The Project X Research Program: Muons

R. Tschirhart
Fermilab

NuFact Meeting
William & Mary
July 25th 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

Project-X:

- Evolution of the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.

Project-Y: Origins…

- **The Origin of Mass:**

  How do massless chiral fermions become matter particles?
  (buzzword: "Higgs")

- **The Origin of Matter:**

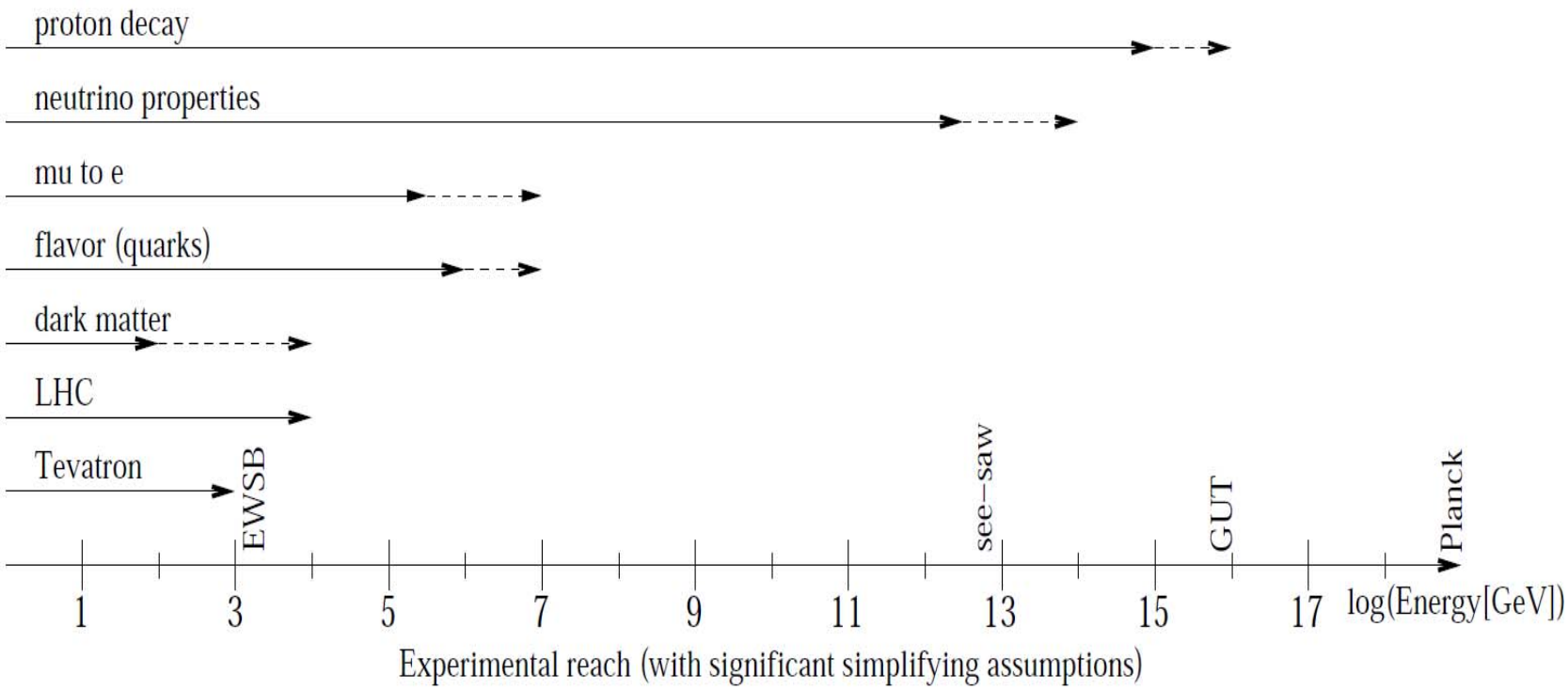
  Why are there so many different kinds of matter particles with different properties?
  (buzzword: "Flavor")

- **The Origin of the Universe:**

  Where did matter come from in the first place and why didn't it all annihilate with antimatter?
  (buzzwords: "Baryogenesis", "Leptogenesis")

-Joe Lykken

The Zoltan plot



Y. Grossman, Project X Physics Study June 2012

The Project-X Research Program

- ***Neutrino experiments***

A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating near detectors on the Fermilab site and massive detectors at distant laboratories.

- ***Kaon, muon, nuclei & neutron precision experiments***

These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), nucleon instability and world-leading precision measurements of ultra-rare kaon decays.

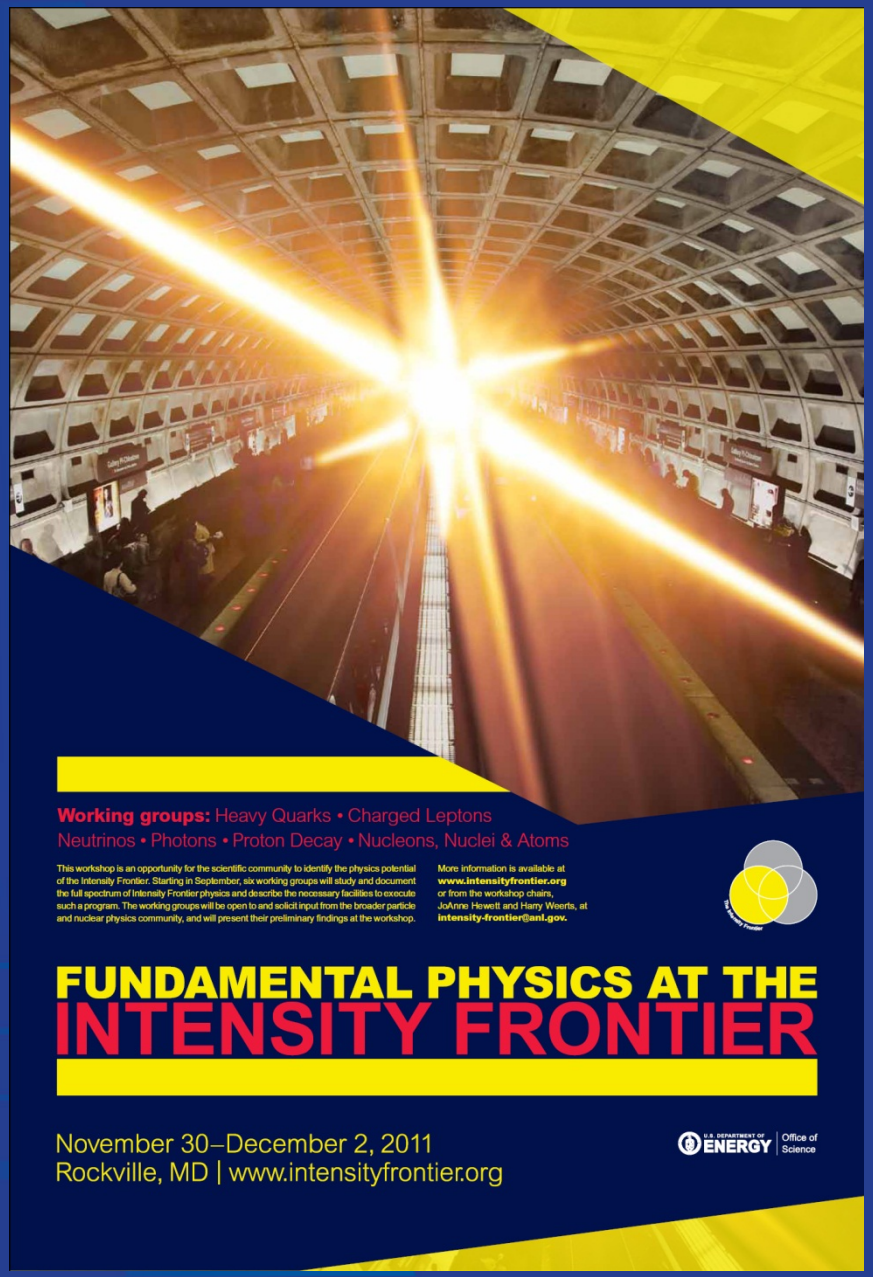
- ***Platform for evolution to a Neutrino Factory and Muon Collider***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

Detailed discussion on Project X website



(http://www.intensityfrontier.org/)

- 500+ Attendees
- Six very active working groups:
  - Charged leptons
  - Heavy Quarks
  - Hidden Sector
  - Neutrinos
  - Nucleons/Nuclei/Atoms
  - Proton Decay
- Project X potential discussed in each group

The Project X Physics Study Followed this Success…

June 2012 Physics Study: June 14th-22nd

Summer 2012 through Spring 2013:

Continue to evolve existing white papers into a comprehensive staged program with compelling physics at each stage.

October 11th-13th 2012 (CPM2012):

US particle physics town meeting at Fermilab preparing for “Snowmass”, summer 2013.

“Snowmass”, summer 2013 (CSS2013):

July 29th – August 10th

Event to develop US particle physics strategies.

Harry Weerts & Joanne Hewett are Intensity Frontier conveners.

Conveners for PXPS Experimental Concepts and Sensitivities

Neutrinos:

Andre de Gouvea (Northwestern University), Patrick Huber (Virginia Tech) , Geoff Mills (LANL)
Ko Nishikawa (University of Chicago/FNAL), Steve Geer (FNAL)

Muon Experiments:

Bob Bernstein (Fermilab), Graham Kribs, (University of Oregon)

Kaon Experiments:

Kevin Pitts (University of Illinois UC), Vincenzo Cirigliano (LANL)

EDMs:

Tim Chupp (University of Michigan) , Susan Gardner (University of Kentucky), Zheng-Tian Lu (ANL)

n-nbar oscillations:

Chris Quigg (FNAL), Albert Young (North Carolina State University)

Hadron physics:

Stephen Godfrey (Carleton University), Paul Reimer (ANL)

Conveners for PXPS
Enabling Technologies and Techniques

High rate Precision Photon Calorimetry:

David Hitlin (Caltech), Milind Diwan (BNL)

Very Low-Mass High-Rate Charged Particle Tracking:

Ron Lipton (FNAL), Jack Ritchie (University of Texas, Austin)

Time-of-Flight System Performance below 10 psec:

Mike Albrow (FNAL), Bob Wagner (ANL)

High Precision Measurement of Neutrino Interactions:

Kevin McFarland (Rochester University), Jonghee Yoo (FNAL), Rex Tayloe (University of Indiana)

Large Area Cost Effective (LACE) Detector Technologies:

Mayly Sanchez (Iowa State University), Yury Kamyshkov (University of Tennessee)

Lattice QCD:

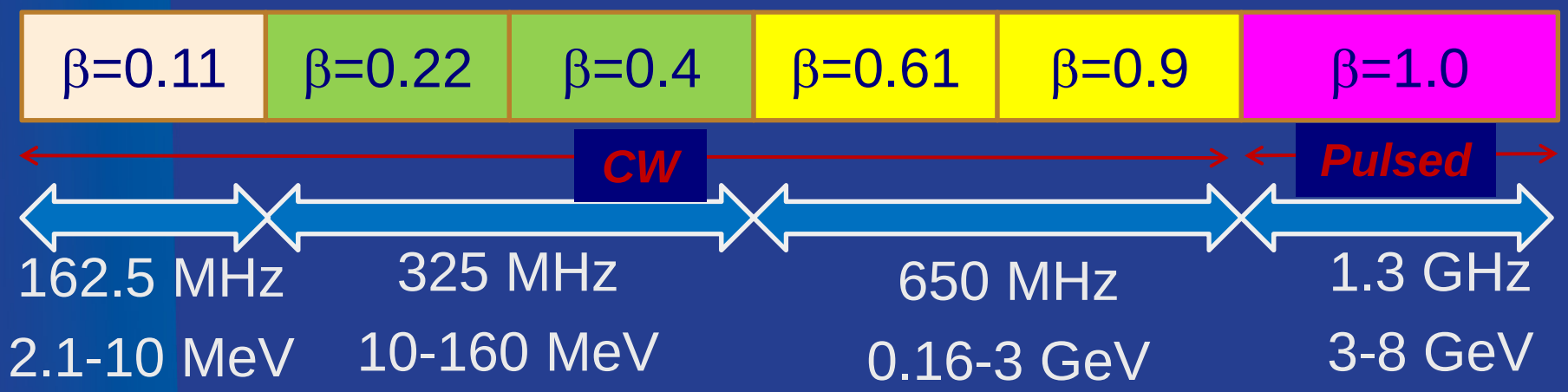
Ruth Van de Water (BNL), Tom Blum (University of Connecticut)

Project-X Accelerator Parameters (see PXPS website)

CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	1.0-3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power @ 3 GeV	3000	kW
Beam Power to 3 GeV program	2870	kW
RCS/Pulsed Linac		
Particle Type	protons/H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	0.002/4.3	msec
Cycles to MI	6	
Particles per cycle to Recycler	2.6×10^{13}	
Beam Power to 8 GeV program	170	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.3	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2450	kW

simultaneous

Project X SRF Linac Technology Map



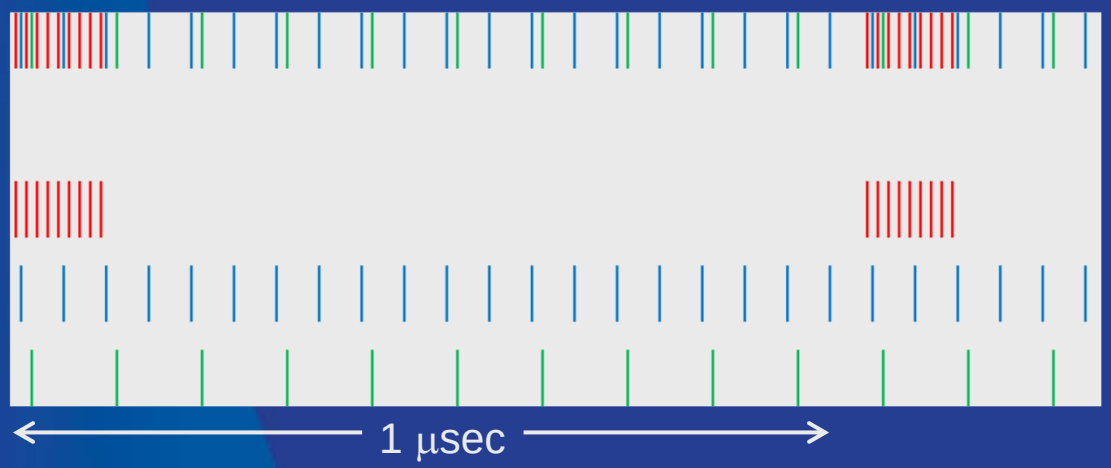
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	9/6/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/18/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

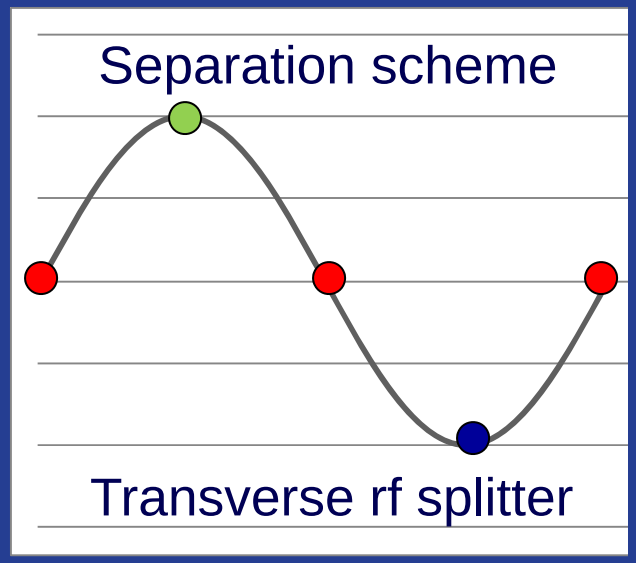
Operating Scenario for High Power Campus

1 μsec period at 3 GeV

Muon pulses (12e7) 162.5 MHz, 80 nsec	700 kW
Kaon pulses (12e7) 27 MHz	1540 kW
Nuclear pulses (12e7) 13.5 MHz	770 kW

Ion source and RFQ operate at 4.4 mA; 77% of bunches are chopped @ 2.1 MeV ⇒ maintain 1 mA over 1 μsec





Example Research Program, definitive space of accelerator parameters on PXPS Indico site

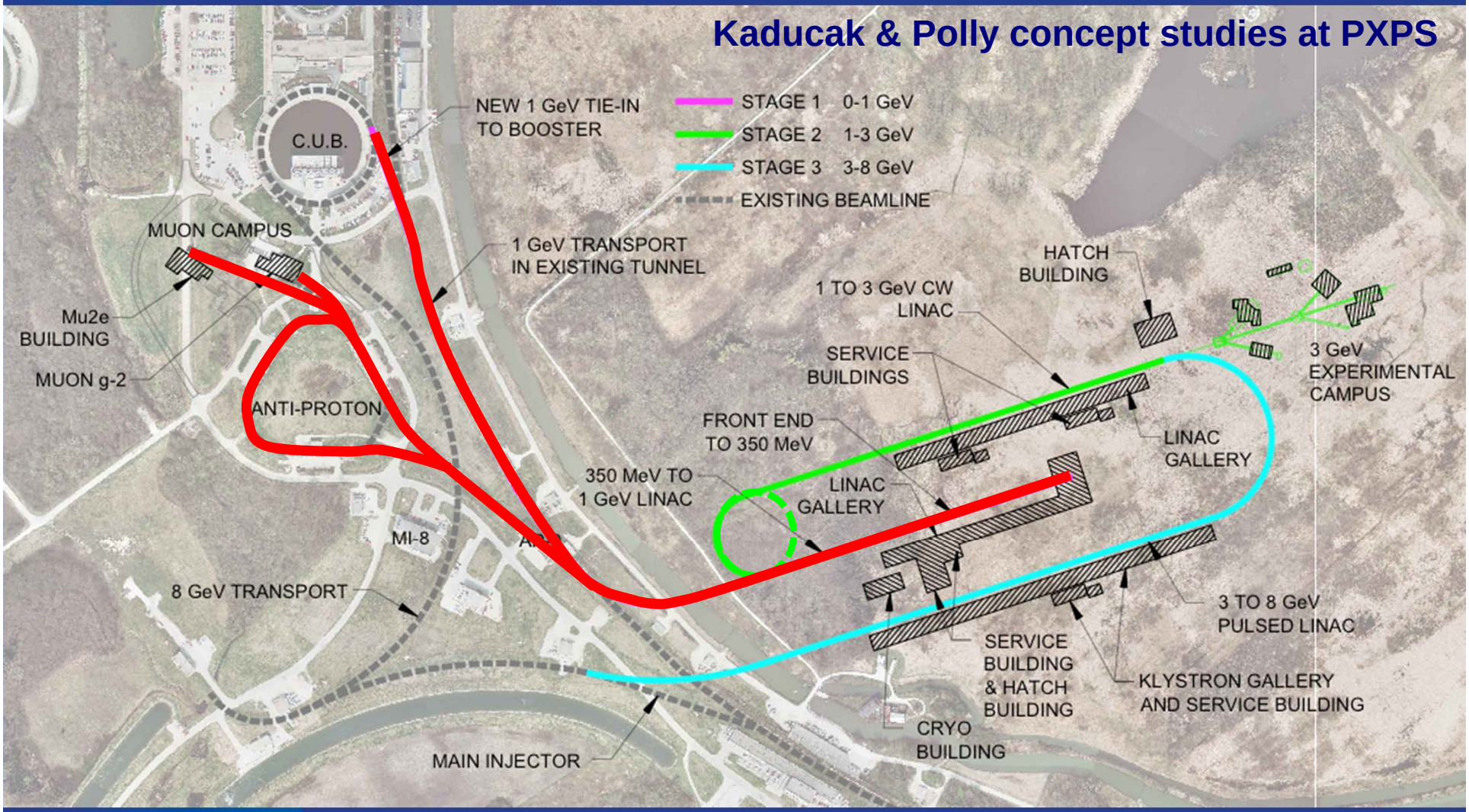
Project X Campaign

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 +0-50kW**	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.

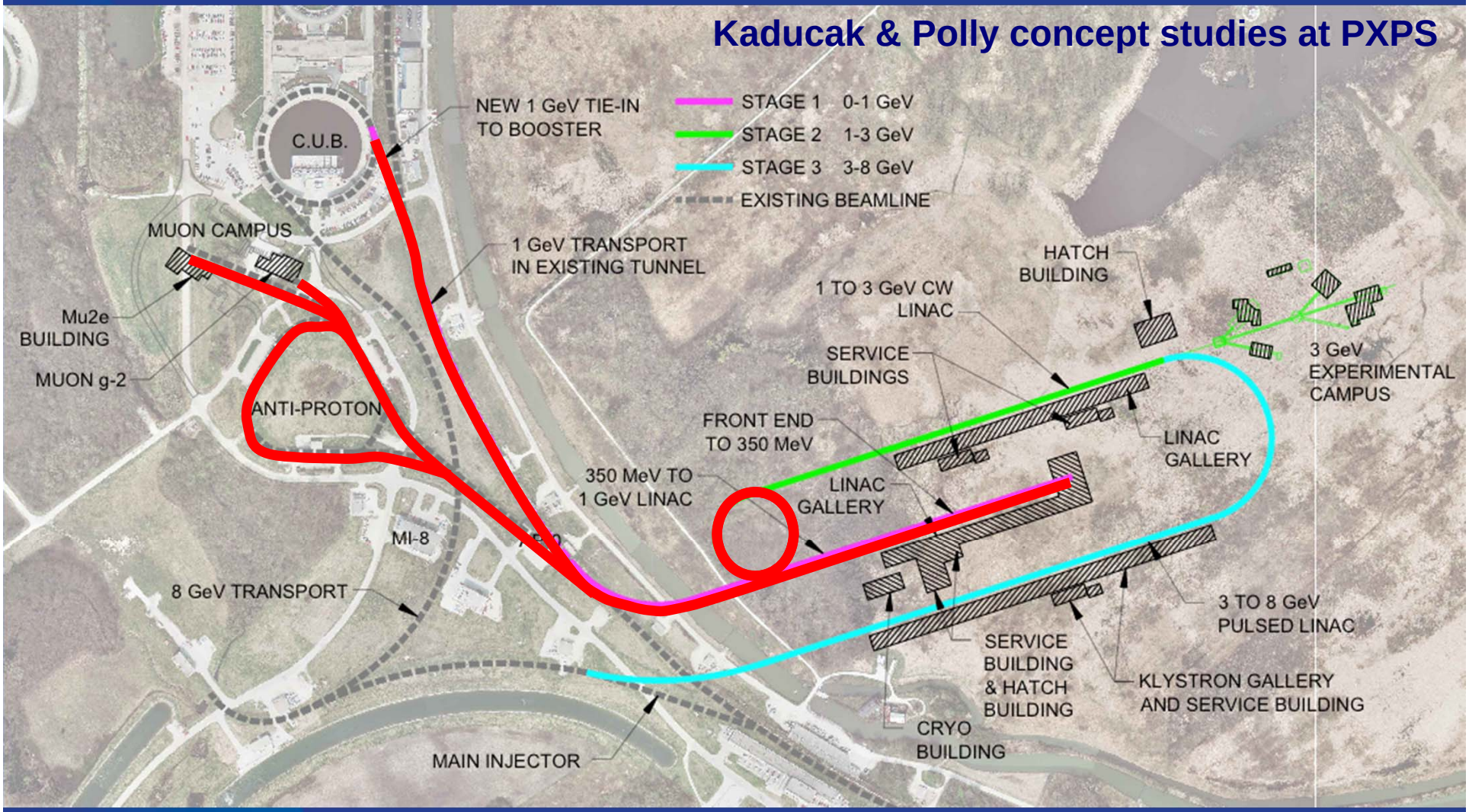
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Kaducak & Polly concept studies at PXPS



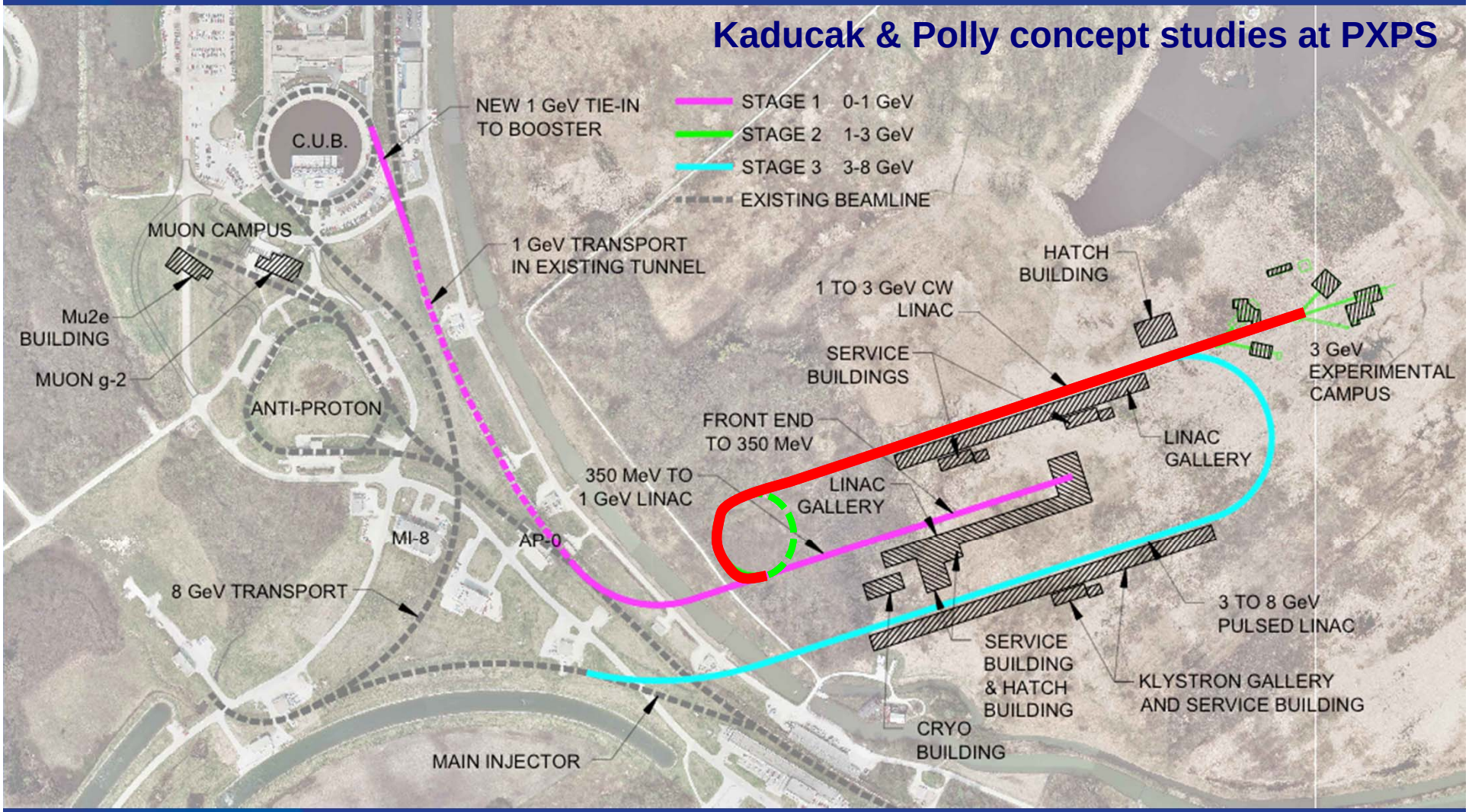
Stage 1: CW Linac (1 GeV, 1 mA) feeds Booster allowing 60-70% more beam at 8 and 120 GeV. 900 kW of CW beam remains at 1 GeV, and can be used in combination with existing AP0, former anti-proton rings, and new Muon Campus

Kaducak & Polly concept studies at PXPS



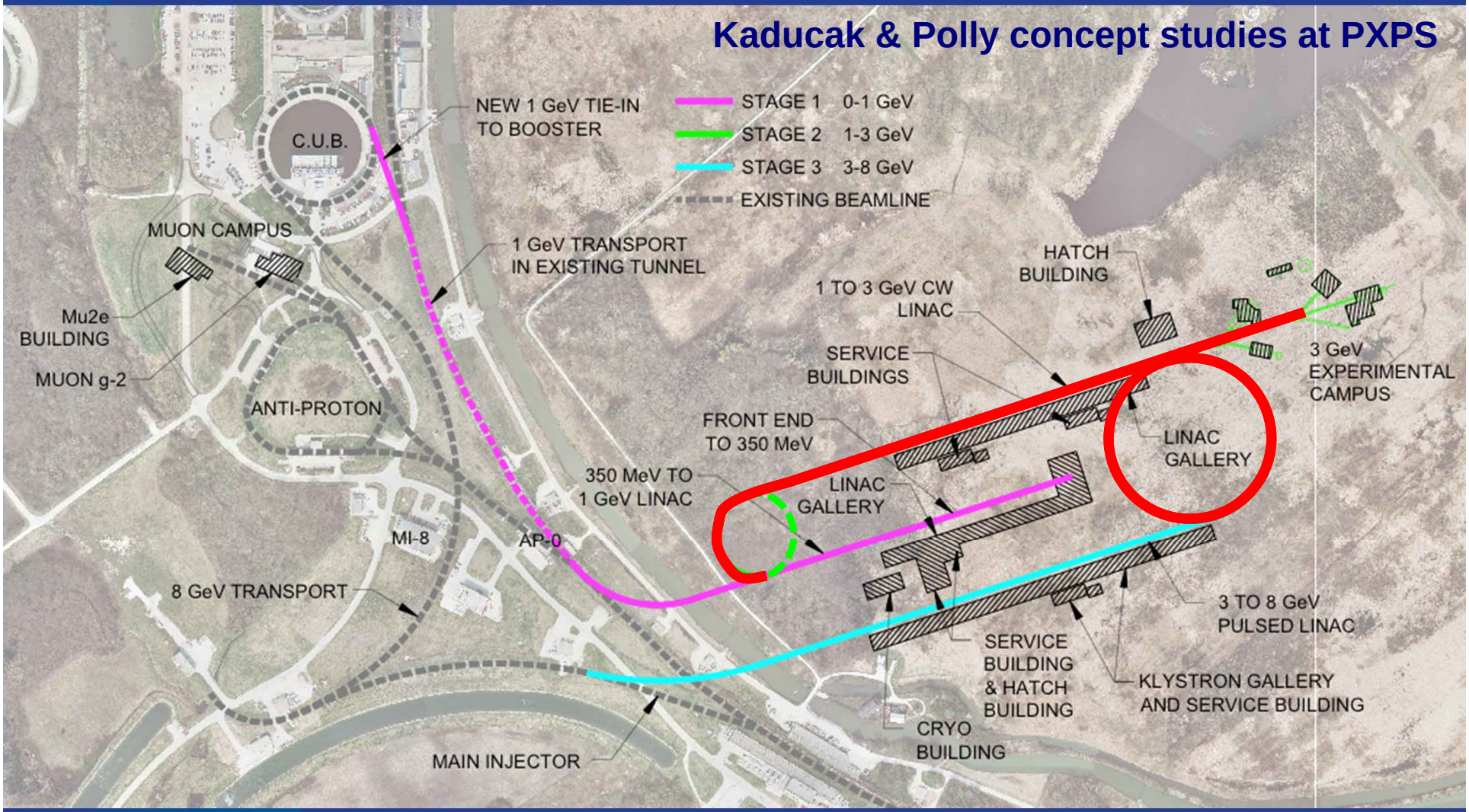
Stage 1a: A compressor ring allows non-CW experiments to be mounted in the existing 1 GeV experimental areas.

Kaducak & Polly concept studies at PXPS



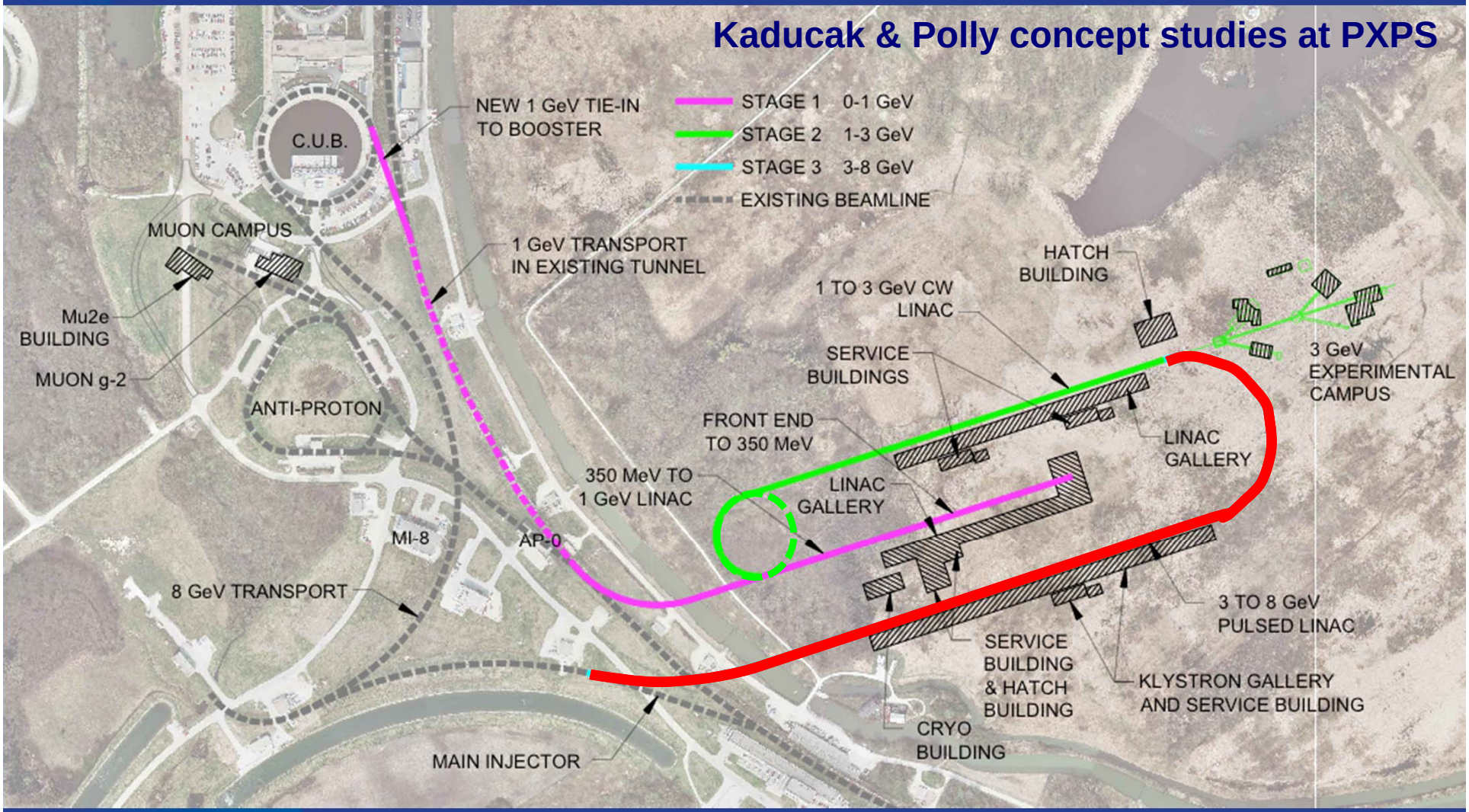
Stage 2: CW linac for 1 to 3 GeV constructed to feed new 3 MW experimental campus. Reuses first 180˚ of 1 GeV bunching ring for transport.

Kaducak & Polly concept studies at PXPS



Stage 2a: A compressor ring allows non-CW experiments to be mounted in the 3 GeV experimental areas.

Kaducak & Polly concept studies at PXPS



Stage 3: Pulsed linac constructed to feed Recycler. Reuses first 180˚ of 3 GeV bunching ring for transport.

Science Enabled with Stage-1

- Promotes the Main Injector to a Mega-Watt class machine for neutrinos, and increases the potential beam power for possible slow-spill experiments (e.g. ORKA).
- Potentially unshackles the $\mu \rightarrow e$ (Mu2e) experiment from the Booster complex: Potentially increases sensitivity of Mu2e by x10 - x100 with 1-GeV CW drive beam, consideration of a $\mu \rightarrow 3e$ program.
- World class ultra-cold neutron and ISOL-edm programs optimized for particle physics: e.g. edms & neutron$\Leftrightarrow$anti-neutron oscillations.
- Increases the available integrated 8 GeV power for other experiments (e.g. short-baseline neutrinos) from the Booster complex by liberating Mu2e.

Broad World-class Program in Neutrinos and Rare Processes

Science Enabled with Stage-2

- World leading kaon physics program: Megawatt power (x10 over competing facilities) can drive multiple experiments.
- World class muon physics program: Mu2e descendant migrates to a higher power campus. Megawatt power for conversion experiments (x10 over competing $\mu \rightarrow e$ facilities), opportunities for major next steps in other channels (e.g. $\mu \rightarrow 3e$, others).
- Maintains Main Injector beam power at lower energies (e.g. 60 GeV) enhancing the neutrino spectrum for long baseline experiments.

Science Enabled with Stage-3 (RDR)

- Main Injector power upgrade to >2 Mega Watts for 60-120 GeV beam, doubling power to long baseline Main Injector Neutrinos and Main Injector near-detector neutrino physics.

- 8 GeV beam power for experiments is doubled to now x10 the MiniBooNE era, which will support a new generation of short-baseline neutrino physics.

Science Enabled with Stage-4 (Beyond RDR)

- 4000kW @ 8 GeV and 4000kW at 60 GeV for the ultimate super beams.
- Double super-beam technique can tune illumination of the first and second maxima of long-baseline experiments of very massive next generation long-baseline detectors.
- Driver for an extremely powerful muon storage ring neutrino source, ultimately leading to a neutrino factory as motivated by the physics.

A Partial Menu of World Class Science Enabled by Project-X

Muon Physics: **Mu2e upgrade is a candidate Day-1 experiment**

- **Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.**
- Next generation $(g\text{-}2)_\mu$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \to 3e$
- $\mu^+ e^- \to \mu^- e^+$
- $\mu^- A \to \mu^+ A'$; $\mu^- A \to e^+ A'$; $\mu^- e^- (A) \to e^- e^- (A)$
- Systematic study of radiative muon capture on nuclei.

Mu2e Search for $\mu^- \rightarrow e^-$ conversion at 10^{-16}

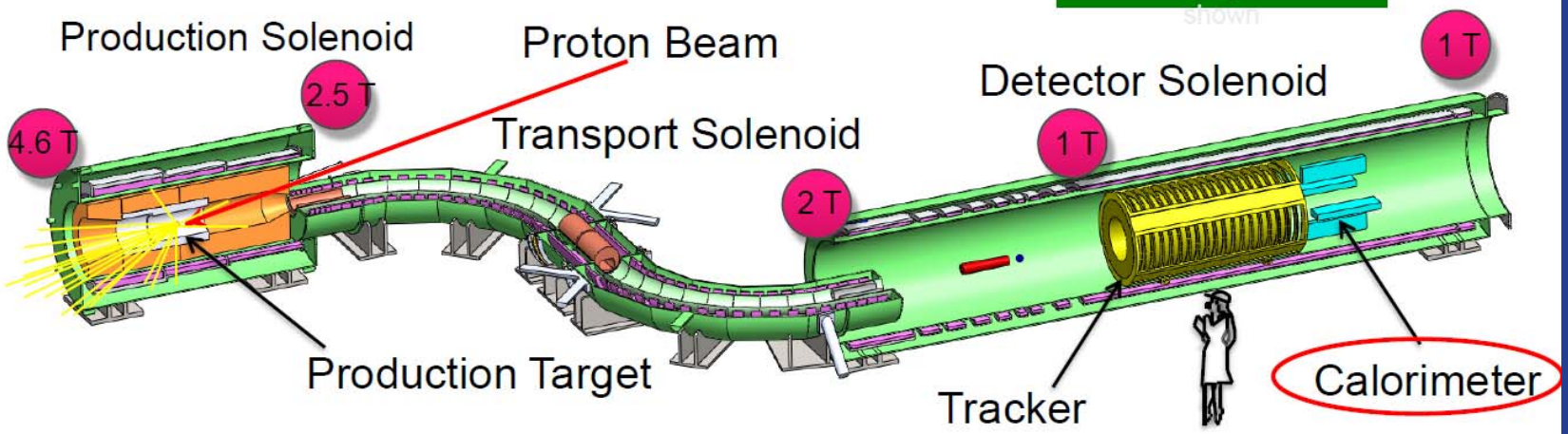
Production Solenoid
- Production target
- Graded field

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

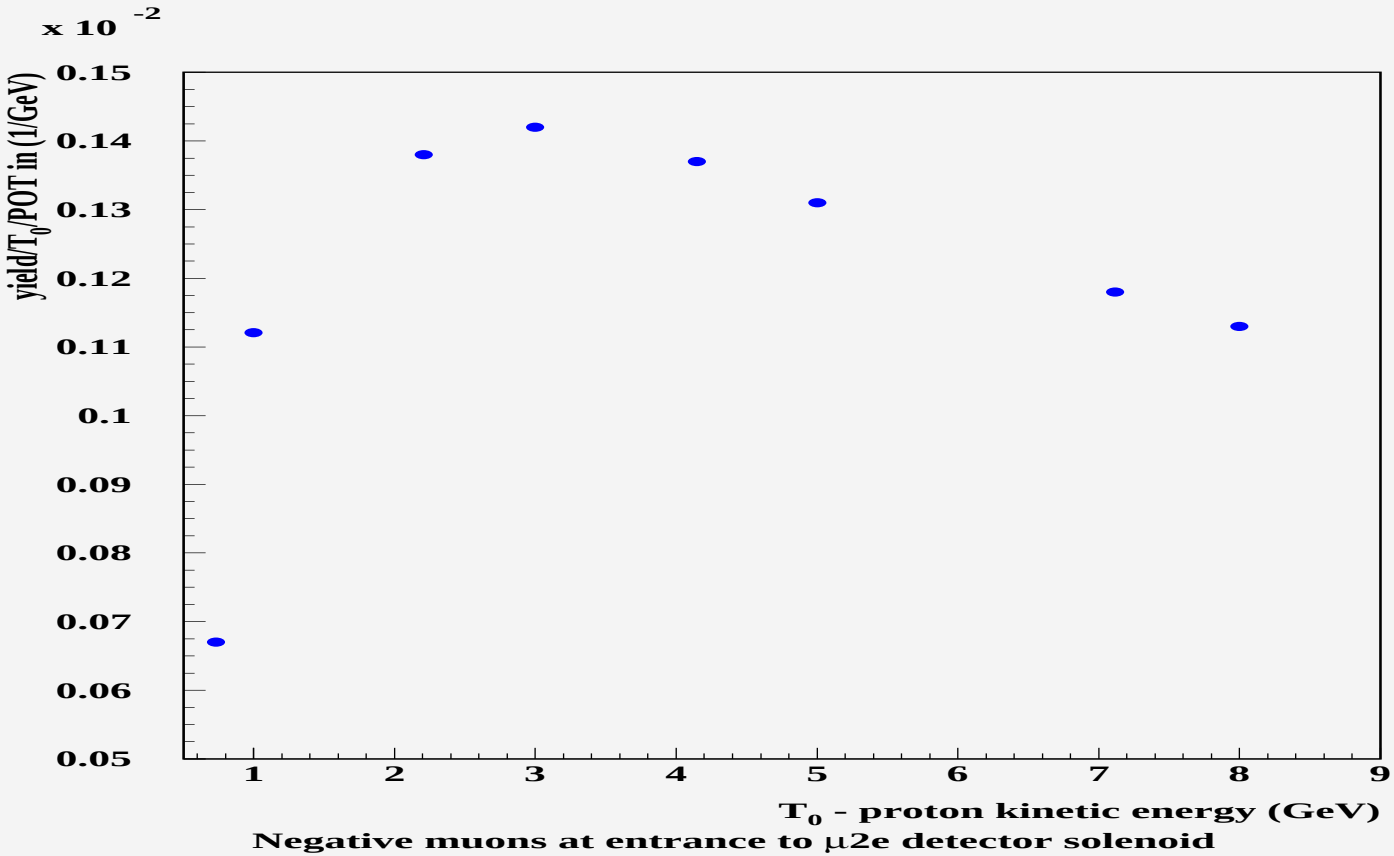
Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown



What is the optimum proton beam energy to drive a MELC/MECO/Comet-Mu2E experiment?

Yield / Watt



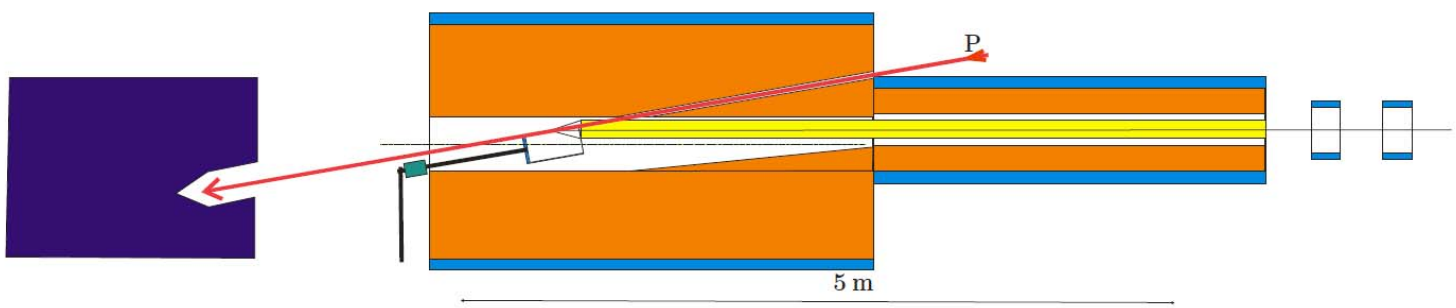
S. Striganov et al PXPS, work in progress

Issues That a Next-Generation Conversion Experiment must face…

- Target systems. High-Z stationary targets do not scale well with power.
- Radiation damage: Production Solenoid, Readout systems (e.g. SiPMs).
- Readout speed, rate robustness.
- Spectrometer resolution…much better than 100 keV/c??
- Spectrometer calibration: Internal (Michel edge, $\pi e2$)?
  External (electron injection)?
- Background Rejection!

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

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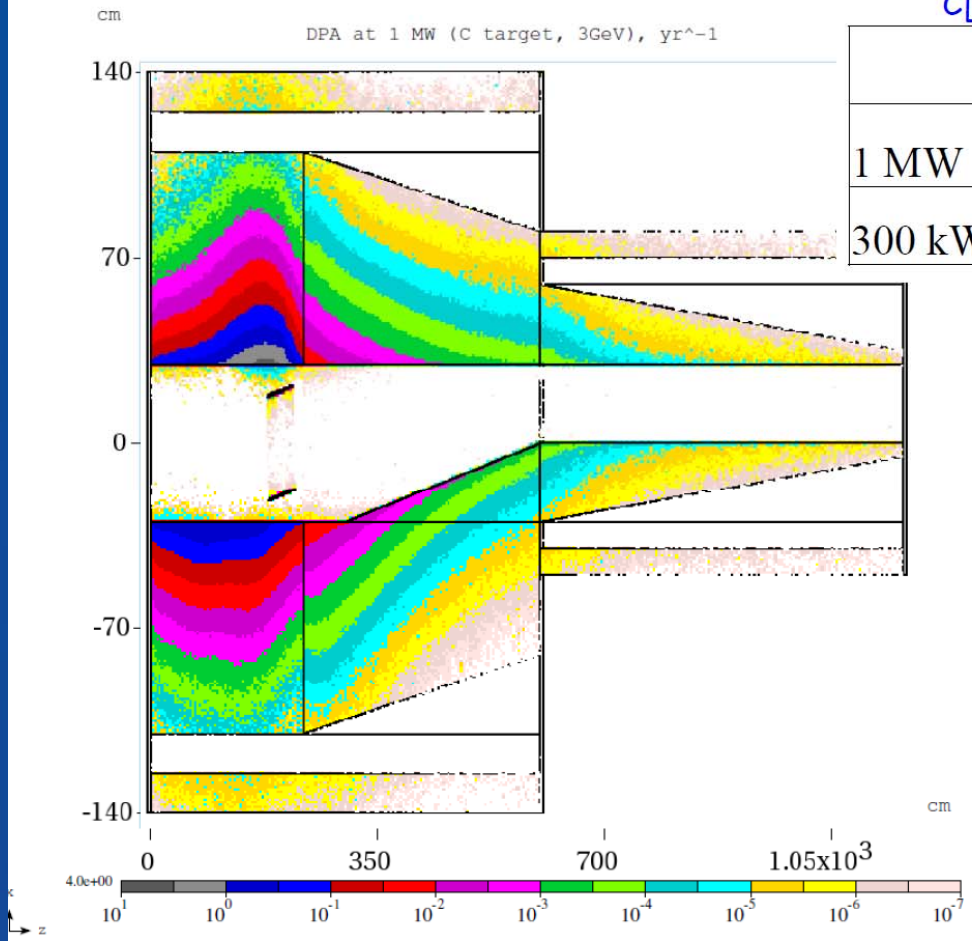
V. Lebedev, Fermilab AAC 2011

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 → 3 T for the same stored energy

Muon Task Force, Valeri Lebedev

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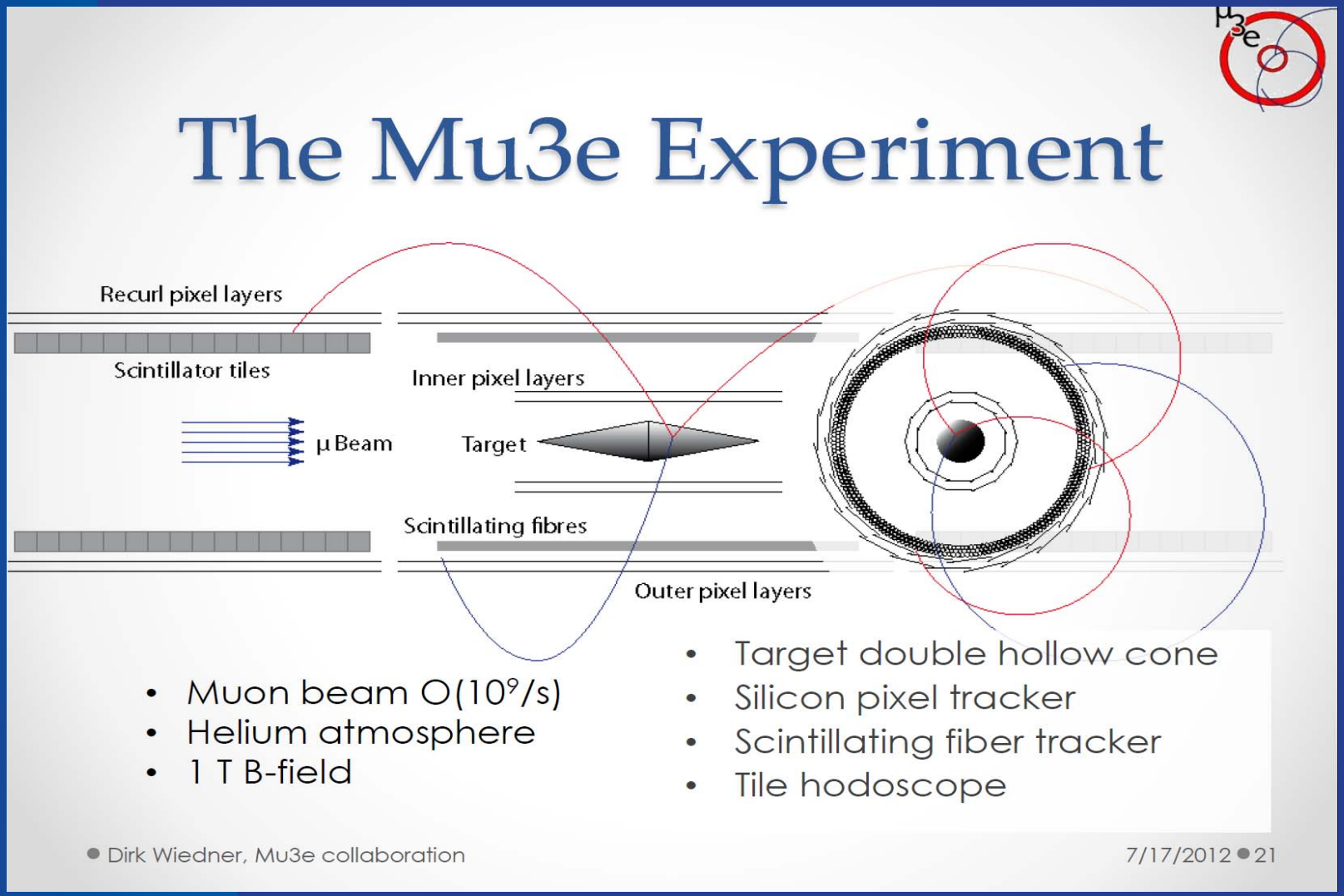
V. Lebedev, Fermilab AAC 2011

Opportunities with Project –X to meet these Challenges

- Much better proton pulse timing. ~10 nsec as compared to 200 nsec (Mu2e, COMET) for the same power level, <100 nsec at 1 MWatt!. Radiative Pion Capture background much reduced.
- No anti-proton background.
- High power can mean fewer stopping target foils, possibly colder beams.
- Can realize optimum cold-muon-yield/driver-power

0.1% X_0 per layer, 100 psec track timing…

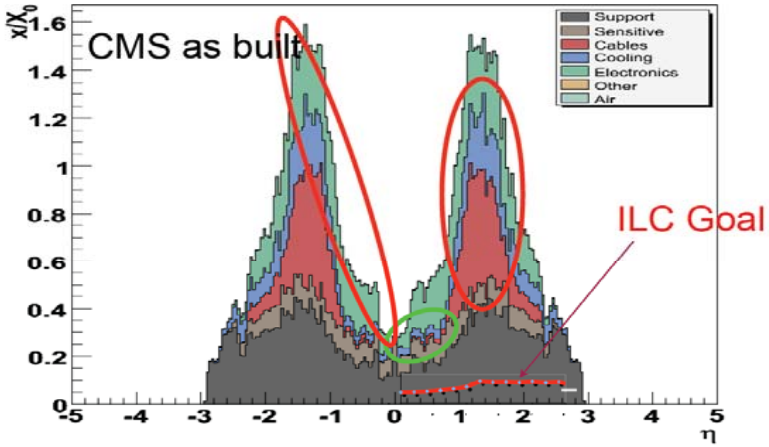


Dirk Wiedner, Mu3e Initiative at PSI

Project-X era muon experiments must journey far beyond the state of the art in tracking…

Power Consumption

- Limiting Power consumption is crucial for low mass pixelated detectors (CMS Tracker- 17 kAmp)
  - Move electronics off-detector
  - Limit power to allow air cooling
  - Use CO_2 cooling
- There are basic power-speed and detector tradeoffs



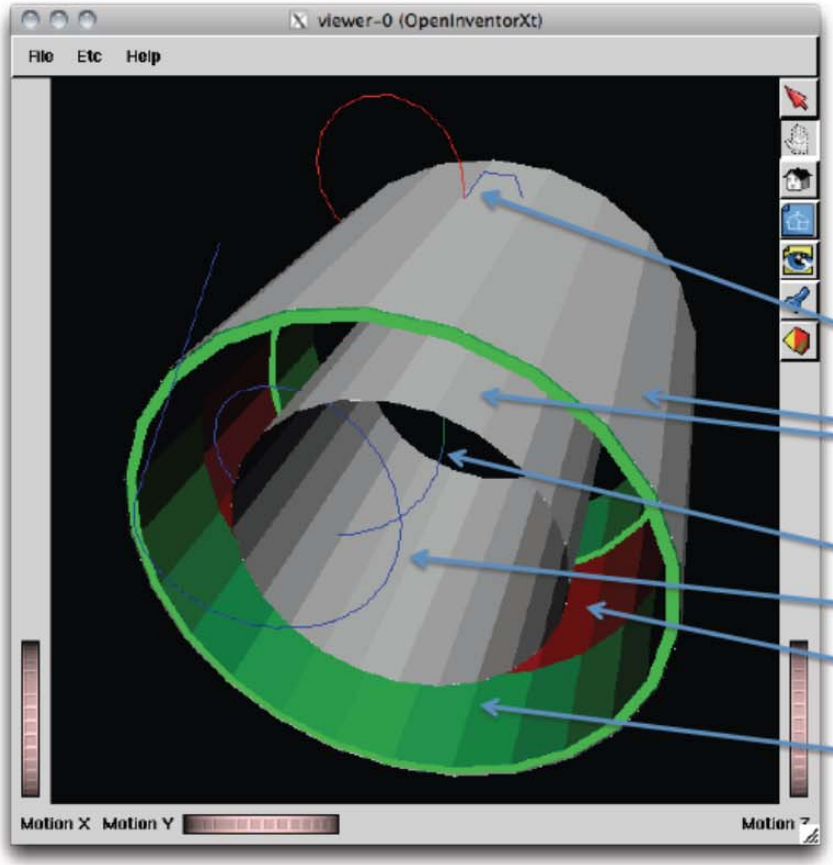
	# Pixels / chip	Pixel area [mμ²]	Idig [mA]	Iana [mA]	Power/ chip [mW]	Power/ pixel [μW]	Power density [mW/cm²]
ALICE	8192	21'250	150	300	810	99	466
ATLAS	2880	20'000	35	75	190	67	335
CMS	4160	15'000	32	24	121	29	194
CMS	no on-chip regulators				87	21	142

(R. Horisberger)

R. Lipton, Tracking Summary PXPS

μ→eγ with converted γ (DeJong)

The simple minded geometry seems to work. Needs many m^2 pixel tracking



Target radius ~2 cm

B = 0.5 T
Positron R = 35 cm

Converted photon

Double pixel layers
R = 47 cm and 75 cm

μ -> *e* γ decay from stopped muon

Positron

Converter

Calorimeters or tof
triggering, tof

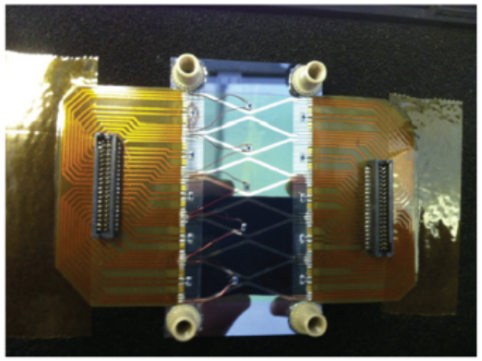
Many design constraints and options - need mass to convert photons, minimal mass for tracking, separation of layers, resolutions ....

Frtiz Dejongh, PXPS

CERN NA62 “Giga-tracker” at PXPS

Gigatracker - Cooling and Performance (Velghe)

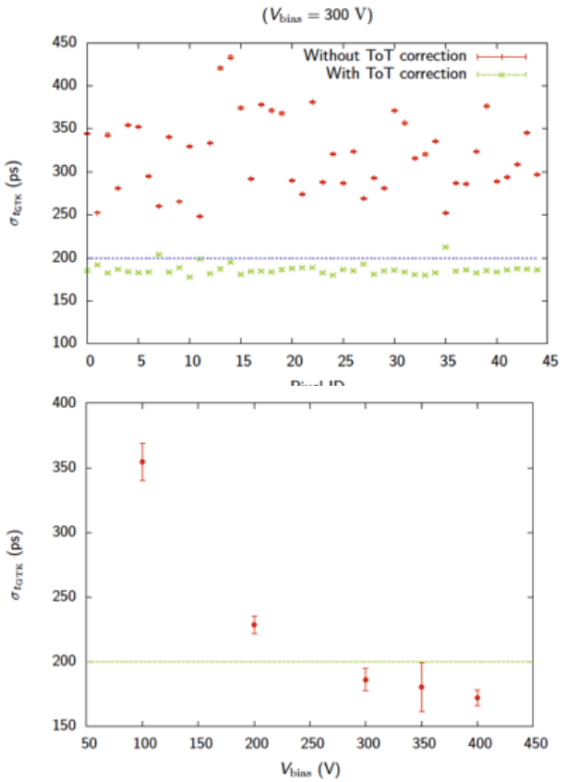
Baseline - micro channel cooling



Material in the acceptence area: 0.13%X_0

Frame Option

45 pixel prototype performance

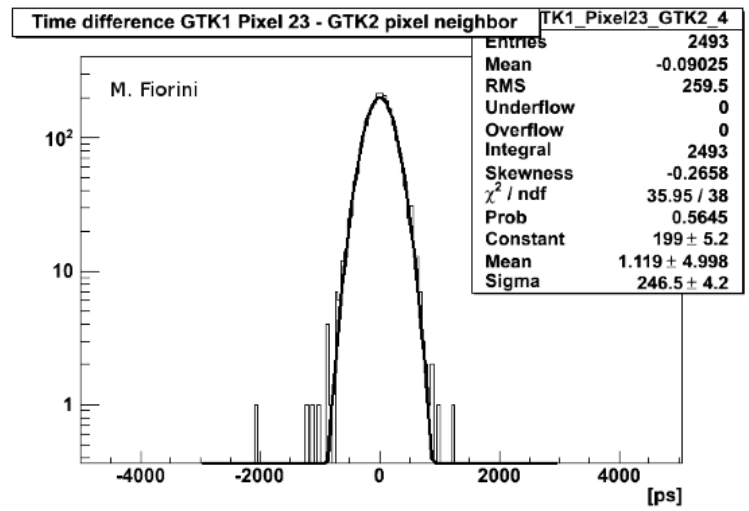


Thursday, June 21, 12

CERN NA62 “Giga-tracker” at PXPS

Timing depends on:

- Impact position on pixel,
- Sensor bias voltage,
- Electronic noise of the frontend,
- Energy straggling in the sensor bulk,



After ToT correction: $V_{\mathrm{bias}} = 300\ \mathrm{V} \rightarrow \sigma_t = 246\ \mathrm{ps}/\sqrt{2} = 175\ \mathrm{ps}$

GigaTracker is

- Fast, $\sigma_t < 175\ \mathrm{ps}$ at $V_{\mathrm{bias}} = 300\ \mathrm{V}$
- Thin, $X/X_0 < 0.5\%$
- Innovative, it takes advantage of micro channel cooling, the frame option looks promising

Bob Velghe, PXPS

Summary

- Project-X is a staged evolution of the best assets of the Fermilab accelerator complex with the revolution in super-conducting RF technology.
- Each Stage of Project-X is an opportunity to drive several next generation muon experiments forward.
- Project X opportunities will be based on the successes of the current generation now being planned and designed. Programs in the design phase now should be cognizant of potential Project-X gains.