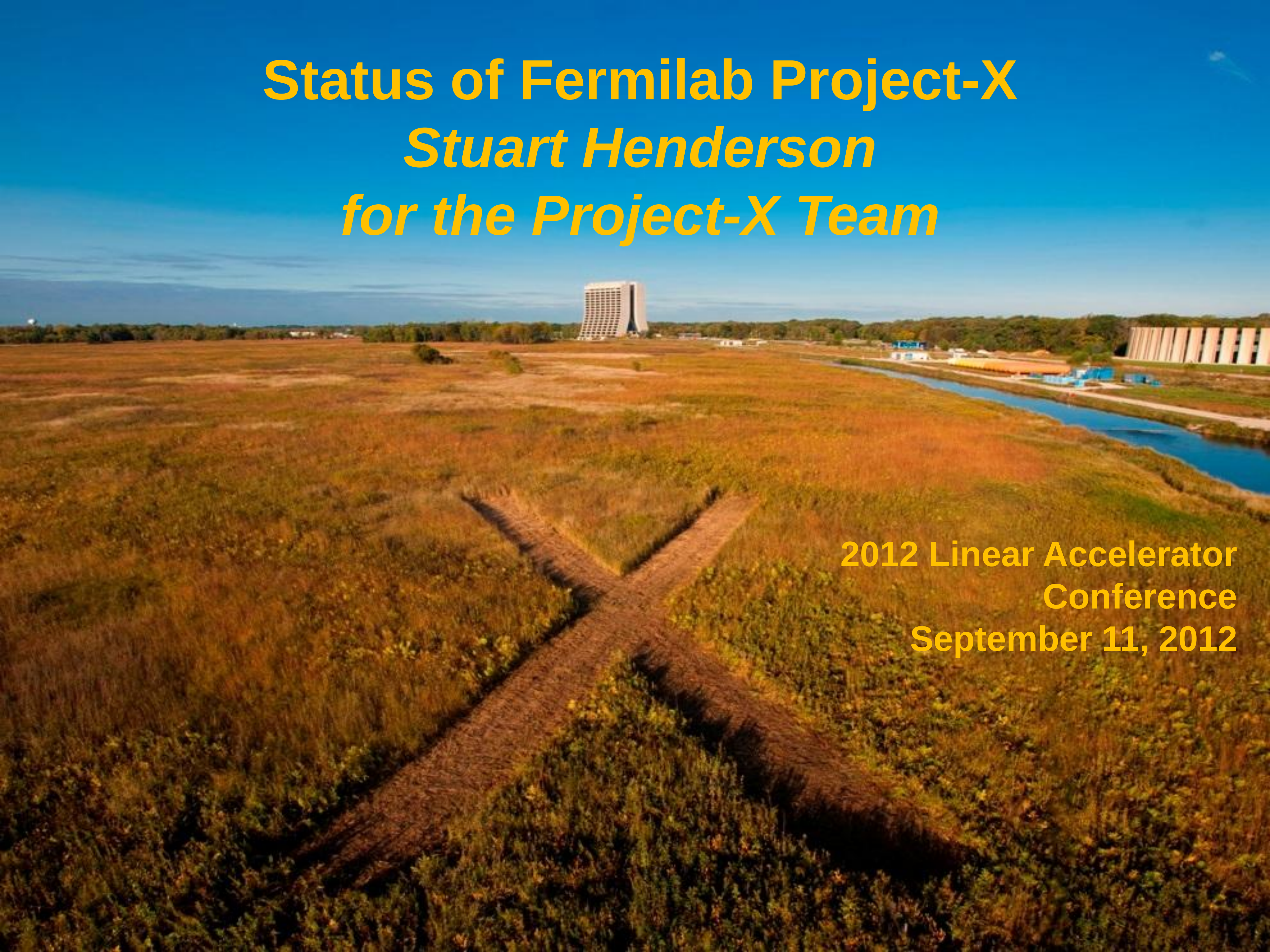
Status of Fermilab Project-X

Stuart Henderson
for the Project-X Team



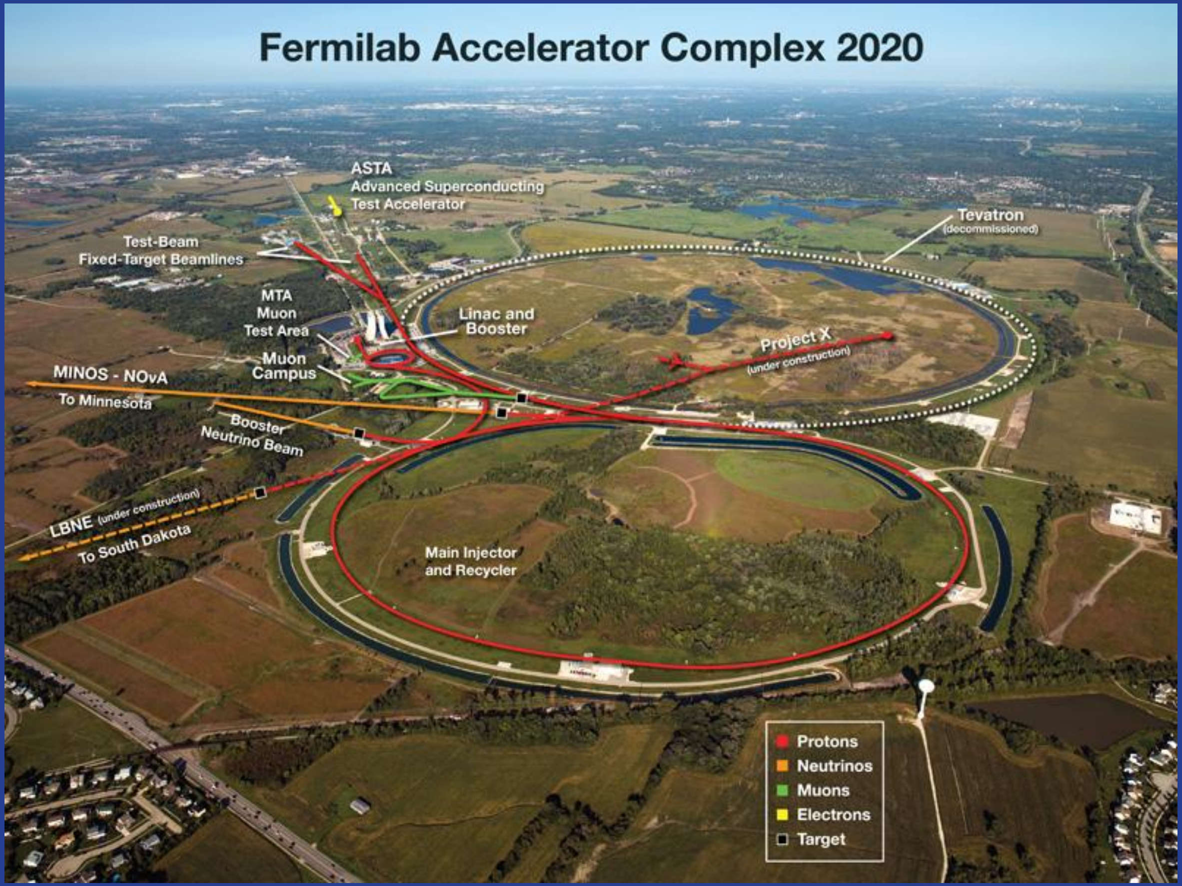
2012 Linear Accelerator Conference
September 11, 2012

The Project-X Collaboration

15 formal collaboration members supplemented with several informal collaborative relationships

Project-X Will…

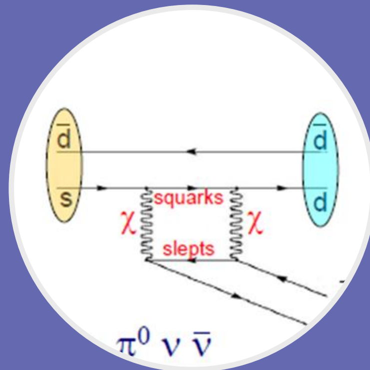
- Be the leading high power proton accelerator facility in the world
- Provide unique capability to deliver multi-MW beams to multiple experiments simultaneously, with variable bunch formats, across a broad range in energy: 1-120 GeV
- Enable a world-leading program in Intensity-Frontier particle physics and applications beyond HEP
- Extend the capabilities of the Fermilab's existing accelerator complex
- Be carried out as a collaboration between 15 institutions in the US and India



Project-X Scientific Mission

Long Baseline Neutrino Experiments

2 MW at 60-120 GeV



Kaon, Muon, Nuclei & Neutron precision experiments

3MW at 3 GeV

Platform for evolution to a Neutrino Factory and Muon Collider

Future upgrade to 4MW

Energy Applications: materials irradiation and transmutation

1 MW at 1 GeV

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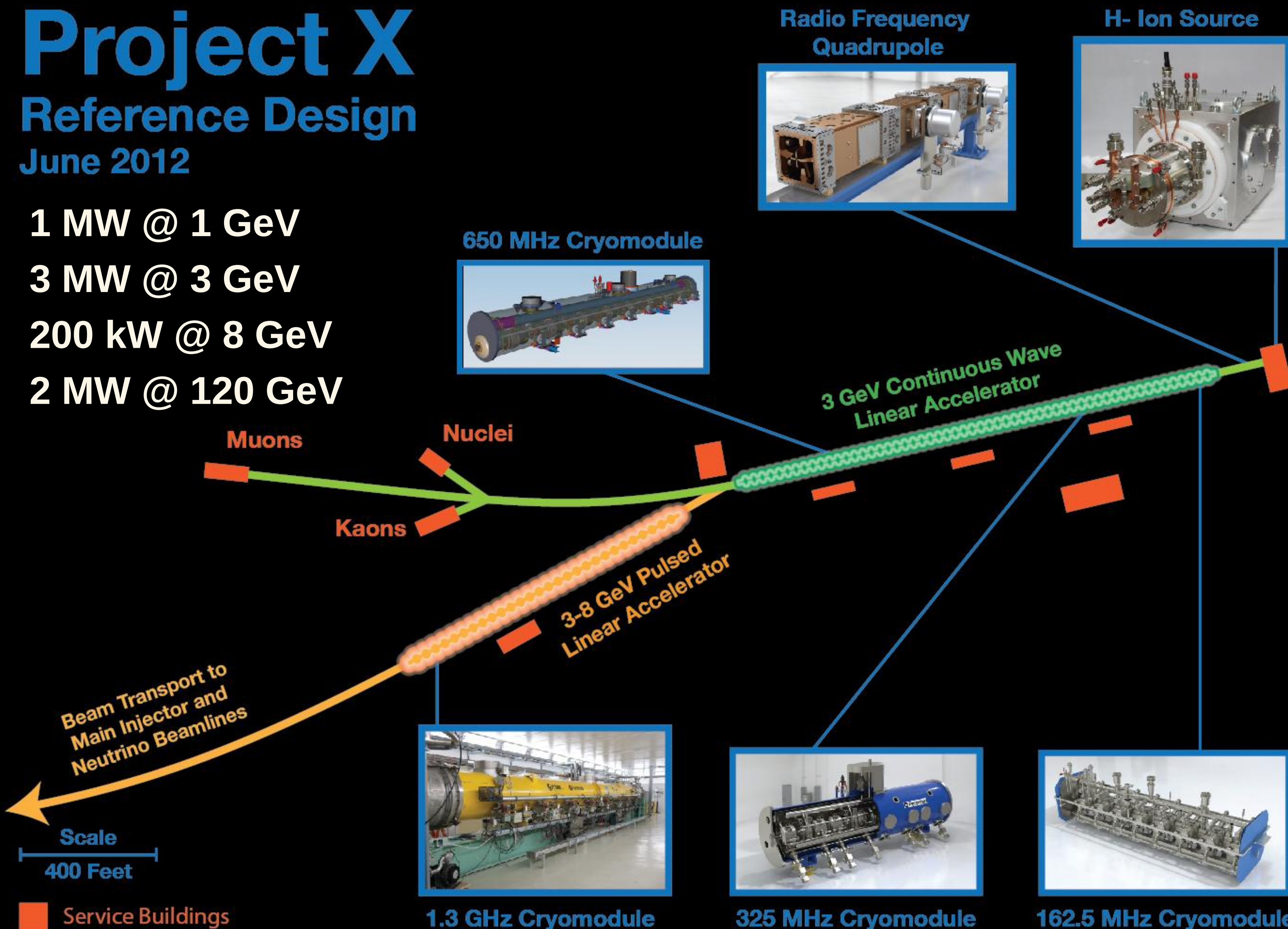
Project X Reference Design June 2012

1 MW @ 1 GeV

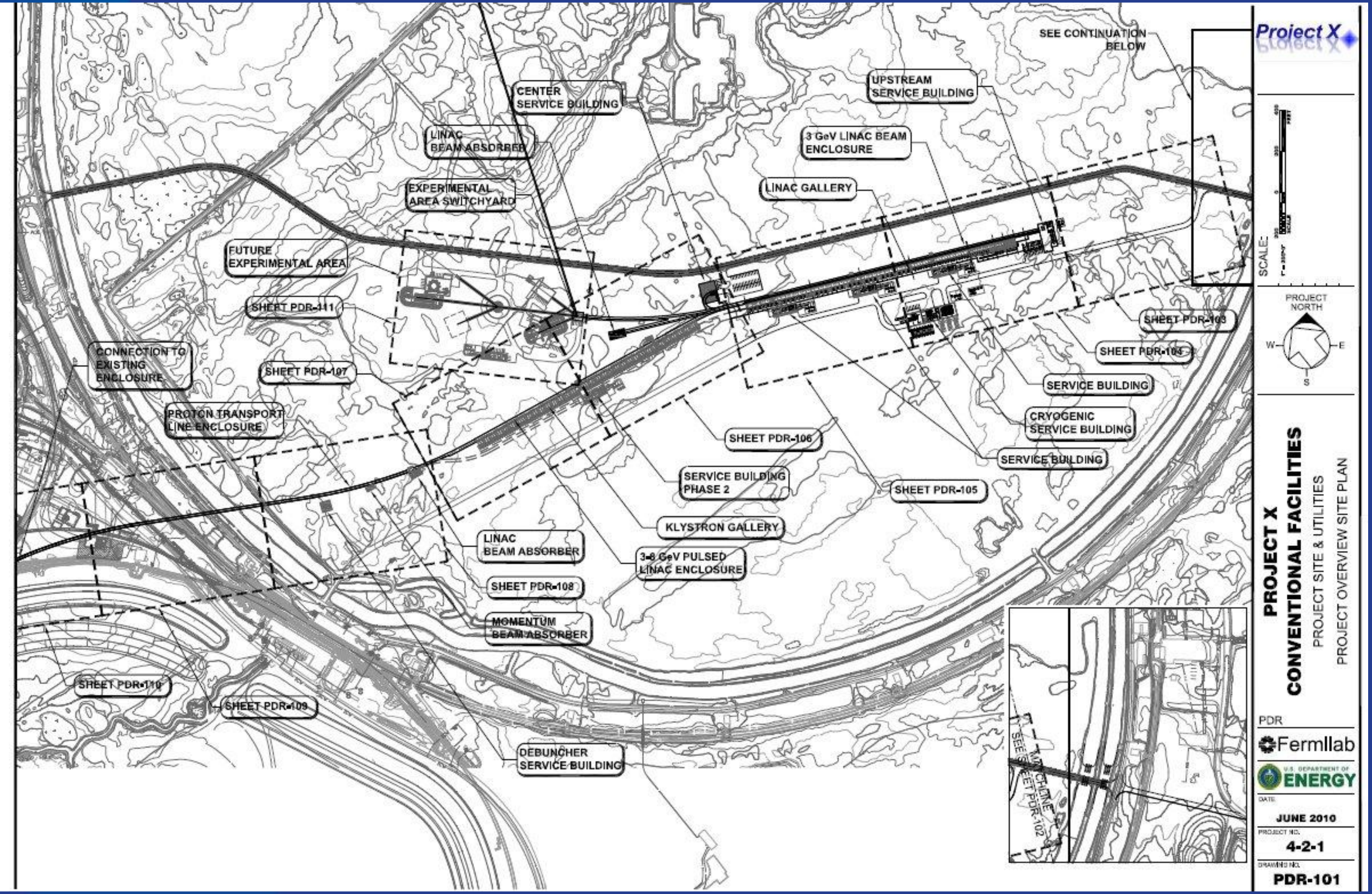
3 MW @ 3 GeV

200 kW @ 8 GeV

2 MW @ 120 GeV



Project X Reference Design Siting



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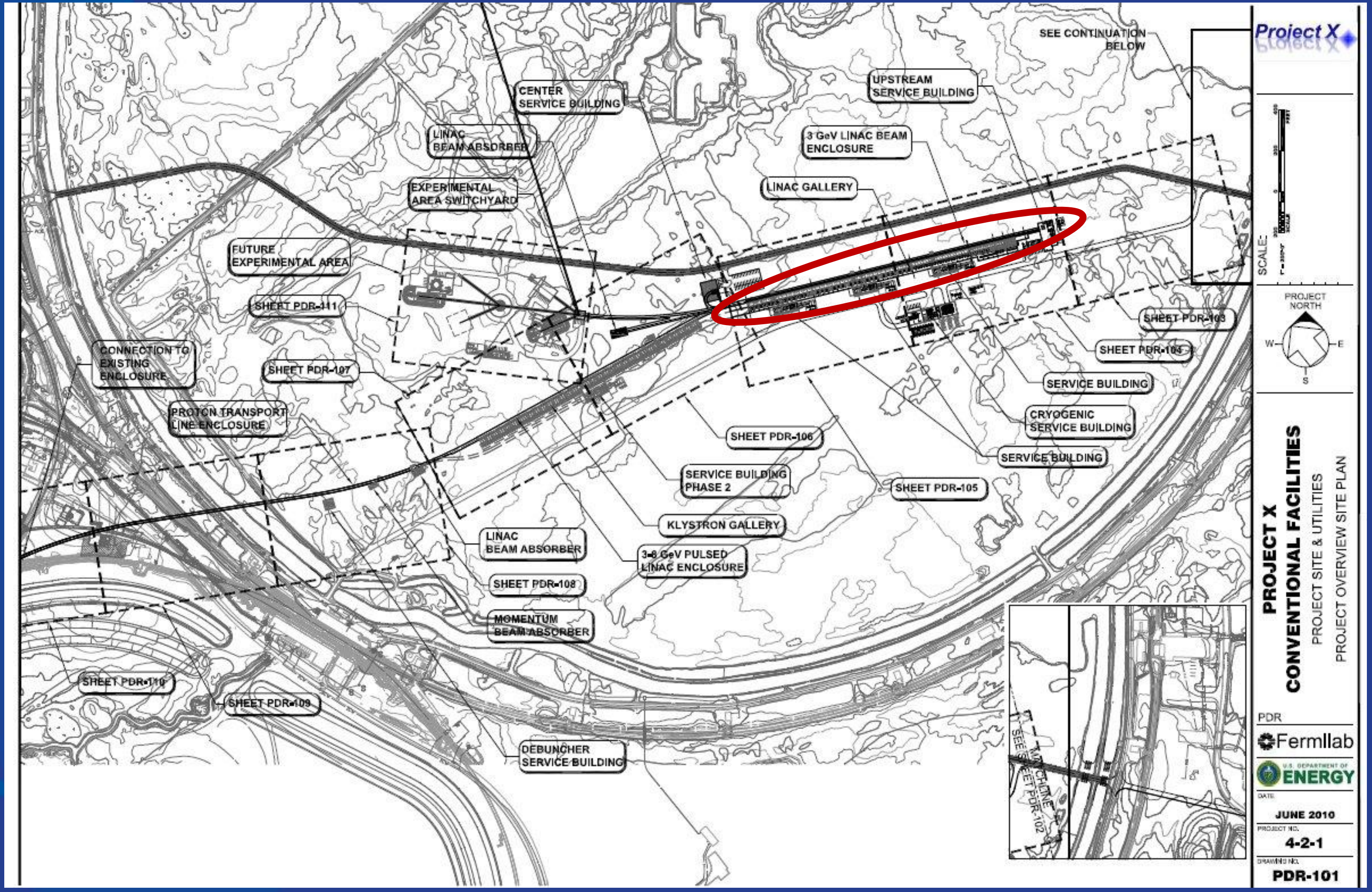

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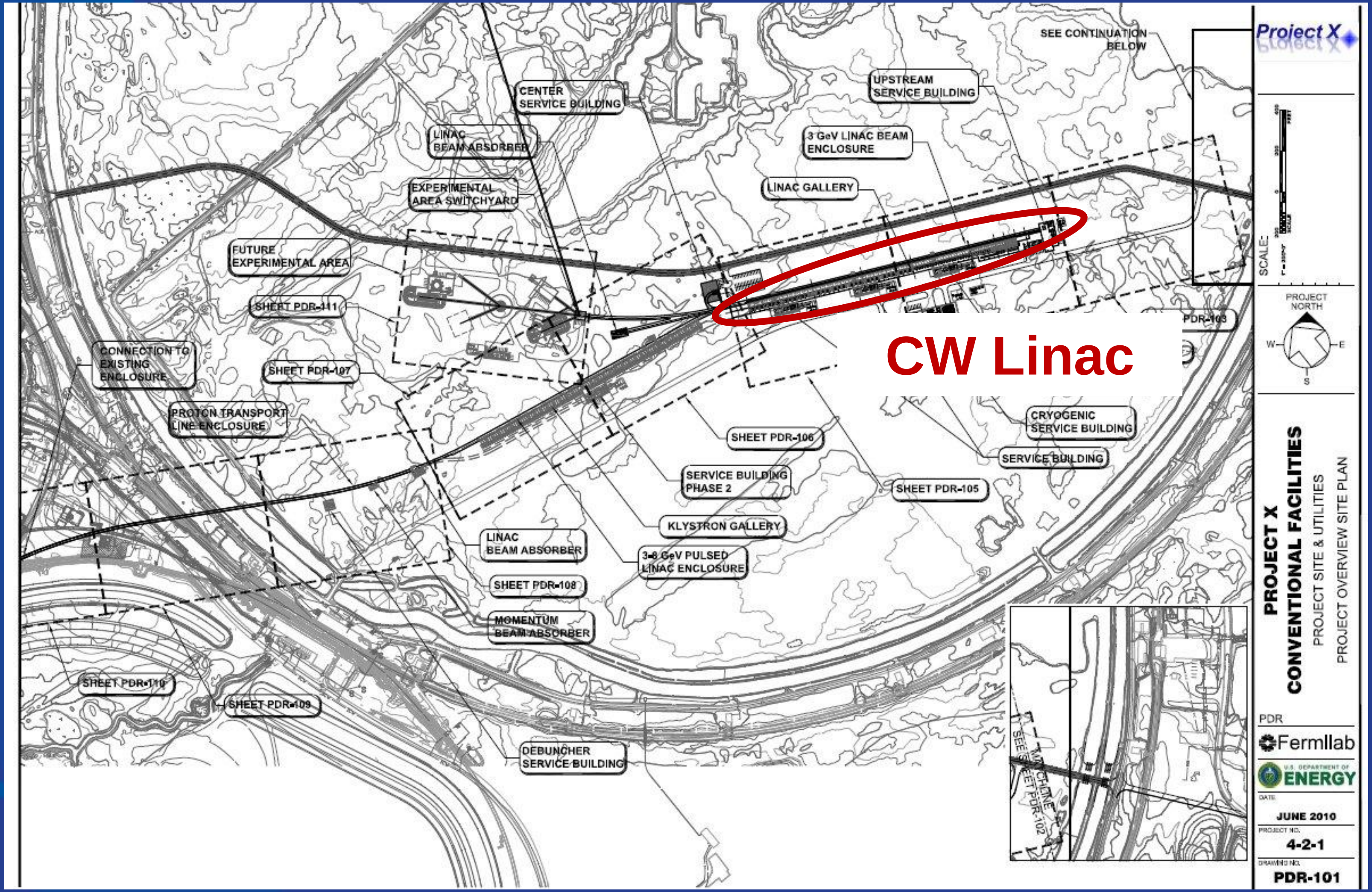

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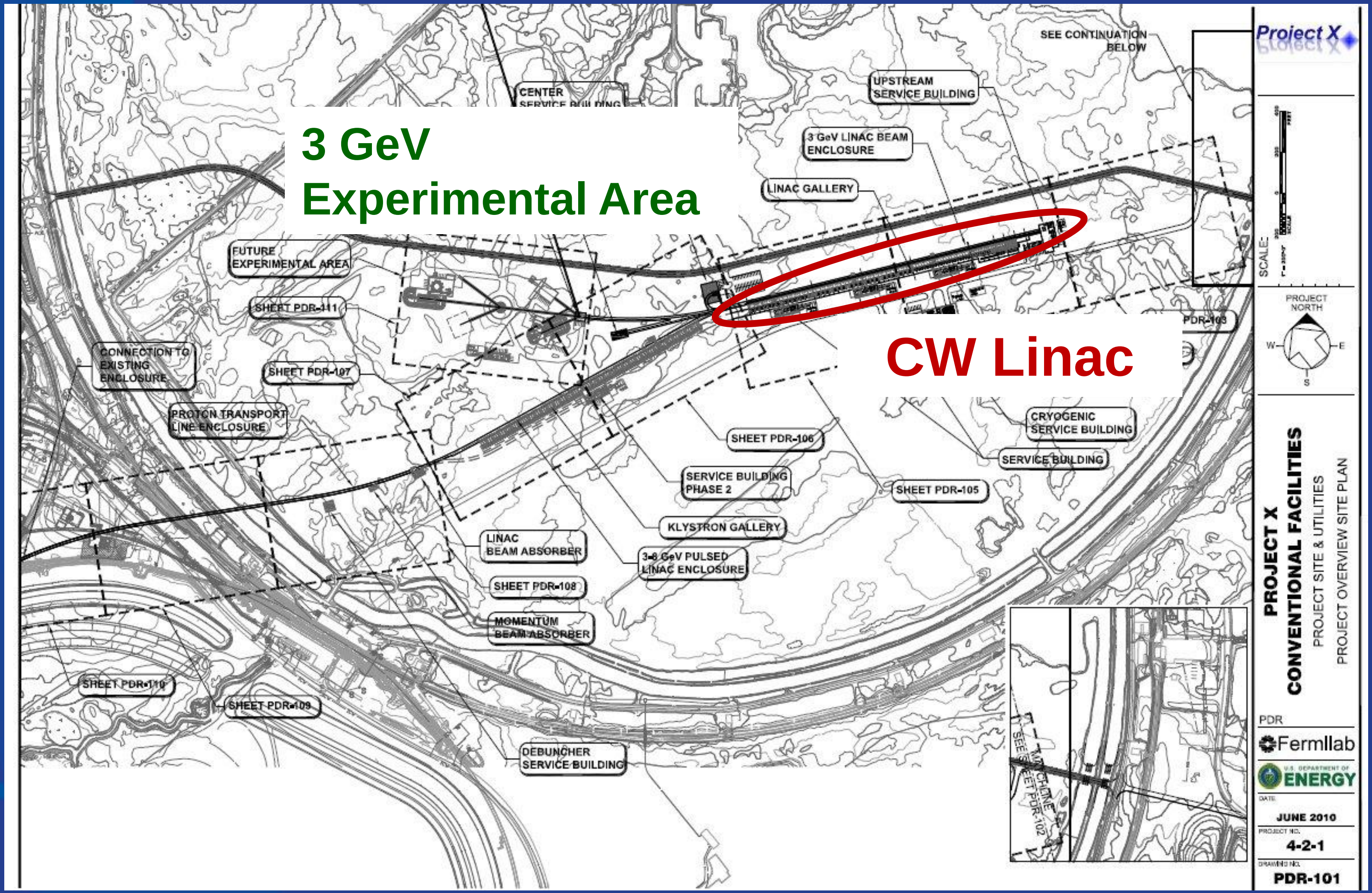

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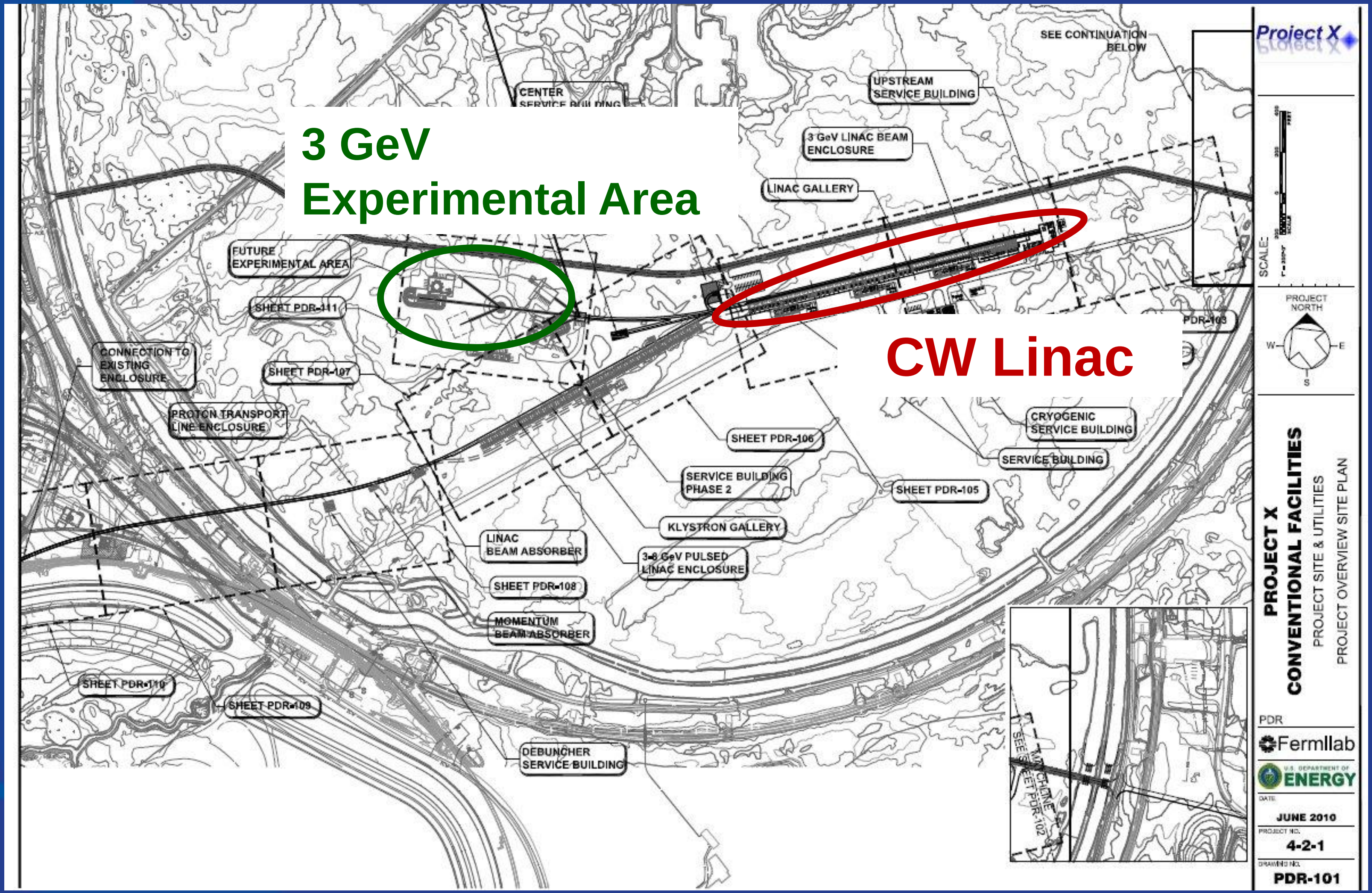

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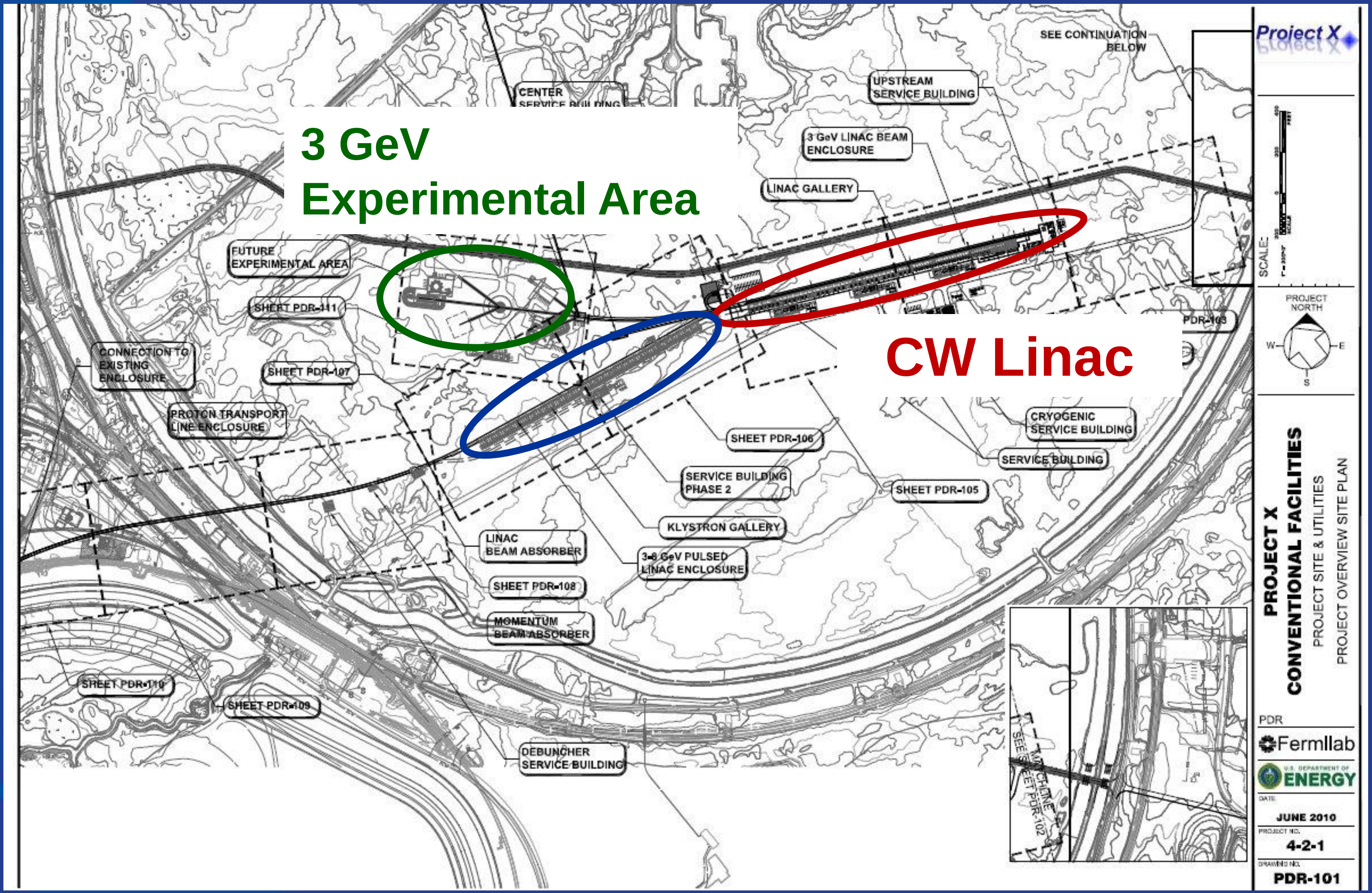

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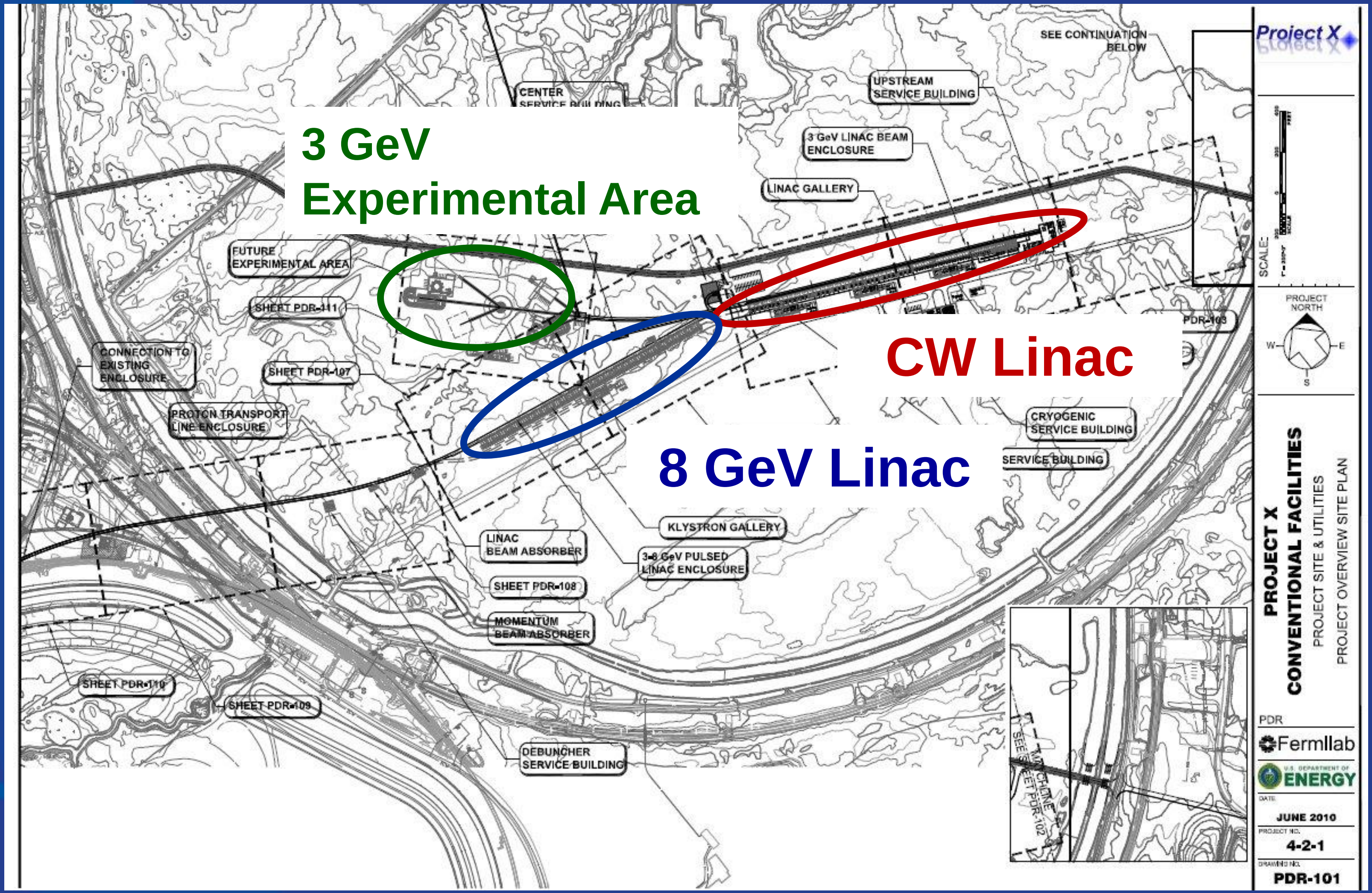

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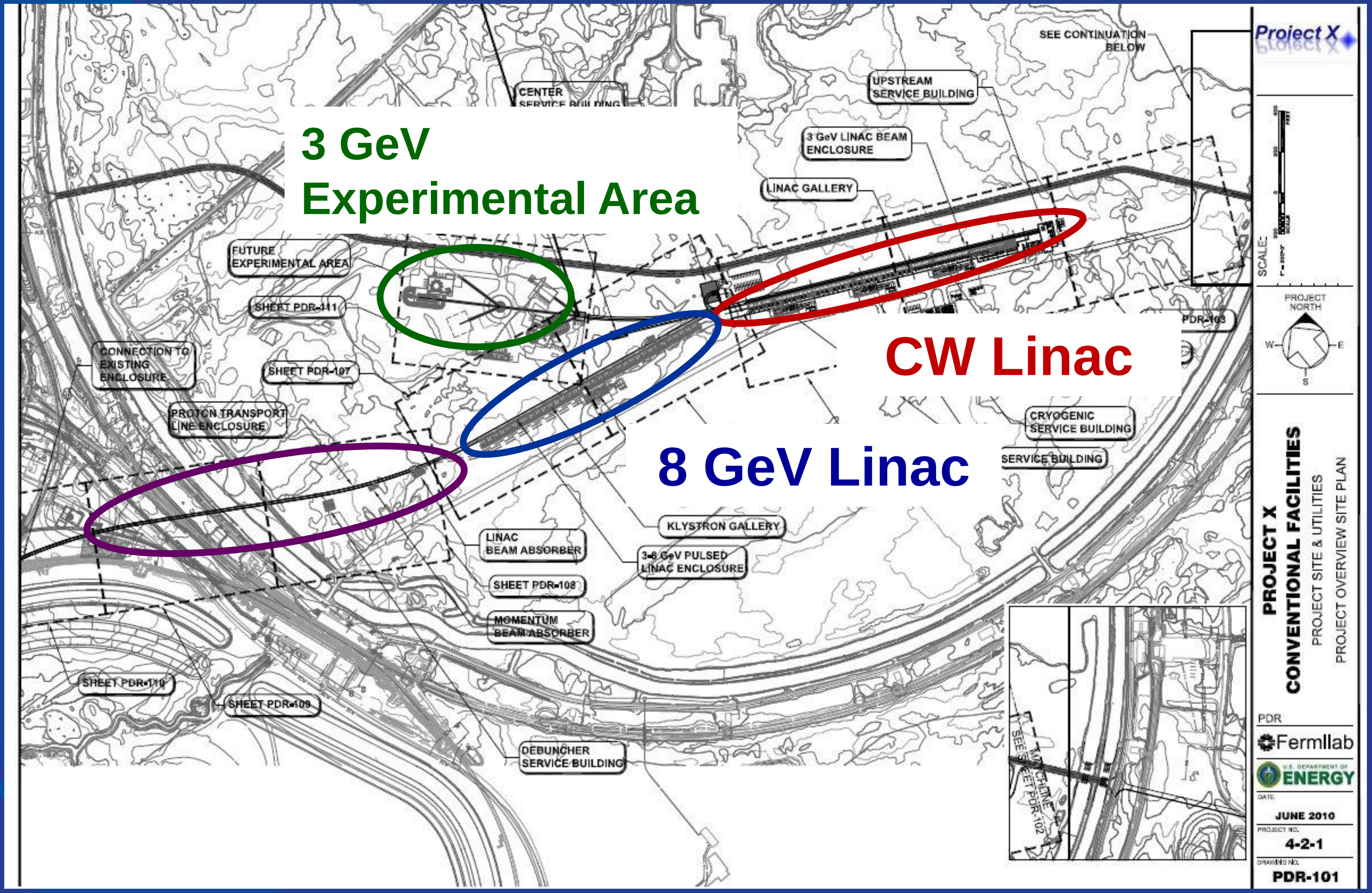

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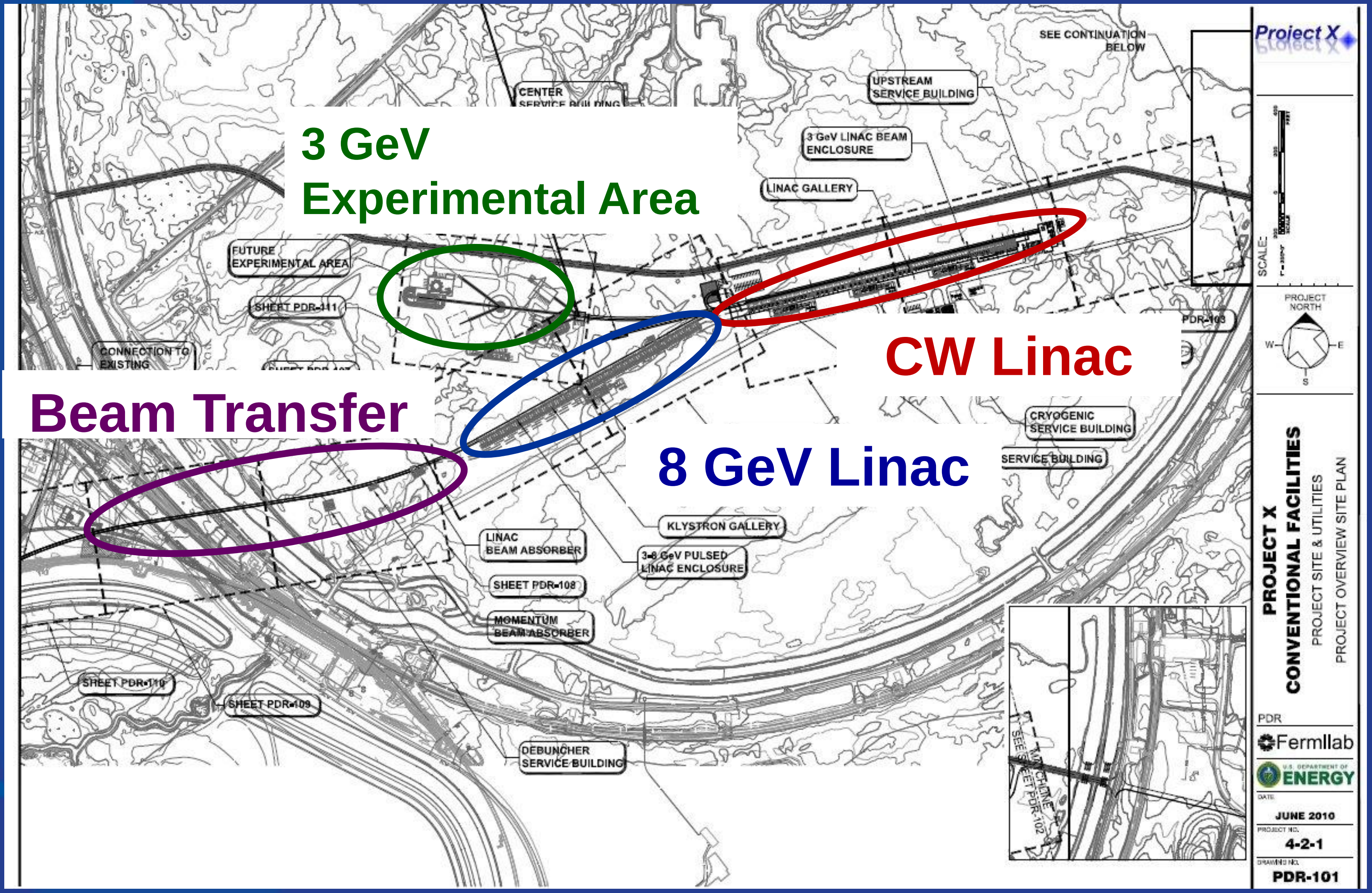

Reference Design Performance Goals

CW Linac	
Particle Type	H-
Beam Energy	3.0 GeV
Average Current	2 mA/1mA (1 GeV/3GeV)
Beam Power to 1 GeV Program	1 MW
Beam Power to 3 GeV Program	2.87 MW
Pulsed Linac	
Beam Energy	8.0 GeV
Pulse Rate and Width	10 Hz, 4.3 msec
Cycles to Main Injector/Recycler	6
Particles per Cycle to MI/Recycler	2.7×10^{13}
Linac output beam power	340 kW
Beam Power to 8 GeV Program	170 kW
Main Injector/Recycler	
Beam Energy	120 GeV (max)
Cycle Time	1.2 sec
Particles per Cycle	1.5×10^{14}
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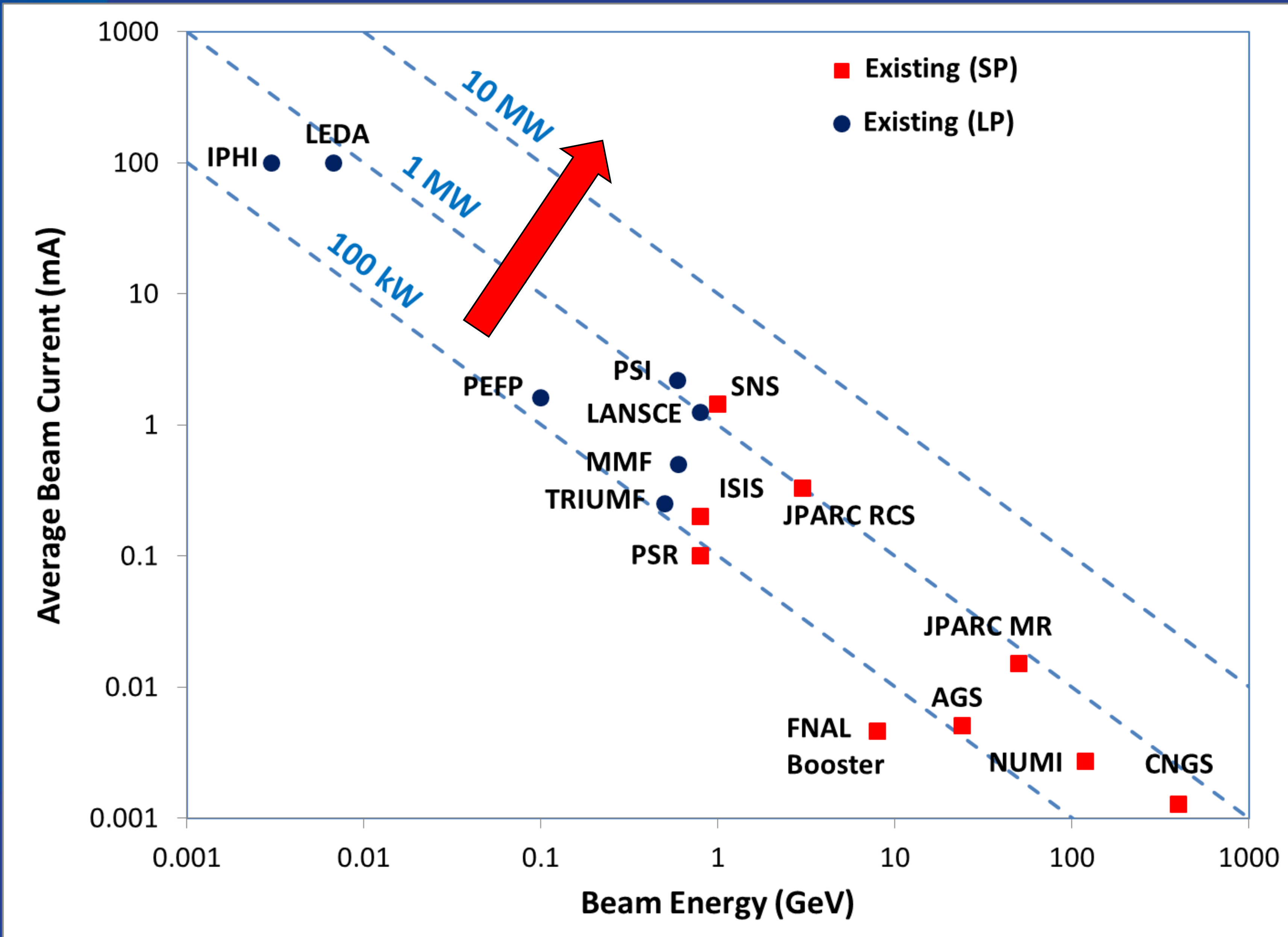

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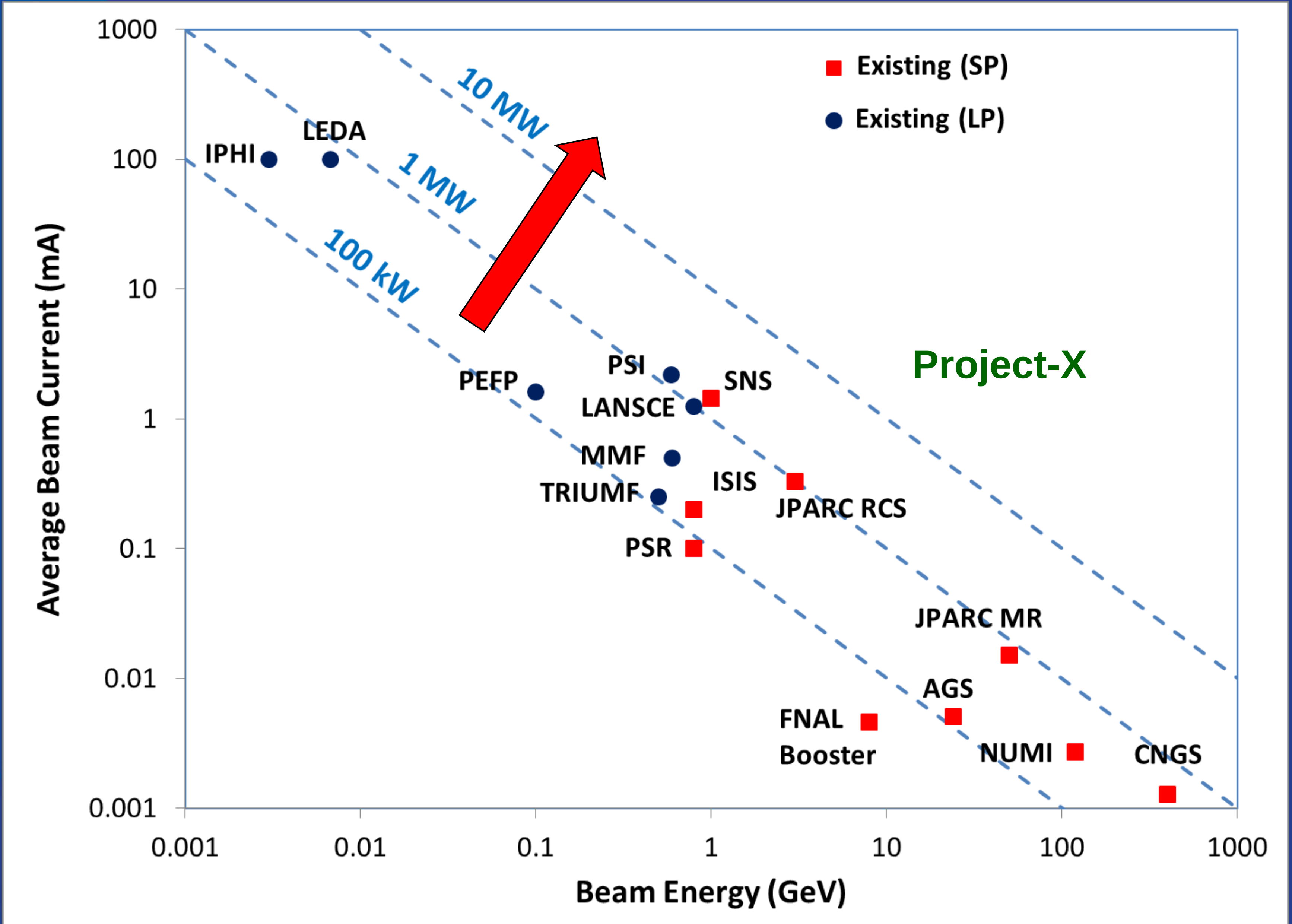

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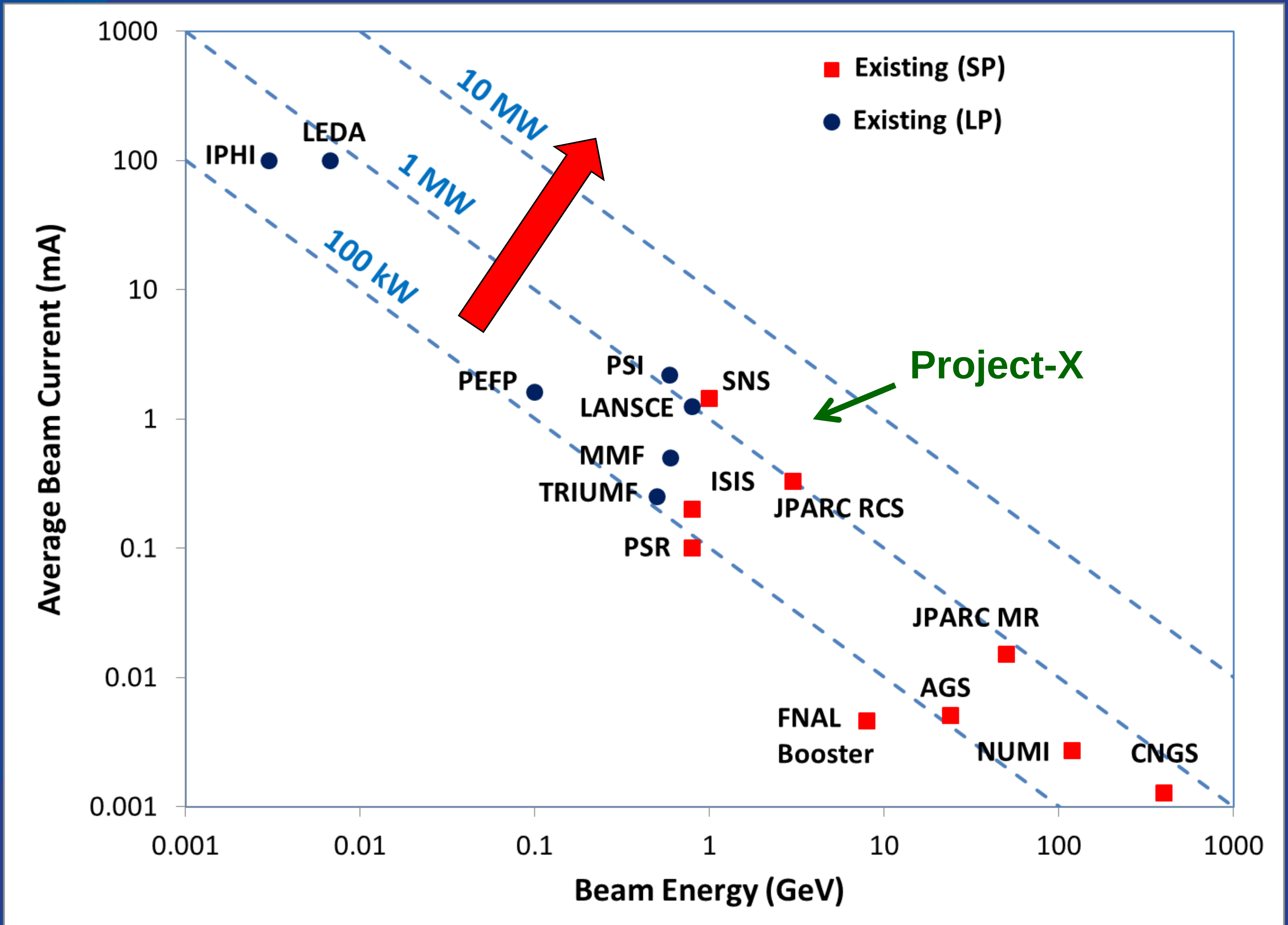

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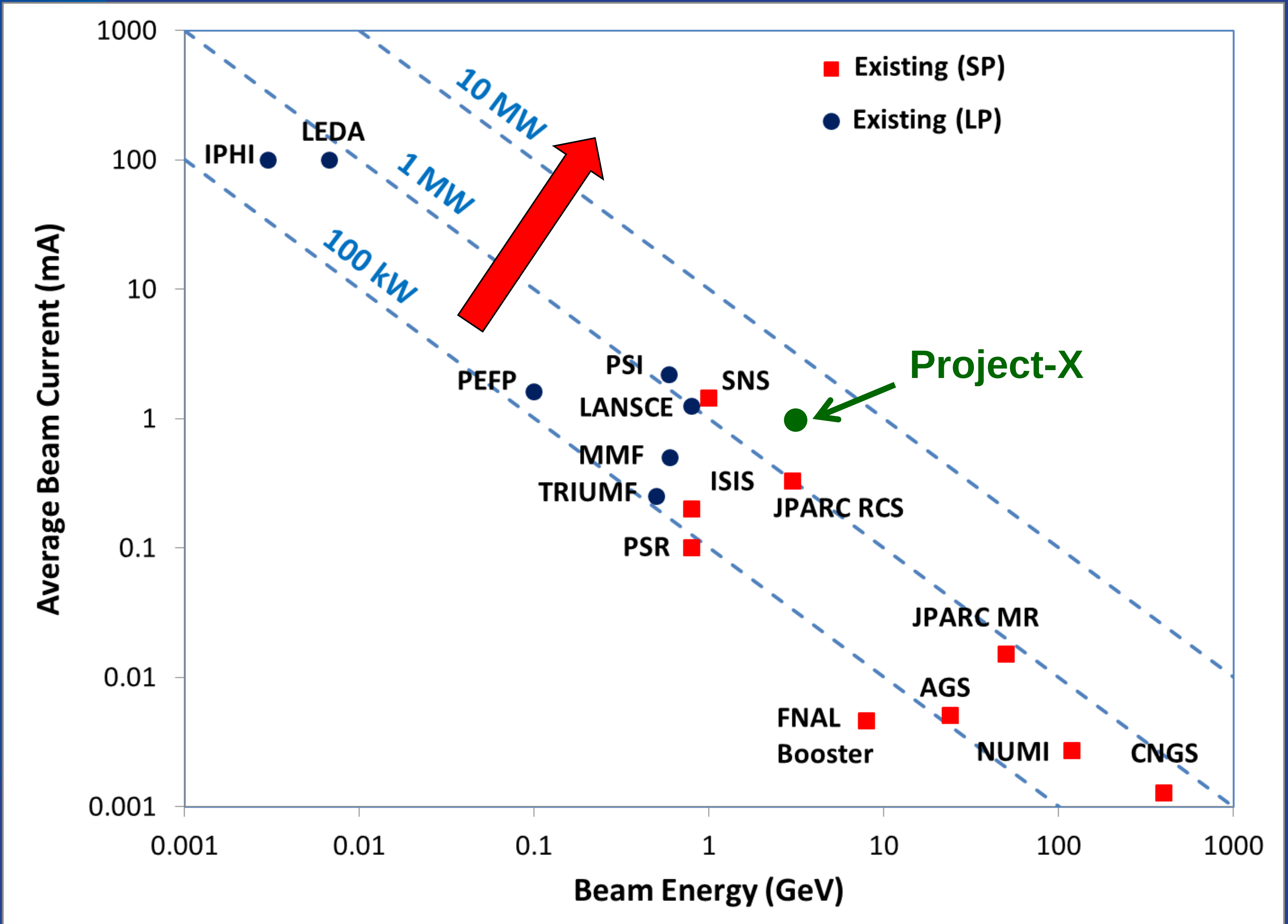

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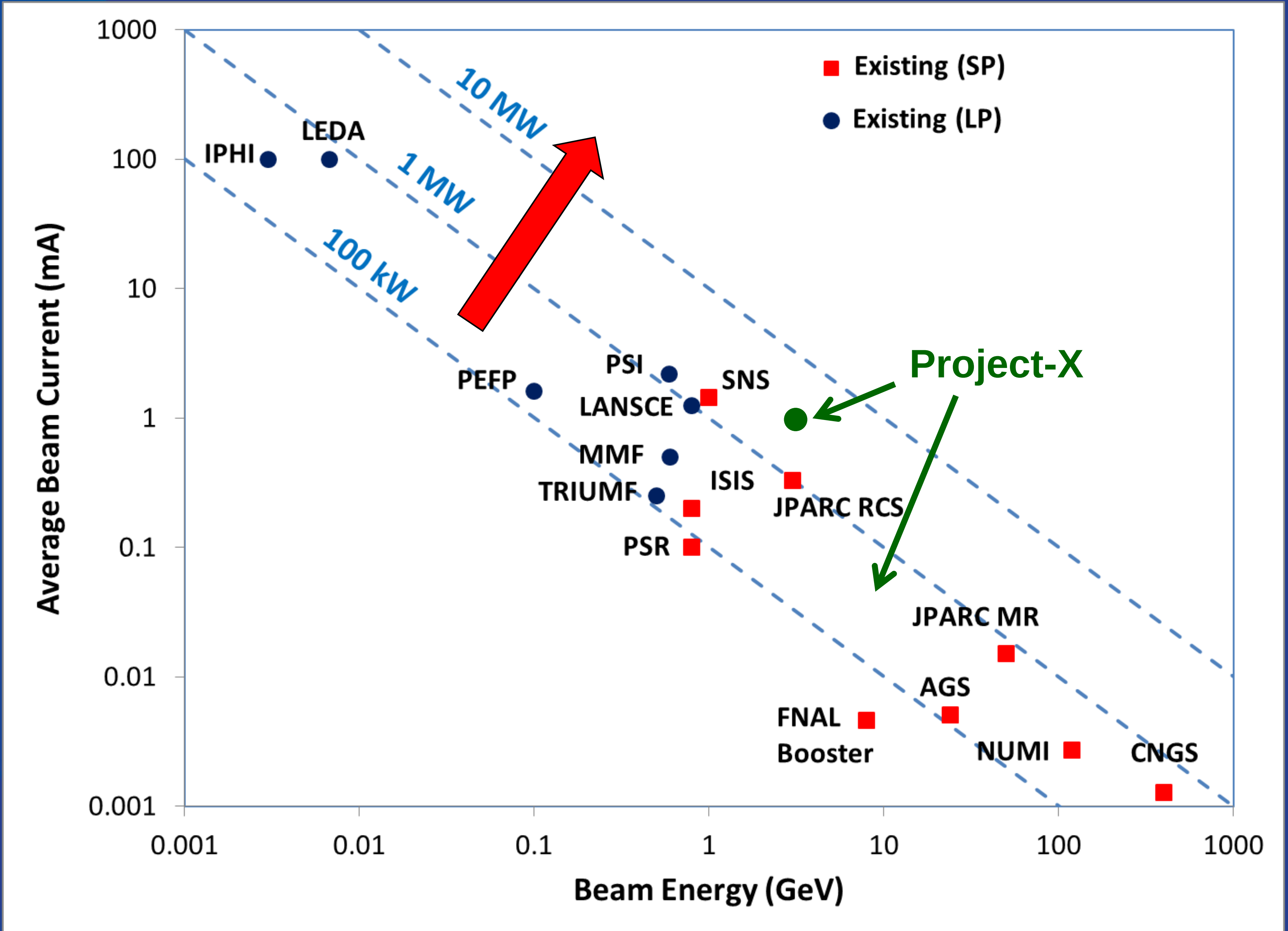

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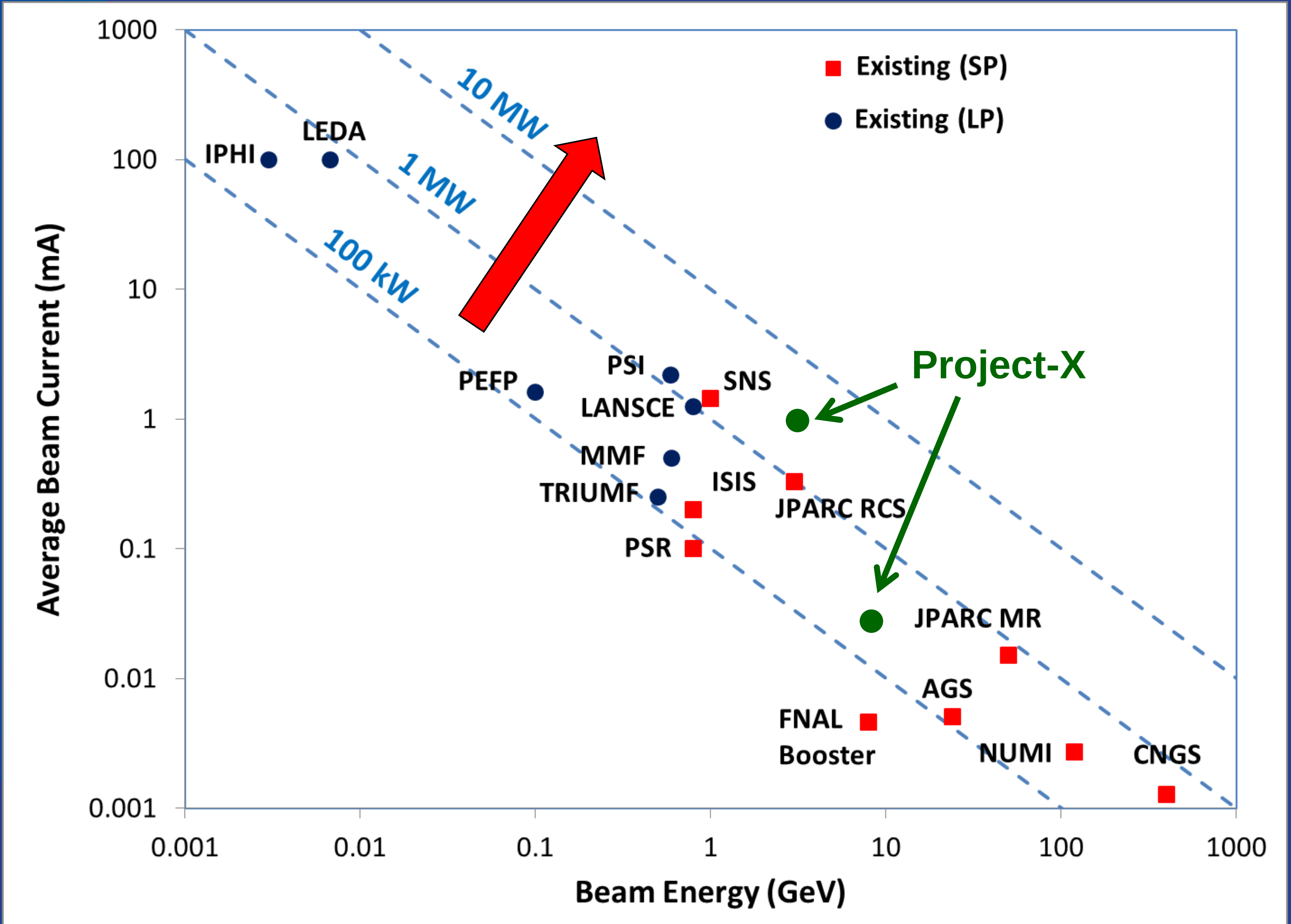

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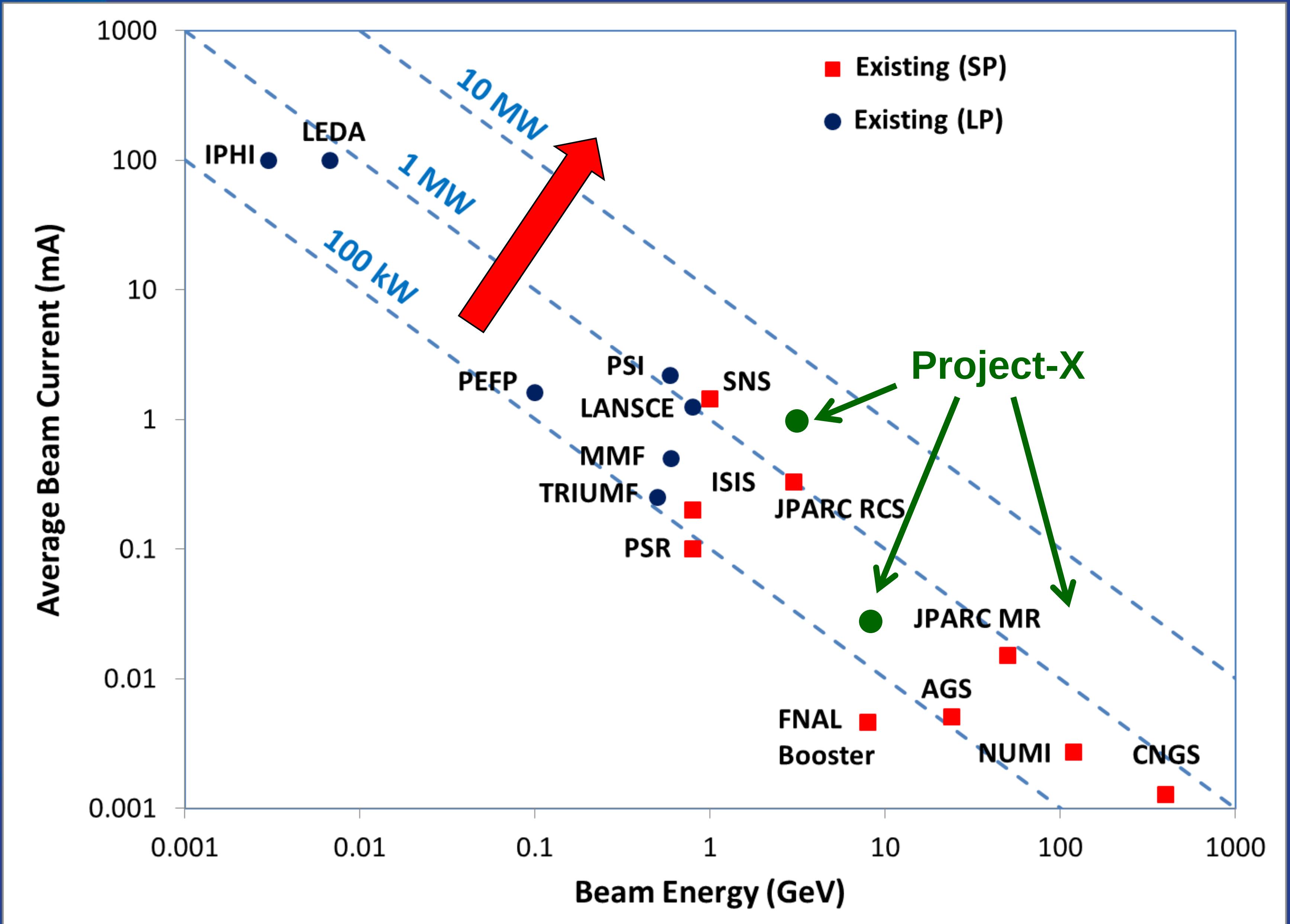

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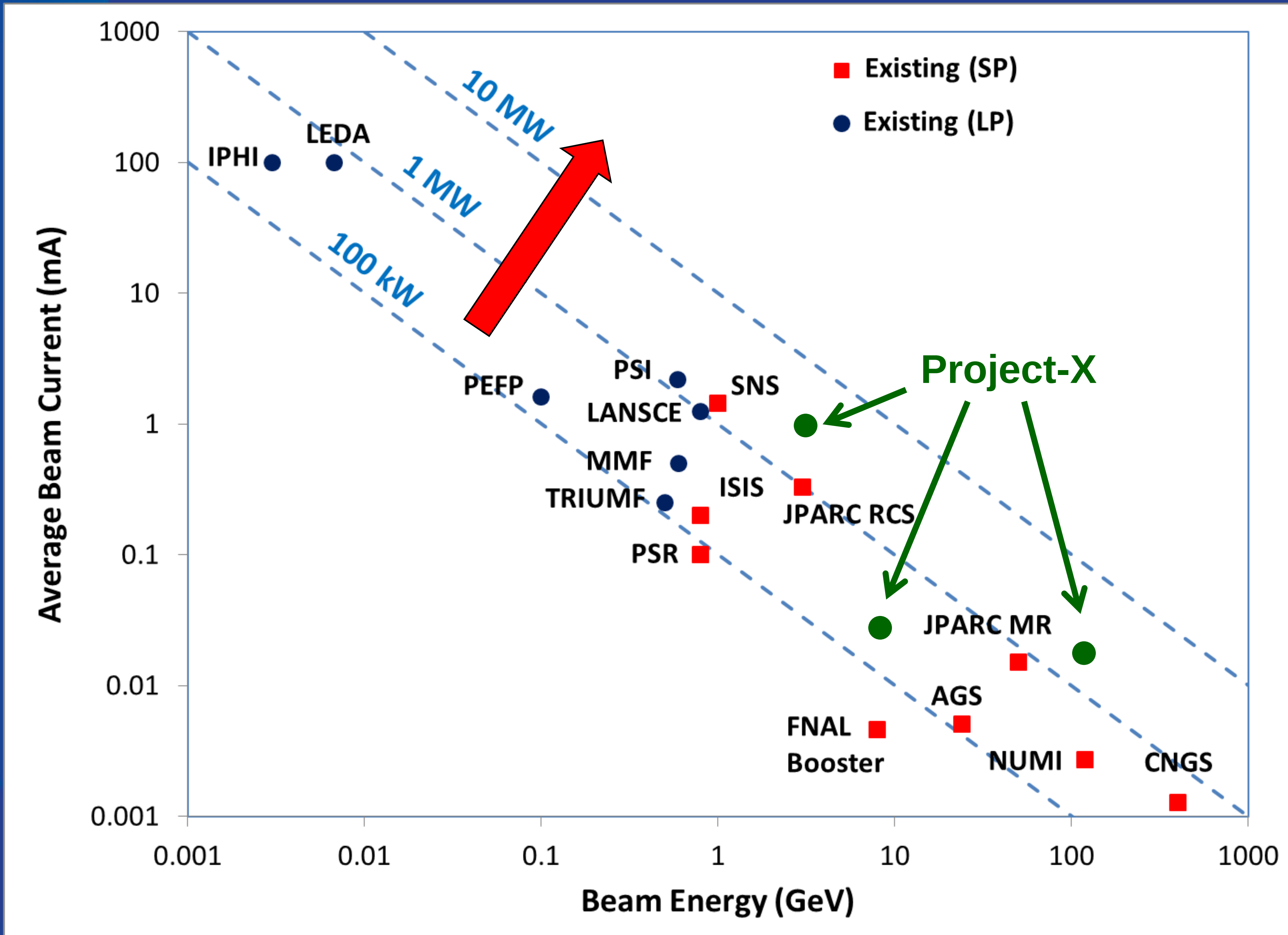

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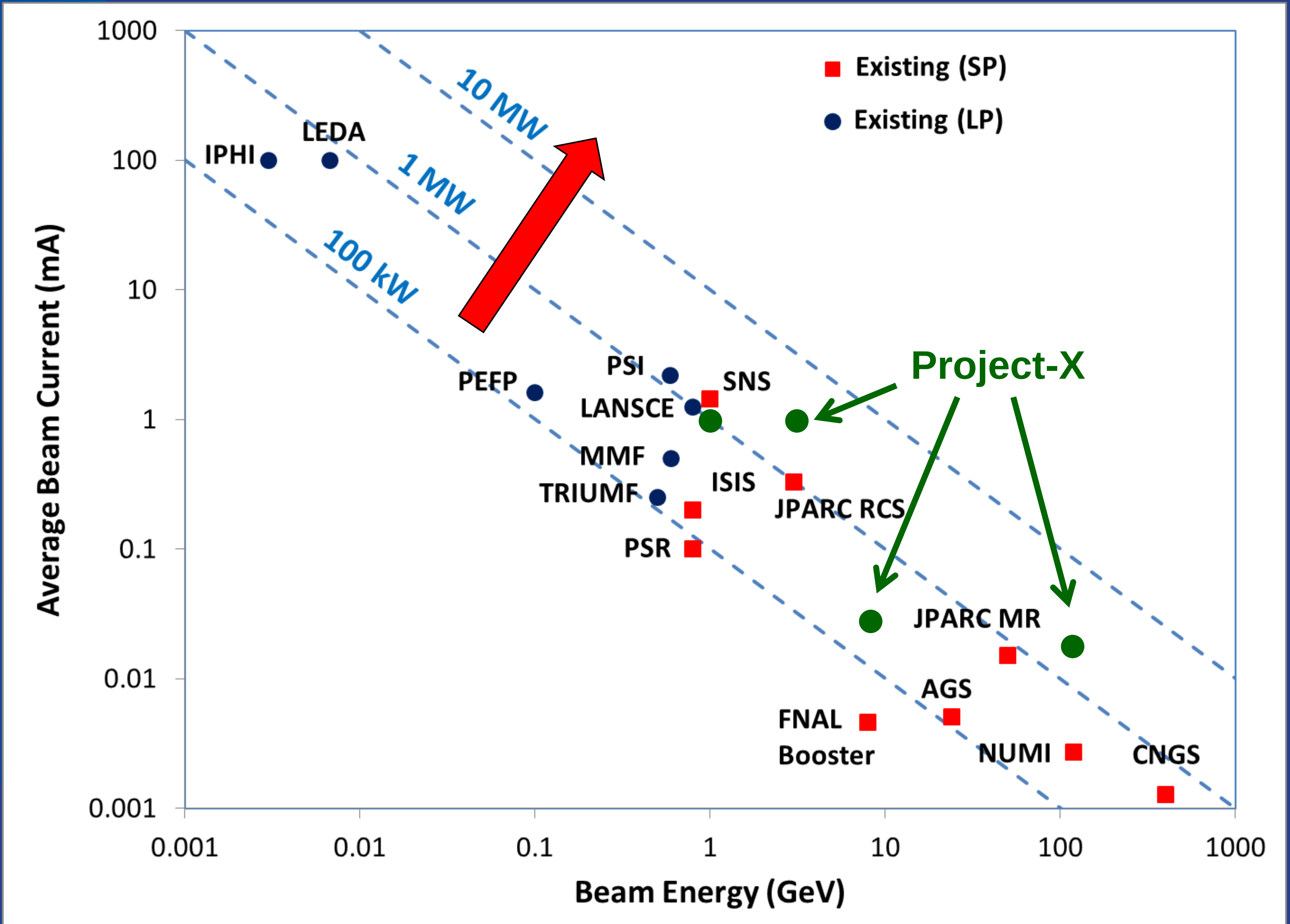

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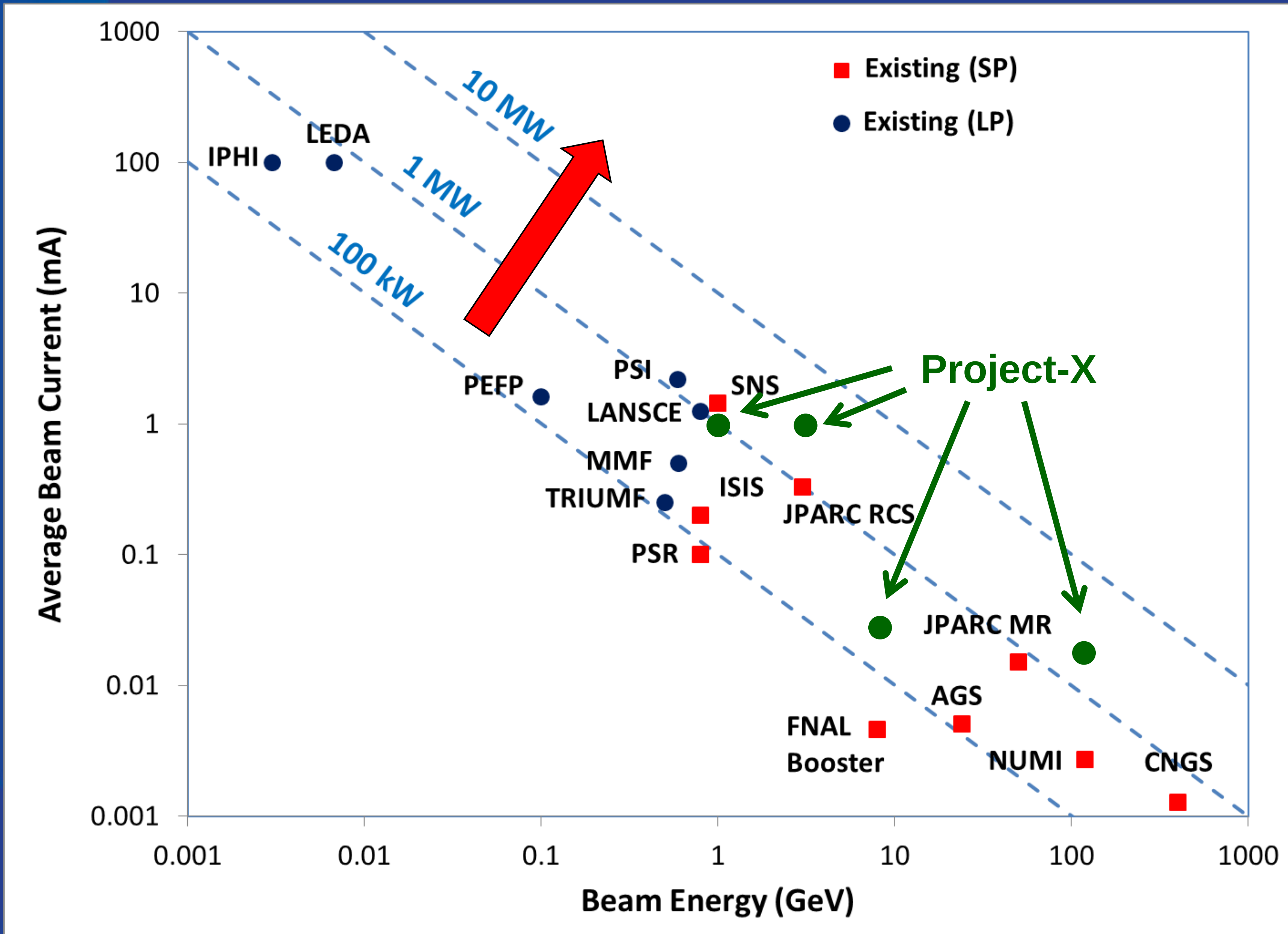


Key Challenges and Novel Approaches

- Operate multiple high-power programs simultaneously
  - Each program requires specific bunch formats, made possible with a beam Chopper system and RF deflector system
- Utilize SRF technology
  - Readily meets the CW requirement
  - Takes advantage of all benefits of SCRF vs. NCRF
- Front-end has many challenges:
  - CW RFQ of moderate average H- current
  - Challenging chopper system
  - Utilization of SRF structures after RFQ (vacuum, chopped beam handling, emittance/halo control)
- Accelerating and handling high power beams
  - High power beams require very careful control and understanding of emittance/halo growth
  - Each program requires high-power targetry development

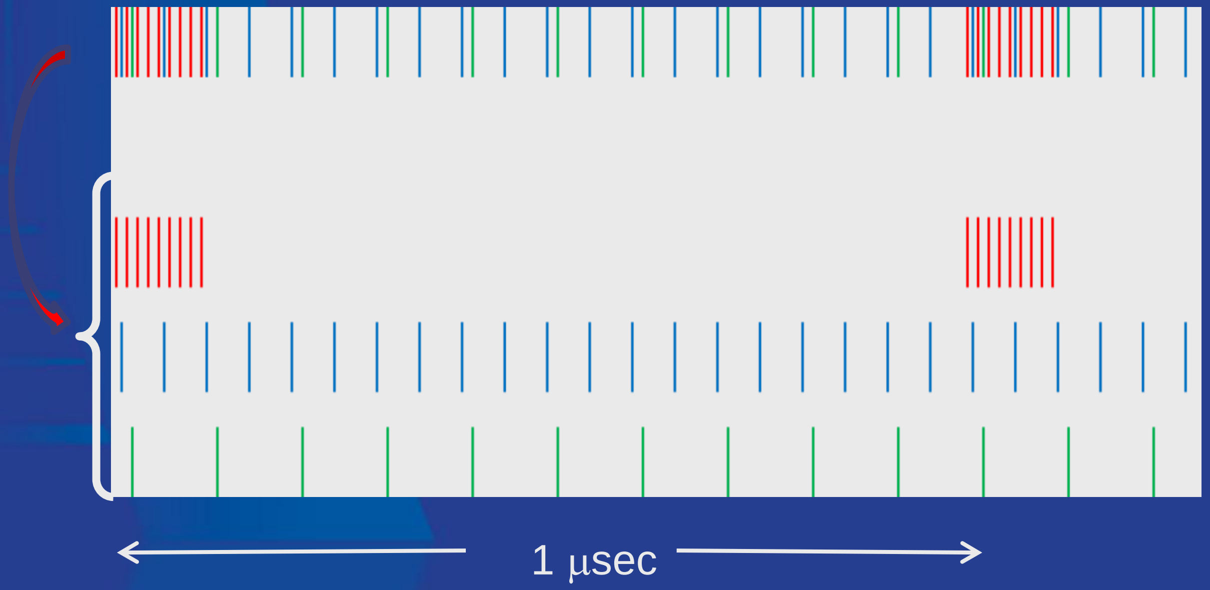
Project X Operating Scenario for 3 GeV CW Linac

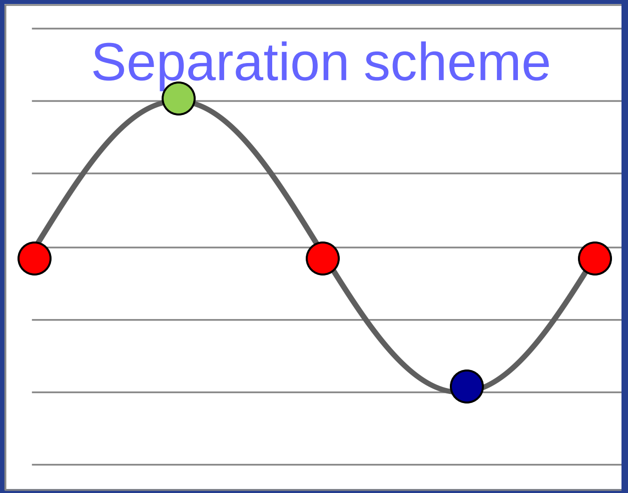
Ion source and RFQ operate at 4.4 mA

77% of bunches are chopped @ 2.1 MeV ⇒ maintain 1 mA over 1 μsec

1 μsec period at 3 GeV

Kaon pulses (17e7) 20 MHz	1540 kW
Nuclear pulses (17e7) 10 MHz	770 kW
Muon pulses (17e7) 80 MHz, 100 nsec burst @ 1 MHz	700 kW





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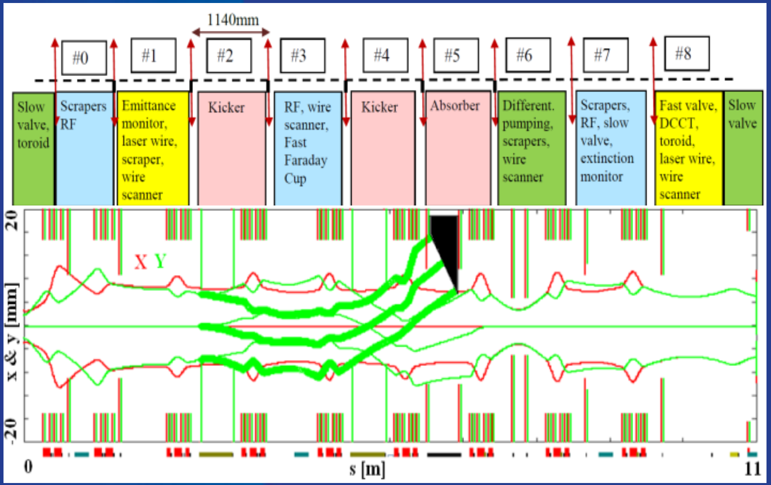
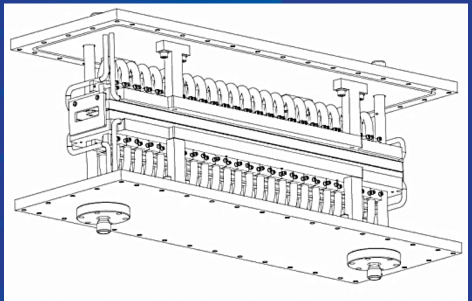
Project X MEBT Chopper

MOPB095, A.V. Shemyakin

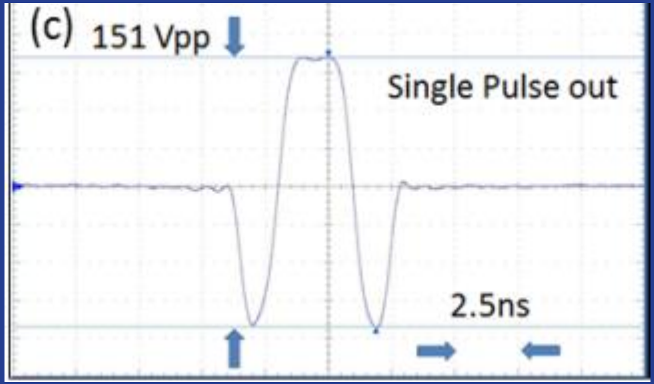
MEBT chopper system removes undesired bunches from a continuous train of bunches from the RFQ at 162.5 MHz



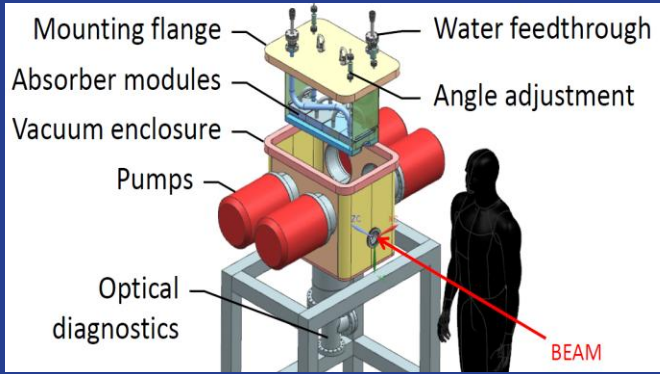
- Chopper employs two kickers (180-deg apart in betatron phase) and an absorber
- Each kicker is a 50-cm long, 16-mm gap slow structure (20 mm/ns). Each plate: ± 250 V pulse
- R&D on two types: 50 – and 200 – Ohm



Mechanical schematic of a 50-Ohm kicker

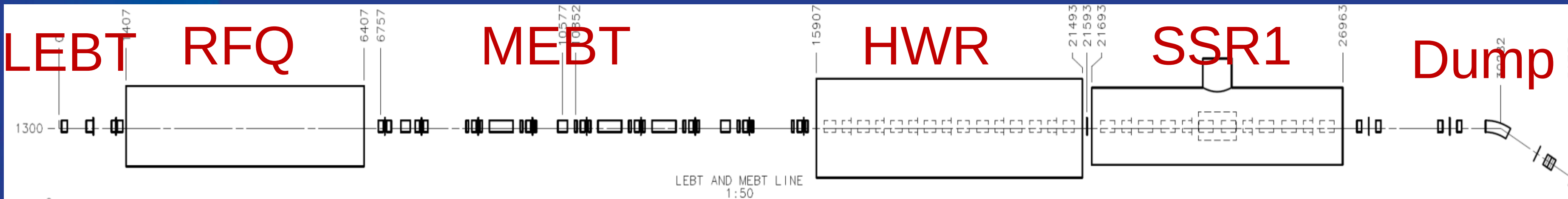


Test of a 150-W amplifier as a kicker driver: output signal for a single pulse



MEBT absorber: TMZ alloy, 40 cm long. Requirements: 21 kW beam, ~2mm rms rad, 29 mrad grazing angle.

Project X Injector Experiment (PXIE)



LBNL FNAL,SLAC ANL FNAL

32 m, 30 MeV

PXIE is the centerpiece of the Project X R&D program

- Integrated systems test for Project X front end components to validate the concept, thereby minimizing the primary technical risks within the Reference Design.
- Systems test goals
  - Operate at full Project X design parameters: 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV

PXIE will address and assess the following critical issues:

- Ion source lifetime
- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Emittance preservation and beam halo formation through the front end
- Effectiveness of MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam
- Kicker extinction

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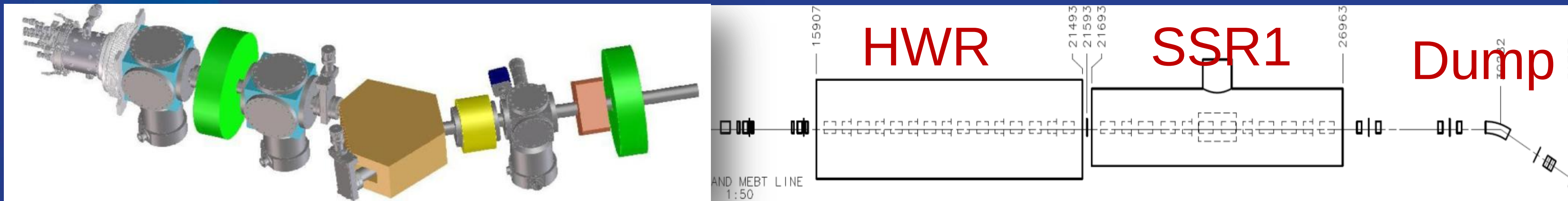

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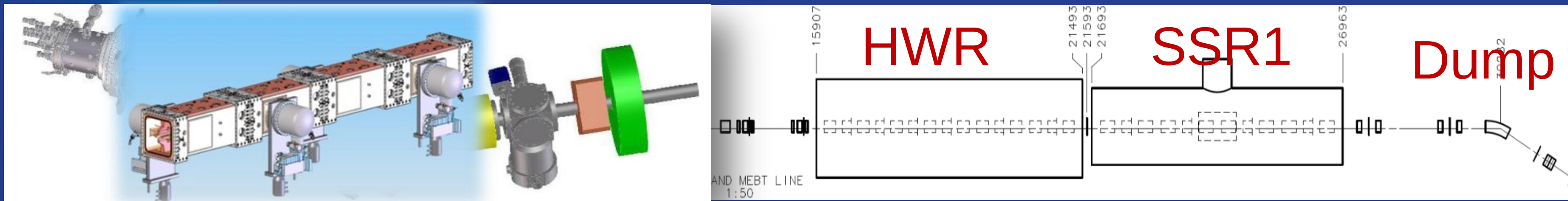

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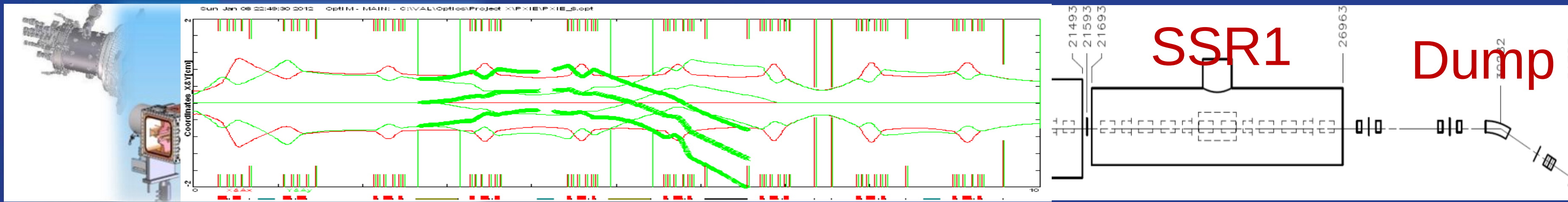

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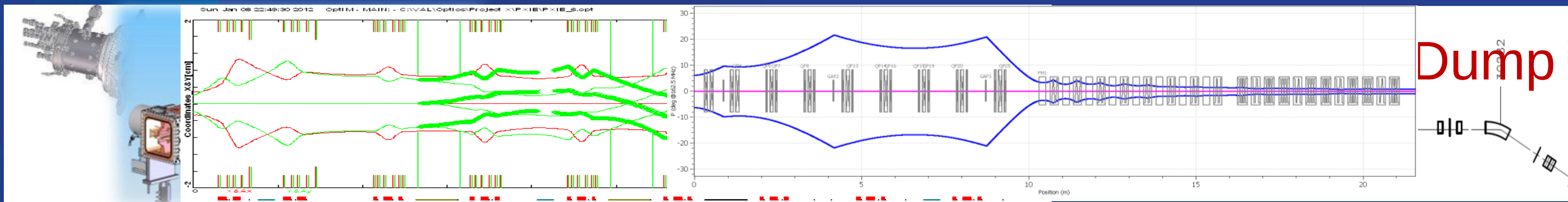

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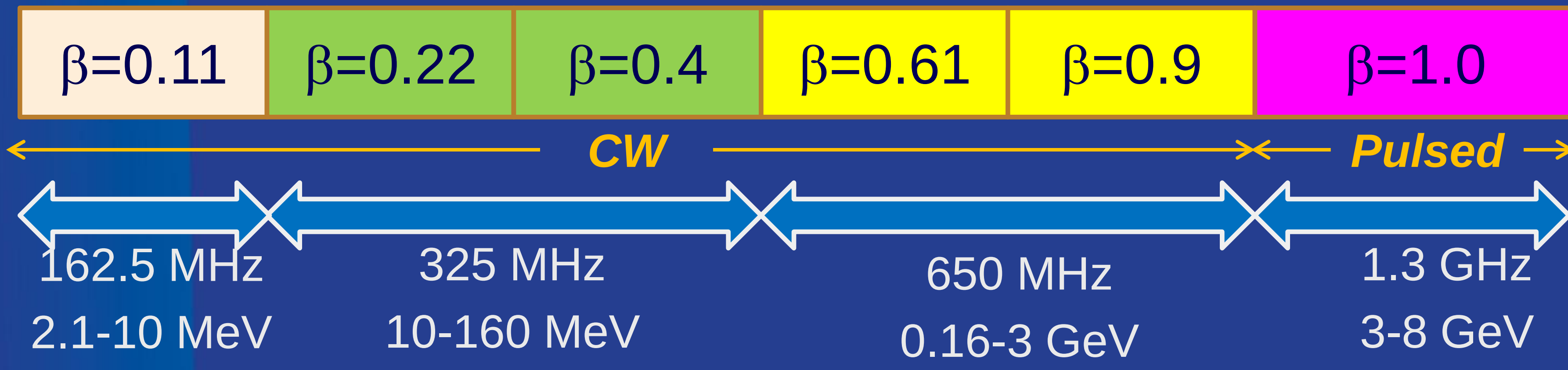
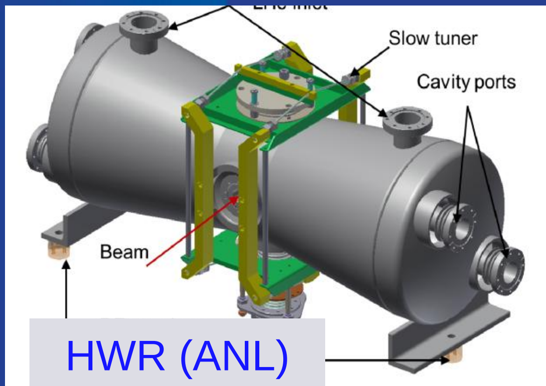
Superconducting RF Technology Map



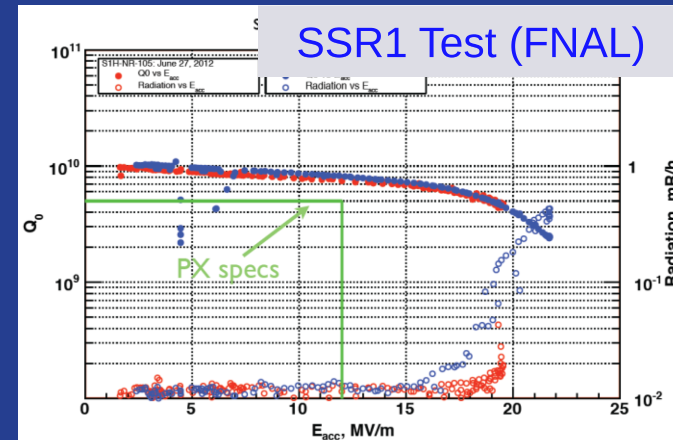
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	8/8/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/10/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

SRF Development for Project X (FNAL, ANL, JLAB, Indian Institutions)



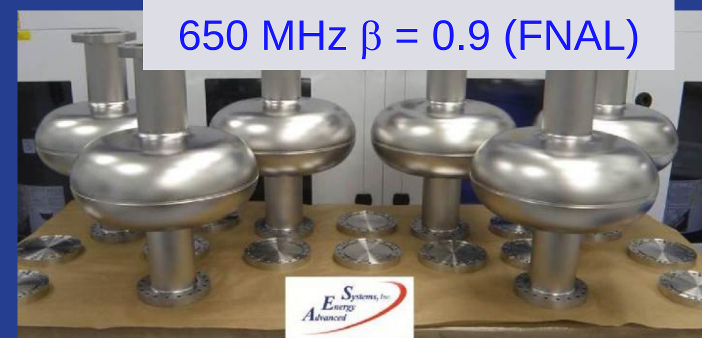
HWR (ANL)

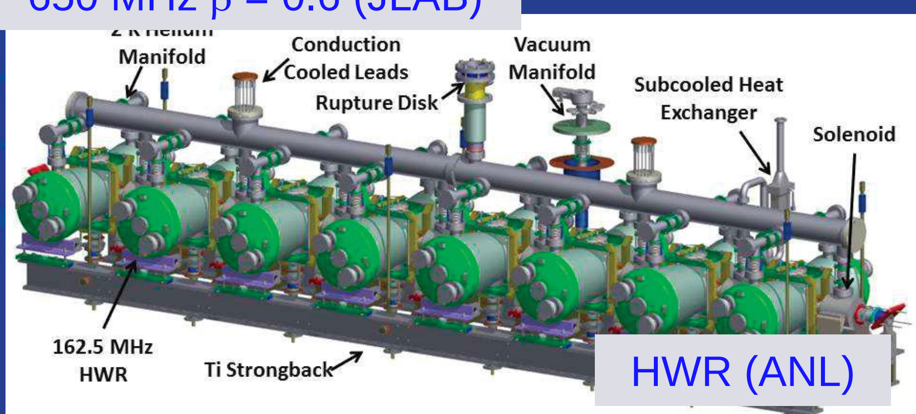

SSR1 (FNAL)



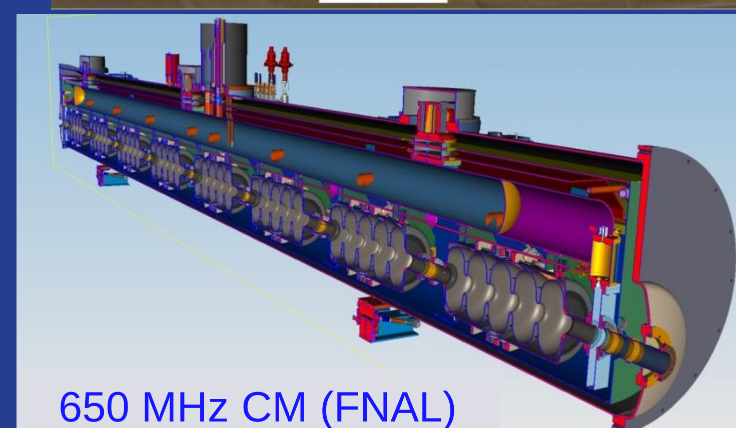
SSR1 Test (FNAL)

650 MHz β = 0.6 (JLAB)


650 MHz β = 0.9 (FNAL)

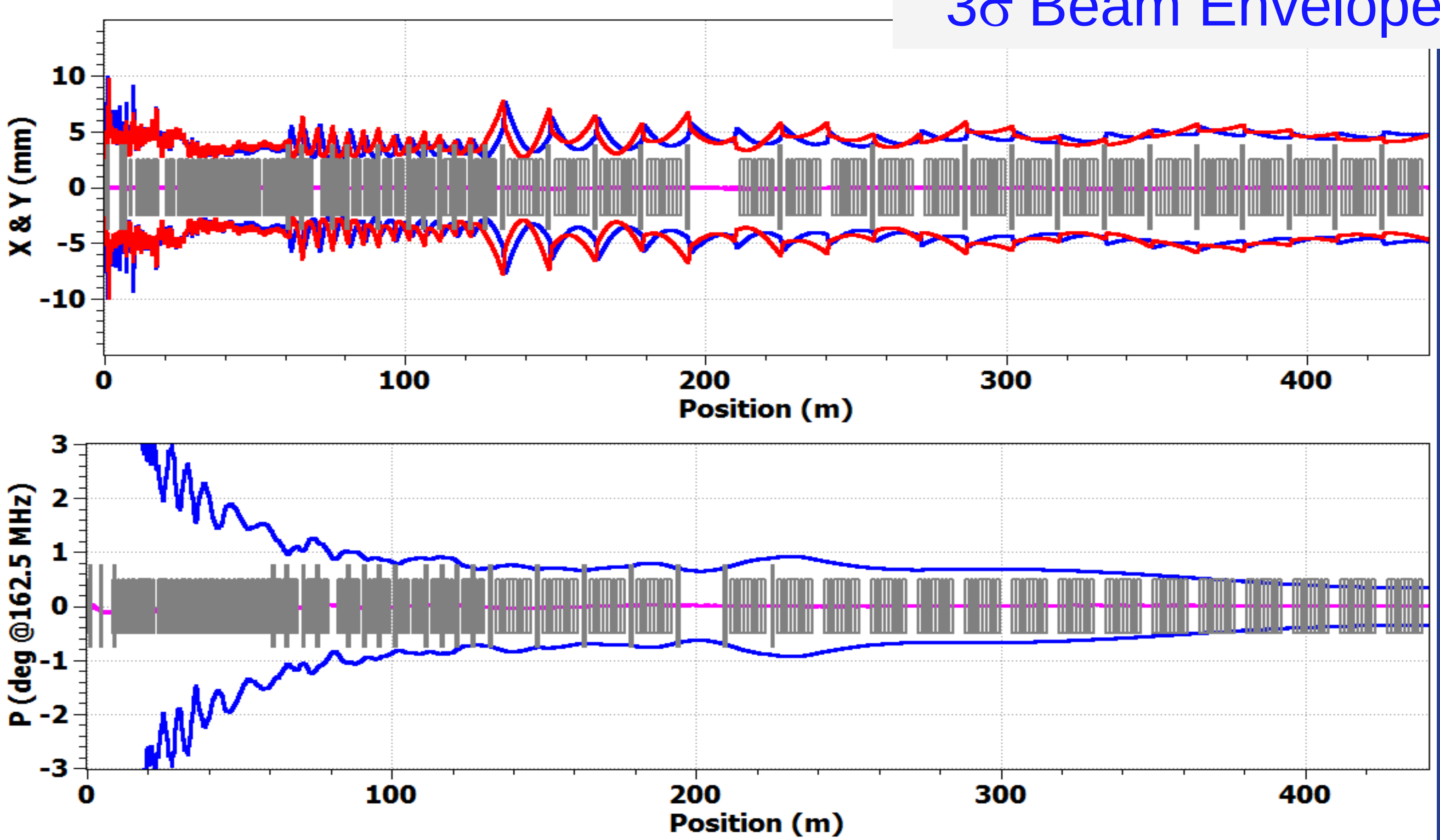


HWR (ANL)


650 MHz CM (FNAL)

3 GeV Linac Beam Dynamics Studies (Examples)

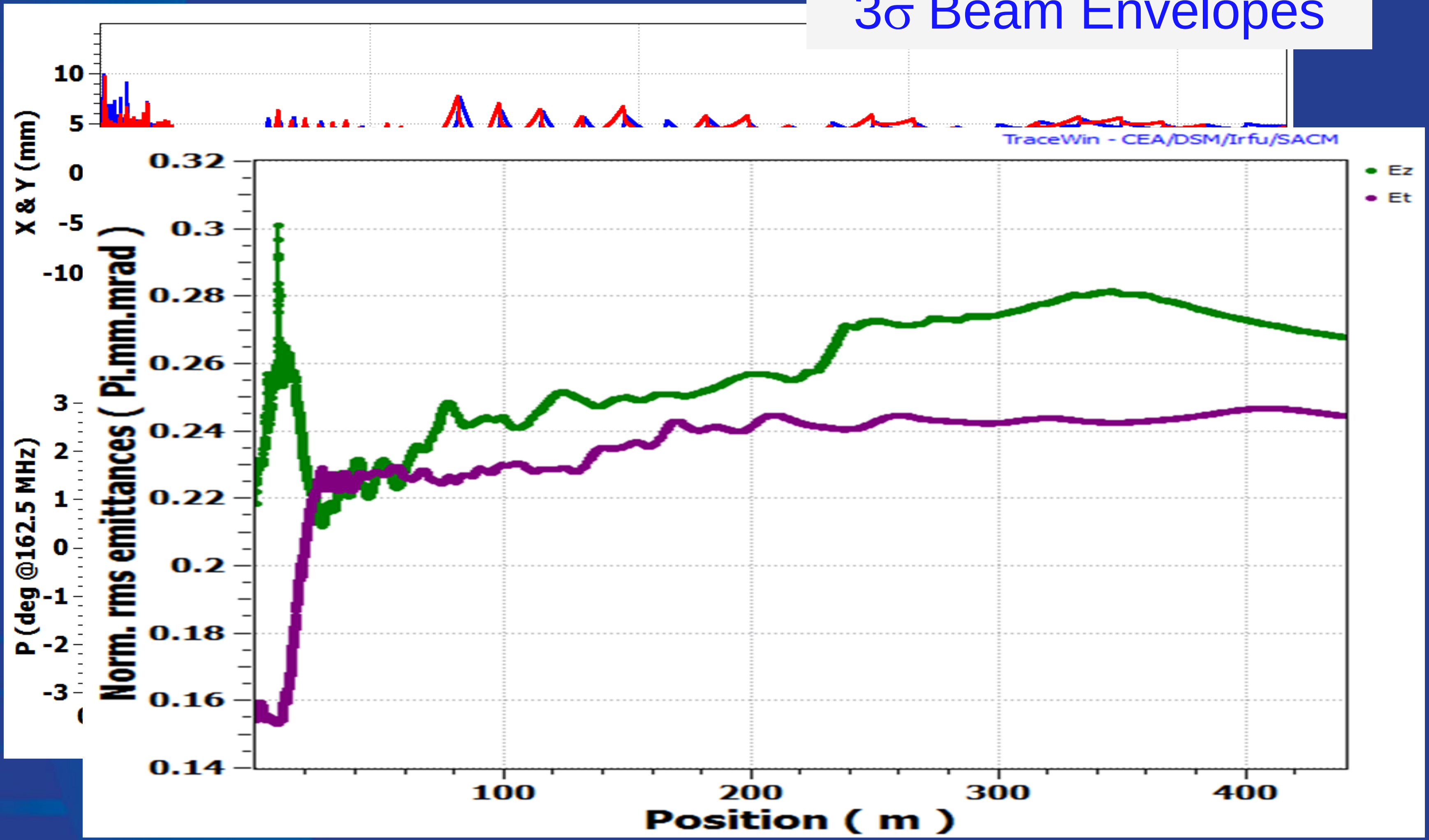
3σ Beam Envelopes



THPB014, N. Solyak et. al

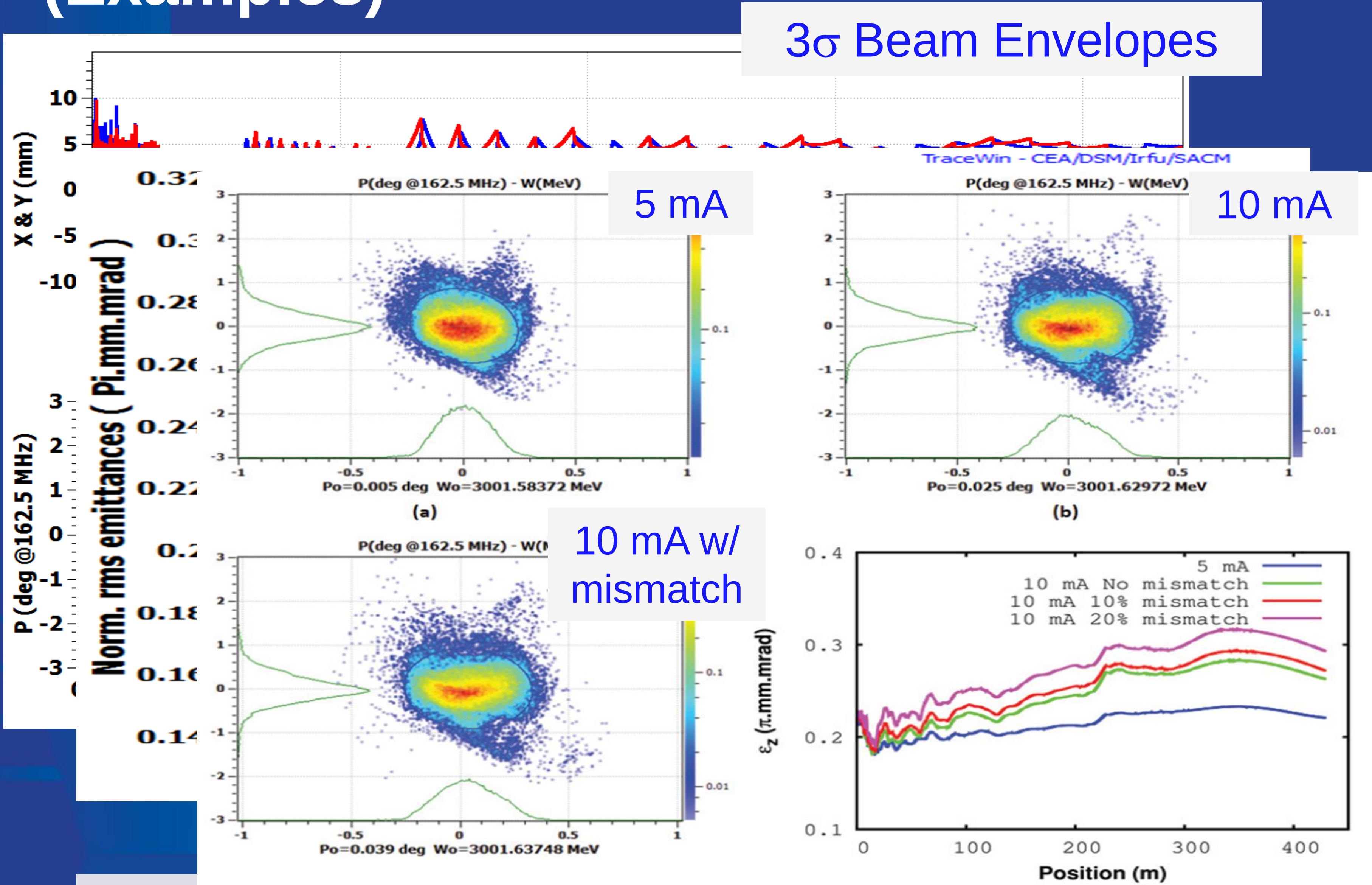
3 GeV Linac Beam Dynamics Studies (Examples)

3σ Beam Envelopes



THPB014, N. Solyak et. al

3 GeV Linac Beam Dynamics Studies (Examples)



THPB014, N. Solyak et. al

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The Project-X Project

- Cost estimate for full Project-X Reference Design is approximately $1.8B in U.S. accounting
- We are working toward construction in the latter half of the decade, focusing now on critical R&D
- We are formulating a staged construction approach
  - With significant physics opportunities at each stage
  - Cost of each stage substantially <$1B
  - Achieve full Reference Design capabilities with the final stage

Output Power from the…	Fermilab complex w/ planned Upgrades	Stage-1: 1 GeV CW Linac driving Booster	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR
Main Injector (120 GeV)	700 kW	1200 kW	1200 kW	2450 kW
Booster (8 GeV)	80 kW	120 kW	160 kW	N/A
1 GeV CW Linac	N/A	1000 kW	1000 kW	1000 kW
3 GeV CW Linac	N/A	N/A	3000 kW	3000 kW
8 GeV Pulsed Linac	N/A	N/A	N/A	340 kW

Conclusion

- The Project X Reference Design represents a unique facility which will form the basis for a world-leading Intensity Frontier program for decades
  - Platform for future development of a Neutrino Factory or Muon Collider
- We are considering a staged construction approach
  - With first stage based on a 1 GeV CW linac feeding the existing Booster
- The R&D for Project X is focused on SRF structure and cyomodule development, and on demonstrating the challenging requirements of the front-end in the PXIE
- Our R&D program supports a staged construction start for Project X as early as 2017.

To Learn More…

MOPB078, A. Grassellino et. al. “High Q Studies for Nb Cavities: Heat Treatments and NbN R&D at FNAL”

MOPB095, A.V. Shemyakin, “Design of MEBT for the Project X Injector Experiment at Fermilab”

TUPB046, P.N. Ostroumov et. al., “R&D Towards CW Ion Linacs at ANL”

TUPB054, A. Sukhanov et. al., “Coherent Effects of High Current Beam in Project X Linac”

TUPB062, G.I. Cancelo et. al., “A Conceptual Design of the Low Level RF Control System for Fermilab’s Project X 3 to 8 GeV Pulsed Linac

TUPB067, Z.A. Conway et. al., “Development of a Superconducting Half-Wave Resonator for PXIE

TUPB068, Z.A. Conway et. al., “Cryomodule Designs for Superconducting Half-wave Resonators

THPB015, P. Varghese, “Performance of Ferrite Vector Modulator Control Loops in the LLRF System of the Fermilab HINS 6-Cavity Test”

THPB003, S.C. Joshi et. al., “R&D Activities on High Intensity Superconducting Proton Linac at RRCAT”

THPB014, N. Solyak et. al., “Lattice Design and Beam Dynamics Studies for Project X”

THPB016, M. Popovic, “Concept: Low Energy, Low Intensity NF from Projet X”

THPB017, M. Popovic, “A Concept: 8 GeV CW Linac, Staged Approach”

THPB018, V.A. Lebedev, “Project X and its Physics Program”

THPB019, V.A. Lebedev et. al., “Progress with PXIE MEBT Chopper”

THPB054, G.V. Romanov et. al., “EM Design Features of CW RFQ for the Project X Injector Facility

THPB055, J.-F. Ostoguy, “Numerical Simulations of Project X/PXIE RFQ”

Siting Options

- Most straight forward implementation is via the Reference Design siting
- Alternative based on “parking lot” linac to west of existing linac enclosure
  - ~$70M savings @ Stage 1
- Other alternatives under development. Issues:
  - Cost minimization in initial stage
  - Implementation of Stages 2-4
  - Connections to Muon Campus

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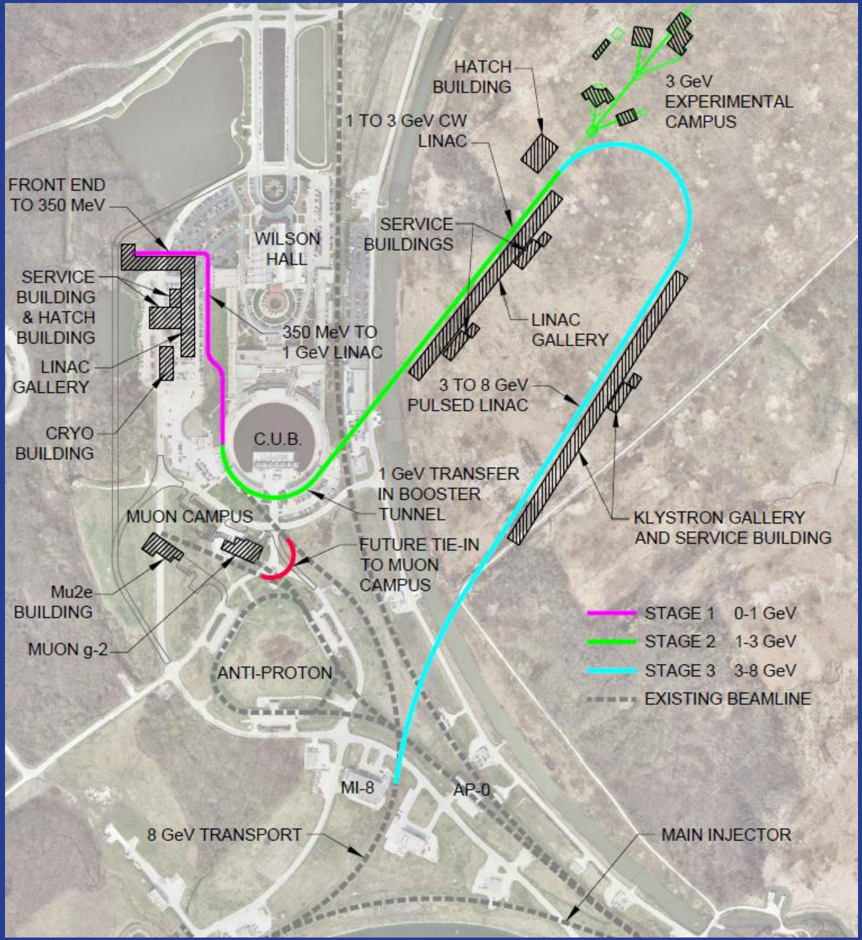
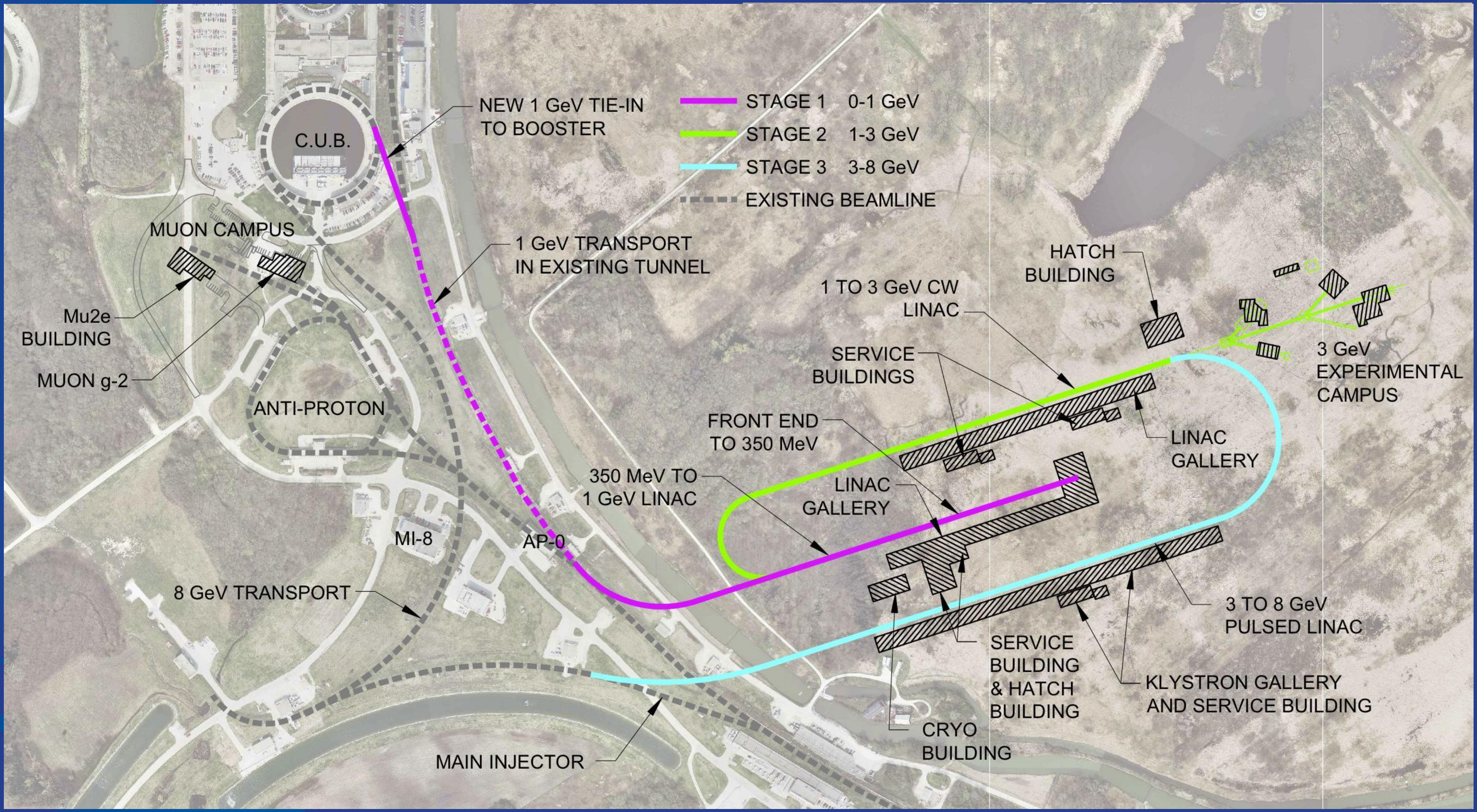


Siting Options



Staged Physics Program

⟵ Project X Campaign ⟶

Program:	NOνA + Proton Improvement Plan	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

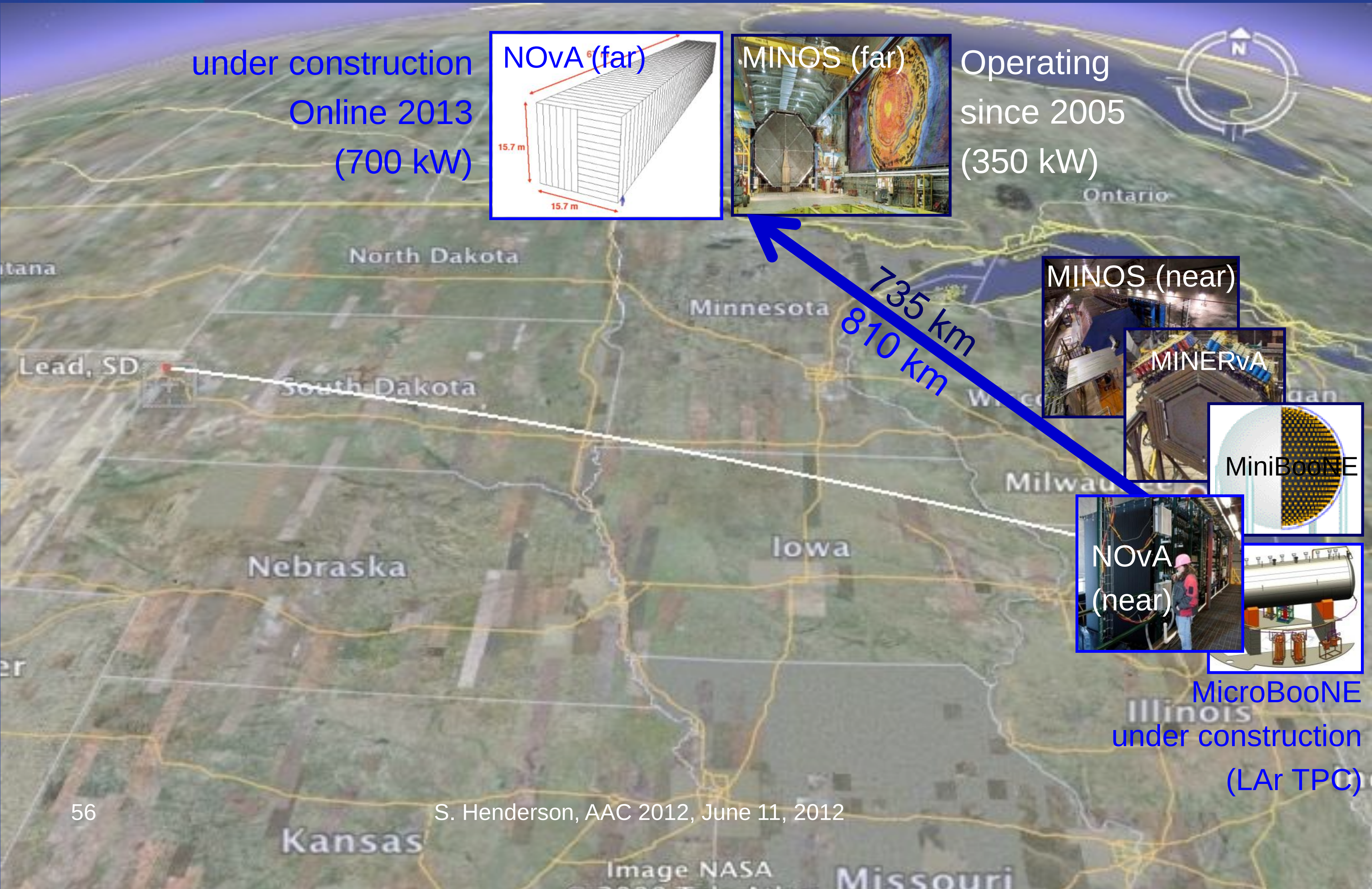
* Operating point in range depends on MI energy for neutrinos.

** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.

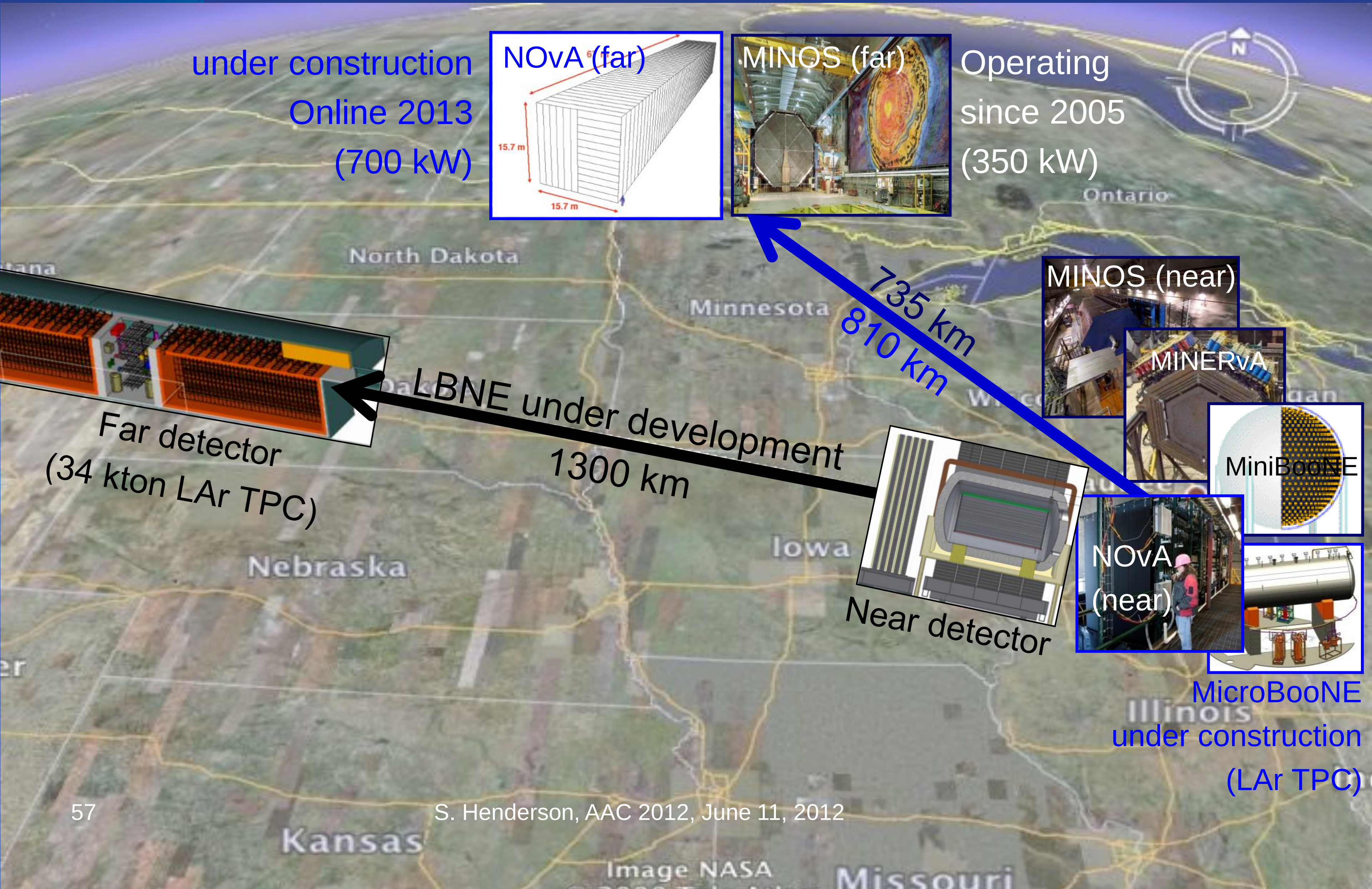
Intensity Frontier: Neutrino Sector

Operating since 2005 (350 kW)

Intensity Frontier: Neutrino Sector

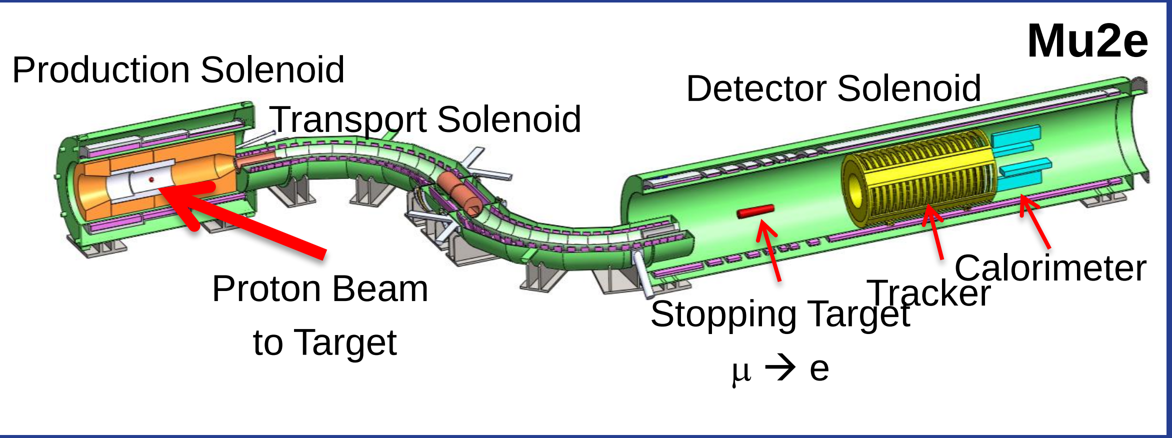


Intensity Frontier: Neutrino Sector

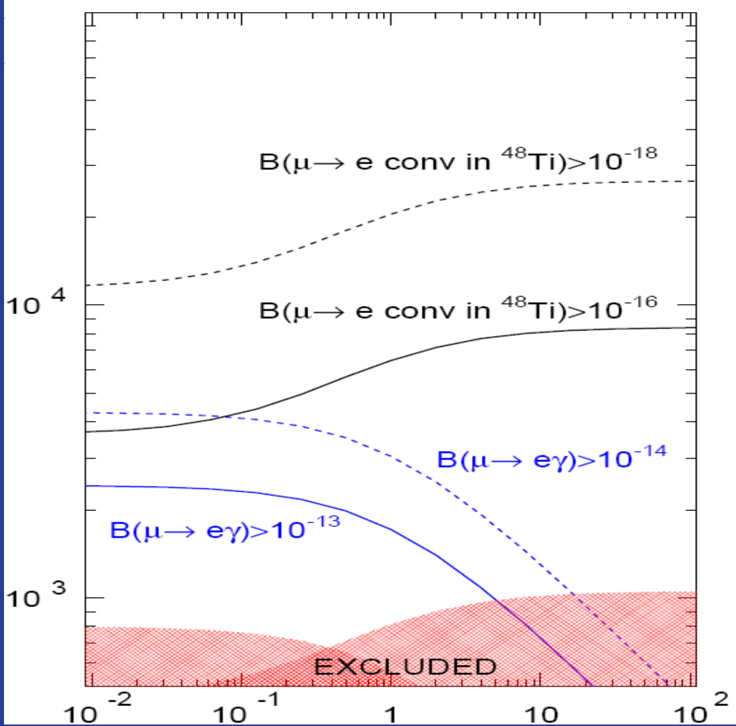


Intensity Frontier: Precision and Rare Processes

Search for Muon to electron conversion in the field of a nucleus



New Physics Scale (TeV)



With Project-X

Model Parameter

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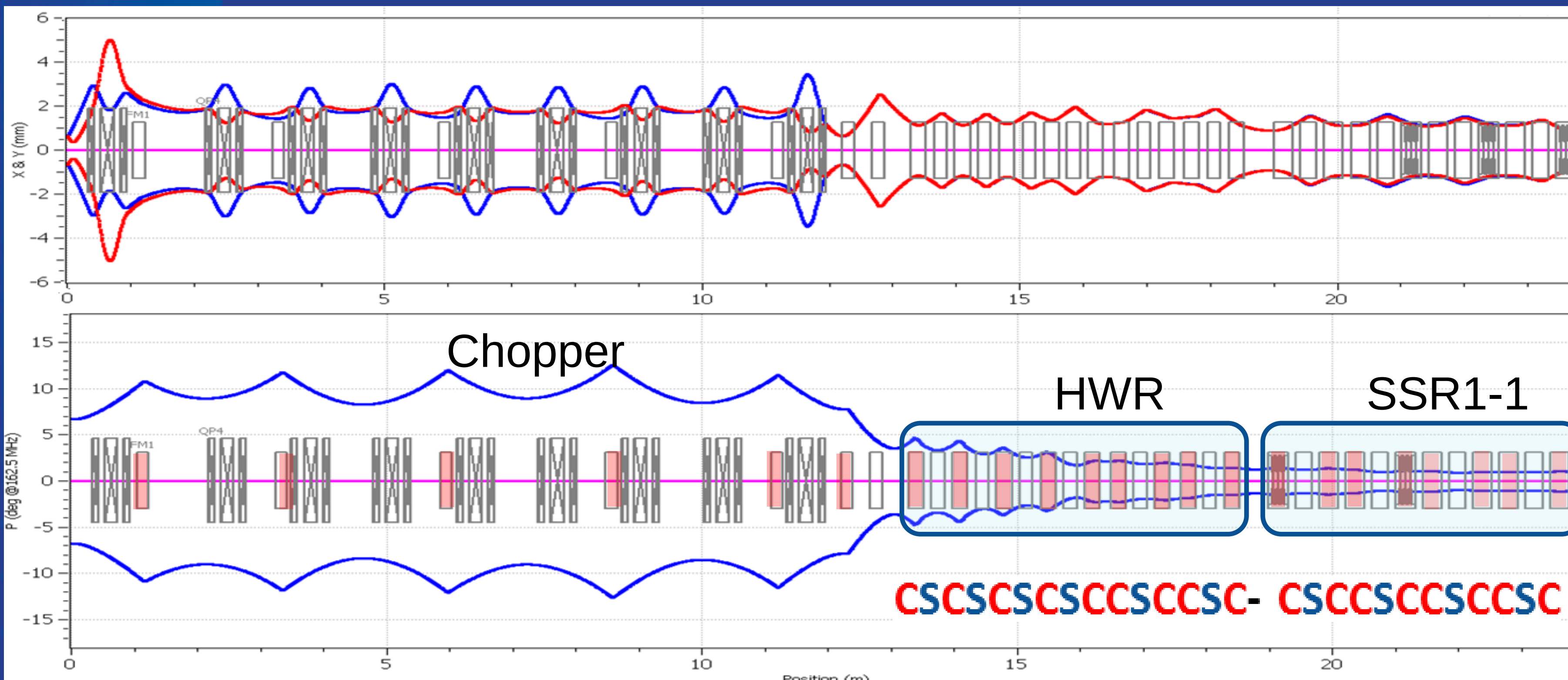
Collaboration Activities

- Two MOUs covering the RD&D Phase

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

- Informal collaboration/contacts with CERN/SPL, ESS China/ADS, UK, Korea/KoRIA
- Weekly Friday meeting: https://indico.fnal.gov/categoryDisplay.py?categId=168
  - Collaborator participation via webex
  - Meeting notes posted
- Semi-annual Collaboration meetings

PXIE Beam Envelopes

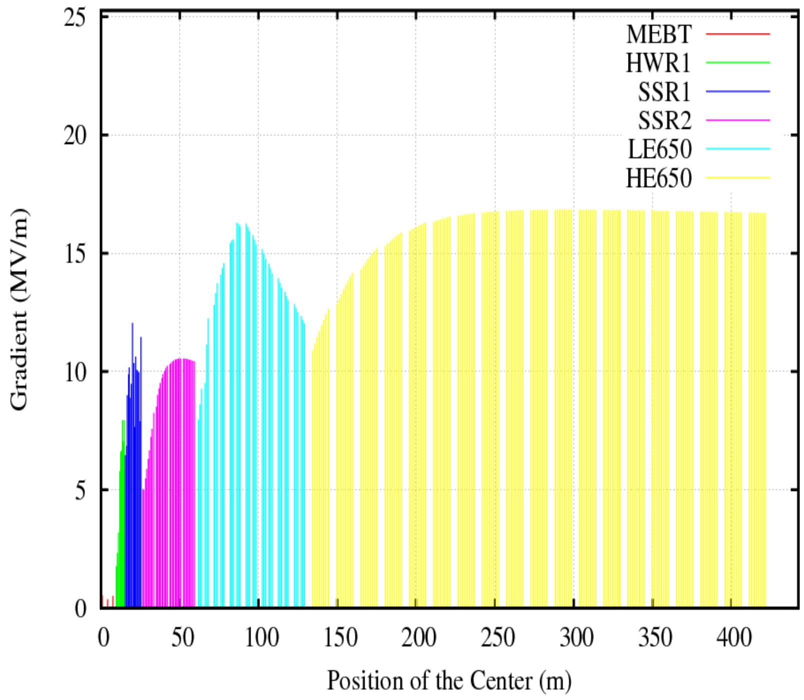


Emittances: 0.14, 0.14, 0.217 π·mm·mrad;

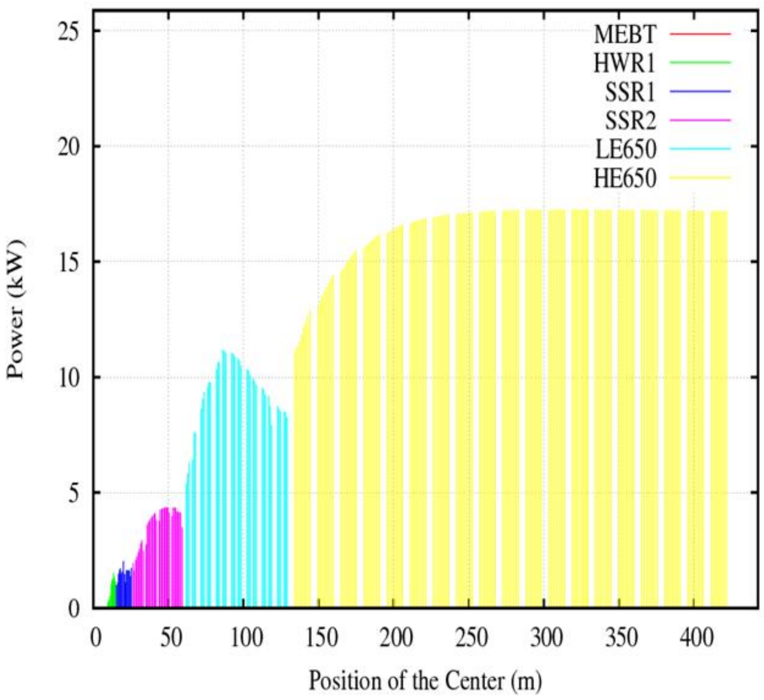
Current 5 mA@162.5 MHz; Energy: 2.1 MeV – 10.8 MeV – 22.1 MeV

SRF Acceleration Parameters

Energy Gain



Beam Power



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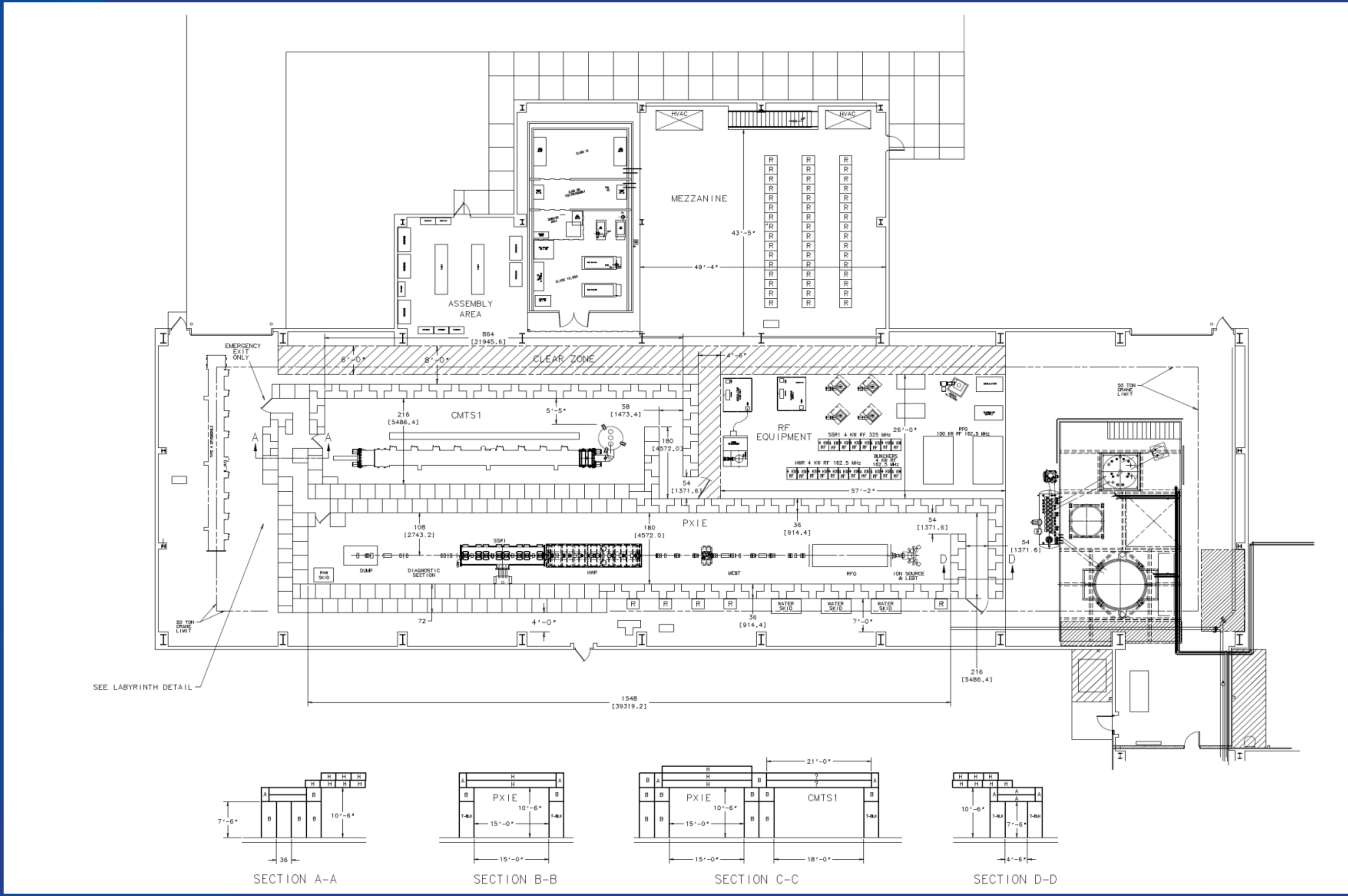
PXIE @ CMTF



MEZZANINE
ASSEMBLY AREA
CLEAR ZONE
CMTS1
RF EQUIPMENT
PXIE
EMERGENCY EXIT ONLY
SEE LABYRINTH DETAIL
30 TON CRANE LIMIT
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D

Staging Options
Stage 1

- Scope
  - 1 GeV CW linac injecting into upgraded Booster
  - Connection to Muon Campus
  - Possible new EDM/Neutron campus (1 GeV)
- Performance
  - Main Injector: up to 1.2 MW at 120 GeV, 0.9 MW at 60 GeV
  - Muon Campus: >80 kW to Mu2e @ 1GeV
  - EDM/Neutron Campus: up to 900 kW @ 1 GeV
  - 8 GeV Program: up to 42 kW
- Utilization of the existing complex
  - Booster, Main Injector and Recycler (with PIP)
  - LBNE target system
  - Muon Campus
  - 400 MeV Linac retired – eliminates major reliability risk

Staging Options
Stage 2

- Scope
  - Upgrade 1 GeV linac to 2 mA, still injecting into Booster
  - 1-3 GeV CW linac
  - 20 Hz Booster upgrade
  - 3 GeV Campus
- Performance
  - Main Injector: up to 1.2 MW at 60-120 GeV
  - 3 GeV Campus: 3 MW
  - EDM/Neutron Campus: 1 MW @ 1 GeV
  - 8 GeV program: up to 84 kW
- Utilization of the existing complex
  - Booster, Main Injector and Recycler (with PIP)
  - LBNE target system

Staging Options
Stage 3

- Scope
  - 3-8 GeV pulsed linac
  - Main Injector Recycler upgrades
  - Short baseline neutrino facility/experiment
- Performance
  - Main Injector: 2.4 MW at 60-120 GeV
  - 3 GeV Campus: 2.9 MW
  - EDM/Neutron Campus: 1 MW @ 1 GeV
  - 8 GeV program: up to 170 kW
- Utilization of the existing complex
  - Main Injector and Recycler
  - LBNE beamline/target
  - 8 GeV Booster retired – eliminates major reliability risk

Staging Options
Stage 4

- Scope – beyond the Reference Design
  - Current upgrade of CW and pulsed linac: 5 mA x 10% DF
  - Main Injector/Recycler upgrades
  - LBNE target upgrade
  - Step toward a NF or MC
- Performance
  - Main Injector: 4 MW at 60-120 GeV
  - 3 GeV Campus: 2.7 MW
  - EDM/Neutron Campus: 1 MW @t 1 GeV
  - 8 GeV program: 3-4 MW
    - (Requires an accumulator ring for low duty factor)
- Utilization of the existing complex
  - Main Injector and Recycler
  - LBNE beamline/target

Performance by Stage

projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1061

DRAFT 6-6-12

Long Baseline Neutrino Program (Main Injector Fast Spill)

	Stage 1		Stage 2		Stage 3		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Maximum Beam Power*	1200	900	1200	1200	2450	2450	kW
Protons per pulse	7.5×10^{13}	7.5×10^{13}	7.5×10^{13}	7.5×10^{13}	1.5×10^{14}	1.5×10^{14}	
Pulse length	9.5	9.5	9.5	9.5	9.5	9.5	µsec
Number of bunches	504	504	504	504	504	504	
Bunch spacing	18.9	18.9	18.9	18.9	18.9	18.9	nsec
Bunch length (FWHM)	2	2	2	2	2	2	nsec
Pulse repetition period	1.2	0.8	1.2	0.6	1.2	0.6	sec

8 GeV Program

	Stage 1 (Booster)		Stage 2 (Booster)		Stage 3 (Pulsed Linac)		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Minimum Beam Power*	42	0	84	0	172	0	kW
Protons per pulse	6.6×10^{12}	6.6×10^{12}	6.6×10^{12}	6.6×10^{12}	2.7×10^{13}	2.7×10^{13}	
Pulse length	1.6	1.6	1.6	1.6	4300	4300	µsec
Number of bunches	81	81	81	81	140,000	140,000	
Bunch spacing	18.9	18.9	18.9	18.9	30	30	nsec
Bunch length (FWHM)	2	2	2	2	.04	.04	nsec
Pulse repetition rate	15	15	20	20	10	10	Hz

Performance by Stage

projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1061

DRAFT 6-6-12

3 GeV Program	Stage 1		Stage 2		Stage 3		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Beam Power	NA	NA	3000	3000	2870	2870	kW
Protons per second	NA	NA	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	
Pulse length	NA	NA	CW	CW	CW	CW	μsec
Bunch spacing**	NA	NA	Programmable		Programmable		nsec
Bunch length (FWHM)	NA	NA	.04	.04	.04	.04	nsec

1 GeV Program	Stage 1		Stage 2		Stage 3		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Beam Power	984	984	980	980	1000	1000	kW
Protons per second	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	
Pulse length	CW	CW	CW	CW	CW	CW	μsec
Bunch spacing**	Programmable		Programmable		Programmable		nsec
Bunch length (FWHM)	.04	.04	.04	.04	.04	.04	nsec