Project X ACD and its Upgrades for Neutrino Factory or Muon Collider

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**Project X Steps**

- Some definitions (project management for a large DoE project)
  - ICD (Initial Configuration Document) is required by DoE for CD0 (mission need statement)
    - ACD (Alternative Configuration Document) is also required by DoE at CD0
  - Other steps: CD1 ⇒ CD4 (critical decisions) lead to the project design, construction and commissioning

- Fermilab is working on the Project X ICD
  - Project X was initiated in the summer of 2007 and has been considered as a next step in the Fermilab program.
    - Tevatron operations will be terminated in 2-3 years.
  - “First” ACD proposal (November 2008) - tried to address problems of Muon collider but did not bring any good for physics program and did not get support
  - Next ACD proposal appeared in April 2009
    - Subject for this presentation
    - Looks as something what we would like to build
    - New committee was created to strengthen the physics program
    - Strong support at PAC (end of June 2009, Aspen, Colorado)
      ⇒ ACD was renamed to ICD-II
What is Project X?

- New proton injector or a replacement for 40 years old Booster
- 8 GeV SC linac +
  - Modifications in Recycler and MI
Project X Objectives

Major Project X objectives (ILC time, stands for now as well)

- Support of the neutrino program in MI with 2 MW beam power in the energy range of 60 to 120 GeV
- Development of SCRF technology capabilities at Fermilab for future applications (ILC, neutrino factory, muon collider)

Is it enough?

- Present neutrino program (~200-300 people) ⇒ Future neutrino program
- CDF & D0 (1500) ⇒ CMS (external) + ??? (internal)

To succeed we need a strong physics program

- Transition from the energy frontier to the intensity frontier implies experiments at very high repetition rates from ~30 MHz (kaons) to ~60 Hz (g-2).

What else we have in plans for intensity frontier

- Experiments with muons
  - $\mu$-to-e (muon to electron conversion in field of nucleus with lepton number violation) is a front runner
  - $g$-2 (muon $g$-2 measurements, inherited from Brookhaven)
- Rare Kaon decays ($K_L \rightarrow \pi^0 \nu \nu$, $K^+ \rightarrow \pi^+ \nu \nu$, $K_L \rightarrow \pi^0 e^+ e^-$)
**Problems with ICD-I**

- μ-to-e is considered as the most important experiment
  - It will be using all existing infrastructure (Recycler, Accumulator and Debuncher) leaving no place for other experiments for many years
  - $g$-2 has time conflict because competes for the same infrastructure (Recycler and Debuncher) and cannot be ran at the same time
    - Lengthening Tevatron Run II worsens the problem
  - Kaon experiments require different time structure of the beam and cannot be ran simultaneously
    - There is another possibility - a usage of Tevatron as a stretcher. We are looking into this as well
- From the High Energy Physics point of view:
  - CDF & D0 $\rightarrow$ μ-to-e + decommissioning of the Antiproton source
- There is also problem with μ-to-e upgrade because of limited power for the beam slow extracted from Debuncher
What is the ICD-II

Pulsed 2 mA H⁻ source, 5% duty factor

**MEBT** consists of rebuncher cavities, beam chopper, focussing and transverse trims, and necessary instrumentation

Combination done at ~5 MeV and needs to keep p+ and H⁻ 180° out of phase

RFQ in each section to ~5 MeV

10 mA DC p+ source

Main Injector

1.6e¹⁴ at 1 Hz

2-8 GeV section

An SC Linac?

A Rapid Cycling Synchrotron?

RF Splitter

Kaons

μ±e

RF Splitter uses transverse RF cavity for beam splitting

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Split 8 GeV linac into 2 parts

- **0-2 GeV, 2-MW (1 mA) CW linac**
  - peak current up to 10 mA to have ability to create a desired beam structure for different beam physics experiment without sacrificing average beam power

- **2-8 GeV acceleration**
  - 10 Hz synchrotron looks as a preferred choice for now
    - Operates below transition energy
  - 2-8 GeV, 0.22-MW pulsed linac
    \[ \beta = 1 \text{ (ILC-like)}: \]
    
    - 40 ms @ 1Hz or variations for 2.2 MW at 60 GeV (300 kW at 8 GeV)

At least 1 mA of CW linac is required

- For synchrotron by inj. time (10 Hz, 4 ms of 100 ms cycle, \( \Delta p/p = 8 \cdot 10^{-3} \))
- For pulsed linac it is set by total duration of pulses (5 Hz, 8 ms)
  - Present ICD 5 ms @ 1Hz (5 Hz, 1 ms)

Higher current would make pulsed linac easier

CW linac beam can be split to several experiments by RF separators

- 3 experiments with independent beam time structures
  - \( f = f_{RF} / 3 \) (~100 MHz, ~1-3 ps rms bunch length)
ICD II effect on the Physics Program

- Machine Parameters are set by Experiments
- \( \mu \)-to-\( e \) (1 GeV would be enough)
  - much better than the present scheme,
    - some loss in pion yield is compensated by power
    - Smaller background (less neutrons, antiprotons, high energy pions)
    - Negligible intensity variation (serious problem for slow extraction)
    - Easy to control time structure of the beam (~10% duty factor)
    - Extinction
      \( \Rightarrow \) Proton linac does not accelerate electrons or protons with other momentum. The chopper is the only system determining beam extinction
    - addresses strong competition from JPARC and future upgrade
- Kaons require at least 2 GeV energy
  - Flexible time structure and short bunches are extremely useful
    - Time of flight experiments
- \( g-2 \) can be ran with “fast” extraction from Recycler
- Program with antiprotons is discussed
- Additional program is possible
  - Transmutation, medical isotopes production and nuclear physics
**CW Linac**

**Design criteria**

- Linac structure is similar to the ICD-I linac
- Major differences are
  - Reduced accelerating gradient to optimize the cryogenic system (cost optimization results in a wide minimum 15 – 18 MV/m)
    - 25 MV/m ⇒ 16 MV/m
  - Reduced peak current
    - 32 mA ⇒ 10 mA
    - Less problems with beam space charge
  - SC structures start at 2.5 MeV instead of 10 MeV
    - Reduction of RF power

* Disclaimer: all parameters of the ICD-II are not final. The ICD-2 document is expected to be finished by Sep. 1, 2009
Front end

- Dual beam
  - H- for injection to RCS
  - Proton for 2 GeV experimental program
- Bunch-by-bunch chopping
- 2.5 MeV, normal conducting RFQ

Diagram:

- Dual beam
  - H- for injection to RCS
  - Proton for 2 GeV experimental program
- Bunch-by-bunch chopping
- 2.5 MeV, normal conducting RFQ
### SC linac

| Section        | Energy range MeV | β     | Number of cavities/lenses/CM | Type of cavities and focusing element | Power/cavity, kW (I_{av}=1 mA) |
|----------------|------------------|-------|------------------------------|---------------------------------------|--------------------------------|
| Bunching SSR0 (β_{G}=0.11) | 2.5              | 0.073 | 2/3/2                       | Single spoke cavity, Solenoid          | 0.5                            |
| SSR0 (β_{G}=0.11)     | 2.5-10           | 0.073-0.146 | 16/16/2                                      | Single spoke cavity, Solenoid          | 0.5                            |
| SSR1 (β_{G}=0.22)     | 10-32            | 0.146-0.261 | 18/18/2                                      | Single spoke cavity, Solenoid          | 1.3                            |
| SSR2 (β_{G}=0.4)      | 32-117           | 0.261-0.5   | 33/17/3                                      | Single spoke cavity, Solenoid          | 4.1                            |
| TSR (β_{G}=0.6)       | 117-400          | 0.5-0.713   | 42/42/7                                      | Triple spoke cavity, quads             | 8.5                            |

β_{G} is cavity geometrical phase velocity.
**SC linac (Elliptic cavities, ILC type)**

### Parameters of 1.3 GHz cavities

| Section     | Energy range MeV | $\beta$  | Number of cavities/quads/CMs | Type                    | Max Power/cavity (on crest), kW ($I_{av}=1$ mA) |
|-------------|------------------|---------|-------------------------------|-------------------------|-----------------------------------------------|
| S-ILC ($\beta_G=0.81$) | 400-1200 | 0.71-0.9 | 84 / 42 / 14 | Squeezed elliptical | 15                                            |
| ILC ($\beta_G=1$)     | 1200-2000       | 0.9-0.95 | 75 / 15 / 10                      | 9-cell ILC           | 16                                            |
Synchrotron

Design criteria

- Repetition rate of 10 Hz is set by 2 MW to MI operating at 60 GeV (6 injections during 0.8 s cycle)
  - Recycler is used for intermediate beam storage
- No transition crossing
- Transverse acceptance (40 mm mrad (norm) + 6 mm orbit distortions) - the same as for MI
- High periodicity FODO structure
  ⇒ Small diameter vacuum chamber
  ⇒ Small and inexpensive magnets
- Stainless steel vacuum chamber
  - It shields laminations of magnets resulting in small impedances
    - The impedance value is rather limited by the eddy currents excited by the bending field than by the wall resistivity
  - Ceramic vacuum chamber would be more expensive and would require larger size magnets with limited gain in impedance
- Dual harmonic RF to reduce the beam space charge at injection
  - RF frequency the same as in MI
**RCS parameters**

| Parameter                          | Value  |
|------------------------------------|--------|
| Energy, min/max, GeV               | 2/8    |
| Repetition rate, Hz                | 10     |
| Circumference, m (MI/6)            | 553.2  |
| Tunes                              | 18.44  |
| Transition energy, GeV             | 13.36  |
| Number of particles                | 2.67E13|
| Beam current at injection, A       | 2.2    |
| Harmonic number                    | 98     |
| RF frequency, MHz                  | 50.33 – 52.81 |
| Maximum RF voltage, MV             | 1.6    |
| 95% n. emittance, mm mrad          | 25     |
| Space charge tune shift, inj.      | 0.06†  |
| Norm. acceptance, mm mrad          | 40     |
| Injection time for 1 mA, ms        | 4.3    |
| Linac energy cor. at inject.       | 1.2%   |
| RF bucket size, eV s               | 0.4    |
| Number of RF cavities              | 16     |
| Cavity shunt impedance, kΩ         | 100    |

†For the KV-like distribution presented below and bunching factor - 2.2.

- Racetrack
- Dispersion is zeroed by missed dipole
- One type of quadrupoles
- All quads and dipoles are on the same bus
- Corrector pack includes dipoles quads and sextupoles

**Beam envelopes for quarter of the ring:**

\[ \varepsilon_n = 40 \text{ mm mrad} \left( E_k = 2 \text{ GeV} \right), \Delta p/p = 5 \cdot 10^{-3} \]
**Magnets**

### Dipoles

| Parameter                        | Unit | Value |
|----------------------------------|------|-------|
| Field at 8 GeV (672 A)           | T    | 0.874 |
| Magnet gap                       | mm   | 44    |
| Effective length                 | m    | 2.13  |
| Number of turns/pole             |      | 24    |

### Quadrupoles

| Parameter                        | Unit  | Value |
|----------------------------------|-------|-------|
| Gradient at 8 GeV (672 A)        | T/cm  | 0.1743|
| Pole tip radius                  | mm    | 25    |
| Effective length                 | m     | 0.659 |
| Number of turns/pole             |       | 7     |

100 Rectangular dipoles and 134 quads (6 of them with increased aperture for inj. & extr.)
**Vacuum chamber**

- **Round**
  - External diameter - 44 mm
  - Stainless steel - 0.7 mm

- **Bend in dipoles, R=34 m**
  - Sagitta - 1.67 cm

- **Eddy currents (dipoles)**
  - $\Delta B/B = i \cdot 1.4 \cdot 10^{-3}$
  - Power loss ($B_m=8$ GeV) - 11 W/m

- **Growth rate of the transverse instability due to wall resistivity at lowest betatron sideband**
  - $0.006$ turn$^{-1}$

**Dipole resonance circuit**

- **Resonance circuit is similar to the Booster one**
  - One choke and one capacitor per cell (2 dipoles and 2 quads)

\[\begin{align*}
L_d &= 25 \text{ mH}, \quad R_d = 33 \text{ m}\Omega \\
L_{choke} &= 32 \text{ mH}, \quad R_{choke} = 12 \text{ m}\Omega \\
C_0 &= 13 \text{ mF} \\
V_c &= 725 \text{ V} \\
\text{Total power} &= 900 \text{ kW} \\
\text{Total DC} &= 1.2 \text{ kV} \\
\text{Total AC (ampl)} &= 1.1 \text{ kV}
\end{align*}\]
Beam acceleration

Accelerating voltage, MV

1. First harmonic amplitude
2. Second harmonic amplitude
3. Accelerating voltage

Accel. phase and bunch length, deg

1. Bucket length
2. 95% bunch length
3. Accelerating phase, $\phi_0$

Bucket height and $\Delta P/P$

1. Bucket height
2. $\Delta p/p$ [95%]
3. $\sigma_p$

Bucket area, eV s

1. $\sigma_L^{95}$
Transverse painting at Injection (rms norm. linac emit. – 0.5 mm mrad)

- Optimization of injection beta-functions: $\beta_L \approx \beta_R / 2$
- KV-like distribution with 25 mm mrad KV boundary
  - 99% in 35 mm mrad
  - x-y anti-correlated painting
  - angles correlated with positions to minimize betatron amplitudes

- Secondary foil passages make a major contribution to the foil heating
  - 55 hits per particle or $1.2 \cdot 10^5$ passages per particle per mm$^2$
Longitudinal painting at injection (rms. long. linac emit. - $5 \cdot 10^{-5}$ eV s)

- Linac energy is changing $\pm 0.5\%$ to match the RCS energy during 4.2 ms injection
  - Constant offset of 0.07\% between linac and RSC momenta
  - 73\% duty factor
- High synchrotron frequency helps to make uniform distribution
- Debunching and phase rotation of the linac beam is required
- Resulting bunching factor $-2.2$
Possible upgrade paths

RCS without any upgrades

- Low longitudinal density is the major limitation of the beam power. To mitigate it:
  - Beam is accelerated in two trains of 24 buckets (50% duty factor)
    - Bucket size is reduced from 0.4 to 0.13 eV s to fit required $\varepsilon_L$
    - Space charge time shift - 0.12
  - Two turn injection in the compressor ring with consecutive adiabatic bunching and bunch rotation

- It results in $P=340$ kW at 10 Hz (single bunch)
  - $\sigma_s = 60$ cm, $\sigma_p = 0.1\%$, $\varepsilon_{95} = 6\pi \sigma_s \sigma_p p / (\beta c) \sim 3.3$ eV·s

- The only additional requirement (upgrade) is doubling the current of H- source (2 mA $\rightarrow$ 4 mA)
  - And, of course, the 8 GeV compressor ring with circumference half of the RCS
Possible Upgrade Paths (2)

New 20 GeV 20 Hz RCS

- Peak power of the SC linac has to be increased by at least 12 times to 12 mA
  - 1.5 times larger energy (3 GeV, pulsed)
  - 2 times shorter injection to RCS (20 Hz)
  - 2 times larger beam current in RCS (larger injection energy)
  - 2 times larger circumference (20 GeV)

- Synchrotron can be built using the same technology as 8 GeV synchrotron
  - 3 trains of bunches, 3 turn injection to the compressor ring

- It results in $P=1.7$ MW at 20 Hz (single bunch)

- Upgrades
  - RF of SC linac
    - it can be converted to the pulsed (preferred and chipper) operation or operation with two RF sources for concurrent pulsed and CW operations
    - 24 MW CW RF is not excluded as well
  - And, 20 GeV compressor ring with circumference one third of the RCS
Possible Upgrade Paths (3)

Linac extension to 8 GeV

- Follows scenario presented in Berkeley (Jan. 2009, NFMCC meeting)
- 1 MW at 15 Hz single bunch
  - Power will grow proportionally to the repetition frequency and number of bunches
  - i.e. four bunches 4 MW at 15 Hz
Conclusions

- ICD-II proposal retains the 2-MW MI program but moves 8-GeV slow extraction program to 2 GeV
- It does not exclude experiments which use fast extraction from the Recycler

Benefits

- Diverse physics program at low energy
  - expected to bring the price below ICD-I
  - ⇒ Pricing should be finished by the end of August
- Potential improvements of μ-to-e sensitivity can be more than an order of magnitude - it makes it really competitive

Drawbacks

- More expensive upgrade to MW scale beam power required for neutrino factory or muon collider
- Both Synchrotron and Pulsed linac can coexist with CW linac
  - Final choice will be compromise between Cost - Political implications - Long term plans
Backup viewgraphs
### Structure of periodicity element

| Name | S[cm] | L[cm] | B[kG] | G[kG/cm] | S[kG/cm/cm] |
|------|-------|-------|-------|----------|-------------|
| qF   | 65.9  | 65.9  | 0     | 2.141    | 0           |
| o2   | 85.9  | 20    |       |          |             |
| sF   | 105.9 | 20    | 0     | 0        | 0.22*       |
| o1   | 135.9 | 30    |       |          |             |
| bD   | 349.116 | 213.216 | 10.7123 | 0       | 0           |
| o    | 419.116 | 70    |       |          |             |
| qD   | 485.016 | 65.9  | 0     | -2.134   | 0           |
| o2   | 505.016 | 20    |       |          |             |
| sD   | 525.016 | 20    | 0     | 0        | -0.38*      |
| o1   | 555.016 | 30    |       |          |             |
| bD   | 768.232 | 213.216 | 10.7123 | 0       | 0           |
| o    | 838.232 | 70    |       |          |             |

*Sextupole strengths nullify natural chromaticities: \( \nu_x = -25 \) and \( \nu_y = -25 \)

Strength of the magnets are shown for 10 GeV beam kinetic energy

![Graph showing beta and dispersion](image-url)
**Injection**

- Strip $H^-$ injection: in a straight line, horizontally (radially outside)
- 3 quads in the injection region have increased aperture
  - 12 turns per pole (instead of 6)
  - $a = 33.2$ mm (instead of 23.48 mm)
- 3 injection dipoles in one straight section
  - B1 - DC septum, B2 and B3 - permanent magnets or powered by DC
- 3 fast correctors for x-y painting in each plane

**Injection cell structure**

| Name | L[cm] | B[kG] | G[kG/cm] |
|------|-------|-------|----------|
| qD   | 65.9  | 0     | -1.74    |
| oInj | 40    |       |          |
| B1   | 21    | -6.9  |          |
| oInj1| 52.608|       |          |
| B2   | 126   | 2.3   |          |
| oInj2| 26.304|       |          |
| iFOIL| 0     |       |          |
| oInj2| 26.304|       |          |
| B3   | 21    | -6.9  |          |
| oInj | 40    |       |          |
| qF   | 65.9  | 0     | 1.74     |

Local orbit bump for painting;
Maximum corrector strength - 15 kG cm
Swiping time - 4 ms
Injection (continue)

- Total power of injected beam
  - 75 kW for 60 GeV MI operation
  - 37 kW for 120 GeV MI operation

- $H^-$ field stripping limits B2 field
  - Stripping probability is $4 \times 10^{-5}$

- B3 strips $H^-$ which missed foil
  - Survival probability $\sim 10^{-17}$
  - Average deflection before stripping - 3 mrad
Injection (continue)

- Single and multiple scattering in the foil (thickness - 450 μg/cm²)
  - Emittance increase due to multiple scattering is not a problem
    - Emittance increase per foil crossing:
      \[ \Delta \varepsilon_{xn95\%} = 8.5 \times 10^{-3} \text{ mm mrad}; \quad \Delta \varepsilon_{yn95\%} = 3.3 \times 10^{-3} \text{ mm mrad} \]
      \[ \Rightarrow \text{ for expected 50 crossings per particle } \Delta \varepsilon_{n95\%} < 0.5 \text{ mm mrad} \]
  - Particle loss due to single scattering
    - For 40 mm mrad acceptance the loss has approximately equal contributions from nuclear and electromagnetic scatterings
      \( (\sigma_{em} \approx 200 \text{ mbarn}, \sigma_n \approx 340 \text{ mbarn}) \)
      \[ \Rightarrow \text{ beam loss } - 1.4 \times 10^{-5} \text{ per foil crossing} \]
    - With expected 50 crossings per particle
      \[ \Rightarrow \text{ Total loss } \sim 0.07\% \text{ or } 200 \text{ W for 300 kW operation} \]

- Injection beam dump is located after QF. It will intercept particles scattered in the foil and \( H^0 \).
  - It has to be rated to 3 kW

- Stripped electrons are reflected from field of B3 dipole and intercepted by electron beam dump (located radially inside)
  - Total power - 300 W for 300 kW operation
Extraction

Extraction structure

| Name   | L [cm] | B [kG] | G [kG/cm] |
|--------|--------|--------|-----------|
| qF     | 65.9   | 0      | 1.746     |
| ky1e   | 1e-06  | -4.89e+7 |          |
| oS     | 353.216 |        |           |
| ky2e   | 1e-06  | -2.25e+7 |          |
| qD     | 65.9   | 0      | -1.740    |
| oEKICK | 26.608 | 0.448  | 0         |
| kEKICK | 300    |        |           |
| oEKICK | 26.608 |        |           |
| qF     | 65.9   | 0      | 1.746     |
| oQL    | 346.4  | 0      | -1.457    |
| qL     | 79.39  | 0      |           |
| oSep   | 30.73  | 7.75   |           |
| kESEP  | 285    |        |           |
| oSep   | 30.7336|        |           |
| qF     | 65.9   | 0      | 1.74      |
| ky3e   | 1e-06  | -9.90e+7 |          |

- QL has increased aperture and length and decreased gradient (a = 40 mm)
- QDMs are the same as injection quads with increased aperture (a = 33.2 mm)
- Vertical kick
- Vertical orbit bump of 16 mm at septum location with normal machine correctors
- Septum kicks in horizontal plane (width - 10 mm)
Transverse Instabilities and their damping

- Eddy currents in vacuum chamber excite magnetic field correction
  - Eddy current reflection in the steel of dipoles increases the correction and makes it non-linear even for the round vacuum chamber
  \[
  \frac{\Delta B_y}{B_0} = i \left( 1 + \frac{\pi^2}{12} + \frac{\pi^4}{240} \frac{y^2}{a^2} + \ldots \right) \frac{ad}{\delta_r^2}, \quad \delta_r = \frac{c}{\sqrt{2\pi\sigma\omega_{ramp}}}
  \]
  - That requires minimum $\sigma d$ for the wall

- Transverse impedance for the lowest mode is also determined by $\sigma d$
  \[
  \text{Re}(Z_\perp) = Z_0 \frac{c^2}{4\pi^2 \sigma R \omega a^3 d}, \quad \sqrt{ad} \geq \delta \geq d
  \]

- Instability will be stabilized by $\perp$ dampers (low frequencies) and by chromaticity (high frequencies)