Infrastructure Requirements

for a

Superconducting Resonant Frequency

Accelerating Cavity

Manufactuing Facility

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Table of Contents

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Section 1. - Introduction

Superconducting Resonant Frequency Accelerating Cavity (SCRFAC) R&D has been ongoing for several years at Laboratories and Universities around the world. From this research an abundance of knowledge has be accumulated about the infrastructure that is needed to successfully develop, assemble and test Superconducting Accelerating Cavities.

The primary components in the design of an SCRF cavity are the ultra pure niobium cavity cells. To perform correctly at superconducting temperatures the purity and hence the cleanliness of all Niobium parts must be maintained throughout the manufacturing process. This process involves a series of intricate and precise forming, grinding, welding, machining, chemical etching, rinsing, and tuning procedures that may need to be repeated multiple times to achieve the desired end result. In order to achieve peak performance, consistent quality and uniformity, manufacturing efficiency, and the needed cleanliness throughout this process, a highly integrated very clean, controlled, manufacturing environment would be most appropriate.

If an integrated manufacturing facility would be built in one place for the purpose of evaluating component parts, assembling parts into finished cavities, and evaluating quantities of completed SCRFAC's, what might such a facility contain and cost? This paper is intended to describe an integrated facility based on the known and understood fundamental cavity design specifications and manufacturing practices that are used today to produce similar type cavities at various institutions around the world.

Today DESY is the recognized model facility. However, some of their practices and procedures are yet perceived to be in the developmental stages. The virtues of these practices and procedures are still being developed. Hence a very detailed description of each step in the manufacturing process and of the complete facility is avoided here.

The scope of the facilities and infrastructure characterized assumes that it would be capable of producing cavities having gradients and power capabilities equivalent to or better than those being achieved on experimental units today and would be capable of producing these cavities in a repeatable, efficient and accurate fashion, from one unit to the next. The infrastructure presented does not take into account any assumed production rate but is sized for development of pre-production evaluation samples.

Cavity component parts are assumed to be produced in industry or with industry support under Vendor Quality Assurance Surveillance. Vendors as well as the manufacturing infrastructure are to have the necessary analysis and test equipment to determine the performance variances due to allowable tolerance variations in the materials, design, manufacturing processes, and assembly techniques. It will also be able to completely evaluate the performance of finished products on a 100% basis.

Section 2. - SCRF Cavity Infrastructure

SCRF Cavities are composed of three basic components: the cavity cells, the input and output end flange assemblies, and a surrounding helium vessel that is capable of "tuning" its encased cavity. The key to the success in the manufacturing of a well performing cavity is to keep it ultra clean and free of any and all contaminants. Class 100 clean rooms are needed for this purpose.

Half-cells and beam tubes are formed from high purity (RRR 300+) niobium (Nb) sheets 2.8mm thick. The material is first eddy current scanned for impurities and if found acceptable the material is wire EDM cut into flat disc shaped blanks.

Half-cells are deep-drawn from the circular blanks, which are then coined at the iris. After annealing in a clean, single purpose oven, half-cells re-coined and re-stamped again. The draw-coin-anneal-coin-draw sequence has proven to produce minimum deviations from the design shape. Half cells are then checked for accuracy using coordinate measuring equipment and by RF testing.

Half cell iris and equator ends are then machined to a proper size and length, allowing for shrinkage due to welding. Equators have some extra length for tuning consideration. Once machining is complete parts may again be checked for accuracy. These parts are then ultrasonically cleaned and then chemically etched in preparation for Electron Beam Welding (EBW). EBW is the only type of welding that can satisfactorily weld Nb components together without the introduction of destructive contaminants into the weld areas. The iris's of two individual half cells are EBW together to create "dumbells". Once created, dumbells are measured and tested, then cleaned, rinsed, dried, and etched before being EBW together to produce the basic cavity cellular body.

In a similar way End Assembly Beam Tubes are formed and seam EBW from niobium sheet. Pull-outs are mechanically created for input and HOM couplers. Flanges are machined from niobium-titanium plate. All end assembly parts are cleaned, rinsed, dried, etched and sequentially EBW together to create the completed Input and Output End Cell Assemblies. Once qualified by acceptance testing, the end assemblies are EBW to the cavity cellular body to complete the bare cavity assembly.

The completed cavity is now leak checked and mechanically measured. The assembly is then chemically etched by either or both Buffered Chemical and/or Electro Polish processes followed by the application of a special hi-pressure rinse using ultra pure water to fully clean the material and remove all remnants from chemical treatment.

Once cleaned and dried, the cavity assembly is then performance acceptance tested in a vertical dewar pior to being EBW into its helium vessel. Once the cavity is encased into its helium vessel it can be more easily handled with less cleanliness precautionary measures taken. Final testing of each helium vessel encased cavity is performed horizontally a cryomodule on a special test stand. Once qualified the cavity assemblies are ready to be assembled into their multi-cavity support structure and ultimately into their multi-cavity cryomodule.

The Manufacturing Process Cycle

Vendor Supplied Components

- Raw Niobium Material
- Formed and Machined Components

Internal Cavity Section Welding

- Half Cells
- Dumbells
- Multi Cells

Iris Weld

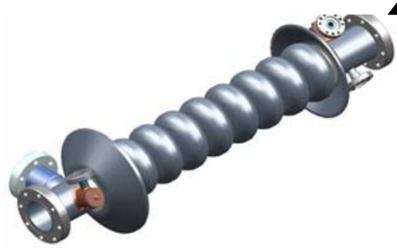
Equatorial Weld

Inspect
Machine
Etch
Clean
Test

End Section Fabrication Welding

- Antenna
- Formteil
- HOM Coupler
- Beam Tube
- Input Coupler
- Flanges
- End Half Cells
- Adapter Ring

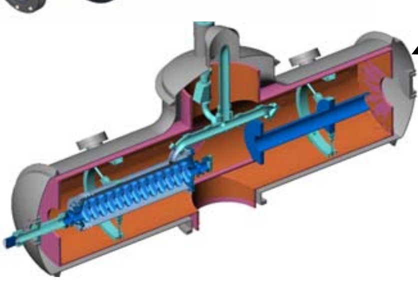
Bare Cavity Vertical Test



Install He Vessel

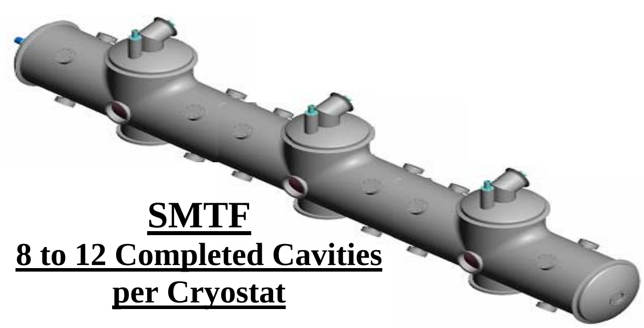
Completed Cavity

Completed Cavity Horizontal Test



1 or 2 Helium Vesseled Cavites
in Cryo Module Test Stand

Delivery



SMTF
8 to 12 Completed Cavities
per Cryostat

Integrated SCRF Manufacturing Facility Infrastructure

Dirty	Machine Shop Electron Beam Weld Facility	Storage: Chemicals, Fixtures, Raw Material, Tooling	UPW Generation & Storage
Dirty	Material Testing Vesseled Cavity Vert. & Horiz. Testing	Chemical Cleaning Facility	Vacuum Generation
Clean	Cavity Assembly	General Water Rinse & Special High Pressure Rinse	Cryogenic Supply Plant
Clean	Cleaned Component Storage	Inspection Facility Component & Sub-Assy. Test Facility Bake Out Furnace	RF Input Power Plant

In order to carry out the needed research and development for design, manufacturing, and performance optimization as well as the actual assembly and testing of the product, a complete integrated and localized R&D, Manufacturing, and Test Facility would be most efficient and appropriate. Having such an integrated facility would optimize R&D efforts, maximize production efficiency and quality control and assurance efforts, and minimize the potential for the introduction of contaminants and for damage that might occur from outsourcing conditions.

A localized and complete research and developmental manufacturing and test facility also offers the much needed opportunity to take a moderately developed design and a prototype manufacturing technology and meld them together into a developed reproducible efficient production manufacturing process. Along the way all if not more of the following areas at issue can be explored and optimized:

- Achievable Gradient Improvement
- Cost Efficient Cavity Design, Construction, Processing Techniques and Procedures
- Input and HOM Coupler Design and Function
- Input Coupler and Cavity Tuning Procedures
- Dark Current Capture at Low Frequency
- Lorentz Force Detuning and Control
- High Peak Power Processing
- RF Control
- Ability to Measure Qo and HOM's
- Ability to Measure Wakefields
- Cryo Plant Design Optimization
- Input Coupler Design and Vibration Effects
- Microphonics and Radiation Pressure Effects
- Niobium Properties Analysis (high purity) and Thermal Breakdown Characterization
- Input Coupler Optimization and Integration
- Injector Design Optimization and Integration

The "Integrated SCRF Manufacturing Facility Infrastructure" block diagram describes the basic integrated facility's infrastructure that must be in place and available in order to develop, produce, and evaluate the performance of complete Helium Vessel encased Superconducting RF Accelerating Cavities.

The following describes in some detail the elements of an integrated localized facility's infrastructure:

1.Normal Facilities (non-clean room conditions)

a. Machine Shop – Stores and maintains forming and welding fixtures; Performs Weld Prep Grinding Operations on Half Cell Iris and Equators; Performs machine trimming of dumbell equators.
   The following machinery is forseen:
   1) Grinding Machine for weld prep
   2) Sanding and Polishing Machines for weld blending
   3) Lathe and Mill for Cell Trimming and Drilling

b. Electron Beam Welding Facility - Cavity Components are EB Welded under Vacuum to Produce Full Penetration Voidless, Smooth Welds. Machine should be capable of obtaining a vacuum of $1x10^{-6}$ torr within 10 to 15 minutes, faster if cost effective using oilless pumps. Must be able to produce Defocussed Broad Beam with High Current and Low Voltage.

1) Welding Head Assembly
2) Vacuum Chamber
3) Mounting Table for Components – Must Rotate and Translate
4) Control System
5) Power Supply
6) Trained Operator

c. Chemical Processing Facility

1) Buffered Chemical Polishing Facility - Etches Grain Boundaries Faster than Grain Cell; Tends to Leave Sharp Edges at Perimeter of Grain Cell; Edges Become Suspected areas of Electron Emission at higher gradients.
2) Electro Polishing Facility - Etches Grain Cell Faster than Boundaries; Tends to Moderate Sharp Edges at Grain Cell Perimeter; Offers Lower Q Slope Potential; Provide Opportunity to Achieve Highest Gradients.

d. Facility for Raw Material Testing, Some Interim Component Testing, He Vessel Encased Horizontal Cryomodule Testing

e. Storage for Chemicals, Tooling, Fixtures, Raw Materials –
Welding Fixtures Include:

- HOM Coupler to End Tube
- Flange Extension Tube to HOM Coupler
- Flange Extension Tube to HOM Coupler
- Coupler Extension Tube to End Tube
- Half Cell to Transition Adapter
- Helium Vessel Flange to Half Cell Transition Adapter
- End Tube Assy to Vessel Flange Assy.
- HOM Coupler Flange to End Tube Assy.
- Main Coupler Flange to End Tube Assy.
- End Tube Flanges to End Tube Assy
- Half Cell to Half Cell at Dumbell Iris
- Dumbell to Dumbell
- End Assy to Dumbell Assy
- End Tube Seam (Hard Anodized Mandrel)

Forming Fixtures Include:

- Tube Pull Out and Holding and Forming Fixture
- Tube Ring Forming Fixture
- Half Cell Forming Fixture
- Nb Beam Tube Forming Mandrel

2.Clean Room Facilities

a. Cleaned Component and Sub-Assembly Inspection and Testing Facility – Performs incoming material Quality Assurance (QA) testing, component and sub-assembly testing and QA, and final assembly dimensional analysis

1) 2D and 3D Surface Contour Analyzer
2) Inspection Gauges
3) Surface Finish Analyzer
4) Precision Scale for Post Etch Weight Analysis
5) Precision, High Resolution Bore Scope with Computer Interface
6) Nitrogen, Argon, Vacuum Bagging

7) Nitrogen / Argon Purge Cabinet

b. Cleaned Component, Sub-Assembly, Tooling and Fixture Storage Facility - Retains Cleaned In-Process Parts, Assembly Tooling, Hand Tools, and Test and other QA Test Equipment.

c. General pure water rinse and special High Pressure Rinse Facility

1. Class 1000 Clean Area - Transfer Room Initial Wash - $\geq$ 3 bar, 10 MΩ DI, $\geq$ 0.2um filter
2. Class 100 Clean Area - Etching Jacket Disassembly Tanks; Static Rinsing Tanks, $\geq$ 3 bar; 10 MΩ DI High Pressure Rinsing System, $\geq$100 bar, UPW; Ultrasonic Cleaning Stations; Nitrogen/Argon Drying Station; Ionized Air Cleaner

d. Bake Out, Annealing, and Post Purification Processing Furnace Facility

1. Stress Annealing – Diffuses Oxygen away from Nb surface and into material (< 800^0C); Removes Surface H_20 (Achievable at 150^0C).
2. Hydrogen Degassing (600 – 800 ^{0}C) - Done to Rid the Nb of trapped H_2 gas – Q disease.
3. Post Purification (1400-1500^0C) for 4-8 hrs. in UHV –Used to help take out O_2 to improve RRR, and Reduce Field Emissions by Burning Away Small Impurity Particulate, Resulting in Increased Accelerating Fields.
4. Furnace must be capable of maintaining a vacuum of 1 x 10^{-7} torr and should be capable of purging with Nitrogen gas to speed up post process cooling.

e. Component and Sub-Assembly Handling, Assembly, and Fixturing Facility

4. Supporting Facilities:

a. Ultra Pure Water Generation/Supply and Storage Facility -50% UPW, 50% 10Mς - Used for cleaning, rinsing, and etching components and assemblies.

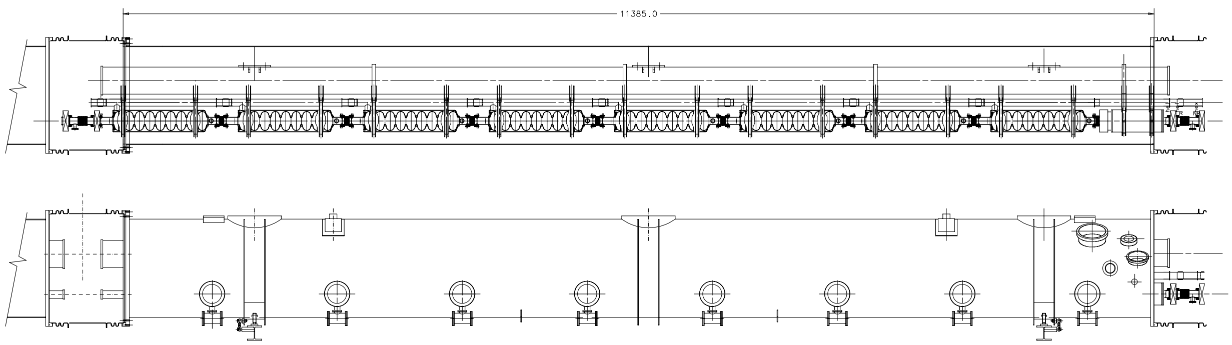
b. Vacuum Generation Facility - Provides Internal Cavity Vacuum, Cryomodule Insulating Vacuum, Input Coupler Vacuum and EBW Chamber Vacuum. Needed to properly perform Cold Tests on SCR cavities and sub-assemblies; Must be capable of obtaining $1x10^{-8}$ torr before cool down (assumes $1x10^{-10}$ torr can be reached after cool down); Should be capable of maintaining proper vacuum on 5 cavities simultaneously; Must be composed of "Oil Free" Pumps with close off valves; Vac Pipes must be Electro-Polished

c. Cryogenic Supply Facility – Produces Liquid Helium @ 1.8 deg. K and capable of supplying enough cooled helium to test a single cavity.

d. RF Input Power Supply Facility

Section 3.   - Cryomodule Structure and Supporting Infrastructure

To build a TESLA style cryomodule requires an infrastructure capable of receiving and storing a cryostat vessel and coldmass components, assembly and alignment of the coldmass in a clean environment, and space and equipment necessary to assemble and align the coldmass into the cryostat. This process is well documented by the work currently being performed at DESY in Hamburg, Germany. The process at DESY will be described below.



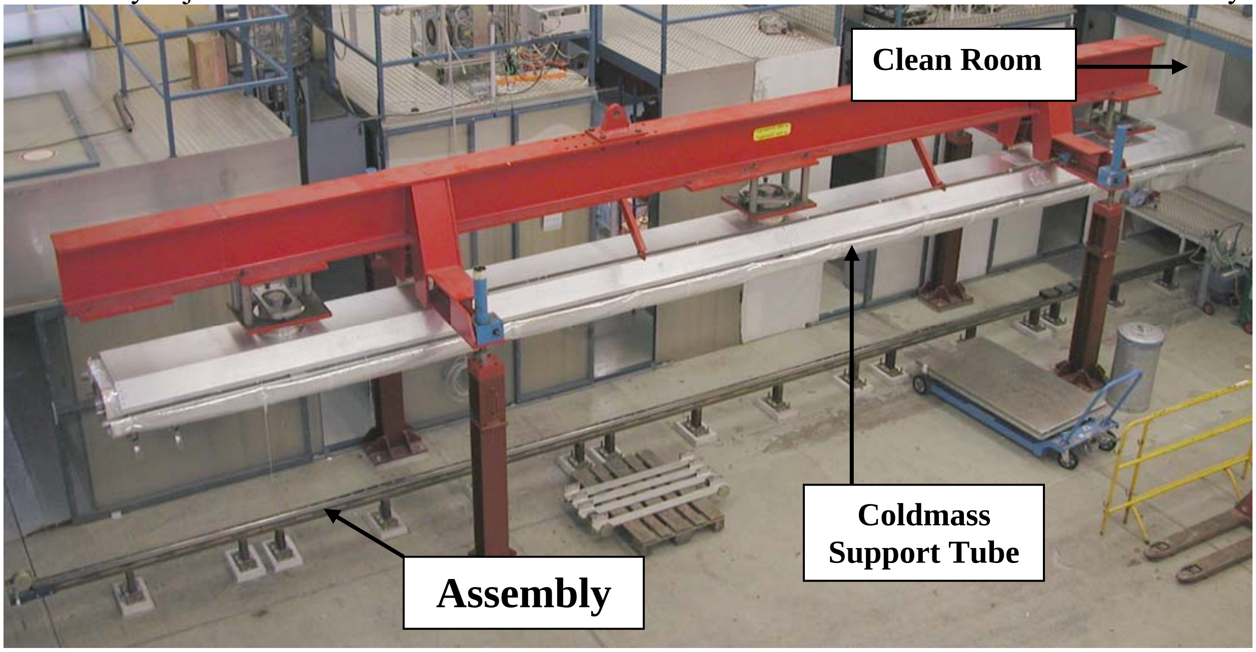
DESY, TTF, β=1 Cryomodule

The cryostats for the TTF (Tesla Test Facility) were designed at INFN and fabricated in Italy to DESY's specifications. Using outside suppliers, who specialize in vessel construction, makes perfect sense. Vendors are fairly easy to find and, due to competition, costs are minimized. The vessel is shipped completed, cleaned, and closed off to debris. A facility must be large enough to store the 12 meter long cryostat before it is assembled with the coldmass. Future, 12 cavity cryostats could be as long as 16 meters.

Receiving and Storing Cryostats at DESY

The coldmass Helium Vessels/RF Cavities are assembled in a clean room, on a mounting stand, supported by a rail system. As the coldmass is assembled, the components are aligned to each other and connected with beam pipe and bellows. It is imperative that the cavities remain absolutely clean during this phase of the assembly. Any interior particles to the cavity will destroy the RF properties.

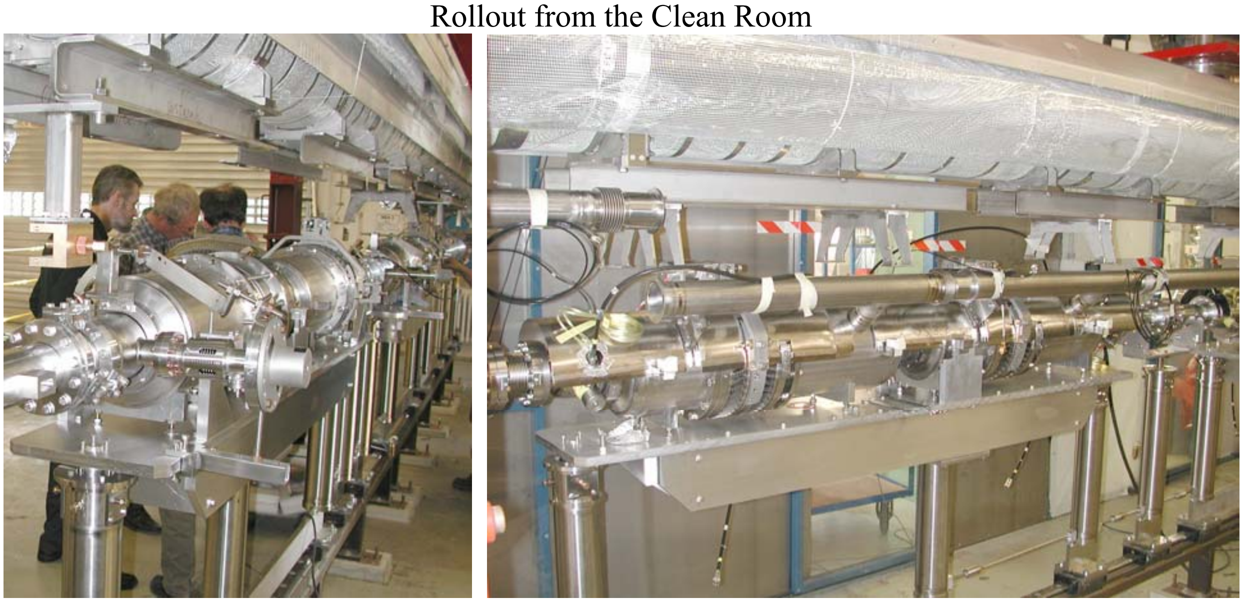
As the Helium vessel assembly takes place, the coldmass support is assembled outside of the clean room, but in-line with the assembly rail system. The coldmass support tube is mounted on a vertically adjustable frame so that it can be lowered onto the helium vessel/beam line assembly.



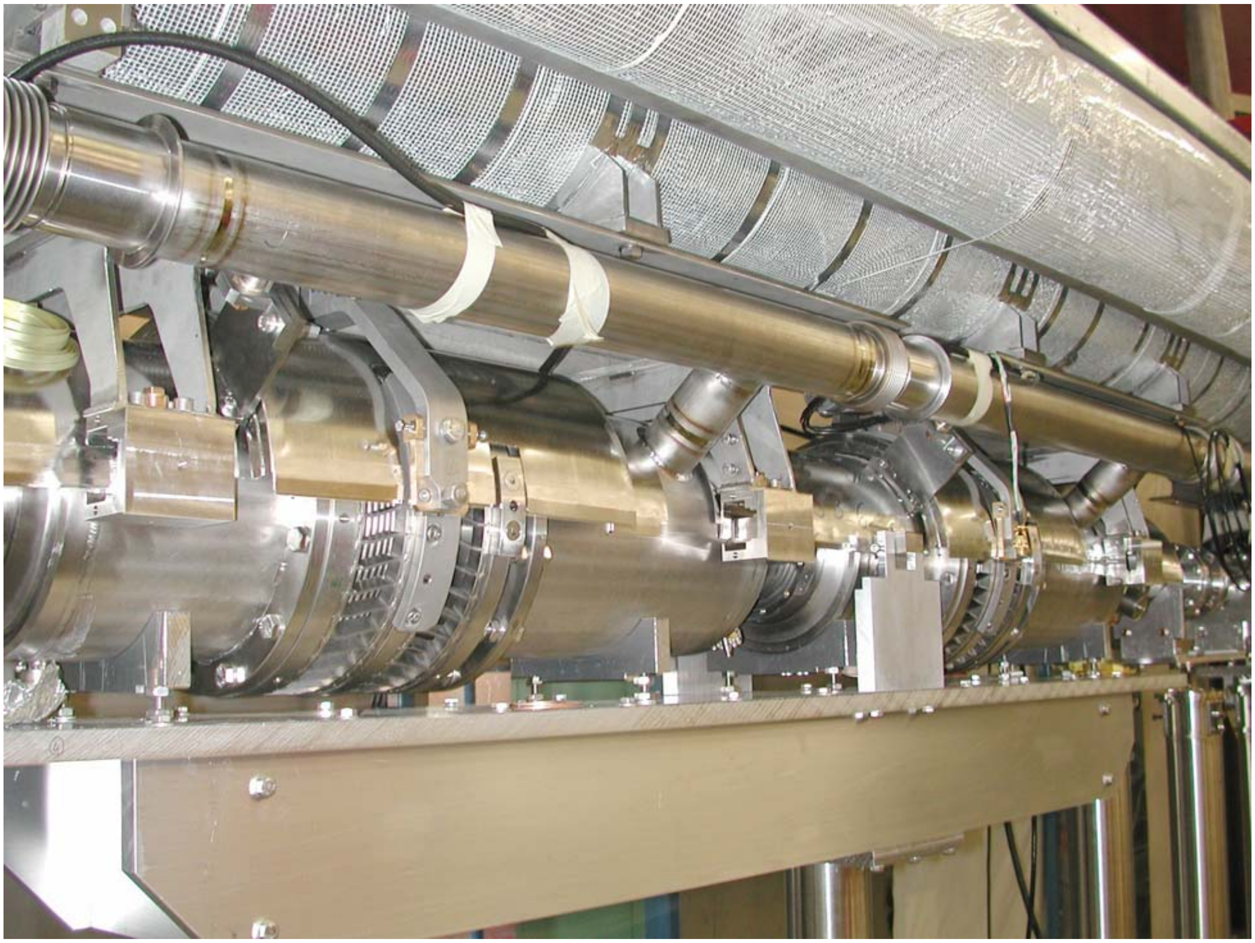
DESY's Coldmass Assembly Area (External to Clean Room)

After the helium vessels, main couplers, quadrupole magnets, beam pipe, and bellows are aligned and assembled together, all open ports are capped off. The assembly is then rolled out of the clean room and put into position under the support structure. Many items such as magnetic shields, cryogenic piping, adjustable support blocks, and instrumentation are attached to the SRF system assembly before being connected to the support tube.

Rollout from the Clean Room



External Parts are Assembled and Electrical Devices are Tested



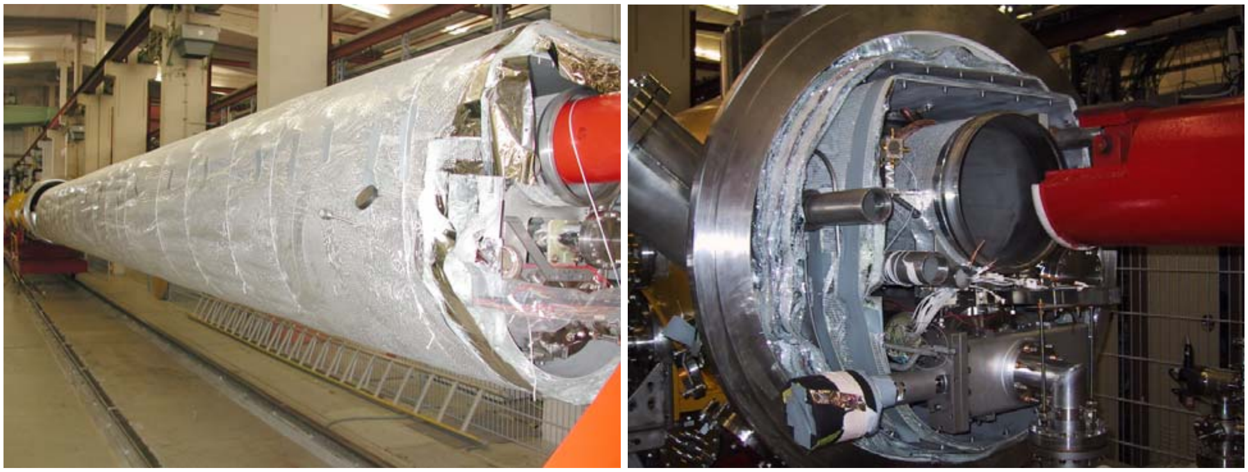
Support Tube is Lowered into Position and Connected to the RF Assembly

The rail system support table is removed leaving the RF system completely suspended by the support tube. Components required on the bottom of the assembly can now be added. All remaining RF system components and insulation are now assembled prior to the installation of the cryogenic heat shields and piping hardware. All hardware is procured from outside suppliers and assembled at DESY.

Magnetic Shields and some Insulation shown installed

Assembly Ready for Installation of Cryogenic Shields and Piping

Two layers of heat shields, one at ~5K and the other at ~80K are installed as well as the heat shields that enclose the main couplers. The remaining piping and insulation are also installed. The completed, insulated coldmass is then transferred from the support frame onto a cantilevered strong-arm that inserts into the coldmass support tube. On a rail system, the coldmass is inserted and connected into the cryostat and aligned.



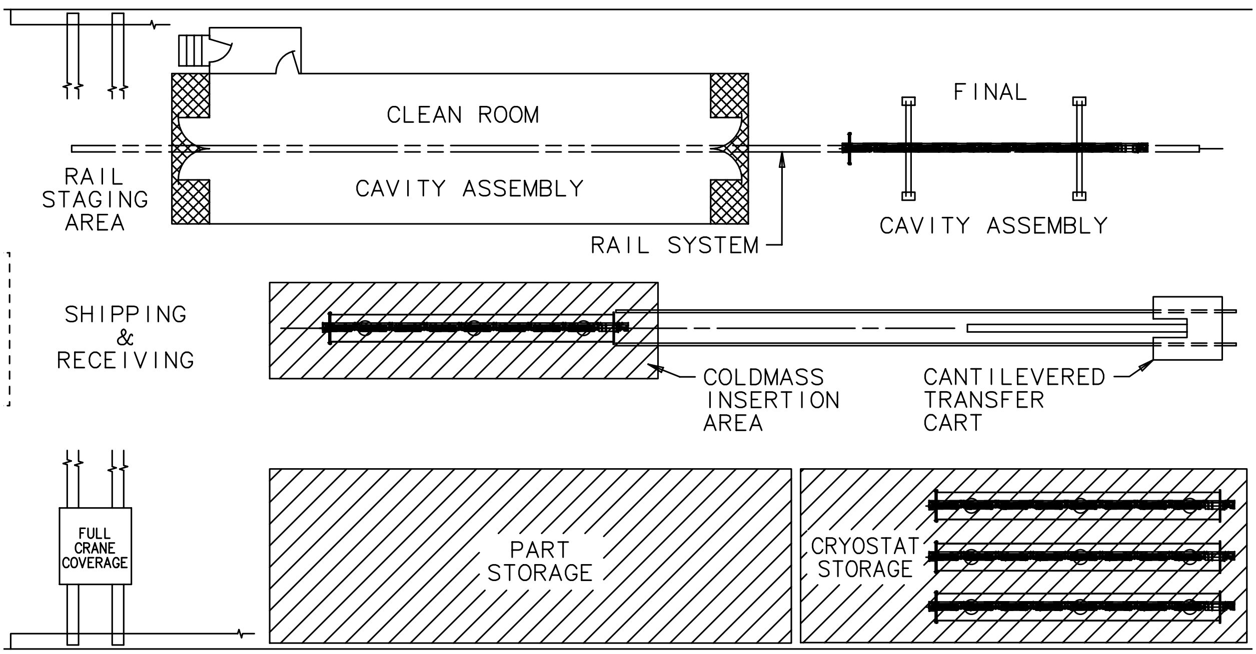
Coldmass Before and After Insertion into the Cryostat

Once inserted into the cryostat, the remaining connections from external to internal are made. This includes external main coupler connections and cryogenic and vacuum system components.

A Cryomodule being installed into the Beam Line

A facility to assemble the cryomodule requires adequate space, cleanliness, and equipment. The major components are discussed below. It should be noted that quite a bit of specialized tooling and fixtures are required for assembly and alignment that is not included in this short description.

A dedicated building, or portion of a building is required to handle the logical receiving, assembly, and shipping of a ~16 meter long cryomodule and its components. As the long cryostat shells are received, they must be stored. A facility should be able to hold at least 4 cryostats; two empty, one completed but not yet shipped, and one undergoing fabrication. Storage racks should be sized and labeled to accommodate all of the components for fabrication and a separate area for storing tooling and fixtures. The facility should have a delivery area large enough to allow for a semi truck's payload to be removed via the overhead crane. The crane capacity should be above 20 tons.



The assembly line is composed of three sections: a pre-staging area; a clean room; and a final, "non-clean" assembly area. These three sections are in-line with each other and share a common, floor mounted, transport rail. The rail allows for the mounting of individual assembly tables to support each of the items in the SRF assembly. Each mounted table sits on rollers and is connected to the next table via adjustable strong-arms. As the assembly proceeds, more tables are added until the entire SRF system is assembled and aligned.

The first table is added in the pre-staging area where a quadrupole magnet or SRF cavity is placed via the overhead crane. The item is mounted to its support table and then pushed into the clean room for additional work.

In the class 1000 clean room, the components are aligned, tested, and get additional components, such as main couplers, added. The clean room should be approximately 6 meters wide by 20 meters long with an elevated floor to allow for the installation of the support transport rail system. Additional SRF cavities or magnets or beam line pipe or bellows are added to the assembly until all of the coldmass main components are in place. Ports exposing the internal cavities are closed off and the entire structure is advanced on to the “non-clean room” assembly area.

Items from the part storage shelves are assembled onto the RF cavity system until the entire coldmass is formed. After the coldmass is assembled, the overhead crane picks up the assembly and transfers the coldmass to the “cantilevered transfer cart.” The transfer cart rolls on rails to insure proper alignment with the cryostat vessel. Once the coldmass rolls into the cryostat vessel, the support system is connected so that the coldmass is supported by the cryostat and no longer by the transfer cart, which can now be removed. After all connections are made and the coldmass is aligned to the vessel, the cryomodule can then be stored until ready for shipping.

Section 4. - Test Stands for Single Cavity Performance Evaluation

1. Vertical Test Stands

A Vertical Test Stand (VTS) is used for cavity fabrication R&D purposes and to provide a mean to perform a cavity acceptance test after it is fabricated. All naked (bare) cavities need to be tested in Continuous Wave (CW) mode in a vertical cryostat to evaluate cavity performance at high fields. Cavities that do not pass these tests must be reviewed and repaired by additional processing. Typically each test takes approximately 1-2 days. Every known laboratory that is seriously involved in SRF R&D has at least one VTS. Often a facility will have multiple VTS's and may have one for each frequency used. This eliminates the need to recalibrate the RF measurement circuits with each change in frequency and will optimize the amount of LHe used for testing (a smaller VTS can be used for R&D cavities with a small number of cells versus a larger VTS for full-scale production type cavities). For example, J-lab has eight Dewars in its vertical test area. For the new projects being considered there will be a need for VTS's to work with three different frequencies, 325 MHz, 1.3 GHz, and 3.9 GHz. At 1.3 GHz there will be a benefit of having a small VTS pit for R&D purposes as well as a larger one for full size cavities.

So, in total there is a suggested need for 4 VTS pits:

1. 325 MHz –1/4-wave, 1/2-wave, or spoke cavities
2. 1.3 GHz– 9-cell TESLA type cavity
3. 1.3 GHz– 3-cell R&D cavity
4. 3.9 GHz – 13-cell CKM or 9-cell 3-d harmonic cavity

For each frequency, a power source is needed with a CW power of about 0.3-1 kW.

Historically pits (or vertical Dewars) have been made and installed below ground level, so that radiation problems could be resolved in the most natural way as DESY and CU have done. They also can be placed above the ground using concrete radiation shielding as a means of absorption such as used at MSU and FNAL. In addition, magnetic shielding must be provided so as to maintain the magnetic field inside the pit at a level of about 10 mGs or less.

Stands must be equipped with a vacuum system capable of providing the needed vacuum inside the cavities to be tested. They must also have a sufficient supply of Lhe available for cooling. The associated vacuum pumps must have sufficient capacity to pump out He fumes to achieve temperatures of 1.8 K. An appropriate thermometry system is required to investigate how uniform the cavity surface heating is at high field levels.

Vertical Test Stand Hardware Requirements

- Vertical Dewar
- Cryogenic system to achieve ~1.8K
- CW 0.3-1kW RF power source (TWT)
- Vacuum system
- Low power level RF control system
- Data acquisition system

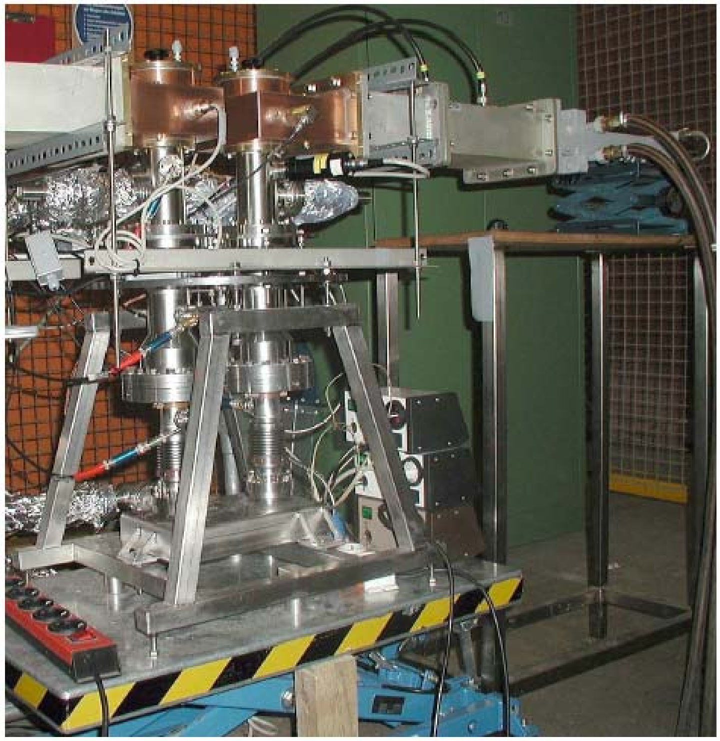
A rough estimate of the cost to build one stand is 600 k.

2. High Power Coupler Processing Stands (HPCPS)

The last phase of high power coupler fabrication is power conditioning. The RF power coupler is one of the critical components of the accelerating cavity. The power needed for cavity operation at the accelerating gradient 25/35 MV/m is about 250/500 kW in 1.3 ms pulse length. Two couplers are cleaned and assembled to a test stand in a clean room. The process of conditioning starts with coupler baking at 150 C for 3days to degas the surfaces in order to reach vacuum levels of about 10^{-10} torr after baking. Processing is usually done with a traveling wave. Power is cycling from low level to ~1MW, starting from a 20 μs short pulse and then increasing the pulse length up to 1.3ms. The total processing time is typically 100-120 hrs. After this test is completed all coupler parts are stored in dry nitrogen.

The overall process of conditioning takes up to week to complete, and every coupler that is used in an RF structures must be conditioned. To be sure that couplers can withstand standing waves, the required power level in the traveling wave mode is about four times that of the expected cavity input power: ~100 kW for 325 MHz systems, ~2 MW for the 1.3 GHz system, and ~200 kW for the 3.9 GHz system. Because of the relatively high power, pulse power sources (klystrons) are used, that require modulators. In principle, a power source can be shared with a beam facility that uses the same corresponding frequency, but if a significant amount of couplers are to be processed, and the facility is in permanent use, this sharing no longer is practical. This is however a good option for the first and early stages of the facility operation.

The HPCPS does not require any cryogenics for operation, but a vacuum system is still required as well as radiation shielding (although not so thick as in the case of the VTS). Low power level RF is also required to provide the needed interlocks and spark protection.



Hardware Required:

- Klystron-1.3GHz, 2MW*1.3ms, 2-5Hz, (include: Modulator, Interlock system etc.)
- RF distribution system (loads, circulators, waveguide components)
- Vacuum system
- Baking system
- X-ray shielding and control
- Data acquisition and system

A rough estimate of the cost to build a stand for each frequency (not taking into the account the klystron and modulator) is ~250 k$.

References: Dwersteg B. et al, TESLA RF power couplers development at DESY, Linac96.

3. Horizontal Test Stand

A Horizontal Test Stand (HTS) serves as an assembled single cavity test stand. After the acceptance tests using the VTS, a bare cavity is assembled into a helium tank, equipped with tuners and a power coupler, and is ready to be assembled as part of a string of cavities that goes inside a cryostat. This assembly needs to be done in a clean environment. Before this happens however, the completed cavity must be tested to assure it still meets its field strength and quality factor requirements.

Using a HTS is a common practice when many cavities must be built. Examples of this are CHECHIA at DESY and CMTF at J-lab. The most important need for an HTS is to evaluate a TESLA-type module that requires a significant amount of assembly work to be done installing its eight cavities and has the highest risk of a failure. The HTS that is currently being built for the A0 facility at Fermilab can serve later as a HTS for the 3.9 GHz accelerating (3-d harmonic) system.

The same generator can be used to feed the stand that is used for the HPCPS.

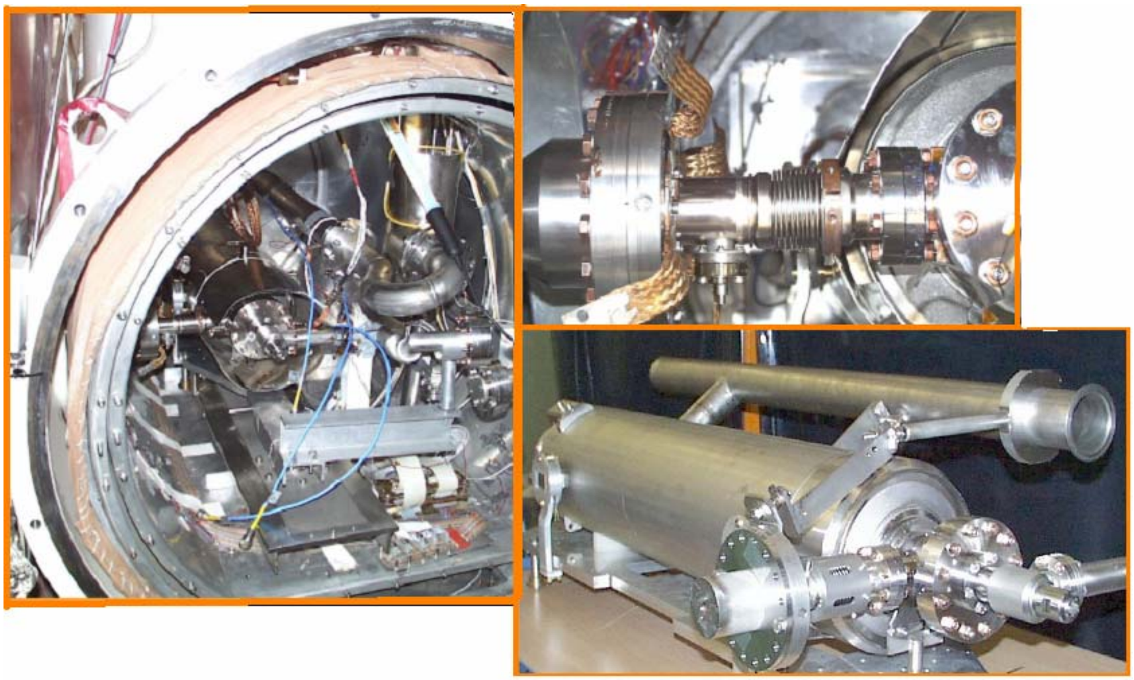


Fig.3 TESLA cavity assembled in horizontal cryostat

This stand requires a source of 1.8 K LHe, so it must be placed close to the cryo-system. It must also be equipped with high vacuum system, and there must be sufficient radiation and magnetic shielding provided. As part of the design of the stand, provisions must be made so that cavities can be easily assembled inside the cryo-module and so that the cryostat itself can be easily modified for use with cavities of different designs. The DAQ and low level RF systems that would be expected to be used, would be similar to those used at the VTS.

The estimated cost to build this facility (not including power source, modulator and cryo-system) is about 500 k.

4. Cavity Tuning Test Stand

After fabrication cavities have to be measured and tuned. Tuning includes mechanical cell-to-cell alignment and RF frequency, spectrum, and field flatness tuning. A special test stand needs to be built for this purpose. This stand includes a table, a mechanism for cavity rotation, a system of mechanical sensors to measure individual cell offset, a special device for correction offsets, a computer controlled pulling device for RF bead-pull measurements, and a low level RF system for frequency and spectrum measurements. The Figure below shows a DESY cavity tuning stand equipped with electronics.

The estimated cost to built this stand is about 150k$, not including RF network analyzer.