Project X Experimental Facilities Target Facilities

PASI 2013 WG1
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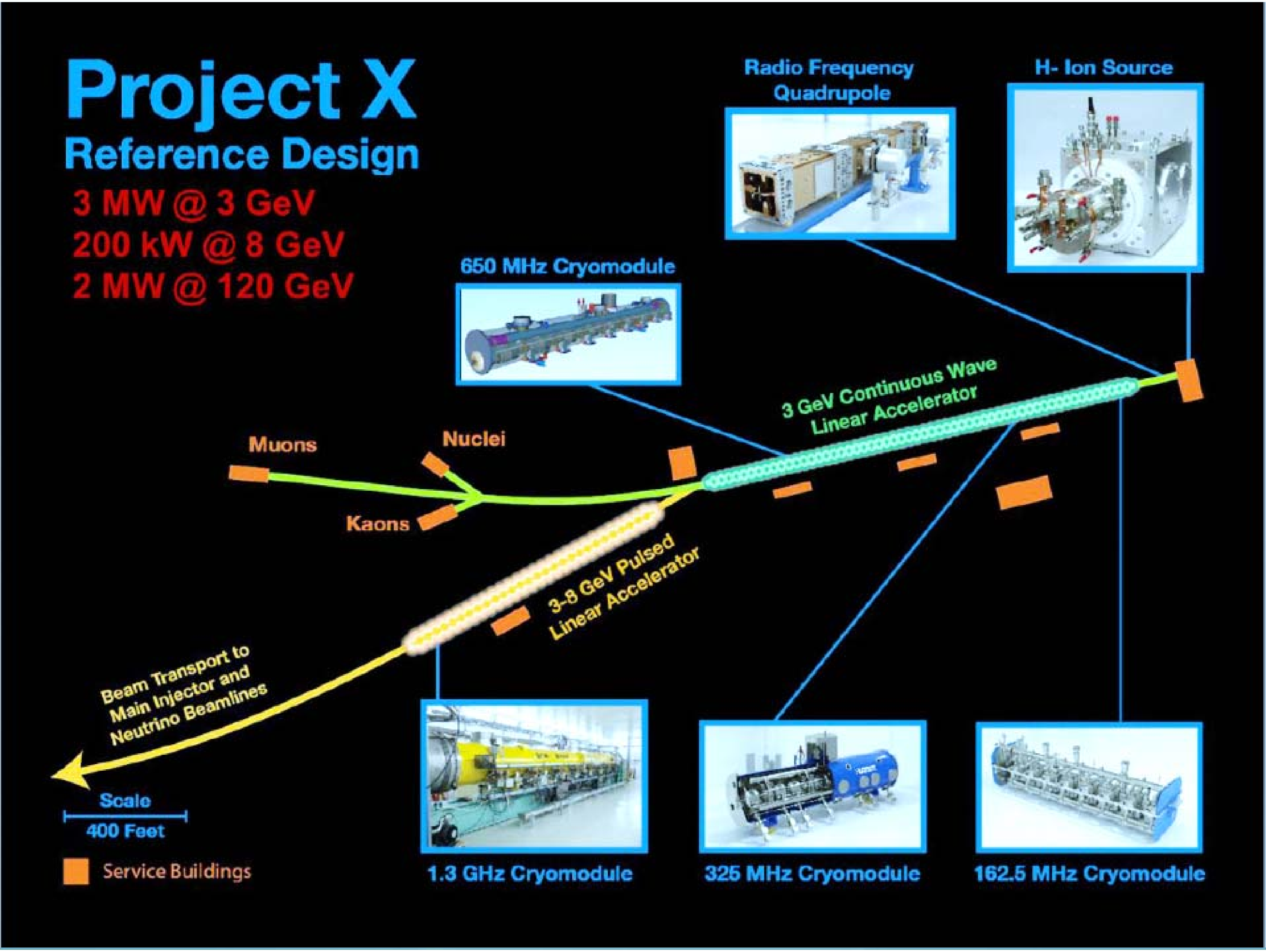
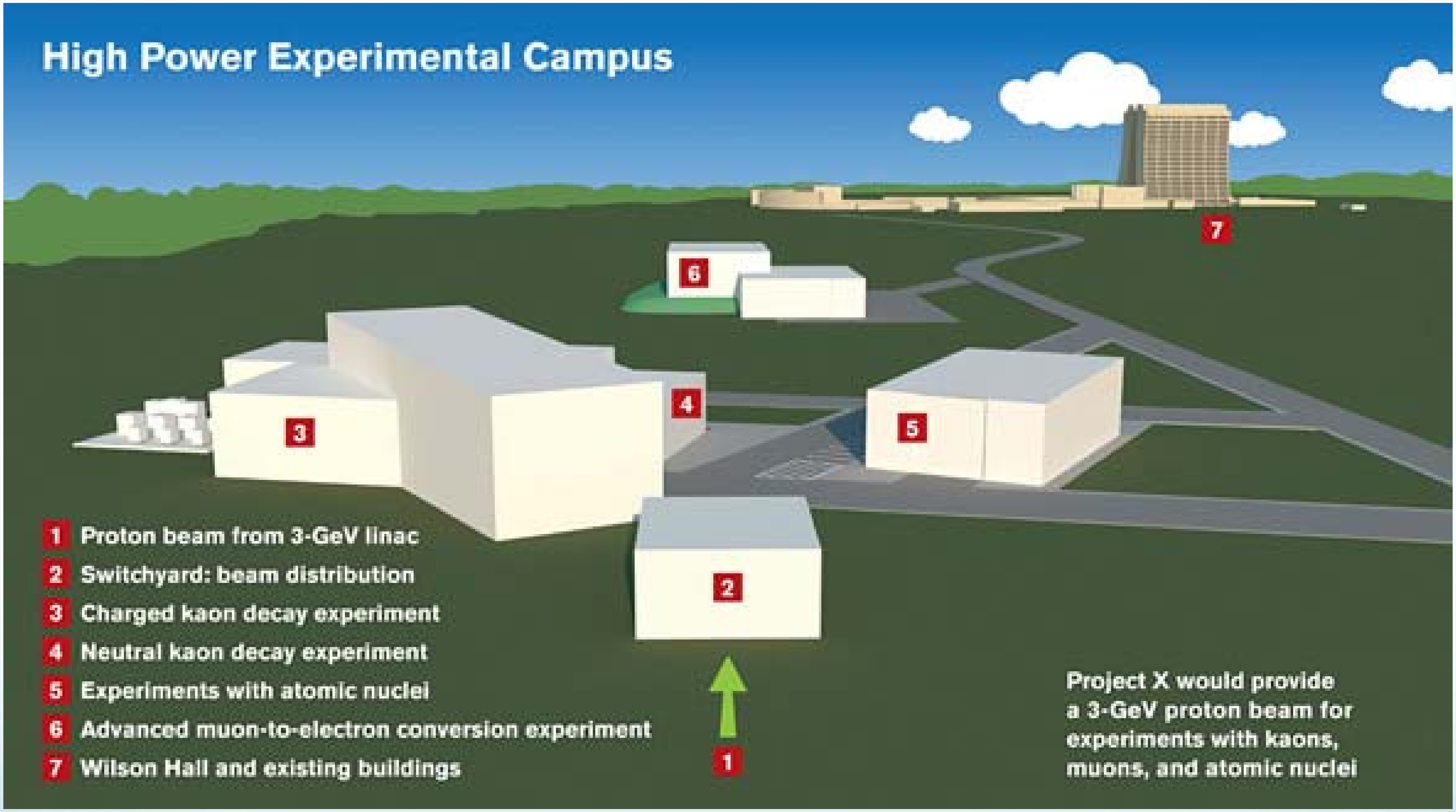
w/ several slides stolen from R. Tschirhart (FNAL)
(Apr. 4, 2013)

What is Project X?

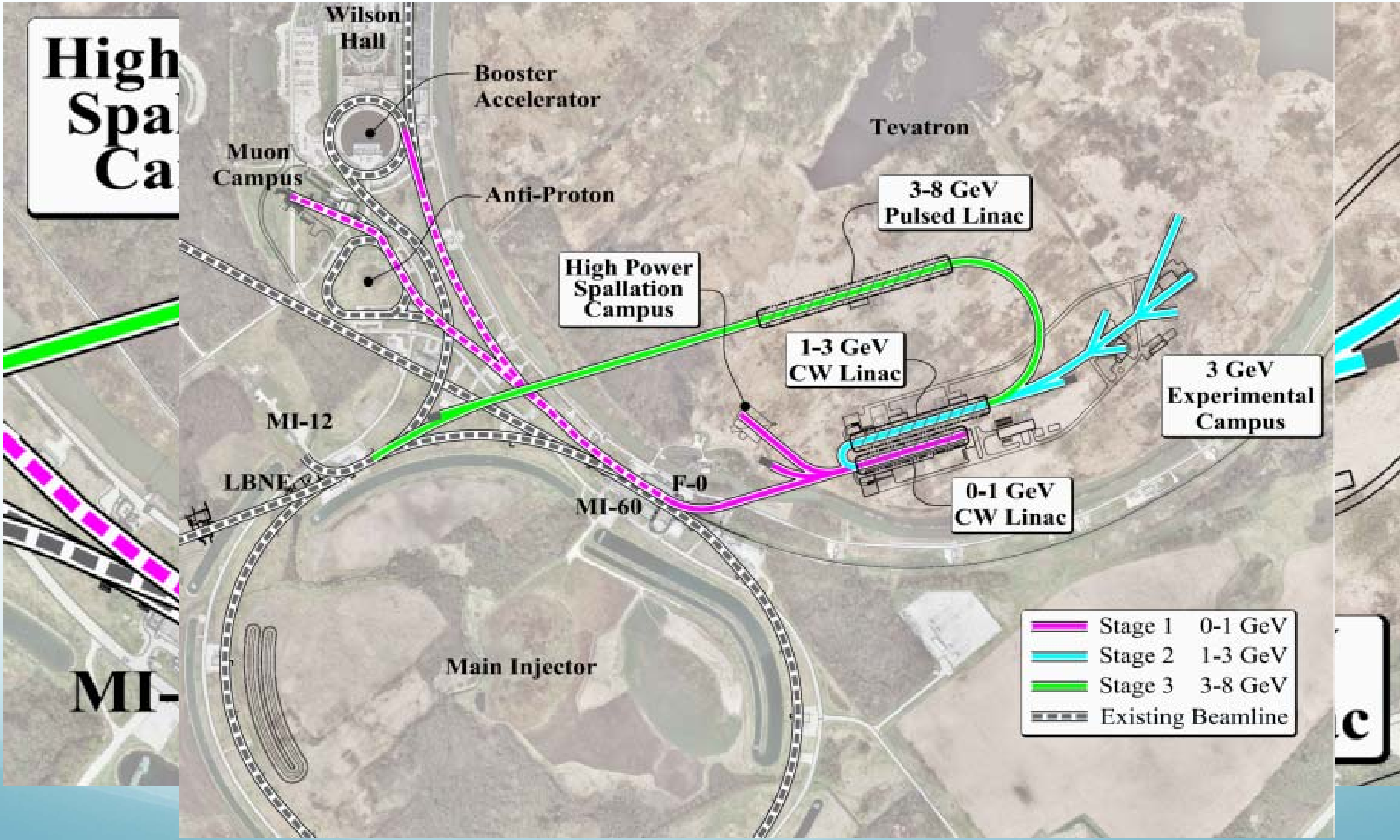
- Project X is a proposed proton accelerator complex at Fermilab that would provide the particle physics world with powerful and sensitive tools to explore a new scientific frontier. This facility would provide particle beams to multiple experiments searching for rare and hard-to-detect phenomena that will further our understanding of fundamental physics.
- “Project X” was a temporary title used at a 2007 planning meeting where the first version was introduced. The name, for better or worse, has stuck.


Project X
Reference Design
3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV
Radio Frequency Quadrupole
H- Ion Source
650 MHz Cryomodule
3 GeV Continuous Wave Linear Accelerator
Muons
Nuclei
Kaons
3-8 GeV Pulsed Linear Accelerator
Beam Transport to Main Injector and Neutrino Beamlines
Scale
400 Feet
Service Buildings
1.3 GHz Cryomodule
325 MHz Cryomodule
162.5 MHz Cryomodule

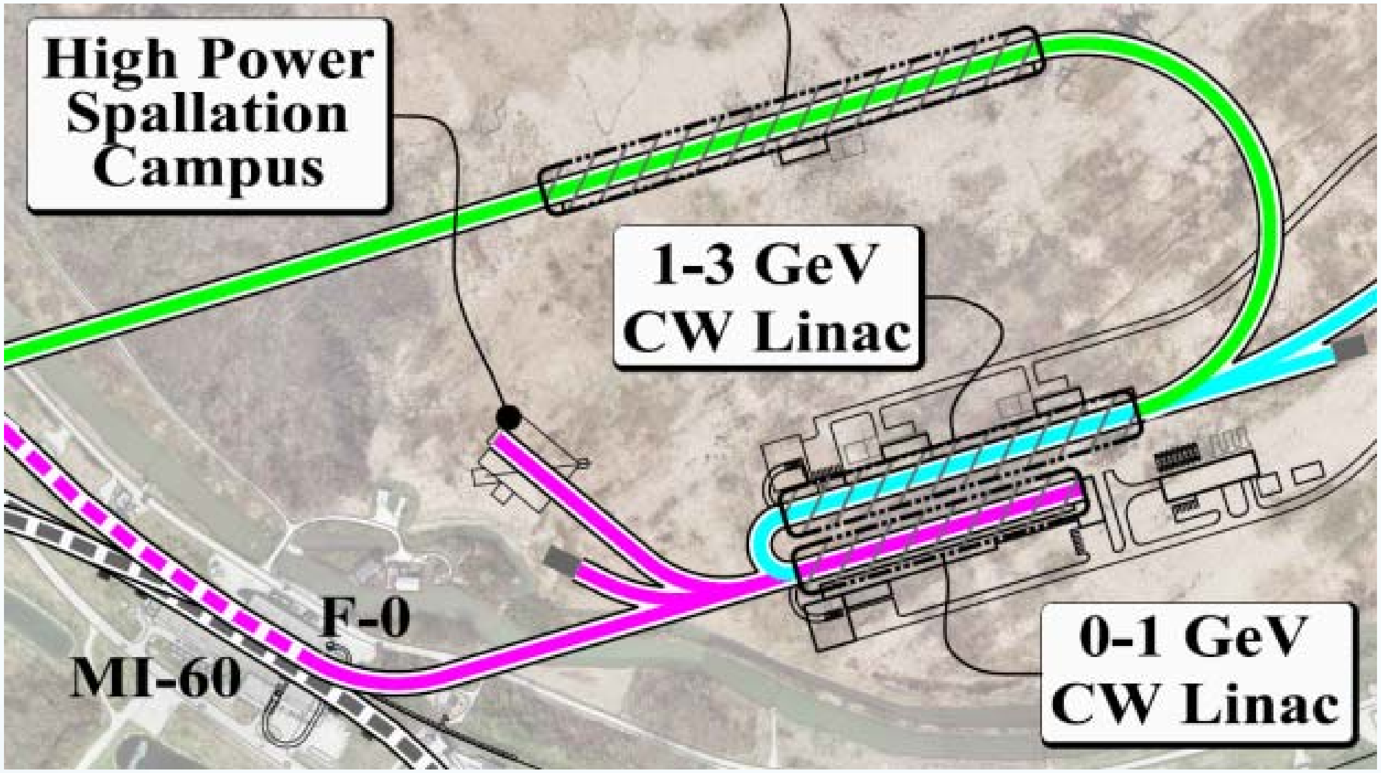

High Power Experimental Campus
1 Proton beam from 3-GeV linac
2 Switchyard: beam distribution
3 Charged kaon decay experiment
4 Neutral kaon decay experiment
5 Experiments with atomic nuclei
6 Advanced muon-to-electron conversion experiment
7 Wilson Hall and existing buildings
Project X would provide a 3-GeV proton beam for experiments with kaons, muons, and atomic nuclei


Proposed Project X Site
To NOvA Neutrino Experiment
To LBNE Neutrino Experiment
Wilson Hall
Access road
Legend
New buildings
Project X beamlines
Muons
Nuclei
Kaons
Beam Transfer
3-GeV Continuous Wave Linear Accelerator
8-GeV Pulsed Linear Accelerator
Particle Source
Main Injector Accelerator
Tevatron Ring
Fermilab site boundary
The proposed Project X will tie into the existing Fermilab accelerator complex and provide a powerful proton beam for experiments at different energies.

Now a staged approach

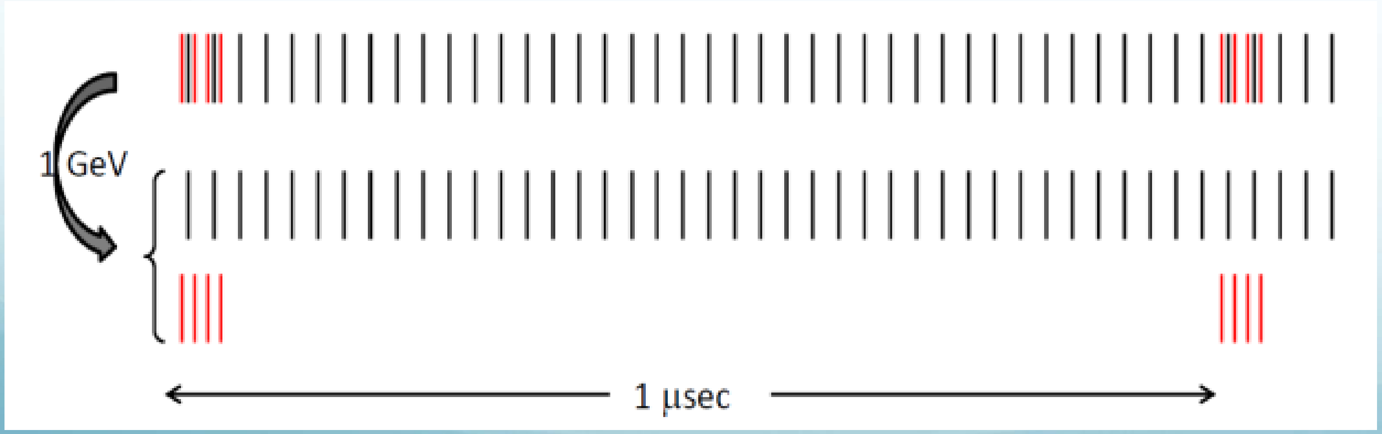


Stage-1 Beam timing



Campus Super-Cycle:

Every 1200 msec the linac drives the Booster exclusively for 60 msec corresponding to a 5% dedicated duty factor for the Booster. The 95% balance of the timeline is CW operations.



CW Operations

Spallation Campus

Muon Campus

Example Power Staging Plan for the Research Program

LBNE
Muon
Kaon
Neutron

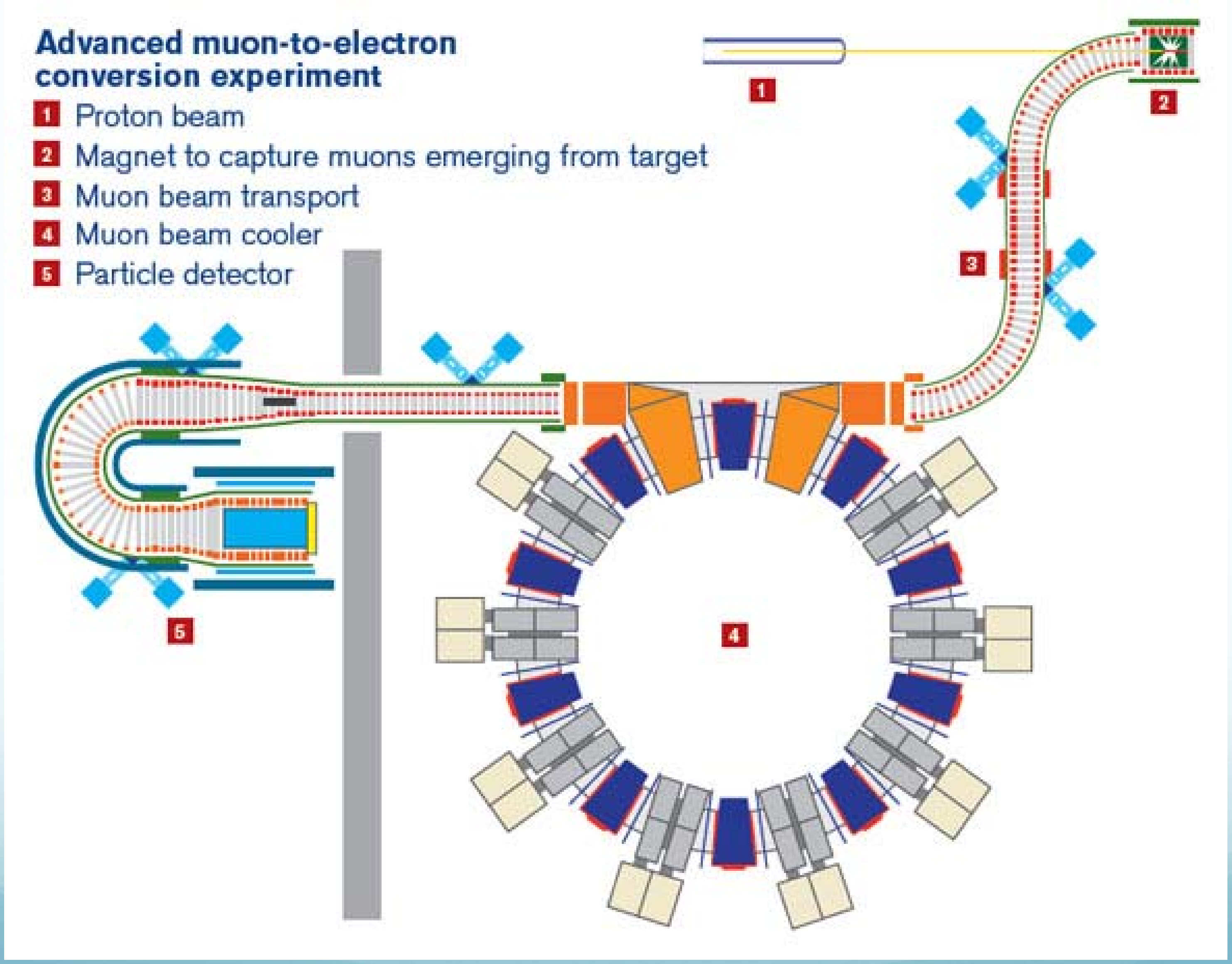
Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 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.

Project X Powered Target Facilities

- LBNE
- BooNE
- Muon Facility
- Kaon Facility
- Spallation Neutron Facility (AKA Energy Station)

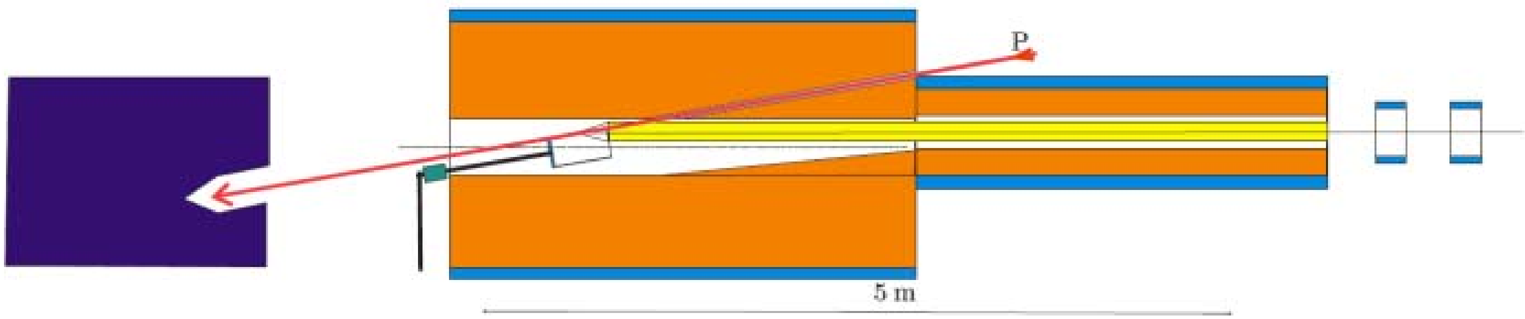
Muon Facility pre-notional concept



Muon Facility: pre-notional concept

Target and Target Cooling

- Optimal target length should be ~1.5 of nuclear interaction length
  - ⇒ i.e.: carbon ~60 cm; tantalum ~15 cm
- The beam leaves ~10% of its energy in the target;
- For 1 MW beam power the power left in the target is ~ 100 kW
- Large beam power prohibits usage of pencil-like target
  - Heat cannot be removed from pencil target: $dP/dS \geq 2$ kW/cm^2 for R~0.5cm
  - Mercury stream is another possibility but it has significant problems with safety. Therefore it was not considered.
- Cylindrical rotating target looks as the most promising choice
  - Carbon (graphite) and tantalum targets were considered
  - Tantalum or any other high Z target has a problem with heating



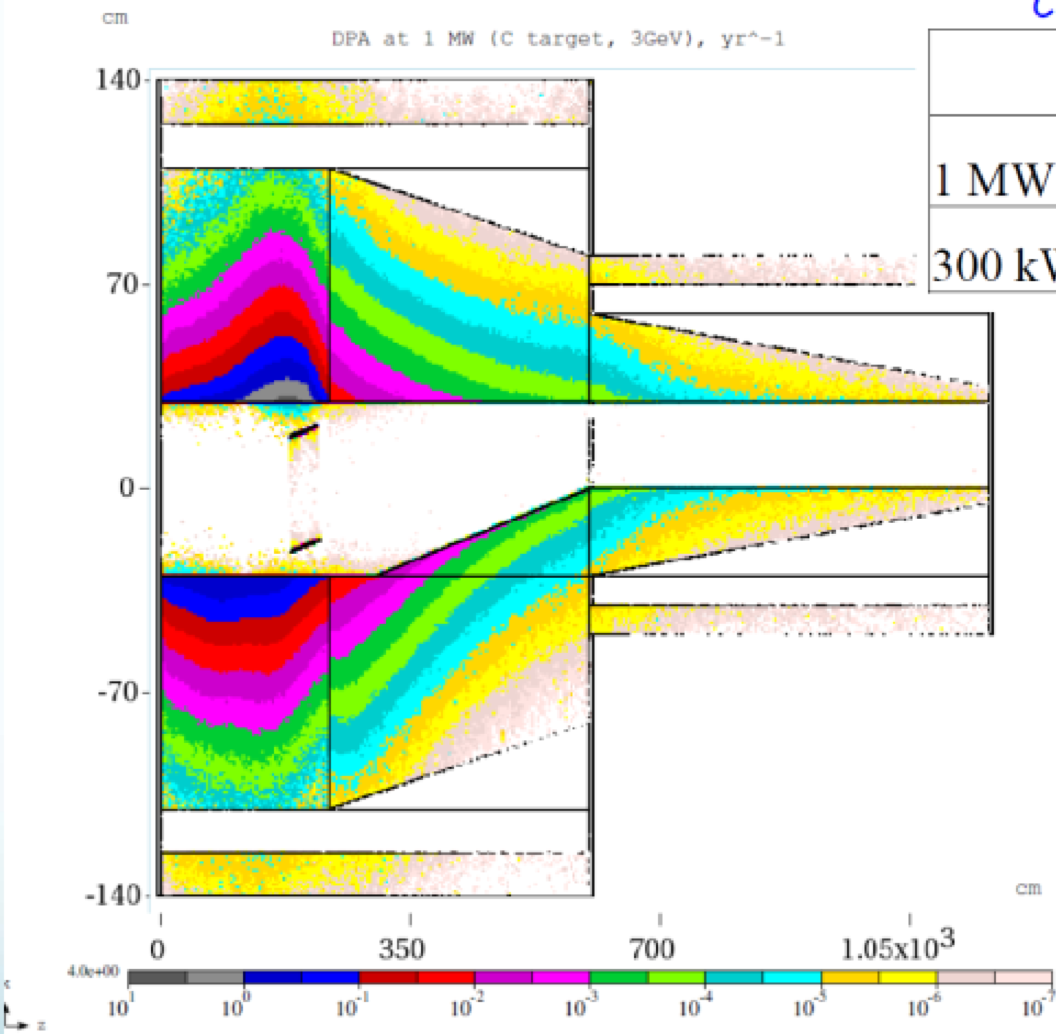
Muon Task Force, Valeri Lebedev

11

V. Lebedev, Fermilab AAC 2011

Muon Facility: pre-notional concept

Effects of radiation



Shielding estimate

C[t] / W[t] /Rmax [cm]

	C target	Ta target
1 MW	140/80 (110)	180/100 (125)
300 kW	100/55 (95)	110/65 (100)

This preliminary absorber design satisfies typical requirements for SC coils

- peak DPA 10^{-5} year^{-1})
- power density (3 μW/g)
- absorbed dose 60 kGy/yr
- Dynamic heat load is 10 W

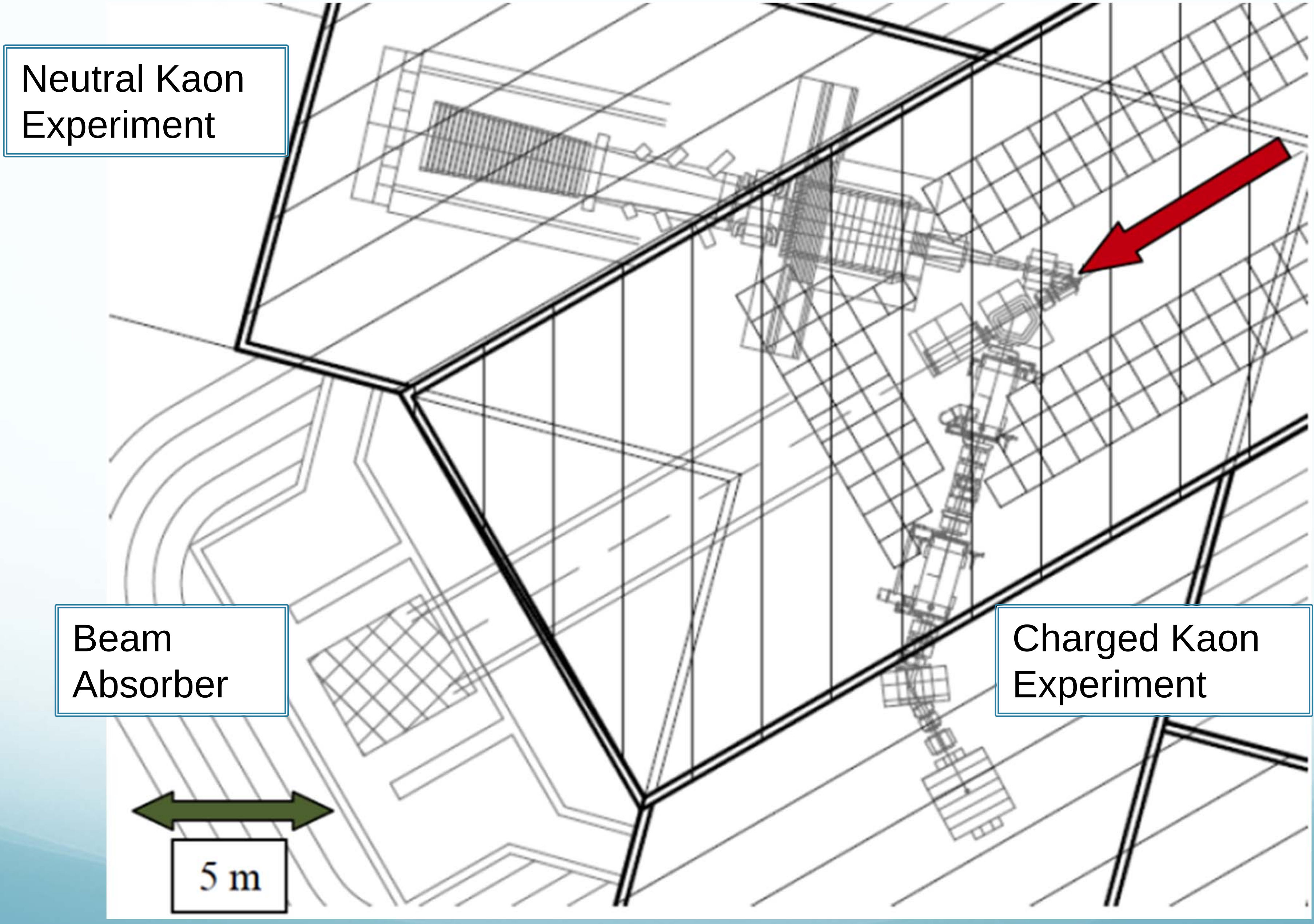
- Transition from 25 kW of μ-to-e to 1 MW increases the shield radius from ~80 cm 110 cm => B = 5 T $\rightarrow$ 3 T for the same stored energy

Muon Task Force, Valeri Lebedev

13

V. Lebedev, Fermilab AAC 2011

Kaon Facility: pre-notional concept

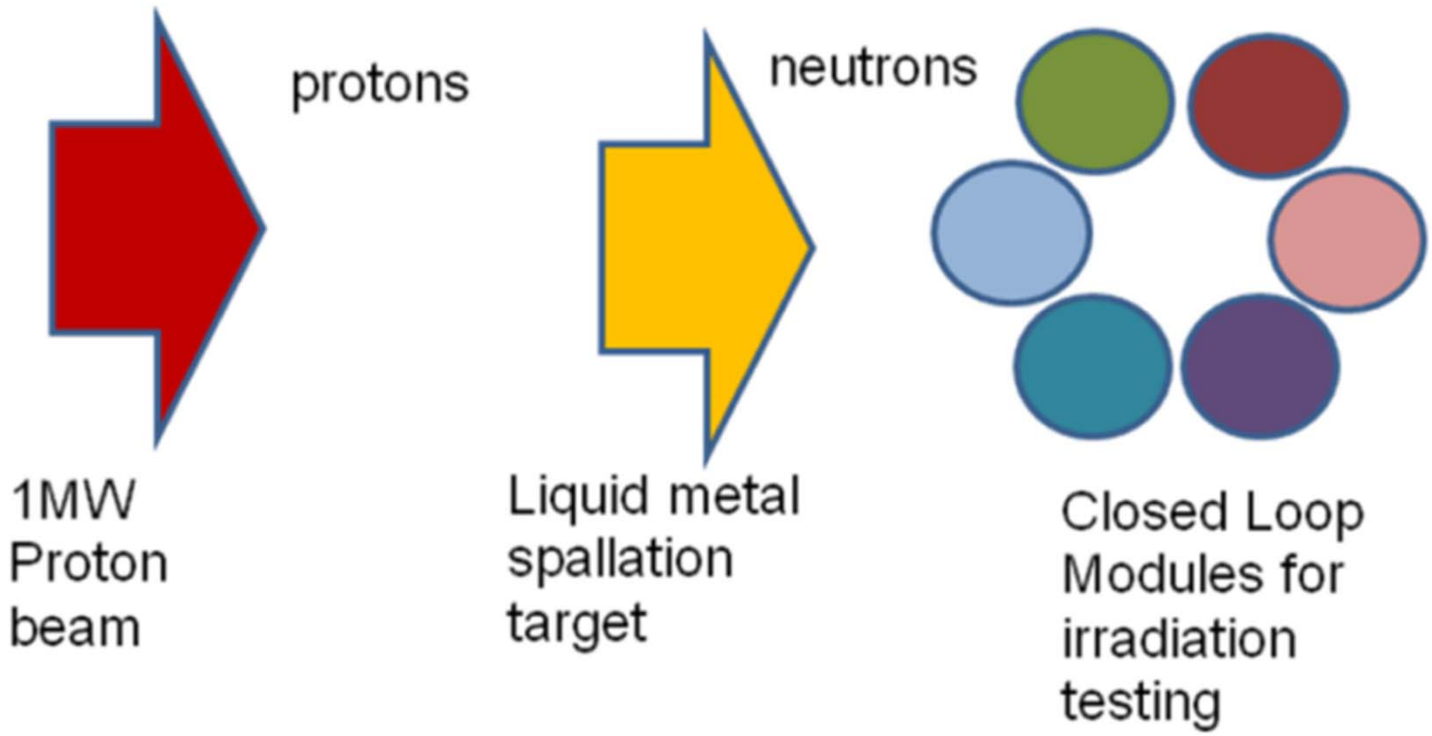


Kaon Facility: pre-notional concept

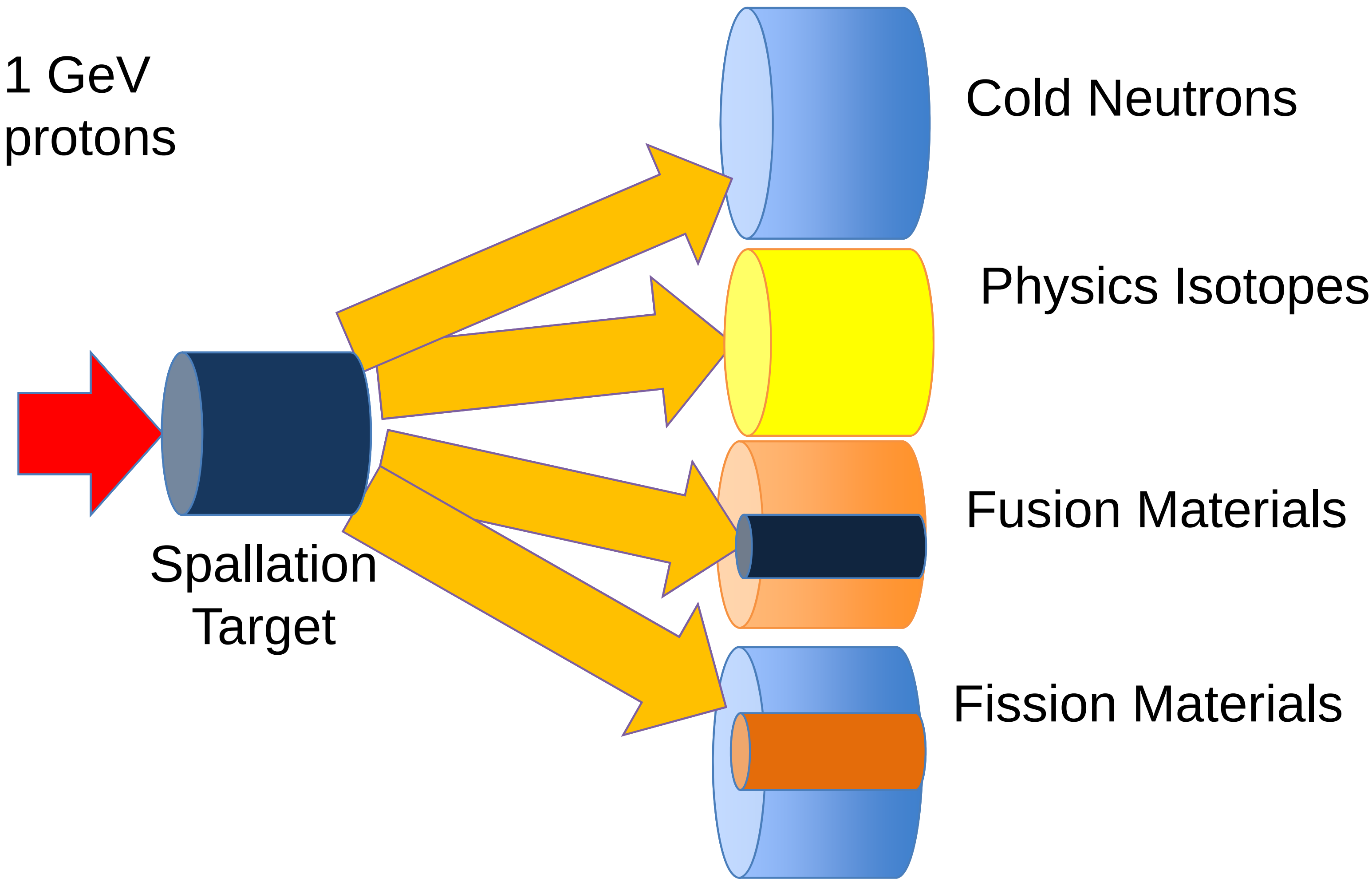
- Target options
  - Lower power experiments have used solid platinum
  - At 1+ MW carbon (graphite or composite) materials are being considered
  - Liquid gallium "waterfall" has also been proposed
- BNL enlisted to develop concepts
- Kaon, Muon, and Neutron facilities will share beam through a switchyard (when a facility is down, others can receive more beam)
  - Must design to take advantage of beam greater than 1 MW! (or design for upgrade later)

PNNL Energy Station Concept

- A new approach utilizing the flexibility of an <u>accelerator neutron source</u> with <u>spectral tailoring</u> coupled with a careful design of a <u>set of independent test loops</u> can provide a flexible neutron test station for DOE NE applications



Energy Station → Integrated Target Station



Project X Energy Station Workshop
January 29-30, 2013

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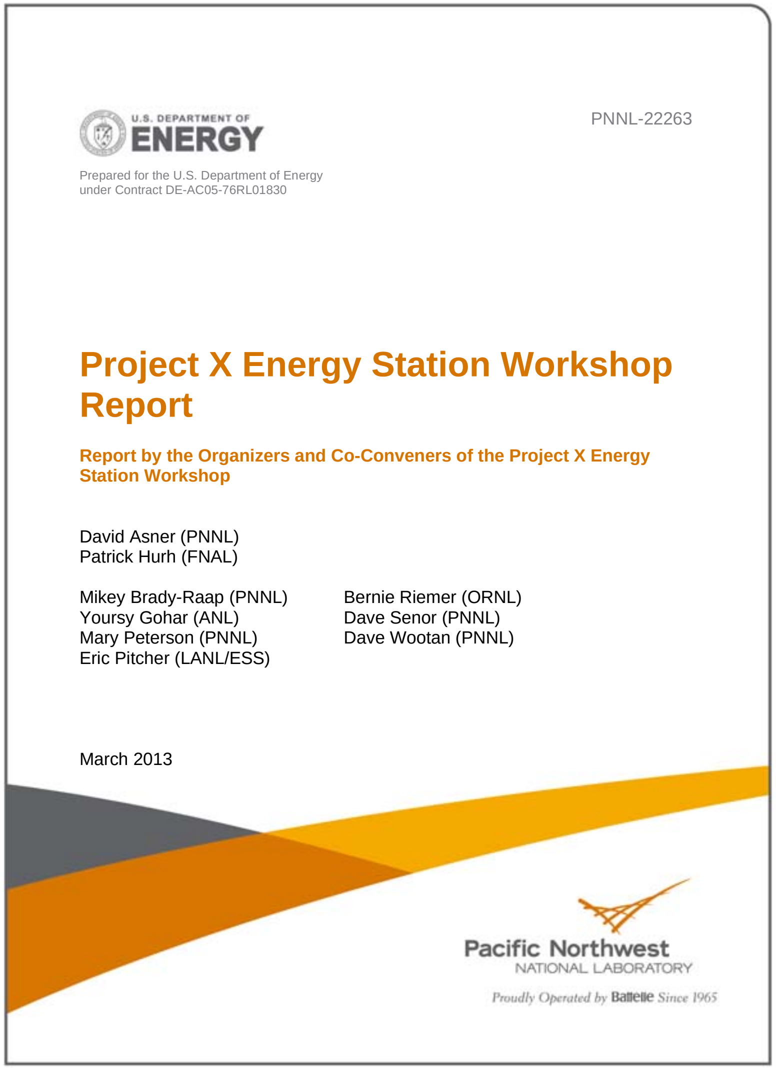
U.S. DEPARTMENT OF ENERGY

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PNNL-22263

Project X Energy Station Workshop Report

Report by the Organizers and Co-Conveners of the Project X Energy Station Workshop

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March 2013

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Workshop objectives

- Identify & explore the nuclear and fusion energy relevant R&D that would be possible in an Energy Station associated with the Project X Linac
- Discuss the hypothesis that an Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate early research concepts.
- Identify the synergy and benefit that the Project X Linac could bring to the nuclear & fusion energy communities.

Energy Station → Integrated Target Station

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Goal

- Develop integrated spallation target station concept to serve DOE-NE, DOE-SC-FES/HEP/NP experimental needs

Rational

- CW spallation neutron source could augment limited US irradiation testing capability
- Synergy between Physics experimental needs and materials testing for fusion, fission communities

Project X – Stage 1

- Could provide ~1 MW of beam dedicated to a spallation neutron source for nuclear materials and fuels research (Energy Station) or shared with a physics mission facility with similar neutron source requirements (Integrated Target Station)

Project X Integrated Target Station has the potential to benefit several areas (beyond HEP)

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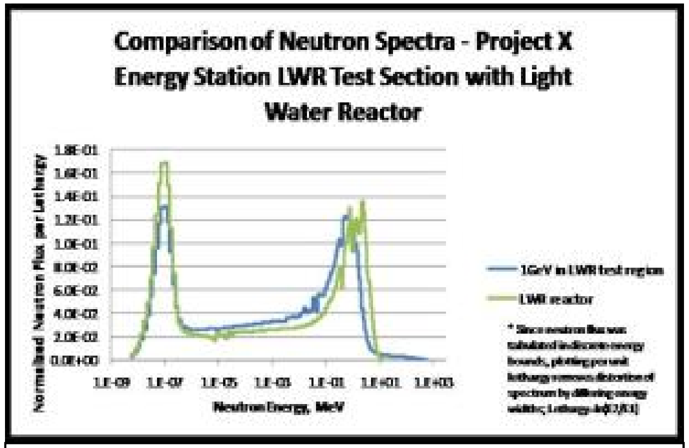
- Highest priority opportunities within the US Nuclear and Fusion energy programs are irradiation of fusion and fast reactor structural materials.
- Must provide a fusion and fast reactor relevant neutron flux at a minimum of 20 dpa per calendar year in a reasonable irradiation volume.
- Enable the in-situ real-time measurements of various separate-effects phenomena in fuels or materials, which would be very valuable to the modeling and simulation technical community. Such capabilities are more feasible in an accelerator-based system than a reactor
- integral effects testing of fast reactor fuels, including driver fuel, minor actinide burning fuel, and transmutation of spent fuel.
- support DOE Office of Nuclear Energy plus Office of Science programs
  - Materials Program - Fusion Energy Sciences (FES)
  - Isotope Production Program – Nuclear Physics (NP)
  - ultra cold neutrons – Nuclear Physics (NP)

Project X Energy Station Concept



Thermal Spectrum Test Module: LWR, HTGR, MSR

Closed Loop Test Modules

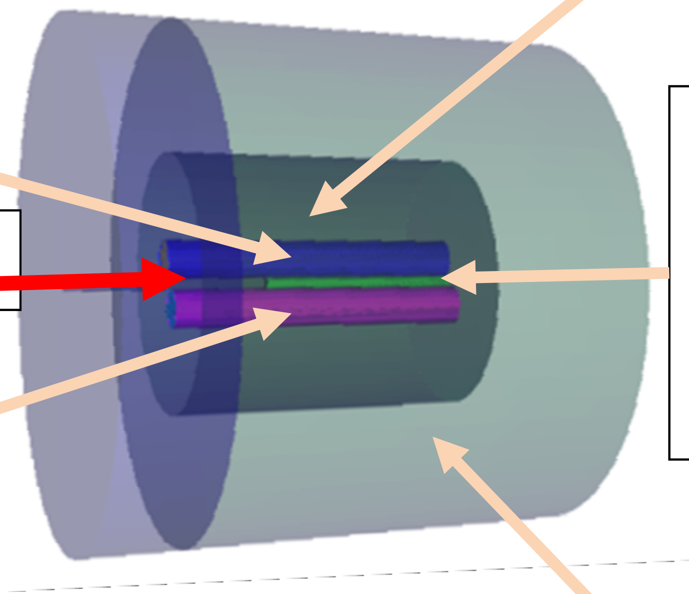
- Removable/replaceable/customizable
- Independent cooling system
- n spectrum/material/temp/pressure to match reactor conditions
- ~30 cm dia

Lead Matrix Test Region

- Solid lead with gas or water cooling
- ~ 2 m diameter, 3 m length
- Low n absorb/ High n scatter
- High n flux/ Fast n spectrum
- Acts as gamma shield

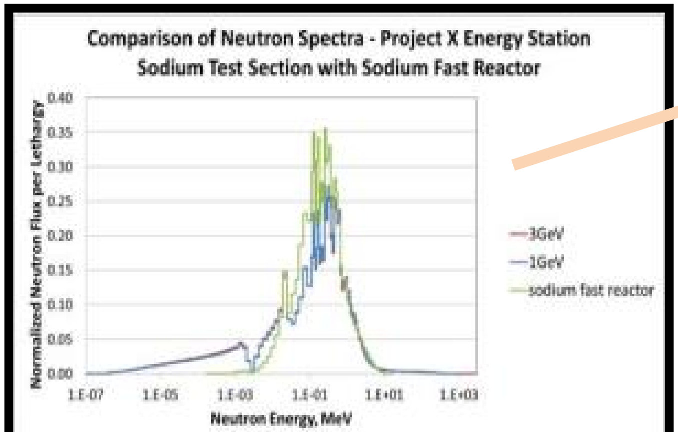
Project X Proton Beam

- 1mA @ 1 GeV (1 MW)



Spallation Target

- Liquid Pb-Bi
- >30 neutrons/proton
- 1 GeV protons penetrate ~50 cm in lead
- Neutrons Similar to fission spectrum
- Samples can be irradiated in proton beam
- Adding W or U can increase n flux density
- Small volume ~ 10 cm dia, 60 cm length
- Cleanup system for spallation products



Fast Spectrum Test Module: SFR, LFR, GFR

Reflector

- Steel/iron/nickel
- High n scatter
- Flattens n flux distribution

Energy Station is Unique Combination of Existing Technologies

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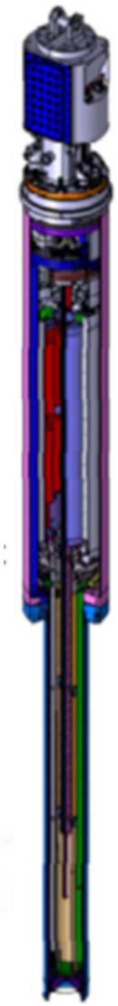
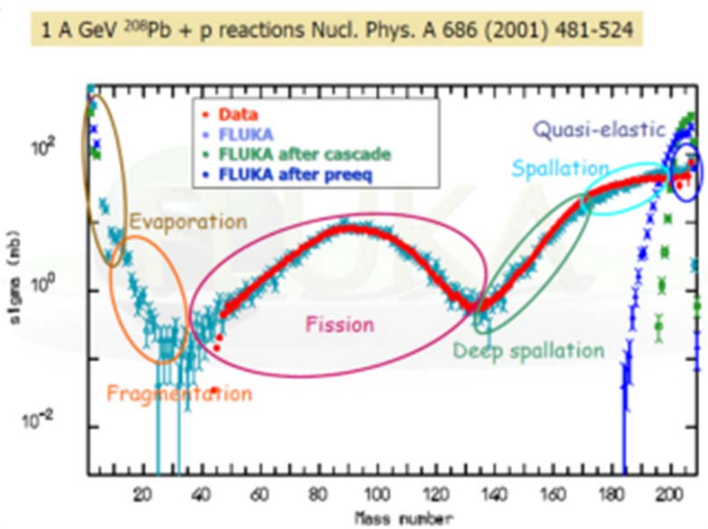
- Proton beam CW - 1 GeV - 1 mA - 1 MW
- Spallation Target:
  - Liquid lead or lead-bismuth release ~30 neutrons/proton
  - Neutron spectrum similar to fission spectrum but with high energy tail
  - Technology has been demonstrate at MEGAPIE
- Test Matrix
  - Solid lead or other (zircalloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple solid block with cooling, holes for test modules
- Closed Loop Test Modules
  - Independently tailored irradiation environments (LWR, HTGR,SFR,LFR)
  - Independent heating/cooling system for each to control temperatures
  - Concept utilized in FFTF (sodium), BOR-60 (sodium, lead), ATR (press. Water)
- Reflector to minimize leakage neutrons

Energy Station Components – Spallation Target

- Spallation Target:
  - 6.24e15 p/s proton beam
  - Nominal 10 cm diameter
  - High neutron yield Pb or LBE ~30 neutrons/proton
  - 1 GeV protons penetrate ~50 cm in lead
  - Neutron spectrum similar to fission but with high energy tail
  - Coolant is target material, no stress issues in target
  - Beam window may be life limiting
    - Experience base from ISIS, SINQ, MEGAPIE, SNS, is ~7-22 dpa/yr on front window for SS316, T91, Inconel
    - For our 10 cm diameter ES window, ~8 dpa/yr
  - Need careful oxidation control, on-line cleanup
  - Spallation products like fission products
  - >400 KW energy deposited
  - Potential for in-beam materials testing

MEGAPIE (0.8 MW) LBE target has been demonstrated





Energy Station Components – Test Matrix

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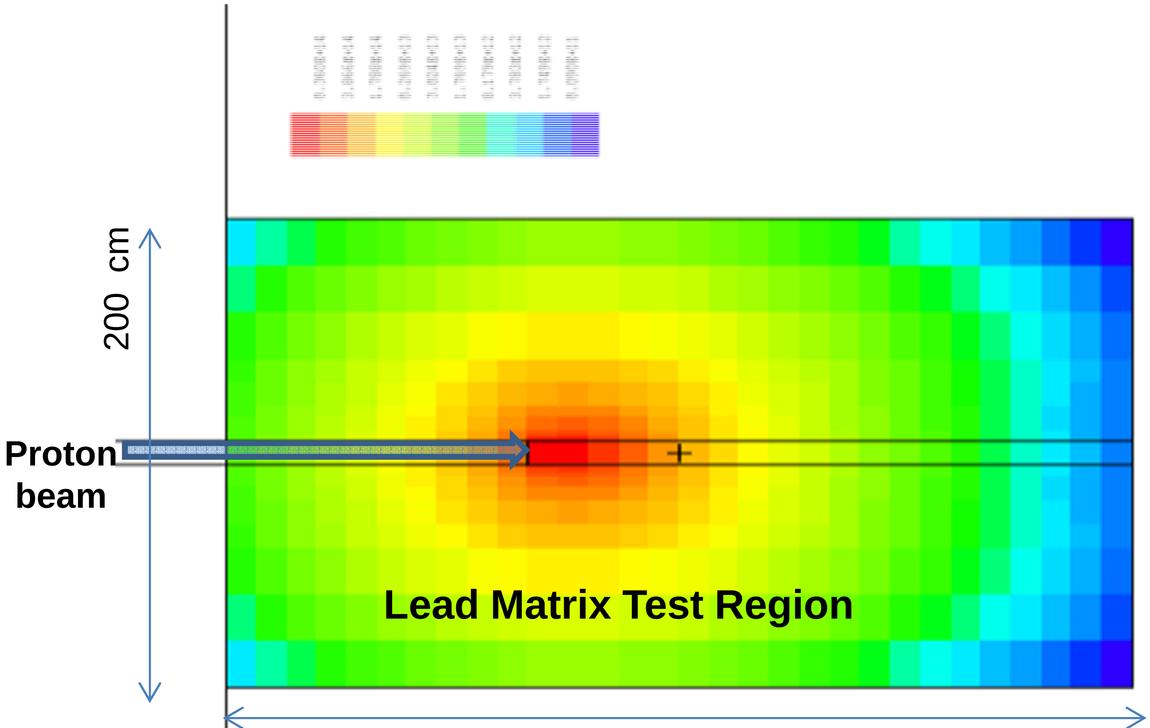
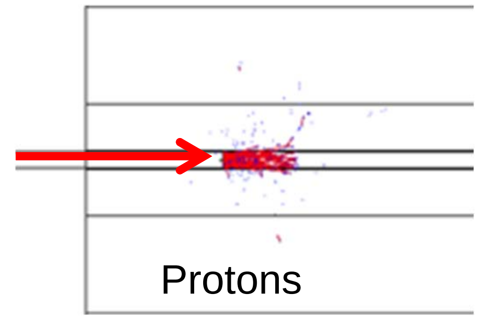
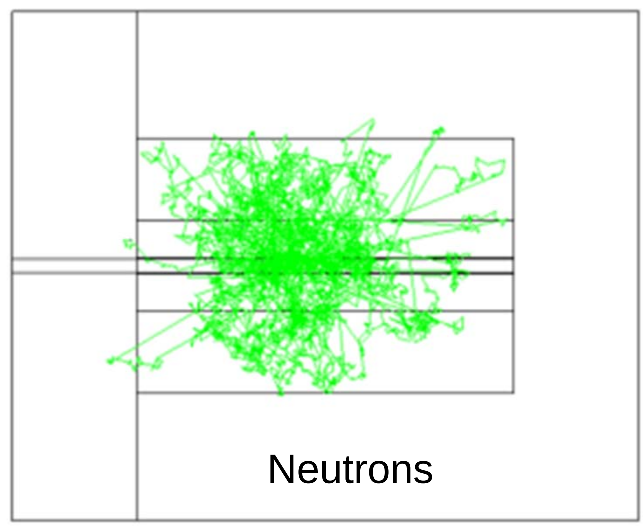
- Test Matrix
  - Solid lead or other (zircalloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple thermal analysis indicates heating may allow solid lead matrix
  - Beam tubes could provide additional testing flexibility



Neutron flux Distribution in Lead Matrix Test Region

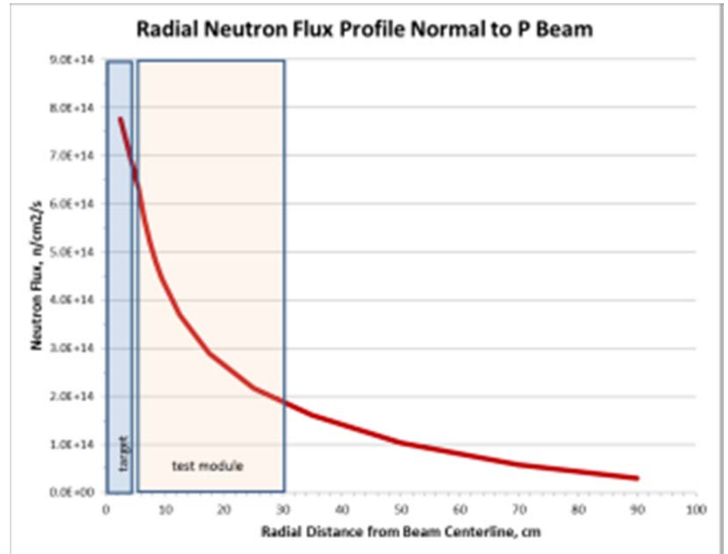


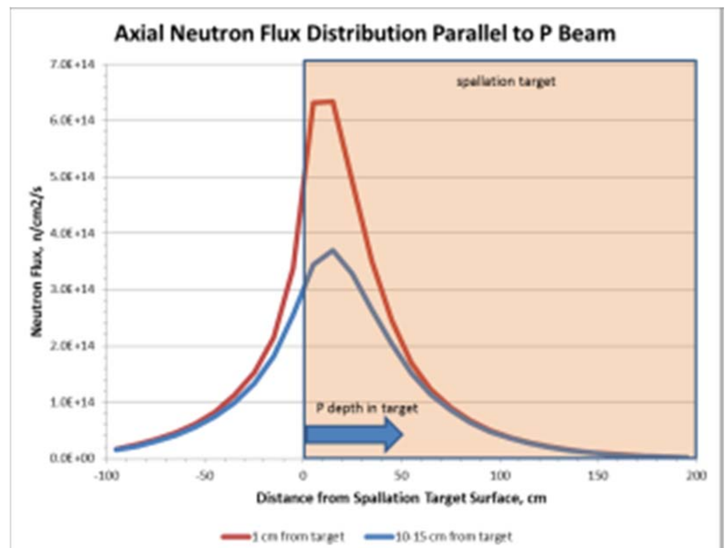


High Flux Volumes Available in Test Matrix Region

Neutron Flux Range (n/cm2/s)	Axial Extent (cm)	Outer Extent (cm)	Volume (liters)
>5e14	30	8	~2.8
>3e14	50	15	~23
>1e14	110	60	~600
>5e13	160	80	~2000
>1e13	250	100	~9000

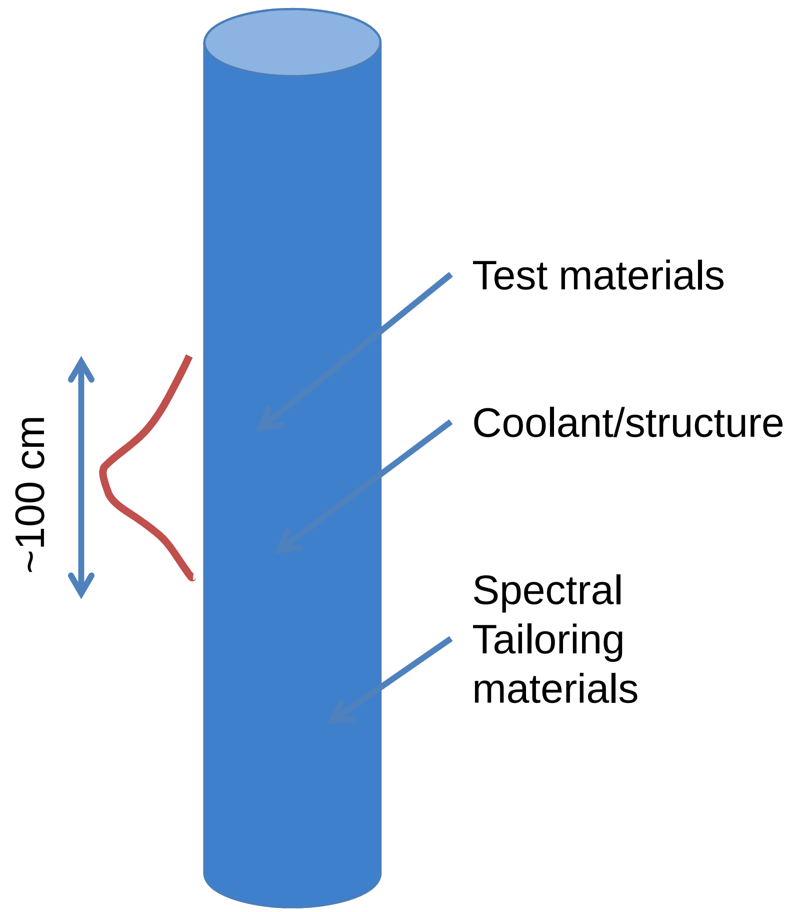
- 1 GeV protons penetrate ~ 50 cm in lead or LBE target, generate ~30 neutrons/proton
- Neutron flux falls off radially but lead matrix helps
- Axial profile peaks ~20 cm below target surface, provides ~100 cm >1e14 n/cm2/s





Energy Station Components – Closed Loop Test Modules

- Number of modules can be varied
- Each module can have unique independent coolant and materials and operate at independent temperatures (sodium, lead, molten salt, water, helium)
- Neutron spectrum can be tailored from fast to thermal to match reactor conditions (the gamma to neutron ratio can also be tailored)
- Miniaturized test specimens can maximize testing in high flux region
- Modules are Removable, Replaceable, shipped offsite for post irradiation examination (PIE)



Spectrum Tailoring Can Simulate A Different Reactor in Each Module

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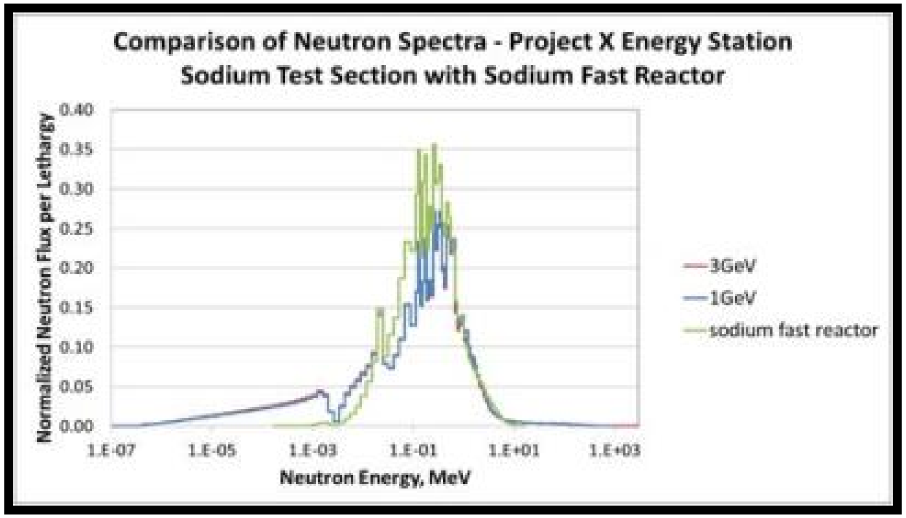
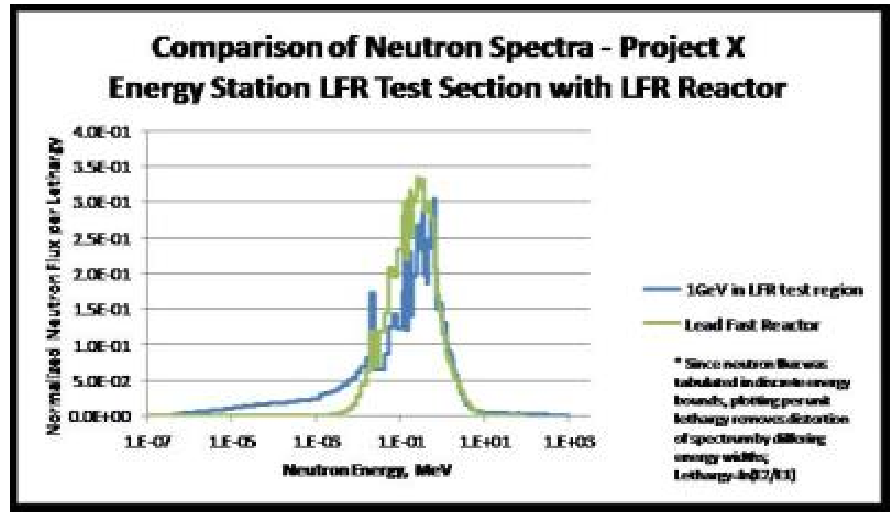
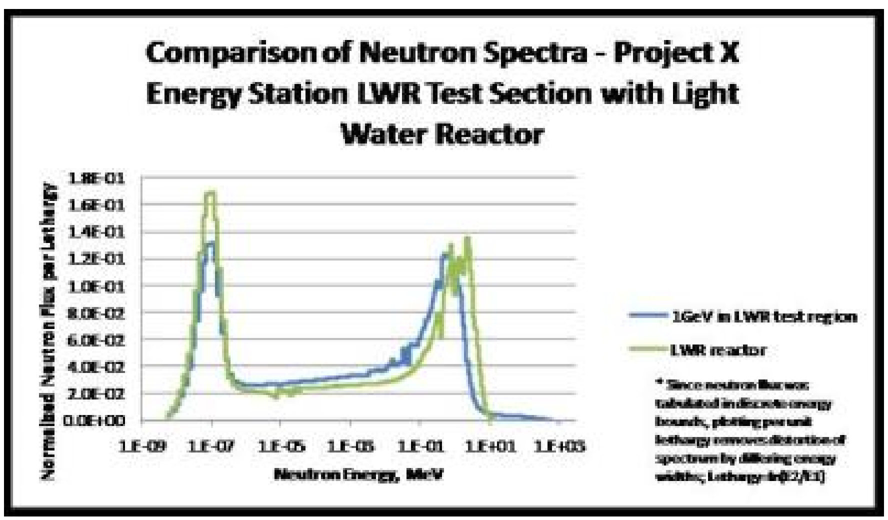


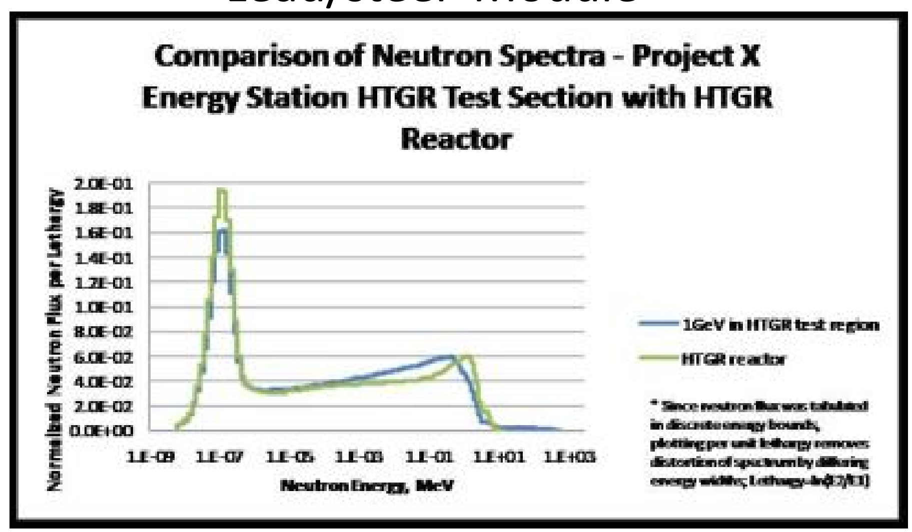
Sodium/steel Module



Lead/steel Module

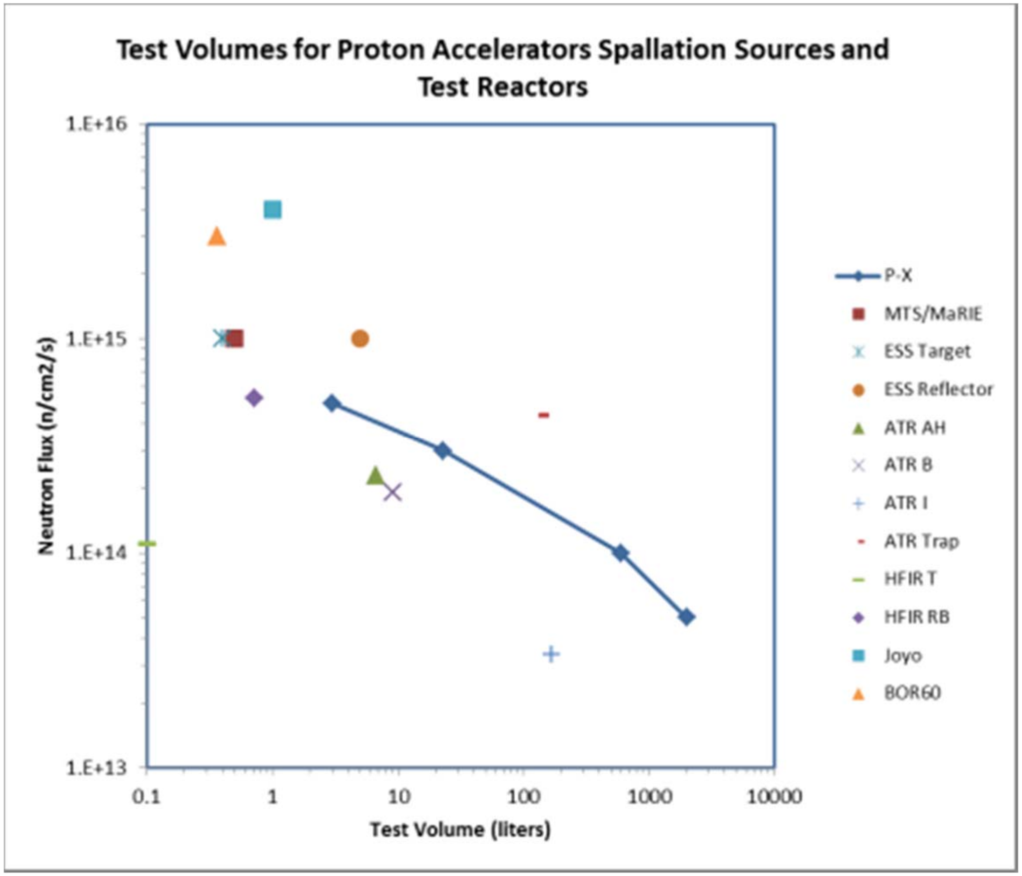


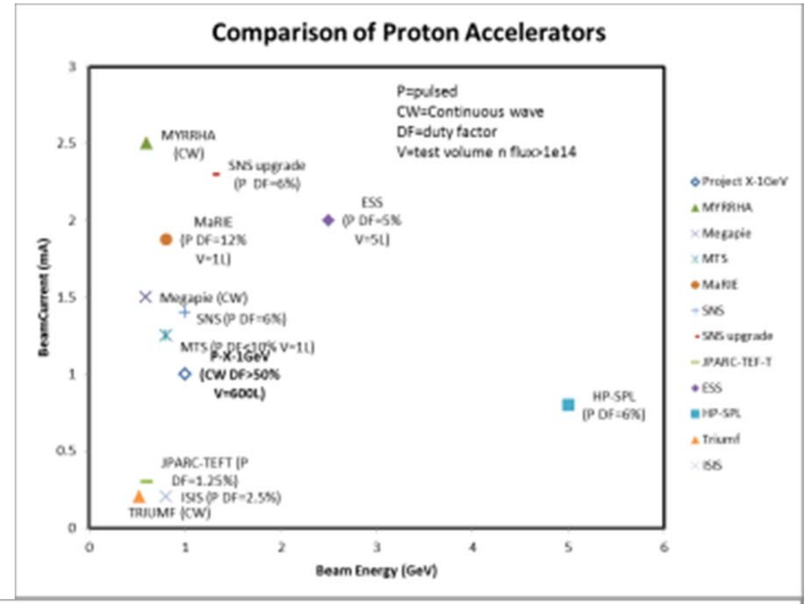
Water/Zr Light Water Module

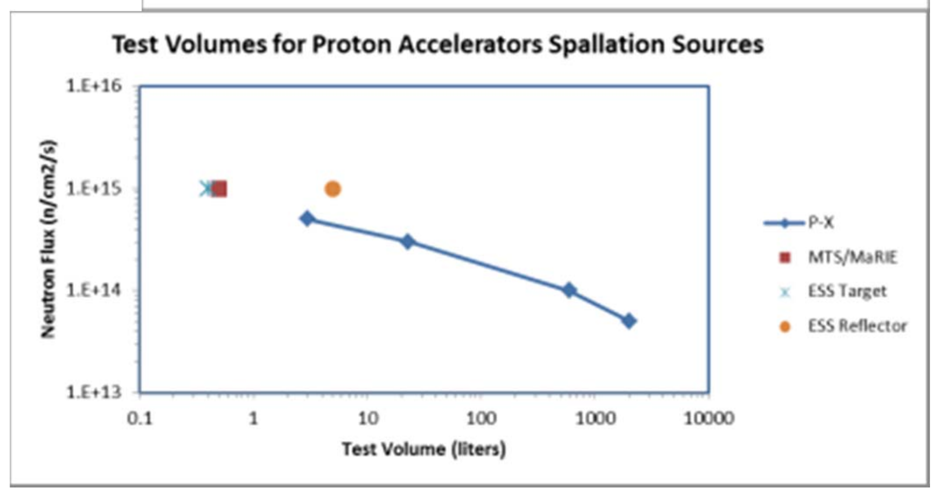


Graphite/He Module

How Does Energy Station Compare?







- Irradiation volumes at high flux comparable to reactors
- Accelerator parameters are in range of other proposed systems

Energy Station Capabilities

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- Flexible design allows support to multiple missions for DOE-NE, SC-FES, SC-NP
- Benefits of test reactor volumes and neutron fluxes without reactor issues – licensing, fuel supply, safety, waste
- Robust technology allows it to be designed and constructed with today's technology in order to fill gaps in tomorrow's technology
- Continuous wave, high availability, high beam current provides potential for irradiation tests to high fluence
- Energy distribution of spallation neutrons similar to fast reactor fission spectrum but with high energy tail up to proton energy
- Ability to tailor neutron spectrum from fast to thermal as well as the gamma to neutron flux ratio
- H and He generation in materials higher than in reactor allowing accelerated aging testing
- Potential for beneficial isotope production and/or neutron beams simultaneous with irradiation testing

Actions identified to evolve concept

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- Develop conceptual target designs that serve *both* particle physics and nuclear energy missions – Integrated Target Station (ITS)
- Develop an ITS testing program plan that capitalizes on the unique characteristics of a high-intensity accelerator and spallation source
- Define/refine the technical requirements to support the proposed testing program plan
- Compile relevant design parameters to support the high-priority mission needs and provide them to the beam and target designers
- Investigate the beam on/off issues for both short and long time scales. to determine which transients have the potential to be problematic due to thermal and radiation damage effects
- Further consideration must be given to desired damage rate/sample volume specifications to provide a meaningful irradiation capability
- Neutronics modeling of the notional Project X ITS concept needs to be refined to evaluate beam options (e.g., dual or rastered beam) to optimize flux and flux gradients in maximum usable test volumes.

Opportunities for Collaboration

- Radiation Damage (RaDIATE)
- Target Facility Conceptual Design
  - Energy Station (PNNL involvement)
  - Kaon Facility (BNL involvement)
  - Muon Facility
- Target Technologies
  - High heat flux cooling
  - Liquid metal target technology (kaon, muon, neutron)
  - Beam windows
  - Remote handling