WG4 Summary

New techniques for fabrication of SRF components & CM assembly and design

Conveners: Hiroshi Sakai (KEK), Stephane Berry (CEA), Tug Arkan (FNAL)

Charge

- New fabrication methods

New fabrication methods are being pursued to improve the cost and or quality of cavities or cavity parts including laser welding, internal welding, hydroforming, electro-hydroforming, electro-deposition of Cu to make seamless cavities and 3-D printing.

- Alternative cooling technics

Finally new cryomodules that are being developed for industrial applications are providing an alternative to helium refrigerators by incorporating cryocoolers and conduction cooling.

- Non-standard concepts

Recent developments in non-standard concepts (fabrication, design and assembly) should be reported.

- Robotic Techniques

Cavity processing, cavity string assembly or cryomodule assembly may benefit in terms of quality and reproducibility, especially for mass production, through the incorporation of robotic techniques.

Seamless cavities via electrodeposition — *Lucia Lain Amador*

Developments of Niobium atomize powder for superconducting — *Takeshi Dohmae*

Metal Additive Manufacturing at CERN in general and SRF Niobium — *Romain Gerard*

Electron beam welding for cavity production, collaboration with KEK on int... — *Peter Oving*

Novel Technologies applied to SRF (cavity) fabrication — *Said Atieh*

Fabrication Experience with Balloon SSR Cavity at TRIUMF — *Robert Edward Laxdal*

RFD crab cavities manufacturing experience at CERN — *Marco Garlasche*

Methods and results of laser welding of niobium — *Kyle Branigan*

Stand-Alone Cryocooler-Based Module for the ATLAS Multi-User Upgrade — *Michael Kelly*

An effective thermal link for cooling cryo-magnetic systems :... — *Dr Bertrand Baudouy*

Developing conduction-cooled SRF cavities and first test results — *Dr Ram Dhuley*

Results from a multi-metallic conduction-cooled SRF single-ce... — *Robert Alan Rimmer*

- 24 talks (10+5)min
  - 8 America
  - 7 Asia
  - 9 Europe

includes work from 3 companies

TECHMETA(FR),

II-VI(US),

ULVAC(JP)

- 12 Institutes

Measurement results of moving particles during STF cryomodule assembly under... — *Hiroshi Sakai*

IFMIF/QST on dust particle measurements by using "a vacuum ... — *Takashi Ebisawa*

Cryomodule design, assembly and installation utilizing “KOACH” system — *Nari Yamada*

plasma processing and particulate's composition — *Bianca Giaccone*

Development of the position monitor by white light interferometer method in cry... — *Hiroshi Sakai*

Computer Vision solutions for Robot-assisted technology in SRF assembly at... — *Silvia Zorzetti*

Robotics HPR Application for Elliptical FRIB Upgrade Cavity — *Laura Popielarski*

Robot assisted cavity HPR and assembly at IMP — *Hao GUO et al.*

Remote handling of UHV beam pipe connections in high-radiat... — *Lukasz Piotr Krzempek*

Robotic disk stacking for the production of RF structures — *Riccardo Zennaro*

Chemical & Electropolishing facility for niobium (HL-LHC) and copper (FCC) s... — *Valentin Gerbet*

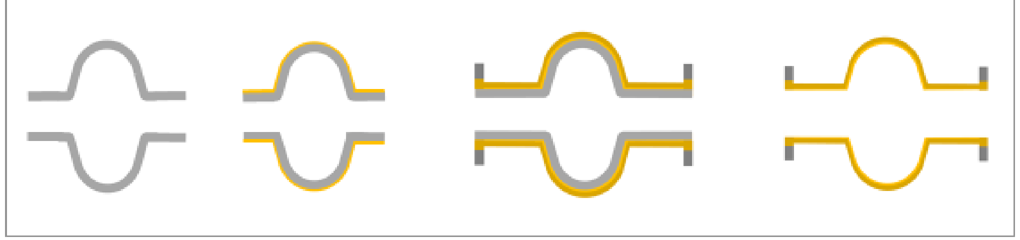
Seeking for a novel fabrication technology large-bore SRF-QWR cavity for 1-ampar... — *Hiroki Okuno*

Seamless cavities via electrodeposition

Lucia Lain-Amador, CERN

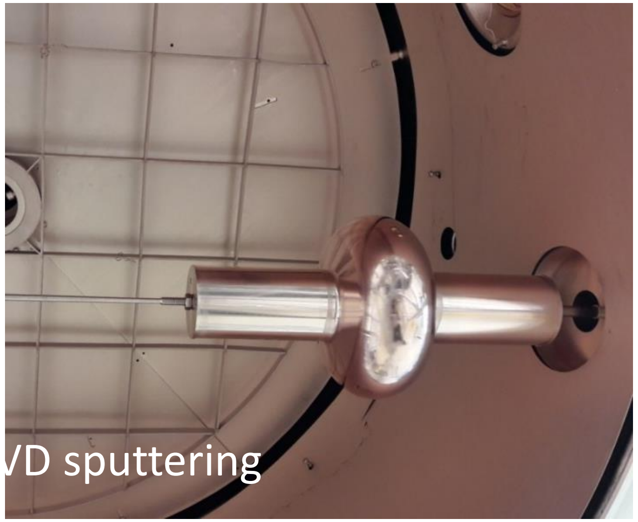
Cu electroforming - approach

The cavity is produced by copper electroforming around a sacrificial aluminium mandrel which is pre-coated with a copper thin film.

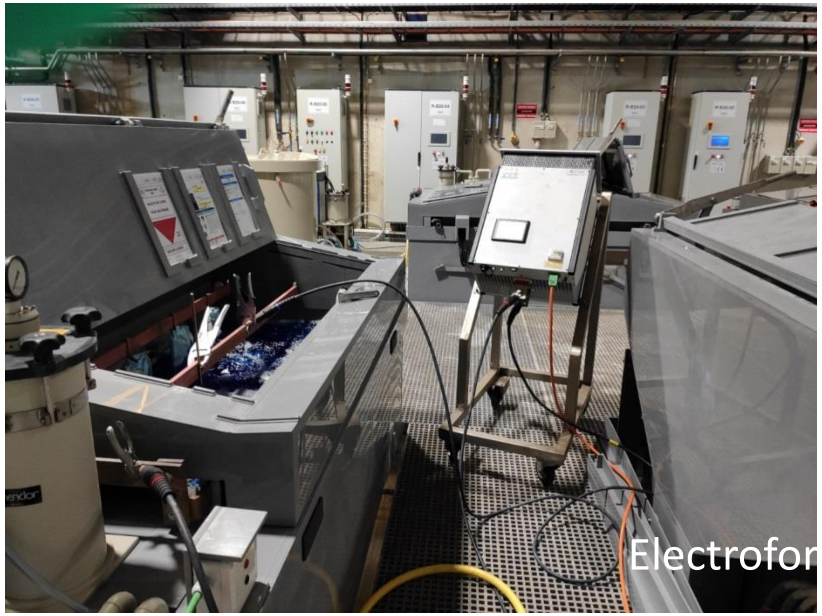


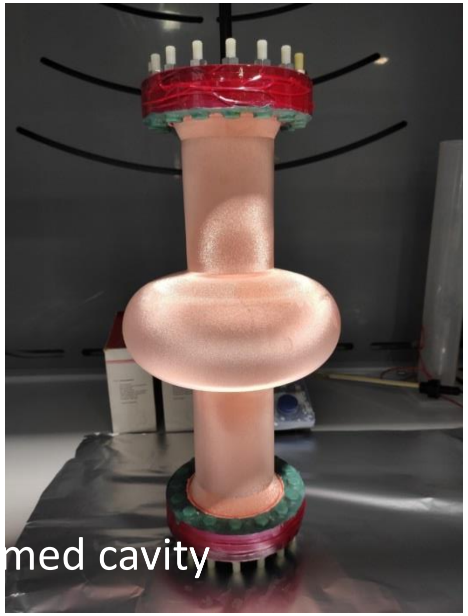
- Seamless cavities (**No EB welding**)
- Stainless steel flanges assembled during electroforming

- First cavity in process



Cu PVD sputtering





Electroformed cavity

Next steps: Mandrel removal

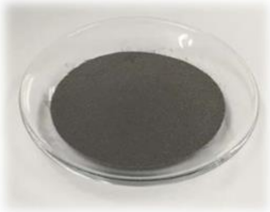
Atomized Nb powder for superconducting

Takeshi Dohmae, KEK

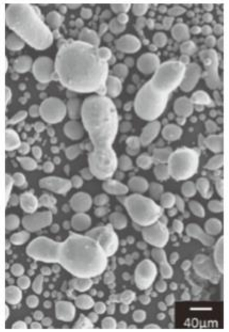
ULVAC SOLUTIONS
Vacuum Technology and Innovative Ideas

Produced powder

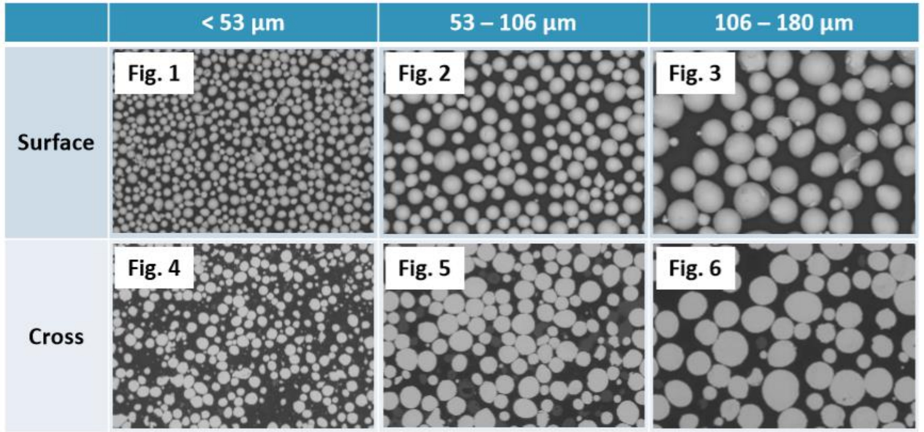
ULVAC SOLUTIONS
Vacuum Technology and Innovative Ideas



Classified Nb Powder.
(Diameter: 53 - 106 µm)

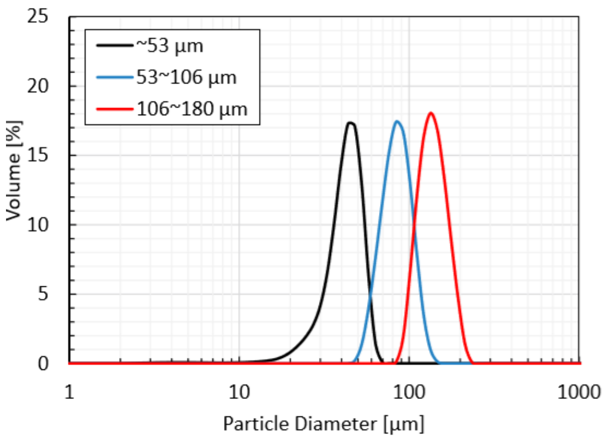


Example of Bad powder



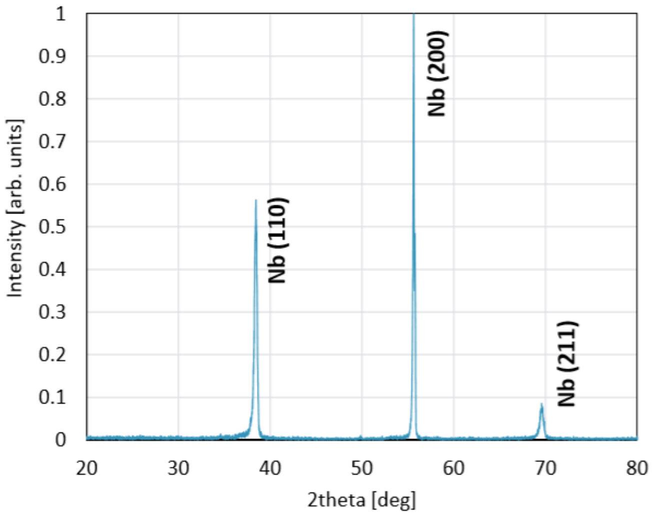
SEM images of Nb Powder.
Fig. 1-3: Surface morphology
Fig. 4-6: Polished cross section

Each powder is well separated and has good sphere-shape



D (µm)	< 53 µm	53 - 106 µm	106 -180 µm
<10%	30.2	66.9	112.4
<50%	44.9	88.5	143.2
<90%	56.9	114.4	186.7
Mean	42.2	87.9	143.9

Particle size distributions of Nb powder
*Method: Laser diffraction analysis



XRD pattern of Nb powder.

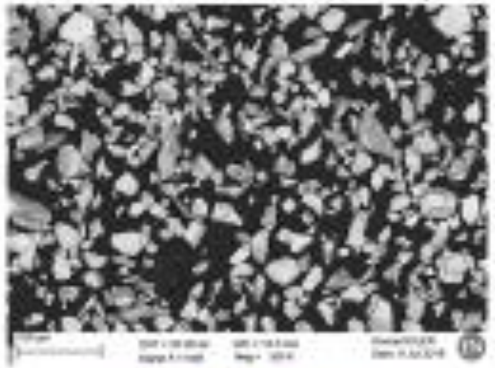
- **Particles are well sorted by size.**
- **Only Nb is observed by XRD analysis.**

- Good potential to be used for 3D printing

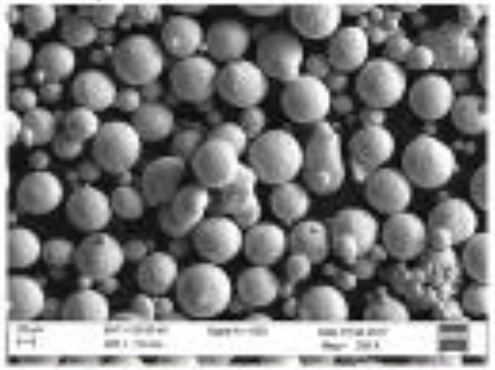
Development of Nb Addit. Manuf. for SRF

Romain Gerard, CERN

Development of the powder

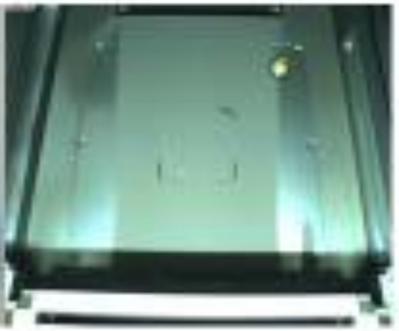


Classical Nb powder
Poor flowability.



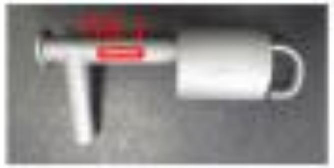
EIGA spherical powder
Good flowability
=> reliable layers

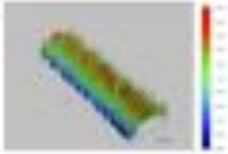
Development of the process



180 parameters to play with.

Development of post-processing techniques



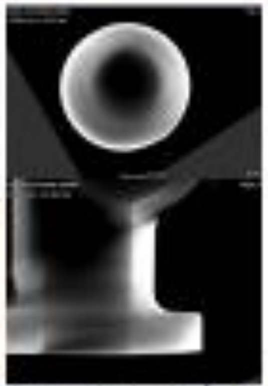


R_a	10.8 μm
R_a	0.07 μm

Titanium gettering
Purification
Heat treatment
(next slides)

i **More info: Said Atieh's talk at 3pm**

Development of design, simulations and quality control



X-ray Microtomography

Internal EBW of 1.3GHz type cavities

Dr. Peter Oving, TECHMETA

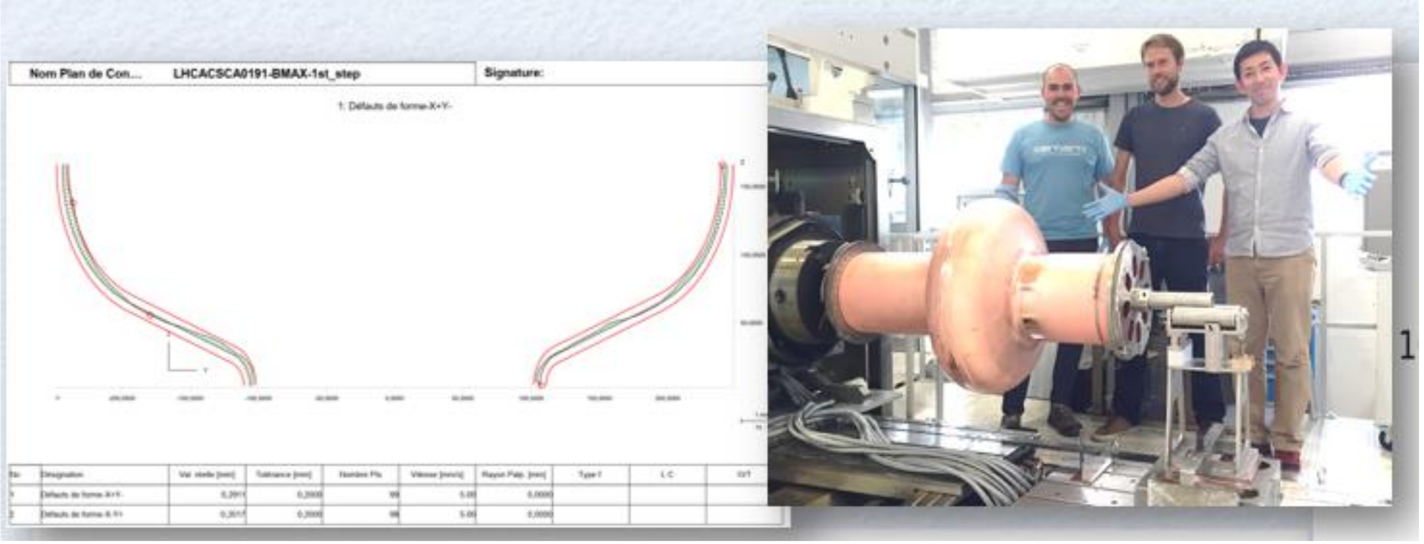
Cooperation Steps for 2020 for 1 cell 1.3 GHz:

- KEK : - 1 cell Tesla-like (Type Cavity) parts preparation
- Techmeta : - Parameter Set Up – Slope In / Weld / Slope Out - Parameter Optimization on Niobium cylinders - Special Dedicated Weld Equipment under construction - Fixture Design & Realization - Inside Welding of 1.3GHz 1 cell Tesla-like Type Cavity
- KEK : - Welded Cavity surface preparation (EP etc.) for Cryo Test - Cryo Test and RF performance measurements

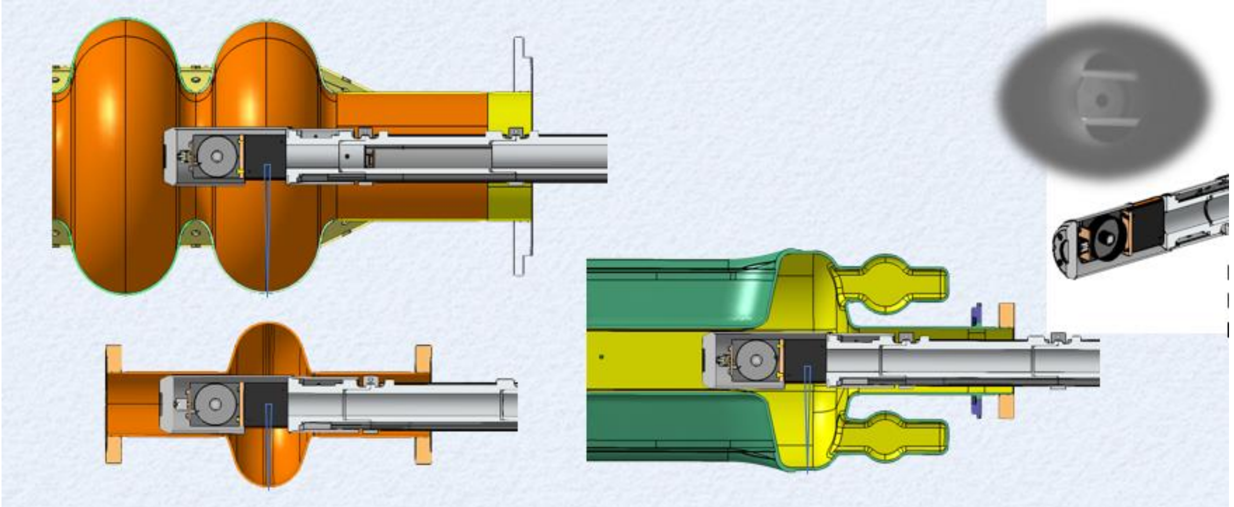
Novel Technologies Applied to SRF Fabrication at CERN

Said Atieh, CERN

- Electrohydraulic forming



- Electron Beam Welding (computer-aided and internal deflector)



Fabrication Experience with Balloon SSR

Bob Laxdal, TRIUMF

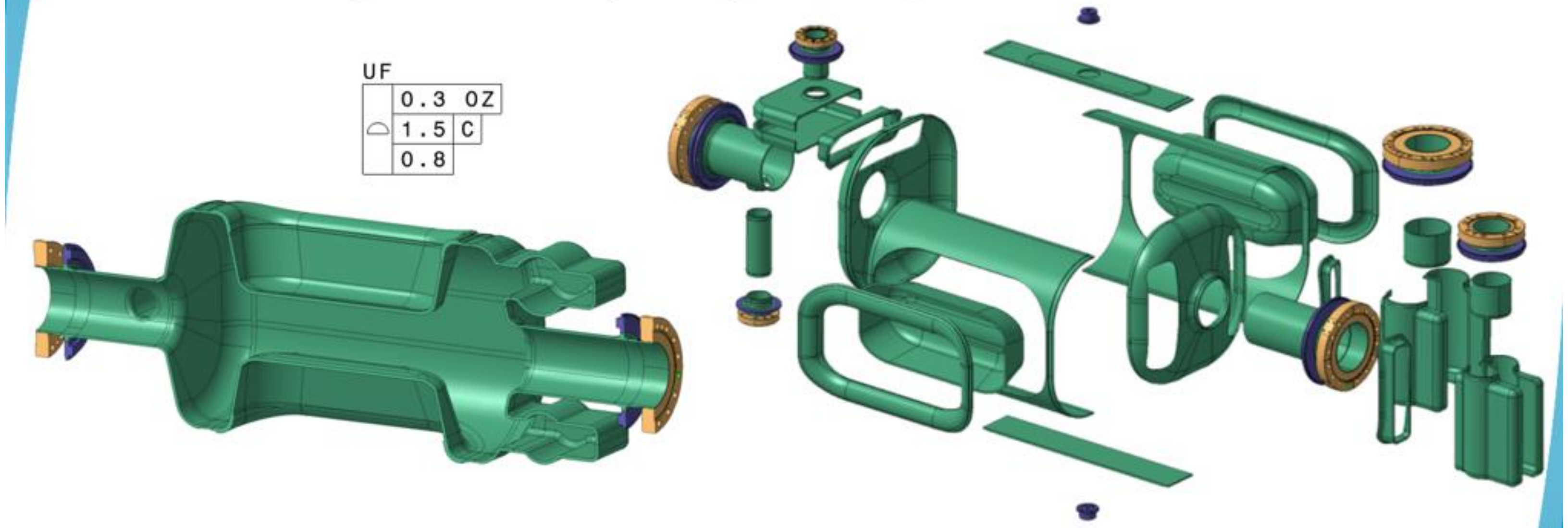
- The balloon variant of single spoke resonator is designed to mitigate problematic multipacting around operational field level.
- The first balloon SSR variant has been designed, fabricated and tested at TRIUMF meeting all the aims of the prototyping stage of the project
- Spinning of the shells has been successfully used for rapid, low cost prototyping

RFD crab cavities manufacturing experience

Marco Garlasche, CERN

Design Specificities vs. Fabrication Challenges

- Tight **tolerances**
- High sensitivity to final **surface quality**
- Bulk Niobium sheets, **thickness** up to 6.35 mm
- **Non axial-symmetric** shapes, **high forming ratios**



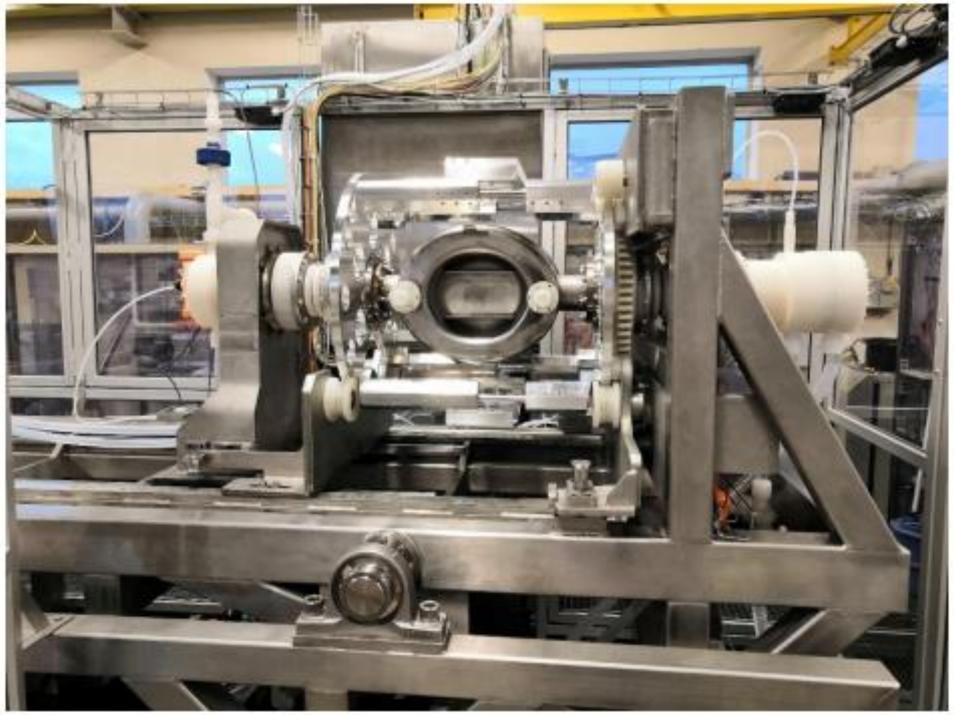
- **Major intertwining of fabrication techniques:**
  Shaping + Machining + Electron Beam Welding

but also metrology, brazing, assembly, adjustment, surface treatments…

Motivations

BCP of RFD & DQW complex geometries

Electropolishing of 400MHz cavities



<u>Advantages of horizontal polishing</u>

- Flushing of produced gas
- Less defects (bubbles)
- Increased homogeneity

Drawback → complexity and cost (316L SS, PVDF, FKM, …)

<u>Advantages of vertical polishing</u>

- Transposable to an industrialised process

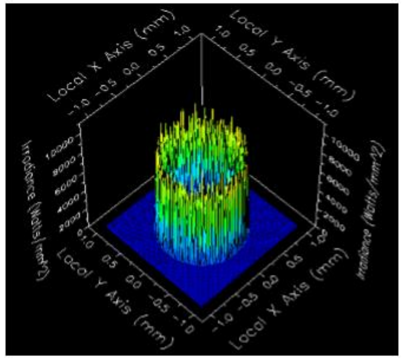
Methods and results of laser welding of niobium

Kyle Branigan, II-VI company

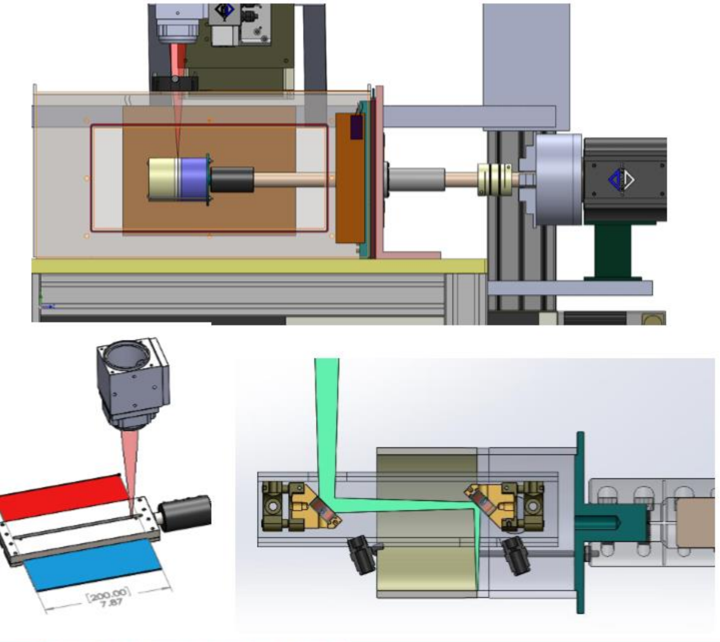
- **Low profile welds**
- **Consistent, repeatable process**
- **2⁺m/min weld speed**
- **RRR Testing underway**
  - Further work
    - Sheet B additional BCP
    - Anneal and repeat measurement
    - EBW on base sheet for comparison
- **Additional Experiments Possible**
  - High RRR Sheet
  - Tube-to-Tube
  - Mixed Materials
  - Beam Shaping
  - High Speed
  - Reduced Weld Width

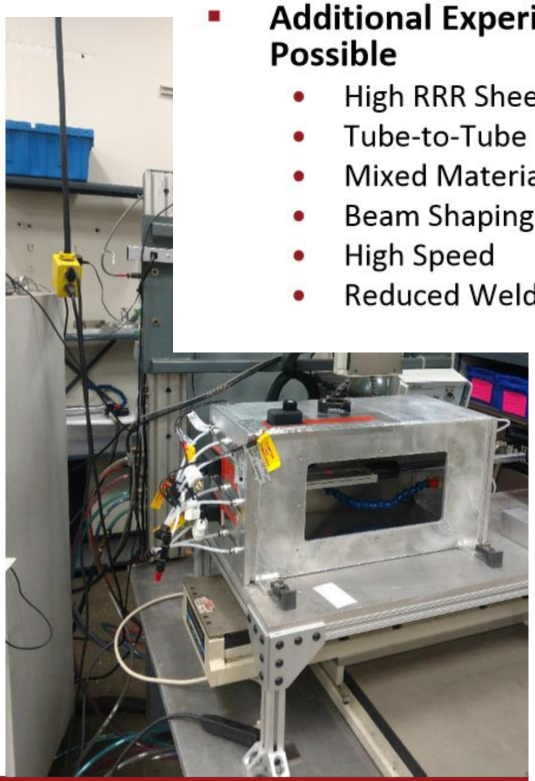
RRR Values (KEK Dec '19)	Sheet A (25 micron BCP)	Sheet B (5 micron BCP)
Base material 1 C	71.4	71.4
Base Material 2 C	73.6	71.9
HAZ B	73.7	73.1
Weld Bead A	71.7	61.3

Preliminary



Weld Setup



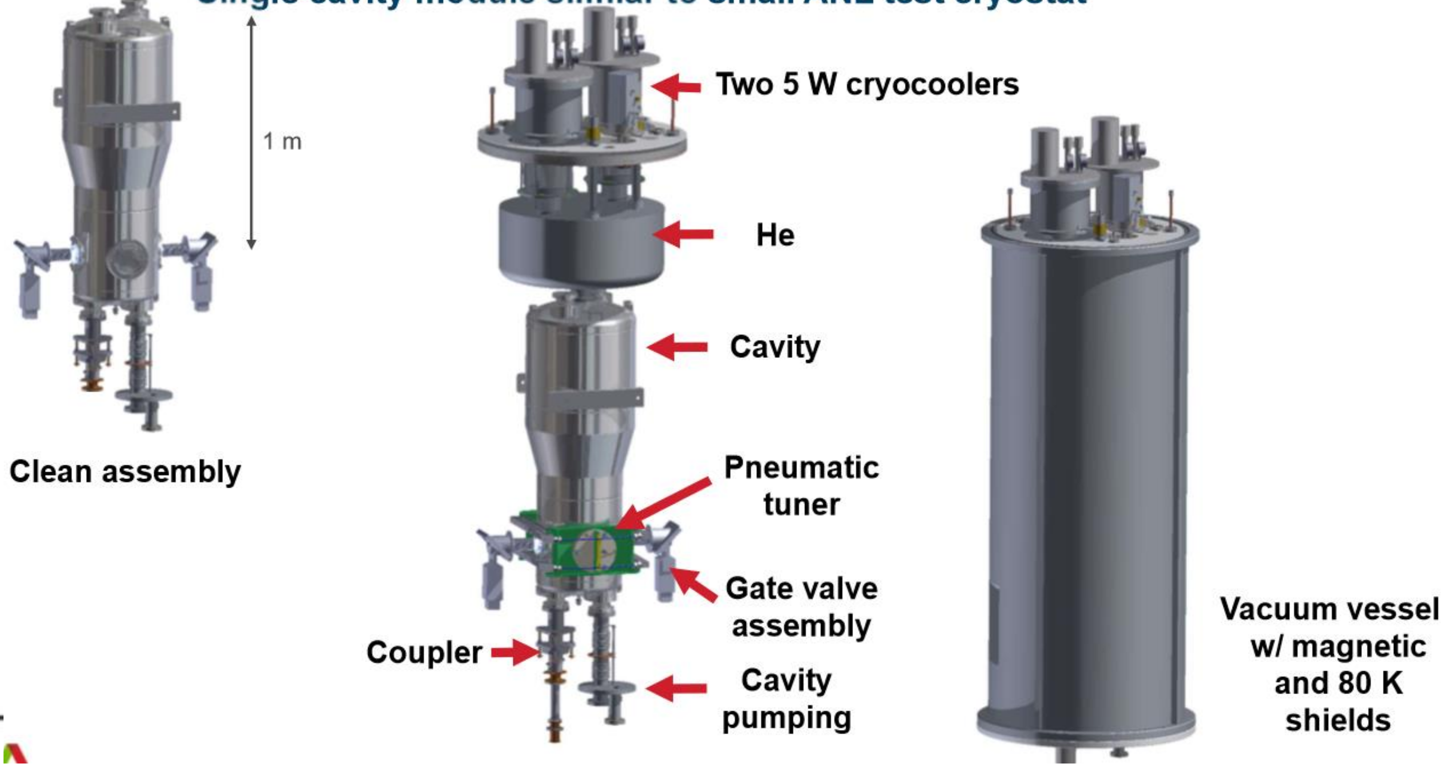


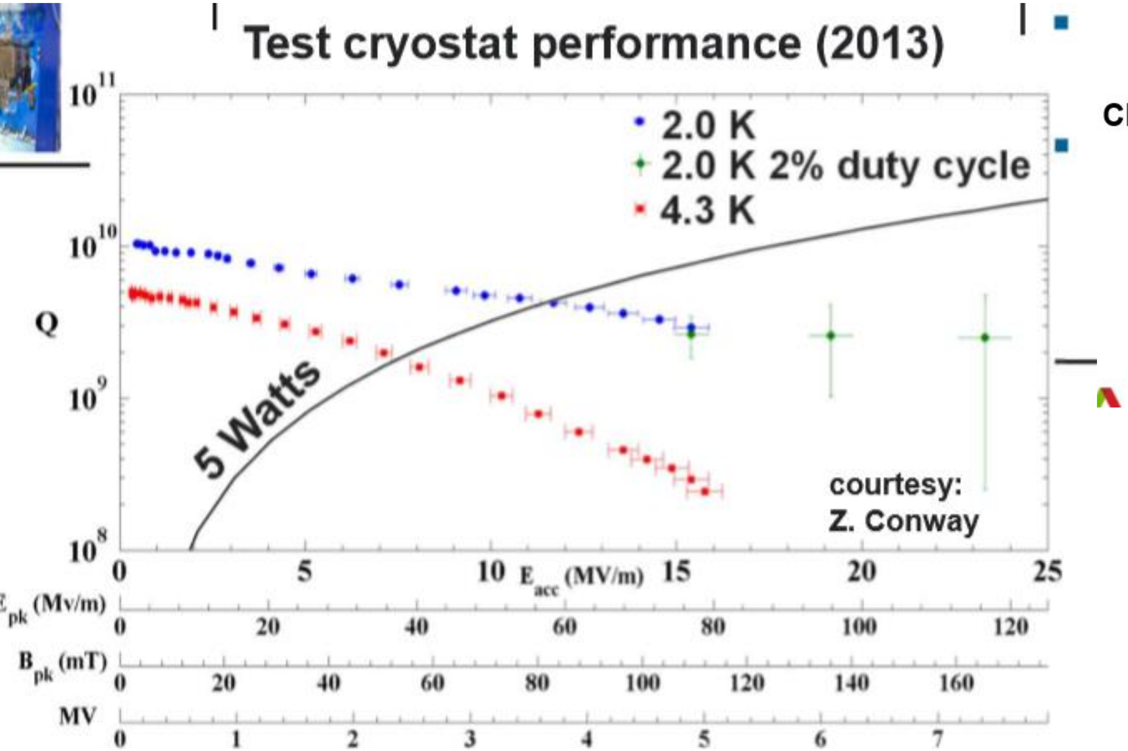
Stand-Alone Cryocooler-Based Module for the ATLAS Multi-User Upgrade

Mike Kelly, ANL

Assembly and Integration of Cavity/Cryomodule

Single cavity module similar to small ANL test cryostat





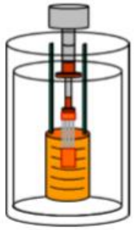
Planned operation here:
V_{ACC}=2 MV for 5 W input power at 4.3 K (key is R_{BCS}~2 nΩ at 4.3 K)

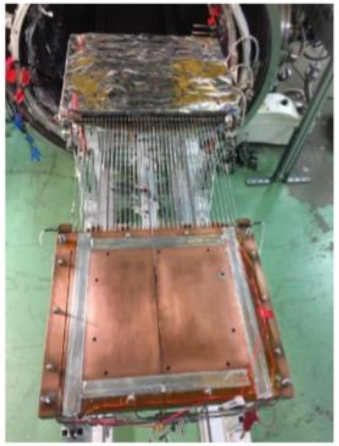
An effective thermal link for cooling cryo-magnetic systems : The Pulsating Heat Pipe

Bertrand Baudouy, CEA

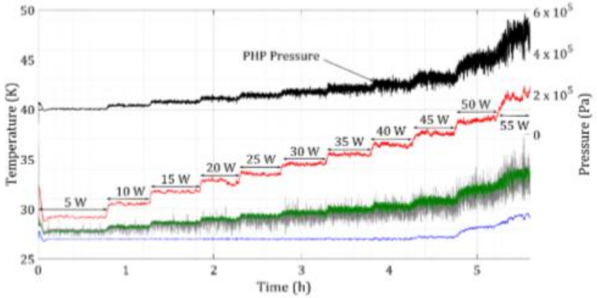
- Oscillations of liquid slugs and vapor bubbles
  - Capillary forces create a separation of liquid slugs and vapor plugs
  - Pressure change due to expansion and contraction at phase transition
    - Vaporization in the evaporator creates overpressure
    - Movement of the vapor plugs surrounded by a liquid film
    - Liquefaction of the vapor in the condenser

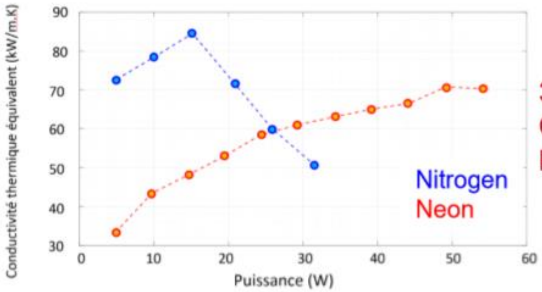
- Bruce *et al.* and Maria Barba PhD
  - Flat PHP horizontal , Ø 1.5 mm SS tubes, 36 turns
  - Condenser and evaporator section : 330 mm long
  - Adiabatic section: 300 mm long
  - Nitrogen, neon and argon





Fluid	Heat input (W)	Condenser temperature (K)	Evaporator temperature (K)
Ne	50	27	37
N2	25	75	82





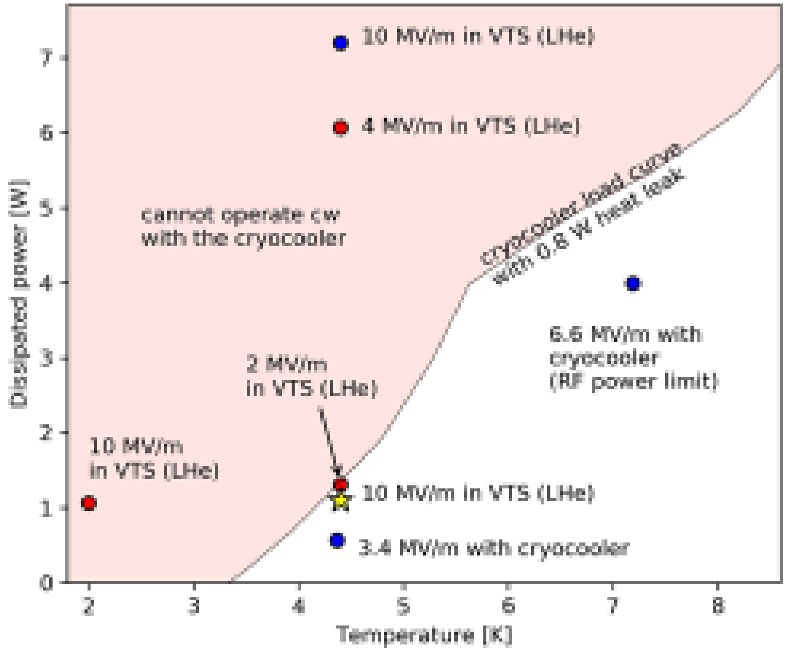
30 W
Cu 200 = 60 kg
PHP = 400 g

Developing conduction-cooled SRF cavities and first test results

Ram Dhuley, FNAL

- Nb3Sn

Operating regime of a PT420

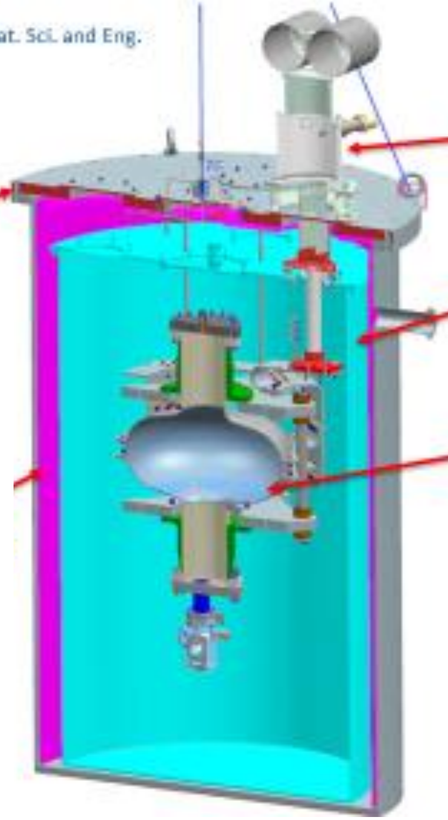


● Niobium cavity (no Nb_3Sn)
- limited in performance with a 4 K cryocooler

● Nb_3Sn coated cavity
- E_{acc} can be pushed up by letting the cryocooler operate warmer than 4.4 K.
- Better coating and magnetic hygiene is needed to reach 10 MV/m cw.

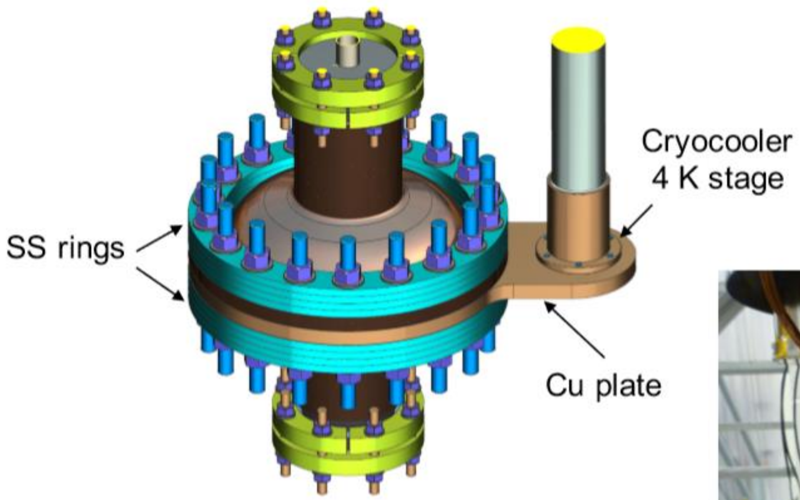
☆ Improved Nb_3Sn coating
- New coating has produced 10 MV/m in VTS with dissipation manageable with the cryocooler at 4.4 K. (S. Posen *et al.* SRF2019)

R.C. Dhuley *et al.*, IOP Conf. Series: Mat. Sci. and Eng. (to appear)

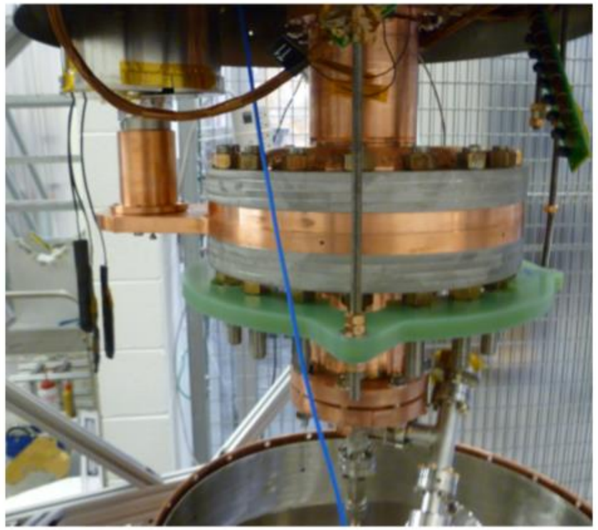


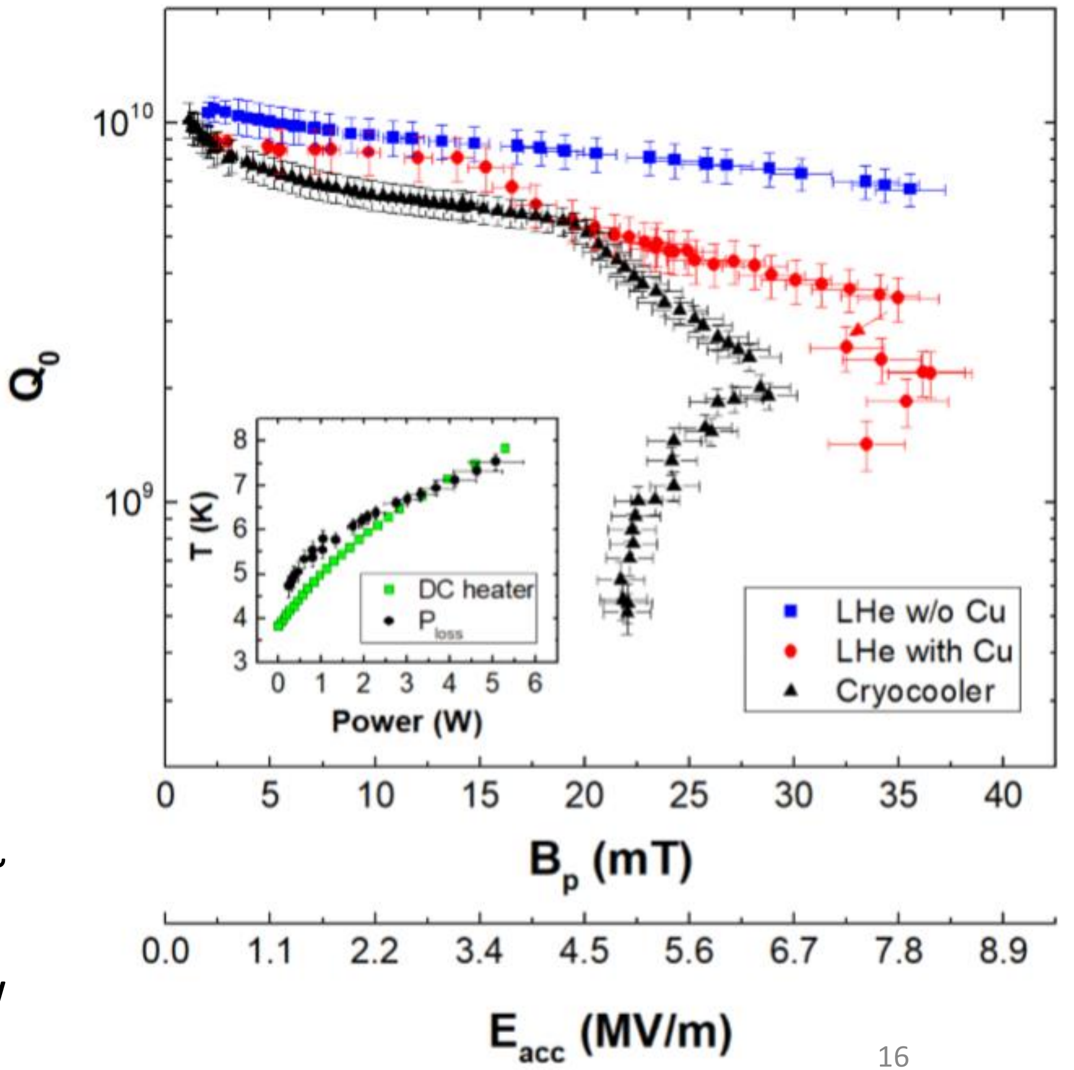
Results from a multi-metallic conduction-cooled SRF single-cell cavity

Bob Rimmer, JLAB



Cryocooler: Gifford-McMahon type, Sumitomo RDE-418D4, cooling power: 2 W at 4 K





-We were able to demonstrate operation of the cavity up to Bp ~ 29 mT (Eacc ~ 6.5 MV/m), limited by defects in the Nb3Sn film
-The cavity exhibited remarkable thermal stability even with 5 W of power dissipation

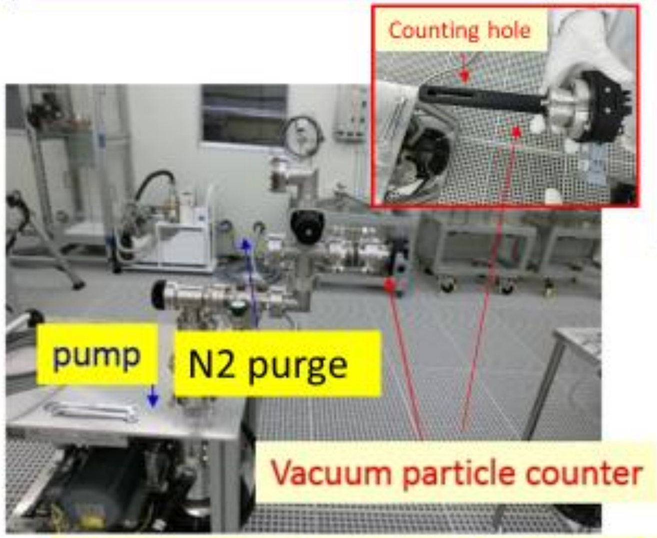
Measurement results of moving particles during STF cryomodule assembly

Hiroshi Sakai, KEK

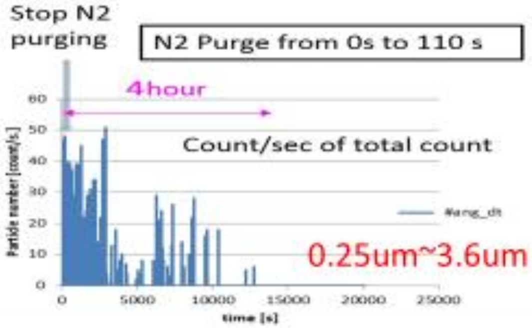
Test of vacuum particle sensor

Setup of vacuum particle sensor

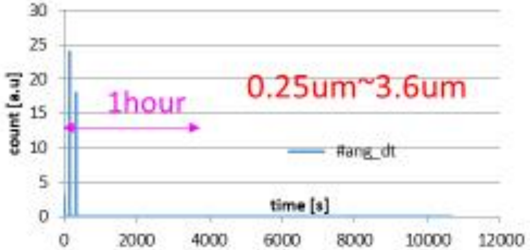
Particle measurement results after purging N2 with/without filter



We saw many particles after purging N2 gas w/o filter.
Many particle come and stay in vacuum during 4 hours.



Particle was smaller than w/o filter case. Filter works to reduce particle contamination. But we saw the particle count during N2 purging both with and without filter of 5L/min flow



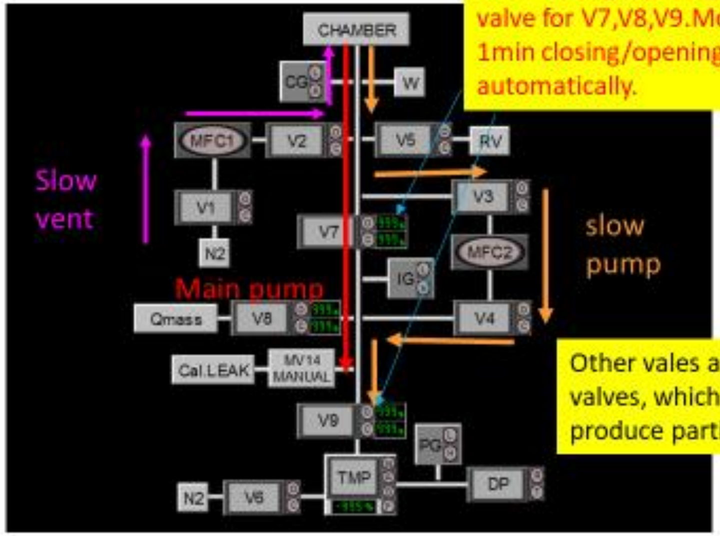
Venting is more dangerous than pumping. More slow pumping venting speed and optimization are needed to make slow pumping & venting system.

4

Summary & future plan

- Slow pumping & venting system works well. Slow closing/opening valve is important.
- This clean assembly work in new local clean booth and slow pumping/venting system with vacuum particle monitor helps keep clean environment of cryomodule assembly.
- Vacuum particle monitor give the important information duting slow pumping/venting

Already made 2nd slow pump in KEK



Slow closing/opening gate valve for V7,V8,V9.More than 1min closing/opening time automatically.

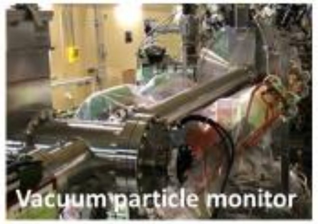
Other vales are needle valves, which did not produce particulates

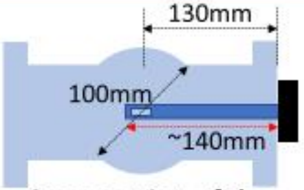
Measurement of particle contamination in vacuum at IFMIF

Takashi Ebisawa, QST

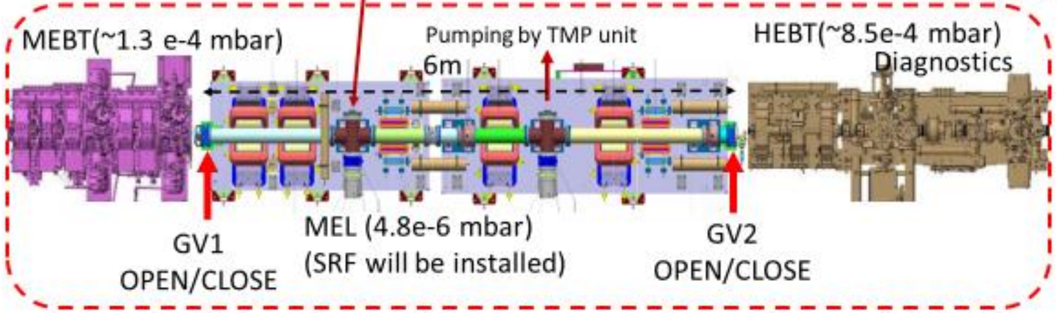
Setup and experiment

Vacuum particle monitor
Principle: Laser scattering
Resolution: 0.3~3.6 μm
Developed by Wexx Company

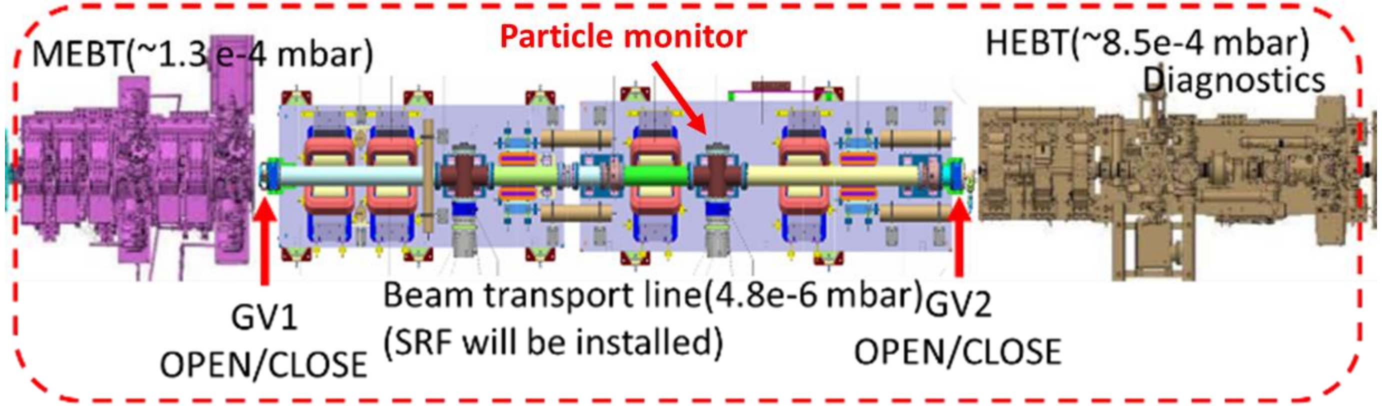




Cross section of the vacuum chamber



To visualize particle moving in beam transport line, a vacuum particle monitor was installed in vacuum chamber. Detector was located around the center of the beam axis. After pumping the beam line and open GV, we measured particle counting in vacuum.



GV	OPEN	CLOSE
GV1 (MEBT side)	0.3μm x 356	0.3μm x 264
GV2 (HEBT side)	No count	No count

Several hundreds of 0.3 μm particles were detected by GV operation of MEBT side.
Repeating the valve operation, 0.5μm particles were detected.
No detection by GV operation of HEBT side.

GV	OPEN	CLOSE
MEBT side	No count	No count
HEBT side	0.3μm x 42	0.3μm x 80

Several tens of 0.3 μm particles were detected by GV operation of HEBT side.
No detection by GV operation of MEBT side.

Cryomodule assembly and installation utilizing `KOACH' system

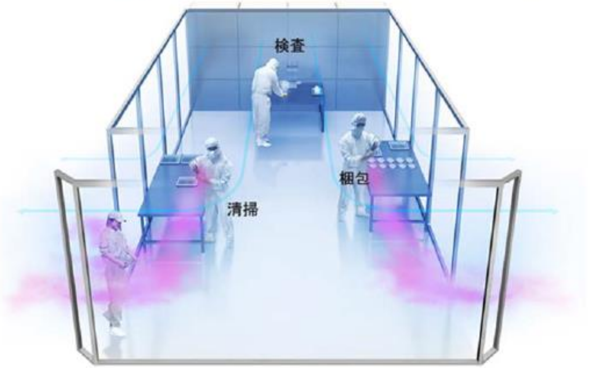
Kazunari Yamada, RIKEN

KOKEN KOACH clean system

We introduced KOACH clean system for assembling work.
https://www.koken-ltd.co.jp/english/product/clean/super/

- ISO class 1 super clean environment
- High coherent side laminar flow (wind speed: 0.3~0.5 m/s)
- Short clean-up time
- Short construction period (～1 week) for clean room type
- Reasonable price
- Low running cost

Room type for cryomodule assembly



KOACH F1050-F (Floor KOACH) + guide screen

Clean area: W1050 mm × H850 mm/one module
< L20,000 mm

Open zone type for connection in situ

KOACH C900-F (Stand KOACH)

Clean area: W900 mm × H700 mm × L1800～2300 mm

Open tabletop type for VT connection

KOACH T500-F (Table KOACH)
Clean area: W496 mm × H310 mm × L700 mm

Assembly and installation of cryomodule


Preparation of SC-QWR


Before connection


After vacuum connection


Assembly in semi-clean room



Transport to installation site

ISO class 1
↓
ISO class 8
↓
Installation site


Installation


After alignment

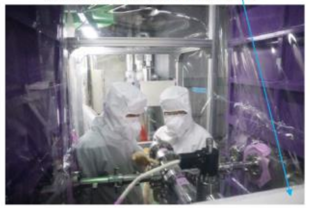
Connection work in situ

One side of Stand KOACH was used with local antistatic-vinyl enclosure.


KOACH C900-F (Stand KOACH)



Connection of vacuum pump assembly

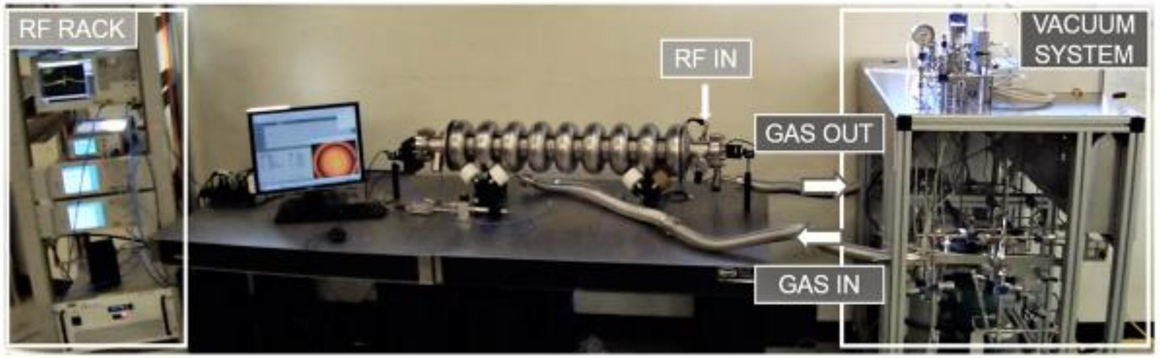

Connection between CM1 and CM2


Connection between differential pumping system and CM1

Plasma processing and particulate analysis

Bianca Giaccone, FNAL

Plasma cleaning apparatus



- Plasma processing is performed cell by cell
- Cleaning is performed at room temperature with 75-200 mTorr of $Ne\text{-}O_2$
- Cavities are assembled with valves on both end sides, for injection and evacuation of the gas
- Neon and Oxygen are sent to the cavity mixed (few % of O_2)
- RGA is used to analyze by-products

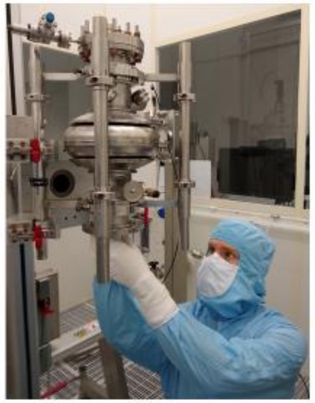
Fermilab

-Plasma processing applied to cavities subject to simulated vacuum failure outside clean room has shown little or no improvement in the performance.
-SEM/EDS analysis of the particles collected from single cell cavity shows that the majority of the contaminants are metal based.

Particle Collection Methodology

Cavity: slowly vented, cleaned, blown and disassembled in clean room.
A piece of clean room lint-free cloth is used to wipe each half iris and equator.
Carbon disks are used to collect the particles from the cloth.

Gunshot Residue Stubs



Procedure followed similar to JLab work: doi:10.18429/JACoW-SRF2017-TUPB106

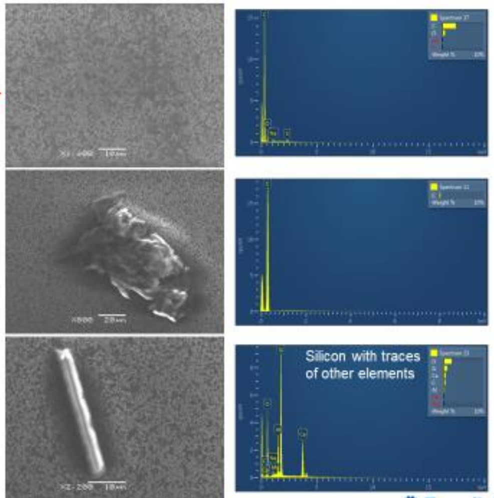
Fermilab

SEM-EDS particle analysis: clean carbon stub

- A clean carbon stub is always used as reference

Carbon tape background

Few particles found on clean carbon stubs:
- Organic
- Silicon
- Calcium

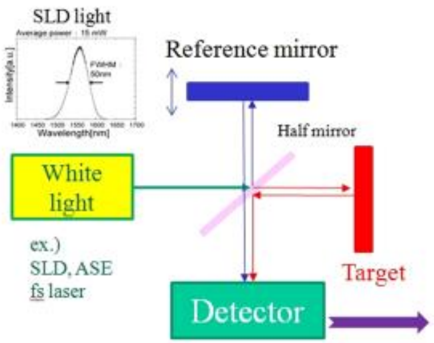


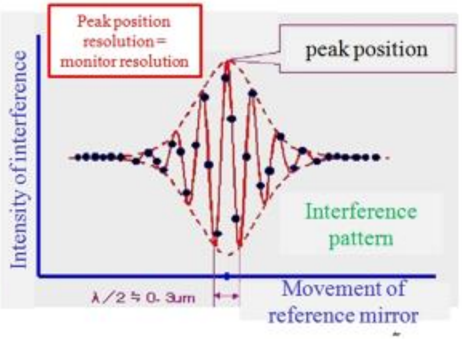
Position monitor by white light interferometer in cERL cryomodule

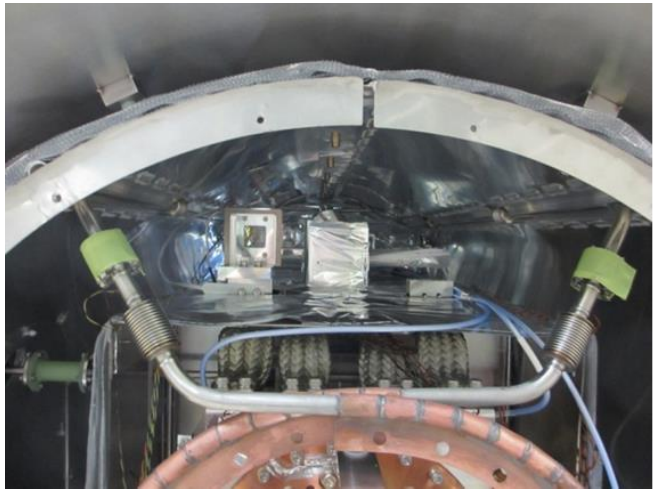
Hiroshi Sakai, KEK

1) Principle of the WLI monitor

- WLI monitor was based on the peak detection of the interference pattern when distances of the measured target and the reference mirror are the same.
- While we keep the peak detection under scanning the reference mirror precisely, we know the relative displacement of the target at every second.
- High resolution of less than 1µm with large dynamic of more than 10mm can be available with non-destructive (non-contact) manner.







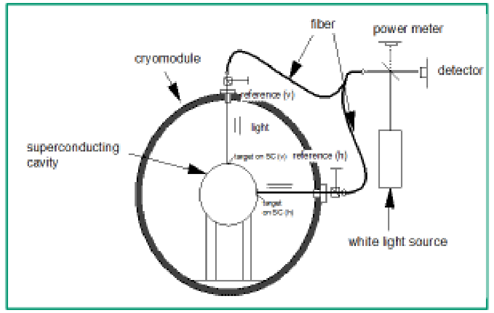
Alignment target with cross line

Feature of WLI monitor (compared with other position monitor like wire position monitor)

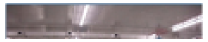
1. Measure the cavity position directly from the outside the cryo-vessel even thanks to the white light interferometry.
2. Less than 1 µm resolution of this monitor will be achieved with the large dynamic range of more than 100mm.
3. When the monitor was broken, we easily repaired the sensor without opening the cryomodule.
4. Small aperture of view ports can be placed for monitoring and thus reduce the thermal radiation.

Schematic drawing and requirement of WLI monitor to cERL cryomodule

Parameters	Requirements of new WLI monitor
Stability	< +-10µm
Dynamic range	> +-30mm
Measurement points	2 positions of x-y values



- First test satisfied our requirement of less than 10um resolution under the principle of white light interference method. But we saw thermal drift.
- By setting the reference mirror on the way from the light source to the target, we drastically cancelled thermal drift come from the fiber of the WLI monitor and found that the resolution of this monitor was 3 µm at a test bench, in spite of the fiber length of more than 80 m.
- By improving this monitor, we kept monitoring the cryomodule every 5 seconds for half year during high power test and beam operation including two-times thermal cycles from room temperature to 2 K. We found the reproducibility of the cavity displacements with 50 µm level between after warming up and cooling to 2 K. The upgraded WLI monitor could monitor the displacements for a long time with +- 5 µm resolutions



Computer Vision solutions for Robot-assisted technology in SRF

Silvia Zorzetti, FNAL

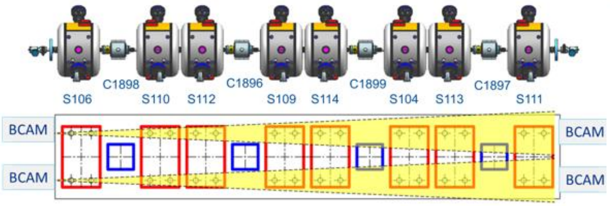
Alignment measurements & Feedback loop for robot

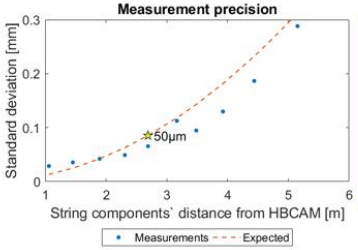
Tens of micron — sub microns

Coldmass insertion

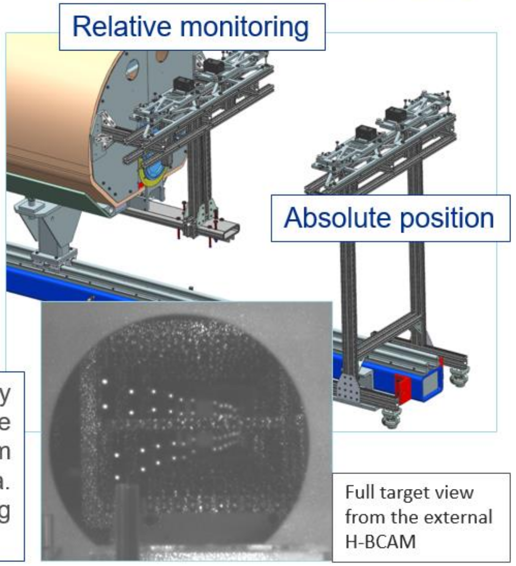
Position monitoring during insertion

- Two cameras attached on the thermal shielding
- Two cameras installed at the ground and used as a reference





The measurement uncertainty for each component in the string assembly depends from the distance to the camera. Acquired data are matching with the expected precision.

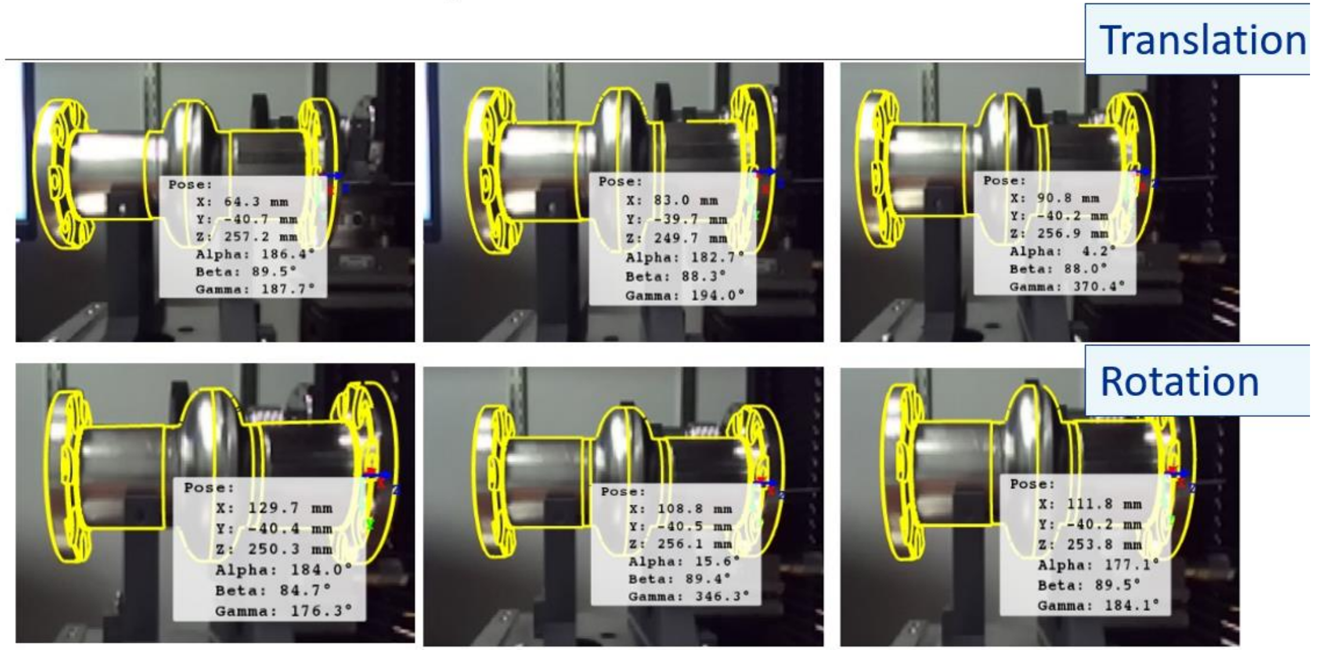


Full target view from the external H-BCAM

Pose reconstruction with point clouds - image

Performance evaluation

- The cavity is mounted on translation stages to validate the position monitoring
- Sub-micrometric accuracy for the translations



Robotics HPR Application for FRIB Upgrade Elliptical Cavity

Laura Popielarski, FRIB

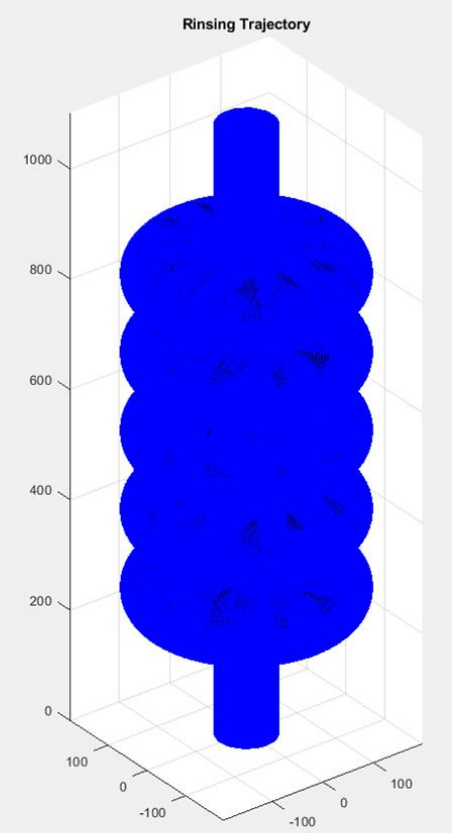
- FRIB HWR requires cleaning through 7 ports and four rotations by a 7th-axis motor
- FRIB elliptical requires cleaning through one port and zero rotations by 7th axis motor
- Elliptical internal surface area = 1.677 m^2
- FRIB 0.53 HWR = 1.366 m^2

FRIB elliptical cavity assembled with supporting frame

FRIB HWR cleaning through seven ports

FRIB elliptical cleaning through one port

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University



TESLA TECHNOLOGY TTC COLLABORATION

Robot assisted cavity HPR and assembly at IMP

Hao Guo, Teng Tan, IMP

- Heaviest cavity

for CADS is ~180kg

Robot assisting on string assembly

Cavities moving and fixing on the bracket

Solenoid assembly and fixing on the bracket

Coupler assembly assisting

Nitrogen cleaning assisting

Robot assisting on HPR process

Horizontal HPR for HWR-015 cavities

Vertical HPR for HWR-015 cavities

HPR for 325MHz QWR Nb/Cu cavities

HPR for 1.3GHz Elliptical cavities

-Reduced manpower in cleanroom
-Increased productivity

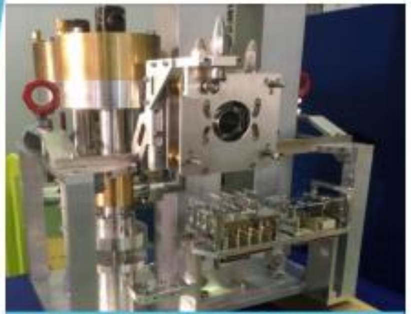
Remote handling of UHV beam pipe connections in high-radiation zones

Lukasz Krzempek, CERN

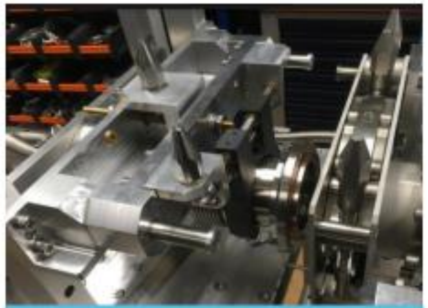
VAX prototype and tests

VAX chain clamps:

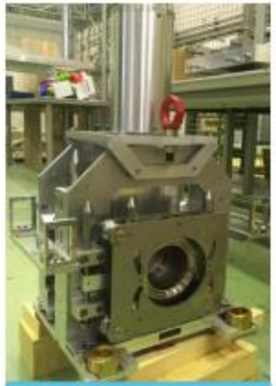
- Torque control;
- Tightening screw's turns control;
- Robot friendly interface;
- Minimum number of steps for the robot to operate the tightening (locking) screws;
- Chain clamp size determines number of segments (chain links) so that working conditions potentially could be affected by the gravity.



VAX Module 2 – chain clamp DN40



VAX Module interconnection – chain clamp DN100 in b.112



VAX Module 3 – chain clamp DN100 in b.186

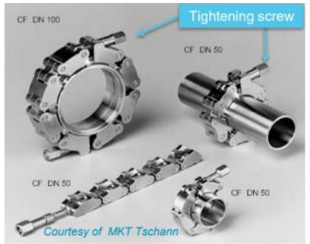
VAX Module 1 – remote handling in b.186

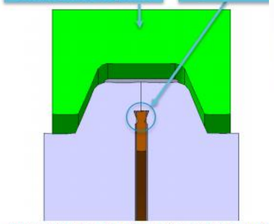
VAX remote operation:

- intervention of robot (gripper or gripper with extension tool);
- Intervention of personnel from 'safe' area using extension tool.

Quick CF Flanges (conical)

Quick CF Flanges

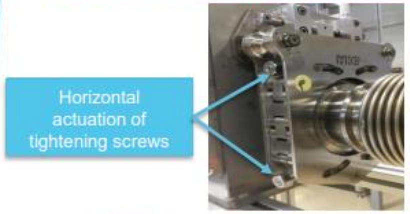


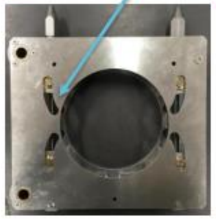


Cross section of a typical chain clamp assembl

Overview chain clamps CF	
Material	Stainless steel 1.4435
Temperature range	-200 to +350°C

Combination of chain clamp and bellows compression tool





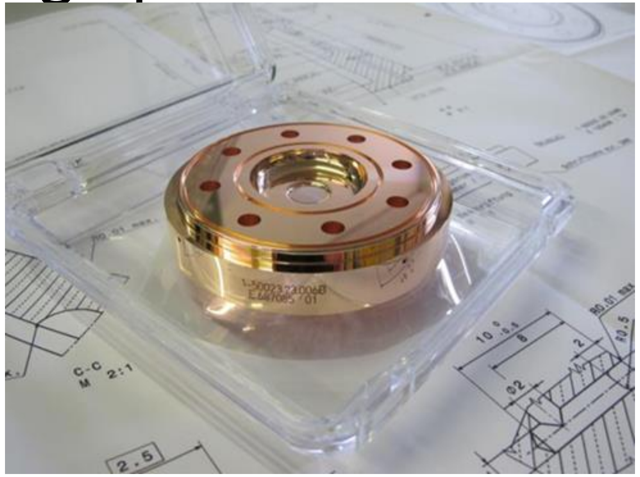
Chain clamp in open position

Chain clamp in close position

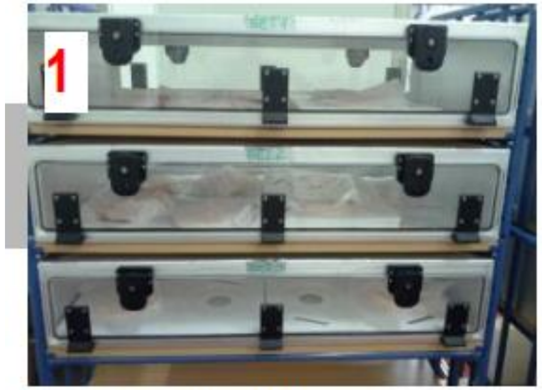
Robotic disk stacking for the production of RF structures

Riccardo Zennaro, PSI

- High precision machining

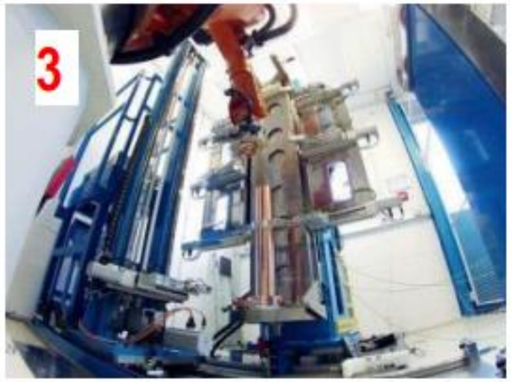


AS production and tuning-free technology



Storage under N2

Cup washing



Disk stacking

- Heating for assembly
- Long structure stacking with precision using robotic system

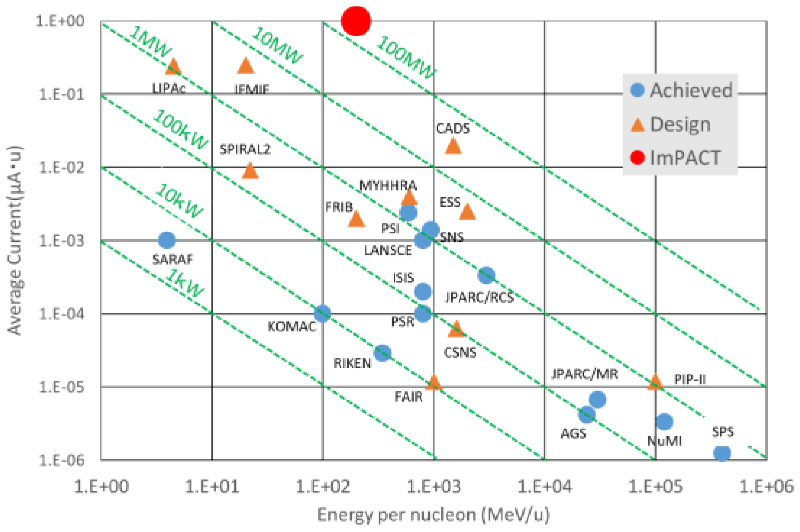
Vacuum brazing

Structure reversed to horizontal position on a temporary girder

Bead pulling

Summary

- We proposed **1 ampere class single cell linac to realize nuclear transmutation of High level nuclear waste using accelerator.**
- 1-ampere class single cell linac (Deutron, 1A, 200 MeV/u)
  - **no RFQ**
  - **Can accept large size beam**
  - **Low frequency rf system**
- **Large bore rf cavity**
  - Two types of the cavities should be fabricated.
- **Thin Nb film on Cupper vs. Bulk Nb**
  - General comparison
  - **Simple and smooth shape of QWR for thin Nb film method (x2 HIE-ISOLDE)**
  - **Proposal of a new fabrication method of HWR using thin NB film method**



E_d [MeV/u]

We need more than 100 times of the available maximum beam power in the world.

4