DE-SC0004835

Determination of the Equation of State of Asymmetric Nuclear Matter

Final Technical Report

Period covered: 01/01/2011 – 12/30/2016

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Final Report for DE-SC0004835:

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Abstract

A new Time Projection Chamber (TPC), called the SπRIT (SAMURAI pion Reconstruction Ion Tracker) TPC was constructed and used successfully in two experiments with the SAMURAI spectrometer at RIKEN, Japan to study the equation of state of neutron rich matter. As a result of the project, the SπRIT collaboration, an international collaboration consisting of groups from US, Japan, Korea, Poland, China and Germany, has been formed to pursue the science opportunities provided by the SπRIT TPC. After completion of the TPC and the two experiments, the collaboration continues to develop the software to analyze the SπRIT experiments and extract constraints of symmetry energy at supra-saturation densities. Over 250 TB of data have been obtained in the last SπRIT TPC experimental campaign. Construction of the TPC provided opportunities for the scientists to develop new designs for the light-weight and thin-walled field cage for the large pad plane and for the gating grid. Two PhD students (1 US and 1 Korea) graduated in 2016 based on their research on the TPC. At least four more doctoral theses (2 US, 1 Japan and 1 Korea) based on physics from the SπRIT experiments are expected.

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I. Major Goals/Objectives of the Project

The major goals of the project can be summarized as:

a. To study the equation of state (EoS) of asymmetric nuclear matter and the "nature of neutron stars and dense nuclear matter" via heavy ion collision experiments. Study of the nature of dilute and dense neutron-rich matter is one of the important research objectives listed in the 2015 Nuclear Physics Long Range Plan.
b. To maintain the US leadership in EoS research during the construction of FRIB by building detectors and doing experiments in facilities in Japan and GSI.
c. To construct the "SπRIT" Time Projection Chamber (TPC) to detect pions, which are predicted to be sensitive to the symmetry energy term in the equation of state of the neutron-rich matter.
d. To carry out a science program with the TPC at RIKEN with radioactive beams.

II. Project Results

The results of the project are reported in separate sections. Section A lists specific accomplishments that resulted from work supported by the award. Section B discusses the new technology and techniques developed to achieve these goals. The list of milestones and their accomplishment are discussed in Section C. Finally, publications resulting from this project are listed in Section D.

A. Accomplishments

a. As part of the international effort to extract the symmetry energy constraints at high density, we collaborated with the ASY-EOS group in the Au+Au collisions at E/A=400 MeV at GSI in 2011. A paper [1] was published on this experiment.
b. The international SπRIT collaboration has been formed to attract manpower and resources from groups in Japan, Korea, Poland, Germany and China to build auxiliary detectors, help with the construction of the SπRIT detector and collaborate with the experimental campaigns. The collaboration will continue after this grant.
c. We finished construction of the SπRIT Time Projection Chamber (TPC) at MSU in May, 2013 and shipped it to RIKEN, Japan in Feb, 2014.
d. We successfully commissioned the SπRIT TPC with beams outside the SAMURAI magnet in October, 2015 (https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/1510MT_test/commission.htm). The commissioning of the TPC inside the SAMURAI magnet was also successfully completed in April 7-10, 2016 (https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/index.htm). We were able to construct particle identification plots that distinguish p, d, t and pions from the commissioned data.
e. We successfully executed two approved TPC experiments in May, 2016

1. 108Sn+ 112Sn and 112Sn+ 124Sn reactions;
https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/1605Sn108/index.htm
2. 132Sn+ 124Sn and 124Sn+ 124Sn reactions;
https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/1605Sn132/index.htm

f. We have also constructed a web site to educate the public about the TPC, the science of our experiments using the cosmic data taken with the TPC. https://groups.nscl.msu.edu/hira/cosmic

B. New Technology or Techniques

Even though the SπRIT TPC design was initially based on the EOS TPC [2], construction of the new detector involved developing new fabrication techniques. These techniques can be used in future detector construction. The new detector utilized state of the art self-triggering TPC electronics, and requires a new suite of analysis software to properly analyze the collected data. We list the items which constitute new technology or techniques that arose from this project:

1. The SπRIT TPC

A Time Projection Chamber (TPC) called the SAMURAI Pion-Reconstruction and Ion-Tracker (SπRIT) has been constructed at Michigan State University as part of an international effort to constrain the symmetry-energy term in the nuclear Equation of State (EoS). The SπRIT TPC has been used successfully in conjunction with the SAMURAI spectrometer at the Radioactive Isotope Beam Factory (RIBF) at RIKEN to measure yield ratios for pions and other light isospin multiplets produced in central collisions of neutron-rich heavy ions, such as 132Sn+124Sn and neutron deficient system of 108Sn+112Sn. The SπRIT TPC can function both as a TPC detector and as an active target.

2. SπRIT TPC Field Cage

The field cage for the SπRIT TPC was produced using fabrication techniques chosen to address unique features from central heavy ions collisions at around 300 MeV/u, yet the TPC can be usable as an active target in future experiments with rare or explosive gases. The walls of the field cage and gas enclosure are thin enough so that light charged particles can penetrate through the wall to trigger multiplicity detectors outside the detector. To be portable, the walls must be light but strong enough to provide rigidity to the field cage whose interior dimensions are 145 cm long 97 cm wide by 49 cm high. The field cage walls should provide uniform electric fields, form a gas tight volume that will allow distinct counter and insulation gases and made with materials that does not contaminate the counter gas. To address these issues, the side and front walls are constructed of 1.6 mm thick halogen-free G10 printed circuit boards (PCBs) with 6 mm wide copper strips with 4 mm gaps between strips. This corresponds to a 1 cm pitch on both the interior and exterior sides of each PCB. The exterior strips are offset by 5 mm from the interior strips to better define the field everywhere within the field cage. The corners are produced from quarter sections of G10 tubing, with conductive paint used to produce the conductive strips that connect the strips from adjacent walls. The cathode surface at the bottom of the field cage is constructed from graphite-coated aluminum honeycomb that is bonded to the field cage walls by epoxy. This graphite coats the partially oxidized aluminum cathode with a surface of well-defined conductivity and high electron work function. The latter may help to suppress ionization by scattered light from a pulsed ultra-violet laser if one is used to calibrate the TPC. The field cage is connected to the top plate with an O-ring surface, making the counter gas and insulation gas to be two distinct gas-tight volumes.

3. TPC Gating Grid Driver

A simple but novel driver system has been developed to operate the gating grid of SπRIT TPC. This system connects the wires of the gating grid to its driver via custom-made low impedance transmission lines. The driver is a simple circuit consisting of 4 MOSFET switches forming two pairs of a fast N-type and a fast P-type MOSFET switch and two power supplies. When the gating grid is open, all wires have the same voltage allowing secondary electrons produced in the ionization of the detector gas molecules to pass through to the anode wires. When the grid is closed, the wires have alternating higher and lower voltages causing the electrons to terminate at the more positive wires and the positive ions to terminate at the negative wires. Rapid opening of the gating grid is achieved by shorting the positive and negative wires via two custom-made low impedance transmission lines to attain the average bias potential rapidly with one pair of the MOSFET switches. This gating driver has been used successfully in experiments with the SπRIT TPC to open the high capacitance (16 nF) gating grid in about 0.35 μs. By adding a second pair of N-type and P-type MOSFET switch, the gating grid can be closed and the wire voltages restored to their original (closed) values in 3 μs. A preprint on the gating grid has been submitted for publication [3]. A prototype of this gating grid driver was given to a TPC group at TAMU for testing.

4. Incorporation of the Generic Electronics for TPC (GET) in the SπRIT TPC

Signals induced on the pad plane of the SπRIT TPC, consisting of 112x108 pads are read out using the GET electronics [4]. The GET system has four AGET (ASIC for Generic Electronics for TPC) chips mounted on an AsAd front-end board, which is attached to the detector and reads the analog signals from up to of 256 channels. Four of these AsAd boards are connected to one CoBo module, which collects the trigger information from the AsAd boards and passes the trigger information on to the MUTANT board. For triggered events, the CoBo boards take the digital data from the AsAds and assembles them into event buffers. Up to 10 CoBo modules and one MUTANT boards can be plugged into one μTCA crate. Synchronous trigger signals are generated by the MUTANT using the trigger information provided by the CoBo boards in the same μTCA crate and user defined hit patterns or multiplicity values that are compared to the fired channels, and these triggers are delivered to CoBo modules through the back-plane of the crate.

The state of the art GET electronics system was put into production in 2014 by the GET collaboration of which NSCL is a member. The SπRIT readout uses 48 AsAd (ASIC Support and ADC) boards, 12 CoBo (Concentration Board) modules and 2 MUTANT (MUltiplicity, Trigger ANd Time) modules. The SπRIT TPC is the first device with a large enough number of channels to require more than one μTCA crate and more than one MUTANT. Specifically, the GET electronics is used in the SπRIT TPC to read out 12096 signals from the 12096 pads on the pad plane of the SπRIT TPC. To do so, the SπRIT TPC is equipped with 48 AsAd boards, each with its own ZAP board (protection and adapter circuit) which connects the AsAD to 252 pad electrodes. Only 63 channels (corresponding to 63 pads) out of a possible 64 are read out by each AGET chip. Two μTCA crates are used, each containing a MUTANT and 6 CoBo modules, and the two data acquisition machines are used to balance the load of data transmission. Since one binary encoded data file is produced by each CoBo, 6 binary files are transferred to each data acquisition machine for each event.

A prototype of the GET electronics was first tested with the SπRIT TPC in September of 2014. With half of the GET electronics (24 ASAD board) installed on the SπRIT TPC the following year, a bug was discovered in the functionality of the GET system for positive analog input signals. This problem was corrected and the full GET read out was installed in the Fall of 2015. We have successfully used the GET system in two experiments with Sn beams on Sn targets even though the partial readout features of the GET system were not functioning properly. The adoption of the GET electronics with TPC provided an unprecedented opportunity to test and improve the GET electronics in a large scale experiment.

5. Analysis software

The analysis software can be separated into two distinct parts:

1. GETDecoder for general use in GET electronics
2. SpiRITROOT for analysis of SπRIT TPC data

We developed the GETDecoder module that determines the data type of the files, unpacks in parallel the raw data from the CoBo modules, and merges them while converting the output file into a recognizable format by widely-used ROOT [5] analysis package for later analysis. Creating multiple GETDecoders simultaneously for each file is advantageous because it not only saves computing time by a factor of 6 in our case with 12 CoBo files but also reduces the disk space usage by eliminating the pre-merging process. The GETDecoder has been adopted by the MSU Active-Target/TPC group to decode their TPC data.

The SpiRITROOT software is developed to provide consistent analysis tools to the SπRIT users for both simulation and data analysis. It is written on top of the FairRoot framework [6], which was developed for the FAIR experiments in Germany and later redesigned for any experimental setup. The analysis software is unique in analyzing the TPC data for tracking and extraction of momentum and energy loss for low energy experiments.

C. Milestones

A management plan with milestones was filed with the DOE PM in November, 2010. A Baseline Change Proposal was filed on September 4, 2013 and was approved by PM. A no-cost extension was filed in May, 2015 for one year and also approved by the PM. Table 1 contains a summary of the Milestones with associated Figures 1-10.

Table 1: Milestone dates

Milestone			**Location**	**Milestone PMP DATE**	**Actual Date**	**Figures / Notes**
1	Conceptual Design	Chamber	NSCL+TAMU	Q3/2011	3/15/2011	Figure 1
2	Detailed Design	Chamber	NSCL+TAMU	Q4/2011	8/15/2011	Figure 1
3	Construction	Chamber	NSCL+TAMU	Q3/2012	6/30/2012	Figure 2
4	Conceptual Design	Detector	NSCL	Q2/2011	3/15/2011	Figure 3
5	Detailed Design	Detector	NSCL	Q4/2011	9/30/2011	Figure 3
6	Construction and Assembly	TPC	NSCL	Q3/2013	5/15/2013	Figure 3
7	First Test with cosmic	TPC	NSCL	Q4/2013	7/27/2013	Figure 4
8	contingency	TPC	NSCL	Q4/2013	9/30/2013	
9	Shipping to RIKEN	TPC	NSCL	Q2/2014	2/25/2014	Figure 5
10	Test with GET prototype	TPC	NSCL+RIKEN	Q4/2013	9/30/2013	Figure 6
11	Test with full GET	TPC	RIKEN	Q3/2014	8/1/2015	Figure 7/Note1
12	Install & Test	TPC	RIKEN	Q4/2014	7/30/2014	Figure 8/Note 2
13	Commissioning	TPC	RIKEN	Q2/2015	Oct-2015	Figure 9/Note 3
14	π+/π- experiment	TPC	RIKEN	Q3/2015	May-2016	Figure 10/Note4
15	n/p experiment		GSI	Q2/2015	6/1/2016	

Note1: In early 2014, we found a bug in during the test when half of the GET electronics was installed. After the GET collaboration agreed that the bug was caused in the manufacturing of the electronics, we had to ship back all the ASAD modules to France for repair. The modules were returned in the summer of 2014. This caused a delay for the completion of the test with full GET electronics and in the SπRIT experimental program by nearly a year.

Note2: Initial installation was performed at the 30 degree configuration of the SAMURAI magnet rather than at the 0 degree configuration used in the SπRIT experiment. This was necessary to avoid conflicting with the setup of the magnet at the time of insertion testing.

Note3: The delay in the commissioning was caused by the delay implementing the repaired GET electronics as explained in Note 1.

Note4: The delay in finishing the π+/π- experiment with the TPC is a result of the cascade effect caused by the GET electronics (see Note 1) and delay in the commissioning run (see Note3). Due to this problem, we requested and were granted a "no cost" extension of the project for one year in 2015.

A. Milestones 1 & 2

The design of the enclosure included considerations for coupling the TPC inside the SAMURAI magnet. To maximize drift length and therefore the performance of the detector, it was necessary to maximize the vertical height of the enclosure while still fitting inside the SAMURAI magnet. Figure 1 shows a to-scale foam model constructed by undergraduate students at MSU and shipped to RIKEN Japan in July 2011. After checking the fit with the foam model (Figure 1), detailed design of the TPC enclosure was finalized. The design also incorporated thin windows to allow particles to exit the TPC and be detected by auxiliary detectors.

Milestone 3: To allow mobility of the detector, removable motion attachments were made during the construction of the TPC at TAMU. The enclosure was delivered to the NSCL in July 2012. The enclosure was then fitted with the thin windows and prepared for coupling with the detector (Figure 2, left panel). The motion attachment was designed so that the enclosure, i.e. the entire TPC, could be rotated to the vertical position for transportation (Figure 2, right panel).

Figure 1: Testing the design inside the SAMURAI magnet chamber

Figure 2: Chamber enclosure construction

Milestone 4, 5 & 6: The detector design was spatially dependent on the constraints of the enclosure and the SAMURAI magnet. The conceptual design was based on the EOS TPC [2] but modernized and adapted to our particular constraints. In particular, having separate counter gas and insulation gas volumes, maximizing the drift length of the detector and incorporating the then under development GET electronics were important requirements. The detailed design included the design of all components of a field cage to maintain a constant electric field, the design of wire planes for charge amplification, and a 12,096 channel pad plane to readout the induced charge signals. To interface with the enclosure safely, a voltage step down was also designed and constructed to safely step down the high voltage potential of the field cage to the ground potential of the enclosure. Figure 3 shows the exploded view of the TPC with pictures of the various components.

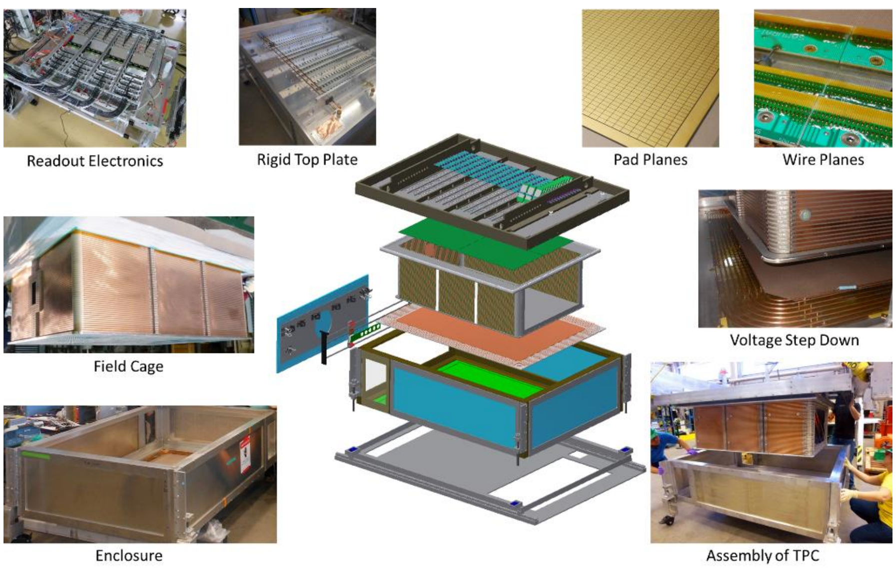


Figure 3: Designed and constructed TPC components

Milestone 7: Cosmic rays were used to test the functionality of the TPC (Figure 4). We tested the detector with STAR front end electronics first on 15 July 2013, with a subsequent test utilizing prototype GET electronics on 27 July 2013.

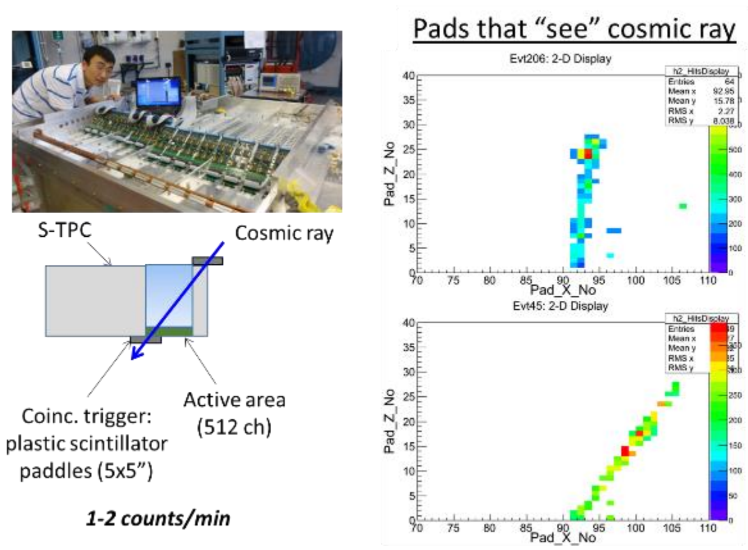


Figure 4: First cosmic detected in the TPC

Milestone 9: The TPC was shipped to RIKEN in February 2014. Many considerations were made for the shipping of the TPC. A crate with a “floating” inner box (see Figure 5) was designed and built by the packaging department at MSU, taking special care to dampen vibrations near the resonant frequency of the wires. In addition, the temperature inside the crate had to be held near room temperature, as bonded materials inside the TPC with differing coefficients of thermal expansion could become separated due to temperature fluctuations, and the wire tension could be affected by shrinking and re-expanding. Special phase-changing materials were packed inside the shipping crate to keep the temperature constant to within one degree during transit in winter conditions. The TPC was specially fitted with HEPA filters to allow breathing with changing pressures without becoming contaminated. Various monitors are used to monitor the temperature and vibrations of the box during shipping.

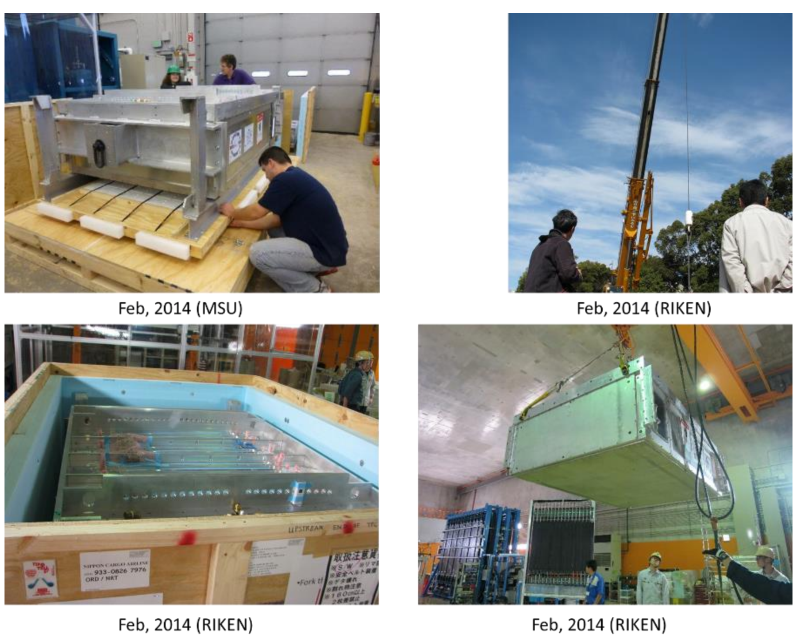


Figure 5: Shipping to RIKEN

Milestone 10 & 11: The partial testing of the GET electronics was initialized before shipping to RIKEN, using cosmic and a radioactive source in the summer of 2013 as shown in Figure 6. Further testing proceeded when the detector arrived at RIKEN in early 2014, with testing probing both the TPC and the GET electronics. After half of the GET electronics were installed (Figure 7, left panel), a bug in the AsAD board was found. All the AsAD boards had to be returned to France for repair and shipped back to RIKEN before full installation of the GET electronics on the TPC. This was accomplished in the summer of 2015, see Figure 7, right panel. When the full GET electronics were in place, the testing was completed utilizing cosmic as well as pulser tests.

Milestone 12: The successful use of the detector requires a safe method of inserting the TPC into the SAMURAI magnet. A rail system was designed for the TPC to rest on inside the magnet chamber, with an adjoining rail system on a table outside the magnet. This allows a smooth, controlled insertion. Fig. 8 shows the team who successfully inserted the TPC into the SAMURAI chamber at 30 deg configuration in July 2014 (See note 2). The same method was utilized in the experiments that were performed with the TPC.

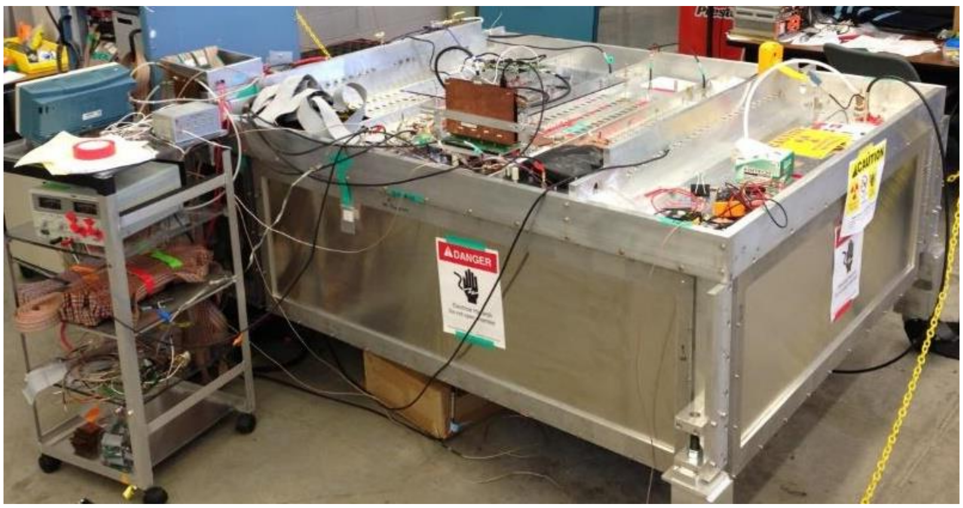
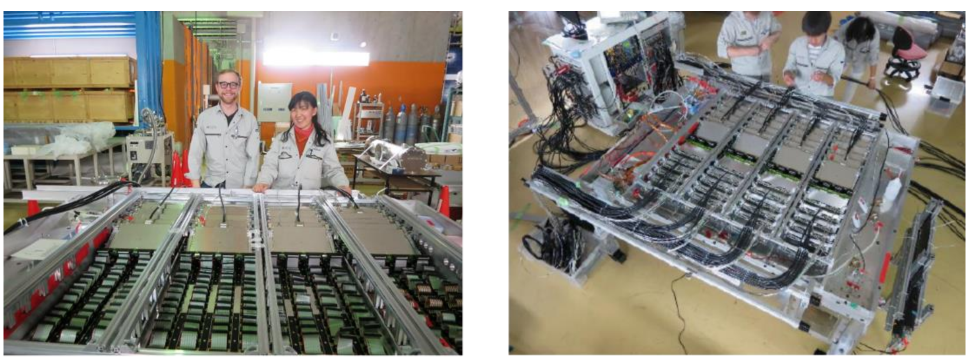


Figure 4: Testing with GET electronics prototype at NSCL

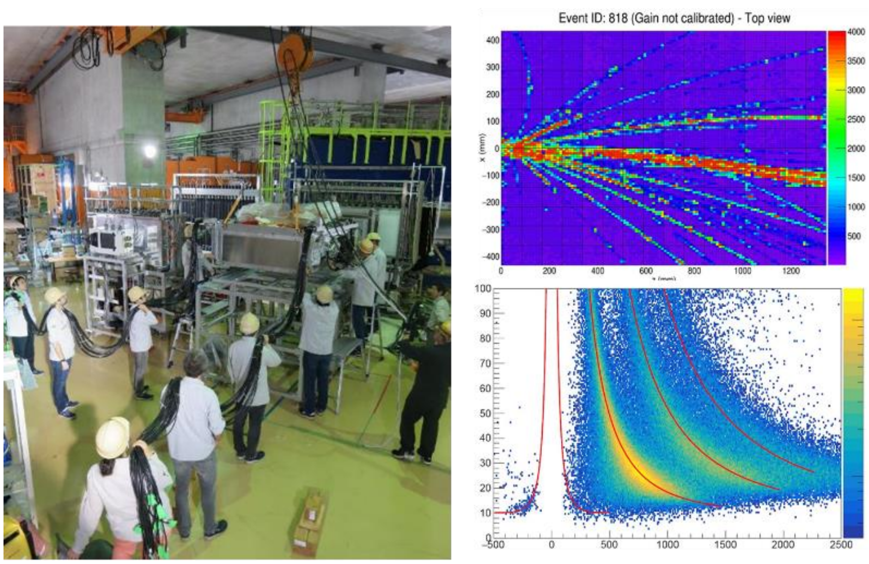


Partial installation of GET electronics

Full installation of GET electronics

Figure 5: Installation of full GET electronics

Figure 6: Installation of TPC into SAMURAI magnet



Oct, 2015　　　　　　　　　　April, 2015

Figure 7: The commissioning of the TPC with RI beam

Milestone 13: The commissioning of the TPC was delayed due to the delay in testing the GET electronics, as discussed in Note 3 of Table 1. The commissioning consisted of two parts: a parasitic beam run with a ^{79}Se beam outside of the magnetic field, which was performed in October 2015, and a dedicated beam run inside the magnet chamber using a ^{132}Sn beam, performed in April 2016. The left panel of Figure 9 shows a snapshot when the TPC was installed directly outside the SAMURAI spectrometer. The top right plot is the pad-plane view (with 12096 pixels) of a collision of 79Se beam on Sn target. Without the magnetic field, the charged particle tracks are essentially straight. In the dedicated beam commissioning, the SπRIT TPC was installed inside the SAMURAI magnet, allowing particle identification. The right bottom plot is the particle identification spectra of particles emitted from the Sn+Sn collisions and detected in the TPC.

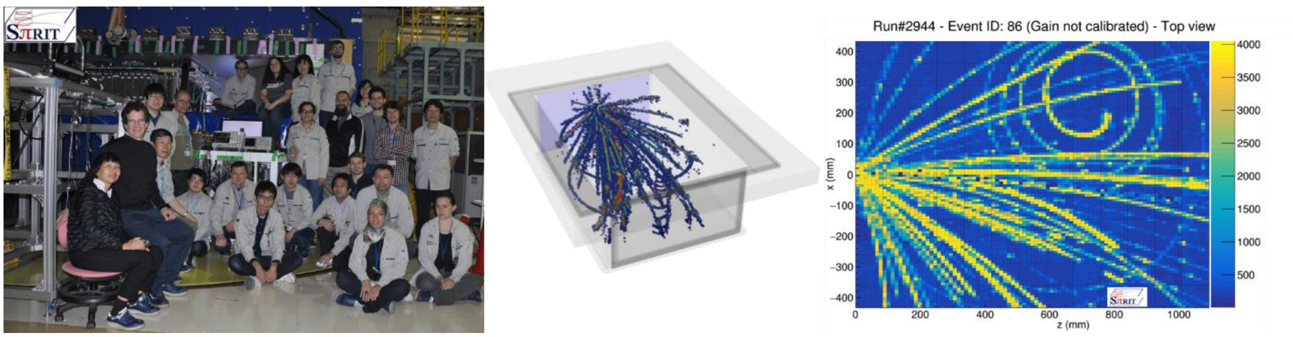


Figure 8: Successful experimental campaign

Milestone 14: The pion ratio experiment was performed in May 2016, consisting of 4 beams on two different targets, along with a cocktail beam used to calibrate the gain of the detector. A summary of the performed experiments is listed in Table 2. Over 250 TB of data were accumulated, with analysis ongoing. The left photo in Figure 10 shows most of the experimentalists taking part in the two experiments. The middle plot is a 3D track analysis of a Sn+Sn reaction. The dramatic spiral, more clearly seen from the top view of the event during on-line monitoring shown in the right figure is a rare low energy pi- particle which curves in the opposite direction from the positively charged ions.

Table 2: Summary of performed experiments

Experiment summary		
Beam	**Target**	**Gated events**
108Sn	112Sn	~1.0 x 10^7
112Sn	124Sn	~5.9 x 10^6
124Sn	112Sn	~5.3 x 10^6
132Sn	124Sn	~1.0 x 10^7
Z=1-3 cocktail	Blank	~6.8 x 10^5

D. Publications

Below is a list of publications as a result from this project.

SπRIT: A time-projection chamber for symmetry-energy studies, R. Shane, A.B. McIntosh, T. Isobe, W.G. Lynch, H. Baba, J. Barney, Z. Chajecki, M. Chartier, J. Estee, M. Famiano, B. Hong, K. Ieki, G. Jhang, R. Lemmon, F. Lu, T. Murakami, N. Nakatsuka, M. Nishimura, R. Olsen, W. Powell, H. Sakurai, A. Taketani, S. Tangwancharoen, M.B. Tsang, T. Usukura, R. Wang, S.J. Yennello, J. Yurkon, "SπRIT: A time-projection chamber for symmetry-energy studies," *Nucl. Inst. Meth. A*, vol. 784, p. 513-517, 2015. http://www.sciencedirect.com/science/article/pii/S0168900215000534

Beam commissioning of the SπRIT Time Projection Chamber, G. Jhang, J. Barney, J. Estee, T. Isobe, M. Kaneko, M. Kurata-Nishimura, G. Cerizza, S. Clementine, J. W. Lee, P. Lasko, J. Łukasik, W. G. Lynch, A. B. McIntosh, T. Murakami, P. Pawłowski, R. Shane, S. Tangwancharoen, M. B. Tsang, H. Baba, B. Hong, Y. J. Kim, H. S. Lee, H. Otsu, K. Pelczar, H. Sakurai, D. Suzuki, Z. Xiao, S. J. Yennello, Y. Zhang, and for the SπRIT Collaboration, Journal of the Korean Physical Society, Vol. 69, No. 2, July 2016, pp. 144-151. http://link.springer.com/article/10.3938/jkps.69.144'

Results of the ASY-EOS experiment at GSI: The symmetry energy at suprasaturation density, P. Russotto, S. Gannon, S. Kupny, P. Lasko, L. Acosta,M. Adamczyk, A. Al-Ajlan, M. Al-Garawi, S. Al-Homaidhi, F. Amorini, L. Auditore, T. Aumann,Y. Ayyad, Z. Basrak, J. Benlliure, M. Boisjoli,K. Boretzky, J. Brzychczyk, A. Budzanowski, C. Caesar, G. Cardella, P. Cammarata, Z. Chajecki,M. Chartier, A. Chbihi, M. Colonna, M. D. Cozma, B. Czech, E. De Filippo, M. Di Toro, M. Famiano, I. Gasparic, L. Grassi, C. Guazzoni, P. Guazzoni, M. Heil, L. Heilborn, R. Introzzi, T. Isobe, K. Kezzar,7 M. Ki˘s, A. Krasznahorkay, N. Kurz, E. La Guidara,G. Lanzalone,A. Le F`evre, Y. Leifels, R. C. Lemmon, Q. F. Li, I. Lombardo, J. Lukasik, W. G. Lynch, P. Marini, Z. Matthews, L. May, T. Minniti, M. Mostazo, A. Pagano, E. V. Pagano, M. Papa, P. Paw lowski, S. Pirrone, G. Politi, F. Porto, W. Reviol, F. Riccio, F. Rizzo, E. Rosato, D. Rossi, S. Santoro, D. G. Sarantites, H. Simon, I. Skwirczynska, Z. Sosin, L. Stuhl, W. Trautmann, A. Trifir`o, M. Trimarchi, M. B. Tsang, G. Verde, M. Veselsky, M. Vigilante, Yongjia Wang, A. Wieloch, P. Wigg, J. Winkelbauer, H. H. Wolter, P. Wu, S. Yennello, P. Zambon, L. Zetta, and M. Zoric, Phys. Rev. C 94, 034608 (2016). https://journals.aps.org/prc/abstract/10.1103/PhysRevC.94.034608

A Gating Grid Driver for Time Projection Chambers, S. Tangwancharoen, W.G. Lynch, J. Barney, J. Estee, R. Shane, M.B. Tsang, Y. Zhang, T. Isobe, M. Kurata-Nishimura, T. Murakami, Z.G. Xiao, Y.F. Zhang and the SπRIT collaboration, submitted to NIMA. Preprint available on arXiv: https://arxiv.org/abs/1612.06708

Pion Production in Rare Isotope Collisions, M.B. Tsang, J. Estee, H. Setiawan, W.G. Lynch, J. Barney, M.B. Chen, G. Cerizza, P. Danielewicz, J. Hong, P. Morfouace, R. Shane, S. Tangwancharoen, K. Zhu, T. Isobe, M. Kurata-Nishimura, J. Lukasik, T. Murakami, and the SπRIT collaboration, submitted to PRC. Preprint available on arXiv: http://arxiv.org/abs/1612.06561

KATANA - a charge-sensitive triggering system for the SπRIT experiment, P. Lasko, M. Adamczyk, J. Brzychczyk, P. Hirnyk, J. Łukasik, P. Pawłowski, K. Pelczar, A. Snoch, A. Sochocka, Z. Sosin, submitted to NIMA. Preprint available on arXiv: https://arxiv.org/abs/1610.06682

In addition to published results, numerous articles were published in the NSCL weekly newsletter. These articles are enumerated in Table 3.

Table 3: Greensheet articles

Article Title/Link	Date
Art from Outer Space	9/9/2016
https://groups.nscl.msu.edu/userinfo/greensheets/2016/The%20Greensheet9%209%202016.pdf	
Viewing Nuclear Reactions	12/4/2015
https://groups.nscl.msu.edu/userinfo/greensheets/2015/The%20Greensheet12%204%202015.pdf	
Studying the Neutron to Proton Ratios in Nuclei	9/4/2015
https://groups.nscl.msu.edu/userinfo/greensheets/2015/The%20Greensheet9%204%202015.pdf	
Precision Measurements of Isospin Diffusion	8/14/2015
https://groups.nscl.msu.edu/userinfo/greensheets/2015/The%20Greensheet8%2014%202015.pdf	
What Keeps the Neutron Star from Collapsing	4/24/2015
https://groups.nscl.msu.edu/userinfo/greensheets/2015/The%20Greensheet4%2024%202015.pdf	
The Symmetry Energy Project	6/13/2014
https://groups.nscl.msu.edu/userinfo/greensheets/2014/The%20Greensheet6-13-2014.pdf	
SPiRIT TPC Arrives in Japan	3/7/2014
https://groups.nscl.msu.edu/userinfo/greensheets/2014/The%20Greensheet3-7-2014.pdf	
Towards Constraining the Nuclear Symmetry Energy	1/3/2014
https://groups.nscl.msu.edu/userinfo/greensheets/2014/The%20Greensheet%201-3-2014.pdf	
TPC Electronics	9/13/2013
https://groups.nscl.msu.edu/userinfo/greensheets/2013/The%20Greensheet%209-13-13.pdf	
TPC Cosmic Detection	5/31/2013
https://groups.nscl.msu.edu/userinfo/greensheets/2013/The%20Greensheet%205-31-13.pdf	
TPC Assembly	5/17/2013
https://groups.nscl.msu.edu/userinfo/greensheets/2013/The%20Greensheet%205-17-13.pdf	

III. Participants and Personnel

The major US participants are listed in Table 4. Betty Tsang, the PI and William Lynch, coPI from Michigan State University are the main persons responsible for the project. They are joined by Sherry Yennello from Texas A& M University and Michael Famiano from Western Michigan University, both of whom are also listed as co-PI. Three MSU students, Jonathan Barney, Justin Estee and Suwat Tangwancharoen, joined the project from the beginning. Suwat Tangwancharoen, supported by the Thai government for 3 years and NSCL for one year, developed the gating grid driver and helped with the construction of the TPC. He graduated in June, 2016. Jonathan Barney and Justin Estee, supported by NSCL, played a major role in designing and construction of the TPC as well as participated in the commission and experimental runs. They are currently analyzing the data. The TPC construction and data analysis will form part of their thesis.

In the proposal, we have asked for 18 months support for 1 MSU postdoc, 1 graduate student at WMU for 48 months and 1 graduate student at TAMU for 48 months. The MSU postdoc is Rebecca Shane who was supported by the project for 20 months with matching contributions from MSU. She worked exclusively on the TPC project, and led the design and construction of the TPC. After the TPC was completed and shipped to RIKEN. She moved to a staff position at the Facility for Rare Isotope Beams in 2014. WMU supported a graduate student, Mohamed El-Houssieny, for 12 months. When Michael Famiano resigned his faculty position at WMU, the support for Mohamed El-Houssieny was terminated. The remaining balance of money was used to hire Prabhaka Palni and Giordano Cerizza to work on the TPC software development in preparation for the testing of GET electronics and experiments. Due to inability to find an appropriate student, TAMU hired a postdoc, Alan McIntosh, who was supported by the grant for two years at 50% level. Alan was mainly responsible in the design and construction of the TPC enclosure and the design and construction of the first version of the TPC target mechanism. He also participated partly in the design of the TPC during the time he was supported by the TPC and participated in running the experiments at RIKEN. In 2013, Alan accepted a staff member position at TAMU. After Alan McIntosh, Michael Youngs was the postdoc from TAMU supporting the project in software development at 50% for one year. Several short term visitors also supported the project, Fei Lu did the first GARFIELD calculations for the initial design of the TPC. He moved back to China to accept a staff position after 6 months. Prabhakar Palni worked on the software for 5 months on contract. He returned to India afterwards. More recently, in the Fall of 2015, Giordano Cerizza and Clementine Santamaria joined the project as regular postdocs. Giordano leads the effort with software development for analysis of the data. Clementine had experience running in RIKEN, worked on the experimental setup and is currently analyzing the secondary beam identifications. All the MSU personnel will be leading the SπRIT collaboration effort to analyze the collected data. The two postdocs, Giordano Cerizza and Clementine Santamaria are currently supported by the DOE science grant.

Finally, nearly 20 US and foreign undergraduate students, including 4 summer interns, have participated in the project. Of the 15 undergraduate workers, two of them, Jonathan Barney and Justin Estee continued in the project as graduate students. Corinne Anderson and Hananiel Setiawan contributed significantly to the project. Both will graduate from MSU in 2017.

Table 4: Major participants and personnel

Name	Institution	Position	Contributions	Supported by grant (months)
Manyee Betty Tsang	MSU	Faculty	PI	0
William Lynch	MSU	Faculty	CoPI	0
Sherry Yennello	TAMU	Faculty	CoPI	0
Michael Famiano	WMU	Faculty	CoPI	0
Jonathan Barney	MSU	Graduate Student	Design, construct, test, thesis	0
Justin Estee	MSU	Graduate Student	Design, construct, test, thesis	0
Suwat Tangwancharoen	MSU	Graduate Student	Gating Grid Driver, thesis	0
Alan McIntosh	TAMU	Postdoc	Enclosure, Target Mechanism	12
Clementine Santamaria	MSU	Postdoc	Experiment, analysis	3
Fei Lu	MSU	Postdoc	Simulation	3
Giordano Cerizza	MSU	Postdoc	Software Design	6
Michael Youngs	TAMU	Postdoc	Software Design	12
Prabhakar Palni	MSU	Postdoc	Software Design	5
Rebecca Shane	MSU	Postdoc	Detector design	20
Corinne Anderson	MSU	Undergraduate	construct, test, simulation	4
Hananiel Setiawan	MSU	Undergraduate	construct, test, simulation	8
Mohamed El-Houssieny	WMU	Graduate Student	STAR FEE testing	12

The project provided invaluable and abundant opportunities for training and professional developments to graduate students, postdocs and undergraduate students. Some specific examples are discussed below. Travel supports from the award, often supplemented from funds in JUSEIPEN and sometimes with local expense from our Japanese hosts, provided opportunities for participation of postdocs and students to work in prominent non-US institutes such as GSI and RIKEN working with a diverse group of scientists.

a. Graduate Students

The project provided training in thesis topics for 3 MSU students. Suwat Tangwancharon graduated in June, 2016. He is currently teaching in a university in Thailand. The project will produce Ph.D. thesis topics for at least two more US students who joined the project as undergraduates and are currently analyzing the data. The award supported the travels of these students to RIKEN, Japan for collaboration meetings and for working on the TPC including doing experiments. Through their contacts in Japan from this projects, two students (Jon Barney, 2014 & Justin Estee 2015) applied successfully to the East Asia and Pacific Summer Institutes for U.S. Graduate Students (EAPSI) and worked on the SπRIT TPC research at RIKEN. In addition to MSU students, the project also supported a master graduate student, (Mohamed El-Houssieny) at Western Michigan University.

In addition to US graduate students, two Korean students (Genie Jhang, JungWoo Lee) and one Japanese student (Kaneko Masanori) will use the TPC data for their thesis work. Genie Jhang graduated in June, 2016 and plans to work as a postdoc at MSU.

One Polish student (Pawel Lasko, Katana array) and one visiting Chinese student (Yan Zhang, veto collimator & gating grid) joined the project to work on the auxiliary detectors.

The award also provided local support for short visits to international students who come to MSU to work on the TPC project. (Genie Jhang; 2 months; Noritsugu Nakatsuka; 1.5 months; William Powell (3 months); Visiting student with his own support : Rensheng Wang (4 months)

b. Undergraduate students

The award, especially during the construction phase of the TPC, provided opportunities to many undergraduate students to participate in research during the school years as well as summer interns. Two of the students (Corinne Anderson and Hananiel Setiawan) have been working consistently through the projects. The others joined the project as hourly undergraduate workers: (MSU: Ben Brophy, C. Anderson, D. Wegscheid, D. Witalka, E. Ersoy, H. Setiawan, J. Dunn, J. Gilbert, J. Barney, J. Estee, K. Kline, K. Andrews, M. Quiroga; WMU: C. Snow, S. Dye; Texas A&M: Matt Chapman)

In addition, the project also attracted summer interns from both US and aboard: US REU student: Kenneth Long; Hong Kong Chinese University: Kai Fai Chan; UK Liverpool University: Jamie Norman

c. Postdoctoral

The award supported postdocs working in US institutions (Fei Lu (MSU, 5 months); Alan McIntosh (TAMU, 12 months); Rebecca Shane (MSU, 20 months); Prabhakar Palni (MSU, 5 months); Michael Youngs (TAMU 6 months); Clementine Santamaria (MSU, 3 months); Giordano Cerizza, (MSU, 6 months).

IV. Impacts

a. Impact on the development of the principal disciplines of the project

The Equation of State (EoS) is a fundamental property of nuclear matter that describes relationships between energy, pressure, temperature, density and isospin asymmetry $\delta=(\rho_n-\rho_p)/\rho$ in a nuclear system. The EoS largely determines the stable phases of matter and the pressure as a function of density, key properties central to answering questions in the Long Range Plan (LRP) concerning *the nature of neutron stars and dense nuclear matter*. At low temperature, the EoS can be separated into a symmetric matter contribution that is independent of the isospin asymmetry and a poorly constrained symmetry energy term, proportional to the square of the asymmetry. Uncertainties in quantities such as the three-body neutron force contribute significantly to uncertainties in the density dependence of the symmetry energy. The experiments are designed to probe the density dependence of the symmetry energy and the nuclear Equation of State (EoS) at supra-normal density. Providing information on nucleon interactions by constraining the symmetry energy therefore helps address fundamental questions expressed in the LRP concerning *the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotope*s.

With the successful execution of the two TPC experiments using the radioactive beams of neutron rich 132Sn and neutron deficient 108Sn on 124Sn and 112Sn targets, the US group retains the leadership in the study of the nuclear Equation of State (EoS) of neutron-rich nuclear matter at supra-normal density.

b. Impact on other disciplines

Macroscopic quantities of asymmetric nuclear matter exist in neutron stars and in type II supernovae over a wide range of densities. Constraints on the EoS and the symmetry energy at sub-saturation and supra-saturation densities can improve our understanding of neutron star properties such as stellar radii and moments of inertia, crustal vibration frequencies, and neutron star cooling rates that have been investigated with ground-based and satellite observatories. Consequently, the goal of determining the EoS has been a major motivation for recent analyses of X-ray observations aimed at extracting the correlation between neutron star masses and radii. Results of the experiments will provide significant constraints on the Equation of State of dense neutron-rich matter at densities that are highly relevant to mass-radius relationship of neutron stars. These constraints will address the present disputes concerning the extracted radii of neutron stars.

c. Impact on the development of human resources

The project provides thesis topics for 3 MSU students.

1. Suwat Tangwancharon graduated in June, 2016 based on his work on the TPC construction and development of the gating grid driver. He is currently teaching in a university in Thailand.
2. Jon Barney is currently analyzing the data from the experiments which will be his thesis.
3. Justin Estee is currently analyzing the data from the experiments which will be his thesis.

The award has provided opportunities for 9 postdocs most of whom receive none or short term support to participate in experiments at GSI and RIKEN as well as involving in the construction and running TPC experiments.

1. Alan McIntosh, (TAMU, supported for 24 months at 50%, 2011-2013). He is currently a staff member at the Cyclotron Institute at Texas A&M University.
2. Fei Lu (supported for 5 months in 2011) returned to China and is currently a staff member of SINAP, China.

3. Rebecca Shane, (supported for 39 months at 50%, 2011-2014). She is currently a staff member at FRIB.
4. Prabhakar Palni , (supported for 5 months, 2014). He returned to India.
5. Michael Youngs (supported for 12 months at 50%, 2013-2014)
6. Clementine Santamaria (3 months, 2015). She is currently being supported by another DOE grant working on the analysis of the TPC data analysis.
7. Giordano Cerizza (6 months, 2015-2016). He is currently being supported by another DOE grant working on the analysis of the TPC data analysis.
8. Pierre Morfouace (supported by NSF grant, 2015-), participated in experiments.
9. Zbigniew Chajecki (supported by NSF grant, 2011-2014), participated in early design and construction of TPC. Currently he is a faculty member of Western Michigan University.

In addition, the award supported many undergraduate students: B. Brophy, C. Snow, C. Anderson, D. Wegscheid, D. Witalka, E. Ersoy, H. Setiawan, J. Dunn, J. Gilbert, J. Barney, J. Estee, K. Kline, K. Andrews, M. Chapman, M. Quiroga, S. Dye. Many of them continue their science studies in graduate schools: J. Gilbert, J. Barney, J. Estee, K. Andrews.

The undergraduate students, graduate students and the postdocs form a workforce pipeline for areas which have a shortage of personnel trained in nuclear science, such as homeland security, the nuclear energy industry as well as the health industries that use nuclear-medicine technologies.

The award supported the travels of graduate students and postdocs to RIKEN, Japan for collaboration meetings, construction of the TPC and working on TPC experiments thus providing these junior scientists opportunities to work in world-premiere facilities, interacting with scientists worldwide, preparing our future science leaders for tomorrow's global work place.

d. Impact on Physical, institutional and information resources that form Infrastructure

The construction of the TPC required institutional resources such as space, design help, fabrication and testing. The timing of the project was such that we were able to use some of the extra resources available before FRIB project ramped up its construction. Our simulations of the experiments with state of the art transport model simulations utilized the High Performance Computing Center (HPCC) at MSU. The experiments required high speed data acquisition speed, up to 10 Gb/s from the combined 12 CoBo boards [4], and a high speed data transfer rate (up to 350 Mb/s) from the DAQ machine to offsite preliminary storage. The 250 TB recorded data were then transferred for offline analysis to a local computer cluster at an average speed of 75 MB/s. All these currently tax the systems in the University and steps are being taken to solve the problems and provide advance glimpse of what DAQ and analysis resources will be needed when FRIB comes on line.

e. Impact on Technology transfer

We are one of the first groups to test the state of the art readout electronics, the Generic Electronics for TPC. NSCL is a member of GET collaboration which is being commercialized with the help of the MSU technology transfer office.

We have submitted a provisional patent application for the gating grid driver of the TPC.

f. Impact on society beyond science and technology

Using the cosmic events accumulated between experiments, we have developed a website, https://groups.nscl.msu.edu/hira/cosmic/CosmicGallery.html, for the general public describing cosmic rates, our detectors and our experiments. This side project is an attempt to stimulate interest for K-12 students as well as the general public about nuclear science and nuclear detectors in a visually engaging fashion. We have also published many articles in the NSCL weekly newsletters (Table 3) in a level aimed at the general staff members of the lab.

V. Financial

a. Project Funding

Table 5: Planned and received budgets by fiscal year

Fiscal Year	Planned (in thousands)	Received (in thousands)
2011	$426	$800
2012	$262	$400
2013	$292	
2014	$173	
2015	$47	
Total	$1,200	$1,200

b. Financial Summary ($)

Table 6: Financial summary. BAC: Budget At Completion.

Financial Summary – 12/21/2016		Planned BAC *	Actual Cost	Cost Variance
1.1	Design	$50,000	$49,822	178
1.2	Procurement	$59,000	$93,254	($34,254)
1.3	Construction, Installation and Testing Subtotal	$214,000	$175,749	$38,251
1.4	Experimental Programs	$55,000	$40,104	$14,896
1.5	Communication	$49,000	$45,812	$3,188
1.6	Project Personnel	$504,000	$511,204	($7,204)
1.7	Indirect Cost	$269,000	$284,055	($15,055)
	Total	$1,200,000	$1,200,000	$0

c. Cost Variance Analysis

Over-spending in Procurement is balanced by the budget in Construction and Installation as in occasions we choose more expensive parts to save efforts and cost in installation. Understanding in travel for experiments reflects partial support provided by RIKEN to selected students and postdocs who went there for long setup. Also many of the trips to RIKEN were partly covered by JUSEIPEN as we timed our travels to combine with activities supported by JUSEIPEN. Increased in personnel cost and increase in indirect cost is mainly due to exit of Famiano (Western Michigan) from the project. To fill his expertise in software development for online analysis and data acquisition, we used the balance of the money originally assigned to Famiano (~90K) to support visitors and a postdoc to do software development.

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