U.S. Plans for
High Power Proton Drivers

Steve Holmes
Fermilab

Workshop on Physics with a Multi-MW Proton Source
CERN
May 25, 2004

Outline

- Motivations
- Performance Goals
- Conceptual Descriptions
- Summary

High Power Proton Drivers
Motivations

- John Ellis has described the broad range of opportunities enabled by very high intensity proton machines, and Shoji Nagamiya has described the J-PARC facility aimed at capitalizing on some of these opportunities.
- Within the U.S. we have SNS under construction, and both Fermilab and BNL in the initial stages of developing concepts for 1-2 MW proton sources. From the point of view of Fermilab and BNL, with traditions in high energy and nuclear physics, the primary motivations are:
  - Neutrino physics
    - Super beams
    - Driver for a muon storage ring/neutrino factory
  - Rare decays (kaons, muons)
  - Pulsed neutrons
  - Injector for a very large hadron collider
- Similar ideas are being developed in Europe (Roland G. & Chris P.)

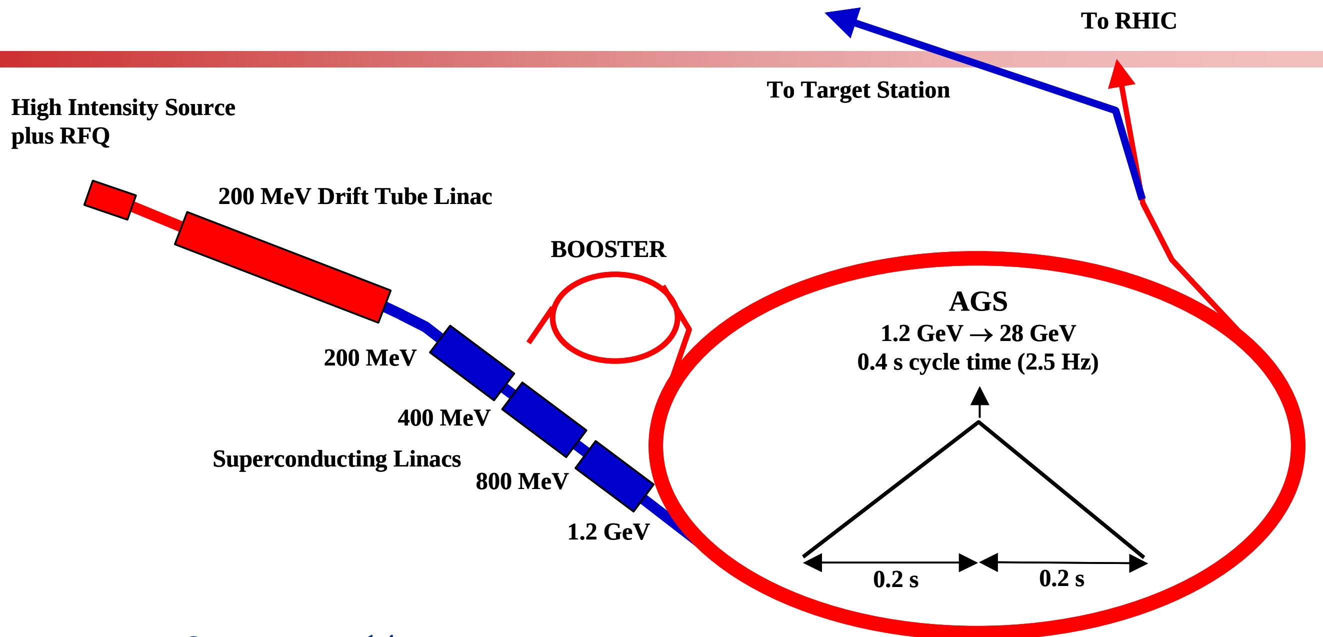
High Power Proton Drivers
Fermilab and Brookhaven

- Fermilab and Brookhaven concepts have several elements in common:
  - Increase the repetition rate of the existing machine (MI or AGS)
  - Decrease the fill time of the existing machine by using a (sc) linac
  - Increase the injected beam intensity by using a linac (or synchrotron)
  - Rely on previously developed SCRF technologies
- Both conceive of upgrade paths that could go another factor of 2-4
- The BNL concept features a 1.2 GeV superconducting linac as the injector into the (upgraded) AGS
- Fermilab has two implementations under evaluation, each with capability to inject into the Main Injector and to provide stand-alone 8 GeV beams:
  - 8 GeV synchrotron (with 600 MeV linac injector)
  - 8 GeV superconducting linac

High Power Proton Drivers
Performance Goals

	Fermilab Options				Brookhaven		
	Present	Synchrotron	Linac		Present	AGS Upgrade I	
Linac							
Kinetic Energy	400	600	**8000**		200	**1200**	MeV
Peak Current	40	50	25		40	30	mA
Pulse Length	90	90	1000		60	720	μsec
Protons/pulse	2.3E+13	2.8E+13	1.6E+14		1.5E+13	1.4E+14	
Repetition Rate	15	15	10		15	2.5	Hz
Average Beam Power	0.02	0.04	**2.00**		0.007	0.06	MW
Booster							
Kinetic Energy (Out)	8	8			1.5		GeV
Protons per Pulse	5.0E+12	2.5E+13			1.5E+13		
Repetition Rate	7.5	15			6.7		Hz
Protons/hour	1.4E+17	1.4E+18			3.6E+17		
Average Beam Power	0.05	**0.5**			0.02		MW
Main Injector				**AGS**			
Kinetic Energy (Out)	120	**120**	**120**		24	**28**	GeV
Protons per Pulse	3.0E+13	1.5E+14	1.6E+14		6.0E+13	9.0E+13	
Repetition Rate	0.54	0.65	0.67		0.33	2.50	Hz
Protons/hour	5.8E+16	3.5E+17	3.8E+17		7.2E+16	8.1E+17	
Average Beam Power	0.3	**1.9**	**2.0**		0.1	**1.0**	MW

Brookhaven AGS Upgrade



- Direct injection of ~ 1×10^{14} protons via a 1.2 GeV sc linac extension
  - low beam loss at injection; high repetition rate possible
  - further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)
- 2.5 Hz AGS repetition rate
  - triple existing main magnet power supply and magnet current feeds
  - double rf power and accelerating gradient
  - further upgrade to 5 Hz possible (x 2)

Brookhaven AGS Upgrade
Parameters

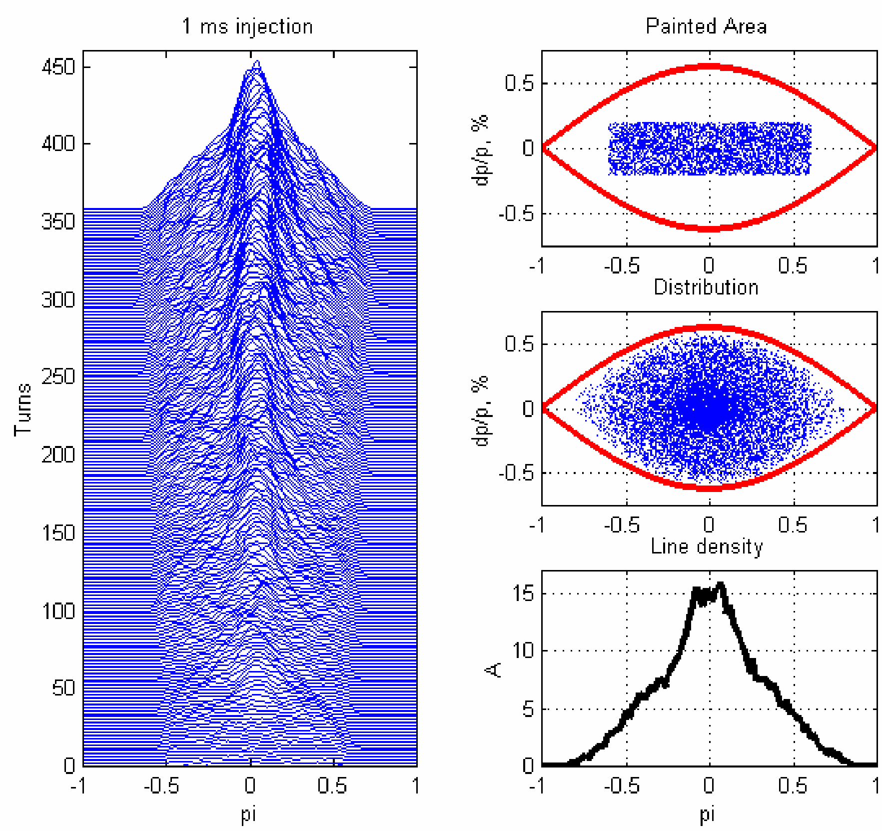
	Present	1 MW	2 MW
Total beam power [MW]	0.14	1.00	2.00
Injector Energy [GeV]	1.5	1.2	1.5
Beam energy [GeV]	24	28	28
Average current [μA]	6	36	72
Cycle time [s]	2	0.4	0.4
No. of protons per fill	0.7×10^{14}	0.9×10^{14}	1.8×10^{14}
Average circulating current [A]	4.2	5.0	10
No. of bunches at extraction	6	24	24
No. of protons per bunch	1×10^{13}	0.4×10^{13}	0.8×10^{13}
No. of protons per 10^7 sec.	3.5×10^{20}	23×10^{20}	46×10^{20}

Brookhaven AGS Upgrade

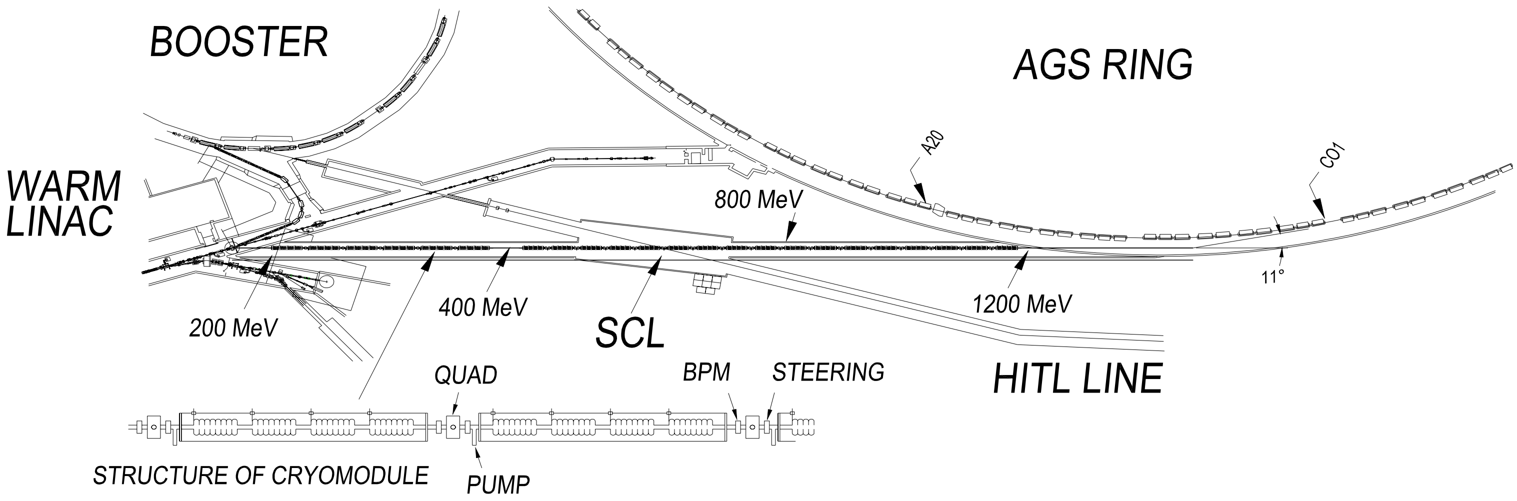
AGS injection Simulation

Injection parameters:

Injection turns	360
Repetition rate	2.5 Hz
Pulse length	1.08 ms
Chopping rate	0.65
Linac average/peak current	20 / 30 mA
Momentum spread	± 0.15 %
Inj. beam emittance (95 %)	12 π µm
RF voltage	450 kV
Bunch length	85 ns
Longitudinal emittance	1.2 eVs
Momentum spread	± 0.48 %
Circ. beam emittance (95 %)	100 π µm



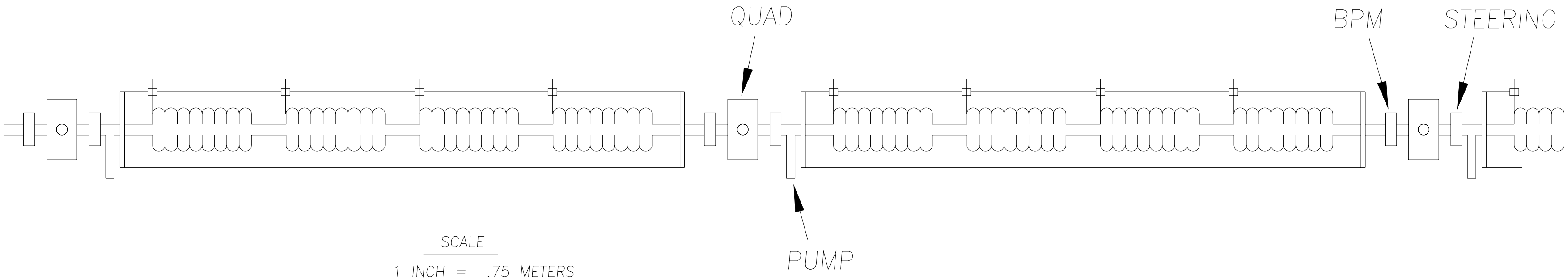
Brookhaven AGS Upgrade
Location of the 1.2 GeV SCL



Brookhaven AGS Upgrade

1.2 GeV Superconducting Linac

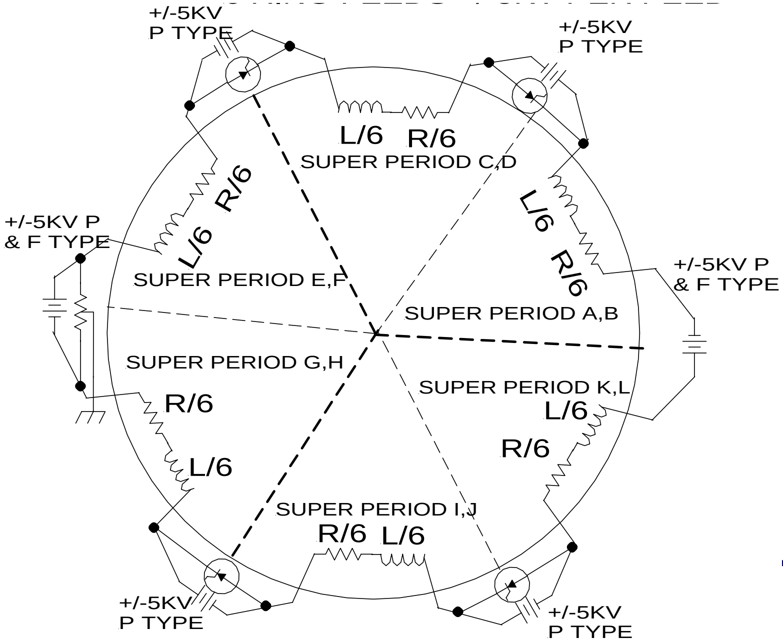
Beam energy	0.2 → 0.4 GeV	0.4 → 0.8 GeV	0.8 → 1.2 GeV
Rf frequency	805 MHz	1610 MHz	1610 MHz
Accelerating gradient	10.8 MeV/m	23.5 MeV/m	23.5 MeV/m
Length	37.8 m	41.4 m	38.3 m
Beam power, linac exit	17 kW	34 kW	50 kW



Based on SNS Experiences

New AGS Main Magnet Power Supply

	Upgrade	Present
– Repetition rate	2.5 Hz	1 Hz
– Peak power	110 MW	50 MW
– Average power	4 MW	4 MW
– Peak current	5 kA	5 kA
– Peak total voltage	± 25 kV	± 10 kV
– Number of power converters / feeds	6	2



AGS RF System Upgrade

Use present cavities with upgraded power supplies

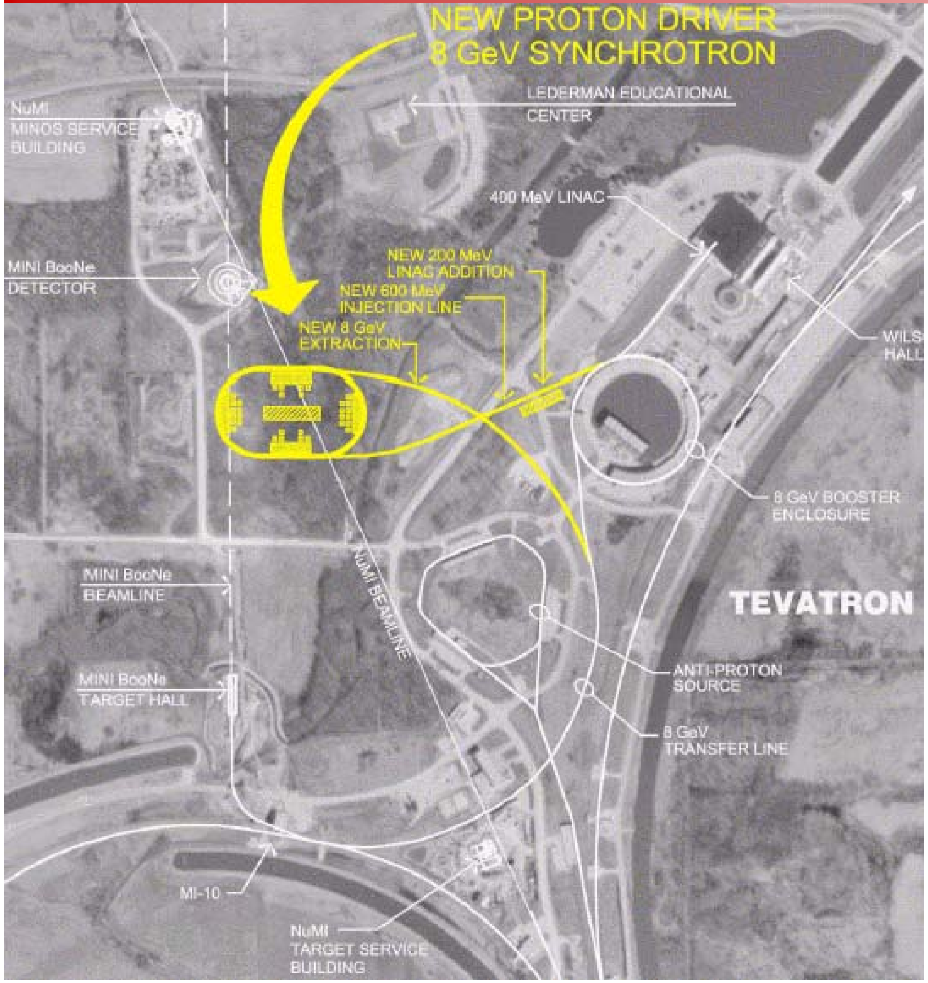
	Upgrade	Present
Rf voltage/turn	0.8 MV	0.4 MV
RF voltage/gap	20 KV	10 KV
Harmonic number	24	6 (12)
Rf frequency	9 MHz	3 (4.5) MHz
Rf peak power	2 MW	0.75 MW
Rf magnetic field	18 mT	18 mT
300 kW tetrodes/cavity	2	1

Fermilab Proton Driver

- Original Concept: 8 GeV Synchrotron (May 2002, Fermilab-TM-2169)
  - Long term proton demand seen as exceeding what reasonable upgrades of the existing Linac and Booster can support
  - Basic plan: 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 ($3\times10^{13} \rightarrow 1.5\times10^{14}$)
  - Reduce the 120 GeV MI cycle time 20% from 1.87 sec to 1.53 sec
    - ➢ Requires substantial upgrades to the Main Injector RF system
  - The plan also includes improvements to the existing linac (new RFQ and 10 MeV tank) and increasing the linac energy (400 $\rightarrow$ 600 MeV)

Net result $\Rightarrow$ increase the Main Injector beam power at 120 GeV by a factor of 6 (from 0.3 MW to 1.9 MW)

Fermilab Proton Driver
8 GeV Synchrotron



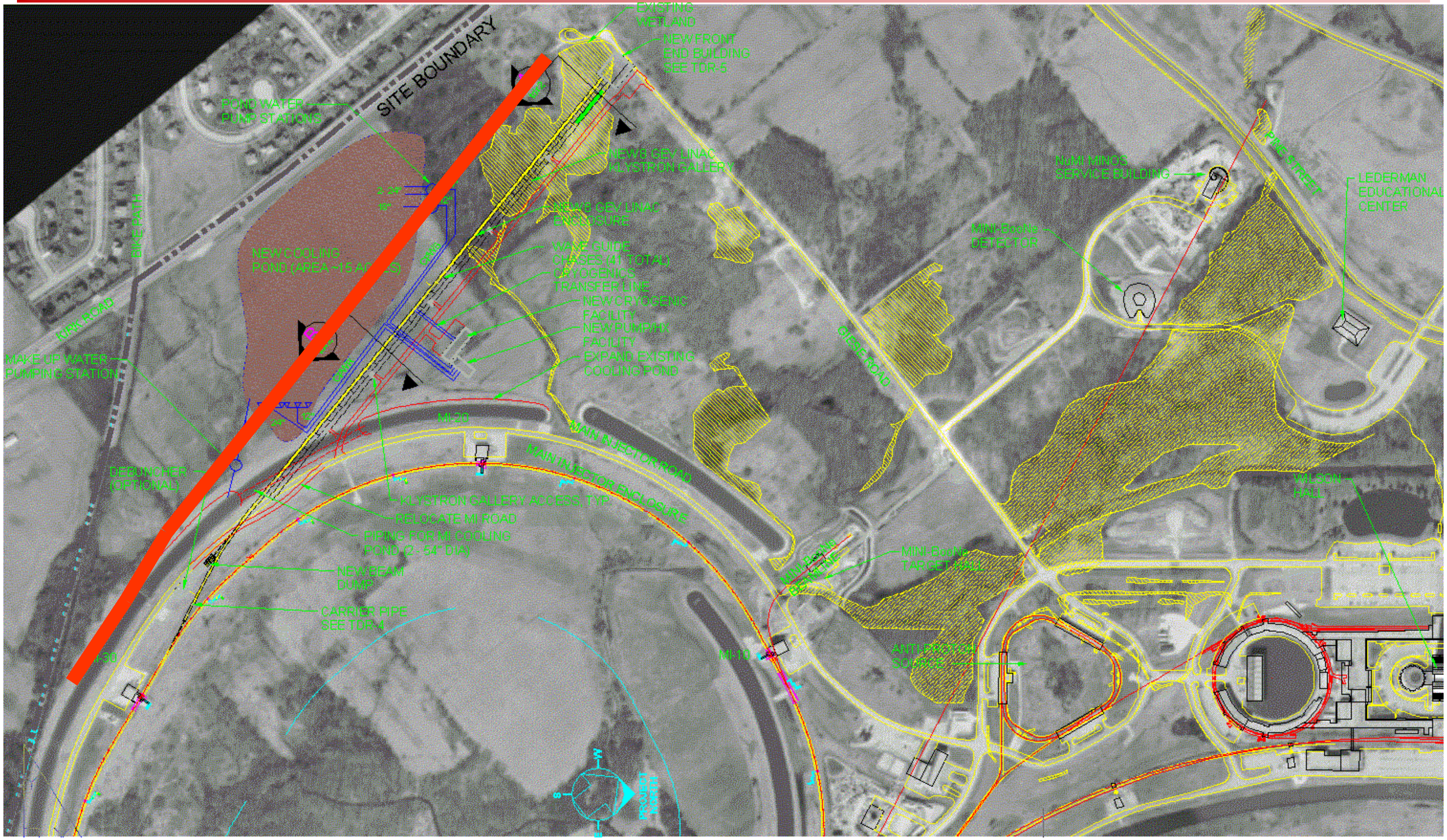
- Synchrotron technology well understood
- Large aperture ($100\times150\text{mm}^2$) magnets
- Modern collimation system to limit equipment activation
- Provides 0.5 MW beam power at 8 GeV; 1.9 MW at 120 GeV assuming upgrade of Main Injector ramp rate by 30%
- Likely less expensive than an 8 GeV linac

Fermilab Proton Driver
8 GeV Superconducting Linac

- Basic concept inspired by the observation (by Bill Foster) that $/GeV for SCRF has fallen dramatically
  - ⇒ Consider a solution in which H^- beam is accelerated to 8 GeV in a superconducting linac and injected directly into the Main Injector
- Attractions of a superconducting linac:
  - Many components exist (few parts to design vs. new synchrotron)
    - Copy SNS, RIA, & AccSys Linac up to 1.2 GeV
    - "TESLA" Cryo modules from 1.2 → 8 GeV
  - Smaller emittance than a synchrotron
  - High beam power simultaneously at 8 & 120 GeV
    - Plus, high beam power (2 MW) over entire 40-120 GeV range
  - Flexibility for the future
- Issues
  - Uncontrolled H^- stripping
  - Halo formation and control
  - Cost

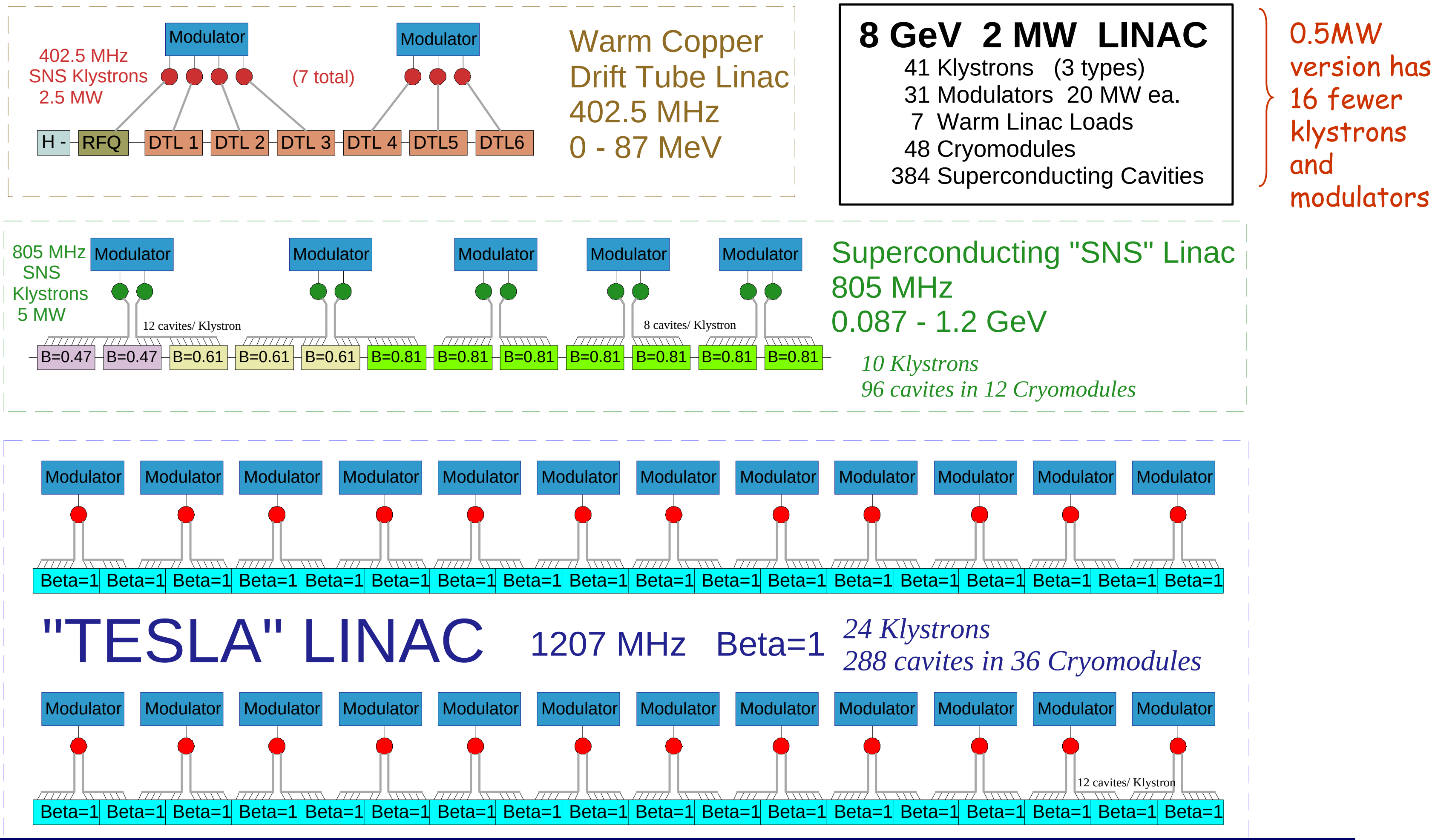
Fermilab Proton Driver

8 GeV SC Linac: Possible Site



Fermilab Proton Driver

8 GeV SC Linac: RF/Structure Layout



Fermilab Proton Driver
8 GeV SC Linac Parameters

8 GeV LINAC

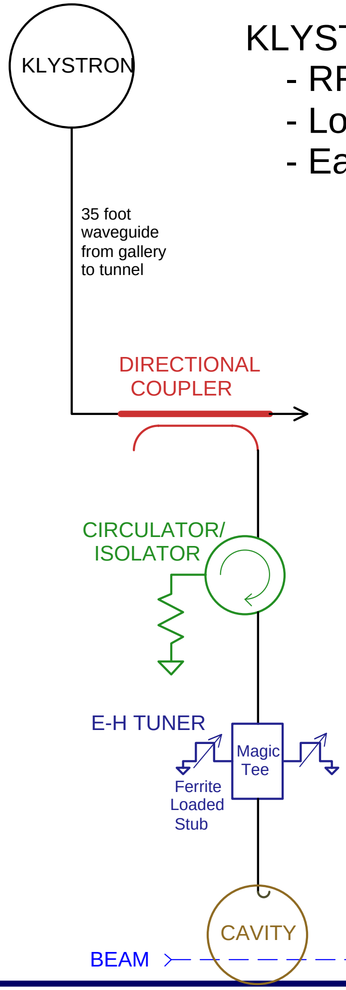
Energy	GeV	8	
Particle Type	H- Ions, Protons, or Electrons		
Rep. Rate	Hz	10	
Active Length	m	671	
Beam Current	mA	25	
Pulse Length	msec	1	
Beam Intensity	P / pulse	1.5E+14	(can be H-, P, or e-)
	P/hour	5.4E+18	
Linac Beam Power	MW avg.	2	
	MW peak	200	

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	

Fermilab Proton Driver

8 GeV SC Linac: RF Distribution



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

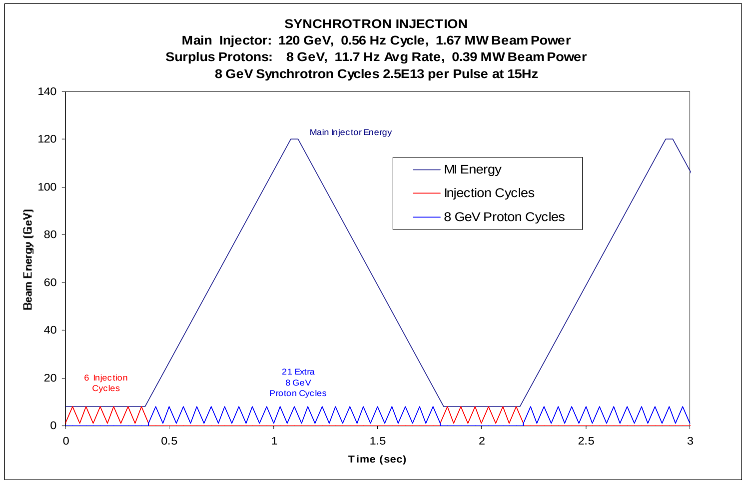
DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

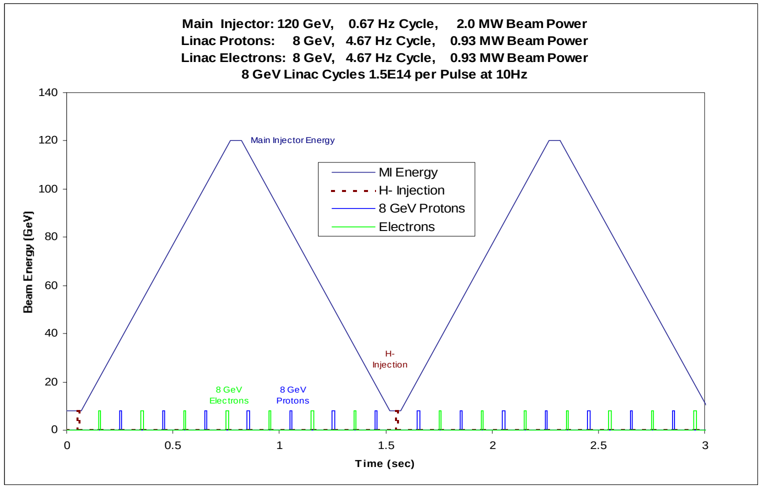
CIRCULATOR / ISOLATOR
- Passes RF power forward towards cavity
- Diverts reflected power to water cooled load

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

SUPERCONDUCTING RF CAVITY
- Couples RF Power to Beam

Fermilab Proton Driver
Main Injector Cycle Times

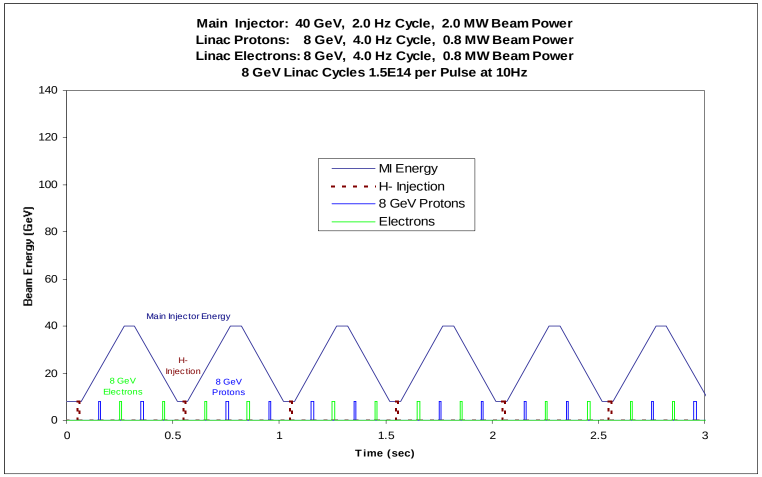




8 GeV Synchrotron

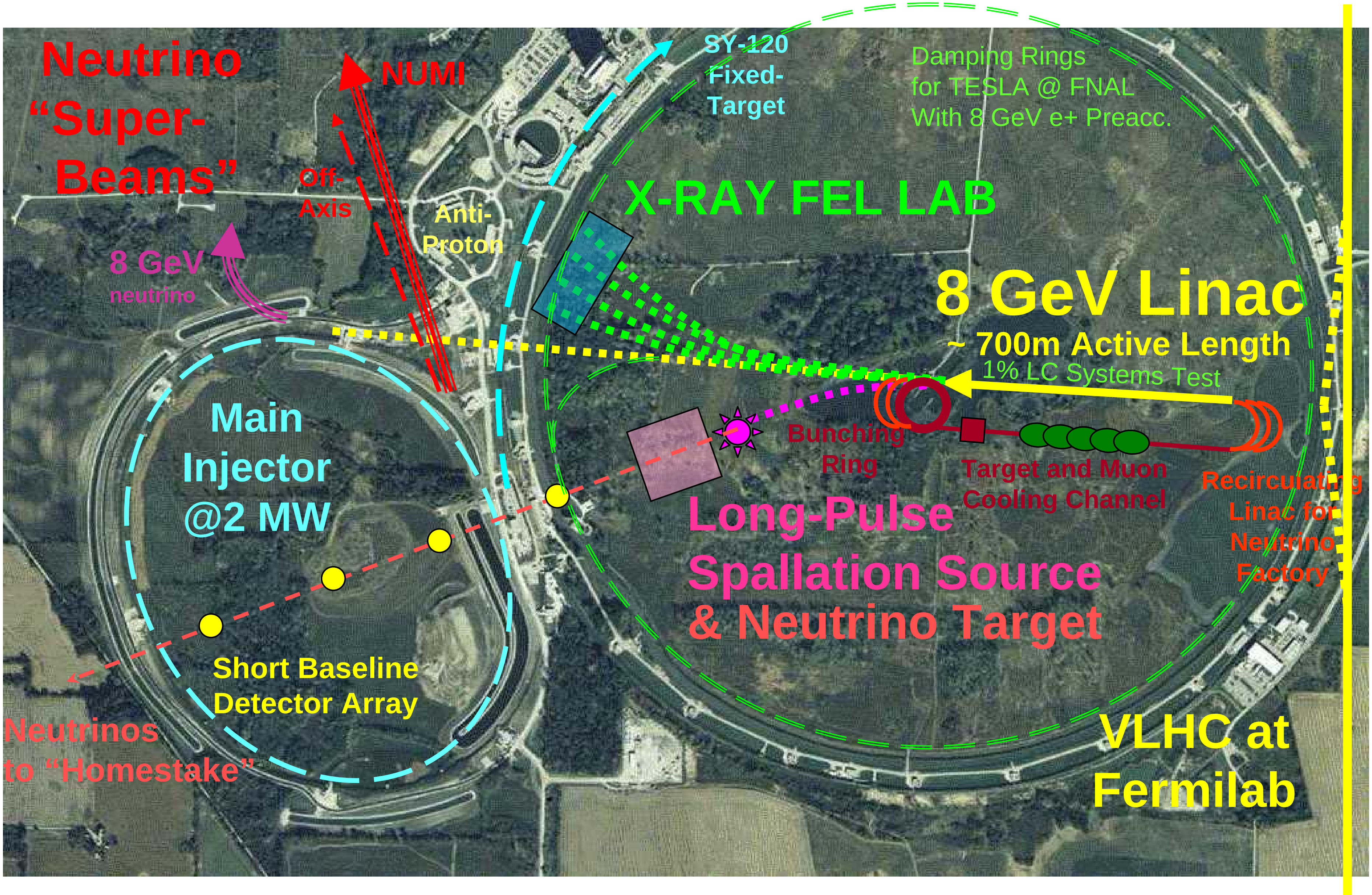
8 GeV Linac

Retains full beam power at lower energy (40 GeV)



Fermilab Proton Driver

8 GeV SC Linac: Other possible missions (from the mind of Bill Foster)



Fermilab Proton Driver

8 GeV SC Linac: Frequency Options

- Standardize on SNS /RIA (/FNAL/BNL) (805 MHz)
  - Develop "modified TESLA" 1207.5 MHz cavities
  - Develop Modified Multi-Beam Klystron
  - Develop new spoke resonator family if SCRF

OR?

- 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

⇒It would be nice to standardize to the extent possible among the proton machines that anticipate using SCRF technologies (including SPL)

Conclusions

- Design concepts for Proton Drivers in the 1-2 MW have been developed by both BNL and Fermilab.
- Both are motivated by a variety of physics opportunities, headlined by neutrino physics.
- Both are conducting R&D on critical technical and cost components.
- The Fermilab Long Range Plan identifies a 2 MW proton source as the preferred option in the event a linear collider is either constructed elsewhere, or delayed
  - We are preparing documentation sufficient to support a “statement of mission need”, aka Critical Decision 0 within the U.S. Department of Energy project management system.
- BNL is preparing a design study that could serve as the basis of a subsequent proposal.