FLRPC: Proton Driver

Bob Kephart
March 24, 2004
Outline

• FLRPC: Proton Driver Working Group
• Proton Driver Design Studies
  – 8-GeV synchrotron
  – 8-GeV Superconducting Linac ← bulk of the talk
  – MI upgrades
• FLRPC: 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
  - 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

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

DOE Program Review:
March 24, 2004
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 x 10^{13} \rightarrow 1.5 x 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 \rightarrow 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 \(\Rightarrow\) 200 MHz PA’s would still be a vulnerability, aging linac equipment still an issue
  - Cycle time is still 15 Hz \(\Rightarrow\) it would still take 5/15 of a sec to fill MI with 6 booster batches \(\Rightarrow\) limits upgrades to the MI cycle time (Beam power is proportional to \# p/cycle x cycles/sec)
  - Large aperture rapid cycling magnets \(\Rightarrow\) 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 (2 π mm-mrad, 95% normalized) which is “phase space painted” into MI (40 π ) aperture in 1 ms ➔ 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
Other Possible SCRF Linac Missions

- **Principle Mission: Proton superbeams for Neutrinos**
  - 8 GeV or 120 GeV from MI (NUMI/Off-axis = NOvA)

- **Also:**
  - Protons for future 120 GeV fixed target experiments and continued anti-proton production

- **Other possibilities:**
  - Protons:
    - Could Drive a Future Neutrino Factory
    - Could Drive a Spallation Neutron source
    - Could serve as a low emittance injector to a future VLHC
  - Accelerate electrons?
    - Could drive an x-ray FEL
    - Could be useful for LC beam or technology studies
Technological Synergies

- Lots of labs 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), MIT (Bates)
    - Electron cooling in RHIC (BNL), eRHIC (BNL)
    - BNL proton superbeam proposes 1.2 Gev SCRF Linac
    - SC linac is being discussed as part of the LHC upgrade
    - Medical isotope production, etc
A Draft Design Study exists

**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/8gevlinac

- 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**.
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)
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

402.5 MHz SNS Klystrons
2.5 MW

DTL 1 DTL 2 DTL 3 DTL 4
RFQ
Modulator Modulator (7 total)

Warm Copper Drift Tube Linac
402.5 MHz
0 - 87 MeV

805 MHz SNS Klystrons
5 MW

Modulator Modulator Modulator Modulator Modulator Modulator Modulator

12 cavities/ Klystron
8 cavities/ Klystron

Beta=1 Beta=1 Beta=1 Beta=1 Beta=1 Beta=1 Beta=1

402.5 MHz 0 - 87 MeV

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>8 GeV</td>
</tr>
<tr>
<td>Particle Type</td>
<td>H- Ions, Protons, or Electrons</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>Hz 10</td>
</tr>
<tr>
<td>Active Length</td>
<td>m 671</td>
</tr>
<tr>
<td>Beam Current</td>
<td>mA 25</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>msec 1</td>
</tr>
<tr>
<td>Beam Intensity</td>
<td>P / pulse 1.5E+14 (can be H-, P, or e-)</td>
</tr>
<tr>
<td>Linac Beam Power</td>
<td>MW avg. 2</td>
</tr>
<tr>
<td></td>
<td>MW peak 200</td>
</tr>
</tbody>
</table>

## MAIN INJECTOR WITH 8 GeV LINAC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI Beam Energy</td>
<td>120 GeV</td>
</tr>
<tr>
<td>MI Beam Power</td>
<td>2.0 MW</td>
</tr>
<tr>
<td>MI Cycle Time</td>
<td>sec 1.5</td>
</tr>
<tr>
<td></td>
<td>filling time = 1msec</td>
</tr>
<tr>
<td>MI Protons/cycle</td>
<td>1.5E+14</td>
</tr>
<tr>
<td>MI Protons/hr</td>
<td>3.6E+17</td>
</tr>
<tr>
<td>H-minus Injection</td>
<td>turns 90</td>
</tr>
<tr>
<td></td>
<td>SNS = 1060 turns</td>
</tr>
<tr>
<td>MI Beam Current</td>
<td>mA 2250</td>
</tr>
</tbody>
</table>
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

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

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

**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

MICROWAVE INPUT POWER
from Klystron and Circulator

E-H TUNER
ELECTRONIC TUNING WITH BIASED FERRITE

Reflected Power
(absorbed by circulator)

ATTENUATED OUTPUT TO CAVITY

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

TWO COILS PROVIDE INDEPENDENT PHASE AND AMPLITUDE CONTROL OF CAVITIES

Attractive Price Quote from AFT (<< Klystron)
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 at 8 GeV
  - Still delivers 2 MW from MI at 120 GeV

- **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
  - 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

SYNCHROTRON INJECTION
Main Injector: 120 GeV, 0.56 Hz Cycle, 1.67 MW Beam Power
Surplus Protons: 8 GeV, 11.7 Hz Avg Rate, 0.39 MW Beam Power
8 GeV Synchrotron Cycles 2.5E13 per Pulse at 15Hz

Time (sec)
0 0.5 1 1.5 2 2.5 3

Beam Energy (GeV)
0 20 40 60 80 100 120 140

- MI Energy
- Injection Cycles
- 8 GeV Proton Cycles

6 Injection Cycles
21 Extra 8 GeV Proton Cycles
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

**Main Injector:** 40 GeV, 2.0 Hz Cycle, 2.0 MW Beam Power

Linac Protons: 8 GeV, 4.0 Hz Cycle, 0.8 MW Beam Power

Linac Electrons: 8 GeV, 4.0 Hz Cycle, 0.8 MW Beam Power

8 GeV Linac Cycles 1.5E14 per Pulse at 10Hz

- # neutrinos ~ same
- Reduces tail at higher neutrino energies.
- May be a useful operating mode

**MI cycles to 40 GeV at 2Hz, retains 2 MW MI beam power**
## Comparison of PD options

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

- 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.
FLRPC: 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

• Understanding the physics of neutrino oscillations, the mass hierarchy, and perhaps CP violation in the neutrino sector requires a new generation of long baseline neutrino experiments ➔ a new intense proton source (Proton Driver)
• 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 has requested (charge) that the 8 GeV linac design be developed including cost & schedule information so that a technology choice can be made.
• Documentation in support of establishment of mission need, including both technical design and physics studies, will be produced in the next year.
• It is likely this will lead to a request for CD-0 from the DOE