Concept and R&D Plans for Project X
Introduction

- Intensity Frontier: Needs and Physics Justification
- Project X
  - Description
  - Technical Concepts
  - Timescale
- R&D Plans and Contributing Programs
  - HINS
  - ILC/SRF
- Collaboration Plans
- Conclusions
Physics of Flavor

- Flavor phenomena are essential to understanding physics within and beyond the SM
- SM is incomplete:
  - Neutrino masses (flavor)
    - Only experimental hint of BSM physics.
    - via See-Saw mechanism, point to new physics at a very high mass scale (unification scale).
    - \[ m_\nu M = (m_{\text{quark}})^2 \]
  - Baryon Asymmetry of the Universe (flavor)
    - Electroweak baryogenesis - LHC and ILC.
    - Leptogenesis - Neutrino CP violation would support it.
  - Dark Matter
  - Dark Energy
The Fermilab long-term plan incorporates three strategic directions:

- **Hadron Machines** (TeV, LHC, ...)
- **Lepton Machines** (ILC, $\mu$-Coll,...)
- **Intense $\nu$, $\mu$, $K$, ... beams**

**Strategic Context for Long Range Plan**
- $\nu$ change from one kind to another. Do charged leptons do the same?

In SM

- Explore virtual particles and couplings ($\mu$2e sensitivity: $Br \sim 10^{-17}$)

- K Rare Decays:

  Standard Model

  $Br(K^+ \rightarrow \pi^+\nu\nu) = 8 \times 10^{-11}$

  $Br(K_L \rightarrow \pi^0\nu\nu) = 3 \times 10^{-11}$

$9^{\text{th}}$ ICFA Seminar – G. Apollinari (FNAL)
Intensity Frontier Vision (P5)

- **Intensity Frontier**
  - Observe new physics as VIRTUAL PARTICLES contributing to RARE PROCESSES and causing departures from the Standard Model expectations in some related physical observables (BRs, CP asymmetries, FB asymmetries, etc.)

- **Future (P5) Vision**
  - (P5) recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL ... R&D on the technologies for a large multi-purpose neutrino and proton decay detector.
  - A neutrino program with a multi-megawatt proton source would be a stepping stone toward a future neutrino source, such as a neutrino factory based on a muon storage ring ... to develop a muon collider as a long-term ... return to the energy frontier.
    - Ex: $\sin^2 2\theta_{13}$ discovery potential from $\sim10^{-2}$ to $\sim5\times10^{-4}$ with 2 MW source

Fermilab approach to the Intensity Frontier

- Developed a program based on a new injector for the FNAL complex:
  - Can exploit the large infrastructure of accelerators: Main Injector (120 GeV), Recycler (8 GeV), Debuncher (8 GeV), Accumulator (8 GeV) - would be very expensive to reproduce.
  - New source uses TESLA/ILC technology and helps development in the US
  - Provides the best program in $\nu$ and rare decays in the world
  - Positions the US program for an evolutionary path leading to a neutrino factory and muon collider

- Scope of new injector is based on:
  - 2 MW at 120 GeV
  - Affordable
  - Flexible beam delivery at low energy (8 GeV)
  - Upgradable to multi-MW (~4 MW) at 8 GeV
Working backwards:

- 2013: CD-3 – Start Construction
- 2012: CD-2 – Establish Baseline*
- 2011: CD-1 – Establish Baseline Range
  - Requires a complete Conceptual Design Report
- 2009: CD-0 – Approve mission need
  - Requires new cost (range) estimate which will be reviewed by DOE. Based on Initial Configuration Document* (nearing completion – to be published on Nov 1st, 2008).

*(CD = Critical Decision)*

*It is anticipated that the final configuration and operating parameters of the linac will be refined through the R&D program in advance of CD-2. The ICD document is to provide a basis for a cost estimate necessary for a CD-0 in 2009.*
Project X: present concept (Sep 08)

8 GeV slow and fast spills up to 800 kW

Flavor and low energy neutrino program

ILC-like 8 GeV H⁻ Linac:
20 mA x 1.25 msec x 5 Hz
1 MW

120 GeV fast extraction
2.1 MW
1.6E14 protons/1.4 sec

Main Injector
1.4 sec cycle

Recycler
1 linac pulse/fill

Stripping Foil

0.4 GeV Front End
0.4 - 8 GeV ILC style linac

Initial operational scenario for two users:
- long baseline neutrino oscillation experiment (DUSEL)
- muon-to-electron conversion experiment

9th ICFA Seminar – G. Apollinari (FNAL)
The Intensity Frontier: Project X for the Next Decade

(Toward DUSEL)

- **Tevatron Collider**
  - MiniBooNE: 250 kW at 120 GeV for Neutrinos
  - SciBooNE: 17 kW at 8 GeV for Neutrinos

- **Soudan**
  - DUSEL: 700 kW at 120 GeV for Neutrinos
  - NOvA: 16 kW at 8 GeV for Precision Measurements
  - MINERvA: >2 MW at 60-120 GeV for neutrinos

- **8 GeV ILC-like Linac**
  - MINOS: 20 mA x 1.25 msec x 5 Hz

- **(National Project with International Collaboration)**
Project X Initial Operation Scenario

- **5 Hz Ticks**
- **Beam Pulses**
- **MI Beam Intensity**
- **& Energy**
- **Accumulator Intensity**
- **Debunker Intensity**
- **Beam Transfers**

**Time 0**
- Linac
- Recycler
- Accumulator
- Debunker
- Main Injector

- $1.6 \times 10^{14}$ per pulse from Linac (5 Hz)
- $1.6 \times 10^{14}$ through Recycler to Main Injector (every 1.4 sec)
- $8 \times 10^{13}$ through Recycler to Accumulator (every 1.4 sec)
- $8 \times 10^{13}$ through Accumulator to Debunker (every 1.4 sec)
- 7 Linac Cycles per MI Cycle: 1 to MI, 1 to mu2e
- 5 available for diagnostics/commissioning/future experiments
**Project X**

1000 kW 8GeV Linac

- 28 Klystrons (2 types)
- 461 SC Cavities
- 58 Cryomodules

**325 MHz** 0-10 MeV

- 1 Klystron (JPARC 2.5 MW)
- 16 RT Cavities

**325 MHz** 10-120 MeV

- 1 Klystron (JPARC 2.5 MW)
- 51 Single Spoke Resonators
- 5 Cryomodules

**325 MHz** 0.12-0.42 GeV

- 3 Klystrons (JPARC 2.5 MW)
- 42 Triple Spoke Resonators
- 7 Cryomodules

**1300 MHz** 0.42-1.3 GeV

- 4 Klystrons (ILC 10 MW MBK)
- 64 Squeezed Cavities (β=0.81)
- 8 Cryomodules

**1300 MHz** 1.3-8.0 GeV

- 19 Klystrons (ILC 10 MW MBK)
- 304 ILC-identical Cavities
- 38 ILC-like Cryomodules

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Project X – G. Apollinari (FNAL)
Project X Linac Alignments

- ILC-like technology parameters based on:
  - 1.3 GHz, pulsed beam at 20 mA x 1.25 msec x 5 Hz rate (1.6 x 10^{14})

- 325 MHz RFQ to 2.5 MeV
- 325 MHz RT accelerating structures to 10 MeV
- 325 MHz SC spoke-type structures to 0.4 GeV
- SC solenoid focusing in 2.5-120 MeV range

- ILC squeezed structures to 1.2 GeV
- Standard ILC structures to 8 GeV
- SC focusing quadrupole magnets for transverse focusing from 120 MeV to 8 GeV
  - Standard ILC focusing lattice in final four RF units

- Development of High Intensity Proton source supporting a ν-factory and μ-collider:
  - Typically requires 2-4 MW @ 10± 5 GeV proton energy, 50 Hz rep.
  - Natural Evolution: Project X → Neutrino Factory → Muon Collider
R&D Plan: Major Technical Issues

- **325 MHz Linac (0-420 MeV)**
  - No special accelerator issues are posed by a 420 MeV Linac with initial PrX intensity
  - Technology Choice
    - Room Temperature vs. Superconducting (HINS), upgrade Path
  - Present PrX requirements pushing envelope of existing H- sources

- **1300 MHz Linac (0.42 – 8 GeV)**
  - PrX gradient less stringent than for ILC (25 vs. 31.5 MeV/m)
  - 20 mA x 1.25 msec x 5 Hz (1 MW @ 8 GeV) vs. ILC 9 mA x 1 msec x 5 Hz
  - Higher power to individual cavities (500 kW over 300 kW).
    - Power Coupler Development and HOM
  - Production rate of cryomodules (needed 1 cryo/month)
  - Use of IQM vs Vector Sum.
  - Loss cavity/cryomodule during operation
R&D Plan: Major Technical Issues

- **8 GeV Transfer Line**
  - Control and mitigation of losses
  - Stripping Efficiency and lifetime

- **Main Injector (and Recycler)**
  - Electron Cloud Instabilities (x3 more proton/bunch than current operations)
    - Simulations, Beam pipe coating
  - Transition Crossing in the Main Injector
  - Second Harmonic RF system
Project X Upgradability

- Initial configuration exploits alignment with ILC
- But it is expandable:
  - increase the rep rate
  - increase the pulse length
- We are studying the possibility to develop existing 8 GeV rings (Recycler, Debuncher, Accumulator) to deliver and tailor beams, allowing full duty cycle for experiments with the correct time structure: $K$ decays, $\mu \rightarrow e$ conversion, $g-2$.
- Would position the program for a multi-megawatt (2-4 MW) source for intense muon beams at low <8 GeV energies - very difficult with a synchrotron.
1.5-4 TeV Muon Collider at Fermilab

V. Shiltsev talk
## PrX R&D Plan and HINS Program

<table>
<thead>
<tr>
<th>Ion Source</th>
<th>RFQ</th>
<th>MEBT</th>
<th>Room Temp</th>
<th>SSR1</th>
<th>SSR2</th>
<th>TSR</th>
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<tr>
<td>E_{out}</td>
<td>50 keV</td>
<td>2.5 MeV</td>
<td>2.5 MeV</td>
<td>10 MeV</td>
<td>30 MeV</td>
<td>120 MeV</td>
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<td>Z_{out}</td>
<td>0.7 m</td>
<td>3.7 m</td>
<td>5.7 m</td>
<td>15.8 m</td>
<td>31 m</td>
<td>61 m</td>
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<tr>
<td>Cavities</td>
<td>2 buncher cavities and fast beam chopper</td>
<td>16 copper CH-spoke cavities</td>
<td>18 single-spoke SC $\beta=0.2$ cavities</td>
<td>33 single-spoke SC $\beta=0.4$ cavities</td>
<td>66 triple-spoke SC $\beta=0.6$ cavities</td>
<td></td>
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<tr>
<td>Gradient</td>
<td>10 MV/m</td>
<td>10 MV/m</td>
<td>10 MV/m</td>
<td>10 MV/m</td>
<td>10 MV/m</td>
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<td>Focusing</td>
<td>3 SC solenoids</td>
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<td>18 SC solenoids</td>
<td>18 SC solenoids</td>
<td>18 SC solenoids</td>
<td>66 SC quads</td>
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<td>Cryomodules</td>
<td>2</td>
<td>3</td>
<td>11</td>
<td>11</td>
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</table>

Project X – G. Apollinari (FNAL)
HINS - RT (10 MeV) Section

copper cavities

helium transfer line

solenoids

548.33  516.88  541.31  549.338  564.927  580.532  596.125  611.733  627.323

268.33  285.2  262.7  296.75  291.5  297.6  303.25

TYPE 1  TYPE 1  TYPE 1  TYPE 1  TYPE 2  TYPE 2  TYPE 2  TYPE 3

519.38  543.41  552.838  588.977  585.282  602.225  617.183  632.

3-spoke Copper Cavity

RFQ

Project X – G. Apollinari (FNAL)
HINS- Cavity and Modulator Tests

Amplitude Control with Vector Modulator

First Room Temperature Cavity

High-power Vector Modulator

Phase Shift Control with Vector Modulator

120°/28.5 μs
4.2°/μs

20 μs

Project X – G. Apollinari (FNAL)
- First SC spoke cavity fabrication has been received from Zanon
- Second cavity has been completed at Roark, IN, ready for processing
- Fabrication of two additional cavities is beginning in India
There is a single 1.3 GHz development program at Fermilab, supporting the ILC/GDE program and simultaneously understanding Project X requirements.

At an appropriate time (before CD-2) the Project X cryomodule design will be developed.

- The expectation is that it will be similar, but not identical, to the ILC design (including choice of gradient and focusing needs).
- CM development plans lead to CM4 being a PrX prototype
- Development strategy coordinated with ILC on basis of “plug compatibility”

ILCTA-NML is being constructed under the SRF Infrastructure program to support beam testing of a complete rf unit.

- This configuration supports substantial progress toward ILC (S1 and S2) goals: demonstration of stable high-power operations.
ILC/SRF Infrastructure Development

Single cell EP @ ANL

VTS @ FNAL

HTS @ FNAL

Project X – G. Apollinari (FNAL)
ILC/SRF: NML Test Facility

First US-build 1.3 GHz Cryomodule installed in NML Facility
August 6th, 2008

Project X – G. Apollinari (FNAL)
Project X Collaboration Plan

Disclaimer: This is not formally agreed to, although institutions have been invited to comment as this has been developed.

- Intention is to organize and execute the R&D Program via a multi-institutional collaboration.
  - Goal is to give collaborators complete and contained sub-projects, meaning they hold responsibility for design, engineering, estimating, and potentially construction if/when Project X proceeds via an MOU Program.
  - It is anticipated that the Project X R&D Program will be undertaken as a “national project with international participation”. Expectation is that the same structure of MOUs described above would establish the participation of international laboratories.
  - Potential US Laboratory Collaborators:
    - ANL, BNL, Cornell, LBNL, ORNL/SNS, MSU, TJNAF, SLAC
  - First Collaboration Meeting: Nov 21-22, 2008
Additional Information

- **Project X**

- **P5 Report**

- **FNAL Steering Group Report**

- **Intensity Frontier Physics Workshops**
Conclusions

The goal of physics research in the next decade is to push the knowledge envelope on three frontiers: Energy, Intensity and Astrophysics.

The proposal of Project X, an 8 GeV Proton Source that provides beam for a 2 MW physics program, meets the requirements to support the Intensity Frontier research program.

An upgradable Project X can provide a stepping stone to the Energy Frontier.

Several R&D Efforts (HINS, ILC/SRF, etc) are actively addressing Project X technical issues.

Project X Collaboration Meeting
- FNAL, Nov. 21st-22nd 2008
- http://projectx.fnal.gov/meeting_11_08/nov_08_collab_mtg.html
Successive Phases of $\nu$ Flavor Physics Reach

$\sin^2 2\theta_{13}$

Mass Ordering

CP Violation

Phase

Multi MW Source

3 $\sigma$ Discovery Potential for $\sin^2 (2\theta_{13}) < 0$

Discovery Potential $\sin^2 m^2_{31}$

3 $\sigma$ Discovery Potential for $\delta = 0$ and ($\pi/2$)
Beam Structure

1.25 msec Linac beam pulse
4 msec full scale

Linac beam chopped for
700 nsec RR Abort Gap
40 μsec full scale

Linac 325 MHz beam
chopped for RR RF
multiple linac bunches per
53 MHz RR RF cycle
100 nsec full scale

Total charge averaged over full pulse
length gives pulse current
20 mA
Sets peak RF power requirement!

Bunch charge averaged over RF cycle gives bunch
current = pulse current/(1-chopping fraction)
32 mA peak
Sets ion source requirement!

Project X – G. Apollinari (FNAL)
## Evolution of Linac Parameters in Project X Design

<table>
<thead>
<tr>
<th></th>
<th>Proton Driver Phase 1 Design</th>
<th>Proton Driver Phase 2 Design</th>
<th>HINS capability</th>
<th>Project X Base Design (Nov-07)</th>
<th>Project X ICD (Sep-08)</th>
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<tbody>
<tr>
<td>Particle</td>
<td>H-</td>
<td>H-</td>
<td>H+ then H-</td>
<td>H-</td>
<td>H-</td>
</tr>
<tr>
<td>Nominal Bunch Frequency/Spacing</td>
<td>325 3.1</td>
<td>325 3.1</td>
<td>325 3.1</td>
<td>325 3.1</td>
<td>325 MHz 3.1 nsec</td>
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<tr>
<td>Particles per Pulse</td>
<td>15.6</td>
<td>15.6</td>
<td>37.5 *</td>
<td>5.6</td>
<td>15.6 E13</td>
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<tr>
<td>Pulse Length (beam)</td>
<td>3</td>
<td>1</td>
<td>3/1</td>
<td>1</td>
<td>1.25 msec</td>
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<tr>
<td>Average Pulse Current</td>
<td>8.3</td>
<td>25</td>
<td>~20</td>
<td>9</td>
<td>20 mA</td>
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<tr>
<td>Pulse Rep. Rate</td>
<td>2.5</td>
<td>10</td>
<td>2.5/10</td>
<td>5</td>
<td>5 Hz</td>
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<tr>
<td>Chopping -6% @ 89KHz and 33% @ 53MHz</td>
<td>37.5% 37.5%</td>
<td>0 - 37.5%</td>
<td>37.5%</td>
<td>37.5%</td>
<td>37.5%</td>
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<tr>
<td>Bunch Current</td>
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<td>39.8</td>
<td>32</td>
<td>14.3</td>
<td>32 mA</td>
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<tr>
<td>Bunch Intensity</td>
<td>2.5 41</td>
<td>7.6 122</td>
<td>6.1</td>
<td>2.7 **</td>
<td>6.1 E8</td>
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</tbody>
</table>

* full un-chopped 3 msec pulse at klystron-limited 20 mA
** ILC bunch intensity is 2E10 (electrons)
HINS Goals

- Use of a single high power klystron to drive multiple accelerating cavities with individual high power vector modulators for amplitude and phase control
  - OBJECTIVE → RF cost savings

- Performance of a focusing lattice comprised of superconducting solenoids to form axially-symmetric beam
  - OBJECTIVE → control of emittance growth and beam loss

- Use of superconducting spoke resonator RF structures for beam acceleration starting at 10 MeV
  - OBJECTIVE → RF cost savings

- High-speed (nanosecond) beam chopping at 2.5 MeV
  - OBJECTIVE → beam loss control in Linac and subsequent synchrotrons

- Overall performance evaluation of a Linac based on these design concepts and the resulting beam quality up to 60 MeV

- A “first-of-its-kind” design for high-intensity, pulsed beams