Plans for a Proton Driver

Bob Kephart

January 12, 2004

Outline

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

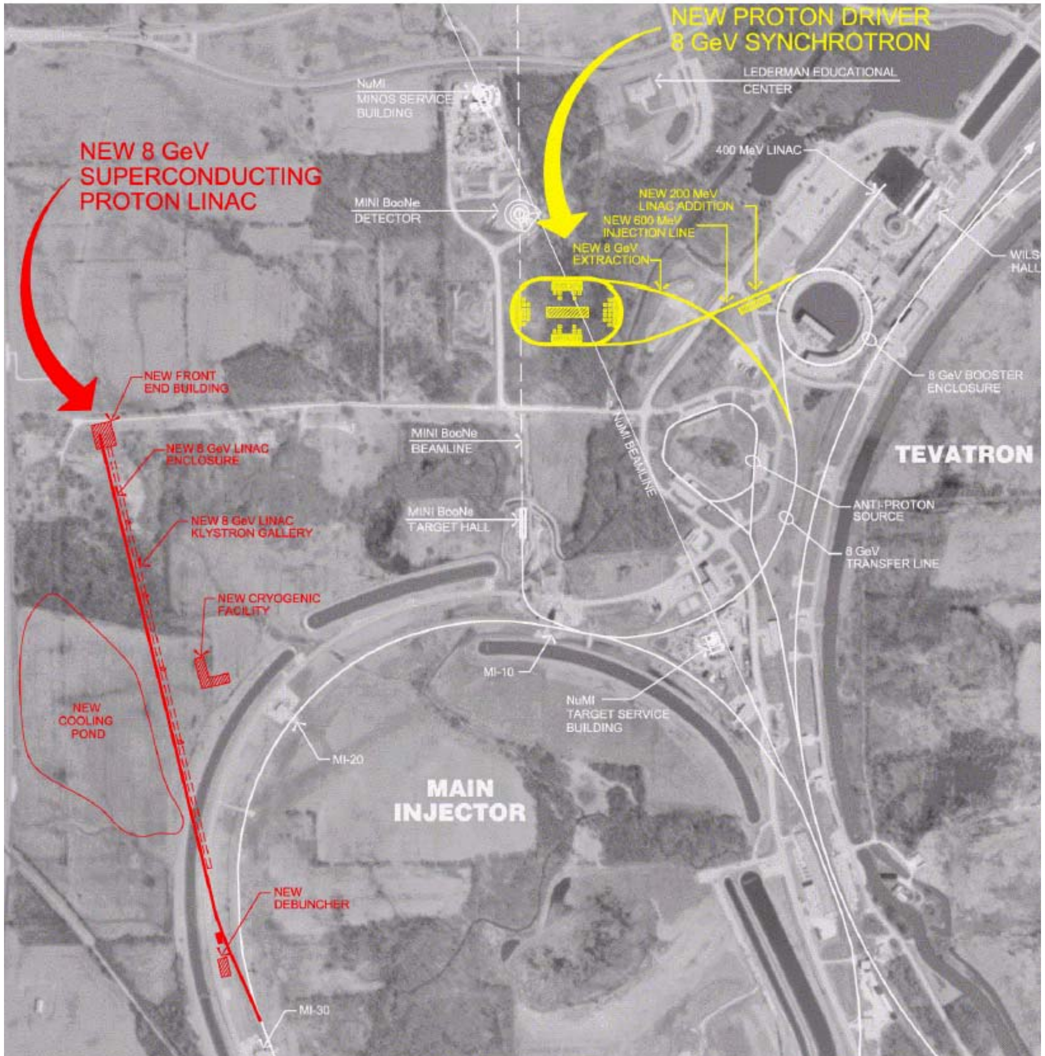
Studies of the FNAL Proton Source

- **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:**
  - ✓ 8 GeV Synchrotron (TM 2169) 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)

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

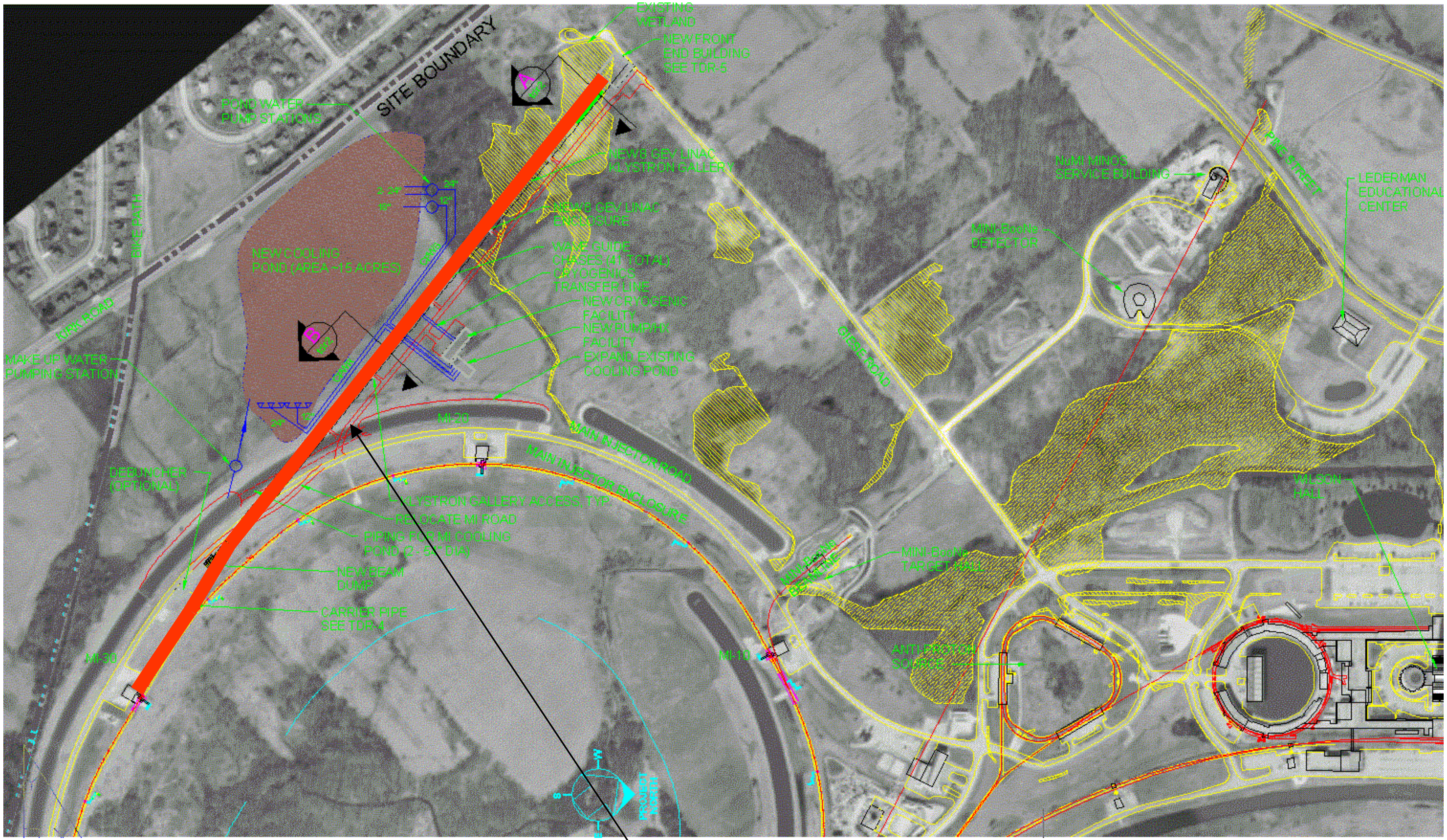
PD: 8 GeV Synchrotron

- **Synchrotron technology well understood**
  - Can be executed quickly
  - Likely to be cheaper than an 8 GeV linac
- **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)
  - Significant interruption of operations to upgrade linac and break into various enclosures (vs Run II)

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 (2 π mm-mrad, 95% normalized) which is "phase space painted" into MI (40 π) aperture in 1 μ sec→ MI "fill time" that is negligible vs MI ramp times (more later)**

8 GeV Linac Siting for Design Study

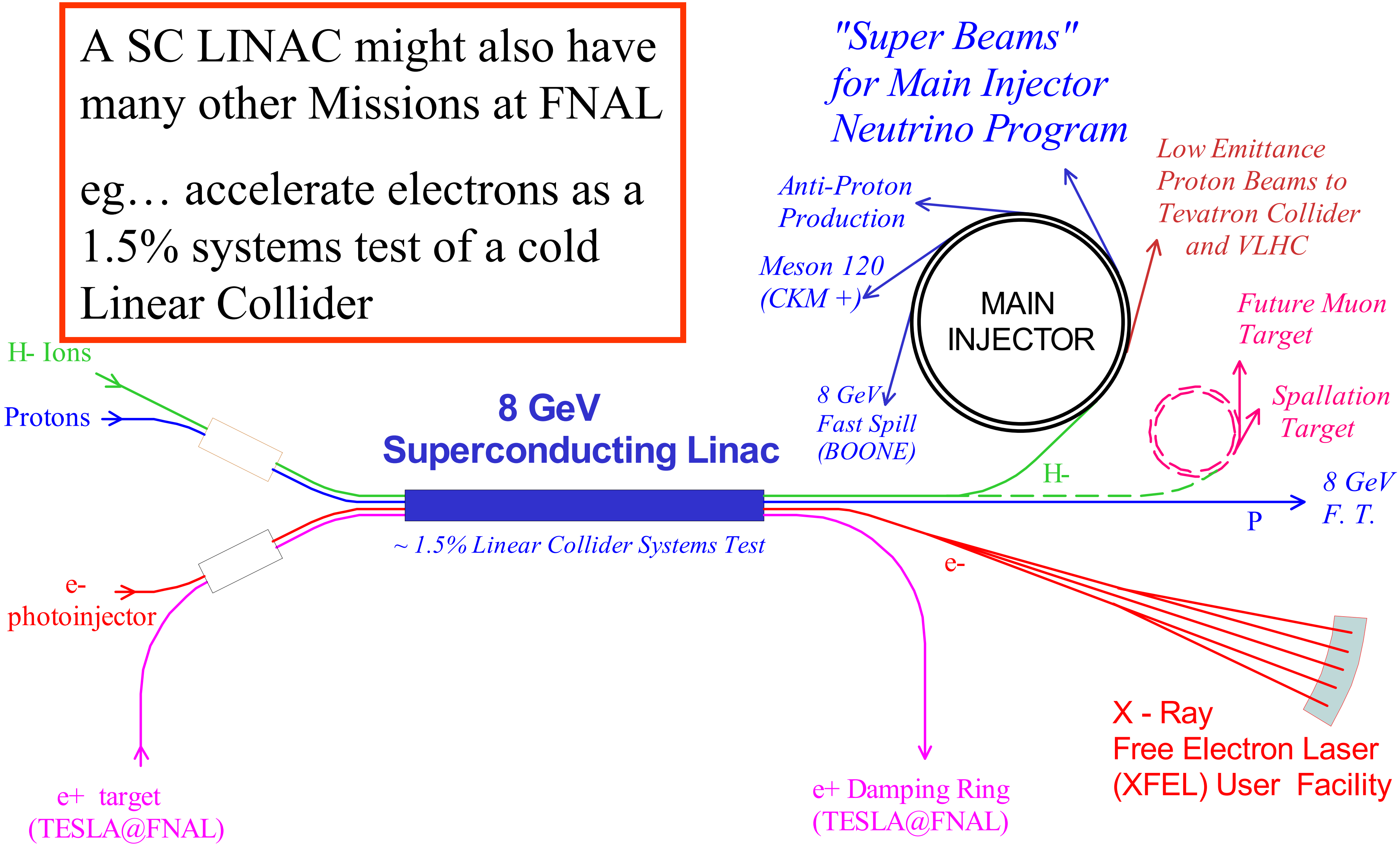


- **Sited tangent to the Main Injector**

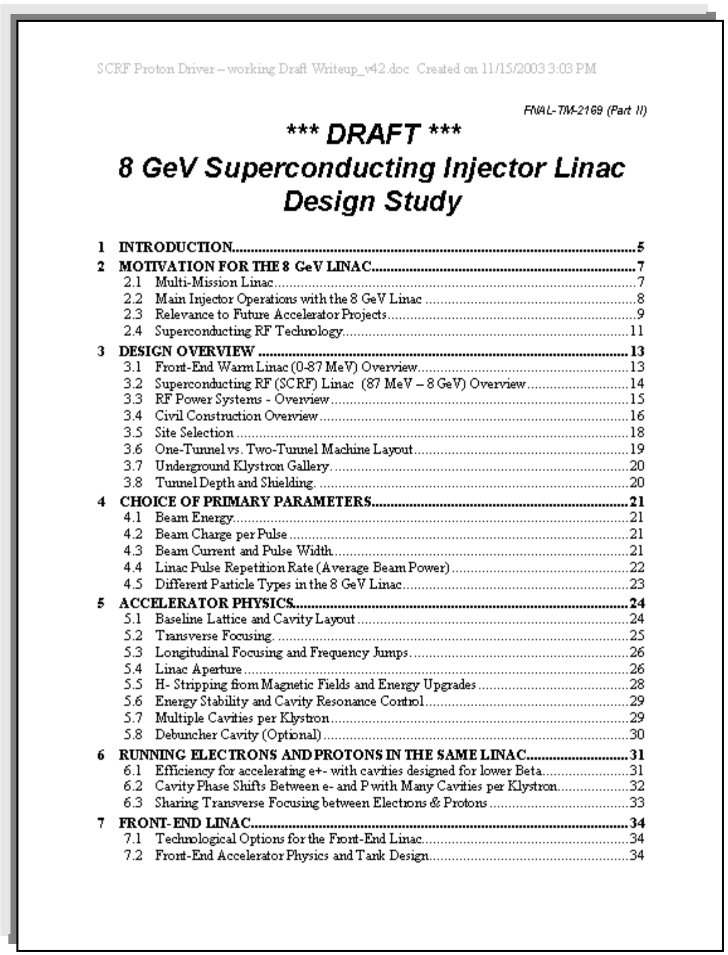
Multi-Mission 8 GeV Injector Linac

A SC LINAC might also have many other Missions at FNAL

eg… accelerate electrons as a 1.5% systems test of a cold Linear Collider



A Draft Design Study exists


SCRF Proton Driver – working Draft Writeup_v42.doc Created on 11/15/2003 3:03 PM

FNAL-TM-2169 (Part II)

*** DRAFT ***

8 GeV Superconducting Injector Linac Design Study

- **Web Link:**

http://tdserver1.fnal.gov/project/8GeVLinac/DesignStudy/

122 page document

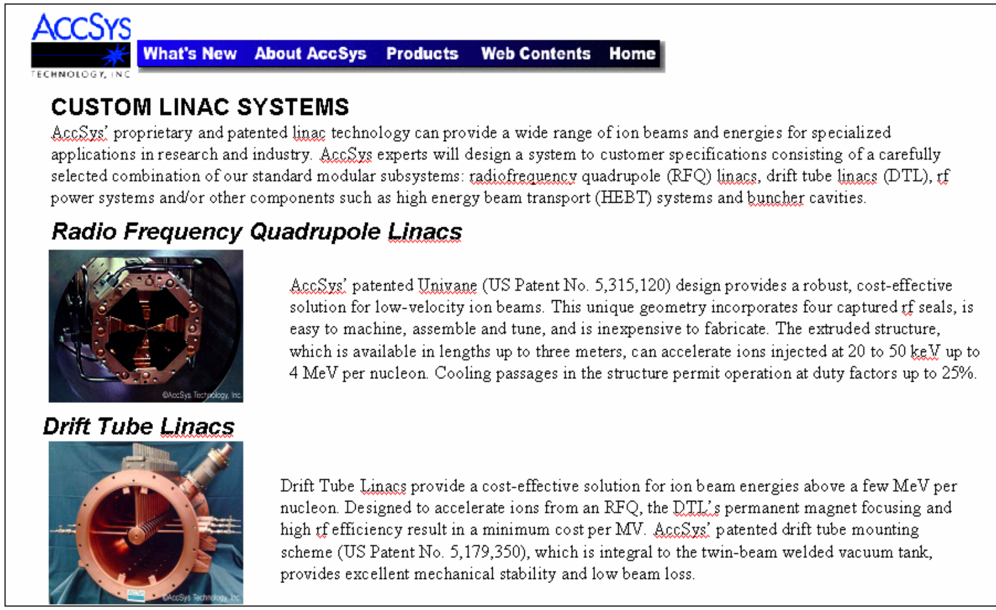
- **Plan: Next Few Weeks:**
  - Finish Edits
  - Merge with PD II Design Study
- **Technically it looks to be feasible**
- **Principle issue is the cost**
  - SNS was very expensive but there are reasons that this was so…
  - TESLA appears to be very cheap / Gev
  - Need to do a careful Technical Design Report including optimization and costs
- **That's the plan (more later)**

Basic plan for an 8 GeV SC Linac

- **Commercial 402.5 MHz RFQ & DTL up to 87 MeV**
  - Accelerator Physics design ~ cloned from SNS
- **805 MHz Superconducting Linac up to 1.2 GeV**
  - Three sections: Beta = 0.47, 0.61, 0.81
  - Use cavity designs developed for SNS & RIA
  - TESLA-style cryomodules for higher packing factor
- **1.2 GHz “TESLA” cryomodules from 1.2-8 GeV**
  - This section can accelerate electrons as well
  - RF from one Klystron fanned out to 12 cavities
  - Current design study assumed TESLA 500 gradients (25 MV/m) to achieve 8 GeV, if TESLA 800 gradients (35 MV/m) are practical ➔ can operate at 12 GeV or could reduce the cost accordingly

AccSys Source/RFQ/DTL

- **AccSys PL-7 RFQ with one DTL tank**



CUSTOM LINAC SYSTEMS

AccSys' proprietary and patented linac technology can provide a wide range of ion beams and energies for specialized applications in research and industry. AccSys experts will design a system to customer specifications consisting of a carefully selected combination of our standard modular subsystems: radiofrequency quadrupole (RFQ) linacs, drift tube linacs (DTL), rf power systems and/or other components such as high energy beam transport (HEBT) systems and buncher cavities.

Radio Frequency Quadrupole Linacs

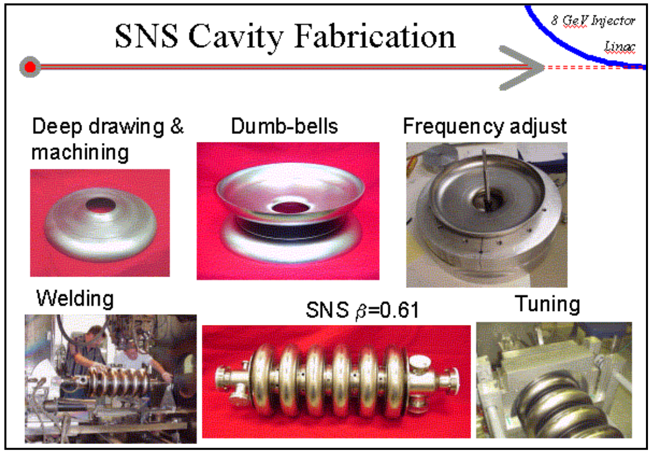
AccSys' patented Univane (US Patent No. 5,315,120) design provides a robust, cost-effective solution for low-velocity ion beams. This unique geometry incorporates four captured rf seals, is easy to machine, assemble and tune, and is inexpensive to fabricate. The extruded structure, which is available in lengths up to three meters, can accelerate ions injected at 20 to 50 keV up to 4 MeV per nucleon. Cooling passages in the structure permit operation at duty factors up to 25%.

Drift Tube Linacs

Drift Tube Linacs provide a cost-effective solution for ion beam energies above a few MeV per nucleon. Designed to accelerate ions from an RFQ, the DTL's permanent magnet focusing and high rf efficiency result in a minimum cost per MV. AccSys' patented drift tube mounting scheme (US Patent No. 5,179,350), which is integral to the twin-beam welded vacuum tank, provides excellent mechanical stability and low beam loss.

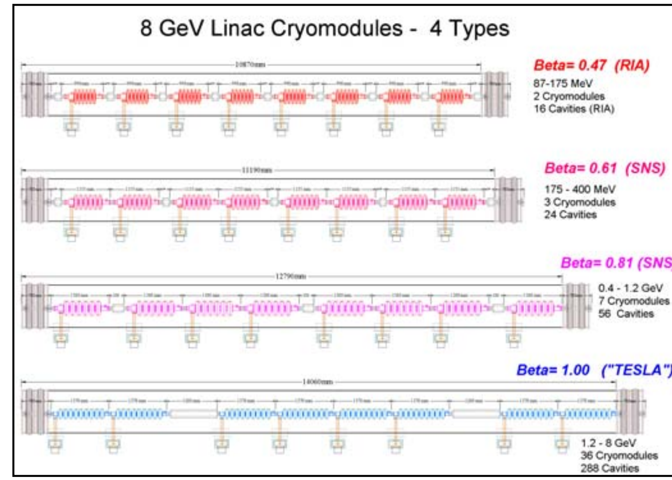
- **The low RF duty factor of the SC linac means one may be able to buy the linac front end commercially vs design and build it (SNS = expensive)**
- **AccSys has shipped multiple RFQ/DTL units for medical purposes in recent years. Front end needed for SC linac is very similar**
- **Vendor Estimate is ~$27M base cost for turn-key operation @87MeV. (Less if FNAL provides the RF Power source)**

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

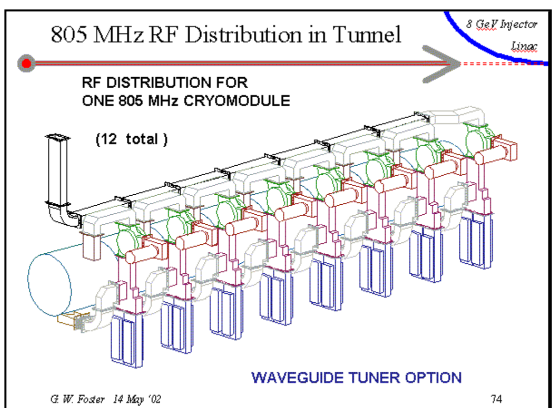


SNS Cavites

FNAL/TTF Modulators



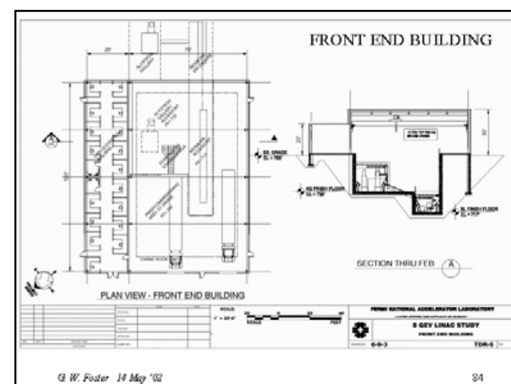
"TTF Style" Cryomodules



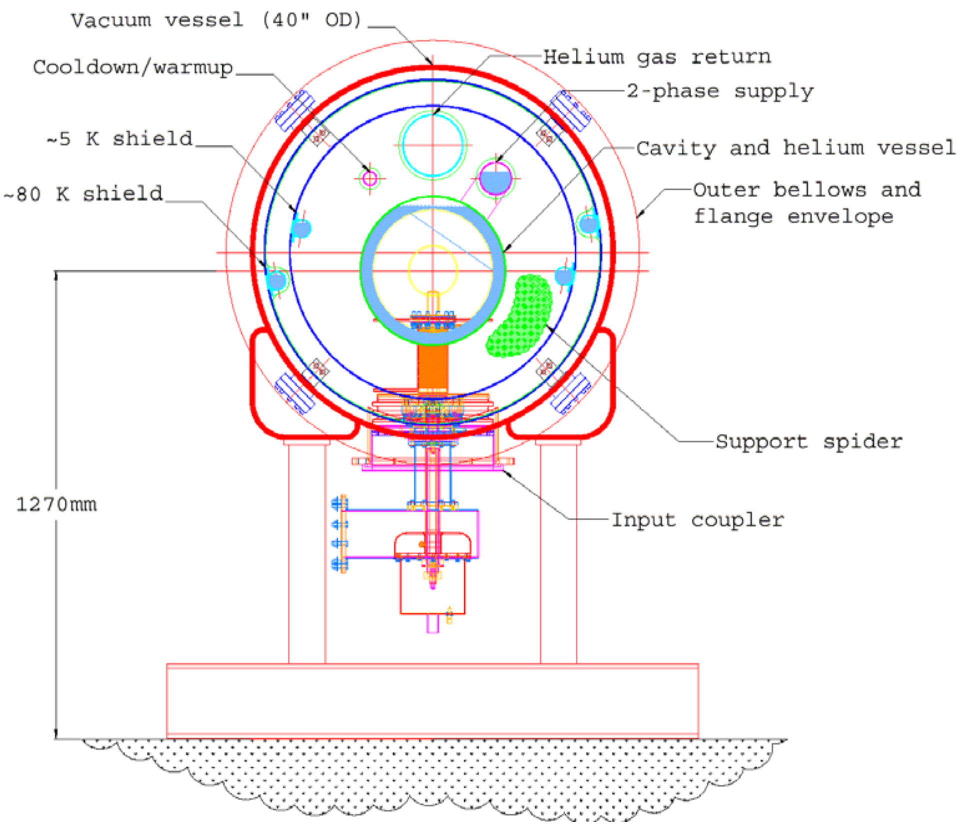
RF Distribution*

*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

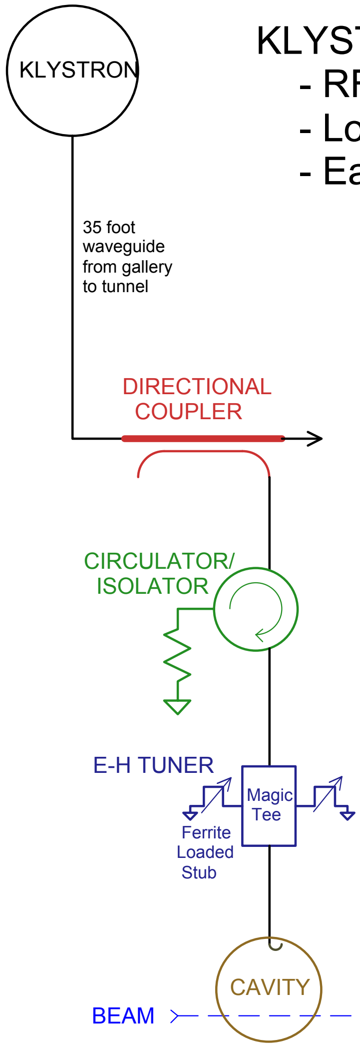
RF Couplers are KEK / SNS design, conductively cooled for 10 Hz operation

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

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



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

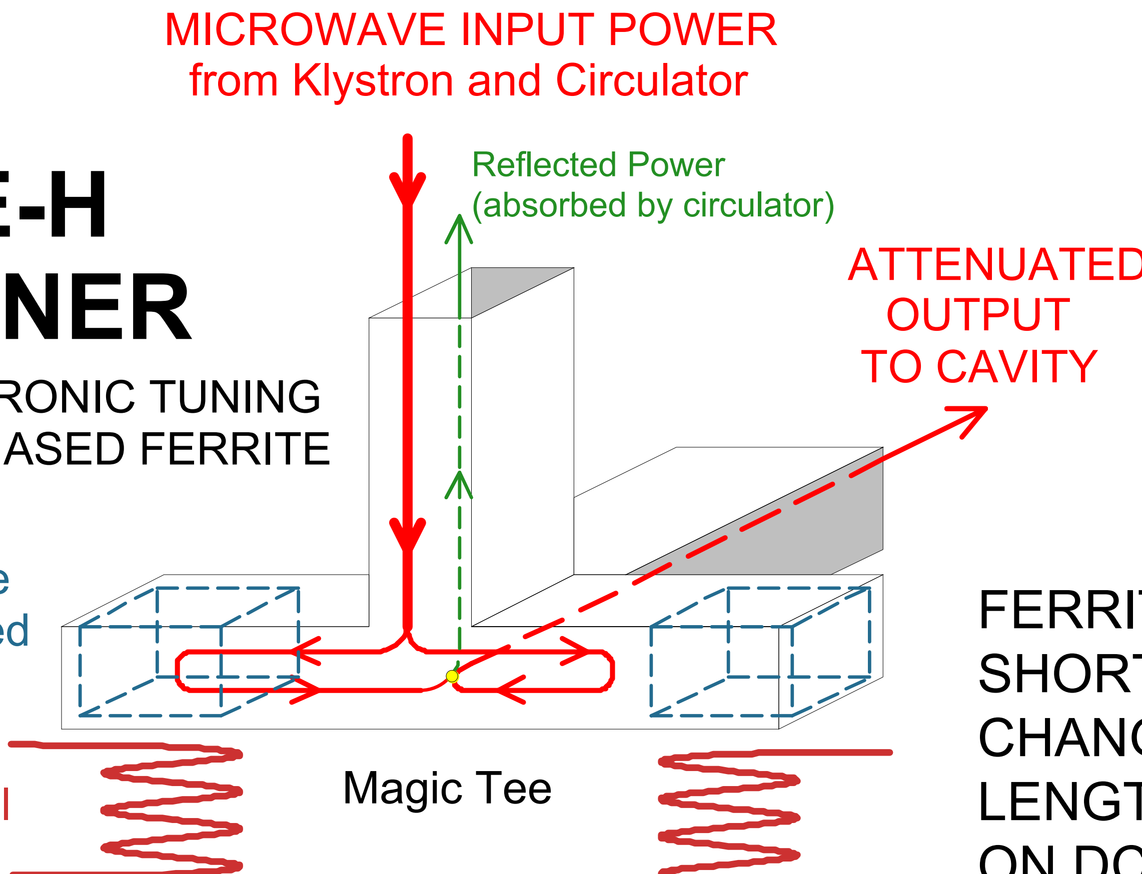
DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

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

ELECTRONICALLY ADJUSTABLE E-H TUNER



E-H TUNER

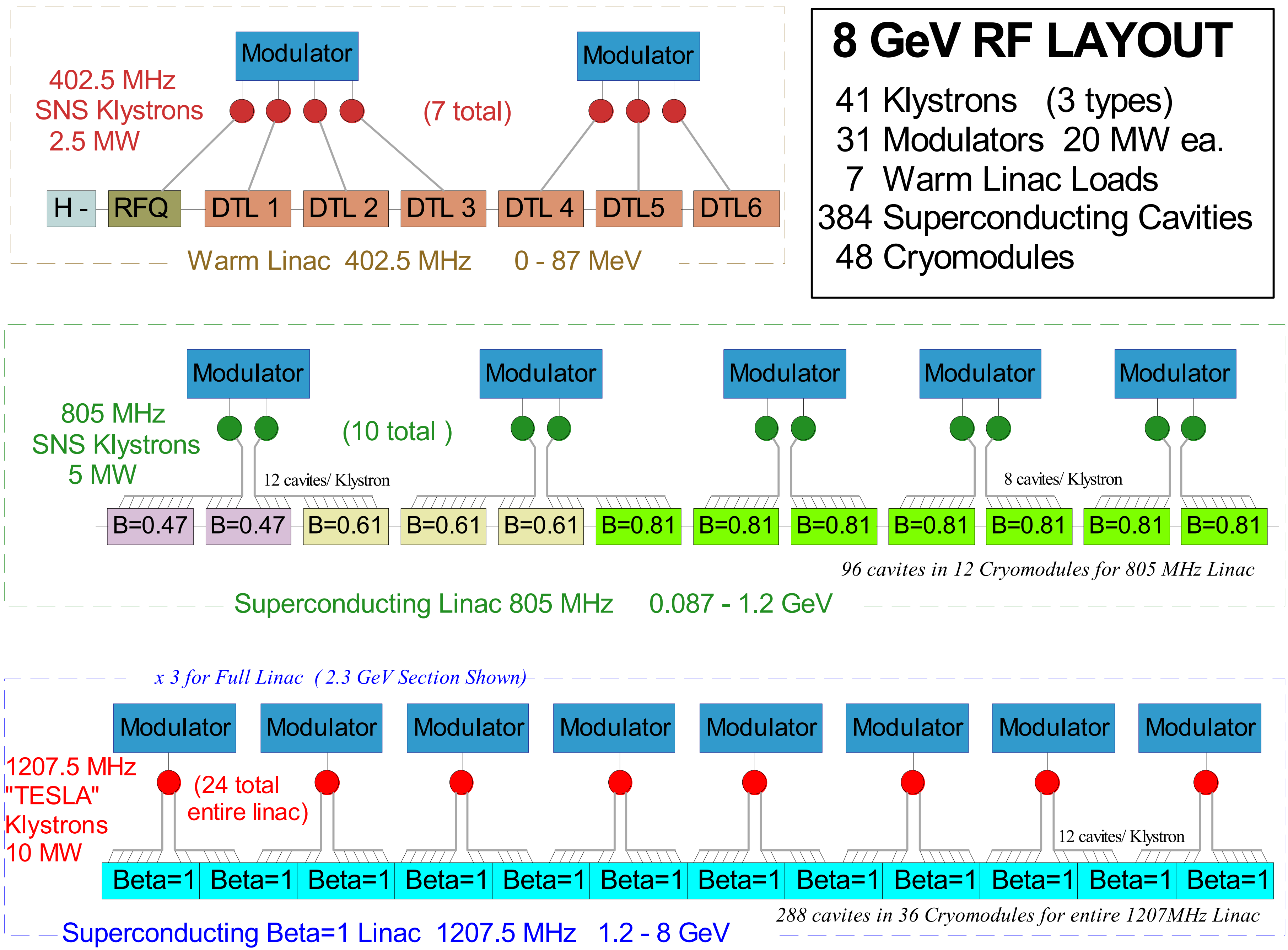
ELECTRONIC TUNING WITH BIASED FERRITE

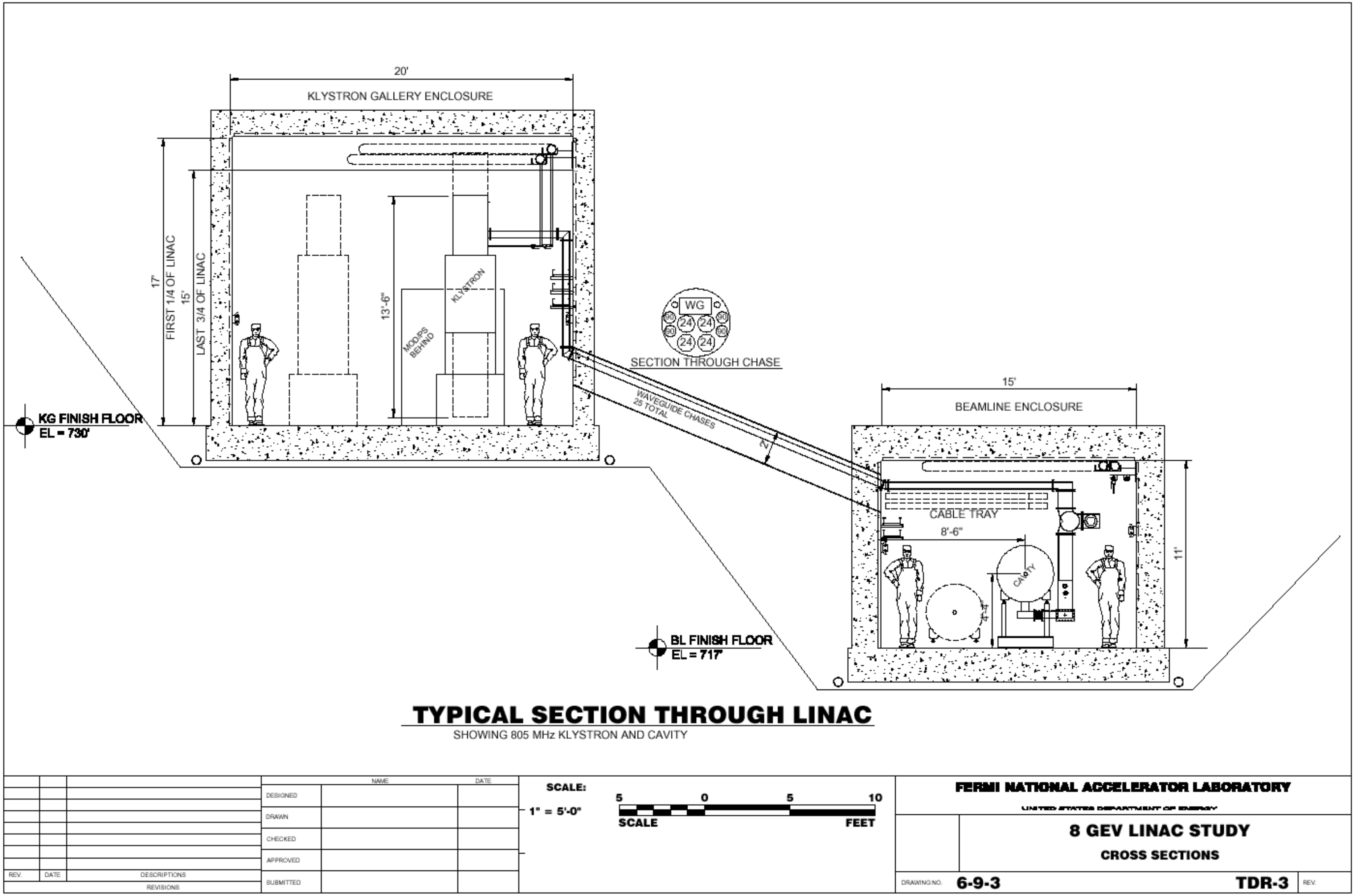
Attractive Price Quote from AFT

(<< Klystron)

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

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


8 GeV RF LAYOUT
41 Klystrons (3 types)
31 Modulators 20 MW ea.
7 Warm Linac Loads
384 Superconducting Cavities
48 Cryomodules
Modulator
402.5 MHz
SNS Klystrons
2.5 MW
(7 total)
H -
RFQ
DTL 1
DTL 2
DTL 3
DTL 4
DTL5
DTL6
Warm Linac 402.5 MHz 0 - 87 MeV
805 MHz
SNS Klystrons
5 MW
(10 total)
12 cavites/ Klystron
8 cavites/ Klystron
B=0.47
B=0.61
B=0.81
96 cavites in 12 Cryomodules for 805 MHz Linac
Superconducting Linac 805 MHz 0.087 - 1.2 GeV
x 3 for Full Linac (2.3 GeV Section Shown)
1207.5 MHz
"TESLA"
Klystrons
10 MW
(24 total
entire linac)
12 cavites/ Klystron
Beta=1
288 cavites in 36 Cryomodules for entire 1207MHz Linac
Superconducting Beta=1 Linac 1207.5 MHz 1.2 - 8 GeV



20'
KLYSTRON GALLERY ENCLOSURE
17'
FIRST 1/4 OF LINAC
15'
LAST 3/4 OF LINAC
13'-6"
KLYSTRON
MOD/PS BEHIND
KG FINISH FLOOR
EL = 730'
WG
SECTION THROUGH CHASE
WAVEGUIDE CHASES
25 TOTAL
15'
BEAMLINE ENCLOSURE
CABLE TRAY
8'-6"
CAVITY
11'
BL FINISH FLOOR
EL = 717'
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
8 GEV LINAC STUDY
CROSS SECTIONS
DRAWING NO. 6-9-3
TDR-3
REV.

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	

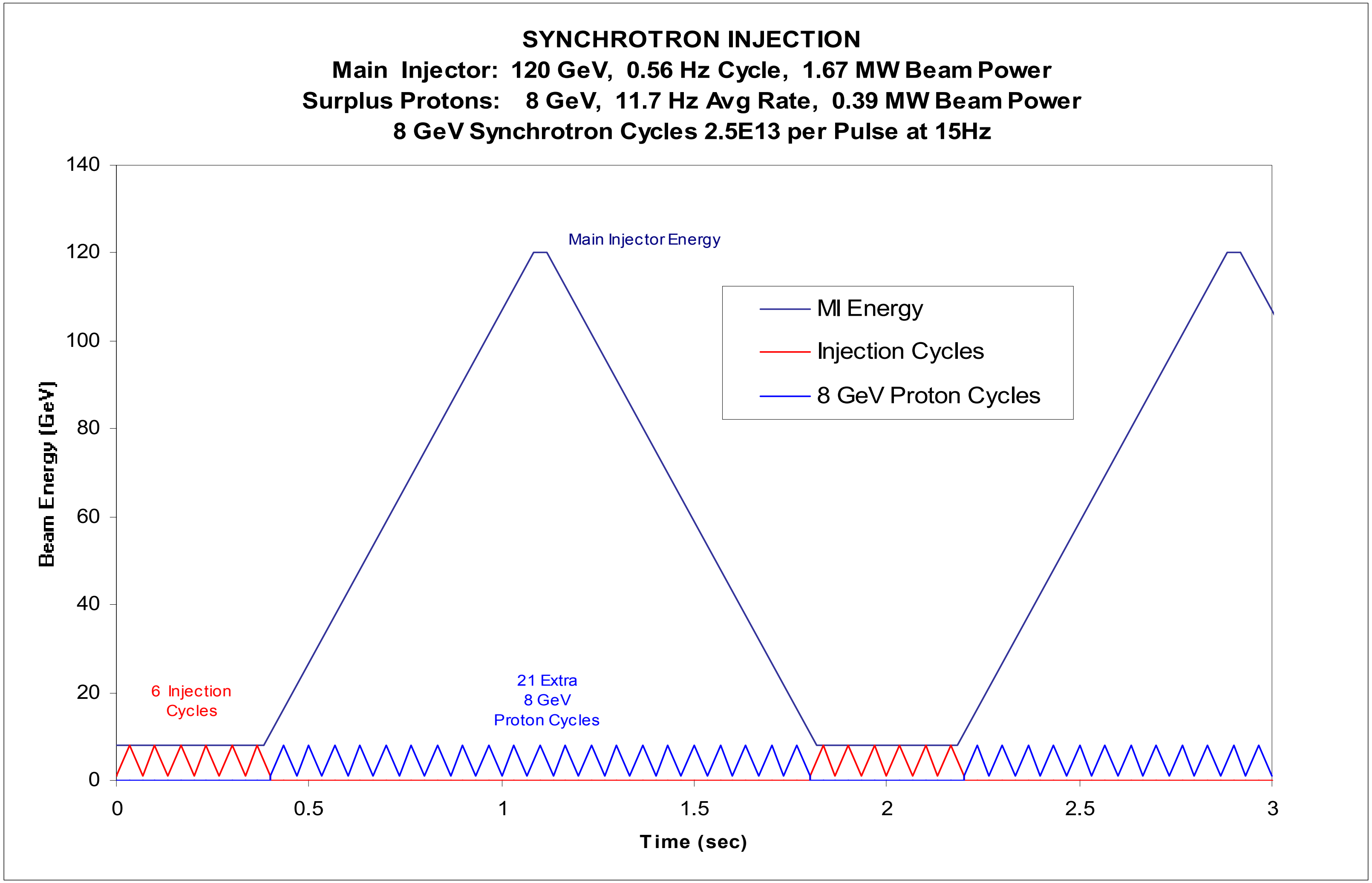
Main Injector with 8 GeV Linac

- **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 ~2π (or even ~0.5π (95%) at low currents)
  - phase space painting needed at high currents
  - avoids space charge limitations present at lower energy

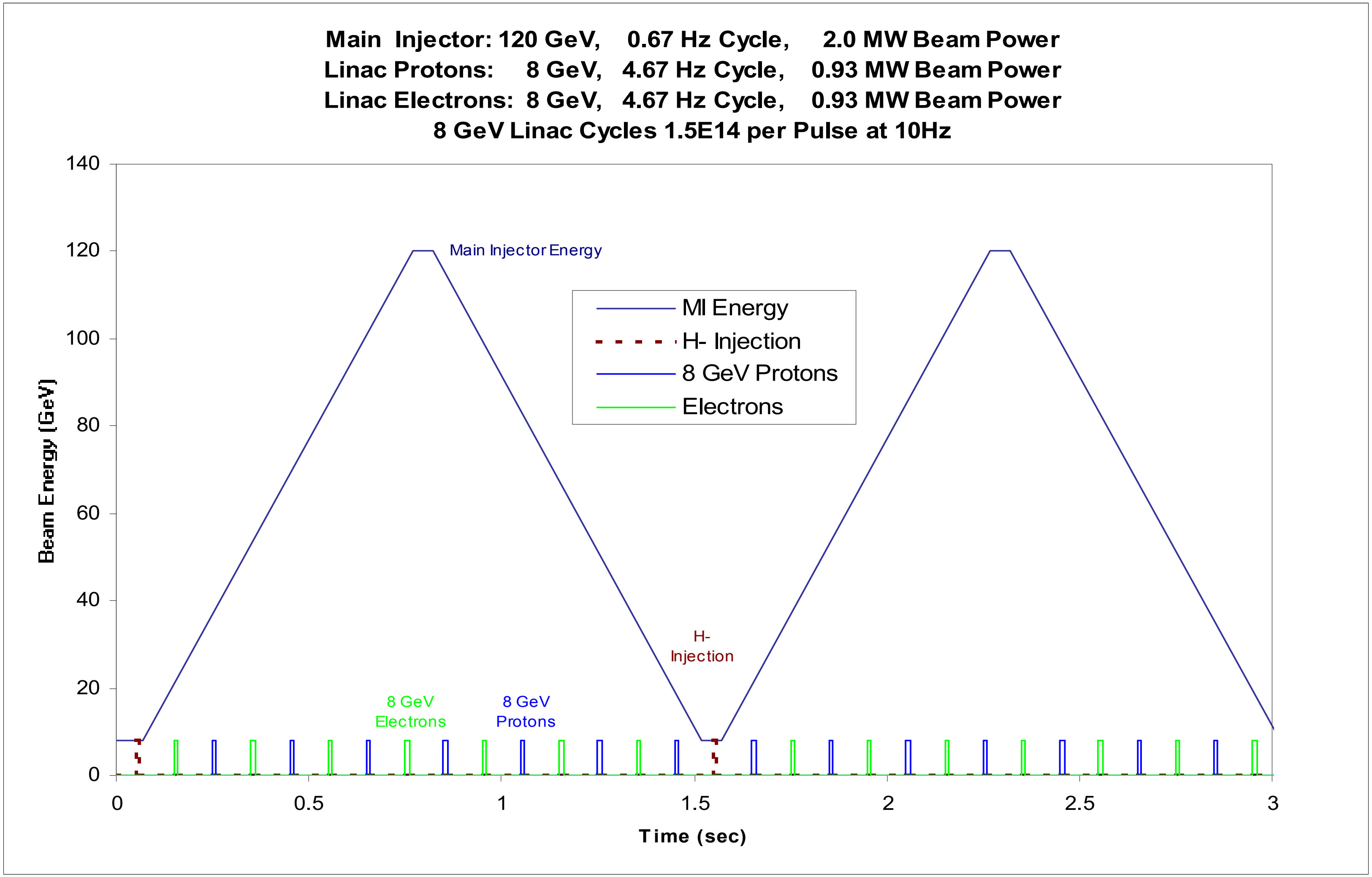
→ *can put a LOT of beam in MI !*

- **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 ?)

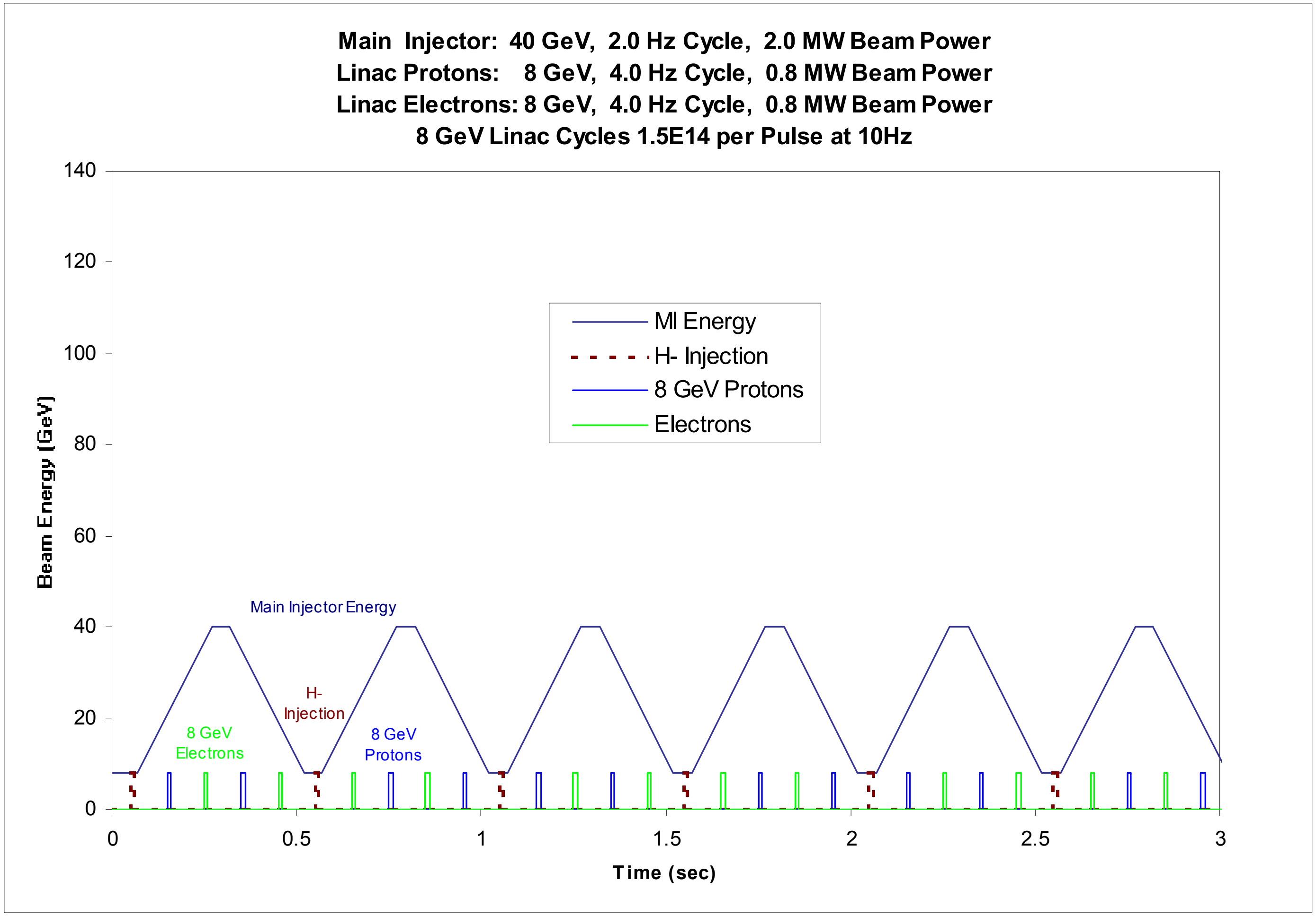
120 GeV Main Injector Cycle with 8 GeV Synchrotron



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

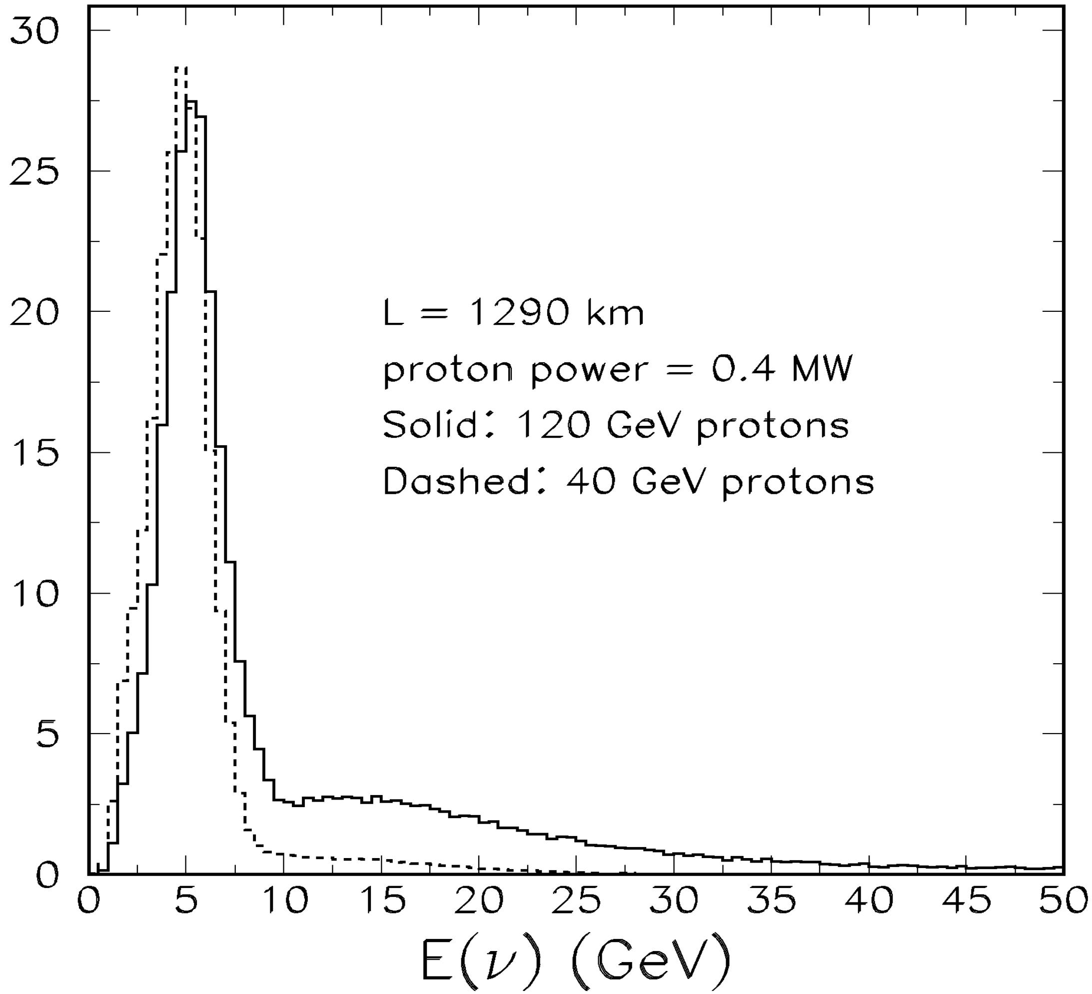


Linac Allows Reduced MI Beam Energy without Compromising Beam Power



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)

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**
- **The membership of the LRP committee and its charge can be found at this web site:**

http://www.fnal.gov/directorate/Longrange/Long_rang_planning.html

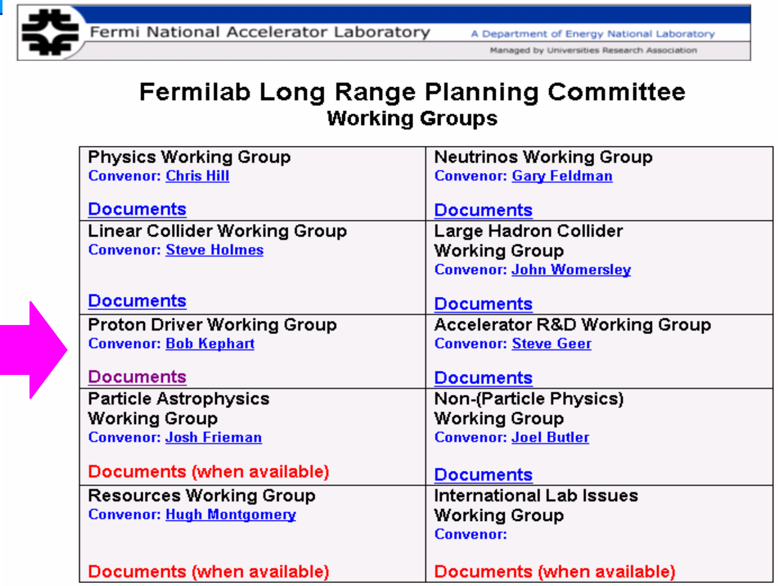
- **Excerpt from the charge to the LRP committee:**

  "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. …."

FLRP:PD Working group

PD Subcommittee:

Bob Kephart, chair
Steve Geer
Chris Hill
Peter Meyers
Sergei Nagaitsev



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)

Technical Advisors

Dave Finley	**Past BD Head (proton economics)**
John Marriner	**Past BD Head**
Shekar Mishra	**Past deputy head MI project**
Victor Yarba	**SCRF R&D (started TD RF group)**

Proponents

Weiren Chou	**Synchrotron based Proton Driver**
Bill Foster	**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" this past weekend**
  - Prelimary Proton Driver Recommendations
- **Final Report and recommendations in Feb 2004**
- **PD meetings has now evolved into a regular Proton Driver R&D/Design meeting**
  - More people joining the effort

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 (μs)	25	90	1000	1000
Booster (cycles at 15 Hz)				
Extraction kinetic energy (Gev)	8	8	-	-
Protons per cycle	5 x 10^{12}	2.5 x 10^{13}	-	-
Protons per hour	9 x 10^{16} (5 Hz)	1.4 x 10^{18}	-	-
8 GeV Beam Power (MW)	0.033 (5 Hz)	0.5	2	2
Main Injector				
Extraction Energy for NuMI (Ge	120	120	120	120
Protons per cycle	3 x 10^{13}	1.5 x 10^{14}	1.5 x 10^{14}	1.5 x 1014
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 x 10^{16}	3.5 x 10^{17}	3.5 x 10^{17}	6.6 x 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**

Preliminary 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 (AKA Proton Driver) will be proposed for construction at Fermilab in the not too distant future
- Similar in scope to the Main Injector Project (cost/schedule)
- An 8 GeV Superconducting Linac appears to be both possible and technically attractive
- The FNAL management plans to request a complete Technical Design Report for an 8 GeV SC linac including cost & schedule information in the next year
- This will make it possible to submit a Proton Driver project to the DOE for approval and funding