Fermilab

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Beam Test Facilities Operations - ASTA/A0/PXIE

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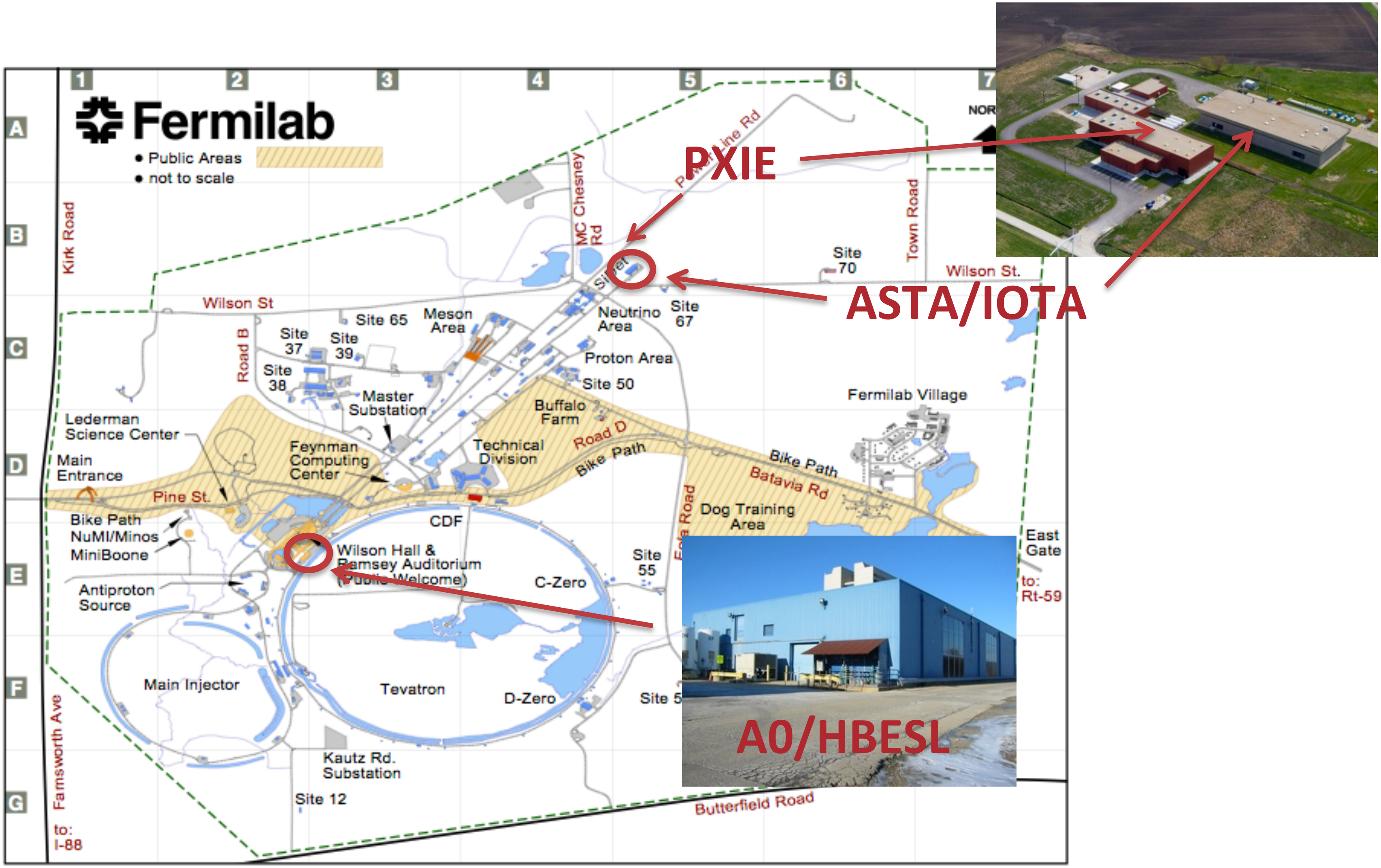
Mini-review of Fermilab Accelerator Test Facilities Program

17 March 2015

Talking points

- Details of each Facility (scope, users, cost, status, etc.)
  - ASTA/IOTA
  - PXIE
  - AO/High Brightness Electron Source Laboratory (HBESL)
- Summary

Beam-based Test Facilities



PXIE

ASTA/IOTA

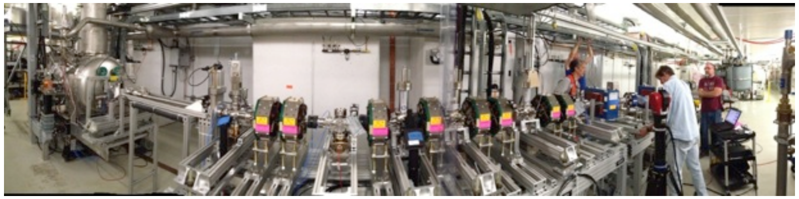
A0/HBESL

Cost Model

- Each Test Facility has two Distinct Costs
  1) Cost to maintain the building, infrastructure and subsystems in a "ready to operate" state (Jerry's talk)
     - Maintenance and upkeep of building
     - Operation and maintenance of utilities (air, water, HVAC, etc.)
     - Support of office space, meeting rooms, etc.
     - Minimal labor for accelerator system support to keep in an operational state (RF, Controls, safety systems, etc.)
  2) Cost to Operate the Test Accelerator (this talk)
     - This may or may not be part of the Test Facilities B&R, depending on the user/customer and purpose of the specific Test Facility
     - M&S needed to operate the accelerator or test stand (cryogens, laser systems, RF, controls, instrumentation, etc.)
     - Labor needed to operate the accelerator or test stand (operators, scientists, engineers, technicians, etc.)

IOTA/ASTA Overview (courtesy V. Shiltsev)

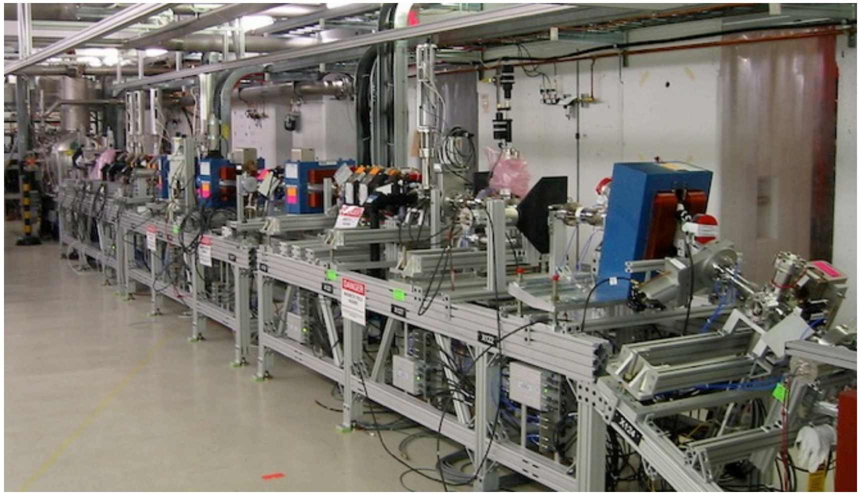
- Fermilab's Major Accelerator R&D Beam facility
  - Unique R&D facility close to completion: IOTA ring, high-brightness photo-injector, SRF cryomodule, proton RFQ
  - ~90M$ invested by OHEP since 2006
  - **Science goal:** Experimentally demonstrate novel techniques of integrable beam optics and space charge compensation, SRF research
  - **Technical challenge:** fabrication high-precision nonlinear magnets; injector for delivery of pencil electron beam and high-current low energy proton beam, beam thru SRF CM
  - **FY15 highlights:** Big part of IOTA ring built; commissioned 55 MeV e- injector and SRF CM2 at 250 MV
  - Operations start: 2017 (full IOTA)

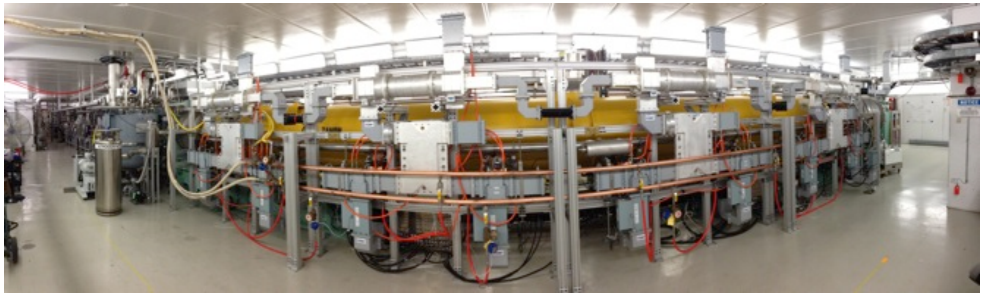


- Partnerships
  - DOE labs: ANL, BNL, ORNL, Jlab, LBNL
  - U.S. universities: 6
  - International: 4

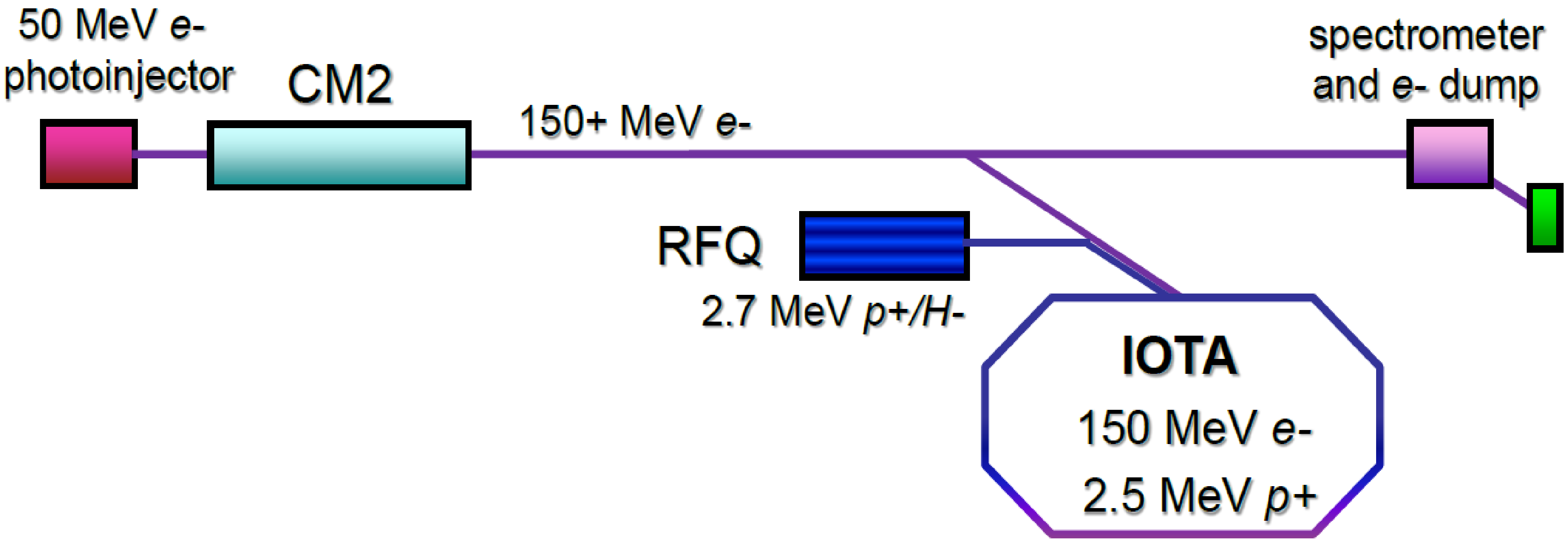
IOTA/ASTA Status

- Electron operation to 5 MeV routine
- Installation of 50 MeV injector complete
- Beam commissioning to up to 55 MeV planned for the coming weeks
- CM2 demonstrated average cavity gradient of 31.5 MV/m (> 250 MeV acceleration)

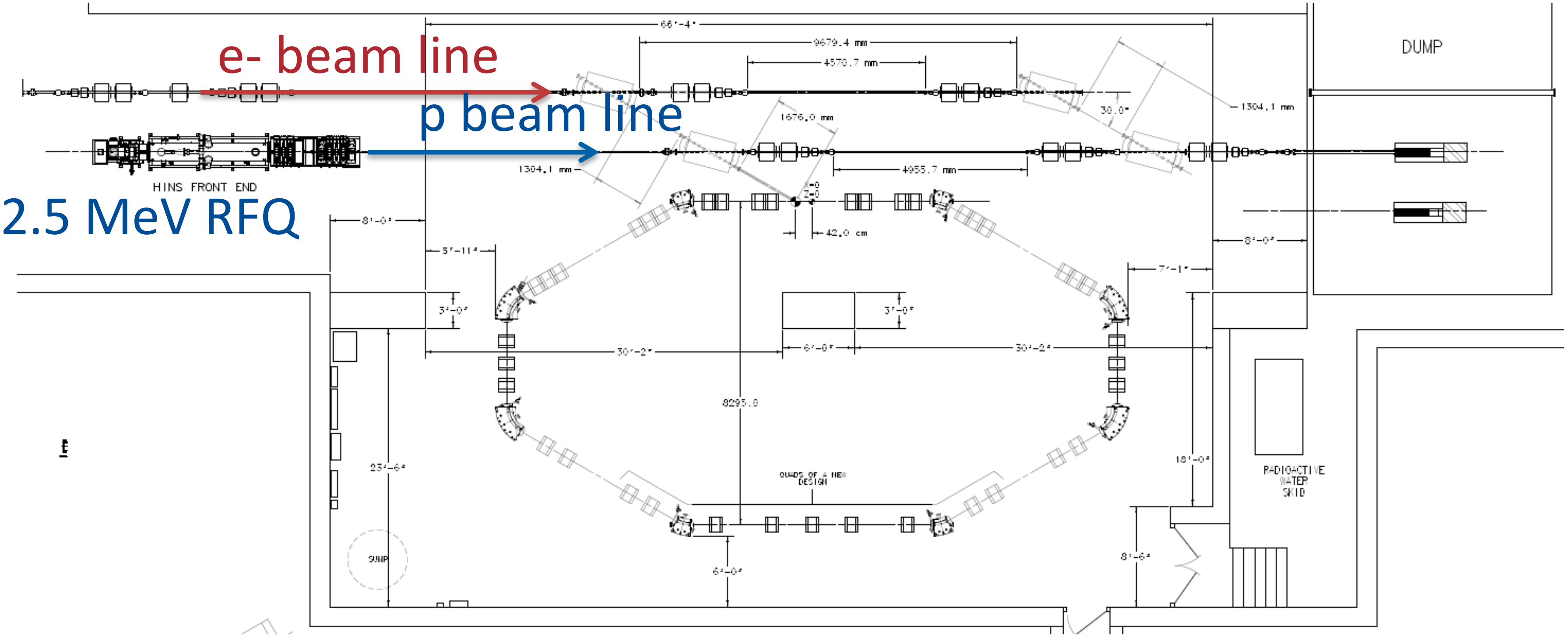




IOTA/ASTA schematic – plans through FY17



IOTA Ring: 2.5 MeV p+ or 150 MeV e- / 40 m



e- beam line

p beam line

2.5 MeV RFQ

Integrable Optics Test Accelerator

- Unique features:
  - Can operate with either electrons or protons (up to 150 MeV/c momentum)
  - Large aperture
  - Significant flexibility of the focusing lattice
  - Very tight control of the optics quality and stability
  - Set up for very high brightness operation (with protons)
- Based on conventional technology (magnets, RF)
- Cost-effective solution
  - Balance between low energy (low cost) and discovery potential

IOTA Goals for Integrable Optics

The IOTA experiment has the *goal to demonstrate the possibility to implement nonlinear integrable optics with a large betatron frequency spread ΔQ>1 and stable particle motion in a realistic accelerator design*

Benefits of nonlinear integrable optics include

- Increased Landau damping
- Improved stability to perturbations
- Resonance detuning

ASTA/IOTA Accelerator Operations

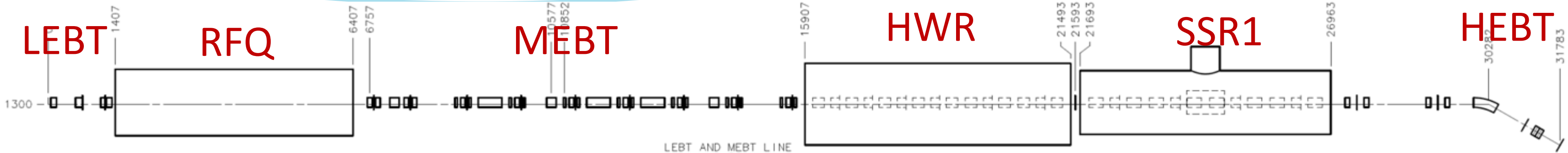
- The *ASTA Accelerator Operations* budget supports operation of the ASTA accelerator, including gun, laser lab, injector, cryomodule and beamlines
- IOTA to come on-line in FY17

Description	Direct M&S FY14 - actual ($k)	Direct M&S FY15 ($k)	Direct M&S FY16 ($k)	Direct M&S FY17 ($k)
Cryogens (Helium & Nitrogen)	184	104	107	220
Commissioning/Experimental Support	22	20	30	30
RF Operations (High and Low Level)	19	10	25	25
Controls	12	23	20	15
Instrumentation incl. Machine Protection System	7	20	20	20
Laser Lab	35	20	30	30
General Operations Support (elec., mech., misc.)	10	17	20	20
Total Direct M&S ($k)	**289**	**214**	**252**	**360**
Labor (FTE's)	**3.8**	**2.8**	**4.1**	**4.5**

PXIE overview (courtesy of Paul Derwent)

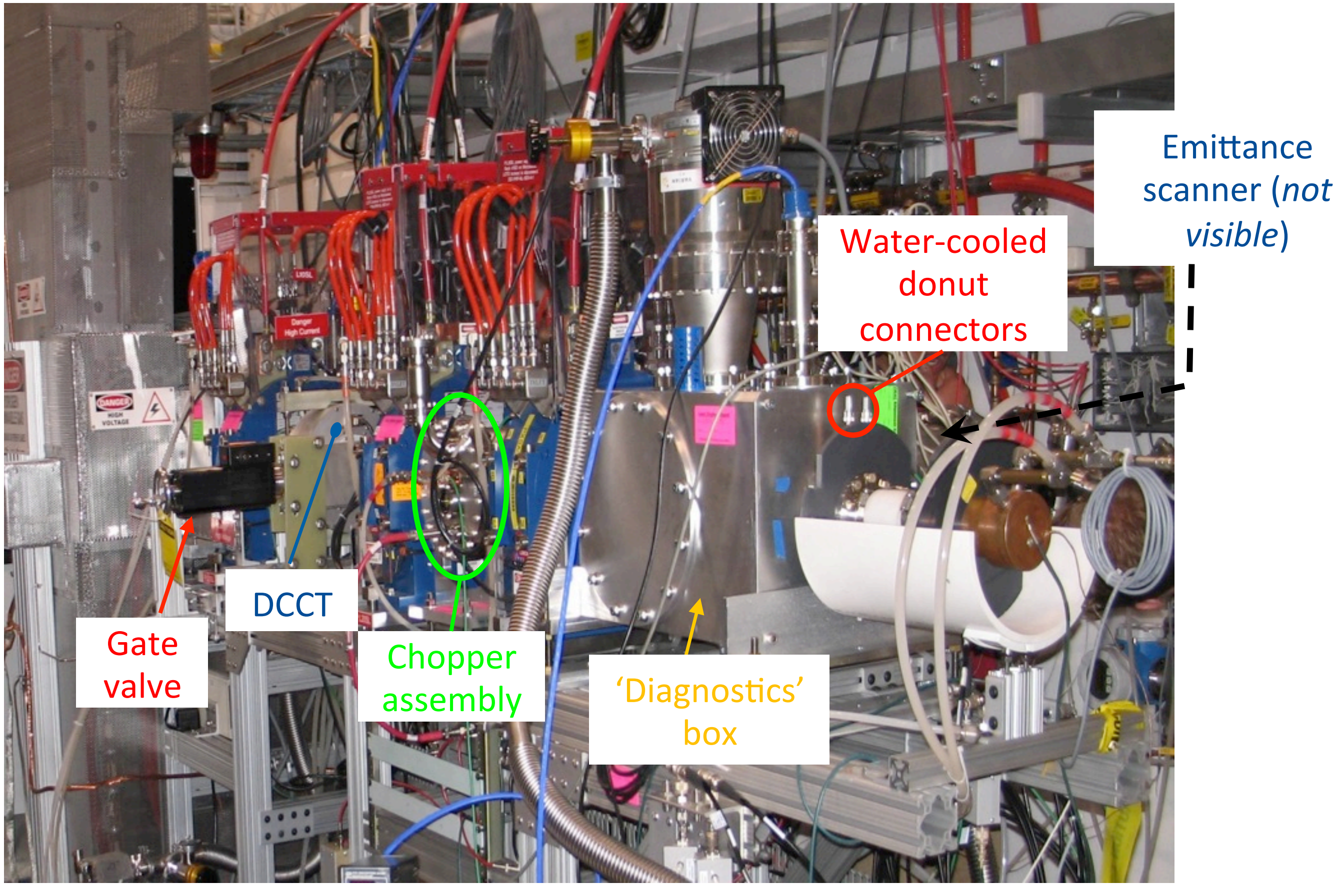
- Is a key element of the PIP-II R&D
- Goal: PIP-II construction start in 2019
- Goal of the R&D Program is to mitigate risk: technical/cost/schedule
- Technical Risks
  - Front End
    - CW ion source through SSR1
  - H- injection system
  - High Intensity Recycler/Main Injector operations
  - High Power targets
- Cost Risks
  - Superconducting RF
    - Cavities, cryomodules, rf sources – CW to long-pulse

PXIE



~ 40 m long

PXIE overview (courtesy of Paul Derwent)



Emittance scanner (*not visible*)

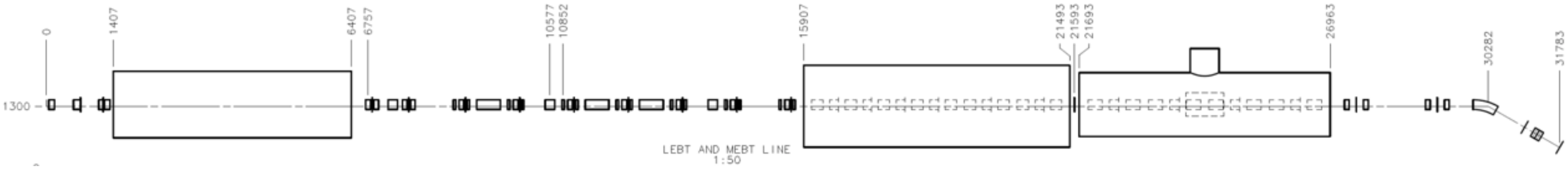
Water-cooled donut connectors

Gate valve

DCCT

Chopper assembly

'Diagnostics' box



LEBT AND MEBT LINE
1:50

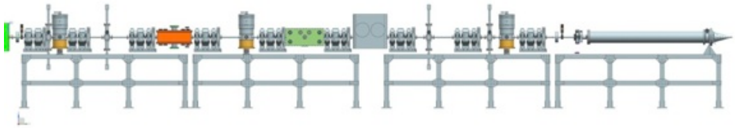
PXIE Goals (courtesy of Paul Derwent)

- Validate the PIP-II 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 Functional Requirement Specification and determined by multi-experiment operation
    - $<10^{-9}$ – as desired by μ-to-e experiment (no formal specification)
- Obtain experience in design and operation of SC proton linac
  - SSR1 cryomodule will be designed and built by Fermilab

PXIE time line (courtesy of Paul Derwent)

- Stage 1 complete – early FY17 (~Nov 2016)
  - Ion source, LEBT, prototype chopper
  - RFQ at full power
  - beginning installation of SSR1 cryomodule
    - SSR1 CM – cold and rf powered, no beam
  - Full MEBT with prototype kickers, (possibly) prototype absorber, temp. dump, bunchers, diagnostics
  - Cryo system
  - Beam delivered to the end of MEBT with nearly final parameters (2.1 MeV, 1 mA CW, 80% arbitrary chopping)
- Stage 2 complete – Mar 2018
  - installation of HWR cryomodule, cold and ready for beam
  - HWR CM – cold and rf powered, no beam
- Stage 3 complete – September 2018
  - Full diagnostics line
  - final MEBT kickers, final 50 kW beam dump, 1-mA CW beam delivered to the dump

MEBT plan (technically driven, with no contingency)



- Aug 2015 – pulsed beam from RFQ
- Nov 2015 – CW beam
- Dec 2015 – Feb 2016 – installation of full – length MEBT
  - With prototype kickers (50 Ohm and 200 Ohm) and 5 kW prototype absorber
  - Final bunching cavities, final magnets, SNS beam dump at the end
  - Incomplete diagnostics (e.g. no wire monitors, extinction monitor, laser wire etc.)
- Mar – Jul 2016- initial MEBT commissioning
  - The main goal is to pass the beam to the chopper to test its elements
  - Make decision on the kicker technology; start the final chopper design
- Aug- Nov 2016 – all cryo work and SSR1 installation
- Dec 2016- Aug 2017 – MEBT characterization
  - In parallel with SSR1 commissioning
- Sep – Dec 2017 – final MEBT installation (concurrent with HWR’s)
- FY18 – demonstration of bunch-by-bunch separation

PXIE Deliverable

- Major PXIE deliverable is the first 25 MeV of the PIP-II linac
  - Current plan is to move PXIE (from the ion source through SSR1) from CMTF to the new linac gallery

- Secondary Deliverables (assumed in meeting the major one!)
  - CW RFQ
  - Demonstration of bunch by bunch chopping
  - Vacuum interface between MEBT and Cryo section

PXIE Milestones

Milestone	Estimate
Beam through the LEBT*	Q1 FY15
LEBT Beam Meets Specs	Q2 FY15
LEBT Beam Commissioning Complete	Q3 FY15
Beam through the RFQ*	Q3 FY15
RFQ Commissioning Complete	Q2 FY16
Beam through the MEBT*	Q4 FY16
MEBT Chopper Technology Finalized	Q4 FY16
PXIE Stage 1 Complete*	Q2 FY17
MEBT Beam meets Specs	Q1 FY17
PXIE Stage 2 Complete*	Q4 FY17
Beam through the HWR	Q2 FY18
Beam through the SSR1	Q3 FY18
MEBT Commissioning Complete	Q2 FY17
PXIE Stage 3 Complete*	Q4 FY18
HWR Commissioning Complete	Q4 FY18
SSR1 Commissioning Complete	Q4 FY18
PXIE Beam Commissioning Complete*	Q4 FY18

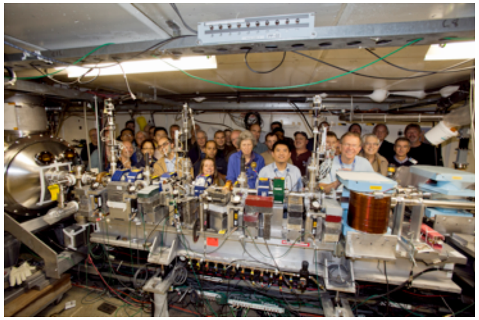
PXIE Accelerator Operations

- The *PXIE Accelerator Operations* budget supports operations and maintenance of PXIE specific support systems and infrastructure (PXIE specific chillers, hydrogen system, vacuum equipment, etc.) including cost of cryogens for operations. (Test Facilities – New)
- Philosophy: PIP-II pays to build, Test Facilities Operations pays to operate and maintain

Description	**Direct M&S FY14 - actual ($k)**	**Direct M&S FY15 ($k)**	**Direct M&S FY16 ($k)**	**Direct M&S FY17 ($k)**
Cryogens (Helium & Nitrogen)	0	0	0	150
PXIE-specific water chillers (Ion Source, RFQ, etc.) and Hydrogen system (ion source)	0	0	20	20
RF Operations (High and Low Level)	0	0	15	15
Controls	0	0	15	15
General Operations Support (elec., mech., misc.)	0	0	20	20
Total Direct M&S ($k)	**0**	**0**	**70**	**220**
Labor (FTE's)	**0.0**	**0.0**	**0.5**	**1.0**

A0/HBESL Overview

- A0 is the birthplace of SRF activities at Fermilab
  - Photoinjector – 14 MeV SRF facility for AARD
  - Clean room for parts cleaning, assembly, cavity test prep, and storage
  - ‘North cave’ for SRF cavity tests
  - Coupler test stand (3.9 GHz input couplers)
- Storied history for AARD, PhD’s at Fermilab
- ‘Ground zero’ for many FLASH/ACC39 activities



A0/HBESL Status

- Photoinjector gun repurposed as HBESL
- ‘Capture Cavity 1’ upgraded and to be installed as part of ASTA Injector
- Coupler stand in operation by means of a *Work For Others agreement* with DESY for assembling and conditioning XFEL 3.9 GHz couplers
- Occasional North cave operation
  - 3.9 GHz spare cavity qualification (for DESY/FLASH)
  - 3.9 GHz cavity R&D (single and 9-cell)
  - 2.4 GHz magnetron testing
  - other ‘niche’ tests
- Future of these facilities very murky
  - possible HBESL relocation to IARC
  - 3.9 GHz test capability being developed at IB1/TD
  - A0 to be repurposed
  - Clean room activities (incl. staff) largely moved to CMTF

A0/HBESL Operations

- The *A0/HBESL Operations* budget is minimal in support of HBESL (GARD – Test Facilities) and 3.9 GHz SRF work
- WFO with DESY is full cost recovery

Description	Direct M&S FY14 - actual ($k)	Direct M&S FY15 ($k)	Direct M&S FY16 ($k)	Direct M&S FY17 ($k)
Cryogenic Operations & Maintenance (3.9 GHz)	0	0	45	0
Consumables for 3.9 GHz SRF tests	0	0	9	0
HBESL RF Support	1	2	2	0
HBESL Laser operations	4	4	4	0
HBESL General Infrastructure/misc.	22	6	6	0
Total Direct M&S ($k)	**27**	**12**	**66**	**0**
Labor (FTE's)	**0.3**	**0.2**	**1.3**	**0.0**

AD Test Facilities Budget Summary

AD Test Facilities Summary		Direct M&S ($k)	Loaded M&S (23.53% OH)	Direct SWF (FTE)	Loaded SWF (~$200k/FTE)	FY14 Total ($k)	FY15 Total ($k)	FY16 Total ($k)	FY17 Total ($k)
Cryogenic Operations									
	FY14	$603	$745	10.5	$2,100	$2,845			
	FY15	$506	$625	10.6	$2,120		$2,745		
	FY16	$524	$647	16.5	$3,300			$3,947	
	FY17	$545	$673	16.5	$3,300				$3,973
SRF Facilities									
NML Facility Operations									
	FY14	$278	$343	3.0	$600	$943			
	FY15	$182	$225	3.0	$600		$825		
	FY16	$275	$340	3.3	$660			$1,000	
	FY17	$225	$278	3.8	$760				$1,038
CMTF Facility Operations									
	FY14	$300	$371	2.0	$400	$771			
	FY15	$248	$306	2.3	$460		$766		
	FY16	$350	$432	3.2	$640			$1,072	
	FY17	$330	$408	3.4	$680				$1,088
MDB Facility Operations									
	FY14	$239	$295	2.4	$480	$775			
	FY15	$77	$95	2.4	$482		$577		
	FY16	$254	$314	2.6	$520			$834	
	FY17	$14	$17	3.0	$600				$617
Beam Test Facilities Operations									
ASTA Accelerator Operations									
	FY14	$289	$357	3.8	$760	$1,117			
	FY15	$214	$264	2.8	$560		$824		
	FY16	$252	$311	4.1	$820			$1,131	
	FY17	$360	$445	4.5	$900				$1,345
AO/HBESL Operations									
	FY14	$27	$33	0.3	$50	$83			
	FY15	$12	$15	0.2	$34		$49		
	FY16	$66	$82	1.3	$260			$342	
	FY17	$0	$0	0.0	$0				$0
PXIE Accelerator Operations									
	FY14	$0	$0	0.0	$0	$0			
	FY15	$0	$0	0.0	$0		$0		
	FY16	$70	$86	0.5	$100			$186	
	FY17	$220	$272	1.0	$200				$472
MTA Operations									
	FY14	$69	$85	0.0	$0	$85			
	FY15	$0	$0	0.0	$0		$0		
	FY16	$175	$216	2.2	$440			$656	
	FY17	$355	$439	3.4	$680				$1,119
					Total:	**$6,620**	**$5,786**	**$9,169**	**$9,651**

Summary

- Fermilab has a set of unique beam-based test areas that are de-coupled from the main accelerator complex
- DOE has made a significant investment in ASTA/IOTA that is well on its way to showing a return
- PXIE is a well defined program intended to address technical risks for PIP-II
- A0/HBESL support is diminishing, but activities pioneered there still have validity
- Funding plan and schedules reflects these realities, the next couple of years are critical

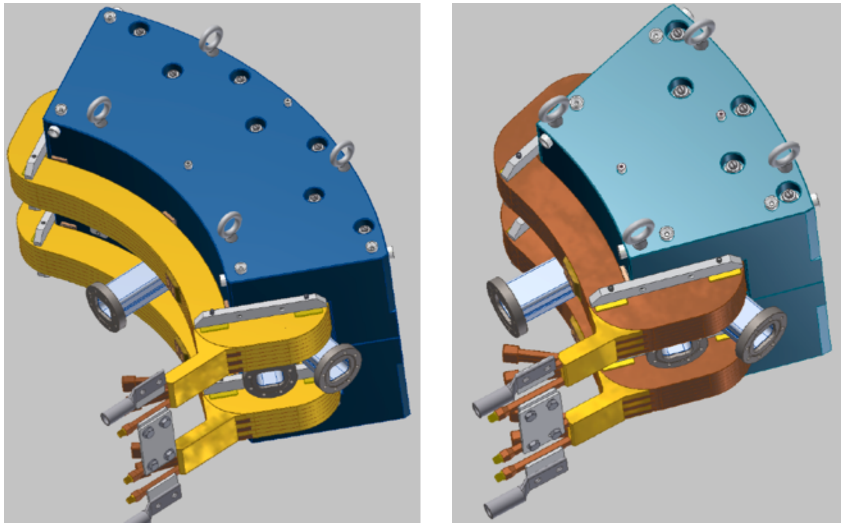
Thank you….

Backup slides

IOTA Parameters

Nominal kinetic energy	150 MeV *e-*, 2.5 MeV *p+*
Nominal intensity	e^-: 1×10^9, p: 1×10^{11}
Circumference	40 m
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 ÷ 0.1
Betatron tune (integer)	3 ÷ 5
Natural chromaticity	-5 ÷ -10
Transverse emittance r.m.s.	*e-*$^-$: 0.1 μm, *p+*: 2μm
SR damping time	0.6s (5×10^6 turns)
RF Voltage, freq.,harmonics	e^-: 1 kV, 30 MHz, 4
Synchrotron tune	e^-: 0.002 ÷ 0.005
Bunch length, momentum spread	e^-: 2 cm, 1.4×10^{-4}

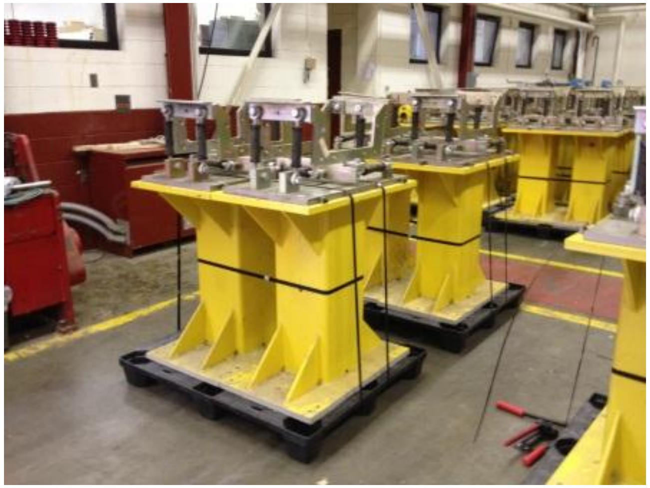
IOTA Ring Elements in Hand



Dipole magnets (ordered)

32 quads from JINR (Dubna) received

Vacuum chambers
for dipoles (received)



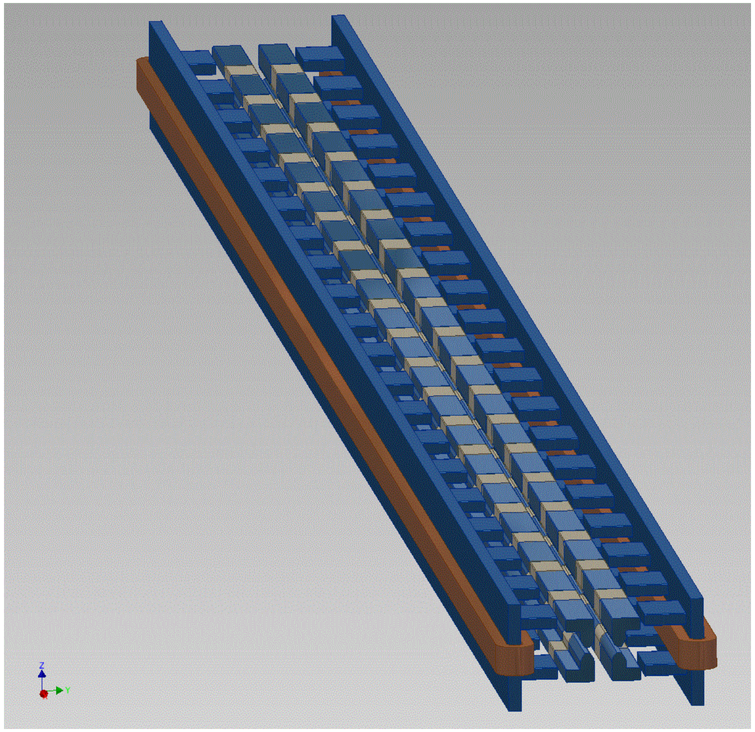
Magnet support stands
from MIT (received)

Also:

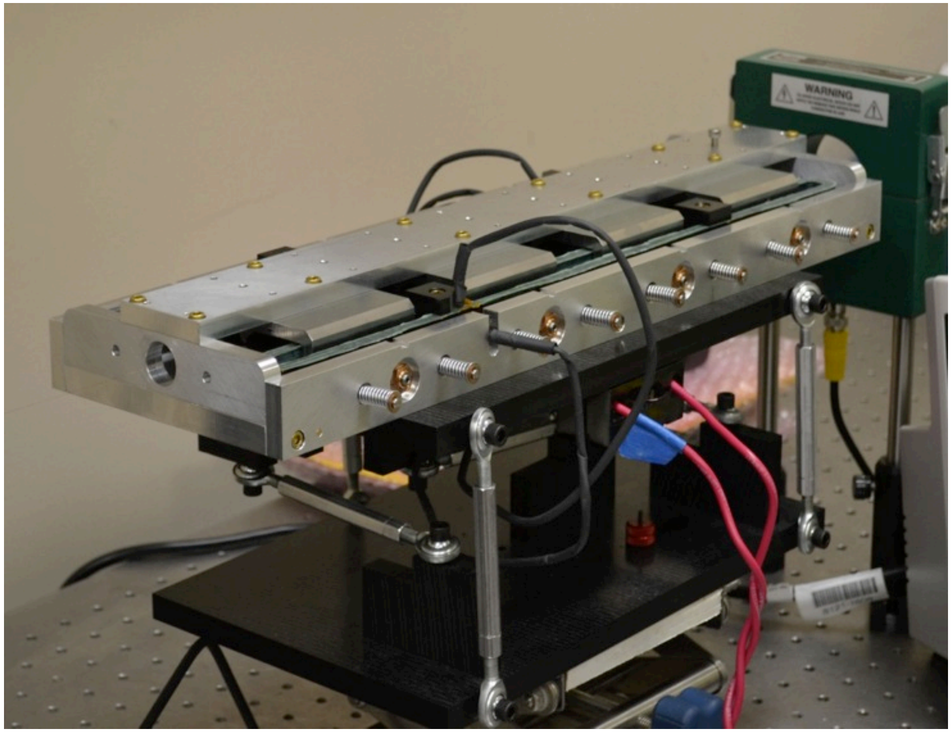
BPM bodies and electronics
Vacuum system
Dipole power supply
Corrector power supplies

IOTA Nonlinear Magnet

- Joint effort with RadiaBeam Technologies (Phase I and II SBIR)



FNAL Concept: 2-m long nonlinear magnet



RadiaBeam short prototype. The full 2-m magnet is designed and fabricated in Phase II

IOTA Staging – Phase I

Phase I will concentrate on the academic aspect of single-particle motion stability using e- beams

- Achieve large nonlinear tune shift/spread without degradation of dynamic aperture by "painting" the accelerator aperture with a "pencil" beam
- Suppress strong lattice resonances = cross the integer resonance by part of the beam without intensity loss
- Investigate stability of nonlinear systems to perturbations, develop practical designs of nonlinear magnets
- The measure of success will be the achievement of high nonlinear tune shift = 0.25

IOTA Staging – Phase I

- The magnet quality, optics stability, instrumentation system and optics measurement techniques must be of highest standards in order to meet the requirements for integrable optics
  - 1% or better measurement and control of β-function, and 0.001 or better control of betatron phase
- This is why Phase I needs pencil e^- beams as such optics parameters are not immediately reachable in a small ring operating with protons
- **High quality electron beam at a certain energy and phase-space quality is absolutely essential to characterize the IOTA ring**

IOTA Staging – Phase II

After the IOTA commissioning, we will move the existing 2.5 MeV proton/H- RFQ into the ASTA hall to inject protons into the IOTA ring.

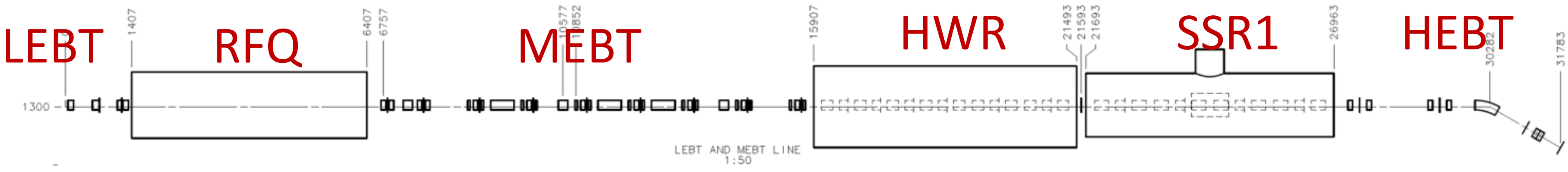
ΔQ_{SC} =0.6 for one-turn injection

*multi-turn injection possible


2.5 MeV RFQ

- Allows tests of Integrable Optics with protons and realistic space charge beam dynamics studies
- Allows space charge compensation experiments
- Unique capability

PXIE layout

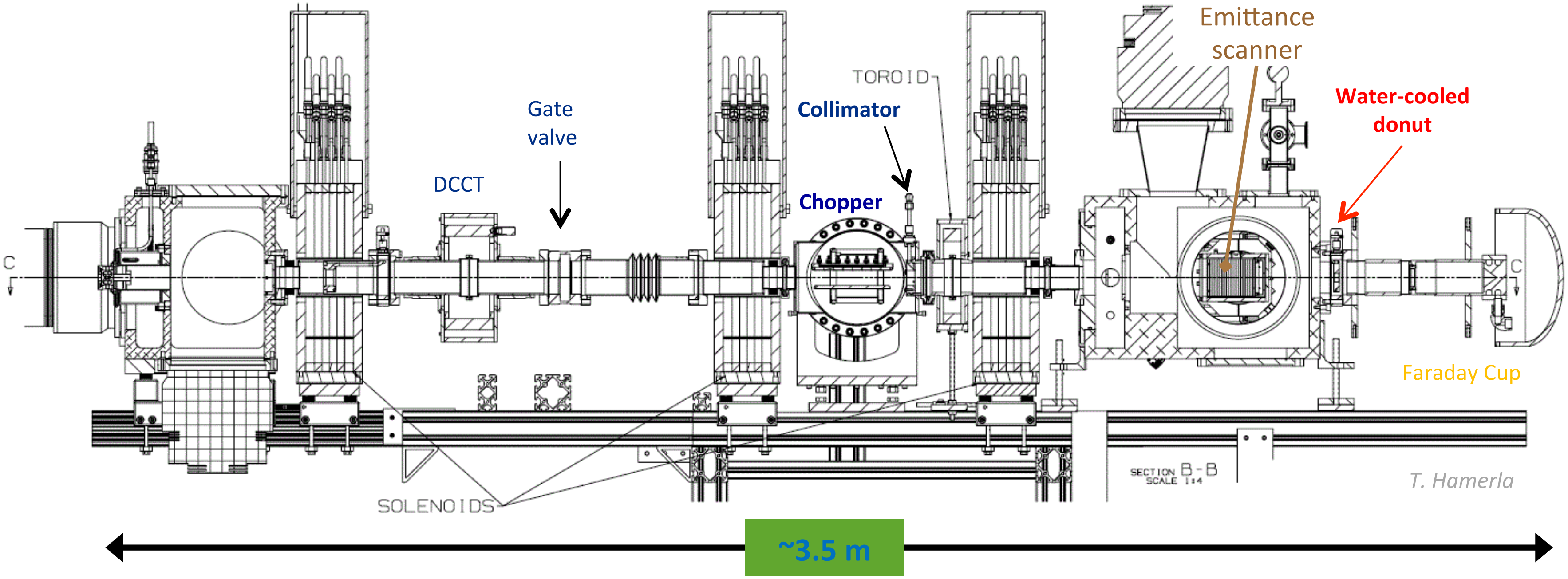


~ 40 m long

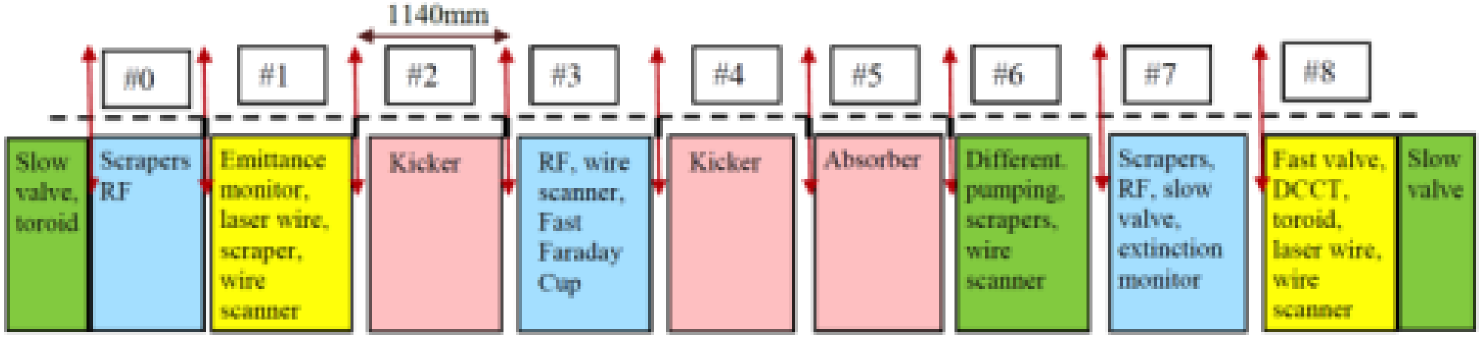
- CW H- source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping
- CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
- MEBT with integrated wide-band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of 4 mA average beam current
- Low beta superconducting cryomodules: 1 mA to ~25 MeV
- Beam dump capable of accommodating 2 mA at 25 MeV (50 kW) for extended periods.
- Associated beam diagnostics, utilities and shielding

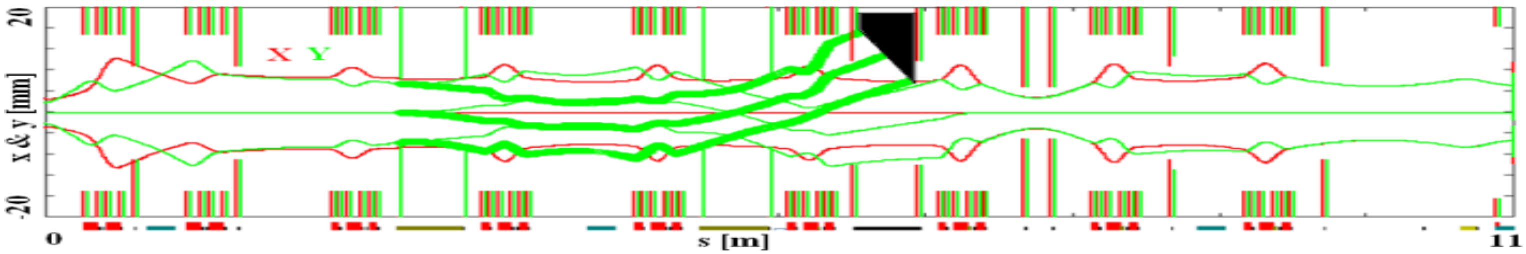
PXIE Current setup: LEBT installed (30 keV)

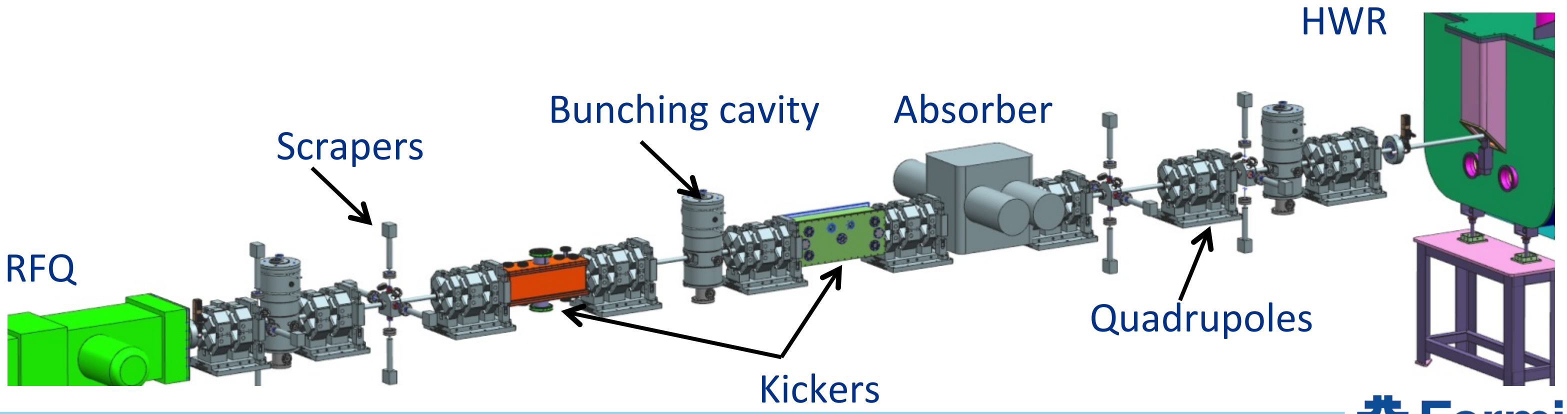
- All focusing elements, chopper, instrumentation have been installed *except* for the LEBT/RFQ Interface and its ‘scraper’
  - Also, most of the controls, PS… have been moved to their final location
  - The construction and installation of the bend has been delayed until FY16



PXIE MEBT layout: to be built 2015-16







PXIE Summary

- PXIE is a well defined program to address technical risks for PIP-II
  - 25 MeV H- Linac
  - Bunch by bunch chopping
  - Operation of SRF in close proximity to absorber
- Set of milestones and goals
  - focus in FY15 is delivery and commissioning of RFQ
  - focus in FY16 is building out the full MEBT