中國科學院 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

SRF2019, July 01-05, 2019, Dresden

Overview and SRF Requirements of CiADS Project

Yuan He, Weimin Pan, Yueweiming, Zheng Gao, Tiancai Jiang, Teng Tan, Shenghu Zhang, Xingmeng Liu, Jinying Ma, Weilong Chen, Jiangqiang Wu, Zhijun Wang, Feisi He, Zhongquan Li, Jianping Dai, etc.

On behalf of Accelerator team of CiADS

Institute of Modern Physics, High Energy Physics, Chinese Academy of Sciences

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

Outlines

- Introduction of Chinese ADS Project and Progress
- Requirements and Design of SRF of CiADS
- Status and Stability Issues of CAFe Operation
- Techniques Development for the ADS Future
- Summary

Issues of Sustainable Development for Nuclear Power

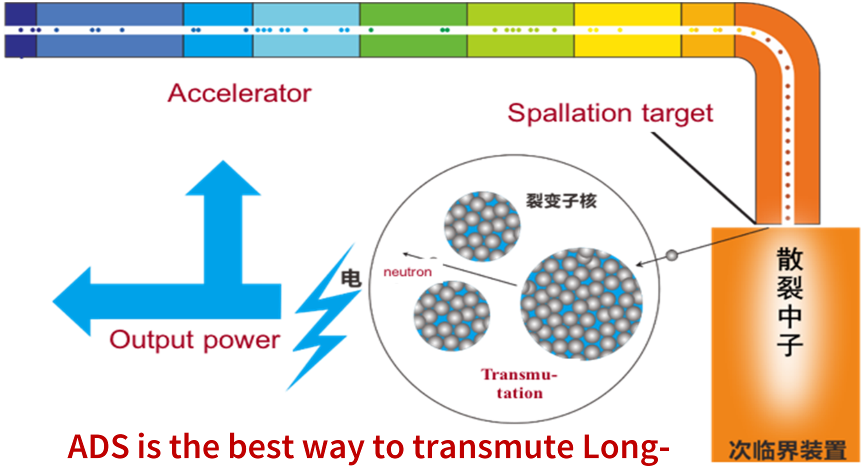
- **Current status of China (including Taiwan, China) nuclear power (by the end of 2018)**
  - 46 nuclear power reactors in operation, 42.858 GWe (3th , total 452 and 399.354 TWe in the world)
  - Produced electricity: 286.5 TW.h, 4.22%
  - 11 reactors under construction, 10.982 GWe, (1st , total 54 in the world)

- **Management and safe disposal of nuclear waste**
  - 1 GWe PWR ~25 ton/year;
  - ~2200 ton/year in 2030 in China; ~10000 ton/year now in the world
  - burying permenantly deeply several hundreds meters in the earth?

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

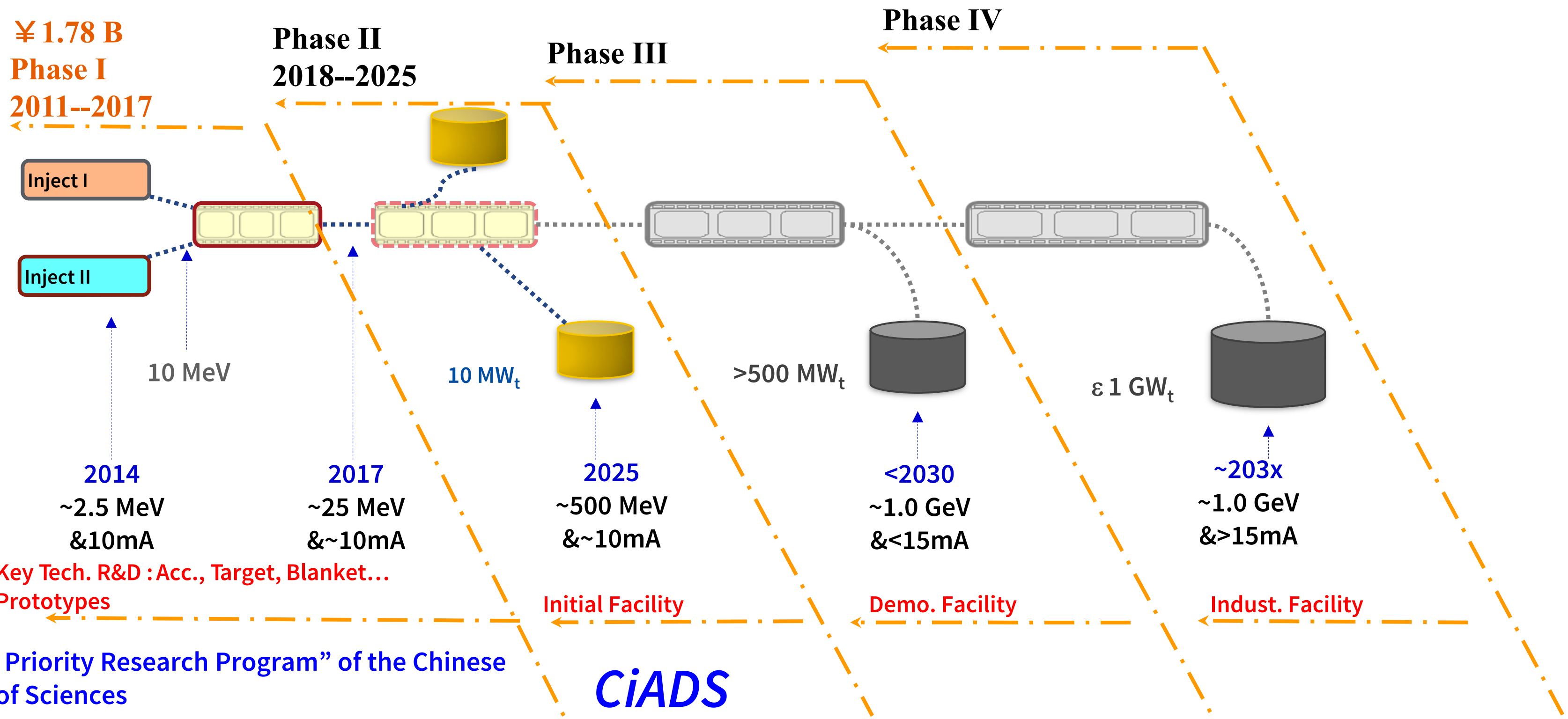
↓ ADS and FR in Advanced Nuclear Fuel Cycles – A Comparative Study, NEA/OECD, 2002

Site of geographic disposal in US, capacity ~ 70000 ton



ADS is the best way to transmute Long-life fission products

ADS/ADANES Roadmap in China



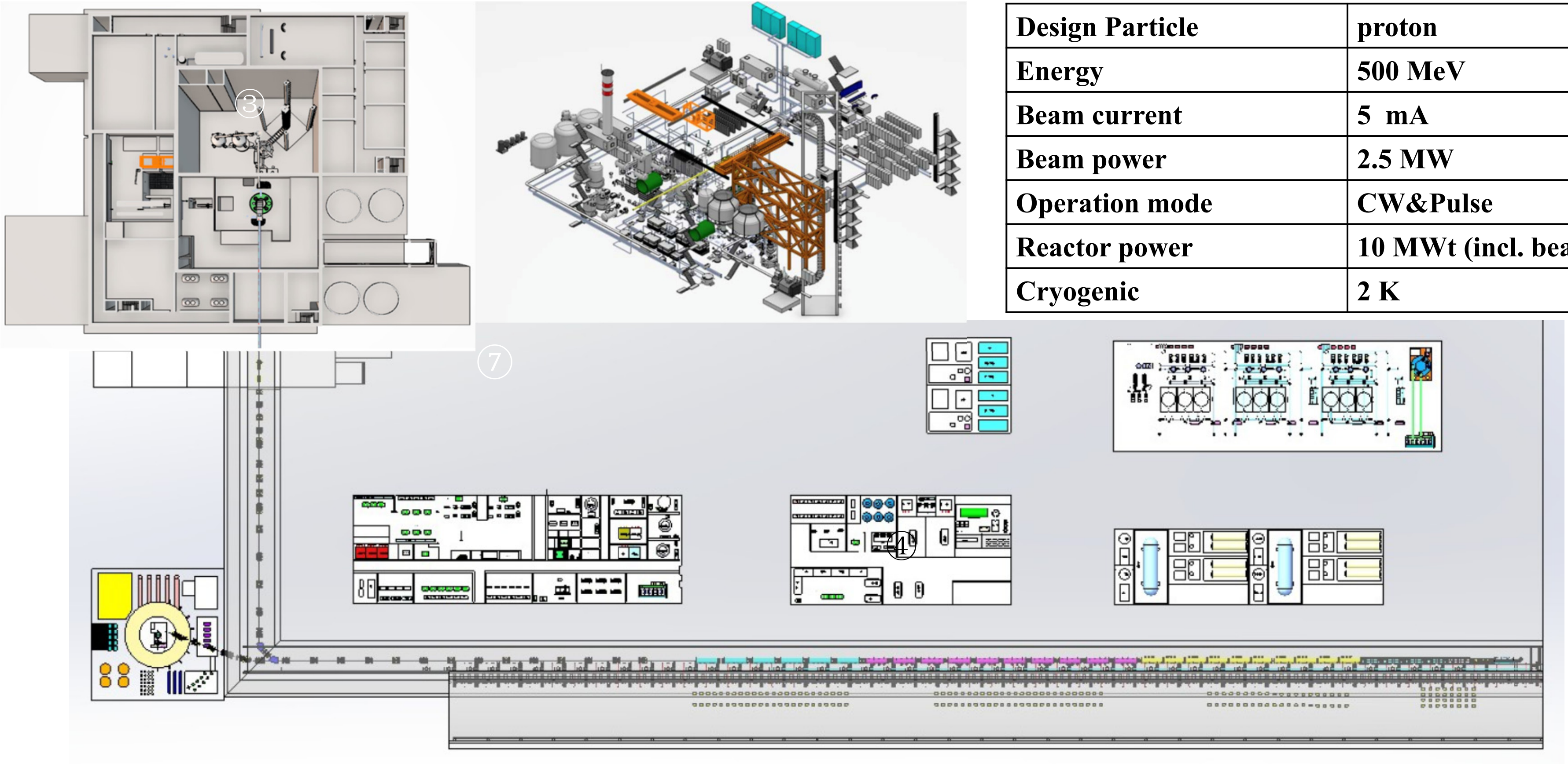
"strategic Priority Research Program" of the Chinese Academy of Sciences

China initiative Acc. Driven System (CiADS) 2018-2025

China Initiative Accelerator Driven System

- A MW ADS demo facility
- Approved in Dec. 2015
- Leading institute: IMP
- Budget: ~4 B CNY (Gov. + CGN)
- Location: Huizhou, Guangdong Prov.
- Partners: CIAE, CGN, IHEP, etc.
- Ground broke in August 2018

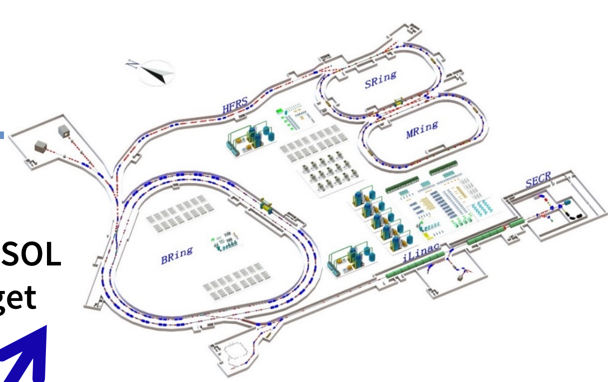
Layout of CiADS



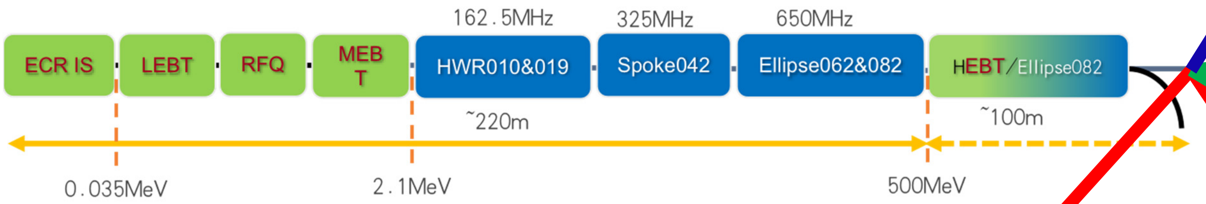
Design Particle	proton
Energy	500 MeV
Beam current	5 mA
Beam power	2.5 MW
Operation mode	CW&Pulse
Reactor power	10 MWt (incl. beam)
Cryogenic	2 K

Terminals plan of CiADS

- T1: low power dump 50 kW; accelerator study; nuclear physics
- T2: liquid metal target 250 kW ~ MW; material irradiation,
- T3: granular target 100 kW ~ MW; target study
- T4: 10 MW fast reactor, LBE target, Keff ~0.97; demo of ADS
- T5: upgrade ISOL target: iLinac of HIAF is post-acc, to 100 MeV



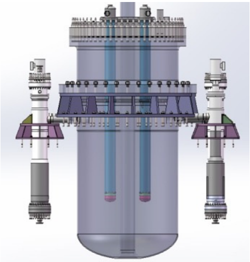
T5:ISOL target



T1：dump, low-power exp. , ……

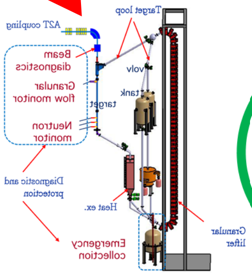
T2：liquid metal target, high-power neutron source

- Energy: 500 MeV (upgrading to 1.5GeV)
- design current：10 mA
- beam loss：1W/m
- modes：pulse&CW（Hus gap for reactor）
- energy stability：±1%@100ms
- current stability：±2%@100ms
- position stability：±1mm
- profile stability：vv±1mm



T4：LBE sub-critical reactor

~10 MW



T3：granular target exp.
2.5 MW
licenses

Reliability Requirements of ADS

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

green “ready”
yellow “may be ready, but demonstration or further analysis is required”
Red “more development is required”

MYRRHA:
- **Beam-trip-duration tolerance is 3 s.**
- **< 3 s, rapid recovery**
- **> 3 s, <10/3months**
- **MTBF 250 hours**

CiADS:
- **Beam-trip-duration tolerance is 10 s.**
- **< 10 s, rapid recovery**
- **10 s ~ 5 min, <2500 /year**
- **> 5 min, < 50 /year**

Whitepaper: “Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production ” 2010

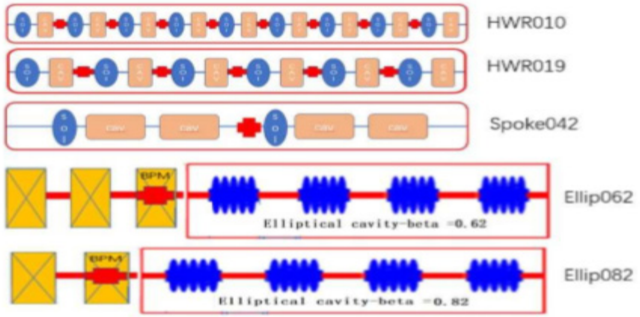
© Springer International Publishing Switzerland 2016
J.-P. Revol et al. (eds.), Thorium Energy for the World, DOI 10.1007/978-3-319-26542-1_13

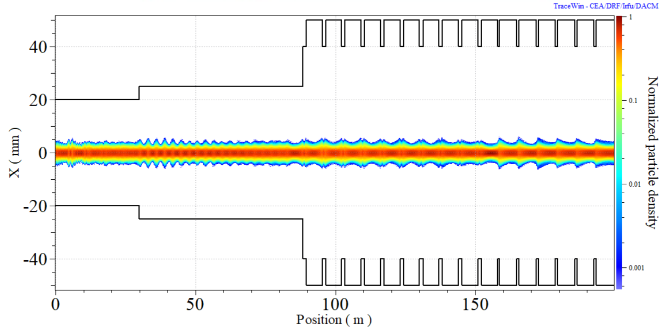
Outlines

- Introduction of Chinese ADS Project and Progress
- **Requirements and Design of SRF of CiADS**
- Status and Stability Issues of CAFe Operation
- Techniques Development for the ADS Future
- Summary

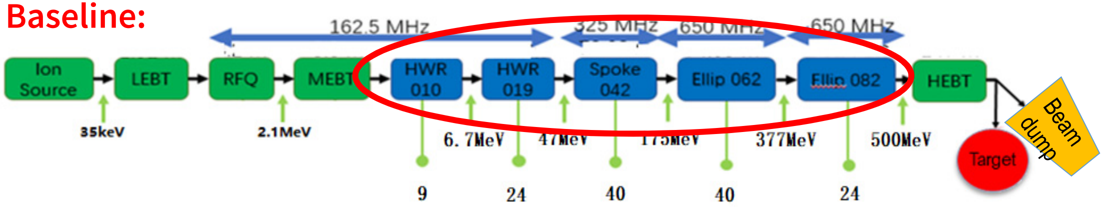
Design of SC section

- 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





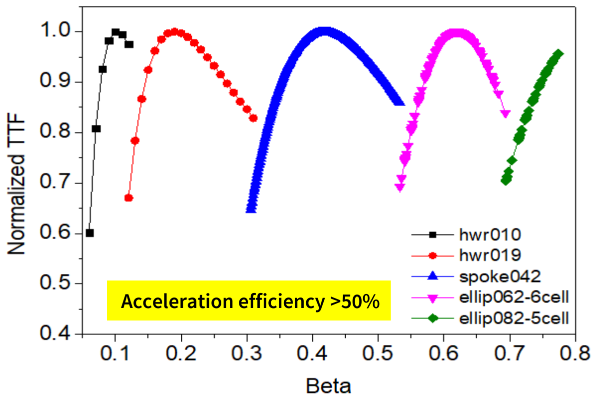
Baseline:

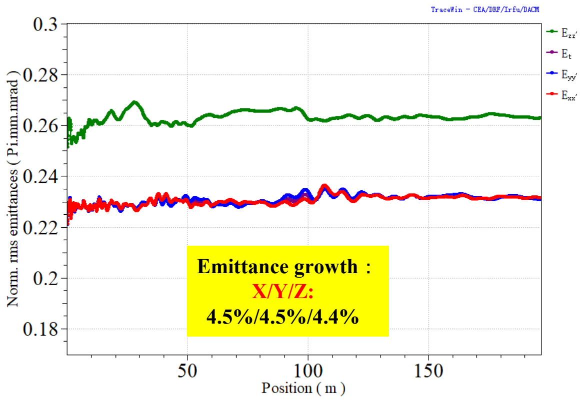


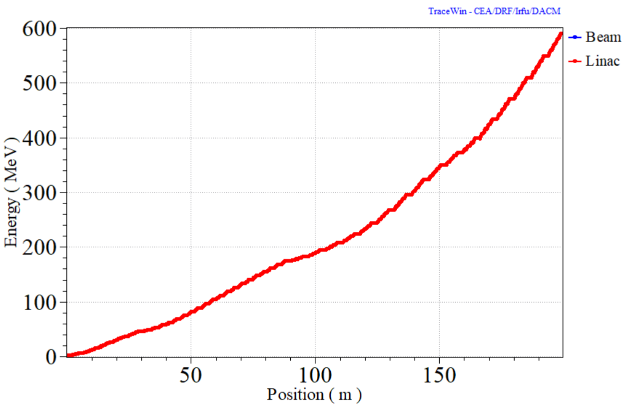
Optimization of "smoothness" from 2 to 10 degs !!

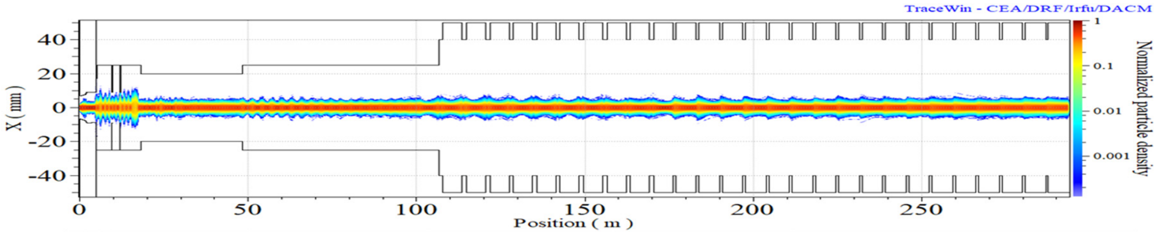
	HWR010	HWR019	Spoke042	Ellip062	Ellip082
f (MHz)	162.5	162.5	325	650	650
βopt	0.10	0.19	0.42	0.62	0.82
Number of cells	2cell	2cell	3cell	6cell	5cell
Epeak(MV/m)	26/30	28/33	28/33	28/33	28/33
Num of cavities	9	24	40	40	24
Focusing elements	SC sol	SC sol	SC sol	triplet	doublet
Num of magnets	9	24	20	10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

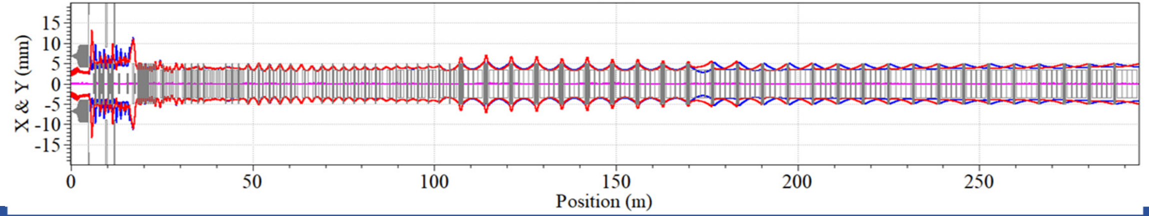
End to end simulation

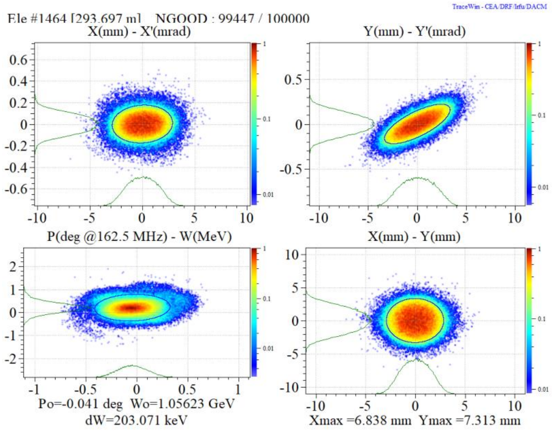










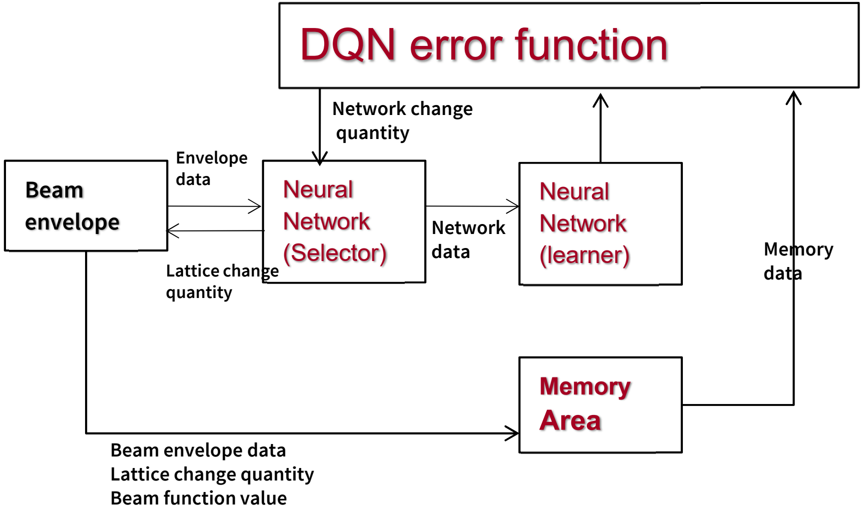


Cavity Failure Compensation for Rapid Recovery

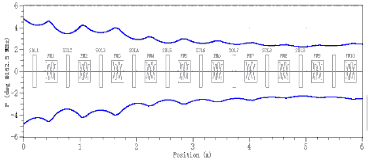
- Adaptive compensations scheme +AI

① Find the output energy threshold of each cavity type based on the velocity acceptance and matching requirements
② Matching at low energy
③ Compensate energy at high energy
④ Iterative optimization to get the minimum cavity voltage redundancy

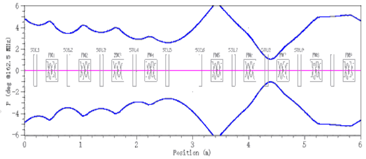
Type	010	019	042	062	082
Redundancy	20%	15%	10.7%	6%	10%



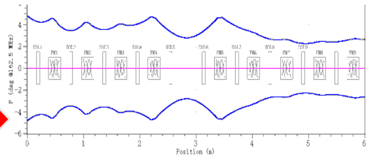
DQN reinforcement algorithm flow chart



design



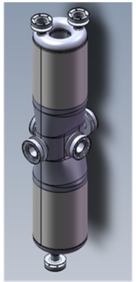
Cavity failure



Adaptive Compensation

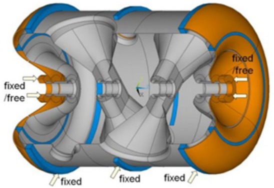
SRF Cavity Design-Requirement

- EM design
  - ✓ Ep, Bp, Eacc
  - ✓ G, R/Q
  - ✓ MP
- Mechanical analysis
  - ✓ df/dp
  - ✓ LFD
  - ✓ Tuning force
  - ✓ Mechanical mode
  - ☐ stress

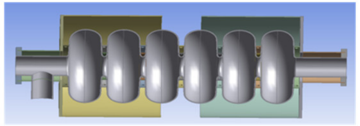


HWR010

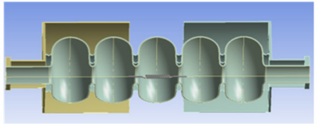
HWR019



Double Spoke042



ellip 062



ellip 082

Cavity		HWR010		HWR019		Spoke042		062-6cell		082-5cell	
Frequency	MHz	162.5		162.5		325		650		650	
Beam Aperture	mm	40		40		50		100		100	
β		0.10		0.19		0.42		0.62		0.82	
Cell		2		2		3		6		5	
Temperature	K	2		2		2		2		2	
He pressure fluctuations	Pa	±10		±10		±10		±10		±10	
Maximum He pressure	bar	2		2		2		2		2	
HBW	Hz	150		70		60		120		100	
df/dp	Hz/mbar	20		20		-		-		-	
LFD	Hz/(MV/m)^2	39		8		6		8		4	
microphonics		fm	Δf	fm	Δf	fm	Δf	fm	Δf	fm	Δf
	Hz	50	10	50	10	50	10	50	10	50	10
	Hz	100	5	100	5	100	5	100	5	100	5
	Hz	150	4	150	4	150	7	150	7	150	7
	Hz	200	4	200	4	200	5	200	5	200	5

SRF Cavity Design

Beam dynamics

Cryogenic system

LLRF

Cavity		HWR010	HWR019	Spoke042	062-6cell	082-5cell
Leff	m	0.185	0.351	0.582	0.818	0.896
L(mechnical)	m	0.21	0.47	0.8	1.173	1.256
Ep/Eacc		5.9	4.21	3.84	3.13	2.38
Bp/Eacc	mT/(MV/m)	12.1	6.12	6.95	4.77	3.92
Ep(operation)	MV/m	26	28	28	28	28
Bp	mT	53.3	49.7	50.7	42.7	46.9
TTF		0.82	0.89	0.8	0.73	0.74
Veff	MV	0.81	2.33	4.24	7.32	10.5
V0	MV	0.99	2.63	5.3	10	14.3
Eacc	MV/m	4.41	6.65	7.29	8.95	11.7
G	Ω	28.4	65.9	109	193	237
G/Q	Ω	153	339	432	347	514
Ploss (2K)	W	2.77	4.43	11.4	14.0	16.0
Q0		1.6E+09	3.6E+09	3.6E+09	1.1E+10	1.4E+10
R0	Ω	15	15	25	10	10
Rbcs(2K)	nΩ	0.17	0.17	0.68	2.73	2.73
Rs	Ω	18.2	18.2	30.0	17.6	17.6
Rtrap (20mGs)	Ω	3.02	3.02	4.28	4.84	4.84
df/dp	Hz/mbar	<abs(-10)	<abs(-10)	<abs(-10)	<abs(7)	<abs(4)
LFD	Hz/(Mv/m)^2	<abs(-5)	<abs(-4)	<abs(-4)	<abs(-1)	<abs(-1)

Outlines

- Introduction of Chinese ADS Project and Progress
- Requirements and Design of SRF of CiADS
- **Status and Stability Issues of CAFe Operation**
- Techniques Development for the ADS Future
- Summary

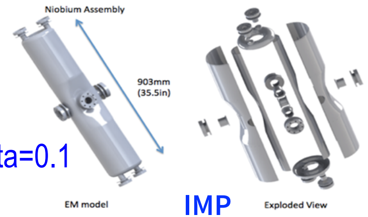
Chinese ADS Front-end Demo linac (CAFe)

China Initiative Accelerator Driven System

- **IMP collaboration with IHEP 2011 ~ 2017**

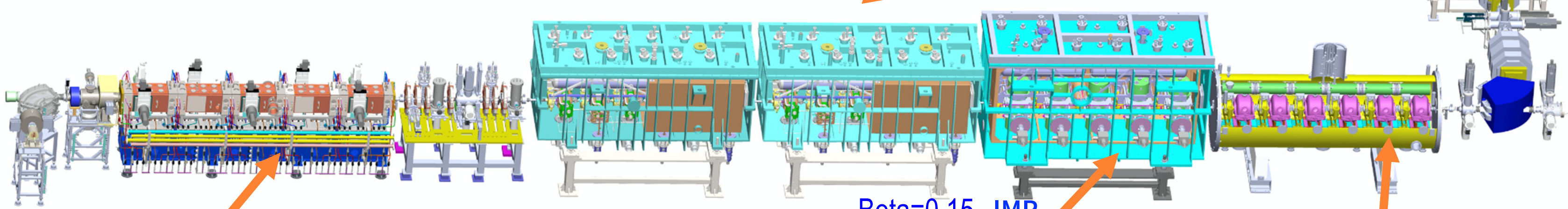
ions	P, H_2^+, α
frequency	162.5 MHz
current	10 mA
E in RFQ	40 keV
E out RFQ	3.1 MeV
Energy	25/30/40MeV
Temp.	4.5 K

162.5 MHz Half-wave Cavity



Beta=0.1

IMP



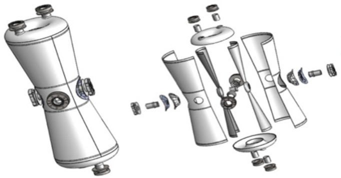
DUMP

HEBT

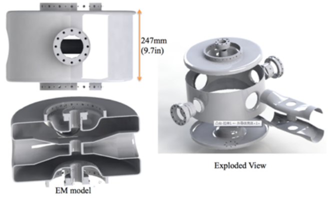
ADS RFQ：2014-2017
(cooperation with LBL)
CMIF RFQ：2018-

Beta=0.15 IMP

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.**

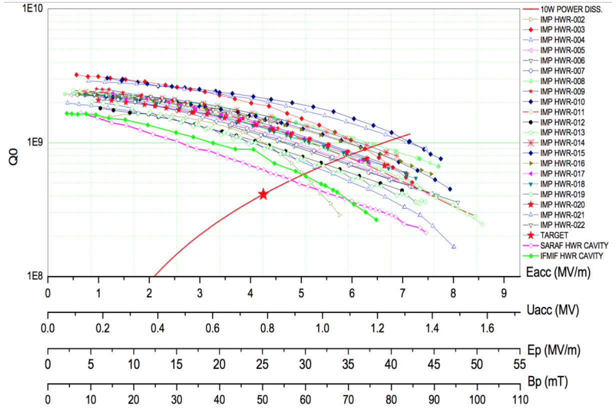
- Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.

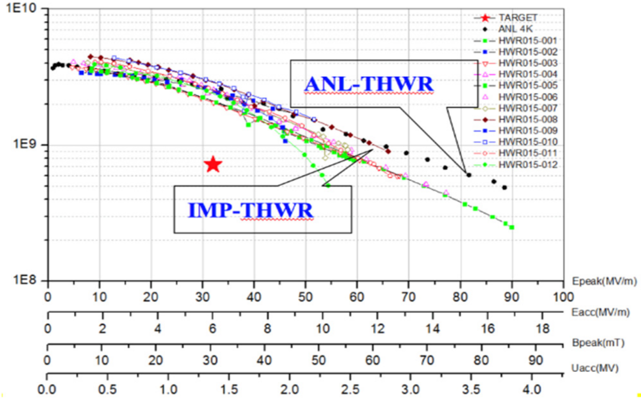
Specifications and VTA of Resonators

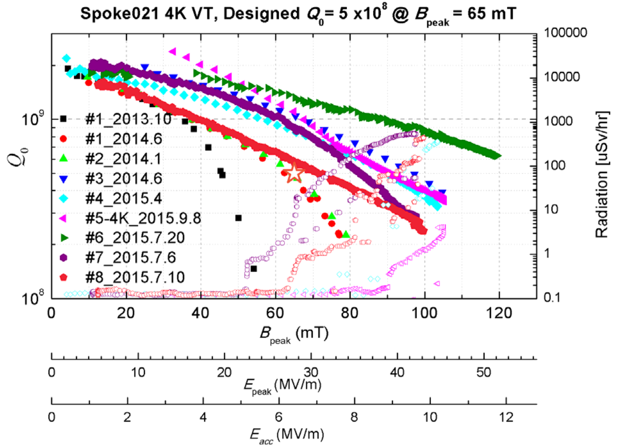
	HWR010
f (MHz)	162.5
βopt	0.10
Vmax (MV)	1.06
Epeak (MV/m)	28
Bpeak (mT)	50
Eacc(MV/m)	4.7
Epeak/Eacc	5.9
Bpeak/Eacc (mT/(MV/m))	12.1
G = Rs×Q0 (Ω)	28.4
R / Q0	153

	HWR015
f (MHz)	162.5
βopt	0.15
Vmax (MV)	2.56
Epeak (MV/m)	32
Bpeak (mT)	40
Eacc(MV/m)	6.5
Epeak/Eacc	4.89
Bpeak/Eacc (mT/(MV/m))	6.11
G = Rs×Q0 (Ω)	51
R / Q0	292

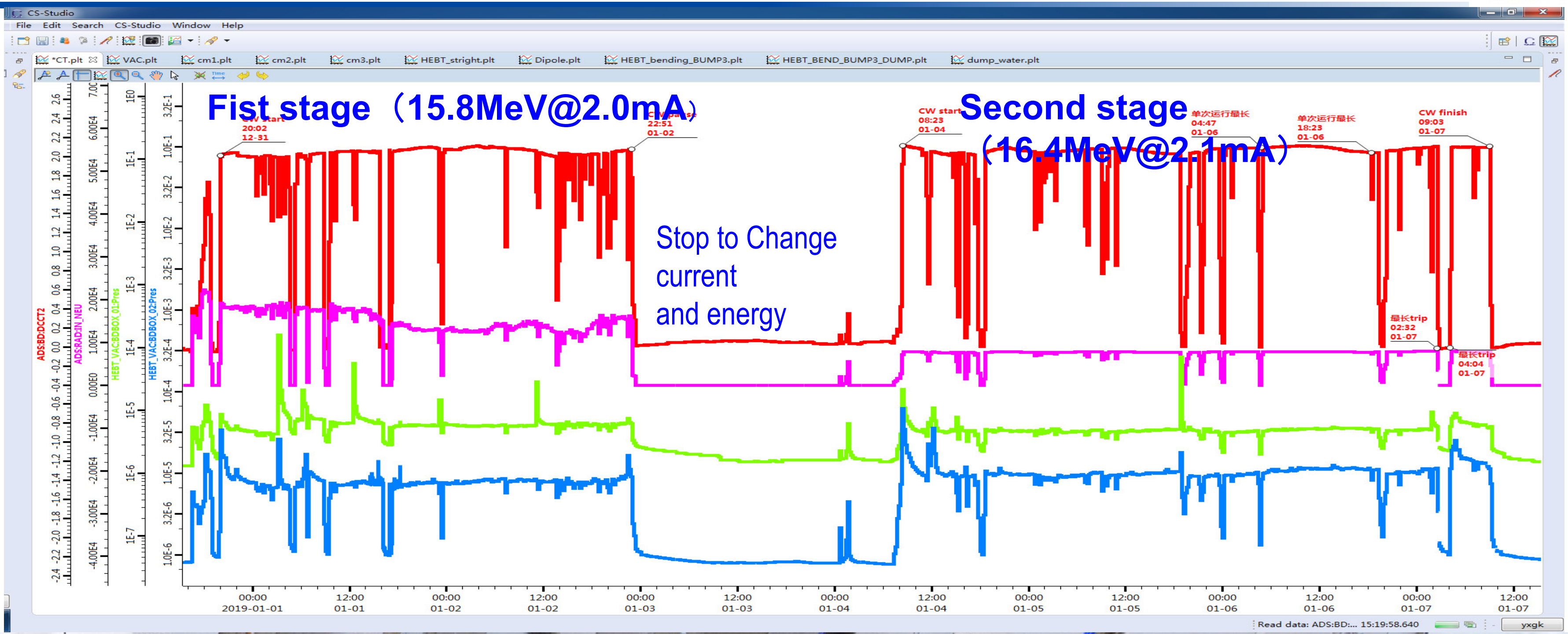
	Spoke024
f (MHz)	325
βopt	0.246
Vmax (MV)	6.48
Epeak (MV/m)	32.5
Bpeak (mT)	68
Eacc(MV/m)	8.38
Epeak/Eacc	3.88
Bpeak/Eacc (mT/(MV/m))	8.13
G = Rs×Q0 (Ω)	87
R / Q0	206



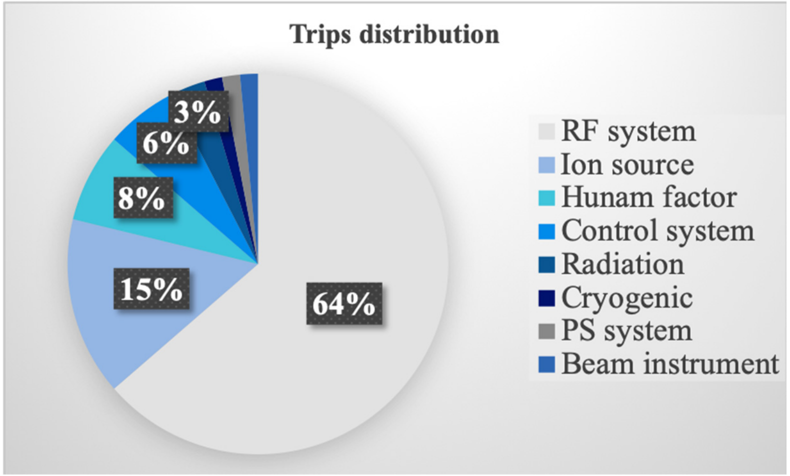


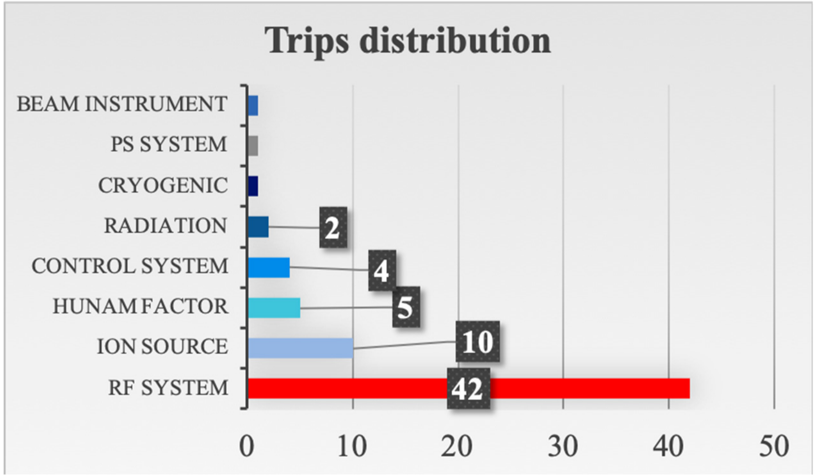


High-power Test of Operation Reliability



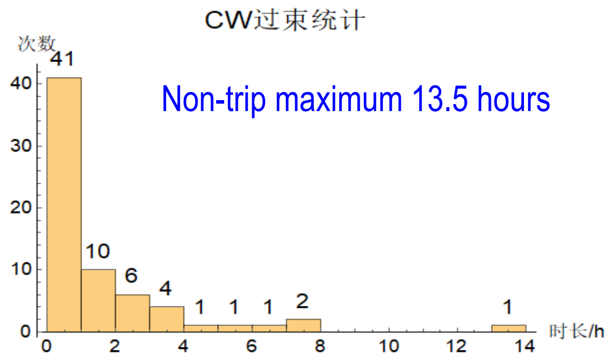
RAMI of CW beam with active MPS





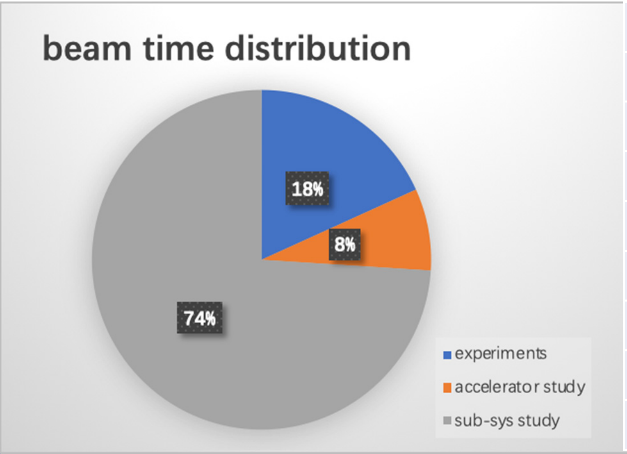
- Operation time 129.2 hours, downtime 12.3 hours, availability ~89%
- Trips is 66 and 64% due to RF system, mostly LLRF.
  - 1st stage: 2018/12/31 18:44 - 2019/01/02 23:42
  - 2nd stage: 2019/01/04 08:08 - 01/07 09:03
- Max power is 45 kW with 2.55 mA @17.5 MeV

Availability	MTBF	MTTR	Availability	MTBF	MTTR
0.89	90.7 min	11.1 min	0.89	113.7 min	14.6 min

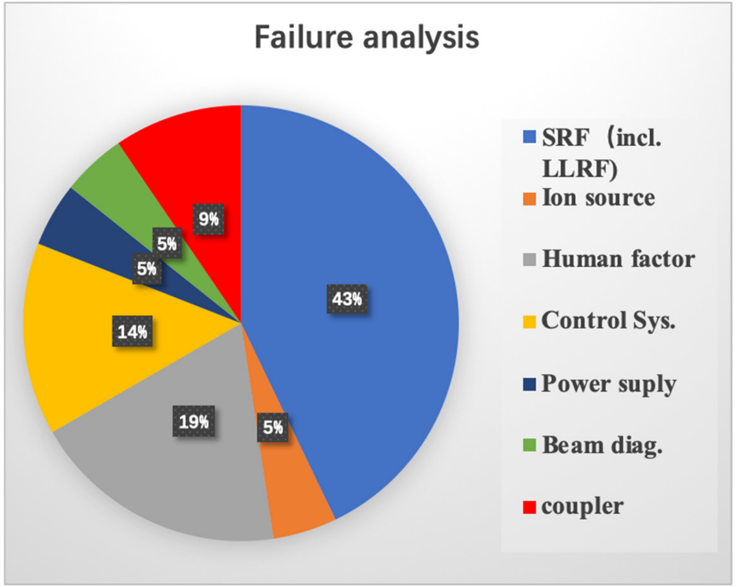


Operation for Users

- 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



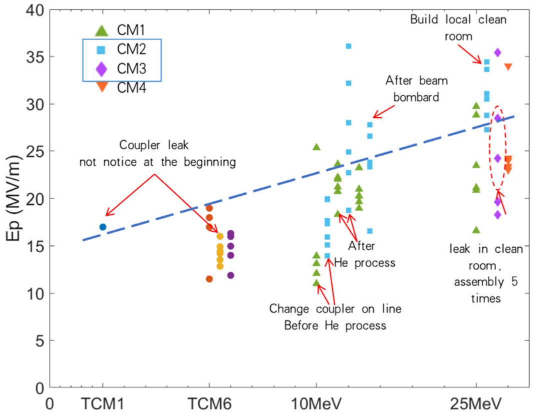
source	trips
RF (incl. RFQ, LLRF)	9
IS	1
human	4
control	3
PS	1
Diagnostic	1
coupler	2
total	9

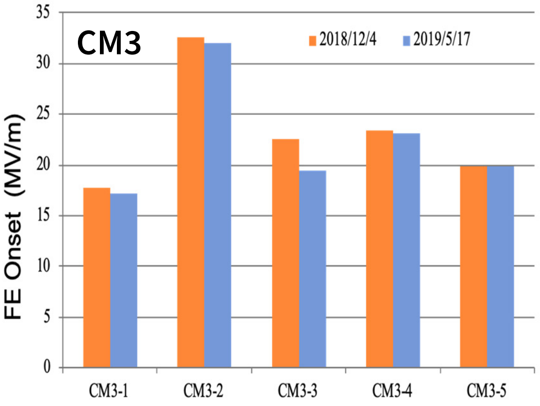


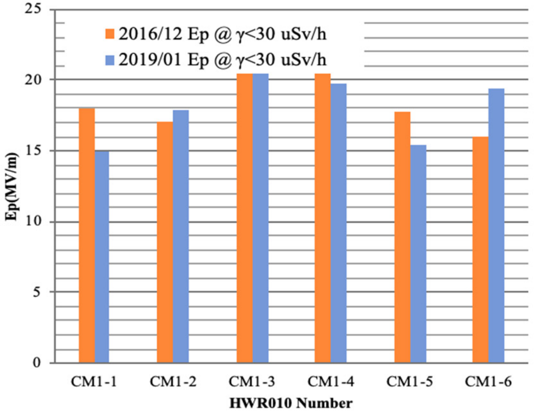
Stability Issues of CAFe

- Degradation from VTA to installation in tunnel
- Degradation during operation (couple arc, MP, beam loss)
- Field emission cause window break
- Microphonics and ponderomotive cause phase unlock

Operational Gradient Degradation

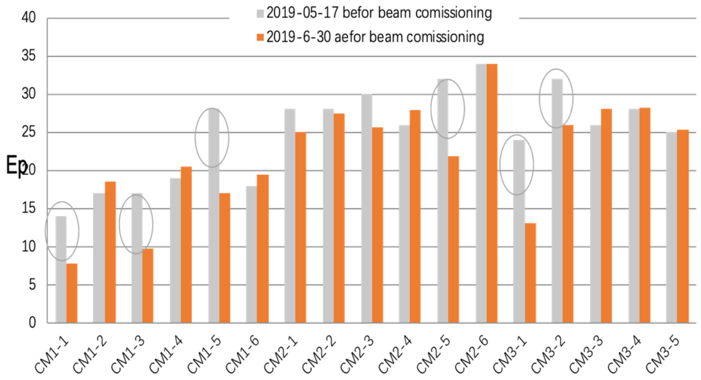






- 2018/12/4: before CW commissioning
- 2019/5/17: after CW commissioning, return to room temperature, RF conditioning
- FE onset almost not change

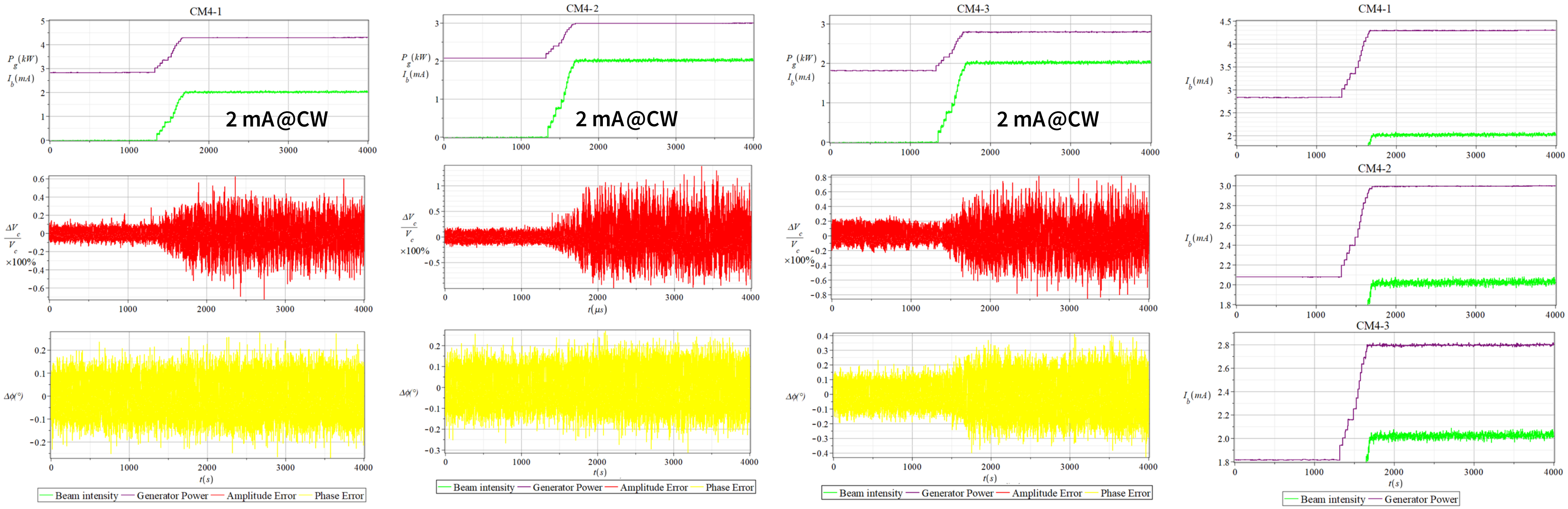
- CM1 removed after 10 MeV test
- Warm back to room temperature, vacuum ~100 Pa, 2017/01 to 2018/09
- Re-install after RF condition, Ep average 18 MV/m with γ 30 uSv/h limit (ball shape, EGM).
- **Average performance almost not change after the CM1 not used for one year in room temperature, vacuum ~100Pa**

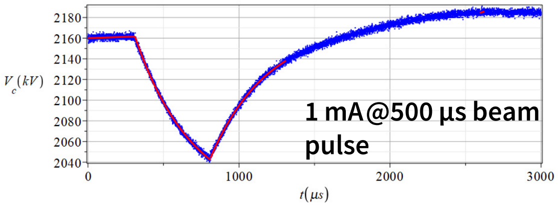


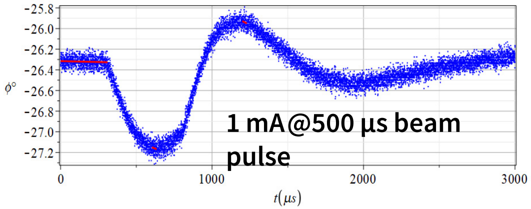
Compare at same γ-dose

- 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





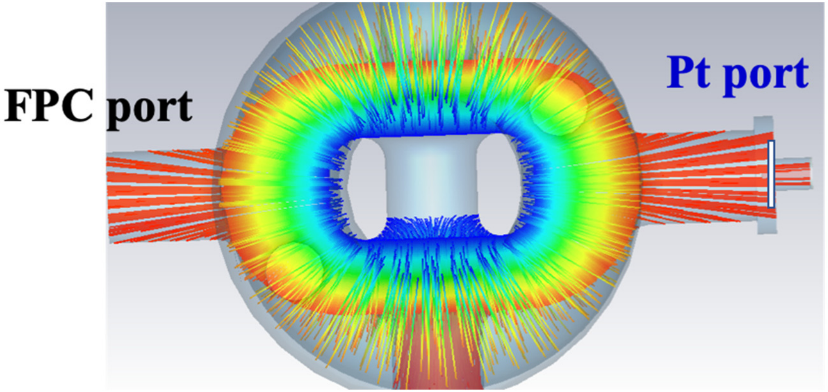


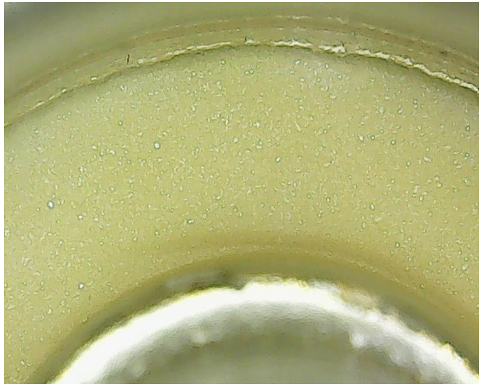
HWR010@CM2-1, no feedforward, weak amplitude feedback;

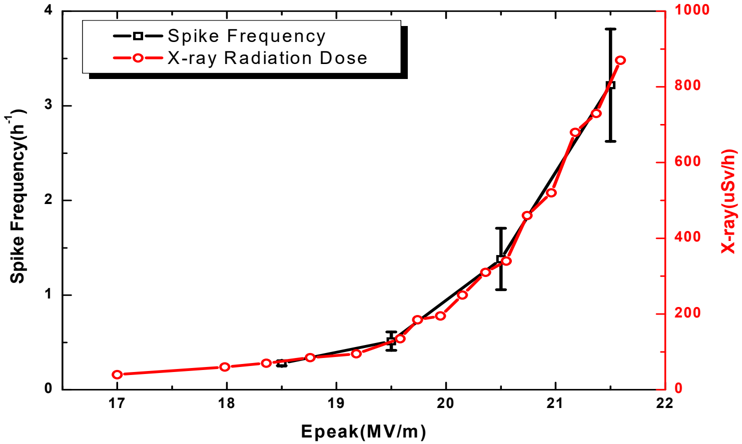
Possible reason:

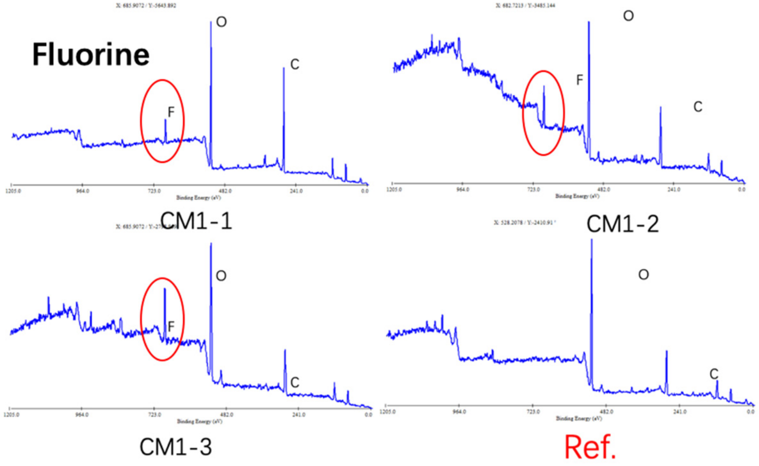
1. **Excessive k_p in the feedback loop;**
2. **Large time delay in the feedback loop;**
3. **Ponderomotive effects.**

Windows broken of FPC and Pt Caused by FE

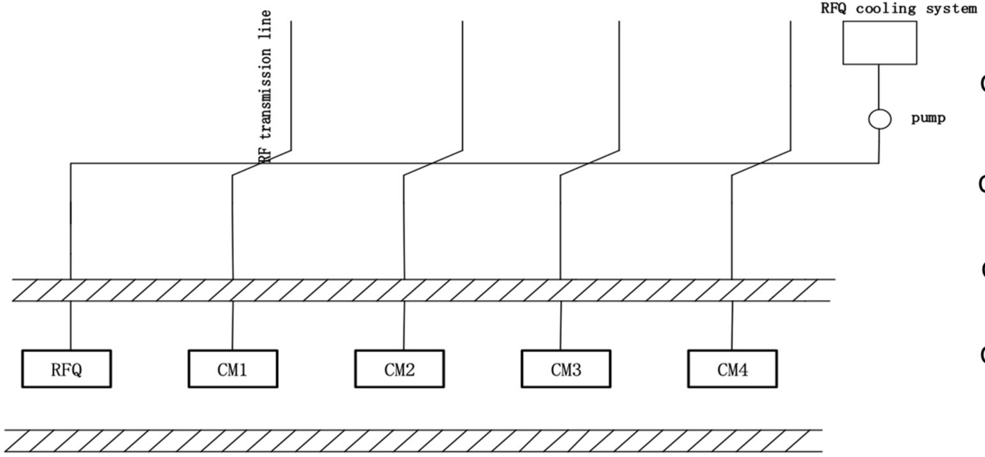




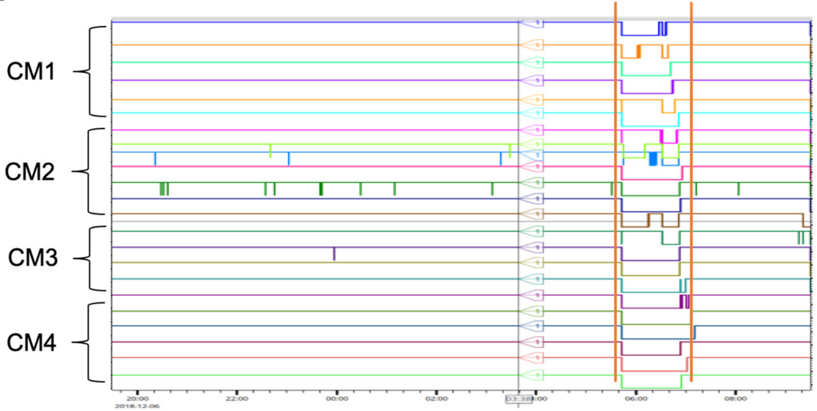




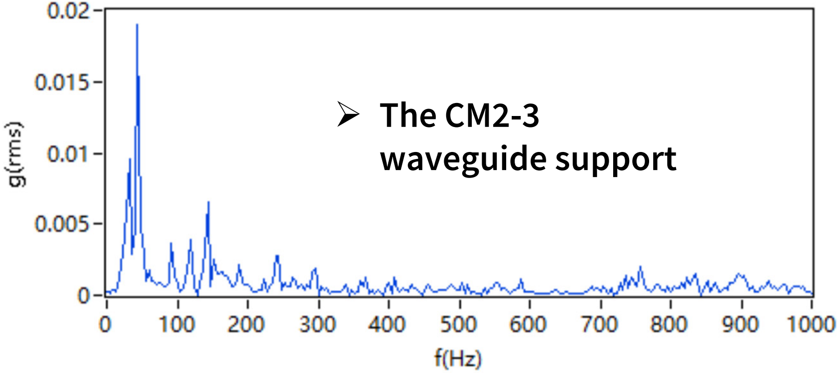
Microphonics of SRF resonators in CM2



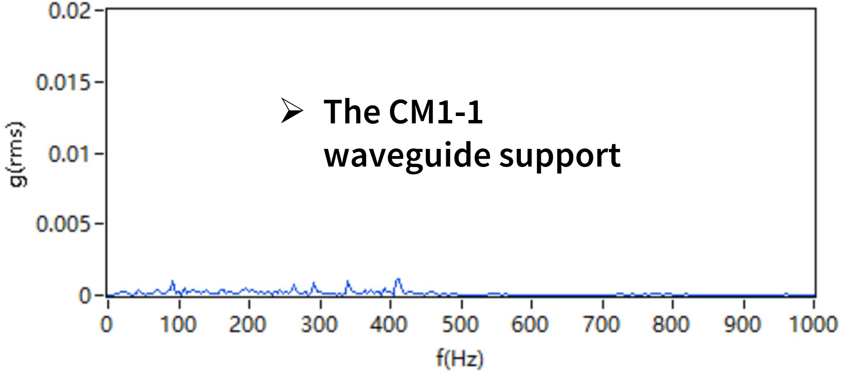
CM1 to CM4 trips（7:30 p.m. Dec.6 -- 9:30 a.m. Dec.7）



Helium pressure fluctuation

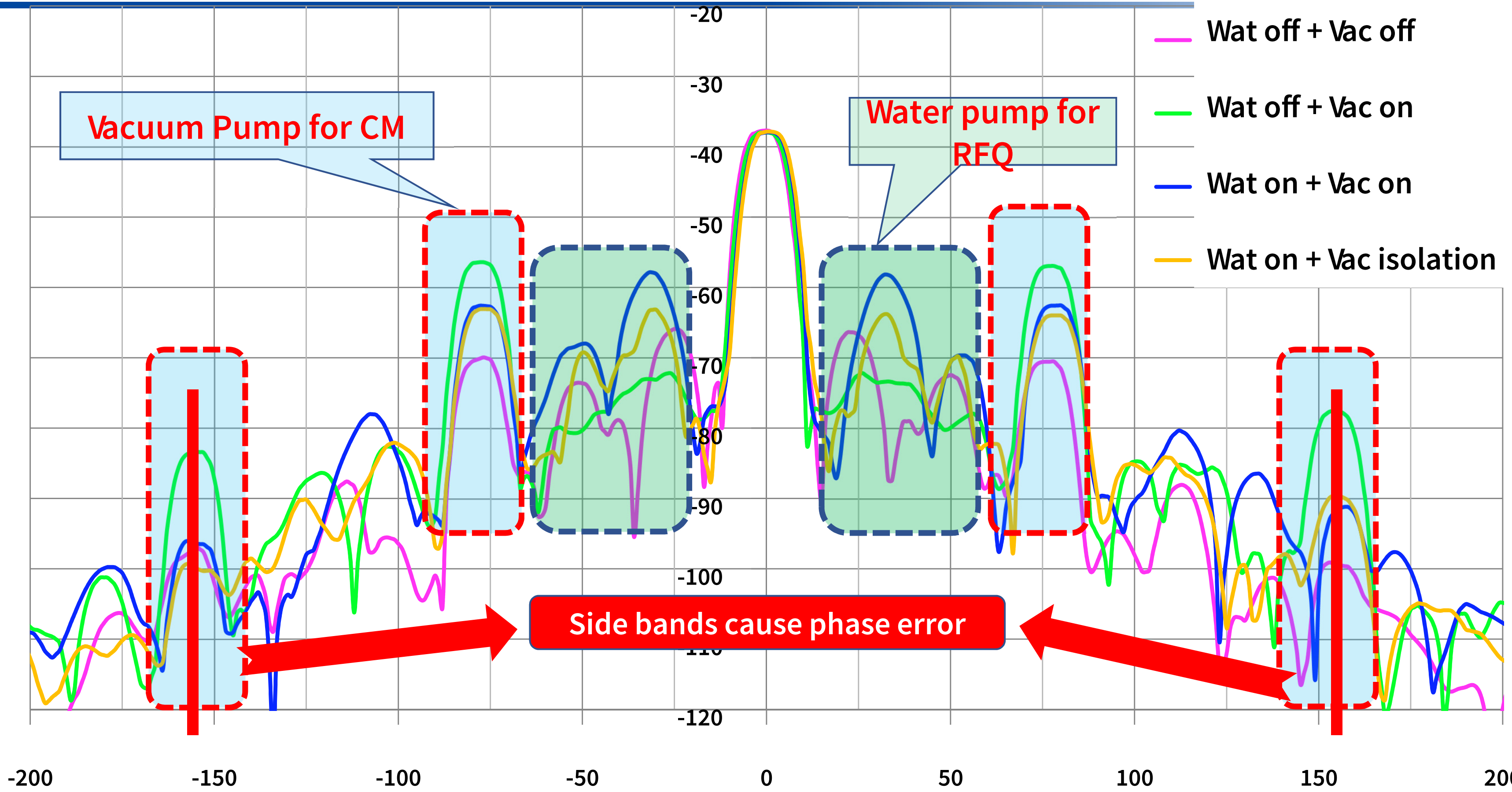


- The CM2-3 waveguide support



- The CM1-1 waveguide support

Vibration Sources to CM2-3

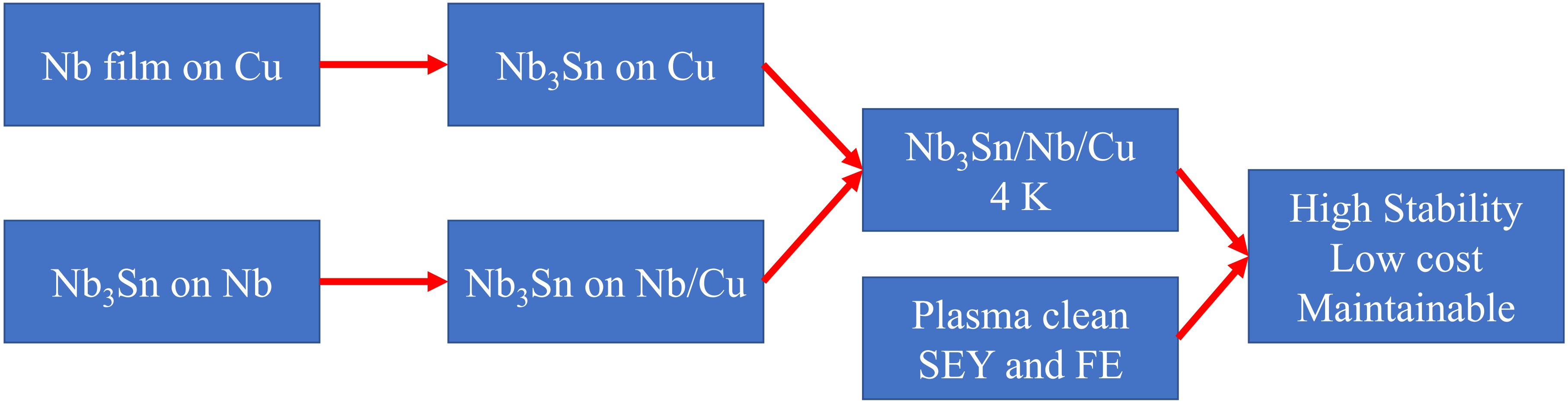


Outlines

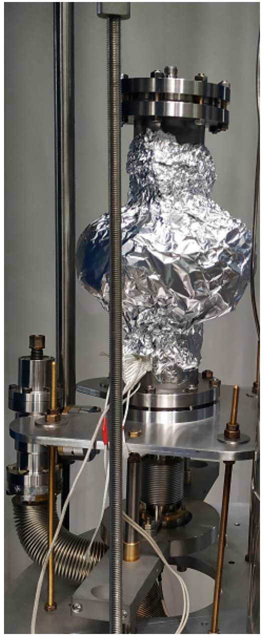
- Introduction of Chinese ADS Project and Progress
- Requirements and Design of SRF of CiADS
- Status and Stability Issues of CAFe Operation
- Techniques Development for the ADS Future
- Summary

What do we think for the future ADS

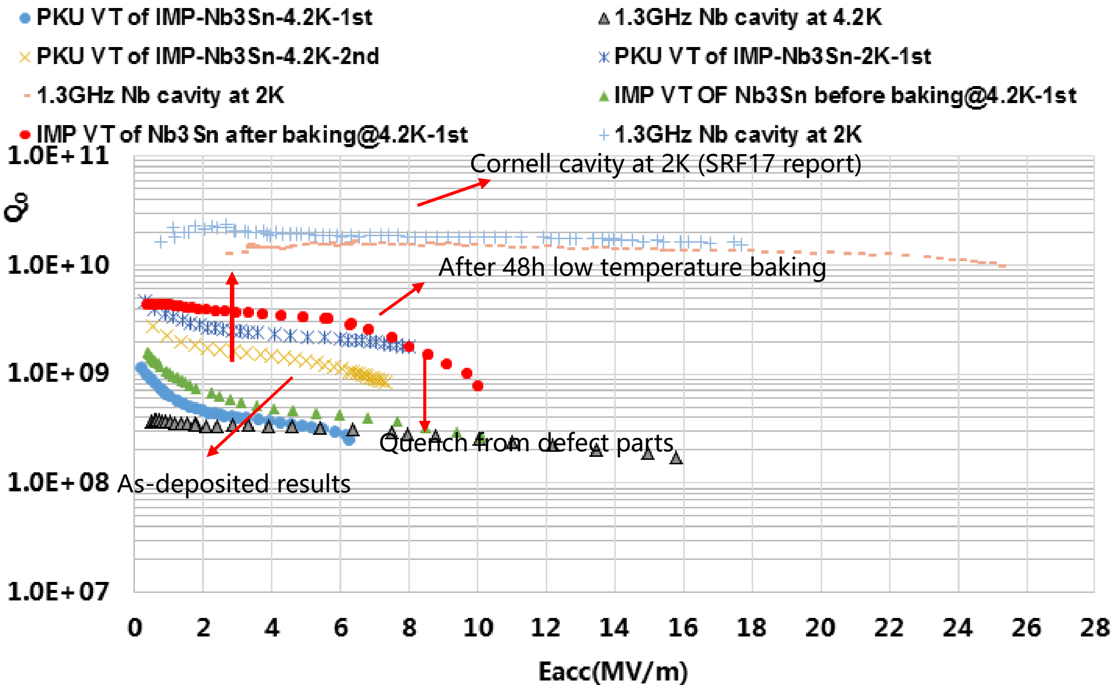
- High stability, low cost, performance recovery every year in-situ
- Copper based thin film cavity and plasma + He cleaning are our choice for the future project demo
- Recipe of stable CW RFQ, MP and arc free



Nb_3Sn on bulk Nb



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



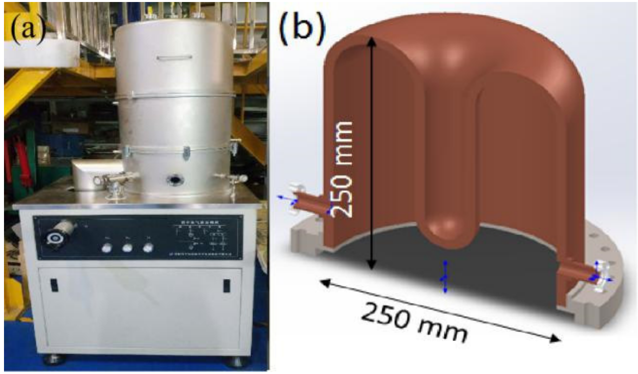
Some remarks on Nb_3Sn tested at 4.2K:

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.

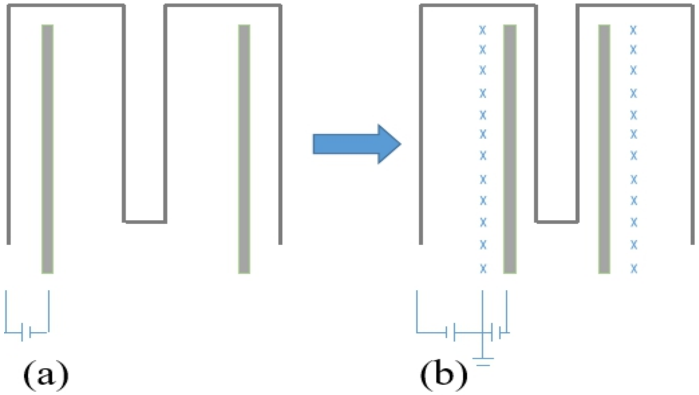
Nb on Copper Development

The inferior coating near the cavity opening caused 2 unsuccessful cavity tests in 2018.

Main problems are short sputtering cathode and large difference between inner and other conductor.

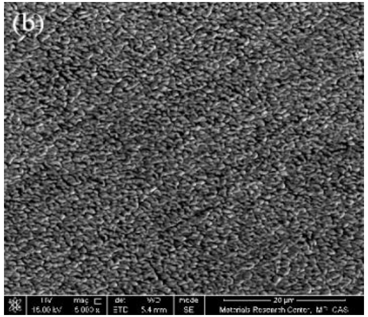


Growth rate ratio: less than 1:5
Good coverage near the cavity opening



Diode scheme

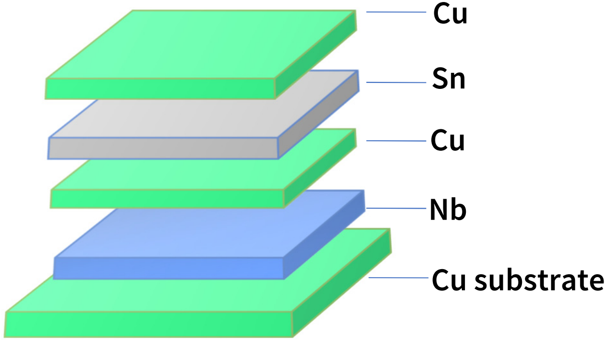
unbalanced triode scheme

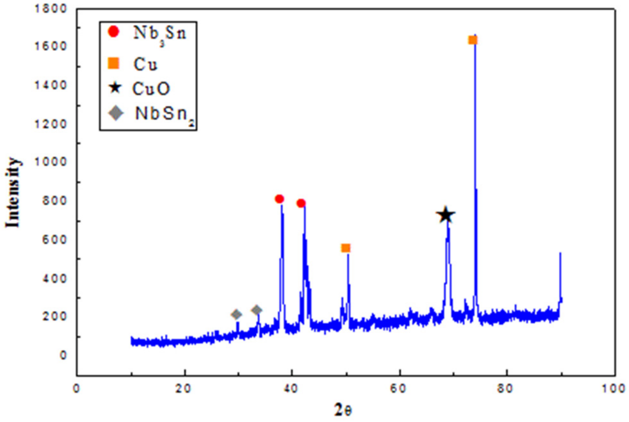


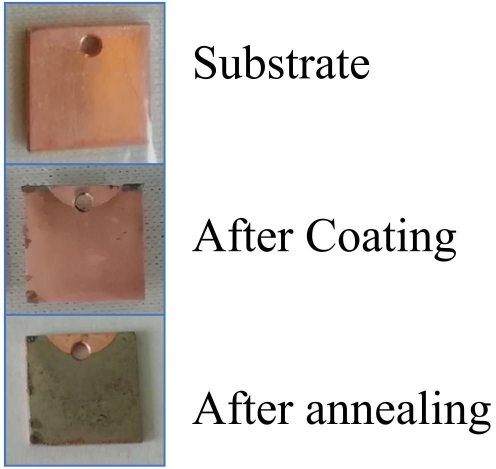
SEM image of sample near the opening

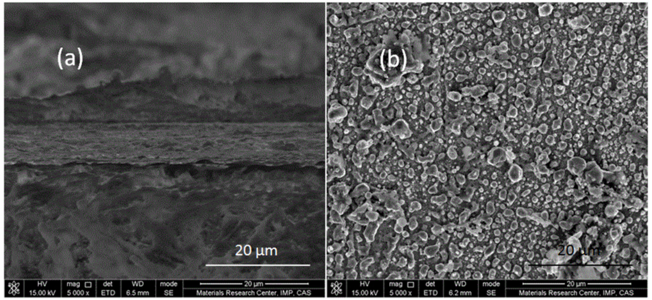
Nb_3Sn on Copper Development

Nb_3Sn was synthesized via electroplating + annealing.





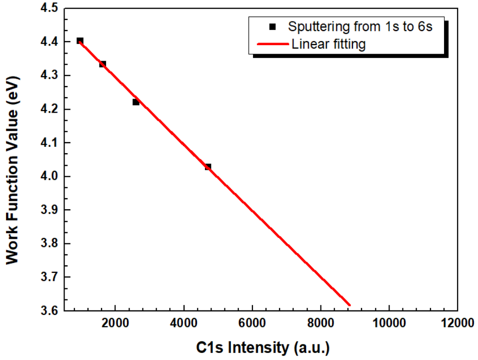




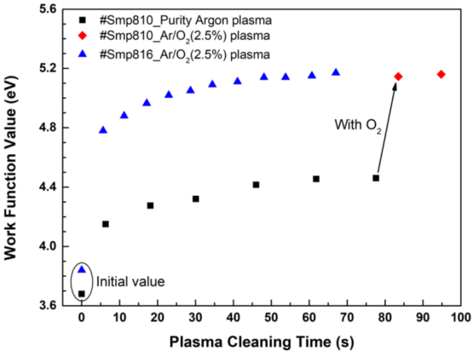
Plasma cleanings for HWR cavities

Friday, 11:55-12:10
Talk: FRCAB6

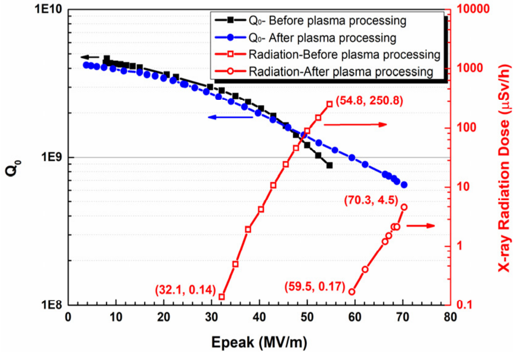
• Cleaning on Nb samples, HWR cavities and mechanism of CH-contamination



Work function vs. C1s intensity

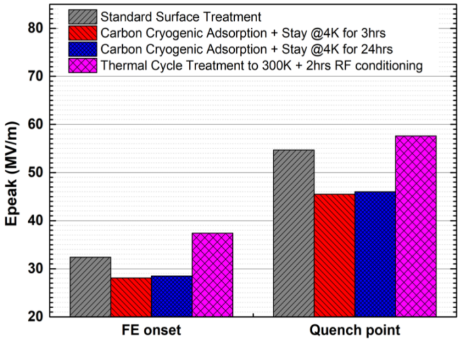


Ar/O2 plasma cleaning on samples

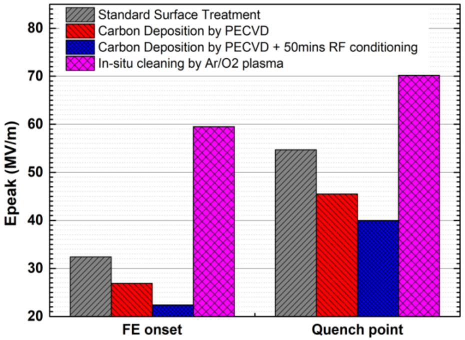


HWR performance improvement by Plasma

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 of Chinese ADS Project and Progress
- Requirements and Design of SRF of CiADS
- Status and Stability Issues of CAFe Operation
- Techniques Development for the ADS Future
- Summary

Summary

- The CiADS started earthwork in August 2018. It is planned to commission in 2024.
- The front-end demo 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.
- The MTBF of high-power operation is around 2 hours. The stability issues of CAFe are gradient degradation, microphonics, beam loading oscillation, and EMC. The issues were found and will be removed. More than 100 kW beam power, and higher stability is the goal in 2019.
- The thin-film SRF on copper and in-situ cleaning are the developing technologies in IMP for the future ADS.

Thanks the team and worldwide collaboration!

- **Talk**

Contributions from IMP

- FRCAB6, Friday 11:55-12:10, The Effect of helium processing and plasma cleaning for low beta HWR cavity.
- FRCAB3, Friday 11:10-11:25, The design of an automated high-pressure rinsing system for SRF cavity and the outlook for future automated cleanroom on strings assembly

- **Poster**

- MOP002, Low temperature heat treatment of Nb/Sn multilayers and Nb/Cu/Sn multilayers.
- MOP003, Development of Nb3Sn cavity coating at IMP.
- MOP073, Suppressing multipacting in high power couplers with a new DC bias structure.
- MOP085, The destructive effects to the RF coupler by the plasma discharge.
- MOP096, Operation of cryomodule for Chinese ADS front-end demo linac.
- MOP103, Consideration of the remanent magnetic field for SRF cavities at IMP.
- TUP075, New progress for niobium sputtered 325MHz QWR cavities in IMP
- TUP076, Electrochemical deposition of Nb3Sn on the surface of Cu subtracts.
- TUP088, Vacuum barrier design of ADS injector helium cryogenic system.
- THP064, The cryostat results of carbon contamination and plasma cleaning for the field emission on the SRF cavity.
- THP010 , The mechanism of electropolishing of Nb in ionic liquid.