0 process.
- Development and documentation of the physics case. I would like this to include both support for a forefront neutrino program at Fermilab in the decade of 2010 and beyond, and identification of other opportunities that could potentially be enabled with a Proton Driver facility.
- Completion of comparably scoped cost estimates for the linac and synchrotron options based, to the extent practical, on a common basis of estimate and on common implementation strategies.
  - The cost estimates should specifically include modifications to the Main Injector required to meet the established 2 MW @ 120 GeV criterion.
  - The cost estimates should assume a complete replacement of the existing linac.
  - The implementation strategy should be based upon minimal disruption to the ongoing collider (Run II and BTev) and neutrino programs.
  - The goal is to understand the cost differential between the linac and synchrotron and what benefits are realized for the (presumably) higher cost.
- Documentation and external review of accelerator physics and technology issues for both options, specifically including anticipated beam loss and beam handling issues for both machines. The goal is to put the accelerator physics basis of the superconducting linac at the same level as the (more traditional) synchrotron-based solution.
- Examination and documentation of the siting issues associated with both machines, for both the baseline mission of providing Neutrino Super-Beams and for future development of facilities on the Fermilab site.
- Development and elucidation of an overall strategy for implementing a Proton Driver that is in concert with the shorter term plan of the existing Proton Source and Main Injector improvements being developed under the leadership of Eric Prebys.
- As with any such responsibility you may be asked from time to time to report on Proton Driver progress to various review committees, help with the lab's long range financial planning for such a project, and help inform the Fermilab User Community about the exciting physics prospects of such a facility.

In organizing and undertaking this assignment I would like to collaborate closely with interested parties in all our divisions and sections. I would further ask you to involve institutions outside of Fermilab who might have potential interests in either collaboration on development, construction, and operations of the Proton Driver itself or in the scientific research programs enabled by the facility. I would suggest that a workshop or workshops exploring the accelerator physics and technologies, along with the scientific opportunities would be an important component in proceeding in this direction. The lab will be happy to support you in the arrangements of such workshop(s)

It is my intention that once this information is available the Fermilab directorate will carry out a review that will compare the two prospective Proton Driver technologies with the goal of identifying the option that is best for Fermilab. This will allow the laboratory to proceed expeditiously with a complete Conceptual Design Report for the selected option, along with cost estimates, resource loaded schedules and other required CD-1 documentation, following the establishment of mission need via a formal CD-0 from the Department of Energy.

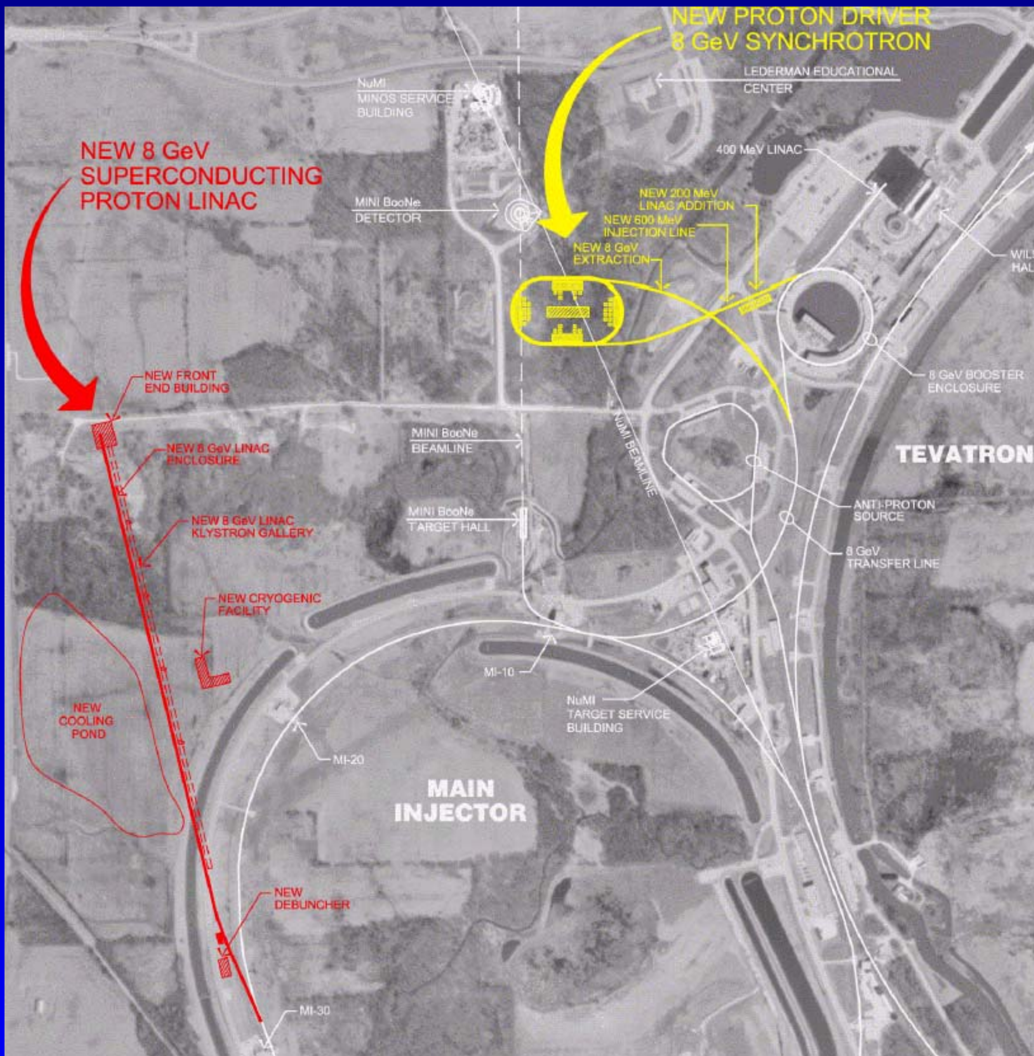
Action to implement the vision for the future outlined by the Fermilab Long Range Planning Committee is important to securing a healthy and productive future for both Fermilab and for the U.S. The steps described here are an important component of identifying how to best structure Fermilab's future program in areas that address many of the most important questions in science over the coming decade. Steve Holmes will serve as the Directorate point of contact on this activity, and both Steve and I look forward to working closely with you, and the participating divisions, sections, and outside institutions on this. Thank you.

Cc
Div/section heads
Associate Directors
W. Chou
S. Mishra
E. Prebys
J. Jackson

Proton Driver Charge

- Physics (S. Geer) and Machine (GW Foster)
- Goal: CD-0 Documentation by End of Calendar '04
- Both Synchrotron and SCRF Linac (emphasized)
- Common Performance Specs and Cost Basis
- External Review of Accelerator Physics
- Investigation of Outside Collaboration

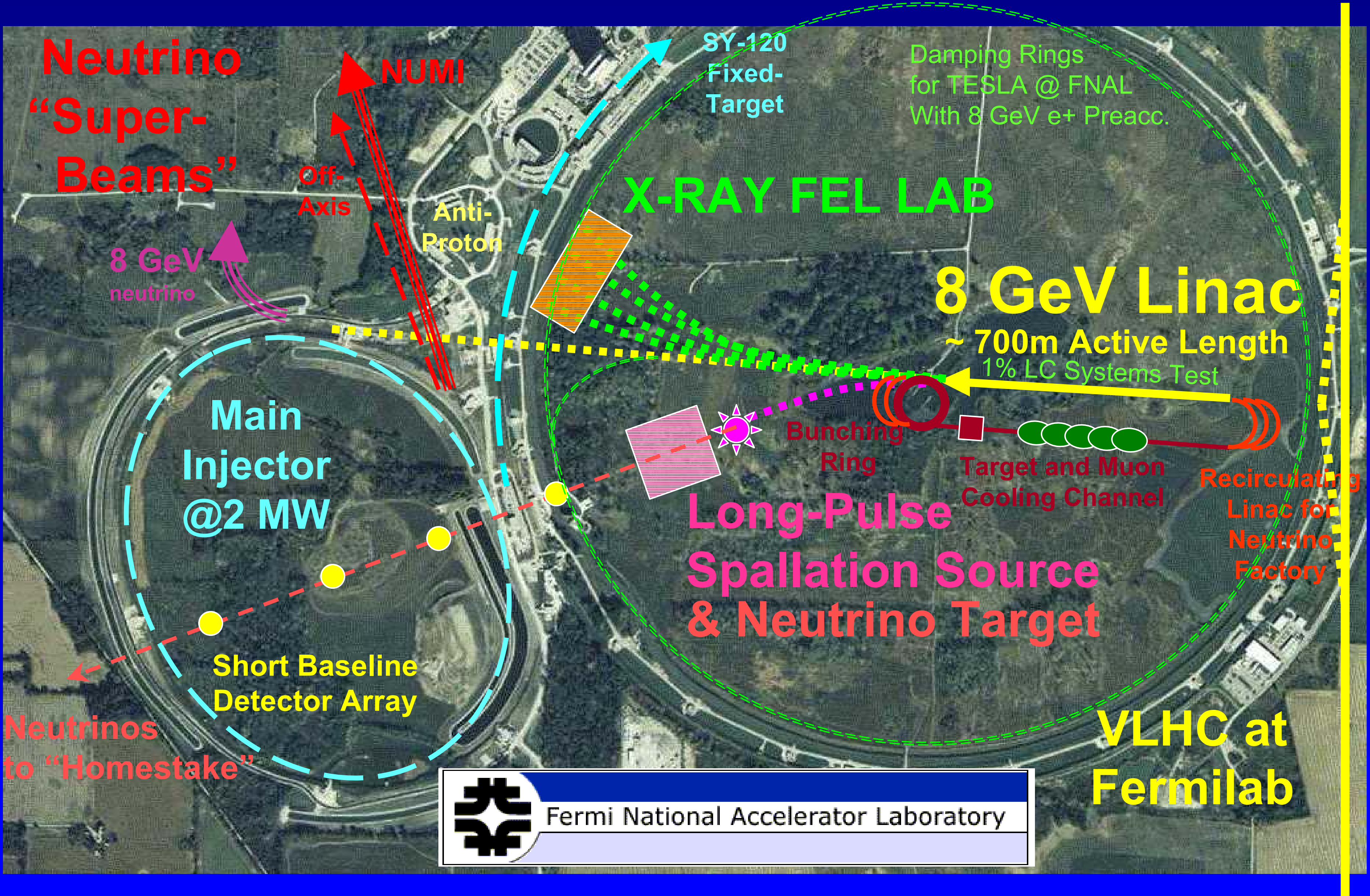
8 GeV Synchrotron & Linac



- SYNCHROTRON
  - Sited West of the existing booster
  - Re-uses existing linac enclosure
- 8 GeV LINAC
  - Baseline Site injects at MI-30 straight section

8 GeV Superconducting Linac

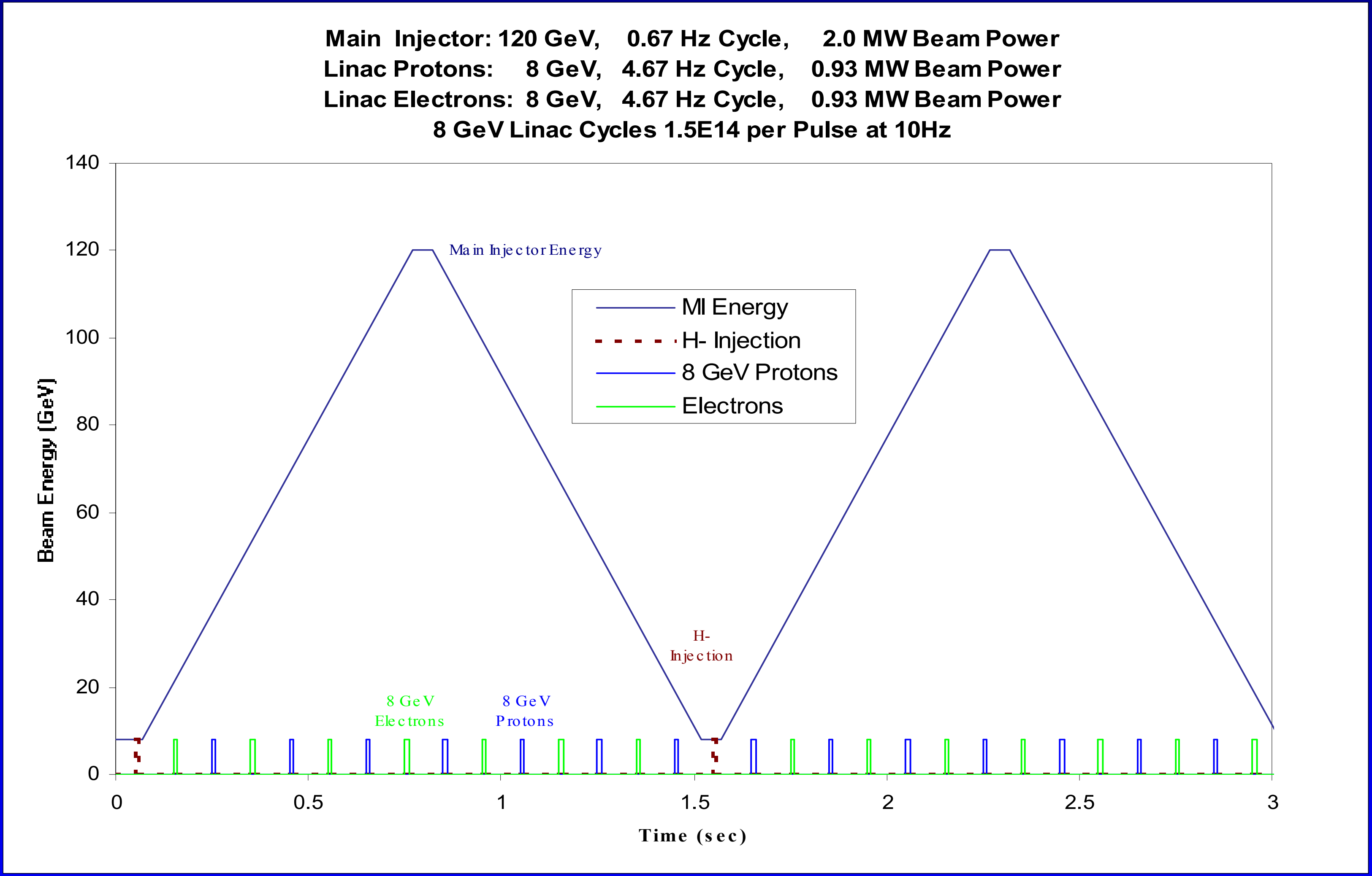
With X-Ray FEL, 8 GeV Spallation & Neutrino Sources and Neutrino Factory



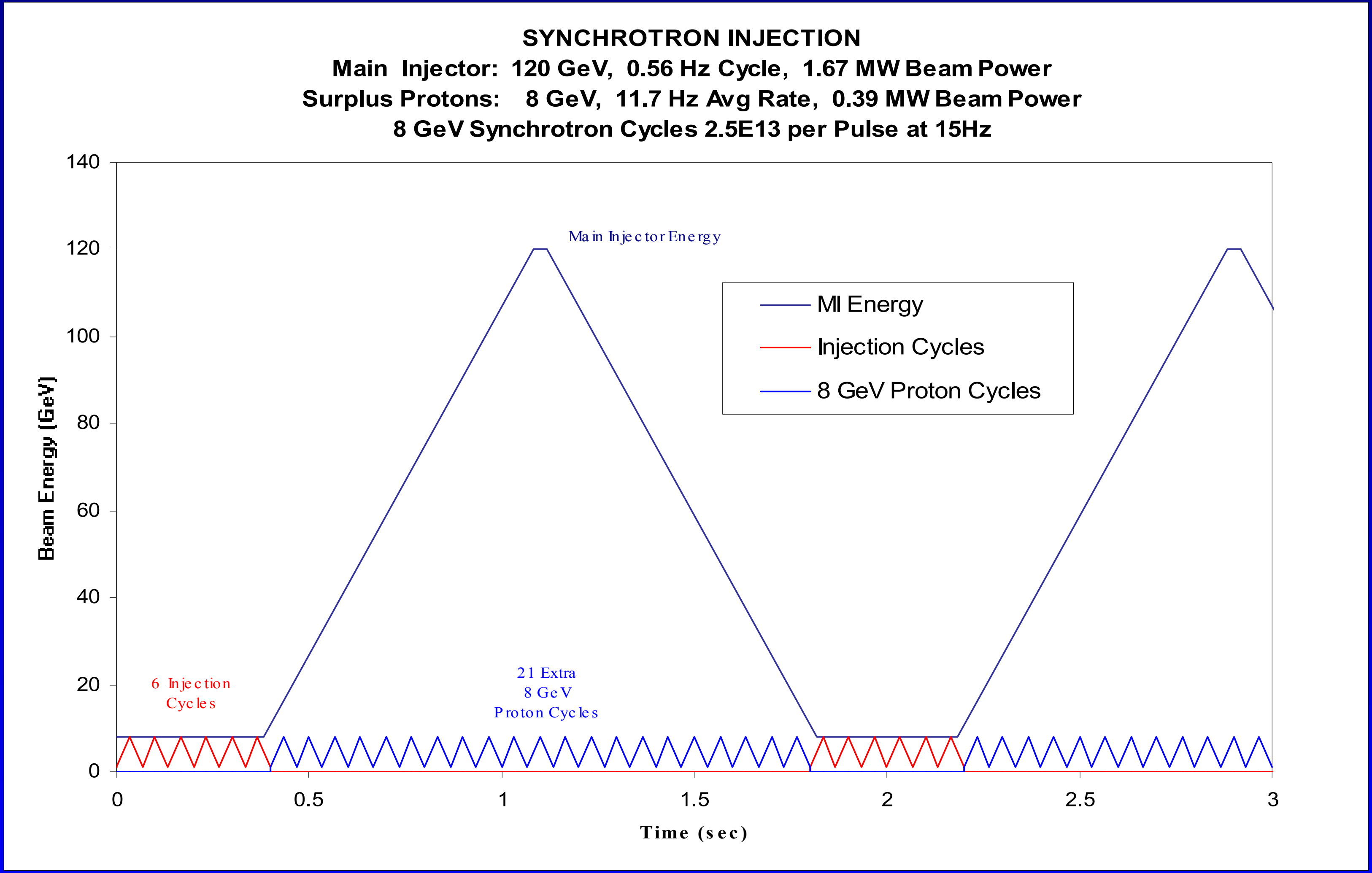
Common Physics Performance Specifications

- 2 MW Beam Power in Main Injector
  - Need 1.5E14 Protons / cycle in MI
  - Synchrotron option needs increased ramp rate
- 0.5 MW Stand-Alone 8 GeV Beam Power
  - Reduction of Linac power from 2 MW
- *Investigation Only* of Follow-on Missions
  - (remove $ for e-, mu … from Linac baseline)

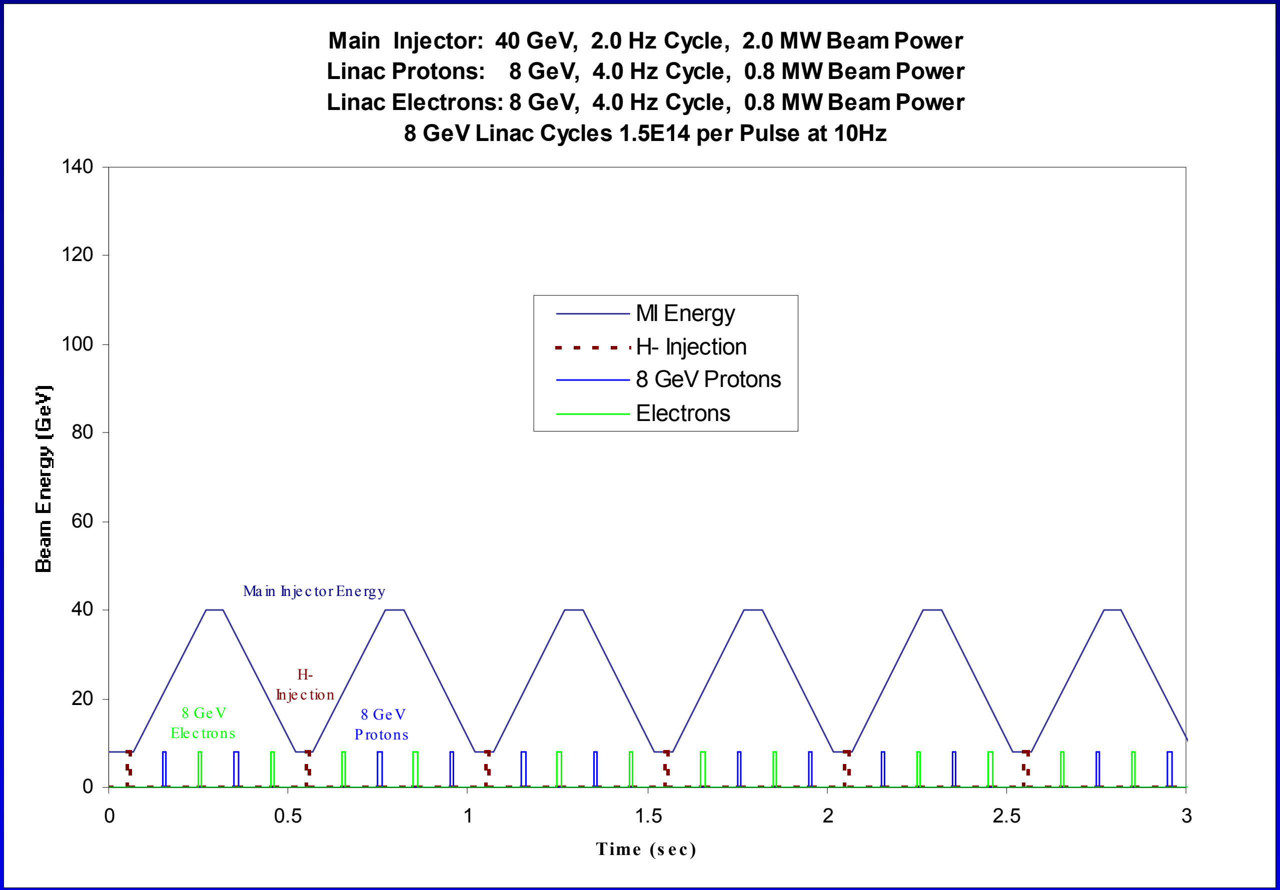
120 GeV Main Injector Cycle with 8 GeV Linac, e- and P



120 GeV Main Injector Cycle with 8 GeV Synchrotron



Linac Allows Reduced MI Beam *Energy* without Compromising Beam *Power*



- # neutrino evts. ~ same vs. E
- Reduces tail at higher neutrino energies.
- *Permits Flexible Neutrino Program*

MI cycles to 40 GeV at 2Hz, Retains 2 MW MI beam power

2MW @40 GeV

NOT SPECIFIED

FOR SYNCHROTRON

Baseline Design

- Only bare H- Linac or Synchrotron

  0.5 MW Stand-Alone Power *(& 2 MW upgrade path)*

- Main Injector Intensity Upgrades for 2MW
- Reference Experimental Program -TBD

Main Injector Intensity Upgrade

- RF: Major upgrade. Need a second power amplifier for each cavity (and 4 more cavities for synchrotoron option).
- Power supply: moderate upgrade (for synchrotron option)
- Magnet: OK.
- Shielding & Beam Dump: OK.
- Cooling capacity: OK for magnet, needs to be doubled for RF.
- Gamma-t jump system: New.
- Large aperture quad: New. *(In Progress for Run II / NUMI)*
- Collimation system: New. *(In Progress for Run II / NUMI?)*
- Passive damper and active feedback: (New..?)
- Stop band correction: New.
- NuMI and other 120 GeV Beamlines: Under study.

http://www-bd.fnal.gov/pdriver/

Synchrotron Design Studies

Synchrotron Parameters	**PD1**	**PD2**
Ring circumference (m)	711.3	474.2
Linac energy (MeV)	400	600
Synchrotron peak energy (GeV)	16	8
Protons per cycle	3 E13	2.5 E13
Protons per bunch	2.4 E11	3 E11
Repetition rate (Hz)	15	15
RF frequency (MHz)	53	53
Normalized transverse emittance (mm-mrad)	60	40
Beam power (MW)	1.2	0.5

Proton Driver II Synchrotron

Parameter Table

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)	15π	40π
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (μA)	12	60
Beam power (MW)	0.1(*)	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 near future it will run at 7.5 Hz for the MiniBooNE experiment

Physics Program Interruptions

- Synchrotron design to assume complete replacement of existing copper front end
  - Not the case for Design Study
- Synchrotron's Re-use of Civil Construction for Front End will require careful schedule consideration

Superconducting Linac
Parameter Table

Project Info:
tdserver1.fnal.gov/project/8gevlinac

8 GeV LINAC			
Energy	GeV	8	
Particle Type	H- Ions, ~~Protons~~, or Electrons		
Rep. Rate	Hz	10	
Active Length	m	671	
Beam Current	mA	25	
Pulse Length	msec	1	
Beam Intensity	P / pulse	1.5E+14	(can be H-, P, or e-)
	P/hour	5.4E+18	
Linac Beam Power	MW avg.	2	
	MW peak	200	
MAIN INJECTOR WITH 8 GeV LINAC			
MI Beam Energy	GeV	120	
MI Beam Power	MW	2.0	
MI Cycle Time	sec	1.5	filling time = 1msec
MI Protons/cycle		1.5E+14	5x design
MI Protons/hr	P / hr	3.6E+17	
H-minus Injection	turns	90	SNS = 1060 turns
MI Beam Current	mA	2250	

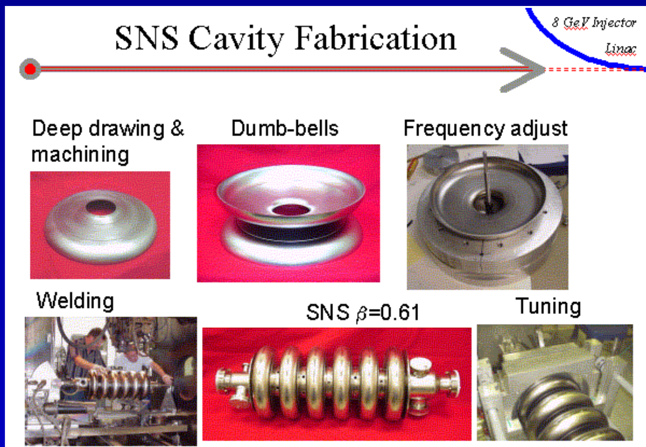
Linac Design Study

- 130 Page Design Study
- Longer (technical) versions of this Talk
- Cost Estimate Spread Sheet w/ BoE

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

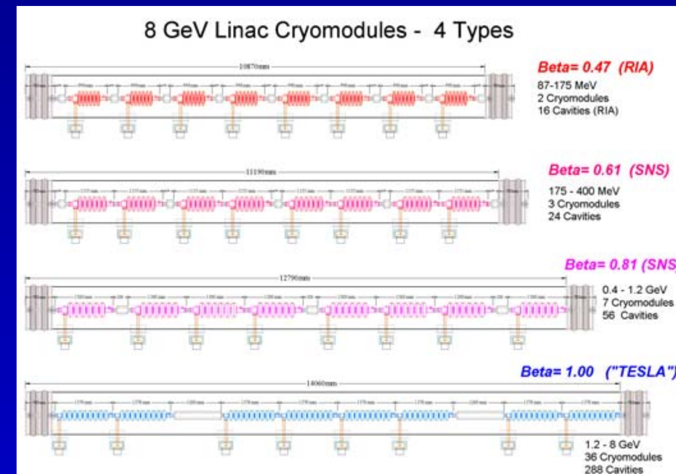
8 GeV Superconducting Linac

TECHNICAL SUBSYSTEM DESIGNS *EXIST* AND *WORK*

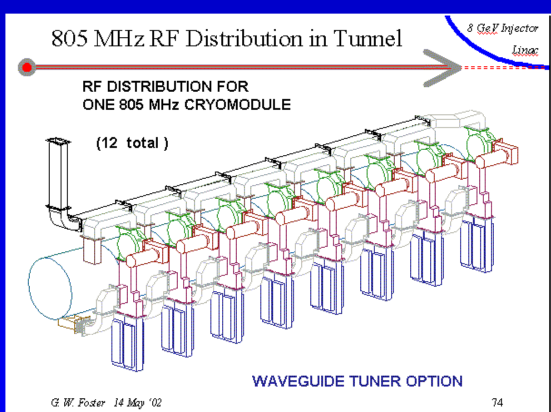


SNS Cavites

FNAL/TTF Modulators

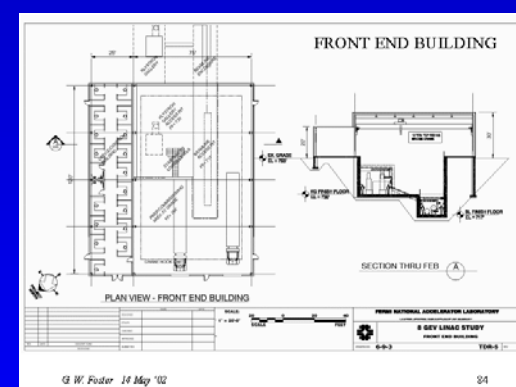


"TTF Style" Cryomodules

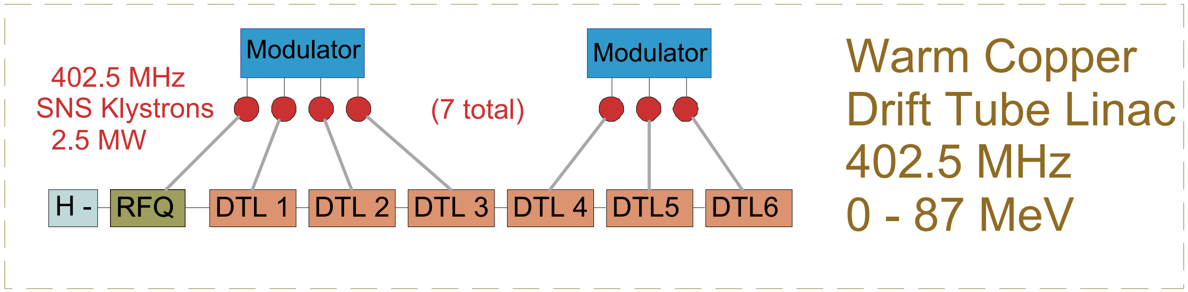


TESLA RF Distribution
*** w/ phase shifters**

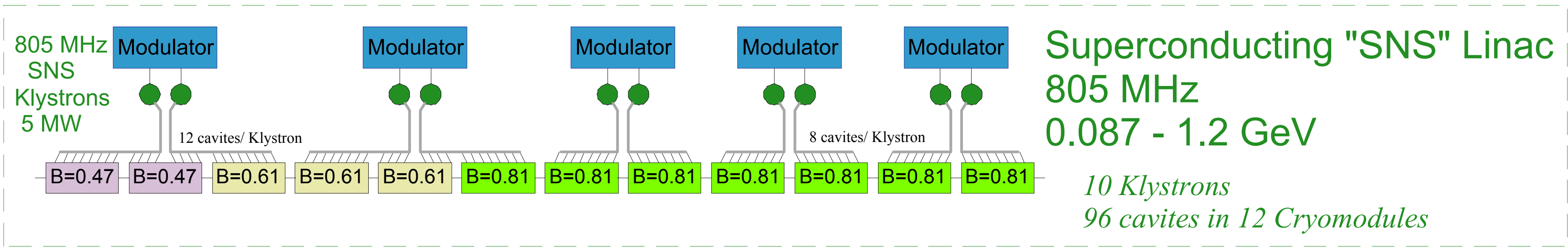
Civil Const. Based on FMI

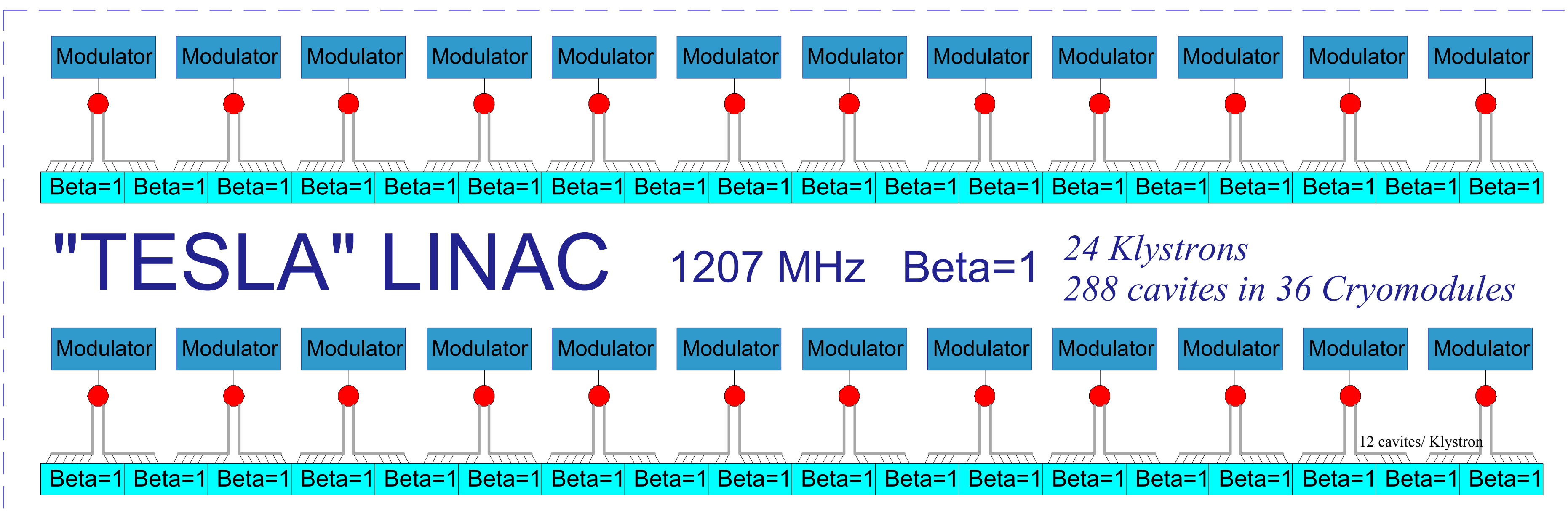


8 GeV Linac Baseline 2 MW

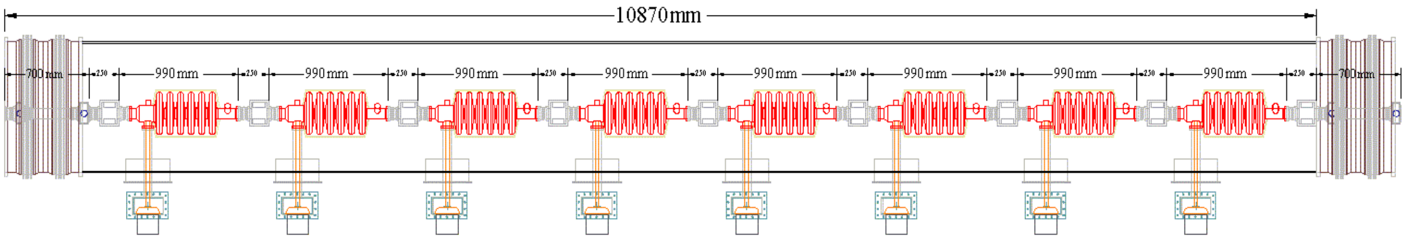


8 GeV 2 MW LINAC
41 Klystrons (3 types)
31 Modulators 20 MW ea.
7 Warm Linac Loads
48 Cryomodules
384 Superconducting Cavities



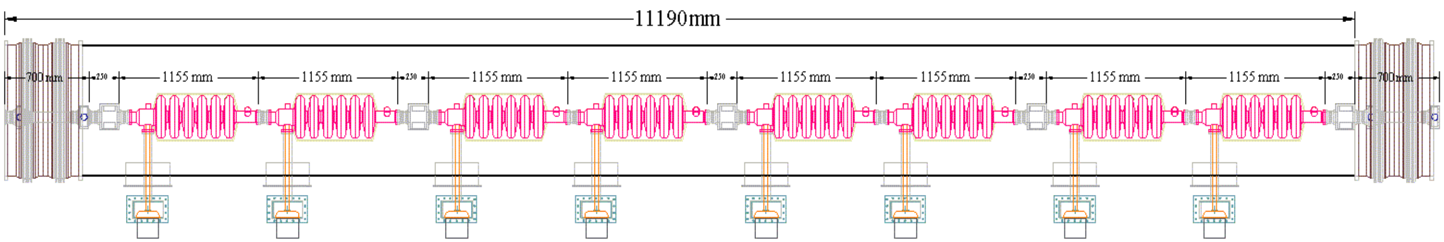


8 GeV Linac Cryomodules - 4 Types



Beta= 0.47 (RIA)

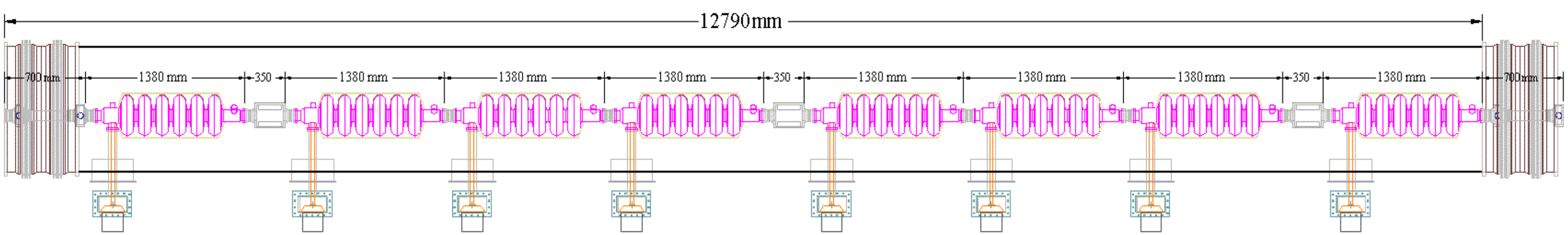
87-175 MeV
2 Cryomodules
16 Cavities (RIA)



Beta= 0.61 (SNS)

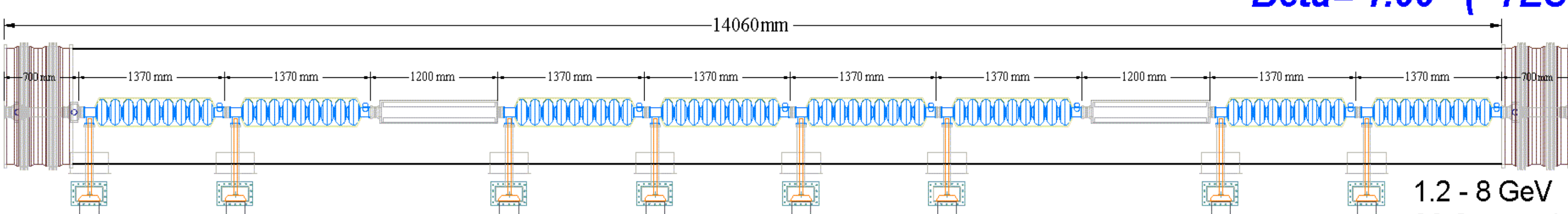
175 - 400 MeV
3 Cryomodules
24 Cavities

Beta= 0.81 (SNS)



0.4 - 1.2 GeV
7 Cryomodules
56 Cavities

Beta= 1.00 ("TESLA")



1.2 - 8 GeV
36 Cryomodules
288 Cavities

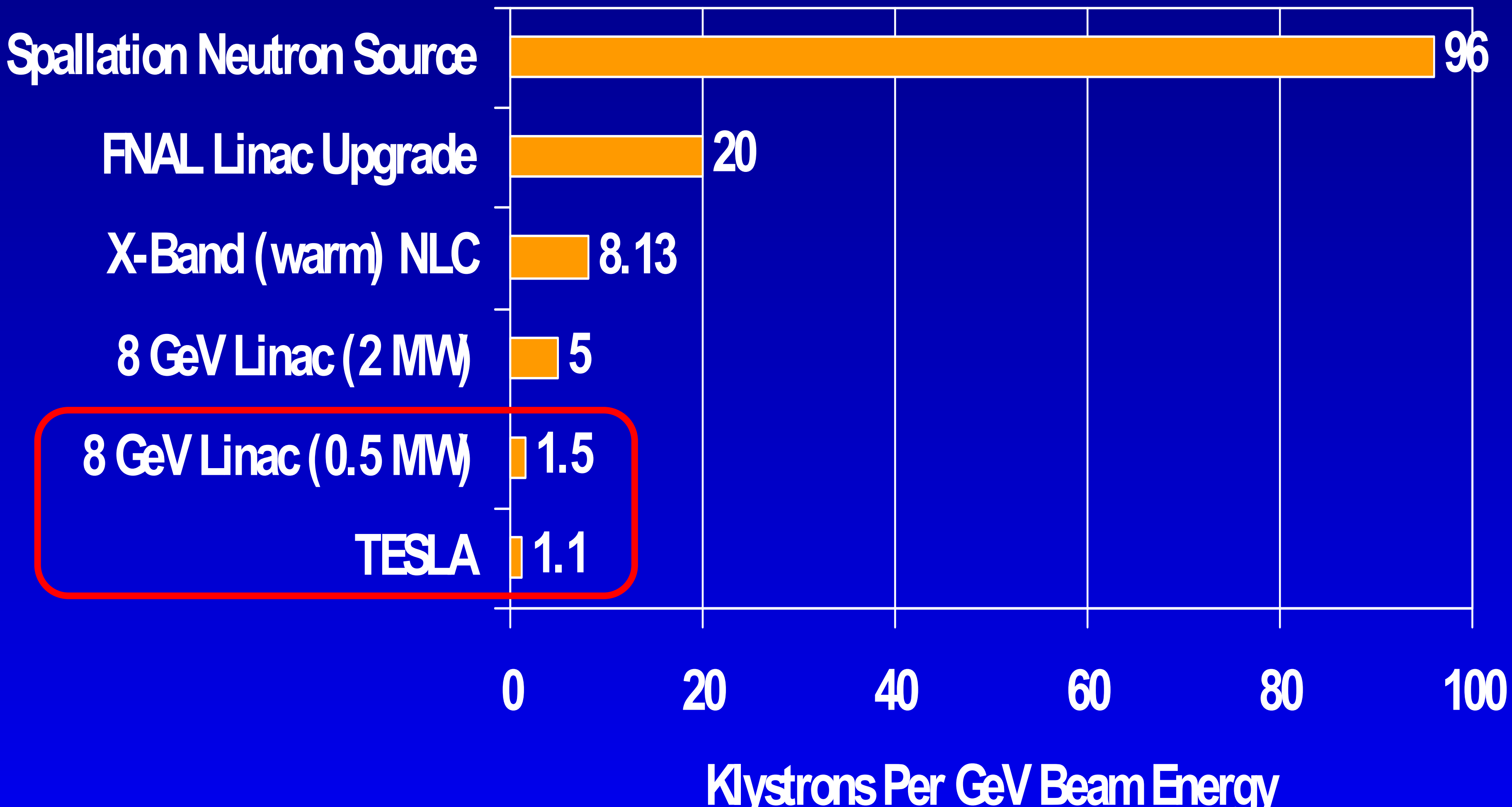
9 Cell Beta=1 Cavities, 1207.5 MHz

Reducing Average Power and Cost of 8 GeV Linac

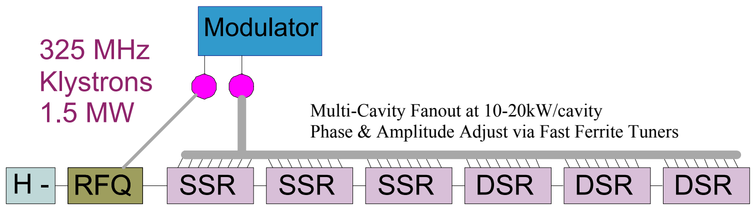
- Drop Beam Current by factor 3 (25mA→8mA)
- Extend Pulse Width by factor 3 (1ms→3ms)
  - Maintain same charge/pulse (1.5E14 protons)
  - Maintain 2 MW in MI
- Drop Repetition Rate x 4 (2 MW → 0.5 MW)
  - Maintain 1.5% Duty Factor on Klystrons

DROPS KLYSTRON COUNT x3, UTILITIES x4

Cost Driver: Klystrons per GeV



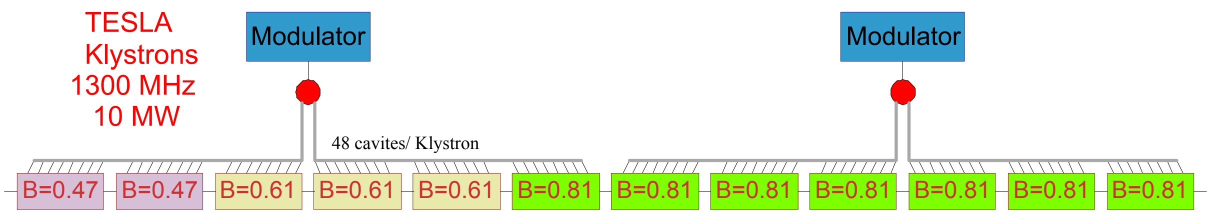
0.5 MW with TESLA Frequencies & SCRF F.E.



"Pulsed RIA"
SCRF Linac
325 MHz
0 - 120 MeV

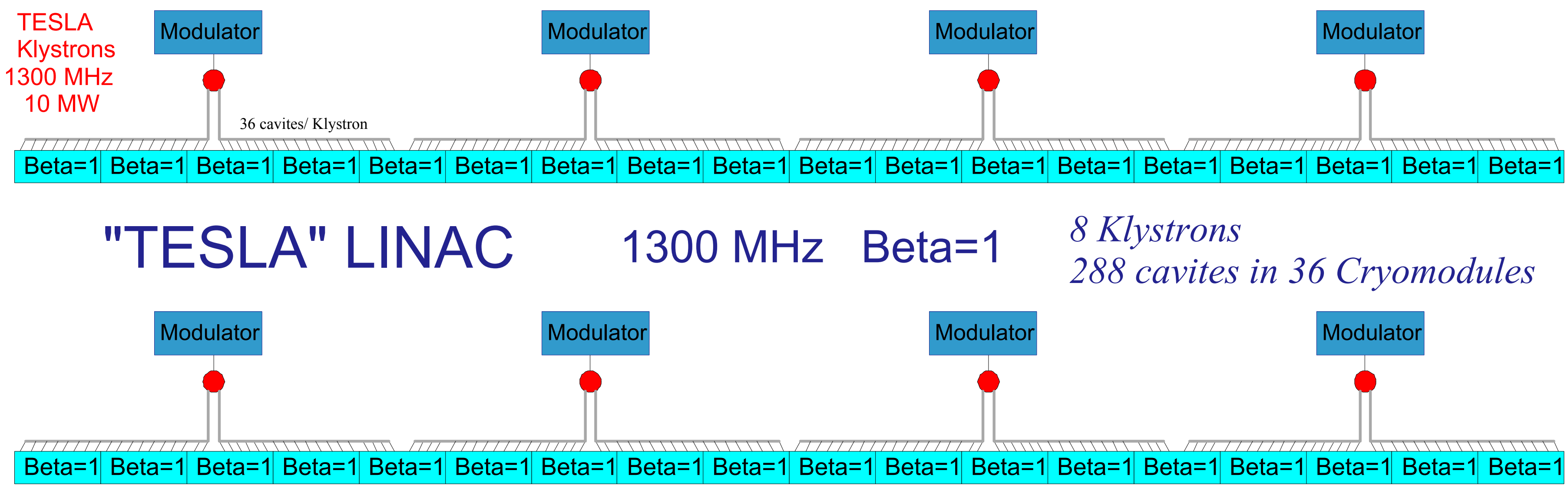
8 GeV 0.5 MW LINAC

12 Klystrons (2 types)
11 Modulators 20 MW ea.
1 Warm Linac Load
54 Cryomodules
~550 Superconducting Cavities

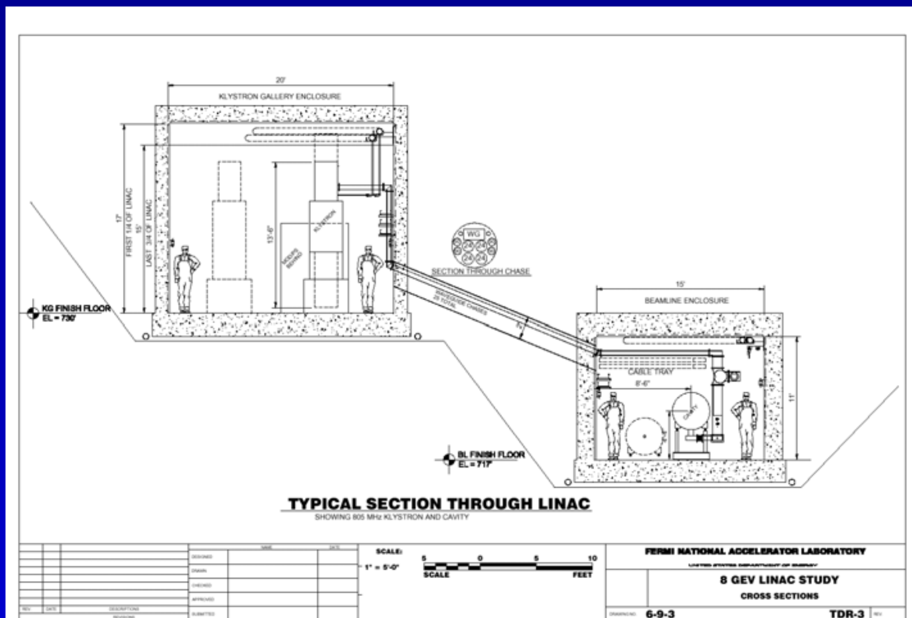


"Squeezed TESLA"
Superconducting Linac
1300 MHz 0.087 - 1.2 GeV

2 Klystrons
96 cavites in 12 Cryomodules



Linac Civil Construction



- Baseline Design: Two-tunnel with underground Klystron Gallery
- "Linear Collider ETF"

- Cheaper: Above-ground Klystron Gallery
- Much Cheaper: 12 Shacks spaced by ~50m

Scope of Civil Construction

- It has been common in recent large projects (APS, SNS…) to bundle new office and lab space with a new project.
- The *Linac* design study assumes new office & tech areas modeled on Main Injector.
- The *Synchrotron* study assumes *none*.
- Best answer probably depends on FNAL staffing plan in post-Tevatron era.

Project Organization

- Organized by Design Groups
  - groups span divisions: (AD, TD, PPD, ESH…)
  - same groups work both Linac and Synch.
    - Power supply, RF, civil, beam lines, …
- Weekly meetings already in progress

Modulators for Klystrons

- Biggest single component in RF costs
- Pfeffer, Wolff, & Co. (FNAL BD) have been making TESLA spec modulators for years
- FNAL Bouncer design in service at TTF since 1994

Modulator Circuit

- IGBT / Capacitor Discharge circuit
- Bouncer to maintain flat top
- Redundant Switch with Ignitron Crowbar

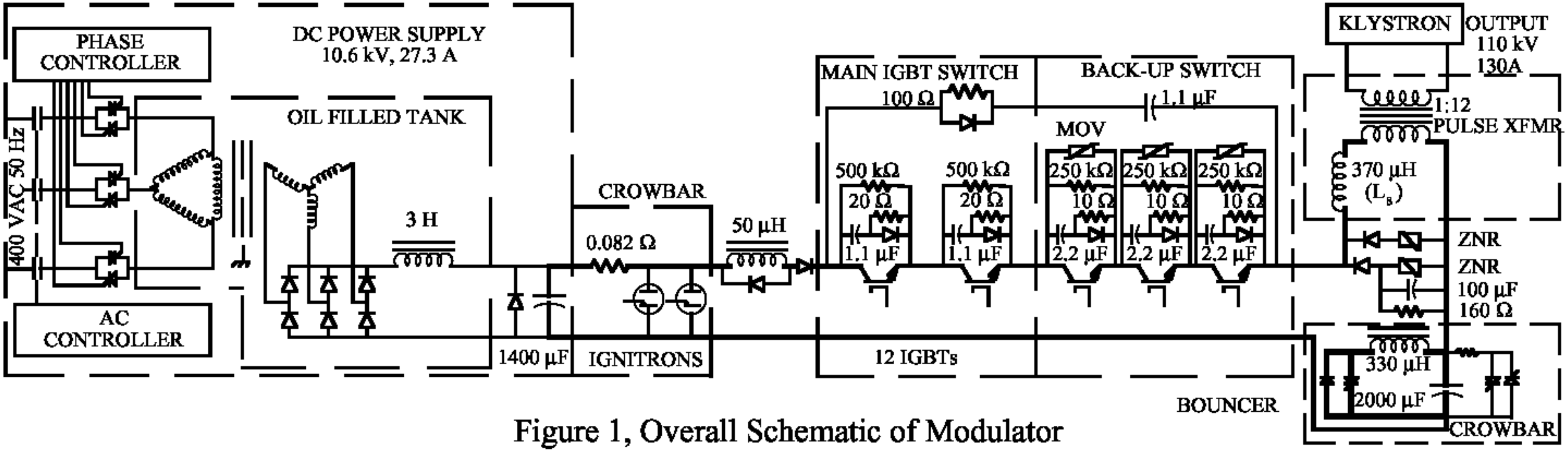


Figure 1, Overall Schematic of Modulator

H. Pfeffer, D. Wolff, & sons.

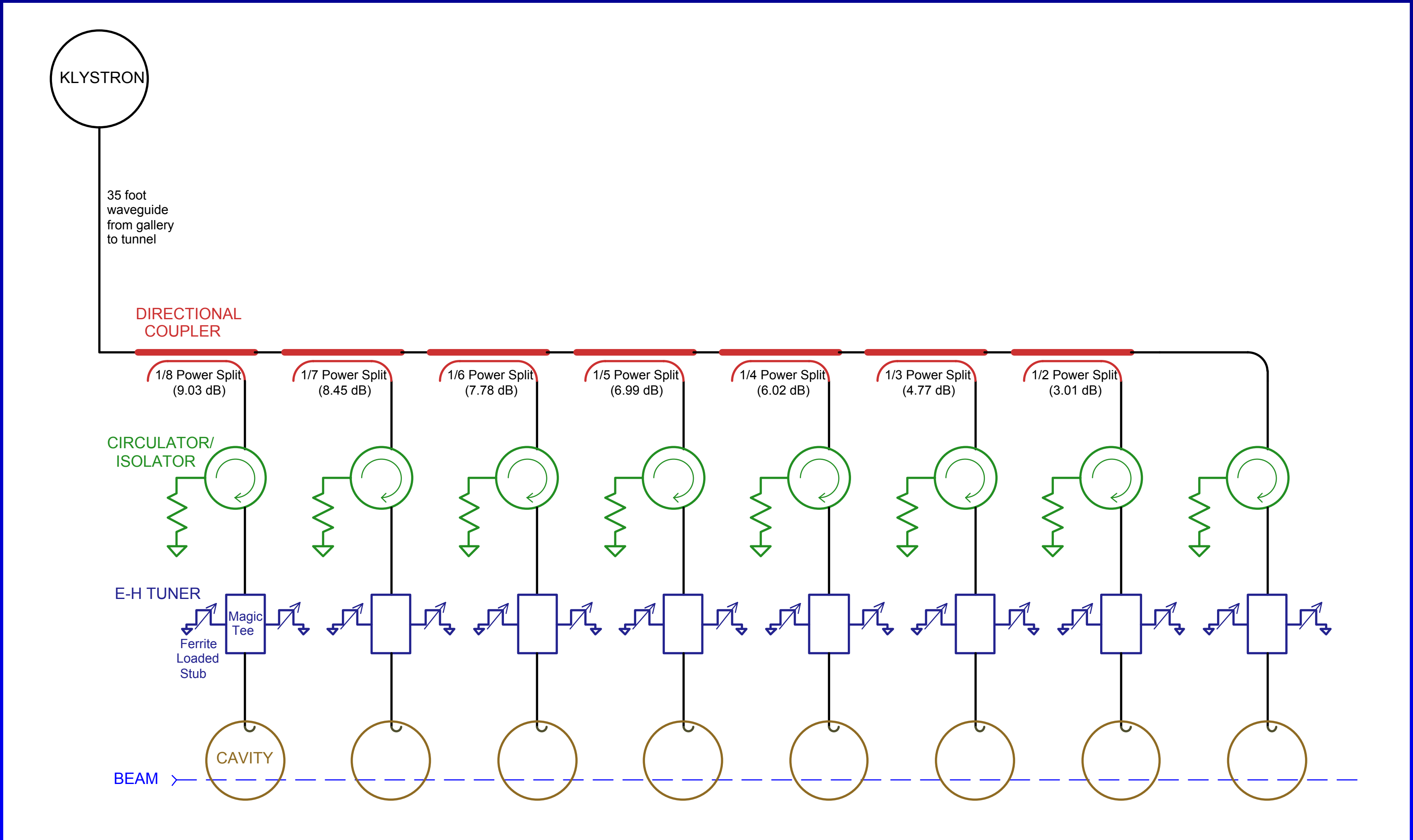
Fast Ferrite Phase Shifter R&D

- Provides fast, flexible drive to individual cavites 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 - $60M / GeV).

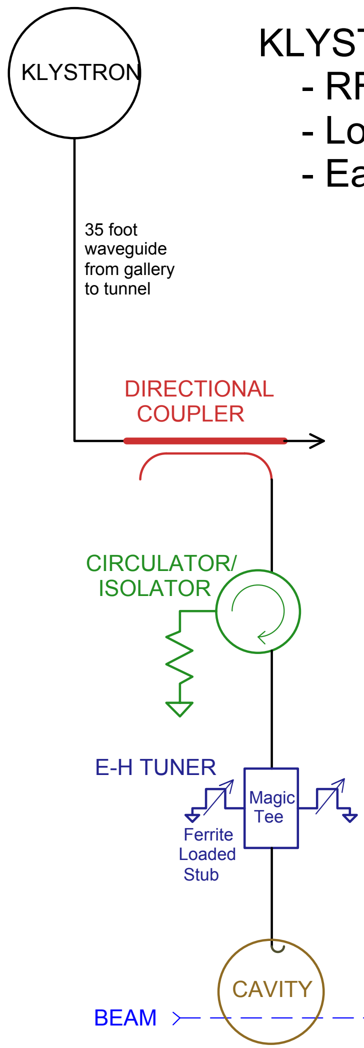
Making this technology work is important to the financial feasibility of the 8 GeV Linac.

RF Fan-out for 8 GeV Linac

~10 RF Engineers & Physicist in AD & TD



RF Fanout at Each Cavity



KLYSTRON
- RF Power Source
- Located in Gallery above tunnel
- Each Klystron Feeds 8-16 Cavities

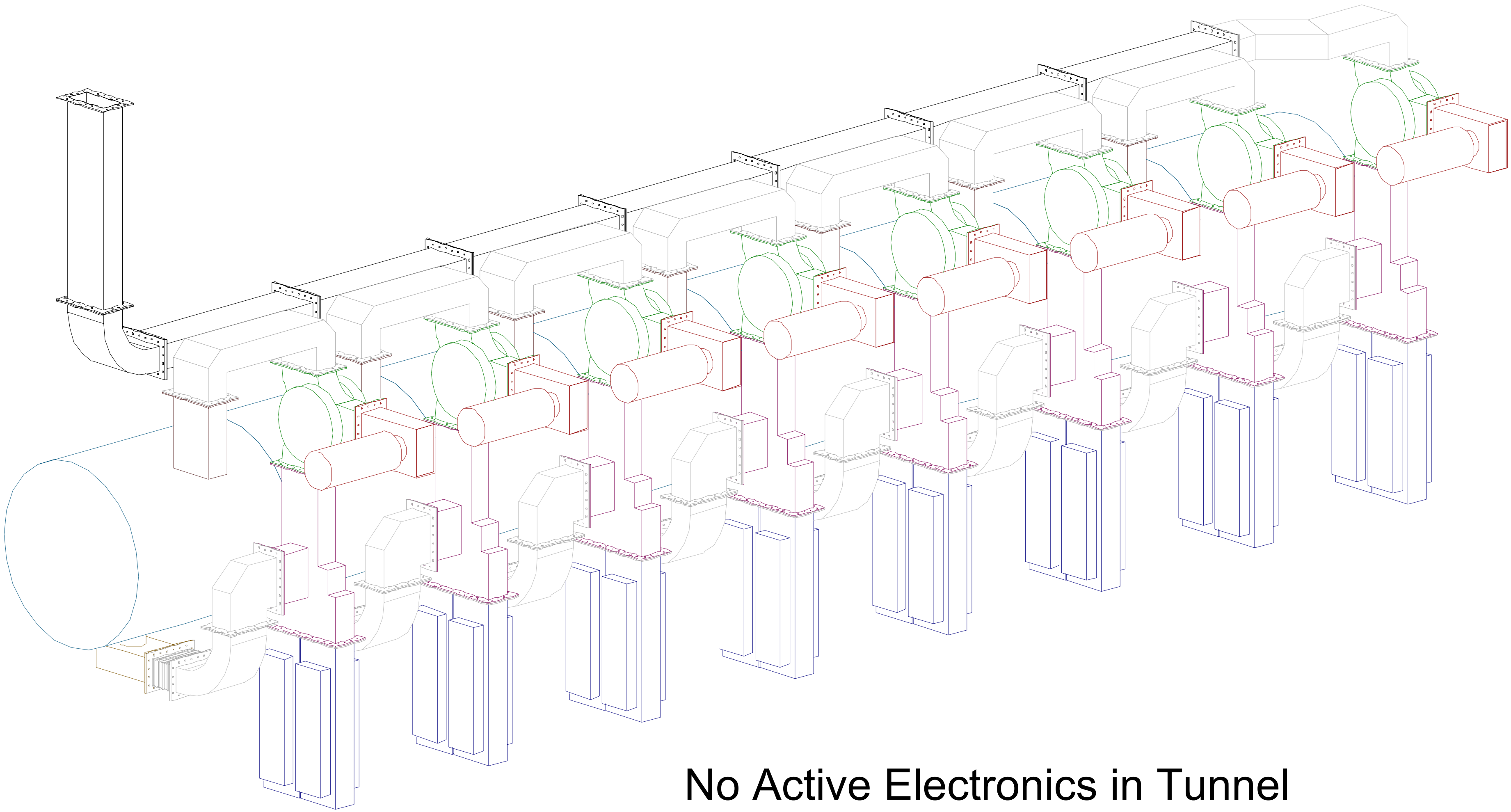
DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

CIRCULATOR / ISOLATOR
- Passes RF power forward towards cavity
- Diverts reflected power to water cooled load

E-H TUNER
- Provides Phase and Amplitude Control for Cavities
- Biased Ferrite Provides Electronic Control

SUPERCONDUCTING RF CAVITY
- Couples RF Power to Beam

805 MHz RF Distribution



No Active Electronics in Tunnel
– only Ferrite & Bias Coils.

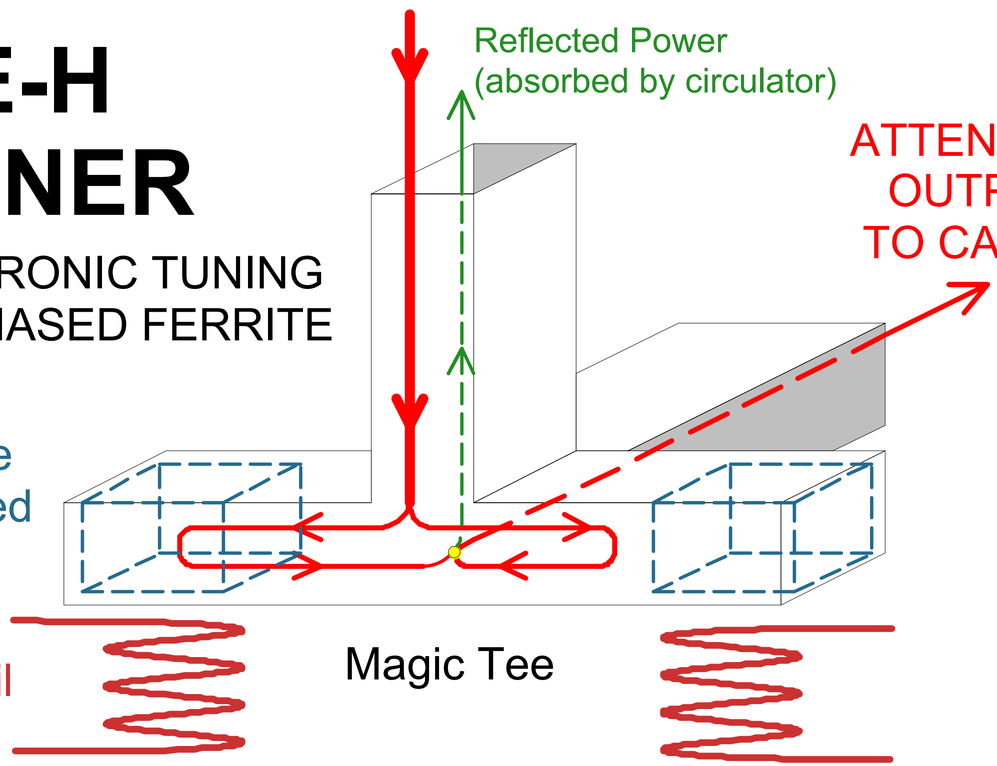
ELECTRONICALLY ADJUSTABLE E-H TUNER

Attractive Price
Quote from AFT

(<< Klystron)

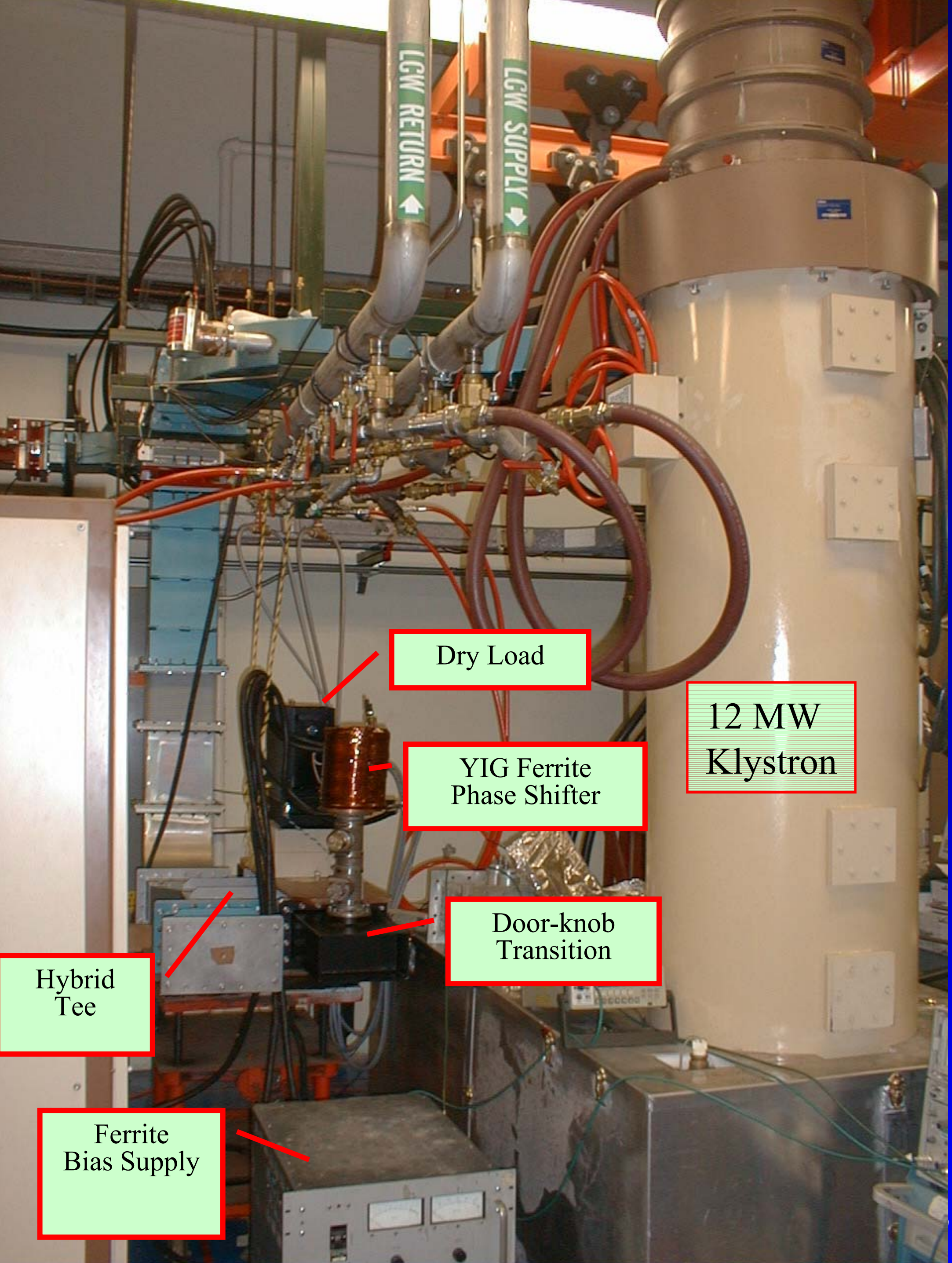
E-H TUNER

ELECTRONIC TUNING WITH BIASED FERRITE



FERRITE LOADED SHORTED STUBS CHANGE ELECTRICAL LENGTH DEPENDING ON DC MAGNETIC BIAS.

TWO COILS PROVIDE INDEPENDENT ***PHASE AND AMPLITUDE*** CONTROL OF CAVITIES



Ferrite Phase Shifter High-Power Test Stand

A. Moretti, D. Wildman, N. Solyak, Y. Terechkine

- 805 MHz Klystron
- 12 MW x 100usec

  (need: 0.5 MW x 1 msec)

First goal:

See if existing YIG tuner functions at 500kW. *(yes!)*

Ultimate Goal:

0.2 dB loss for
360 deg. phase shift
in 100~500usec.

Driver

SCRF Front End (Pulsed RIA)?

- RIA group at Argonne has made great progress using spoke resonators to achieve high accelerating gradients for beta<1 cavities.
- Using these in 1msec pulsed mode looks considerably cheaper than a warm-copper front end *(if one already has the cryoplant).*
- Ongoing collaboration testing RIA cavities in Pulsed mode at ANL (FNAL ~$1M SCRF).
- Common design and shared production possible depending on RIA time scale.

COLLABORATION

- Design Collaboration already very useful
  - Synchrotron AP Workshops
  - Linac Cost Study (access to SNS/JLAB data)
- Production Collaboration
  - Will develop both *In-House* and *Collaborative* cost estimates for major components
  - Scope of final collaboration may depend to some extent on LC technology decision

Collaboration Hunting List
(alphabetical)

- ANL (Spoke Resonators & SCRF processing)
- BNL (H- transfer line similar to SNS)
- JLAB (SCRF and cryomodule production)
- MSU (beta=0.47 elliptical cavities)
- SNS (beam controls & project cost experience)
- TESLA worldwide component R&D (* pulsed RF)
- Proposed Nationwide SCRF Collaboration

Timeline

- Next 3 Months: Finalize Machine Baselines
  - Investigate Technology Options (shifters, beam pipe)
  - Resolve Siting Issues
  - Complete Accelerator Physics Design
    - largely beam lines & controls systems
- Technical Review and Freeze Baselines (~June)
- Cost & Schedule (~6 months)
  - For both Synchrotron & Linac
- CD-0 documentation Complete by December