中国科学院高能物理研究所
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中国科学院
CHINESE ACADEMY OF SCIENCES

FPCs Development at IHEP

RF Group (IHEP)

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- General
- Issues on design, fabrication and test
- Issues on online operation

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General

- In the past ten years, several kinds of power couplers have been developed at IHEP for different projects.

Facility	Cavity type	Freq.	Coupler type	Power	Status
BEPCII	single cell elliptical (SCC)	500MHz	Coax, fixed, capacitive single window	Test: CW, 420 kW Oper: CW, 150 kW	Beam operation
C-ADS	Spoke (SCC) β=0.12,0.21	325MHz	Coax, fixed, capacitive single window	Test: CW, 10 kW Oper: CW, 10 kW	Beam commissioning
C-ADS	HWR (SCC) β=0.10,0.15	162.5MHz	Coax, fixed, capacitive single window	Test: CW, 10 kW Oper: CW, 10 kW	Beam commissioning
ILC R&D	Nine cell elliptical (SCC)	1300MHz	Coax, fixed, capacitive double windows	Test: 1MW,1.5ms,5Hz	Cavity integration
C-ADS	RFQ-I (NC)	325MHz	Coax, fixed, inductive single window	Test: CW, 105 kW Oper: CW,100 kW	Beam commissioning
C-ADS	RFQ-II (NC)	162.5MHz	Coax, fixed, inductive single window	Oper: CW,80 kW	Beam commissioning

FPC for BEPCII SCC

- Designed based on KEKB 508MHz SCC coupler;
- Four prototypes were fabricated, and three tested at KEK, one tested at IHEP;
- 1#CPL_2010 assembled with spare cavity system and joined the HT successfully;
- 2#CPL_2010 have being operating with beam successfully since last November (Maximum RF power: 120kW)

Window-inner conductor assembly

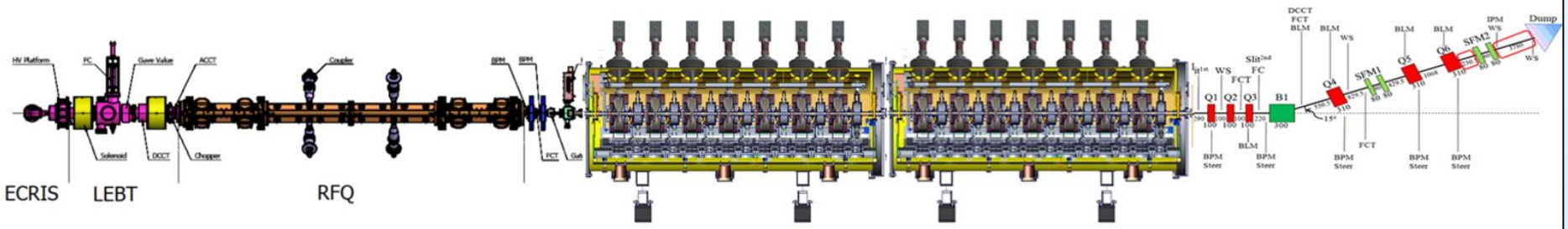
High power test stand for 500MHz FPCs

CPL #	RT on stand test results
1#CPL_2008	270kW,CW,TW (Tested at KEK)
2#CPL_2010	300KW,CW,TW (Tested at KEK)
1#CPL_2010	420kW,CW,TW (Tested at KEK)
3#CPL_2008	180kW,CW,TW (Tested at IHEP, limited by the power source)

FPC for C-ADS Spoke SCC

- 14 formals were integrated with the cavity system and joined the beam commissioning of Injector-I for C-ADS;
- 10.1MeV at a pulse beam current of 10.03mA was reached in last month.

The general layout of **Injector-I** for C-ADS



FPCs assembled with CM1 of Injector-I

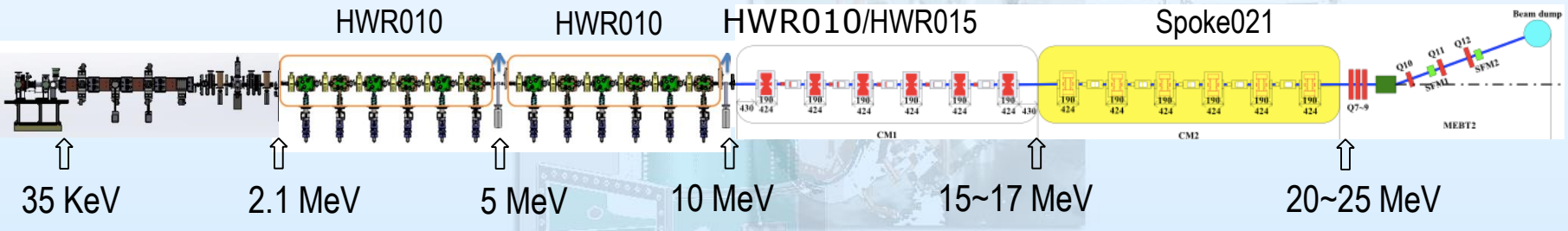
FPCs assembled with CM2 of Injector-I

Window-inner conductor assembly

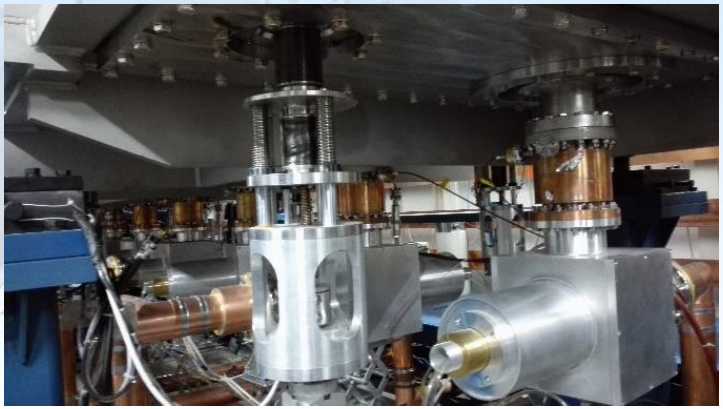
FPC for C-ADS HWR SCC

- 2 prototypes and 18 formals were fabricated and high power tested successfully;
- 12 formals joined the beam commissioning of Injector-II for C-ADS;
- Due to error **interlock** bypass, two windows cracked during 10 MeV beam conditioning.

The general layout of **Injector-II** and main linac for C-ADS



Components after fabrication



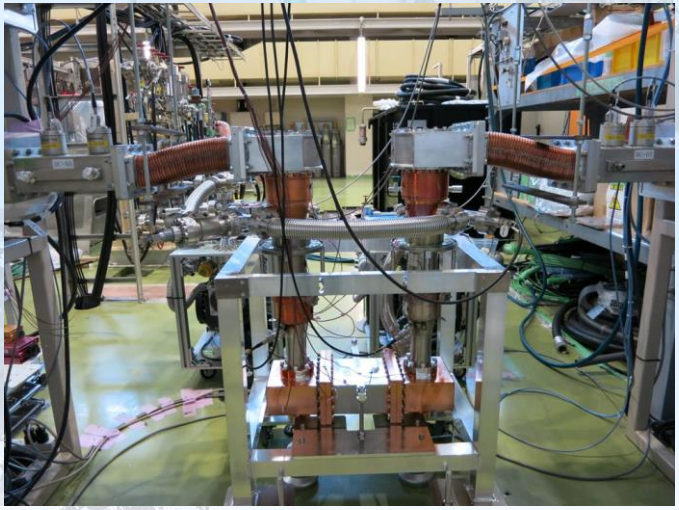
FPCs assembled with CM1 of Injector-II

Injector-II is under 10 MeV beam conditioning now

FPC for ILC R&D 9-cell SCC

- Two prototypes were fabricated in the end of 2012; and received high power test at KEK in March, 2013 (Supported by Eiji. Kako);
- High power test results: 1MW, 1.5ms, 5Hz;
- One prototype have been integrated with a SRF accelerating unit for ILC R&D developed at IHEP.

After fabrication

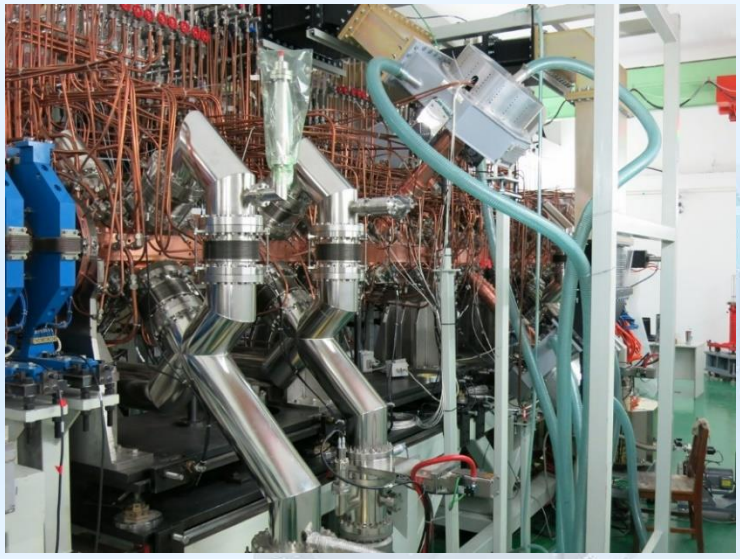


High power tested at KEK

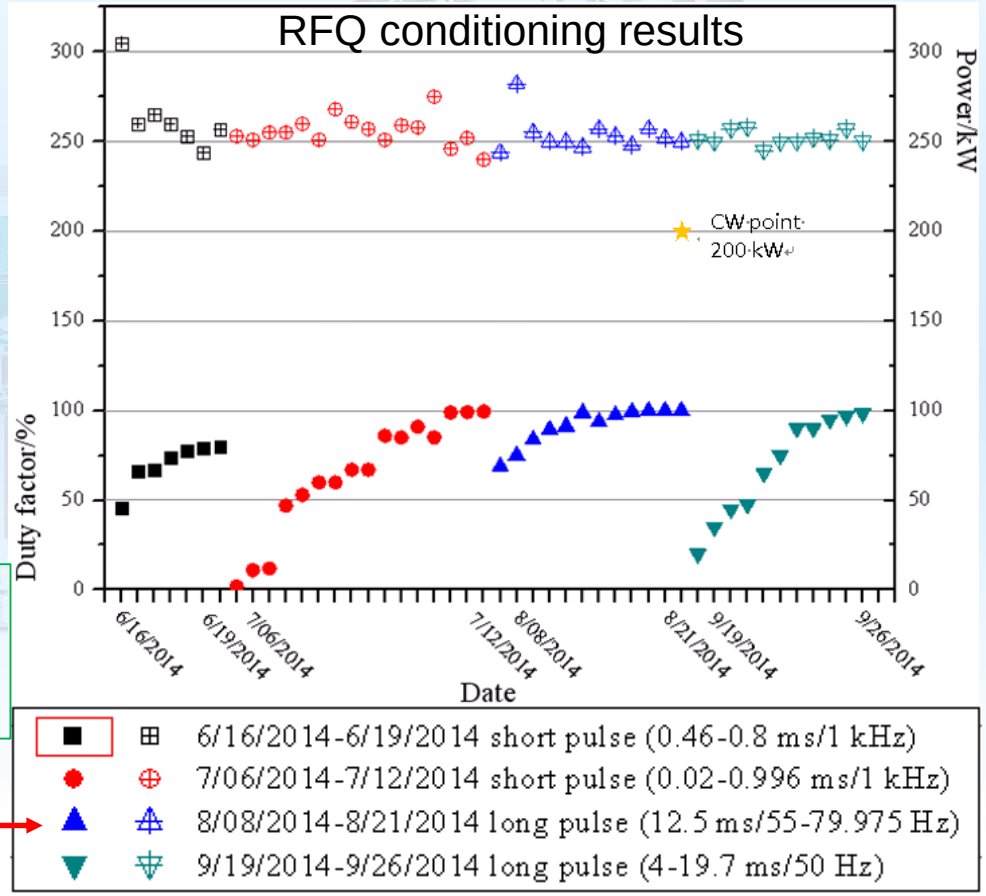
Integrated with cavity

FPC for C-ADS 325MHz RFQ

- The window & inner conductor assembly were tested up to CW,100 kW in August, 2012;
- Four formals were fabricated and installed on the RFQ cavity in the early of 2014;
- The conditioning of the RFQ system started on May,2014; and maximum power reached: 250kW, DF 99.97% (each FPC 62.5kW).



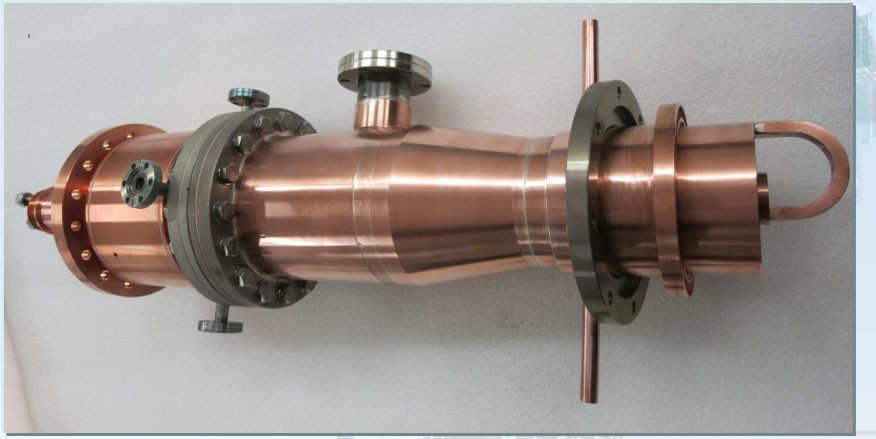
- Beam commissioning is still ongoing
- Reached: 11mA, 3.2MeV, DF: 90%
- Goal: 10mA, 3.2MeV, CW



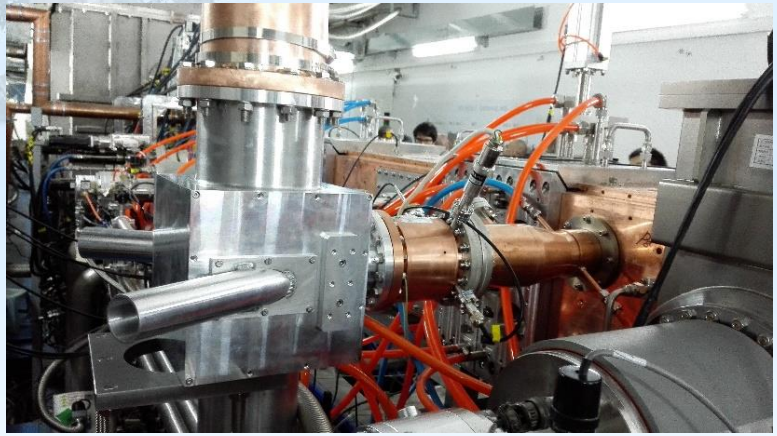
99.97% duty

FPC for C-ADS 162.5MHz RFQ

- Designed as the spare coupler for C-ADS injector-II RFQ;
- The fabrication of two prototypes were completed in September, 2014;
- One has joined the beam commissioning of Injector-II since October, 2015; which operated stably.



The coaxial part



Online operation

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Design tools discussion

- **Benchmark and comparison work is necessary!**
- **Hope to get the comparison about different codes.**

	Task	Tool
RF	Impedance matching	• HFSS • CST • ACE3P
	Qext calculation	• CST • HFSS • ACE3P
	MP simulation	• Multipac • CST • ACE3P
	Other RF related parameters(Ep, RF loss, RF power leak etc.)	• HFSS • CST
Mechanical	Thermal-stress analysis	• ANSYS APDL • HFSS-ANSYS Workbench • CST
	Heat load calculation	• ANSYS APDL • Others?
	Other mechanical related issues(displacement, modes resonant etc.)	• ANSYS APDL • ANSYS Workbench

Window number

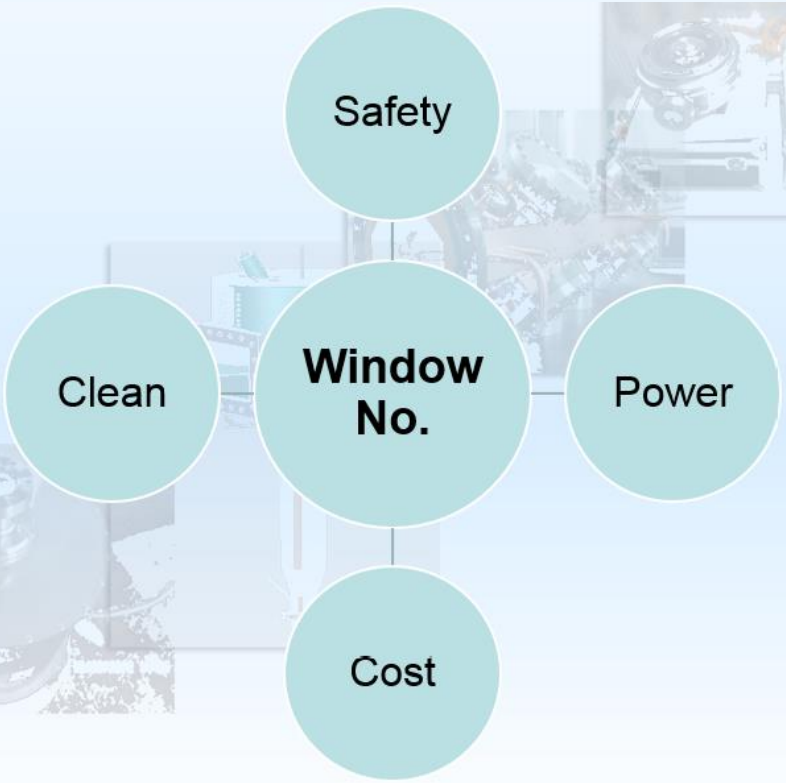
- How to decide the number of the window for a FPC?

	Pros	Cons
Single window	• Simpler design; • Easy to cool; • Better power handling	• Potential contamination to the cavity; • Less vacuum safety
Double window	• Better vacuum safety; • Better for cavity cleanness	• Complicated design and higher cost; • Worse power handling; • Hard to cool, especially the bellow and cold part

	Typical single window FPC		Typical double windows FPC	
Name	LHC 400MHZ SCC	KEKB 508MHz SCC	TTF-III 1.3GHz SCC	Cornel ERL injector SCC
Window type	Cylindrical	Disk, coax	Warm: cylindrical Cold: cylindrical	Warm: cylindrical Cold: cylindrical
Power	500kW,CW	800kW,CW	< 8kW (average)	75kW,CW
Cavity gradient	5 MV/m	7 MV/m	>20 MV/m	14 MV/m
No. of cavity per CM	4	1	8 (European XFEL)	5

Window number, cont.

- Any suggestion about the window number selection?

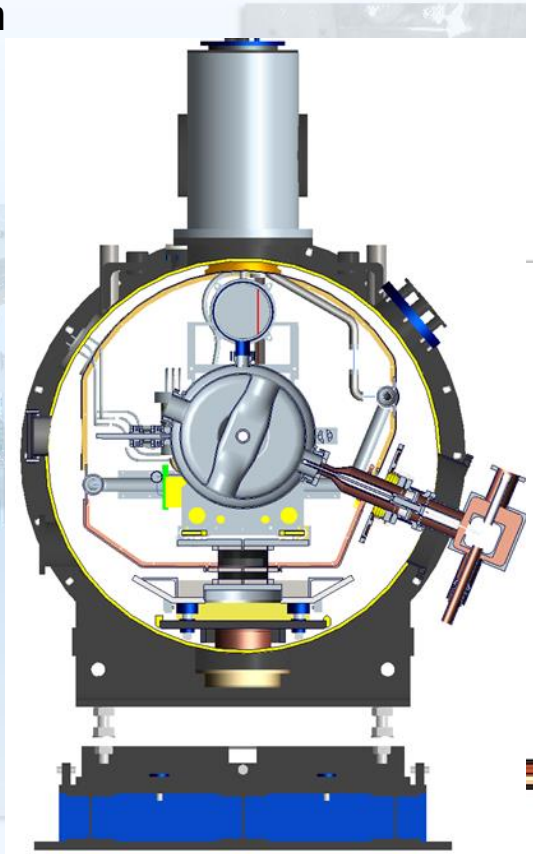


issues	condition	Suggestion
Cavity normal gradient → clean	High gradient; High Q	Double windows
Power requirement → design, cooling, cost,	High average power	Single window
Cavity No. per CM → safety	Single cavity	Single window

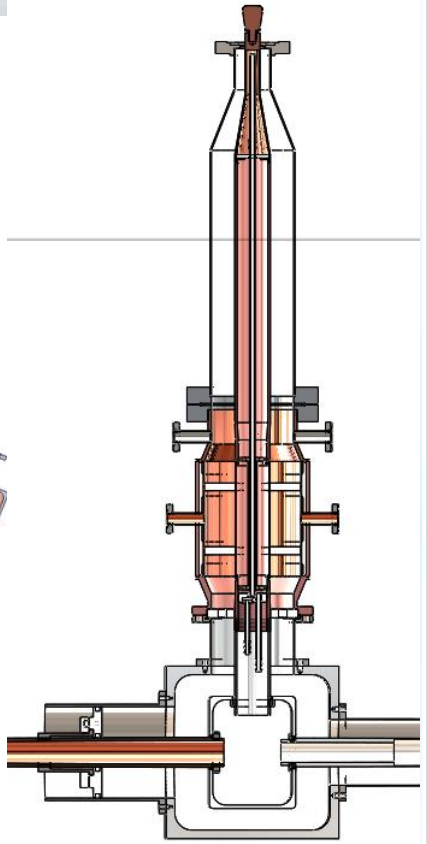
Window number, cont.

- We developed some new designs
  - Single warm window with short vacuum part, which can be assembled with cavity in class 10 clean room:
  - Special cryo-module design to assure the coupler can be assembled with cavity in class 10 clean room.
  - Two warm windows → improve the vacuum safety (Designed by Yongming Li, IMP)
- Any comments about above designs?

CM1 of Injector-II for C-ADS: cuboid shape cryo-module



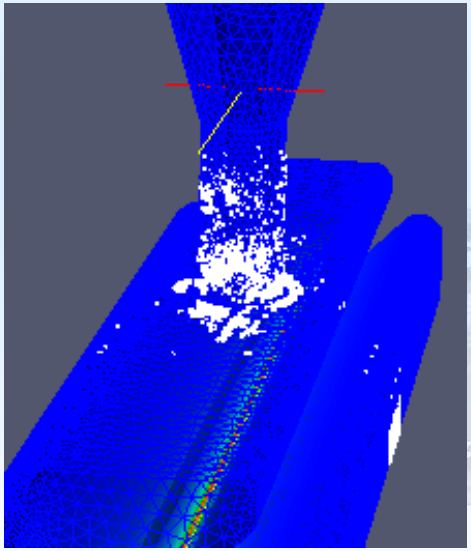
CM4 of main linac for C-ADS : short vacuum part



C-ADS main linac cryo-module: two warm windows

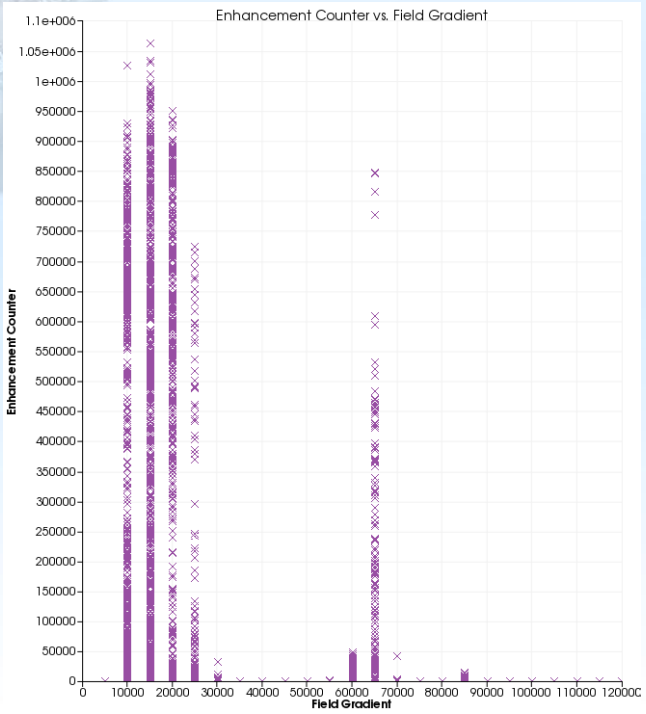
MP simulation

- Tool: CST-tracking/pic, ACE3P-s3p/track3p, Multipac (2D). Which one is the best?
- There is obvious MP trace on the coupler antenna tip close to the coupling port of the 325MHz RFQ, which agrees well with the simulation.
- So, it's necessary to simulate the MP around the coupling port area.



Simulated MP particles

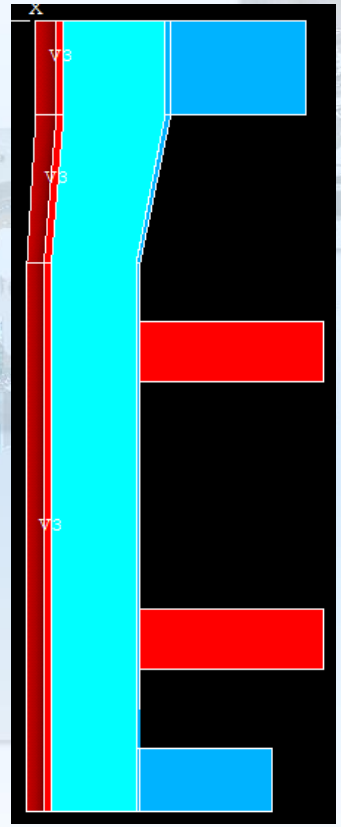
MP trace on the antenna tip



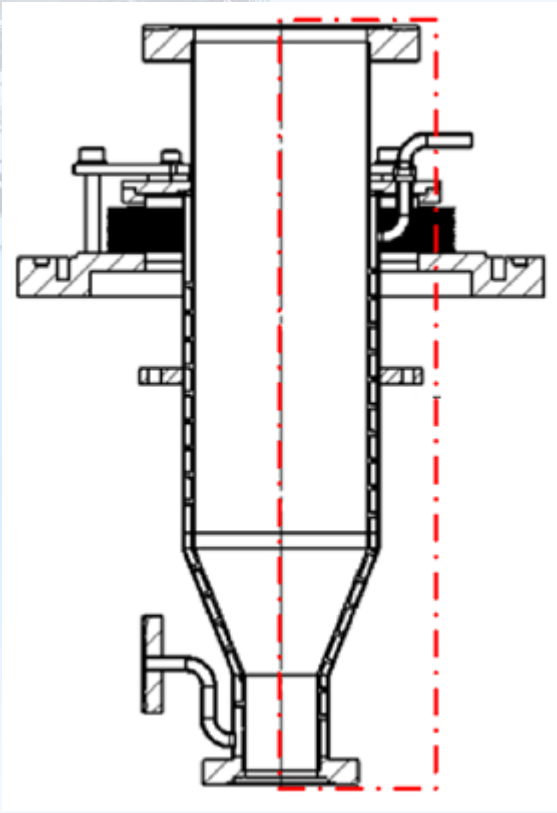
Simulated MP power levels

Heat load calculation

- For the “thermal anchor” cooling, both static and dynamic heat load can be calculated by ANSYS APDL.
- **Question:**
  - For the “GHe cooling” , how to get an accurate heat load estimation? (difficult to define the boundary condition)
  - Tool:
    - AYSYS Workbench—CFX
    - Others?



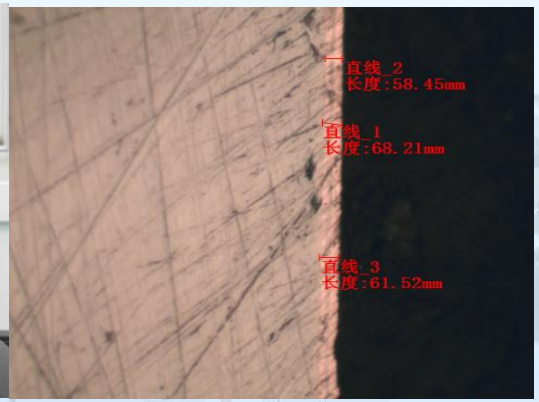
Thermal anchor



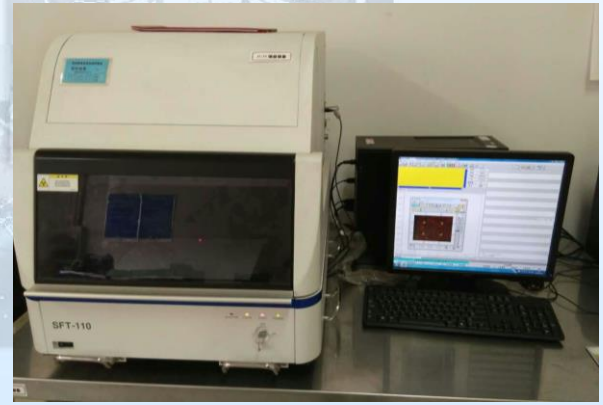
GHe cooling

Copper plating

- In our case, all pieces were brazed first, copper plated afterward.
- Quality check: Liquid Nitrogen thermal shock and ultrasonic cleaning.
- Copper plating thickness was measured by two methods.
- **Question:** Is it necessary to do 400~800 ℃ heat treatment after plating?

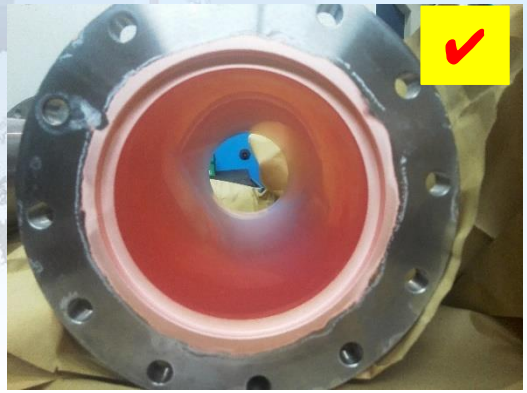


Measured by microscope



Measured by X Ray Coating Thickness Gauge

Bad coating: blemishes and oxidation

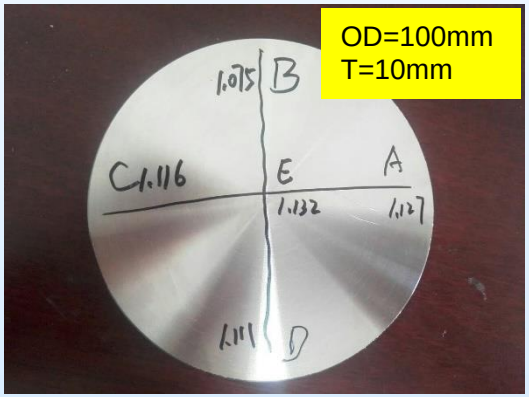


Good coating

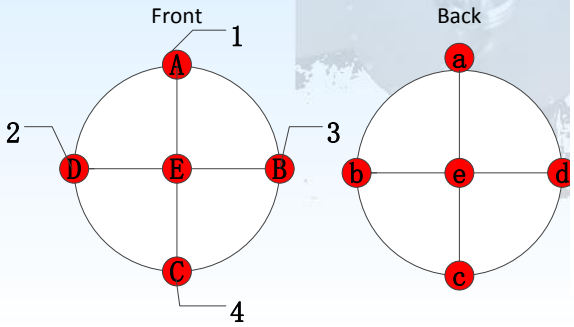
Liquid Nitrogen thermal shock

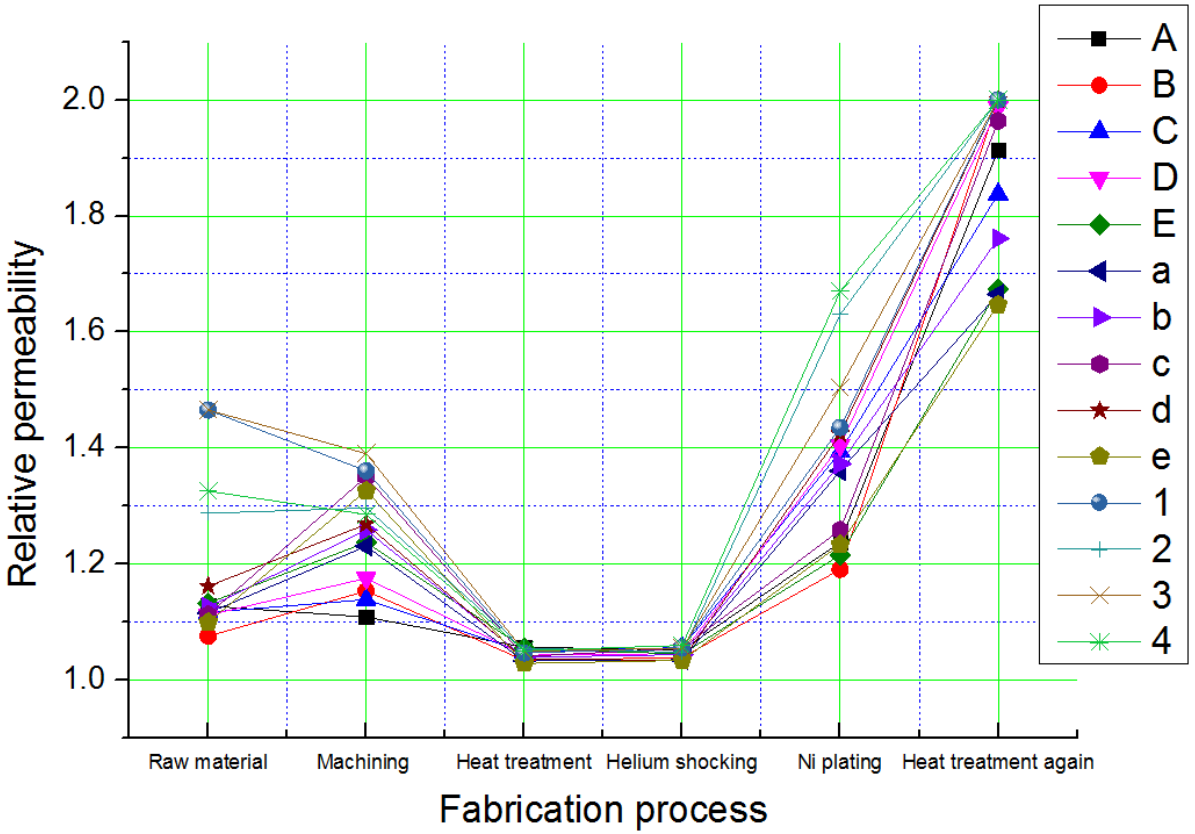
Relative permeability of S.S-1

- The $\mu_r$of Stainless steel is **unstable and irregular** during the whole fabrication process



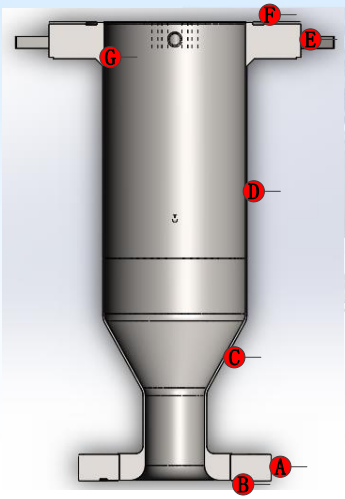
Sample A

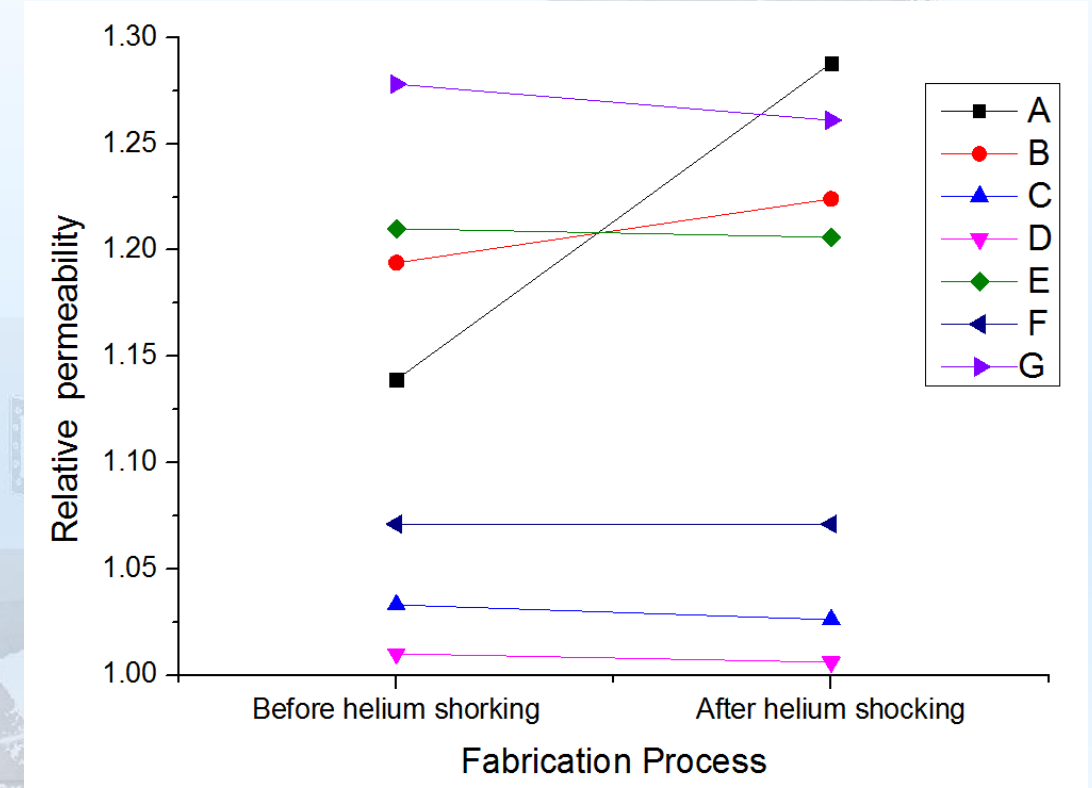




Relative permeability of S.S-2

Sample B





Relative permeability of S.S-3

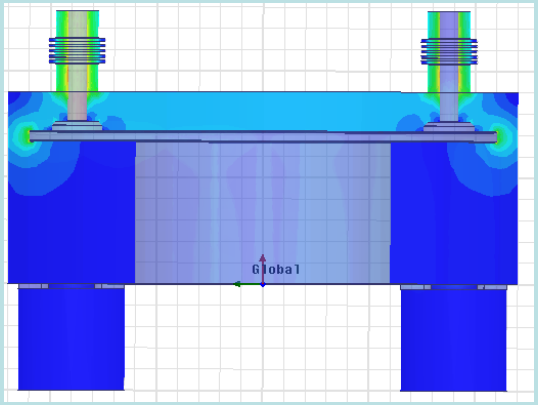
- **Question: How to keep μ_r stable and as low as possible?**

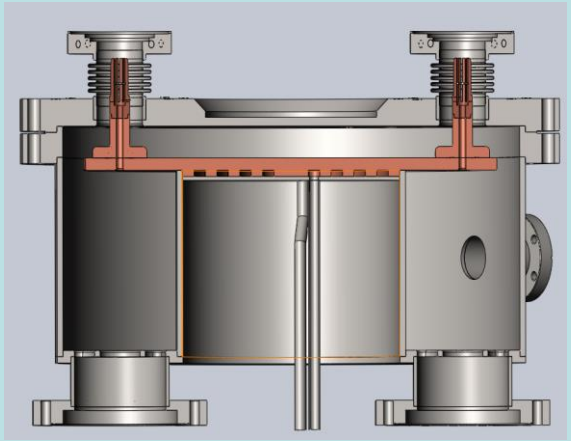
	Fabrication process	Sample A	Sample B
1	Machining	μ_r↗	
2	Heat treatment (800℃, Hydrogen)	μ_r↘	
3	Helium shocking	μ_r no change	μ_r local ↗
4	Nickel plating	μ_r↗	
5	Heat treatment again (800℃, Hydrogen)	μ_r↗	

Test benches for high power test

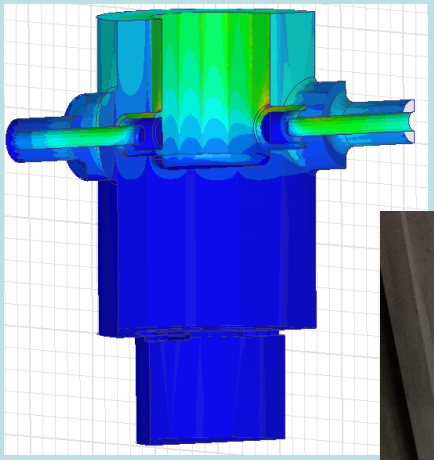
- Two test benches (162.5MHz & 325MHz)based on an approximate capacitor-loaded coaxial cavity has been developed.
- One new 325MHz test bench based on QWR cavity developed: more compact

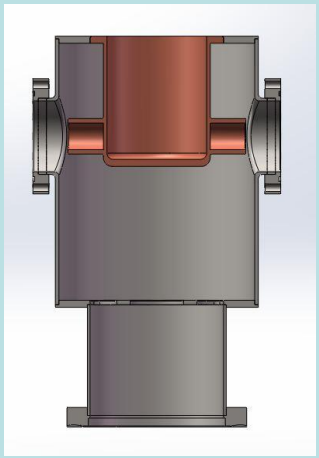
162.5 & 325MHzTest benches based on capacitor-loaded coaxial cavity





325MHz Test benches based on QWR cavity



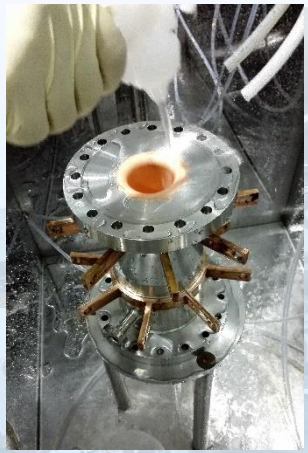


Pre-processing before test

Question: Is it necessary to do HPR for the coupler pre-processing?

- Ultrasonic clean
- ⇩
- Ultra pure water rinsing
- ⇩
- Dry with ultra pure N2
- ⇩
- Assembled in clean room
- ⇩
- 150 ℃baking for 24~48 hours

Outer conductor ultrasonic clean



Pure water rinsing

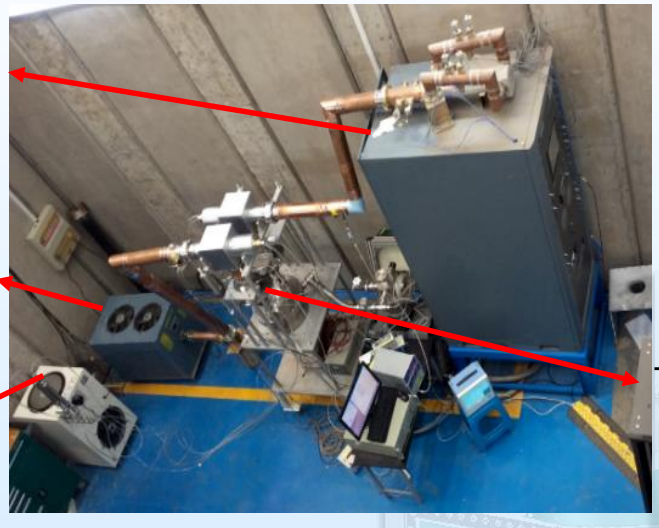
Dry with ultra pure N2

Particle monitoring during assembly

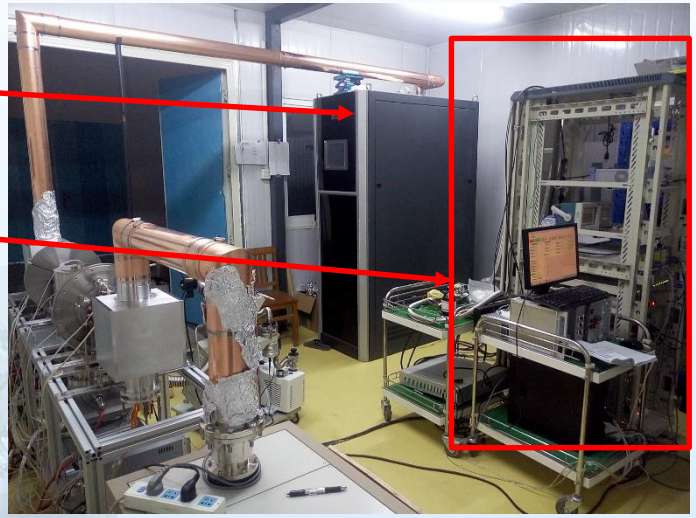
Assembled in clean room

Baking

High power test systems

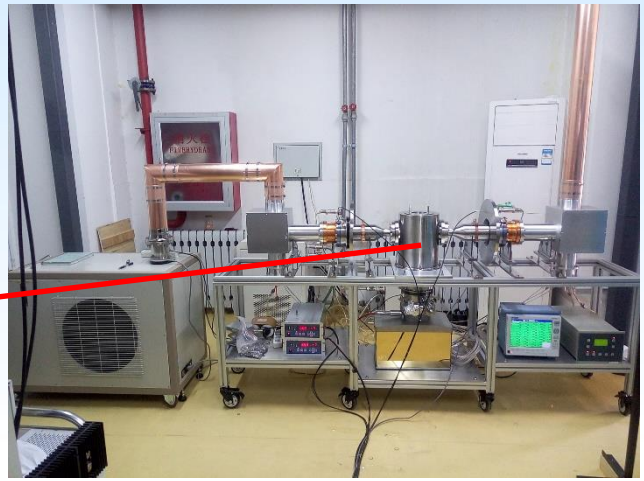


162.5MHz HWR010 CPL test system



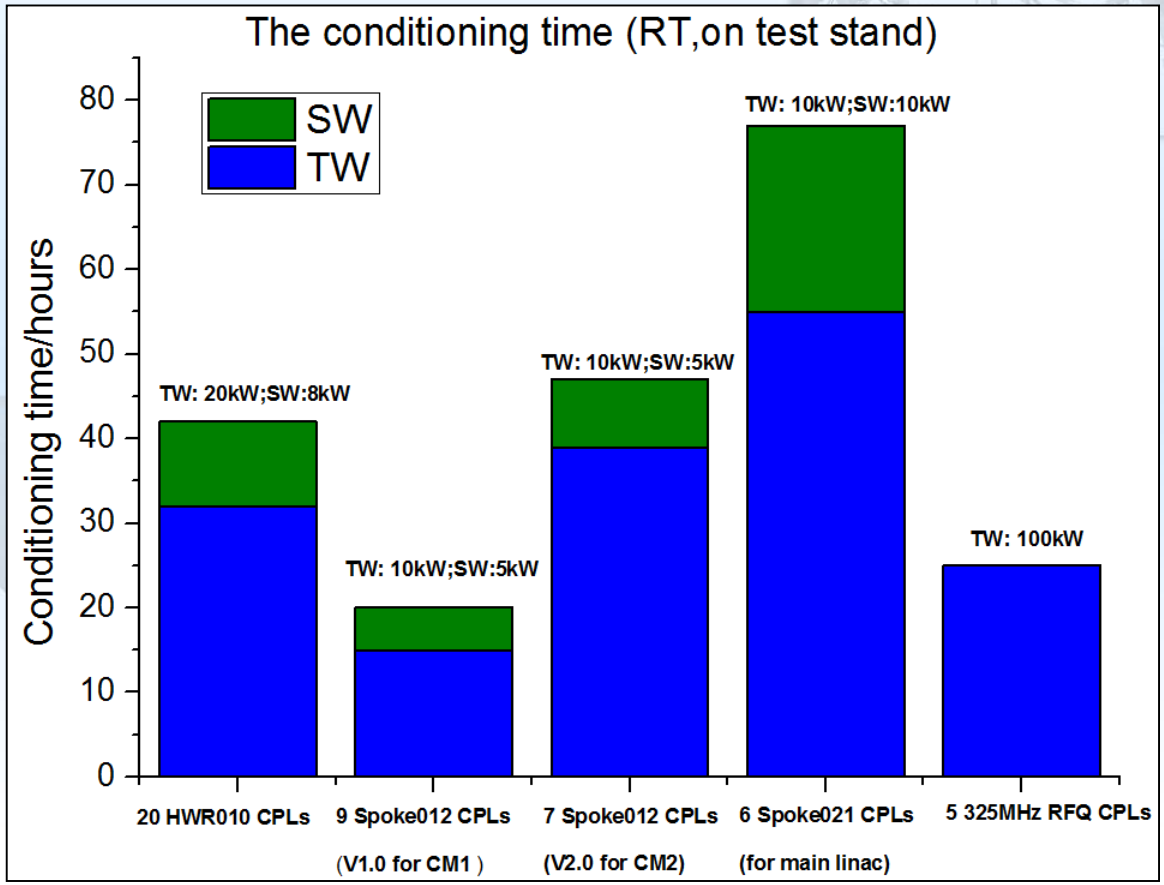
325MHz Spoke021 CPL test system

325MHz Spoke012 CPL test system



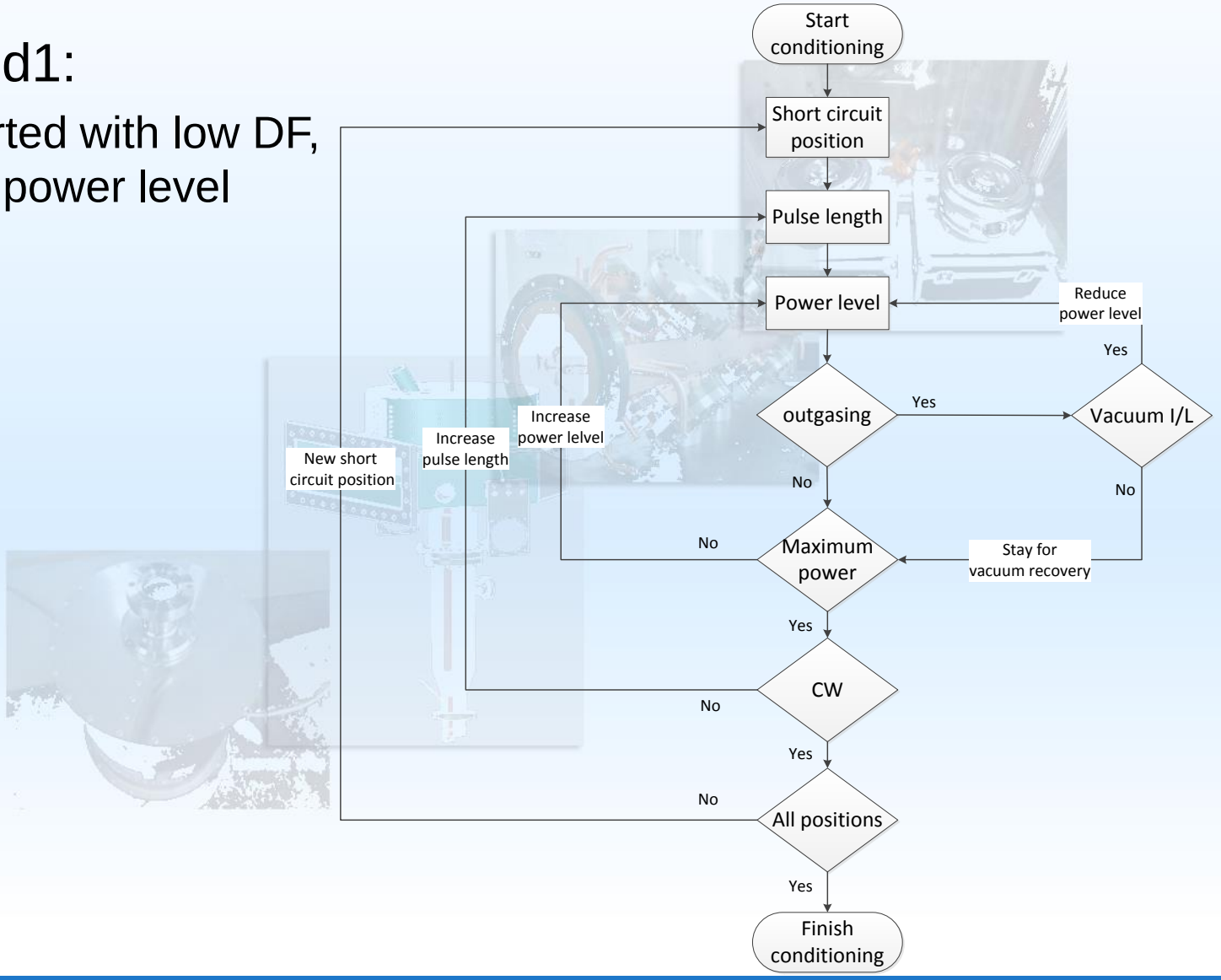
High power test results

- More than 40 couplers has been high power tested up to the nominal power level since 2012.
- Both traveling and standing wave with removable short circuit conditioning are done in RT test stand.



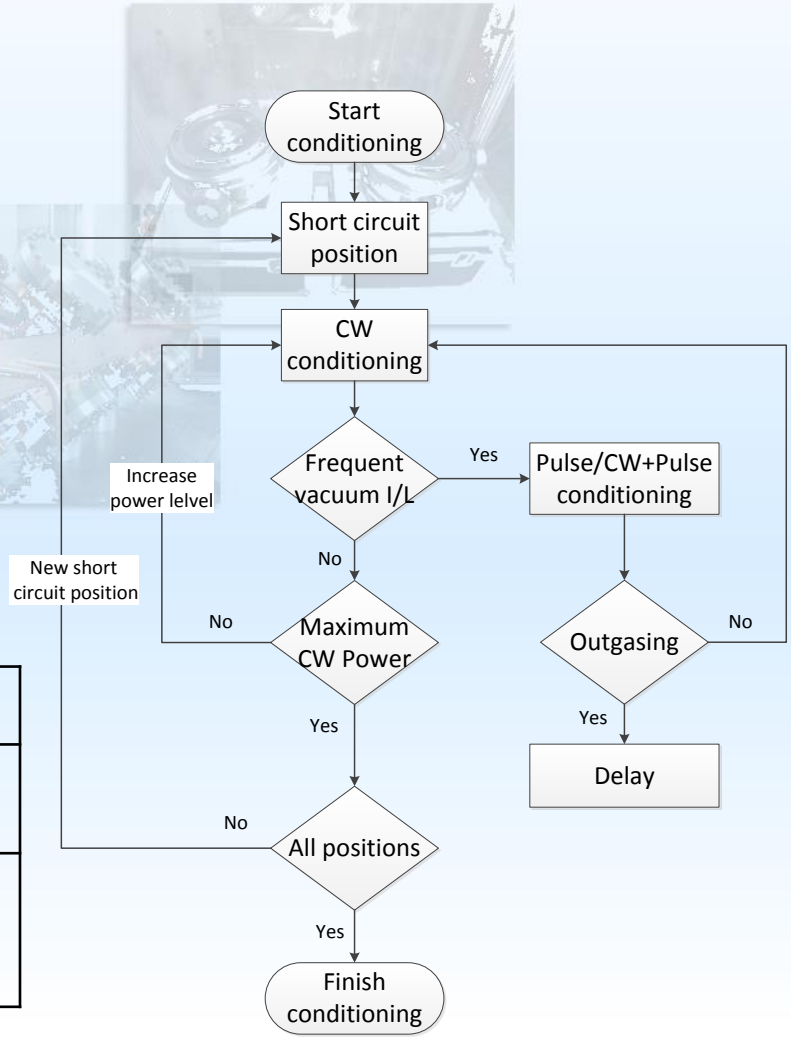
High power conditioning

- Method1:
  - Started with low DF, low power level



High power conditioning, cont.

- Method2:
  - Started with CW, low power level
  - Change to pulse or 'CW + pulse' conditioning when vacuum interlock happened frequently
- **Question:**
  - Which method is better?



	Pros.	Cons.
Method1	• More safe	• ?
Method2	• More efficient sometimes	• More dangerous if serious outgasing and arc happened

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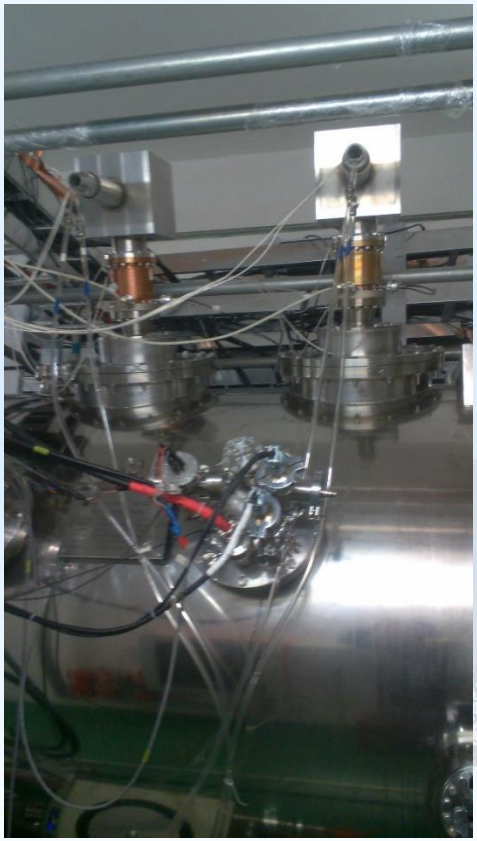
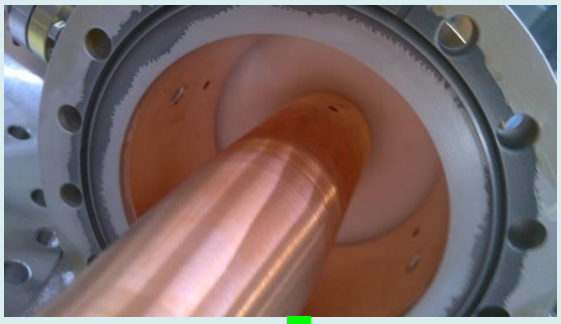
FE induced window crack problem (phenomena)

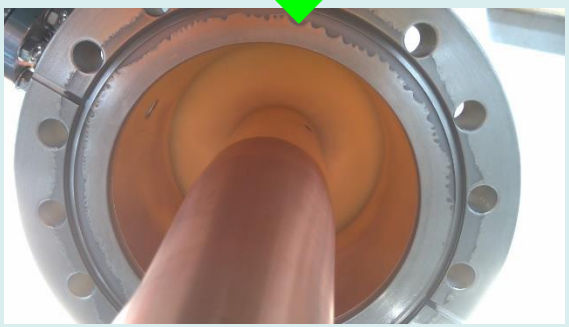
- Two Spoek012 FPCs assembled with the TCM were encountered fatal window crack during the in-cryomodule RF processing without beam.



In-cryomodule RF processing of Spoke couplers for TCM of C-ADSInjector-I

The cracked window inspection





The color of the vacuum side of the ceramic surface changed from white to yellow

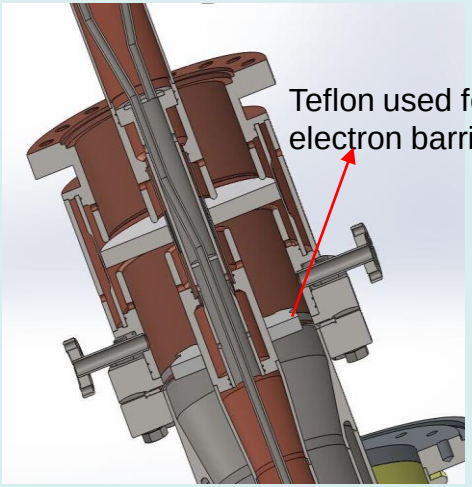
Questions: color change reason?

No electron and ion bombarding mark

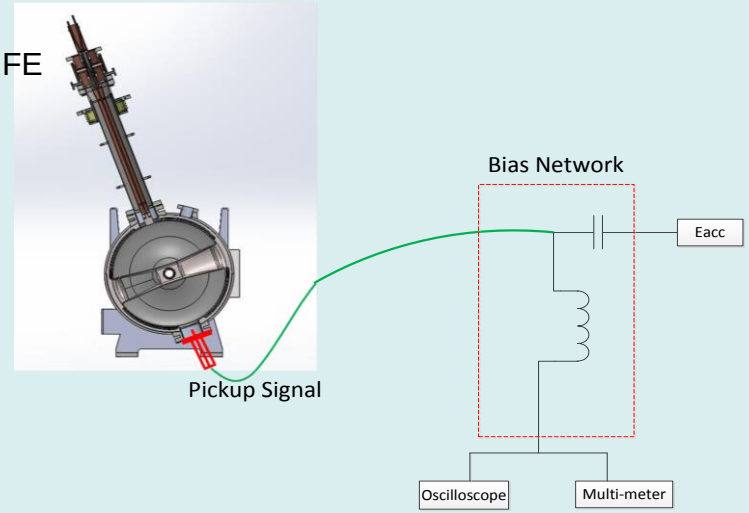
FE induced window crack problem (analysis)

- A series of experiments were done to find the window crack reason.
- **Important experience:** cavity FE may resulted in fatal ceramic crack, especially for the low beta SCC with coupler located in the cavity wall instead of beam pipe.

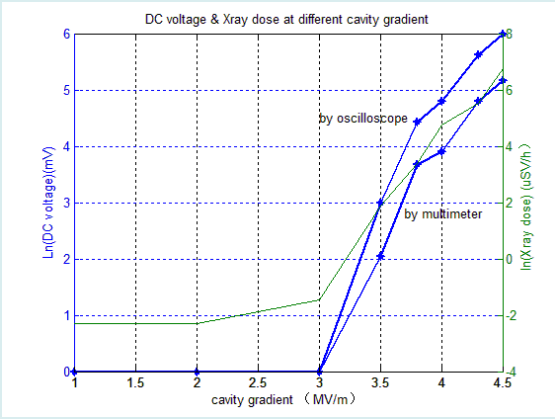
Ceramic crack reason investigation



The ceramic never cracked after Teflon plate shielding.



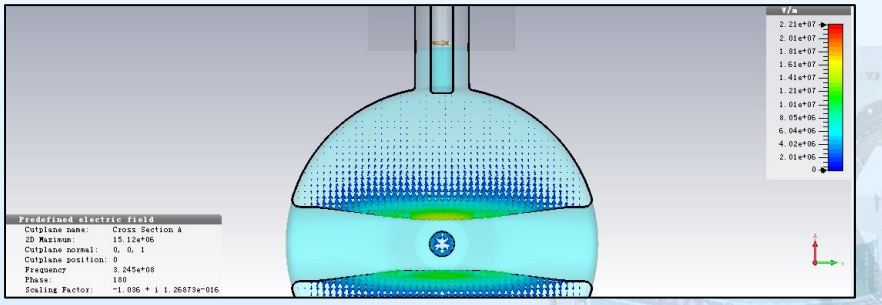
A “bias network” was connected with the pickup signal to capture the voltage produced by FE electrons.



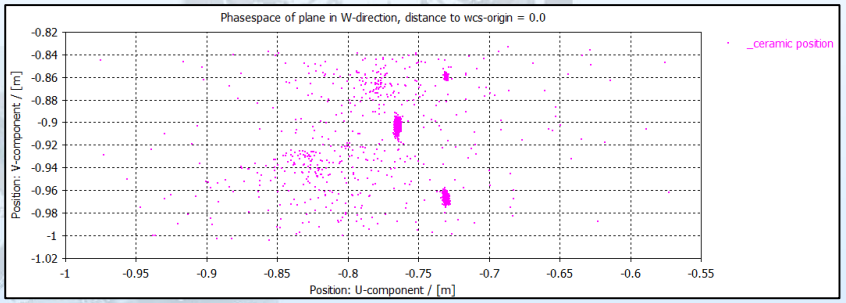
The expected DC voltage was detected accompanying the X-ray dose arising.

FE induced window crack problem (analysis, cont.)

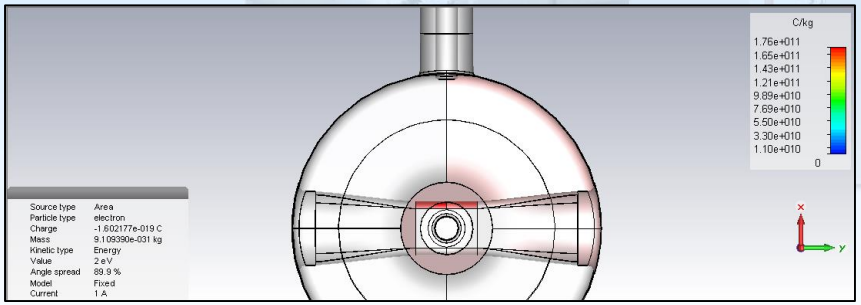
- Then, the FE effect was simulated using CST particle studio.



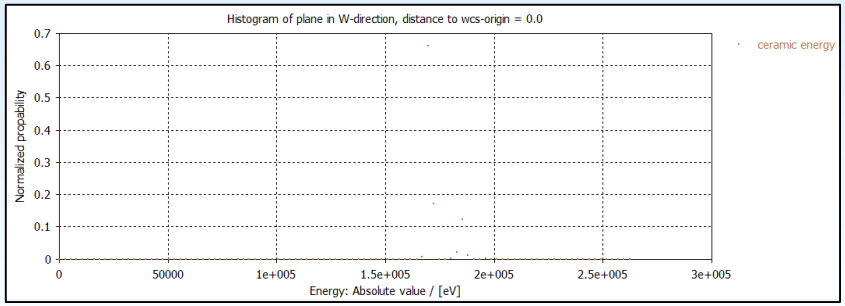
E-field at 5MV/m, 180 degree: strong transvers E-field



Simulated particle position impacted on the ceramic surface



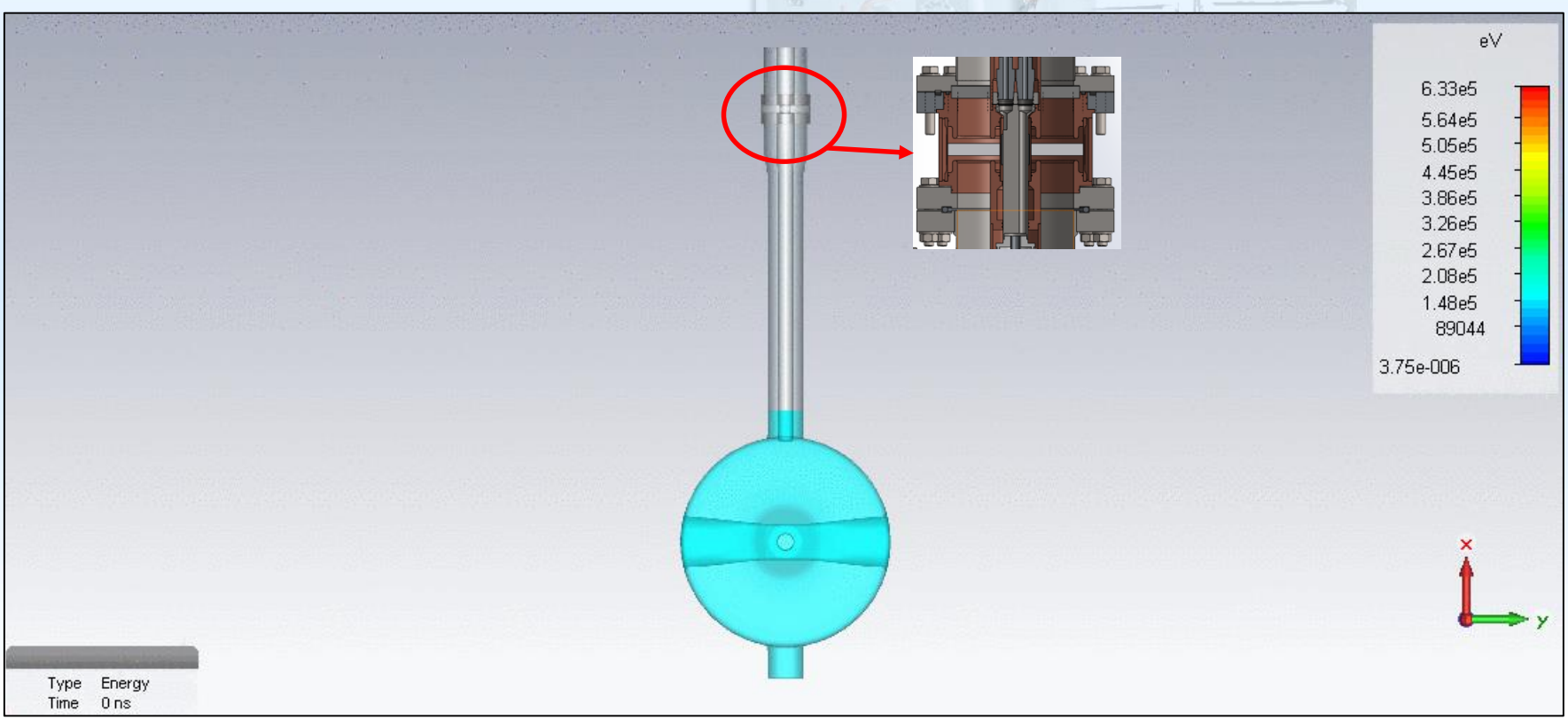
Given particle source emitted surface



Simulated particle energy impacted on the ceramic surface

FE induced window crack problem (analysis, cont.)

- Simulation result shows that the FE induced electrons can fly out from the coupler port and impacted directly on the ceramic.

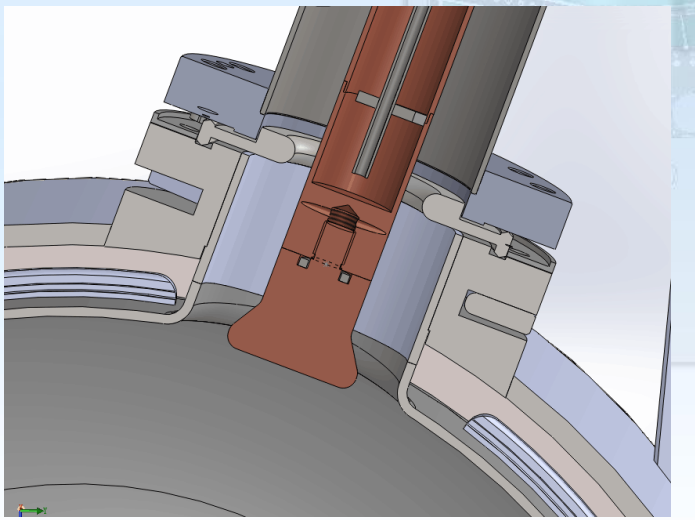


FE induced window crack problem (analysis, cont.)

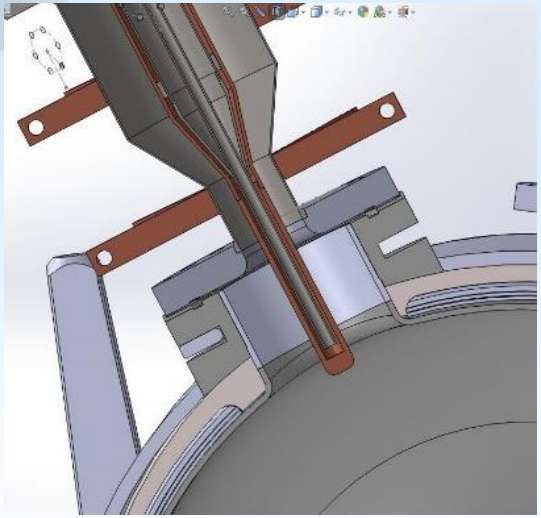
- Ceramic leak reason guess:
  - First, serious FE happened in the cavity, then electrons flied out from the coupling port and impacted directly on the vacuum side of the ceramic, which made the ceramic charged;
  - Second, electrostatic discharging happened once exceeding the ceramic breakdown voltage;
  - Finally, the strong energy released from the discharging made the ceramic punctured along the thickness direction and resulted in fatal vacuum leak.
- **Questions: what's the real damage force?**
  - **Direct electron impacting force?**
  - **Discharging energy→ puncture force?**

FE induced window crack problem (Solution)

- Solution:
  - Improve the coupler assembling environment: process and cleanness;
  - Special gasket or antenna tip to shield the FE-induced electrons;
  - Radiation dose also interlocked during online operation to avoid FE
  - Change the window position by 90 degree bending (similar with APT coupler)
- **Questions: Other suggested solutions?**



Spoke FPC for CM1 of C-ADS Injector-I



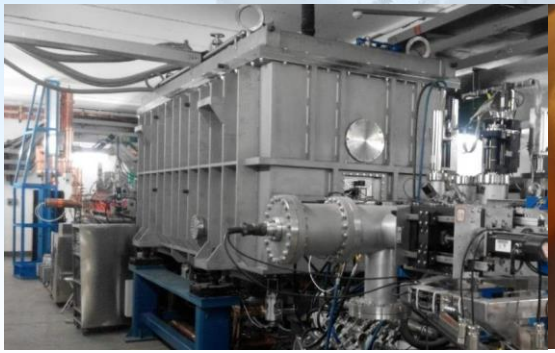
Spoke FPC for CM2 of C-ADS Injector-I

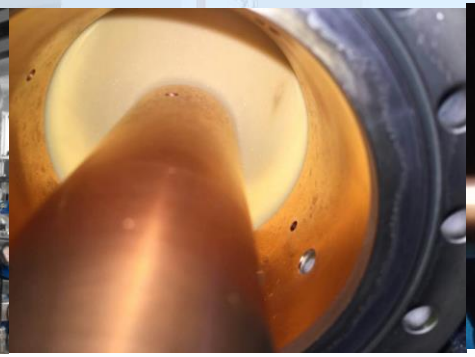
Online operation interlock

- Two HWR010 FPC for CM1&2 of C-ADS injector-II leaked.
  - Running for 1 year, two coupler in CM6-1 were leaking, Vacuum interlock: 5E-4Pa **(Interlock too loose!)**
  - CM1 running for 10 days, 2 couplers window leaked **because of the bypass of vacuum interlock.** Before the accident, cavities were running well. After that, the nearby cavities also degraded.

- **Questions:** Safe interlock value (for SCC)

Items	value
Vacuum	1E-6Pa?
Window Temp.	Warm:? Cold:?
Arc sensitivity	?
e-current	?
others	?

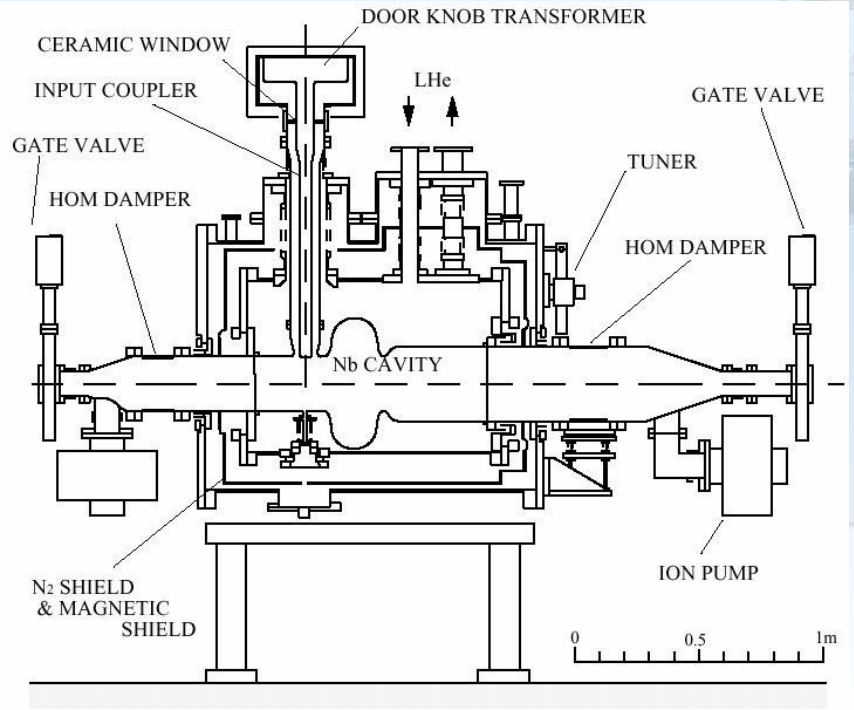




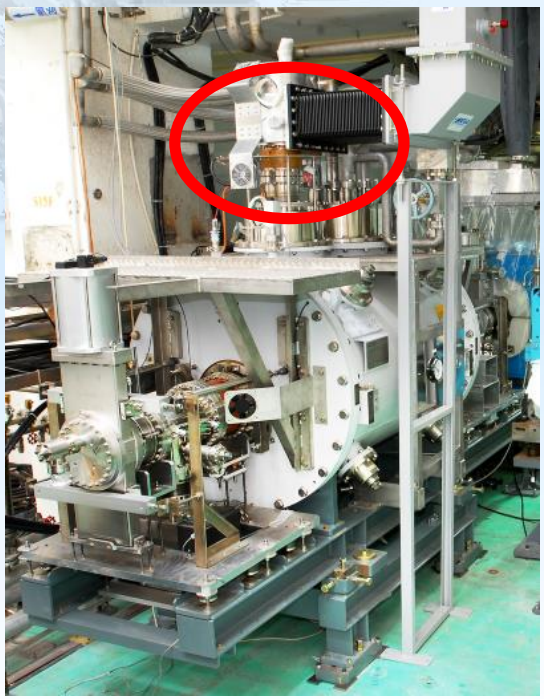
Question: color change reason?

BEPCII FPC replacement

- The west window for BEPCII 500MHz SCC cracked suddenly during beam operation on Nov. 18,2015;
- Vacuum pressure after cracked: 2E-2Pa; Leak rate: >3E-4 mbar.l/s
- Actually, the window had been overheating for one year before it cracked, which just alleviated by baking and strong air cooling [1];



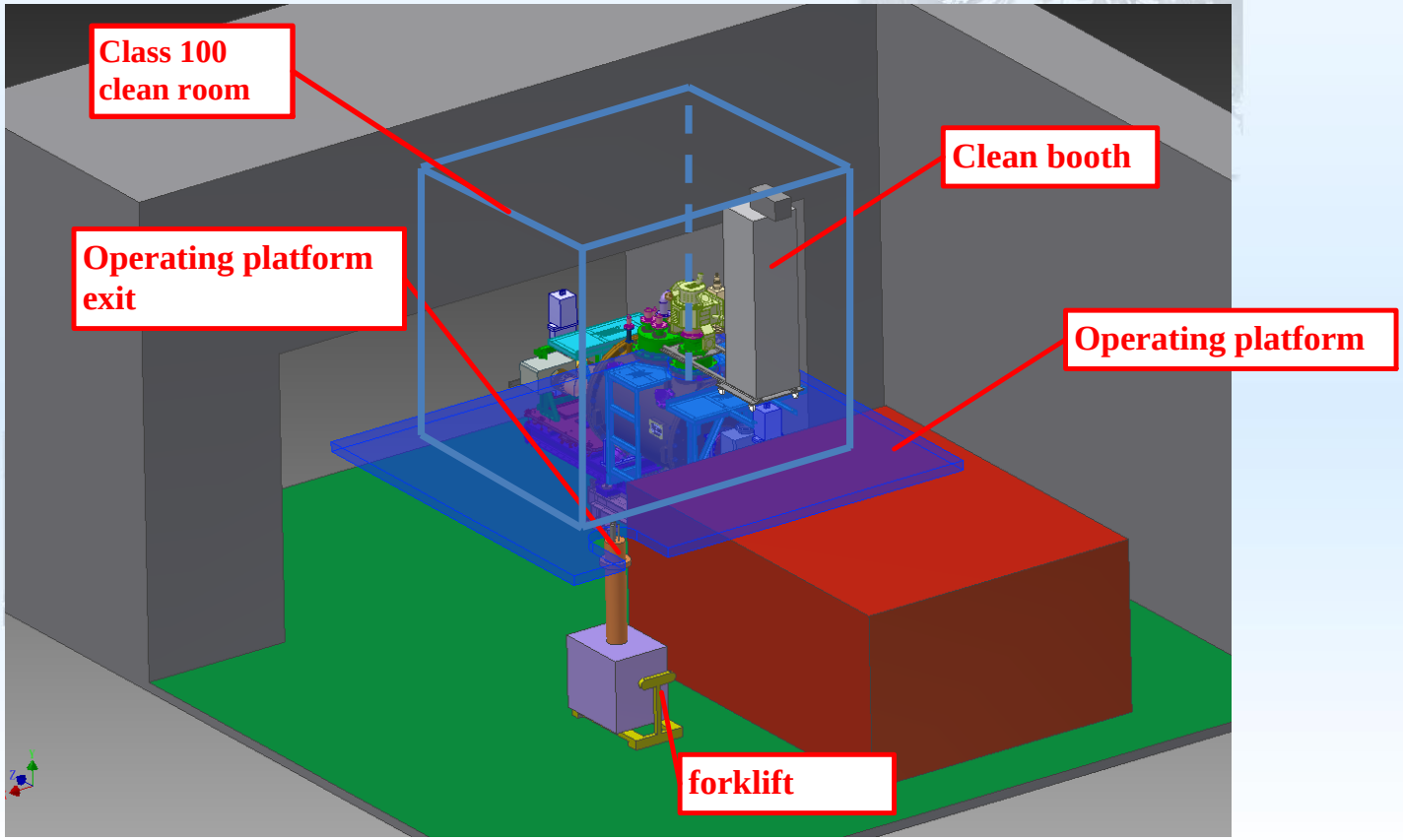
BEPCII 500MHz SCC system(schematic)



BEPCII 500MHz SCC system
(In tunnel)

BEPCII FPC replacement, cont.

- The cracked window replacement was processed in tunnel.
- One removable clean room (class 100) and a local clean booth were adopted.



Schematic of window replacement

BEPCII FPC replacement, cont.

- High purity N2 inflated to keep a plus pressure;
- It took 2 hour for the whole process of window replacement.

Old window taken out

The coupler port covered with clean PVC plate (down) and plastic film (up)

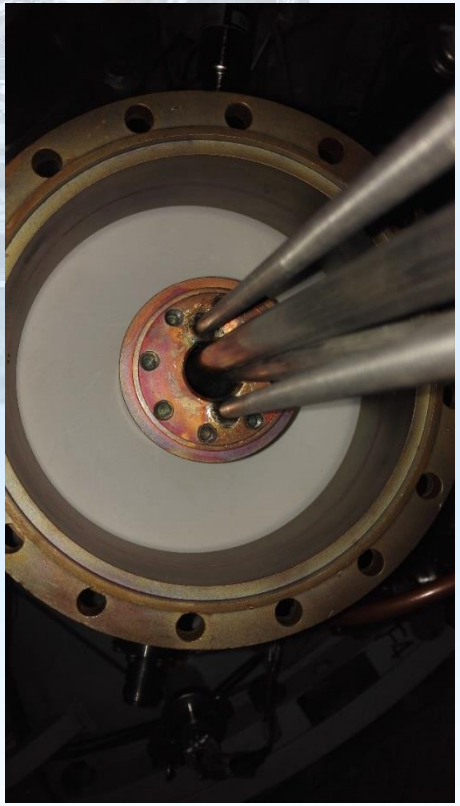
New window pick up from the container by clean booth

BEPCII FPC replacement, cont.

- The cleanness was monitored continuously by the dust particle counter.

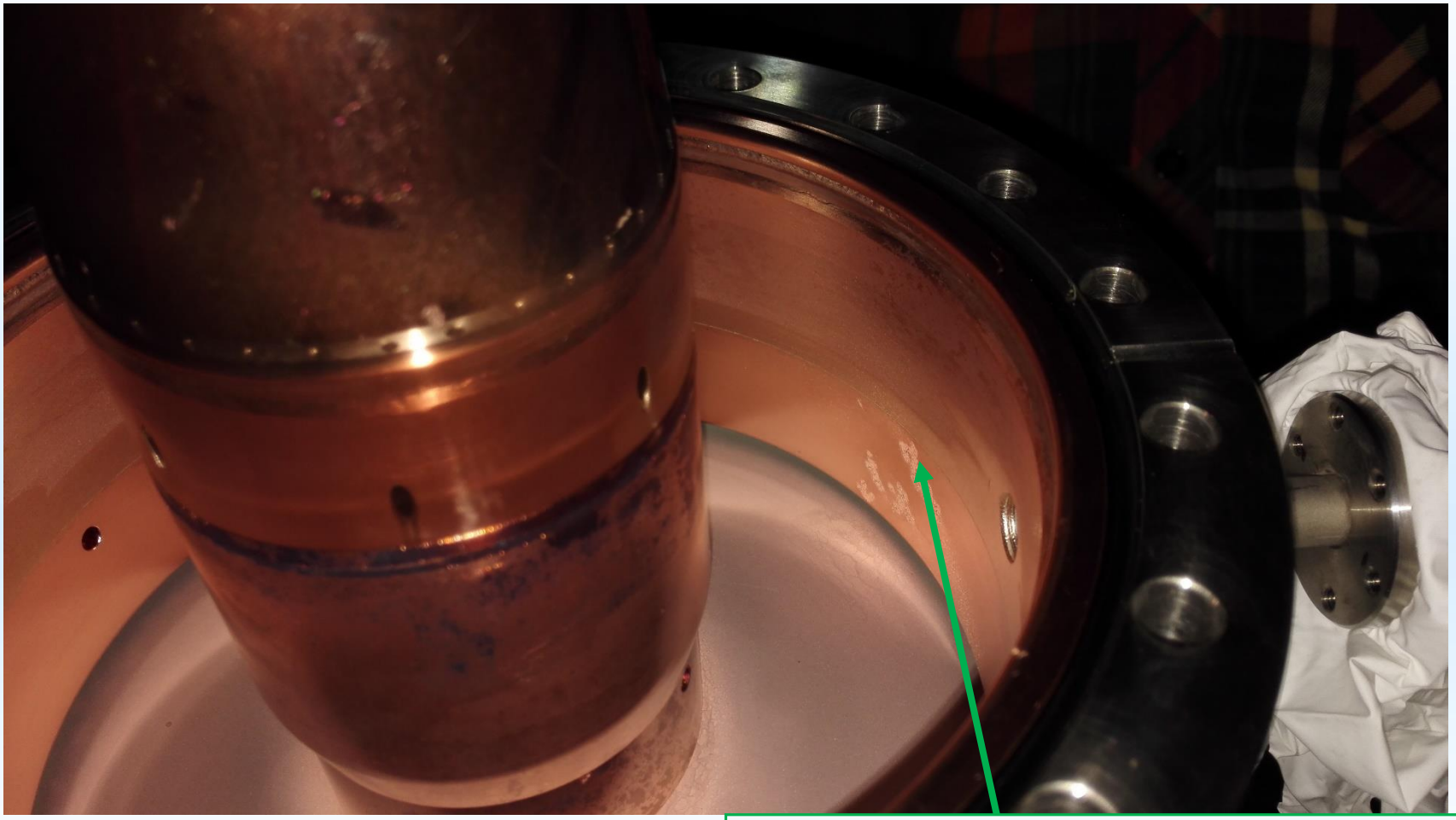
New window move into place

New window waiting for put down: particle measuring



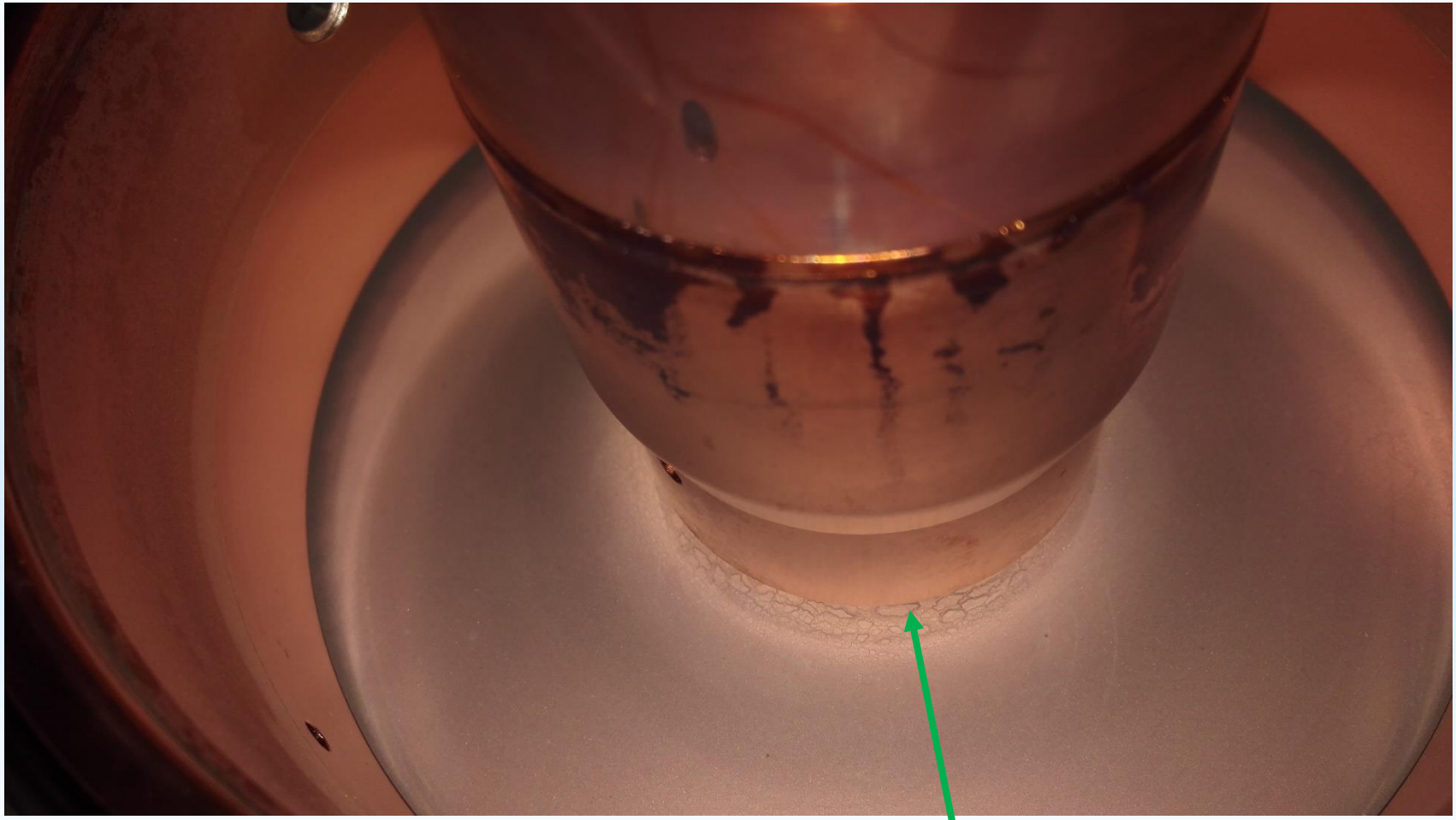
Air-side of the new window

BEPCII FPC replacement, cont.



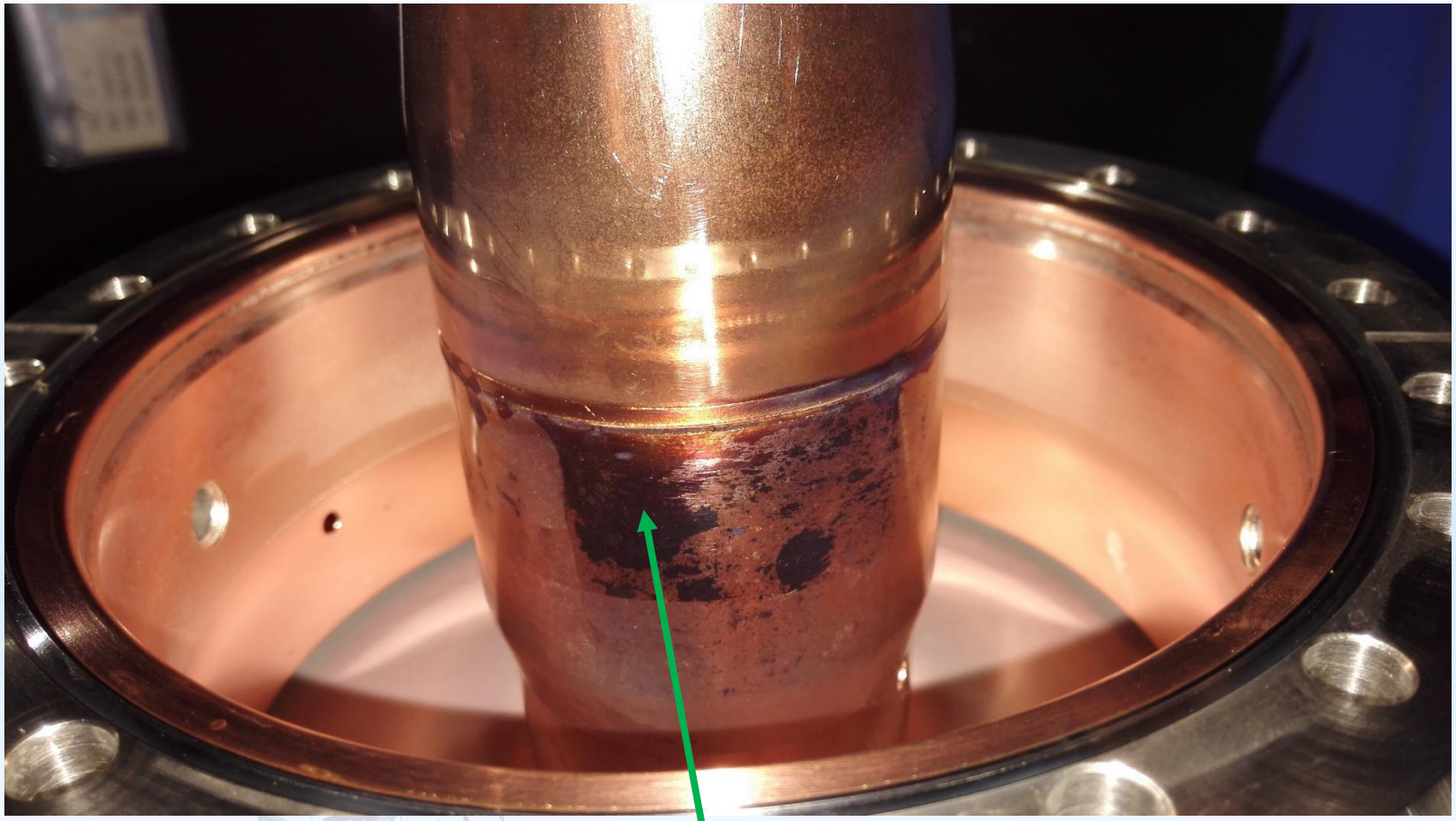
- There are three snow figures on the outer conductor of the window vacuum side
- Feel rough

BEPCII FPC replacement, cont.



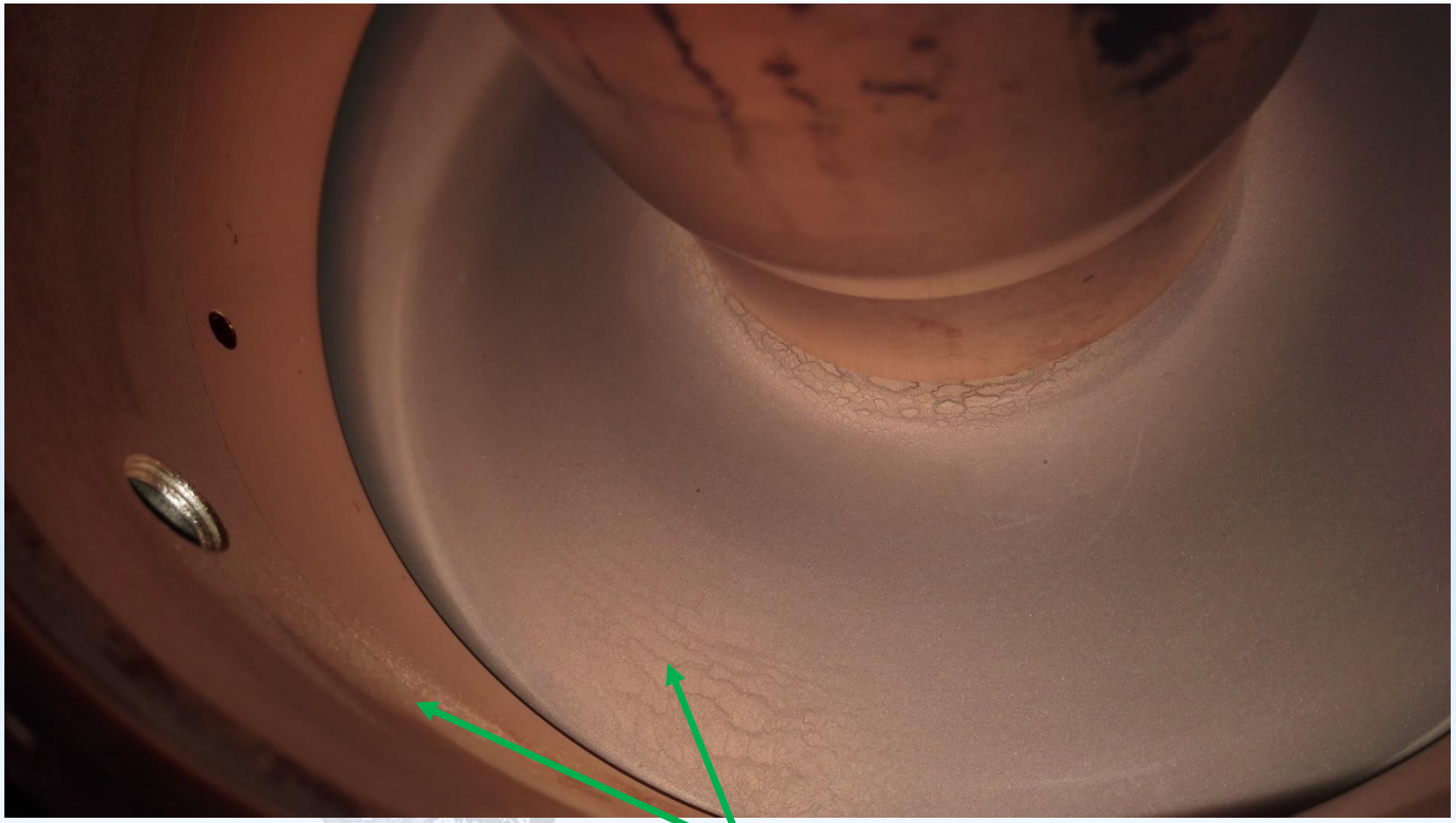
- There is a fish scale ring close to the inner choke

BEPCII FPC replacement, cont.



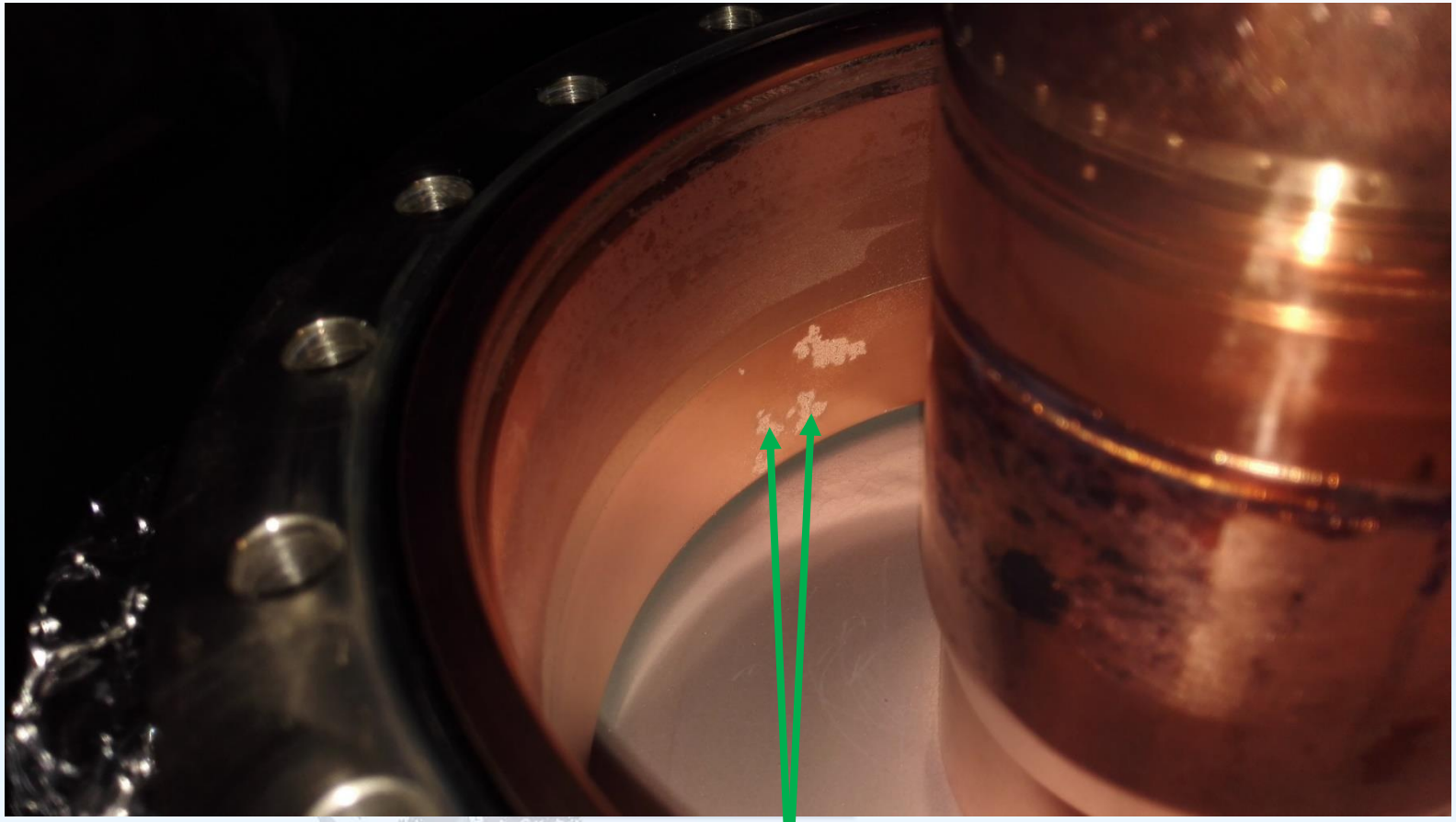
- The color close to the window –inner conductor EBW seam turn dark.
- The dark matter to be analyzed.

BEPCII FPC replacement, cont.



- The fish scale also can be found on the ceramic near the outer conductor snow figure
- And the color of the ceramic turns dark on the whole.

BEPCII FPC replacement, cont.



- The fish scale also can be found on the ceramic near the outer conductor snow figure.

Personal guess about the window damage

- The snow figure formation reason guess:
  - Serious discharging happened → ions bombarding the outer conductor of the window → snow figure formed
- The fish scale figure formation reason guess:
  - Serious discharging happened → ions bombarding the inner and outer conductor of the window and the inner choke → copper sputtering and condensed on the ceramic → after long period operation → fish scale figure formed
  - The fish scale figure is also the source of the excessive heating of the west window.
- **The arc interlock was found disabled due to the fiber damaged by radiation. I think it's the chief culprits of the window crack accident.**
- **Question: How to deal with the radiation reduced fiber damage → arc interlock disabled**
- **Any comments?**

Thank you for your attention !