Plasma in-situ cleaning for low beta HWR cavity

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(2018-06-12)

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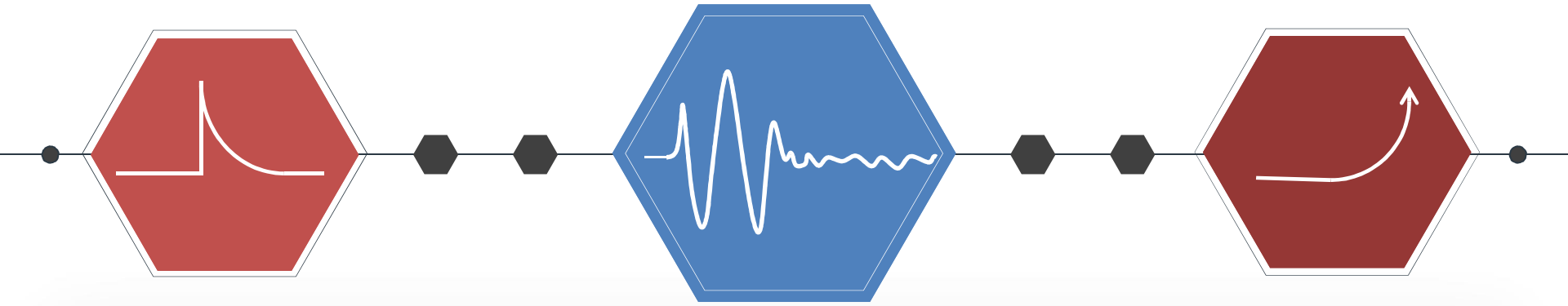
Content

- Background
- Sample study and work function
- Contamination and plasma cleaning on VT
- Conclusion

Background

- **The electron loading effect degrades SRF performance**



Vacuum degradation

Residual gas

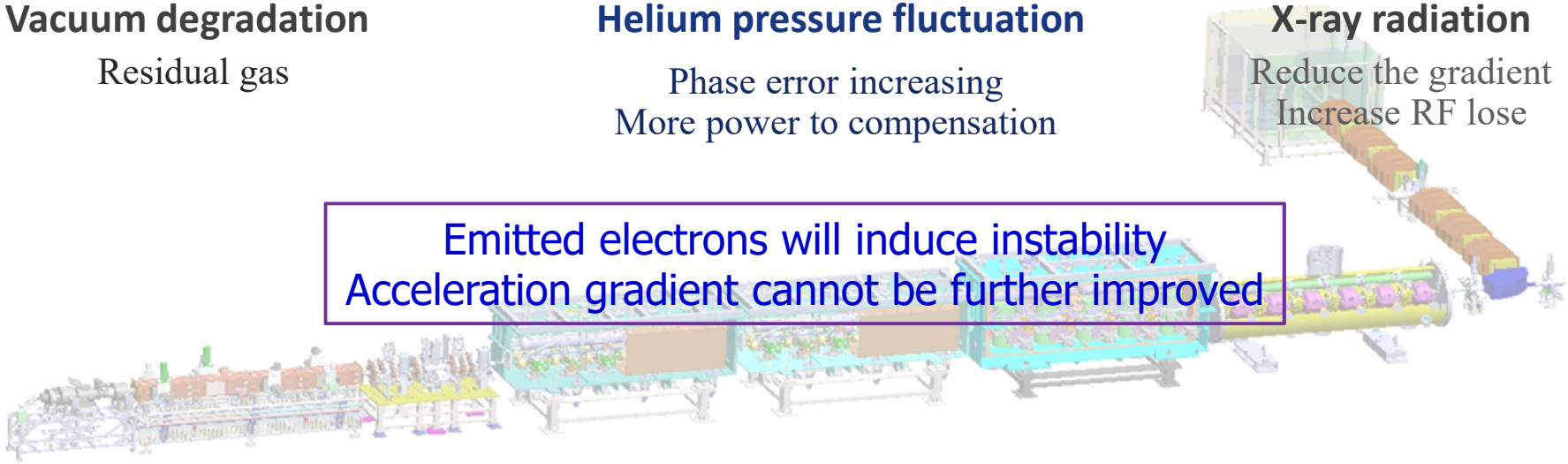
Helium pressure fluctuation

Phase error increasing
More power to compensation

X-ray radiation

Reduce the gradient
Increase RF lose

Emitted electrons will induce instability
Acceleration gradient cannot be further improved



Background

➢ Surface property and field emission current

Emission electron current

From Fowler-Nordheim equation:

$$J = a\frac{(\beta E)^2}{\phi}\cdot\exp(-b\frac{\phi^{3/2}}{\beta E}+\frac{c}{\phi^{1/2}})$$

Where: $a = 1.54\times10^{6}$

$b = 6.53\times10^{3}$

$c = 10.4$

and β: field enhancement factor

ϕ: electron work function

For $\Delta J = 0 \Rightarrow \frac{dE_{acc}}{E_{acc}} = \frac{3}{2}\frac{d\phi}{\phi}$ [M. Doleans *et al*, 2013]

β Physical morphology

- Cavity surface preparation

  reduce surface roughness（EP~133nm, BCP~286nm） [M. Raskovic *et al, 2010*]
- Condition online, modify local sharp

  High Pulse Power/Helium condition[J. Knobloch *et al*, 1999]

ϕ Chemical state

- Niobium Oxide [A.T. Wu *et al,* 2011]
- C-H contamination [P.V. Tyagi *et al,* 2016]
- Gas absorption [R. Ballantini *et al*, 1999]

Reducing surface roughness and improving work function can relieve emission current

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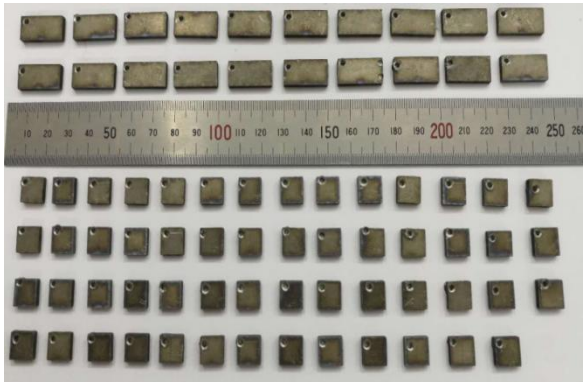
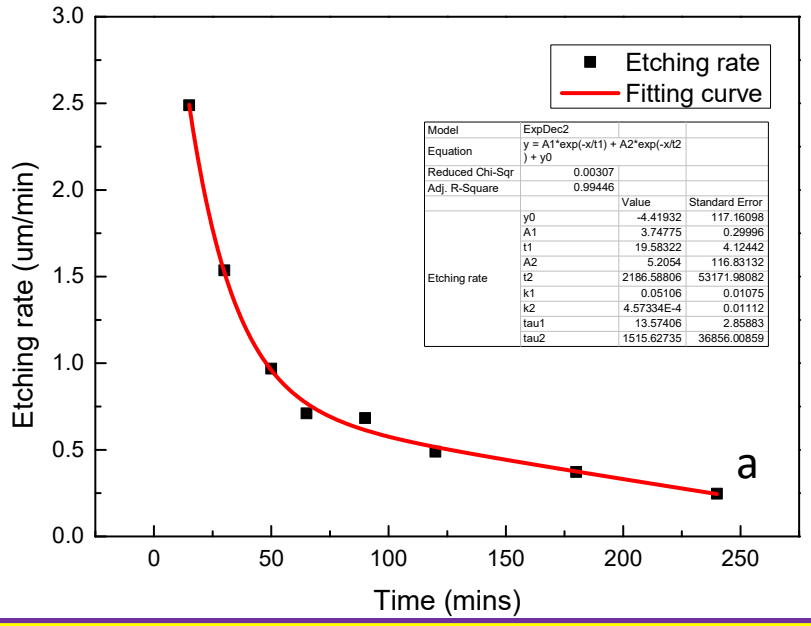
Sample preparation

- **BCP & heating treatment**
- BCP Followed by the SC cavity standard processing
- HF：HNO3：H3PO4 = 1:1:2
- Temperature control: T <18°C during BCP
- Heating treatment parameters: 600°C x 10 hours





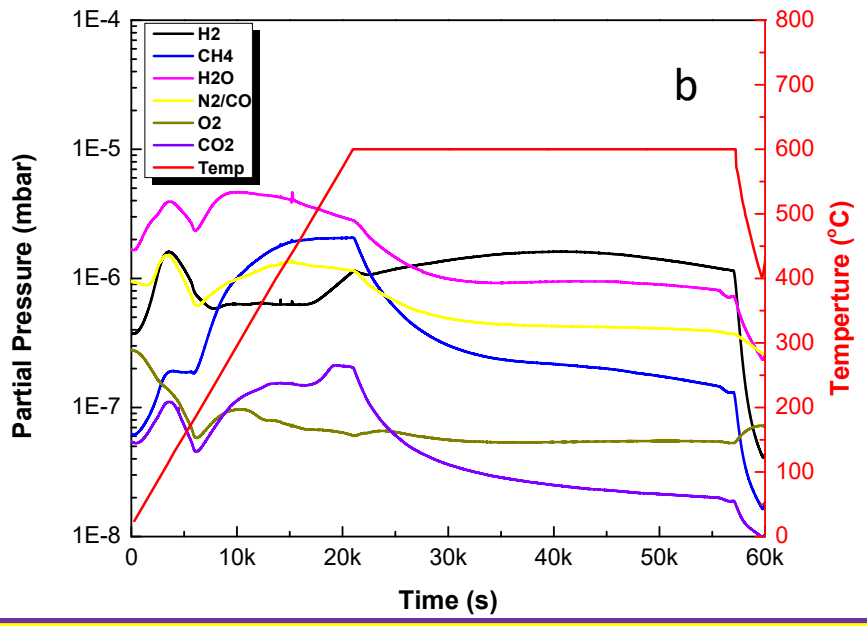
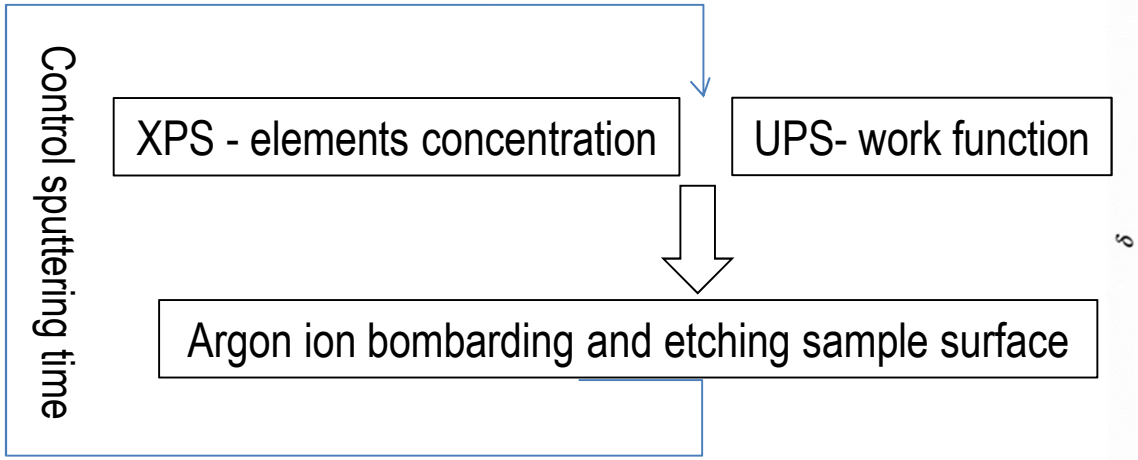
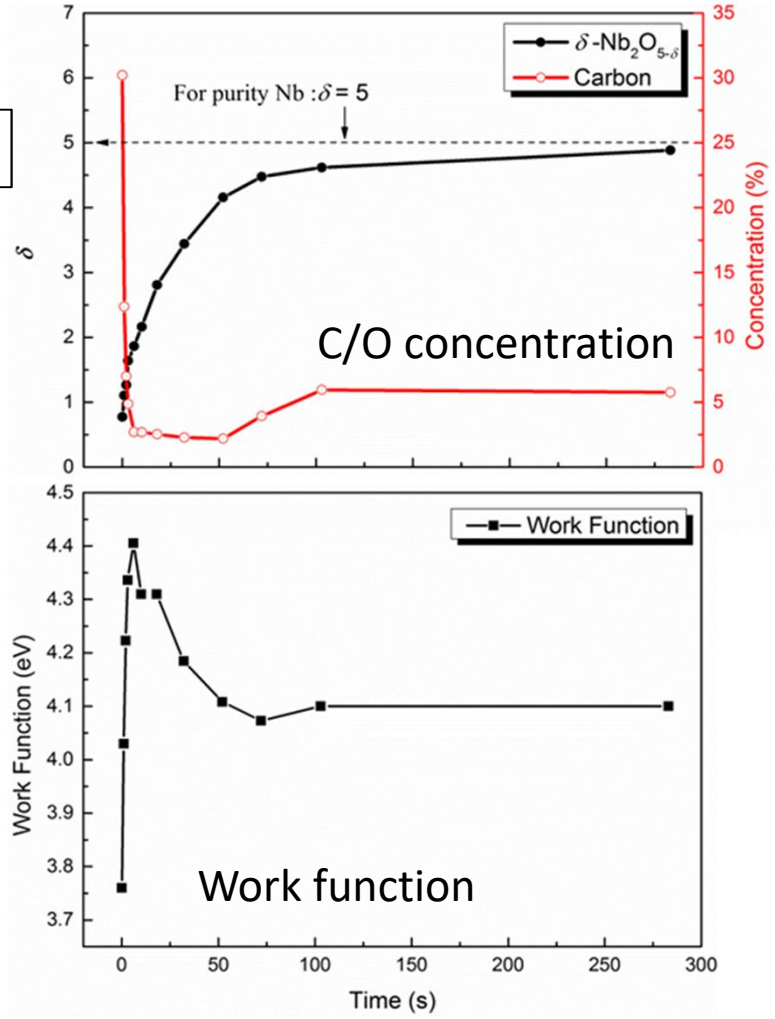


Fig. (a) During BCP, etching rate decays exponentially with time. (b) Residual gas precipitation during heating processing

Surface analysis

➢ Work function vs. elements concentration



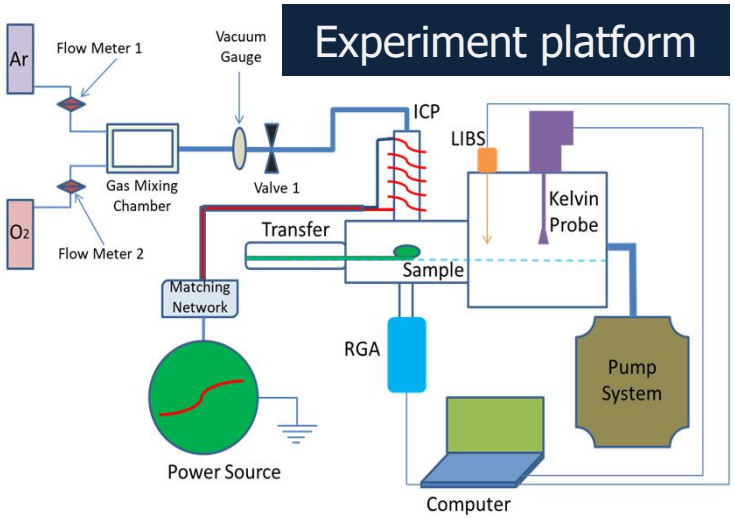


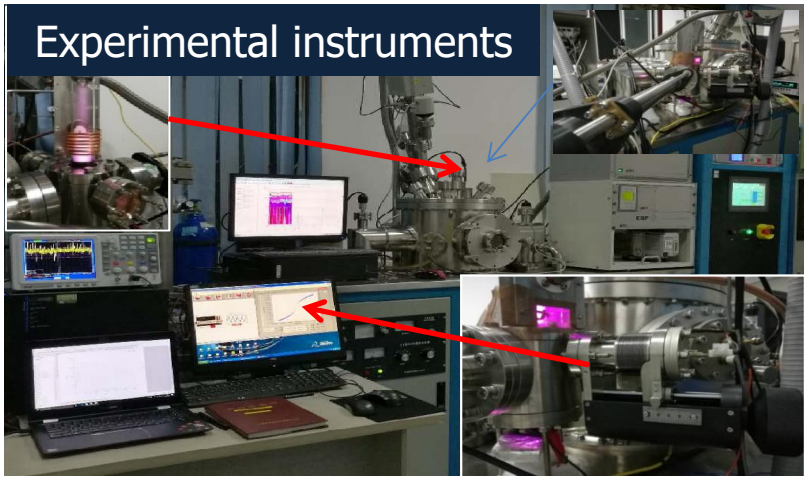
The number concentration rate of niobium and oxygen elements was normalized to the δ in the formation of $Nb_2O_{5-\delta}$. Φ_{Nb2O5}=5.2eV.

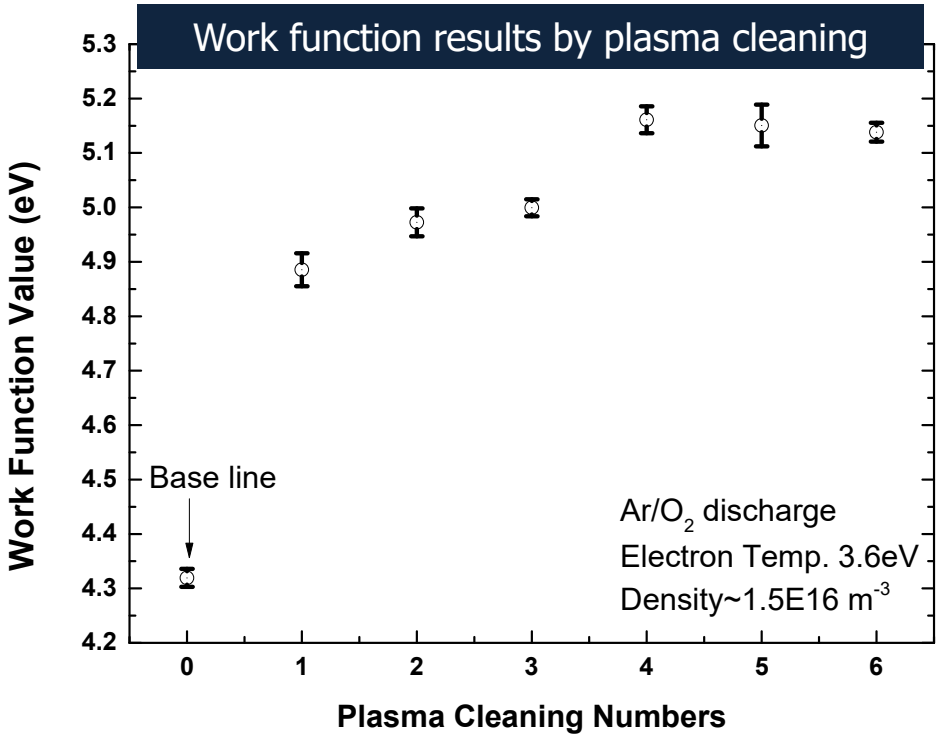
$$\frac{2}{5-\delta} = \frac{C_{Nb}}{C_O}$$

Carbon contamination largely degrease the work function value, but niobium oxide increase the value

Plasma cleaning on samples







1. The property of ICP source for the sample cleaning study was similar with discharge on the Taper HWR cavity, Te~1eV and ne~1E16m^{-3}
2. Sample cleaning reveals that Ar/O2 plasma can largely improve the work function value of niobium.

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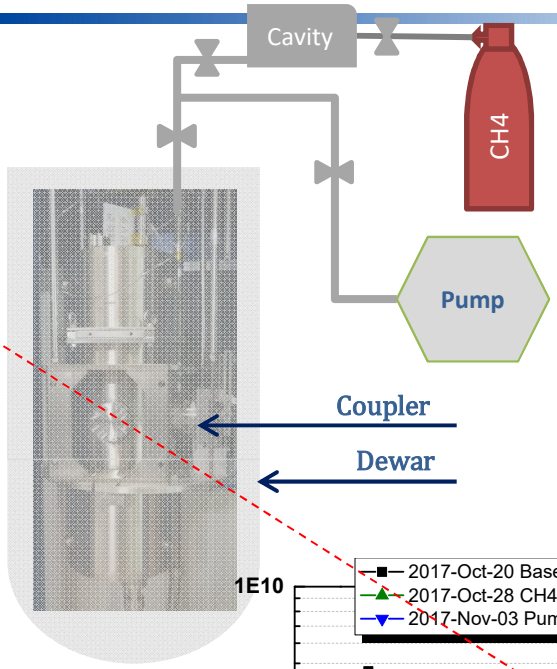
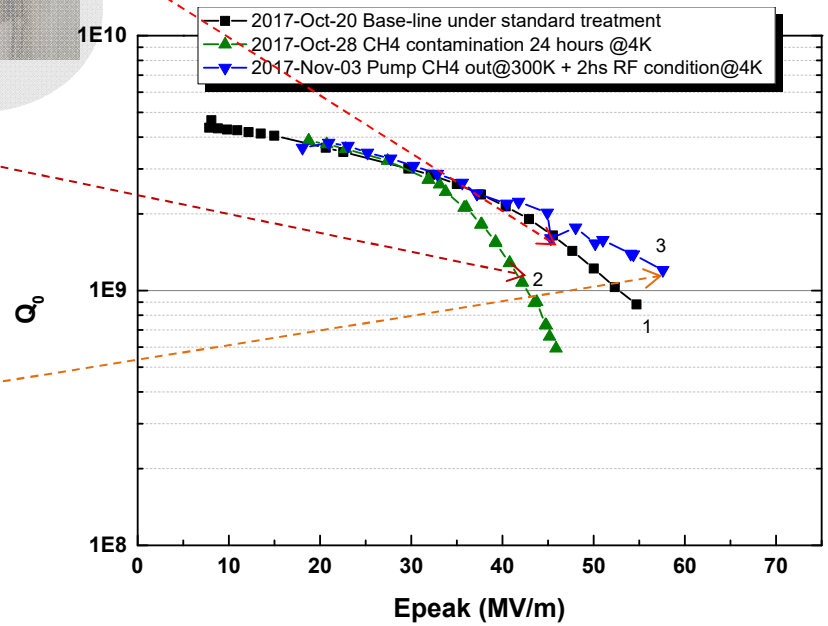
Contamination by cryogenic adsorption

Standard surface processing
Cooling down 4K
Vertical Test
Cycle to 300K
CH4 inlet-11mL X 3h
Cooling down 4K
Keep 4K X 24 h
Vertical Test
Cycle to 300K
CH4 pumping out
Cooling down 4K
Vertical Test

Base line
Contamination ?
Influence ?



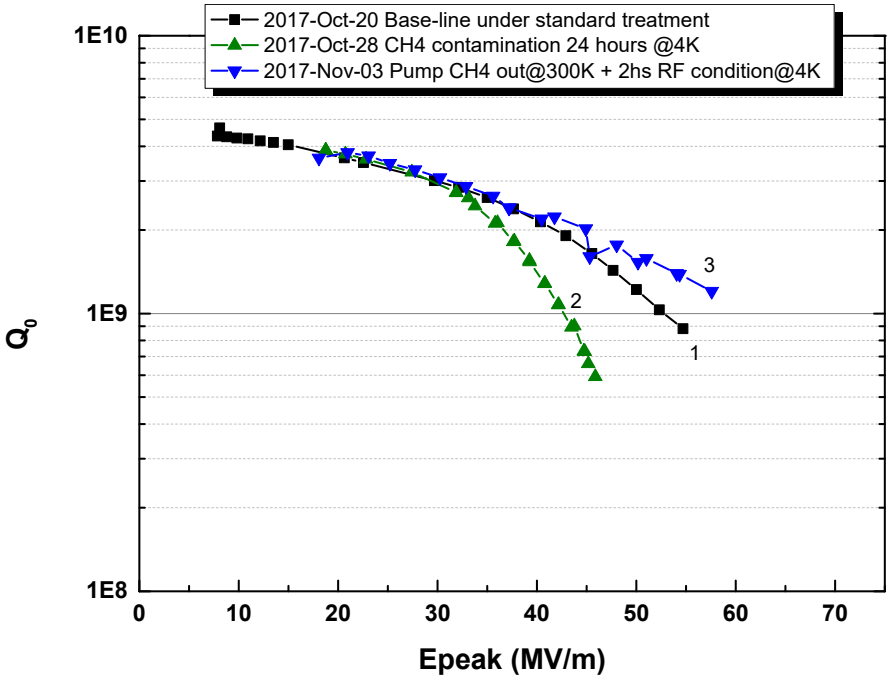


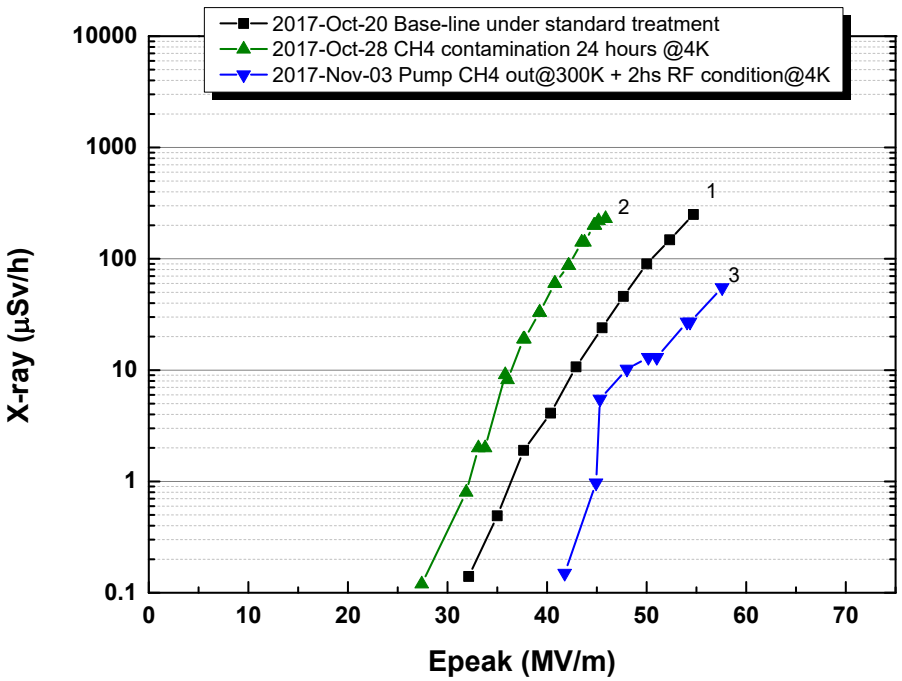
Experimental set-up for CH4 cryogenic absorption

Carbon contamination on SC cavity

➢ Carbon cryogenic absorption results

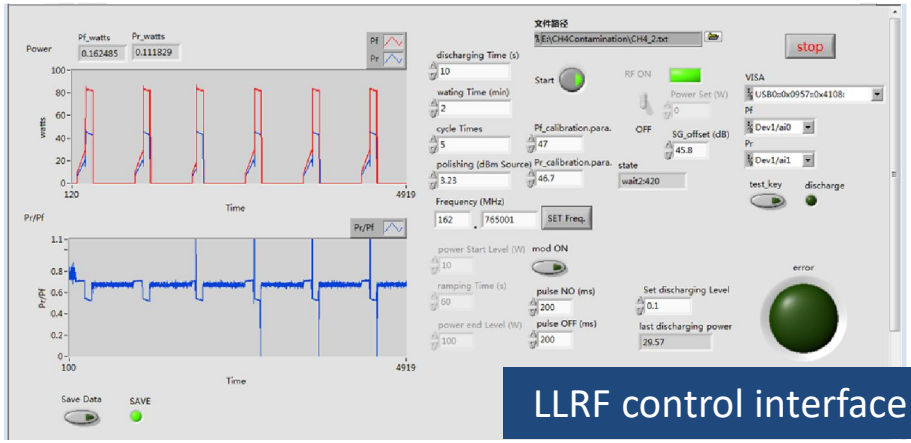
- carbon cryogenic absorption enhanced FE in SC cavity, which is in accordance with the degradation of work function of Niobium sample.
- This type of contamination can be eliminated by the thermal cycle to room temperature.
- **Speculation:** the performance degradation of the accelerator after long time running is related to the carbon chemical deposition.

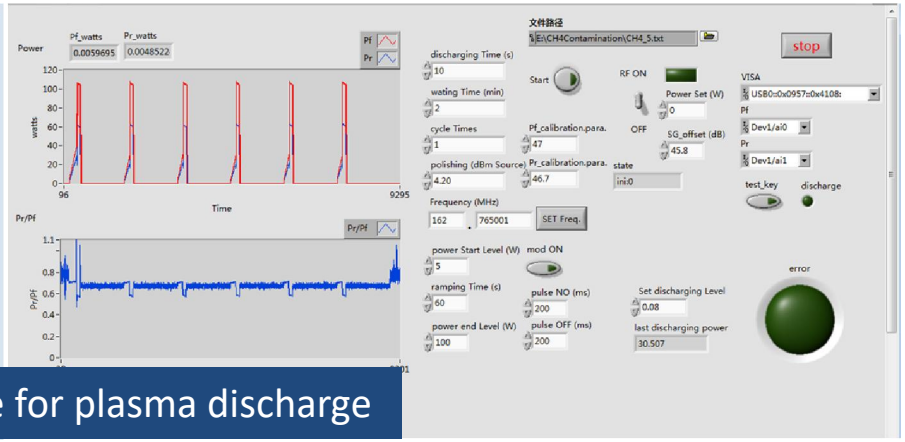




Experiment on carbon chemical deposition

- **Ar/CH4(3%) deposition by plasma**
  - $CH_4 \xrightarrow{\text{Plasma}} CH_3$
  - CH3 active groups react with Niobium surface
- **Experiment parameters**
  - Processing time: 10 mins
  - RF power: 80~100W





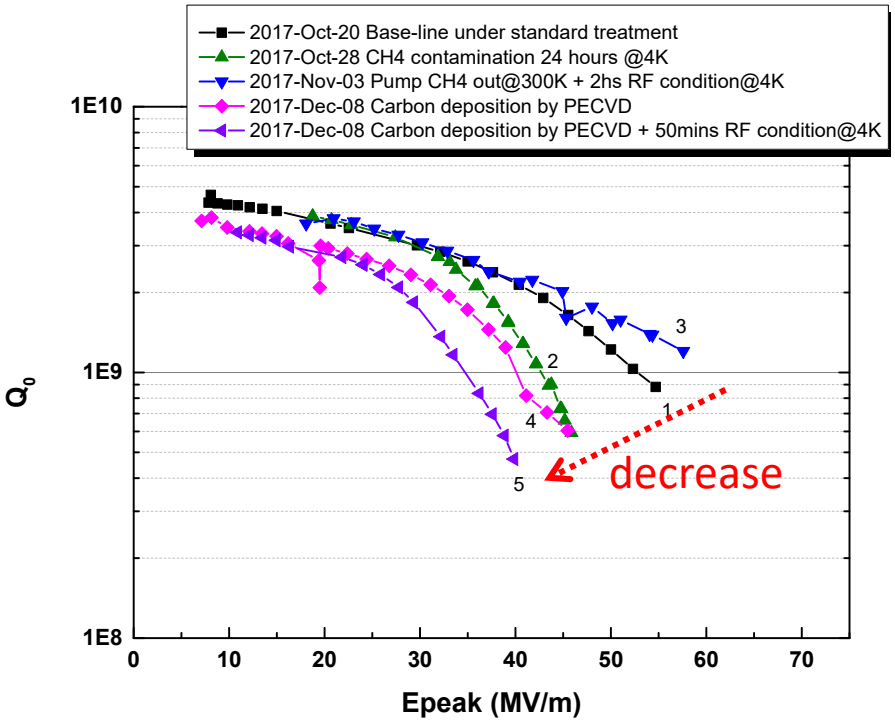
LLRF control interface for plasma discharge

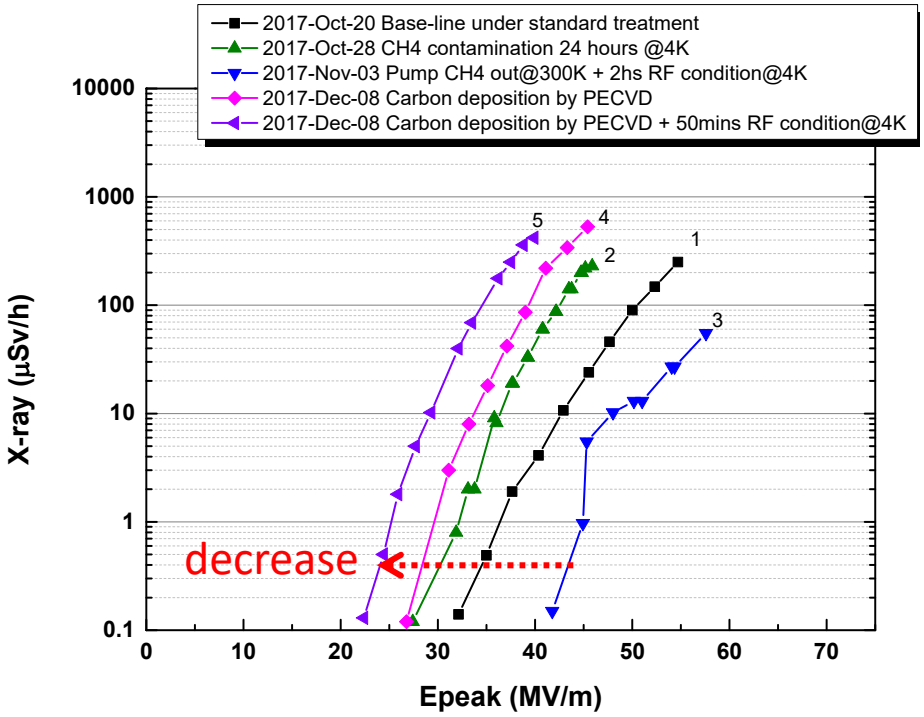
Method： Carbon PECVD with the help of RF plasma

Carbon contamination on SC cavity

➢ Carbon chemical deposition results

- Max Epeak and FE set-point decreased because of carbon deposition.
- MP effect appeared around 16MV/m.
- Additional RF power processing degraded the performance further. It might be because the carbon contamination transferred to strong electric field region.

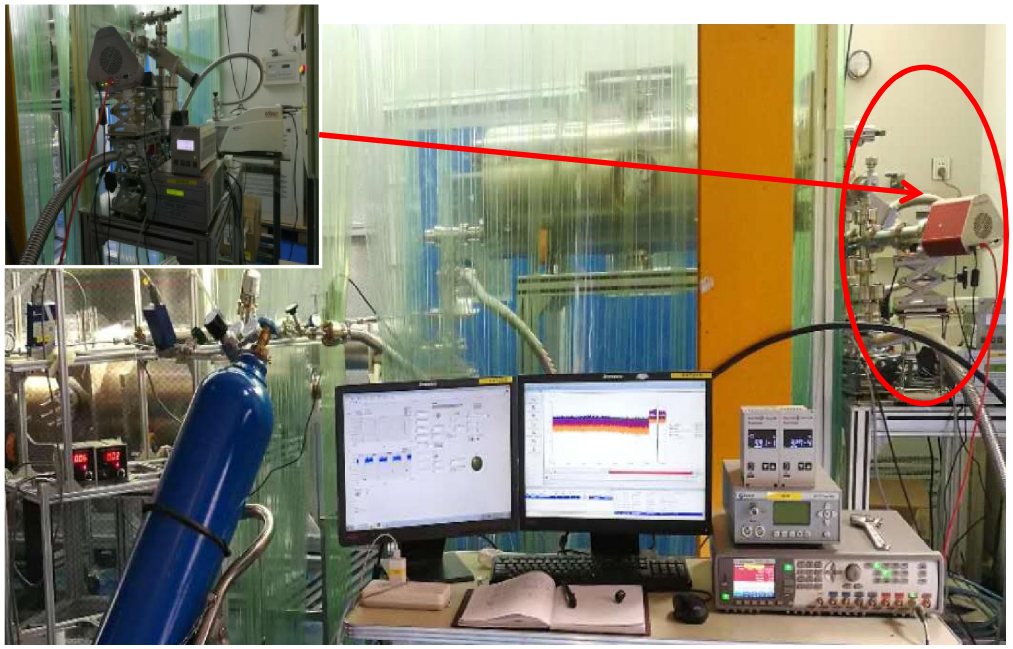




Plasma cleaning on SC cavity

➢ RF plasma cleaning on room temperature

- Plasma cleaning processing completed after the cavity deposited with carbon by PECVD
- A quadrupole mass spectrometer was installed for residual gas monitor, the production of the plasma interaction with niobium surface
- Discharge parameters, such as pressure, oxygen volume ratio and RF power, were optimized for the uniform distribution inside cavity



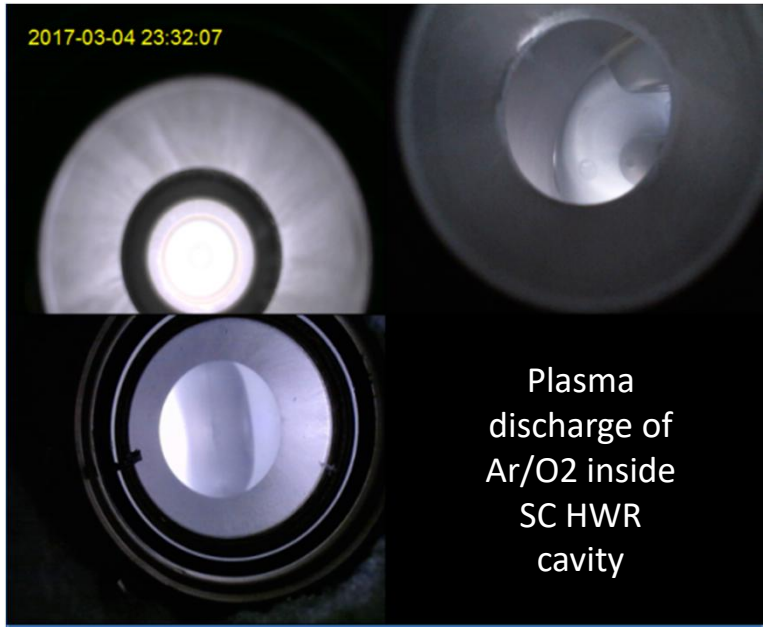
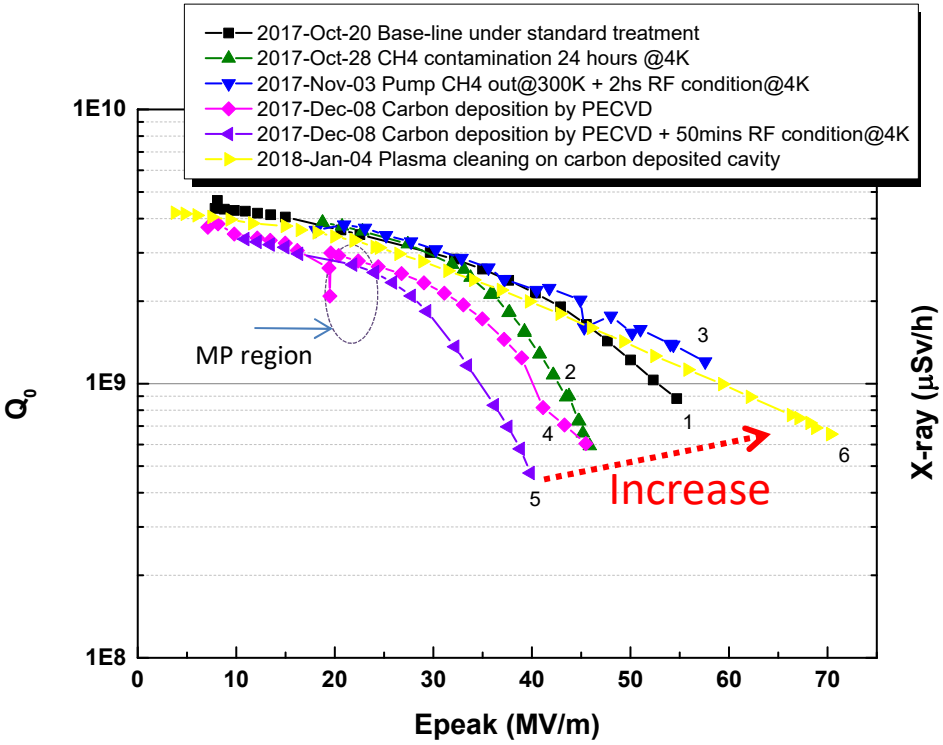


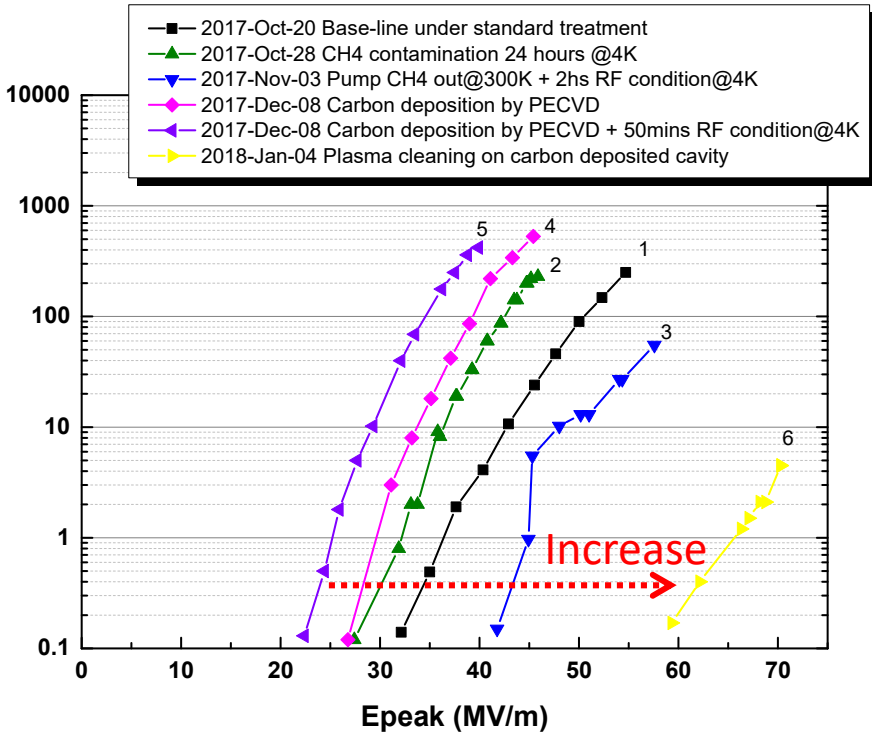
Fig. Plasma cleaning setup for HWR (left) and picture of discharge on the cavity (right)

Plasma cleaning on SC cavity

➢ Performance recovery results

- Max Epeaks increased from 57MV/m to 70MV/m (23%) after plasma cleaning
- Set on point of the FE increased from 32MV/m to 58MV/m (43%), and max x-ray radiation dose decreased from 200 to 4.5 uSv/h





Conclusion and future plan

➢ Summary

- XPS surface analysis shows carbon element is the major contaminant, UPS experiment reveals that carbon contamination largely degrades the work function of Niobium surface.
- Carbon contamination can decrease the performance of SC cavities. The physical absorption can be reversed by thermal cycle. Conversely, the chemical deposition can not be eliminated by conventional method, such as power condition.
- Ar/O2 RF plasma can helps to improve the work function value of niobium surface.
- The performance of carbon deposited cavity can be recover by the processing of RF plasma cleaning.

➢ Next step

- Investigation on the surface damage effects of niobium for plasma cleaning.
- Try to in situ plasma processing on the cryomodule or linac.

Thanks

ANY QUESTION?