Dynamical Behavior of the SpinQuest Target Polarization due to Beam Heating and Radiation Damage

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Outline

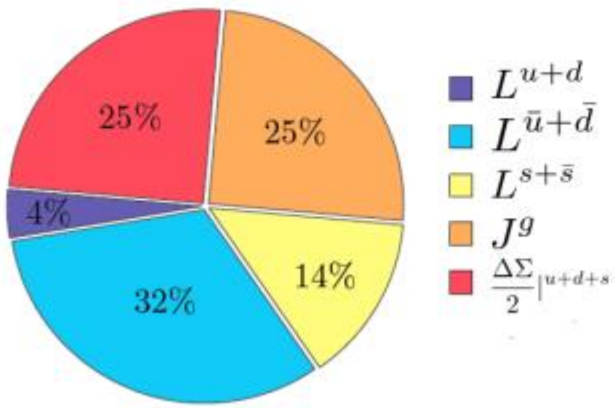
- SpinQuest experiment at Fermilab
- Polarized-target at SpinQuest
- Dynamics-Nuclear Polarization (DNP)
- Nuclear-Magnetic Resonances (NMR)
- LabView-based polarization simulation
- Target-temperature profile
- Beam current in the target
- Results: $P(z, t)$
- Summary

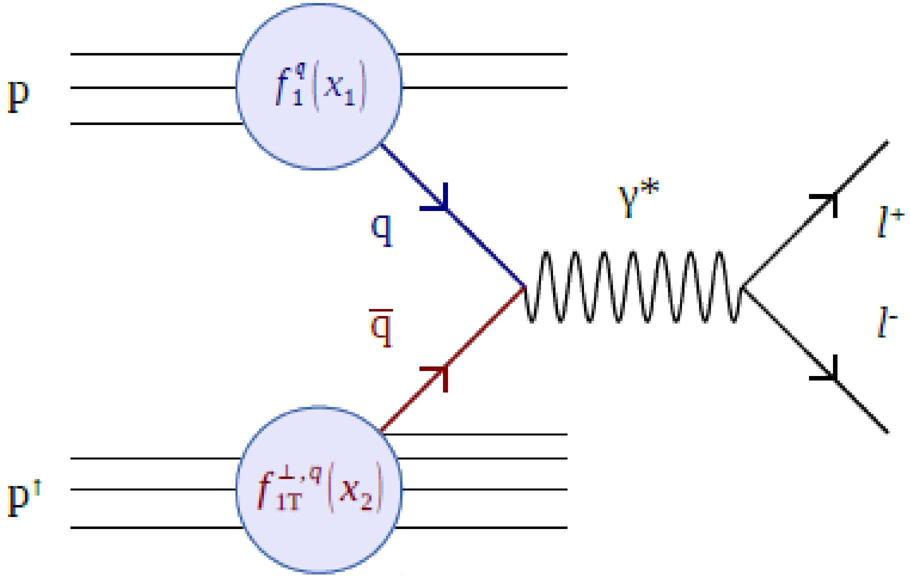
The main goal of this study is to obtain the polarization profile of the target as a function of z-position and time, $P(z, t)$ for the SpinQuest target

SpinQuest Experiment at Fermilab

- The main goal is to understand the proton-spin puzzle (how do the Proton get its spin?)
- Orbital-angular momentum of sea quarks could contribute up to half of the proton's spin
- Perform the first measurement of the Sivers asymmetry in Drell-Yan pp scattering from the sea quarks
- A non-zero Sivers asymmetry from SpinQuest is "smoking gun" evidence for sea quark Orbital-Angular Momentum
- Please see the talk by **Yoshiyuki Miyachi** for a more information about SpinQuest physics

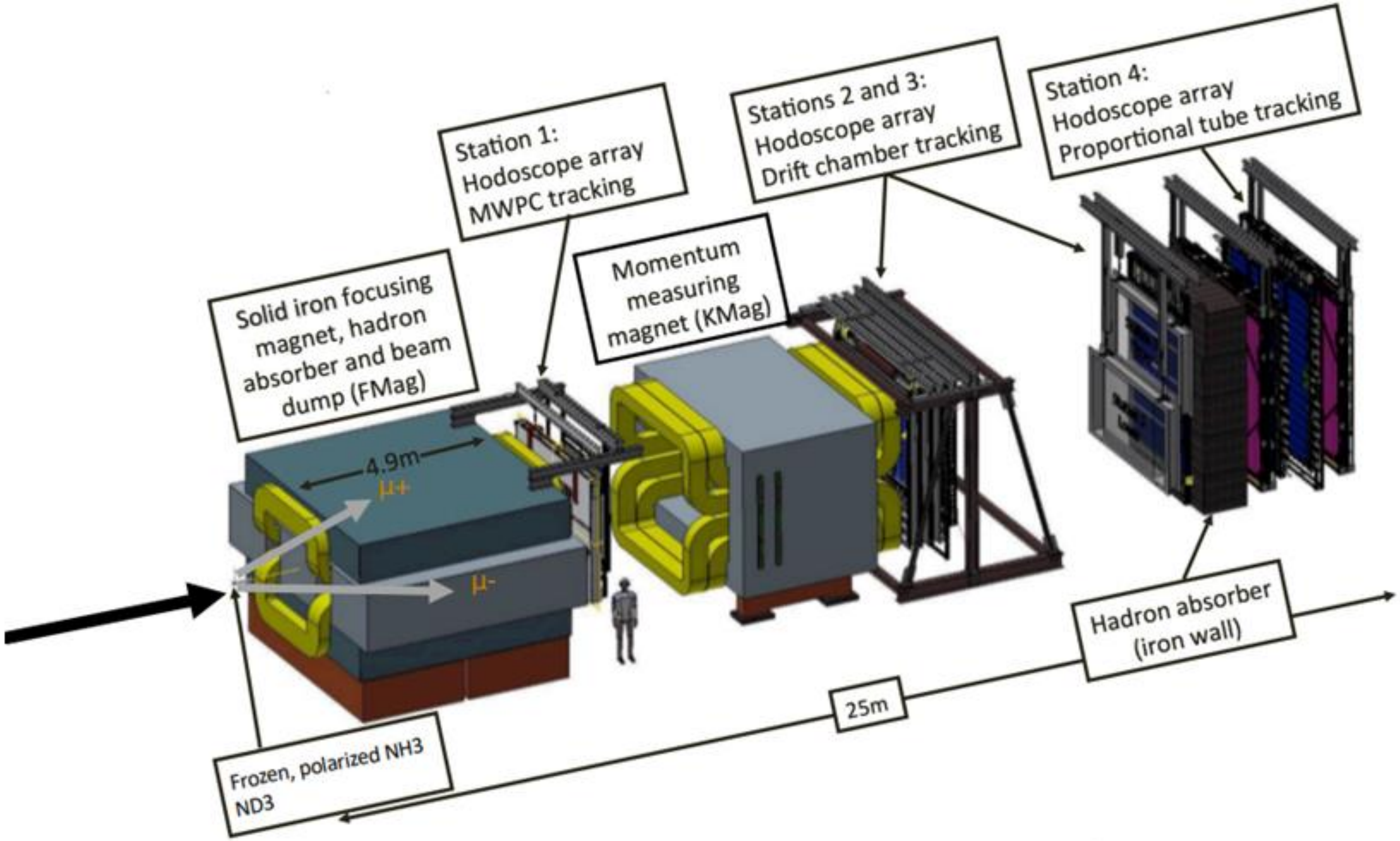
K.-F. Liu *et al* arXiv:1203.6388





SpinQuest Experiment at Fermilab

- ❑ 120 GeV unpolarized proton beam
- ❑ Push the intensity frontier on solid-polarized target: ~ 5 x 10^{12} protons/spill
- ❑ 4.4 second of beam spill each minute
- ❑ Transversely polarized proton/deuteron target
- ❑ Target materials: NH3/ND3
- ❑ Please see the talk by **Ishara Fernando** for a more information about the <u>SpinQuest polarized target</u>

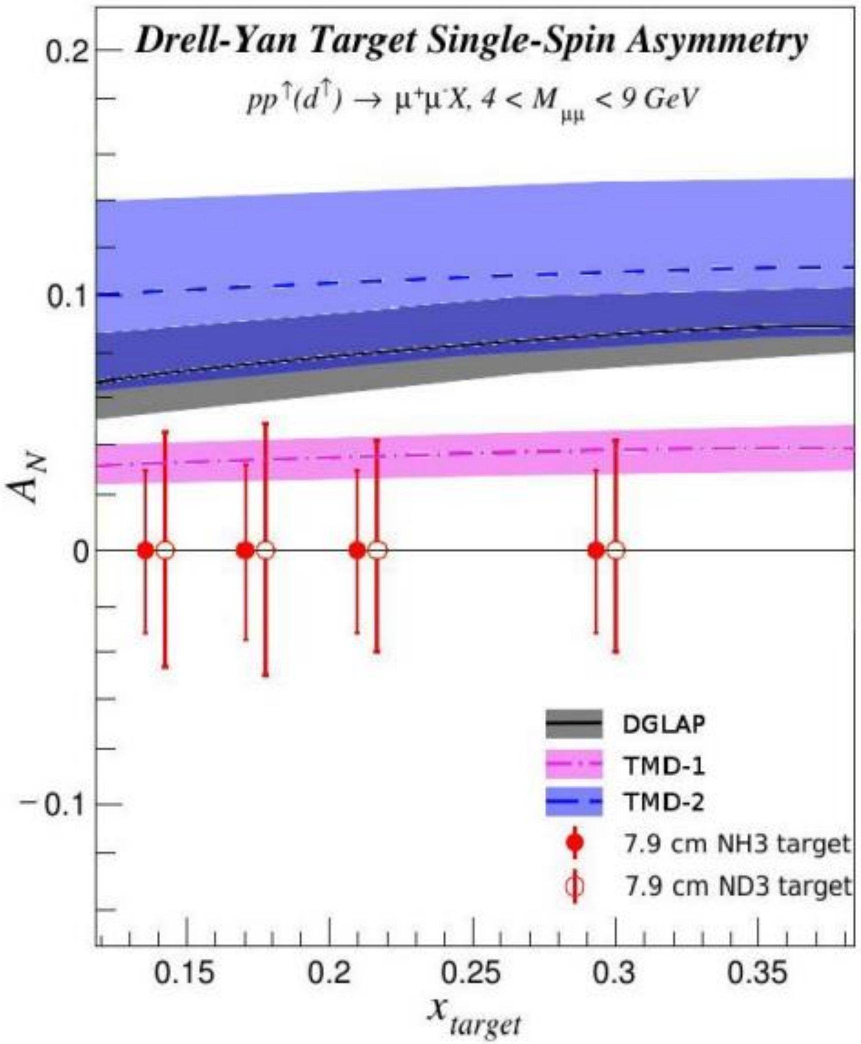


Systematic-Uncertainties Projection

Beam(2.5%):
- Relative Luminosity (~1%)
- Drifts (<2%)
- Scraping (~1%)

Analysis sources(3.5%):
- Tracking Efficiency (1.5%)
- Trigger and Geometrical Acceptance (<2%)
- Mixed background (3%)
- Shape of DY (~1%)

Target(6-7%)
- TE calibration (P-2.5% D-4.5%)
- Polarization inhomogeneity (2%)
- Density of target (ammonia) (1%)
- Uneven radiation damage (3%)
- Beam/target misalignment (0.5%)
- Packing fraction (2%)
- Dilution factor (3%)



DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003

Polarized Target at SpinQuest

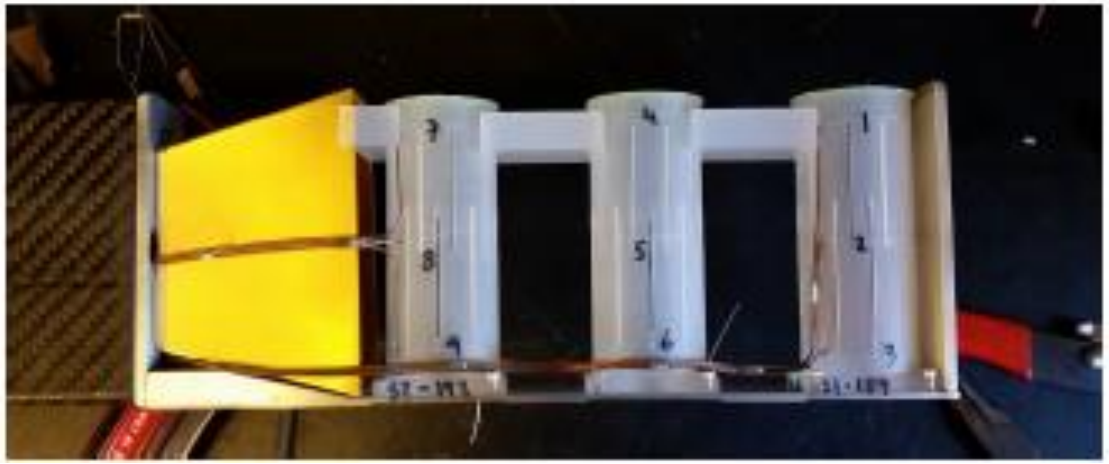
- We need to fully understand the target-related systematics uncertainty (biggest contributor to overall systematics)

- Dynamic-Nuclear Polarization (DNP) method to polarize the target materials

- Nuclear-Magnetic Resonances (NMR) to measure the polarization

- 8 cm of target cups with the materials are doped with the paramagnetic free radicals (irradiated) at National Institute of Standard and Technology

- 3 NMR coils in each target cups to measure the polarization at 3 different z positions (upstream, center and downstream of the target)



- We need to understand the complete polarization profile along the z as a function of time (dynamic behavior)

The main goal of this study is to obtain the target-polarization (for NH3 material) as a function of z and time $P(z, t)$

Dynamic-Nuclear Polarization (DNP)

- The coupling between (unpaired) electron & proton introduces hyper-fine splitting H_{SS}

$$H = -\mu_e B - \mu_p B + H_{SS}$$

- Applying an RF-field at the correct frequency, we can drive the nucleons state into desired proton-state

- ~140 GHz RF signal is generated continuously

- The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization

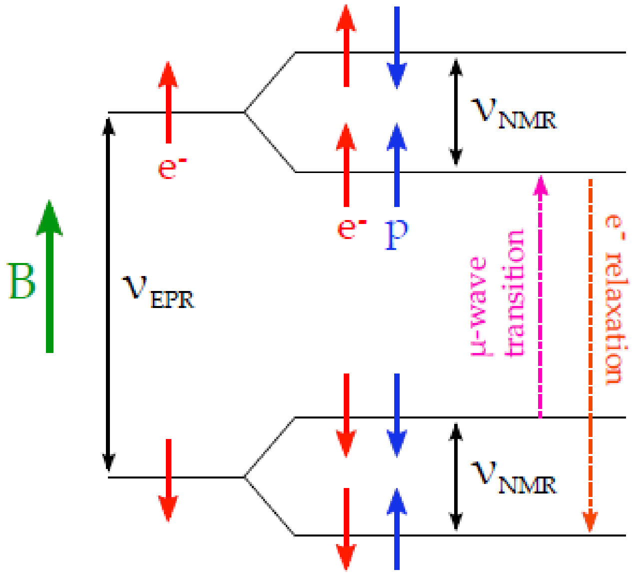
- Allow to achieve proton polarization of greater than 90%

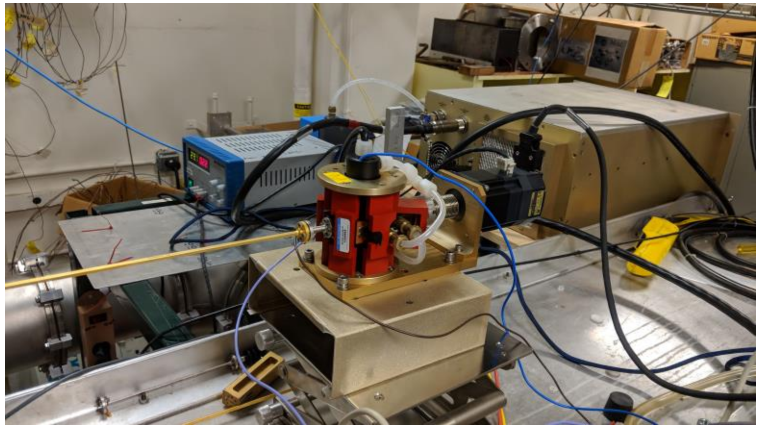
- The optimal RF frequency changes as we flip the spin direction

- The optimal frequency also changes as the target accumulate radiation damage from the beam.

- Therefore, the frequency is adjusted by adjusting the cavity size using a stepper motor (~2% adjustment)

Solid effect DNP process:





Dynamic-Nuclear Polarization (DNP)

- We use thermal-mixing model to simulate the DNP mechanism
- In general, thermal-mixing model perform better than solid-state model (especially for ND3)
- The **short-term** behavior (T dependance) of the solid-polarized target from thermal-mixing model*

$$T_{1e}P_n' = \left(-\frac{T_{1e}}{T_{1n}} - \frac{C}{2}(\alpha+\beta) - \phi\right) P_n + \frac{C}{2}(\alpha-\beta)P_e$$

$$T_{1e}P_e' = \frac{1}{2}(\alpha-\beta)P_n + \left(-1 - \frac{1}{2}(\alpha+\beta)\right) P_e + P_{e0}$$

- T_{1e} = Electron relaxation time
- T_{1n} = Nucleon relaxation time
- C = Ratio of the number of electrons to the number of nuclei
- α, β is a function of RF frequency (gaussian shape) and determine the transition rate between states

- P_{e0} = equilibrium-electron polarization = $-\tanh(^2/_T)$
- ϕ is a parameter to compensate the shortcoming of the model

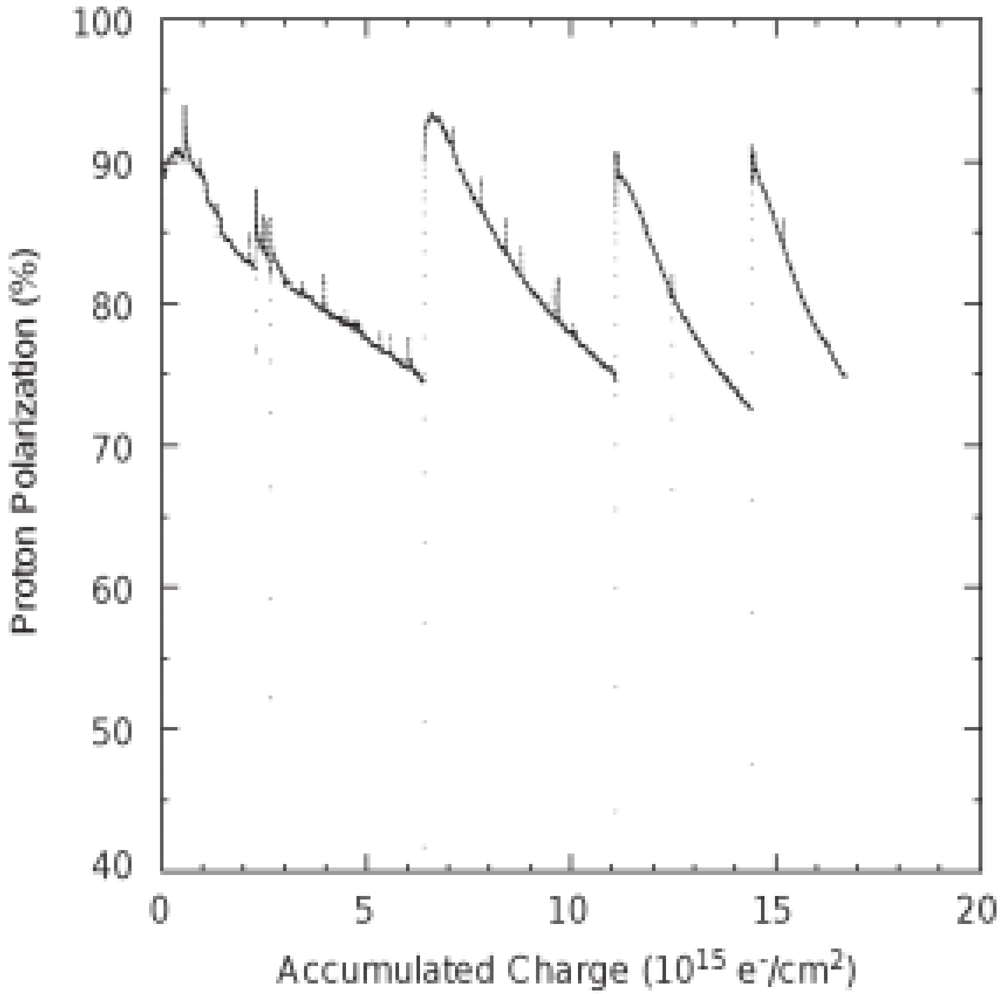
*O. S. Leifson and C. D. Jeffries, Phys. Rev. 122, 1781–95 (1961)

Dynamic-Nuclear Polarization (DNP)

- The **long-term** polarization behavior is determined by the accumulation of radiation dose from the beam

- There is no theoretical model to explain the polarization dynamics due to the accumulation of the dose

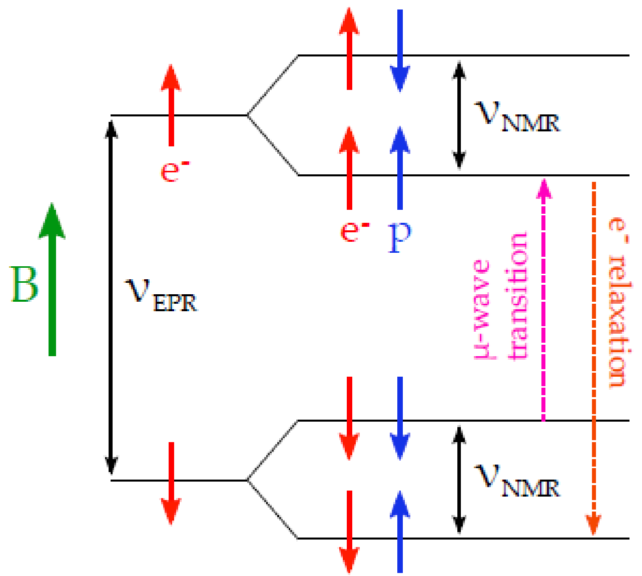
- The long-term behavior is described by an exponential function with the fit parameter determined from the experiment



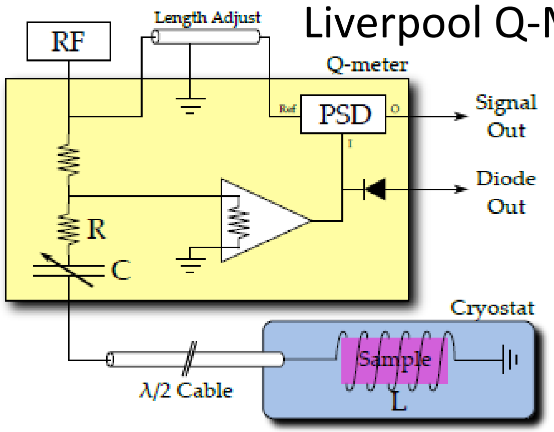
Proton-polarization decay from SLAC E155 due to accumulated dose from the beam

Nuclear-Magnetic Resonances (NMR)

- Polarization of the proton is measured using NMR technique
- An RF field at the Larmor frequency of the proton (213 MHz at 5 T) can cause a flip of the spin
- The RF field is produced by 3 NMR coils inside the target cup
- An RLC Circuit is tuned to the Larmor frequency of the target materials
- The power generated or absorbed due to spin flip change the circuit impedance that can be observed



Liverpool Q-Meter

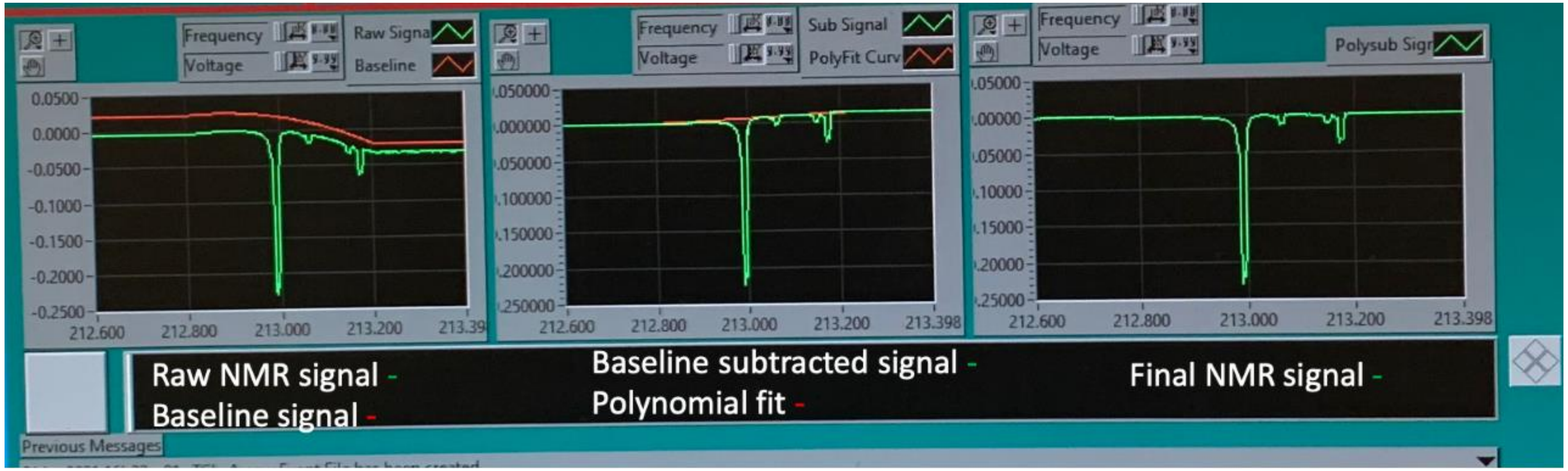


Courtesy of James Maxwell

Nuclear-Magnetic Resonances (NMR)

- Q-Curve is produced by sweeping the RF around the Larmor frequency
- The signal area after background subtraction is proportional to the polarization
- The proportional constant is obtained at Thermal-Equilibrium measurement

$$P = tanh\left(\frac{\mu B}{kT}\right)$$



Notes: SpinQuest experiment will use a new NMR system developed by LANL-UVA based on the original Liverpool Q-meter design

LabView-Based Simulation

❑ A LabView based simulation was developed to study the dynamic behavior of the polarized target:

- Simulate the polarization response to RF frequency as determined by the thermal-mixing equations
- Incorporate the long-term dynamics due to the accumulation of radiation dose
- Compliment the frequency adjustment by stepper motor
- Mimic the real-time NMR measurement system which used at several polarized-target experiments

❑ Input for the simulation:

<u>Target temperature:</u>

- Determined by solving heat-transfer equation.
- Two sources of heat load: beam-target interaction and microwave
- The heat load from the beam-target interaction is obtained from GEANT4 simulation
- The heat load from the microwave is determined from the previous experiment

<u>Beam current:</u>

- Consist of primary beam current & secondary charged particle production
- The secondary charged particle production is obtained from GEANT4 simulation

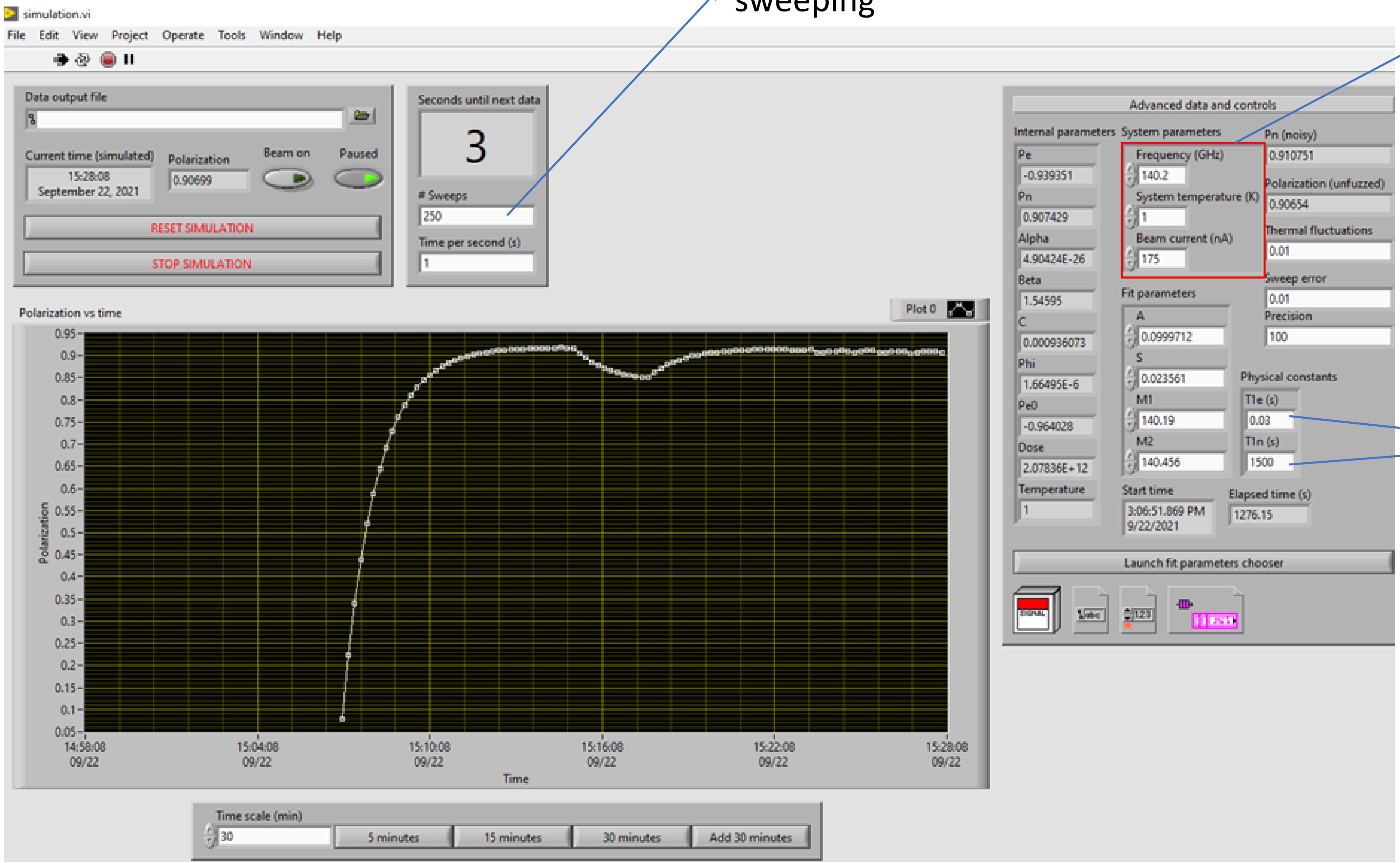
<u>RF frequency</u>

- Multiple RF frequency around the Larmor frequency are sweeping to produce the Q-curve (simulating NMR measurement).
- Background and noise are also generated

LabView-Based Simulation

Number of frequency sweeping

- RF frequency
- Temperature
- Beam current



Electron & Nucleons relaxation time

Target-Temperature Profile

- Target temperature is obtained by solving the heat-transfer equation

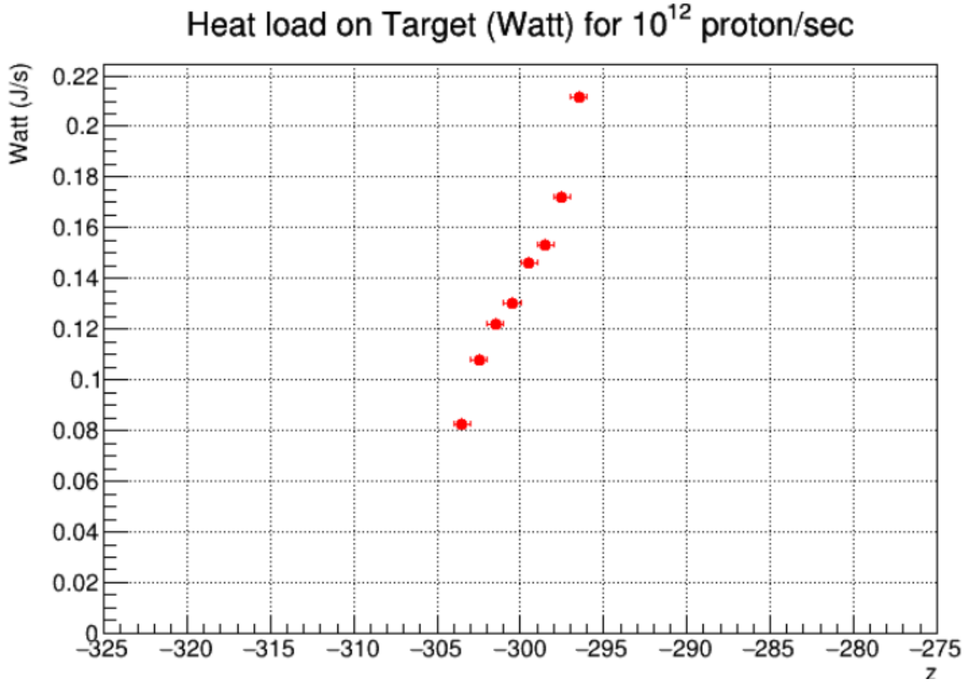
$$c\frac{\partial T}{\partial t} = \nabla(\kappa\nabla T) + P_{ext} + P_{He}$$

c = volumetric heat capacity
κ = thermal conductivity
P_{ext} = heat load on the target
P_{He} = heat transferred to the He

- The heat load on the target (P_{ext}) comes from the microwave and the beam-target interaction.

- Microwave deposited 0.5 Watt to the target

- The heat load from the beam-target interaction is obtained using GEANT4 simulation



This figure shows the heat load along the z position of the target ($-304 < z < -296$). The downstream of the target receive most heat load as expected

Target-Temperature Profile

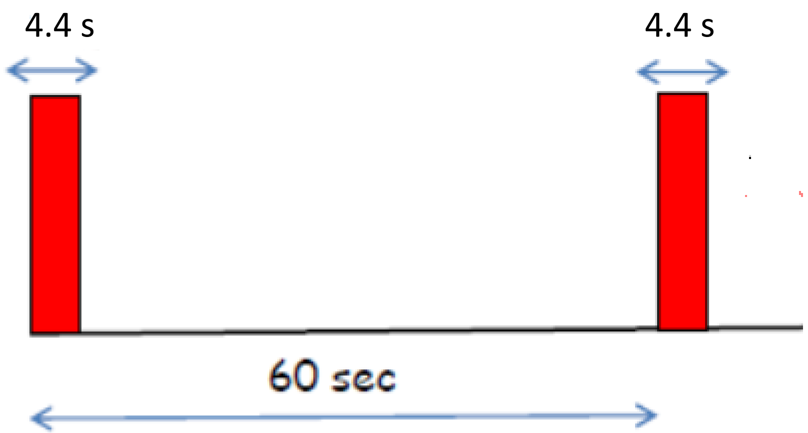
- The heat transferred to the He (P_{He}) is determined by $P_{He} = R_{\alpha}\left(T^4 - {T_{He}}^4\right)$, where T_{He} is the He temperature (1 K) and R_{α} is Kapitza coefficient

- The NH3 bead is modelled as a spherical bead with r = 0.7 mm

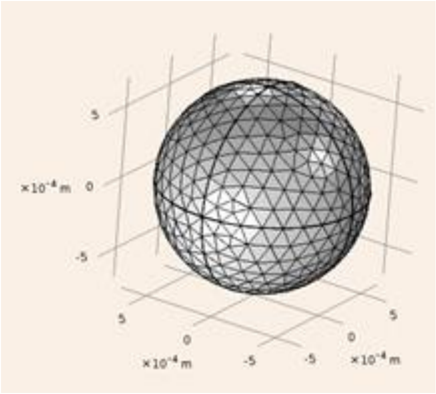
- The heat-transfer equation is solved using **Finite-element Method (FEM)** utilizing **COMSOL** software

- FEM divides a large system into smaller, simple parts called finite elements by the mesh construction of the object. The equations that model these finite elements are then assembled into a larger system of equations that models the entire problem.

- The temporal-beam profile for SpinQuest is considered



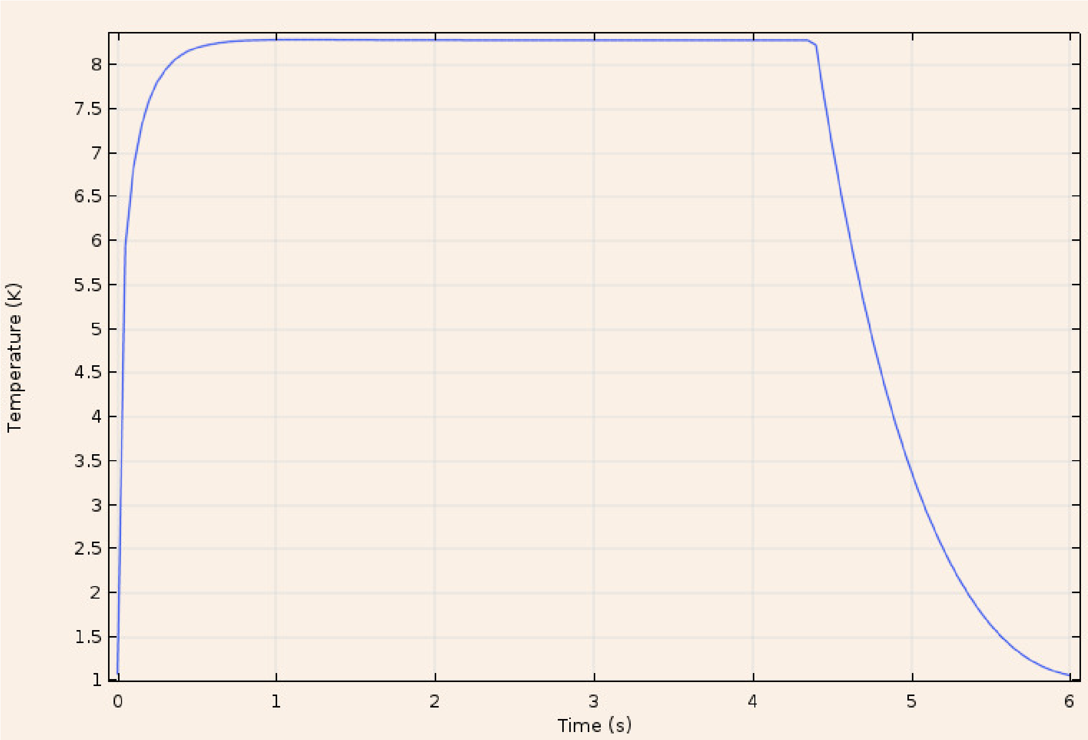
The spill length is 4.4 second each minute



Tetahedral-mesh construction

Target-Temperature Profile at 1 x 10^{12} protons/seconds

T



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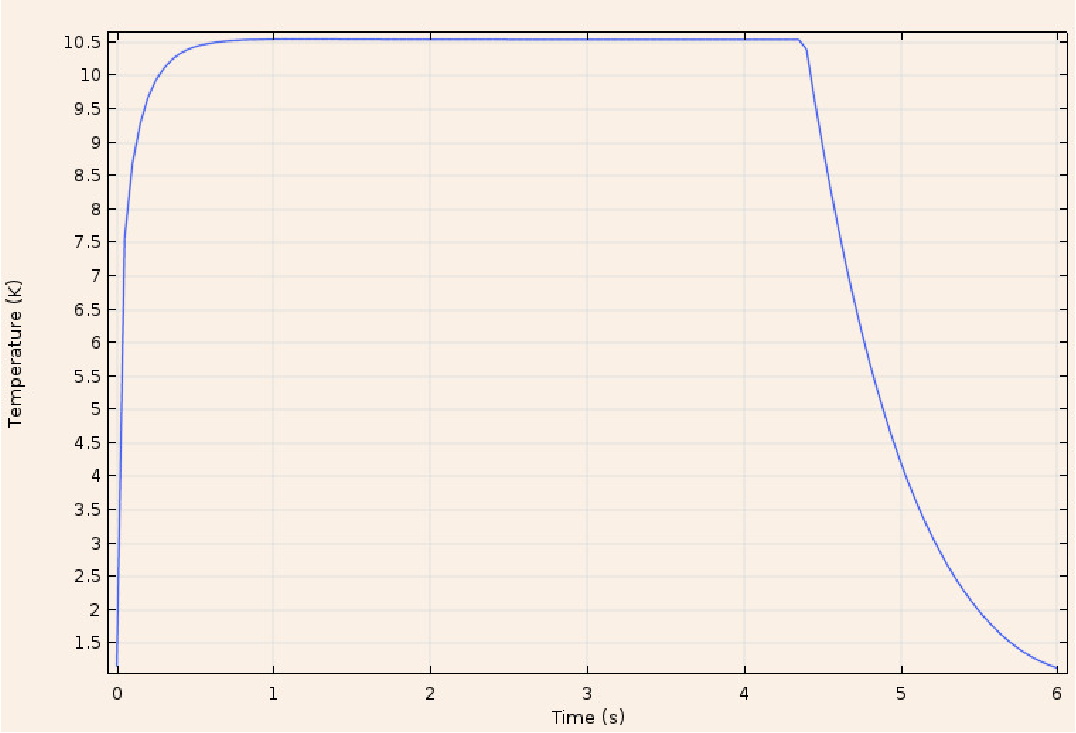


Time (s)

Time (s)

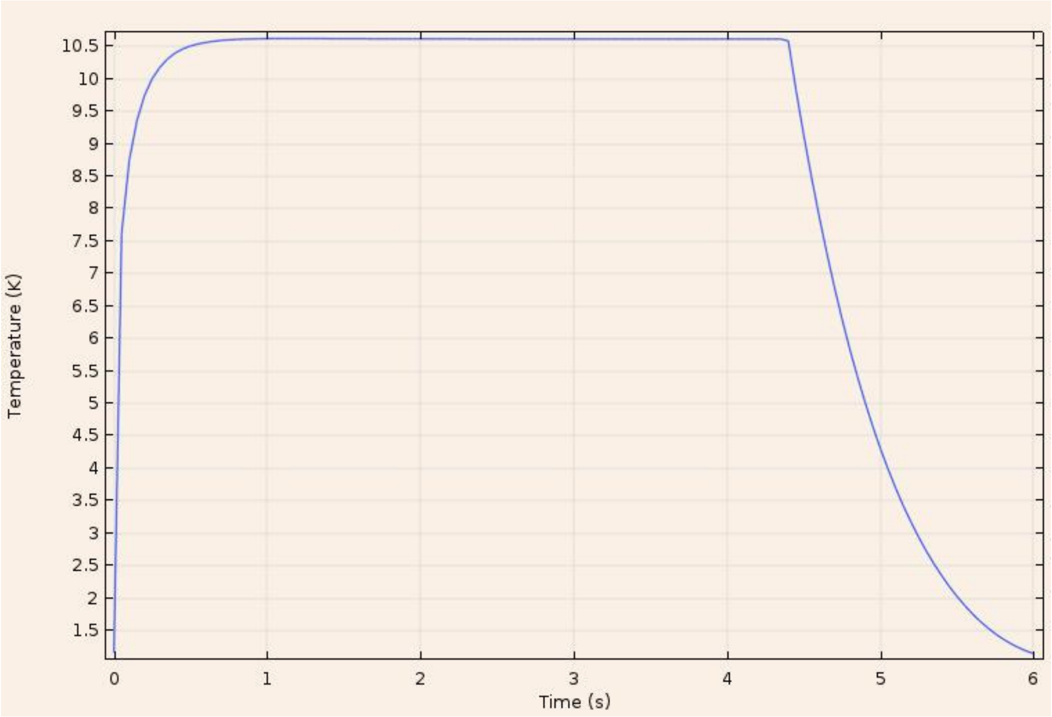
Upstream Target ($z = -304$) $T_{max} = 8.3$ K

Downstream Target (z=-296) $T_{max} = 10.5$ K

- The base temperature is 1 K
- The superfluid regime is effective on removing heat from the target (large Kapitza coefficient and T^4 equation)

Target-Temperature Profile at 2.7 x 10^{12} protons/seconds

T



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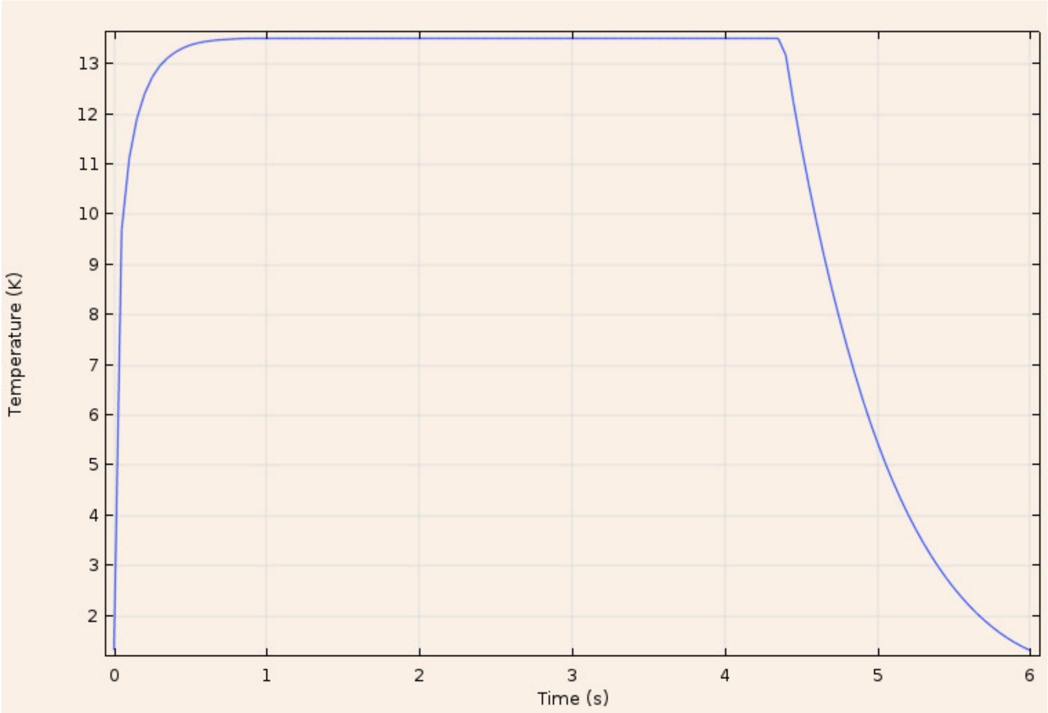


Time (s)

Time (s)

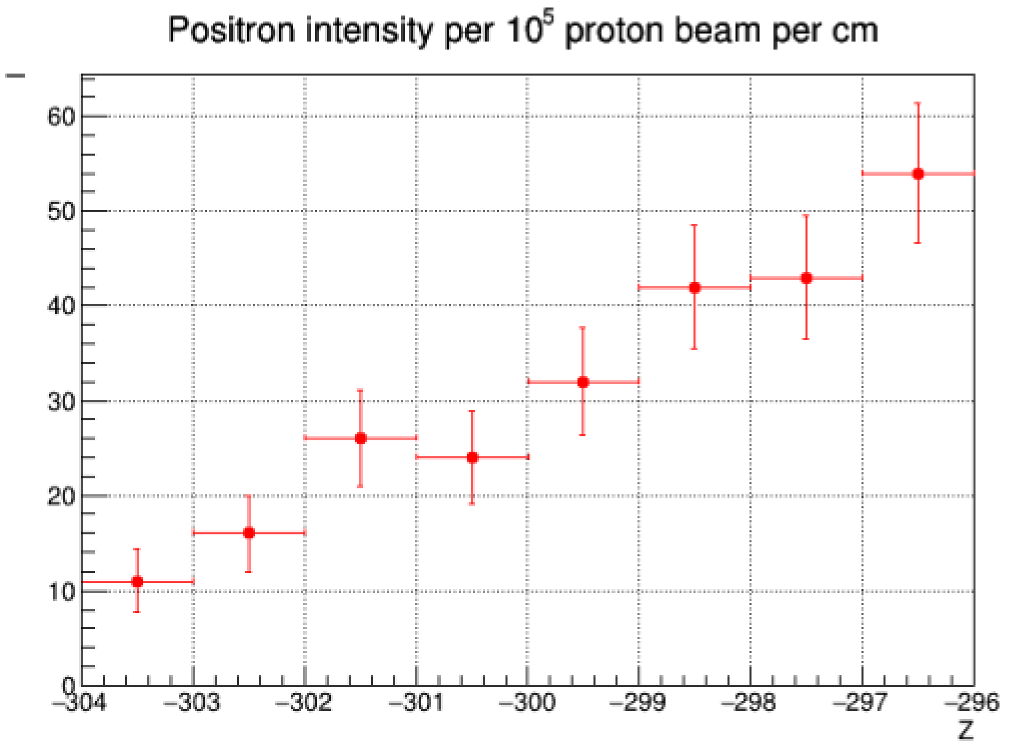
Upstream Target ($z = -304$) $T_{max} = 10.6$ K

Downstream Target (z=-296) $T_{max} = 13.4$ K

- Based on the Superconducting magnet quench simulation, the maximum instantaneous intensity before quenching the magnet is 2.7 x 10^{12}
- The plots above show the temperature in the downstream/upstream of the target during the beam spill
- The base temperature is 1 K

Beam Current in the Target

- ❑ The primary beam current is 160 nA (correspond to ~ 1 x 10^{12} protons/second)
- ❑ We also consider the beam from secondary charged-particle production obtained from GEANT4
- ❑ Total beam current in the target is shown in the following table

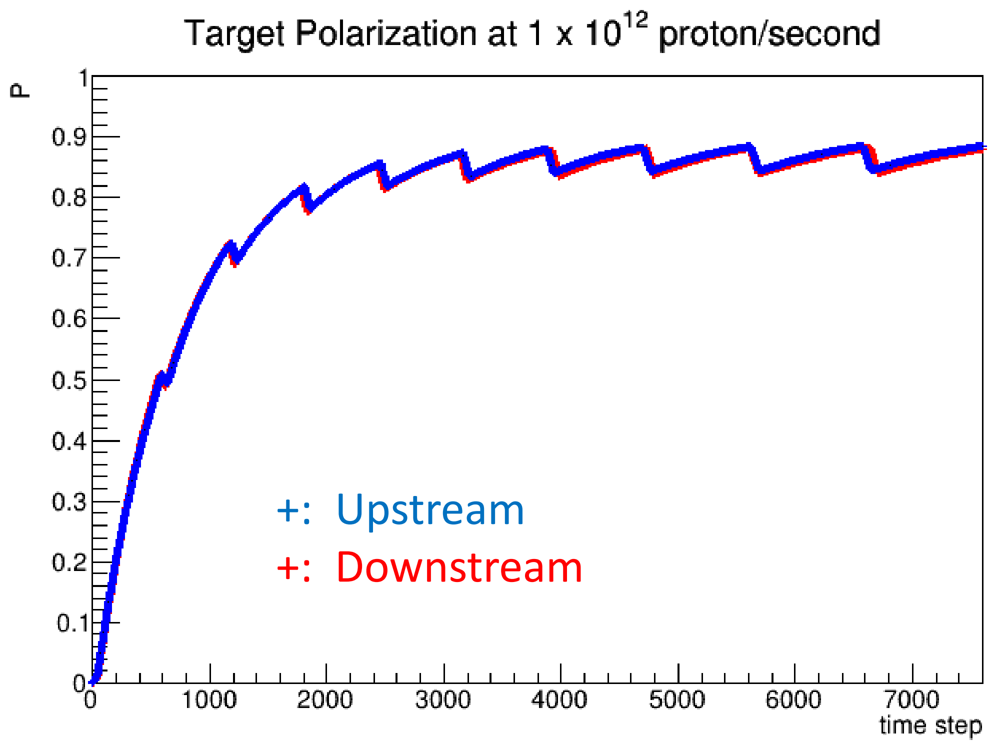


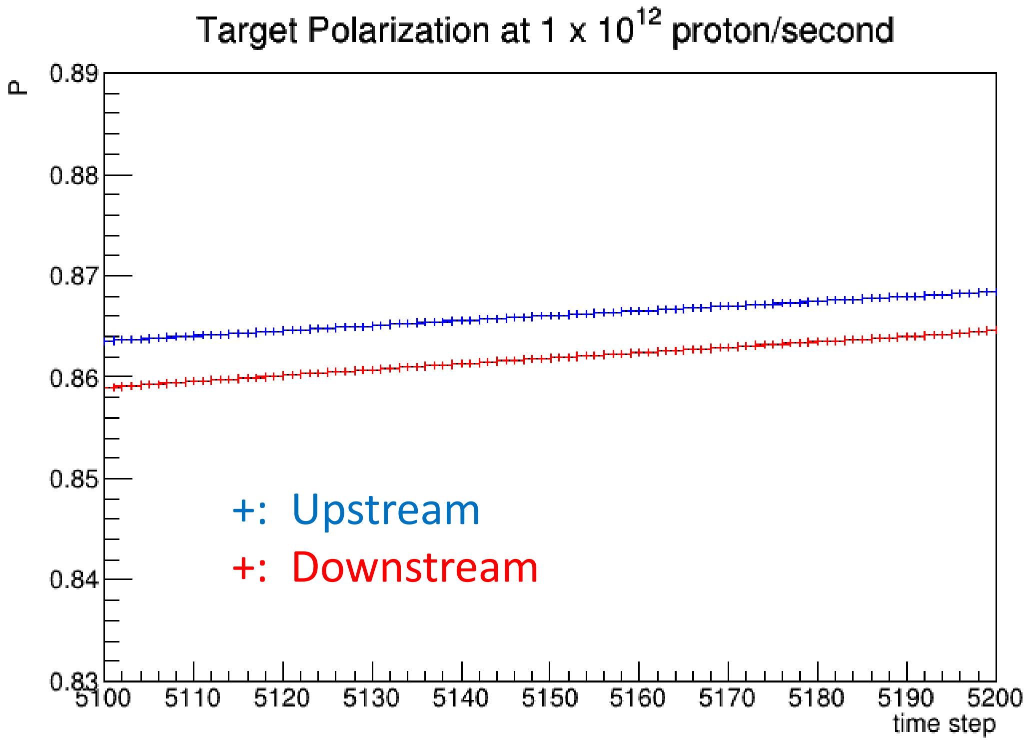
Secondary positron production along the target

Beam current in the target (nA)

	1 x 10^{12} protons/seconds	2.7 x 10^{12} protons/seconds
Downstream	177.13 nA	478.24 nA
Upstream	174.39 nA	470.84 nA

Results: Short term effect

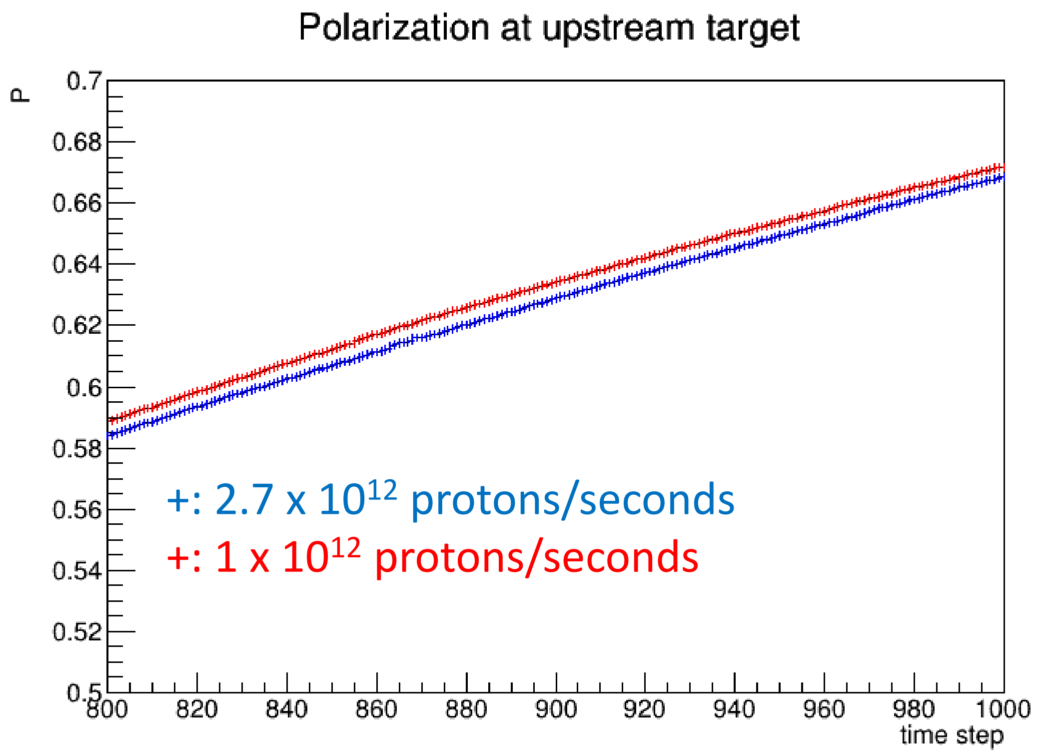




1 time step = 79 ms

- These plot show the target polarization for ~ 10 minutes (1 time step = 79 ms) at two different target positions
- The polarization drop ~4% during the beam spill
- The polarization difference between upstream & downstream ~ 0.4 %

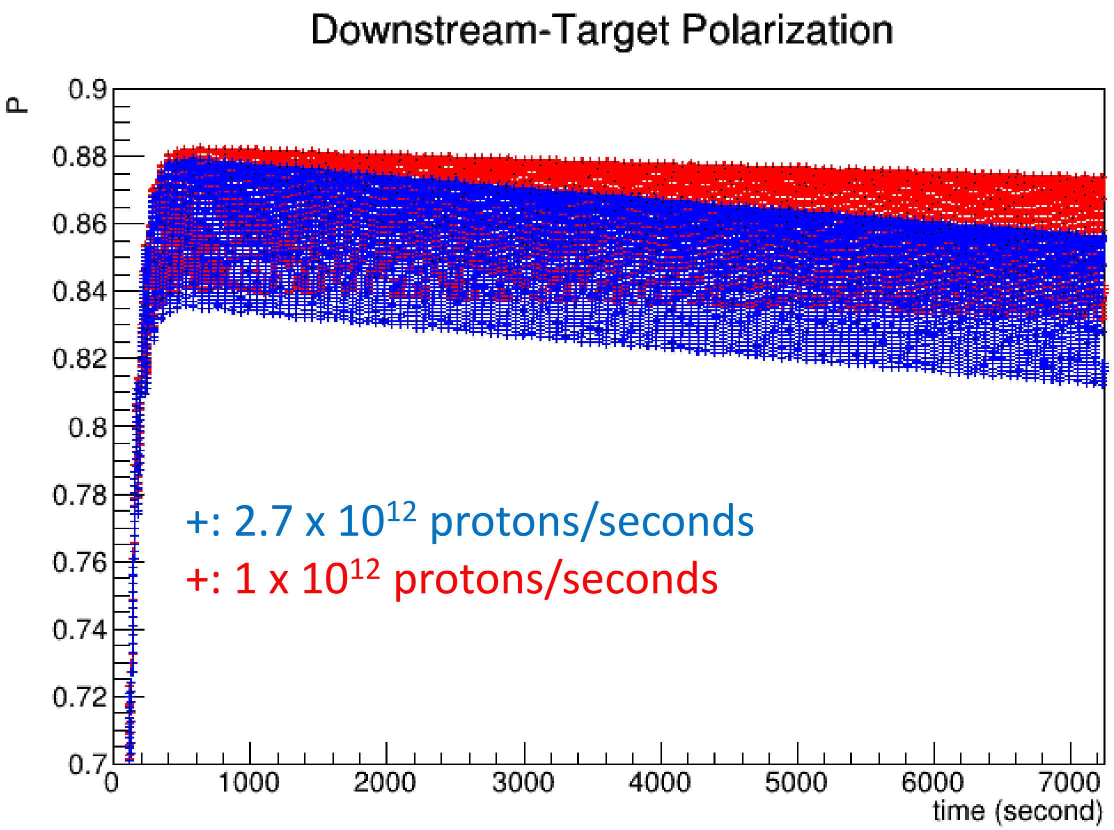
Results: Short term effect



1 time step = 79 ms

- This plot show the (zoom in) polarization at upstream target for the proposed intensity (1 x 10^{12} protons/seconds) and maximum intensity before quenching the superconducting magnet (2.7 x 10^{12} protons/seconds) after ~ 1minutes of beam
- The difference in the target polarization is ~ 0.5%

Results: Long term effect



- This plot show the polarization at downstream target for the proposed intensity (1 x 10^{12} protons/seconds) and maximum intensity before quenching the superconducting magnet based on the quench simulation(2.7 x 10^{12} protons/seconds) after 2 hours of beam
- After 2 hours of beam, the maximum polarization drop less than 1% for the proposed intensity and ~2% for the maximum intensity (before quenching the magnet)
- The polarization difference between two intensities grow from ~0.5% after 1 minute to ~2% after 2 hours of beam
- Need to run longer to see when we need to anneal the target and decide what is the best proton intensity to run considering the long-term target polarization

Summary & Outlook

- ❑ A LabView based simulation was developed to study the dynamic behavior of the polarized target:
  - Polarization Responses to the RF frequency as determined by the thermal-mixing equations
  - Incorporate the long-term dynamics due to the accumulation of radiation dose
  - Compliment the frequency adjustment by stepper motor
  - Mimic the real-time NMR measurement system which used at several polarized-target experiments
- ❑ Input for the simulation:
  - Target temperature -> Obtained by solving heat-transfer equation using FEM & utilizing COMSOL
  - Beam current -> Incorporate primary beam and secondary charged-particle production obtained from GEANT4
  - RF frequency
- ❑ Short-term effect:
  - The polarization drop by ~4% during the beam spill
  - The polarization difference between upstream and downstream target ~0.4%
  - The polarization difference between the proposed intensity (1 x 10^{12} protons/seconds) and maximum intensity before quenching the superconducting magnet (2.7 x 10^{12} protons/seconds) is ~ 0.5%
- ❑ Long-term effect:
  - After 2 hours of beam, the maximum polarization drop less than 1% for the proposed intensity and ~2% for the maximum intensity (before quenching the magnet)
  - Need to run the simulation longer to see when we need to anneal the target & decide what is the best proton intensity to run considering the long-term target depolarization

Thank You

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