Project Closeout Report

FRANCIUM TRAPPING FACILITY AT TRIUMF

for the
U.S. Department of Energy
Office of Science
Office of Nuclear Physics (SC – 26)

Date

September 30, 2014

Project Closeout for the Francium Trapping Facility at TRIUMF Vancouver, BC, Canada

Concurred by:

____ Date: 01/13/2015

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Date: 2015.01.13 13:49:24 -05'00'

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Jehanne Gillo
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1. Introduction

This is a report of the construction of a Francium Trapping Facility (FTF) at the Isotope Separator and Accelerator (ISAC) of TRIUMF in Vancouver, Canada, where the Francium Parity Non Conservation (FrPNC) international collaboration has its home. This facility will be used to study fundamental symmetries with high-resolution atomic spectroscopy. The primary scientific objective of the program is a measurement of the anapole moment of francium in a chain of isotopes by observing the parity violation induced by the weak interaction. The anapole moment of francium and associated signal are expected to be ten times larger than in cesium, the only element in which an anapole moment has been observed. The measurement will provide crucial information for better understanding weak hadronic interactions in the context of Quantum Chromodynamics (QCD). The methodology combines nuclear and particle physics techniques for the production of francium with precision measurements based on laser cooling and trapping and microwave spectroscopy. The program builds on an initial series of atomic spectroscopy measurements of the nuclear structure of francium, based on isotope shifts and hyperfine anomalies, before conducting the anapole moment measurements, these measurements performed during commissioning runs help understand the atomic and nuclear structure of Fr.

This program addresses the need for experiments probing fundamental symmetries of nature in heavy, exotic nuclei (in this case francium) as identified in the NSAC RIB final report [1]. The report says that experiments that probe "fundamental symmetries of nature will similarly be conducted at a FRIB (Facility for Rare Isotope Beams) through the creation and study of certain exotic isotopes. These nuclei could enable important experiments on basic interactions because aspects of their structure greatly magnify the size of the symmetry-breaking processes being probed." The future FRIB facility will have experiments that utilize atomic spectroscopy to extract nuclear physics information. The FTF develops transportable solutions to the many challenges of doing precision atomic physics measurements in an accelerator environment.

The FTF can also be usable for measurements of optical parity non-conservation, nuclear structure (hyperfine anomalies and octupole deformations) in francium, and a search for an electron dipole moment (EDM). The FTF infrastructure is designed to be transportable if the opportunity arises for re-location to the future Facility for Rare Isotope Beams (FRIB). The FTF can also be adapted to measurements of anapole moments, nuclear structure, and eventually EDM in other atomic systems due to the broad applicability of the proposed methods and the wide tunability of the laser and microwave instruments.

The FTF project includes a modular laboratory room with dedicated temperature and humidity control for the lasers and optics as well as appropriate RF and magnetic noise isolation. The room houses lasers, optics, detectors, microwave equipment and vacuum hardware and is able to handle the radioactive beam of Fr with the appropriate radiation safety precautions.

The total estimated cost (TEC) for the FTF is 0.82 million actual year 2009 dollars and it was dedicated in its entirety to the procurement of equipment.

Development and implementation of the FTF has been accomplished primarily with the group at the University of Maryland (UMD) with collaboration of the other members of the FrPNC collaboration (Prof. Gerald Gwinner from U. Manitoba is the spokesperson), in particular Prof. Seth Aubin from the College of William and Mary (CWM) and Prof. Dan Melconian from Texas A&M (TAM). The construction of the FTF has had the benefit of counting with two members of the FrPNC collaboration: Dr. John Behr and Dr. Matthew Pearson, who are staff at TRIUMF (See appendix A for the membership).

2. Management

The FTF project manager (CPM), Luis A. Orozco, has been responsible and accountable for day-to-day management and execution of the FTF project and served as point contact between UMD and DOE on matters related to the FTF. The CPM has worked closely with the FrPNC collaboration regarding budget, schedule, change control, and contingency issues. The CPM has been responsible for identifying all potential environmental, safety, and health (ES&H) hazards and security risks and for ensuring their proper mitigation. The CPM is a core member of, and is supported by, the Department of Physics at the University of Maryland.

3. Project Baseline

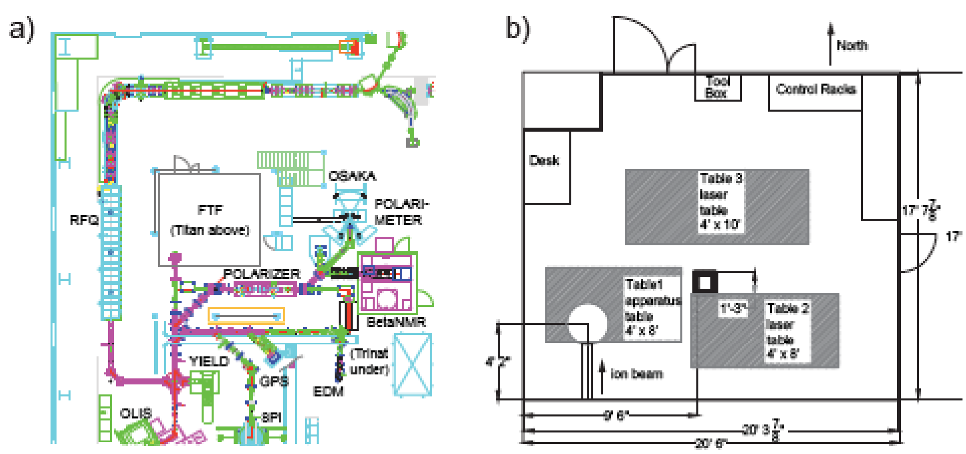


Figure 1 a) FTF in the ISAC I Hall at TRIUMF. b) Layout of the FTF with the francium beamline, optics tables and control equipment in August 2012.

3.1. Technical Scope and Deliverables Baseline

Francium is produced at TRIUMF with an actinite target. They have shown that multiple isotopes, neutron deficient and neutron rich, can be delivered as low energy (tens of kilovolts) ion beams to an experimental area (See Fig. 1). TRIUMF delivers a beam of up to 100 million ions/sec Fr of a given isotope at about 20 KV into the FRF.

The scientific goal of the FrPNC collaboration requires about 10^6 cold trap atoms in a dedicated environment. The Fr ions are first collected, cooled, and trapped in a first chamber (collecting) and captured in a high-efficiency magneto optical trap (MOT). They are then moved to a second chamber (science) for conducting anapole moment, optical PNC, and other measurements.

During the Commissioning run of the FTF in September 2012 we were able to capture three different Fr isotopes with a maximum of 2.5×10^5 atoms in the MOT (See Fig. 2). The number increased more than ten-fold in the Commissioning run of December 2012 we reached a few million trapped atoms in the first (collecting) chamber. This has allowed us to begin performing spectroscopic measurements that will be useful for the weak interaction studies.

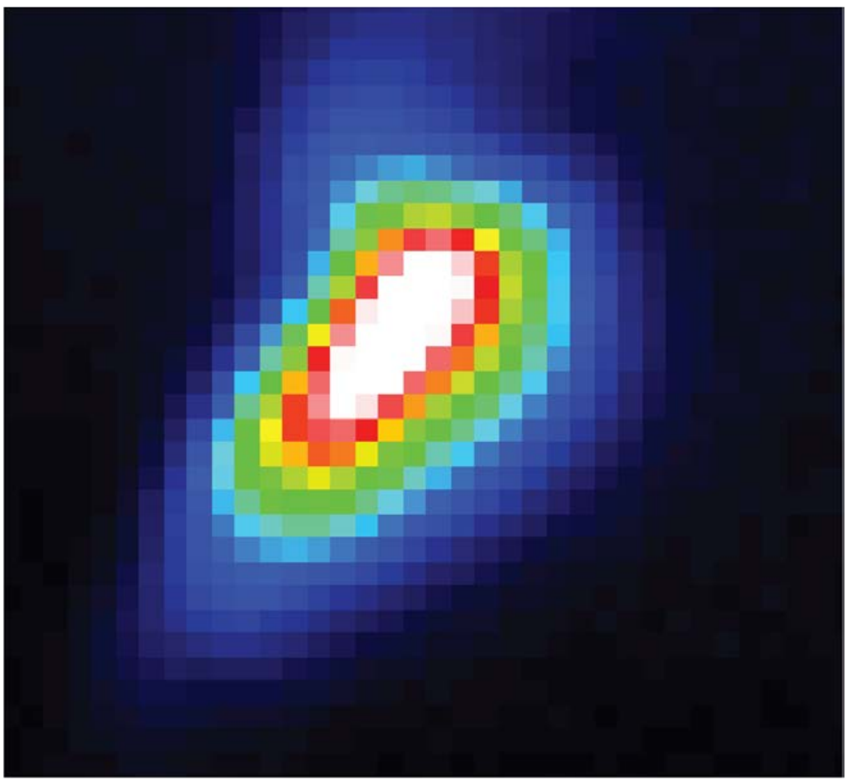


Figure 2 False color CCD image of the MOT fluorescence of a cloud of about 10^5 Fr atoms at the FTF. The pixel size is 6.7 by 6.7 microns.

The FTF consists of the RF isolated room (see Fig. 1a for the layout at ISAC) that houses the traps, lasers, microwave and ancillary electronics, together with the new equipment that this project helped procure.

3.1.1 Shielding and interfaces technical baseline and performance.

3.1.1.1 Faraday Cage

The FTF is in an RF shielded (Faraday Cage), temperature and humidity stabilized room within the ISAC beamline facility. The room (made by Universal Shielding Corporation has a footprint of 20 ft × 18 ft with a 12 ft height and houses the entire experiment, including the optics tables, lasers and other sensitive equipment that require temperature and humidity stability (see Fig1b).

Figure 3 Photograph of the shielded room housing of the FTF in the ISAC Hall.

We measured he background RF noise at the location of the FTF without the Faraday cage was 21 V/m at 35 MHz and 2.7 V/m at 106 MHz, the most relevant frequencies from the RFQ of the linac on the west side of the FTF (see figure 1a). Universal Shielding Corporation designed and constructed a galvanized steel Faraday cage, which was installed in the laboratory of the FTF. The floor, ceiling, and walls are made of metal-covered wood composite, with the appropriate fire retardants. The doors required double sets of grounding strips to ensure no RF leakage into the room. The room has penetrations with RF filters to allow water, air, the beamline, telephone, Ethernet, and other signals and services to enter the room.

When the room is properly closed, the Faraday cage attenuates the RF amplitude by more than 100 dB at 35 MHz to levels lower than the noise floor of our measuring instrument. The construction should be possible to disassemble so that it can be relocated to the Rare Isotope Beam facility if the opportunity arises.

The temperature and relative humidity of the ISAC area of TRIUMF have a short-term stability of ±3 C and ±15% relative humidity, respectively. The instruments necessary for the atomic spectroscopy and parity non-conservation experiments require an environment with temperature stability in the range of 22-24 C and stability better than stability of at least ± 1 C and ± 5% relative humidity. The modular laboratory has helped provide this level of stability, but over the course of the year there have been drifts. Persistent gradients in the room temperature seem related to the way the air enters the room, and we have room for changing some of the patterns of flow that we will explore when all the equipment is running at the same time in the room. The stability is necessary for ensuring the reliable and repeatable operation of the instrumentation.

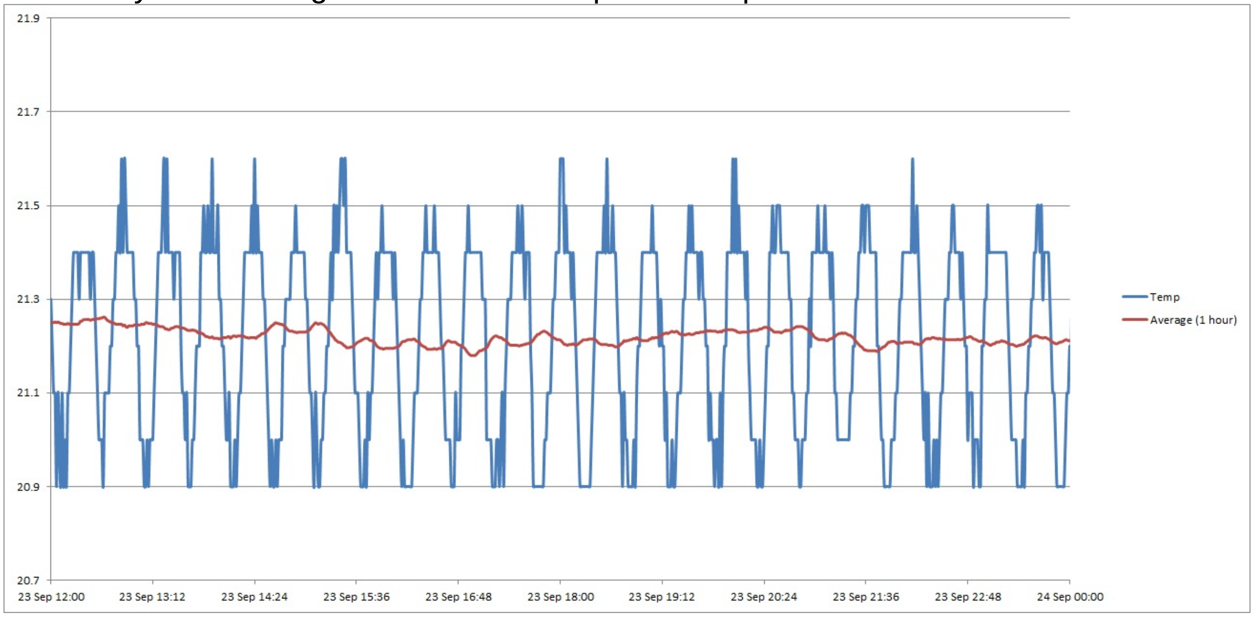


Figure 4 Temperature measured inside the FTF for half a day in September 2014.

The temperature and humidity stabilization of the FTF is realized by an HVAC system designed and constructed under TRIUMF. The Temperature was specified to have a stability of ±1.0 C or better (see Fig. 4). The result is now good on the minute-to-minute and the day-to-day performance (see Fig. 5). We will continue to monitor to ensure the seasonal performance. The modular laboratory has helped provide this level of stability. Recent adjustments of the HVAC system have improved its performance.

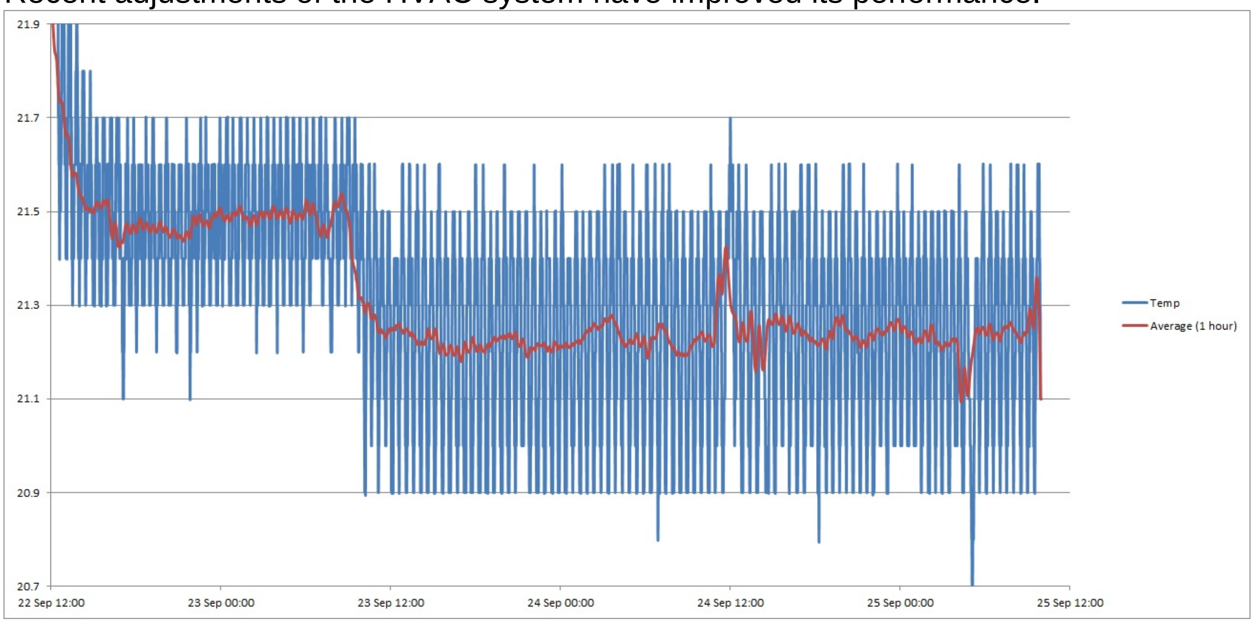


Figure 5 Temperature measured inside the FRF during four days in September 2014.

For personnel safety, there is an emergency nuclear ventilation system in case of accident that connects to the appropriate systems at ISAC.

3.1.1.2 Interfaces: New cell to decrease backgrounds. Better capture

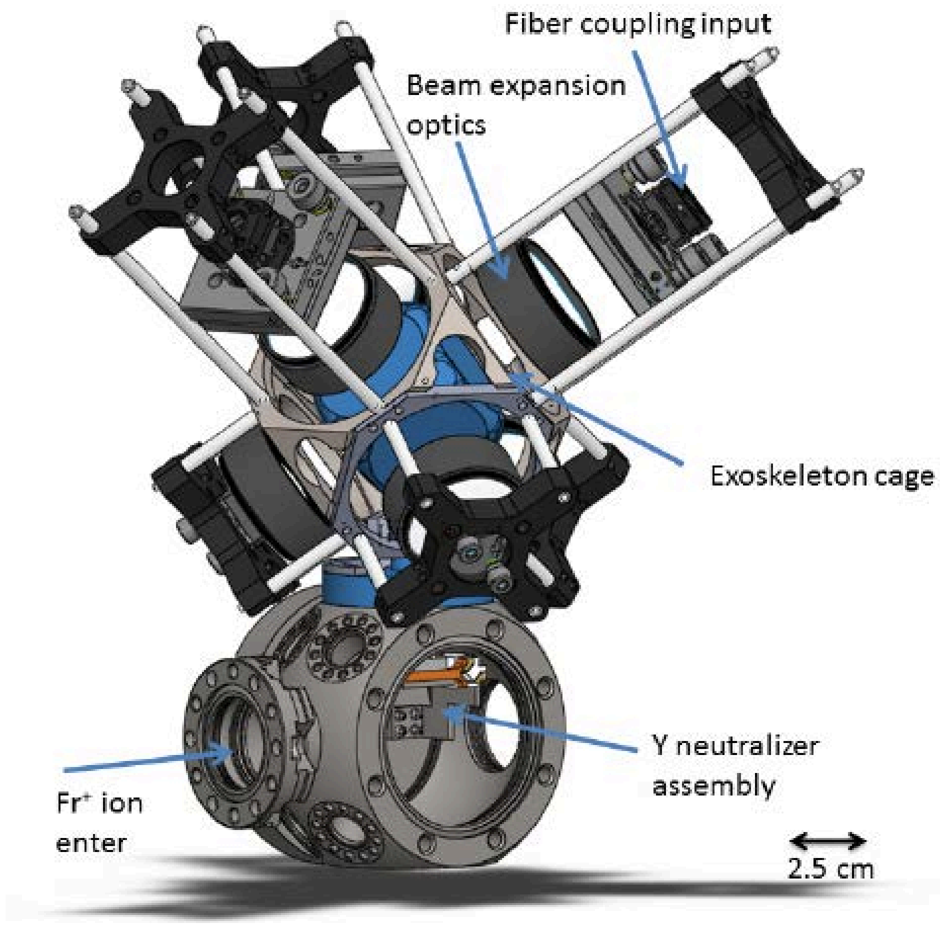


Figure 6 Drawing of neutralizer chamber with the glass cell (highlighted in blue) for the MOT and the required optics. Not shown are the magnetic field coils. The size of the larger CF flanges is 4.5 in.

The capture assembly (see Fig. 6) is connected to the beamline, designed and constructed by TRIUMF, and sits about 1.6m above the floor. It consists of three main parts: the neutralizer, the glass-cell for the MOT, and the diagnostics with a Faraday cup and a detector (see Fig. 7). A stainless steel chamber (houses the collimator and the dual-position neutralizer. The collimating aperture of 9.5mm diameter (not shown in Figs. 6, 7) is held on a groove grabber at the entrance of the chamber and is used for tuning the ISAC ion beam. The high-efficiency neutralization and capture scheme developed at Stony Brook has been used as a starting point for the design of the Y neutralizer. There are two important improvements on the previous design. All related parts are mounted on one 4.5-inch conflat flange and attached on one side, as to mitigate possible safety concerns related to the decay products of francium if we have to replace the neutralizer. The current to the yttrium foil is now delivered by fixed contacts instead of the continuous wire used before that was the dominant failure mode (when breaking) in the previous design. The design allows for the atoms to be transferred from the capture MOT to the science chamber (not shown in Figs 6 or 7).

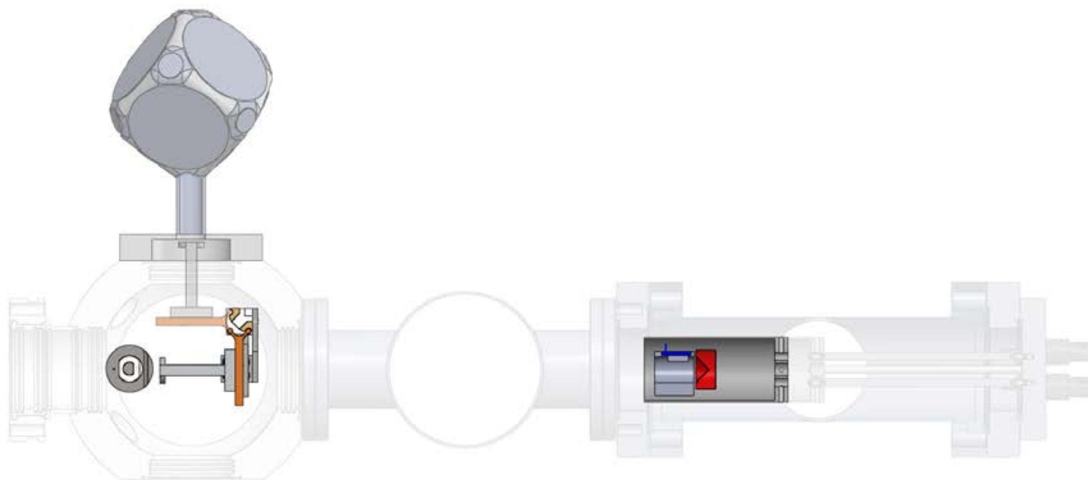


Figure 7 Setup with Faraday cup and alpha particle detector and Faraday cup.

3.1.2 Microwave equipment Technical Baseline and Performance

The anapole moment measurement will require microwave equipment at 46 GHz. The source stability in frequency (in amplitude) should be better than 1×10^{-11} (1×10^{-3}) and requires disciplining it with an atomic clock. The frequency stability corresponds then to 0.5 Hz and the frequency synthesizer should provide this. The polarization of the microwave field requires a stability of 1×10^{-6} rad per roundtrip on the cavity, but current studies could relax this requirement. The cavity Q should be better than 10^3 at the required frequencies.

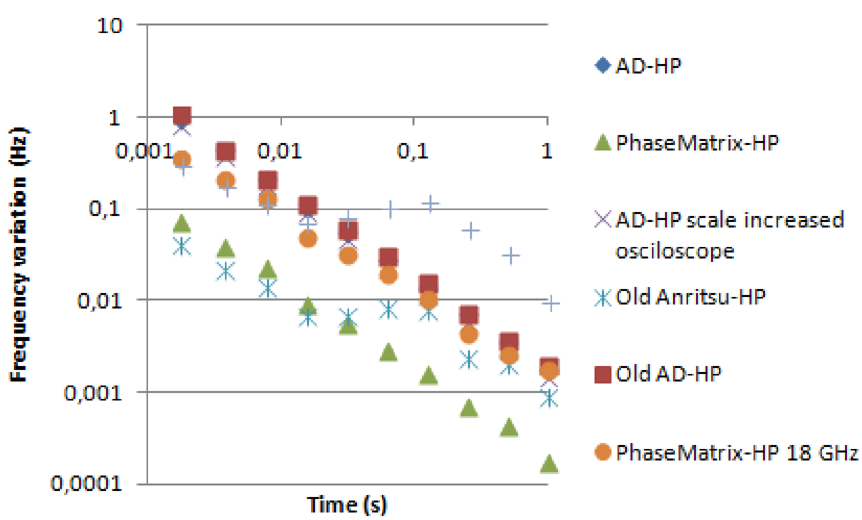


Figure 8 Frequency stability test for various generators. We got the Phase Matrix.

Figure 8 shows results from a study we carried out to decide which microwave frequency synthesizer to get. The plot shows how much the frequency drifts over a particular time interval by beating two units together. The most important contenders were PhaseMatrix and Anritsu and the tests were done around 8 and 18 GHz. We use as reference an HP synthesizer. We can see that at short times the Phase Matrix is good, probably because it has a better quality oscillator, but also at longer times.

When we test the phase between the HP and the PhaseMatrix with a frequency of 18 GHz and 12 dBm the noise increases by a factor of 5 or more with respect to the result at 8 GHz (filled triangles in green). With the Anritsu unit going from 8 to 18 GHz made the result 7 times worse, so comparing Anritsu and PhaseMatrix at short times they give similar results. The difference is at longer times where the PhaseMatrix keeps improving whereas the Anritsu is stuck, so at 100 ms the PhaseMatrix is 11 times better. At 100 ms and 18 GHz the frequency deviations are 10 mHz for the PhaseMatrix, and scaling ideally to 50 GHz would be a factor of 3 more in frequency and the noise grows by a factor of $3^2=9$ going into 90 mHz which satisfies by more than a factor of five the 0.5 Hz that we need. So in summary the PhaseMatrix is superior and we have purchased one unit.

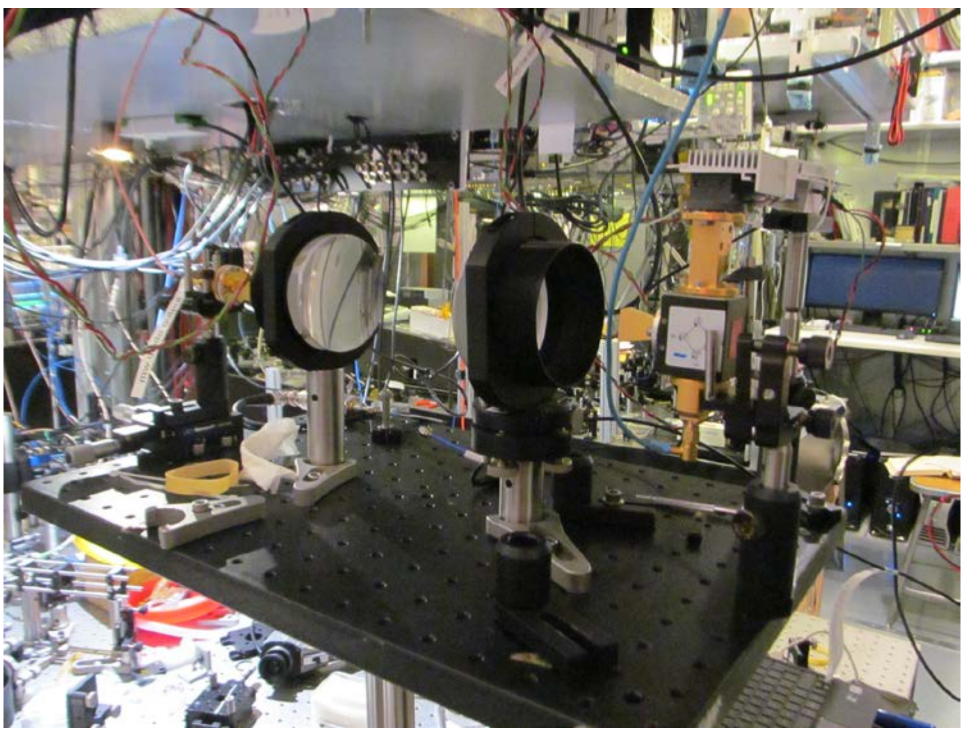


Figure 9 Photograph of the microwave Fabry Perot at the FTF in air. The emitting and receiving horms are visible in front and in the back of the mirrors.

Figure 9 shows a photograph of the recently finished microwave cavity that is not yet under vacuum show a Full width at half maximum (FWHM) of less than 700 KHz and a Q better than 60×10^3 (see Fig. 10). The polarization quality is $2.5\times10^{-4}\pm 2.5\times10^{-4}$ at the output with the measurement limited by the quality of our existing polarizer and the signal to noise ratio at the minimum of the transmission. The Finesse of the 12.5 cm resonator (free spectral range 1.2 GHz) is 1700 with the enhancement close to 500. The average number of roundtrips within the mirrors (FSR/HWHM) is 3400. So our current limit on the polarization is that it rotates at most $5\times10^{-6} \pm 5\times10^{-6}$ radians per roundtrip on the cavity. We expect to improve the measurement in the near future to confirm that we have achieved the requirement that is within a factor of five in the error that we have.

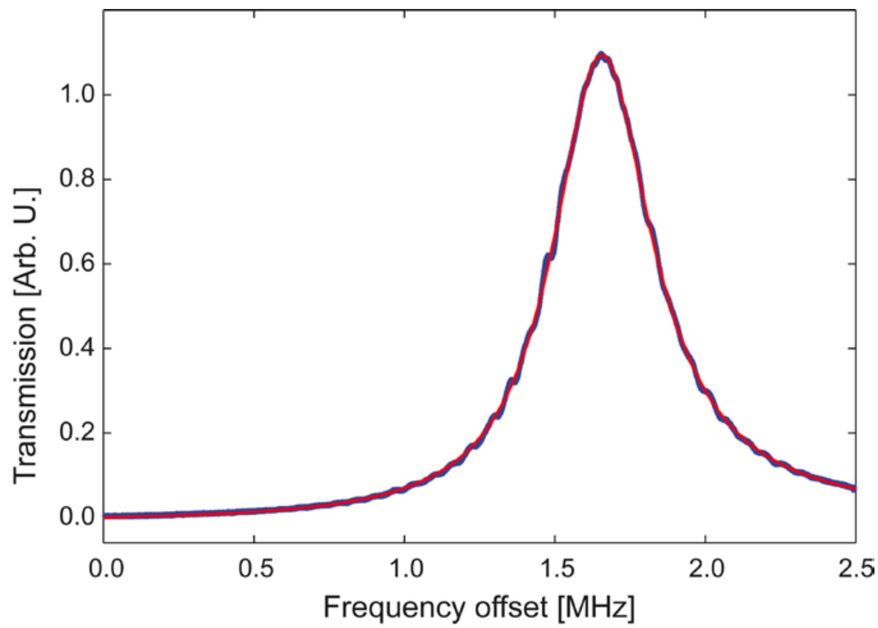


Figure 10 TEM_{00} mode resonance on the Fabry Perot Cavity operating at 47 GHz. The Q factor is better than 60×10^3.

3.1.3 Optics Tables

Technical Baseline

The compliance with a load of 250 lb of the optical tables should be as good or better than 10^{-3} in/lb at 10 Hz and 10^{-5} in/lb at 100 Hz. The residual Q under those circumstances should be less than 10. In order to reduce the susceptibility of the apparatus to residual magnetization and associated hysteresis, the table with the trap, will be non-magnetic, for example constructed with 304 steel.

We have three laser tables from Newport where one of them is non-magnetic. The picture in Fig. 11 shows the FTF inside in August 2012, one month before the commissioning run and two of the tables are clearly visible, while the third is in the back and the trap sits on it. The tables were procured to meet the requirements described above. Measurements of the magnetization show contributions lower to those expected, which is excellent.

3.1.4 Frequency Stability Technical Baseline

The frequency stability of the lasers is important an a frequency comb should provide a very high stability (better than 1×10^{-10} in one second) with comparable accuracy in optical frequencies locking multiple laser frequencies in regions of the electromagnetic spectrum between 550 nm and 1000 nm.

We have purchased a wavemeter instead of the Frequency Comb as we have realized that the laser stability requirement can be relaxed to than 1×10^{-8} in one second. This performance is reached by units such as the Finesse that we have acquired. This unit further allows us to monitor all the lasers of the FTF. The accuracy and the precision of the instrument were specified in the procurement process, the instrument should be calibrated and its calibration traceable to NIST. The instrument performs as expected compared to a lower resolution unit and atomic standards that we have developed in the FTF.

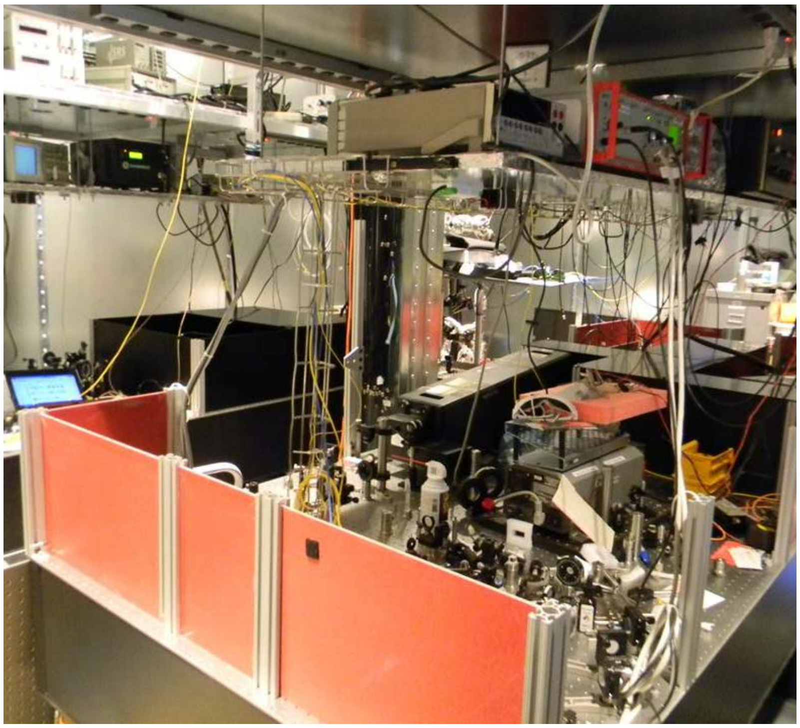


Figure 11 Interior of the FTF in August 2012.

3.1.5 Raman Lasers Technical Baseline

The phase relationship between the two frequencies for the Raman excitation should be stable to better than 100 rad/sec. If two lasers are used, they should be phase-locked. Another alternative would be a single laser phase modulated and then amplified that reaches the same stability.

We have purchased a SolsTiS laser from MSquared that can serve both as trapping and Raman lasers as we have found new ways to do the preparation and interrogation of the experiment. The power delivered by this unit and its frequency stability (less than 100 KHz) ensures that we can do all that we required. We have measured the performance with a Fabry Perot unit and it is better than the specifications of the instrument on their Fig. 12 shows a photograph of the laser at the FTF. The picture shows some of the modulators necessary for the work we need to do. We will not require an amplifier for this application as the power is enough and it is all sent to the traps with high power optical fibers.

Further modulation is done with a fiber modulation that works on AM and FM.

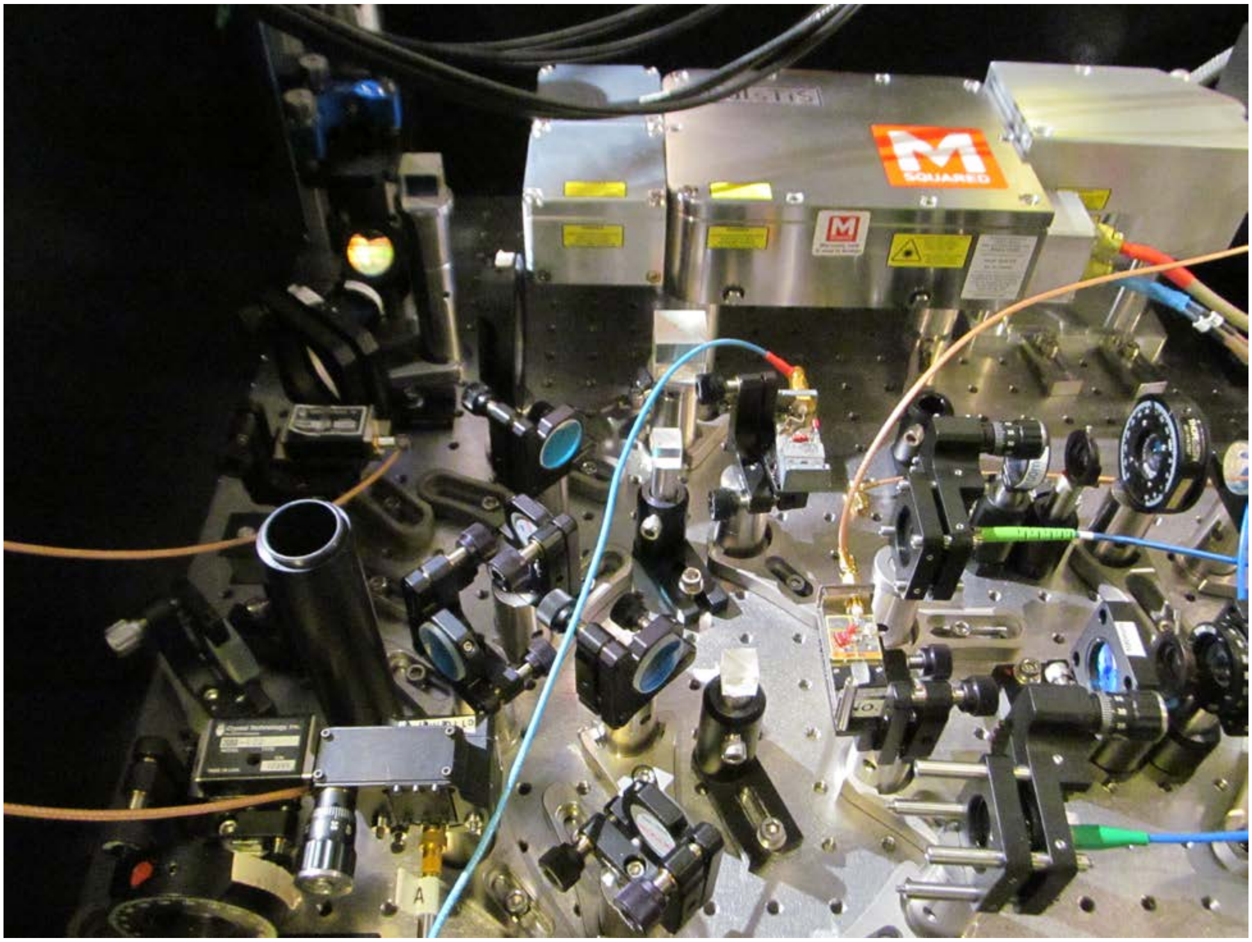


Figure 12 Photograph of SolsTiS Laser at the FTF.

3.2. Cost Baseline

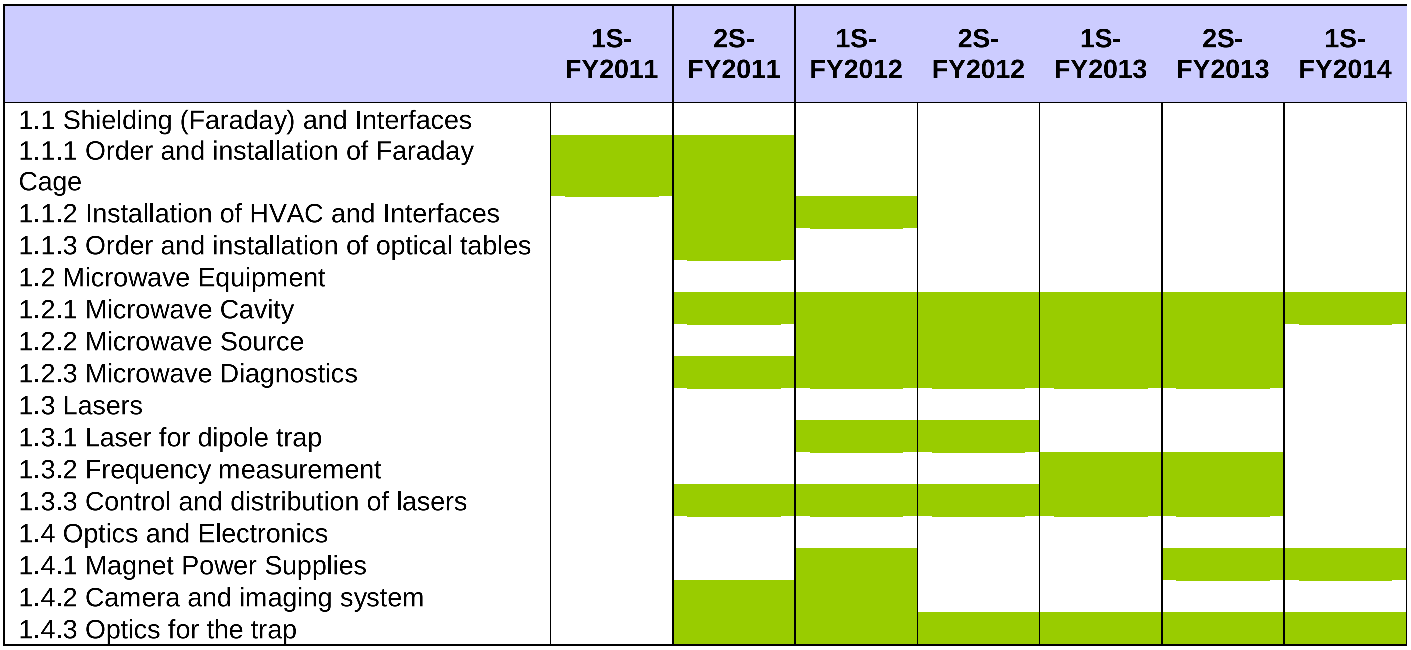
Financial Summary	Current BAC	Plan to Date	Actual + Liens to Date	Cost Variance	Current ETC
1.1 Shielding (Faraday) and Interfaces	240,895	310,000	306,316	3,684	(69,105)
1.2 Microwave	118,623	140,000	126,837	13,163	(21,377)
1.3 Lasers	346,173	200,000	214,259	(14,259)	146,173
1.4 Optics and electronics	114,309	170,000	172,588	(2,588)	(55,691)
Sub Total	**820,000**	**820,000**	**820,000**	**(0)**	**0**
Contingency	0	0	0	0	0
Total Estimated Cost	**820,000**	**820,000**	**82,000**	**0**	**0**

a) BAC = Budget at Completion
b) ETC = Estimate to Complete

3.3. Schedule Baseline

Milestone Status:

Milestone	Planned Date	Actual Date
Milestone 1: Submit requisition of Faraday Cage	Complete	March 15, 2011
Milestone 2: Place order for Faraday Cage	Complete	June 15, 2011
Milestone 3: Installation of Faraday Cage at TRIUMF	Complete	October 20, 2011
Milestone 4: Pack, ship, and receive at TRIUMF laboratory from UMD	Complete	September 15, 2011
Milestone 5: Order lasers (Delivery in 6 months)	Complete	September 10, 2011
Milestone 6: Order and receive Optical Tables	Complete	October 13, 2011
Milestone 7: Electrical Installation of Faraday Cage at TRIUMF	Complete	November 10, 2011
Milestone 8: Laser trap working off line with neutral Rb	Complete	December 14, 2011
Milestone 9: Arrival of lasers (Milestone 5)	Complete	December 15, 2011
Milestone 10: Installation and commissioning of lasers (Milestone 5, 9)	Complete	March 1, 2012
Milestone 11: Commissioning of beam line	Complete	January 15, 2012
Milestone 12: Construction of HVAC system	Complete	March 30, 2012
Milestone 13: Commissioning of HVAC system	Complete	July 16, 2012
Milestone 14: Commissioning of Trap	Complete	Sept. 2, 2012
Milestone 15: First Physics run	Complete	Oct. 29-Nov.2 2012
Milestone 16: Improvements to trap	Complete	Jan. 1, 2013-Sept. 20, 2013
Milestone 17: Second Physics run	Complete	Sept. 19, 2013- Sept. 22, 2013
Milestone 18: Commissioning of Microwave system	Complete	March 30, 2014
Milestone 19: Commissioning of Science Chamber with stable Rb.	Complete	June 1, 2014
Milestone 20: Project Completed	Complete	September 30, 2014



3.4. <u>Funding ($k):</u>

Fiscal Year	Planned	Received
2011	$600	$600
2012	$198	$198
2013	0	0
2014	$22	22
Total	**$820**	**$820**

4. Closeout Status

As of today (September 22, 2014) all the money has been spent or is encumbered. We expect to have no funds left at the end of the grant.

5. Transition to Operations

The FTF is fully operational at this point. We have had two successful commissioning runs, where not only we demonstrated the ability to cool and trap a variety of Fr isiotopes, but also performed spectroscopic measurements in them.

During the process of commissioning (two out of three runs) we have operationally tested working together more than 80% of the instruments of the FTF. The remaining instruments we have tested off-line and we are satisfied with their performance, for example the microwave system.

As a result of our two commissioning runs we have published an article where we present the facility in Nuclear Physics News Vol. 23, Issue 4, p 17 (2013):
The Fancium Trapping Facility at TRIUMF. DOI:10.1080/10619127.2013.821918

A paper about the details of the facility with many performance parameters is published at:
M. Tandecki, J. Zhang, R. Collister, S. Aubin, J.A. Behr, E. Gomez, G. Gwinner, L.A. Orozco, and M.R. Pearson "Commissioning of the Francium Trapping Facility at TRIUMF," JINST **8**, P12006 (2013). doi:10.1088/1748-0221/8/12/P12006 .

A third paper has just been accepted at JINST and will be published shortly about an off line source that we developed at the FTF. Two science papers are in the processes.

The support from the Subatomic Physics Evaluation Committee at TRIUMF to our work has been excellent. They have given us the highest scientific priority and we expect to have runs to execute weak interaction measurements in 2015 (refer to the attached letter below).

The transition to operations has been happening while we were assembling the FTF. We have plenty of experience in the area of precision measurements. The francium trapping success in the early fall of 2012 was an important benchmark in the project and we are now ready to start working on the weak interaction measurements.

Aug. 7, 2014

Dr. Luis Orozco
Joint Quantum Institute
Department of Physics
University of Maryland
College Park, Maryland
20742-4111
USA

Dear Dr. Orosco,

At its meeting held July 7 & 8, 2014, TRIUMF's Subatomic Physics Experiments Evaluation Committee (SAP-EEC) reviewed your proposal for experiment number S1218 at the Francium Trapping Facility and recommends the approval of six shifts for tests of the science chamber in the fall of 2014 and another six shifts for validation of the chamber in the forthcoming year.

This EEC proposal is part of a challenging science program, together with experiment S1065, at the Francium Trapping Facility, which was installed at TRIUMF's ISAC facility with funding from the US Department of Energy. I am happy that the facility has been set-up and commissioned successfully and the collaboration is now moving forward towards the physics measurements on atomic parity violation in francium.

TRIUMF is firmly committed to supporting a program of fundamental symmetry tests using high-Z mass-separated short-lived isotopes and the Francium Trapping Facility plays a central role in this strategy.

Sincerely,

Reiner Kruecken

Dr. Reiner Kruecken
Science Division Head