FNAL SRF infrastructure

10/25/2012

Introduction

Superconducting Radio Frequency (SRF) is the enabling technology for accelerator based particle physics in the 21st century. It is at the heart of essentially all new proposed accelerator facilities for discovery science in High Energy Physics (HEP) and is envisioned for multiple other projects within the Office of Science and has many potential transformative applications in industry. Any sustainable plan for U.S. accelerator based HEP or for accelerator stewardship within OHEP must be based on world-leading capabilities in SRF

Fermilab's SRF Program has been organized to achieve the following goals:

- Intensity Frontier − Prepare to initiate (staged) construction of Project X in the latter half of the decade by developing the necessary technology and by engaging India as a partner providing a substantial in-kind contribution
- Energy Frontier − Position the U.S. to eventually recapture the energy frontier with a lepton collider
- Accelerator Stewardship − Complete the ARRA investment in SRF capabilities to serve as a resource for the Office of Science, and to allow FNAL to play a substantial role in future national and international SRF projects.
- SRF Materials Research - Pursue fundamental research aimed at an improved understanding of SRF surfaces and materials leading to increases in SRF cavity performance and reduced costs.
- SRF Industrialization and U.S. competitiveness – Develop U.S. SRF industrial base with world class technical capability
- Advanced Accelerator R&D − Leverage the ILC and ARRA investment at NML to establish a world class program in accelerator science and technology.

Fermilab's staff is quickly gaining recognition for their ability to produce world class results and contribute to the advancement of the field. FNAL's SRF infrastructure is now comparable to any facility worldwide and prepares Fermilab and the DOE/OHEP to play a pivotal role in future SRF-based accelerator projects.

Key Messages:

- SRF technology is essential to most large future accelerator projects.
- The technology requires a large upfront investment both in terms of infrastructure and staff.
- New cavity frequencies and shapes requires several years of design, prototyping and test
- SRF Infrastructure takes years to put into place but much of it can be designed to be generic so it can accommodate a variety of cavity and cryomodule types for future projects.
- Fermilab's SRF infrastructure is approximately 77% complete with a Cost to Complete of ~$37.3M
- Many of Fermilab's SRF facilities are in steady state operation producing results that: reduce risk to Project X; train staff; contribute to SRF technology advancement; and improve the U.S. industrial base.
- The technology is capable of spectacular performance but is demanding. It takes time and actual hands on experience to train people to acquire the skills (cavity processing, test, clean room assembly, etc.)
- Trained SRF staff is one of the most valuable assets an institution can possess
- Cavity fabrication is best done in industry. However the available U.S. companies are small businesses and are very sensitive to Federal spending on SRF technology.

SRF and Project X

For each part of the SRF Infrastructure described in this paper and for the Cavity and Cryomodule Development Program Section, we have tried to point out the "Importance to Project X". Project X is a new high intensity Proton source at FNAL based on SRF linacs. It has a cost estimate in excess of $1B and will be the backbone of the Fermilab and the U.S. High Energy Physics Programs for the foreseeable future. Much of the technical, schedule and cost risk for the project is related to the SRF cavities and cryomodules. A strong SRF R&D program that proves cavity and cryomodule designs via prototypes, exercises the fabrication process and U.S. vendors, provides well understood costs and operational experience, and develops a capable technical staff is the key to mitigating Project risks and reducing costs. The SRF Infrastructure Plan (developed in 2006) provides the facilities to carry out this R&D. The construction of the SRF infrastructure has been shown to be consistent with the 2006 Plan and in line with the original cost estimate. The SRF facilities are world-class and when completed will provide Fermilab and the DOE/Office of High Energy Physics with unique capabilities to prepare for Project X and participate in other Office of Science SRF-based projects. The experience gained so far in building the facilities and fabricating 1300 MHz cavities and cryomodules has established Fermilab as an SRF capable institution. Completing the SRF infrastructure and Project X R&D Program will allow a more accurate Project X cost estimate and considerably reduce the technical risks so that the project can be executed as planned.

U.S. SRF Industrialization and Competitiveness

From the start, the SRF R&D Program has placed an emphasis on developing the U.S. industrial base and improving their competitiveness with respect to SRF technology. Fermilab has a long history, dating back to the Tevatron Superconducting Magnet R&D Program, of working closely with U.S. industry to advance new technologies. One of the SRF Program's guiding principles is to not compete with U.S. industry but rather to work with them to jointly develop new designs and fabrication processes. Fermilab's SRF infrastructure plan complements the capabilities of U.S. industry and provides the facilities that are too costly for vendors to build, such as large cryogenic systems, RF power stations and test areas. Fermilab works with industry through a variety of vehicles including general procurements, Small Business Innovation Research (SBIR), Work for Others (WFO), and Cooperative Research and Development Agreements (CRADA). Across all funding sources, the SRF Program has continued to nurture a learning environment in which U.S. industry can take advantage of the expertise available at the Lab and participate in the SRF-related projects.

The American Recovery and Reinvestment Act of 2009 provided additional funding ($52.6M) for SRF activities. The majority of these funds were used to purchase SRF components such as cavities, cryomodule parts, couplers and RF power sources from U.S. vendors. These large purchases coupled with Fermilab's commitment to work with vendors to develop the necessary skills and expertise to fabricate these components has made a difference. Fermilab's SRF initiatives have helped develop four U.S. cavity manufacturers and provided an opportunity to "level the playing field" for these companies with respect to European competitors who are firmly engaged in XFEL activities. ARRA also funded the initiative to embed electropolish technology at one of the U.S. cavity vendors, thus transferring this processing step to industry. The 10 MW horizontal klystron developed by an U.S. vendor is one of only a few such devices available in the world. The new superfluid cryoplant being assembled by a U.S. vendor in the Midwest will provide cryogenic services for cryomodule testing. Testing is a crucial step in verifying the fabrication and quality of SRF components and providing valuable feedback to U.S. industry.

Project X Cavity & Cryomodule Development program

Location: FNAL Technical Division and U.S. Industry

Purpose and description: The purpose of this activity is to develop and test prototypes of the cavities and cryomodules required to construct Project X, a new high intensity Proton source at FNAL based on SRF linacs. All activities including labor and cavity/cryomodule parts are funded by the HEP General Accelerator R&D B&R.

The Project X reference design requires six different SRF cavities operating at 4 different frequencies, each optimized for the changing velocity β of the H^- ions. All cavities operate at sub-harmonics of 1300 MHz, the frequency chosen for the European X-ray Free Electron Laser (XFEL) Project and for ILC R&D. This choice allows us to capitalize on a large existing world-wide set of infrastructure, expertise, and industrialization efforts. Project X employs a 3 GeV Continuous Wave (CW) linac operating at 1 mA average current. The challenges of building the CW RFQ and broadband chopper for Project X have led to the choice of 162.5 MHz operating frequency for the Radio Frequency Quadrupole (RFQ). Project X is unique in that CW operation requires that SRF cavities provide acceleration immediately downstream of the RFQ at the very low energy of 2.1 MeV. This is accomplished with 162.5 MHz Half Wave Resonators (HWR). Eight β = 0.11 HWR's and eight superconducting solenoid/corrector packages will be housed in a single compact cryomodule that will accelerate beam to 10 MeV. Fermilab is collaborating with the ANL SRF group (part of the ANL nuclear Physics Division) to design and build a prototype of this cryomodule for the Project X Injector Experiment (PXIE) front-end demonstrator at FNAL. ANL has extensive expertise with similar cavities and cryomodules and this collaboration represents a very cost effective solution.

From 10 to 160 MeV, H^- ions in Project X will be accelerated by two families of 325 MHz Single Spoke Resonators (SSR). The Development of SSR1 β = 0.22 was started as part of the High Intensity Neutrino Source (HINS) program at Fermilab so is advanced with two initial prototypes vertically tested at 2 K with excellent performance; one cavity was subsequently dressed with a helium vessel, tuner, and coupler and then tested at 4.8 K with pulsed power. With the adoption of a 3 GeV CW linac for Project X, the SSR1 design has been modified for CW operation and 10 prototype SSR1s were ordered from U.S. Industry. These are arriving now and being processed and tested. They are destined for a 325 MHz SSR1 cryomodule that will form part of PXIE. The pace of the development and fabrication of this prototype cryomodule is set by available funding. The SSR2 β = 0.47 cavity electromagnetic and mechanical designs are advanced but the pace of further development will also be determined by available funding.

Project X requires two types of 650 MHz cavities and cryomodules to accelerate beam from 160 MeV to 3000 MeV. The 650 MHz LE (Low Energy) cavities are designed to have a geometric β = 0.6 while 650 MHz HE (High Energy) cavities are designed for β = 0.9. Both cavity types will be housed in stand-alone cryomodules with separate heat exchangers due to the large dynamic heat loads. Prototype single cells at both β values are being fabricated and tested. Nine HE cavities have been ordered from U.S. industry. The Project X 650 MHz cavities and cryomodule represent one of the largest cost elements in the project. Their dynamic heat load drives the scale of the required cryogenic plant for Project X. The dynamic heat load depends on the cavity quality factor Q_0 and this in turn drives an R&D program whose goal is to understand SRF surfaces and processes with a goal to increase the Q_0 of these cavities.

The 3-8 GeV pulsed linac in Project X is, by design, closely aligned with XFEL/ILC technology and will be built from nearly identical cavities and cryomodules. This is also a large cost element for Project X but the R&D program benefits from XFEL development as well as the large global ILC R&D effort on cavity and cryomodule development. It also benefits from the ARRA funded cavity and cryomodule industrialization effort which has purchased 30 cavities and parts for 4 cryomodules, from U.S. Industry.

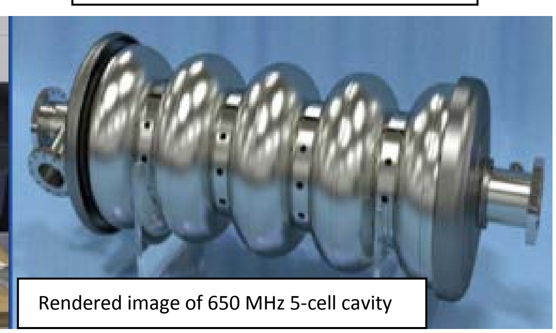
The Project X Cavity and Cryomodule Development Program is carried out in close collaboration with the India which seeks to learn SRF technology for its ADS program. A high level agreement is nearly in place that will result in a large Indian In-kind contribution from India to Project X. It is vitally important that the strength of the FNAL SRF program be such that it can support this collaboration.

Importance to Project X: The SRF cavities and cryomodules in Project X represent large cost elements with significant technical, cost, and schedule risks. The overall goal of the Project X Cavity and Cryomodule Development Program is to lower project costs and retire as much of the technical and project risk as possible prior to the start of Project X.

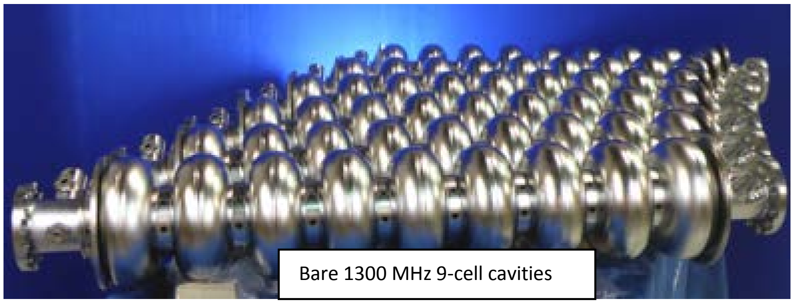
Bare 325 MHz SSR1 cavity

Dressed 325 MHz SSR1 cavity with tuner

Bare 650 MHz 1-cell cavities



Rendered image of 650 MHz 5-cell cavity


Bare 1300 MHz 9-cell cavities

Superconducting Cavity Surface Processing Facility

Location: This facility is physically located in an existing building on the ANL site. It is part of the ANL SRF facility maintained by Nuclear Physics and is jointly funded by FNAL and ANL

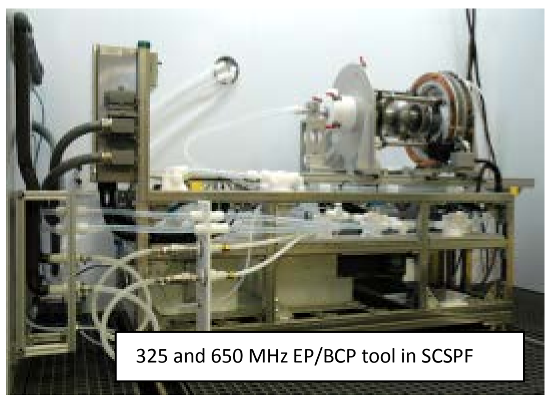
Purpose and description: The purpose of this facility is to "process" the Nb surface of SRF cavities via chemistry to remove the layer of material that was damaged during cavity fabrication. The facility performs both ANL and FNAL work and is staffed with both ANL and FNAL personnel. Basic facility operations costs are shared and the respective labs pay operational and labor costs directly related to work performed for them.

There are two chemical processes that are employed to remove the damaged Nb layer: Buffered Chemical Polish (BCP) and Electro-polish (EP). BCP is simpler but EP produces cavities with better surface finish and better performance. Both processes involve the use of mixtures of strong acids and require rigorous personnel training, careful equipment design and extensive safety reviews. FNAL is working to develop Centrifugal Barrel Polish (CBP) which holds the promise to reduce or eliminate the use of acids and lower costs but this is still in the R&D phase. After chemistry, the cavity is then rinsed with high press ultra-pure water and dried in clean room conditions (class 10) with the goal of producing a clean defect free, particle free SRF surface on the inside of the cavity. The facility at ANL consists of chemistry rooms, acid handling equipment and fume scrubbers, class 10 and class 100 clean rooms, high purity water systems, two high pressure rinse(HPR) systems one built for ANL cavity geometries and one built for FNAL cavity shapes, ultra sonic rinse tank, and various assembly and support fixtures. While much of the equipment is generic, for each cavity shape and frequency specific tooling must be developed for EP, BCP, HPR, cavity handling in the clean rooms, shipping containers, and bare tests.

Importance to Project X: This facility is a critical element of our plans. It must support cavity processing for all cavity shapes and frequencies employed by Project X. FNAL facilities were initially designed and are fully operational for 1300 MHz elliptical cavities in support of the ILC R&D program and 3900 MHz cavities in support of the DESY/FNAL collaboration. The 1300 MHz equipment is exactly the same as that needed for the Project X pulsed linac and will be exercised with ARRA purchased cavities to maintain the capability and to provide feedback to U.S. Industry. These activities are treated as lower priority than work in support of the Project X CW linac which is envisioned to be constructed first. The ANL portion of this facility was originally designed for Quarter Wave Resonators to support the ATLAS NP program at ANL. The first 325 MHz spoke resonators for the HINS effort were processed at ANL several years ago at an older BCP facility in the G150 building but these facilities are being phased out for ES&H reasons and are also judged to be inappropriate for the larger volume of 325 MHz spoke resonator cavities needed for Project X and PXIE. ANL was funded by ARRA to build an upgraded EP tool for their Quarter Wave Resonators. FNAL funded additional features for this EP tool that allow it to be used for Project X 162.5 MHz Half Wave Resonators (HWR), as well as Project X 325 MHz SSR, and 650 MHz elliptical cavities. The Project X R&D plan envisions processing all PX prototype cavities in the ANL/FNAL joint facility (162, 325, 650, 1300 MHz). In addition, when appropriate, we will use JLAB for collaborative work on β=0.6 650 MHz if funds are available for collaboration. FNAL used ARRA funds to establish a BCP and EP capability in U.S. Industry (AES). However current funding levels do not allow FNAL to commission and exercise this capability. The ANL/FNAL, JLAB, and AES facilities are all envisioned to be part of production infrastructure during Project X construction

1300 MHz EP tool in SCSPF


Setting up for BCP in G150


325 and 650 MHz EP/BCP tool in SCSPF


SSR1 cavity on HPR system


Loading 1300 MHz cavity into HPR

Cavity Prep and Cryomodule Assembly Facility

Location: MP9, IB4, and ICB buildings at Fermilab.

Purpose and description (Cavity Prep): Cavity prep and cavity /cryomodule assembly are done in the same three buildings (MP9, IB4, and ICB) with the same set of people and so are grouped together. After a cavity is fabricated (electron beam welded), it is important for it to undergo quality control checks and sometimes visual internal inspection before it moves to the next step of cavity processing. The cavity prep part of the facility incorporates the necessary infrastructure to inspect and prepare cavities for the various stages of processing and testing including vacuum ovens needed to heat treat cavities after certain steps in the cleaning procedure.

During surface processing and HPR SRF cavities absorb Hydrogen into the Nb bulk material. When the cavity is cooled down this hydrogen forms hydrides on or near the SRF surface (note that SRF currents flow in only ~ 50-70 nm of the inside of the cavity). These hydrides are “lossy” resulting in a quality factor (Q_0) that drops with increasing cavity gradient. This is often referred to as Q slope. If the cavity is baked at high temperature (typically 800C for 2 hrs.) in a high vacuum the hydrogen can be removed increasing the cavity Q_0 and flattening the Q slope. Cavity Q_0 is very important for CW operation since the dominant cryogenic losses for a CW linac come from the SRF cavities and these losses scale with Q_0 for a fixed operating gradient and temperature. Prior to 2011, Fermilab had to ship cavities to JLAB or Cornell for baking which was very inefficient. Ovens are not available in industry. Fermilab used ARRA funds to purchase two vacuum ovens, one is sized for 1300 MHz and smaller cavities, and the other sized for 325 MHz Spoke Resonators; 650 MHz elliptical cavities, and other larger cavities. The ovens were located in existing FNAL buildings allowing reuse of installed electrical power and cooling infrastructure. Both are now operational and in use. In addition to Project X cavities we have also baked cavities for ANL and FRIB in these ovens.

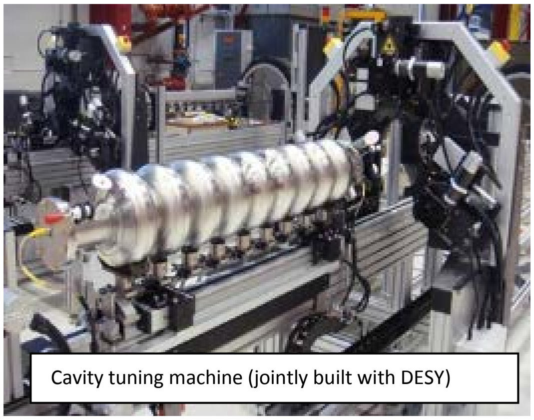
Importance to Project X: We will use the FNAL ovens to bake all Project X prototype cavities (162.5, 325, 650, 1300 MHz). In addition the ovens support the work of the SRF materials group as it develops new processes to increase Q_0 and reduce costs for Project X. The existing ovens can form part of the eventual production facilities for Project X but will likely need to be augmented with additional capacity. Following baking and HPR (and sometimes another light EP) cavities are prepared for bare cavity vertical test. This entails closing all cavity ports and installation of an antenna used to excite the cavity and measure the excitation fields during bare cavity tests in the Vertical Test Systems.

Purpose and description (Cryomodule Assembly): The cryomodule assembly part of the facility includes four distinct functions: cavity dressing, string assembly, cold mass preparation and finally cryomodule assembly. MP9 is a 12,000-square-foot facility that was designed using DESY’s Hall 3 facility as a guide. Fermilab’s facility consists of a clean room, cavity string assembly rail and cold mass assembly fixture that currently supports both the 1300 MHz and 3900 MHz cavity programs and will be modified to support the 325 and 650 MHz cavity programs. ICB is an 18,000 square-foot production floor building, which will accommodate two parallel cold mass assembly areas and final assembly areas in order to achieve the ultimate throughput for the facility - one cryomodule per month

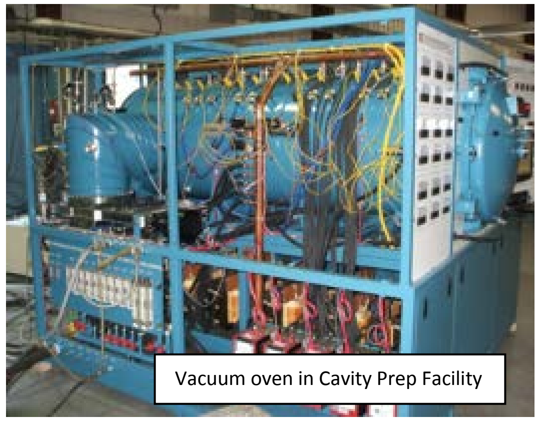
Inside the facility at MP9 cavities are prepared for vertical test. If the test is successful, these cavities then are welded inside a helium vessel. The cavities are then dressed with a power coupler in the clean room. A tuner and magnetic shielding are added before heading off for high power radiofrequency testing in the Horizontal Test Stand. If the cavity meets the desired performance criteria in the test stand it returns to the clean room to be assembled into a string of eight cavities for eventual inclusion in a cryomodule. The string of cavities is then mated with a cold mass and transported to the Industrial Center Building for final assembly. In this area, additional instrumentation is attached and the cavities are aligned. The string assembly is then inserted into a vacuum vessel and the warm couplers are attached, resulting in a completed cryomodule ready for testing in the NML Pulsed SRF Facility.

A large effort went into constructing an optimal clean room. The 2500-square-foot clean room is divided into three sections to accommodate each stage of the assembly process. Rated according to the number of particles per cubic foot, the clean room contains Class 1000, Class 100 and Class 10 areas. The first section, a Class 1000 Ante Clean Room, is a prep room where the cavities and other peripheral parts are submerged in ultrasonic baths and cleaned with ionized nitrogen to reduce the particle count to less than 10, a critical step before entering the next stage of the assembly process. The class 10 area, which is used to assemble the dressed cavities to form a string, has more filters and more floor perforations in it to constantly keep air flowing. Every six seconds 100% of the air in the clean room changes with approximately 90 feet per minute laminar air flow speed. While designing the clean room, Fermilab worked closely with DESY scientists and engineers, who described their ideal clean room scenario, and consultants, who specialize in building clean rooms for major corporations. Strict clean room protocols are enforced for the cavity clean room activities.

Importance to Project X: Although industry will fabricate and possibly do bulk polishing of Project X cavities, Fermilab will most likely do inspection, tuning, final prep, cold testing, and dressing of cavities and assembly of cryomodules. These are steps that are of critical importance and yet not large cost drivers assuming the infrastructure exists. The Cryomodule Assembly Facility which spans three buildings and multiple pieces of large tooling and fixturing would be costly to duplicate. The Cryomodule Assembly Facility will be used to dress prototype cavities and build both SSR1 cryomodule for PXIE and prototype 650 MHz cryomodules for Project X. It is a key element of our R&D program.



Cavity tuning machine (jointly built with DESY)



Vacuum oven in Cavity Prep Facility

Cryomodule Assembly Facility (MP9)

CM1 string assembly in Class 10 clean room

CM1 cold mass with cavity string

CM1 cold mass unloaded in ICB

CM1 cold mass being installed in vacuum vessel

CM1 complete and ready for installation

Vertical Test Systems

Location: IB1 building at Fermilab.

Purpose and description: After surface processing, HPR, baking, and clean assembly, SRF cavities are measured "bare" (i.e. without a He vessel, tuner, or the final power coupler) to determine their performance. In the vertical test stand, a "bare" SRF cavity is immersed in liquid helium and tested inside a vertical dewar to characterize its properties. Cooled down to a temperature of ~2 K, a low power CW (continuous wave) RF voltage is applied to the superconducting cavity. The Q (or quality) factor, a measure of the rate of energy loss, is measured as a function of the excitation voltage of the cavity producing a "Q vs. E" curve. A high Q factor means that the cavity will better retain the RF energy pumped into it, a desirable outcome since these losses end up as heat in the cryogenic system which is difficult to remove at low temperatures. The Project X CW linac particularly needs cavities with high Q since the RF is on all the time (as opposed to a pulsed machine). Vertical tests serve to verify whether the cavity fabrication, surface processing, and clean assembly were successful. Cavities with defects may quench (i.e. a normal zone is created in the SC surface) or may experience Field Emission (FE). FE occurs when the electric field on a portion of the cavity exceeds the work function of the material such that electrons are emitted from the surface leading to currents flowing inside the cavity in the absence of any beam. Particulates or small imperfections can cause large field enhancements and FE in regions of the cavity with high electric fields. Sometimes resonant conditions exist such that the energy gain and subsequent impact of the emitted electrons on the cavity surface causes additional electrons to be produced in a way that leads to a feedback mode and a self-sustaining discharge. This is called multipacting and is combatted by clean surfaces and by designing the cavity to avoid such resonant modes.

Typically, each cavity will spend a few days inside the vertical test stand, including the cool-down and warm-up periods, but a test may require more time if the cavity appears to have a problem. Once the cavity completes the vertical test process, it will be dressed in a helium vessel and continue on to the next qualification test.

The first vertical test stand (VTS1) is fully operational and has been used extensively with 1300 MHz cavities as part of the ILC R&D program. RF power is provided with a 500-watt amplifier. Throughout the design process, Fermilab worked closely with physicists and engineers from DESY, Cornell University and Jefferson Lab. VTS1 has also been modified to allow test of 325 MHz spoke resonators however these tests can only be done on SSR1 with a horizontal orientation since the SSR1 cavities are physically larger. VTS1 has been operating at full capacity for more than two years.

Fermilab received ARRA funds to construct two additional vertical test stands to allow for additional throughput and to accommodate the large lower frequency cavities needed by Project X._ Civil construction is complete, the dewars have arrived and cryogenics modifications are in progress to increase throughput and isolate VTS from other cryogenics activities in IB1. Installation of VTS 2/3 has been throttled by available funding for labor. India has ordered an identical VTS cryostat with the understanding that we will help commission it at RRCAT. A necessary condition is that we first commission our own systems.

The FNAL VTS systems benefit from extensive reuse of equipment originally part of the Tevatron magnet testing facility including the large CTI-4000 He refrigerator.

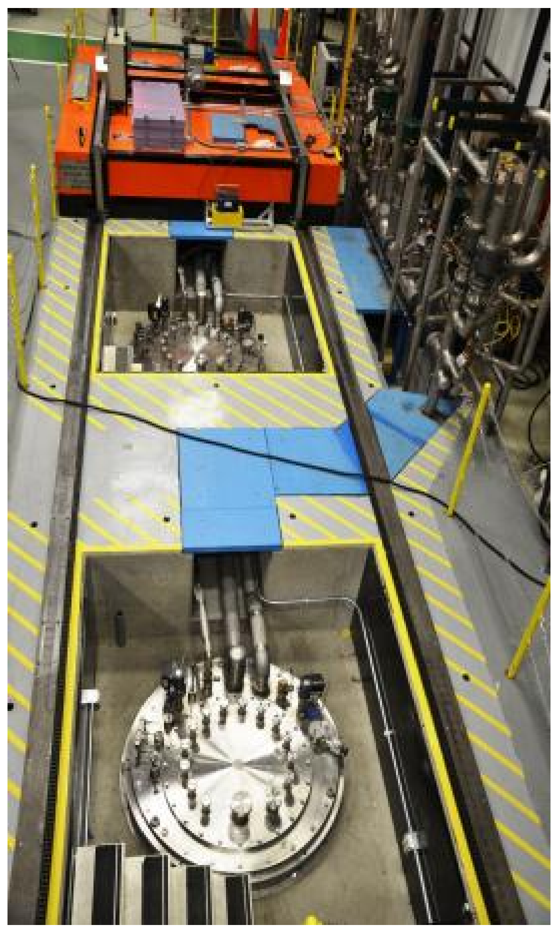
Importance to Project X: We will use VTS to test Project X prototype cavities. (325, 650, 1300 MHz) processed in the ANL/FNAL facility. We also plan to take advantage of the testing capability at ANL for 162.5 MHz HWR tests and at JLAB for collaborative work on 650 MHz cavity development. VTS will become part of PX production infrastructure during the construction phase as will the test capability at JLAB. This capacity may have to be expanded depending on the construction timeline for Project X.

VTS1 installed and operational

VTS3 cryostat ready for installation

VTS3 being installed

VTS1 insert with 1.3 GHz 9-cell



VTS2 and VTS3 installed in pit

Horizontal Test System

The Horizontal Test System at Meson Detector Building incorporates three distinct pieces of infrastructure, each capable of testing SRF cavities of different frequencies and sizes; HTS1 (1.3 GHz), HTS2 (1.3 GHz or 650 MHz) and STF (325 MHz). The systems share the cryogenic system and where applicable RF power and control systems. Savings are achieved by reuse of the Meson Detector building, reuse of 3 Tevatron satellite refrigerators, reuse of Tevatron transfer lines, reuse of large CEBAF vacuum pump.

Horizontal Test System -1

Location: Meson Detector Building (MDB) at Fermilab.

Purpose and description: HTS1 is a facility that tests dressed 1300 MHz cavities at 2 K with pulsed power. Dressed cavities are those which have been installed in their Helium vessels with tuner and fundamental power couplers. Horizontal testing is performed as a final qualification test prior to installation of the dressed cavity in a cryomodule. HTS1 was developed for the ILC R&D program. Cavities are limited by the physical size of the cryostat and the RF power source. HTS1 can test both 1300 and 3900 MHz cavities. Project X 650 MHz cavities will not fit. The cryostat heat exchanger also limits HTS-1 to pulsed power cavity operation. Production testing of any magnitude would also be limited by HTS1 throughput which is about one cavity per 3 weeks. For construction of Project X, we envision spot checking cavities in HTS1 vs. demanding that all cavities pass HTS before installation in a cryomodule.

Importance to Project X: HTS1 is a qualification test apparatus for dressed cavities. It serves as a test bed for coupler, slow tuner, piezo-based micro-phonic control and other developmental studies of importance to Project X. It will also be used to test long pulse operation of 1300 MHz dressed cavities for the Project X pulsed linac. HTS1 cannot accommodate 650 MHz dressed cavities for Project X.

Horizontal Test System -2

Location: Meson Detector Building (MDB) at Fermilab.

Purpose and description: HTS2 tests dressed 650 MHz cavities with CW power for Project X. It is being built collaboratively with India since they also need to test 650 MHz cavities for their ADS machine. The U.S. part is funded with ARRA and SRF B&R funds. The design is such that it can also test 1300 MHz cavities if equipped with a suitable RF source. ARRA funds RF power equipment, India provides the cryostat, the SRF B&R funds labor, the enclosure, cryogenics, and infrastructure. The HTS2 system differs significantly from HTS1 not only in its physical size but also in its design that permits it to provide as much as 100 W at 2K for CW cavity operation.

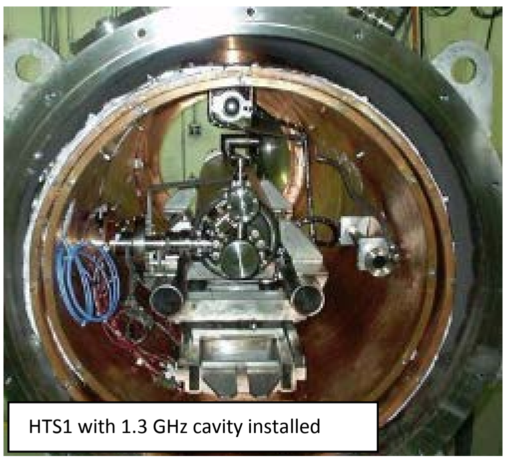
Importance to Project X: HTS2 will test 650 MHz LE and HE dressed cavities. It will serve as a crucial test bed for CW coupler, slow tuner, and piezo based micro-phonic control of these Project X cavities. Horizontal testing will be very important since funding limitations mean that it will be many years before a full Project X 650 MHz cryomodule exists. The 650 MHz cavities and cryomodules in Project X are both the capital and operating cost drivers for Project X. Successful prototypes are crucial to retiring portions of the large project cost and schedule risks associated with these cavities during project execution.

Spoke Test Facility

Location: Meson Detector Building (MDB) at Fermilab.

Purpose and description: The Spoke Test Facility (STF) tests dressed 325 MHz spoke resonators. Originally constructed as part of the High Intensity Neutrino Source (HINS) effort the existing facility tests dressed spoke resonators at 4 K with pulsed RF power. An upgrade is in progress to permit CW RF and 2K operation allowing tests of spoke resonators for Project X. The STF upgrade is funded with SRF B&R funds.

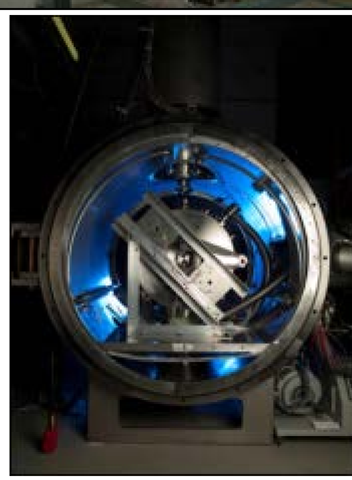
Importance to Project X: STF will test dressed Project X spoke resonators. It will serve as a test bed for 325 MHz CW coupler, slow tuner, and piezo based micro-phonic control of these Project X cavities. It will be used to qualify the SSR1 resonators that will be incorporated into the PXIE SSR1 prototype cryomodule and for the development of the SSR2 cavities for Project X. Successful prototypes of SSR cavities are crucial to retiring technical, schedule, and cost risks associated with these cavities during project execution.



HTS1 with 1.3 GHz cavity installed

Horizontal Test Stand 1 (HTS1)

Spoke Test Cryostat (STC)



STC with 325 SSR1 cavity installed

Cavity Processing Research Laboratory (ICPA-Integrated Cavity Processing Apparatus)

Location: Industrial Building 4 (IB4) at Fermilab.

Purpose and description: Fermilab's Cavity Processing Research Laboratory (CPL) is a facility that contains centrifugal barrel polishing, a horizontal electropolishing tool, a 1000°C vacuum furnace, a high pressure rinse tool utilizing ultrapure water, ISO class 4, 5 and 6 clean rooms for cavity assembly work and various other associated pieces of support equipment. All the operations are designed for single-cell and nine-cell 1.3 GHz Tesla type cavities except for the electropolishing tool which will initially be only for single cell use. Upgrades are currently being pursued for single and five cell 650 MHz cavities.

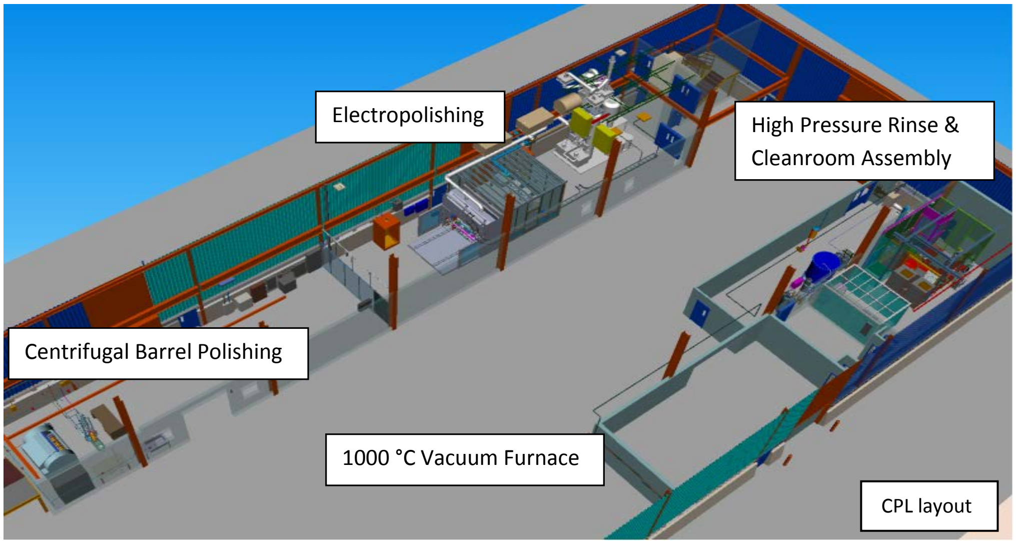
The main goal of the CPL is to develop new baseline cavity processing techniques that can consistently deliver cavities with high accelerating gradients and quality factors. Most of the work done in the facility will be focused on process R&D applicable to Project X and ILC. More fundamental process and materials research will also be done that may benefit accelerators in the future. This may include work on materials other than niobium and thin film deposition.

The centrifugal barrel polishing (CBP) machine is used to create a homogeneous surface that has a mirror finish on the inside of niobium SRF cavities. CBP is an alternative processing technique that polishes the inside of SRF cavities by rotating the cavities at high speeds while filled with an abrasive media. CBP is of great interest because it does not use the toxic chemicals used in electropolishing, can increase performance of cavities, creates a very smooth surface (Ra ~ 15 nm), can remove defects that chemistry cannot remove, and could be an enabling technology for use of other superconducting materials.

Electropolishing (EP) is the baseline technology used for the processing of niobium SRF cavities. The electropolishing tool is used to remove on the order of 120 microns from the inside surface of the cavity. This process can typically yield average surface roughness (Ra) values on the order of 0.1 microns. There are several issues associated with the process such as use of toxic HF acid, hydrogen contamination to the cavity, and sulfur contamination to the cavity. This R&D electropolishing tool will be primarily used to try to minimize some of the known problems with the EP processes.

The High Pressure Rinse (HPR) tool is used as one of the final steps in cavity processing to remove any contaminants from the surface of the SRF cavity. The picture below shows the general layout in the area, the ISO Class 4 (class 10) clean room, and a 9-cell cavity in the HPR tool itself. The HPR and proper dressing of the cavity in the clean room are critical steps in assuring the proper performance of the cavity. Any small contaminants that enter the cavity can cause serious performance limiting problems.

Importance to Project X: Materials R&D coupled with exploration of alternative processing techniques offers a true hope of cost reduction for large SRF-based accelerator projects. The CPL is conducting research which can have an impact on Project X cost and technical risk.



CPL layout

CBP machine

EP cabinet in CPL

Mirror-like surface (after CBP) on 9-cell cavity

Before/After CBP - applied to 1-cell cavity

Cryomodule Test Facility

Location: Cryomodule Test Facility (CMTF) building adjacent to NML

Purpose and description: The Cryomodule Test Facility provides test facilities for stand-alone cryogenic and RF tests of pulsed and CW cryomodules at 2 K. The CMTF infrastructure is generic but initially focused on Project X CW cryomodules which are challenging because of their large ~ 250 W heat loads at 2 K. Originally envisioned for several CM test stands, the building now will house the Project X Injector Experiment (PXIE) as a way of reducing Project X R&D cost. The building and some infrastructure was provided by ARRA. A major ARRA contribution is the large 500 W 2K superfluid refrigeration plant. The compressors for this plant are refurbished Tevatron compressors saving in excess of $ 3 M. Additional savings arise through the reuse of a large SNS vacuum pump. Several cryogenic boxes and test stand components are being provided by India. Reuse of SLAC BABAR refrigerator to supply NML needs saves additional money and allows the ARRA superfluid plant to be dedicated to testing the higher heat load Project X cryomodules. A single test stand (CMTS-1) will be able to test any Project X cryomodule at 2 K with RF.

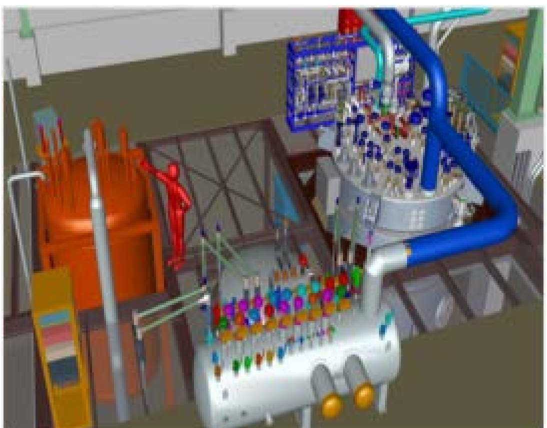
The SRF B&R pays for all SWF as well as the building generic electrical and cryogenic infrastructure including that required for PXIE. The GAD B&R pays for 162 and 325 MHz PXIE cryomodules while the Project X B&R pays for all warm PXIE components and associated labor.

CMTF could eventually be used to test production cryomodule for Project X, ILC, NGLS, ESS, RISP or other future SRF projects

Importance to Project X: The Cryomodule Test Facility provides test facilities for stand-alone cryogenic and RF tests of Project X pulsed and CW cryomodules at 2 K. These cryomodules are technically challenging because they are complex and because of their large ~ 250 W heat loads at 2 K. Collectively they represent one of the largest Project X cost elements and present large cost and schedule risks that the project must mitigate prior to construction.

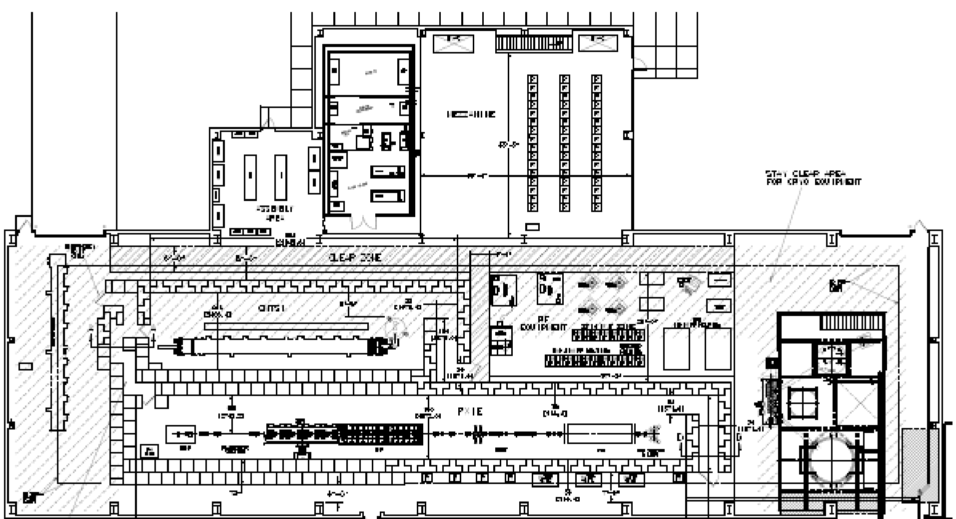
CMTF - nearing the end of construction

Current CMTF building – cave walls expected to be in place by Q2FY13



Planned cryoplant layout in CMTF

Reused TeV compressors for CMTF



Planned CMTF layout with CMTS1 and PXIE

NML Pulsed SRF Facility

Location: NML building & ARRA tunnel extension

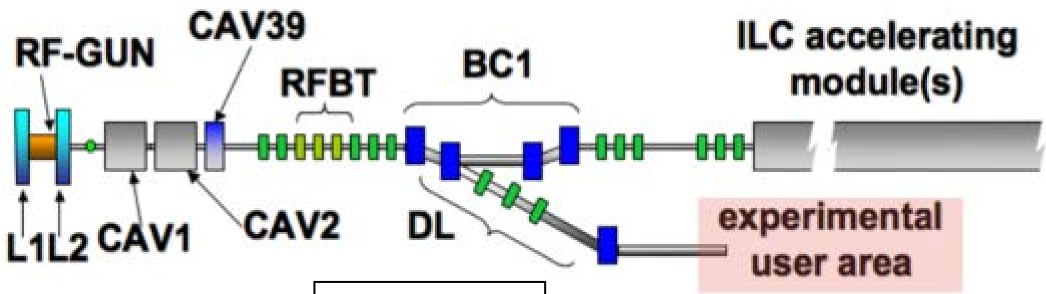
Purpose and description: The NML Pulsed SRF Facility was initially motivated as an RF unit test facility in support of the ILC R&D program. However, from the original proposal it was recognized that this facility would be an important test facility for the Project X pulsed linac and could provide the basis of a world class Advanced Accelerator R&D (AARD) program. A new AARD facility is planned to replace the FNAL A0 facility which has supported an AARD program at FNAL since the late 1990's. Envisioned as a 40 MeV photo-injector coupled with a string of from 3 to 6 ILC/PX 1300 MHz cryomodules, the facility would allow tests of full Project X (and ILC) RF units with nominal beam currents and pulse structures. An RF unit for Project X (or ILC) consists of a 10 MW klystron, modulator, and RF power distribution system mated to 3 to 4 cryomodules each containing eight 1300 MHz cavities. The 40 MeV injector is nearing completion and the facility currently is operational in support of cold testing of 1300 MHz cryomodules with pulsed RF power. Two cryomodules have been built so far with the first cryomodule successfully tested. The second cryomodule is in the final stages of preparation for test.

The construction cost for the NML Pulsed SRF Facility have been dramatically reduced through the reuse of a building formally used to house a fixed target experiment, two Tevatron satellite refrigerators, the SLAC BABAR CTI 4000 refrigerator, a large surplus CEBAF vacuum pump, Tevatron Helium and Nitrogen storage tanks; Tevatron Helium transfer line, etc. The 1300 MHz cryomodule that has been tested provided invaluable experience and staff training for cryomodule installation, RF test, and cryogenic operations all benefitting the future Project X CW and pulsed linac.

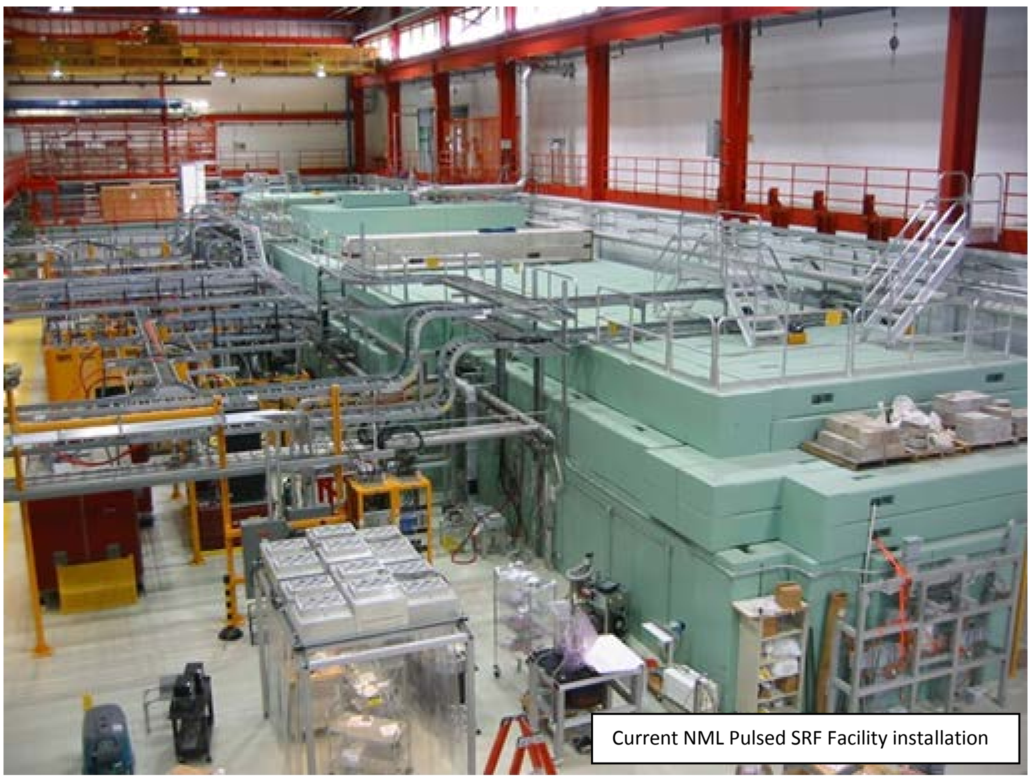
Work towards completion of the Advanced Superconducting Test Accelerator (ASTA) was stopped following the OHEP decision that NML was approved as an ILC activity and that with the end of formal ILC R&D funding completion of ASTA should be in response to an approved and funded AARD proposal. FNAL was permitted to complete the installation of the injector which was in progress and to operate 1300 MHz cryomodules in test stand mode. Nearly all planned beam line magnets, power supplies, and materials have already been purchased using ARRA funds.

Completion of the full ASTA would provide invaluable experience in integration, cryogenics, LLRF, High Power RF, and operation of cryomodules with beam loading and HOM power present. All of this will add greatly to our ability to design, construct, and operate Project X.

Importance to Project X: We already have learned many things from the NML program including methods for installing cryomodules while maintaining Class 10 clean room conditions in the field; methods for coupler conditioning; cryogenic load and pressure regulation; management of Lorentz force detuning; microphonic noise measurement and management; RF power management and testing; cavity tuner diagnostics and repair; LLRF control of multiple cavities from a single RF source, etc. We expect to continue to learn more with NML CM test stand operation of cryomodules assembled at FNAL with U.S. manufactured cavities and components. Acceleration of beam would allow tests of beam loading, HOM, and RF power regulation as well as accurate energy gain per cavity measurements. Completion of ASTA would provide real world operational experience with a complex but accessible SRF linac.

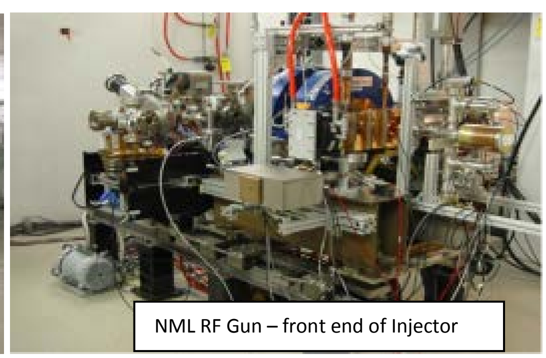


NML 40 MeV Injector



Current NML Pulsed SRF Facility installation

NML CM1 installation



NML RF Gun – front end of Injector