Project X: A Multi-MW Proton Source
at Fermilab

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Outline

- Evolution of the Fermilab Complex
- Project X Goals and Initial Configuration(s)
- Project X R&D Program
- Relationships to other Programs
- Strategy

Project X website: http://www.fnal.gov/pub/projectx/
Strategic Context: Fermilab and the World Program

The Tevatron has now ceded the energy frontier to LHC
  • Operations at 2 TeV will continue through September 2011

Fermilab operates the highest power long baseline neutrino beam in the world.
  • J-PARC is initiating a competitive program
Fermilab is the sole remaining U.S. laboratory providing facilities in support of accelerator-based Elementary Particle Physics.

⇒ The Fermilab strategy is to mount a world-leading program at the intensity frontier, while using this program as a bridge to an energy frontier facility beyond LHC in the longer term.
Evolution of the Fermilab Accelerator Complex

• A multi-MW Proton Source, Project X, is the linchpin of Fermilab’s strategy for future development of the accelerator complex.

• Project X provides long term flexibility for achieving leadership on the intensity and energy frontiers
  
  – Intensity Frontier:
    NuMI → NOvA → LBNE/mu2e → Project X → Rare Processes → NuFact
    • Continuously evolving world leading program in neutrino and rare processes physics; opportunities for applications outside EPP

  – Energy Frontier:
    Tevatron → ILC or Muon Collider
    • Technology alignment
    • Fermilab as host site for ILC or MC
Design Criteria

• A neutrino beam for long baseline neutrino oscillation experiments
  – 2 MW proton source at 60-120 GeV

• High intensity, low energy protons for kaon and muon based precision experiments
  – Operations simultaneous with the neutrino program

• A path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider
  – Requires upgrade potential to 2-4 MW at ~5-15 GeV.
• Initial Configuration-1

• Strong alignment with ILC technologies

• Initial Configuration Document-1 V1.1 released March 2009
  – Accompanying cost estimate ~$1.5B
Initial Configuration - 1

Issues

• IC-1 does a great job of meeting the long baseline neutrino mission, but…

• does not provide a strong platform for mounting a low energy rare processes program
  – The Recycler is ill-suited to providing high intensity slow spilled beam
  – The Debuncher appears limited to <150 kW in this mode
  ⇒ We believe there is a fundamental limit on the amount of beam power that can be delivered via a resonant extraction system
  – Difficulties supporting multiple users with differing spill structure requirements

⇒ These considerations led to the development of IC-2
## Accelerator Requirements: Rare Processes

<table>
<thead>
<tr>
<th></th>
<th>Proton Energy (kinetic)</th>
<th>Beam Power</th>
<th>Beam Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare Muon decays</td>
<td>2-3 GeV</td>
<td>&gt;500 kW</td>
<td>1 kHz – 160 MHz</td>
</tr>
<tr>
<td>(g-2) measurement</td>
<td>8 GeV</td>
<td>20-50 kW</td>
<td>30- 100 Hz.</td>
</tr>
<tr>
<td>Rare Kaon decays</td>
<td>2.6 – 4 GeV</td>
<td>&gt;500 kW</td>
<td>20 – 160 MHz. (&lt;50 psec pings)</td>
</tr>
<tr>
<td>Precision K(^0) studies</td>
<td>2.6 – 3 GeV</td>
<td>&gt; 100 mA (internal target)</td>
<td>20 – 160 MHz. (&lt;50 psec pings)</td>
</tr>
<tr>
<td>Neutron and exotic nuclei EDMs</td>
<td>1.5-2.5 GeV</td>
<td>&gt;500 kW</td>
<td>&gt; 100 Hz</td>
</tr>
</tbody>
</table>
• Initial Configuration-2

• 3 GeV CW linac provides greatly enhanced rare process program
  – 2-3 MW; flexible provision for beam requirements supporting multiple users
• Options for 3-8 GeV acceleration: RCS or (1.3 GHz) pulsed linac
  – Linac would be 1300 MHz with 4-5 msec pulse length
• Initial Configuration Document-2 in preparation for spring release
## Initial Configuration-2

### Performance Goals

#### Linac
- **Particle Type**: $\text{H}^-$
- **Beam Kinetic Energy**: 3.0 GeV
- **Average Beam Current**: 1 mA
- **Linac pulse rate**: CW
- **Beam Power**: 3000 kW
- **Beam Power to 3 GeV program**: 2870 kW

#### RCS/Pulsed Linac
- **Particle Type**: protons/$\text{H}^-$
- **Beam Kinetic Energy**: 8.0 GeV
- **Pulse rate**: 10 Hz
- **Pulse Width**: 0.002/4.3 msec
- **Cycles to MI**: 6
- **Particles per cycle to MI**: $2.6 \times 10^{13}$
- **Beam Power to 8 GeV program**: 200 kW

#### Main Injector/Recycler
- **Beam Kinetic Energy (maximum)**: 120 GeV
- **Cycle time**: 1.4 sec
- **Particles per cycle**: $1.6 \times 10^{14}$
- **Beam Power at 120 GeV**: 2200 kW
1 μsec period at 3 GeV

- mu2e pulse (9e7) 162.5 MHz, 100 nsec 400 kW
- Kaon pulse (9e7) 27 MHz 800 kW
- Other pulse (9e7) 27 MHz 800 kW

Mu2e - 400 kW, each other 800 kW at 20 MHz
Initial Configuration-2
Provisional Siting

PHASE 1
- BELOW GRADE STRUCTURES
  1 - 3 GeV Continuous Wave (CW) Linac
  2 - Experimental Area Switchyard
  3 - Linac Beam Dump Enclosure
- ABOVE GRADE STRUCTURES
  4 - Upstream Service Building
  5 - Linac Gallery
  6 - Typical Linac Service Building
  7 - Cryogenic Service Building
  8 - Center Service Building

PHASE 2 (future)
- BELOW GRADE STRUCTURES
  9 - 3-8 GeV Pulsed Linac
  10 - Proton Transport Line Enclosure
- ABOVE GRADE STRUCTURES
  11 - Klystron Gallery
  12 - Linac Service Building
  13 - Linac Beam Absorber
  14 - Momentum Beam Absorber
  15 - Debuco Service Building
  16 - Experimental Halls
## Initial Configuration-2 Technology Map

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR0 ($\beta_G=0.11$)</td>
<td>325</td>
<td>2.5-10</td>
<td>26 /26/1</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_G=0.22$)</td>
<td>325</td>
<td>10-32</td>
<td>18 /18/2</td>
<td>SSR, solenoid</td>
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<tr>
<td>SSR2 ($\beta_G=0.4$)</td>
<td>325</td>
<td>32-160</td>
<td>33 /18/3</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ($\beta_G=0.61$)</td>
<td>650</td>
<td>160-520</td>
<td>42 /21/7</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>HB 650 ($\beta_G=0.9$)</td>
<td>650</td>
<td>520-2000</td>
<td>64 /8 /8</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>ILC 1.3 ($\beta_G=1.0$)</td>
<td>1300</td>
<td>2000-3000</td>
<td>64 /8 /8</td>
<td>9-cell elliptical, quad</td>
</tr>
</tbody>
</table>
R&D Program
Choice of Cavity Parameters

- Identify maximum achievable surface (magnetic field) on basis of observed Q-slope “knee”
- Select cavity shape to maximize gradient (subject to physical constraints)
- Establish Q goal based on realistic extrapolation from current performance
  - Goal: <20 W/cavity
- Optimize within (G, Q, T) space

(Initial) Performance Goals

<table>
<thead>
<tr>
<th>Freq (MHz)</th>
<th>B_{pk} (mT)</th>
<th>G (MV/m)</th>
<th>Q</th>
<th>@T (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>60</td>
<td>15</td>
<td>1.4E10</td>
<td>2</td>
</tr>
<tr>
<td>650</td>
<td>72</td>
<td>16</td>
<td>1.7E10</td>
<td>2</td>
</tr>
<tr>
<td>1300</td>
<td>72</td>
<td>15</td>
<td>1.5E10</td>
<td>2</td>
</tr>
</tbody>
</table>
R&D Program
Choice of Cavity Parameters

SSR1:
325 MHz
$Q_0 = 1.4 \cdot 10^{10}$ @ 2K

ILC:
1.3 GHz
$Q_0 = 1.5 \cdot 10^{10}$ @ 2K

DESY data (last test) - status March 2009

72 mT

gradient [MV/m]
R&D Program
Choice of Cavity Parameters

SSR1:
325 MHz
$Q_0 = 1.4 \cdot 10^{10} \ @ \ 2K$

ILC:
1.3 GHz
$Q_0 = 1.5 \cdot 10^{10} \ @ \ 2K$

DESY data (last test) - status March 2009

72 mT
# Integrated SRF Plan

## ILC + Project X

<table>
<thead>
<tr>
<th>U.S. Fiscal Year</th>
<th>2008</th>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
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<tbody>
<tr>
<td><strong>1.3 GHz</strong></td>
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<tr>
<td>CM1 (Type III+)</td>
<td>Omnis</td>
<td>Install</td>
<td>CM Ass'y</td>
<td>CM Test</td>
<td></td>
<td></td>
<td>Operate</td>
<td>Complete RF Unit @ Design Parameters</td>
</tr>
<tr>
<td>CM2 (Type III+)</td>
<td>Process &amp; VTS/Dress/HTS</td>
<td>CM Ass’y</td>
<td>sw ap</td>
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<tr>
<td>CM3 (Type IV)</td>
<td>Design</td>
<td>Order Cav &amp; CM Parts</td>
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<tr>
<td>CM4 (Type IV)</td>
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<tr>
<td>CM5 (Type IV)</td>
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<tr>
<td>CM6 (Type IV+)</td>
<td>CM Test</td>
<td>Design CM</td>
<td>6/3 CM</td>
<td>sw ap</td>
<td></td>
<td></td>
<td>Install in CMTF</td>
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<tr>
<td>CM6 (Type IV+)</td>
<td>CW Design</td>
<td></td>
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<tr>
<td>NML Extension Building</td>
<td>Design</td>
<td>Construction</td>
<td></td>
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<tr>
<td>NML Beam</td>
<td></td>
<td></td>
<td>Move injector/install beam components</td>
<td>Beam Available to RF Unit test except during installation periods (contingent upon cryogenic load/capacity)</td>
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<tr>
<td>CMTF Building</td>
<td>Design</td>
<td>Construction</td>
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<tr>
<td><strong>650 MHz</strong></td>
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<tr>
<td>Single Cell Design &amp; Prototype</td>
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<tr>
<td>Five Cell Design &amp; Prototype</td>
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<td></td>
</tr>
<tr>
<td>CM650_1</td>
<td>Design</td>
<td>Order 650 Cav &amp; CM Parts</td>
<td>Process &amp; VTS/Dress/HTS</td>
<td>650 CM Ass'y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>325 MHz</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SSR0/SSR2 Design &amp; Prototype</td>
<td>Design (RF &amp; Mechanical) all varieties of Spoke Resonators</td>
<td>Prototype (as required)</td>
<td>Process &amp; Test (as required)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSR1 Cavities in Fabrication (14)</td>
<td>Procurement</td>
<td>(already in progress)</td>
<td>Process &amp; VTS/Dress/HTS</td>
<td></td>
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<tr>
<td>CM325_1</td>
<td>Design</td>
<td>Procure 325 CM Parts</td>
<td>325 CM Ass'y</td>
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</tbody>
</table>

**Design** | **Procure** | **Process & VTS** | **Dress & HTS** | **Assemble** | **Install** | **Commission & Operate**
NML test facility: ILC and Project X R&D
Project X shares many features with the proton driver required for a Neutrino Factory or Muon Collider

- NF and MC require ~4 MW @ 10± 5 GeV
- Primary issues are related to beam “format”
  - NF wants proton beam on target consolidated in a few bunches; Muon Collider requires single bunch
  - Project X linac is not capable of delivering this format

⇒ It is inevitable that a new ring(s) will be required to produce the correct beam format for targeting.
A multi-institutional collaboration has been established to execute the Project X RD&D Program.

- Organized as a “national project with international participation”.
  - Fermilab as lead laboratory
  - International participation via in-kind contributions, established through bi-lateral MOUs. (First MOU with India in place)
- Collaboration MOU for the RD&D phase outlines basic goals, and the means of organizing and executing the work. Signatories:
  
<table>
<thead>
<tr>
<th>Collaborator 1</th>
<th>Collaborator 2</th>
<th>Collaborator 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>ORNL/SNS</td>
<td>BARC/Mumbai</td>
</tr>
<tr>
<td>BNL</td>
<td>MSU</td>
<td>IUAC/Delhi</td>
</tr>
<tr>
<td>Cornell</td>
<td>TJNAF</td>
<td>RRCAT/Indore</td>
</tr>
<tr>
<td>Fermilab</td>
<td>SLAC</td>
<td>VECC/Kolkata</td>
</tr>
<tr>
<td>LBNL</td>
<td>ILC/ART</td>
<td></td>
</tr>
</tbody>
</table>

- Collaborators to assume responsibility for components and sub-system design, development, cost estimating, and potentially construction.
• Next six months: Complete all preliminary design, configuration, and cost range information for IC-2
  – ICD-2v2.0
  – Cost estimate

• Continue conceptual development on outstanding technical questions
  – Baseline concept for the chopper
  – Concepts for marrying a 3-8 GeV pulsed linac to CW front end
  – Injection into RCS or Recycler

• Pursue R&D aimed at the CW linac
  – Emphasis of srf development at all relevant frequencies
  – Engage external collaborators and identify roles

• U.S. Department of Energy has advised that the earliest possible construction start is FY2015

• We believe that we could construct Project X over a five year time period, assuming a commensurate funding profile

⇒Project X could be up and running ~2020
Summary

• Project X is central to Fermilab’s strategy for development of the accelerator complex over the coming decade
  – World leading programs in neutrinos and rare processes
  – Aligned with ILC and Muon Accelerators technology development;
  – Potential applications beyond elementary particle physics

• The design concept has evolved over the last year, providing significantly enhanced physics capabilities

• Current configuration:
  – >2 MW at 60-120 GeV, simultaneous with 3 MW at 3 GeV
  – Flexibility for supporting multiple experiments
  – CW linac is unique for this application, and offers capabilities that would be hard/impossible to duplicate in a synchrotron

• Project X could be constructed over the period ~2015 - 2019