M-STAR – Magnetism-Second Target Advanced Reflectometer

M-STAR is a polarized neutron reflectometer optimized for studies of magnetism and structure in magnetic heterostructures. It will define new limits in nano and meso-science, spintronics and kinetics studies for materials a few atomic monolayers thick to complicated prototype device-like systems with multiple buried interfaces having small lateral dimensions of only several millimeters. M-STAR will cover a simultaneous wide range of momentum transfer for kinetics studies. The combination of high brightness of the STS source with an advanced optics design is anticipated to provide a gain factor ≈200 over the magnetism reflectometer on FTS.

Science Drivers

M-STAR will address a range of science topics, including topological heterostructures, multifunctional oxide heterostructures, domain dynamics (switching and relaxation), multiferroics, and self-assembled magnetic heterostructures. Many of these exhibit unusual physical properties that are important for science and technology and represent recent key innovations. The availability of high performance polarized neutron reflectometry (PNR) is vital for understanding magnetism in these systems that include:

- A revolutionary new generation of heterostructures has emerged based on integrating topological insulators (TIs) with conventional materials. Proximity with a ferromagnetic insulator (FI) allows the TI surface states to experience ferromagnetic interactions with symmetry breaking at the interface. Examining dual-proximity effects by introducing ferromagnetic order onto the surface of TI thin films is realized by using ultra-thin FI in heterostructures.
- Multifunctional Oxide Heterostructures exhibit unusual physical properties that represent recent key innovations from both the fundamental and device application viewpoints. Epitaxial thin films of ferroelectric and ferromagnetic oxides are anticipated to find application in low-energy consumption devices. Particular interest is on the room temperature magnetoelectric multiferroic, $BiFeO_3$, exchange coupled to a ferromagnet. The nature of exchange coupling and mechanisms of the voltage control of ferromagnetism under dynamic conditions are topics to be addressed.
- In situ studies of kinetics and relaxation processes (domains and re-magnetization process in nanostructures and multilayers) require a broad spectral range and a higher flux combined with complex sample environment. Emergent interface magnetization in several novel interface states is expected to be weak, so these measurements require high statistics up to large Q.

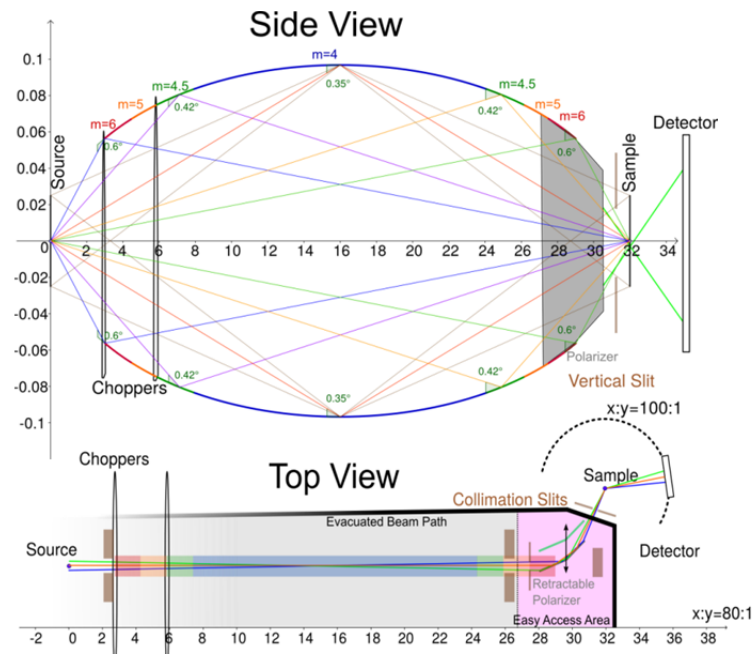
Science Requirements

The studies described above need a polarized reflectometer optimized for samples with lateral dimensions as small as several millimeters.

1. Qmax: ~ 0.4 $Å^{-1}$; Q-range in a single instrument setting: $0.01\ Å^{-1} < Q < 0.2\ Å^{-1}$ (at 5 Hz)
2. Sample sizes that range from 2 x 2 mm^2 to 20 x 20 mm^2.
3. Polarized beam with polarization analysis and an un-polarized beam option.
4. Integrated complex sample environments with an extended temperature range of 3 K < T < 750 K, magnetic field -5 T < H < 5 T, electric field E up to 1MV/cm, pressure and light. Many of these conjugate fields should be simultaneously controlled. Some of the conjugate fields should be variable at a rate of 10-100 kHz.
5. Many complex magnetic systems exhibit high saturation fields and their study requires a superconducting solenoid magnet with a hollow bore to suppress the background. The ability to apply magnetic fields must be integrated with many other sample environments including pressure cells and microwave cavities requiring field uniformity on order a few percent over their relatively large cross-sections ≈100 cm^2.
6. Low background will be provided with the frame overlap mirror and a reflection polarizer.

Technical Description

A proposed concept for M-STAR could be placed on the high intensity coupled moderator or possibly the 3 x 3 cm^2 face of the high peak brightness coupled moderator depending on final optics design. The sample position will be optimized between 20 and 32 m from the moderator to the best trade between the wavelength band and the intensity provided by the focusing optics. With an additional 2 m from sample to detector, M-STAR will reach a minimum wavelength band of 11.6 Å in the first frame. Kinetics studies will require the ability to operate at 5 Hz (suppressing intervening source pulses), doubling the wavelength band accessed. At least two bandwidth choppers will be needed to define the wavelength band and provide the flexibility for 5 Hz operation. The sample geometry could be either vertical or horizontal. M-STAR requires a 50×50 cm^2 detector with 2 mm x 2 mm spatial resolution. The use of polarized neutrons requires special attention to controlling magnetic materials in the vicinity of the instrument and places an additional requirement for minimal magnetic field sensitivity of the detector. M-STAR proposes an optics design that focuses the neutron beam at the sample with relatively high vertical divergence enabling use of small samples and kinetics studies. The focusing optics concept is comprised of elliptical mirrors (see figure).



Key parameters of M-STAR

Parameter	Description
Moderator	High-intensity coupled moderator or 3x3 cm^2 High-peak brightness moderator
Beam Size	variable illuminating samples as small as 2 x 2 mm^2 to as large as 20 x 20 mm^2
Moderator–sample distance	~20 - 32 m (depending on final optics design)
Sample–detector distance	1-3 m variable
Wavelength range	1 Å ≤ λ ≤ 40 Å
Resolution	$\Delta Q/Q > 0.02$
Detector	2-dimensional position-sensitive detector, 2 mm x 2 mm vertical spatial resolution