

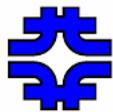
FLRP: Proton Driver

Bob Kephart

March 13, 2004

Outline

- **FLRP: Proton Driver Working Group**
- **Proton Driver Design Studies**
 - 8-GeV synchrotron
 - 8-GeV Superconducting Linac ← bulk of the talk
 - MI upgrades
- **FLRP: PD recommendations**
- **Conclusions**



Studies of the FNAL Proton Source

- Several studies have had the goal of understanding the limitations of the existing source and suggesting upgrades
- Proton Driver Design Study I:
 - 16 GeV Synchrotron (TM 2136) Dec 2000
- Proton Driver Design Study II (draft TM 2169) :
 - ✓ 8 GeV Synchrotron May 2002
 - ✓ 2 MW upgrade to Main Injector May 2002
 - ✓ 8 GeV Superconducting Linac: Feb 2004
- Proton Team Report (D Finley): Oct 2003
 - **Report:** http://www.fnal.gov/directorate/program_planning/studies/ProtonReport.pdf
 - **Limitations of existing source, upgrades for a few 10's of \$ M.**
 - “On the longer term the proton demands of the neutrino program will exceed what reasonable upgrades of the present Booster and Linac can accommodate → FNAL needs a plan to replace its aging LINAC & Booster with a new more intense proton source (AKA a **Proton Driver**)



Fermilab: Long Range Planning

- **In April of 2003 the Fermilab Director formed a committee to provide advice on the long range scientific program of the laboratory. FLRP Membership & Charge:**
http://www.fnal.gov/directorate/Longrange/Long_rang_planning.html
- **Excerpt from the charge to the LRP committee:**
“ I would like the Long-range Planning Committee to develop in detail a few realistically achievable options for the Fermilab program in the next decade under each possible outcome for the linear collider. ”
- **It was clear from the start that a new intense proton source to serve long baseline neutrino experiments was one such option...**



FLRP:PD Working group

PD Subcommittee:

Bob Kephart, chair

Steve Geer

Chris Hill

Peter Meyers

Sergei Nagaitsev

Technical Advisors

Dave Finley

John Marriner

Shekar Mishra

Victor Yarba

Proponents

Weiren Chou

Bill Foster



Fermi National Accelerator Laboratory

A Department of Energy National Laboratory
Managed by Universities Research Association

Fermilab Long Range Planning Committee Working Groups

Physics Working Group Convenor: Chris Hill Documents	Neutrinos Working Group Convenor: Gary Feldman Documents
Linear Collider Working Group Convenor: Steve Holmes Documents	Large Hadron Collider Working Group Convenor: John Womersley Documents
Proton Driver Working Group Convenor: Bob Kephart Documents	Accelerator R&D Working Group Convenor: Steve Geer Documents
Particle Astrophysics Working Group Convenor: Josh Frieman Documents (when available)	Non-(Particle Physics) Working Group Convenor: Joel Butler Documents
Resources Working Group Convenor: Hugh Montgomery Documents (when available)	International Lab Issues Working Group Convenor: Documents (when available)



Past BD Head (proton economics)

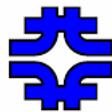
Past BD Head

Past deputy head MI project

SCRF R&D (started TD RF group)

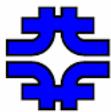
Synchrotron based Proton Driver

SCRF Linac based Proton Driver



FLRP:PD Working group

- **Had a series of 14 meetings**
 - Well attended by Expert Participants
 - 27 additional people made presentations or important contributions to the meetings
 - 3 joint meetings with other LRP sub committees
- **To obtain input from the community an open session took place on Oct 9, 2003**
- **“FLRP Retreat” Jan 9-10**
 - “Draft Proton Driver Recommendations
- **Final Report and recommendations in Mar 2004**
- **PD meetings has now evolved into a regular Proton Driver R&D/Design meeting**
 - More people joining the effort

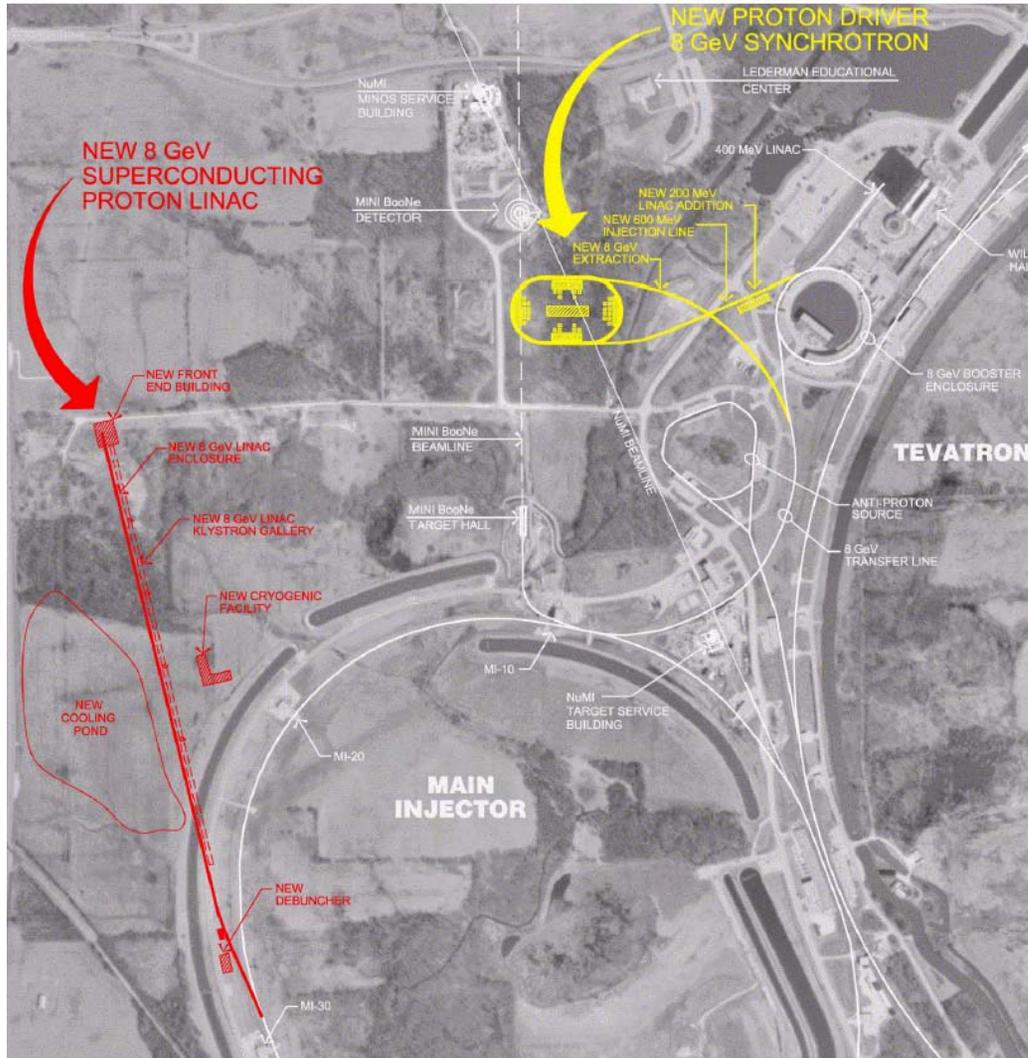


Proton Driver Design Studies

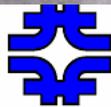
- **8 GeV Synchrotron (TM 2169)**
 - Basic plan is to replace the existing Booster with a new large aperture 8 GeV Booster (also cycling at 15 Hz)
 - Takes full advantage of the large aperture of the Main Injector
 - Goal= 5 times # protons/cycle in the MI ($3 \times 10^{13} \rightarrow 1.5 \times 10^{14}$)
 - Reduces the 120 GeV MI cycle time 20% from 1.87 sec to 1.53 sec
 - The plan also includes improvements to the existing linac (new RFQ and 10 MeV tank) and increasing the linac energy (400→600 MeV)
 - The increased number of protons and shorter cycle time requires substantial upgrades to the Main Injector RF system
- **Net result = increase the Main Injector beam power at 120 GeV by a factor of 6 (from 0.3 MW to 1.9 MW)**



PD: 8 GeV Synchrotron

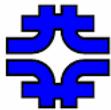


- Sited West of the existing booster
- Twice the shielding of the current booster
- Large aperture magnets
- Collimators contain losses to avoid activation of equipment



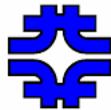
PD: 8 GeV Synchrotron

- **Synchrotron technology well understood**
 - May be cheaper than an 8 GeV linac
 - We have more experience with this kind of machine
- **But...**
 - Doesn't replace entire linac → 200 MHz PA's would still be a vulnerability, aging linac equipment still an issue
 - Cycle time is still 15 Hz → it would still take 5/15 of a sec to fill MI with 6 booster batches → limits upgrades to the MI cycle time (Beam power is proportional to # p/cycle x cycles/sec)
 - Large aperture rapid cycling magnets → development
 - Significant interruption of operations to upgrade linac and break into various enclosures (vs Run II)
 - Losses, instabilities, etc... vs ultimate performance ?



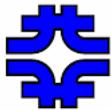
PD: 8 GeV SC Linac

- Basic concept, design, (& slides) are due to **Bill Foster** at FNAL
- Observation: \$/ GeV for SCRF has fallen dramatically → can consider a solution in which H- beam is accelerated to 8 GeV in a SC linac and injected directly into the Main Injector
- **Why an SCRF Linac looks attractive:**
 - Many components exist (few parts to design vs new booster synchrotron)
 - Copy SNS, RIA, & AccSys Linac up to 1.2 GeV
 - Use “TESLA” Cryo modules from 1.2 → 8 GeV
 - Probably simpler to operate vs two machines (ie linac + booster)
 - Produces very small emittances vs a synchrotron
 - Delivers high beam powers simultaneously at 8 & 120 GeV
- **Injection into MI is done with 90 turns of small transverse emittance beam (2π mm-mrad, 95% normalized) which is “phase space painted” into MI (40π) aperture in 1 ms → MI “fill time” that is negligible vs MI ramp times (more later)**



Other Possible SCRF Linac Missions

- **Principle Mission: Proton superbeams for Neutrinos**
 - 8 GeV or 120 GeV from MI (NUMI/Off-axis)
- **Also:**
 - Protons for future 120 GeV fixed target experiments and continued anti-proton production
- **Other possibilities:**
 - Accelerate electrons ?
 - Could drive an x-ray FEL ?
 - Could be useful for LC beam or technology studies ?
 - Spallation Neutron source ?
 - Low emittance injector to a future VLHC ?



Technological Synergies

- **Lots of machines use or plan use of SCRF**
- **This provides many opportunities for collaboration and shared infrastructure/development costs**
- **Other Accelerators:**
 - Existing: ATLAS (ANL), CBEAF, FNPL, TTF-I (DESY)
 - Construction: SNS (ORNL), DESY FEL
 - Proposed:
 - Cold Technology Linear Collider (TESLA),
 - RIA (ANL)
 - Light sources: LUX (LBNL), Cornell light source, PERL (BNL)
 - Electron cooling in RHIC (BNL)
 - eRHIC (BNL)
 - BNL proton superbeam
 - Medical isotope production, etc



A Draft Design Study exists

SCRF Proton Driver – working Draft Writup_v42.doc Created on 11/15/2003 3:03 PM

FNAL-TM-2169 (Part II)

***** DRAFT *****

**8 GeV Superconducting Injector Linac
Design Study**

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- **Web Link:**

<http://tdserver1.fnal.gov/project/8GeVLinac/DesignStudy/>
131 page document

- **Plan: Next Few Weeks:**

- Merge with PD II Design Study

- **Technically it looks to be feasible**

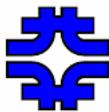
- **Principle issue is the cost**

- SNS was very expensive but there are reasons that this was so...

- TESLA appears to be very cheap / GeV

- Need to do a careful Technical Design Report including optimization and costs

- **That's the plan (more later)**



8 GeV Linac Baseline

Design Study (130 pages): <http://tdserver1.fnal.gov/project/8gevlinc>

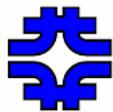
- **Warm Copper DTL**
- **805 MHz SNS & RIA Cavities to 1.3 GeV**
- **Modified TESLA (1207.5 MHz) to 8 GeV**

- **48 “TTF-style” Cryomodules**
- **384 Cavities (assuming TESLA-500 Gradients)**

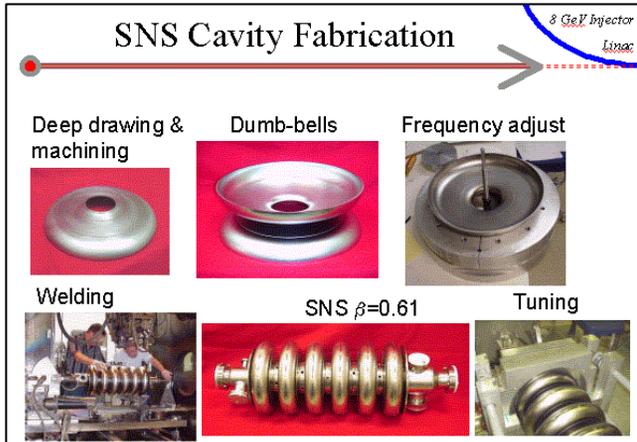
New Technology:

Extend TESLA RF Fan-Out to Proton/H- Linac

- ***41 Klystrons in baseline design***



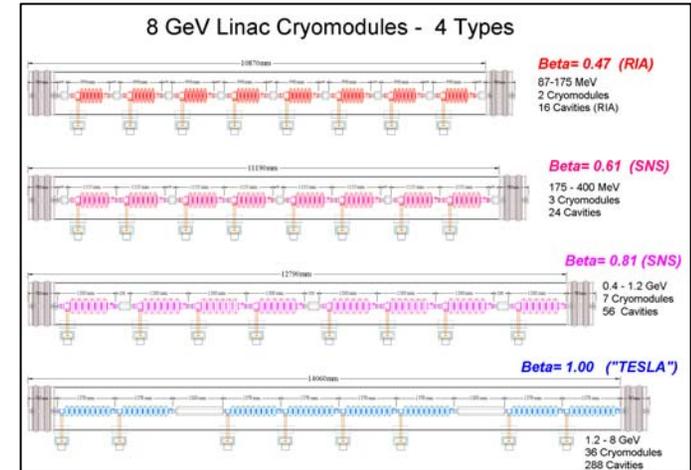
Most other TECHNICAL SUBSYSTEM DESIGNS EXIST and have been shown to WORK



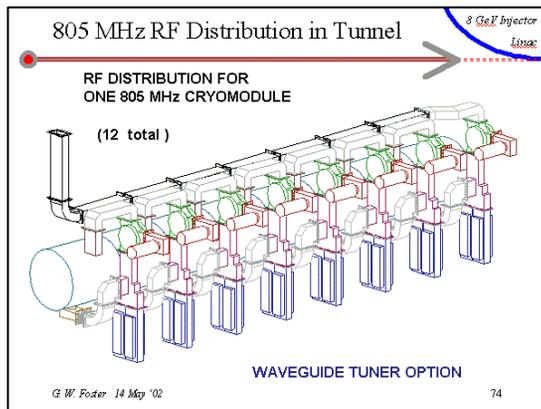
SNS Cavities



FNAL/TTF Modulators



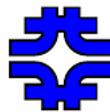
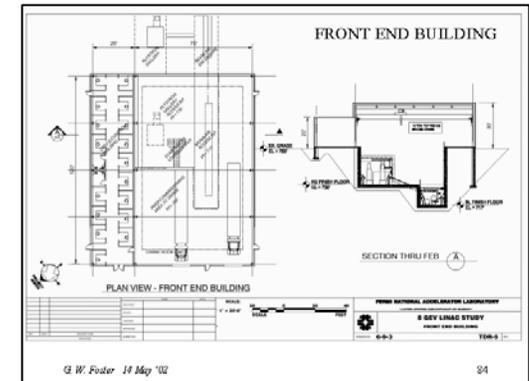
"TTF Style" Cryomodules



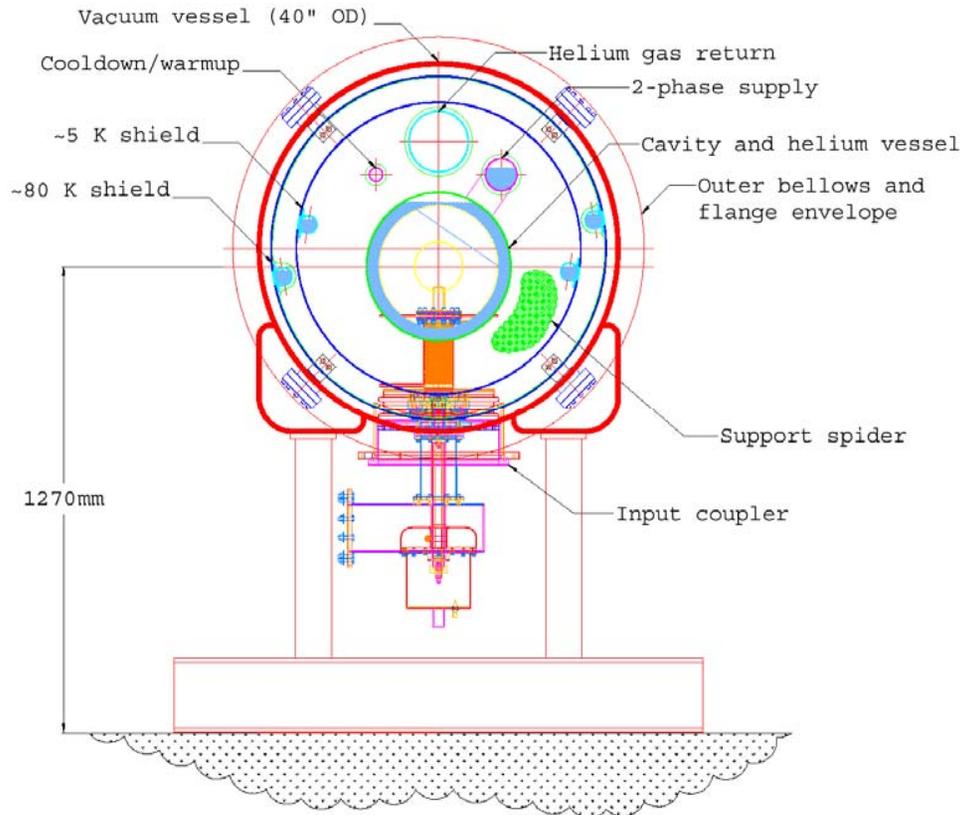
RF Distribution*

*requires ferrite phase shifter R&D

Civil Const. Based on FMI



TESLA-Style Cryomodules for 8 GeV



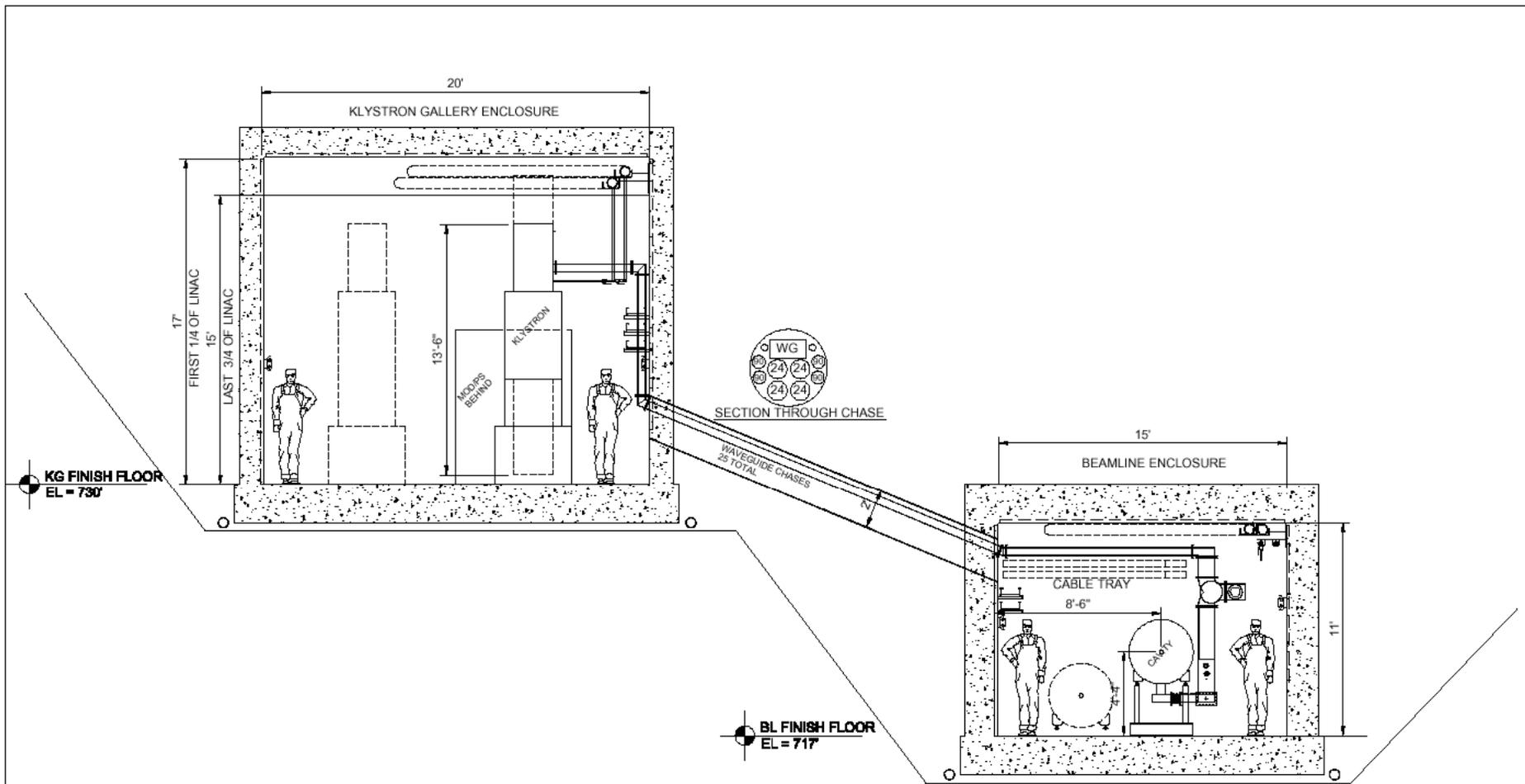
Design conceptually similar to TESLA

- No large cold gas return pipe
- Cryostat diameter ~ LHC

RF Couplers are KEK / SNS design, conductively cooled for 10 Hz operation

**Cold string length ~ 300m vs every module in SNS
=> cheaper (more like TESLA)**

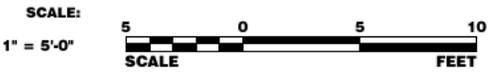




TYPICAL SECTION THROUGH LINAC

SHOWING 805 MHz KLYSTRON AND CAVITY

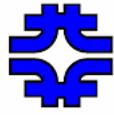
REV	DATE	DESCRIPTIONS REVISIONS	DESIGNED	NAME	DATE



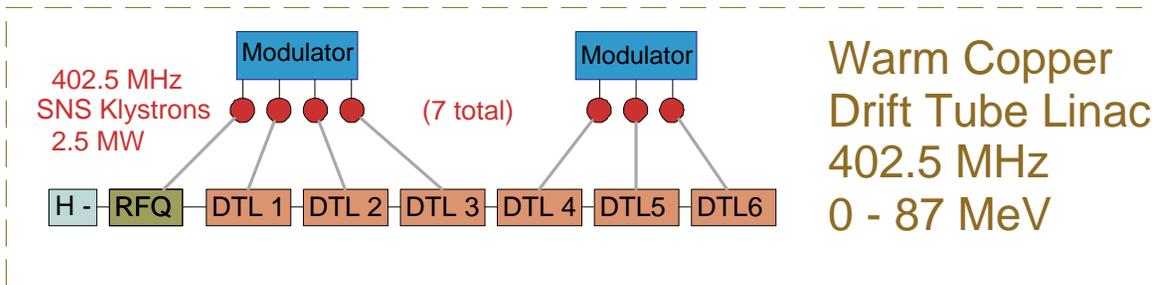
FERMILAB NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

8 GEV LINAC STUDY
CROSS SECTIONS

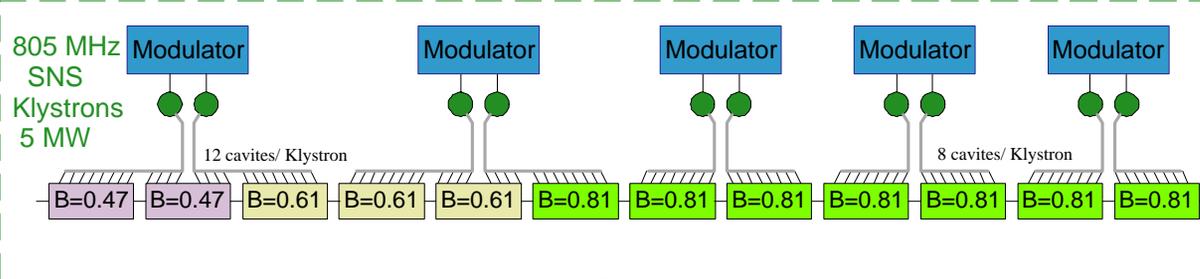
DRAWING NO. **6-9-3** **TDR-3** REV.



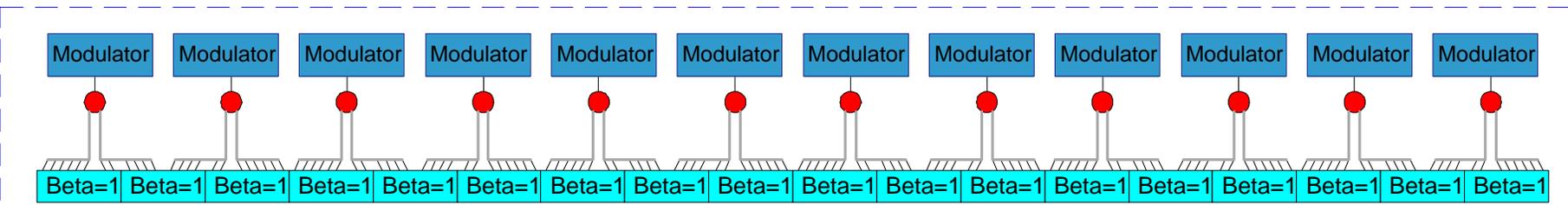
8 GeV Linac Baseline 2 MW



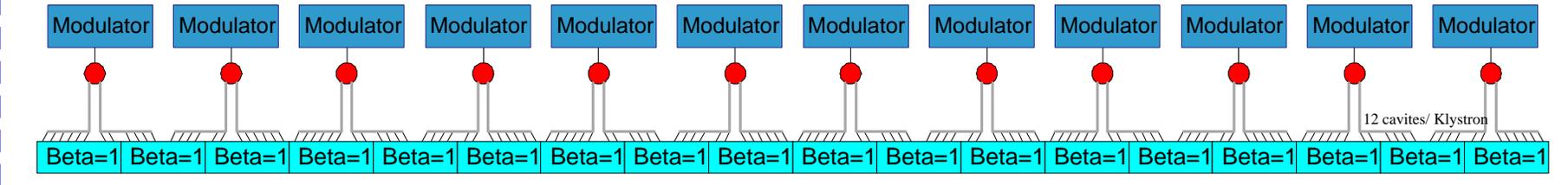
8 GeV 2 MW LINAC
 41 Klystrons (3 types)
 31 Modulators 20 MW ea.
 7 Warm Linac Loads
 48 Cryomodules
 384 Superconducting Cavities



Superconducting "SNS" Linac
 805 MHz
 0.087 - 1.2 GeV
10 Klystrons
96 cavites in 12 Cryomodules



"TESLA" LINAC 1207 MHz Beta=1 *24 Klystrons*
288 cavites in 36 Cryomodules



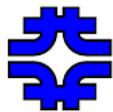
8 GeV Linac Parameters

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	

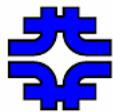
MAIN INJECTOR WITH 8 GeV LINAC

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	

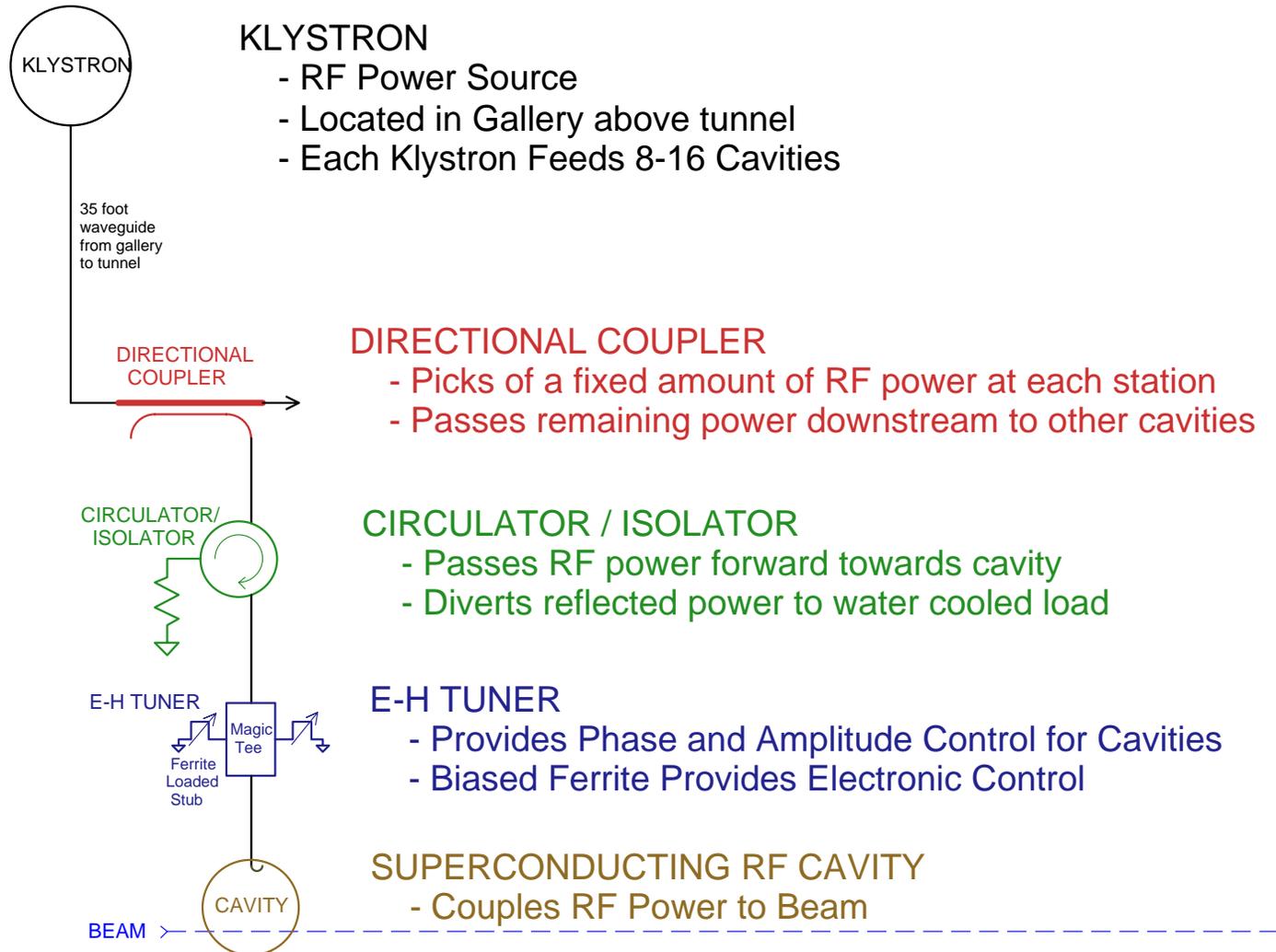


RF System for 1.2→ 8 GeV Linac

- **Assumes TESLA-style RF distribution works**
 - One TESLA multi-beam Klystron per ~12 Cavities
- **Requires a “fast ferrite” E-H tuner to control the phase and amplitude to each cavity**
 - The fundamental technology is proven in phased-array radar transmitters.
 - This R&D was started by SNS but dropped due to lack of time.
 - R&D is required to optimize the design for the Linac, funding in TD FY04 budget to start this effort
 - Also needed if Linac alternates between e and P.
- **Modulators are identical to TESLA modulators**



RF Fanout at Each Cavity

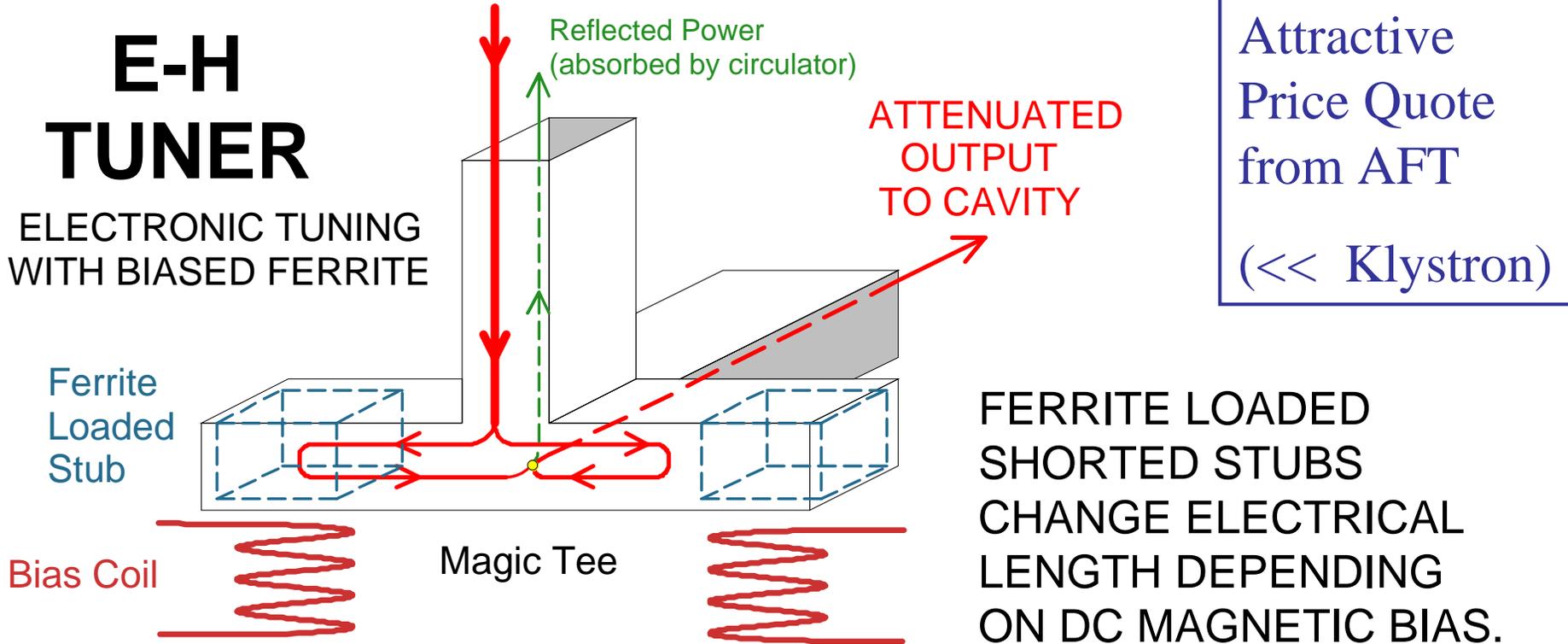


ELECTRONICALLY ADJUSTABLE E-H TUNER

MICROWAVE INPUT POWER
from Klystron and Circulator

E-H TUNER

ELECTRONIC TUNING
WITH BIASED FERRITE



Attractive
Price Quote
from AFT
(\ll Klystron)

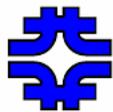
FERRITE LOADED
SHORTED STUBS
CHANGE ELECTRICAL
LENGTH DEPENDING
ON DC MAGNETIC BIAS.

TWO COILS PROVIDE INDEPENDENT
PHASE AND AMPLITUDE CONTROL OF CAVITIES

Cost Optimizations & Options

- **Staging: Extend Klystron Fanout 12:1 → 36:1**
 - Drop beam current, extend pulse width
 - Drop rep. rate & avg. power 2 MW → 0.5 MW
- **Consider SCRF Front End (RIA Spokes)**
- **Assume TESLA 800 surface fields will work:**
 - Baseline 5 GeV linac by assuming TESLA 500 gradients,
 - Deliver 8 GeV linac by achieving TESLA 800 gradients.

384 Cavities → 240 cavities ; Linac Length: 650m → 400



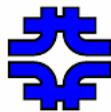
Frequency Options

1. Standardize on SNS / RIA (805 MHz)

- Develop “modified TESLA” 1207.5 MHz cavities
- Develop Modified Multi-Beam Klystron
- Develop new spoke resonator family if SCRF

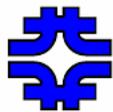
2. Standardize on TESLA (1300 MHz)

- Develop new family of “TESLA-Compatible” $\beta < 1$ cavities
- Already 3 vendors for main MBK
- Develop new spoke resonator family if SCRF

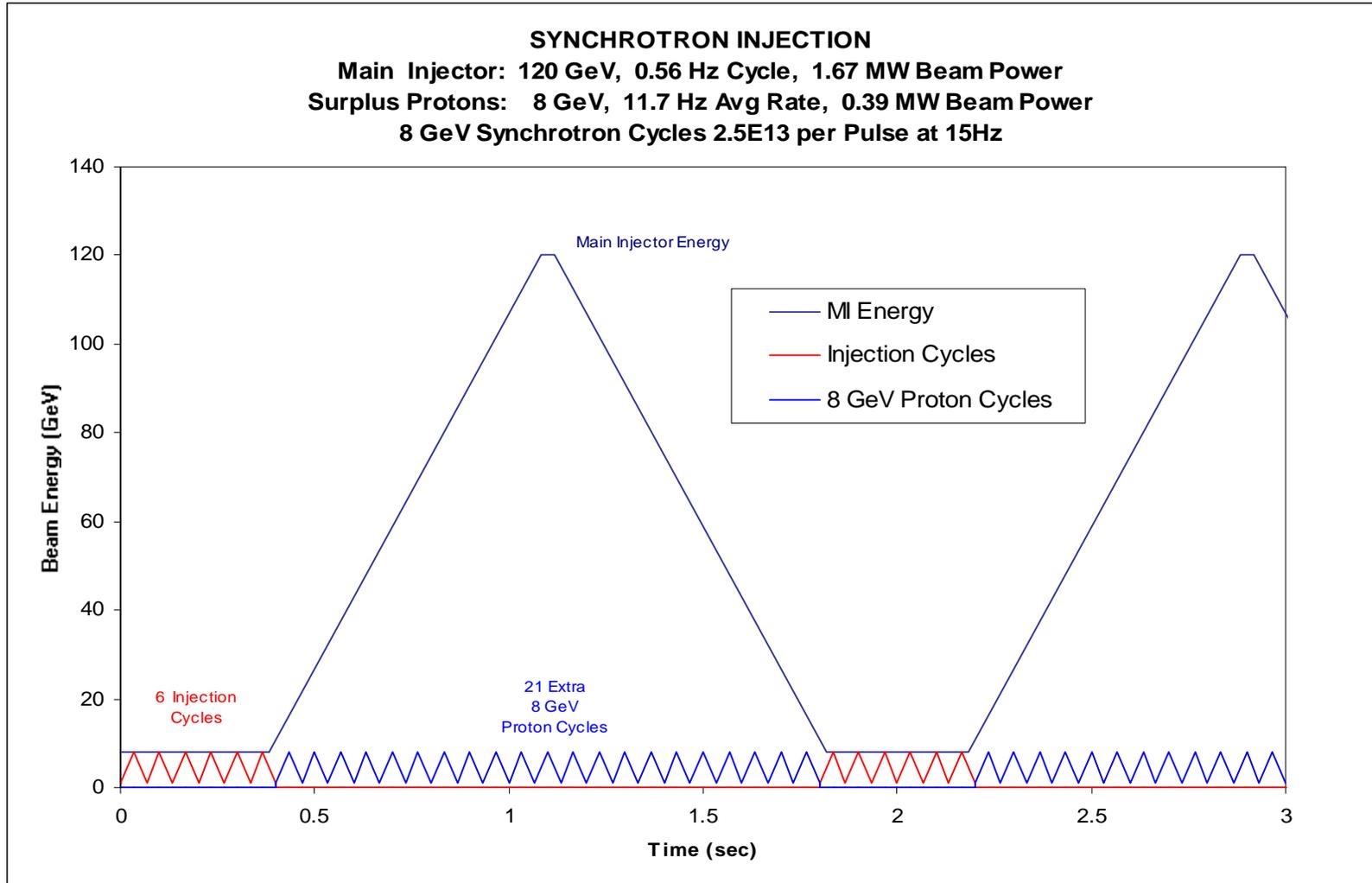


Main Injector with 8 GeV Linac

- **H⁻ stripping injection at 8 GeV**
 - 25 mA linac beam current
 - 90-turn Injection gives MI Beam Current ~ 2.3 A
(SNS has 1060 turn injection at 1 GeV)
 - preserve linac emittances $\sim 2\pi$ (or even $\sim 0.5\pi$ (95%) at low currents)
 - phase space painting needed at high currents
 - avoids space charge limitations present at lower energy
- ***can put a LOT of beam in MI !***
- **1.5 Second Cycle time to 120 GeV**
 - filling time 1 msec or less
 - no delay for multiple Booster Batches
 - no beam gaps for “Booster Batches” -- only Abort gap
 - Even faster MI cycle times can be considered (x 2 ?)

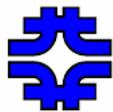
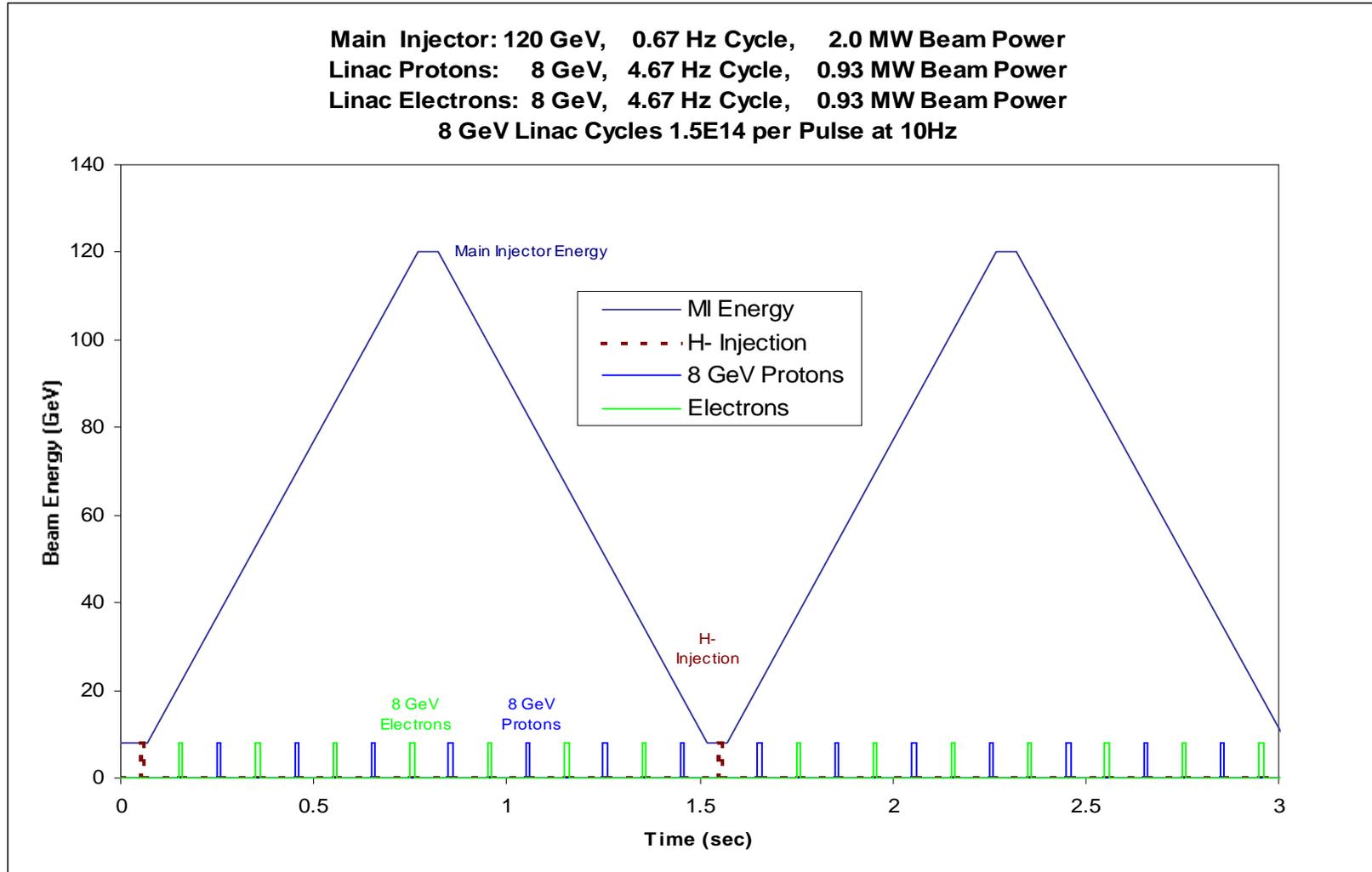


120 GeV Main Injector Cycle with 8 GeV Synchrotron

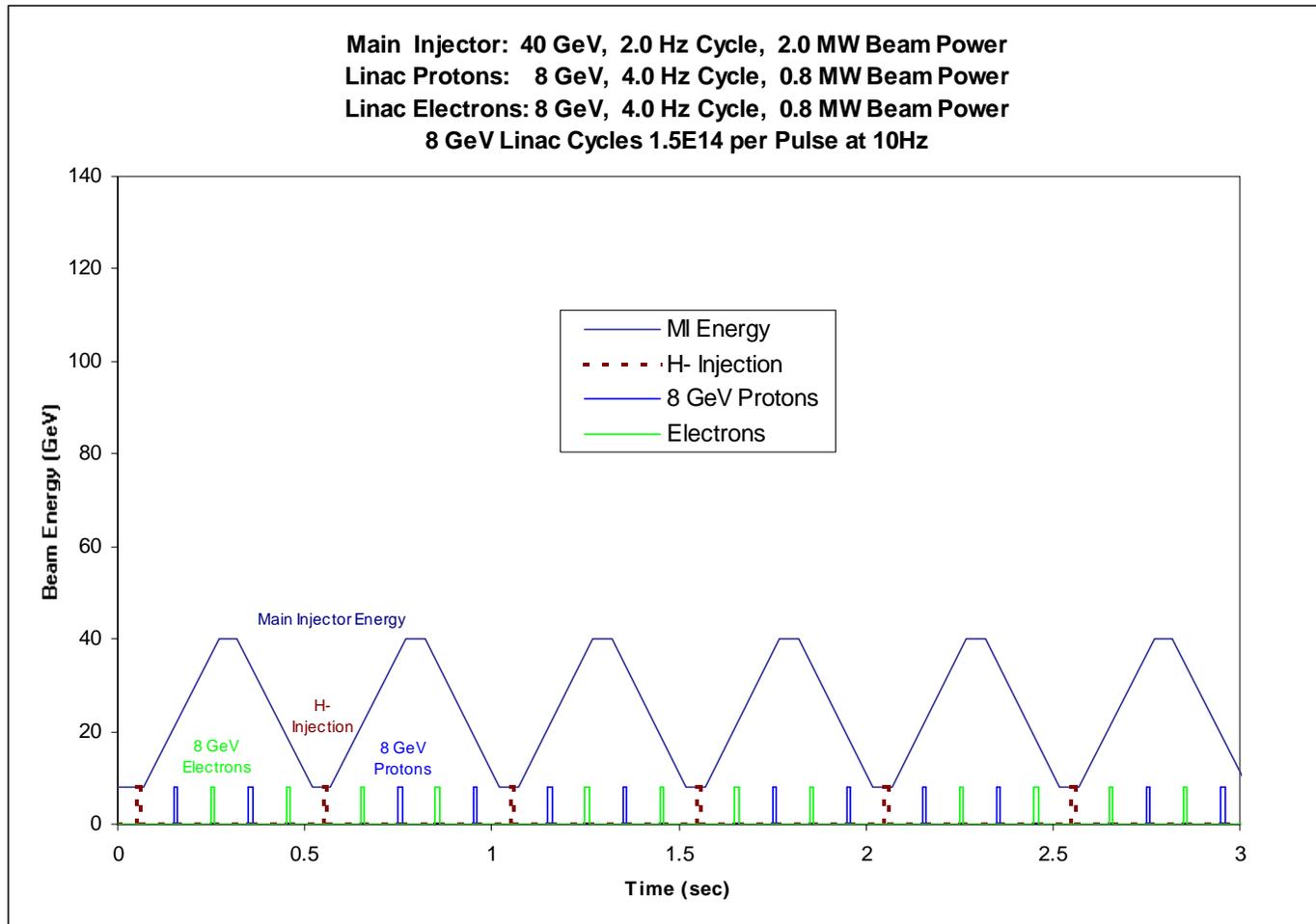


120 GeV Main Injector Cycle with 8 GeV Linac, e- and P

Main Injector: 120 GeV, 0.67 Hz Cycle, 2.0 MW Beam Power
Linac Protons: 8 GeV, 4.67 Hz Cycle, 0.93 MW Beam Power
Linac Electrons: 8 GeV, 4.67 Hz Cycle, 0.93 MW Beam Power
8 GeV Linac Cycles 1.5E14 per Pulse at 10Hz



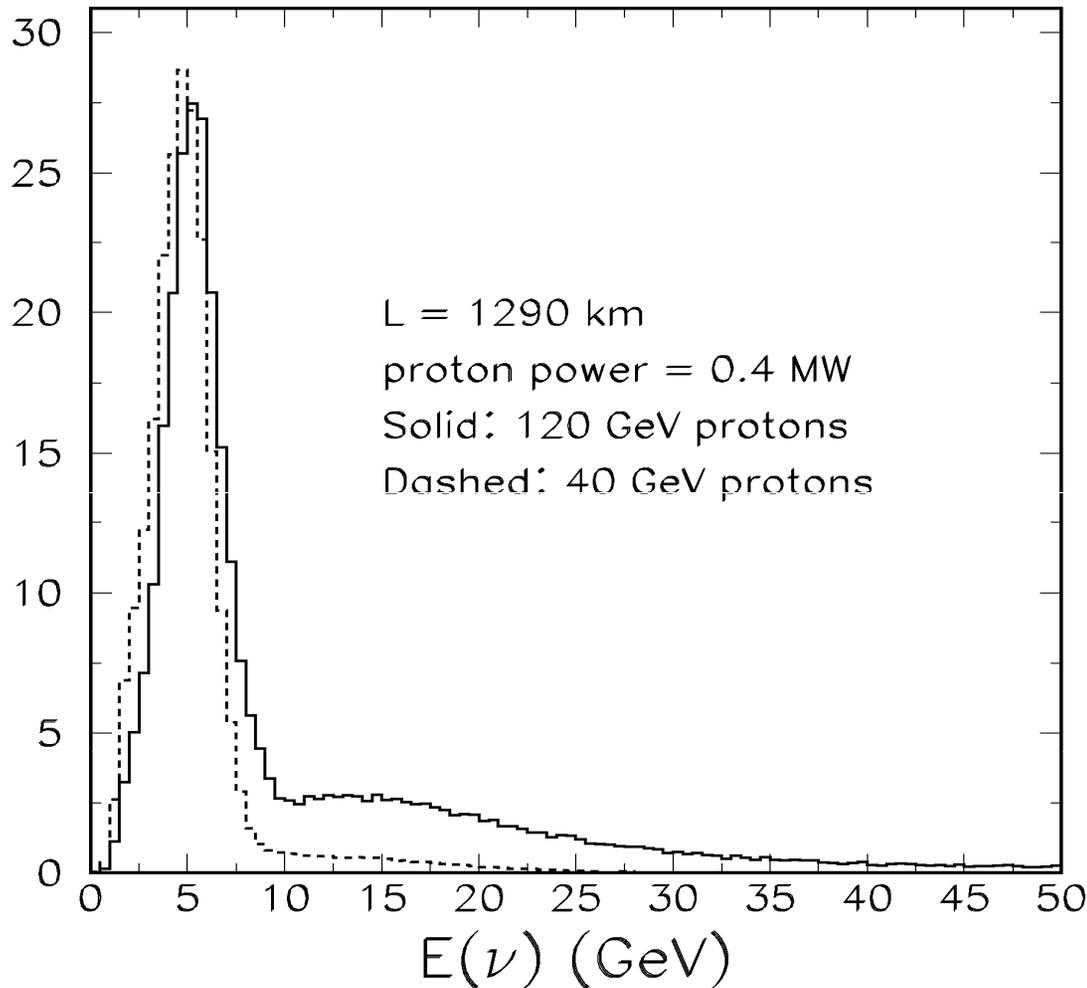
Linac Allows Reduced MI Beam Energy without Compromising Beam Power



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



Running at Reduced Proton Energy Produces a Cleaner Neutrino Spectrum



**Running at 40 GeV
reduces tail at higher
neutrino energies.**

**Same number of
events for same beam
power → may be a
useful operating mode**

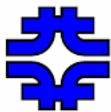
(Plot courtesy Fritz & Debbie)



Comparison of PD options

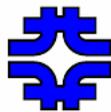
Parameters	Present Proton Source	Proton Driver synchrotron (PD2)	Proton Driver SCRF Linac	Proton Driver SCRF Linac and MI upgrade ?
Linac (Pulse Freq)	5 Hz	15 Hz	10 Hz	10 Hz
Kinetic energy (MeV)	400	600	8000	8000
Peak current (mA)	40	50	28	28
Pulse length (μ s)	25	90	1000	1000
Booster (cycles at 15 Hz)				
Extraction kinetic energy (Gev)	8	8	-	-
Protons per cycle	5×10^{12}	2.5×10^{13}	-	-
Protons per hour	9×10^{16} (5 Hz)	1.4×10^{18}	-	-
8 GeV Beam Power (MW)	0.033 (5 Hz)	0.5	2	2
Main Injector				
Extraction Energy for NuMI (GeV)	120	120	120	120
Protons per cycle	3×10^{13}	1.5×10^{14}	1.5×10^{14}	1.5×10^{14}
fill time (sec)	0.4 (5/15+0.1)	0.4 (5/15+0.1)	0.1	0.1
ramp time (sec)	1.47	1.13	1.4	0.7
cycle time (sec)	1.87	1.53	1.5	0.8
Protons per hour	5.8×10^{16}	3.5×10^{17}	3.5×10^{17}	6.6×10^{17}
Ave Beam Power (MW)	0.3	1.9	1.9	3.6

- **My conclusions: The SCRF Linac PD is more likely to deliver the desired performance, is more “flexible” machine than the synchrotron based PD, and has more “growth” potential**



Draft PD Recommendations

- **We recommend that Fermilab prepare a case sufficient to achieve a statement of mission need (CD-0) for a 2 MW proton source (Proton Driver). We envision this project to be a coordinated combination of upgrades to existing machines and new construction.**
- **We recommend that Fermilab elaborate the physics case for a Proton Driver and develop the design for a superconducting linear accelerator to replace the existing Linac-Booster system. Fermilab should prepare project management documentation including cost & schedule estimates and a plan for the required R&D. Cost & schedule estimates for Proton Driver based on a new booster synchrotron and new linac should be produced for comparison. A Technical Design Report should be prepared for the chosen technology.**



CONCLUSIONS

- **It seems likely that a new intense proton source will be proposed for construction at FNAL in near future**
- **Similar in scope to the Main Injector Project (cost/schedule)**
- **A 8 GeV Synchrotron or a Superconducting Linac appear to be both technically possible. However the SCRF linac has many attractive features if it can be made affordable**
- **The FNAL management will request that the 8 GeV linac design be developed including cost & schedule information so that a technology choice can be made**
- **A Technical Design Report will be developed in the next year for the chosen Technology (charge)**
- **This will make it possible to submit a Proton Driver project to the DOE for approval and funding**

