Design of the PEFP Low Beta Cryomodule

Sun An, Y. S. Cho and B. H. Choi

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양 성 자 기 반 공 학 기 술 개 발 사 업 단

Content

1. PEFP SRF linac introduction

Primary parameters of the PEFP SRF linac

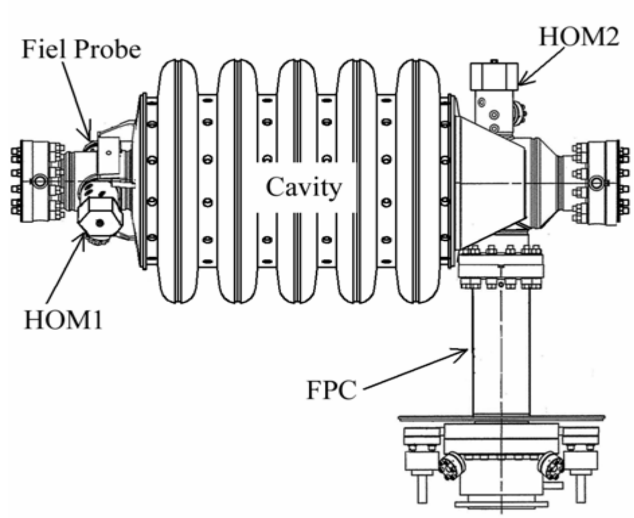
Ion type	**Proton**
Operation mode	**Pulse**
Injector frequency	**350 MHz**
Operation frequency	**700 MHz**
Beam current	**20 mA ***
Pulse length	**1.33 mS ***
Pulse repetition rate	**60 Hz ***
Energy range	**80 MeV~178.6 MeV**
Duty factor	**8.0% ***
Length of the low beta linac	**50 m**
SRF cavity geometrical beta	**0.42**
Number of the Cryomodules	**9**
Cavity number per cryomodule	**3**
Cell number per cryomodule	**5**

* Maximum

2. PEFP Low beta cavity

2. 1 Cavity RF parameters

Parameters	Value
Frequency (MHz)	700
Geometrical beta β_g	0.42
E_{acc} (MV/m)	8.0
E_{pk}/E_{acc}	3.71
B_{pk}/E_{acc} [mT/(MV/m)]	7.47
R/Q (Ω)	102.30
Cell to cell coupling (%)	1.41
Geometrical Factor (Ω)	121.68

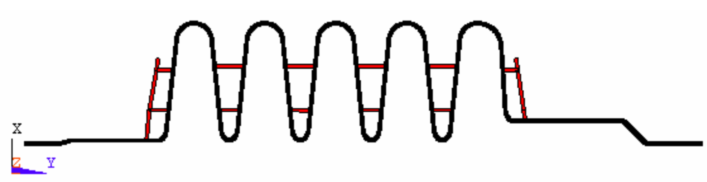


PEFP Low beta cavity

Mechanical property of the low beta cavity

Thickness of the cavity wall	4.3 mm
Lorentz force detuning factor K_L	-1.1 Hz/(MV/m)^2
Frequency sensitivity	187.8 KHz/mm
Field flatness sensitivity	49.1 %/MHz
The tuning sensitivity	4498 N/mm
Maximum Von Mises stress after pump-down at room temperature	12.6 MPa
Dangerous mechanical modes	N/A

2. 2 Stiffening structure and mechanical property

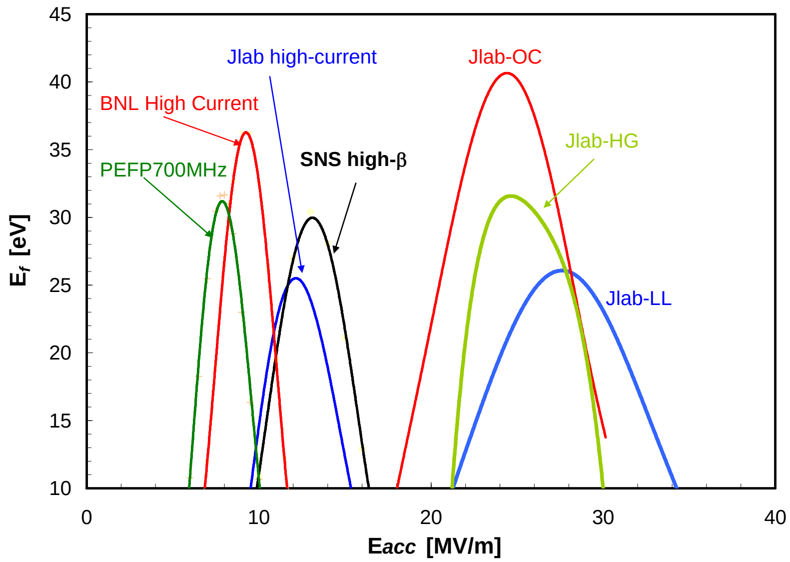


Stiffening structure of the PEFP Low beta cavity

WEPMA135

2. 3 Multipacting simulation

The calculations by **FishPact** written by G. Wu indicate that for PEFP low beta cavity the occurrence of the multipacting is unlikely, because the electrons can not gain sufficient energy to generate secondary electrons when impacting on the cavity surface.



Electron's final energy of the multipacting electrons of the cavities, which include PEFP Low beta cavity, BNL High current cavity, SNS high-β cavity, JLab high-current cavity, JLab high gradient (HG) cavity, JLab low loss (LL) cavity and JLab Original Cornell (OC) cavity.

2. 4 HOM analysis

A normalized HOM-induced voltage, an induced power and a time-averaged induced power especially from the TM monopole modes have been analyzed. The HOM trapping possibility has been established by considering a manufacturing deviation of the HOM frequency and by studying the spectra of the monopole, dipole and quadrupole modes in the low beta SRF cavity. The HOM-induced power in the PEFP cavity has been calculated for different values of Q_{ext}. The simulation by GBBU code developed by Eduard Pozdeyev, shows that the PEFP beam should be stable, if the cavity Q_{ext} of the dipoles is lower than 1.0×10^{9}. **For the PEFP low beta cavities, the HOM coupler's Q_{ext} is lower than 3×10^{5} for reducing the influence of the dangerous modes on the beam instabilities and HOM-induced power.**

The possibly trapped modes and their maximum *R/Q* of the PEFP Low Beta Cavity.

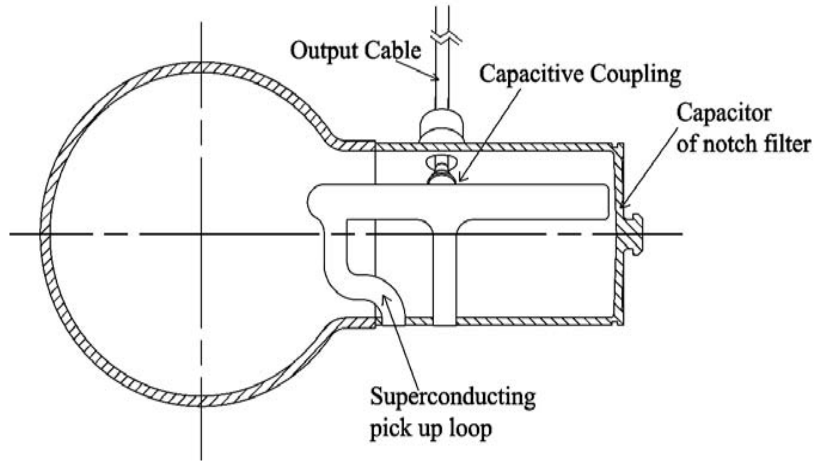
TM Monopoles			Dipoles			Quadrupoles		
Mode ID	f (MHz)	R/Q (Ω)	Mode ID	f (MHz)	R/Q (Ω)	Mode ID	f (MHz)	R/Q (Ω)
M23	2783.1	1.6×10^{-2}	D11	1745.6	1.1×10^{-1}	Q14	2469.8	1.2×10^{-3}
M31*	3144.2	2.5×10^{-2}	D32*	2811.8	4.8×10^{-2}	Q29*	3158.4	2.0×10^{-4}
M32*	3158.9	1.2×10^{-3}				Q30*	3170.7	3.2×10^{-5}
M33*	3166.6	7.4×10^{-2}				Q31*	3170.9	$<\times10^{-5}$

Sun An, Y. S. Cho, B. H. Choi and J. H. Jang, J. Korean Phys. Soc. 59, (2007).

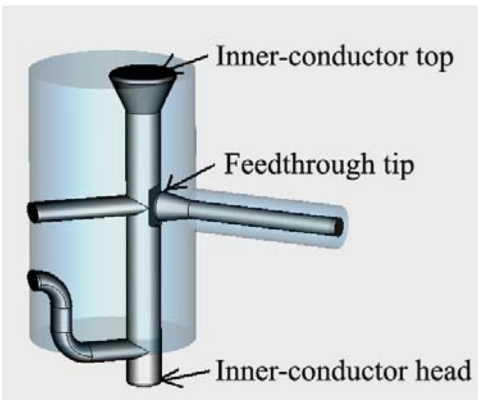
3. 1 PEFP HOM coupler

PEFP HOM coupler's specification

Parameter	Value
HOM damping modes	TM23, TM31, TM32, TM 33, D11, D32
HOM damping mode Q_{ext}	$\leq 3\times10^5$
HOM average RF power on the room load	≤ 1.0 W
TM010 π mode Q_{ext}	$\geq 6.26\times10^{10}$

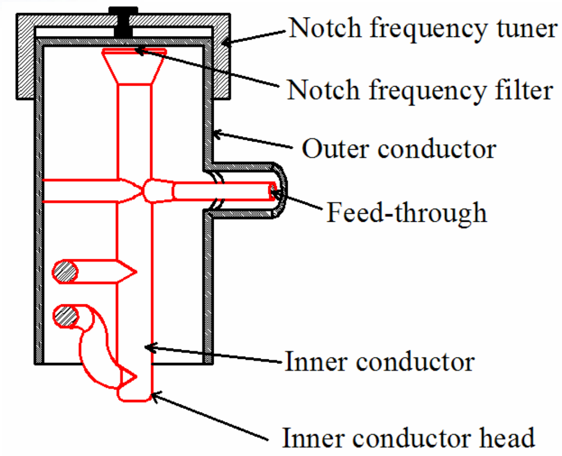


TTF HOM coupler

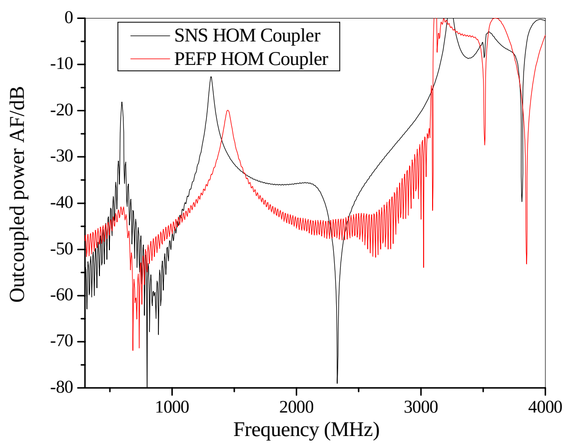


SNS HOM coupler

Although the TTF HOM coupler has been used on many cavities, **there are two faults: notch frequency shift and feed-through tip melting of the capacitive coupling,** which have been found during SNS cavity VTA, cryomodule testing at JLab and the SNS commissioning at ORNL. In order to satisfy PEFP HOM damping requirements, easily control the notch frequency shift and avoid the feed-through tip melting, a new HOM coupler is needed to design.



PEFP HOM coupler



Outcoupled power (AF/dB) of PEFP and SNS HOM couplers.

- The stick of the inner conductor is used to couple electric components of the HOMs, and the hook is for coupling magnetic components of the HOMs. The stubs are used to match capacitors of the notch filter and coupling feed-through, and to optimize the electromagnetic distribution in the coupler. The notch frequency filter is for tuning the notch position.
- The simulation shows the PEFP HOM coupler can achieve the HOM damping requirements with the lower electromagnetic fields at key points.
- In order to control notch frequency shift, the frequency sensitivity has been reduced, and a nut tuner is designed.

Surface field comparison between SNS HOM coupler and PEFP HOM coupler

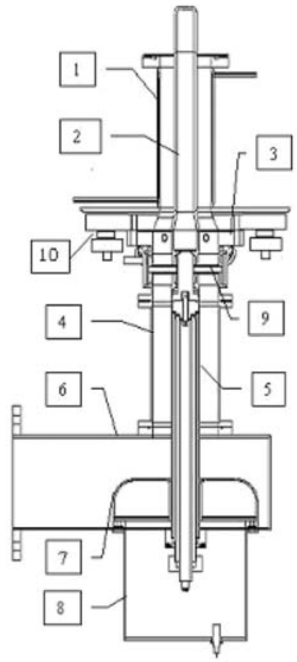
Position	SNS HOM coupler		PEFP HOM Coupler	
	E (V/m)	H (A/m)	E (V/m)	H (A/m)
Cavity surface	1.00×10^{7}	1.85×10^{4}	1.21×10^{7}	1.86×10^{4}
FPC head	8.65×10^{5}	697	7.85×10^{5}	577
Inner-conductor head	3.29×10^{6}	1863	5.64×10^{5}	272
Inner-conductor top	1.25×10^{6}	0	2.00×10^{5}	0
Feed-through tip	5.81×10^{4}	1128	N/A	N/A

3. 2 PEFP Fundamental Power Coupler (FPC)

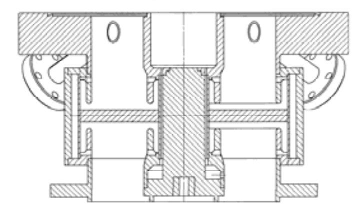
PEFP FPC's specification

Max beam power (kW)	72
Cavity *R/Q* (Ω/m)	227.3
Accelerating voltage ΔV per cavity (MV)	2.8~3.6
FPC Q_{ext}	8.0×10^{5}
Commissioning forward power (kW)	≥216
Pulse length (mS)	1.3 ms
Repetition rate (Hz)	60 Hz
Average transfer power (kW)	5.6

Since PEFP beam property is almost the same as SNS beam, the operation frequency of the PEFP is very near the SNS operation frequency, the current plan is to copy and scale SNS FPC for the PEFP cavities. And the same FPC conditioning procedure will be used for PEFP FPC.



1 – Outer Conductor
2 – Inner Conductor
3 – Window Assembly
4 – Outer Extension
5 – Inner Extension
6 – Waveguide
7 – Doorknob
8 – Waveguide Cover
9 – Ceramic Window
10 – Vacuum Gauge



SNS 805 MHz Fundamental Power Coupler and its window.

3. 3 PEFP Tuner

PEFP tuner specification

Parameter	Value
Cavity frequency sensitivity	187.8 kHz/mm
Cavity bandwidth	875 Hz
Tuner load	21000 N
Range	470 kHz or 2.5 mm
Resolution	44 Hz
Step motor	1
Piezo	N/A

Because PEFP Lorentz force detuning stiffening structure can powerfully control Lorentz force effects, PEFP tuner does not need Piezo.

- The tuner design plan is to scale and copy SNS tuner for PEFP cryomodule.
- The scaled SNS tuner can meet the PEFP tuner requirements.

PEFP Tuner

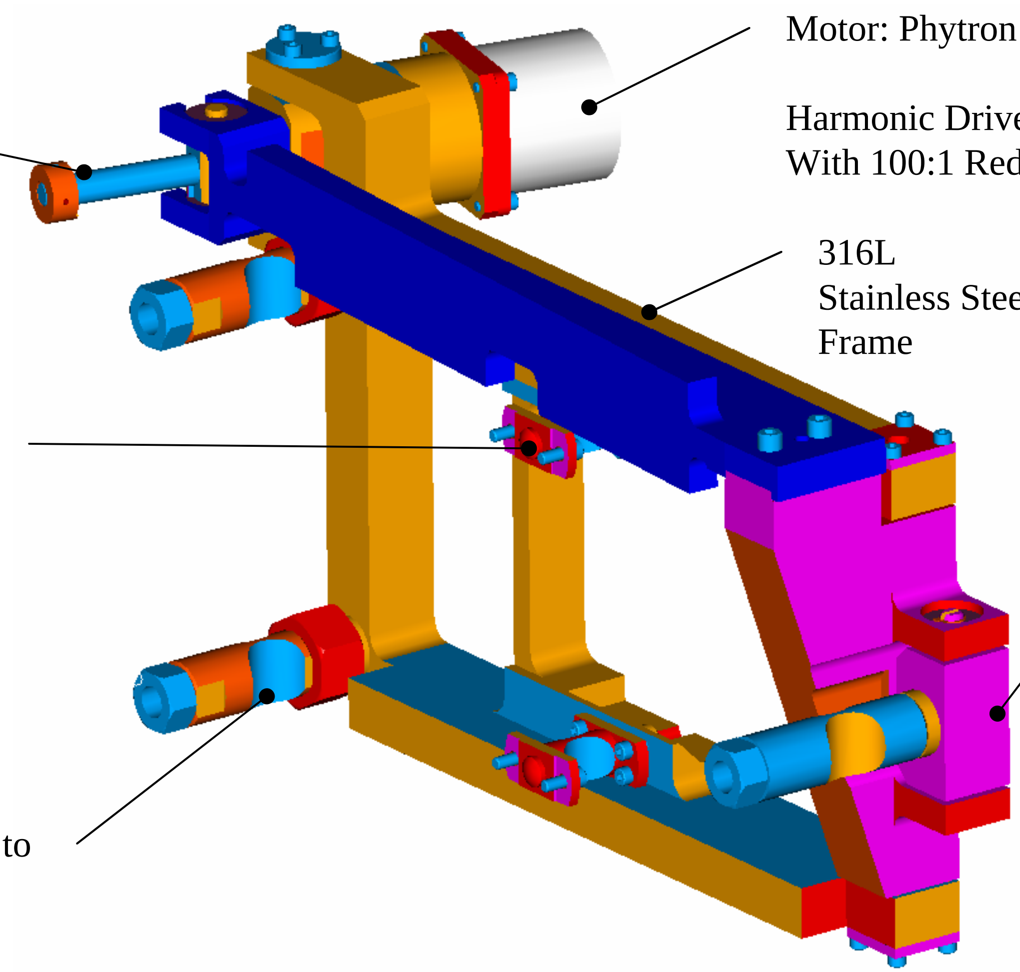
Motor: Phytron VSS-52, 52 in*oz.

Harmonic Drive: HDC-14-100-2ASP
With 100:1 Reduction

Dicronited
Beryllium
Copper
Drive Screw,
M12 x 1.5

316L
Stainless Steel
Frame

Flexure Connection
to Cavity (2X)



"Dummy" link
replaces Piezo
Actuator if
assembly withou
Piezo is desired

Flexure Connection to
Helium Vessel (2X)

4. 1 Introduction and specification

The cooling system of the PEFP cryomodule includes cryogenic circulation, heat insulation, water cooling circuit of the fundamental power coupler, and detectors of temperature, pressure and helium liquid level.

Parameters of the PEFP cryomodule cooling system.

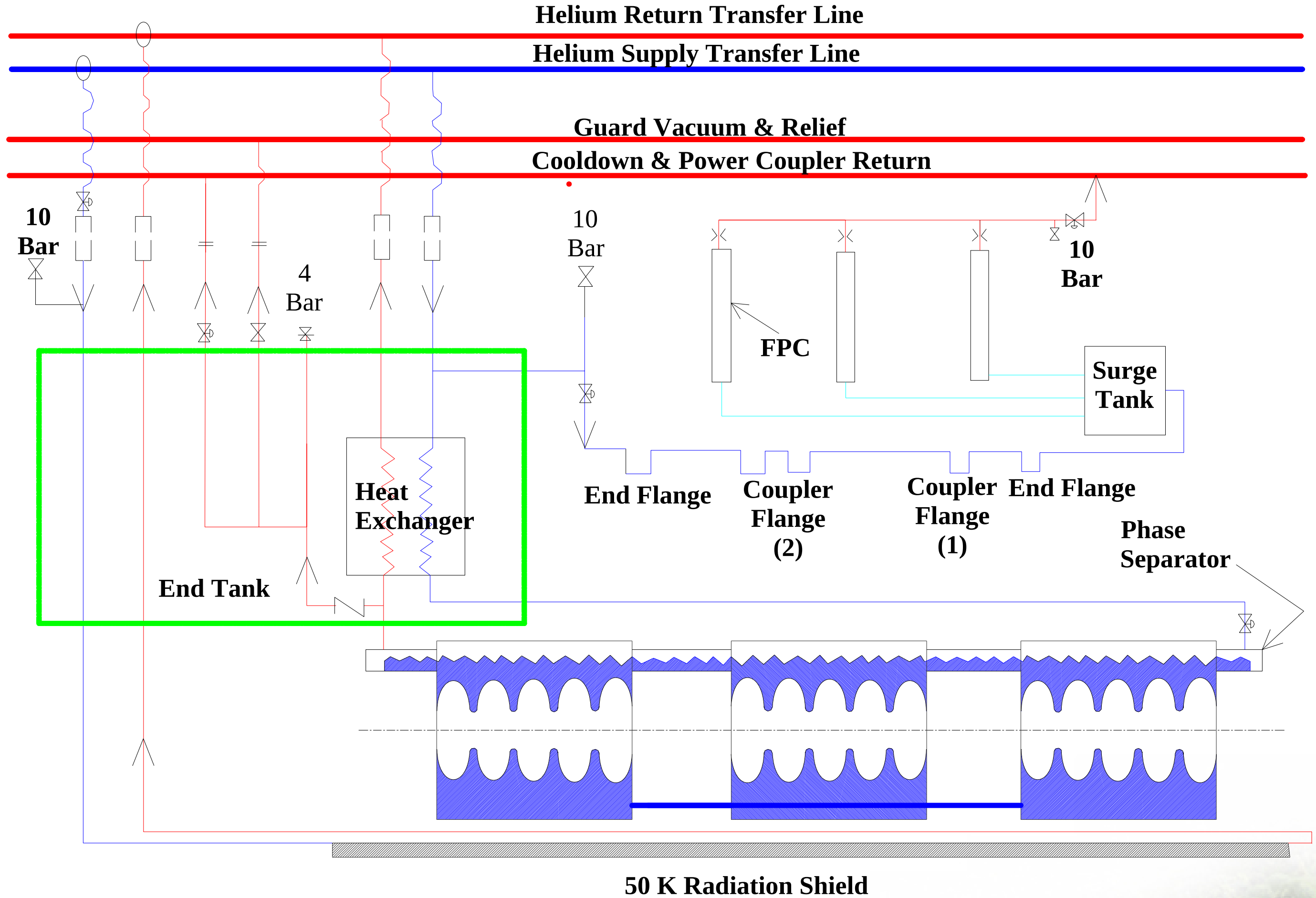
Parameter name	**Value**
Cavities per cryomodule	3
Helium vessels per cryomodule	3
Primary circuit static heat load	24.8 W
Primary circuit dynamic heat load*	16.2 ~ 101.2 W
Pressure in Helium vessel*	0.032 ~ 1.0 Bar
Temperature in Helium vessel*	2.0 ~ 4.2 K
Pressure of the primary circuit helium liquid supply	3 Bar
Temperature of the primary circuit helium liquid supply	5 K supply
50 K shield heat load	163 W
Pressure of the 50 K shield supply	4.0 Bar
Temperature of the 50 K shield supply	35 K
Pressure of the 50 K shield return	3.0 Bar
Temperature of the 50 K shield return	55 K

4. 2 Cryogenic circulation

Primary
Circuit:
3 atm, 5 K

Secondary
Circuit:
0.075 g/s
per coupler

Third Shield
Circuit:
4 atm, 35 K
inlet

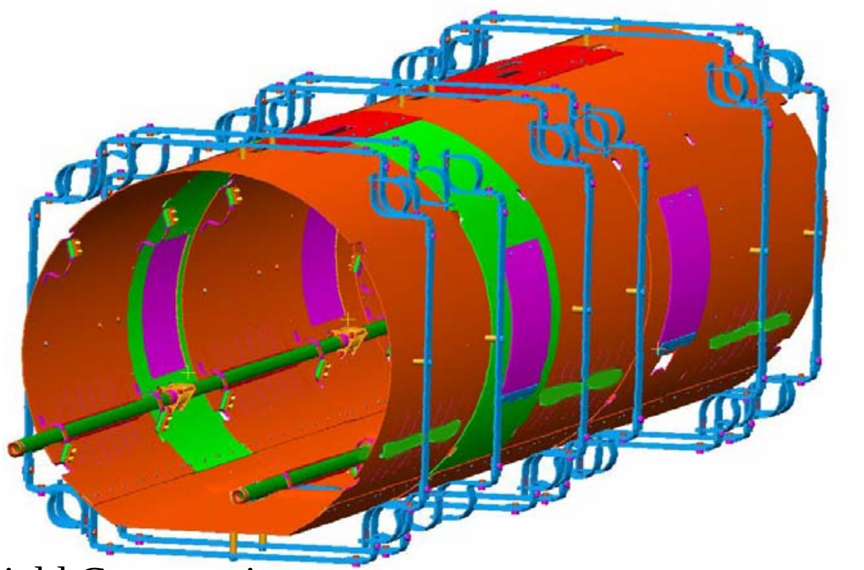


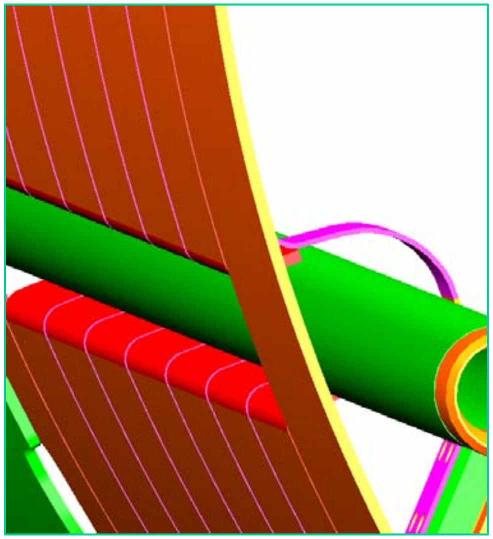
Cryogenic circulation schematic of the PEFP Low beat cryomodule. The blue color means the supply coolant or cold helium liquid; and red color means the return coolant

4. 3 Thermal Insulation

The thermal insulation structures in the PEFP cryomodule are comprised of four parts: 1. thermal radiation shield; 2. multilayer insulation; 3. space frame; and 4. vacuum space.

Thermal Radiation Shields





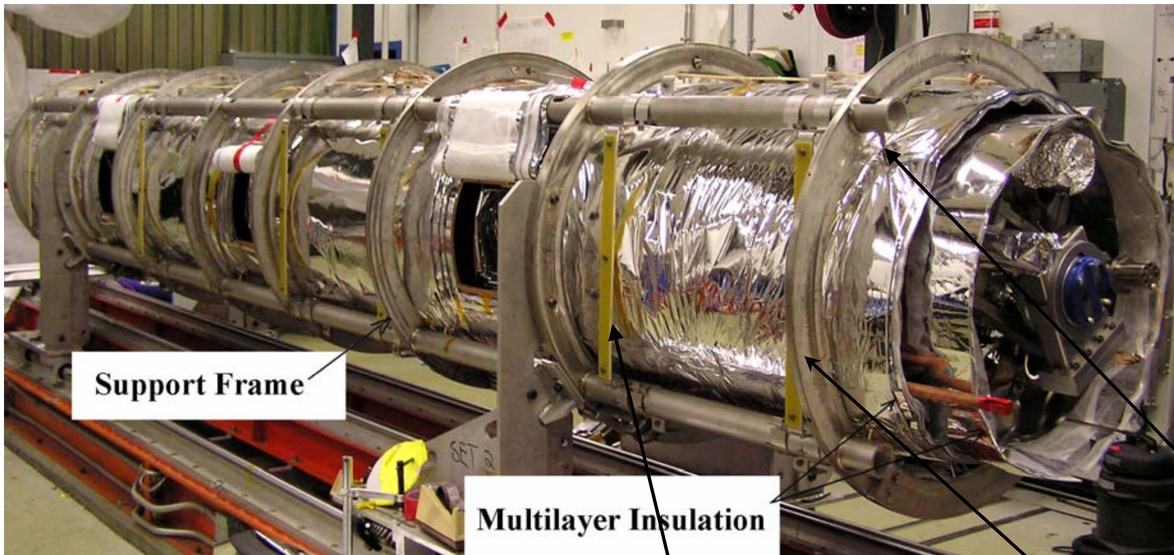
Shield Construction:

Mat'l: Cu, 711.2 mm (28") O.D. x 2.4 mm (0.093") thick

Double Pass, ¾ IPS Sched. 10 Cu pipe

Segmented at each Helium Vessel, Bridges between for access to tuner and alignment

Multilayer insulation and Support frame



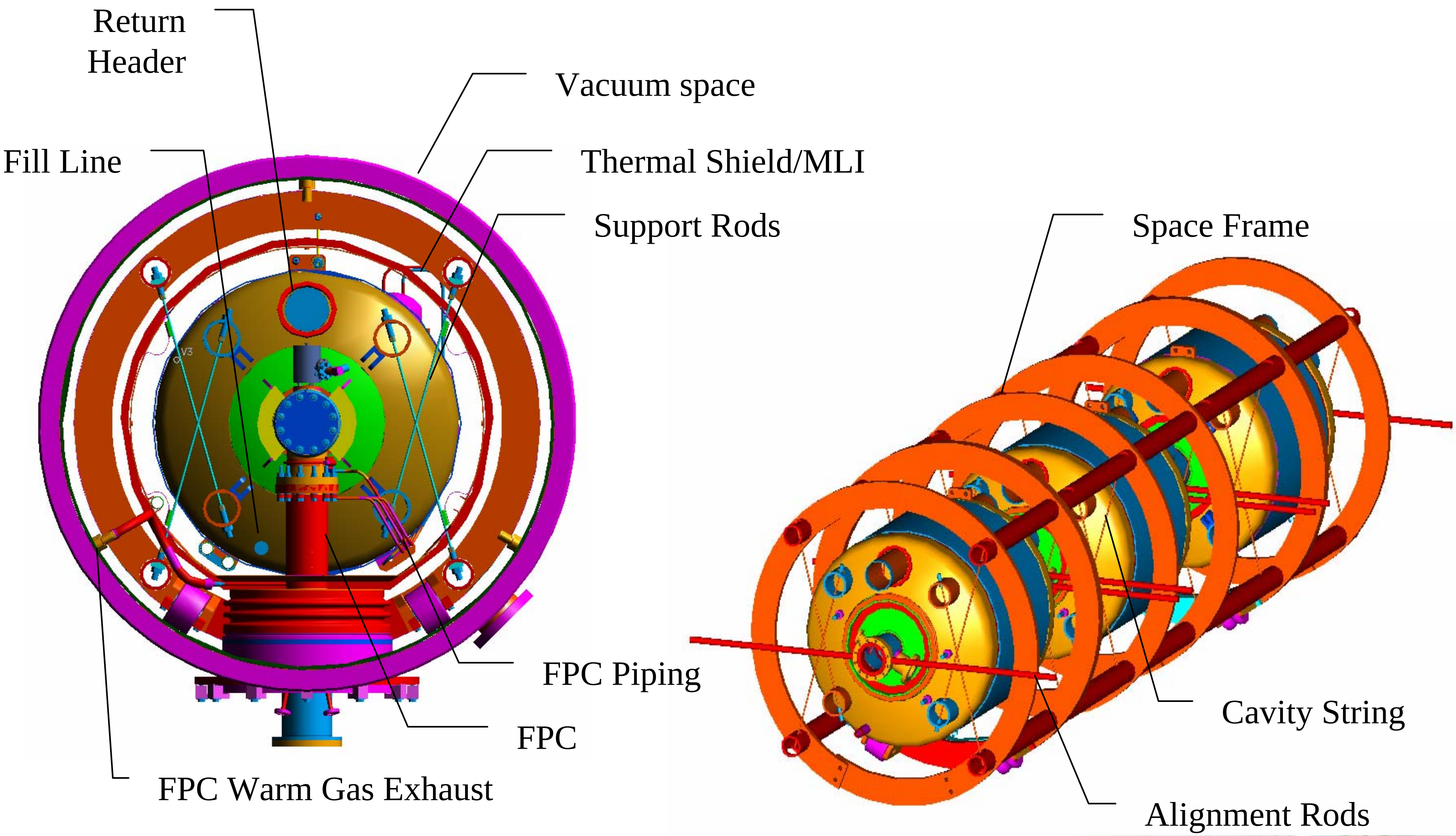
The multilayer insulation is comprised of insulation blankets. Each blanket is constructed of 12 to 14 insulation layers. Each layer consists of one sheet of 0.00254 mm thick double-aluminized Mylar™ and one sheet of Reemay™ #2250 (a spun-bonded polyester 0.00762 mm thick).

Nitronic 50 Austenitic stainless steel (Support cavity)

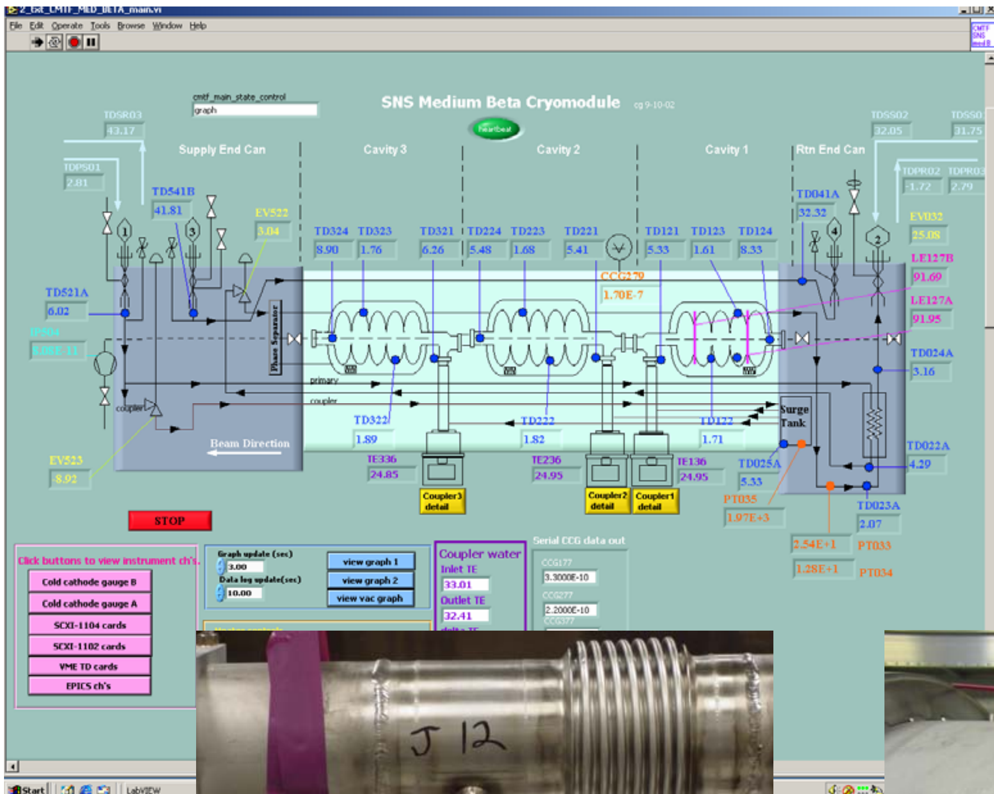
304 stainless steel

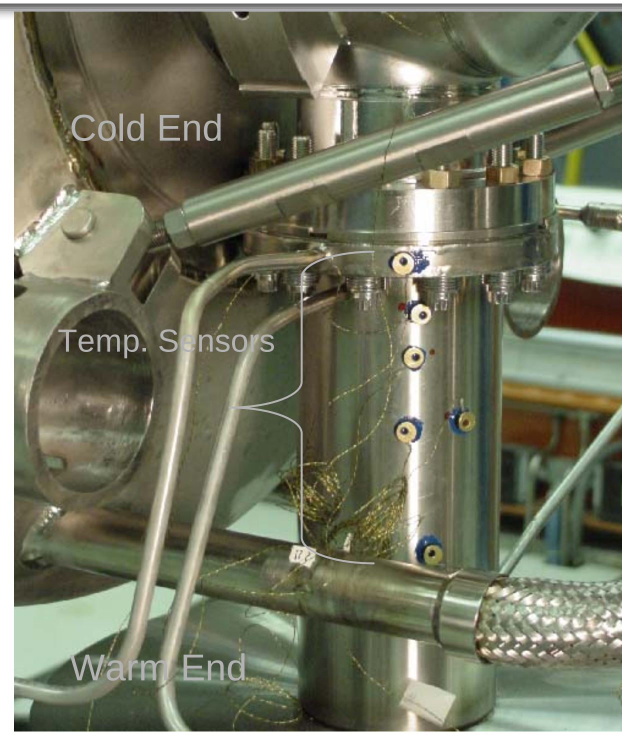
304 Stainless steel and G11CR
(Support 50 K shield)

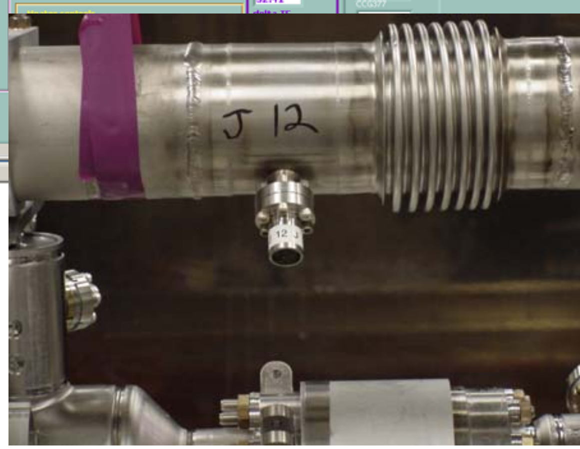
End View of CM Along with Isometric of Space Frame Tooling



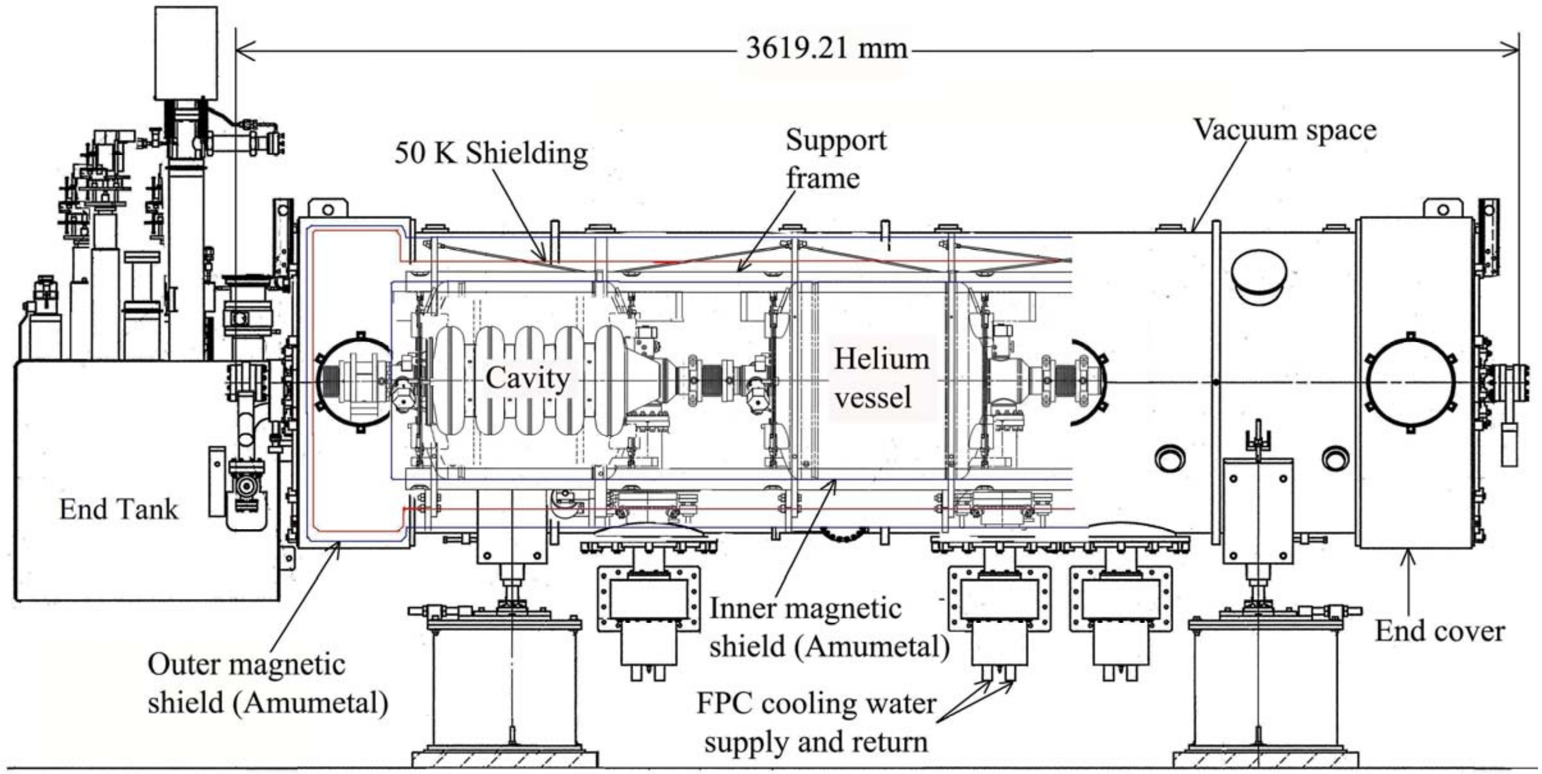
4. 4 Sensor distribution







5. Magnetic shielding structure



Because we did not find the serious cavity intrinsic quality factor Q_0 degradation due to trapped magnetic flux in the SNS cryomodules' testing and commissioning, we are going to copy and scale the SNS magnetic shielding for PEFP cryomodules . If the Q_0 degradation due to trapped magnetic flux is found during prototype testing, we will choose the three-layer structure.

6. Vacuum System

Vacuum requirements for PEFP cryomodule.

	Parameter	Value	Tolerance	Units	Introduction
1	Pressure in warm beam pipe	1E-09	Max.	Torr	Prior to opening gate valves. Value selected to limit gases cryopumped onto cavity surfaces.
2	Pressure in SRF cavity	1.0E-05	Max.	Torr	Prior to cool-down. Selected to control gases cryopumped onto cavity surfaces.
3	Outgassing rate of warm beam pipe	1.0E-07	Max.	Torr*l/s	Selected to limit cryopumping by cavities of gases generated by warm beam pipe; in addition to pressure limit.
4	Pressure in vacuum space	1.0E-04	Max.	Torr	Prior to cool-down.
5	Coupler vacuum	5.E-9	Max.	Torr	Pressure selected to be below threshold for sputtering metal onto ceramic window.
6	Coupler vacuum limits		Note		RF and beam to be inhibited if coupler vacuum remains above 10^{-8} Torr for 10 seconds, 10^{-7} Torr for 1 second, or 10^{-6} Torr instantaneously. Values selected to minimize sputtering of metal onto ceramic window during discharges.
7	Cryomodule outgassing rate at room temperature	1.00E-8	Max.	Torr*l/s	Lowest readily achievable value. Chosen to limit transfer of gas from warm region to cold region, which in turn affects field emission enhancement and RF-induced discharges.
8	Maximum cavity leak tolerances	1E-09	Max.	Torr*l/s	Lowest readily measured value.
9	Maximum vacuum space leak tolerances	1E-09	Max.	Torr*l/s	Value selected to avoid the need for a continuous pump.
10	Maximum helium circuit leak tolerances	1E-09	Max.	Torr*l/s	Lowest readily measured value.
11	Burst valves on beam line	20 - 30	Range	PSIG	Sized to handle worst case scenario with superfluid helium in cavities, followed by evaporation of that helium.
12	Parallel plate relief valves on vacuum vessel	2	Nom.	PSIG	Sized at 2" diameter to handle worst case venting from vacuum space, including helium space venting into vacuum space.

To achieve these requirements, an ion pump is installed on the warm beam pipe on the end tank side, and two Voltage vacuum valves and two manual vacuum valves are put on both beam pipe ends. A relief valve connected to warm beam pipe and two relief valves installed on vacuum vessel protect the cryomodule. A series of vacuum detectors are installed in or on cryomodule to detect the vacuum.

Summary

Achieved

✓Preliminary design.
✓SRF cavity design.
✓Stiffening structure design.
✓HOM analysis and damping requirements.
✓A HOM coupler design.
✓Design of the Cavity dies and fixtures, and their drawings.
✓Warm tuner design and its drawings
✓Dumbbell frequency and length control set design and their drawings.
✓Biding of the cavity dies and fixtures, copper prototype cavity and dumbbell frequency and length control sets.

We are doing:

⏱Copper prototype cavity production and testing.
⏱Cavity warm tuner fabrication.
⏱HOM Coupler fabrication and testing.
⏱ FPC design.

Need to do in future:

➢FPC RF processing.
➢End Tank and End Cover design.
➢Engineering of the Helium Vessel, the Support Frame, 50 K shielding, Magnetic Shielding, and Vacuum Vessel.
➢Engineering of the whole cryomodule.
➢Testing of the parts after the production.
➢Cavity surface processing
➢Cryomodule assembly
➢LLRF and High power system design and construction for the Cryomodule testing.
➢Engineering and fabrication of the Cryomodule tools.

Thank you!