Superconducting RF accelerator for Low Energy RHIC electron Cooling

Sergey Belomestnykh
Collider-Accelerator Department, BNL
August 13, 2013

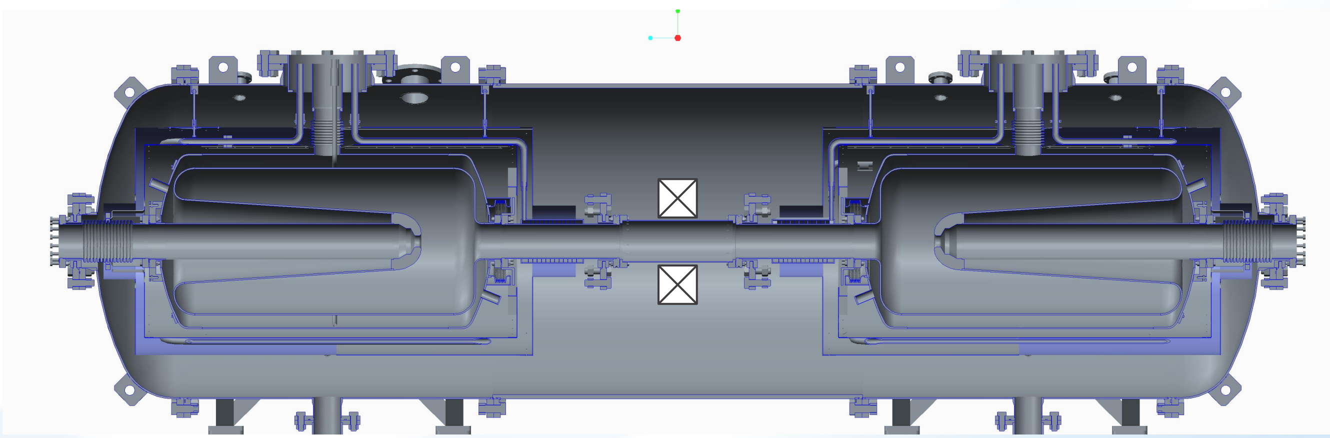
Accelerator Physics Review of LEReC
BNL • August 13-14, 2013

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Introduction

- The electron accelerator (a short linac) will consist of a two-cavity superconducting RF (SRF) cryomodule producing beam with energy up to 5 MeV and a 5th harmonic normal conducting cavity for energy spread correction.
- The cryomodule will house:
  - A photoemission SRF gun of a quarter wave resonator (QWR) type, operating at 100 MHz;
  - A 100 MHz QWR SRF booster cavity;
  - There will be a superconducting solenoid (with magnetic field up to 1 kG) between two SRF cavities.
- 500 MHz normal conducting cavity will correct energy spread due to RF curvature of the SRF cavities.



Parameters of electron beam

Lorentz factor	4.1	10.7	10.7
RHIC RF frequency, MHz	4.55	4.67	28.03
Electron kinetic energy, MeV	1.58	4.96	4.96
Total charge of the bunch train, nC	4 (9 bunches)	7 (5 bunches)	4 (2 bunches)
$\Delta p/p$, rms	5e-4	5e-4	5e-4
Normalized rms mittance, mm-mrad	2.5	2.5	2.5
Transverse rms size, mm	4.3	2.6	2.6
Full bunch length, ns	0.5-1	0.5-1	0.5-1
Electron beam current, mA	18.2	32.7	35.8
Beam power, kW	28.8	162	178

SRF gun overview

- Electron beam will be generated by illuminating a CsK_2Sb photocathode with green (532 nm) light from a laser.
- The photocathode is inserted into a 100 MHz quarter-wave SRF cavity thus forming an SRF photoemission electron gun. The photocathode is located in a high electric field. Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space-charge force. The low RF frequency of the gun reduces effect of RF curvature on the beam.
- The gun will produce bunch trains with relatively long electron bunches, about 750 ps, at 100 MHz bunch repetition frequency. The bunch train repetition rate will be the same as repetition rate of ion bunches in RHIC. The optical system will allow creating dedicated bunch patterns for different RHIC energies and ion bunch lengths.

Choice of the photocathode

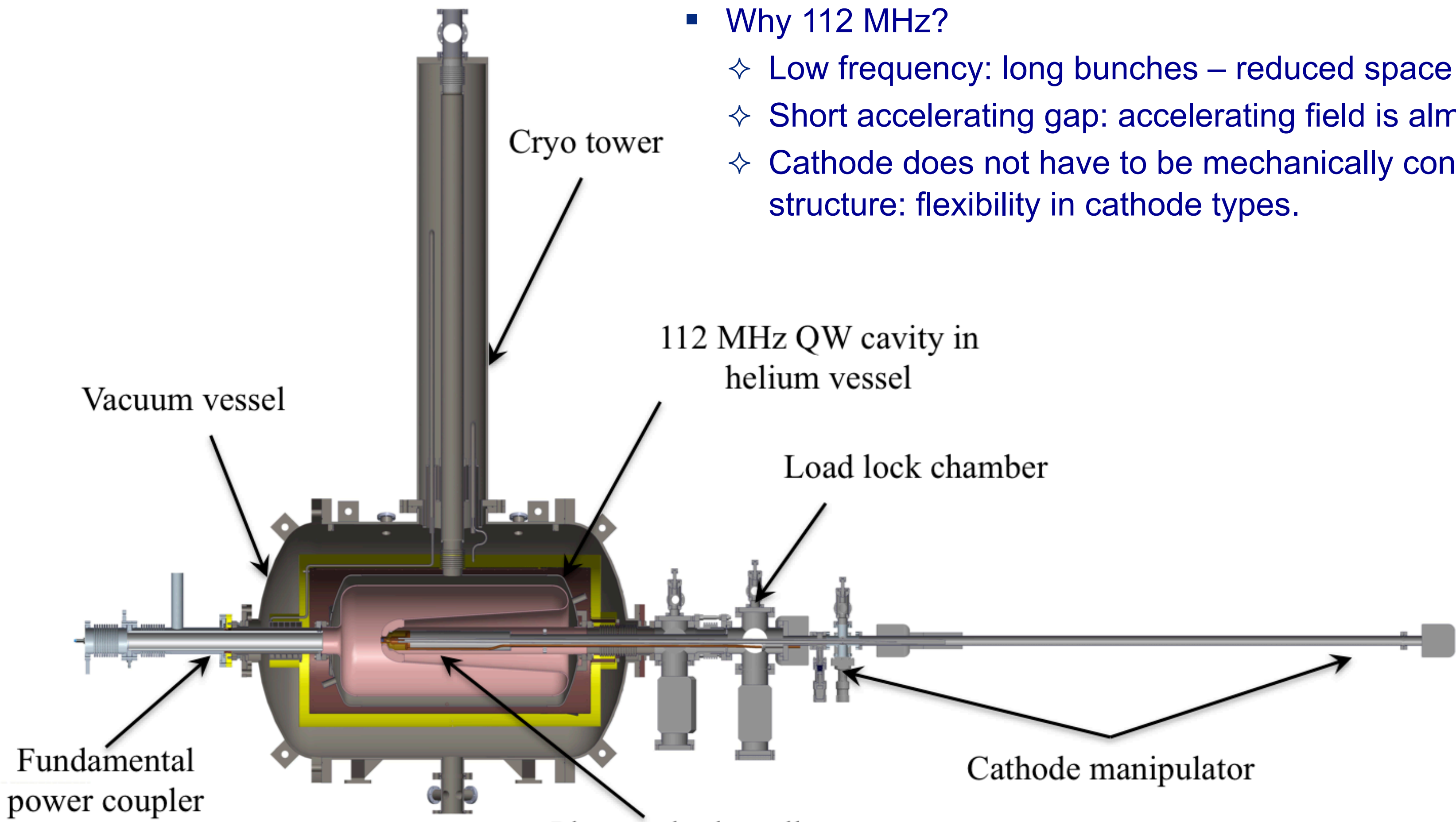
- While the required beam current has yet to be demonstrated from an SRF gun, even higher beam currents were already achieved from photocathodes in a normal conducting RF gun (Boeing RF gun) and a DC gun (Cornell ERL injector).
- Three types of high QE photocathodes are used nowadays in SRF guns: GaAs(Cs), Cs_2Te, and CsK_2Sb.
- On the one hand, cesium potassium antimonide cathodes are more robust than gallium arsenide ones as they have very long lifetime and can be transported without much degradation of their performance.
- On the other hand, they have higher QE than cesium telluride cathodes and can be used with green lasers.
- CsK_2Sb is the most preferred option at present.

SRF gun design considerations

- The SRF gun design will be similar to the 112 MHz SRF gun developed for the CeC PoP experiment at BNL with the following major differences:
    1) The gun cavity shape will be optimized to improve surface fields and reduce wall losses;
    2) The gun will be equipped with two high-power fundamental RF power couplers;
    3) There will be a frequency tuner of an improved design.
- The cathode insertion mechanism and the photocathode stalk will be scaled copies of the 112 MHz gun designs.

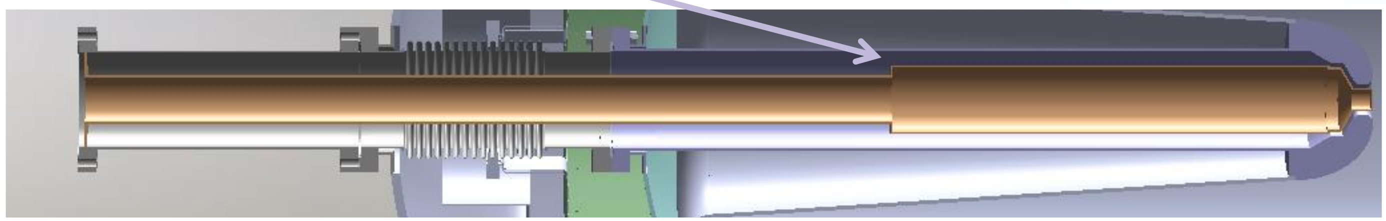
112 MHz SRF gun for CeC PoP experiment

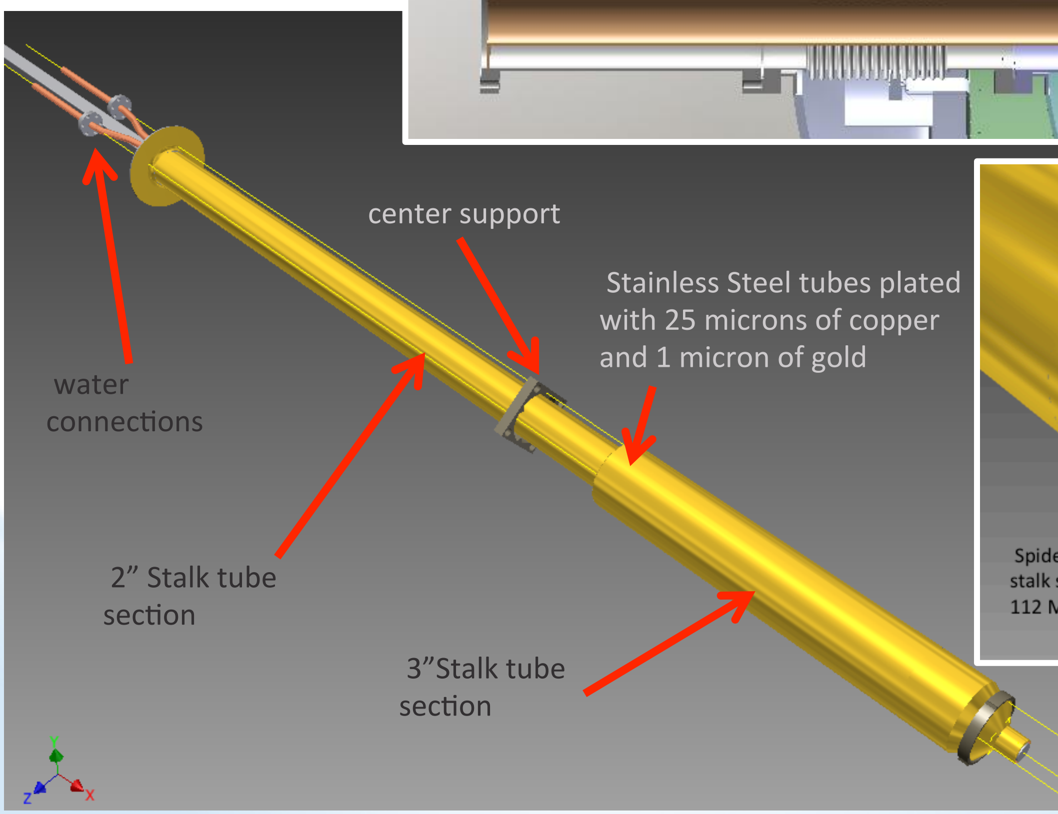
- Superconducting 112 MHz QWR was developed by collaborative efforts of BNL and Niowave and will be used to generate electron bunches for CeC PoP (high charge, low rep. rate).
- Why 112 MHz?
  - ✧ Low frequency: long bunches – reduced space charge effect.
  - ✧ Short accelerating gap: accelerating field is almost constant.
  - ✧ Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.

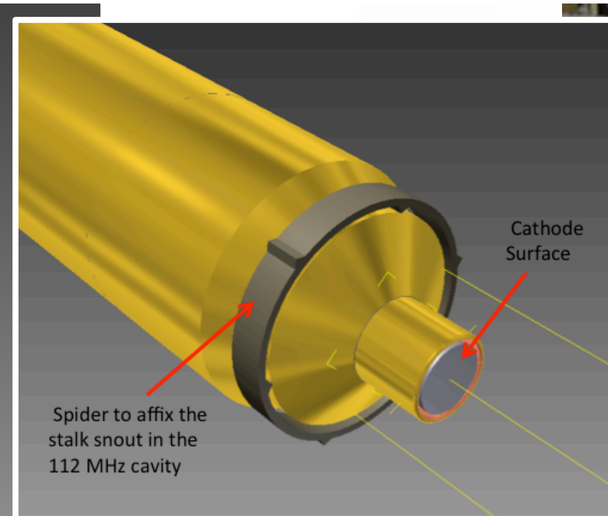


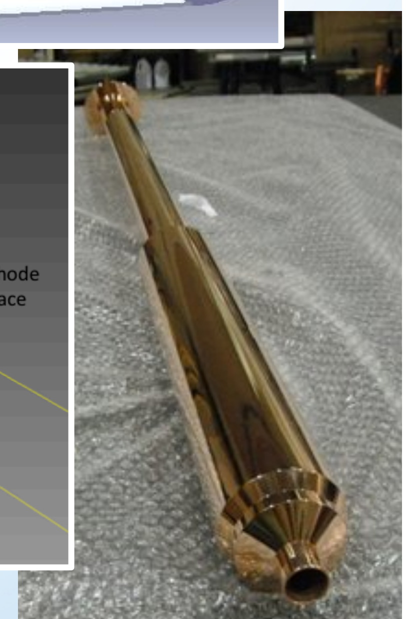
Cathode stalk design

- The cathode stalk is a hollow center conductor of the coaxial line formed by the stalk and the cavity.
- The stalk is shorted at one end and is approximately half wavelength long. It will be permanently installed in the gun.
- A step at λ/4 from the short creates a quarter-wave impedance transformer and reduces RF losses in the stalk from ~65 W to ~25 W.
- The gold plating is aimed to reduce radiation heat load from the RT stalk to the cold (4.5 K) niobium.
- A small cathode puck is inserted inside the stalk and can be replaced when necessary with a new one.



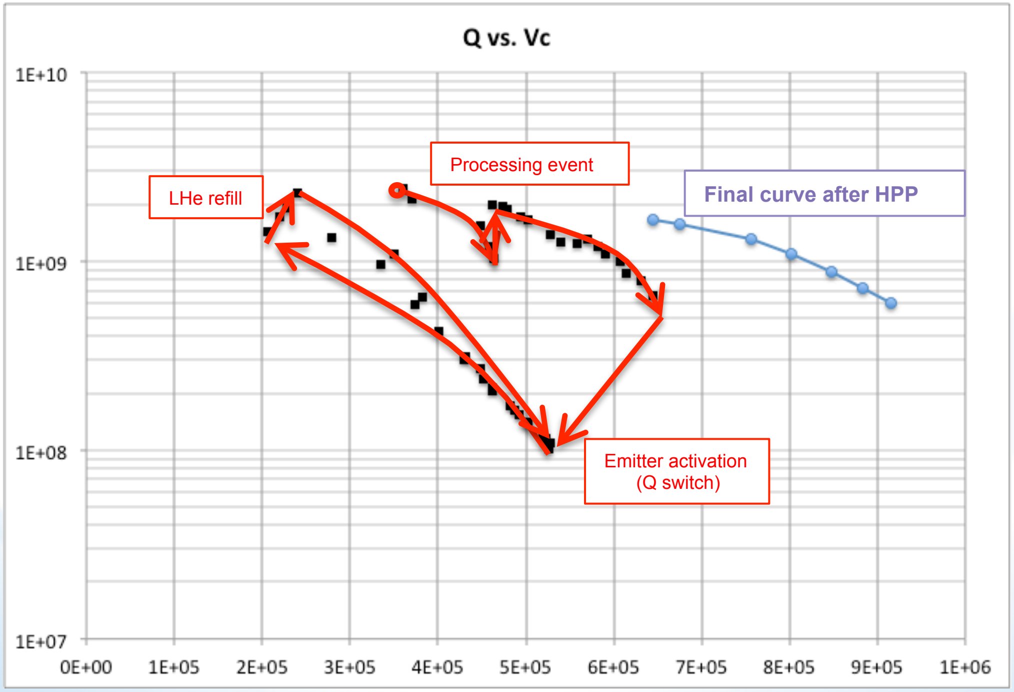


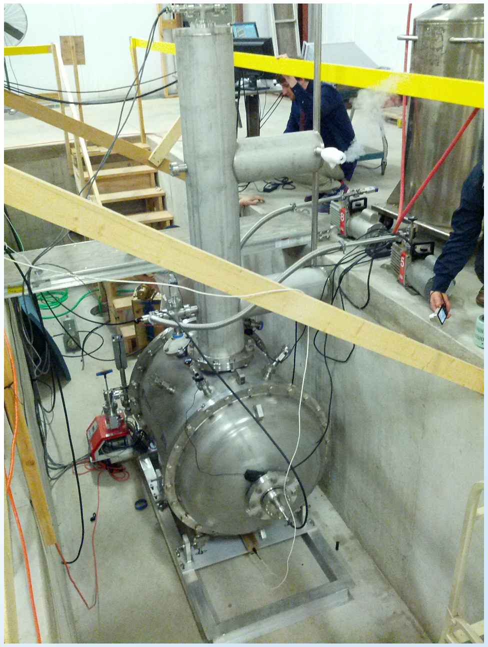




112 MHz SRF gun status

- The gun has been fabricated (as part of SBIR) and cold tested successfully at Niowave.
- To be used for the CeC PoP experiment, it had to be modified to be compatible with installation in RHIC.
- A second cold test of the gun (in a new cryostat) was successfully completed at Niowave last February.
- The gun reached 0.92 MV, limited by insufficient radiation shielding at Niowave.
- With no radiation shielding issue in the RHIC tunnel we should be able to reach higher gun voltage.
- The gun is currently in the RHIC tunnel, being prepared for installation into its final location. It will be tested toward the end of 2013.





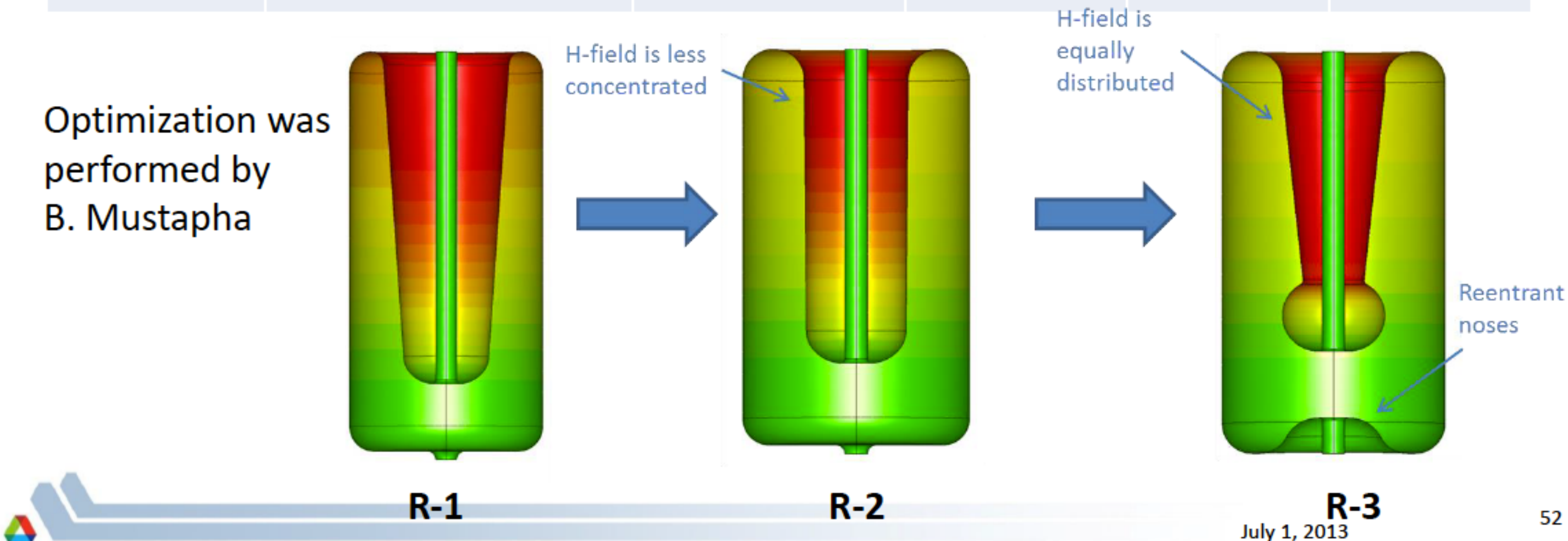
SRF cavity optimization

- The goal is to optimize the gun and booster cavities to limit E_{pk} < 40 MV/m and B_{pk} < 80 mT at 2.6 MV per cavity.
- Cavity radius < 25 cm, to fit in the BNL's vacuum oven and VTF cryostat.
- Beam pipe radius = 2.5 cm, reduced from 5 cm in the 112 MHz gun.
- Preliminary optimization of the cavity shape, performed in collaboration with ANL, shows that achieving the design goals is possible.
- ANL has proven record of designing and building high performing SRF cavities of complex shapes that typically exceed the LEReC requirements for maximum surface fields. Also, they have experience in incorporating superconducting solenoids in SRF cryomodules. We plan to design, fabricate, process and test SRF cavities and superconducting solenoid in close collaboration with ANL.
- The cryomodule will be designed at C-AD, components will be procured from industry or fabricated at BNL and the cryomodule integration will be at BNL.

SRF cavity optimization (2)

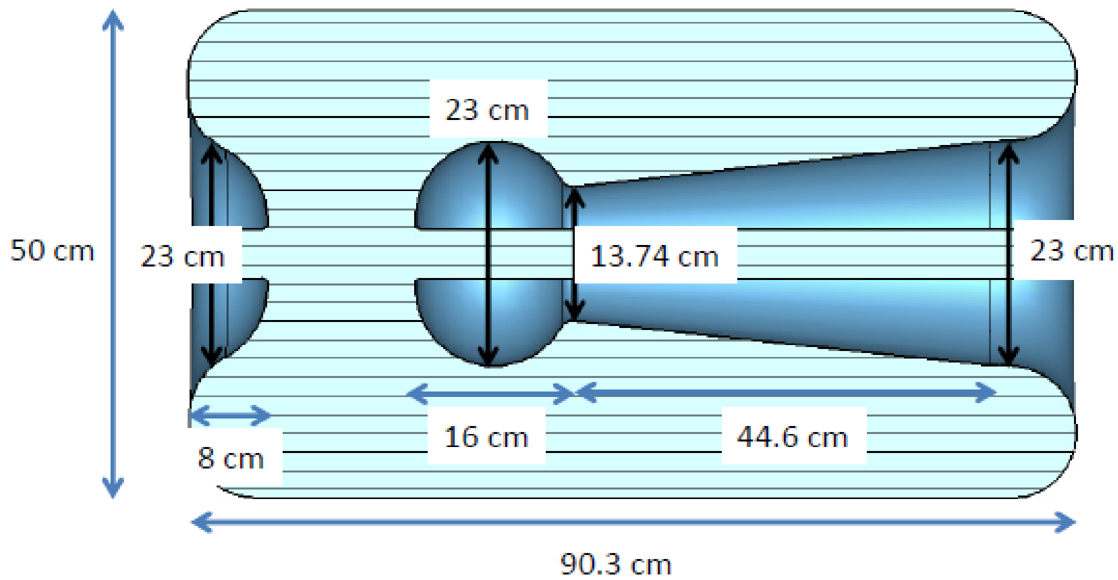
Design	Description	V (MV) @ Epk=40MV/m	V (MV) @ Bpk=80mT	R/Q (Ω)	G factor (Ω)
R-1	Original, 46 cm OD	2.35	2.30	109.57	34.69
R-1	Scaled, 50 cm OD	2.57	2.53	108.64	36.33
R-2	With ANL toroid	2.55	2.30	130.90	44.85
R-3	Toroid bottom	2.60	2.72	162.22	47.63
R-4	Dished bottom	2.58	2.69	155.15	46.97
R-5	Flat bottom	2.54	2.69	159.03	47.58

Optimization was performed by B. Mustapha



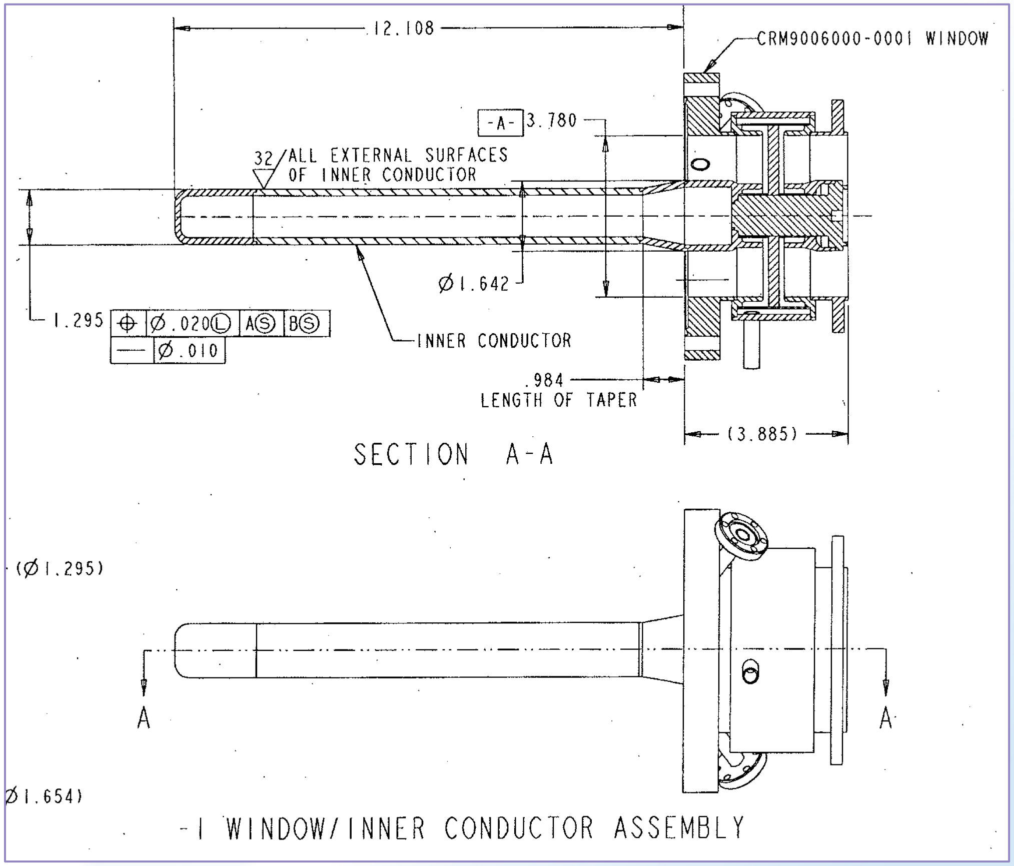
SRF booster cavity

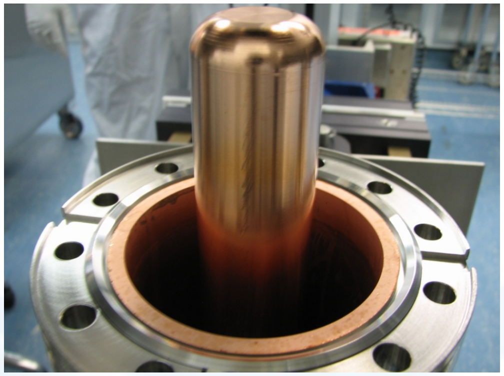
- The booster cavity will be of a similar design as the gun, but with a simplified center conductor as there will be no need to accommodate the photocathode stalk.
- At lower energies the booster cavity might be turned off and detuned to become “transparent” to the beam.



RF power for SRF cavities

- The RF power, up to 93 kW per cavity, will be delivered via two symmetrically located fundamental power couplers.
- The couplers will be of coaxial antenna type.
- Computer simulations show that the SNS-type coaxial RF window has very good RF properties at 100 MHz. At SNS, these windows operate at average RF power exceeding 100 kW.
- At BNL, we use similar windows in FPCs of the ERL SRF gun and five-cell cavity.
- Our preliminary contacts with vendors indicate that cost of a solid state RF power amplifier is practically identical to that of a vacuum tube based amplifier. In this case we prefer using a solid state amplifier.



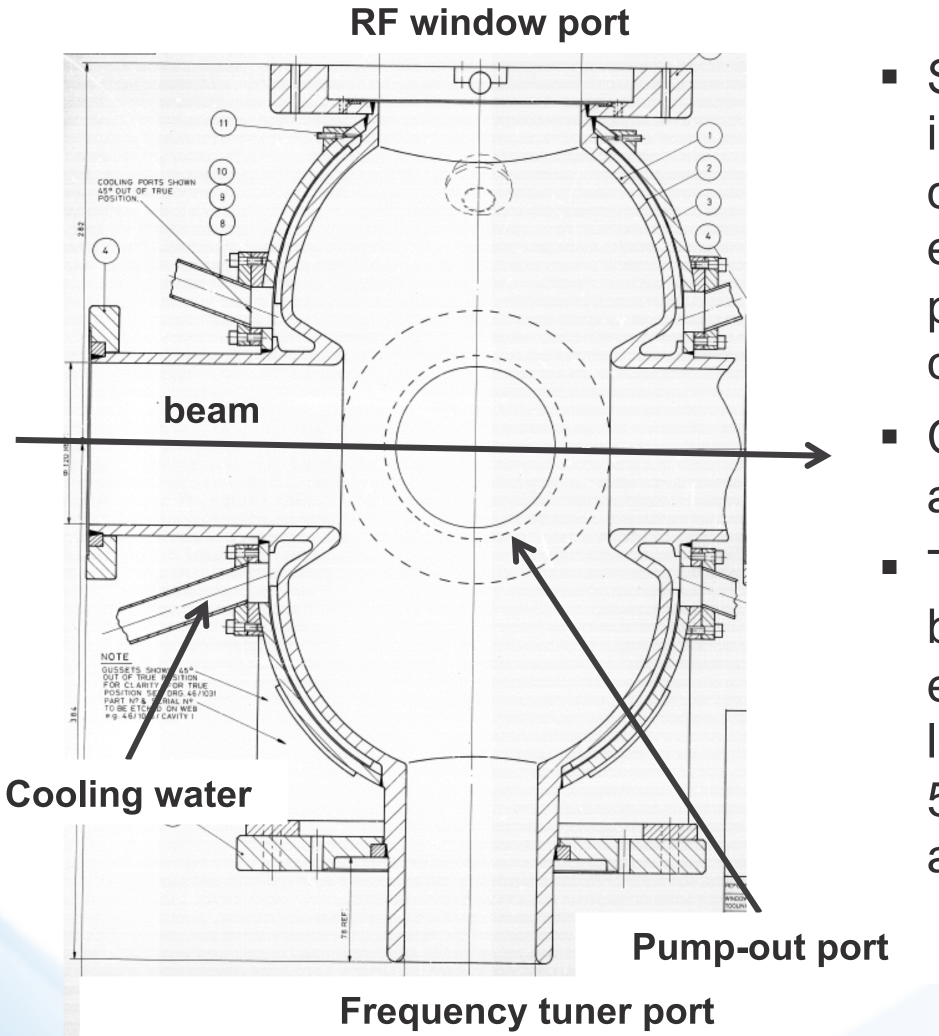


SRF gun and booster parameters

Lorentz factor	4.1	10.7	10.7
RHIC RF frequency, MHz	4.55	4.67	28.03
SRF frequency, MHz	100.00	99.97	99.97
Gun voltage, MV	1.65	2.58	2.58
E_{pk}, MV/m	25.4	39.7	39.7
B_{pk}, mT	48.5	75.8	75.8
R/Q, Ohm	162.2	162.2	162.2
Q_0	3.4e9	3.4e9	3.4e9
Gun RF power, kW	31	85	93
Frequency tuning range, kHz	78	78	78
Booster voltage, MV	0	2.58	2.58
Booster RF power, kW	0	85	93

- Operating temperature will be 4.5 K.
- The cryogenic system will be shared with the CeC PoP 112 MHz SRF gun. It will be installed during this summer's RHIC shutdown and commissioned during Run14.

500 MHz RF system



- Sinusoidal shape of the SRF voltage introduces a quadratic beam energy spread due to on-crest acceleration. To bring the energy spread within required 5×10^{-4}, we plan to use a 5th harmonic normal conducting copper cavity.
- Correction of the energy spread will require an acceleration voltage up to 200 kV.
- This system will share a 50-kW CW IOT-based RF amplifier with the CeC PoP experiment, where two bunching cavities (on loan from Daresbury) will operate at 500 MHz. The amplifier is in house and already installed.

500 MHz RF system parameters

Lorentz factor	4.1	10.7	10.7
RHIC RF frequency, MHz	4.55	4.67	28.03
RF frequency, MHz	500.13	499.82	499.82
Cavity voltage, MV	0.063	0.198	0.198
Shunt impedance, MOhm	5.53	5.53	5.53
External *Q* factor (cavity is matched w/o beam)	31,000	31,000	31,000
Cavity wall dissipation, kW	0.73	7.1	7.1
RF power with beam, kW	0.31	2.1	1.8

CeC PoP 50 kW RF power amplifier

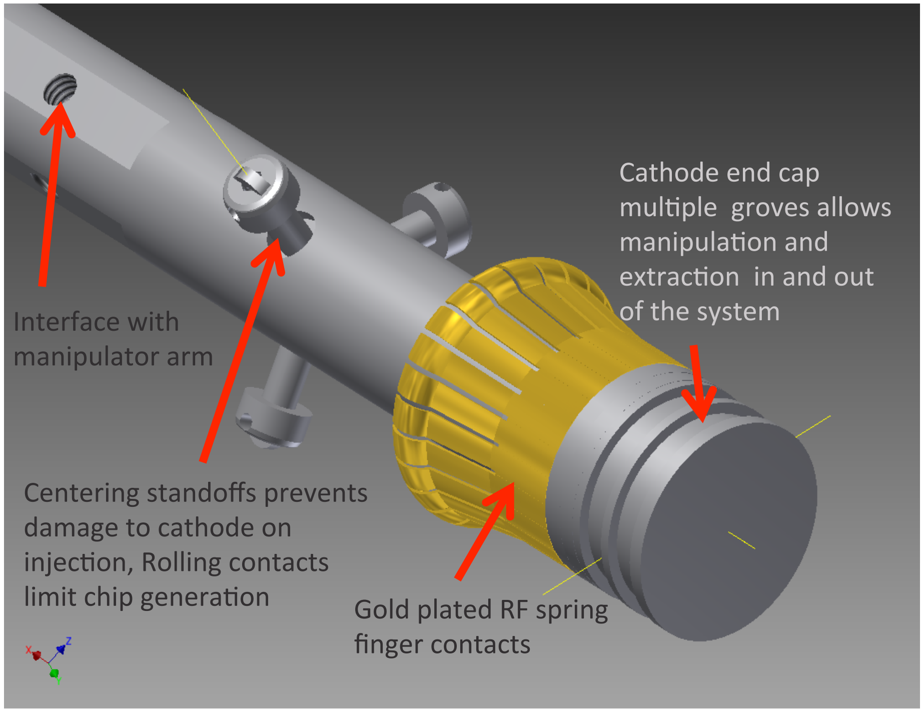
500 MHz bunching cavities

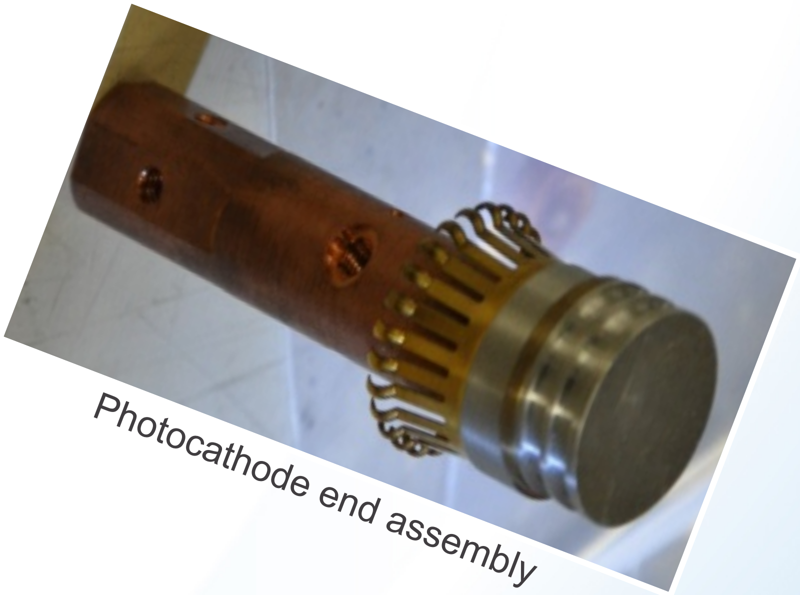
Summary

- The SRF cavities will be designed, fabricated, processed and tested in close collaboration with ANL, where the SRF team has vast experience with SRF cavities of similar shapes.
- The cryomodule will be designed and assembled at BNL. Parts and sub-assemblies will be procured from industry or fabricated in the BNL's central machine shop.
- Specifications for the 500 MHz copper cavity are not challenging at all and we do not see any difficulties in procuring it.
- We will heavily leverage our experience with other SRF projects, most notably CeC PoP and ERL, each having an SRF gun. As the cathode insert in LEReC gun will be similar to that of CeC PoP gun, we will use the same cathode. puck design and the same deposition chamber.
- The LEReC accelerator will be installed in the same IP2 as the CeC PoP experiment, but the two accelerators will not operate at the same time. This will allow us to use CeC PoP cryogenic system and 500 MHz RF power amplifier.
- SRF linac requirements are challenging, but BNL has sufficient experience and capabilities to successfully build such accelerator.

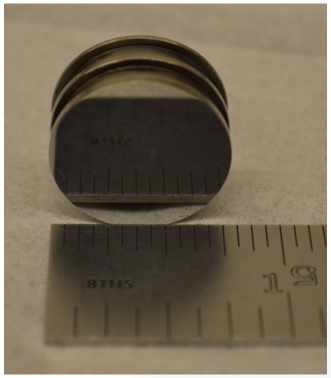
Backup slides

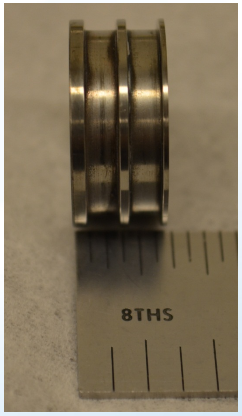
Cathode end assembly





Photocathode end assembly





Cathode puck

SRF capabilities at BNL

What tools do we have?

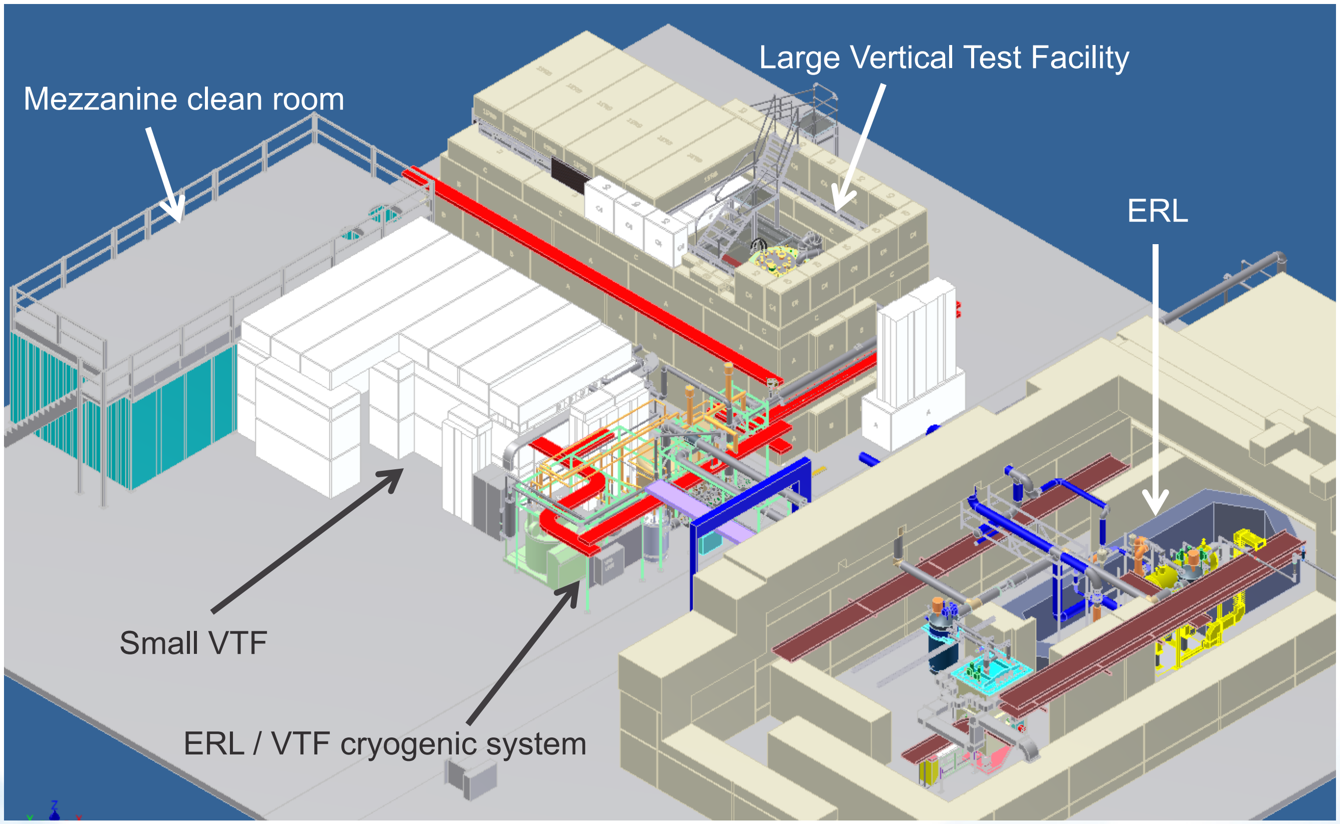
- We design SRF cavities, FPCs, and HOM dampers using 2D and 3D software suits: SUPERFISH and SLANS (2D); CST Microwave Studio and ACE3P (3D).
- Multipacting analysis is performed with: MultiPac and FishPact (2D); CST Particle Studio and ACE3P (3D).
- ANSYS is used for mechanical and thermal analysis.
- The cavities are ordered from industry (AES and Niowave).
- For testing SRF cavities we have a dedicated test facility in building 912.

SRF facilities for cavity processing

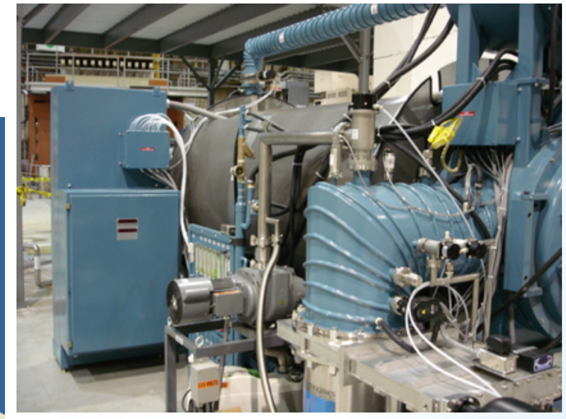
- To achieve good performance, preparation of the SRF cavities involves several important steps:
  - The cavity surface must be free of manufacturing defects. Usually about 150 μm of material is etched out by Buffered Chemical Polish (BCP) process to remove the damaged layer.
  - Any residual particulate contamination is removed by High Pressure water Rinsing (HPR).
  - All subsequent cavity preparations are done in Class 100 or better clean room environment to facilitate particulate-free assembly.
- For the first two steps, we have built a joint BNL/AES facility at AES.
- At C-AD, we have SRF test facilities, which allows us clean preparation of the cavities for vertical tests, baking the cavities in a 800°C vacuum oven, and performance testing in vertical dewars in large and small Vertical Test Facilities (VTF and SVTF) coupled to the dedicated ERL/VTF refrigeration system.
- The whole complex of the testing facilities in Building 912 is partially operational (Mezzanine cleanroom, SVTF, cryogenics, vacuum oven), partially in commissioning (VTF) or construction (Horizontal block house, SRF cryomodule assembly area) stages.

SRF facilities in building 912

The SRF-related infrastructure allows us to do various SRF tests from 56 MHz to 1300 MHz.



800°C vacuum oven for cavity baking

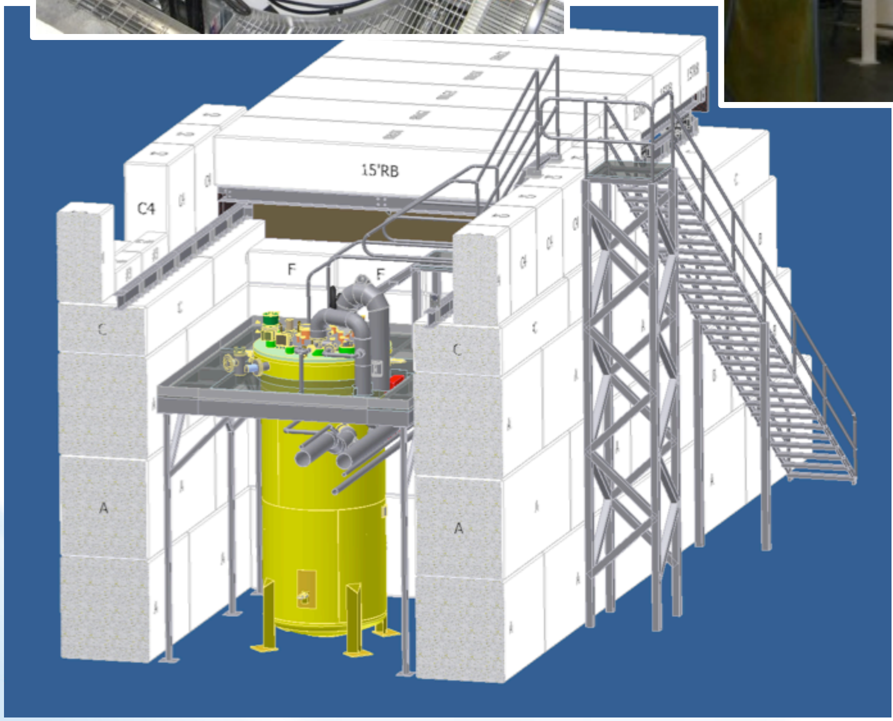


Mezzanine clean room

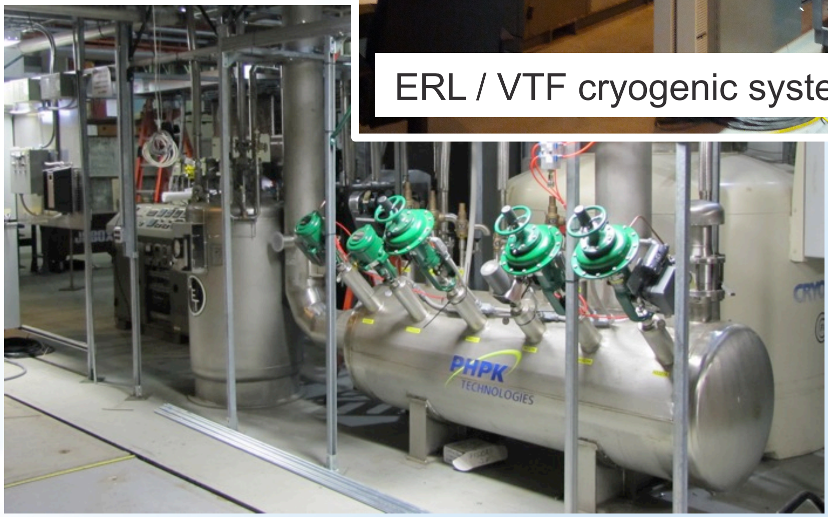
SRF facilities in building 912 (cont'd)

VTF dewar top plate

VTF Dewar



ERL / VTF cryogenic system



ERL/VTF cryogenic system

- 360 W 4 K refrigerator.
- A liquid ring pump is used to reach 2 K operation, capable of handling a 100 watt heat load.
- 1000 gallon LHe storage dewar.
- 38,000 gallon warm helium gas storage tank.