PIP-II and PXIE

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Outline

- Project X → PIP-II
- PIP-II Future and Staging
- PXIE goals
- PIP-II duty factors
- μ-to-e upgrade
- Cryogenic requirements
- Microphonics
- Conclusions

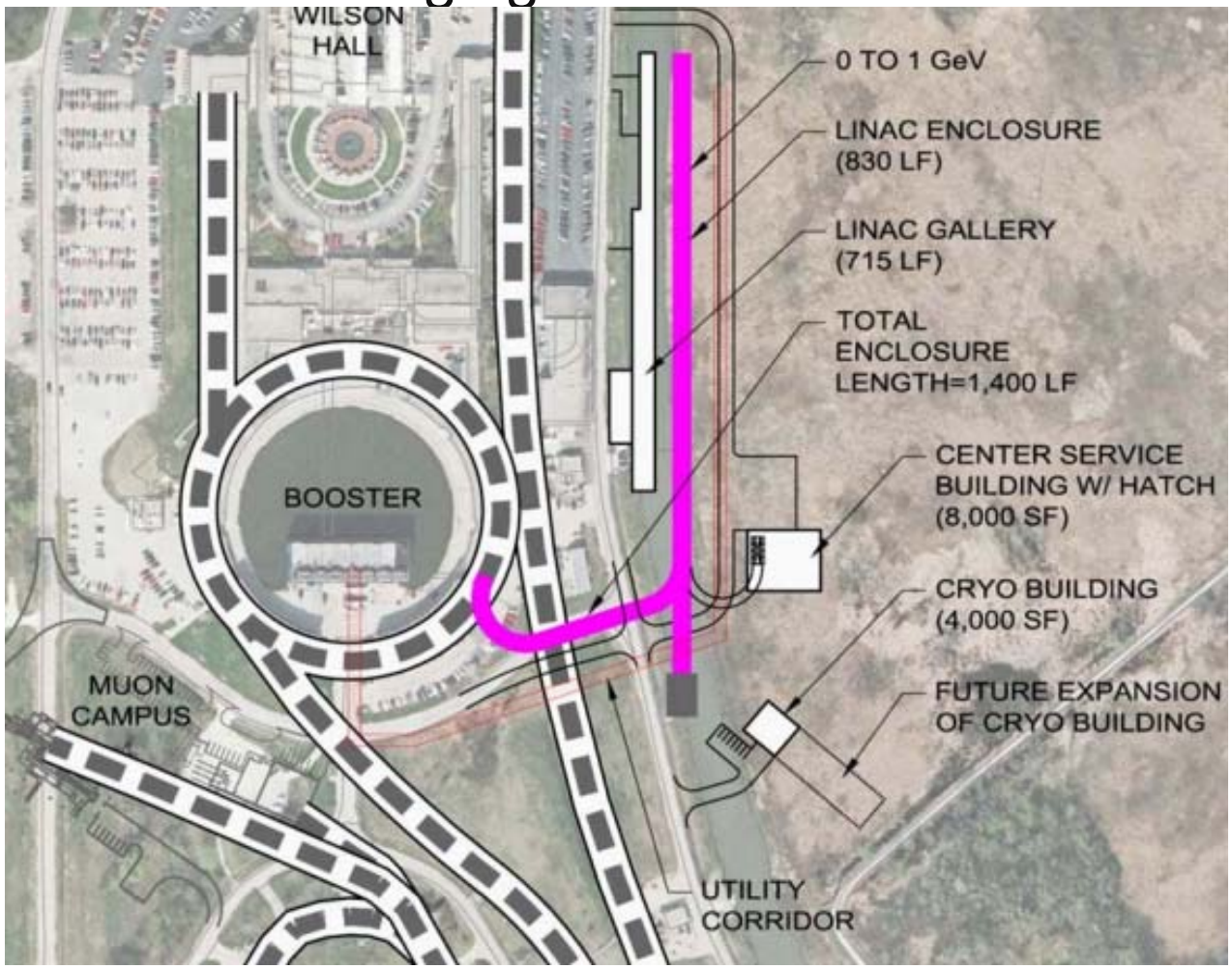
Project X → PIP-II

- What was changed?
  - Beam energy: 1 GeV→ 0.8 GeV
  - Beam current: 1 mA → 2 mA
  - Operation mode: CW → Pulsed (15 Hz, 0.6 ms)
  - At the beginning: a single purpose facility with the goal of
    - support power increase for LBNE by 1.5-1.7 times
  - No RF separation in near plans (has to be possible in the future)
- Why?
  - Cost reduction
    - Cryogenics
    - Use of existing infrastructure
- Long-term goal is the same (but not specified in PIP-II docs)
  - CW operation for intensity frontier experiments
  - That means the design has to be compatible with future CW operation and >2 MW in Main Injector

PIP-II Future and Staging

- Present choice of PIP-II and its technology does not make sense without future staging

1. μ-to-e upgrade
2. Other ~1 GeV experiments
   1. n-nbar
   2. Proton EDM
   3. Neutron EDM
   4. Nuclear energy
   5. …
3. 3 GeV upgrade?



Project X → PIP-II (Structure changes)

- The same as the Project X the PIP-II includes
  - warm frontend – operating in CW
  - HW & SSR1 cryomodules – operating in CW
    - ~5% of cryo-load at 2 K in CW
- Other cryo-modules - only pulsed operation limited by power of the cryo-plant
  - 5% duty factor for cryo
  - Reduced number of HB-650 cryo-modules (7→4)

	Energy (MeV)	CM	Cav per CM	E_{acc} (MV/m)	ΔE (MeV)	Q_0@2K (10^{10})	Static loss per CM @2 K, W	Total loss per CM @2 K in CW, W
HWR	2.1-11	1	8	8.2	1.7	0.5	14	24
SSR1	11-38	2	8	10	2.05	0.5	16	27
SSR2	38-177	7	5	11.2	5.32	1.2	8.8	52
LB 650	177-480	5	6	16.5	11.6	1.5	8.1	153
HB 650	480-800	**4**	6	17.5	17.7	2.0	6.2	153

PXIE goals and plan

S. Nagaitsev, Project X Collaboration Meeting, Nov.27-28,2012

- **Front-End R&D Program (as proposed in Oct 2011)**
- We are building an integrated systems test of the first ~30 MeV of Project X.
  - Validate the concept for the Project X front end, thereby minimizing the primary technical risk element within the Reference Design.
  - Demonstrate wideband chopper; low-β acceleration
  - Operate at full design parameters
- Integrated systems test goals:
  - 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV

Collaboration between Fermilab, ANL, LBNL, SLAC, SNS, India

Beam through β=0.1 , 0.2 CM at ~30 MeV with nearly final parameters (1 mA CW, 5 mA peak, arbitrary bunch chopping)

PXIE goals and plan

S. Nagaitsev, Project X Collaboration Meeting, Nov.27-28,2012

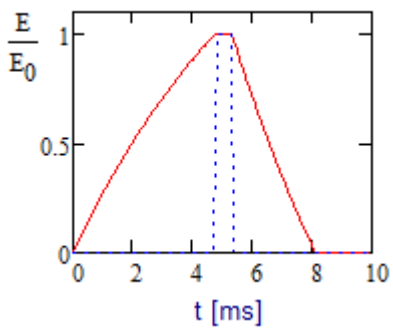
PXIE Goals

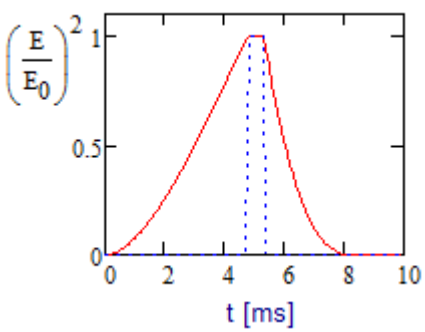
- Validate the Project X concept and eliminate technical risks
  - CW RFQ
  - Bunch-by-bunch chopper (2 kickers and absorber)
  - MEBT vacuum level and MEBT/HWR interface
  - High-current beam acceleration in HWR and SSR1
    - Complications can be due to beam loss of RFQ tails in SC linac
  - Extinction for the removed bunches better than
    - 10^{-4} – specified by the PXIE FRS and determined by multi-experiment operation
    - $<10^{-9}$ – as desired by μ-to-e experiment
- Obtain experience in design and operation of SC proton linac
  - SSR1 cryomodule will be designed and build by Fermilab

- We cannot guaranty the future machine operation in CW without achieving the above goals

PIP-II Duty Factors

- The average RF power has 2 contributions:
  - the energy transferred to the beam (~10%)
  - the energy required to fill and discharge the accelerating cavities (90%)
    - It does not depend on the peak RF power
- For a fixed average power the cost of RF increases with peak power
  - therefore its cost achieves minimum with minimum peak power
    - *i.e.* power equal to the power required for beam acceleration
      => duty factor for the RF power amplifiers ≈12%
    - In this case the cost savings associated with the pulsed power amplifiers (~10% duty factor) is modest and therefore CW capable RF amplifiers are planned





PIP-II Cryogenics

- To minimize the cost a system will be assembled using existing Tevatron cryogenic infrastructure
  - including the Central Helium Liquefier (CHL)
  - transfer line
  - compressors
  - Cryogenic duty factor is ~5%
  - The total cryogenic heat load at 2K is dominated by the static load, and is about 14% of the CW load
- Future upgrade to CW operation would require a new 2K cryogenic plant

Total CM Heat Loads [W]			
	70 K	5 K	2 K
Pulsed	2,860	895	256
CW	2,860	895	1819

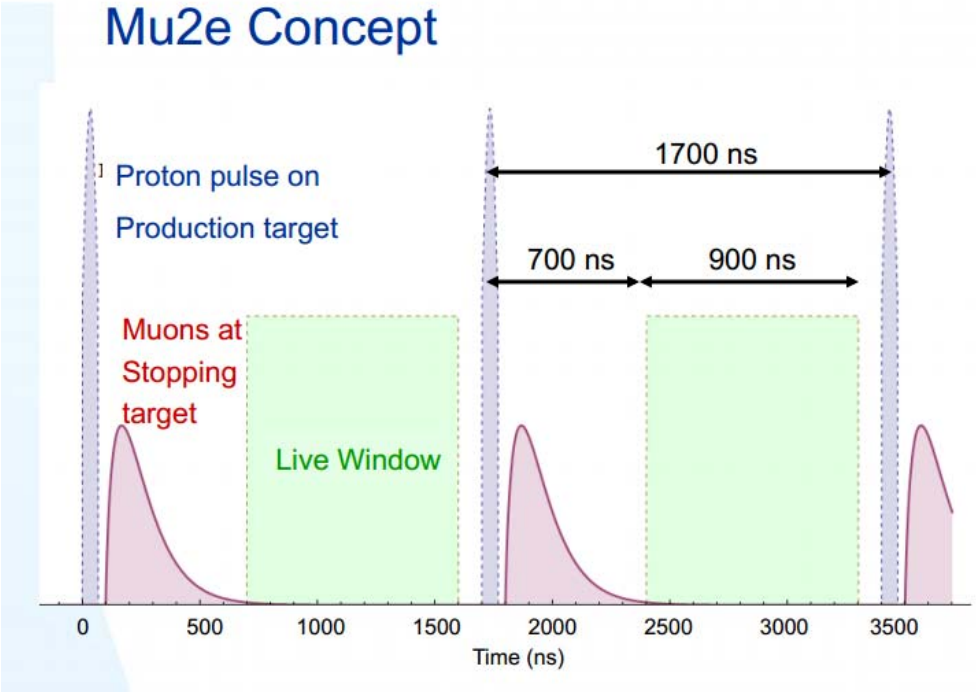
PIP-II Cryogenics (continue)

		Static Load per CM [W]			Dynamic Load per CM [W]	
Type	# of CM	70 K	5 K	2 K	2 K CW	2 K Pulsed, 5%DF
HWR	1	250	60	14	10	10*
SSR1	2	195	70	16	11	11*
SSR2	7	145	50	8.8	43	2.2
LB 650	5	145	45	8.1	145	7.3
HB 650	4	120	30	6.2	147	7.4
Total		**2860**	**895**	**173**	**1646**	**113**

* CW operation

First PIP-II experiment: μ-to-e upgrade

- Present μ-to-e experiment:
  - 7 kW
  - duty factor – 30%
    - Limited by:
      - rebunching in Recycler
      - NOVA operation
      - Booster flux
- μ-to-e upgrade:
  - ~100 kW
  - duty factor – 30% or more
  - Flexible time structure
    - ~100 ns, ~1.5 MHz (depends on the target)



μ-to-e at PIP-II

- Possible beam structure for CW (micro scale)
  - 17 consecutive pulses take 100 ns
  - Rep. time 1.5 μs (244 buckets)
  - => duty factor = 86/1500=0.07
  - Peak current = RFQ current = 6 mA
    => Average current = 0.421 μA (aver. over 1.5 μs)
  - Average power 0.8 GeV * 0.421 μA = 334 kW
- Operation with 30% duty factor => 100 kW
- Can we support 30% duty factor with PIP-II
  - Bunch-by-bunch operation should not be a problem
    - Extinction is infinite because only one experiment is running (both LEBT and MEBT choppers are used)
  - RF is not a problem
  - Cryogenic requirements ?
- Effect of pulsed operation on microphonics ?

Cryogenic Requirements for 30% DF

- Q0 presented in the RDR is quite conservative
- Success of high Q0 program should allow us to achieve ~30% duty factor with cryo-plant built for pulsed operation
  - Required ~28% increase of cryo-power should be within reach
    - (or even within operating margin)

Cryogenic loads at 2 K

Type	# of CM	Static load per CM [W]	Q_0 @ 2K 10^{10}	Dynamic load/CM, 5%DF [W]	Dynamic load/CM, with $3Q_0$, 30%DF [W]
HWR	1	14	0.5	10*	10*
SSR1	2	16	0.5	11*	11*
SSR2	7	8.8	1.2	2.1	4.3
LB 650	5	8.1	1.5	7.2	14.5
HB 650	4	6.2	2.0	7.4	14.7
Total		**173**		**112.7**	**193**

*CW operation

Operation in Pulsed Regime

- The Lorentz force detuning represent a problem which needs to be diligently addressed
  - Cavity design
  - Fast tuner (piezo-based)
  - Low level RF

	E_{acc} (MV/m)	LFD (Hz/(MV/m^2)	Δf_{LFD} [Hz]	Q_{loaded}	$\Delta f = f/Q$ [Hz]	Microphonics ampl. [Hz]
HWR	8.2	-	-	$3.3 \cdot 10^6$	50	20
SSR1	10	1.5*	150	$5.8 \cdot 10^6$	56	20
SSR2	11.2	No data		$7.2 \cdot 10^6$	45	20
LB 650	16.5	<1♦	<272	$1.4 \cdot 10^7$	46	20
HB 650	17.5	<1♦	<306	$1.4 \cdot 10^7$	46	20

* Measured

♦ Estimated

Conclusions

- Q: Why PXIE should be CW? – A: To mitigate the risks
  - RFQ
    - Build as CW and needs to be tested at CW
  - MEBT chopper
    - Helpful for Booster injection
    - Required for the μ-to-e upgrade
  - HW and SSR1 cryomodules
    - Produce sufficiently small cryo-load in CW
    - Little difference for total RF power consumption
    - Microphonics is easier to address in CW
- Success of high-Q work is very important
  - Allows to avoid expensive upgrade for cryogenics
- Correction of the Lorentz force detuning is required
  - Represent additional problem which is not present in CW operation