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An 800 MeV Superconducting Linac to Support Megawatt Proton Operations at Fermilab

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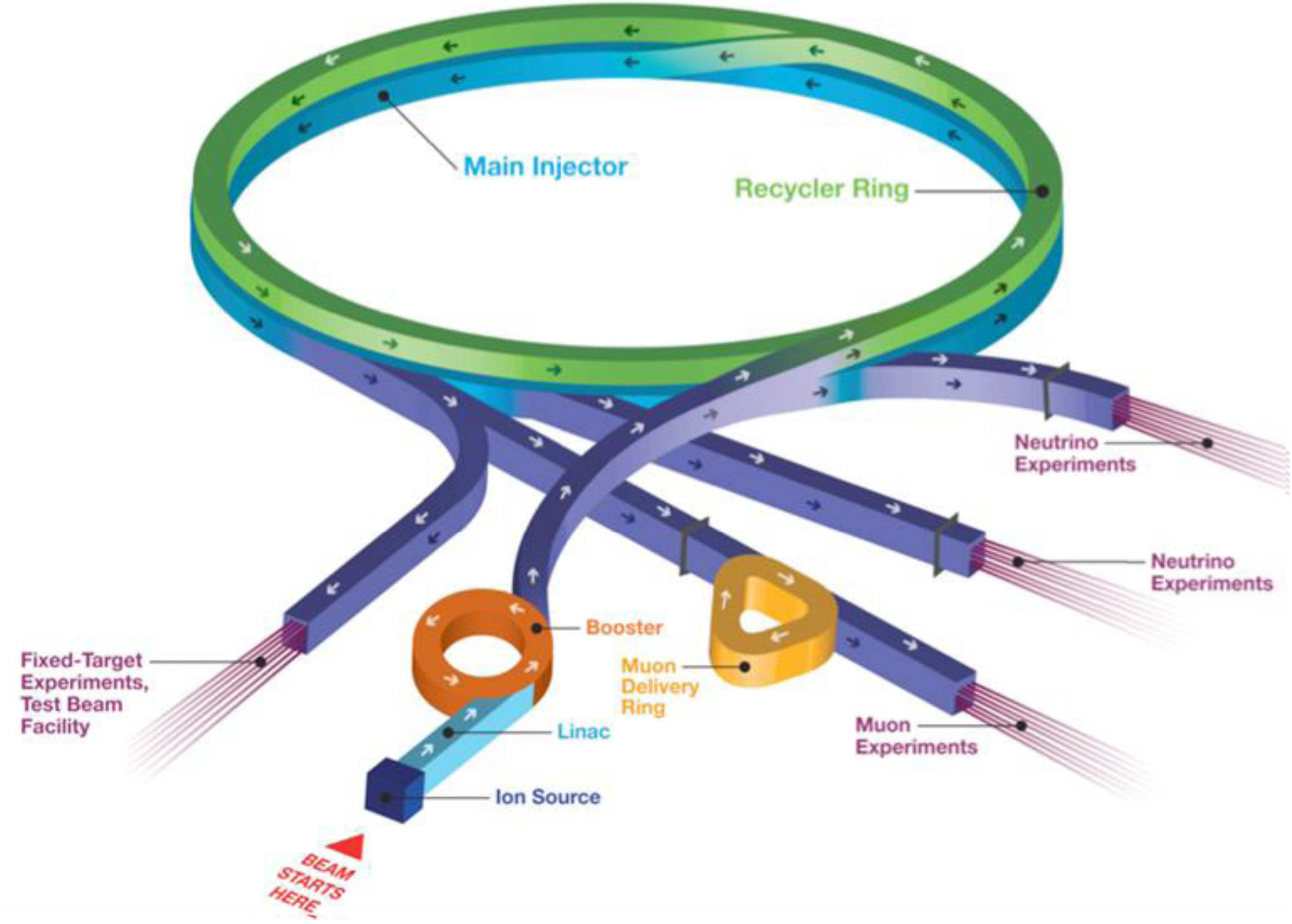
Linac 14

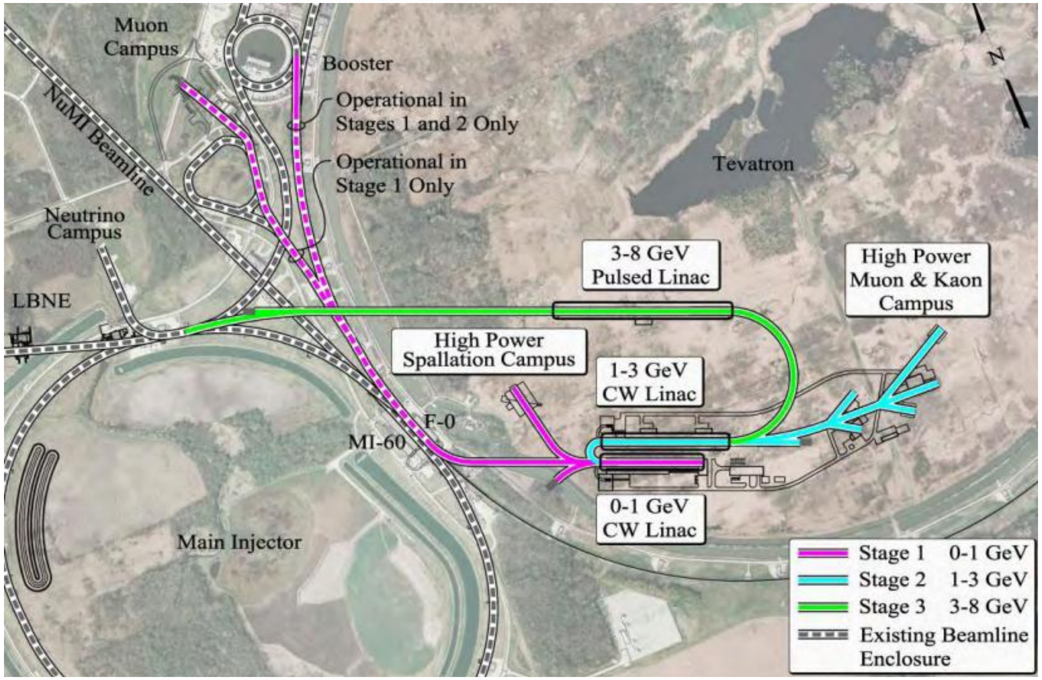
Outline

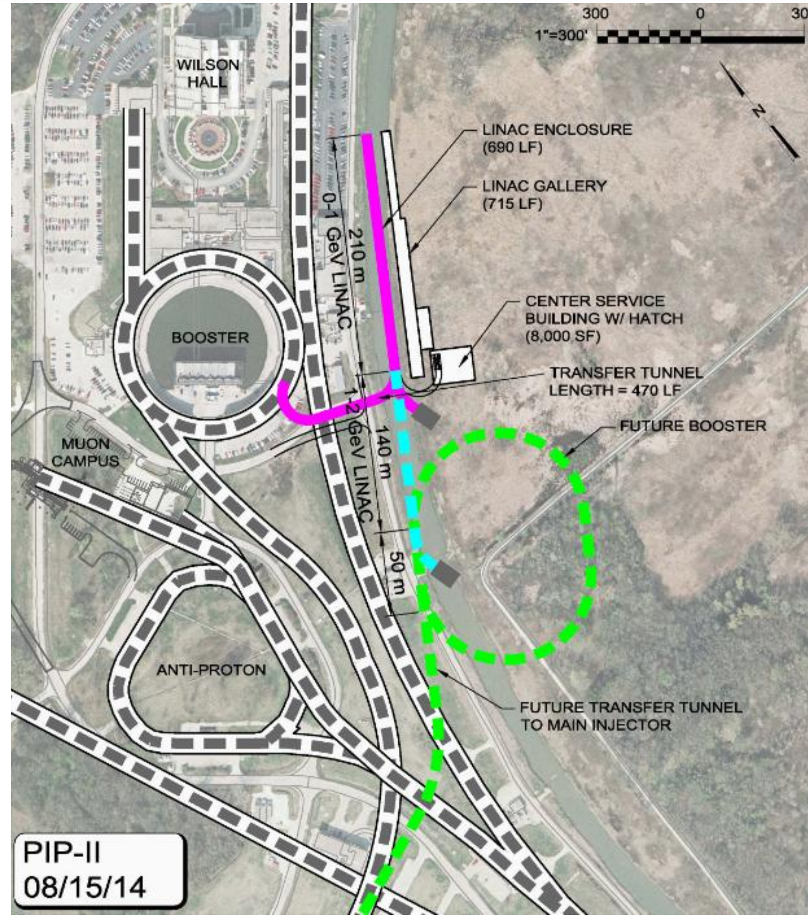
- Fermilab accelerator complex
- PIP-II goals and parameters
- SC linac and subsystems
- PXIE – frontend test
- Summary

Fermilab Accelerator Complex



From Project X to PIP-II





- Project X was conceived as a facility supporting large number of intensity frontier experiments (ν, μ, K)
- PIP-II
  - Will support for the world leading ν experiments
  - Favorably positions Fermilab into the future

From PIP to PIP-II

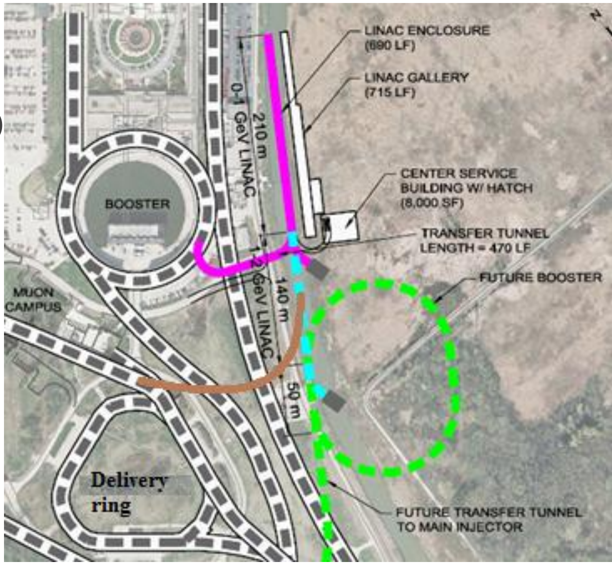
- PIP - Proton Improvement (next few years)
  - Fermilab Booster upgrade to support NoVA at 700 kW
    - 7 Hz -> 15 Hz
- PIP-II (construction: 2019-2024?)
  - Next step in the power increase
    - Major goals
      - 700 kW -> 1.2 MW at 120 GeV (LBNF)
      - More power for 8 GeV program: 80 ->160 kW (SBNE, …)
  - New SC linac to increase E_{inj} (400 -> 800 MeV)
    - Particles per pulse extracted from Booster: $(4.3 \to 6.5)\cdot 10^{12}$ ($\times$1.5)
    - Pulsed operation to reduce cost (reuse Tevatron infrastructure)
  - An experiment in near reach
    - μ-to-e upgrade at 15-30% duty factor (7 kW -> 100 kW)
      - Requires new beam line

Future Directions

- The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements
  - multi-MW to LBNF (1.2 -> 2.4 MW)
  - CW capability brings us to other Project X experiments
    - 0.8 GeV (up to 1.6 MW total, RF separ. -> multiple experiments)
      - μ-to-e upgrade – step 0
      - Other experiments with muons (μ->3e, …)
      - Experiments with neutrons (n-nbar, …)
      - Nuclear physics & EDMs
    - 3 GeV
      - Kaons
      - Front end for a muon-based facility
- The details will be determined by future HEP programmatic choices (~10 years down the road)

FNAL Accelerator Complex Beyond PIP-II

- PIP-II limitations:
  - Slip-stacking in the Recycler is questionable at intensities beyond PIP-II
    - Beam loss and stability at slip-stacking
  - Booster intensity is limited to ~7×10^{12} ppp by impedance and transition crossing



- That sets the strategy for next steps
  - A new 8 GeV source is necessary
  - Possibilities
    - 1.5-2 GeV linac + conventional RCS
    - Lower energy linac + 'supersmart RCS that mitigates beam losses (integrable optics? R&D into space charge effects is initiated)
    - 8 GeV linac
      - Presently looks as more expensive
      - Higher injection energy – Higher beam loss ?

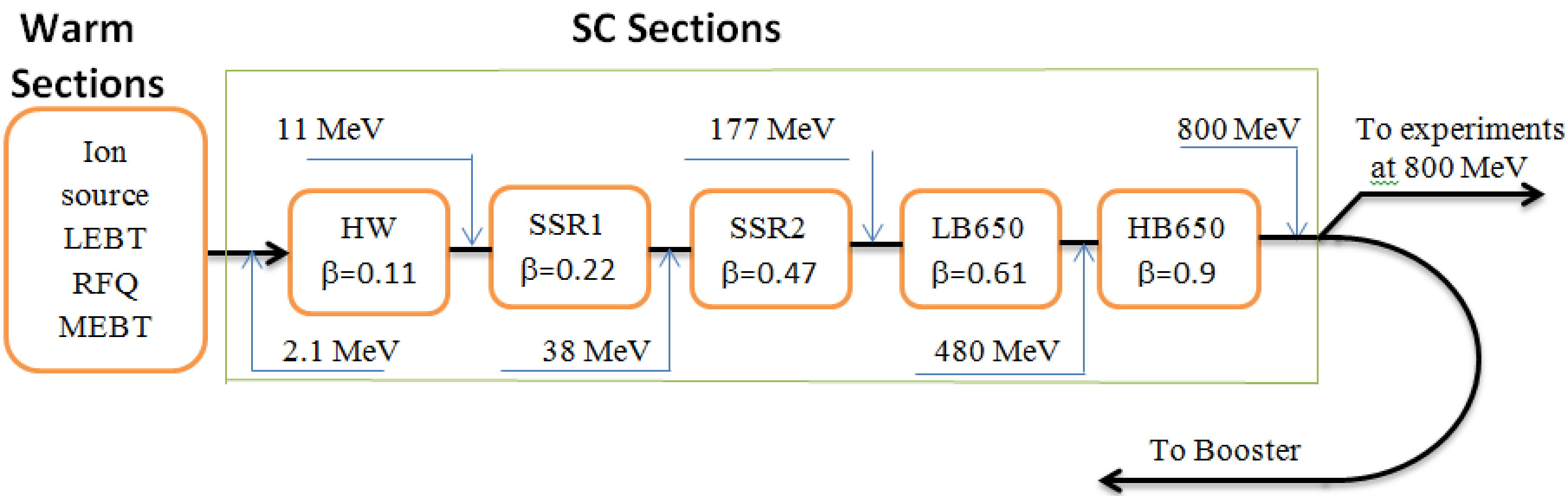
PIP-II Design Choices

- Future program with rare decays requires SRF linac
- That sets further choices
  - Relative to the Project X the PIP-II scope & cost are reduced
  - SRF technology map is unchanged
    - Makes future upgrades easier
  - The scope changes
    - CW linac energy: 3 GeV -> 0.8 GeV
    - Linac operates in pulsed regime
      - To avoid construction of new cryo-plant
        $\Rightarrow$ significant cost reduction (collaboration with India can change this)
    - All other systems are CW compatible
      - creates many possibilities in the future
  - Booster is used to accelerate to 8 GeV
    - upgraded to higher E_{inj} and rep. rate
  - Booster and MI upgrades are not parts of PIP-II project

PIP-II versus PIP

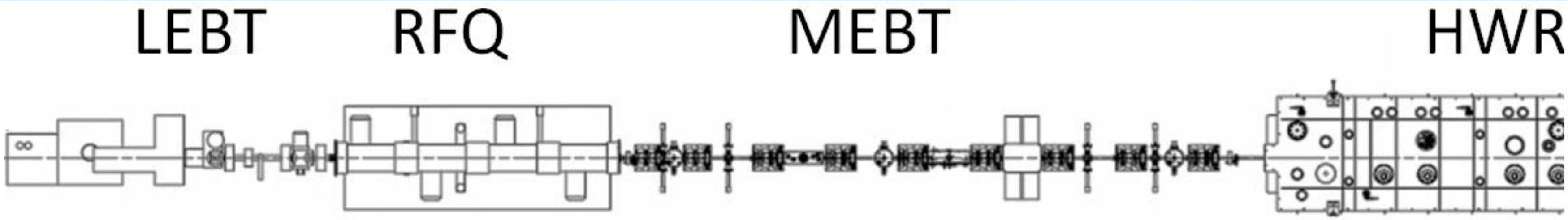
Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.55	ms
Linac Pulse Repetition Rate	15	20	Hz
Linac Upgrade Potential	N/A	CW	
Booster Protons per Pulse (extracted)	4.2×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
8 GeV Beam Power to MI (LBNE)	-	80-120*	kW
Beam Power to 8 GeV Program	-	80-40*	kW
Main Injector Protons per Pulse (12 batches; extr.)	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
Main Injector Cycle Time @ 60 GeV	N/A	0.8	sec
Beam Power @ 60 GeV (LBNE)	N/A	0.9	MW
Beam Power @ 120 GeV	0.7	1.2	MW
Upgrade Potential @ 60-120 GeV	-	>2	MW

Linac Structure



- Room T acceleration to 2.1 MeV
  - 5 types of SC cavities
  - Solenoidal focusing for first 3 types
  - Doublet focusing for LB & HB
  - HW & SSR1 operate in CW other in pulsed regime

PIP-II Warm Frontend

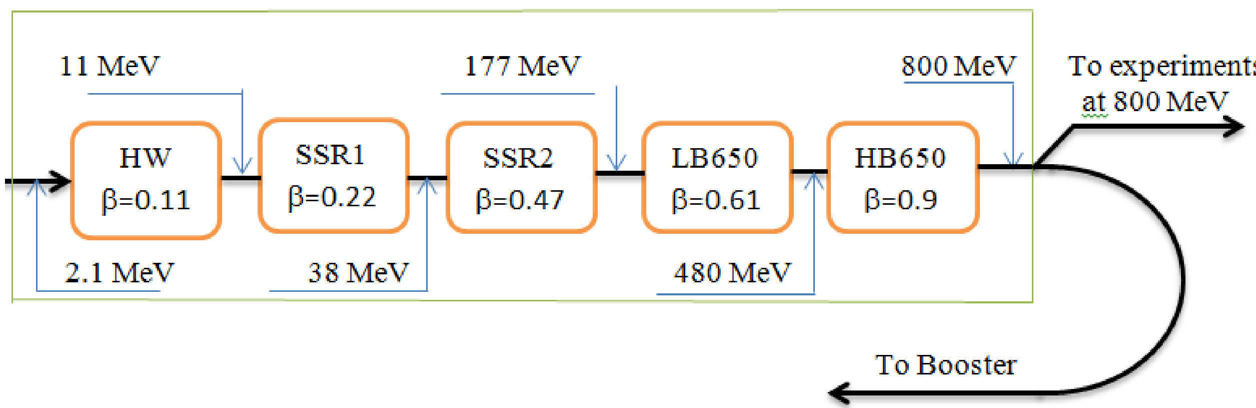


- "Standard" scheme for beam acceleration
  - 30 kV ion source (5 mA nominal, 10 mA max)
    - 2 sources and dipole switch
  - LEBT with beam pre-chopping for machine tuning
    - 3 solenoids, good differential pumping
  - 2.1 MeV CW RFQ
    - f=162.5 MHz set by bunch-by-bunch chopping
  - MEBT (~10 m)
    - Bunch-by-bunch chopper
      - 2 kickers with μ=180^o to minimize voltage; V ≈ ±250 for bipolar feeding
    - 3 RF cavities, 8 periods, quads (7 triplets, 2 doublets), instrumentation
    - Beam absorber (20 kW) & differential pumping

PIP-II SC Linac

- Tight solenoidal focusing in first 3 cryomodules
  - Space charge
  - Variation of cavity ⊥ defocusing along bunch
- External doublet focusing for LB&HB
  - Beam collimation and instrumentation between cryomodules

Section	Energy (MeV)	ΔE/cav (MeV)	R/Q (Ω)	Cav/CM	CM config.	CM length (m)
HWR	2.1-11	1.7	272	8 / 1	8 x (sc)	5.93
SSR1	11-38	2.05	242	16 / 2	4 x (csc)	5.2
SSR2	38-177	4.98	275	35 / 7	sccsccsc	~6.5
LB650	177-480	11.6	378	30 / 10	(ccc)-(fd)	~3.9
HB650	480-800	17.7	638	24 / 4	(cccccc)-(fd)	~9.5



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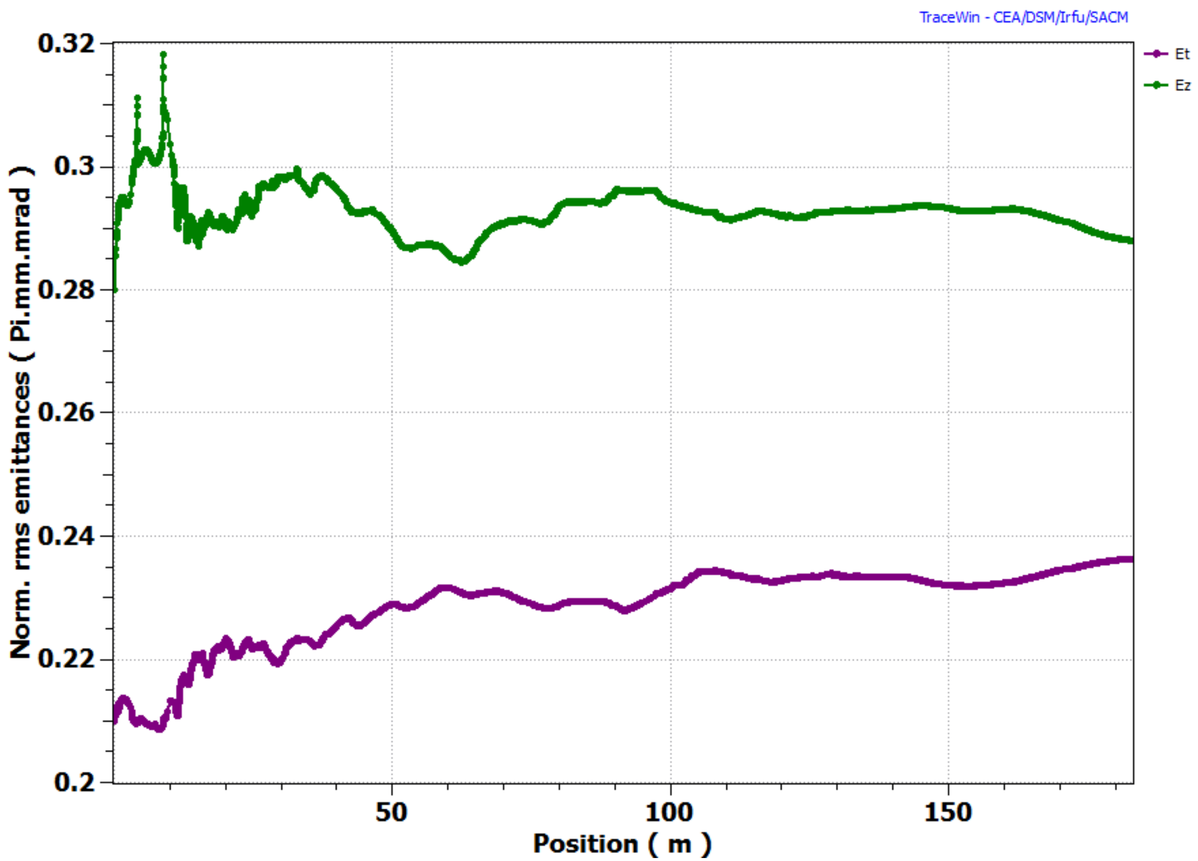
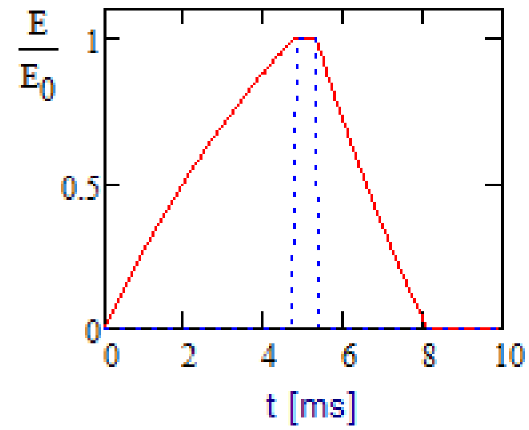
Beam Dynamics in SC linac

- Same as for the Project X linac
  - Moderate emittance growth in the course of acceleration
  - Beam loss is dominated by intrabeam stripping (<0.15 W/m)



RF

- The average RF power has 2 contributions:
  - the energy transferred to the beam (~10%)
  - the energy required to fill and discharge the cavities (90%)
    - It does not depend on the peak RF power
- For fixed aver. power the cost of RF grows with peak power
  - therefore RF 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 ≈15%

- In this case the cost savings associated with the pulsed power amplifiers are modest and therefore CW capable RF amplifiers are planned from the beginning

Microphonics and Lorentz Force Detuning (LFD)

- Low beam loading (2 mA)
  ⇒ narrow cavity bandwidth
  ⇒ microphonics issues
- Microphonics Control Strategies
  - RF power reserve
  - Good regulation of LHe pressure
  - Reduced sensitivity of resonant frequency to LHe pressure
  - Minimizing external vibrations and sensitivity to them
  - Fast tuner driven by sophisticated feedback
- Pulsed operation complicates keeping cavity at resonance due to fast Lorentz force detuning
  - R&D is initiated

Section	Freq. f_0 (MHz)	Maximal detune (peak Hz)	Minimal Half Bandwidth, $f_0/2Q$(Hz)	Max Required Power (kW)
HWR	162.5	20	34	4.8
SSR1	325	20	45	5.3
SSR2	325	20	27	17.0
LB650	650	20	29	33.0
HB650	650	20	31	48.5

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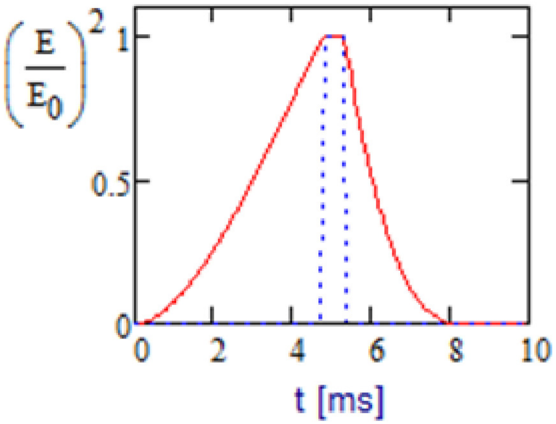
Cryogenics

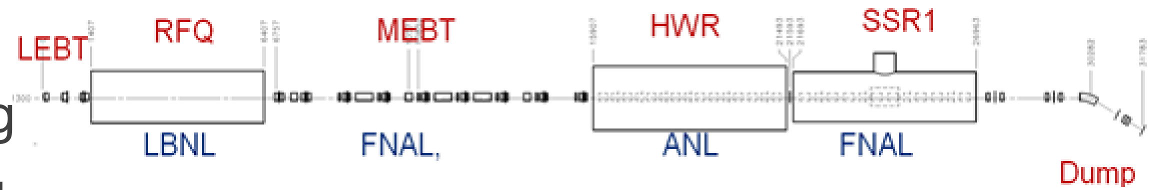
- Cost minimization => reusing existing Tevatron cryogenics
  - Cryogenic duty factor is ~6.6%
- Conservative approach for Q_0:
  - Total cryogenic heat load at 2K (320 W) is dominated by static load (182 W)
    - It is ~17% of the CW load
- Upgrade to CW will require a new 2K cryogenic plant
- Note that
    - HWR & SSR1 cryomodules designed for CW operation
      - They will operate at CW
        - Negligible addition to the total load
- Success of R&D on Q_0 should allow operation at 20-30% duty factor
  - The μ-to-e upgrade without cryo-plant upgrade

	Q_0
HWR SSR1	5×10^9
SSR2	1.2×10^{10}
LB650	1.5×10^{10}
HB650	2×10^{10}



PXIE

- PXIE represents a complete systems test of the frontend
  - Has to retire major risks
    - CW RFQ, Chopper, MEBT differential pumping, low energy acceleration in SC cavities at high power
  - Test stand for suppression of resonance control and LFD
  - Development of SC linac diagnostics (LPM)
- PXIE accelerates beam to ~25 MeV and includes:
  - Warm front end + 2 SC cryomodules
  - HEBT + 50 kW beam dump
- PXIE status



  - LEBT: in commissioning
  - RFQ: comes this spring
  - MEBT: shortened version will be ready for RFQ test this year
  - Cryomodules: Designed, being built, expected to be ready ~2017
  - Beam commissioning ~2018

Conclusions

- Proton Improvement Plan-II supports long term physics research goals by
  - providing increased beam power to LBNF
  - and setting a platform for the future
- PIP-II is in the pre-CD-0 status
  - It has strong support from P5, OHEP, and Fermilab director
  - Plan presented to P5 and DOE proposes five year construction period starting in FY2019
- Strong endorsement of PIP-II in the P5 Report
  - **Recommendation 14:** Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIPII) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Acknowledgements

PIP-II Collaboration

- Collaboration MOUs for the RD&D phase (through CD-2) :

National			IIFC
ANL	ORNL/SNS	BNL	BARC/Mumbai
Cornell	UTenn	PNNL	IUAC/Delhi
Fermilab	TJNAF	LBNL	RRCAT/Indore
MSU	NCSU	ILC/ART	VECC/Kolkata

Ongoing contacts with CERN (SPL), RAL/FETS (UK), ESS (Sweden), RISP (Korea), China/ADS

- PIP-II and PXIE posters at LINAC-14:
  - RT: TUPP047, TUPP051, THPP049, THPP055, THPP056
  - SC: MOPP047, MOPP049, MOPP052, MOPP055, MOPP056, TUPP052, TUIOC02, TUPP048, TUPP049; TUPP052, TUPP053, THPP001, THPP048, THPP050, THPP057

Thank you