**1. DOE award # and name of the recipient (Institution).**

DE-FG02-09ER46556 Massachusetts Institute of Technology.

**2. Project Title and name of the PI.**

"Optics for Advanced Neutron Imaging and Scattering", Professor David E. Moncton.

**3. Date of the report and period covered by the report.**

March 30, 2016. Period covered: May 1, 2015 – December 31, 2015.

**4. A comparison of the actual accomplishments with the goals.**

During the report period, we continued the work as outlined in the original proposal. We have analyzed potential optical designs of Wolter mirrors for the neutron-imaging instrument VENUS, which is under construction at SNS. In parallel, we have conducted the initial polarized imaging experiment at Helmholtz Zentrum, Berlin, one of very few of currently available polarized-imaging facilities worldwide.

**5. A brief description of accomplishments.**

Two major directions are reported here: optical design options for VENUS and the polarized neutron imaging experiment.

**a. Focusing optics for VENUS**

VENUS is a future time-of-flight neutron imaging facility at SNS. It is under construction at the BL-10 position, using decoupled poisoned hydrogen moderator as the neutron source. The initial design of the instrument has been coded into McStas ray-tracing software at ORNL. We have added focusing optics to the code and made preliminary simulations. VENUS will use a long shielded beam tube hosting the shutter, apertures and choppers. Figure 1 shows the schematic diagram of the beam tube. This beam tube will terminate at the entrance to the experimental hutch, which is about five meters long. Focusing optics will have to be positioned either in the hutch or close to the end of the beam tube. We found that at the exit of the ten-meter-long beam tube the beam is too collimated to illuminate Wolter mirrors of large enough diameter. Therefore, focusing optics will be required to focus the beam into a virtual source near the sample position in order to create a divergent beam. Previously, we analyzed the use of removable focusing guides, which might be able to fit into the final section of the beam tube. We concluded that long guide create inhomogeneous phase space and might be very difficult to fit into the beam tube and the hutch.

Therefore, we considered three options for future detailed analysis. A focusing element with a focal length of about 1 m must be installed downstream of the beam entrance to the hutch. The best solution is axisymmetric nested parabolic concentrator. Such concentrator can be placed adjacent to the beam entrance, have the length of 10 cm and focal length of 1 m. It would be made with the same replication technology as Wolter mirrors (see Fig. 3). Initial ray-tracing simulations indicated that such optics could create a beam of large enough divergence for illuminating Wolter mirrors downstream of the sample. Another option for the beam concentrator is Kirkpatrick-Baez mirrors (KB), or nested KB (Montel) mirrors. (Neutron KB mirrors are used successfully at IMAGINE, a new Laue diffractometer at HFIR.) The disadvantage of KB mirrors is that the beam is reflected away from its original direction, so that the downstream setup, including the sample, Wolter optics, and detector, has to be aligned accordingly. The detector position would be shifted by about 0.5 m from its position without the optics, placing it too close to the planned hutch's walls. The advantage of KB mirrors is that relatively short mirrors of m-4 or m-5 can be manufactured. Finally, short nested focusing guides could be used. Such optics may be commercially available, but it may create an anisotropic beam.

**b. Polarized neutron imaging**

We proposed to demonstrate polarized neutron imaging with the help of focusing optics. Such demonstration is not possible right now because the focusing optics has not yet been installed, but the concept has been developed further and demonstration polarized imaging has been done without the focusing optics. Polarized neutron microscope is under construction at NIST and we're planning for the first demonstration experiments in 2016 or the first half of 2017.

Figure 4 shows schematic drawings of the traditional and focusing polarized imaging. In both setups, neutron polarizers and analyzers, as well as data analysis are very similar. Therefore, in preparation for the focusing polarized imaging, we have applied for beamtime at one of the best traditional facilities, PONTO at Helmholtz Zentrum, Berlin (HZB). The scientific motivation for this project is to understand formation of spiral magnetic domains in multiferroic materials and interaction of magnetic and ferroelectric domains.

We have measured a number of transition-metal oxide magnets at PONTO. Although the spatial resolution was not high enough to resolve magnetic domains, clear magnetic signal was observed, especially in Ba- and Sr-hexaferrite single crystals. Figure 5 shows the magnetic hysteresis in $SrFe_{12}O_{19}$ and similar results were obtained for $BaFe_{12}O_{19}$. These materials are soft ferrimagnets with Curie temperature well about room temperature. Domain sizes in these materials were measured by magneto-optics, of 20 μm, below the resolution achievable at PONTO, of 120 μm. (The follow-up experiment at PONTO was conducted after the end of the report period. We have successfully imaged ferromagnetic and, possibly, helimagnetic domains in rare-earth metals.)

The experience at PONTO will be indispensible to help conducting polarized imaging at the US facilities, where higher fluxes and higher resolution will be achievable. NIST is building a Wolter-optics-based neutron microscope, which will have polarization capability. The imaging instrument at HFIR, ORNL, is also preparing for polarized neutron imaging. With the help of focusing optics at NIST, we will have a much higher spatial resolution and neutron flux, than at PONTO. We believe that these new facilities will be powerful enough to resolve helical domains in rare earths and multiferroics.

## 6. Cost status

Authorized Budget (**8/1/13 to 1/31/2015**) = $320,000
Total expenditures **8/1/13 to 12/31/2015** = $320,000

## 7. Schedule status.

The project has ended on schedule.

## 8. Changes in approach.

N/A

## 9. Actual or anticipated problems or delays.

N/A

## 10. Changes of key personnel.

N/A

## 11. A description of products.

A paper in preparation

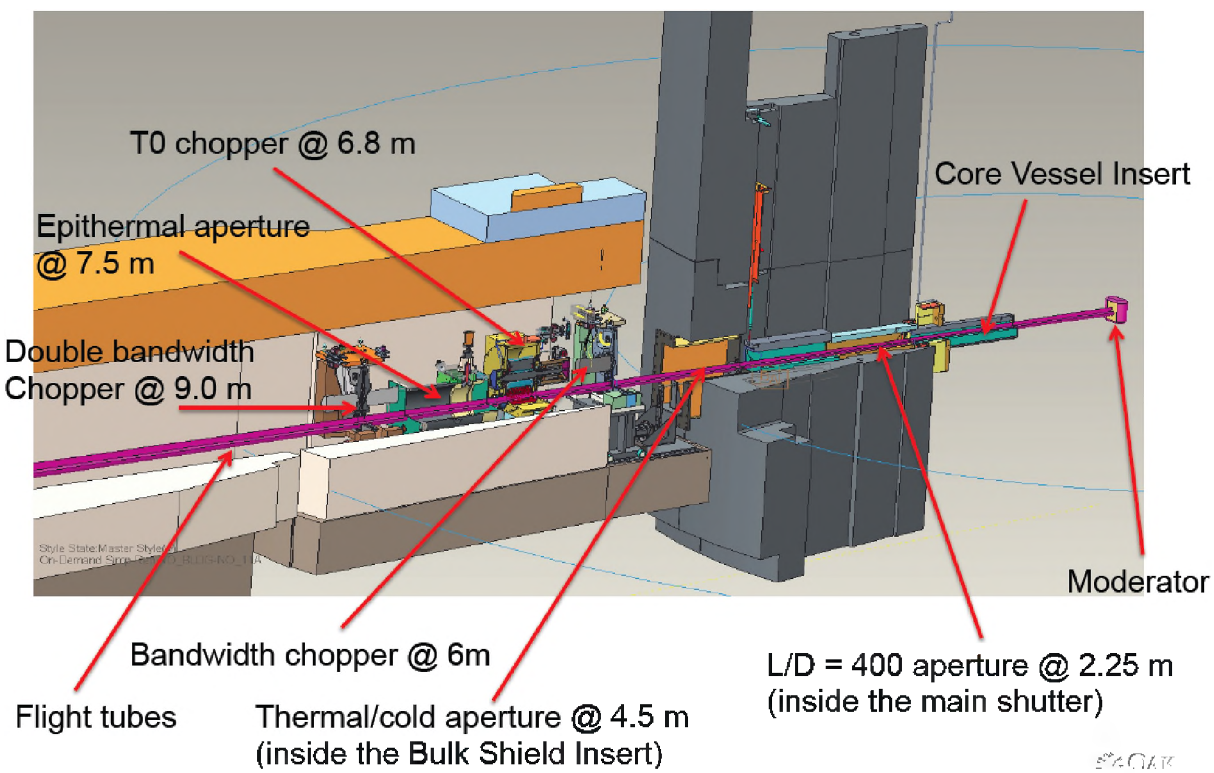


**Figure 1** Schematic drawing of the VENUS's front-end optics (the beam tube) between the neutron moderator and the experimental hutch.

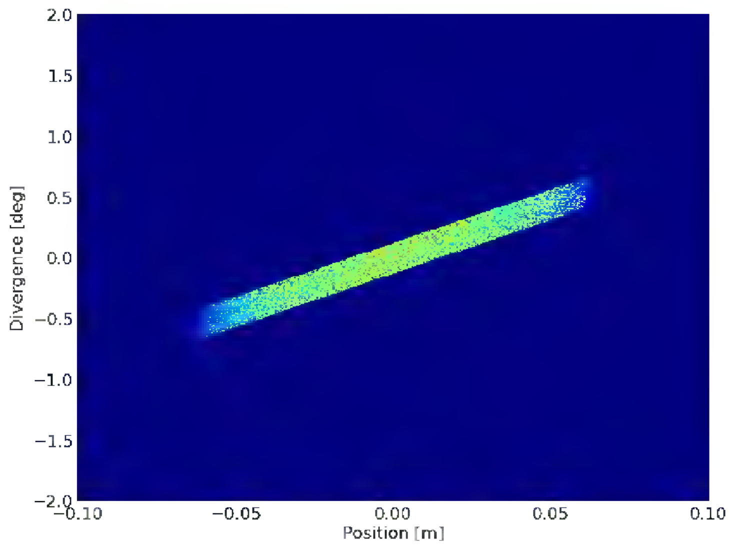


**Figure 2** Phase space of the neutron beam at the exit of the beam tube in planned configuration of VENUS, as simulated using McStas. The maximum divergence is about $\pm 2°$.

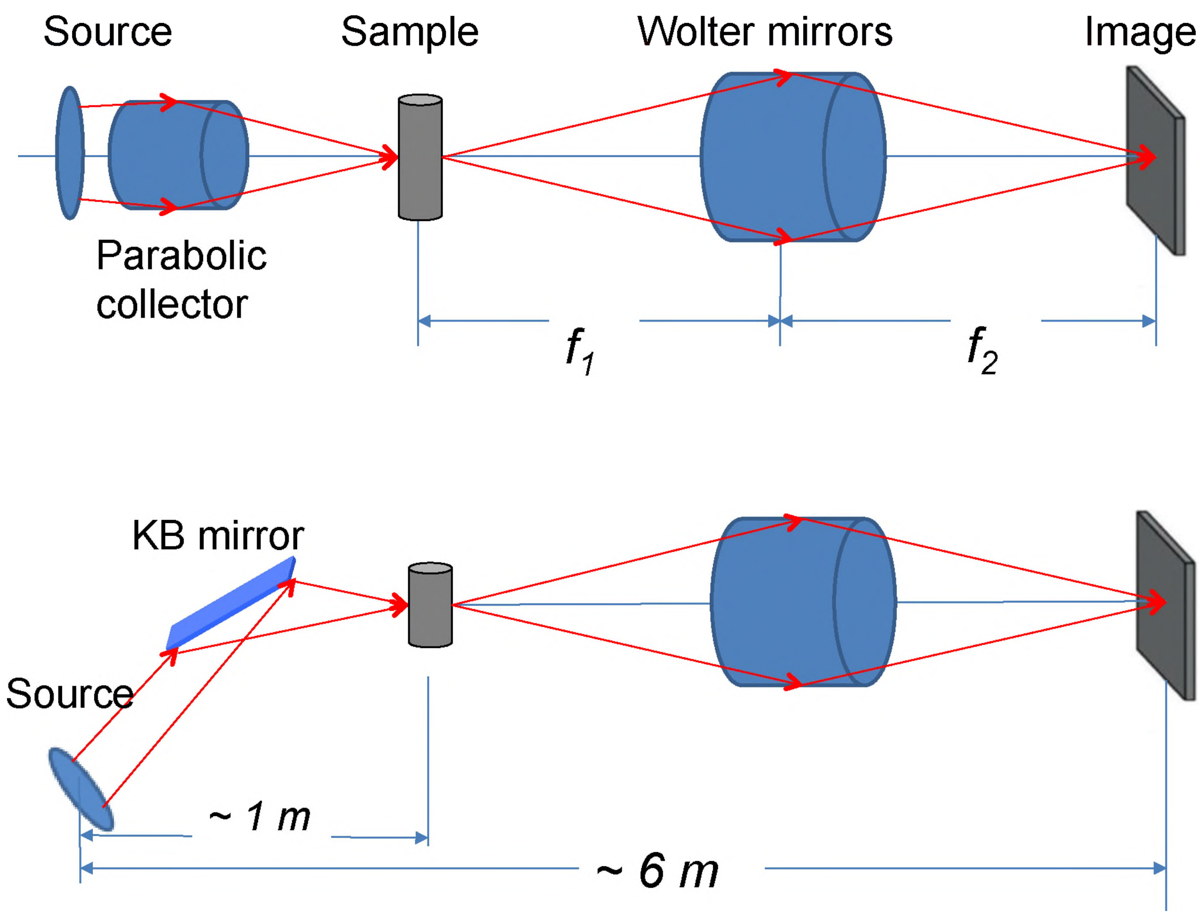


**Figure 3.** Schematic drawings of two possible focusing devices for creating a diverging beam at the sample position.

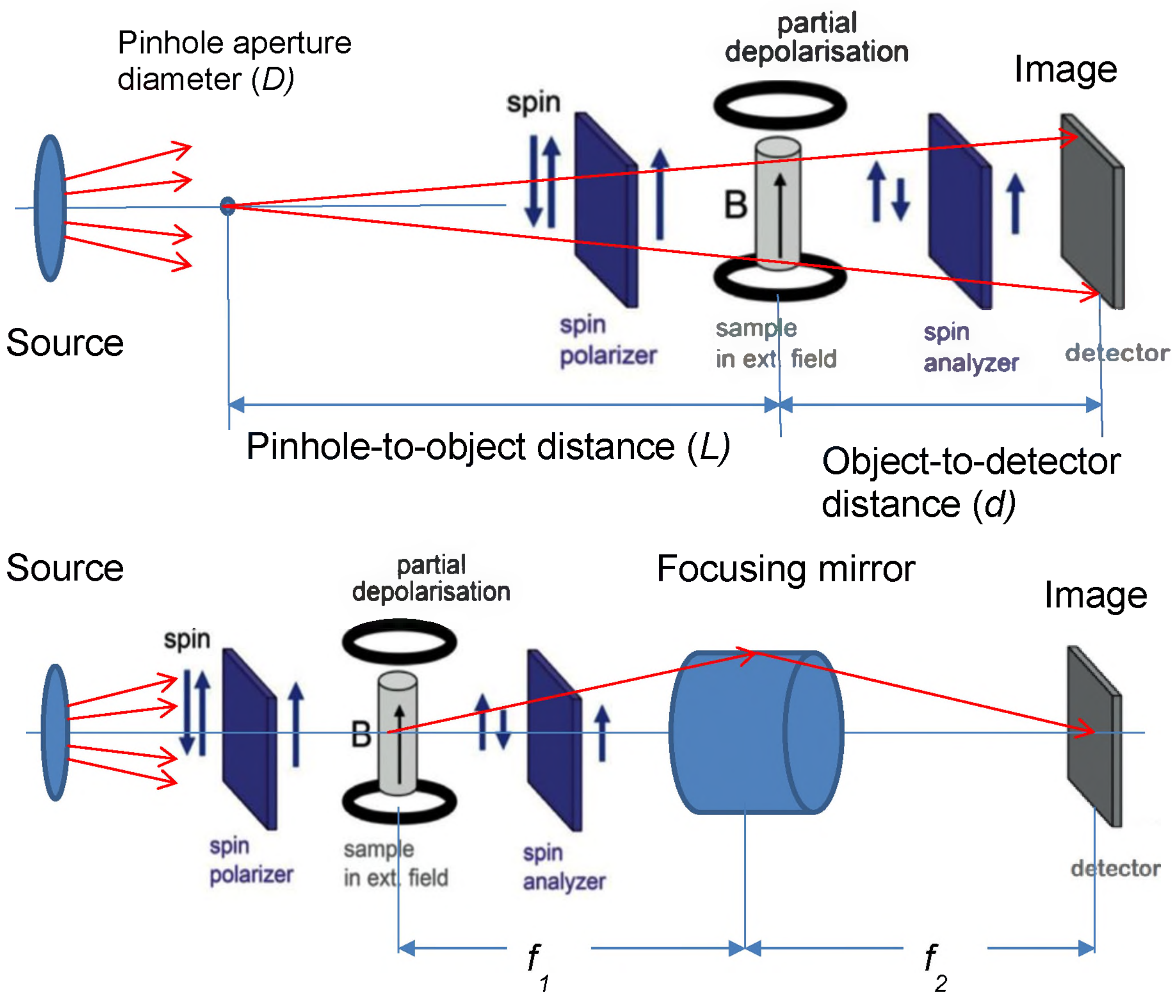


**Figure 4.** (Top) Schematic drawing of magnetic depolarization imaging implemented at PONTO, the HZB magnetic imaging instrument. The object-to-detector distance *d* must be minimized since it limits the spatial resolution. The neutron source at PONTO is a double-crystal monochromator, and the beam is collimated by vertical and horizontal sets of Soller collimators. (Bottom) Schematic drawing of focusing neutron depolarization imaging. The spatial resolution does not depend on the beam collimation, allowing for using a divergent beam from larger neutron sources, and thus increasing the flux on the sample.

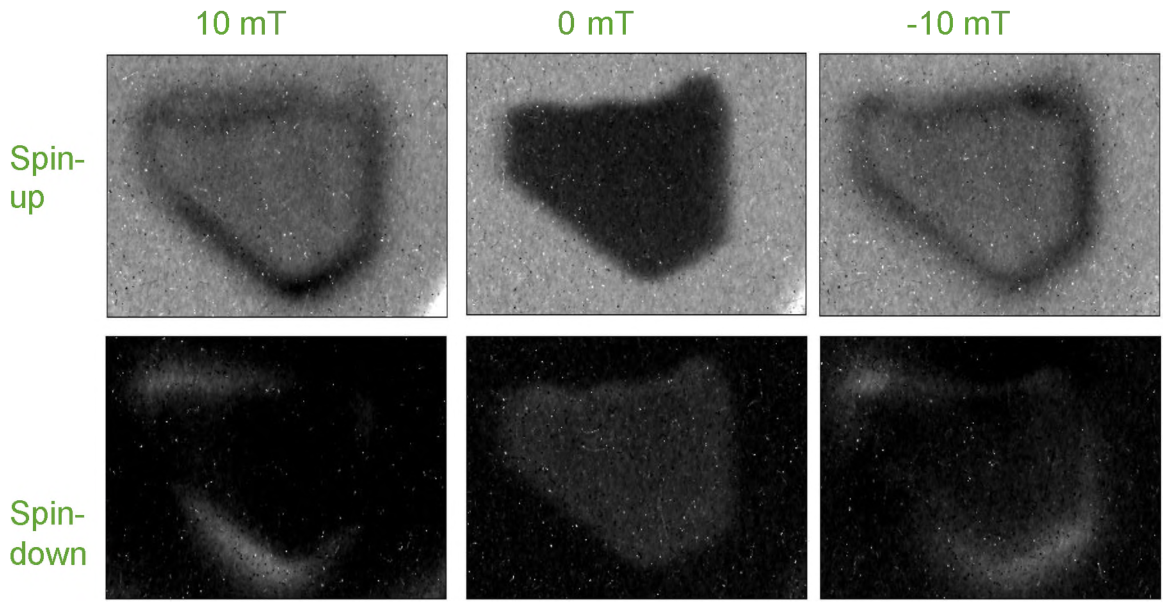


**Figure 5** Spin-polarized images of $SrFe_{12}O_{19}$ at room temperature (below Curie temperature) and different applied fields (-10, 0, and 10 mT). Neutron beam is polarized along the vertical axis. The measurements at the top and bottom rows were made with the polarization up and down respectively. At zero field, the depolarization of the beam is achieved due to a random distribution of small domains below Curie temperature. The magnetic field of 10 mT was applied along the beam. Although domains are too small to be resolved, the change in magnetization was clearly measured.