Project X Accelerator Facility: Initial Configuration

Paul Derwent
Muon Collider Workshop
TJNAF
9 Dec 08
The Intensity Frontier

The Energy Frontier
- Origin of Mass
- Matter/Anti-matter Asymmetry
- Unification of Forces
- New Physics Beyond the Standard Model
- Origin of Universe

The Intensity Frontier
- Neutrino Physics
- Proton Decay

The Cosmic Frontier
- Dark Matter
- Dark Energy
- Cosmic Particles
“a plan to keep U.S. accelerator based particle physics on the pathway to discovery ... in the domain of neutrinos and precision physics with a high intensity accelerator”

if the ILC stays on GDE’s technically driven timeline

➢ NOνA using the Recycler/MI to reach 700 kW at 120 GeV

if ILC construction must wait somewhat longer

➢ SNuMI using the Accumulator/Recycler/MI to reach 1.2 MW at 120 GeV

if the ILC start is postponed significantly

➢ Project X, a linac with the “currently planned characteristics of the ILC” combined with the Recycler/MI to reach 2.3 MW at 120 GeV
The role of the Initial Configuration Document

What is its role?

- Projects have to work within context of DoE order 413.3a (a 54 page document)
  - Program and Project Management for the acquisition of Capital Assets
  - Critical Decision path

- Input to CD-0 “Approve Mission Need”
  - R&D and Conceptual Planning
  - “A Mission Need Statement is the translation of this gap into functional requirements that cannot be met through other than material means. It should describe the general parameters of the project, how it fits within the mission of the Program, and why it is critical to the overall accomplishment of the Department mission, including the benefits to be realized. The mission need is independent of a particular solution, and should not be defined by equipment, facility, technological solution, or physical end-item. This approach allows the Program the flexibility to explore a variety of solutions and not limit potential solutions.”

- but we also need a cost range!!!!! so we need a configuration to cost
Development of the configuration

**Steering Group Report**
- “a linear accelerator with the currently planned characteristics of the ILC combined with Fermilab’s existing Recycler Ring and Main Injector accelerator”
- “the same as or similar to those used in the ILC at a scale of about 1% of a full ILC linac”

**8 GeV H⁻ linac**
- 9 mA x 1 msec x 5 Hz ⇒ 5.6 × 10¹³ particles per pulse
- Strip and accumulate 3 pulses in Recycler
- transfer to Main Injector

**Emphasis on synergy with ILC:**
- scale test
- industrialization
- ⇒ 9 mA x 1 msec x 5 Hz

**May 08 AAC**
- “Project-X, based on a superconducting linac, is important but aside from synergy with ILC, hard to justify unless one thinks of the long-term goals of Project-X – what upgrade potential could be incorporated from the start that would demand a superconducting linac?”

**Jan – May 08**
- R&D plan to develop concepts towards CD-2

**June 08 P5 Report**
The Intensity Frontier -- the P5 Report

P5 report: Fermilab’s physics vision for this proton source has three main elements:

1. A neutrino beam for long baseline neutrino oscillation experiments. A new 2-megawatt proton source with proton energies between 50 and 120 GeV would produce intense neutrino beams, directed toward a large detector located in a distant underground laboratory.

2. Kaon-and muon-based precision experiments exploiting 8 GeV protons from Fermilab’s Recycler, running simultaneously with the neutrino program. These could include a world-leading muon-to-electron conversion experiment and world-leading rare kaon decay experiments.

3. A path toward a muon source for a possible future neutrino factory, and, potentially, a muon collider at the Energy Frontier. This path requires that the new 8 GeV proton source have significant upgrade potential.

These physics objectives define the mission need.

#1

- 1.6e14 / 1.4 sec at 120 GeV: 2.1 MW
  - 20 mA, 1.25 msec, 5 Hz from 8 GeV H⁻ linac
  - Strip in Recycler
  - Single Turn transfer to MI

#2

- 3 pings from Recycler to Accumulator
  - 7e13 / 1.4 (0.7) sec at 8 GeV: 70 (140) kW for mu2e
  - >3(6)× improvement over NOvA era beam power
- Investigate slow spill

#3

- upgrade path to 10 Hz, longer pulse length
Comparison

Steering Group
Project X

Initial Configuration Document

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Operational Scenario

5 Hz Ticks
Beam Pulses
ML Beam Intensity & Energy
Accumulator Intensity
Debuncher Intensity
Beam Transfers

Time 0
Linac
Recycler
Accumulator
Debuncher
Main Injector

1.6e14 per pulse from Linac (5 Hz)
1.6e14 through Recycler to Main Injector (every 1.4 sec)
8e13 through Recycler to Accumulator (every 1.4 sec)
8e13 through Accumulator to Debuncher (every 1.4 sec)
7 Linac Cycles per ML Cycle: 1 to ML, 1 to mu2e, 5 available for diagnostics/commissioning/future experiments

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## Technical Goals

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<tr>
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<td>Particle Type</td>
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<tr>
<td>Particles per pulse</td>
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<td>Length (approx.)</td>
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## Recycler

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<td>r.m.s. normalized transverse emittance</td>
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## Main Injector

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<td>Acceleration Efficiency</td>
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## 8 GeV Extraction

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Facility Scope, Assumptions, and Interfaces

Facility Scope

- An 8 GeV superconducting linac
  - 325 MHz section to 420 MeV
  - 1.3 GHz section 420 MeV to 8 GeV
- Beamline for transport to the Recycler
- Modifications to Recycler for H-injection and transfer to MI
- Modifications to the Main Injector to support acceleration and extraction of high intensity beams

Assumptions

- Existing linac and booster no longer operational
- Existing Tevatron no longer operational (cryo systems available)
- Existing test beam facility in Meson continues at low duty factor
- Existing antiproton source reconfigured and operating in support of mu2e
- A neutrino beamline directed towards DUSEL operating

Interfaces

- DUSEL beamline: Main Injector extraction kicker
- mu2e: Recycler extraction kicker
**Linac Layout**

### Project X

**1000 kW 8GeV Linac**
- 28 Klystrons (2 types)
- 461 SC Cavities
- 58 Cryomodules

**325 MHz 0.12-0.42 GeV**
- 3 Klystrons (JPARC 2.5 MW)
- 42 Triple Spoke Resonators
- 7 Cryomodules

**325 MHz 10-120 MeV**
- 1 Klystron (JPARC 2.5 MW)
- 51 Single Spoke Resonators
- 5 Cryomodules

### Front End Linac

**325 MHz 0-10 MeV**
- 16 RT Cavities

**325 MHz 10-120 MeV**
- Multi-Cavity Fanout
- Phase and Amplitude Control
- 9 or 11 Cavities / Cryomodule

### 1300 MHz LINAC

**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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325 MHz Linac

- builds off the HINS project:
  - “to address accelerator physics and technology questions for a new concept, low-energy, high intensity, long pulse H\(^-\) superconducting linac”
    - Demonstrate beam acceleration using superconducting spoke type cavity structures starting at a beam energy of 10 MeV
    - Demonstrate the use of high power RF vector modulators to control multiple RF cavities driven by a single high power klystron for acceleration of a non-relativistic beam
    - Demonstrate beam halo and emittance growth control by the use of solenoid focusing optics up to 60 MeV
    - Demonstrate fast, 325 MHz bunch-by-bunch, beam chopper
HINS floor plan -- Meson Test Building

- ILC HTC Cave
- Cavity Test Cave
- RF Component Test Facility
- Klystron and Modulator Area
- 60 MeV Linac Cave
- Existing CC2 Cave
- Ion Source and RFQ Area
- 150 ft.
HINS RT Cavity and Vector Modulator in Cavity Test Cave

High-power Vector Modulator

HINS Room Temperature Cavity
HINS RFQ

Successful field measurement bead pull on 6/17/08
Initial delivery to FNAL in July

RFQ in Meson Test area
## Beam Requirements

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<th></th>
<th>Proton Driver Phase 1 Design</th>
<th>Proton Driver Phase 2 Design</th>
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<td>H-</td>
<td>H+ then H-</td>
<td>H-</td>
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<td>325 3.1</td>
<td>325 3.1</td>
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<td>15.6 E13</td>
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<td>Pulse Length</td>
<td>3</td>
<td>1</td>
<td>3/1</td>
<td>1</td>
<td>1.25 msec</td>
</tr>
<tr>
<td>Average Pulse Current</td>
<td>8.3</td>
<td>25</td>
<td>~20</td>
<td>9</td>
<td>20 mA</td>
</tr>
<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>
</tr>
<tr>
<td>Chopping -6% @ 89KHz and 33% @ 53MHz</td>
<td>37.5%</td>
<td>37.5%</td>
<td>0 - 37.5%</td>
<td>37.5%</td>
<td>37.5%</td>
</tr>
<tr>
<td>Bunch Current</td>
<td>13.3</td>
<td>39.8</td>
<td>32</td>
<td>14.3</td>
<td>32 mA</td>
</tr>
<tr>
<td>Bunch Intensity</td>
<td>2.5 41</td>
<td>7.6 122</td>
<td>6.1 98</td>
<td>2.7 44</td>
<td>6.1 E8 pCoul</td>
</tr>
</tbody>
</table>

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325 MHz Linac

- 50 keV H⁻ ion source
- 2.5 MeV RFQ
- Medium energy beam transport
  - 2 rebuncher RF cavities
  - 3 solenoids
  - beam chopper
- Room temperature cavities interspersed with SC solenoids to 10 MeV

- β=0.22 single-spoke resonator SC cavities to 30 MeV
- β=0.4 single-spoke resonator SC cavities to 120 MeV
- β=0.6 triple-spoke resonator SC cavities to 420 MeV
- Vector modulators throughout ... multiple cavities per klystron ... technical risk ...
325 MHz Linac Beam structure

- Beam chopper has to match:
  - 53 MHz structure for the Recycler/Main Injector
  - 700 nsec gap every 11.1 μsec for the Recycler / Main Injector kickers
  - 75 nsec gap every 1.6 μsec for the μ2e pulses (fast kickers)
Use S-ILC for $\beta=0.81$ section: 0.42 – 1.3 GeV

- squeezed ILC cavity -- same frequency but shorter cavity length
- needs to be developed for Project X

Use ILC Type 4 Cryomodules as prototype for $\beta=1$ section

- use same cryomodule everywhere
- 8 Cavities, 1 quad in all cryomodules:
  - CMs are interchangeable - 1 type of spare in $\beta=1$ section

- 25 MV/m

- 2 CM/klystron (instead of 3)
- stand alone quads in regions where more focussing is needed (short cryo module without cavities)?

Warm sections ~4 CMs (cryo junction boxes)

Linac parameters:

- RF: 25 MV/m, 1.5 ms pulse, 5 Hz
- beam: 20 mA, 1.25 ms beam flat-top
RF Power

- 10 MW multi beam klystron
  - 2 cryo modules per klystron

- Keep coupler power at 500 kW max.
  - Average power should be < 5 kW

- Longitudinal dynamics of the non-relativistic H- beam and possible cavities field variations over time (SNS experience) will require use of IQM modulators throughout the Linac.
  - Need of additional RF simulation/experience on cavities field uniformity to prove the ability to control the RF distribution through LLRF under beam-loading conditions in the HE part of the Linac.

- Bunch freq. is 325 MHz – lower voltage transient than ILC
  - Chopping at 52.8 MHz and kicker gaps (700 ns) every 11 µs
  - Bunch – to – bunch charge variation is important
**Project X**

**1000 kW 8GeV Linac**

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

---

**Front End Linac**

**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
- 9 or 11 Cavities / Cryomodule

---

**1300 MHz LINAC**

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

- 19 Klystrons (ILC 10 MW MBK)
- 304 ILC-identical Cavities
- 38 ILC-like Cryomodules
Cavity response vs $\beta$

Net Accelerating Gradient (MV/m)

Kinetic Energy (GeV)

$\beta = 1$ Cavities

$\beta = 0.81$ Cavities

Low Energy Linac

SILC Section

IIC Section
## Cavity and Klystron Counts

<table>
<thead>
<tr>
<th></th>
<th>Cavities</th>
<th>Cryomodules</th>
<th>Klystrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSR (2 types)</td>
<td>51</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5 MW</td>
</tr>
<tr>
<td>TSR</td>
<td>42</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5 MW</td>
</tr>
<tr>
<td>S-ILC</td>
<td>64</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 MW MultiBeam</td>
</tr>
<tr>
<td>ILC</td>
<td>304</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 MW MultiBeam</td>
</tr>
<tr>
<td>Total</td>
<td>461</td>
<td>58</td>
<td>28</td>
</tr>
</tbody>
</table>
Transfer line

- from the output of the linac to the MI tunnel
  - ~1 km long
  - <500 G fields -- mitigate magnetic stripping of the H\(^-\) electrons
  - liquid nitrogen cryogenic shield -- mitigate blackbody stripping of the H\(^-\) electrons

- Acceptance matched to Recycler
  - 25 π mm mr
  - ±0.75% momentum aperture
  - transverse collimation to capture large amplitude particles
  - momentum collimation to capture off momentum particles
  - passive phase rotator cavity to compensate for energy jitter

- Permanent magnets at 8 GeV (possible use of Main Ring or PEP-II HER magnets being investigated)

- losses less than <1 W/m ⇒ >99.9% transmission efficiency
Site Layout

1. Linac Beam Line Enclosure
2. Beam Transport Line Enclosure
3. Linac Beam Absorber
4. Momentum Beam Absorber
5. Upstream Service Building
6. Klystron Gallery
7. Cryogenic Service Building
8. Typical Service Building (x4)
9. Center Service Building
10. Arc Service Building
11. Debuncher Service Building

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**Injection System**

- **Multi turn Stripping System**
  - 1.25 msec = 110 turns in Recycler
  - thin foil injection

- **Transverse / Longitudinal painting ⇒ Kapchinsky - Vladimirsky distribution**
  - linear space charge force within beam radius
  - RMS envelope radius = \( \frac{1}{2} \) beam radius
  - minimize space charge tune shift in the Recycler and Main Injector

![Diagram of Injection System]

- HBC1
- HBC2
- HBC3
- HBC4

- Stripping foil
- Thick foil \( H^0 \rightarrow H^+ \)
- H\(^+\) to inj. absorber

- 8.941 m
- 0.606 m
- 1.068 m

- 75 to 100 mm

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Injection System

- elevation throughout matched to Main Injector elevation
  - adequate shielding
  - interferences with existing enclosures (TeV and AP1)
  - makes the line longer ⇒ vertical bend to reach Recycler elevation

- Beam absorber to catch H⁻ and H⁰
  - 2% stripping inefficiency ⇒ 20 kW
  - design for 100kW
  - designed around MI tunnel
Recycler

- Modified for NOvA by this time
  - proton ring with single turn transfer to MI

- Modifications to lattice for injection system
  - remove injection from MI 8 line!

- Add flexibility to lattice to handle tune shift, operating point, etc.
  - expect 1.6e14 with KV distribution to give ~0.05 tune shift

- 53 MHz RF to capture injected beam
  - with 2nd harmonic RF (w/ V = 1/2 V₀)
  - make identical to MI system

- Fast extraction (1.6 μsec length) for μ2e
  - move NOvA injection kicker and supplies

- Electron cloud mitigation
  - coat the beam pipe?
Main Injector

- Single turn injection from Recycler

- ~3x intensity of NOvA era

Upgrade RF system:
- need more bucket area for acceleration
- second harmonic RF also needed
- 53 MHz design exists, 2nd harmonic does not
  - Very conservative design uses a lot of power to guarantee stability. Is this design optimal?

Electron Cloud mitigation
- TiN coating to decrease secondary emission yield

First order matched $\gamma$ jump (W. Chou et al., PAC 1997)
- 8 pulsed quad triplets
- 2 units in 0.5 msec (16x faster than normal ramp)

Cavity Characteristics

- $Q = 4000$
- $R_{sh} = 100 \, \text{k}\Omega$
- $R/Q = 25 \, \Omega$
- $f_0 = 52.9577 \, \text{MHz}$
- Range ±150 kHz
- Material Cu coated stainless
- Voltage 300 kV

Proton Driver design, Mar 2005
RF Simulations

- Phase mismatch between 325 MHz spacing from linac and 52.8 MHz in RR
  - useful for longitudinal painting to reduce space charge tune shift

53 MHz only

w/ 2nd harmonic

P.S. Yoon, D.E. Johnson, W. Chou
Fermilab-TM-2398
Optimum Energy for long baseline neutrino program?

- deliver > 2 MW for extracted beam energies > 60 GeV (1.8 MW at 50 GeV)
  - varying the MI cycle time
  - holding beam in Recycler to match 5 Hz from linac with varying MI cycle time
- deliver > 500 kW for 8 GeV beam
Cryogenics

- **New Cryo plant**
  - 325 MHz linac: two phase liquid helium at 4.5 K
    - Static heat load (conduction/radiation) dominates dynamic heat load (RF power dissipation)
  - 1.3 GHz linac: saturated He II at 2 K
    - Static and dynamic heat loads of same order
  - Multiple strings in each unit

- Re use Tev ancillary components

- Preliminary heat load estimate
  - 30% uncertainty
  - 50% safety factor
  - 6 kW at 4.5 K equivalent
Site Layout – Conventional Facilities

- 2 - Beam Transport Line Enclosure
- 3 - Linac Beam Absorber
- 4 - Momentum Beam Absorber
- 5 - Upstream Service Building
- 6 - Klystron Gallery
- 7 - Cryogenic Service Building
- 8 - Typical Service Building (x4)
- 9 - Center Service Building
- 10 - Arc Service Building
- 11 - Debuncher Service Building

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Conventional Facilities

- **4 below grade construction:**
  - Linac enclosure
  - Transfer line enclosure
  - Linac dump
  - Momentum dump (injection dump is in MI tunnel)
  - Cut and cover
  - Single tunnel for beamline

- **7 above grade construction:**
  - Upstream service building (ion source)
  - Klystron gallery
  - Cryo service building (plant)
  - 4 additional service buildings

- **Site Prep:**
  - Drainage
  - Roads
  - Landscaping
  - Wetlands mitigation (60 acres)
    - 3:1 for creation ($50k/acre)
    - Buy credits offsite?
  - Space Replacement
    - 150000 square feet

- **Utilities**
  - Power
  - Communications
  - Water
**Instrumentation & Controls**

- Beam loss monitoring
- Beam Position monitoring
- Machine protection system

- develop new instrumentation
  - especially in SCRF sections

- Time Stamping
- 1 M devices and properties
- Machine protection system

- Evolving System
  - through NOvA era
  - support of HINS and NML efforts

  - Mix of EPICS and ACNET
The intention is to organize and execute the RD&D Program via a multi-institutional collaboration.

- Goal is to assign collaborators complete sub-projects ⇒ responsibility for design, engineering, cost estimating, and potentially construction if/when Project X proceeds.
- Project X R&D Collaboration to be established via a Collaboration Memorandum of Understanding (MOU) outlining basic goals of the collaboration, and the means of organizing and executing the work.
- It is anticipated that the Project X RD&D Program will be undertaken as a “national project with international participation”. Expectation is that international participation would largely be via in-kind contributions, established via bi-lateral MOUs.
  - International participation in the Collaboration Meeting to identify areas of common interest.

2 day collaboration Meeting at Fermilab (Nov 21-22)

- 133 registered participants
- 15 institutions (ANL, BNL, CERN, Cockroft Institute, Cornell, DoE, Fermilab, IIT, JLab, KEK, LBNL, MSU, NIU, ORNL, SLAC)
- Structured around 6 Working Groups (Linac, Main Injector, Transfer Line/RR, SRF, Instrumentation, Cryo)
- 2 Plenary Talks, 3 Working Group Sessions, Working Group reports

- [http://projectx.fnal.gov/meeting_11_08/nov_08_collab_mtg.html](http://projectx.fnal.gov/meeting_11_08/nov_08_collab_mtg.html)
Goals

- **Form the RD&D Collaboration**
  - Finalize the Collaboration MOU;
  - Initial meeting of Collaboration Council (see subsequent discussion);
  - Initial discussions with potential international and university collaborators on possible interests and modes of participation.

- **Confirm initial performance goals and configuration**
  - Review, understand, and suggest downstream modifications to the ICD.

- **Establish the RD&D plan**
  - Review, understand, and update as necessary the RD&D plan;
  - Establish initial institutional areas of responsibility;
  - Define deliverables and work plan for FY2009-10;
  - Understand the integration with the ILC and SRF infrastructure programs.
Working Groups

- **Linac**  
  - Beam dynamics
  - Configuration (includes rfpower generation and distribution)
  
- **Main Injector**  
  - I. Kourbanis/T. Roser

- **Beam Transfer Line/Recycler**  
  - D. Johnson/D. Raparia

- **SRF technology**  
  - R. Kephart/G. Apollinari/R. Rimmer
  - Cavities, cryomodules, infrastructure

- **Instrumentation**  
  - M. Wendt/W. Blokland

- **Cryogenic Systems**  
  - A. Klebaner/ D. Arenius
Linac discussion:

- **1 MW at 8 GeV:** Why? don’t seem to need it now?
  - 20 mA 1.25 msec vs 10 mA 2.5 msec
    - need ~500 kW to support MI down to 60 GeV and 8 GeV program
  - design effort on couplers/modulators for SRF cavities
    - modifications to existing coupler designs to meet the power requirements

- **bidirectional beams?**
  - though not explicit, giving this up for now

- **alignment with XFEL cavities (industrialization in Europe) vs with ILC cavities?**

- **use of $\beta = 0.6$ cavities in place of triple spoke resonators?**

- **design margin:** Recycler a fixed energy machine have to match!

- **alignment with CERN SPL effort:**
  - rf power distribution
  - beam chopper

- **upgrade path:** 10 Hz, 2.5 msec (4 MW at 8 GeV)
  - design to include these requirements (couplers & modulators) now?
  - rf power distribution
November 21-22 Collaboration Meeting
some things of interest

- SRF discussion:
  - Develop the required SRF infrastructure so that SRF component fabrication can begin about 1 yr after Px CD3 approval (~2014)
    - 58 cryomodules of 5 types
    - 461 SRF cavities
    - lots of magnets (36 solenoids, 44 quads/correctors)
  - Good start on SRF Infrastructure Collaboration building up on excellent expertise available in Universities and other Laboratories
  - Initial expression of interest are addressing uniformly the whole LINAC both in coverage (no large system is failing to raise interest in at least one institution) and project phases efforts (R&D, design/prototype, production)
  - Technical meetings are needed to further develop the R&D and design/prototyping plans for FY2009-10
    - starting in early 09
Summary

- Developed an Initial Configuration Document to provide
  - >2 MW at 120 GeV
  - additional 8 GeV beam for other experiments
  - upgrade path to higher beam power
    - double the repetition rate (5 Hz → 10 Hz)
    - double the pulse length (1.25 msec → 2.5 msec)
    - conventional facilities, cryo plant, and utilities designed to accommodate these upgrades
  - 325 MHz and 1300 MHz superconducting rf linac
  - multi-turn injection to Recycler
  - Single turn transfer to Main Injector

- CD-0 Spring 2009 → CD-1 Fall 2010 → CD-2 Winter 2012