Development of Nb_3Sn Cavity by Vapor Diffusion Method at IMP

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Outlines

1. Background and demands
2. Nb_3Sn coatings at IMP
   - Before the upgradation of the system
   - Upgradation of the deposition system
   - After the upgradation of the system
   - Construction of the production-style furnace

4. Prospects and discussion

SRF projects in China

SRF has been adopted by most advanced accelerator projects that are being constructed and proposed

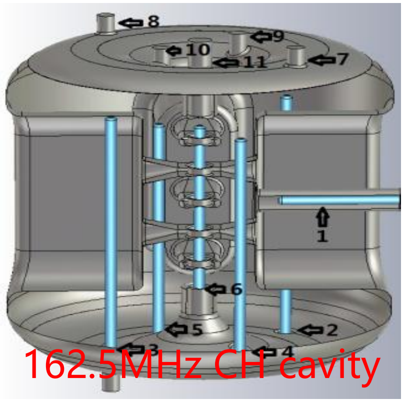
☐ Under construction（China），856 cavities:

- Shanghai High repetition rate XFEL and Extreme light facility （SHINE）：616 cavities（1.3GHz、3.9GHz）；
- China initiative accelerator driven system（CiADS）：137 cavities（162.5MHz、325MHz、650MHz）；
- High-intensity heavy ion accelerator facility（HIAF）：96 cavities（81.25MHz、162.5MHz、325MHz）；
- High energy photo source（HEPS）：7 cavities（166.7MHz、500MHz）。

☐ In design（China）：

- Circular Electron Positron Collider （CEPC）：336 （1.3GHz、650MHz）；
- Dalian coherent light source（DCLS）phase-II;
- China Spallation Neutron Source（CSNS）phase-II；
- ……

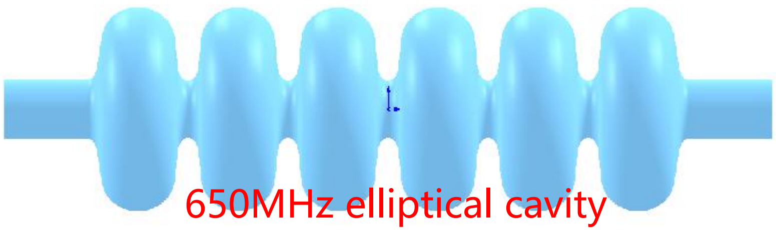
162.5MHz HWR cavity



162.5MHz CH cavity

325MHz Double Spoke cavity

13GHz elliptical cavity



650MHz elliptical cavity

Demands for High Q and High G

High energy Large facility

- Reduce construction cost → Higher gradient
- Reduce operation cost → Higher Q_0

→ Alternative SRF material

$$R_S \approx \frac{1}{2}\sigma_n\omega^2{\mu_0}^2\lambda^3 + R_{res} = \frac{A}{2}\omega^2\left(\lambda_L\sqrt{1+\frac{\xi_0}{l}}\right)^3 \frac{RRR}{\rho_n(300K)}\, e^{-\frac{\Delta(0)}{k_B T_c}\frac{T_c}{T}} + R_{res}$$

Parameter	Niobium	Nb_3Sn
Transition temperature	9.2 K	18 K
Superheating field	240 mT	425 mT

Higher critical temperature
→ Operation at 4.2 K
Higher superheating field
→ Double the limit of niobium

	Nb cavity at 2K/E_{pk}=32MV/m		Nb_3Sn cavity at 4.2K/E_{pk}=32MV/m		Refrigeration power saved /kW
	P_{diss}/W	P_{AC}/kW	P_{diss}/W	P_{AC}/kW	
1.3GHz 9-cell	9.86	7.58	14.8	3.44	4.14
650MHz 062	20.88	16.06	17.83	4.15	11.92
650MHz 082	22.02	16.94	18.80	4.37	12.57

Saved **~2MW** for SHINE, **~0.8MW** for CiADS : Substantial cost savings for large facilities.

The most promising SRF new technology, its engineering application will bring huge impact on both large facilities and industrial-class accelerators.

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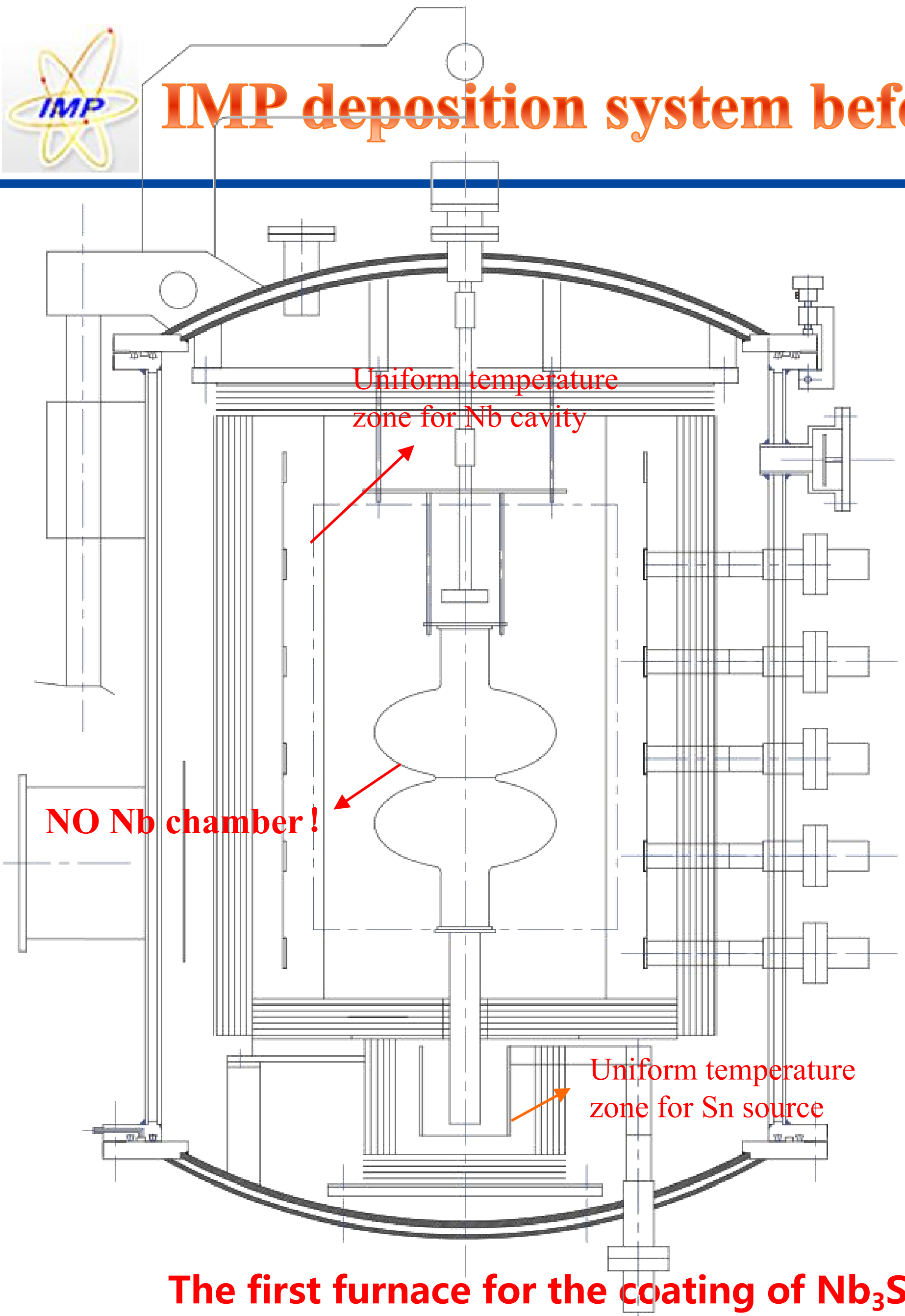
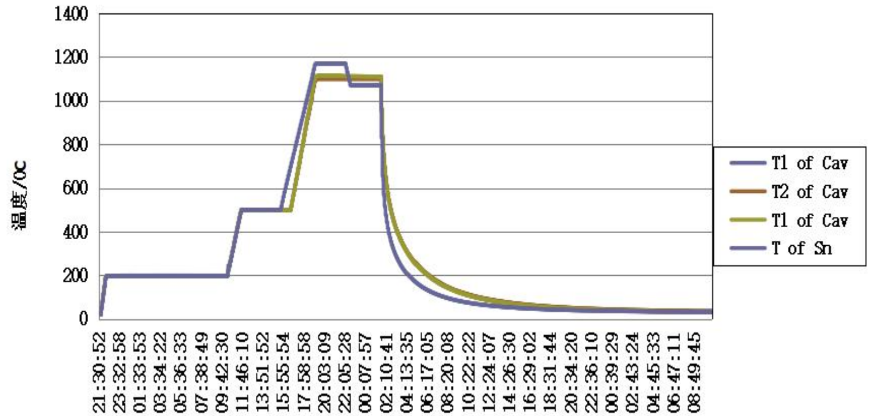
IMP deposition system before upgradation

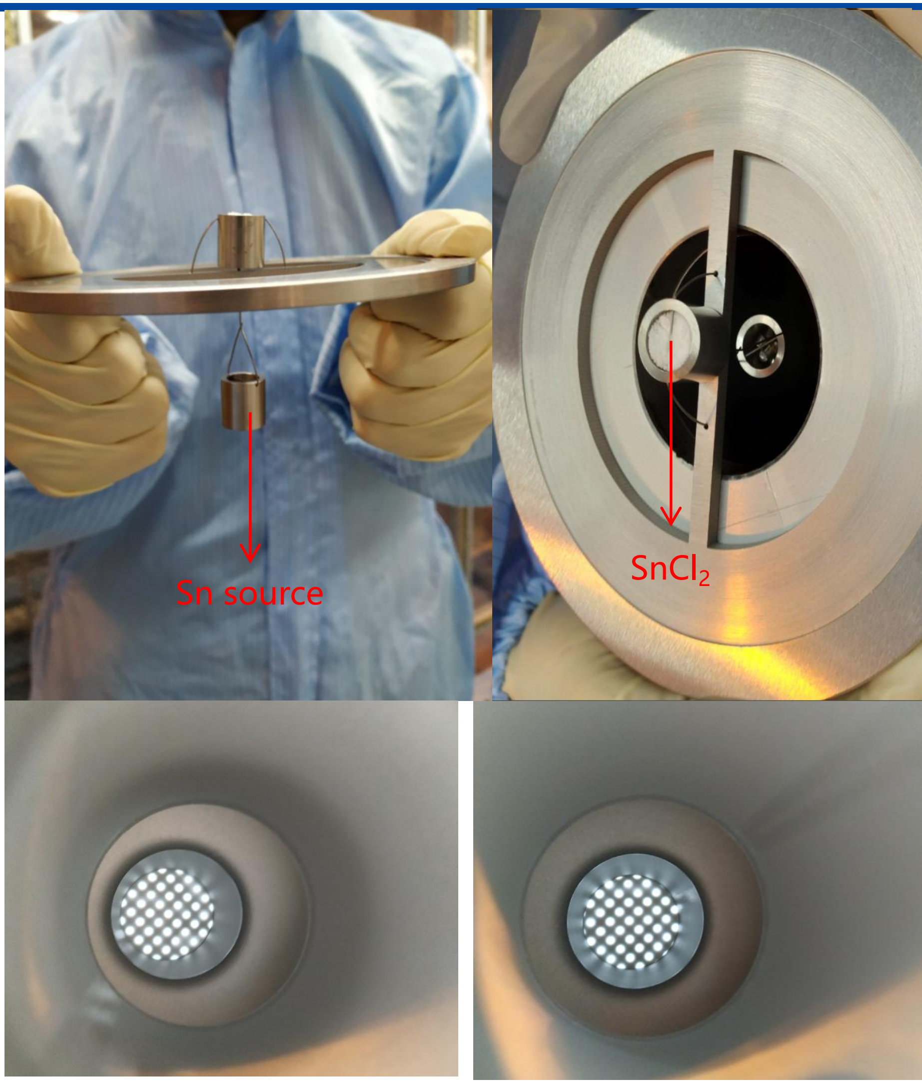


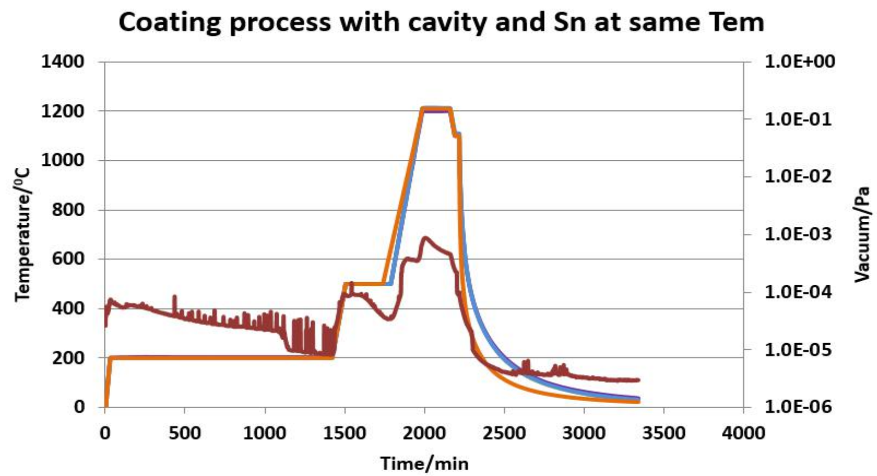
Initial coating condition trial run before upgradation

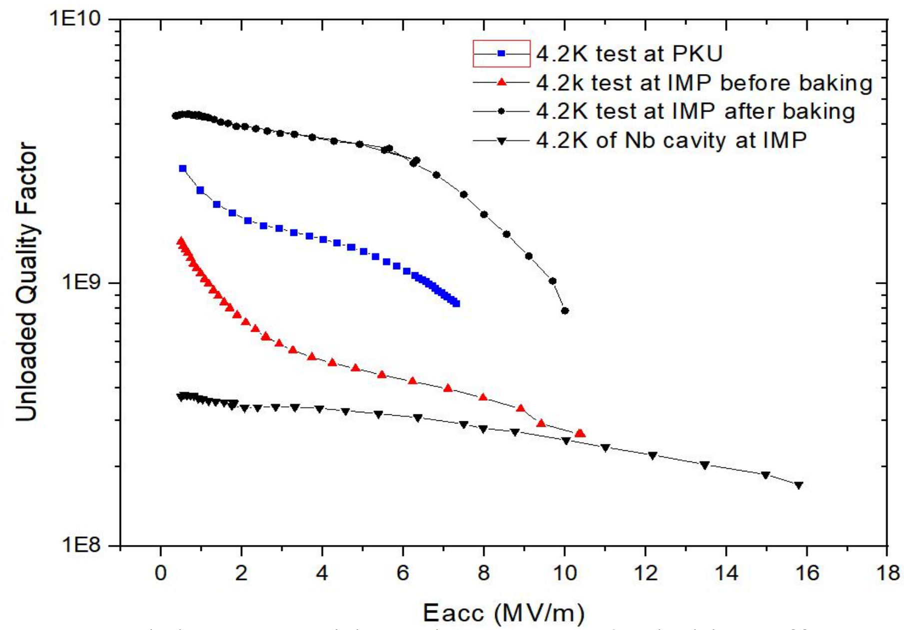


The first furnace for the coating of Nb_3Sn cavity by vapor diffusion method in China

Coating with cavity and Sn source at 1200^{0}C



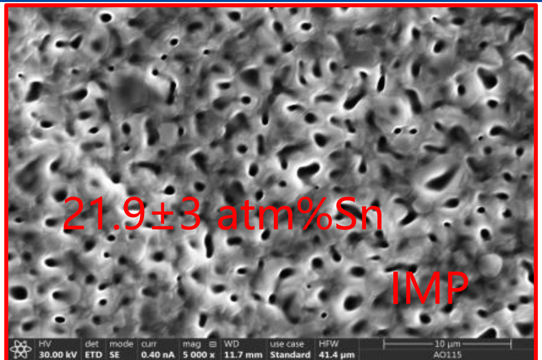


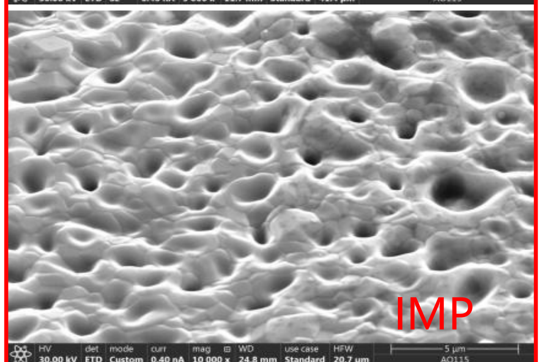


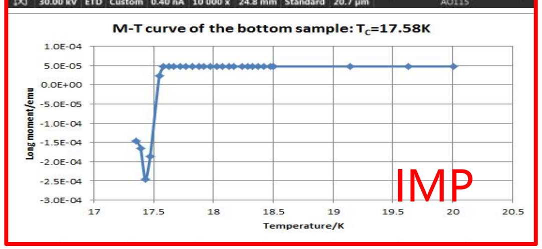
Covered with uniform Nb_3Sn thin film to the naked eye

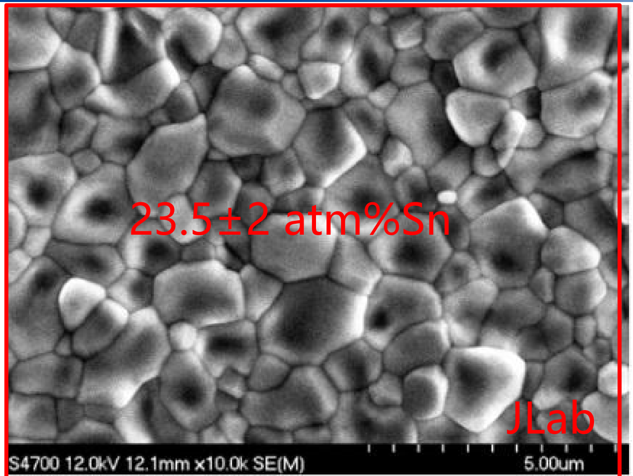
1. Much lower Q with Q slope; 2. 100^{0}C baking effects→ Mechanism and verification lately

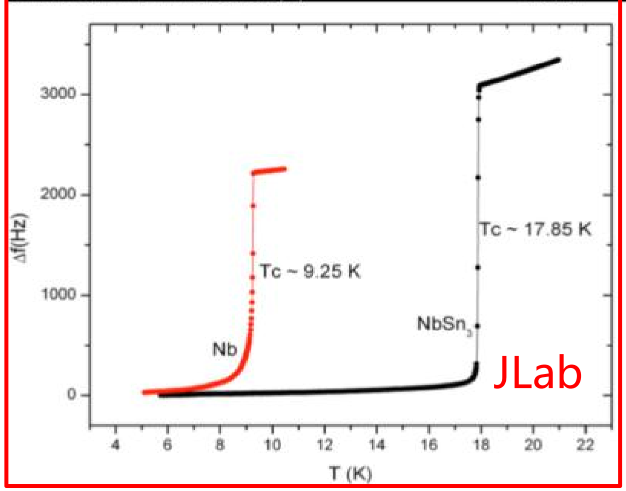
Sample Analysis

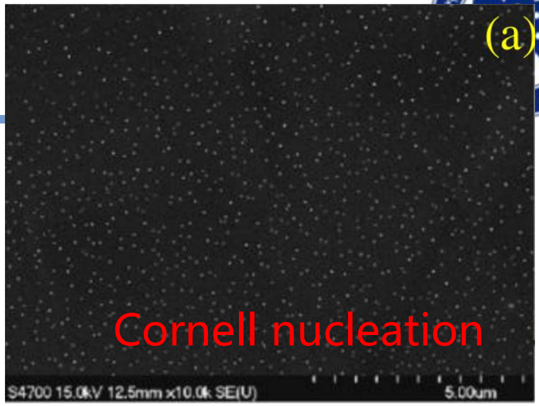


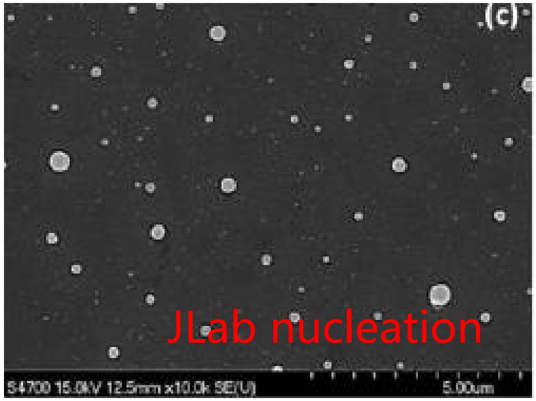


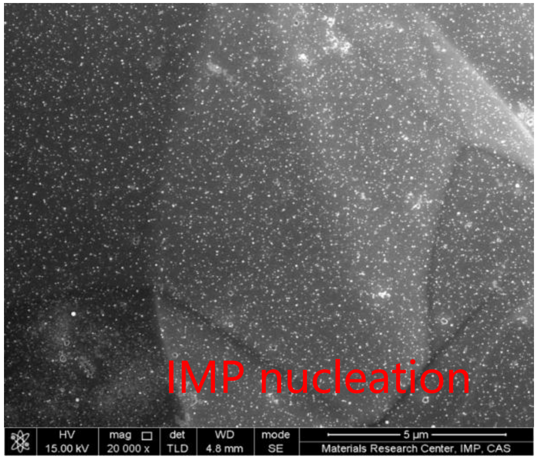






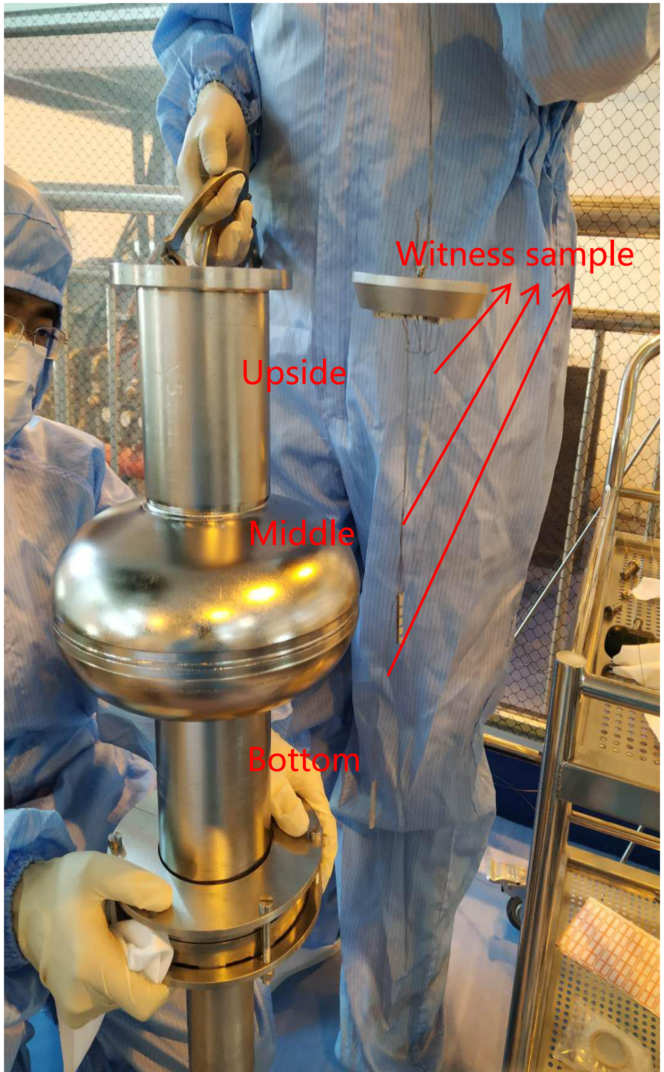


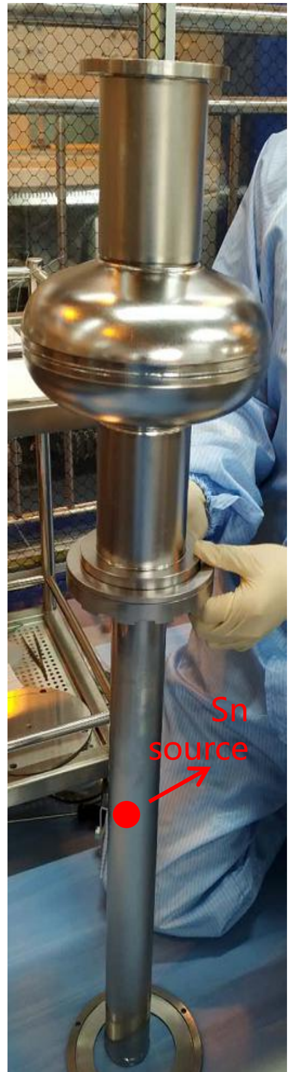




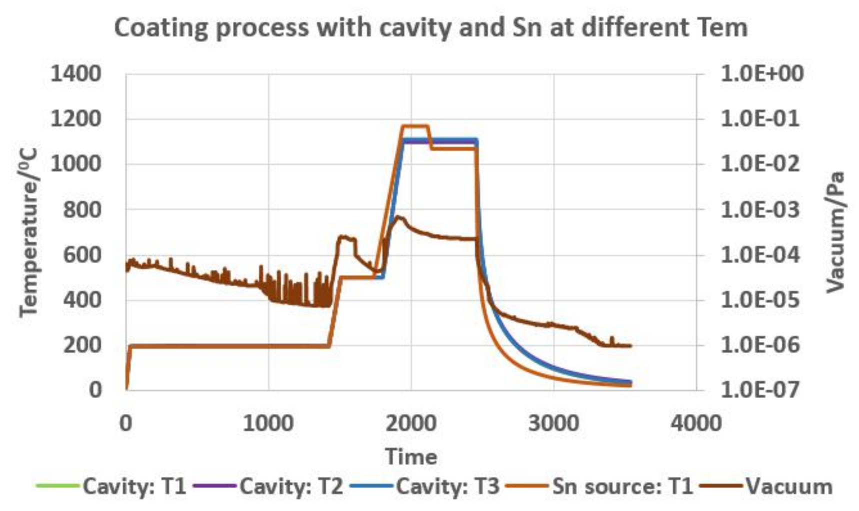
Sn content is low and rich of holes in IMP samples

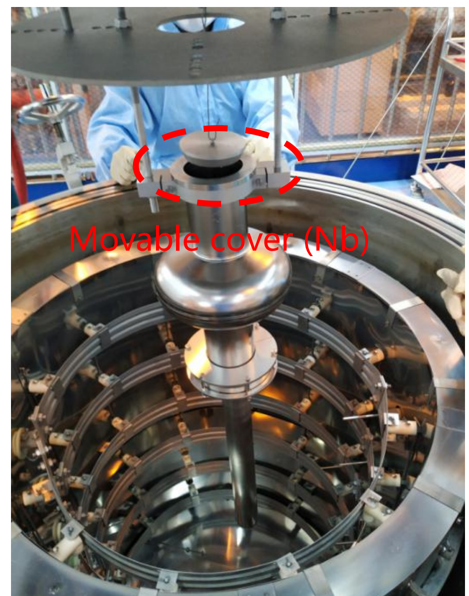
Coating with separate control of cavity and Sn





The same preprocessing as before

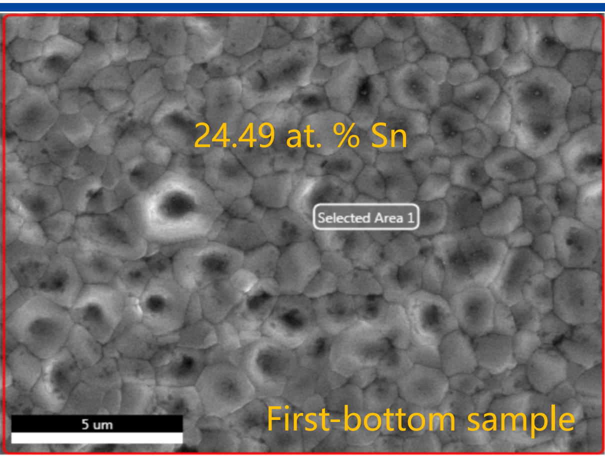


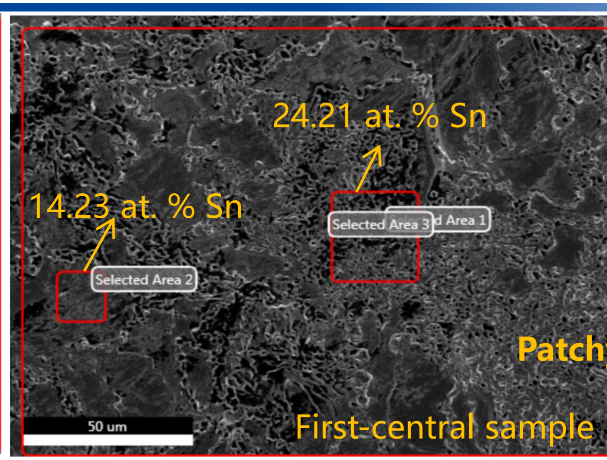


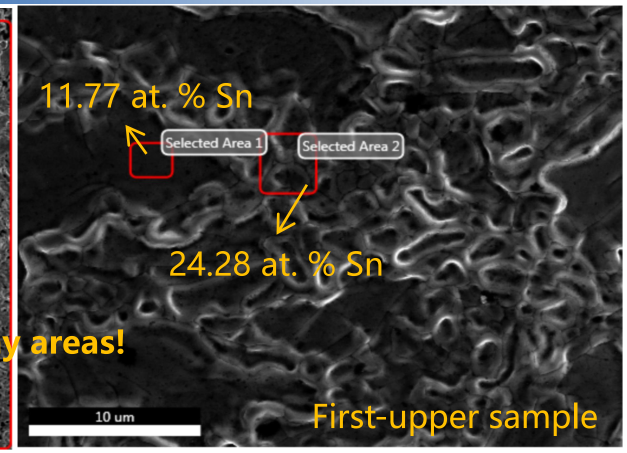
Recipe (based on Cornell) :

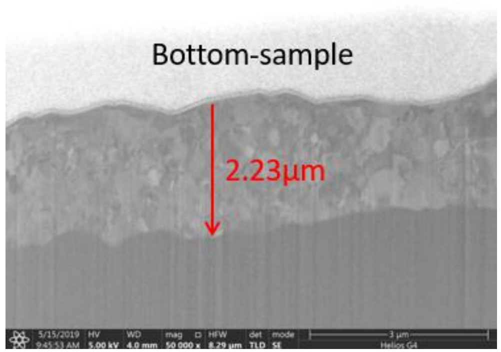
1. Degassing at 200⁰C for 24 hours;
2. Nucleation at 500⁰C for 5 hours;
3. Coating for 3 hours with Sn at1200⁰C & cavity at 1100⁰C;
4. Annealing at 1100⁰C for 6 hours;
5. Cool down naturally;

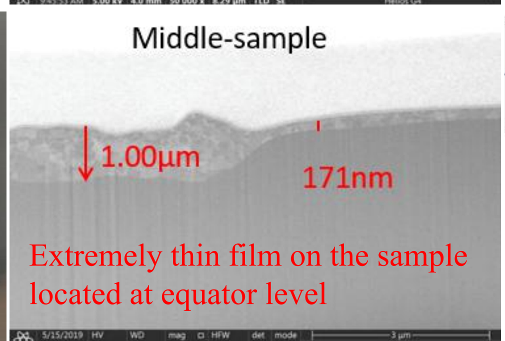
Non-uniform coverage due to unreasonable design

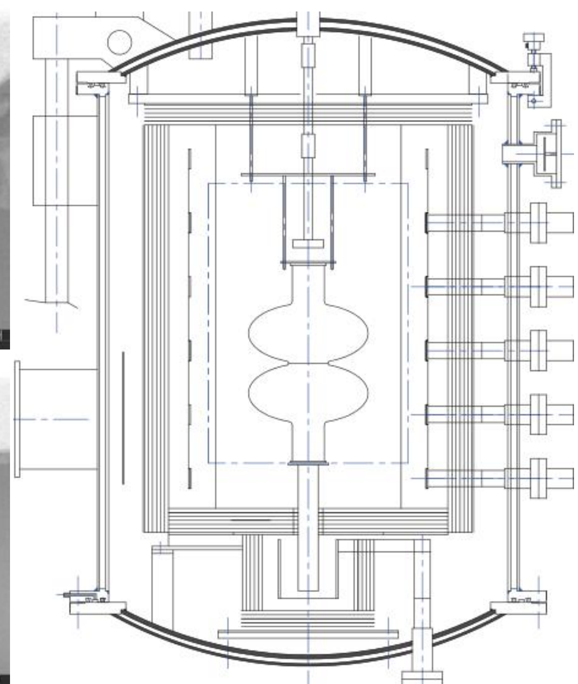






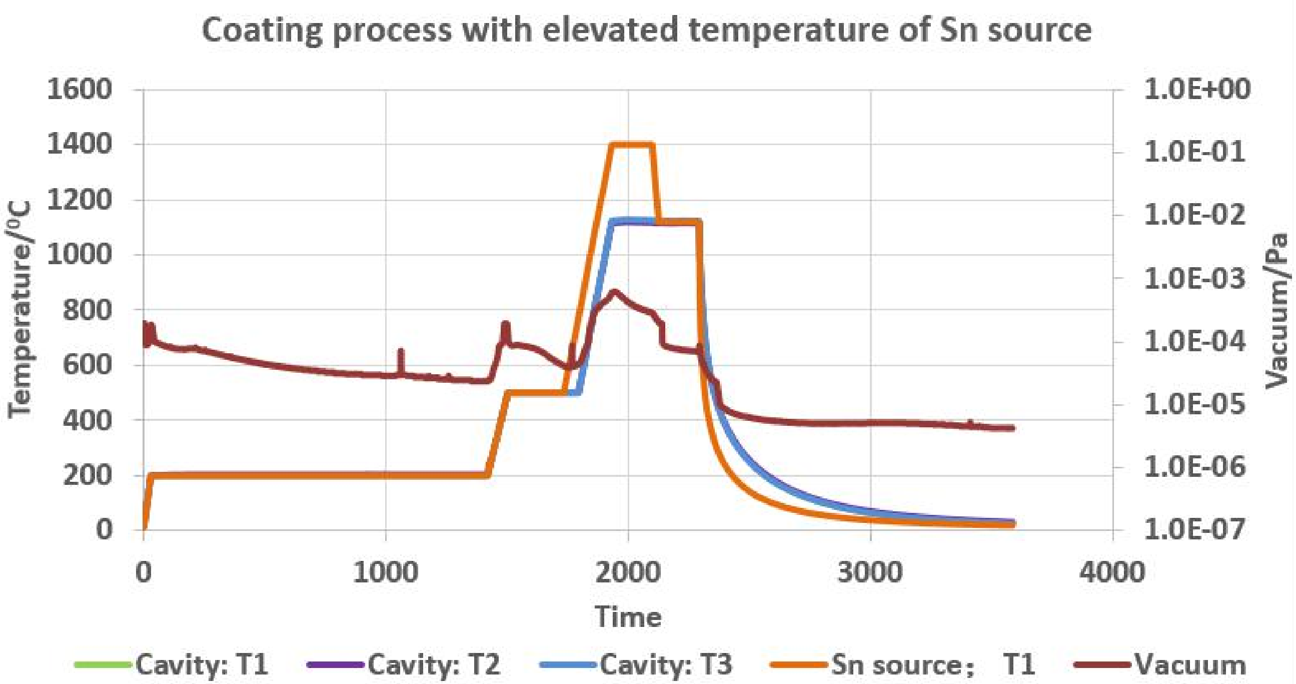


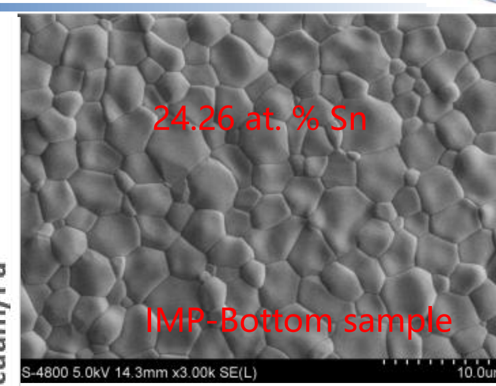


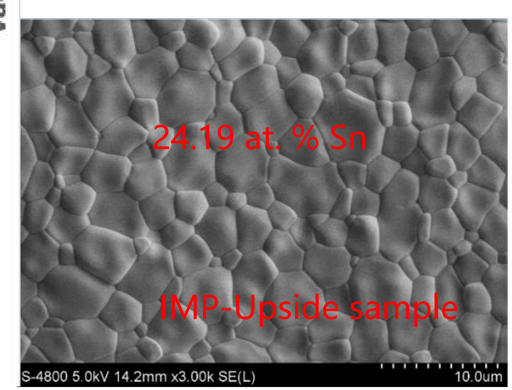


The distance between the Sn source and Nb cavity is too far, resulting in an obvious decrease of Sn pressure in the upside cell

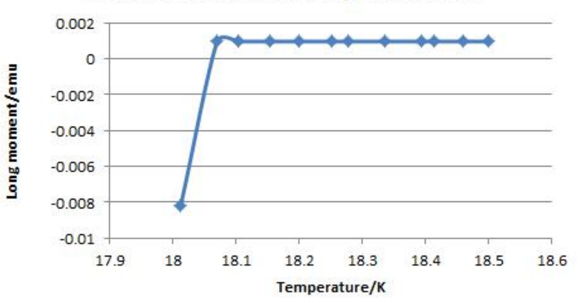
Coating with elevated temperature of Sn source



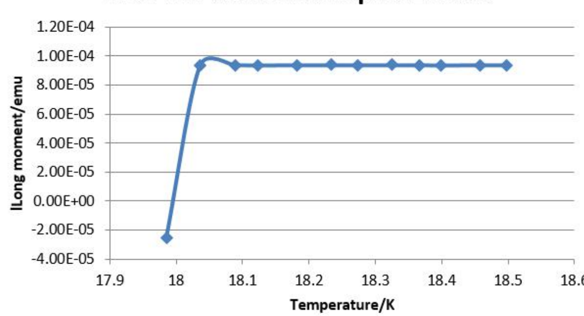




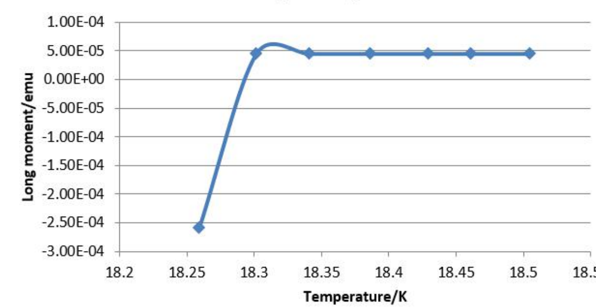
Tc of the middle sample: 18.07K



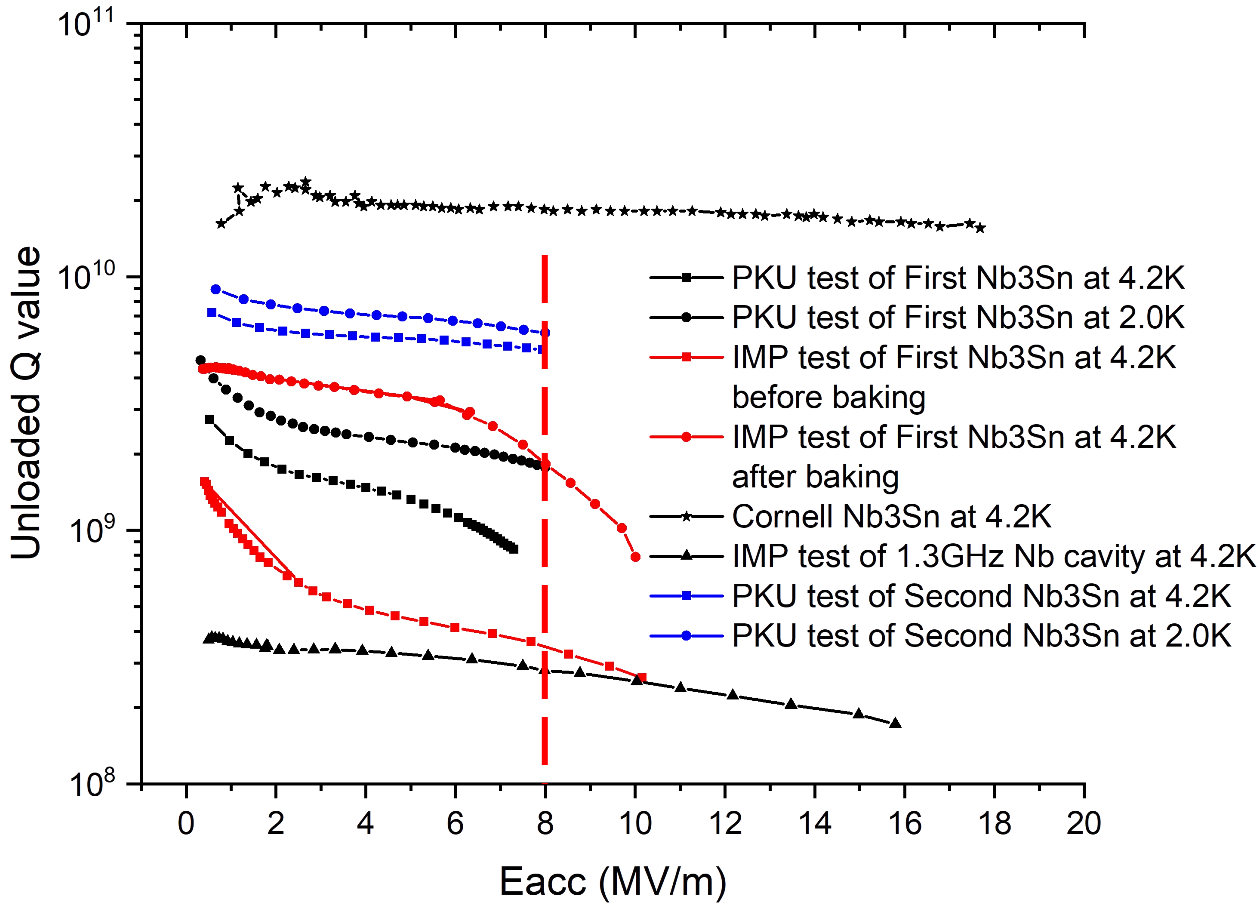
Tc of the bottom sample: 18.03K



Tc of the up sample: 18.3K

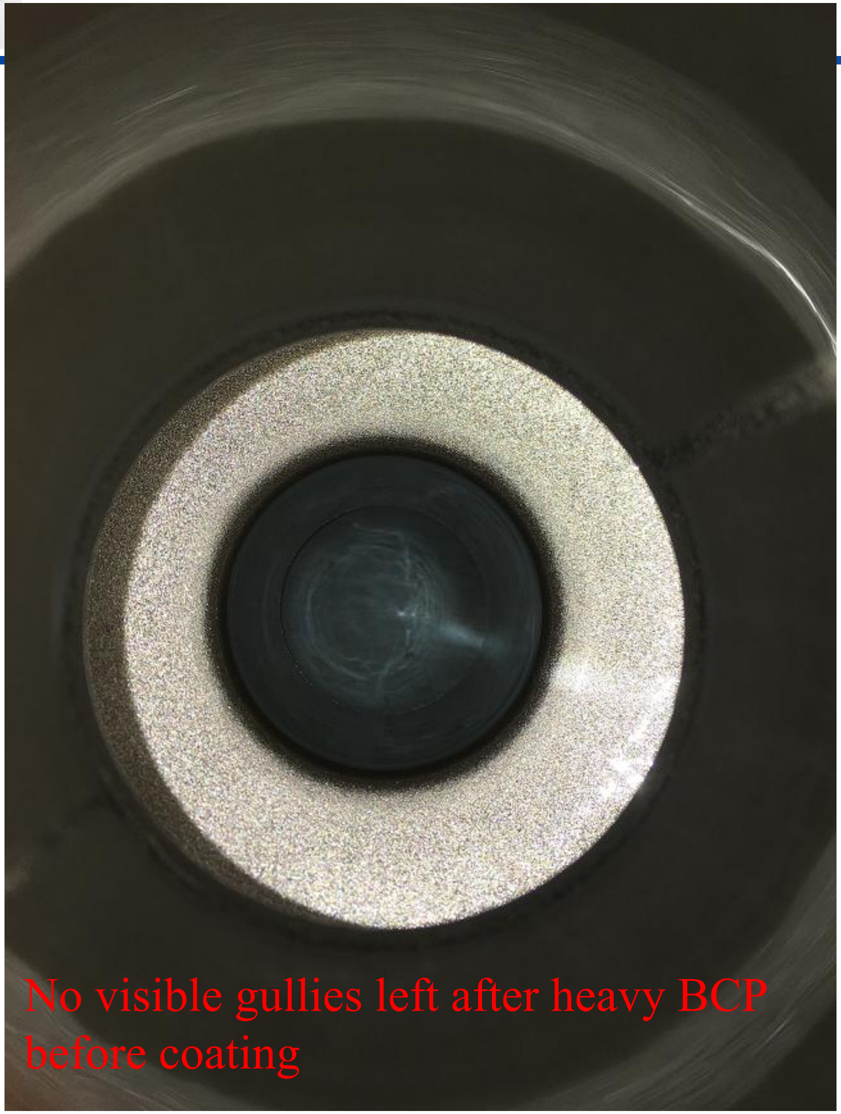


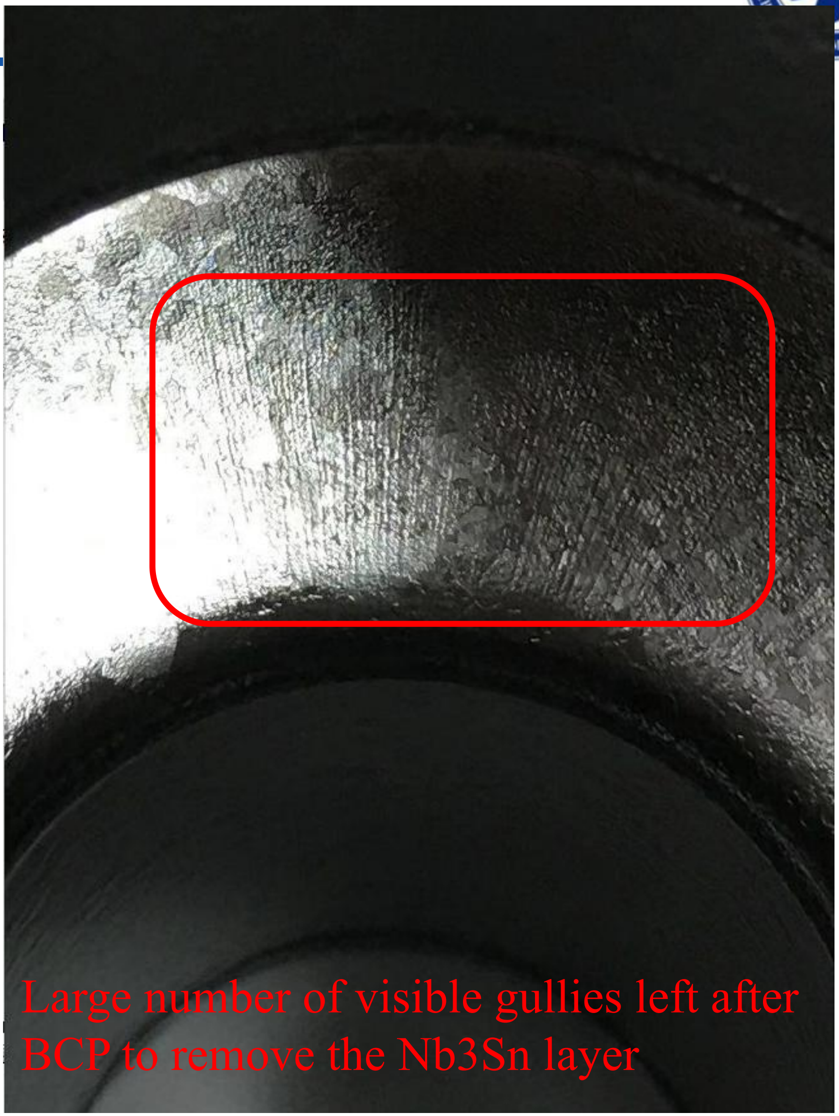
Cold test of the 6th coated Nb3Sn cavity



- Obvious improvement: Q_0~7.6e9 @ 4.2K @ low field region, quenched at Eacc=8MV/m with Q_0~5.5e9;
- Obvious performance gap: Q value is ~three times lower than Cornell value, Eacc,max is ~half of Cornell value;

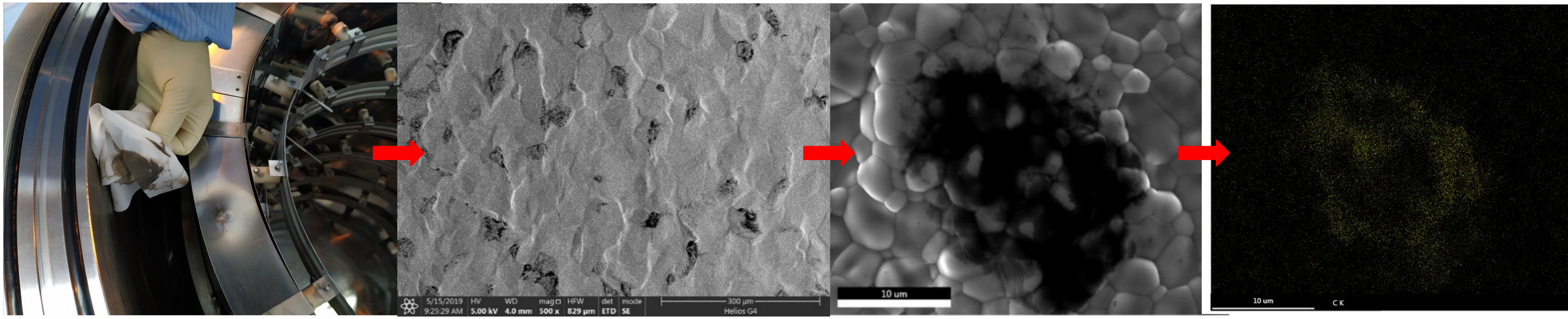
Defects were responsible to the early quench?



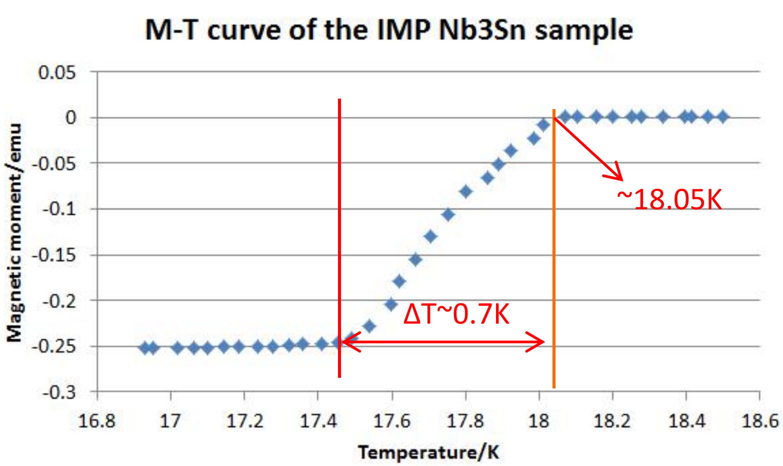


1. Removal of Nb3Sn by BCP needs special requirements and optimization; 2. More suspected caused by mechanical processing and deep-drawing.

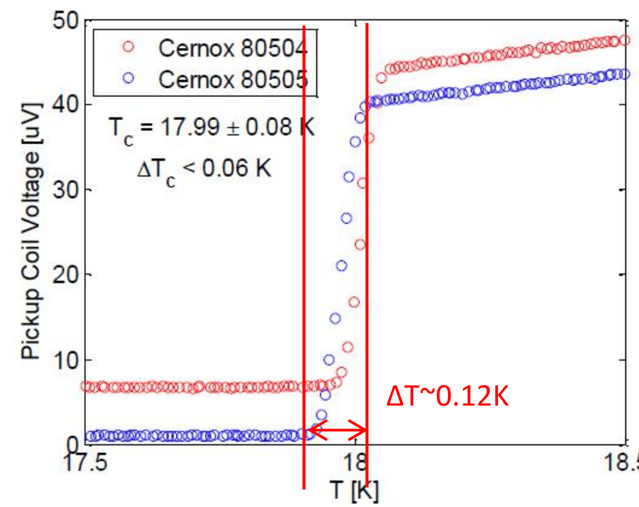
Badly contamination from carbon



No Nb coating chamber + No cleanliness during installation = Badly contaminated coating process!

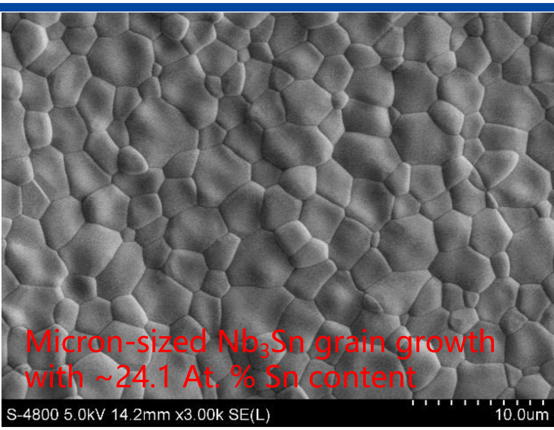


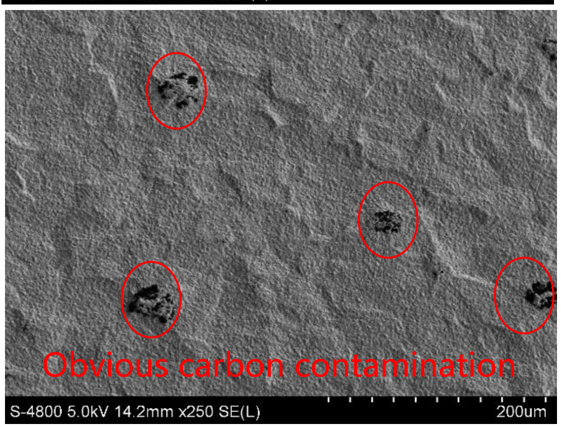
The transition width of IMP Nb3Sn is much larger than that of the Cornell



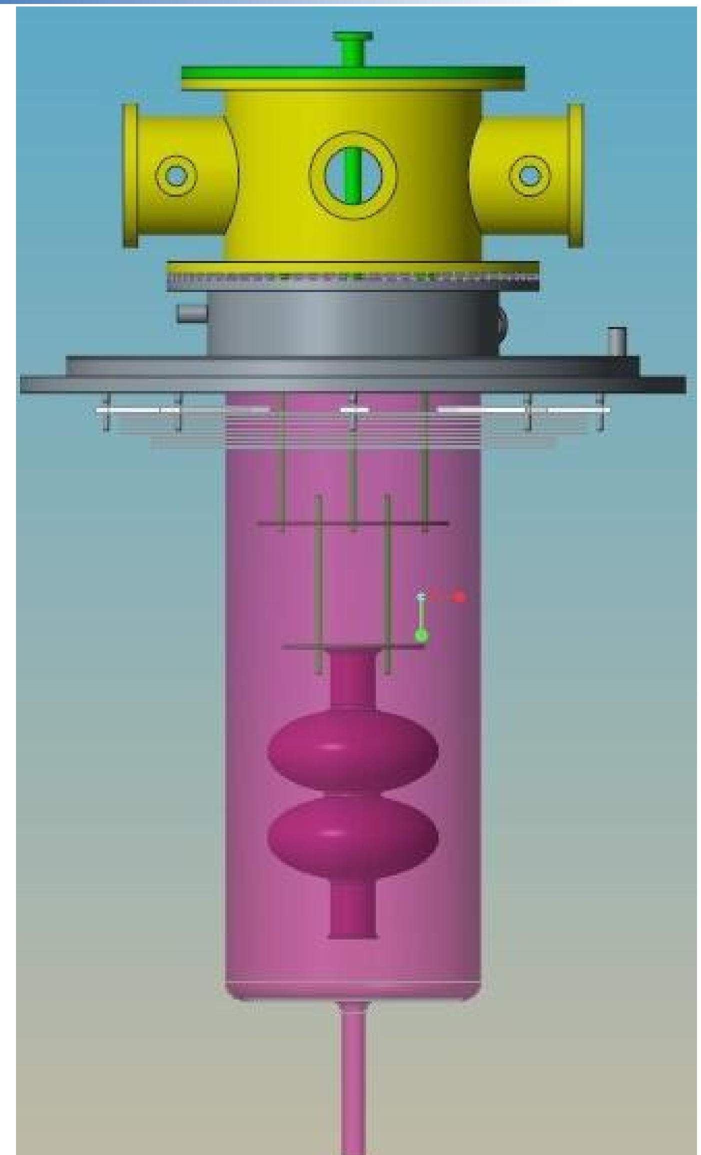
- ΔT depends on the purity of the material, the integrity of the crystal, and the stress state inside;
- The difference comes from the contamination, the coating process, or the test methods?

Urgent need for the upgradation



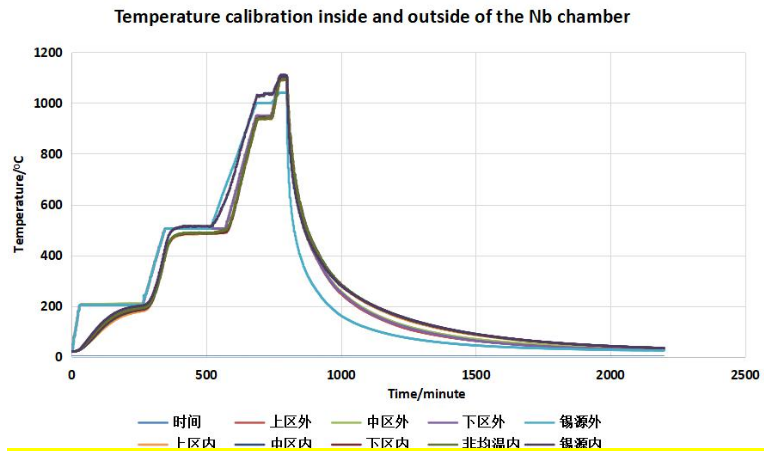


- Minimization of the contamination
- Vacuum-isolated Nb chamber was built
- Shortened distance between Sn and cavity
- Any part in the hot zone were made by W or Nb



Upgradation of the deposition system

The deposition system after upgradation

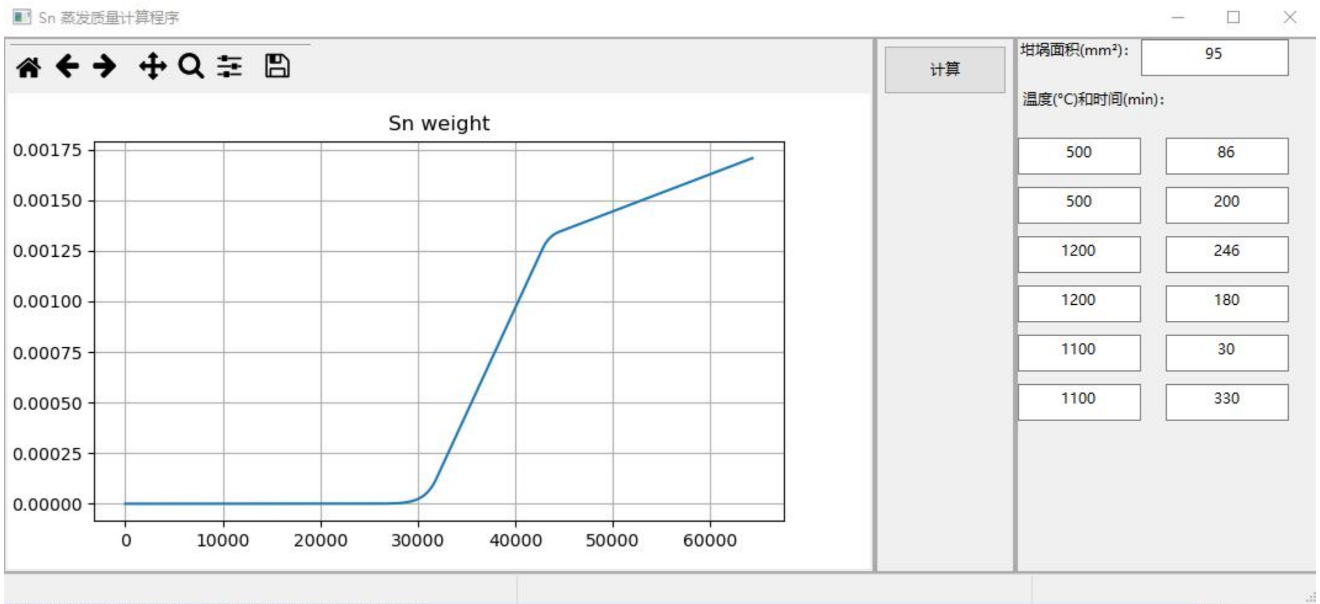


Callibration of the temperature by K-type thermocouples

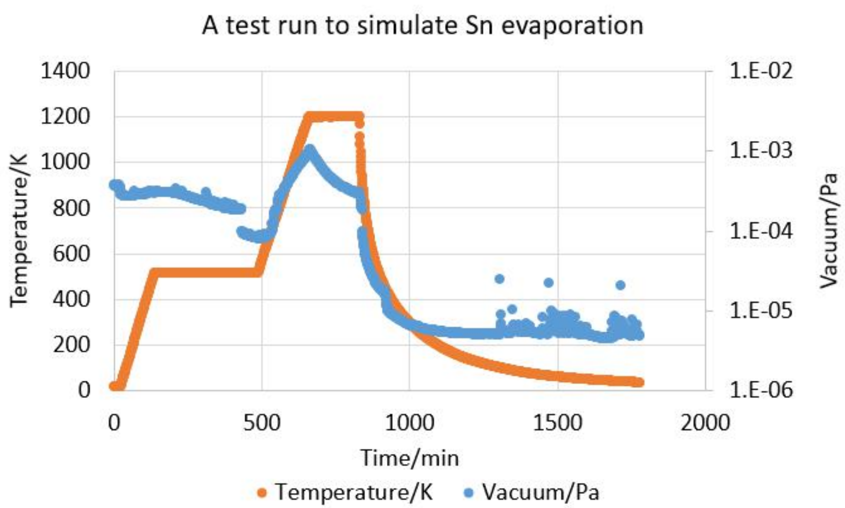
Temerature difference within 10^0C at 1100^0C

Background pressure reached 6.5e-5Pa at 1100^0C

Simulation of the Sn evaporation



- Simulation interface
- Sn evaporation below 500^0C and during cooldown was negleted



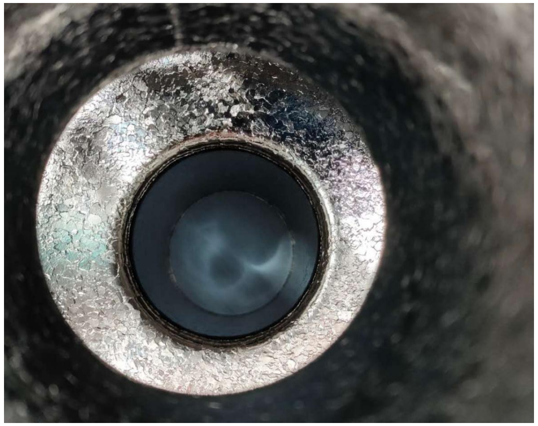
- Actual evaporation from weighing was 0.9262g;
- The simulated value was 0.9483g;
- Error of ~ 2.4%

Recent coating after the upgradation

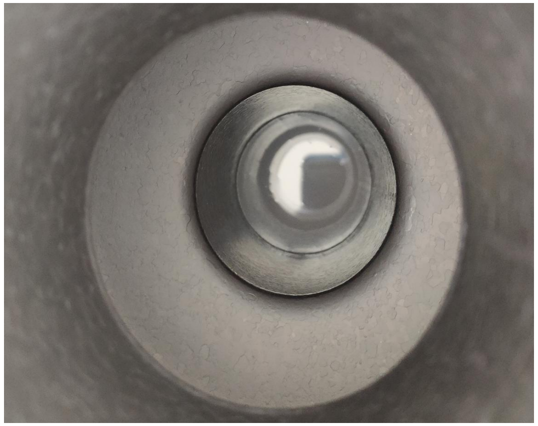
Lowered into the furnance after the upgradation

Callibration by k-type thermocouple		
T outside	T inside	△T
1040	1105	65
1050	1114	64
Simulation results		
1135	1198	63

The calculated △T was 63^{0}C, agrees well with the callibrated △T of 64-65^{0}C

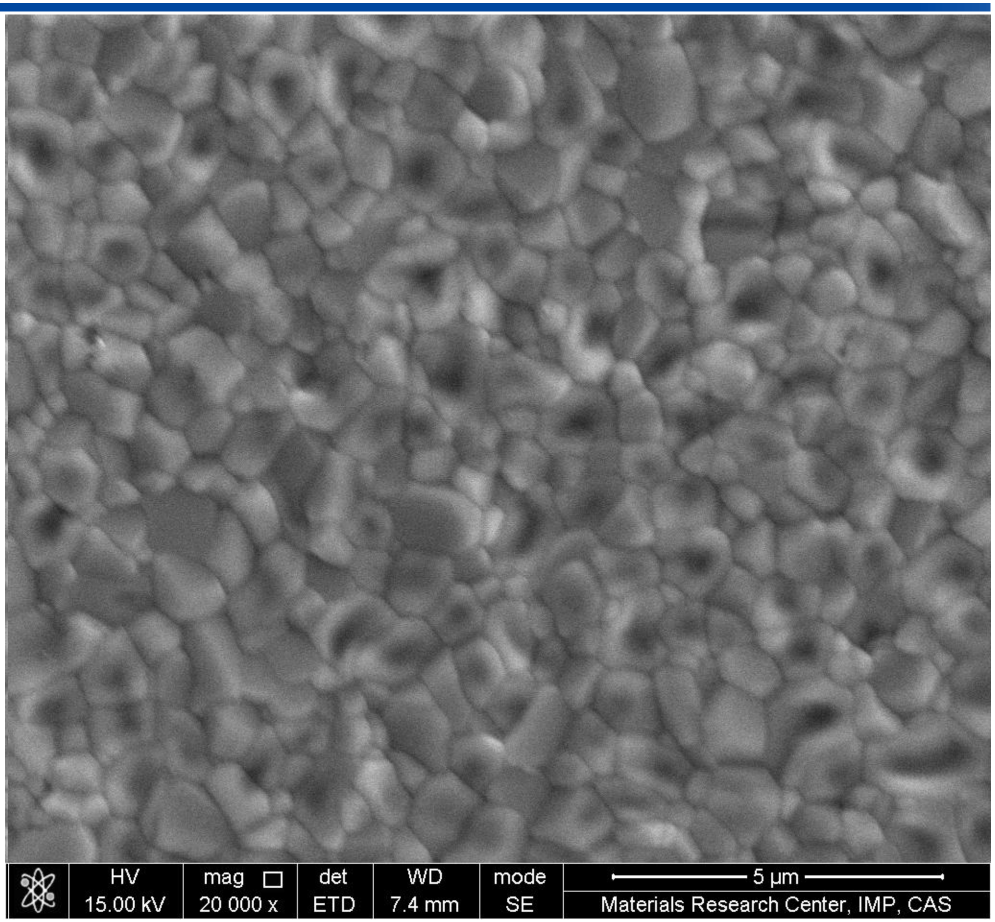


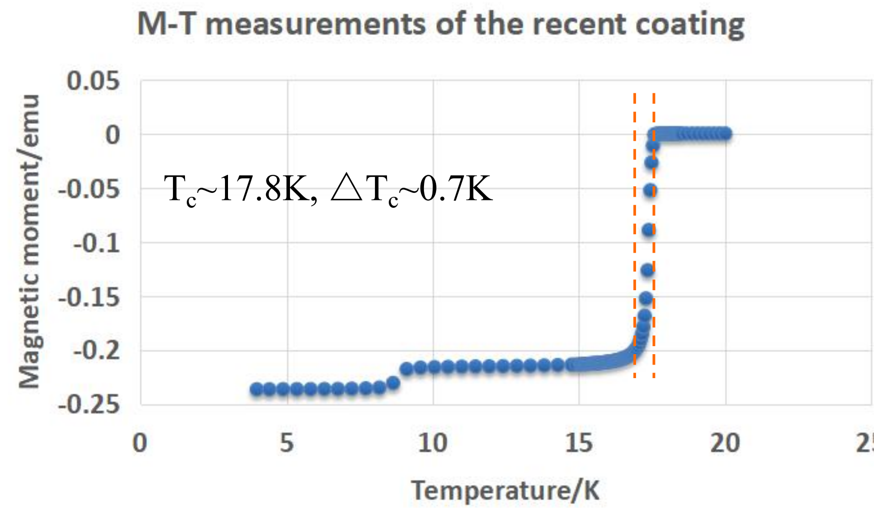
Obvious grain growth after many times of experiments

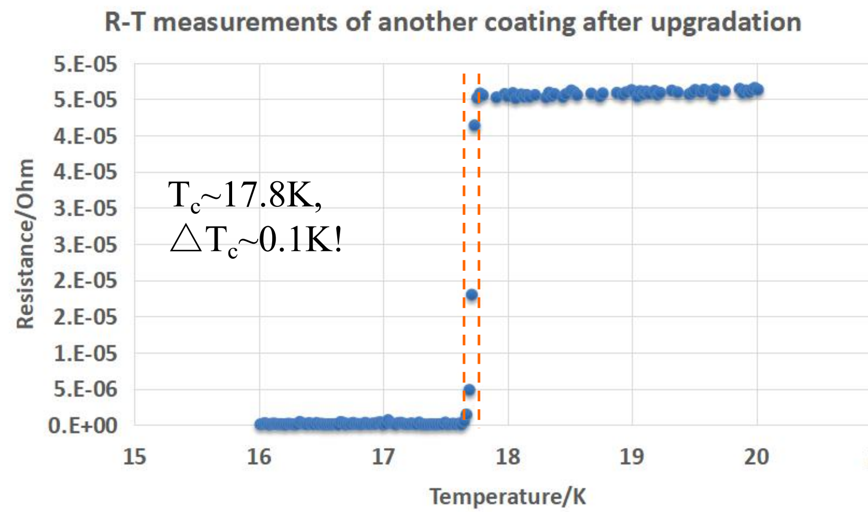


Typical matte grey inner surface after coating

Analysis of the Nb_3Sn film







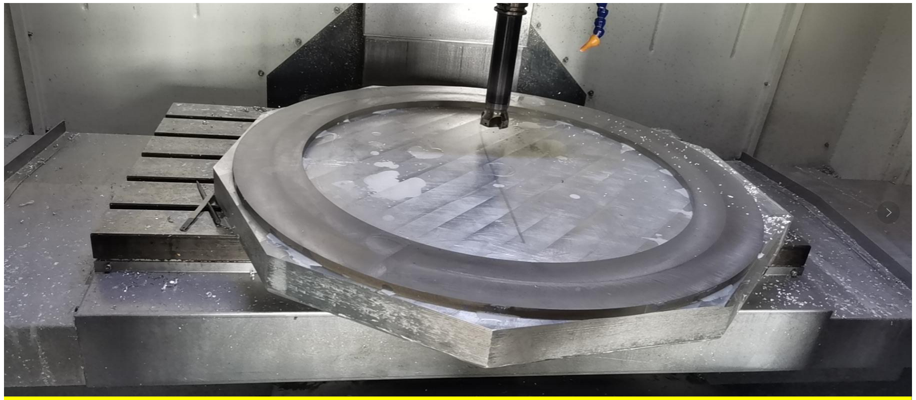
1. No carbon cmination any more;
2. Average Sn content ~23%;
3. The Sn temperature should be elevated slightly.

1. T_c was lower than 18K;
2. $\triangle T_c$ of M-T measurements was still ~0.7K;
3. $\triangle T_c$ of R-T measurements was only ~0.1K;

The newly coated cavity is being prepared for vertical test

Production-type Nb_3Sn Coating Apparatus

Body being processed and assembled



Flange of the Nb chamber

Maching of the Nb chamber after deep drawing

1. Application oriented and capable of coating production-type cavities such as 650MHz 5/6 cell or 1.3GHz 9-cell cavities;
2. Expect the Installation and commissioning to be completed before the Spring Festival and the coating experiment can be carried out in the first half of 2021.

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Conclusion

- Before the upgradation:
  1. Q_0 and Eacc was lower→limit factors were explored;
  2. Coating experience and understanding was accumulated;
  3. The deposition system has been upgraded;

- After the upgradation:
  1. Carbon contamination has been excluded;
  2. Exact temperature calibration has been obtained;
  3. Coating experiment has been carried out;
  4. Low temperature baking effects will be examined and verified in the near future;

- Production-style furnance:
  1. The first multi-cell Nb3Sn cavity would be expected to be coated in the first half of 2021.

Thanks for your attention.
Welcome worldwide cooperation!