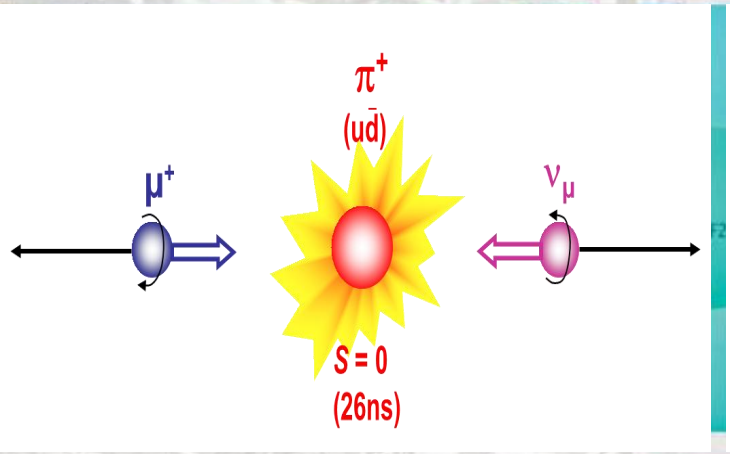
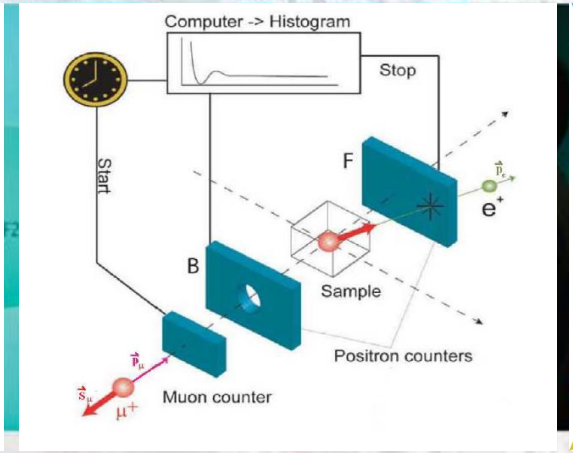
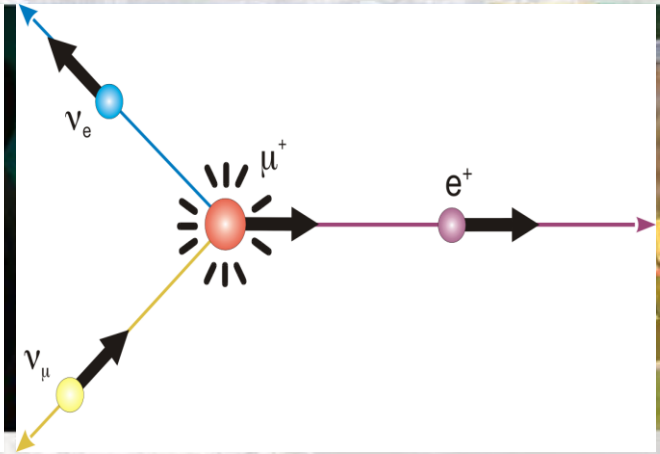
Broader Impacts: Project X and μSR

G. J. MacDougall





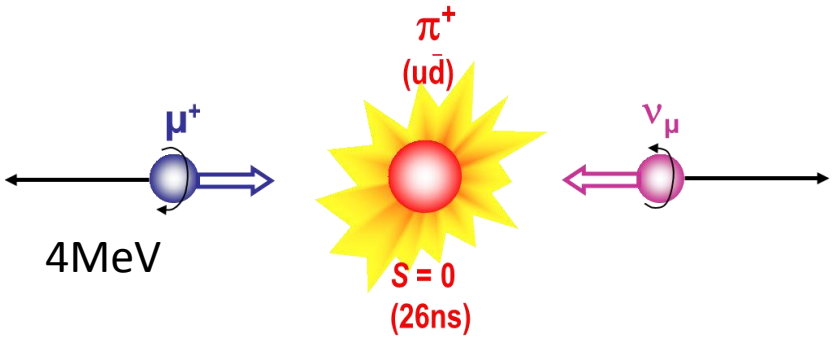


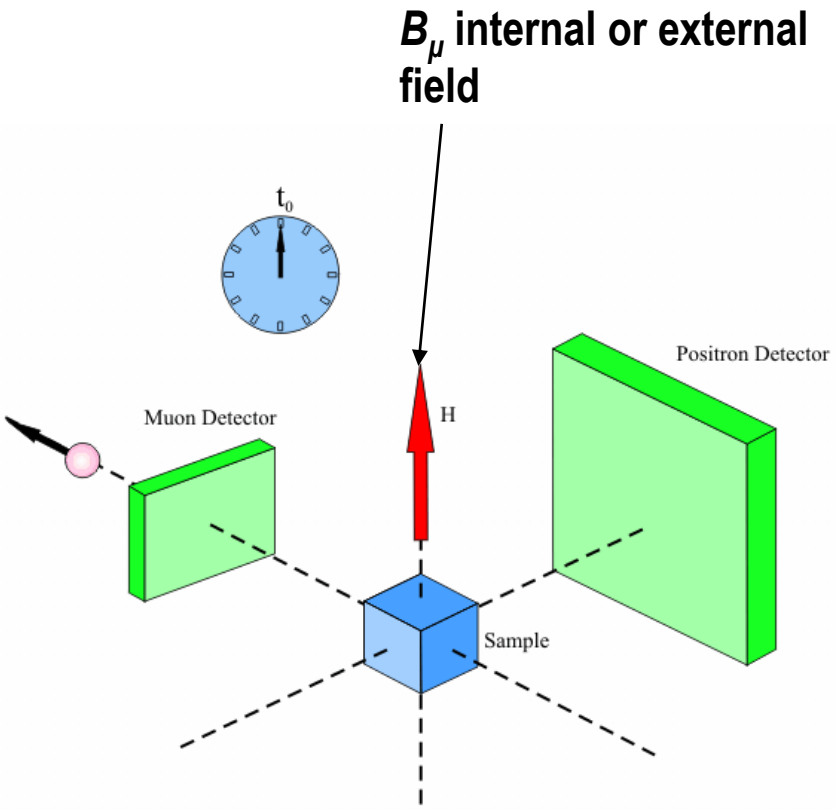
What is μSR?

- μSR is an acronym which can mean muon spin rotation, resonance or relaxation, depending on the context
- Refers to any of a number of experiments which uses *polarized, low-energy* muons to probe problems in materials research (or chemistry).
- Requires a high-current source of >300MeV protons to make a useful beam of polarized muons (via pion production).
- Currently no U.S. capability.
- We are investigating interest in using Project X to provide a user facility for μSR.

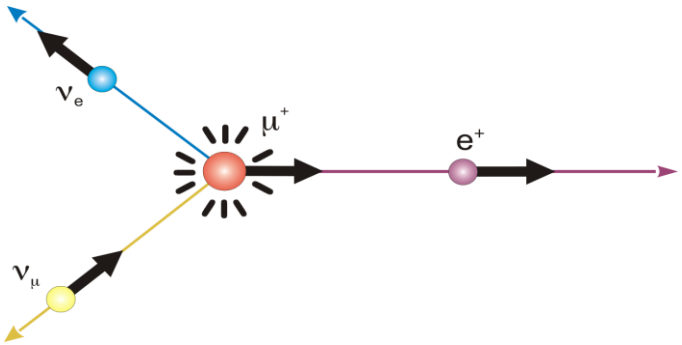
Underlying Concept

Production via pion decay produces polarized muon beam





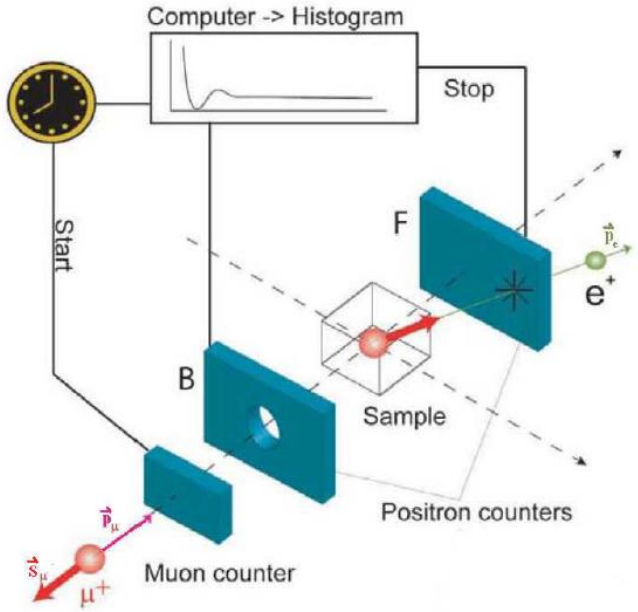
Muon decay emits positron preferentially in final muon spin direction

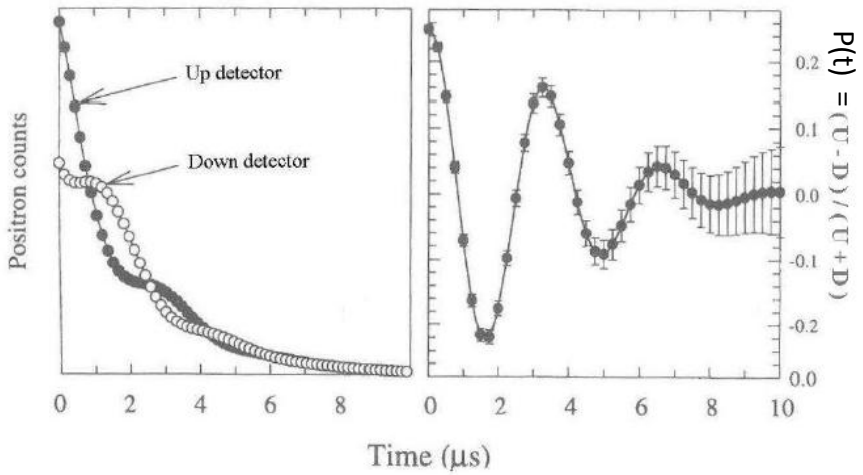


Measurement counts number of positrons emitted in different directions as a function of time

courtesy of G.M. Luke

The μSR polarization function





$$N_F = N_0 e^{-t/\tau} [1 - A_0 P(t)] + B_F$$

$$N_B = N_0 e^{-t/\tau} [1 + A_0 P(t)] + B_B$$

$$\Rightarrow P(t) = \frac{(N_B - B_B) - (N_F - B_F)}{(N_B - B_B) + (N_F - B_F)}$$

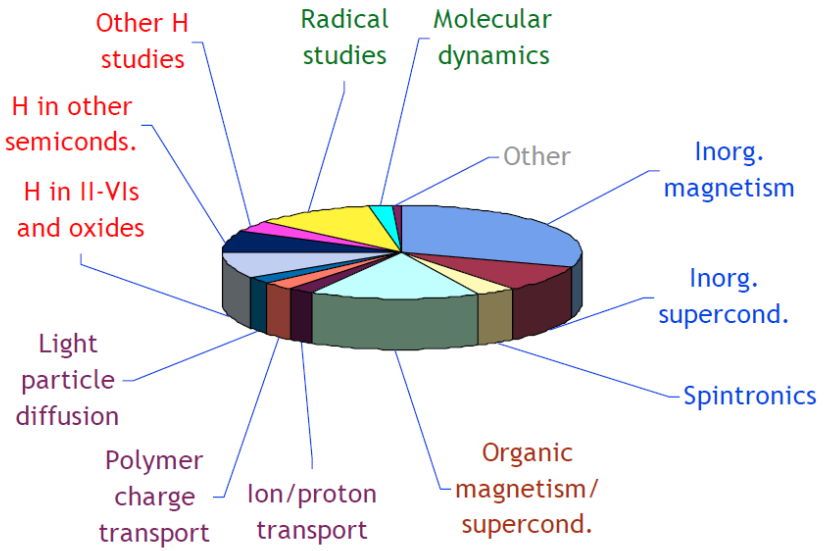
P(t) contains information about the *ensemble average* of the muon spin polarization

Frequency ▶ Average field at the muon site

Relaxation ▶ Width of the field distribution

Who uses μSR?

- Variants of μSR are making meaningful contributions to the areas of:
  - Magnetism
  - Superconductivity
  - Quantum diffusion
  - Hydrogen storage
  - Battery materials
  - Semiconductors
  - Radical chemistry
  - Thin films and heterostructures

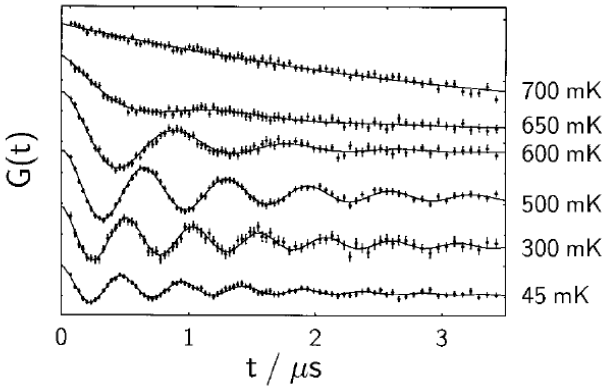


user applications at the ISIS facility [Kilcoyne2012]

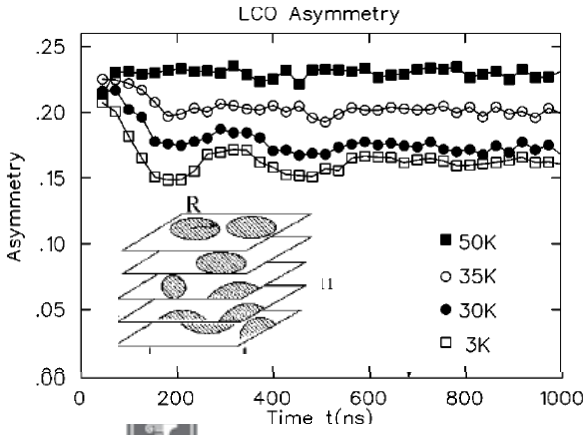
Magnetic Order

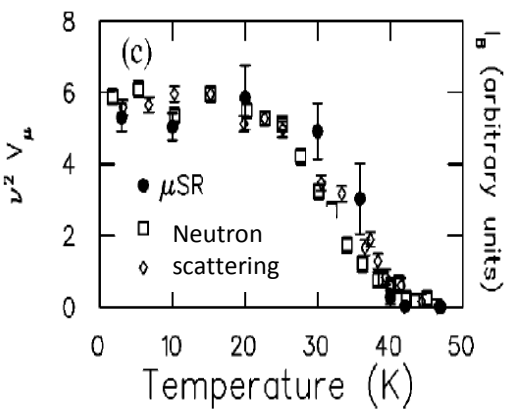
- μSR is a sensitive, real-space probe of magnetic order and fluctuations which serves as a complement to other techniques
  - Sees moments as small as $0.001\mu_B$
  - Measures ordered volume fractions
  - Sensitive to unique range of fluctuation rates
  - Very little constraints on sample properties

e.g. Ordering transition in organic ferromagnet p-NPNN



e.g. Fragmented "stripe" order in $La_2CuO_{4.11}$



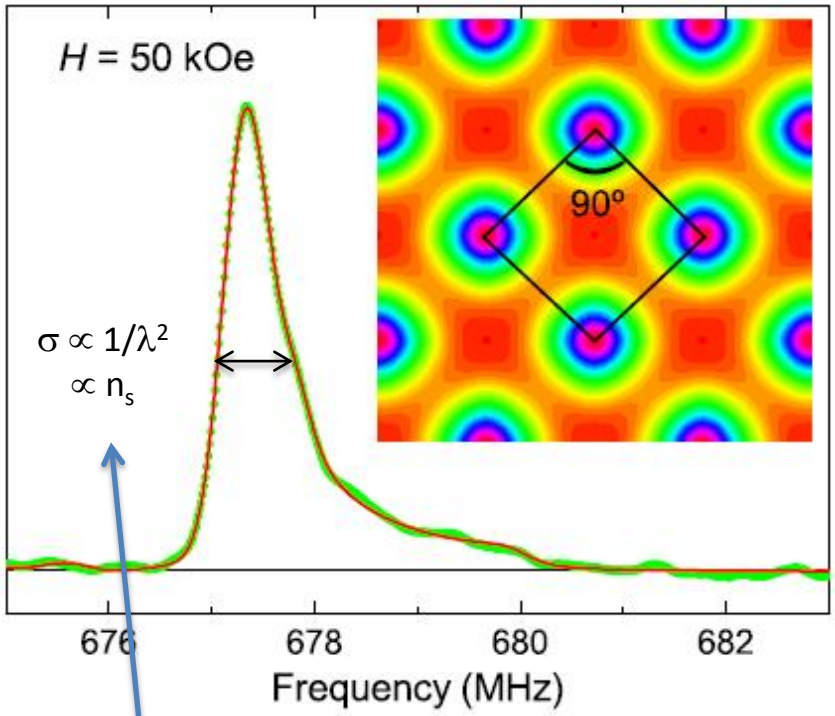


Blundell *et al.*, *Europhys. Lett.*, ***31***, *573. (1995)*

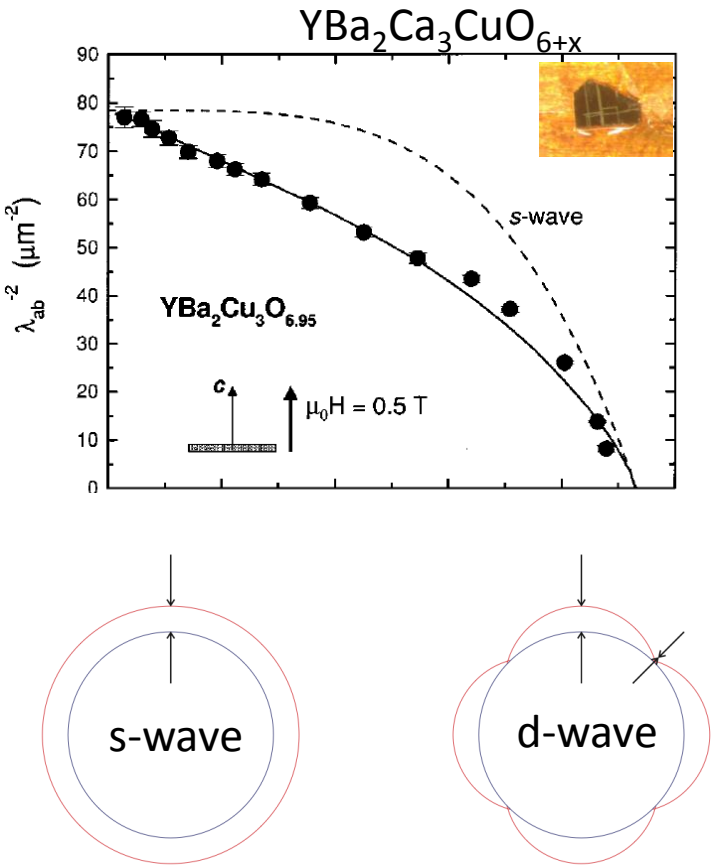
Savici *et al.*, PRB **66**, 014524 (2002)

Superconductivity

- μSR detects superconductivity primarily through the field distribution imposed by vortex lattices

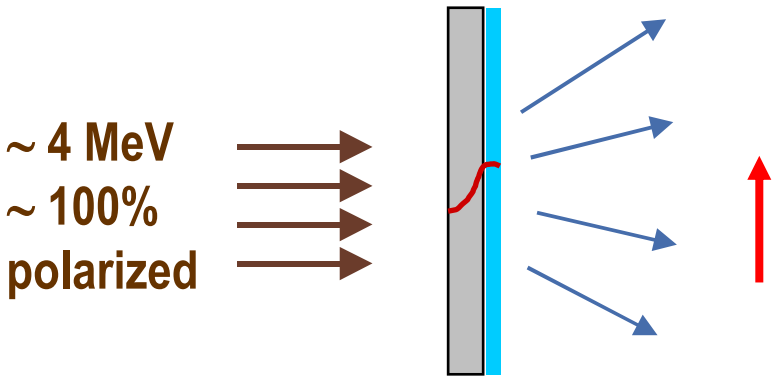


Provides a measure of *penetration depth*



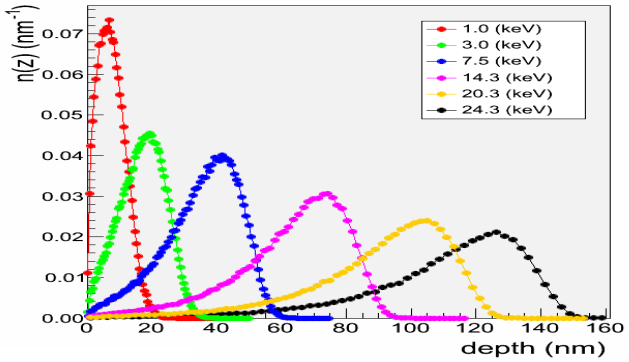
New Horizon: Low Energy Muons

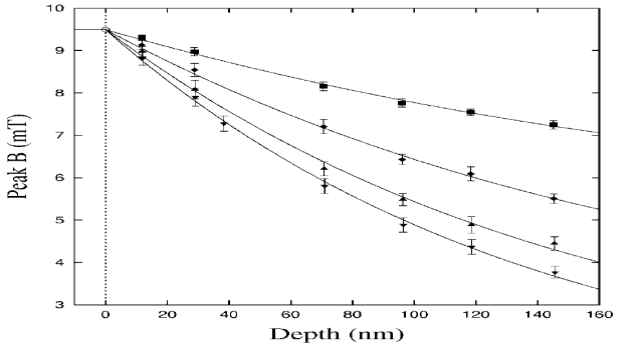
- Recent years have seen the advent of novel "low-energy" μSR (LEM) beamlines (~1-60 keV)
- Moderate surface (4MeV) muons in thin films of gases adsorbed on cooled silver plates and then re-accelerate



Moderator generation

Stopping Profile





courtesy of A. Suter

Jackson *et al.*, PRL **84**, 4958 (2000)

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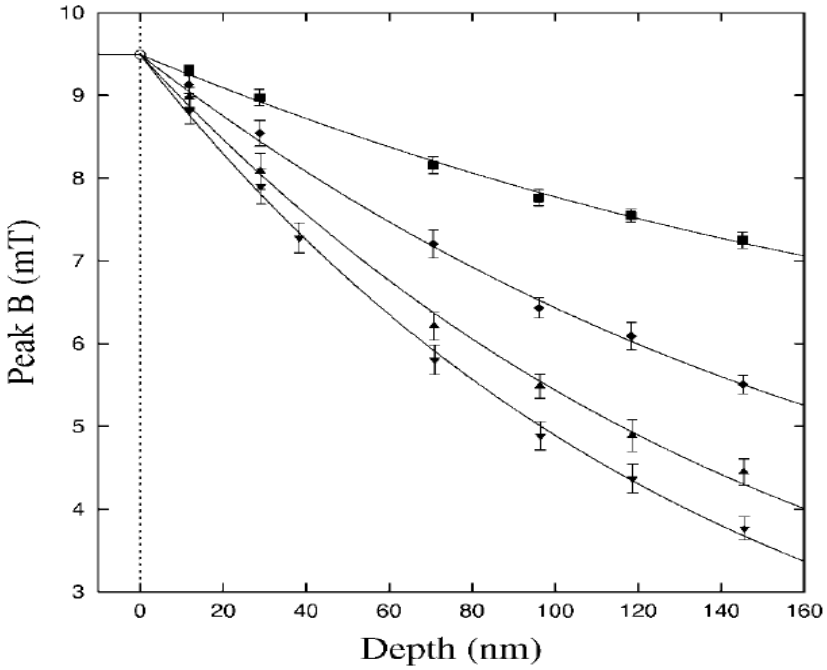
First direct confirmation of the London penetration depth (predicted 1935)!



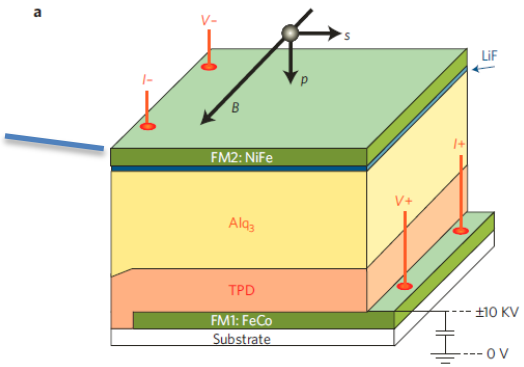
courtesy of A. Suter

Jackson *et al.*, PRL **84**, 4958 (2000)

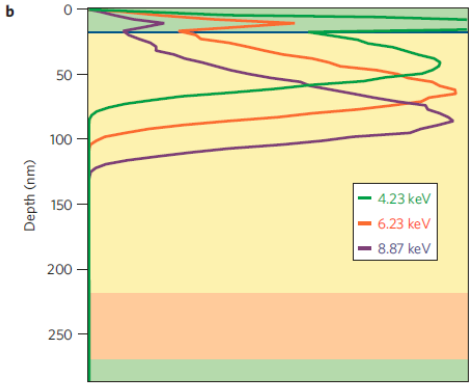
LEM Applications

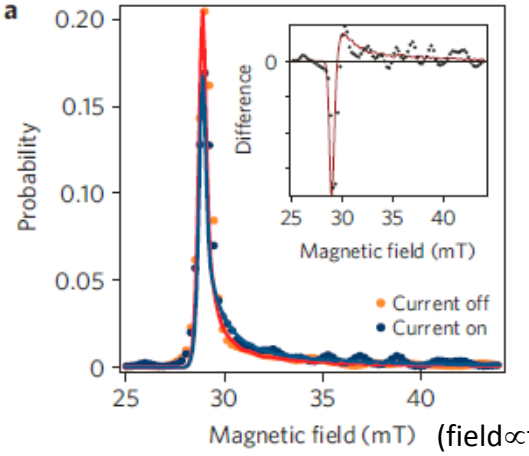
- New avenues of research have been opened in the study of films, nanoparticles, surfaces and heterostructures.
- e.g. measuring spin diffusion lengths in artificial “spin valves”

Source of spin polarized current



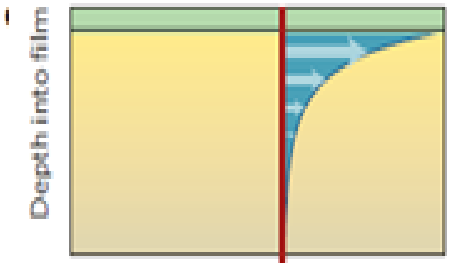
Muons implanted at different depths





Look for excess field when current is turned on

(field∝frequency)



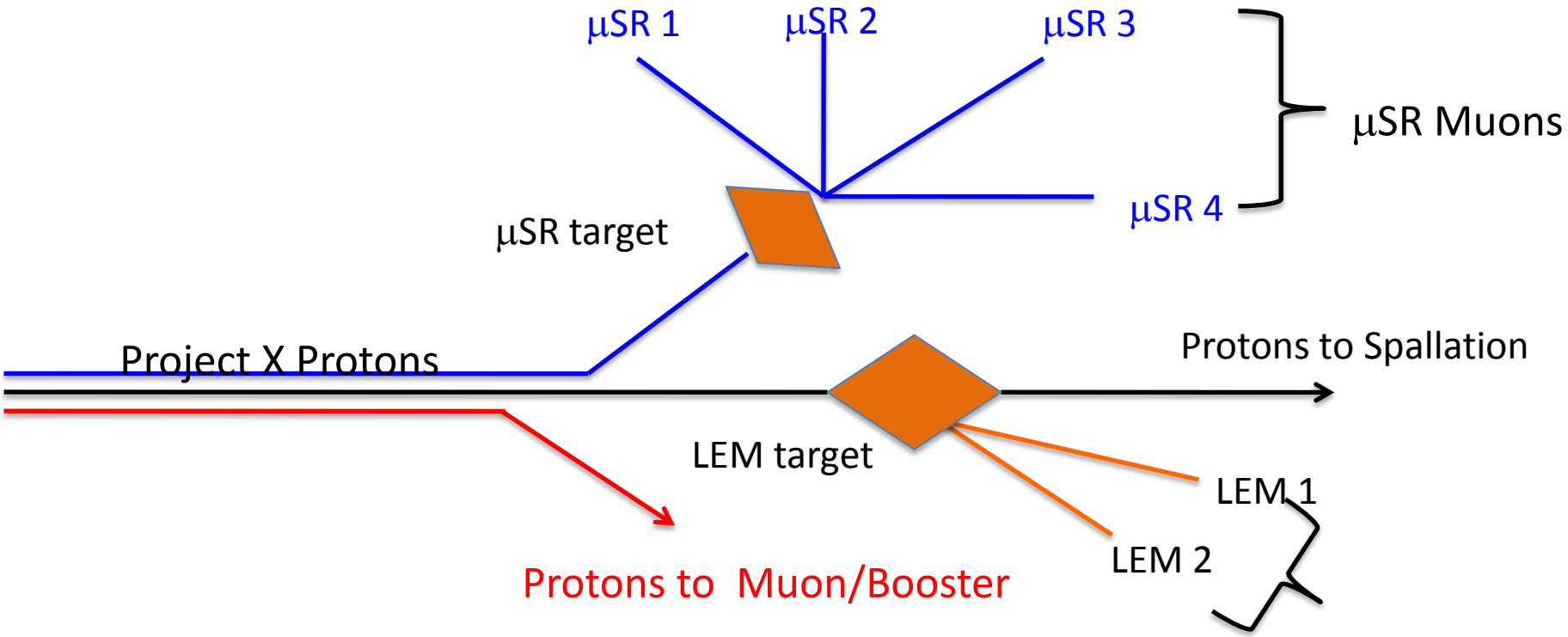
Stop at different depths to get diffusion length

Drew *et al.*, Nature Materials **8**, 109 (2009)

What can Project X provide?

- A US-based μSR facility to strengthen local materials community (20-30% of world μSR user base) and complement existing capabilities
- Uniquely flexible source of high-current protons in 1 GeV range → capable of simultaneously providing muon beams with different timing characteristics
- LEM parasitic beams (roughly doubling world capacity) and dedicated low-power beamlines.
- World leading knowledge of detectors, targets, beam shaping and timing characteristics
  - e.g. multi-channel detectors to overcome pile-up limitations in CW experiments (1-2 order of magnitude efficiency improvement!)

Possible Beam Layout at Project X



- Select endstations using fast kickers.
- Simultaneous operation of pulsed (2E6/sec), continuous beam (50kHz, low background) or LEM (1E4/sec) muons.
- Unique in the world!

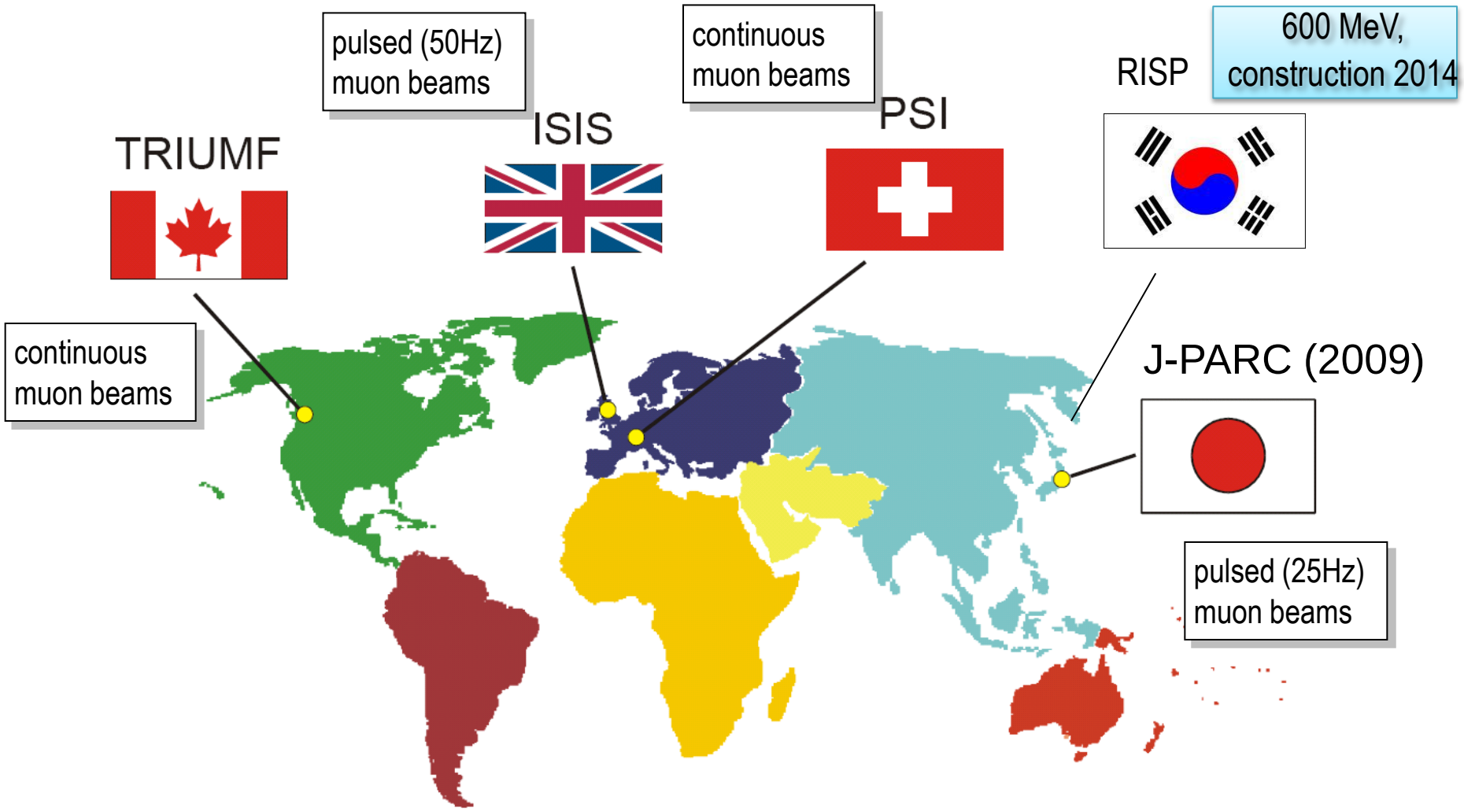
Concluding Remarks

- We believe that Project X can be used to make a state of art μSR facility, with a flexible program unparalleled in the world.
- The facility would add value to the ensemble Project X capability, while offering a powerful new probe to materials researchers.
- Steps have already been taken to engage both world experts in μSR and representatives from other facilities
  - μSR workshop at FNAL, Oct. 2012
  - planning workshop, Feb. 2013
    - visit from E. Won, RISP, Korea
- 45 pages in Snowmass Project X Document
  - Editing team:
    R. Plunkett, R. Tschirhart, A. Grassellino, A. Romanenko (FNAL), G. J. MacDougall (UIUC), R. H. Heffner (LANL)
  - Good starting point for a larger dialogue to understand needs and desires. Please take a look!

The Team

- PX Snowmass volume editing team:
  - R. Plunkett, R. Tschirhart, A. Grassellino, A. Romanenko : **Fermi National Accelerator Laboratory**
  - G. MacDougall : **University of Illinois at Champaign---Urbana**
  - R. H. Heffner **: Los Alamos National Laboratory**
- **The expert consultants:**
  - P. Oddone, S. Henderson, S. Holmes, A. Suter, E. Morenzoni, G. Luke, R. Kiefl, P. Percival, S. Kilcoyne, R. Cywinski, Y. Miyake, C. Polly, S. Striganov.Thanks to V. Lebedev , N. Mokhov, E. Won, and B. Kiburg
- And – you! Your input is needed!

μSR Facilities around the World



Adapted from "μSR brochure" by J.E Sonier, *http://musr.org/intro/musr/muSRBrochure.pdf*