LA-UR- 09-06305

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Title: Possibility of a muon-electron conversion experiment at LANSCE

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Intended for: LANSCE User Group Meeting

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Form 836 (7/06)

Possibility of a muon-electron conversion experiment at LANSCE

Takeyasu Ito, LANL P-25

Coherent neutrinoless conversion of a muon into an electron in the field of a nucleus is a process that violates the conservation of the lepton family number. With the recent discovery of neutrino oscillation, we now know that lepton flavor violation does occur. However, lepton flavor violation with charged leptons has yet to be observed. The rates for charged lepton flavor violating processes mediated by neutrinos are extremely small, because of the smallness of the neutrino masses. This makes charged lepton flavor violation a sensitive probe for New Physics. In fact, there are many extensions of the standard model that predict such processes at levels that are within the reach of the next generation experiments. While such experiments are actively pursued and discussed at laboratories around the world, it has been brought to our attention that the LANSCE accelerator might in fact be the world's best facility to construct and perform a new muon to electron conversion experiment. In this talk, a motivation for a new muon to electron conversion experiment and the possibility at LANSCE will be discussed.

Possibility of a Muon Electron Conversion Experiment at LANSCE: Search for Physics Beyond the Standard Model

Takeyasu Ito

LANL,P-25

Team

- Takeyasu Ito, P-25
- Martin Cooper, P-25
- Xiaodong Jiang, P-25
- Haruo Miyadera, AOT-ABS
- Pete Walstrom, AOT-ABS
- Rod McCrady, AOT-ABS

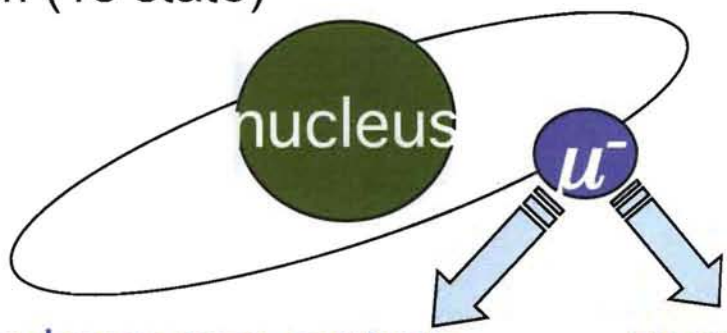
Outline

- Introduction
  - What is muon-electron conversion?
  - Goal of this ER, the objectives for this FY
- Status
  - Beam delivery options (McCrady, Walstrom)
  - LANSCE Linac dark current measurement (Walstrom, McCrady)
  - Muon capture on Al experiment at PSI (Miyadera)
- Future directions

Muon-Electron Conversion

(Neutrinoless coherent muon to electron conversion in the field of a nucleus)

- Muonic atom (1s state)



nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

muon decay in orbit

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

- Neutrinoless muon conversion to electron

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

coherent process

Lepton family numbers change by one unit

  - Single monoenergetic electron of $E_{max} = (M_\mu - B_\mu)$ MeV (~105 MeV)
  - Rate is normalized to the kinematically similar weak capture process:

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N \rightarrow e^- N\right)}{\Gamma\left(\mu^- N \rightarrow \nu_\mu N(Z-1)\right)}$$

$$\Gamma\left(\mu^- N \rightarrow \nu_\mu N(Z-1)\right) = 0.7 \times 10^6/\text{sec for Al}$$

$$= 2.6 \times 10^6/\text{sec for Ti}$$

$$\Gamma\left(\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e\right) = 0.5 \times 10^6/\text{sec}$$

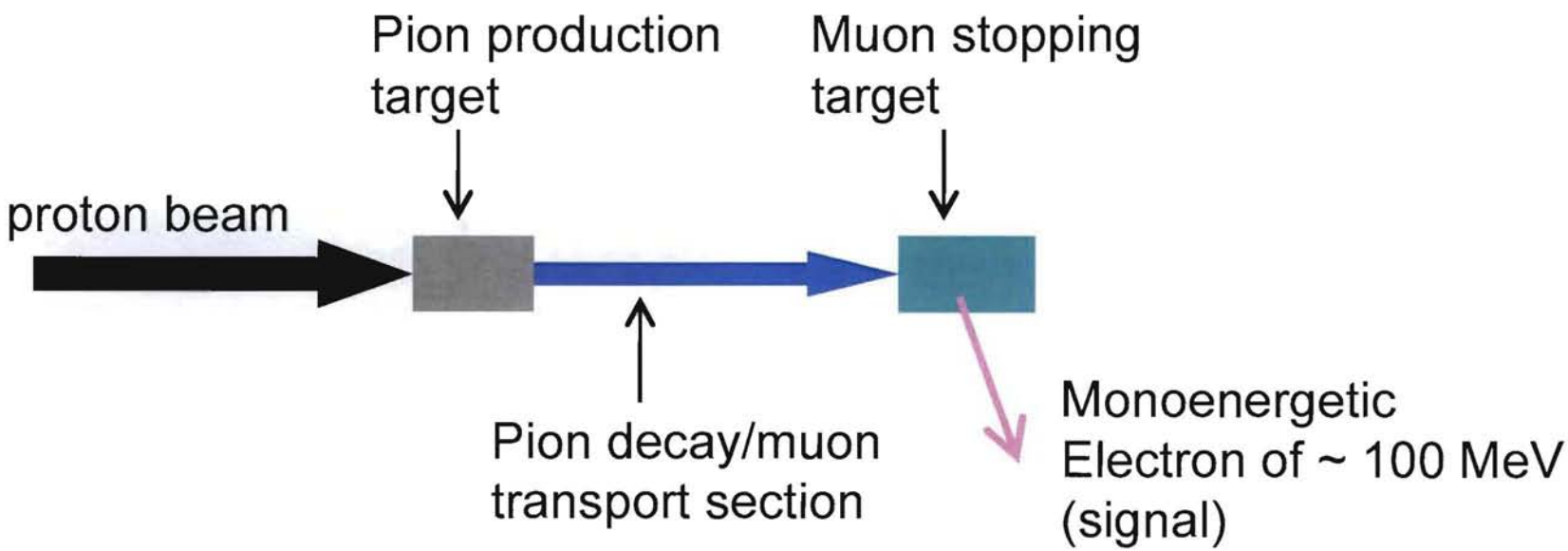
Muon-electron Conversion

- A process in which a muon (the muon is a heavy brother of the electron) is converted to an electron without emission of neutrinos .

$$\mu^- N \rightarrow e^- N$$

- Violates lepton flavor conservation and branching ratio is very small in the Standard Model (BR~10^{-50})
- Violation of lepton flavor conservation is known to occur with neutral leptons (neutrino oscillations) but has not yet been observed with charged leptons.
- Current experimental limit is BR (branching ratio) < 6×10^{-13}
- Sensitive probe of Physics beyond the Standard Model.
- An experiment sensitive to BR~10^{-16} has a great discovery potential, as such an experiment probes energy scale of ~ TeV and higher and many extension of the Standard Model predict muon-electron conversion at that level.

Principle of Muon-electron conversion experiment

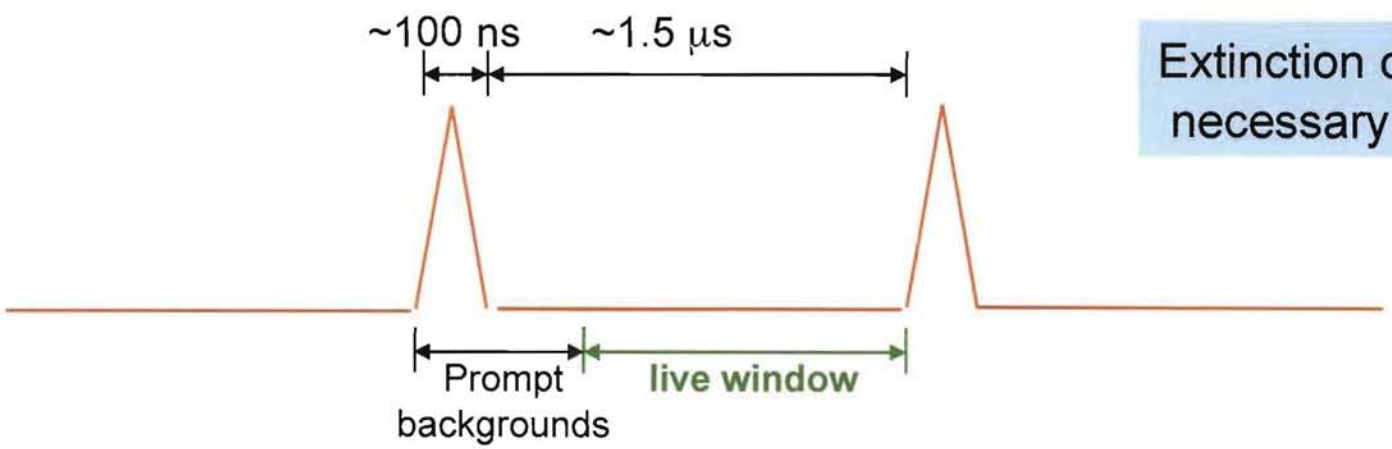


Lobashev's proposal — MELC Experiment

Basic principle

R. M. Dzhilkibaev and V.M.Lobashev, Sov. J. Nucl. Phys. **49**, 385 (1989)

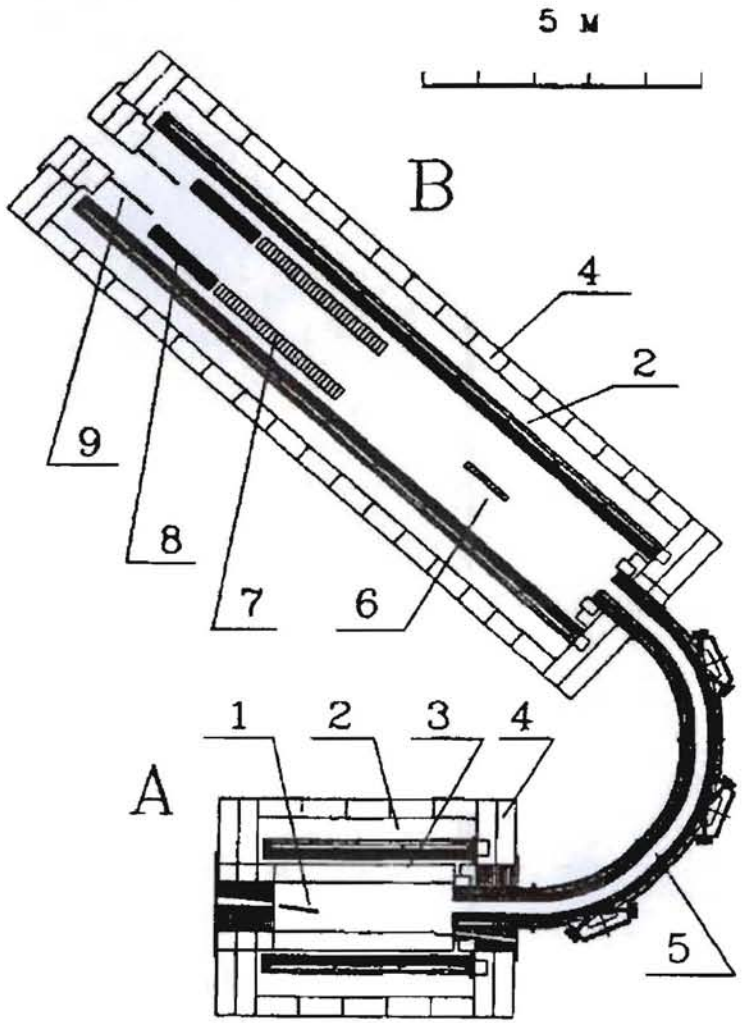
- Solenoidal muon capture system with an axial field gradient
  - More efficient production of pions and muons per proton by a factor of 10^4
- Muon production by pulsed proton beam
  A. Baertscher *et al.*, Nucl. Phys. **A377**, 406 (1982)
  - Removes prompt beam related background



Extinction of ~ 10^{-9} is necessary

MELC Experiment
Solenoidal Muon Capture System

R. M. Dzhilkibaev and V.M.Lobashev, Sov. J. Nucl. Phys. **49**, 385 (1989)
R. M. Djilkibaev and V. M. Lobashev, AIP Conf. **372**, 53 (1995)



1. Muon production target
2. Superconducting solenoids
3. Solenoid shield
4. Magnet yoke
5. Solenoid collimator
6. Muon stopping target
7. Wire chambers
8. Calorimeter
9. Shield against beam

The solenoidal muon capture system increases muon production rate by 10^4

Next generation mu-e conversion experiments

Experi-ment	Acceler-ator	Goal	Beam energy	Beam power	μ stopping rate	Status
MELC	Moscow Meson Factory	$R_{\mu e}$~10^{-16} *	0.6 GeV	120 kW*	10^{11}/sec *	Cancelled
MECO	BNL-AGS	$R_{\mu e}$~2×10^{-17}	8 GeV	51 kW (26 kW)	10^{11}/sec	Cancelled
Mu2e	FNAL	$R_{\mu e}$~2×10^{-17}	8 GeV	23 kW	5×10^{10}/sec	CD-0
Mu2e	FNAL-Project X	$R_{\mu e}<10^{-18}$ (90% C.L)	8 GeV	90 kW (200 kW)		LOI
COMET	J-PARC MR	$R_{\mu e}$~4×10^{-17}	8 GeV	50 kW	2.8×10^{10}/sec	Proposal
PRISM/ PRIME	J-PARC	$R_{\mu e}<10^{-18}$	40 GeV	670 kW	up to 10^{12}/ sec	LOI

* From Djilkibaev and Lobashev, AIP Conf. **372**, 53 (1995)

Possibility at LANSCE

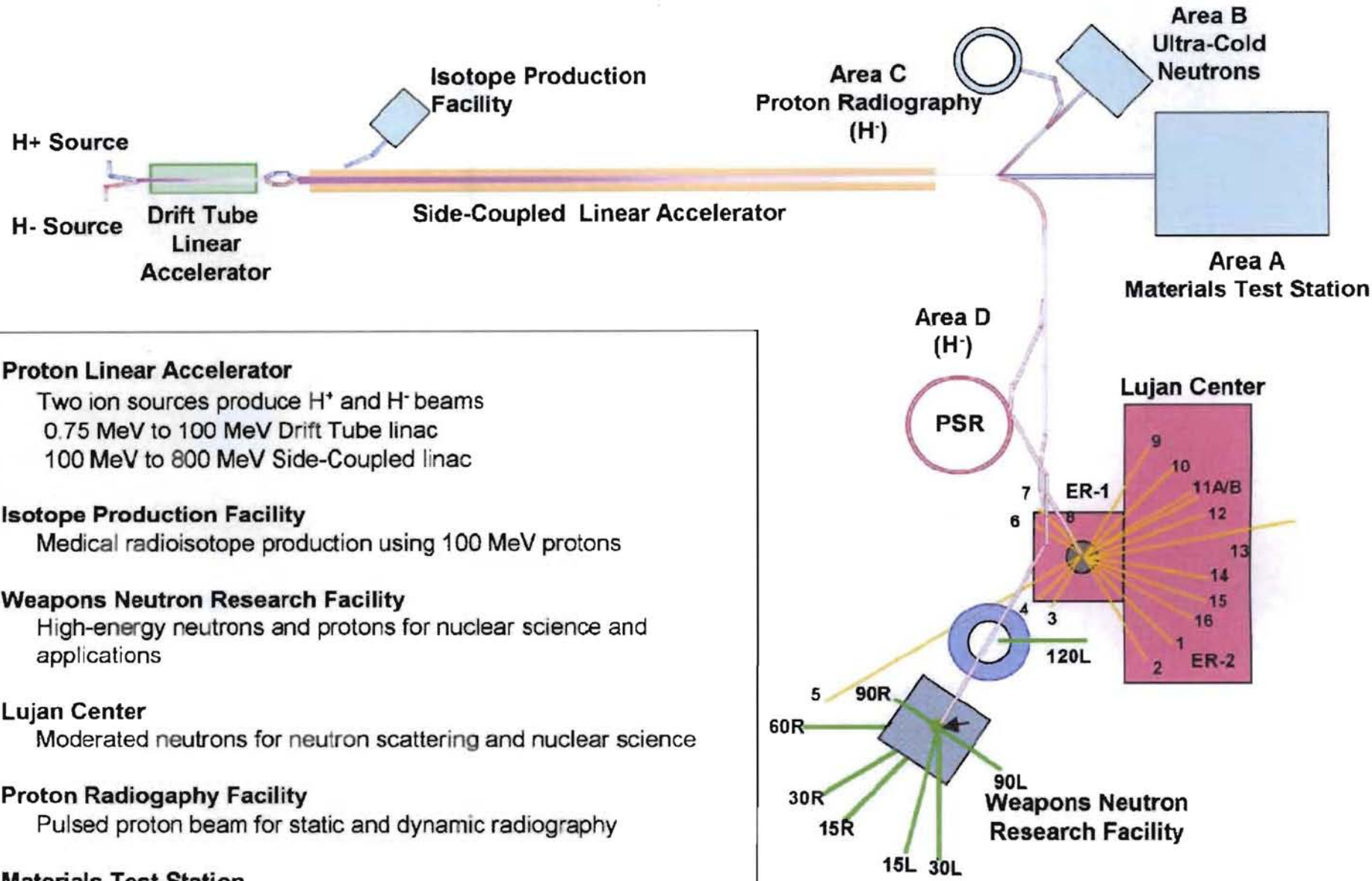
- LANSCE Accelerator - 800 MeV, ~ 1 MW linac
  - One of the highest power linacs in the world
  - More flexible operation possible than at Synchrotrons
- Can a MELC/MECO/Mu2e/COMET type experiment be performed at LANSCE? Can it do better at LANSCE?
  - Is such an experiment compatible with existing and planned operations?
  - Can we achieve the necessary pulse structure and extinction?
  - How does the pion production at 800 MeV compare to that at 8 GeV? How many muons can we stop in the stopping target in a given time?
- Preliminary answer: yes to all
  - Necessary pulse structure can be achieved with the front end chopper.
  - 800 MeV energy is well matched for producing low energy muons (2-5 times more usable muons per unit beam power at 800 MeV than at 8 GeV).
  - It seems possible to mount such an experiment in a manner compatible with existing and planned operations. But a further study is necessary.
  - There seems to be a path forward in the issue of extinction. A further study is necessary.

Goal of the ER

- The goal of the ER project is to develop the idea of the experiment far enough to produce a proposal to the DOE NP for construction of such an experiment, performing necessary simulation studies as well as necessary experimental studies. We adopt the scheme originally proposed by Lobashev which uses short intense pulses of muons. Alternatively, if one of the competing projects (Mu2e at FNAL, COMET at J-PARC) turned out to be funded (or likely to be funded), we will consider joining it so that we can contribute to the science.
- This ER, if successful, will lead to a construction of an experiment that will have an immense scientific discovery potential. This research is well aligned with the Laboratory's Grand Challenge on "Beyond the Standard Model."

Objectives for this year

1. Explore possible beam operation modes, beam delivery options, and possible sites of the experiment.
2. Perform measurements of the LANSCE beam properties (experiment): achieving a high extinction (the ratio of the accelerator current between beam-off vs beam-on, needs to be ~10^{-9}) is very important. We plan to measure the extinction of the LANSCE accelerator achievable just with the front-end chopper, and also measure the phase space distribution of the dark current.
3. Evaluate various detector options for the detector for the extinction measurement .
4. Establish expected sensitivity of the experiment at LANSCE (simulation).
5. Measure the particle spectrum from muon capture on aluminum at PSI in collaboration with Mu2e and COMET (experiment):this is a major physics background process and having high quality data on the final products (particle species and energy spectrum) is crucial in optimizing the design of the experiment.



Proton Linear Accelerator
Two ion sources produce H^+ and H^- beams
0.75 MeV to 100 MeV Drift Tube linac
100 MeV to 800 MeV Side-Coupled linac

Isotope Production Facility
Medical radioisotope production using 100 MeV protons

Weapons Neutron Research Facility
High-energy neutrons and protons for nuclear science and applications

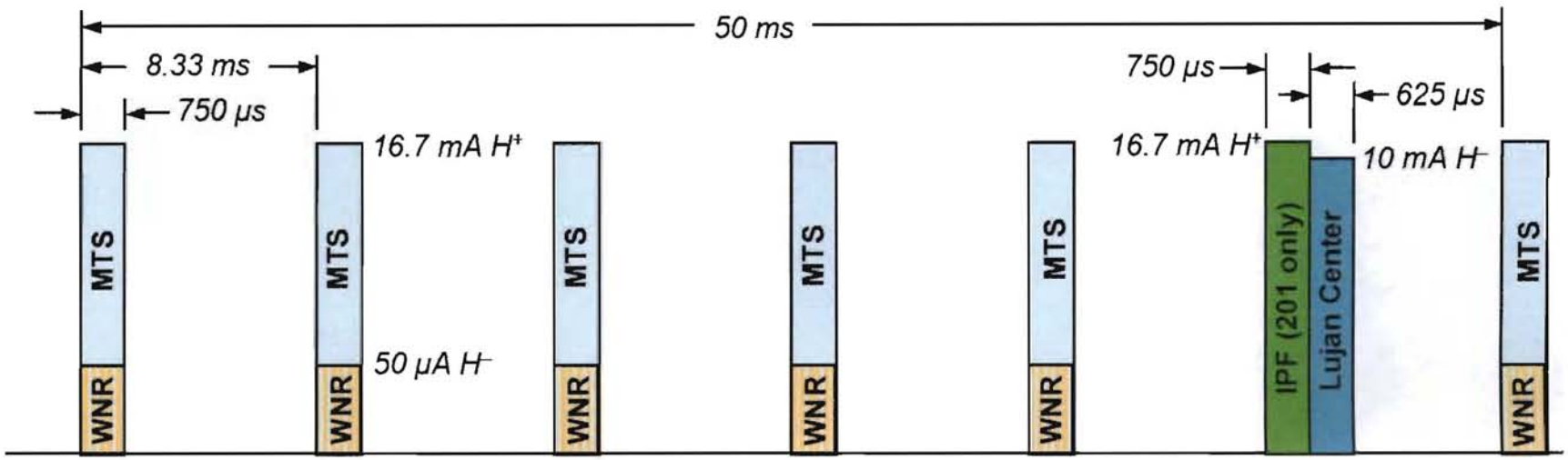
Lujan Center
Moderated neutrons for neutron scattering and nuclear science

Proton Radiogaphy Facility
Pulsed proton beam for static and dynamic radiography

Materials Test Station
High-power fast neutron irradiation of reactor fuels and components

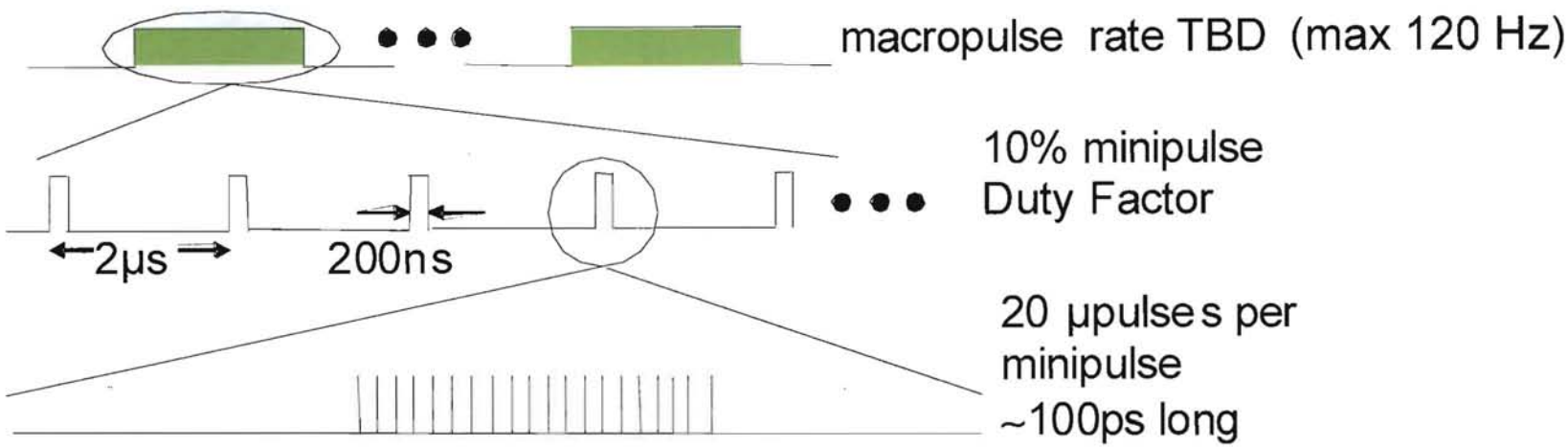
Ultra Cold Neutron Facility
Fundamental physics experiments with UCN

LANSCE Beam Structure with MTS



Target	Time-Averaged Current (μA)
Materials Test Station (MTS)	1250
Isotope Production Facility (IPF)	250
Lujan Center	125
Weapons Neutron Research facility (WNR)	5
Proton Radiography (PRad)	on demand
Ultra-Cold Neutron Source (UCN)	on demand

Proposed μ-e beam time structure
(McCrady, Walstrom)



60kW desired (80μA at 800MeV)

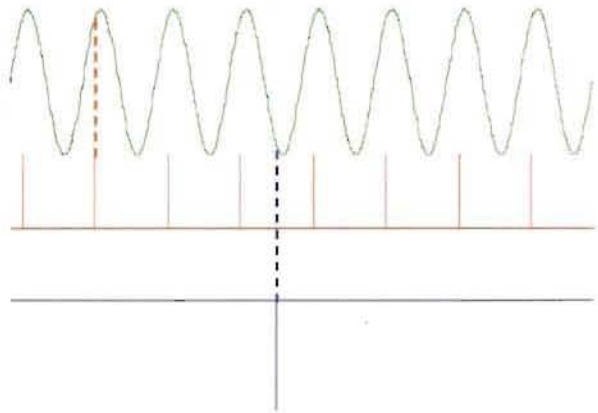
<u>Estimates of maximum beam current:</u>

H^-: 12mA peak current × 10% × 625μs = 0.75 μC per machine cycle
(At 120 Hz, this corresponds to 90 μA)

H^+: 21mA peak current × 10% × 625μs = 1.3 μC per machine cycle
(At 120 Hz, this corresponds to 156 μA)

How can μ-e beam run on other beams' macropulses? (McCrady)

Cycle sharing

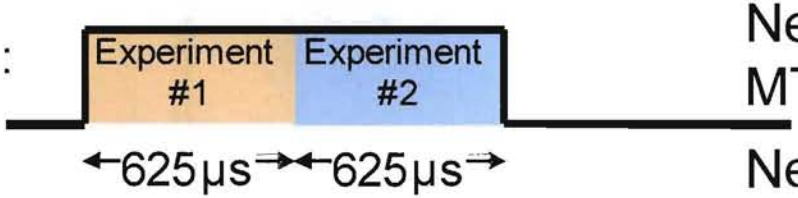


H^+ & H^- in the same macropulse simultaneously.

Total beam current ≤ 21mA

Cycle splitting

linac macropulse :



Need long macropulse. MTS upgrade?

Need relatively fast kicker if sharing one species

Cycle slicing

linac macropulse :

Need *very* fast kicker

Beam delivery options (McCrady, Walstrom)

Option	Description	$H^{+/-}$	Possible current	Comments
Cycle sharing with Lujan	H^+ to μ-e simultaneous with H^- to Lujan	H^+	26μA	•Need pulsed magnet to select MTS / μ-e •Need a chopper for H^+ •20Hz only •Need fast kicker or some other mechanism to get extinction of H^+
Cycle slicing with MTS	Slice 100 Hz H^+ macropulse	H^+	130μA	•Reduces MTS current (10% + kicker "filling" + rise time.) •Enormous potential background •More expensive to send H^+ to Line D (southern LANSCE)
Cycle slicing with WNR	Slice 100 Hz H^- macropulse	H^-	42μA	•The effect of the low-frequency buncher

H^+ vs H^-

H^+	H^-
•Higher peak current •Larger background when H+/H+ cycle slicing •Heed to install a chopper at LEBT	•Can share cycles with H^+ (need to slice with Lujan or WNR) •Easier to send to Southern LANSCE •Smaller peak current

Siting options (McCrady, Walstrom)

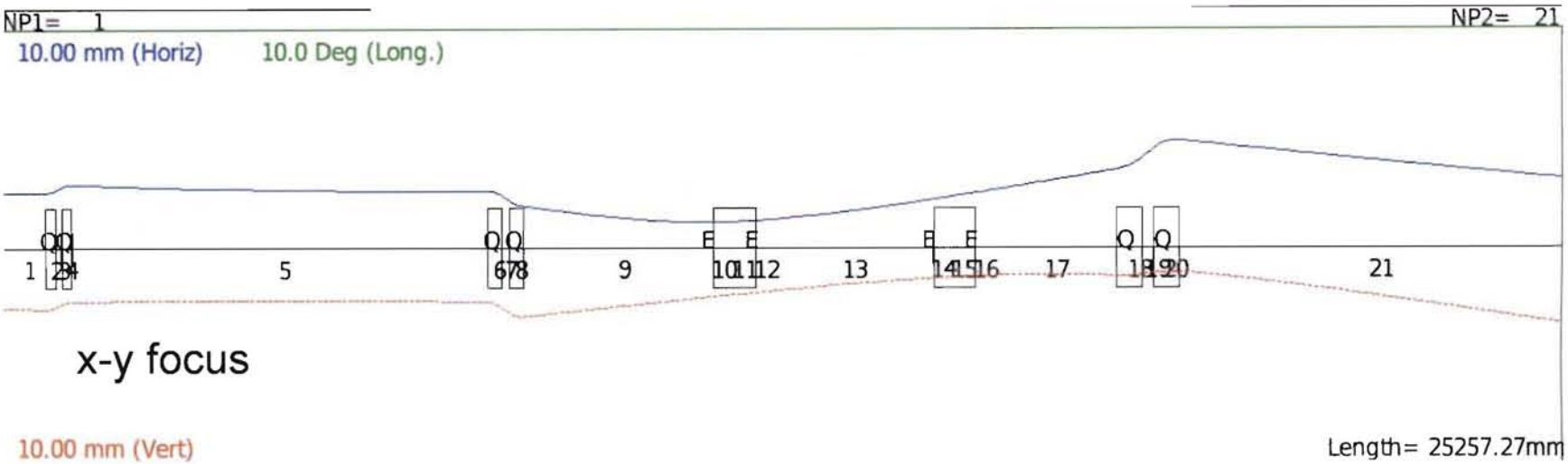
- Line D/E
  - H^- only unless we "think big"
  - New building
- Line A
  - Natural for H^+
  - Squeeze into Area A with MTS?
- Line X
  - Will Area B be available then?
  - H^- presently, but could be converted for H^+

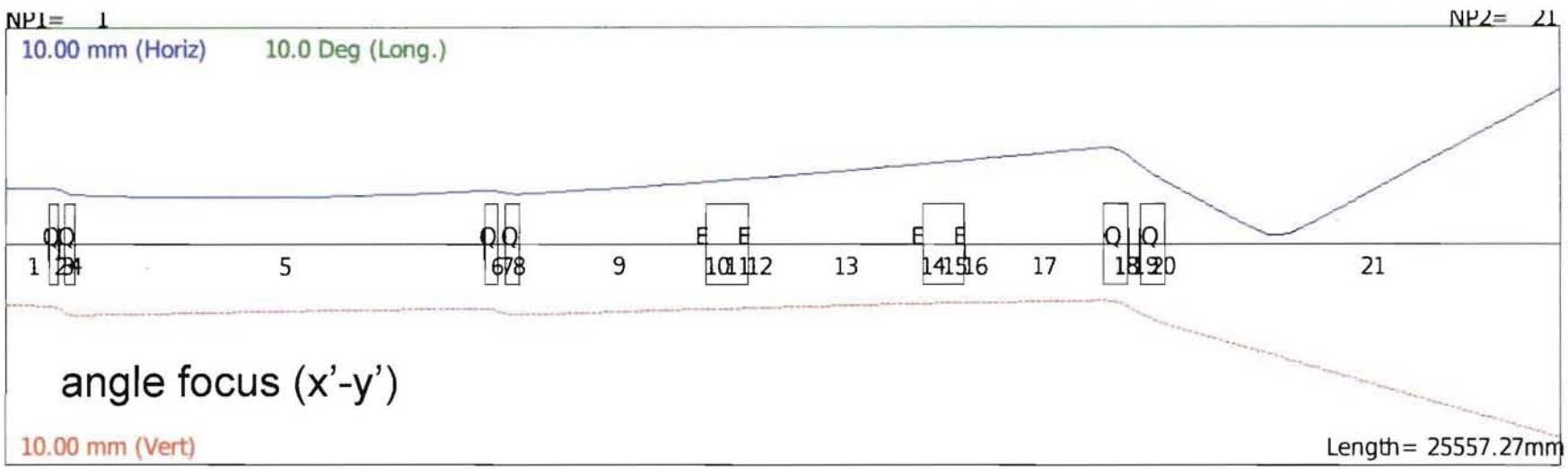
By utilizing existing facilities, the cost can be significantly reduced.

Dark Current Phase-Space Measurement Purpose and Method (Walstrom, McCrady)

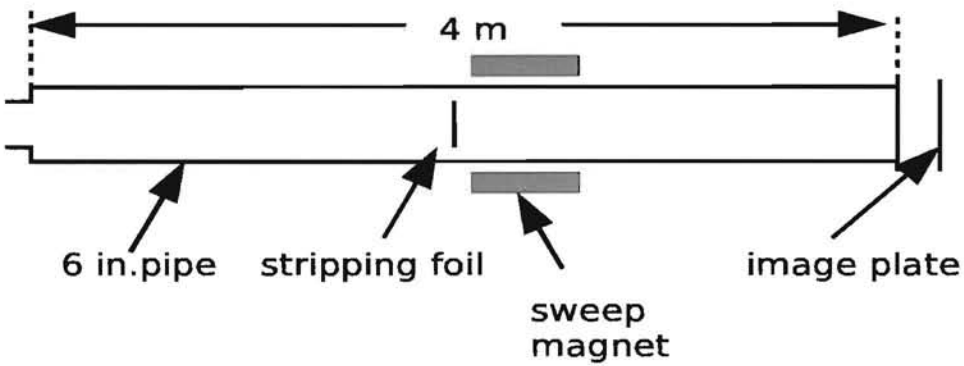
- Mu-e conversion experiment requires a 10^{-9} extinction (= ratio of beam intensity when the beam is off to the intensity when the beam is on).
- It is necessary to measure the base extinction of the LANSCE accelerator. Also it is important to know the phase space distribution of the dark current (the remaining beam when the beam is off) in order to design an appropriate extinction device.
- We are preparing to perform an experiment to measure the 4-D phase-space distribution at the end of the linac. We will use existing beamline quadrupoles to form a magnetic lens to image the dark-current phase space on a an image plate. The image plate is scanned and digitized.
- Single unchopped beam microbunches will be used for intensity calibration.
- Beam time is requested for the machine development period at the end of August.
- The results of this experiment will be used as input for the extinction device (fast kicker) performance study.

Beam envelopes for x-y focus and angle focus (Walstrom)





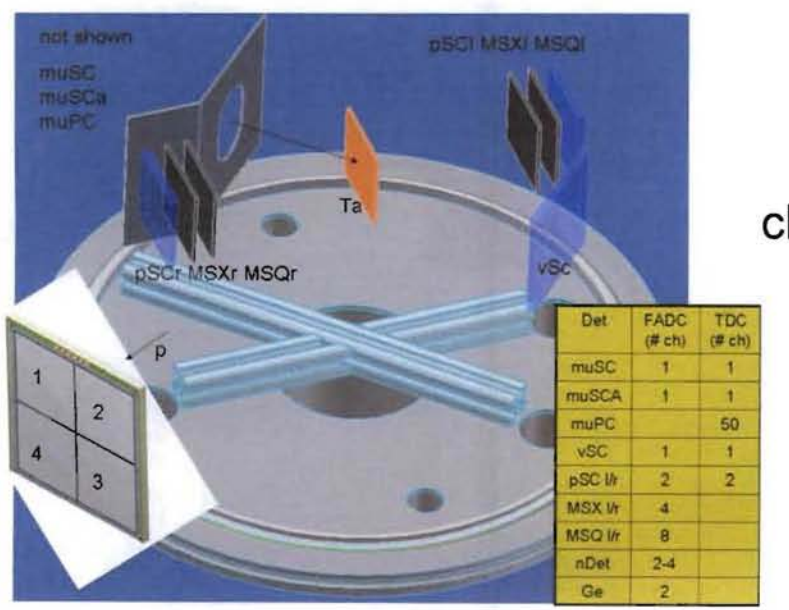
Beamline extension (Walstrom, McCrady)



- Beam pipe extension is being designed and fabricated by AOT-MDE.
- Includes pipe stands, view port, image-plate holder
- Stripping foil on order (125 mm dia. 500 $\mu g/cm^2$ carbon foil)
- To be installed in the switchyard

Measurements of the reaction products of muon capture on Al (Miyadera)

- Goal: measure the energy spectrum of protons, neutrons, and gammas from muon capture on aluminum.
- Method: use low energy beam at Paul Scherrer Institut in Switzerland. This is a joint effort between LANL, Mu2e collaboration, and COMET Collaboration. LANL is in charge of neutron measurement. Liquid scintillator will be used for neutron spectrum measurement.
- Status: beam time schedule for early July. Neutron detector tests were performed at LANL (see next slide).



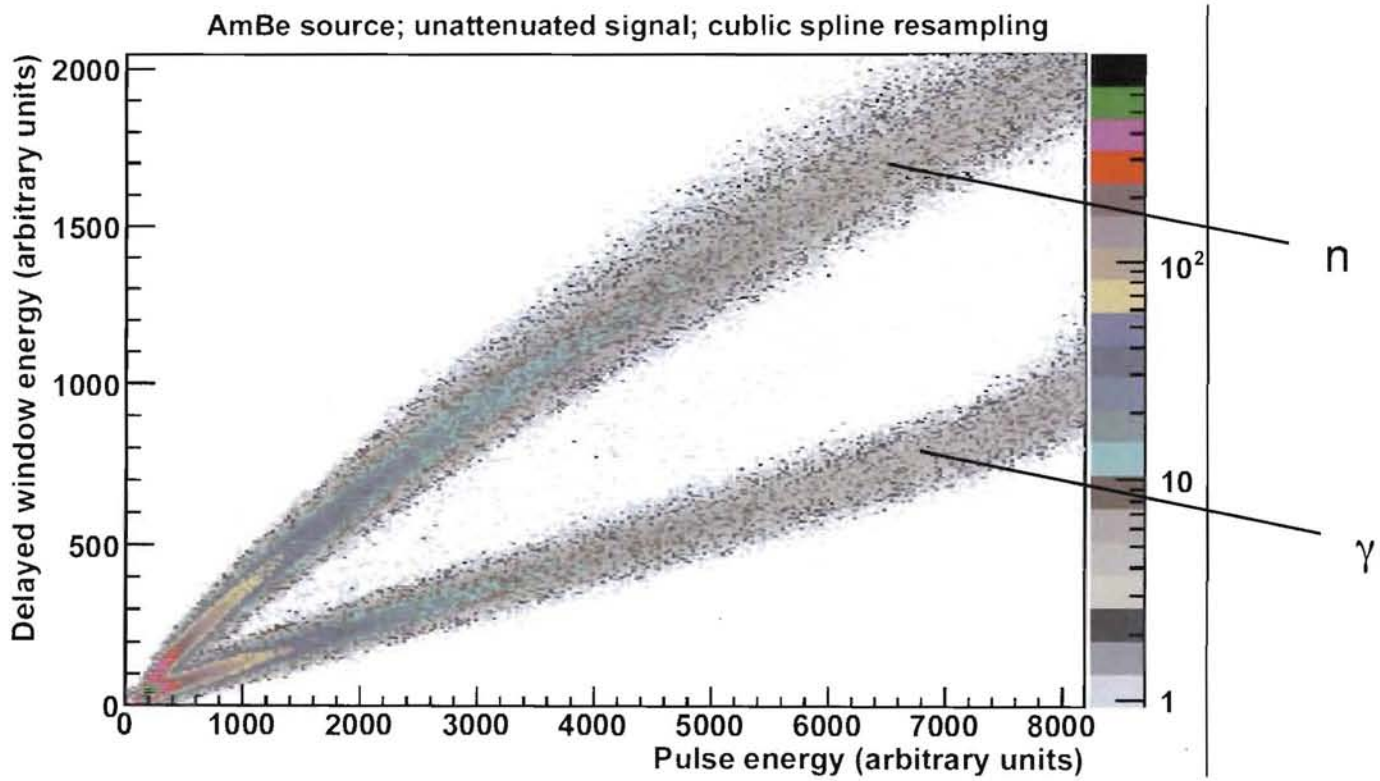
Det	FADC (# ch)	TDC (# ch)
muSC	1	1
muSCA	1	1
muPC		50
vSC	1	1
pSC l/r	2	2
MSX l/r	4	
MSQ l/r	8	
nDet	2-4	
Ge	2	

chematic of the apparatus.

Publishable results expected from this experiment.

Test of liquid scintillation detector at LANL (Miyadera)

- We performed a test experiment at LANL using an AmBe source to evaluate different schemes of neutron/gamma discrimination of liquid scintillator for the PSI experiment to measure muon capture on aluminum.
- Tested schemes include FADC developed by F. Gray of Regis U.
- An excellent neutron gamma discrimination was achieved (a factor of 1.5 better FOM).



Changes in political climate

High Energy Physics program supports research to understand how our universe works at its most fundamental level. This is accomplished by discovering the most elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time itself. HEP is focused on three scientific frontiers in particle physics: the Energy Frontier, the Intensity Frontier, and the Cosmic Frontier. Research includes theoretical and experimental studies by individual investigators and large collaborative teams: some who gather and analyze data from accelerator facilities in the U.S. and around the world; and others who develop and deploy ultra-sensitive ground- and space-based instruments to detect particles from space and observe astrophysical phenomena that advance our understanding of fundamental particle properties. HEP also invents new technologies to meet the challenges of research at the frontiers such as superconducting radio frequency technologies. The Tevatron Collider at Fermi National Accelerator Laboratory continues operations during FY 2010. Its record-breaking performance over the last few years means it remains competitive with the Large Hadron Collider (LHC) in Geneva, Switzerland, for significant discoveries. Support for LHC detector operations, maintenance, computing, and R&D continues in FY 2010 in order to maintain a U.S. leadership role in the LHC program. Construction continues for the NuMI Off-Axis Neutrino Appearance (NOvA) project to enable key measurements of neutrino properties. R&D for proposed new experiments using the NuMI beam and other auxiliary beamlines, such as the Long Baseline Neutrino Oscillation Experiment (LBNE) and the Muon to Electron experiment (Mu2e), will be underway so these experiments can be ready for operation before the end of the next decade. Several national and international collaborative projects to pursue questions in dark matter, dark energy, and neutrino properties continue in FY 2010, including the Cryogenic Dark Matter Search at the Soudan Mine in Minnesota, the Dark Energy Survey experiment in Chile, and R&D for the Joint Dark Energy Mission, the Large Synoptic Survey Telescope, and R&D efforts for experiments that may be located in the National Science Foundation's proposed Deep Underground Science and Engineering Laboratory (DUSEL). HEP also continues supported for advanced accelerator and detector R&D and R&D in superconducting radio frequency technology applicable to a variety of future accelerator projects.

Taken from DOE FY 2010 Congressional Budget Requests Budget Highlights

Possibility of joining the Mu2e project.

- We have started looking into the possibility of joining the Mu2e effort at Fermilab. This was motivated by the following reasons:
  - Since the approval of this ER project, the political wind has shifted greatly in favor of the Mu2e project. This is seen in the fact that the Mu2e is mentioned in the FY2010 President's budget. Also the future of LANSCE-R is rather unclear. LANSCE-R is a necessary condition for muon-electron conversion experiment to happen at LANSCE.
  - Under the circumstances, we have come to realize that a muon-electron conversion experiment will not happen at LANSCE unless DOE decides not to fund the Mu2e. Therefore it is important to be part of the Mu2e collaboration at this point: if the Mu2e project goes forward, we can still contribute to the science. If the Mu2e does not go forward for some reason, we can bring the Mu2e collaboration to LANSCE.
  - Joining the Mu2 will strengthen the case for future DOE-HEP funding.
- First visit to FNAL to discuss the possibility and possible roles is scheduled for July 17th.
- Once the potential role is identified, will join Mu2e officially with LANL management's approval.

Future Work

- Work in progress to complete the objectives for this FY
  - Will complete the planned experiments at LANSCE and PSI by the end of this FY. Both experiments are expected to yield publishable results.
  - Plan to hire a postdoc by the end of FY. Currently interviewing candidates.
  - Continue dialog with FNAL Mu2e.
- For next FY, will continue to work towards establishing the case for mu-e experiment at LANSCE. At the same time, will start work on designing part of the Mu2e experiment, which can also be used as part of the mu-e experiment at LANSCE if it turns out that LANSCE is the place to build the mu-e experiment.
- Will start initial dialog with DOE HEP to discuss possibility of future funding.