中国科学院 CHINESE ACADEMY OF SCIENCES

中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

China Initiative Accelerator Driven System

ESS-IMP collaboration meeting, Dec. 25, 2019, ESS, Lund, Sweden

High Power SRF Linacs at IMP

Yuan He

On behalf of Accelerator team of CiADS

Linear Accelerator Center

Institute of Modern Physics, Chinese Academy of Sciences

Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences

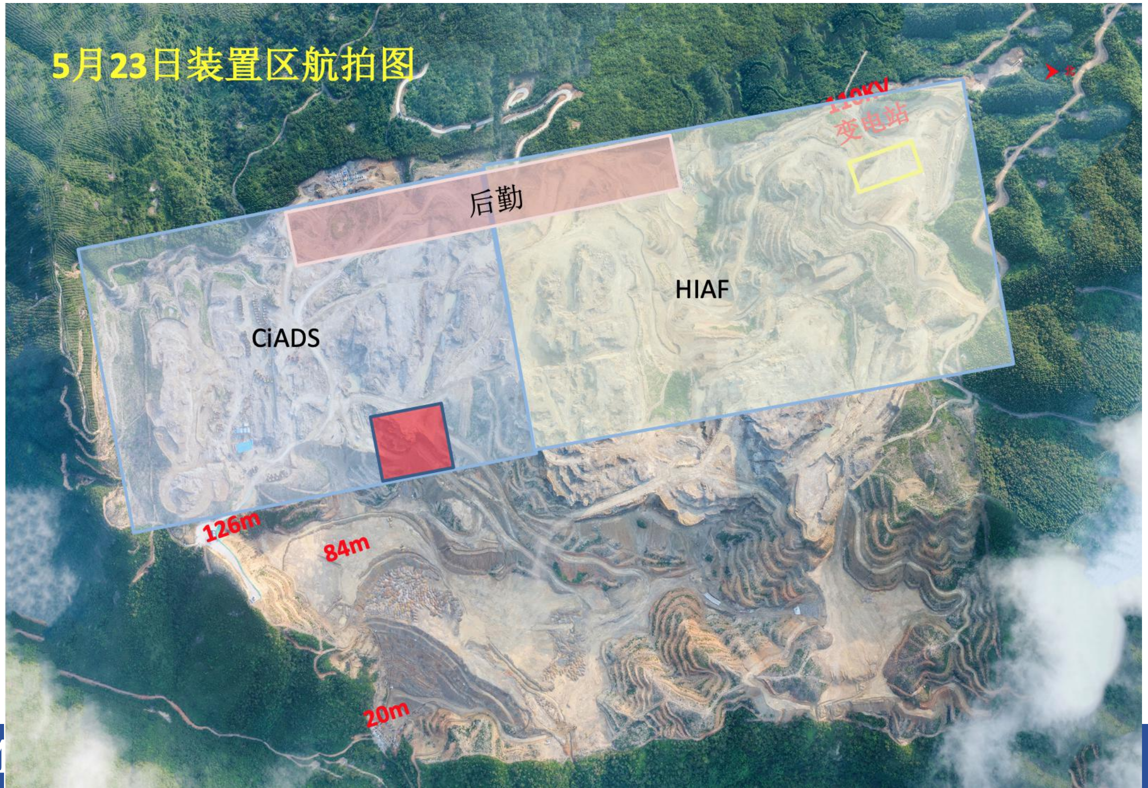
Outlines

- Introduction Projects HIAF and CiADS of IMP
- Development of SRF at IMP
- Status and Stability Issues of CAFe Operation
- Beam physics study on CAFe
- Physics experiments on CAFe
- SRF Activities for the ADS Future
- Summary

CiADS & HIAF

China Initiative Accelerator Driven System

- Approved in Dec. 2015; Leading institute: IMP
- CiADS Budget: ~4B CNY (Gov. + local + Corp.)
- Partners: CIAE, IHEP, CGN, etc.
- HIAF Budget: ~3B CNY (Gov. and local)
- Partner: PKU
- Location: Huizhou, Guangdong Prov.



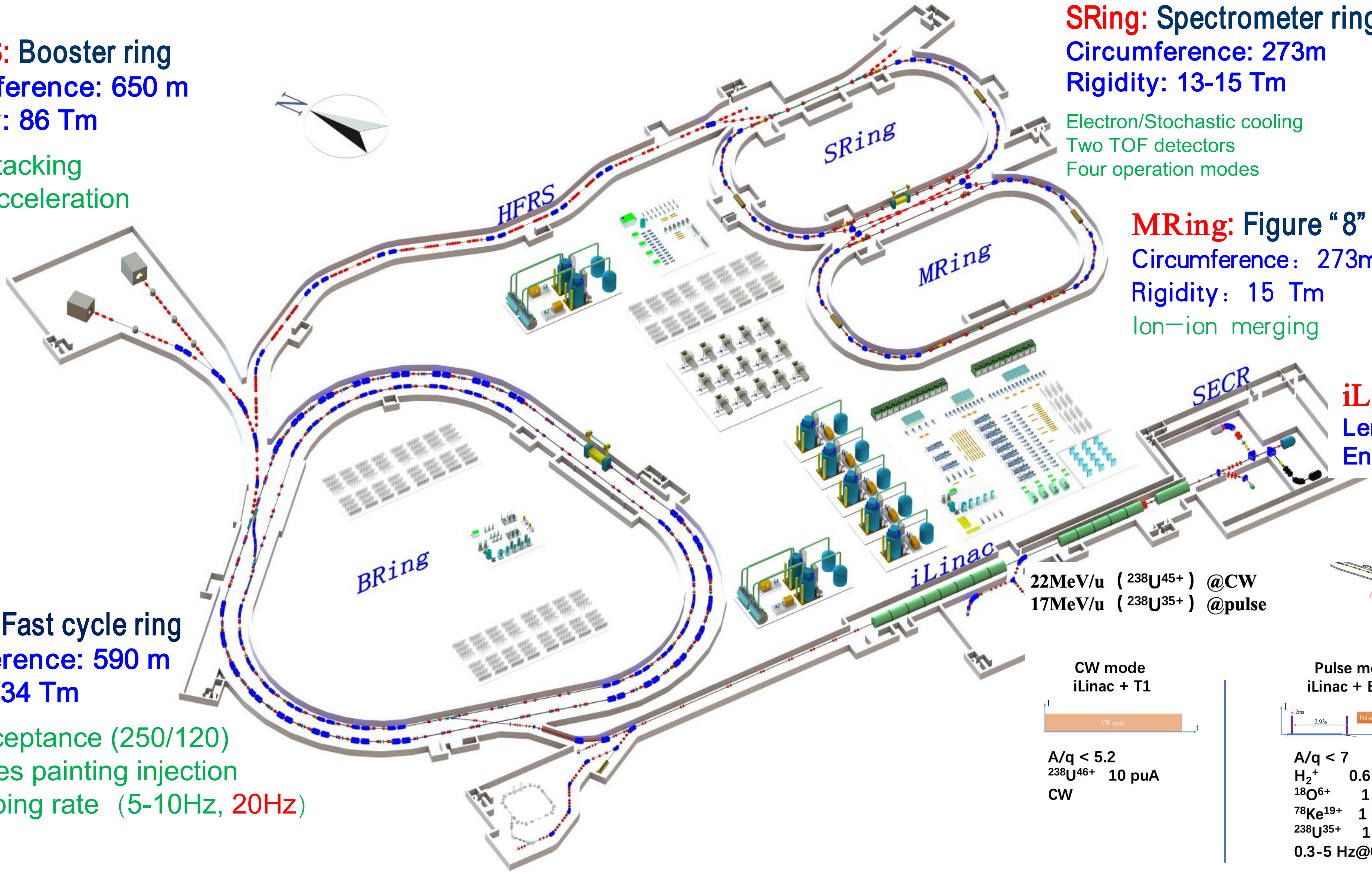
HIAF

BRing-S: Booster ring
Circumference: 650 m
Rigidity: 86 Tm

Beam stacking
Beam acceleration

SRing: Spectrometer ring
Circumference: 273m
Rigidity: 13-15 Tm

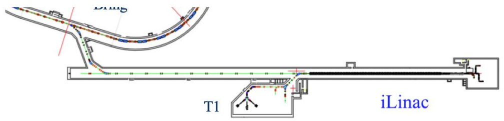
Electron/Stochastic cooling
Two TOF detectors
Four operation modes



MRing: Figure “8” ring
Circumference：273m
Rigidity：15 Tm
Ion—ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17-22 MeV/u($U^{35+-45+}$)

22MeV/u （$^{238}U^{45+}$） @CW
17MeV/u （$^{238}U^{35+}$） @pulse



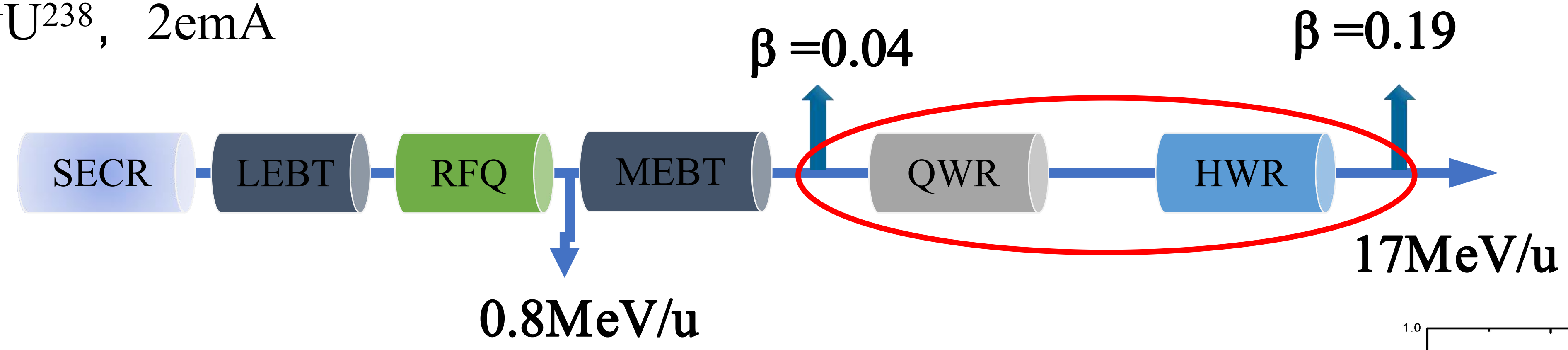
BRing-N: Fast cycle ring
Circumference: 590 m
Rigidity: 34 Tm

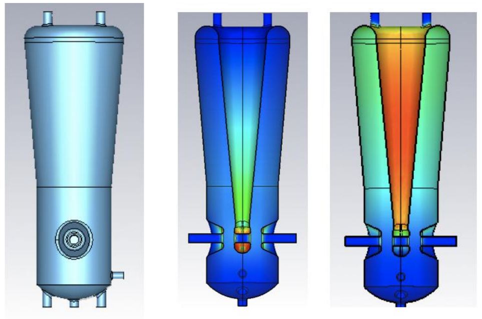
Large acceptance (250/120)
Two planes painting injection
Fast ramping rate （5-10Hz, 20Hz）

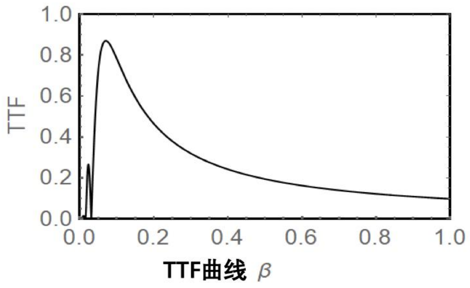
CW mode iLinac + T1	Pulse mode iLinac + Bring	pa iLinac + Bring + T1
A/q < 5.2 $^{238}U^{46+}$ 10 puA CW	A/q < 7 H_2^+ 0.6 emA $^{18}O^{6+}$ 1 emA $^{78}Kr^{19+}$ 1 emA $^{238}U^{35+}$ 1 emA 0.3-5 Hz@0.2-2 ms	A/q < 5.2 ECRs +T1 switch Two beams with A/q >80% T1 + 2 ms Bring 0.3-5 Hz@0.2-2 ms

SRF Resonators of HIAF

Design: $^{35+}U^{238}$, 2emA

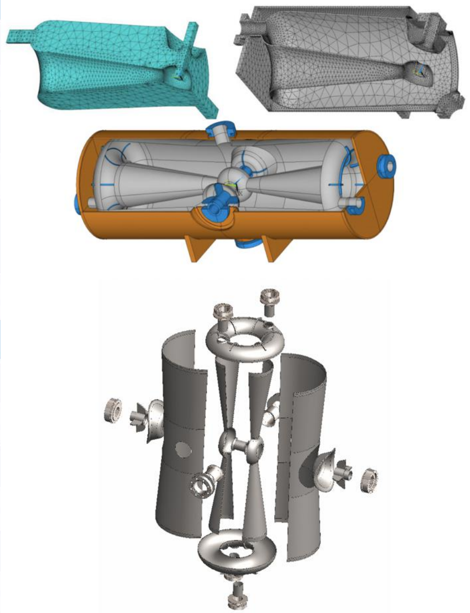






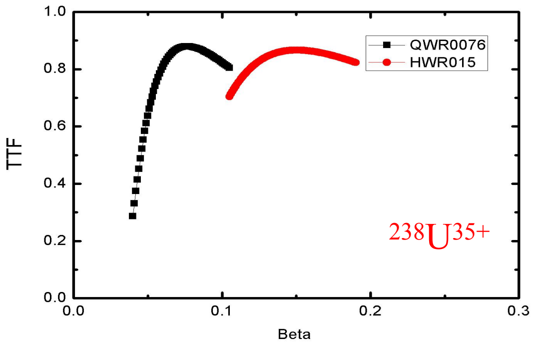
parameter	IMP	ANL
Frequency (MHz)	81.25	72.75
β_{opt}	0.076	0.077
Leff (mm)	280.4	317.5
Epeak/Eacc	4.85	5.0
Bpeak/Eacc (mT/(MV/m))	5.43	7.1
Ra/Q0 (Ω)*G (Ω)	15402	14711

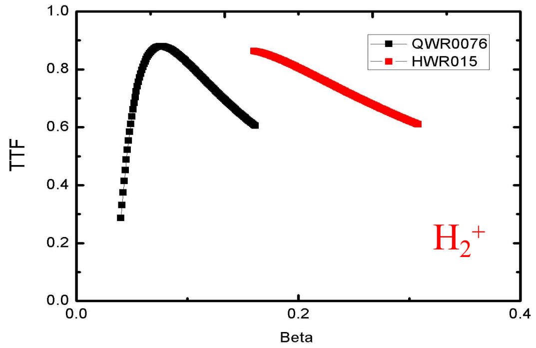
Parameter	
Epmax（MV/m）	33
Ep1(operation)（MV/m）	28
Veff @Ep1（MV/m）	1.62
Eacc@Ep1（MV/m）	5.77
Q0 （Res15nΩ，20mG）	1.67E9
Ploss[2K] @Ep1（W）	3.07



Parameter	
Frequency (MHz)	162.5
β_{opt}	0.15
Effective length (mm)	276
Epeak/Eacc	4.89
Bpeak/Eacc (mT/(MV/m))	6.11
Ra/Q0 (Ω)*G (Ω)	14892

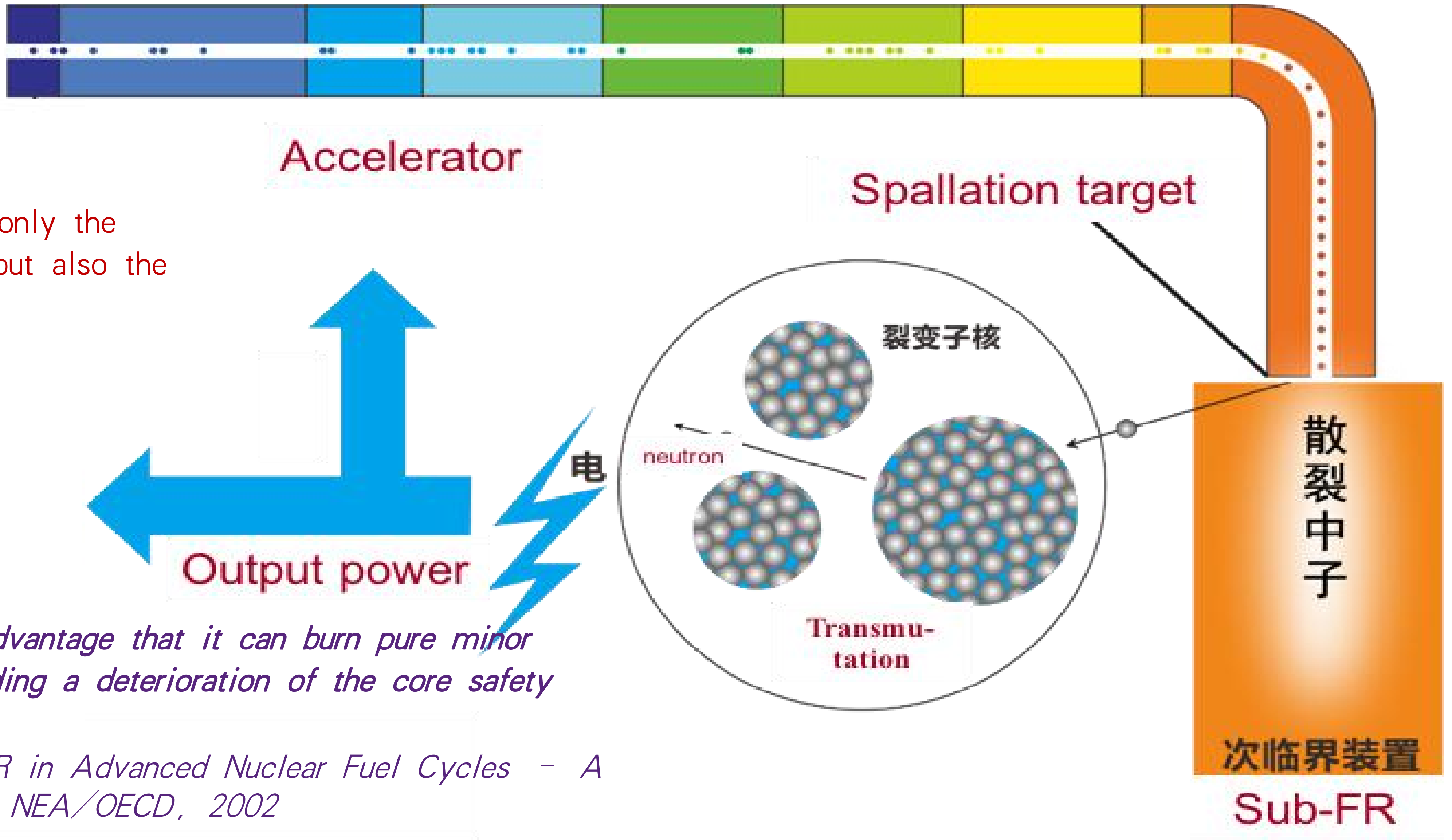
parameter	
Epmax（MV/m）	33
Ep1(operation)（MV/m）	28
Veff @Ep1（MV/m）	1.58
Eacc@Ep1（MV/m）	5.37
Q0 @2K（Res15nΩ，20mG）	2.80E9
Ploss[2K] @Ep1（W）	3.05





One of Solution of Sustainable Development

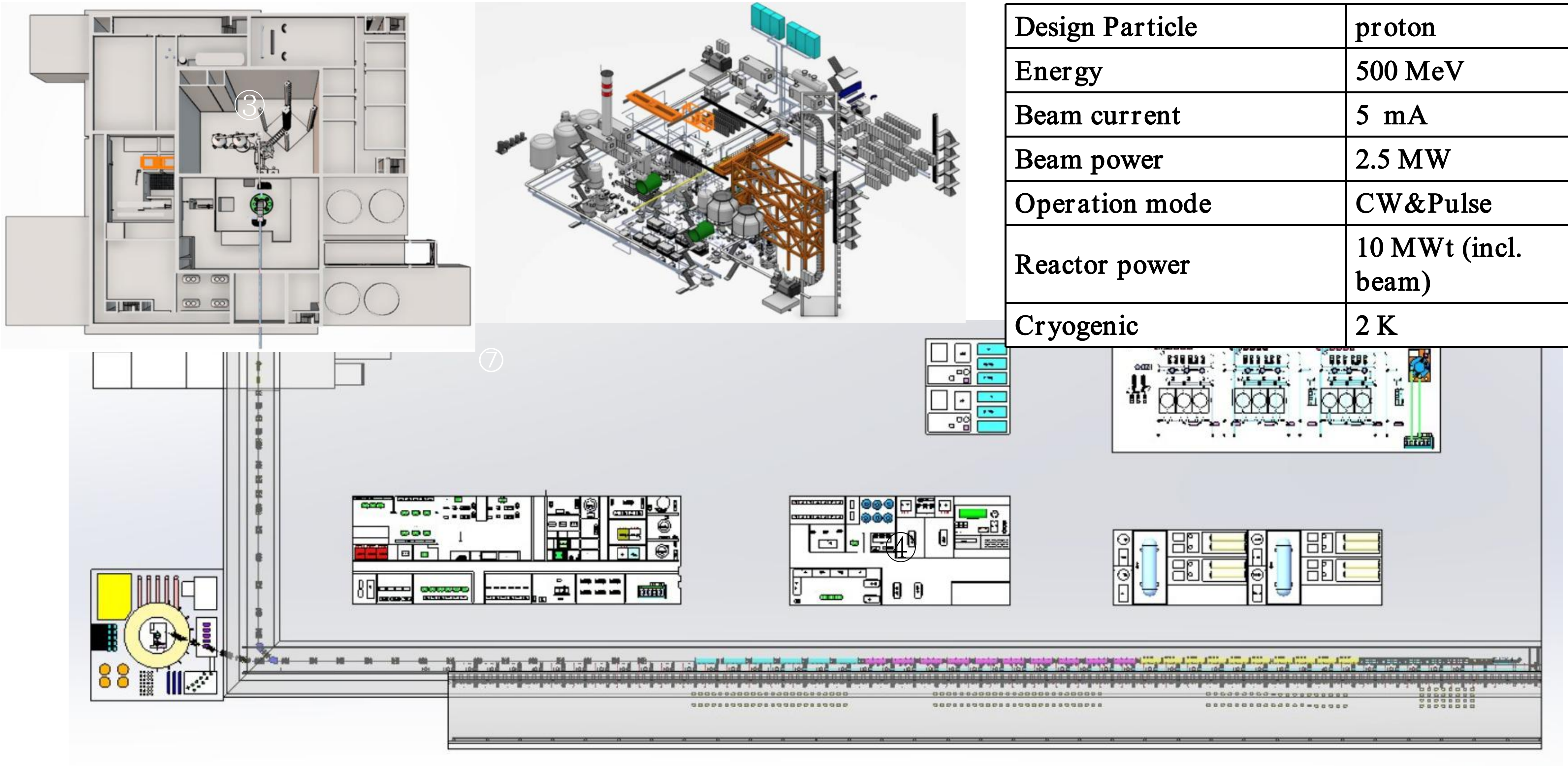
Nuclear waste is not only the issue of sustainable, but also the long-term supply.



"The ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics."

— ADS and FR in Advanced Nuclear Fuel Cycles – A Comparative Study, NEA/OECD, 2002

CiADS

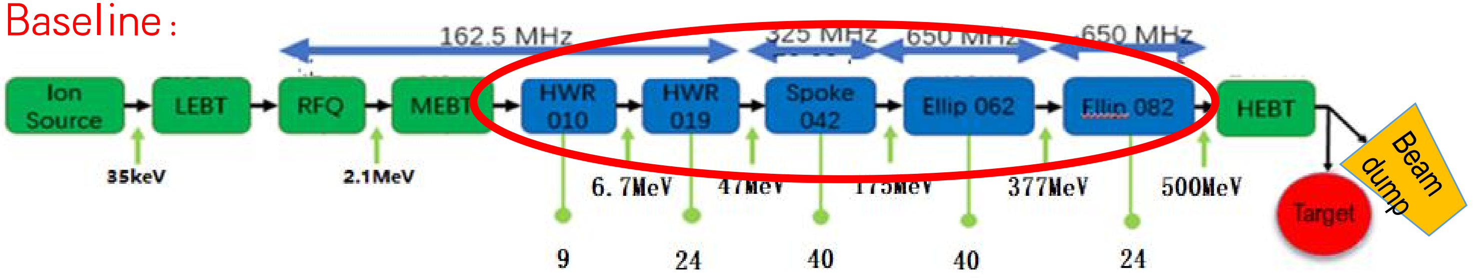


Design Particle	proton
Energy	500 MeV
Beam current	5 mA
Beam power	2.5 MW
Operation mode	CW&Pulse
Reactor power	10 MWt (incl. beam)
Cryogenic	2 K

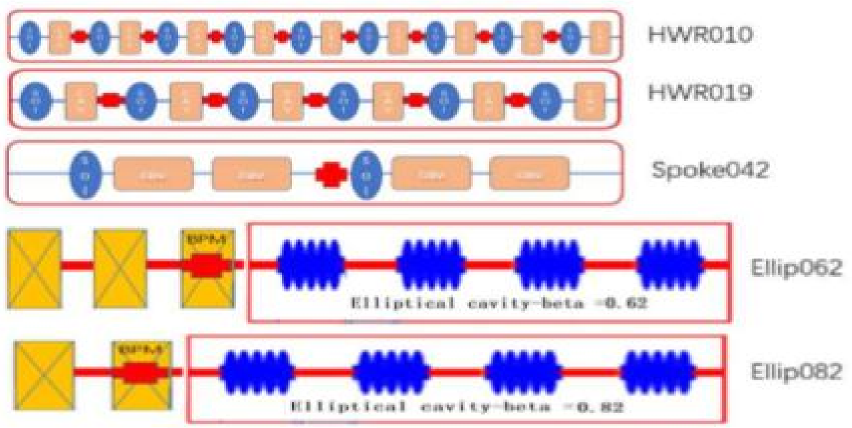
Design of SC section

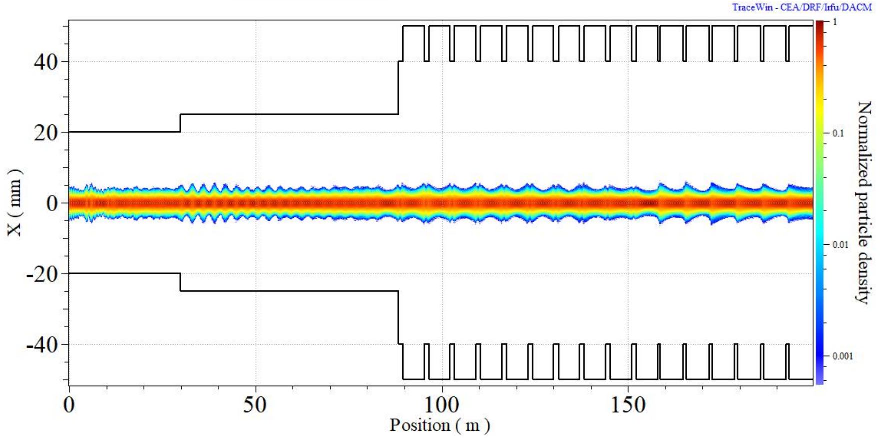
- Physics： phase advance <90; smoothness of focusing strength
- Engineering： minimization and uniformity of the hardwares, such as CM, SC cavities
- Operation： the margin of operation VS design value

Baseline：



Optimization of "smoothness" from 2 to 10 degs !!

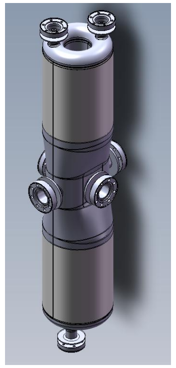


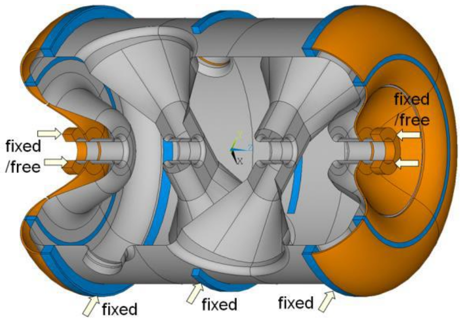


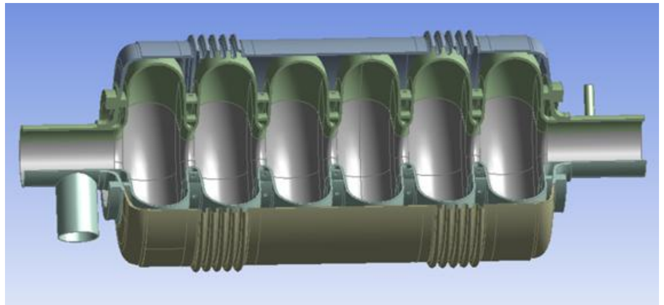
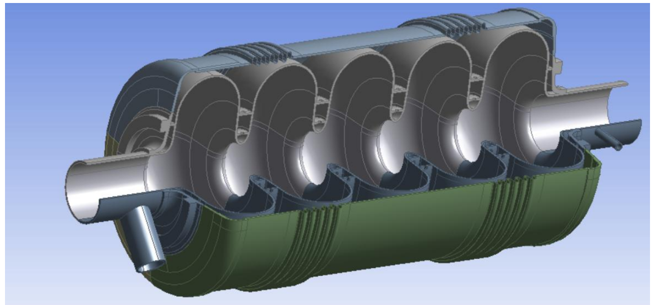
	HWR010	HWR019	Spoke042	Ellip062	Ellip082
f（MHz）	162.5	162.5	325	650	650
βopt	0.10	0.19	0.42	0.62	0.82
Number of cells	2cell	2cell	3cell	6cell	5cell
Epeak(MV/m)	26/30	28/33	28/33	28/33	28/33
Num of cavities	9	24	40	40	24
Focusing elements	SC sol	SC sol	SC sol	triplet	doublet
Num of magnets	9	24	20	10	6
Magnet field(T)	7.5	7.5	7.5	0.9	0.9
Length of CM(m)	6	6	6	6	6
Num of CMs	1	4	10	10	6

Resonators in CiADS

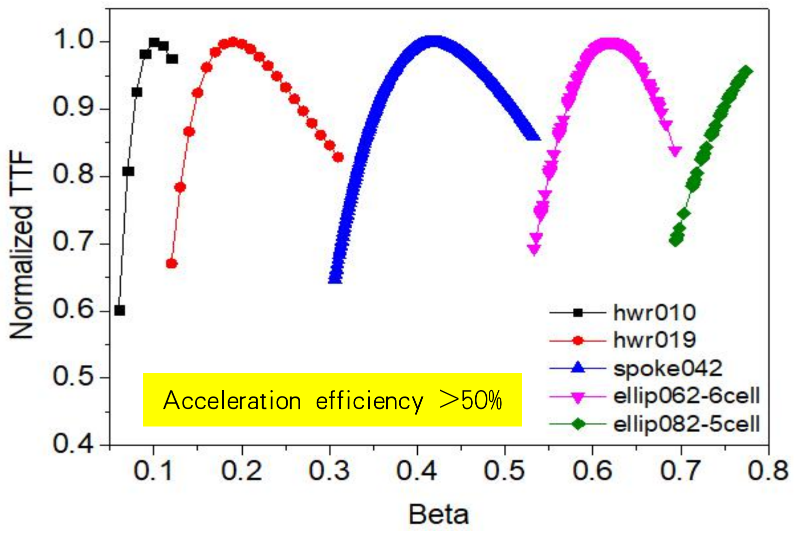
SC Cavity		HWR010	HWR019	SPOKE042	Elliptical062-6cell	Elliptical082-5cell
Beta		0.10	0.19	0.42	0.62	0.82
frequency	MHz	162.50	162.50	325.00	650.00	650.00
Beam Aperture	mm	40.00	40.00	50.00	100.00	100.00
Leff	m	0.185	0.351	0.582	0.824	0.895
L_{ftof}(flange to flange)	m	0.2100	0.4700	0.8300	1.2200	1.2200
Ep/Eacc		5.60	4.25	3.84	2.80	2.10
Bp/Eacc	mT/MV/m	12.71	6.35	6.95	4.86	3.98
Ep1(operation)	MV/m	26.00/30	28.00/33	28.00/33	29.00/33	29.00/33
Bp @Ep1	mT	59.01	41.84	50.68	50.37	54.96
TTF		0.83	0.8867	0.80	0.72	0.74
Veff @Ep1	[MV]	0.86	2.31	4.24	8.54	12.36
V0 @Ep1	[MV]	1.03	2.61	5.30	11.81	16.82
Eacc@Ep1	[MV/m]	4.64	6.59	7.29	10.36	13.81

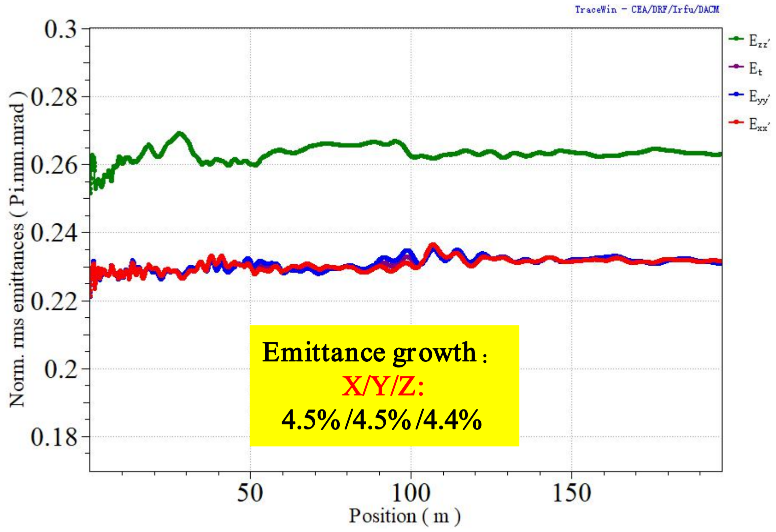


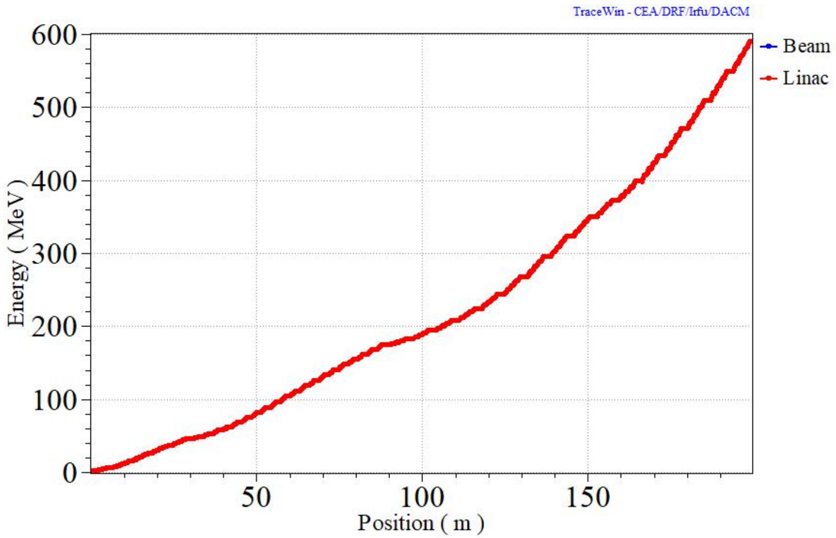


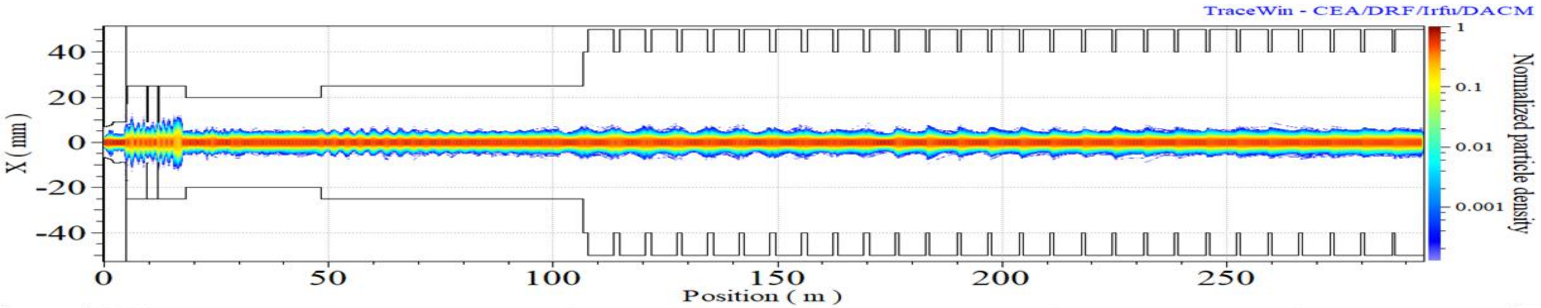



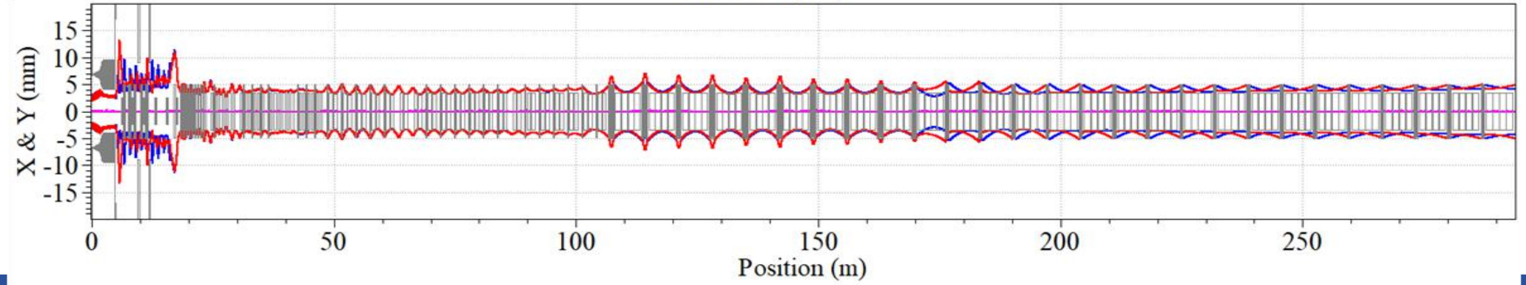
End to end simulation

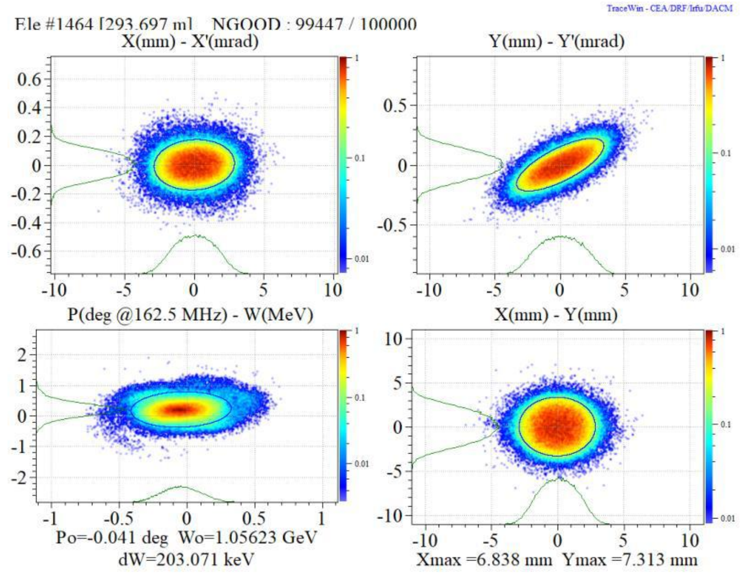












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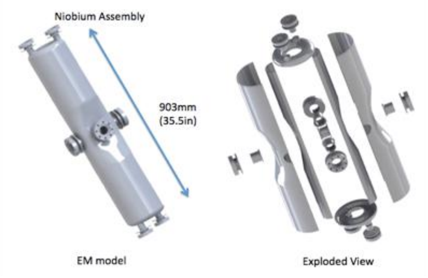
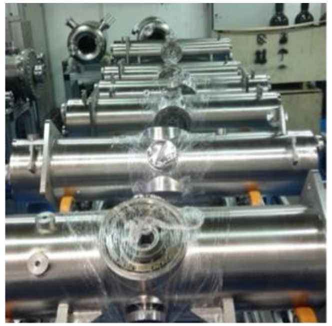
SRF cavities operation with beam

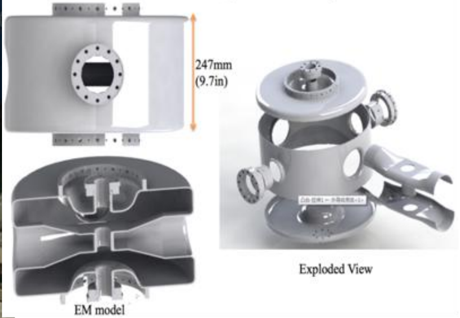
162.5 MHz Half-wave Cavity

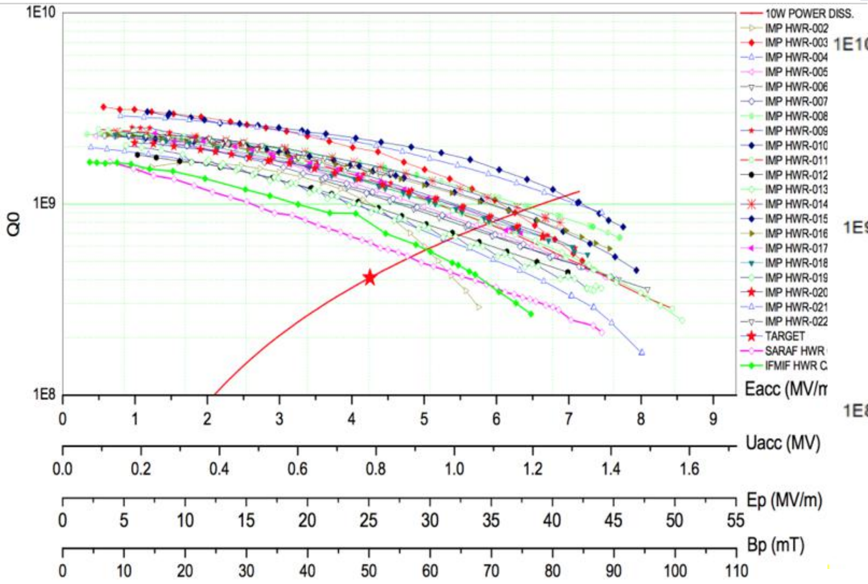


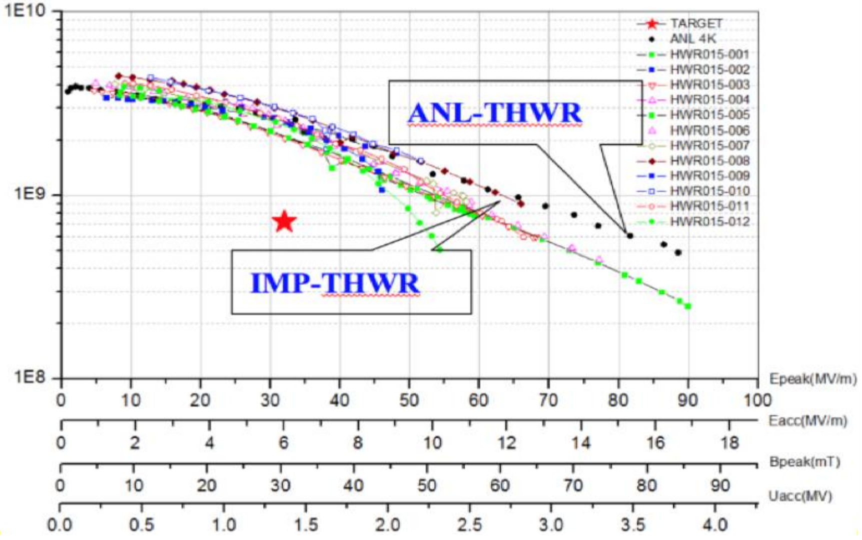


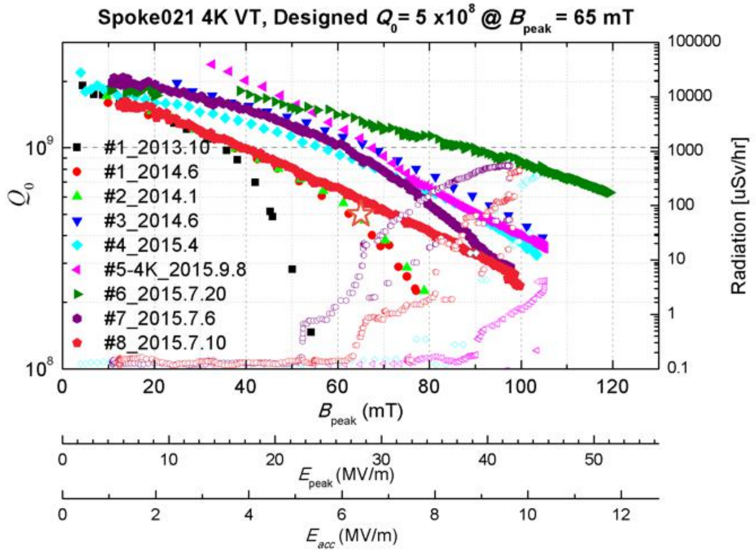
162.5 MHz Taper HWR015

325 MHz Spoke cavity







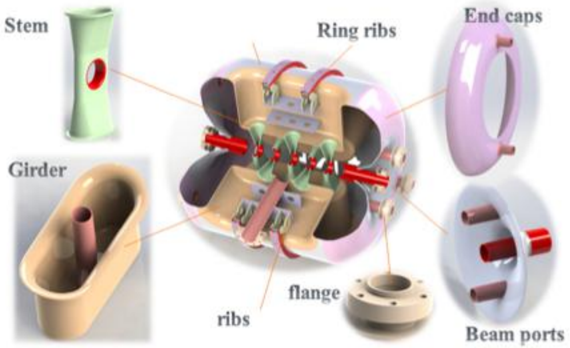


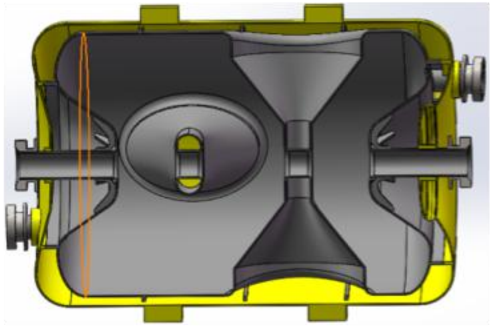
21 in total, 18 online

12 in total, 11 online

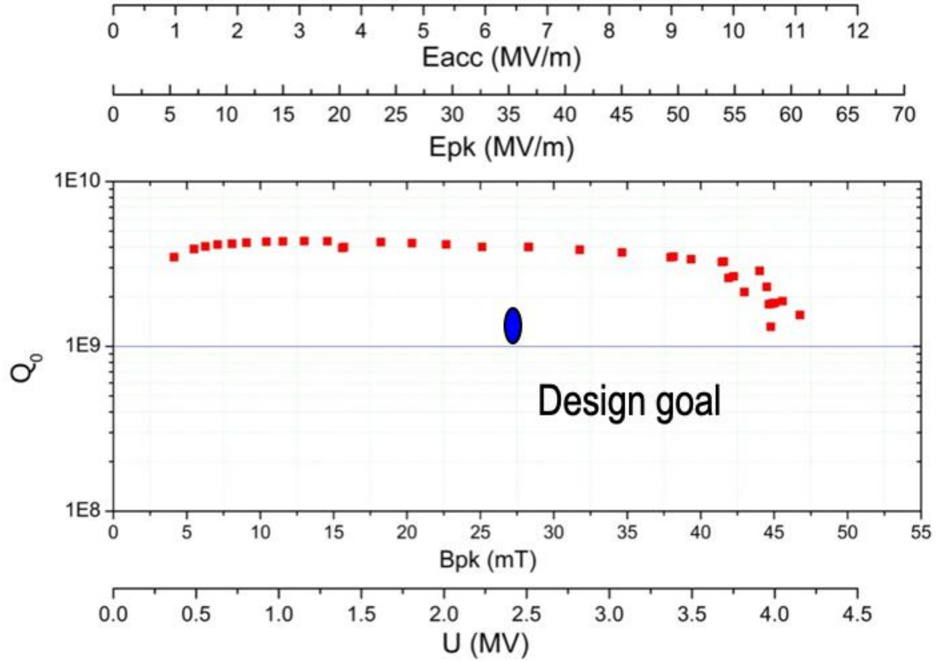
12 in total, 6 online

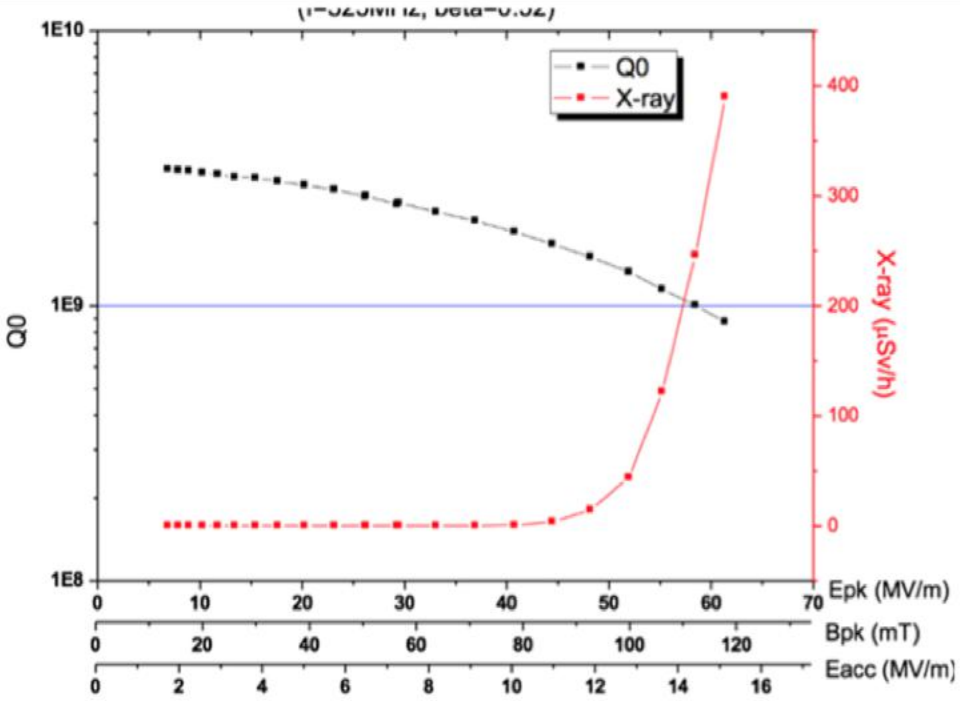
Spoke like cavities





The 4K vertical test results of superconducting CH cavity in IMP
(f = 162.5 MHz, beta = 0.067)

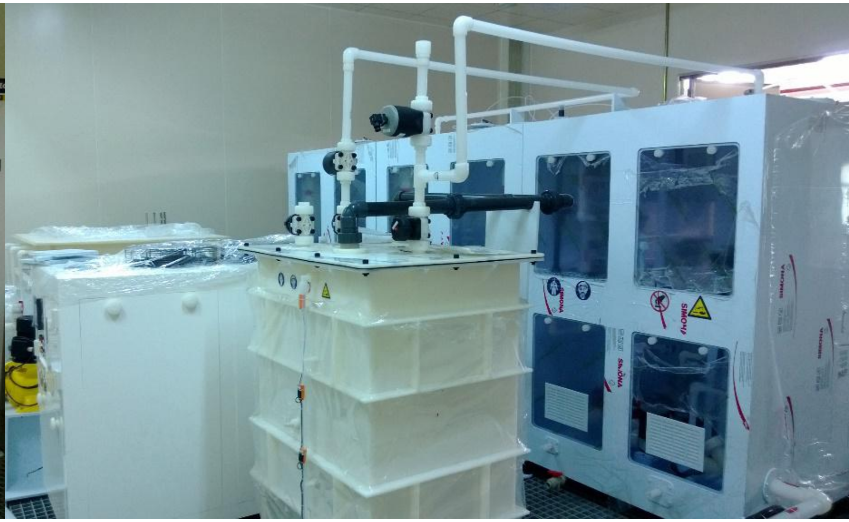




Chemical Laboratory at IMP

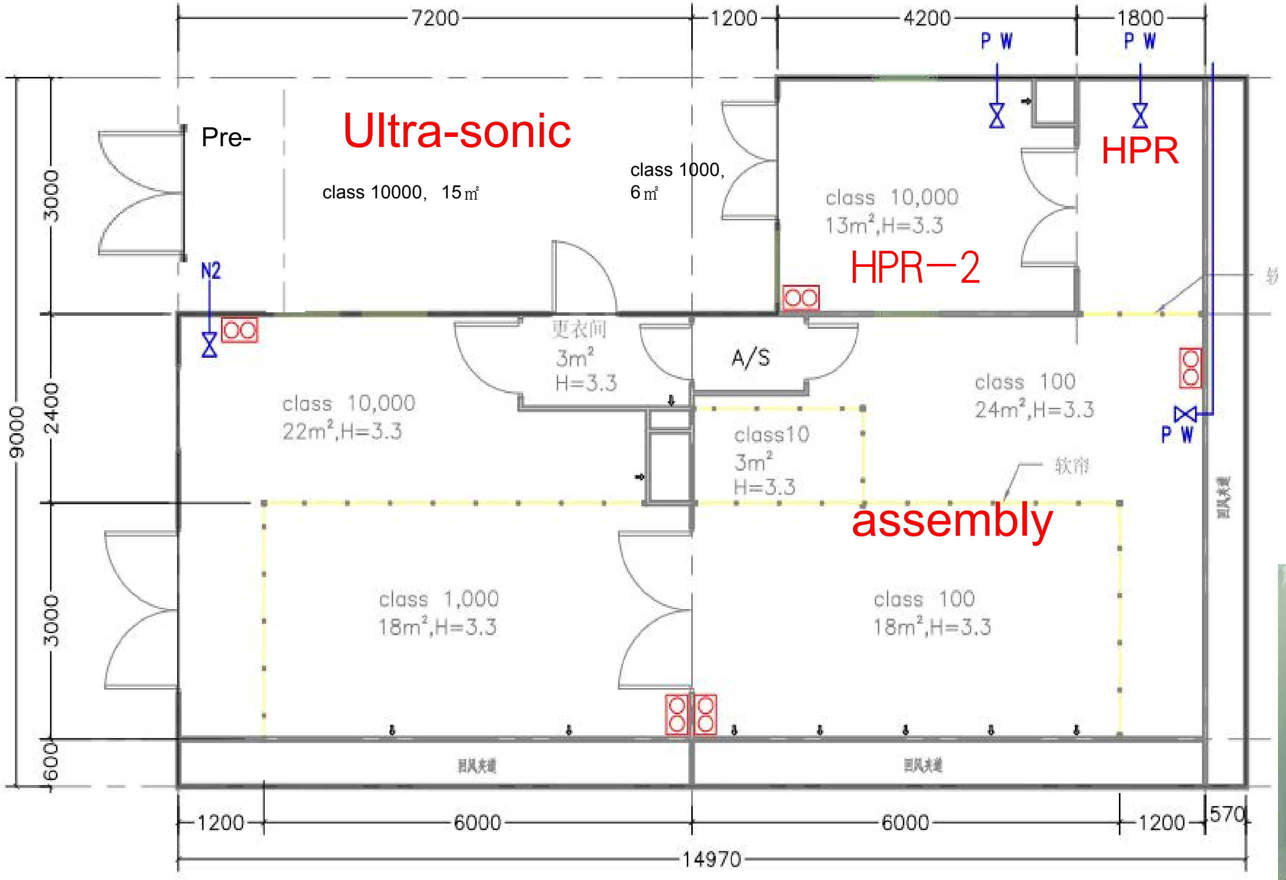


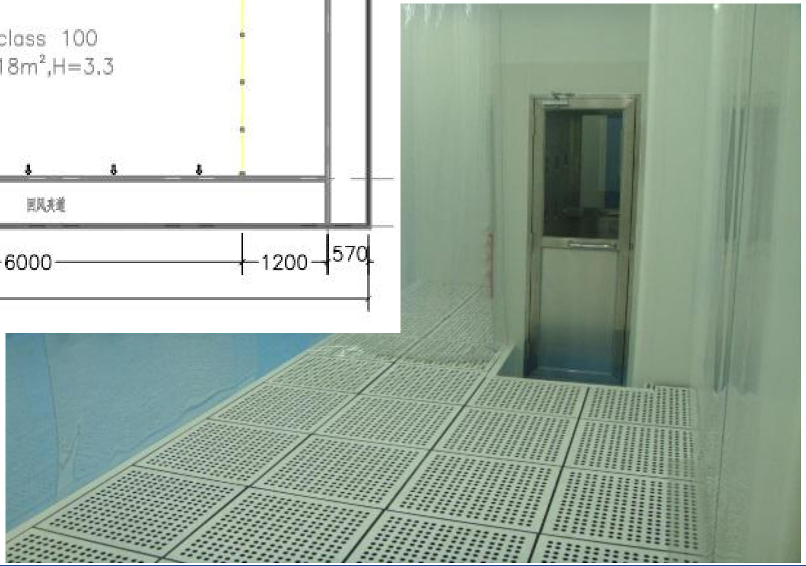




Chemical Laboratory at IMP

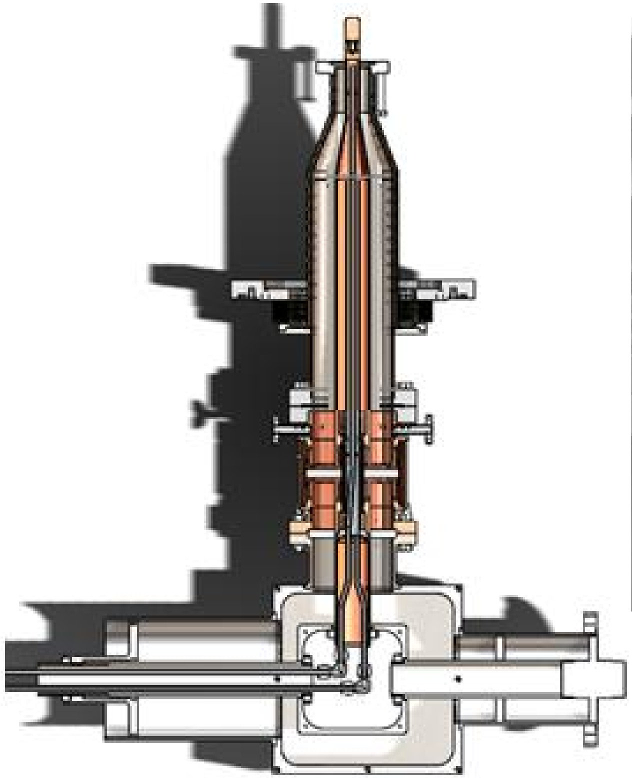
Cleanroom and assembly



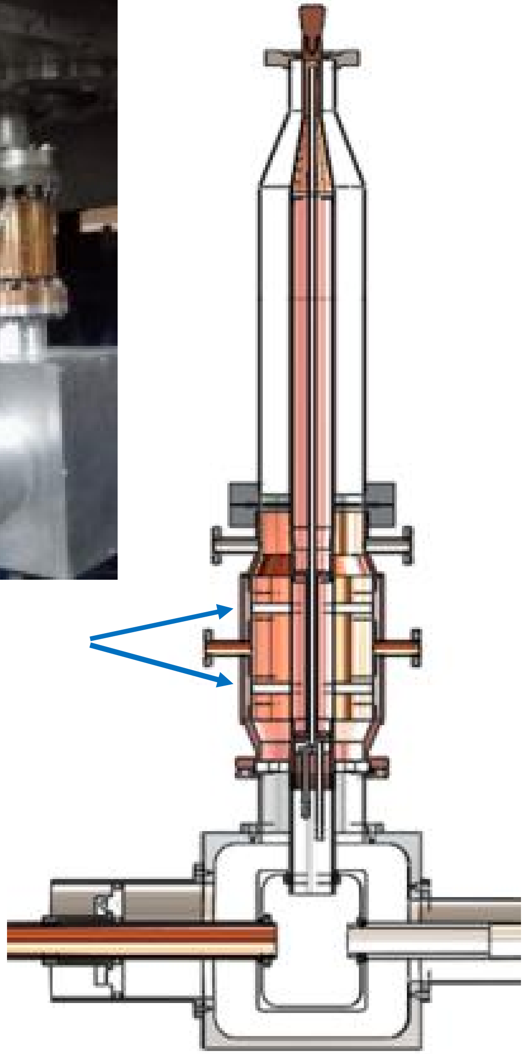


130㎡ cleanroom, Class 100 ~ 68㎡

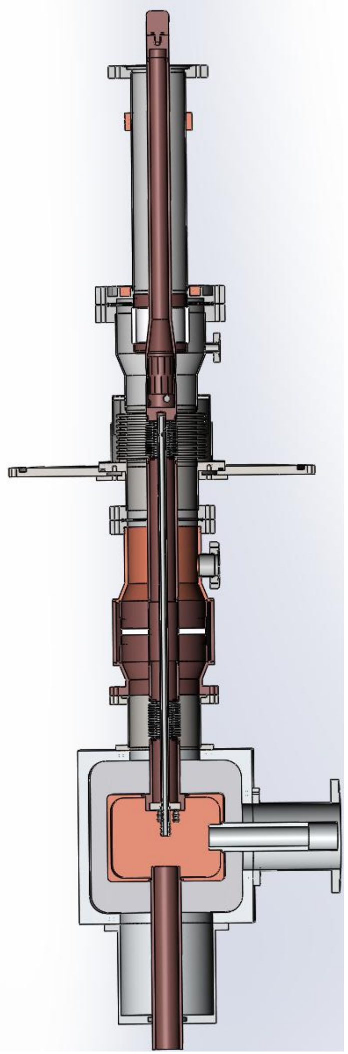
Fundamental Power Coupler



windows



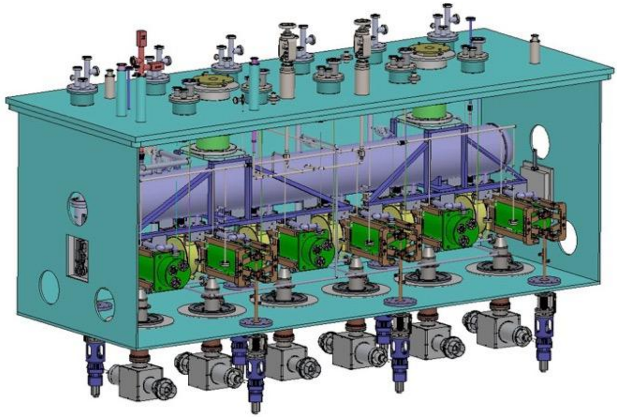
12 online



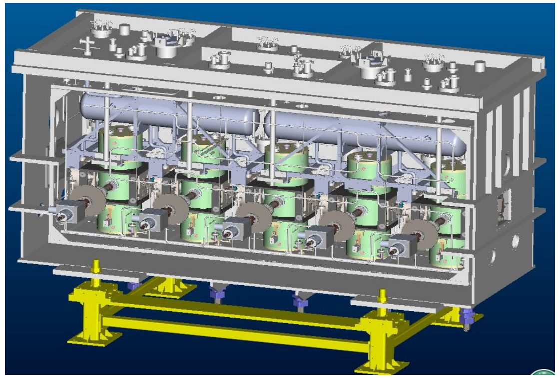
5 online

Cryomodules at IMP

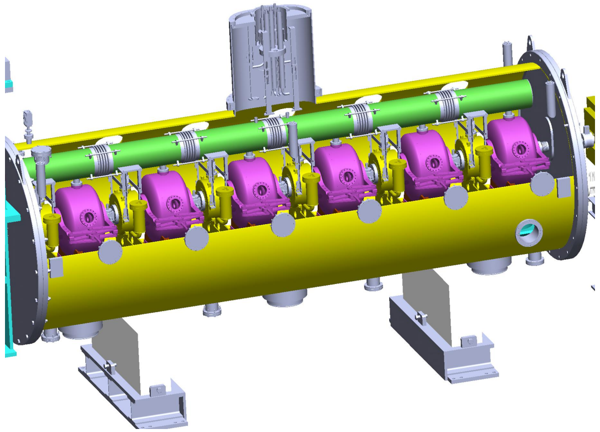
3 CMs HWR010

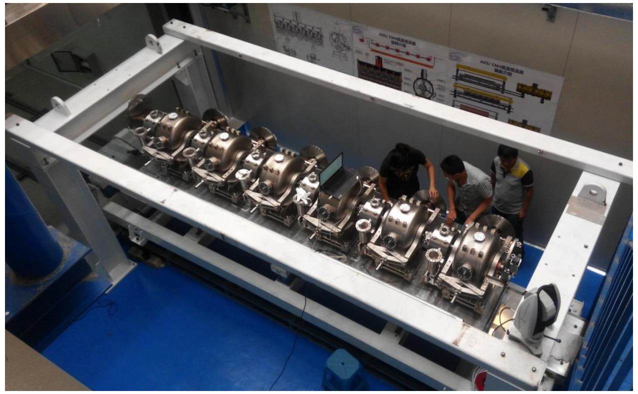


2 CMs HWR015



1 CM SPOKE024





6 CMs have been constructed, and 5 of them operated with CW proton beam.

Cryogenic plant of 850 W at 4.2 K






- Linde L280, 850W/4.2K
- FSD571 main compressor
- DS85 recovery compressor

- Recovery compressor, 15MPa/40m^3*4
- HP He purifier, 15MPa/100m^3

- HP He tank, 15MPa, 8000m^3
- Gas bags, 25m^3*2
- Purity analyzer on line

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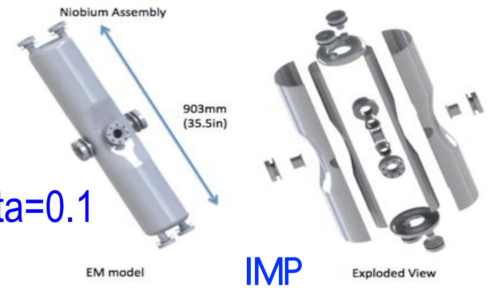
Chinese ADS Front-end Demo linac (CAFe)

- IMP collaboration with IHEP 2011～2017

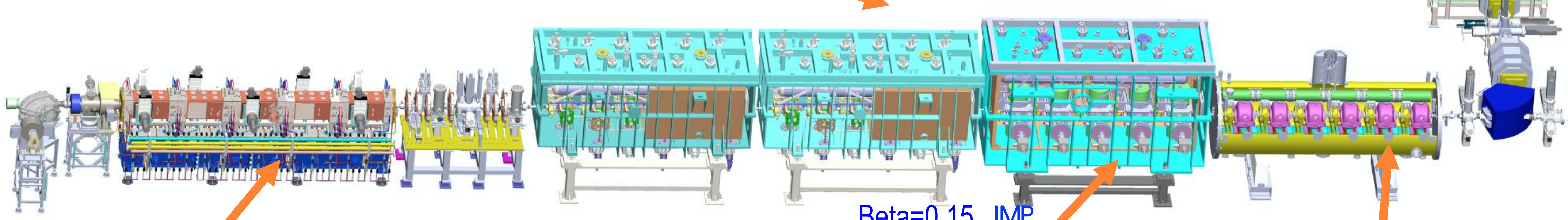
162.5 MHz Half-wave Cavity



Beta=0.1

IMP

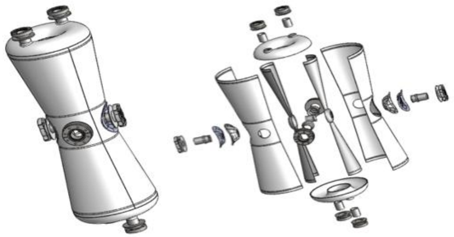
ions	P， H_2^+， α
frequency	162.5 MHz
current	10 mA
E in RFQ	40 keV
E out RFQ	3.1 MeV
Energy	25/30/40MeV
Temp.	4.5 K



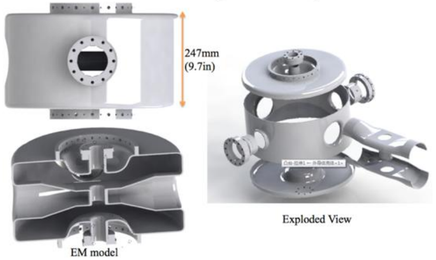
Beta=0.15 IMP

ADS RFQ： 2014—2017
(cooperation with LBL)
CMIF RFQ： 2018—

162.5 MHz Taper HWR



325 MHz Spoke cavity



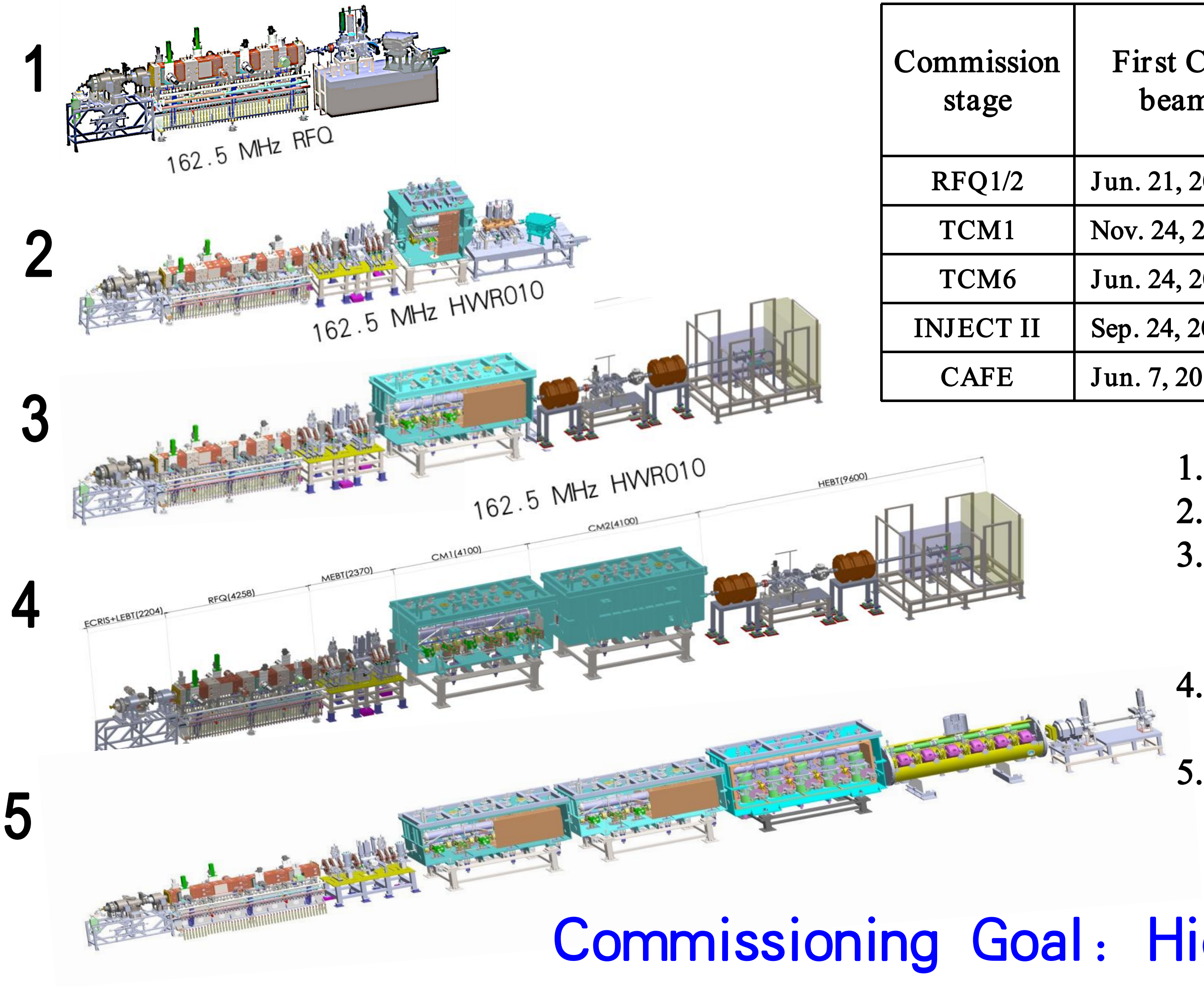
Beta=0.21

IHEP

- Goal: to demonstrate 10 mA CW beam of superconducting front-end Linac for CiADS.

- Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.

Commissioning of Superconducting Linac



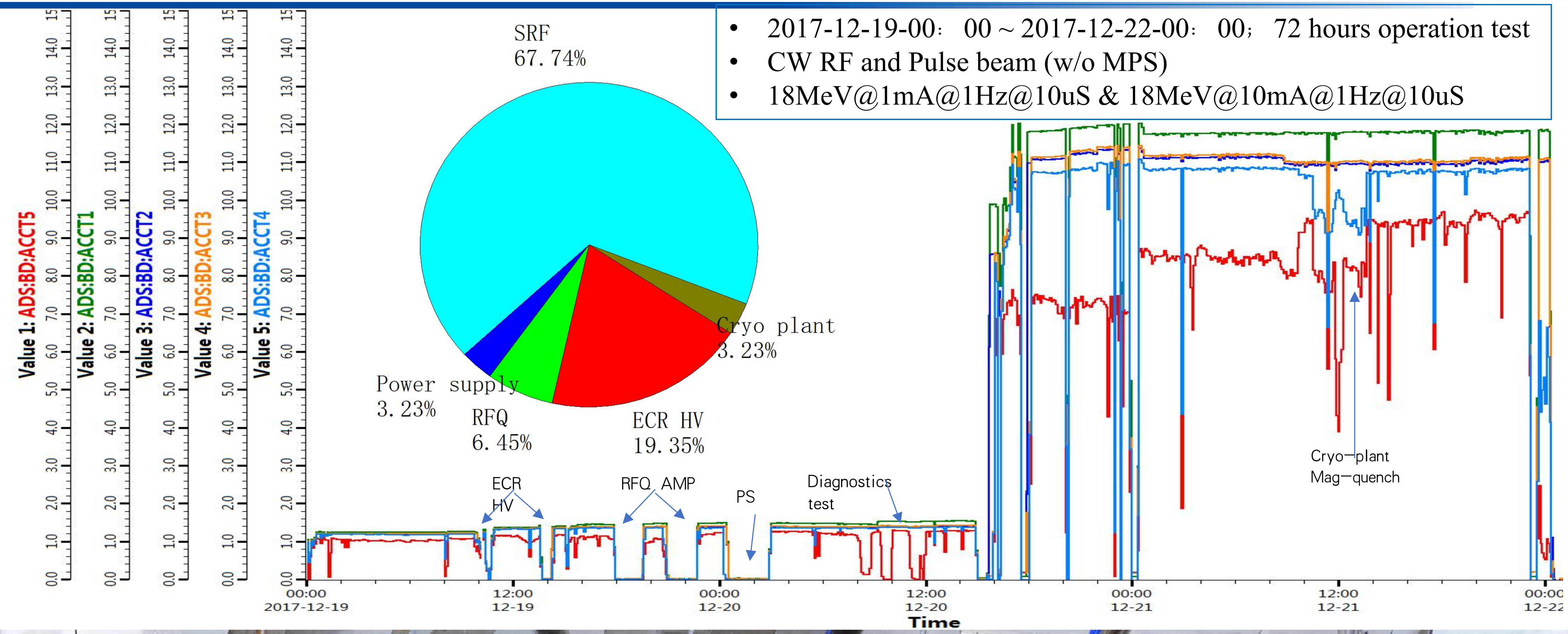
Commission stage	First CW beam	Max Energy (MeV)	Beam time (hours)	CW beam time Total (hours)	CW Current Max(A)	CW Power Max(kW)
RFQ1/2	Jun. 21, 2014	2.15/3	2036/~200	90/~120	11	23
TCM1	Nov. 24, 2014	2.55	208	22.5	11	28
TCM6	Jun. 24, 2015	5.3	400	20	4	21
INJECT II	Sep. 24, 2016	10.2	327	11	2.7	26
CAFE	Jun. 7, 2017	26.1	~500	~140	2.55	45

1. 2014.06.06——2014.07.24, RFQ
2. 2014.09.14——2015.02.13, TCM1
3. 2015.03.26——2015.06.29, TCM6, beam accident, RFQ AMP and coupler broken
   2015.10.28——2016.01.21, TCM6 commissioning
4. 2016.05.01——2016.06.20, injector II, coupler broken
   2016.09.01——2016.12.17, injector II high power
5. 2017.04.28——2017.06.18, CAFe, current leads broken
   2017.10.03——2018.01.23, CAFe, operation stability
   2019.01.04 ——2 mA CW beam, operation stability

Commissioning Goal：Higher power，Higher stability

Operation Reliability Test low power beam in 2017

- 2017-12-19-00： 00 ~ 2017-12-22-00： 00； 72 hours operation test
- CW RF and Pulse beam (w/o MPS)
- 18MeV@1mA@1Hz@10uS & 18MeV@10mA@1Hz@10uS



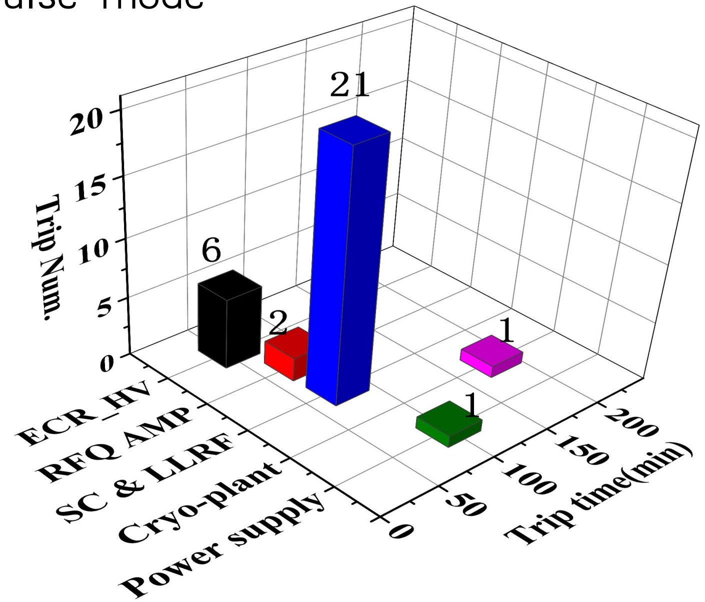
Preliminary RAMI analysis w/o active protection

Operation time	Beam time	Down time	Availability
4050 min	3566 min	484 min	0.88

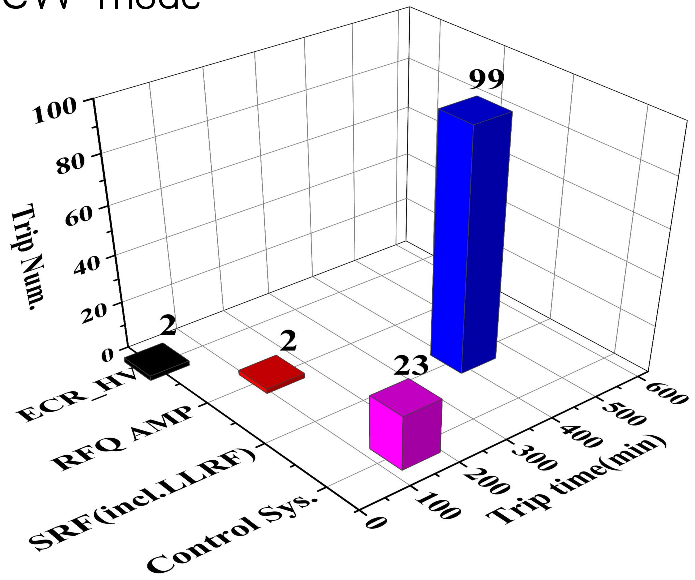
MTBF (min)	MTTR (min)	Beam trips (10s–5min)	Beam trips (>5min)
111.4	16.1	20	10

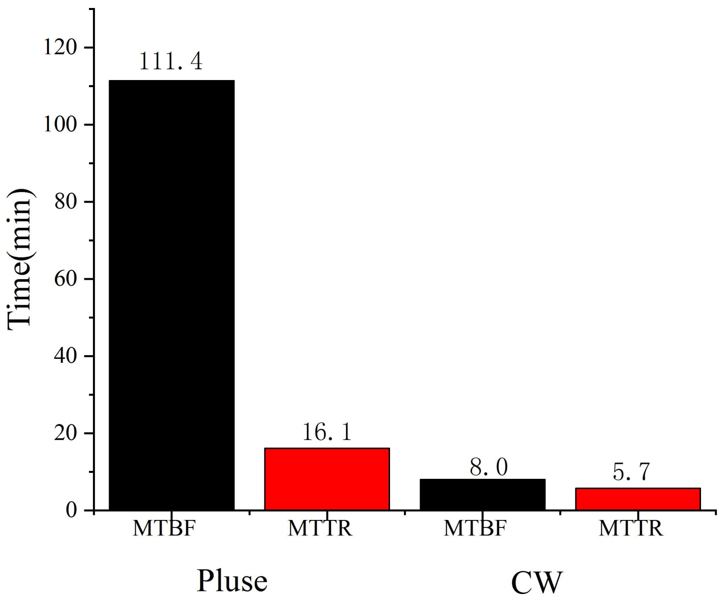
	ECR HV	RFQ AMP	SRF (incl. LLRF)	Cryo-plant	Power supply
Beam trips	6	2	21	1	1
Down time	53 min	77 min	78 min	183 min	100 min

Pulse mode

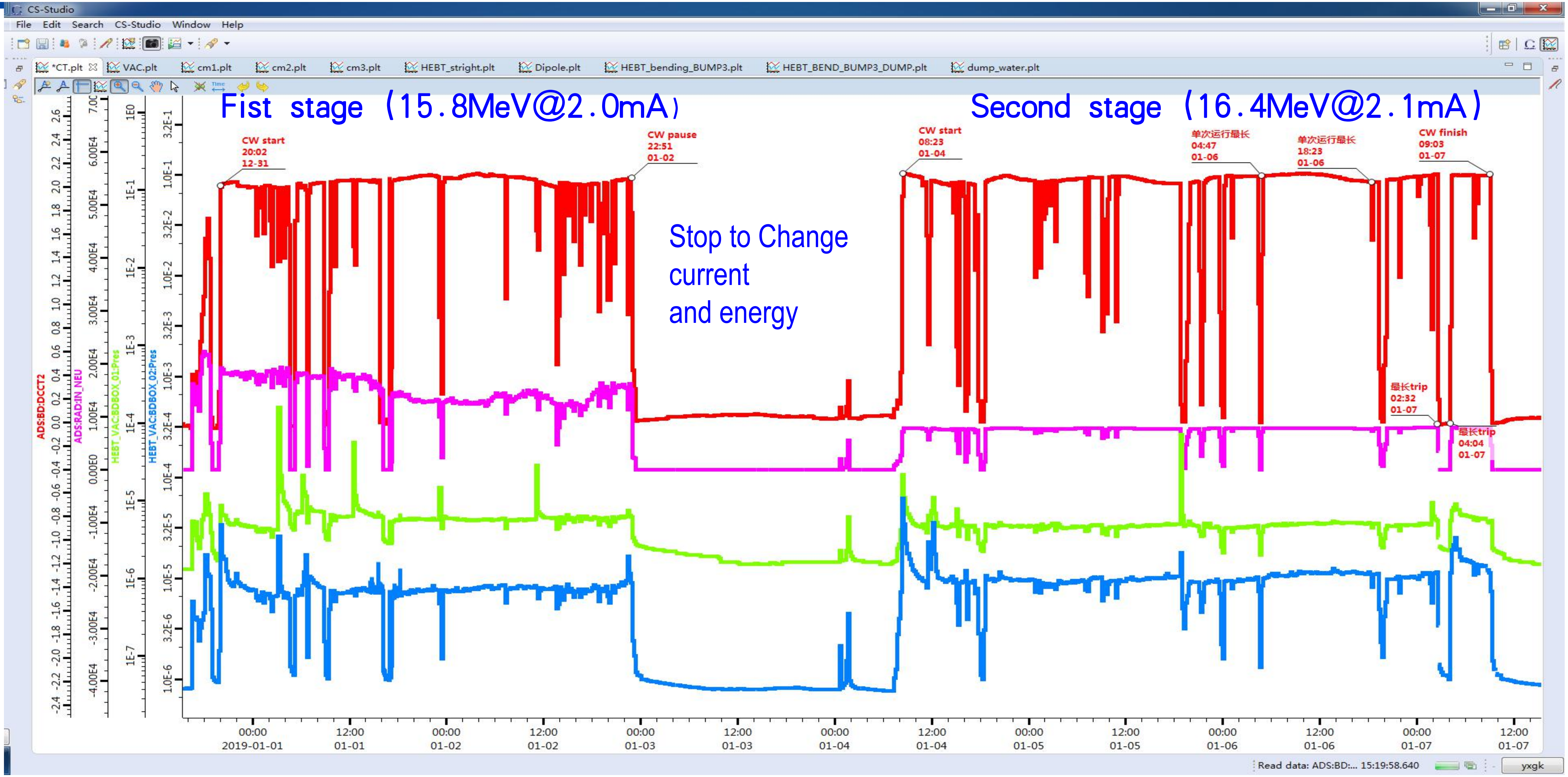


CW mode

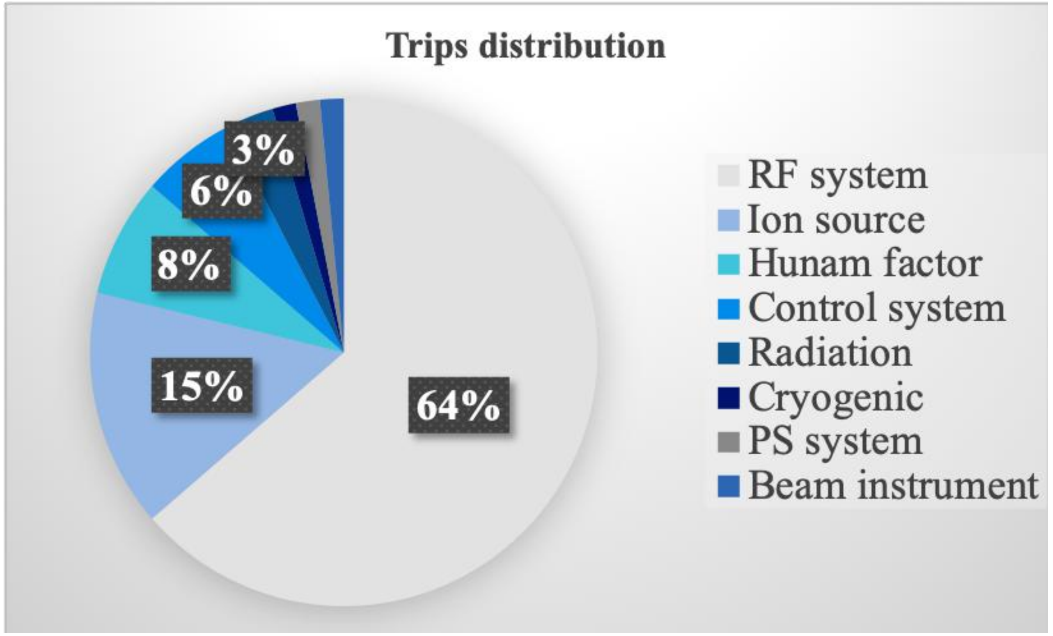


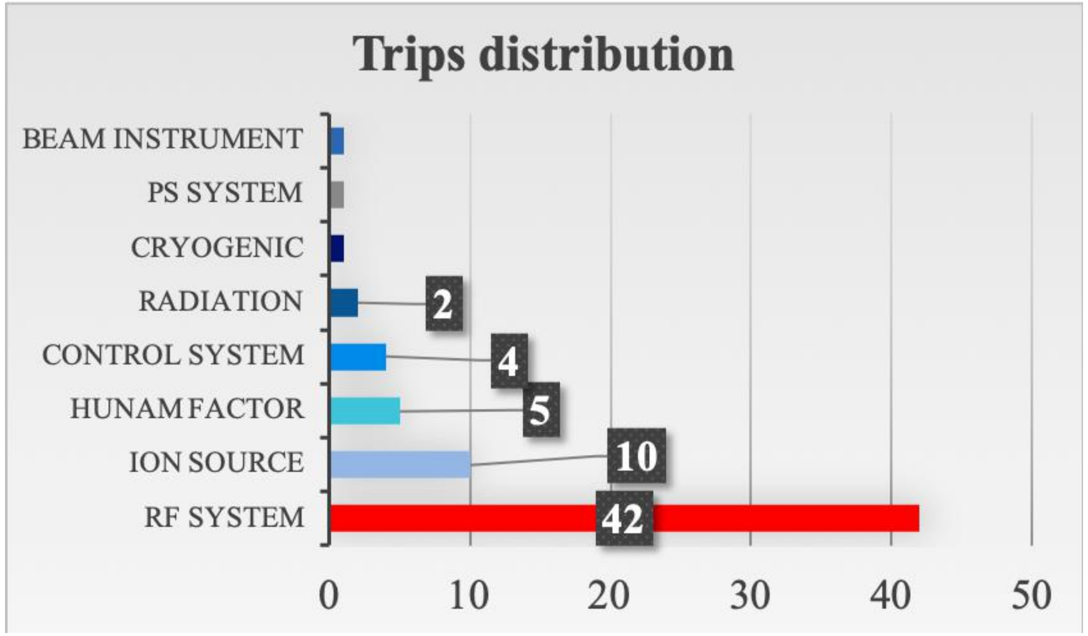


Operation Reliability Test with high power in 2019



RAMI of CW beam with active MPS





•Operation time 7553 min, downtime 737 min, availability 89%

•Max power is 45 kW with 2.55 mA @17.5 MeV

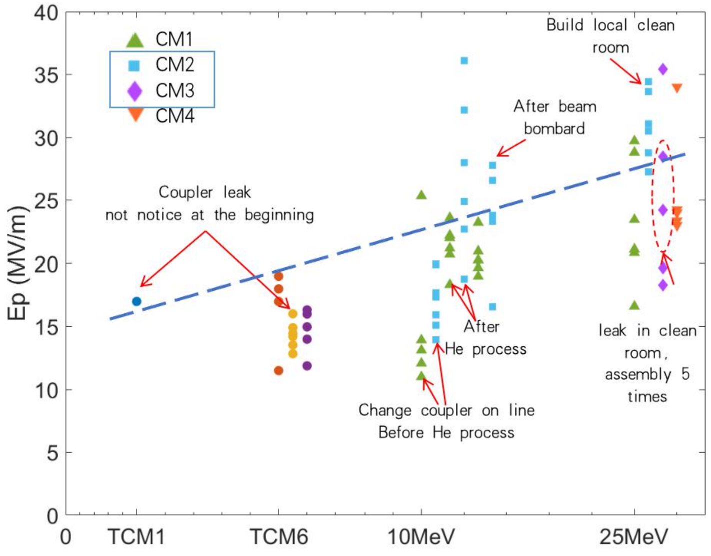
• 1st stage: 2018/12/31 18:44 — 2019/01/02 23:42

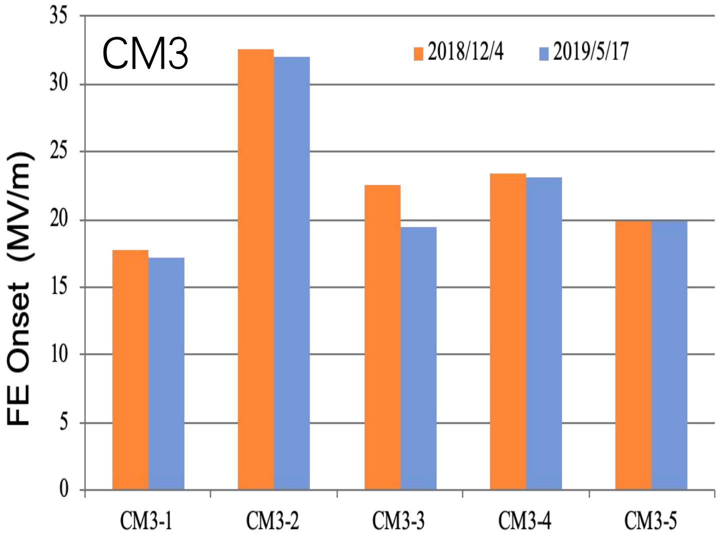
Availability	MTBF	MTTR
0.89	90.7 min	11.1 min

•2nd stage: 2019/01/04 08:08 — 01/07 09:03

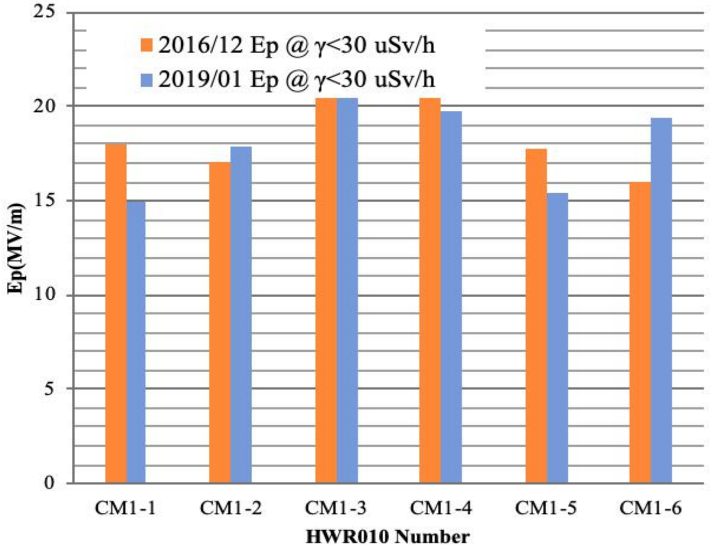
Availability	MTBF	MTTR
0.89	113.7 min	14.6 min

Operational Gradient Degradation

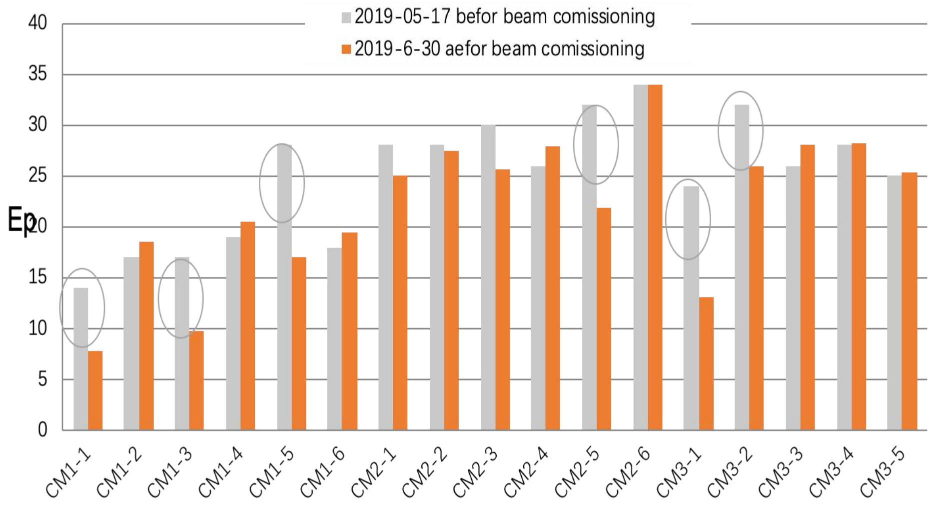




- 2018/12/4: before CW commissioning
- 2019/5/17: after CW commissioning, return to room temperature, RF conditioning
- FE onset almost not change



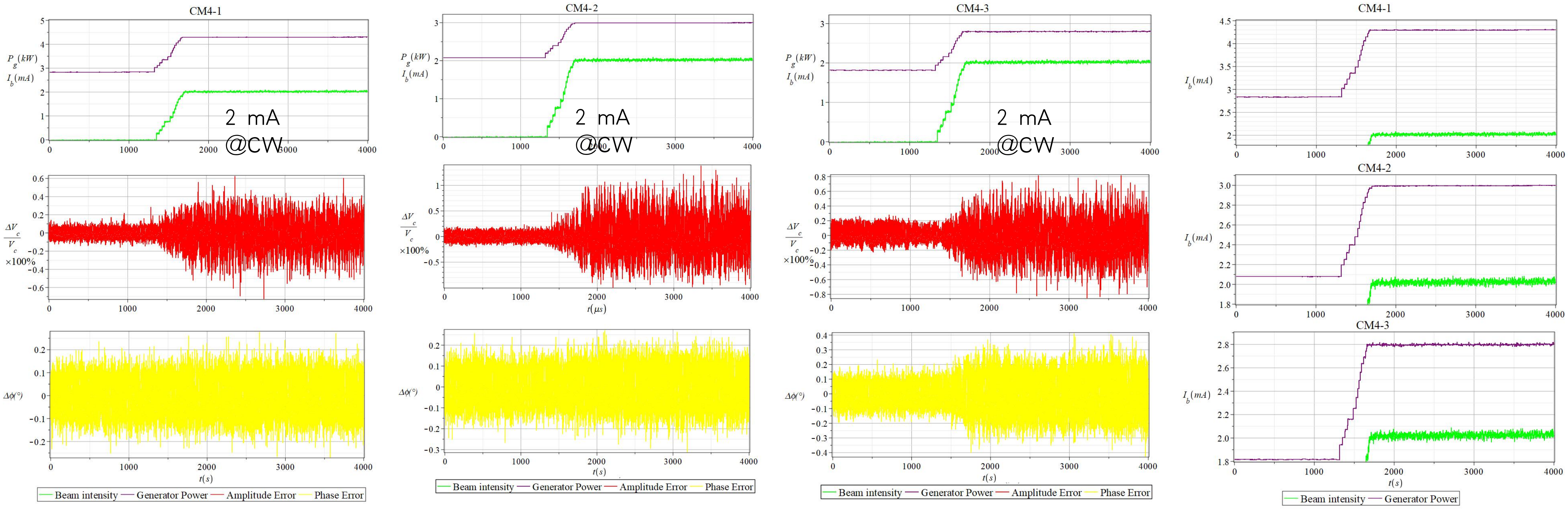
- CM1 removed after 10 MeV test
- Warm back to room temperature, vacuum ~100 Pa, 2017/01 to 2018/09
- Re-install after RF condition, Ep average 18 MV/m with γ 30 uSv/h limit (ball shape, EGM).
- **Average performance almost not change after the CM1 not used for one year in room temperature, vacuum ~100Pa**

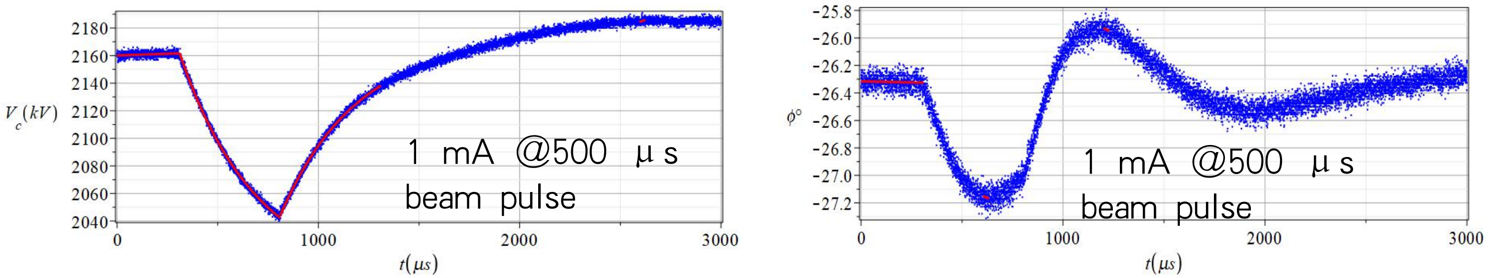


Compare at same γ-dose

- Degradation: CM1-1, CM1-3, CM1-5, CM2-5, CM3-1, CM3-2
- For the 6 cavities, 8.6MV/m decrease

Field oscillation caused by CW beam



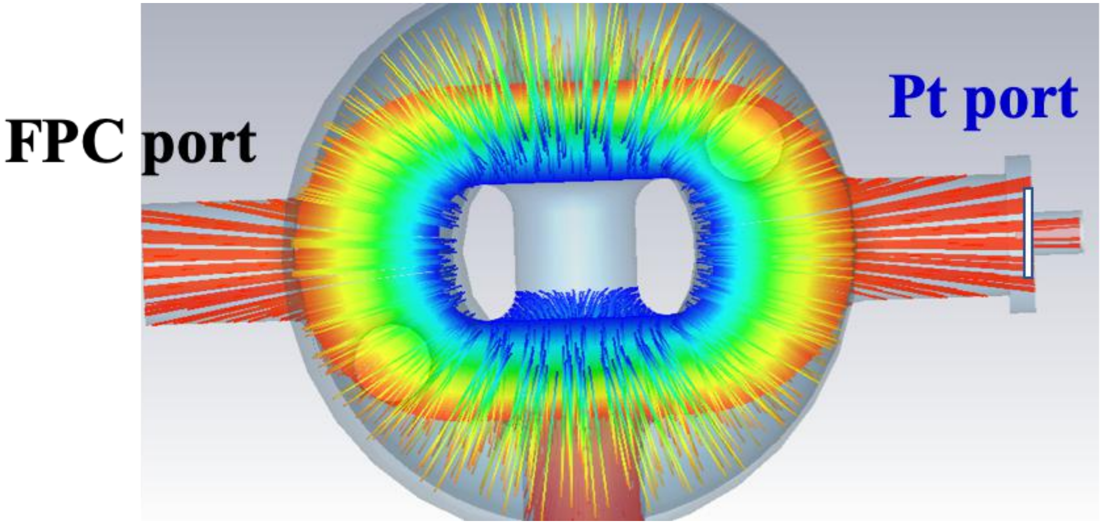


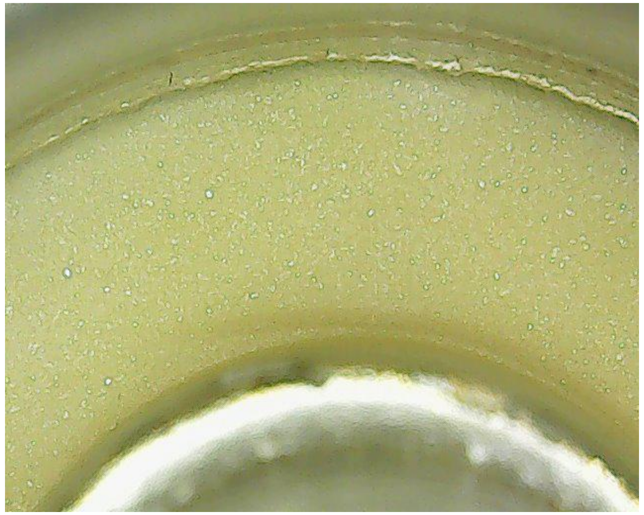
HWR010@CM2—1, no feedforward, weak amplitude feedback;

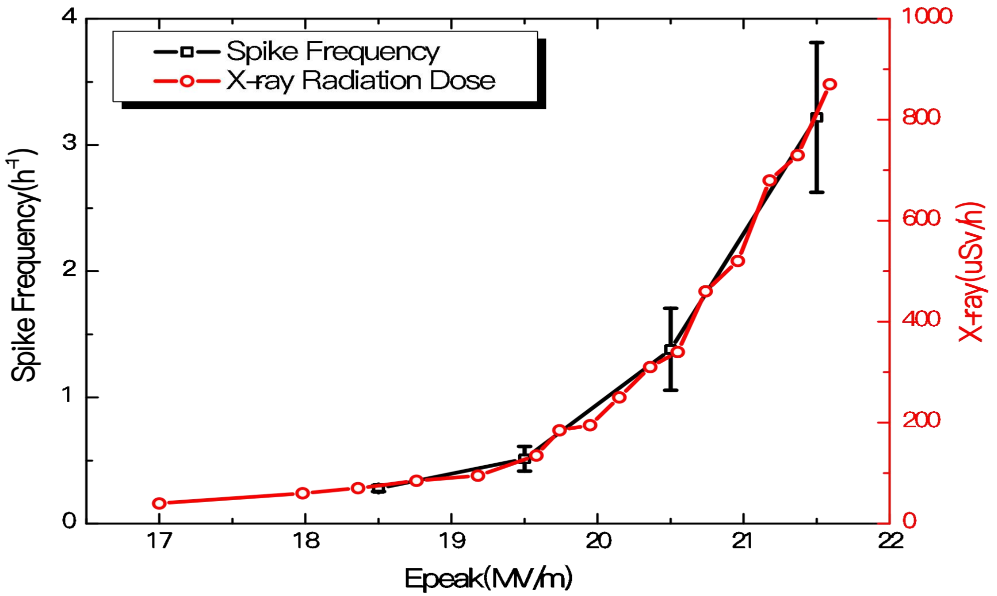
Possible reason:

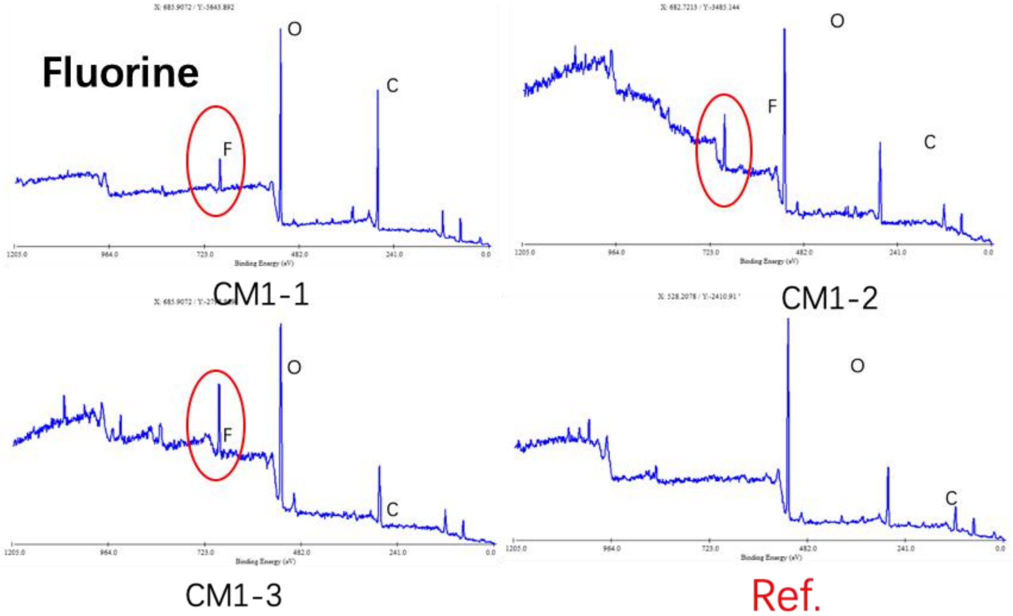
1. Excessive k_p in the feedback loop;
2. Large time delay in the feedback loop;
3. Ponderomotive effects.

Windows broken of FPC and Pt Caused by FE

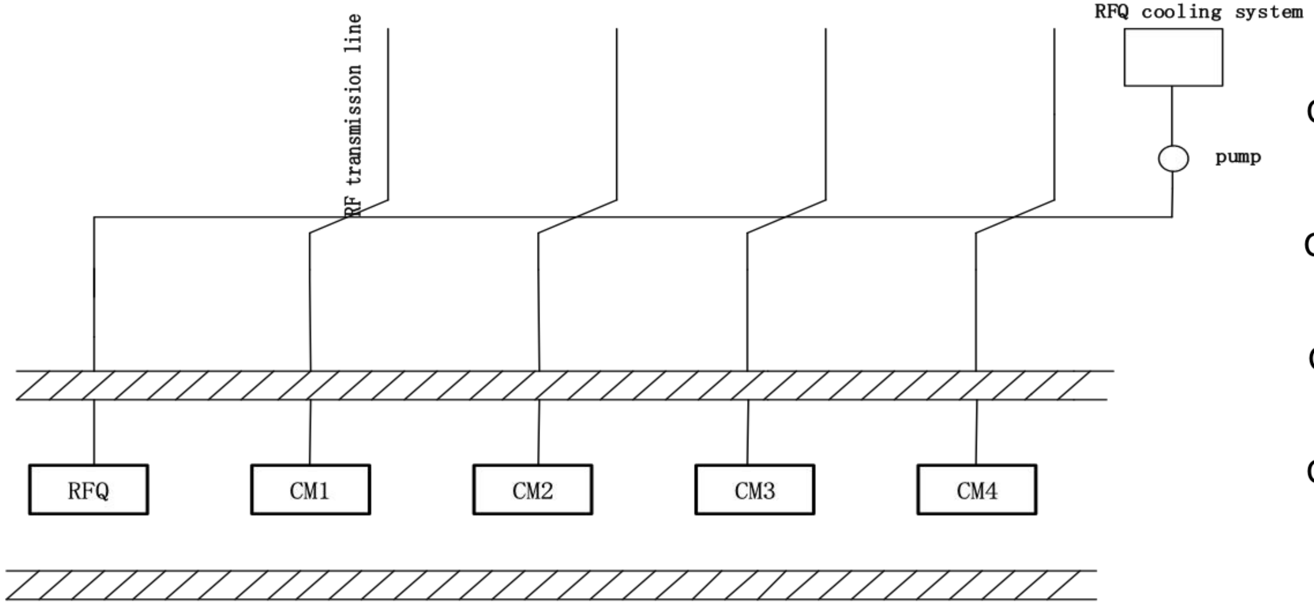




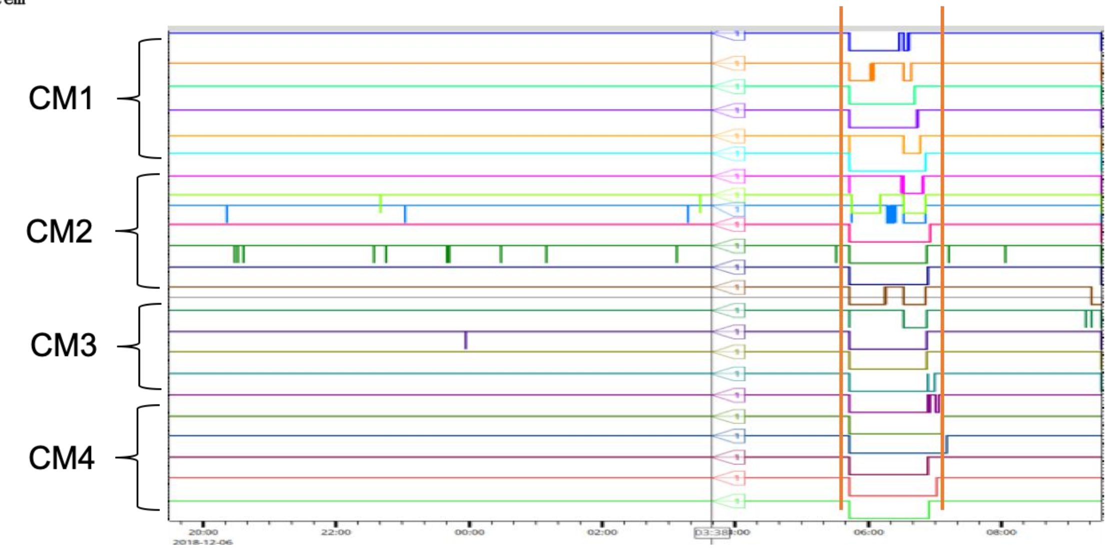




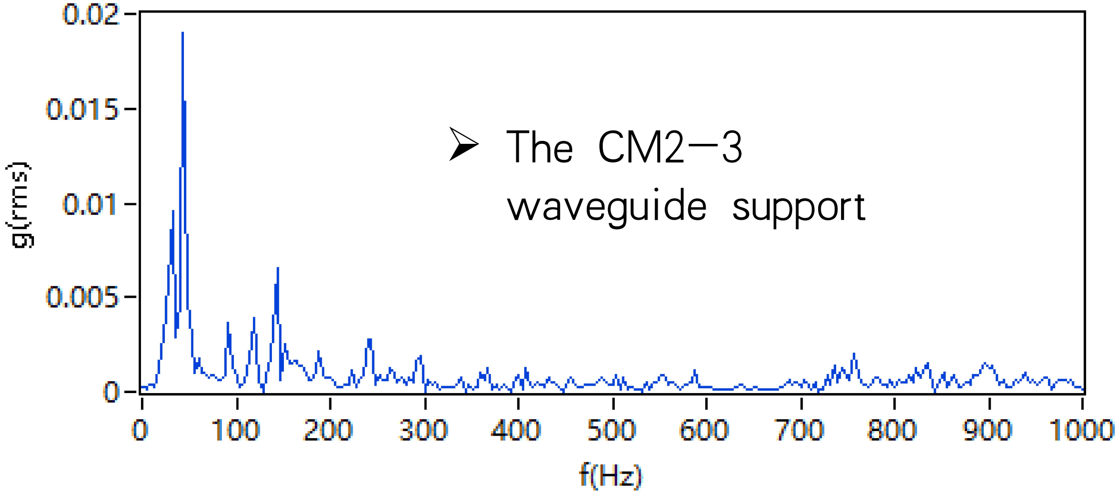
Microphonics of SRF resonators in CM2

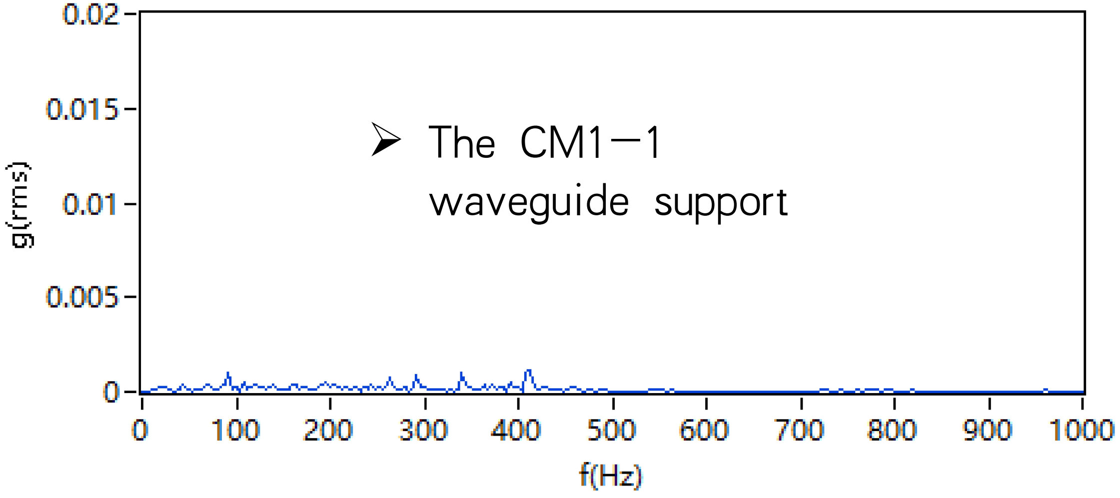


CM1 to CM4 trips（7:30 p.m. Dec.6 -- 9:30 a.m. Dec.7）

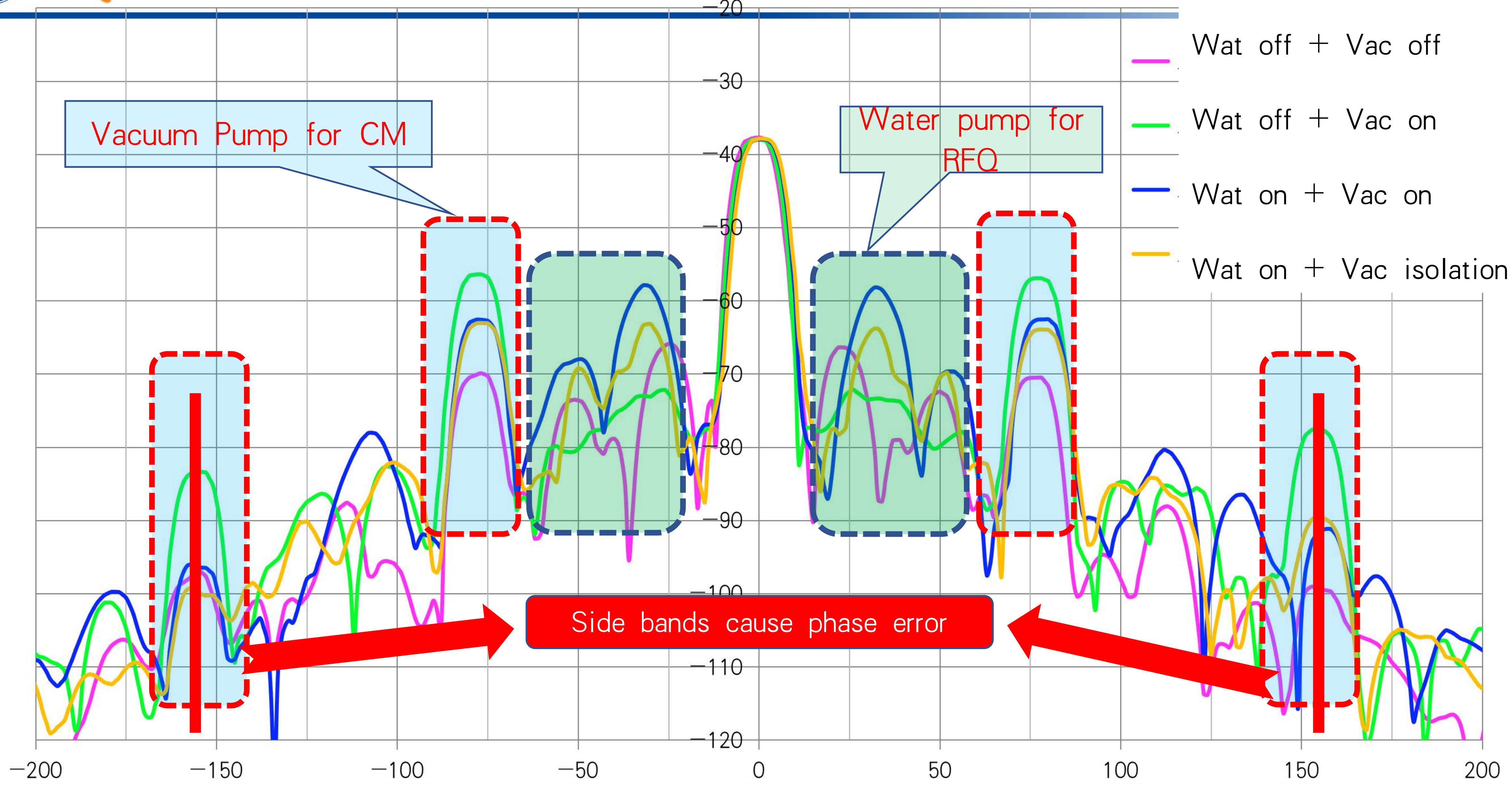


Helium pressure fluctuation





Vibration Sources to CM2-3



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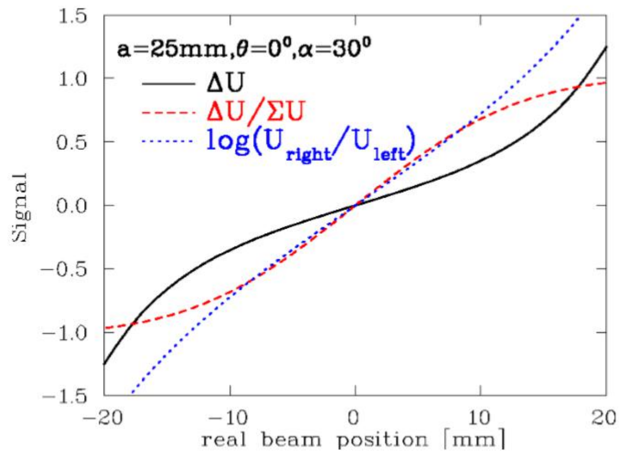
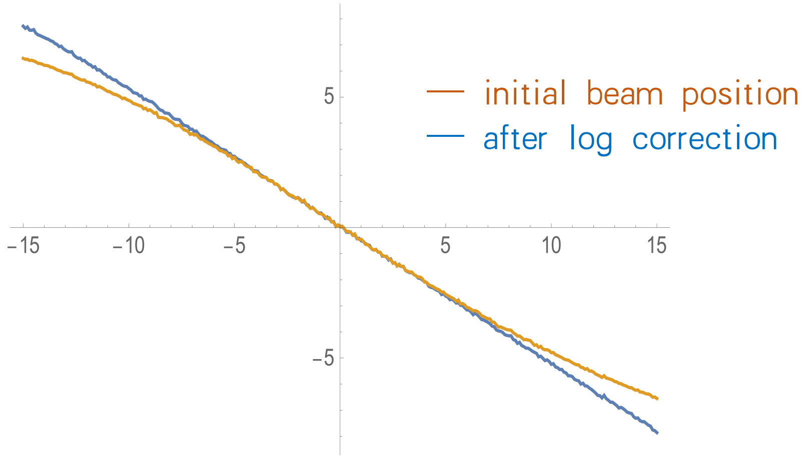
Hardware calibration

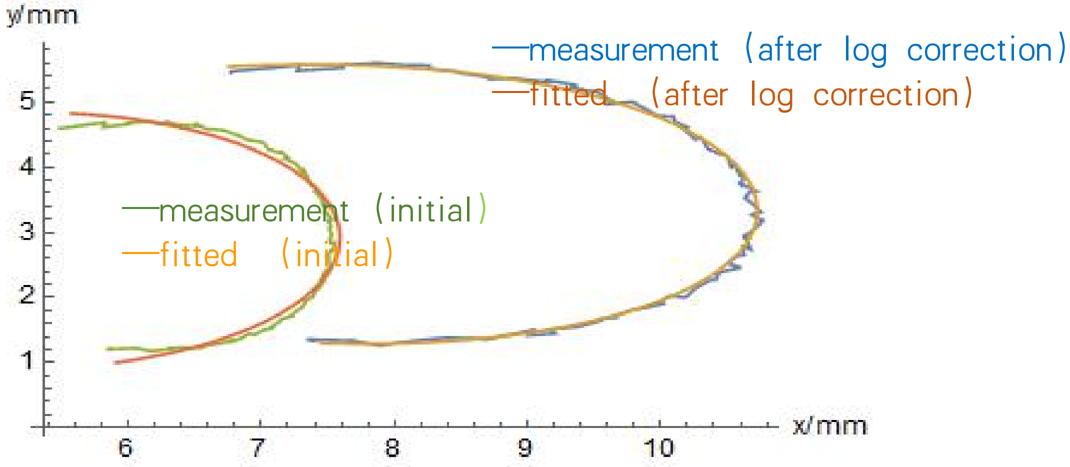
Beam based of correction of BPM model

Question： the measurement beam position is not matching with the simulation results for accelerator reconstruction
Reason: the beam position with severe nonlinearity(>5mm) using the ΔU/ΣU algorithm
Lead to: the real beam positon ≫ measurement ones
Solution: Correct the beam position algorithm of BPM





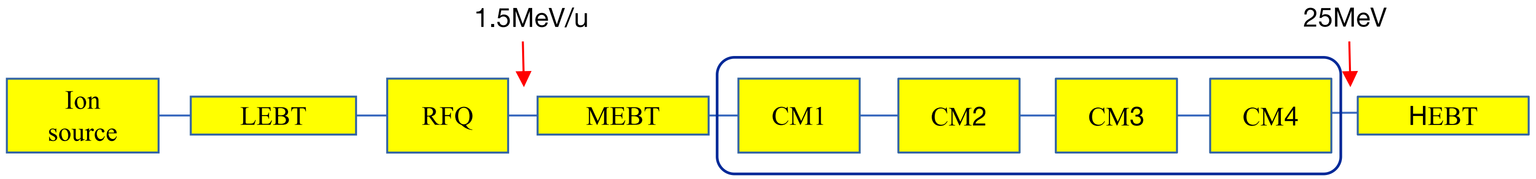
NT section BPM Vs. correct magnet



SC section BPM Vs. solenoid magnet

Hardware calibration

BPM offset calibration



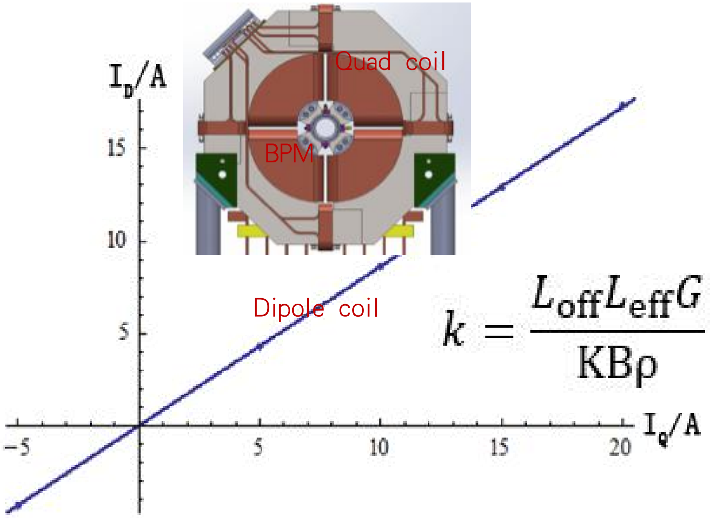
Normal−T section：

- Combined quadrupole model
- The 'null comparison' method

Cold−T section：

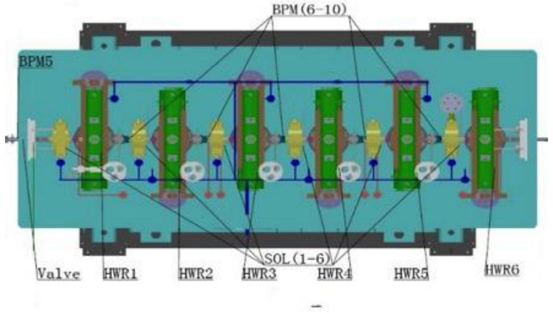
- Solenoid model
- The no−linear fitting

Normal-T BPMs @ BT

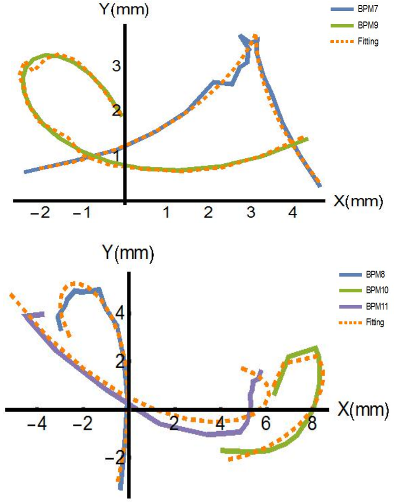


$$k = \frac{L_{off} L_{eff} G}{K B\rho}$$

Cold BPMs@SC Linac



$$\begin{pmatrix} X_0 \\ X_0' \\ Y_0 \\ Y_0' \end{pmatrix} = M^{-1} \cdot \begin{pmatrix} X_1^{(1)} \\ X_1^{(2)} \\ \cdots \\ Y_1^{(1)} \\ Y_1^{(2)} \\ \cdots \end{pmatrix}$$



BPM	X (mm)	Y (mm)
BPM1	0.449	0.559
BPM2	−0.026	0.432
BPM3	0.063	−0.325
BPM4	0.434	0.158

The calibration results of Cold BPMs

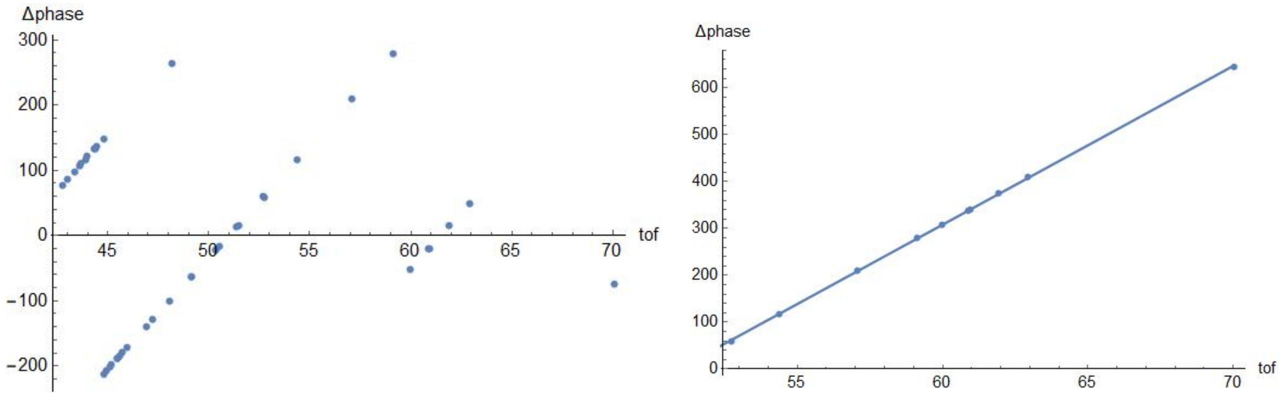
BPM	BPM6	BPM7	BPM8	BPM9	BPM10	BPM11	BPM12
X (mm)	-1.19	-1.19	-0.57	1.37	1.44	1.28	4.66
Y (mm)	-2.82	-1.13	-1.72	-5.76	-1.35	-3.86	-0.47

Hardware calibration

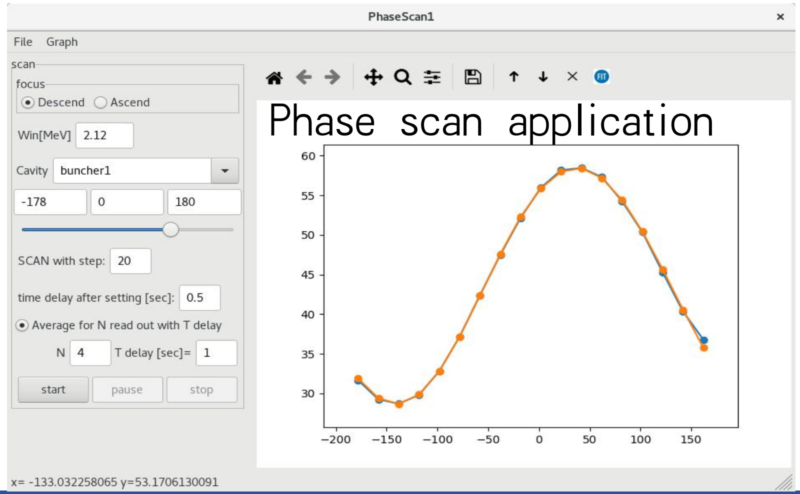
Cavity voltage calibration

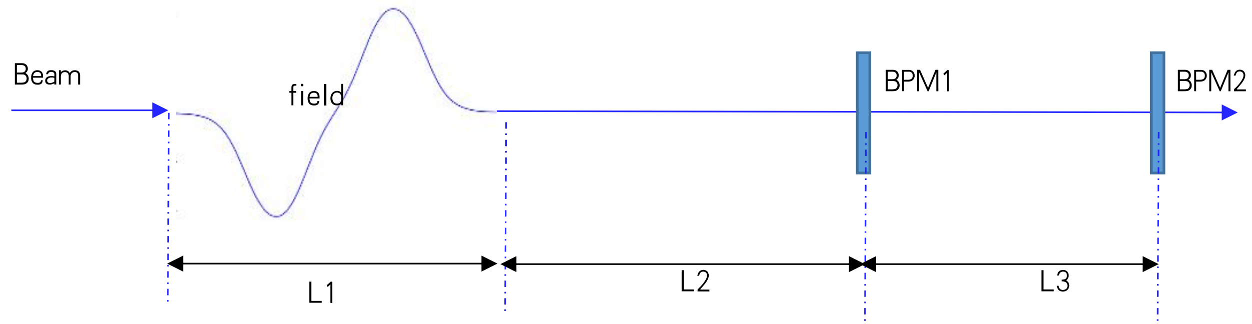
$$\frac{l}{l_{tof}} = \frac{\Delta t}{tof} \Rightarrow l = k \times l_{tof} \times \frac{10^3}{360 \times 162.5}, \quad k = \frac{d\Delta phase}{dtof}$$

- Beam based TOF length calibration of BPMs （L3）
- Correct GAP model of low beta cavity with field map model considering of space—charge effect
- Based of the BPMs TOF for calibrating the length of local cavity and BPM as the phase scan fitting parameters （L1 L2）
- Writing auto phase scan app .



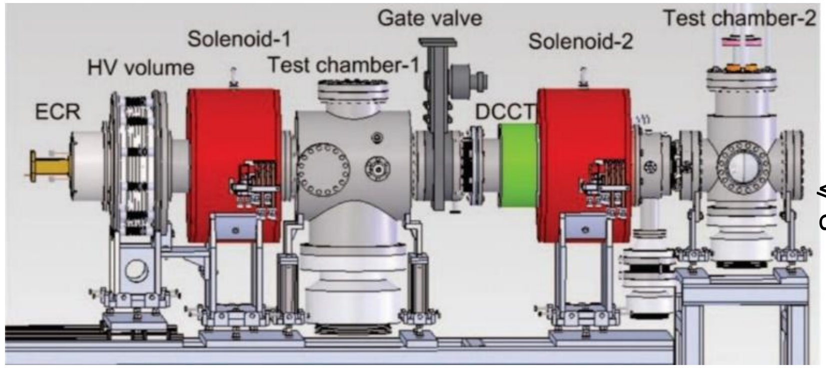
BPM22—BPM23 online length calibration results

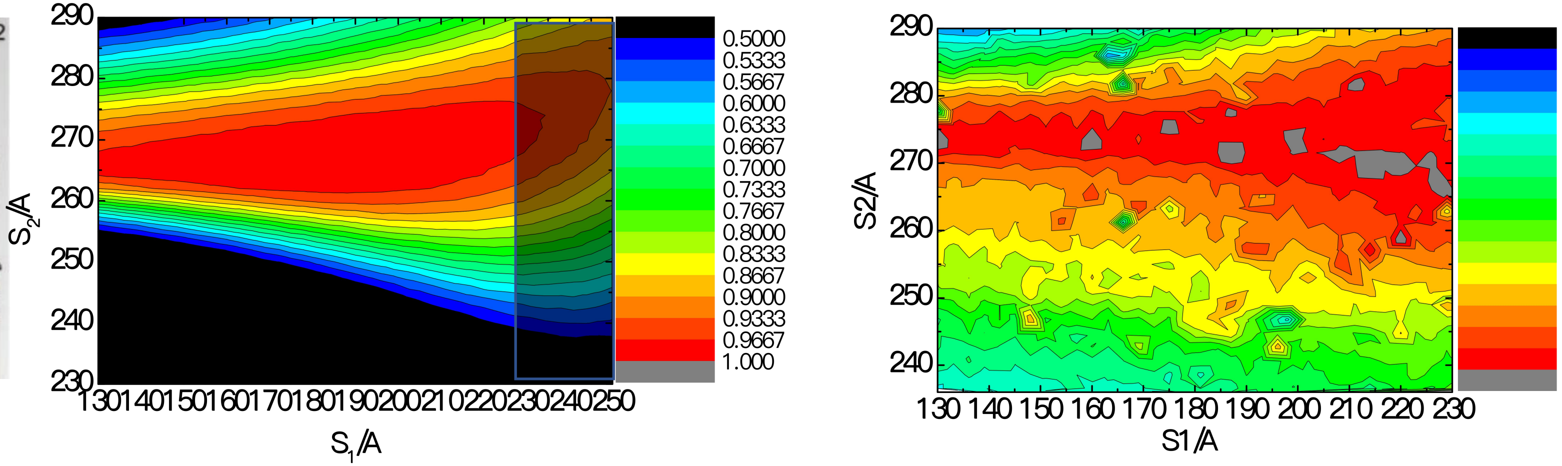




The physical model of phase scanning

Beam match between LEBT and RFQ

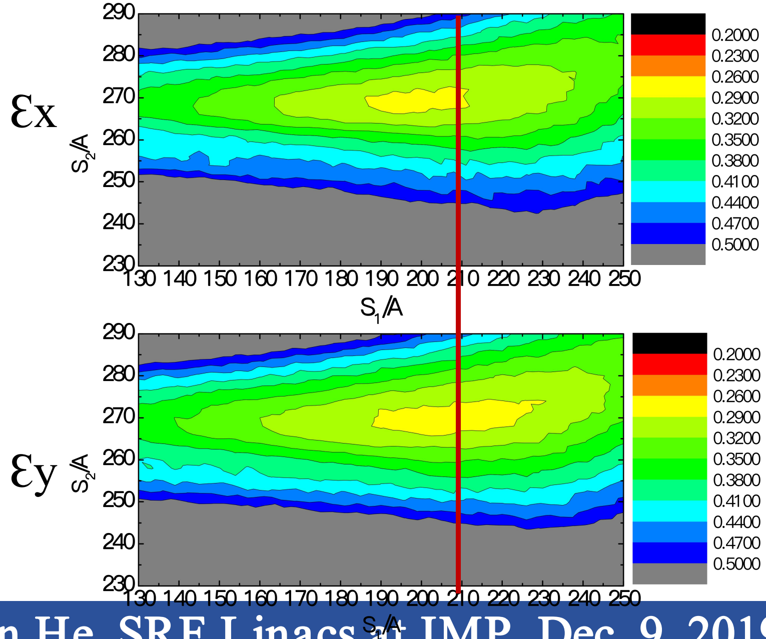


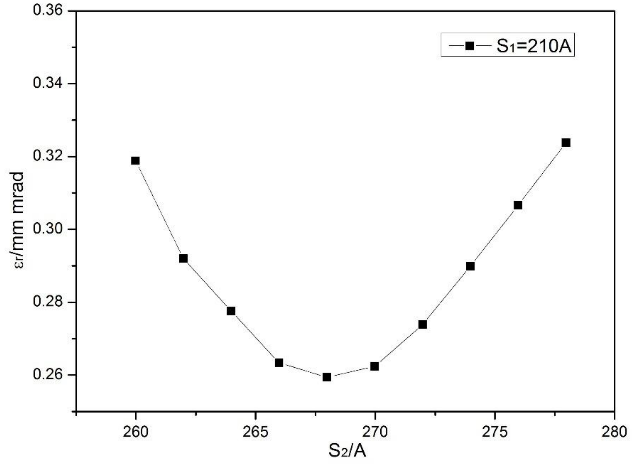


LEBT solenoids match VS. beam transmission of RFQ

Beam current： 2mA

Beam energy： 35keV



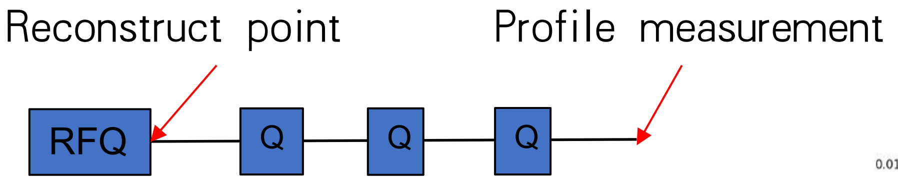


LEBT solenoids match VS. beam emittance out of RFQ

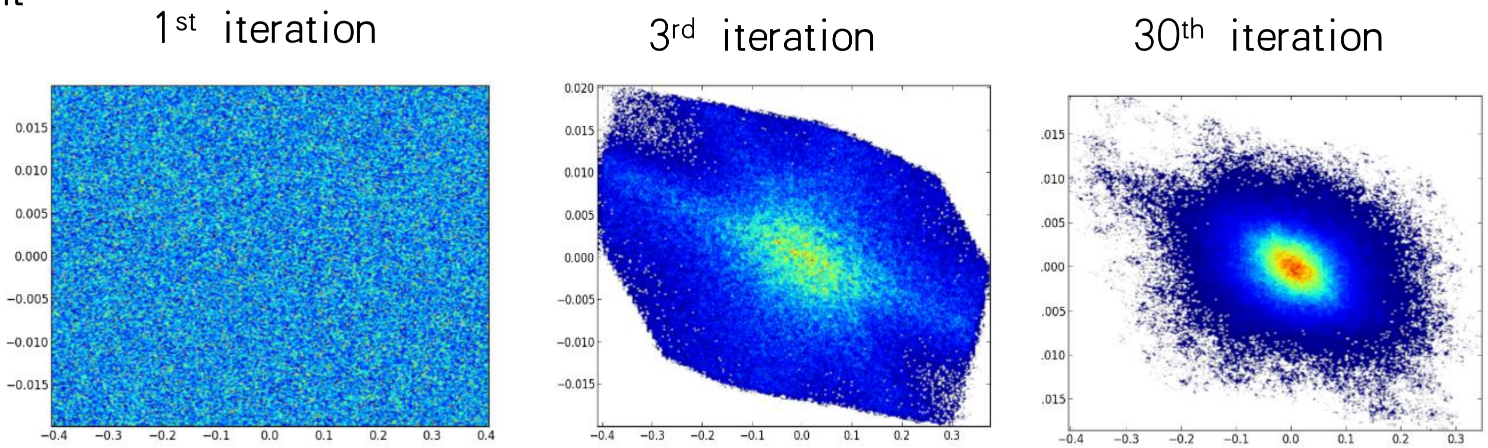
LEBT input parameters

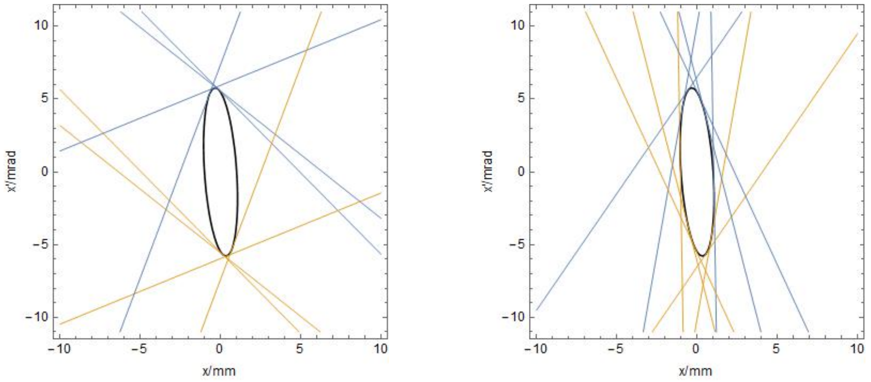
α_x	β_x	α_y	β_y	ε_x	ε_y
0	0.16	0	0.16	0.188	0.188

tomography to reconstruct the emittance

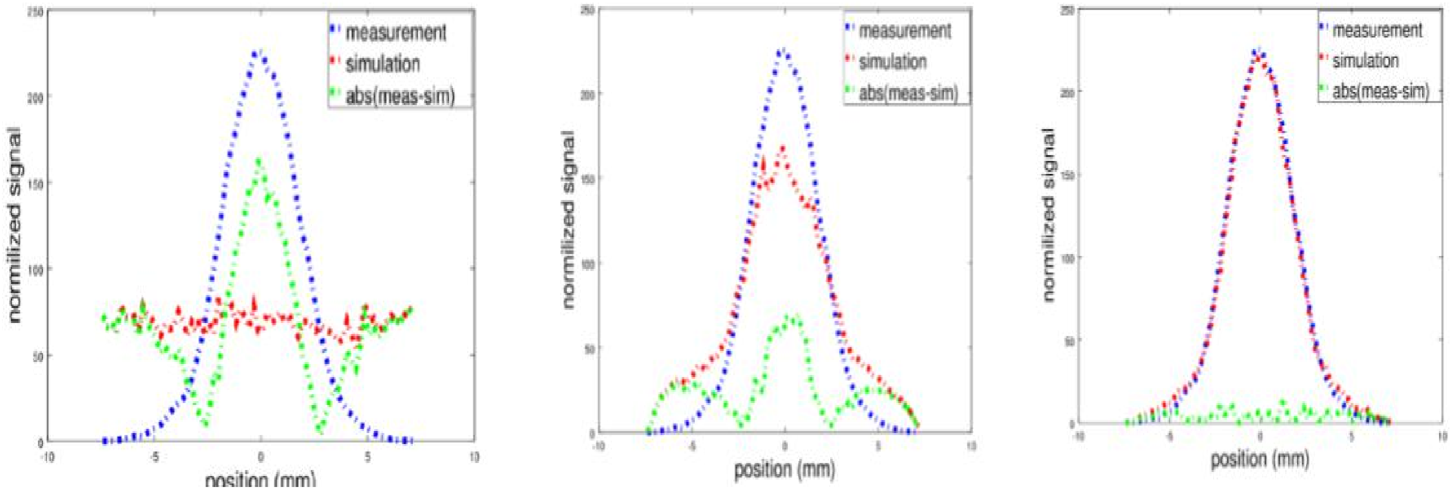


- Reconstruct the distribution of beam in phase space by profile measurements.
- The range of phase advance equally divided benefit for data convergence.



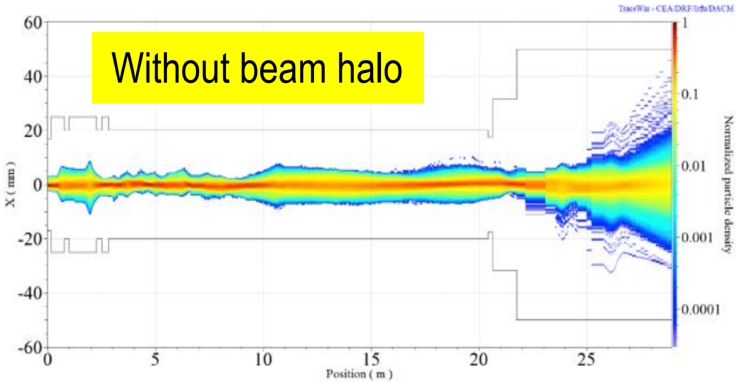


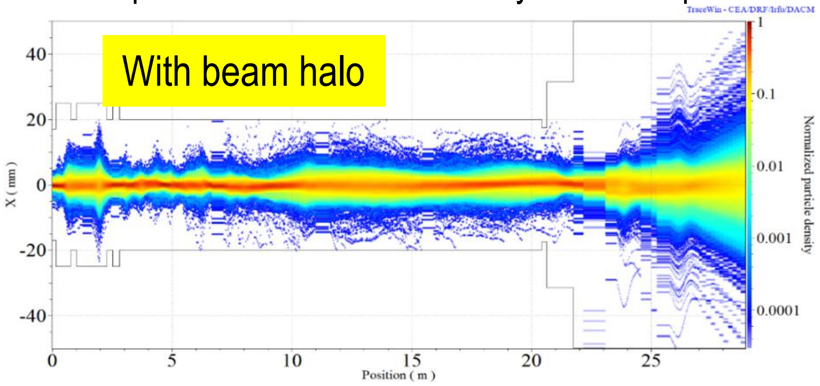
Linear mapping of the measured rms beam size to the initial phase space
left： randomly right：equally

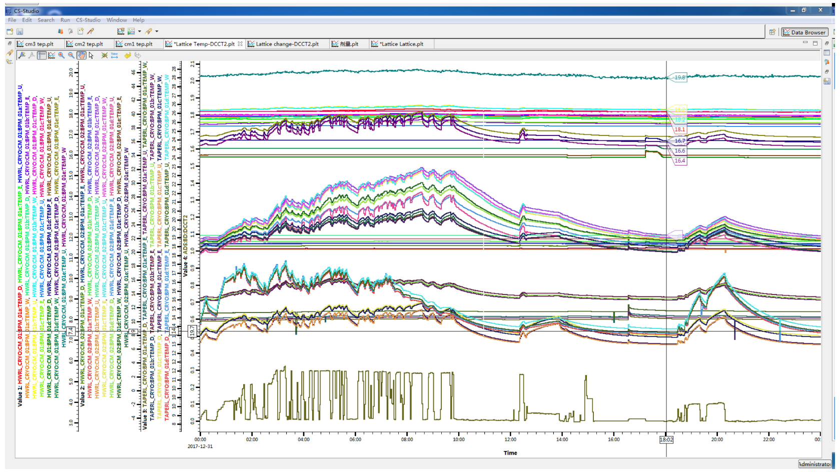


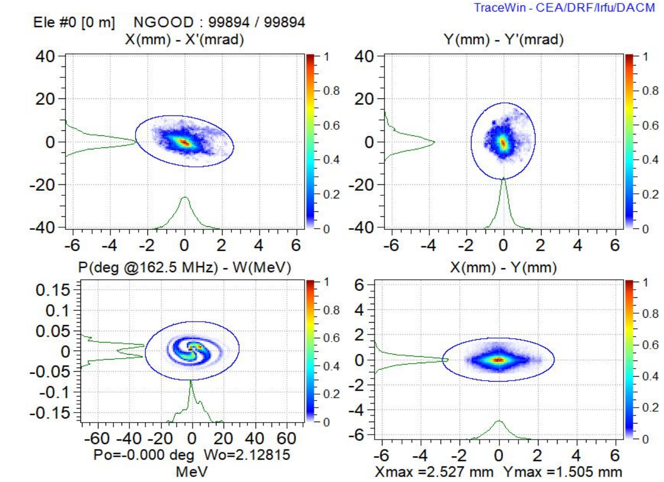
Beam loss study

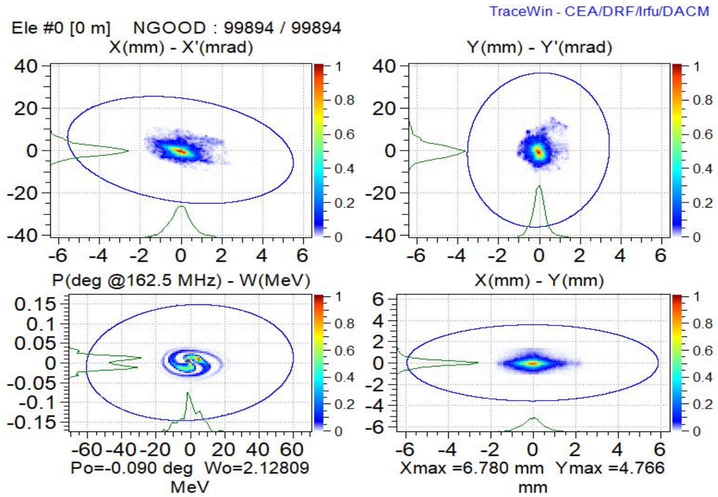
The temperature rises simultaneously in all four quadrants

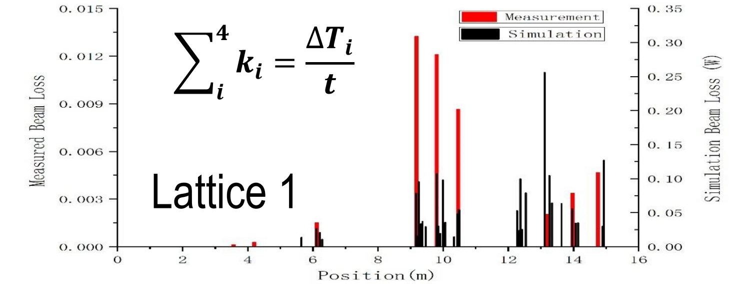




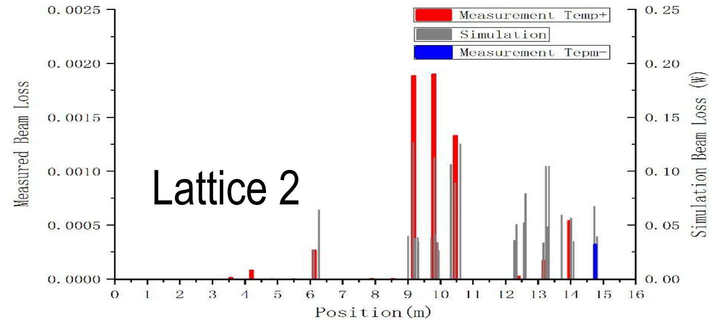








$$\sum_i^4 k_i = \frac{\Delta T_i}{t}$$



	Alpha X/Y/Z	Beta X/Y/Z m/rad	Emit−X/Y/Z (RMS) π.mm.mrad [Norm.]	Emit−X/Y/Z(99.99%) π.mm.mrad [Norm.]
Without beam halo	0.247/−0.05/−0.076	0.226/0.096/0.611	0.112/0.097/0.094	2.065/2.066/2.136
[illegible]	0.247/−0.051/− [illegible]	[illegible]	[illegible]	[illegible]

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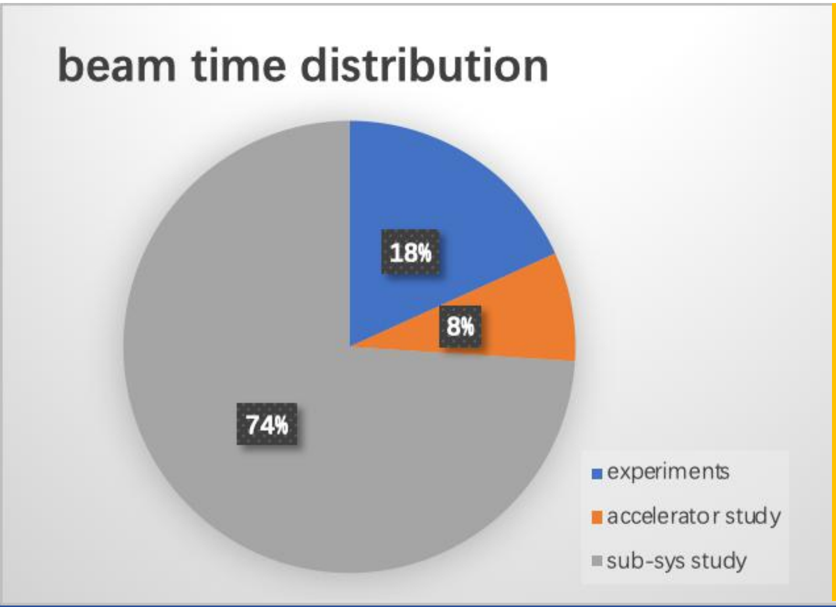
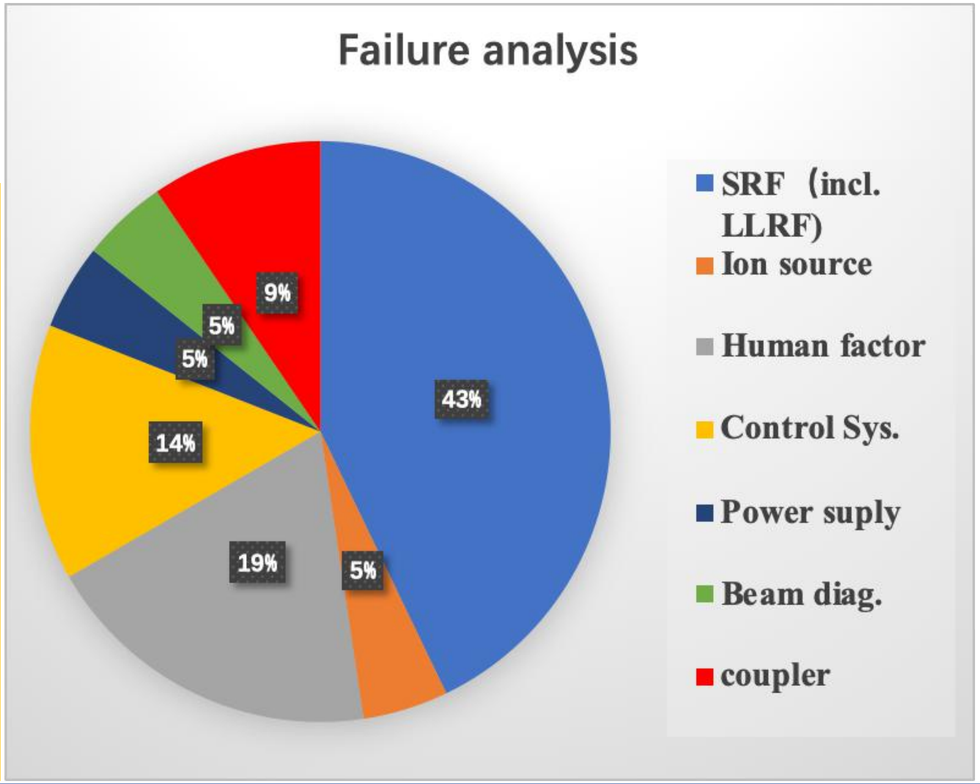
Operation for Users

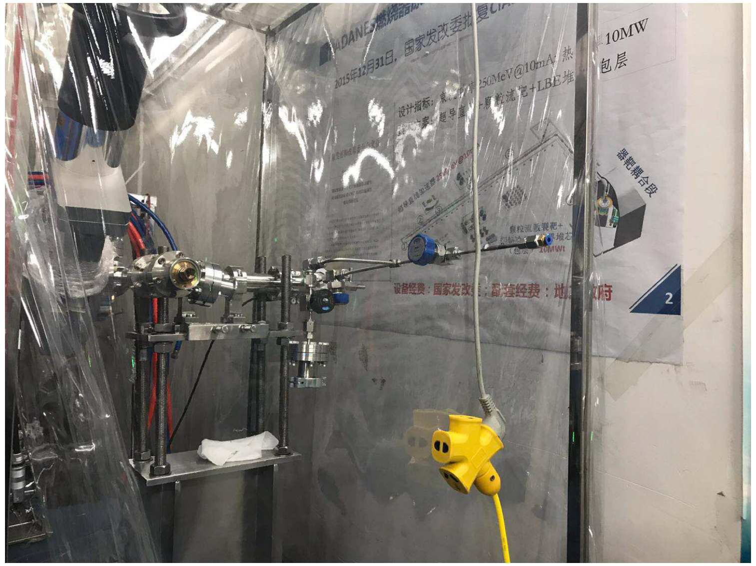
- Operation for users, Dec. 7th – 30th, 2018, May 14th ~June 30th 2019
- Beam: H^+ and $^4He^{2+}$, energy 2.1—32MeV, average current 100nA~125uA
- Available beam time 58.0 hours for 62 experiments
- Downtime: 5.9 hours
- Availability: ~ 0.90

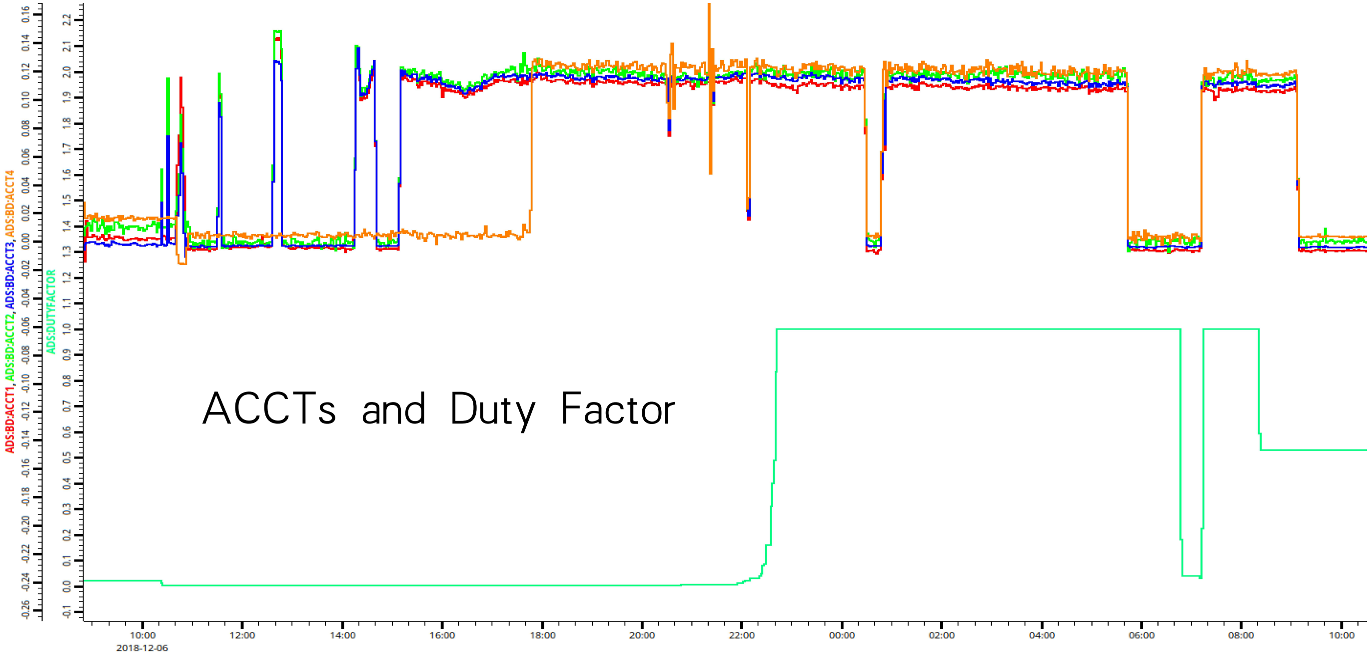


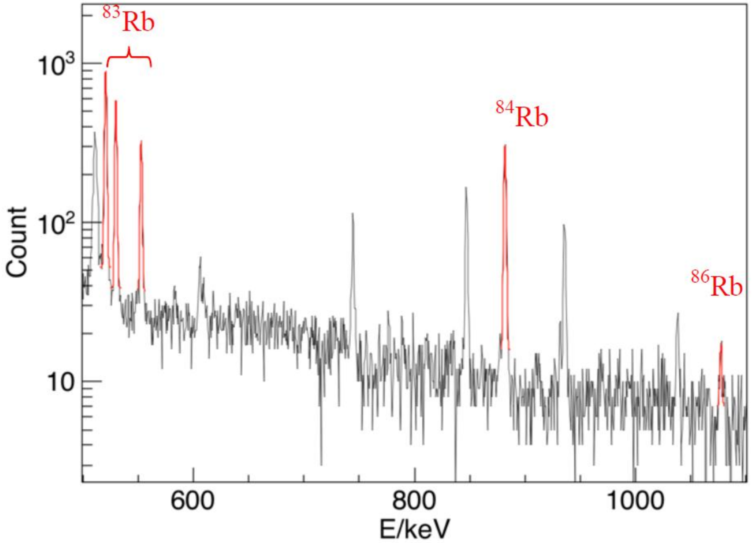
source	trips
RF (incl. RFQ, LLRF)	9
IS	1
human	4
control	3
PS	1
Diagnostic	1
coupler	2
total	9



ISOTOPE PRODUCTION - ^{83}Rb

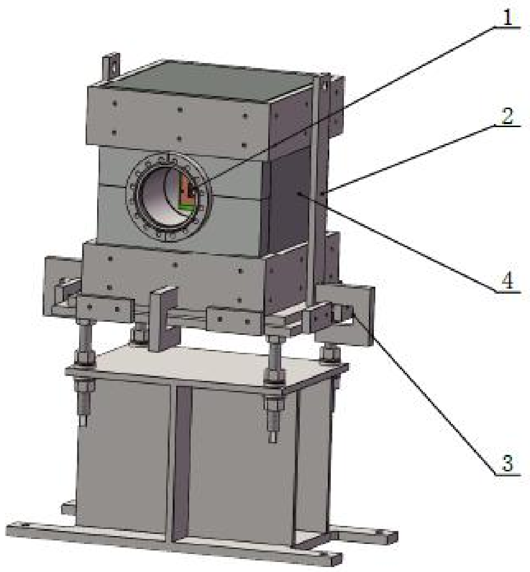


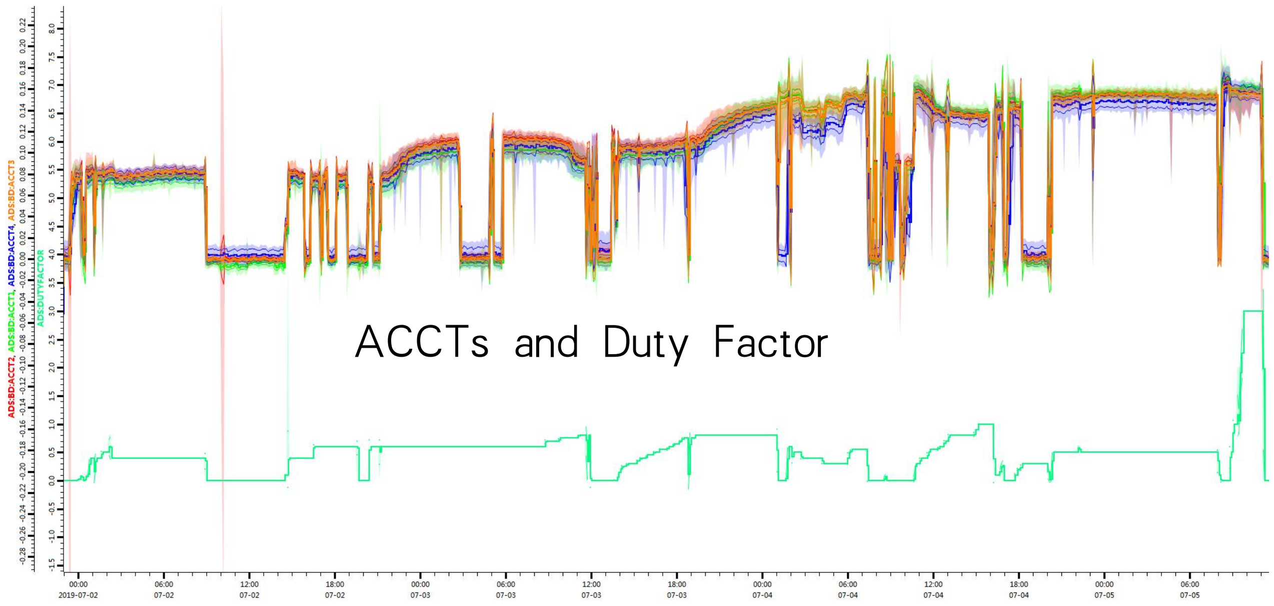


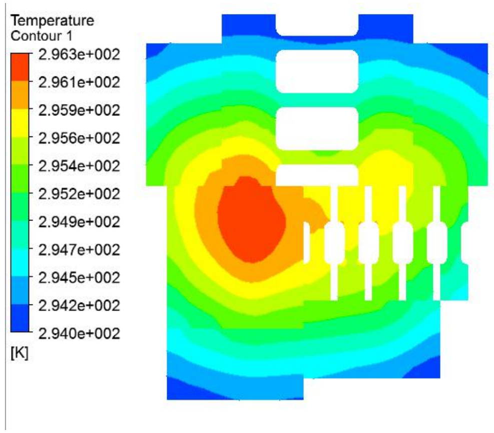


- PANDAX is aimed to find the dark matter particles with liquid Xenon detector. https://pandax.sjtu.edu.cn/
- ^{83}Rb is a useful source to calibrate detectors in PANDAX.
- CAFE provided 10 hours proton beam of 20 MeV 400 us, 25 Hz, 100 uA to bombard on natural Krypton gas and generate ~6 MBq ^{83}Rb.

Material Irradiation







- Helium bubbles is important in nuclear material.
- To study the bulk effect of Helium bubbles, an irradiation chamber is developed to hold and cool the test samples.
- CAFE provided 70.5 hours $^{4}He^{2+}$ beam of 6~28.5 MeV, 0.8 euA to do Helium implantation of test samples.
- The chamber has been dismantled and wait for the Dose decay, before the samples are took out and do mechanical and microscopic measurement.

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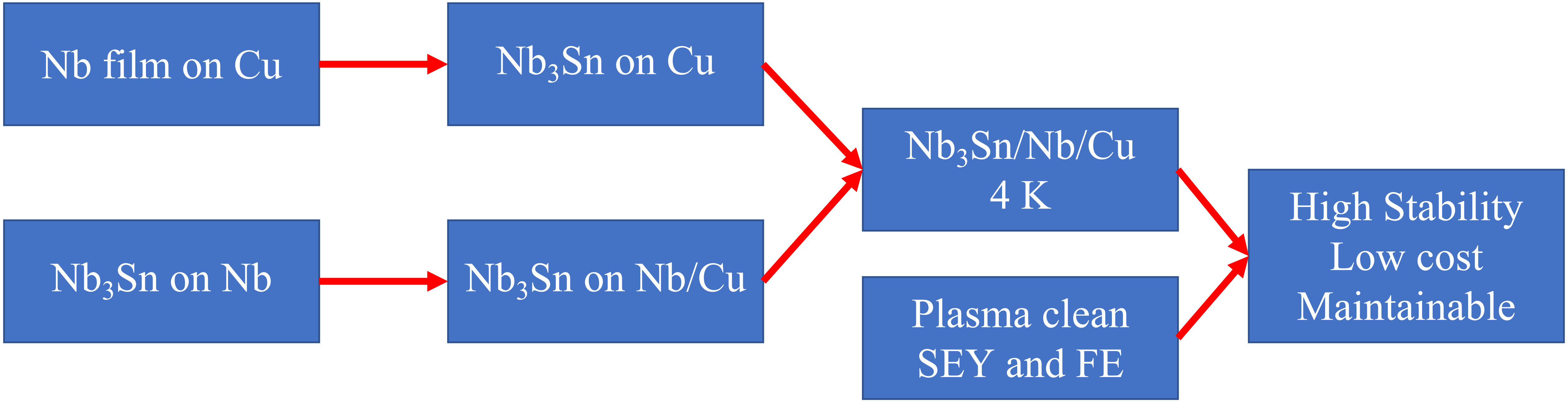
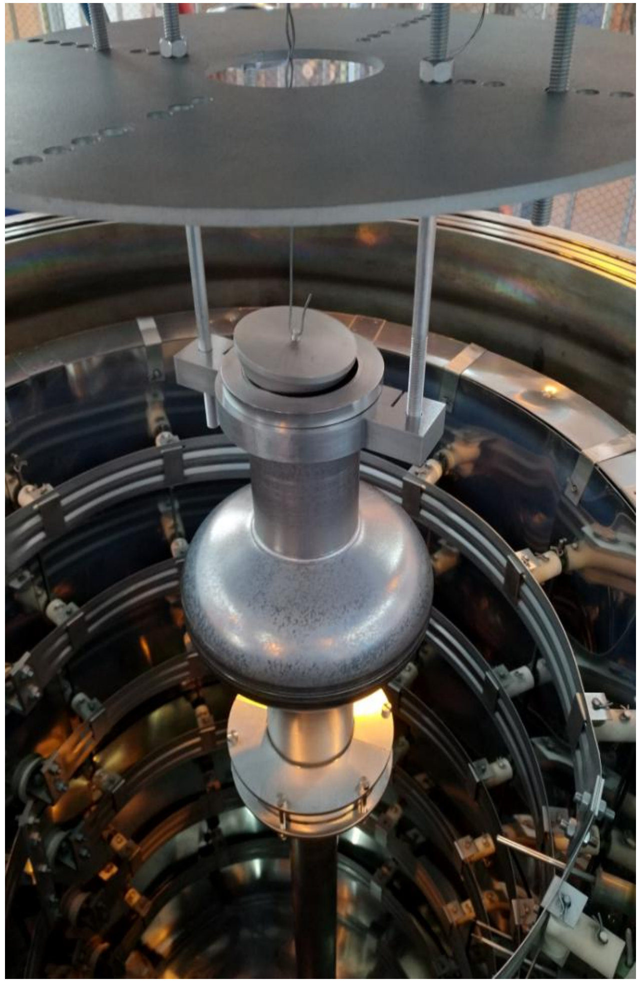
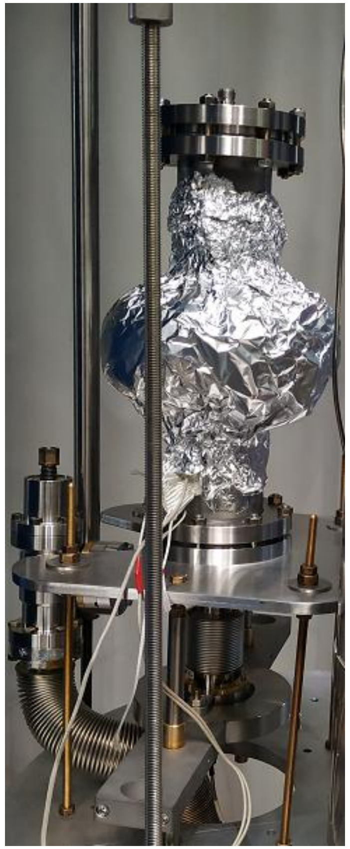
Activities for the future ADS

- High stability, low cost, performance recovery every year in-situ
- Copper based thin film cavity and plasma + He cleaning are our choice for the future project demo
- Recipe of stable CW RFQ, MP and arc free

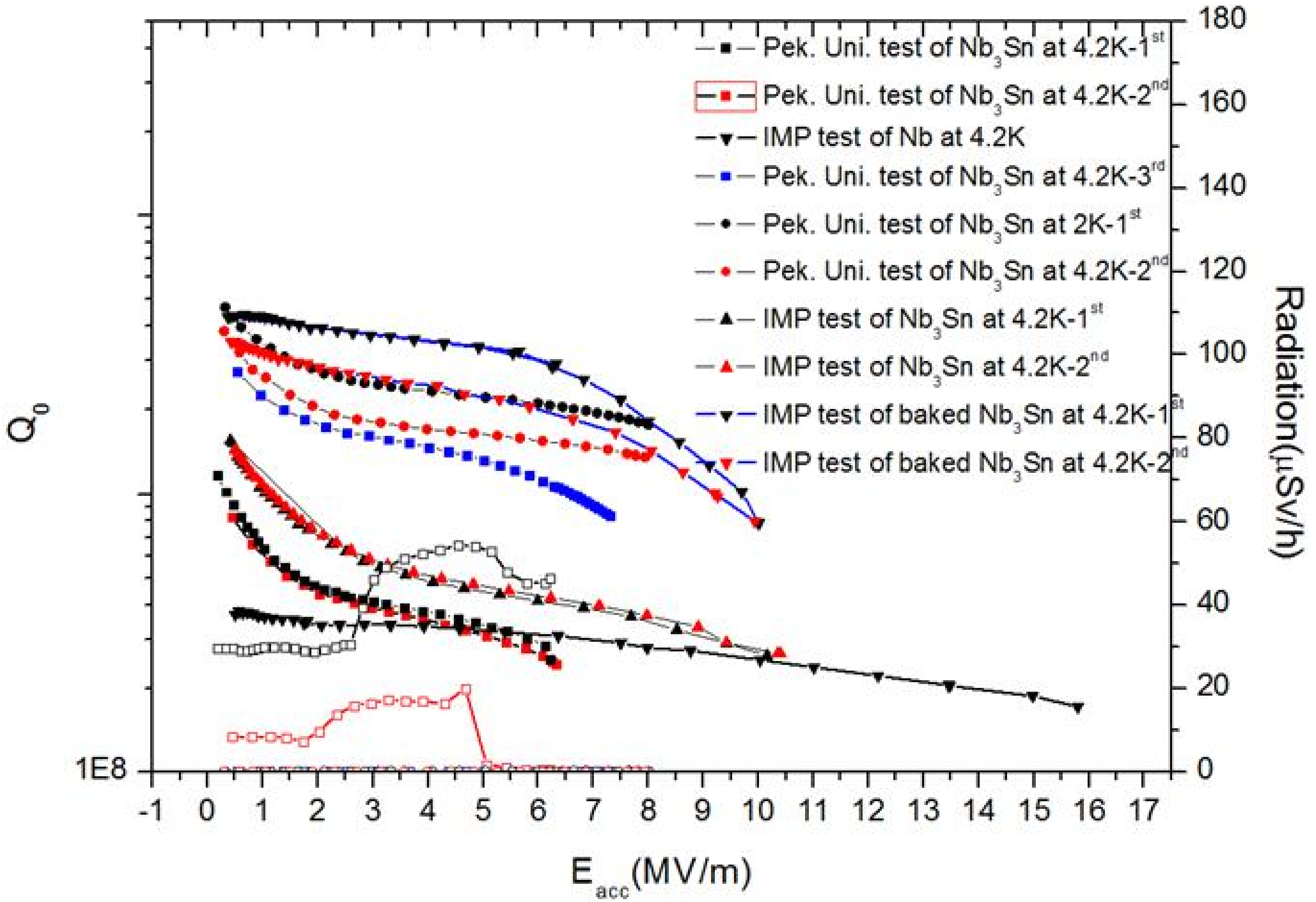


Nb_3Sn on bulk Nb





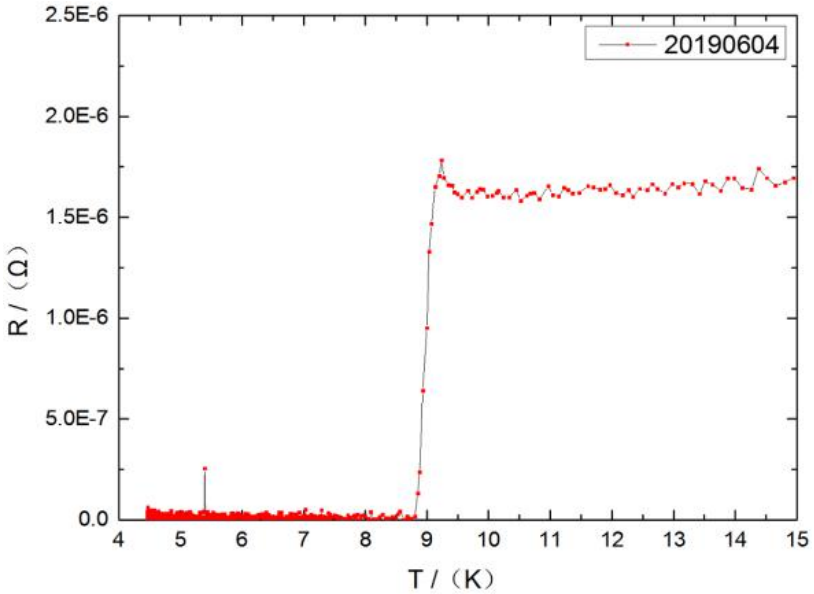
Nb_3Sn on Nb cavity underwent 100^{0}C 48h baking. Vacuum was kept below 1.4e-5 Pa



Some remarks on Nb_3Sn tested at 4.2K:

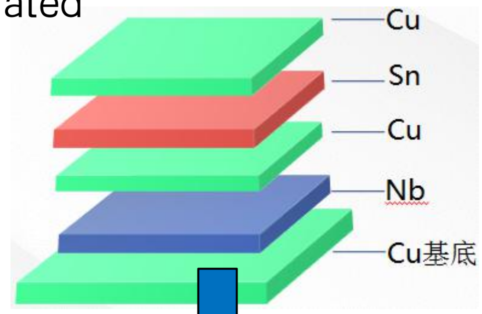
1. As deposited: limited by the material and test system (large remnant B field)
2. After baking: much improved! **Q_0 reaches 4.4e9 at low field. Very small Q slope.** Showing low temperature annealing could be an effective way to process Nb_3Sn cavity made by tin-diffusion.

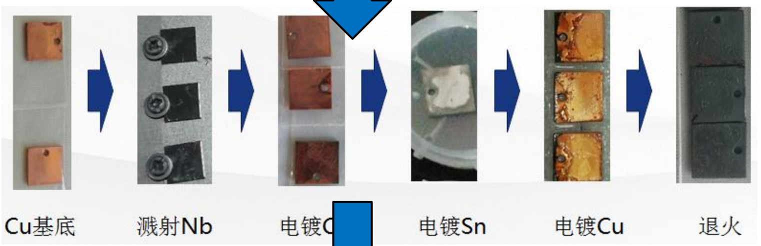
Nb on Copper Development

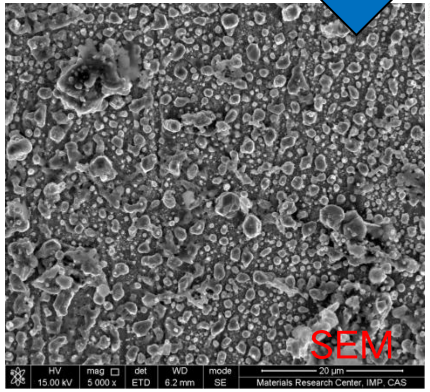


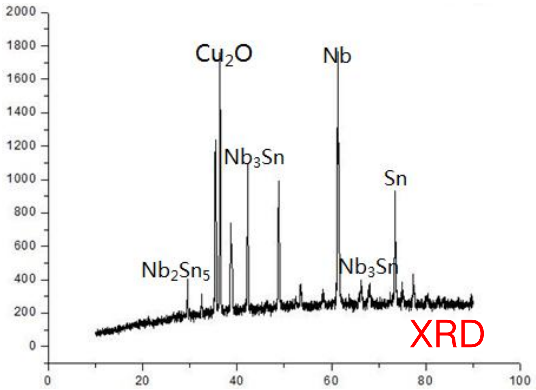
Nb_3Sn on Cu via ternary reaction

Electro-plated

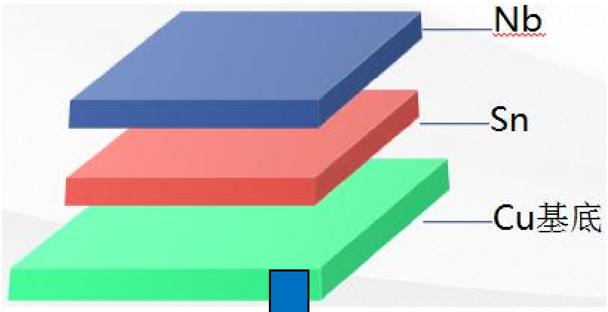


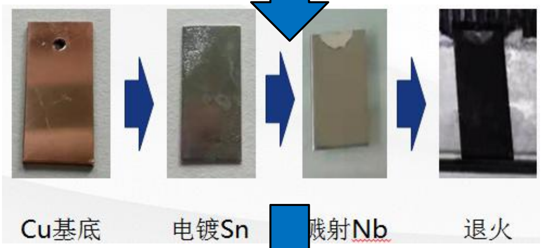


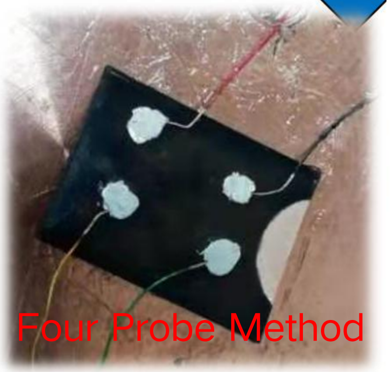


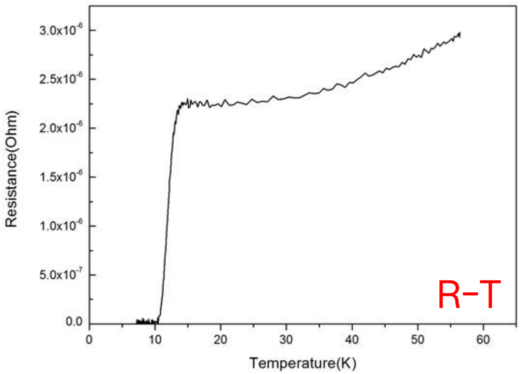


Miscellaneous phase and poor bonding strength







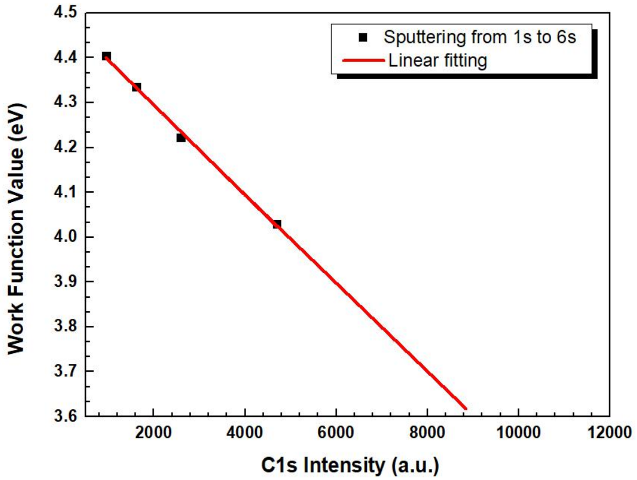


T_c~14K was achieved by optimized method on **Cu substrate**

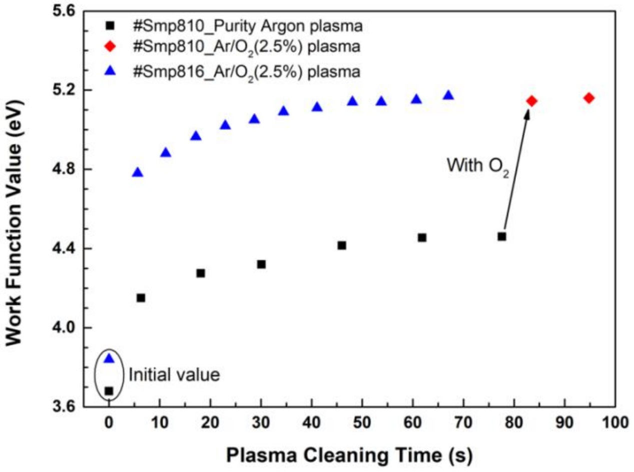
Cu based Nb_3Sn cavity is the future technical route that best meets the needs of CiADS!

Plasma cleanings for HWR cavities

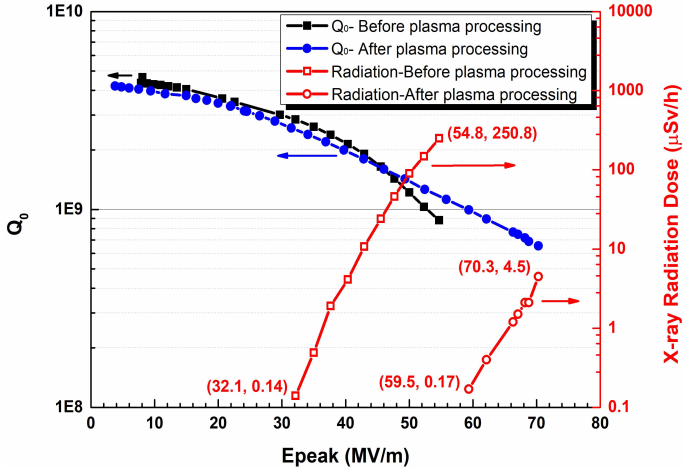
- Cleaning on Nb samples, HWR cavities and mechanism of CH—contamination



Work function vs. C1s intensity

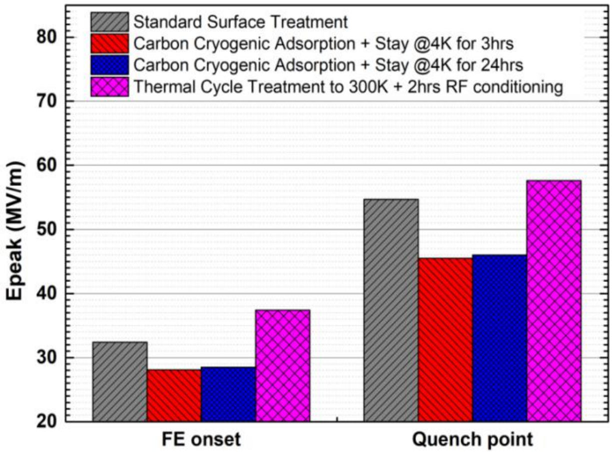


Ar/O2 plasma cleaning on samples

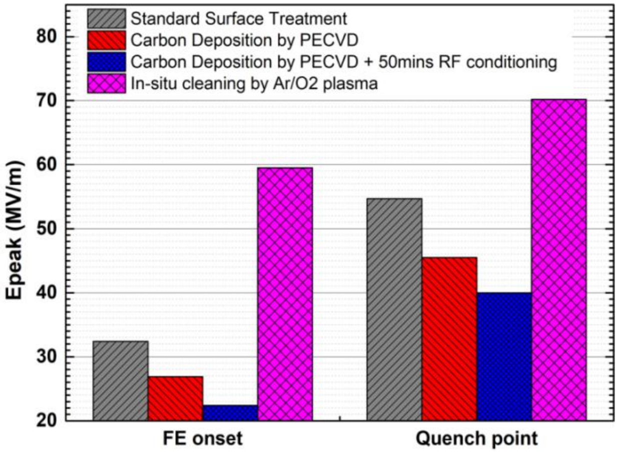


HWR performance improvement by Plasma

Details：
MOP085，
THP064，
THP065



Cryogenic adsorption of hydrocarbons



Hydrocarbons deposition by PECVD

- ➢ Carbon contamination decreases the work function, which can be recovered by the reactive oxygen plasma cleaning;
- ➢ HWR processed by plasma results in the increase of Epk by 29%;
- ➢ Hydrocarbon by the cryogenic adsorption and PECVD can be eliminated by thermal cycle and plasma cleaning.

Outlines

- Introduction Projects HIAF and CiADS of IMP
- Development of SRF at IMP
- Status and Stability Issues of CAFe Operation
- Beam physics study on CAFe
- Physics experiments on CAFe
- SRF Activities for the ADS Future
- Summary

Summary

- The SRF started in IMP since 2010. The low beta cavities such as HWR, Spoke, CH have been developed in IMP and operated.
- The first FPC was designed and fabricated at IMP in 2016. Now, 17 couplers are operating online.
- The ADS front-end demo linac, CAFe (25 MeV superconducting linac) started commissioning in 2017. It has achieved max beam power of 45 kW with 2.55 mA @ 17.5 MeV. It operated at 2 mA more than 100 hours continuously.
- Next commissioning campaign is more than 100 kW beam power, and higher stability in 2019.
- The thin-film SRF on copper and in-situ cleaning are the developing technologies in IMP for the future ADS.

Thanks the worldwide collaboration!

Looking forward to

the deeper collaboration