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February 3, 2000

Status Report of the Proton Driver Design Study

OUTLINE

- Parameter set
- Physical layout
- Technical design issues
- R&D program
- Schedule for completing the TDR

Required number of protons by a neutrino factory:

$$2 \times 10^{20}\ \mu/\text{year for experiments}$$

$$\Downarrow$$

$$1/3 \text{ useful muons} \longrightarrow 6 \times 10^{20}\ \mu/\text{year in the ring}$$

$$\Downarrow$$

$$0.1\ \mu/p \longrightarrow 6 \times 10^{21}\ p/\text{year}$$

$$\Downarrow$$

$$2 \times 10^{7}\ \text{sec/year} \longrightarrow 3 \times 10^{14}\ p/\text{sec}$$

$$\Downarrow$$

$$15\ \text{Hz} \longrightarrow 2 \times 10^{13}\ p/\text{cycle}$$

Proton driver design goals:

$$2.5 \times 10^{13}\ p/\text{cycle}$$

$$\Downarrow$$

$$15\ \text{Hz} \longrightarrow 60\ \mu\text{A average current}$$

$$\Downarrow$$

$$16\ \text{GeV} \longrightarrow 1\ \text{MW beam power}$$

Table 1: Proton Driver Parameters of Present, Phase I and Phase II (1/20/00)

	Present	Phase I (ν-factory)	Phase II ($\mu\mu$-collider)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	50	80
Pulse length (μs)	25	80	200
H^- per pulse	6.3×10^{12}	2.5×10^{13}	1×10^{14}
Average beam current (μA)	15	60	240
Beam power (kW)	6	24	96
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	6.25×10^{12}	2.5×10^{13}
Number of bunches	84	4	4
Total number of protons	5×10^{12}	2.5×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	50π	200π
Longitudinal emittance (eV-s)	0.1	2	2
RF frequency (MHz)	53	1.9	7.5
Extracted bunch length σ_t (ns)	0.2	3	1
Average beam current (μA)	12	60	240
Target beam power (kW)	100	1000	4000

Proton Driver Sub-System Parameters (as of Jan 25, 2000)

1. H^- source and linac:
   - High brightness H^- source: 115 mA, 80 μs, 15 Hz, 0.5-1.0 π mm-mrad
   - RFQ: 100 mA, 60 keV – 2.235 MeV, 201.25 MHz
   - Modified Tank 1: 100 mA, 2.235 – 10 MeV, 1.4 π mm-mrad
   - 400 MeV linac upgrade: 80-100 mA, 80 μs, 1.5-2.0 π mm-mrad
2. Chopper:
   - 2 MHz, ± 4 kV, rise- and fall-time < 30 ns, physical length 15 cm
3. 16 GeV ring lattice
   - No transition crossing
   - Acceptance > 50 π mm-mrad, momentum aperture $= \pm 2.5\%$
   - Triangular shape with 3 zero-dispersion straights, $C \sim 700$ m
4. RF
   - 2 MHz, 1.2 MV, 20 MW
   - Finemet-loaded cavity with cut core, copper disc cooling
5. Magnets
   - Dipole: total 54, 2 types, 1.5 T, gap 5" × 13", $E = 8.9$ MJ
   - Quad: total 102, 3 types, 8.9 T/m, Accumulator LQA design, $E = 2.7$ MJ
6. Power supplies
   - Resonant circuit at 15 Hz, with 12.5% 30 Hz component
   - 27 cells, 14.7 mH/cell, 7500 A, voltage-to-ground 3 kV
   - Trim coil power supply for tracking error correction
7. Vacuum pipe
   - Thin metallic pipe, 5" × 9", eddy current heat ~ 8 kW/m
8. Collimators
   - 2-stage system, embedded in the injection straight
   - Designed for 10% loss at injection, 1% loss at top, efficiency $> 99\%$
   - Allowable loss in "quiet area" for hands-on maintenance: a few W/m

Table 2. High Beam Power Proton Machines

Machine	Protons per Cycle	Repetition Rate (Hz)	Protons per Second	Beam Energy (GeV)	Beam Power (kW)
Existing:					
RAL ISIS	2.5×10^{13}	50	1.25×10^{15}	0.8	160
BNL AGS	7×10^{13}	0.5	3.5×10^{13}	24	130
LANL PSR	2.5×10^{13}	20	5×10^{14}	0.8	64
Planned:					
Fermilab MiniBooNE	5×10^{12}	7.5	3.8×10^{13}	8	50
Fermilab NUMI	4×10^{13}	0.5	2×10^{13}	120	400
Proton Driver	1×10^{14}	15	1.5×10^{15}	16	4000
Europe ESS	2.34×10^{14}	50	1.2×10^{16}	1.334	2500
ORNL SNS	2×10^{14}	60	1.2×10^{16}	1	2000
Japan JHF	3.2×10^{14}	0.3	1×10^{14}	50	780

Technical Design Issues

- Unique feature of this machine - High longitudinal brightness N_b/ϵ_L.
  - High beam power, a few bunches $\longrightarrow$ large N_b
  - Short bunch length $\longrightarrow$ small ϵ_L
- How to preserve longitudinal emittance:
  - Avoid transition (lattice design)
  - Avoid microwave instability
    - Always below transition
    - Keep resistive wall impedance small
  - Avoid coupled bunch instability (low Q cavity)
  - Inductive insert for compensating space charge
  - Longitudinal damper
- How to perform high intensity bunch rotation:
  - Instability
  - Beamloading
  - Effect of higher order momentum compaction α_1
  - Effect of space charge tune spread
- How to get large momentum as well as dynamic aperture in a FMC lattice
- How to compensate beamloading of an intense short bunch (hundreds amperes peak current)
- How to collimate the beam so that the tunnel activation level would allow hands-on maintenance.
- How to do injection when the power supply is dual harmonic.
- How to do painting.
- How to correct tracking errors in a resonant synchrotron using separated function magnets.

- How to design and fabricate high gradient rf cavity.
- How to design and fabricate thin metallic pipe carrying heavy eddy current heat load.
- How to design and test high brightness H^- source.
- How to design and test RF chopper.
- How to design, fabricate and test large magnets requiring big good field region.
- *etc.*

R&D Program

- Hardware R&D
    1. High gradient rf cavity prototyping
    2. Beamloading compensation
    3. Thin metallic beam pipe prototyping
    4. 53 MHz booster rf cavity modification
    5. RF chopper
- Machine experiments
    1. 132 ns coalescing in the Main Injector using Finemet cavity
    2. Inductive insert
    3. 6-lab "contest":
       Six laboratories (BNL, KEK, Fermilab, CERN, Indiana U. and GSI) are to carry out two experiments (bunch compression, microwave instability below transition) on their own machines. The competing items are:
        - Max I_{peak}
        - Max N_b/eV-s
        - Max compression ratio

To: J. Marriner, P. Martin

From: Proton Driver TDR Team

Date: January 10, 2000

Subject: Proposal for coalescing and beamloading compensation experiments
in the Main Injector using a Finemet cavity

Cc: S. Holmes

We propose to install a 7.5 MHz Finemet cavity in the Main Injector for two experiments: (1) beam coalescing for 132 ns bunch spacing, (2) beamloading compensation using a digital system.

1. Motivation:
   As part of the US-Japan collaboration, the proton driver TDR team is building a 7.5 MHz rf cavity using Finemet cores. This cavity is about 0.5 m long and will produce about 16 kV gap voltage. It can be used for a future multi-megawatt proton driver. It can also be used in the Main Injector for beam coalescing to obtain 132 ns bunch spacing, which is required by the Tevatron in Run II. In addition, a digital beamloading compensation system is under design. It will use the same cavity to compensate the transient beamloading voltage. The proposed experiments will test both the cavity and the compensation system.

2. Steps and and schedule:

   (a) Cavity assembly: The Finemet cores, copper cooling disks, case and power tube are in place. Various parts of the power amplifier are being fabricated in the machine shop. The assembly should be completed by February.

   (b) High power test (200 kW): This will be done from February to March in the MI-60 building.

   (c) Cavity installation: The cavity will be installed at 630E of the MI-60 straight section in the tunnel. This work is planned for the March-April period when E-835 is running.

   (d) Coalescing experiment: April and May.

   (e) Beamloading compensation experiment: The system should be ready by June. The experiment will be done during the summer.

   Some details about (d) and (e) can be found in the appendices by D. Wildman and J. Steimel.

3. Required resources:

(a) We need to borrow the following equipments:

- One spare MI modulator
- One spare Recycler wideband amplifier
- One portable anode supply (in MI test station)
- Seven coax cables pulled from MI-60 gallery to the tunnel
- Four hoses to connect to existing water drops in the tunnel
- 2" support to place cavity at correct height in the beamline
- 7.5 MHz LLRF signal, either direct from LLRF (clock frequency) or from 2.5 MHz coalescing drive signal

(b) Manpower and funds:
Most of the installation and test work will be carried out by the proton driver rf working group. The coalescing experiment will be coordinated by D. Wildman, the beamloading compensation experiment by J. Steimel.

Most of the costs will be covered by the proton driver budget code (NPD). Some electrical work for power installation may need contract electricians (cost a few $k). A mechanical tech for vacuum hookup will also be needed.

To: J. Marriner

From: Proton Driver TDR Team
Proton Source Department

Date: January 12, 2000

Subject: A joint proposal for Booster cavity modification

Cc: P. Martin, F. Lange, R. Pasquinelli

We propose to modify a present Booster rf cavity to achieve two goals: (1) to enlarge the aperture from 2.25" to 5", (2) to increase the cavity voltage by 20%.

1. Motivation:

   - Proton Driver
     One application of the proton driver is to serve as a new high intensity booster for the Main Injector. In this scenario, the present booster rf cavity (53 MHz) could be reused, which would be a significant cost-saving measure. Previous studies show that, with appropriate upgrades, the MI could take 2.5×10^{13} protons from each booster cycle, a number consistent with the proton driver Phase I design. However, the present booster cavity aperture (2.25") is too small and has not enough accelerating voltage (55 kV per cavity). This modification would increase the aperture to 5" and voltage to 66 kV to meet the proton driver design goal.
   - Present Booster
     Installation of dogleg magnets around the extraction septa and improved gradient magnet alignment in recent years has increased the useful aperture of the Booster. These efforts have been successful to the point that the rf cavities now represent the next level of aperture limits in the machine. The rf power amplifiers, sitting atop the cavities, are the highest maintenance items in the Booster. Already the cavities are among the highest residual radiation points in the Booster apart from the injection and extraction components. Enlarged cavity aperture, while leading to only fractionally small increases in beam intensity, will certainly reduce radiation levels at the cavities themselves. PA and cavity maintenance will become a critical issue as Booster duty cycle and proton throughput are increased an order of magnitude from present operation for MiniBooNE and NUMI experiments. Cavity aperture improvements will greatly facilitate this maintenance from a radiation safety perspective and result in increased beam up time. Booster operation at higher average pulse rates will lead to more wear and tear on the amplifiers and most likely more

frequent failure. Increased cavity voltage will provide a greater margin of available rf voltage, permitting operation to continue in spite of several station failures. This will reduce the number of unscheduled operational interruptions for PA maintenance.

2. Plan and schedule:

   - Plan A:
     The modification work will be done on a damaged booster cavity and will have two phases:
     - Phase I - Proof-of-principle study and low power test. It consists of three steps:
       (a) enlargement of the beam pipe ID to 5"
       (b) decrease of the anode blocking capacitance to 400 pF
       (c) modification of the tuners
     - Phase II - High power test.

     Phase I will take about 9 months, Phase II another 4-6 months. The design principles can be found in Appendix 1 by J. Griffin, and the detailed plan in Appendix 2 by J. Reid.

   - Plan B:
     A primary objective of this proposal is to demonstrate, in less than two years, a functional high power, prototype cavity/amplifier system sufficiently modified from the present design to provide substantial improved benefits to the existing Booster. Should this objective be threatened by difficulties achieving the 5" aperture and/or 20% voltage increase goals, PLAN B goals of 3" and up to 10% shall be pursued instead. These values are believed adequate to realize most of the potential benefit to the present Booster, if they can be implemented in the machine on a time scale commensurate with NUMI operation.

3. Required funds and manpower:

   - Phase I – M&S fund of $54k.

Mechanical Engineer	1 x 20% x 9 mos.
Electrical Engineer	1 x 50% x 9 mos.
Physicists	1 x 40% x 9 mos.
Mechanical Techs	2 x 30% x 9 mos.
Draftsman	1 x 50% x 4 mos.

   - Phase II – M&S fund of $120k. (Note: This number is smaller than Reid's original estimate because of a change in the ceramic window design.)

Electrical Engineer	2 x 50% x 4 mos.
Physicists	1 x 50% x 4 mos.
Mechanical Techs	2 x 25% x 4 mos.
Draftsman	1 x 50% x 4 mos.

This work will be led by M. Champion under the guidance of the proton driver rf working group. The expected support from the ME department includes two techs (One is M. Rauchmiller, who has already been assigned to this work but won't be back until March due to a surgery; another could be G. Lawrence) and a part-time engineer (probably M. May).

Schedule

- April 2000: Internal review of the proton driver design.
- October 2-6 2000: ICFA workshop on high intensity high brightness hadron beams.
- December 2000: A complete TDR.

- Under consideration - One-day workshop to discuss possible physics program using the proton driver (sometime this summer).