Project X: A multi-MW Proton Source at Fermilab

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Extreme Beam Lecture Series

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Outline

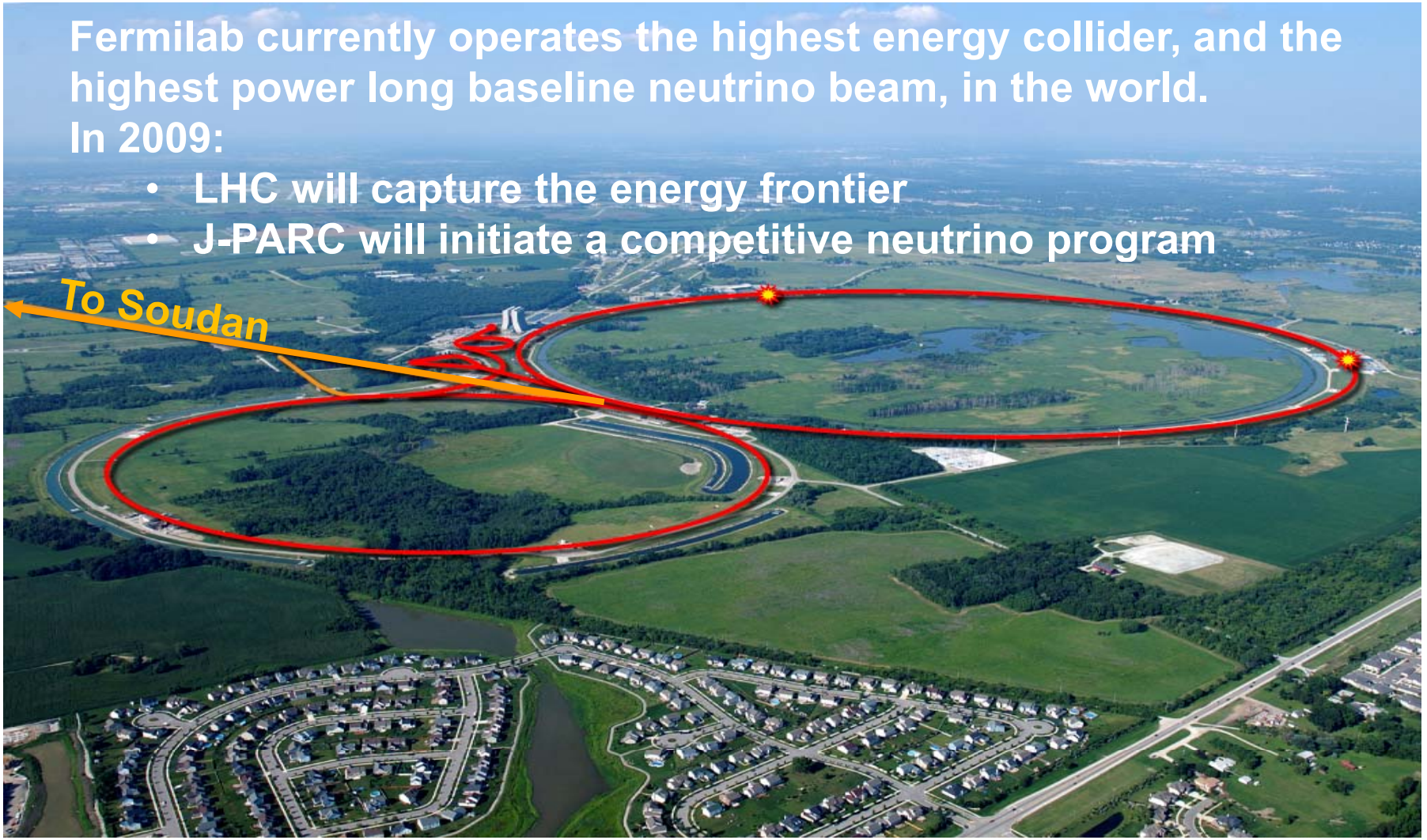
- Strategic Context/Evolution of the Fermilab Complex
- Project X Goals and Initial Configuration
- Project X Research, Design, and Development Plan
- Relationships to other Programs
- Alternative Configurations

Project X website: http://projectx.fnal.gov/

Strategic Context: Fermilab and the World Program

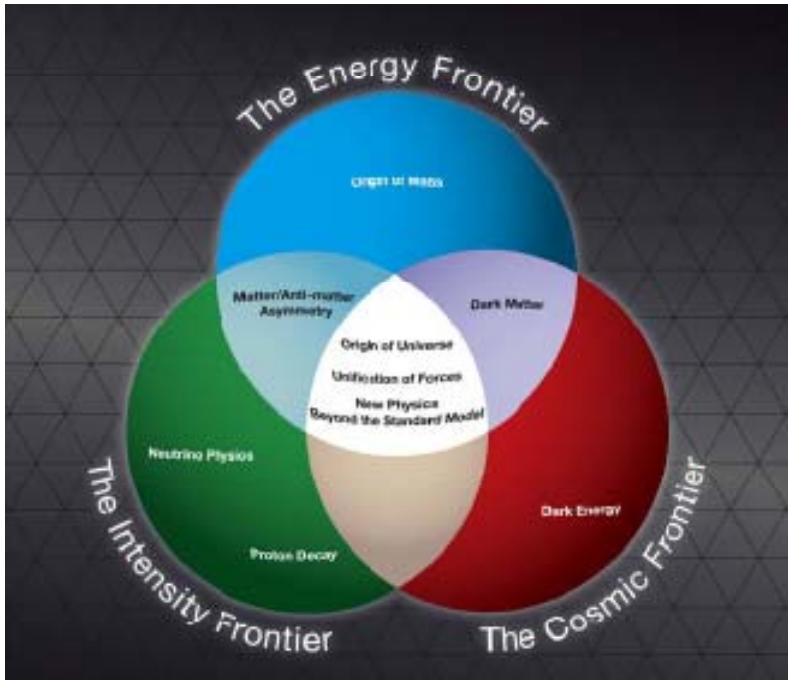
Fermilab currently operates the highest energy collider, and the highest power long baseline neutrino beam, in the world.
In 2009:

- LHC will capture the energy frontier
- J-PARC will initiate a competitive neutrino program



Strategic Context: Fermilab Long Range Plan

- Fermilab is the sole remaining U.S. laboratory providing facilities in support of accelerator-based Elementary Particle Physics.
- The Fermilab long-term strategy is fully aligned with the HEPAP/P5 plan:
  - Energy and intensity frontiers share strong reliance on accelerators



(www.science.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf)

Strategic Context: The World in ~2012

A confluence of events points to the ~2012 time frame as the period of decision on future directions in elementary particle physics:

- Energy Frontier
  - Initial physics results based on significant integrated luminosity from LHC will be available and interpreted
    - Expected to provide guidance on the desired energy reach of a future lepton collider
  - International Linear Collider Technical Design Phase complete
    - Definitive information on the performance and costs of an electron-positron linear collider in the range 500-1000 GeV
  - Complete conceptual design and preliminary cost estimate for a multi-TeV electron-positron linear collider (CLIC)
  - Complete feasibility study for a multi-TeV muon collider

Strategic Context: The World in ~2012

- Intensity Frontier
  - J-PARC operational at up to 750 kW beam power at 30-40 GeV in support of the T2K long baseline (295 km) neutrino experiment
  - NOνA long baseline (810 km) neutrino experiment initiates operations at up to 700 kW beam power at 120 GeV at Fermilab
  - Complete design of a very long baseline (1300 km) neutrino beamline at Fermilab, and an associated multi-MW proton source
  - Complete conceptual design of a J-PARC multi-MW upgrade
  - Next round of neutrino experiments indicate whether the mixing parameter $\sin^2 2\theta_{13}$ is greater than or less than ~0.02

Strategic Context: Evolution of the Accelerator Complex

- Project X, a multi-MW Proton Source, is the lynchpin of Fermilab's strategy for future development of the accelerator complex.
- Project X is designed to provide flexibility in evolving the Fermilab program along lines indicated by what we have learned in 2012
  - Energy Frontier:

    Tevatron → ILC or Muon Collider
    - Technology alignment
    - Project X development retains ILC and MC as options for the Fermilab site
  - Intensity Frontier:

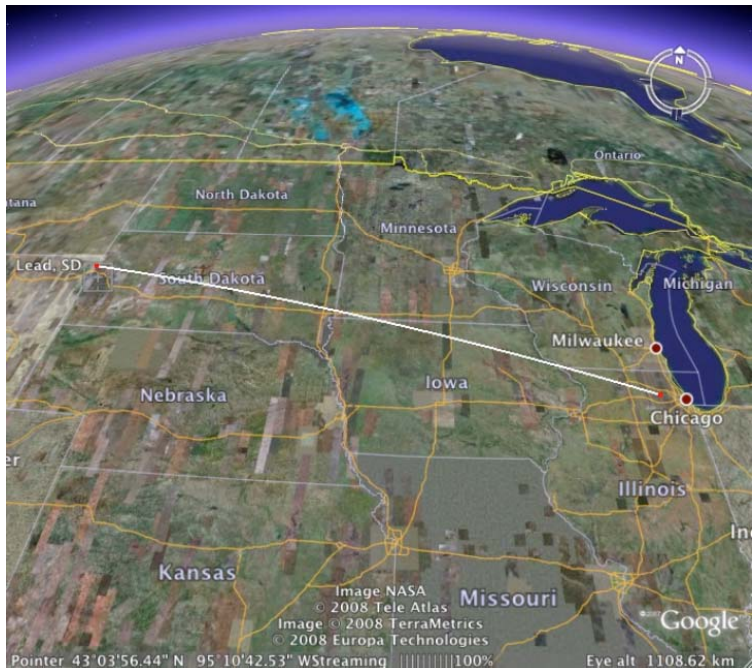
    NuMI→ NOνA→ LBNE/mu2e→ multi-MW Proton Source → NuFact
    - Continuously evolving world leading program in neutrino physics and other beyond the standard model phenomena

Strategic Context: Shared Technologies

- Superconducting rf @ 1.3 GHz
  - Superconducting (e+, e-) linacs: ILC, XFEL
  - Superconducting (H-) linacs: Project X (,SNS)
  - Superconducting recirculating linacs: FELs,Muon Facilities
- High Intensity Proton Acceleration
  - Flexible front end sources: Neutron and isotope sources
  - Loss control and mitigation: Neutron and isotope sources, ILC
  - High intensity limitations (e-cloud): ILC
  - Other high power applications: ATW, ADS

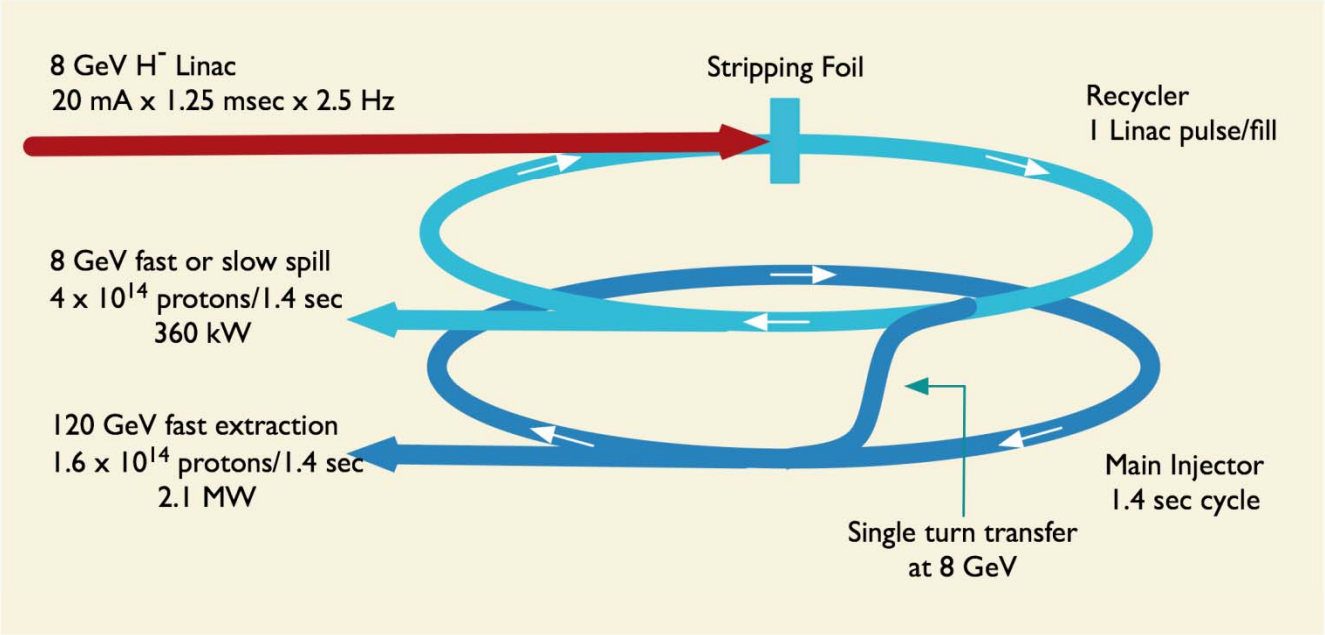
Mission Need

- The P5 report defines mission need for a multi-MW proton source based on :
  - A neutrino beam for long baseline neutrino oscillation experiments.
    - 2 MW proton source at 60 - 120 GeV
  - High intensity 8 GeV protons for kaon and muon based precision experiments
    - Simultaneous operations with the neutrino program.
  - A path toward a muon source for a possible future neutrino factory and/or a muon collider at the Energy Frontier.
    - Requires upgrade potential to 2-4 MW at 8 GeV.



Initial Configuration

- Project X Design Criteria
  - >2 MW of beam power over the range 60 – 120 GeV;
  - Simultaneous with >150 kW of beam power at 8 GeV;
  - Compatible with future upgrade to 2-4 MW at 8 GeV

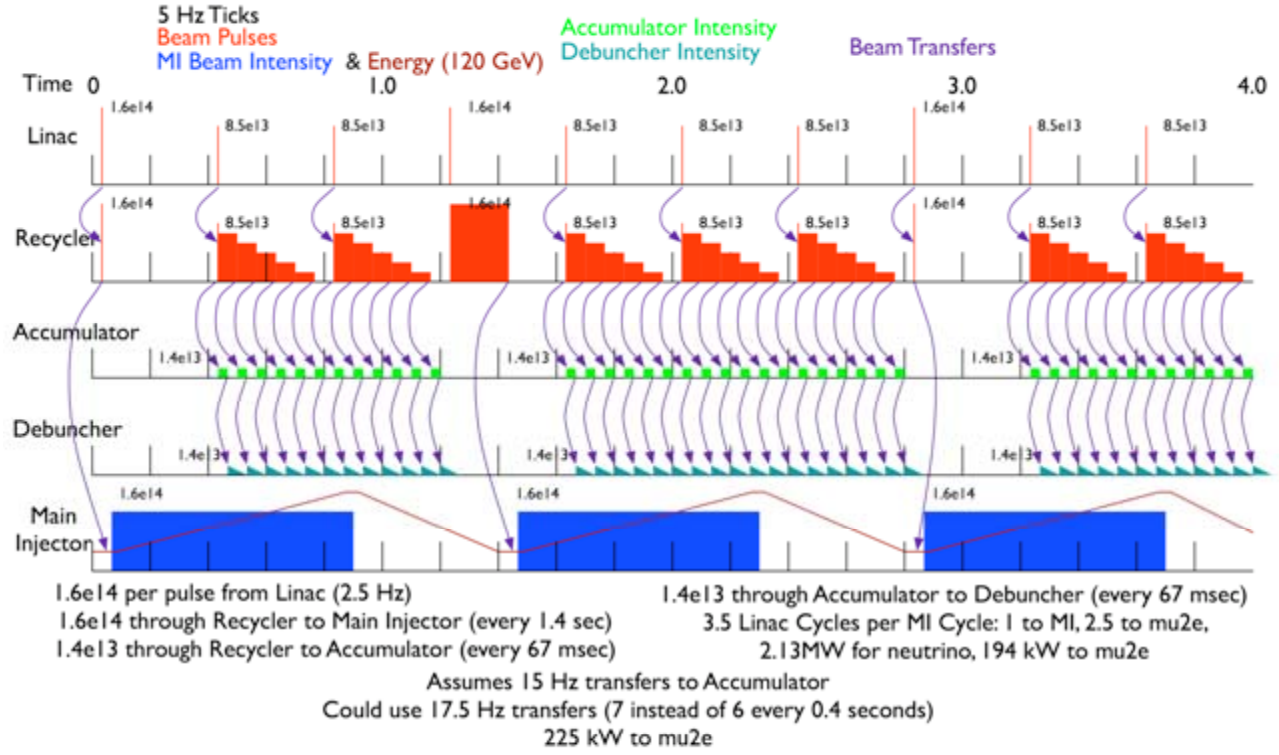


Initial Configuration Performance Goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Particles per pulse	1.6×10^{14}	
Linac pulse rate	2.5	Hz
Beam Power	500	kW
Recycler		
Particle Type	protons	
Beam Kinetic Energy	8.0	GeV
Cycle time	1.4	sec
Particles per cycle to MI	1.6×10^{14}	
Particles per cycle to 8 GeV program	1.6×10^{14}	
Beam Power to 8 GeV program	360	kW
Main Injector		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.7×10^{14}	
Beam Power at 120 GeV	2100	kW

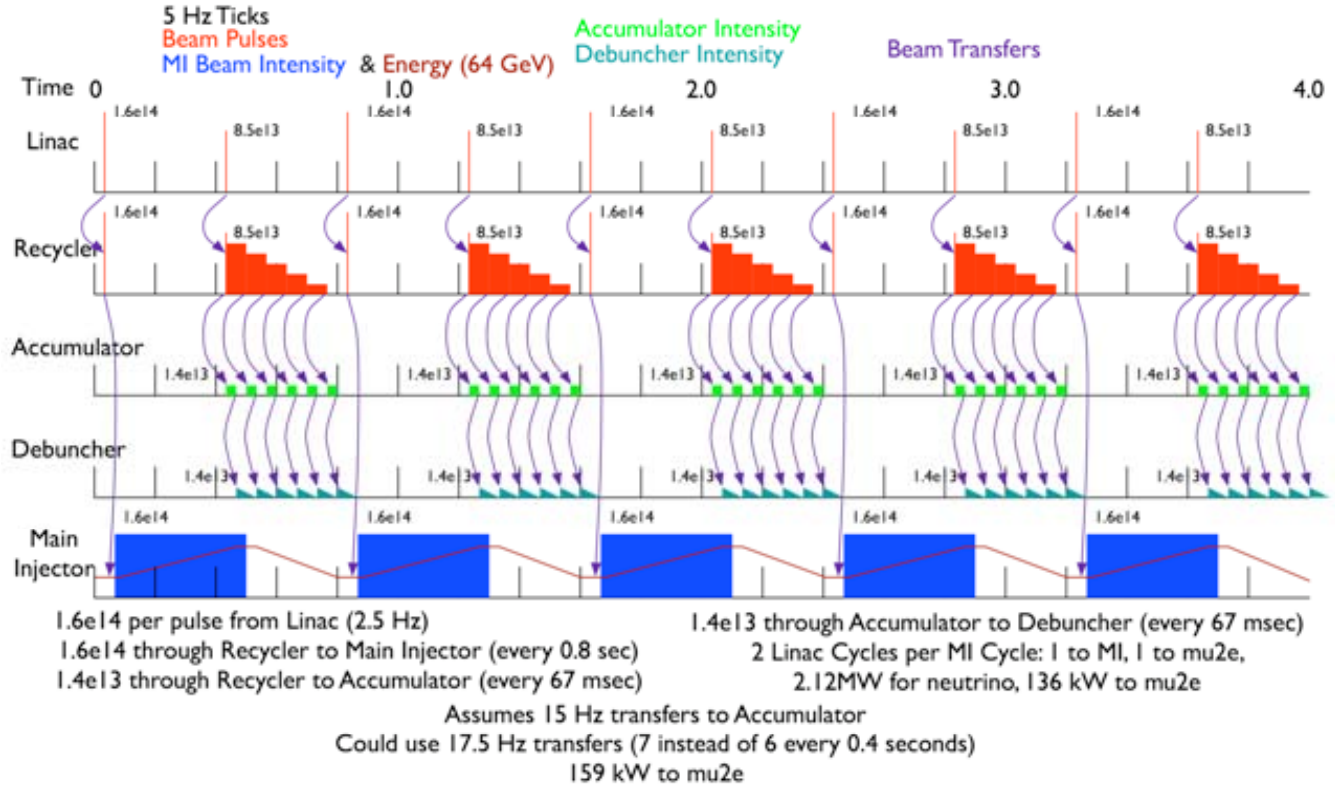
Initial Configuration Operating Scenarios

- Operating scenarios for 120 GeV (2.1 MW)
  - 194 kW at 8 GeV to mu2e experiment in parallel

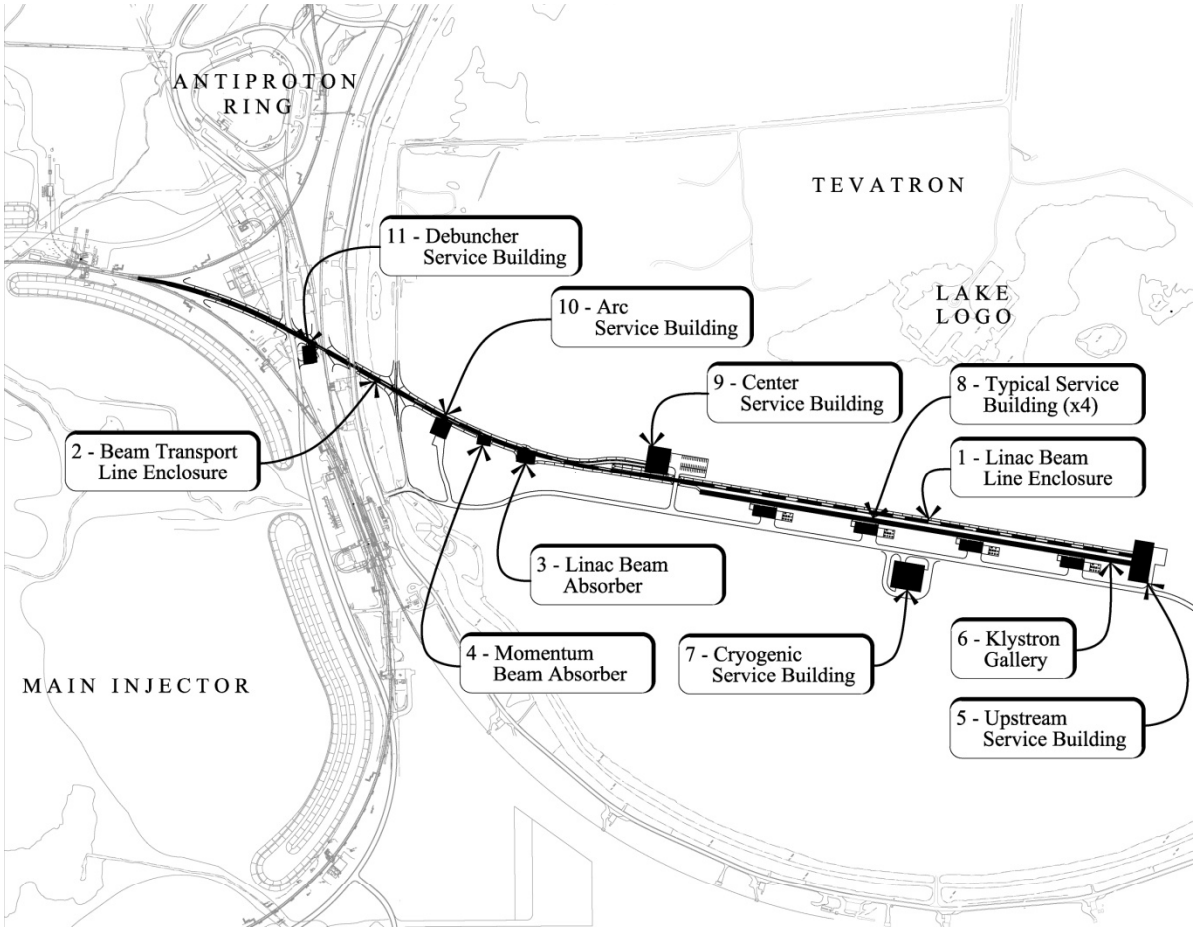


Initial Configuration Operating Scenarios

- Operating scenario for 64 GeV (2.1 MW)
  - 136 kW at 8 GeV to mu2e experiment in parallel



Initial Configuration Provisional Siting



Initial Configuration Operational Challenges

- We know that the IC does not provide an ideal platform for mounting a low energy flavor program.
  - "Golden Book" requirements:

	Train Frequency (MHz)	Pulse Width (nanoseconds)	Inter-Pulse Extinction
Kaon experiments	20-30	0.1-0.2	10^{-3}
Muon conversion experiment	0.5-1.0	50	10^{-9*}
Muon g-2 experiment	30-100	50	---

  - The Recycler is ill-suited to providing high intensity slow spilled beam
    - In the IC the Recycler delivers 15 Hz packets to the Debuncher for slow spill to mu2e.
      - The Debuncher appears limited to <150 kW in this mode
  - The IC does not yet have a solution for the kaon requirements

⇒We are able to generate substantially more beam power in the ICD than we are effectively utilize.

Near-term Strategy

- Develop an Initial Configuration Document
  - Meeting the high level design criteria
  - ICD subject to configuration control
  - ⇒ Released V1.1, March 2009: available at http://projectx.fnal.gov/
- Revise/update the current RD&D Plan
  - Based on the ICD
  - Review existing plan to emphasize reduction of risk
  - ⇒ Released V2.2, March 2009 following mid-February AAC evaluation
- Create a preliminary cost range estimate
  - Based on the ICD
  - ⇒ Complete and subject of Director's Review March 16-17, 2009

Near-term Strategy

- Establish design criteria and operating scenarios for evaluation of alternative configurations
  - Design criteria complete
  - Alternative configuration under development
- Establish a multi-institutional collaboration for the RD&D phase
  - Collaboration established
- CD-0 in 2009
  - Based on: ICD, preliminary cost estimate, P5 mission definition
  - Coordinated with very long baseline and mu2e

RD&D Plan

- The primary goal of the Project X Research, Design, and Development (RD&D) program is to complete a fully developed baseline scope, cost estimate, and schedule in 2012 (CD-2).
  - Design and technical component development;
  - Fully developed baseline scope, cost estimate, and schedule;
  - Undertaken by a multi-institutional collaboration capable of executing both the RD&D plan and the follow-on construction project
- Secondary goals:
  - Coordinate Project X and ILC SCRF development programs;
  - Retain alignment of Project X and the Neutrino Factory and Muon Collider programs, to assure that Project X could serve as the initial stage of either/both facilities

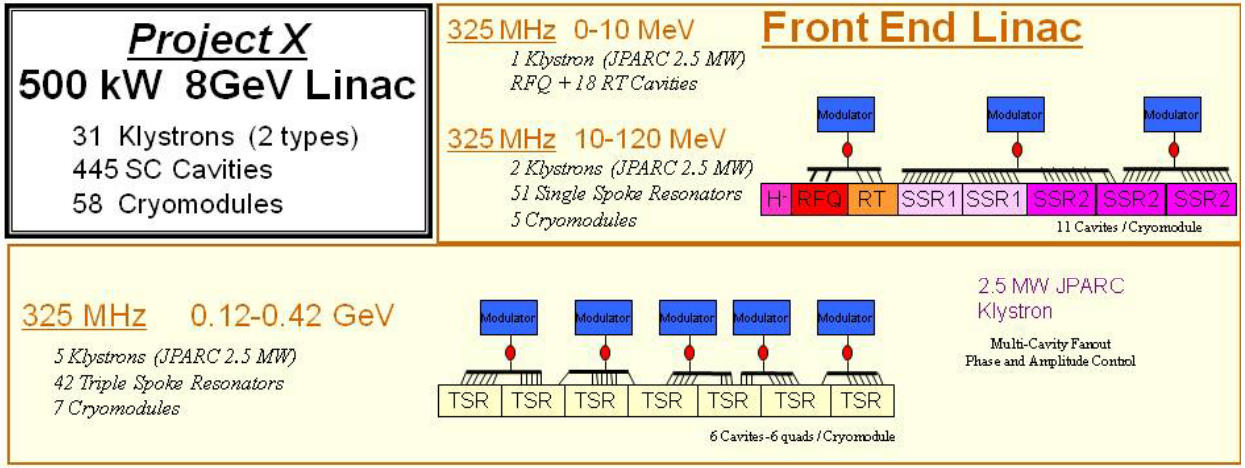
RD&D Plan: Accelerator Challenges

- Linac (325 MHz)
  - Front end: Peak current 32 mA x 1.25 msec x 5 Hz
    - Consistent with SNS performance
  - High speed chopping (325 MHz)
    - Variable chopping patterns
  - Consideration of warm vs. cold front end
    - 30-60 MeV cold front end currently under development (HINS)
- Linac (1300 GHz)
  - 32 mA peak (20 mA average) x 1.25 msec x 5 Hz
    - 3 times the charge/pulse of ILC
  - 25 MV/m gradient
  - RF control of multiple accelerating structures from single rf source

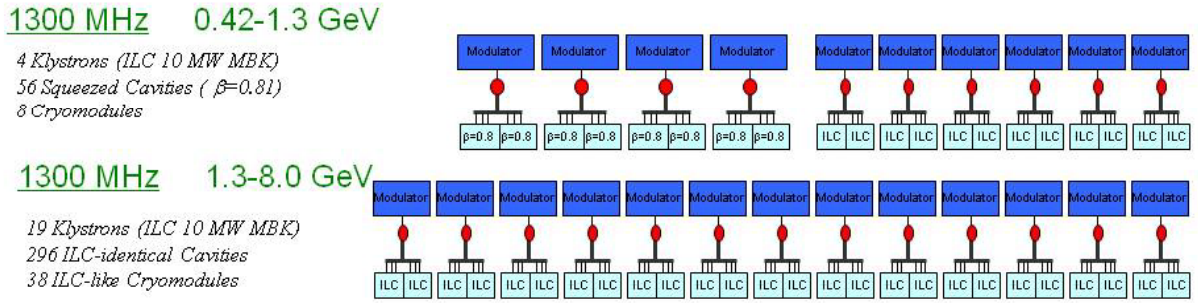
RD&D Plan: Accelerator Challenges

- Beam Transfer Line and Injection
  - Beam transport without stripping
    - Cryogenically cooled beam pipe
  - Loss control and mitigation
  - Injection system:
    - Transverse and longitudinal painting
    - Losses
    - Foil lifetime
- Recycler/Main Injector
  - Space-charge
  - E-cloud
  - Other beam instabilities

ICD Technology Map



1300 MHz LINAC

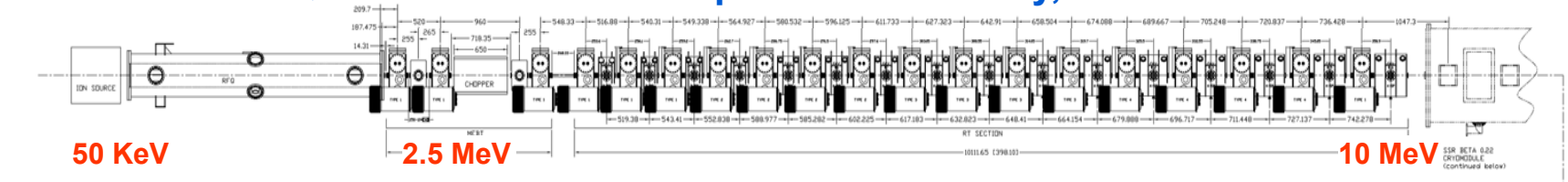


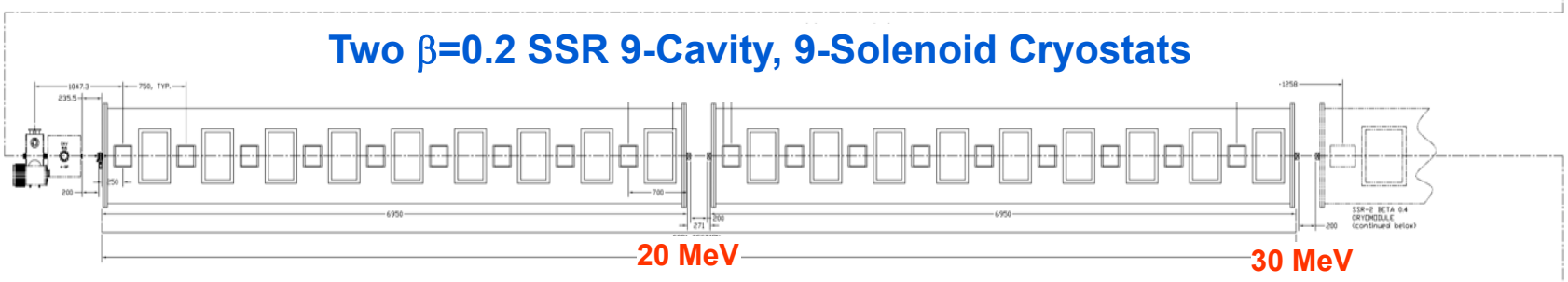
Joint PX/HINS Strategy

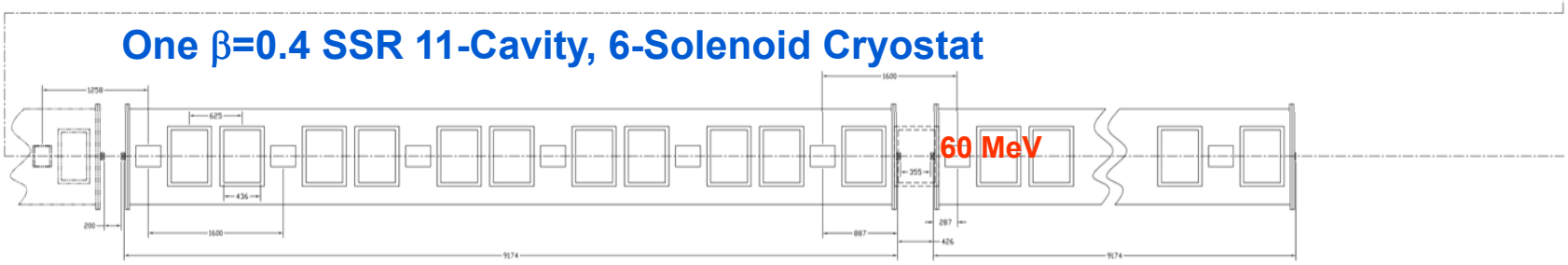
- The High Intensity Neutrino Source (HINS) program was established in 2006 to pursue a new approach to high intensity, low energy ion acceleration
- HINS primary goals:
  - Accelerate an axially symmetric beam (solenoidal focusing) to 30 MeV, utilizing superconducting rf technology beyond 10 MeV
  - Demonstrate effectiveness of RF modulators for phase and amplitude control of individual cavities fed by a common rf source
    - Intermediate goal is 6 cavity (warm) test with beam, demonstrating viability of vector modulator technology, in early 2010
  - Demonstrate high-speed (nsec) beam chopping at 2.5 MeV

$\Rightarrow$ Goal is to complete facility (@30 MeV) in 2012

Joint PX/HINS Strategy

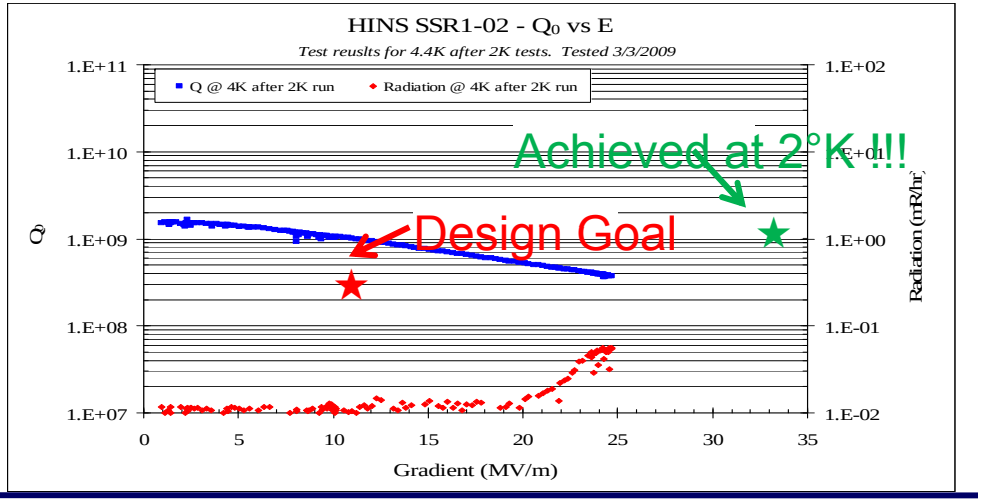






Joint PX/HINS Strategy

- HINS Progress
  - Ion source (H+) installed and operating
  - RFQ received and under rf testing (issues identified)
  - Room temperature spoke resonators tested
  - Prototype VMs tested
  - Two β = 0.22, 325 MHz, SSRs successfully tested in the VTS
  - Requirements: >10 MV/m @ Q0>5E8 @ 4 K

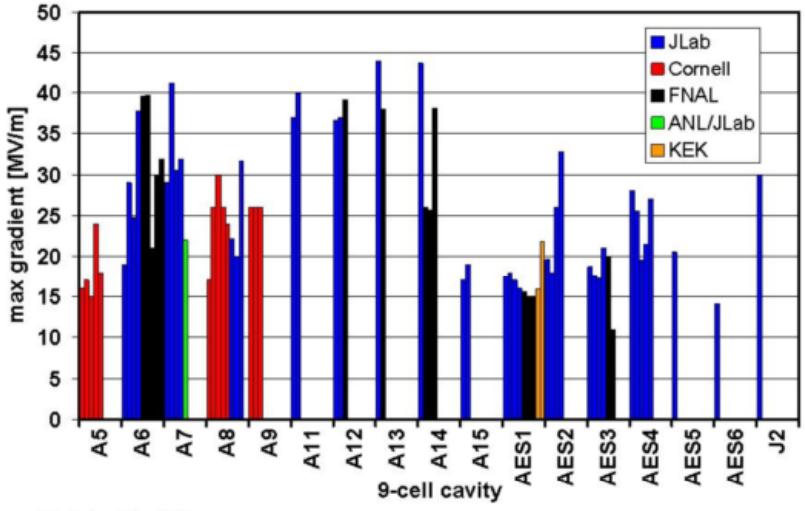


Joint PX/HINS Strategy

- HINS is a candidate for the Project X front end, either in initial or upgraded configuration
  - Designed for 27 mA x 1 msec x 10 Hz
  - ICD utilizes HINS as front end
  - Alternative is a conventional warm front end up to 100-200 MeV
- We expect to make a decision on utilization of HINS as Project X front end in 12-18 months
  - Decision based on performance/cost comparison of HINS and warm technologies
  - Decision will included results from the 6 cavity vector modulator demonstration, testing of individual SSR1 cryomodule, and simulations
  - Decision will include assessment of impact on upgrade potential of Project X to multi-MW at 8 GeV

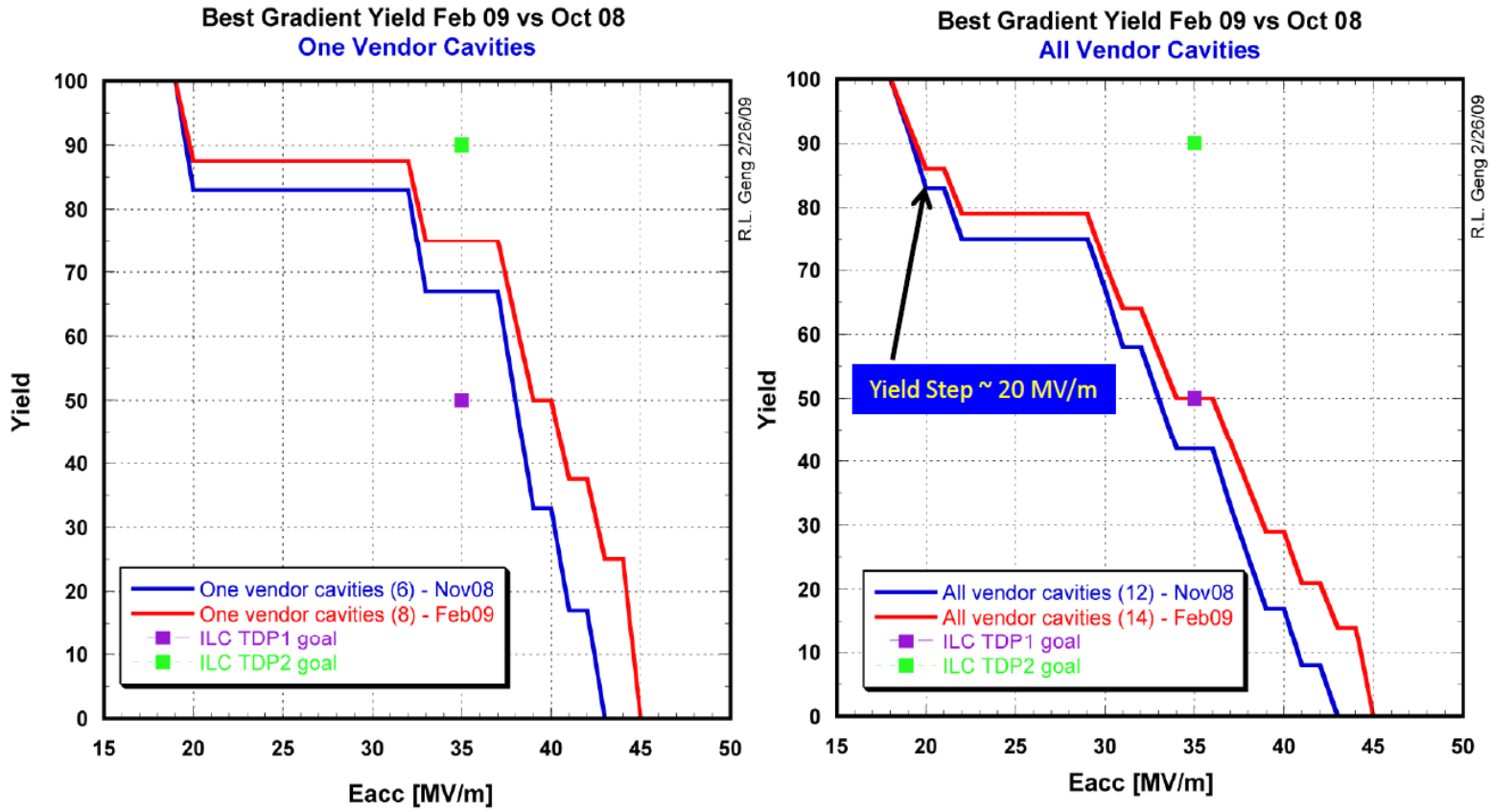
Joint PX/ILC/SRF Strategy

- Project X shares 1.3 GHz technology with the ILC
  - Project X requires 46 ILC-like cryomodules. In detail they will not be identical to ILC:
    - Beam current: 20 mA × 1.25 msec × 2.5 Hz (3×ILC charge/pulse)
    - Focusing required in all CMs
    - Gradient: 25 MV/m
- 4 year construction period
  ⇒ 1 CM/month
- Close coordination of Project X and GDE
  - Common development effort
  - Shared facilities for assembly and testing
  - Yield vs gradient is key metric



SRF Development

Summary of 9-cell Vertical Tests in U.S.



Joint PX/ILC/SRF Strategy

- Industrialization
  - Production of 46 1.3 GHz CMs over a~4 year period represents a significant step beyond current capabilities; however, the production rate remains well <u>below</u> that required by ILC.

  ⇒This activity could represent the initial phase of an industrialization buildup for ILC (in the U.S.).

- Cryomodule Assembly Plan
  - CM1: TESLA Type III (2009)
    - Based on DESY supplied cavities
  - CM2: TESLA Type III (2009)
    - Based on U.S. supplied cavities
  - CM3: Type IV.1 (2011)
    - Project X preliminary
  - CM4: Type IV.2 (2012)
    - Project X prototype

PX/ILC/SRF Schedule

1.3 GHz Cryomodules

U.S. Calendar Year	2008	2009	2010	2011	2012	2013
CM1 (Type III+)						
Assembly	in FY07 OMNIBUS delay	install				
Test			CM1 test@NML	install		
CM2 (Type III+)						
Cav Processing + VTS						
Dressing & HTS (# couplers)		6 6				
Assembly			install			
Test			S1 Demo@NML			
CM3 (Type IV)						
Design & Order Cav & CM Parts	OMNIBUS DELAY	Des Order Cav & CM parts				
Cav Processing + VTS						
Dressing HTS			5 5			
Assembly				install		
Test				S1 Demo@NML		
CM4 (Type IV) ARRA						
Design & Order Cav & CM Parts		Order Cav & CM parts				
Cav Processing + VTS						
Dressing HTS			5	5		
Assembly					install RF unit	
Test					S1 Demo + with beam	
CM5 (Type IV) ARRA						
Design & Order Cav & CM Parts		Order Cav & CM parts				
Cav Processing + VTS						
Dressing HTS				5 5		
Assembly					install	
CM6 (Type IV+) ILC funds						
Design & Order Cav & CM Parts			Order Cav & CM parts			
Cav Processing + VTS						
Dressing HTS					5 5	
Assembly						install
NML extension bldg GPP ARRA		Des Construction				
NML Beam				Move injector	*Beam Available*	
10 MW RF unit test	OMNIBUS DELAY				S2 RF unit test	
Px β=0.8 CM ***(Project X, INDIA)***						
Design & Order Cav & CM Parts		Design	Order Cav & CM parts			
Cav Processing + VTS						
Dressing HTS				2 5	5	
Assembly					Install @ CTS	
CTS Bldg. Beta=0.8 CM Test		Des	CTS building construction			test
S1 Global (2 Cav)						
Cav Processing + VTS						
Dressing & HTS?			2			

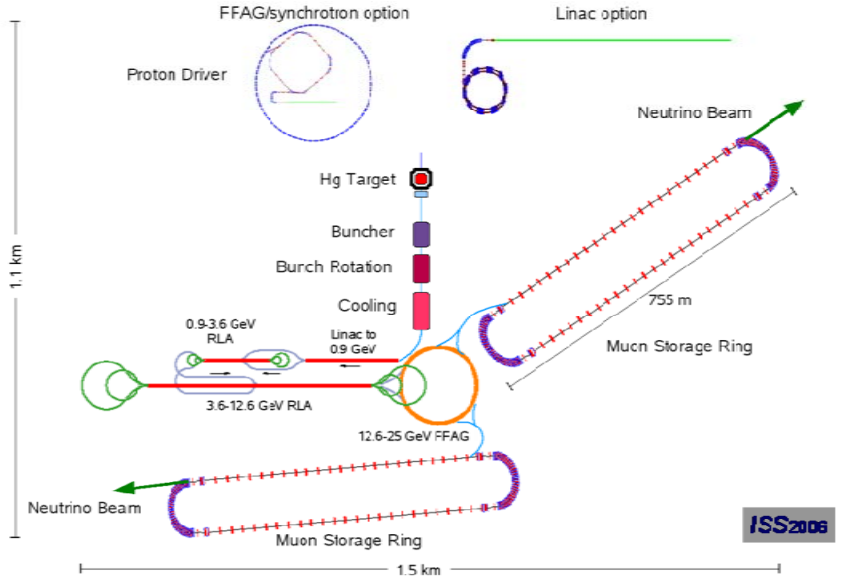
Joint PX/ILC Strategy

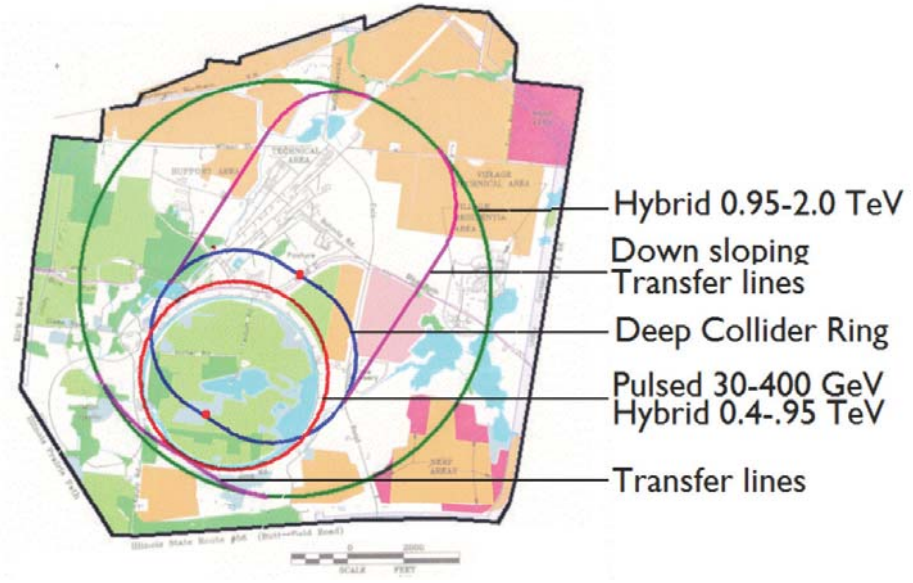
- Other opportunities:
  - Linac beam dynamics
  - e-cloud studies and simulations, including participation in CESR_TA
  - RF power generation, distribution, controls, and diagnostics share many features in common.
  - Conventional facilities designs provide opportunities for common solutions.
  - ILCTA_NML rf unit test will fulfill many of the requirements of S2, and will be available for studies with both PX and ILC beam current parameters.
  - Construction and operational experience with Project X will be invaluable in planning/executing ILC (if PX were to precede ILC, ditto for XFEL)

⇒ Essentially all these efforts are using shared (people) resources.

Joint PX/NF/MC Strategy

Future options for the Fermilab site:





Neutrino Factory (25 GeV)

4 TeV Muon Collider

Joint PX/NF/MC Strategy

- Project X shares many features with the proton driver required for a Neutrino Factory or Muon Collider
  - IDS-NF shows 4 MW @ 10± 5 GeV proton energy
  - Muon Collider requires similar power, but requires charge consolidated into a single bunch
  - It is inevitable that a muon facility will require a ring(s) for accumulation and/or beam compression between the linac and production target.
- Natural evolutionary schemes through neutrino superbeams:

  NOνA$\rightarrow$ Very Long Baseline$\rightarrow$ Neutrino Factory$\rightarrow$ Muon Collider
- Close coordination with NFMCC, MCTF, and IDS_NF

Joint PX/NF/MC Strategy

- Develop upgrade concept for the Project X linac aimed at 2-4 MW
  - The ICD includes such a concept (up to 4 MW): rep rate x8
- Develop a performance specification for a Proton Driver supporting a Neutrino Factory and Muon Collider, consistent with Project X concepts.
  - Issues: Average beam power, repetition rate, particles/bunch, bunch intensity
  - These issues will require a new storage ring(s) downstream of the linac.
- Develop a conceptual design for the NF/MC Proton Driver based on Project X linac and downstream accumulation/packaging ring(s).
- Coordinate with NFMCC, MCTF, and IDS_NF

Collaboration Plan

- A multi-institutional collaboration has been established to organize and 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:

ANL	ORNL/SNS
BNL	MSU
Cornell	TJNAF
Fermilab	SLAC
LBNL	ILC/ART

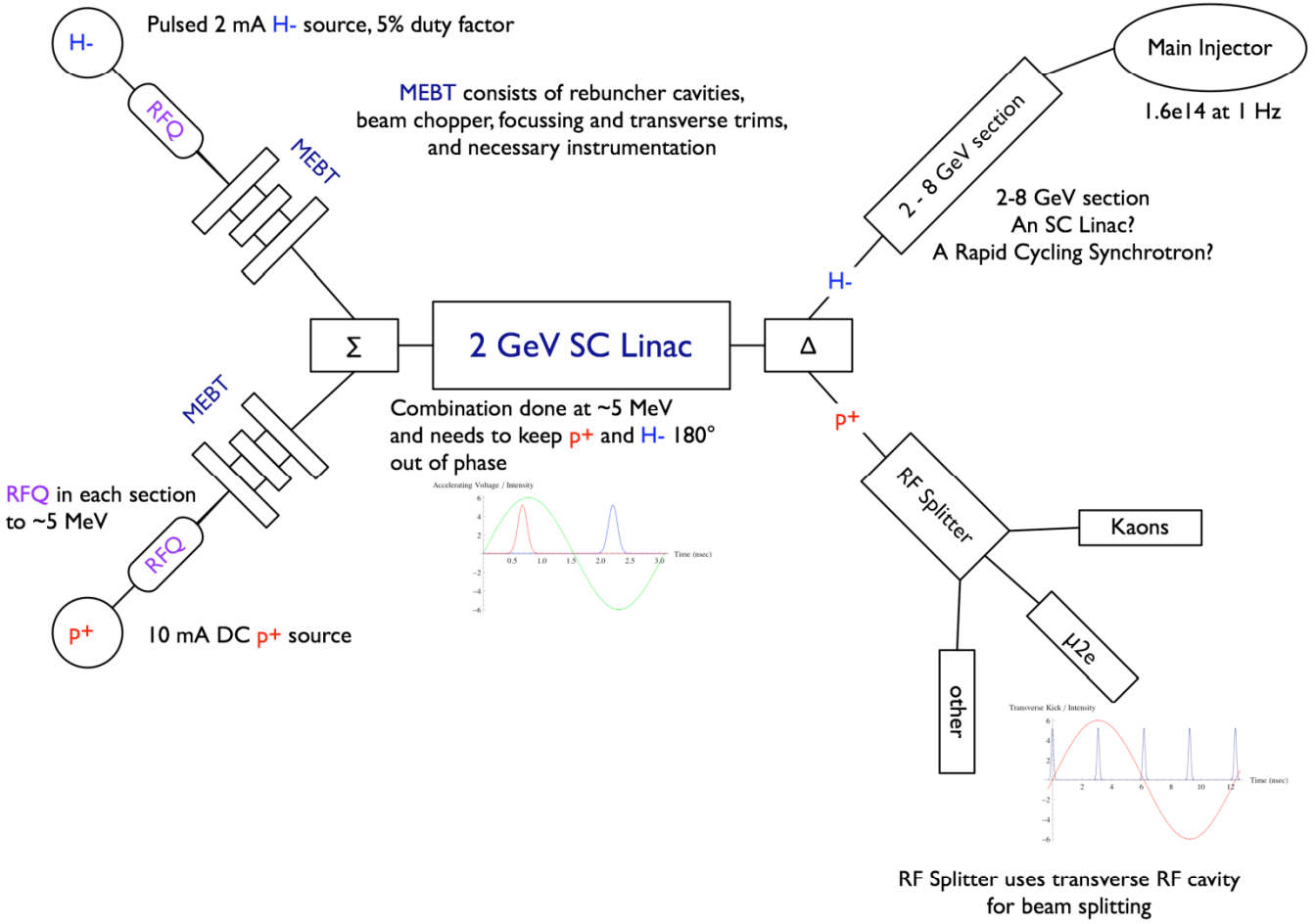
  - Collaborators to assume responsibility for components and sub-system design, development, cost estimating, and potentially construction .

Project X Alternative Configurations

- Consideration of alternative designs is required by the DOE Project Management Order.
- A primary consideration is the low energy program
  - The Recycler as utilized in the ICD has limitations in providing a flexible source of useful beam to the low energy flavor program
- Primary alternatives we are looking at:
  - Linac operated in CW (1 mA) mode up to 2 GeV
  - Rapid cycling synchrotron for acceleration from 2 GeV to 8 GeV

  ⇒ "Mix and match" opportunities for the evaluation phase
  - Upgrade to NF/MC power capabilities requires more thinking
- Alternative configuration document under development (ACD V1.0)
  - Document, and associated cost estimate, to be prepared utilizing same team, methodology, and design criteria as ICD
  - Anticipate release late summer

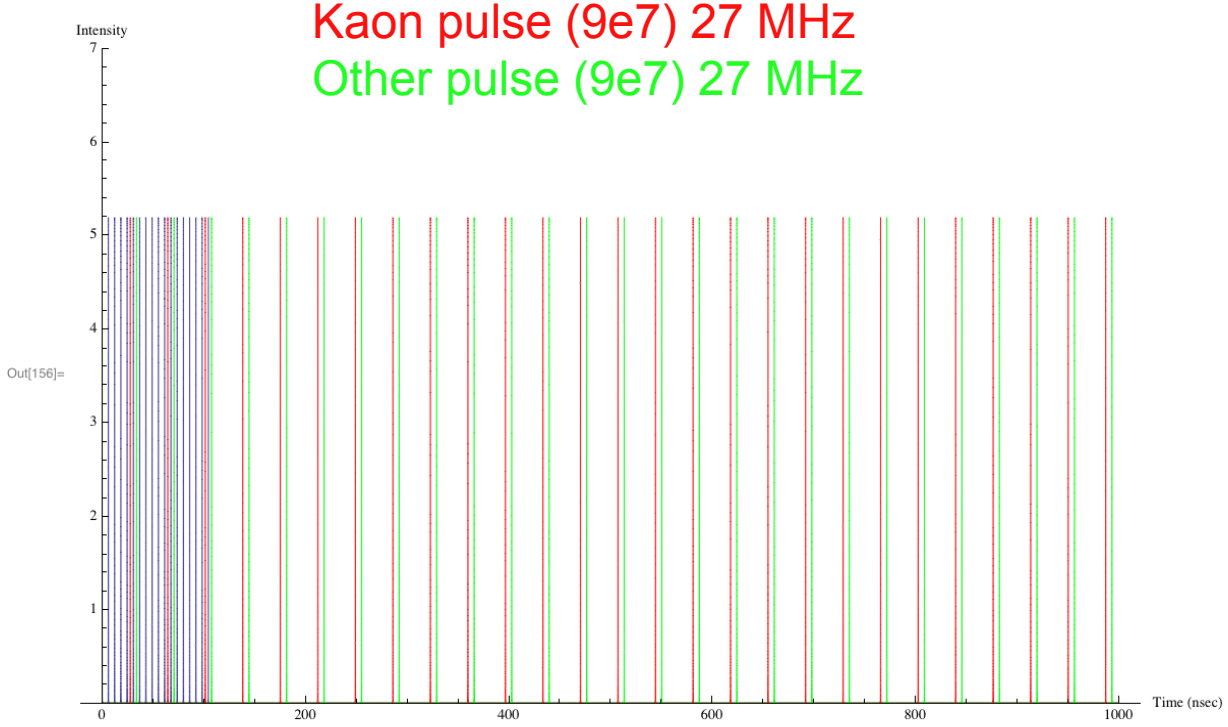
Alternative Configuration



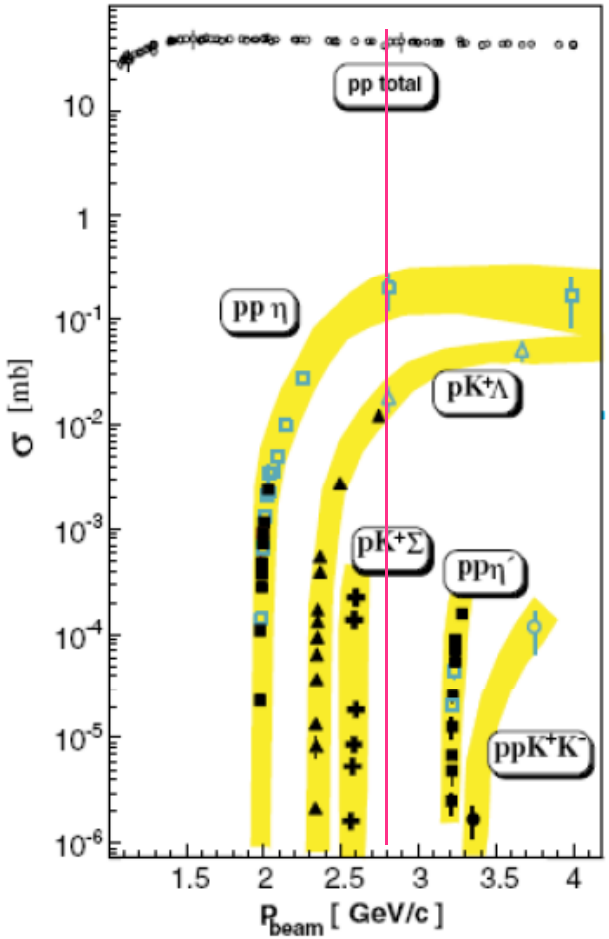
Alternative Configuration Operating Scenario

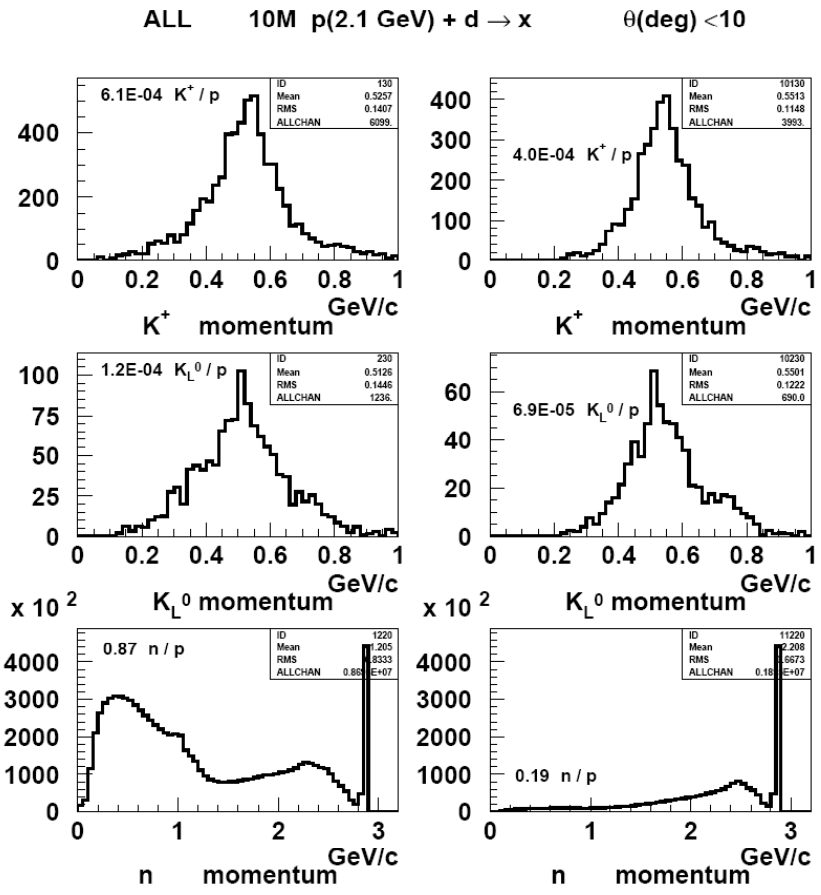
1 μsec period at 2 GeV

mu2e pulse (9e7) 162.5 MHz, 100 nsec	518 kW
Kaon pulse (9e7) 27 MHz	777 kW
Other pulse (9e7) 27 MHz	777 kW



Alternative Configuration Beam Spectra



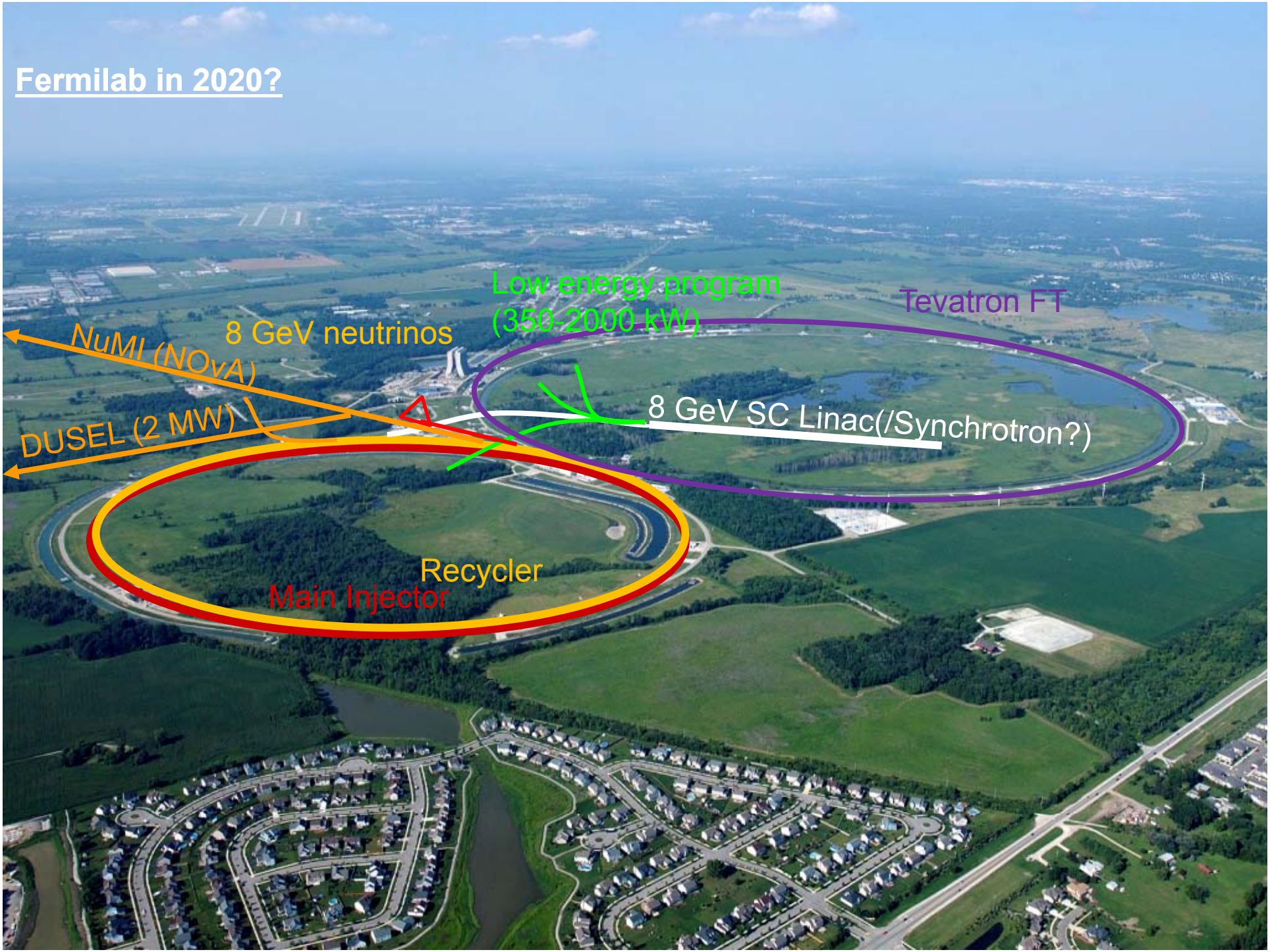


Working Timeline (technically limited)

- FY2009
  - Complete Initial Configuration Document (ICD)
  - Develop Upgrade Concept for 2-4 MW at 8 GeV
  - Form RD&D Collaboration
  - Establish Project Management team
  - Revise RD&D plan and initiate work
  - Complete a preliminary cost estimate based on the ICD
  - Complete Mission Needs Statement
  - Receive CD-0
  - Request PED funds for FY2011
  - Initiate work on Conceptual Design Report
  - Develop NEPA strategy

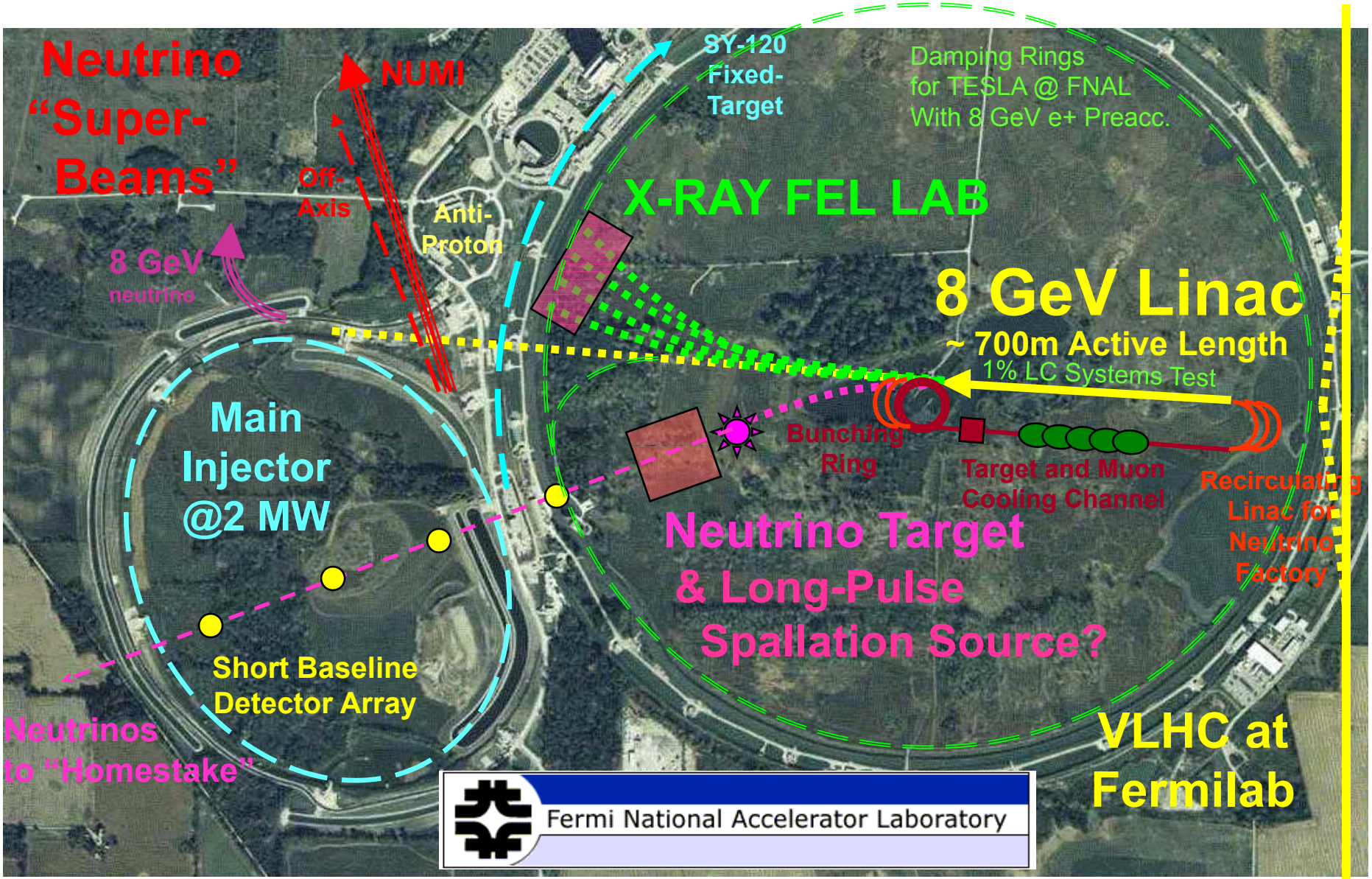
Working Timeline (technically limited)

- FY2010
  - Alternative implementations studies
  - Draft Environmental Assessment
  - Initiate permitting documentation
  - Draft of all CD-1 documentation
- FY2011
  - CD-1
- FY2012
  - CD-2/3a
- FY2013
  - CD-3: Initiate Construction
- ~FY2013~2017
  - Construct


Fermilab in 2020?
Low energy program
(350-2000 kW)
Tevatron FT
8 GeV neutrinos
NuMI (NOvA)
DUSEL (2 MW)
8 GeV SC Linac(/Synchrotron?)
Recycler
Main Injector

8 GeV Superconducting Linac

With X-Ray FEL, 8 GeV Neutrino & Spallation Sources, LC and Neutrino Factory



Summary

- Project X is central to Fermilab's strategy for future development of the accelerator complex:
  - Energy Frontier: Aligned with ILC technology development; Fermilab as potential site for ILC or a Muon Collider
  - Intensity Frontier: World leading program in neutrinos and rare processes; Fermilab as potential Neutrino Factory site
- Initial configuration, and preliminary cost estimate, established
  - >2 MW at 60-120 GeV, simultaneous with >150 kW at 8 GeV
  - Upgradable to 2-4 MW at 8 GeV
  - Alternative configuration under development
- The facility could be constructed over the period ~2013 - 2017
- Integrated effort on Project X, ILC, and Muon Facilities
- Collaboration being formed