CHALLENGES AND PERFORMANCE OF THE C-ADS INJECTOR SYSTEM

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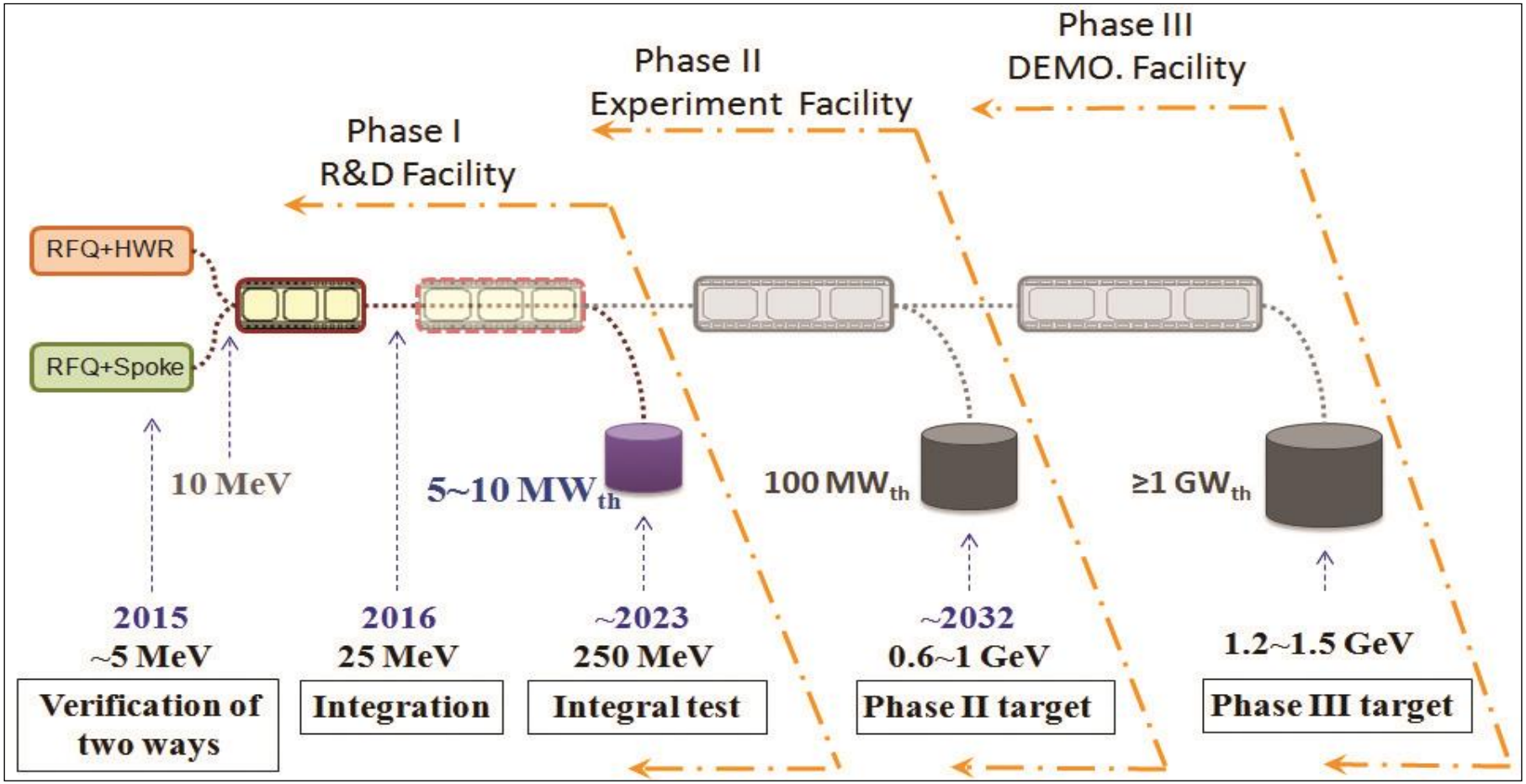
- Introduction of C-ADS
- Design of C-ADS Linac
- R&D of Key Accelerator Technologies
- Commissioning of Injectors
- Challenges of C-ADS Injectors
- Conclusion

Motivation of C-ADS

- Along with the rapid development of nuclear power plants in China, treatment of the nuclear waste has become a crucial issue.
  - **To July 2013**（https://www.iaea.org/NuclearPower/system-and-databases/index.html）
  - -- 18 reactors in operation, 13.860 GWe ; (6th in the world)
  - -- 28 reactors under construction, 27.790GWe ; (1st in the world)
  - **Estimation for the future** (**Slow down after 2011.3**)
  - -- **2020** : ~ 58 Gwe NPP in operation
  - -- **2030** : ~ 10% of NP to total power capacity
  - -- **2050** : 350~400 GWe, ~20% of NP to total power capacity → **almost same as the scale of the total in the world today!**

Nuclear Waste Management is a serious Sustainable NP Development!

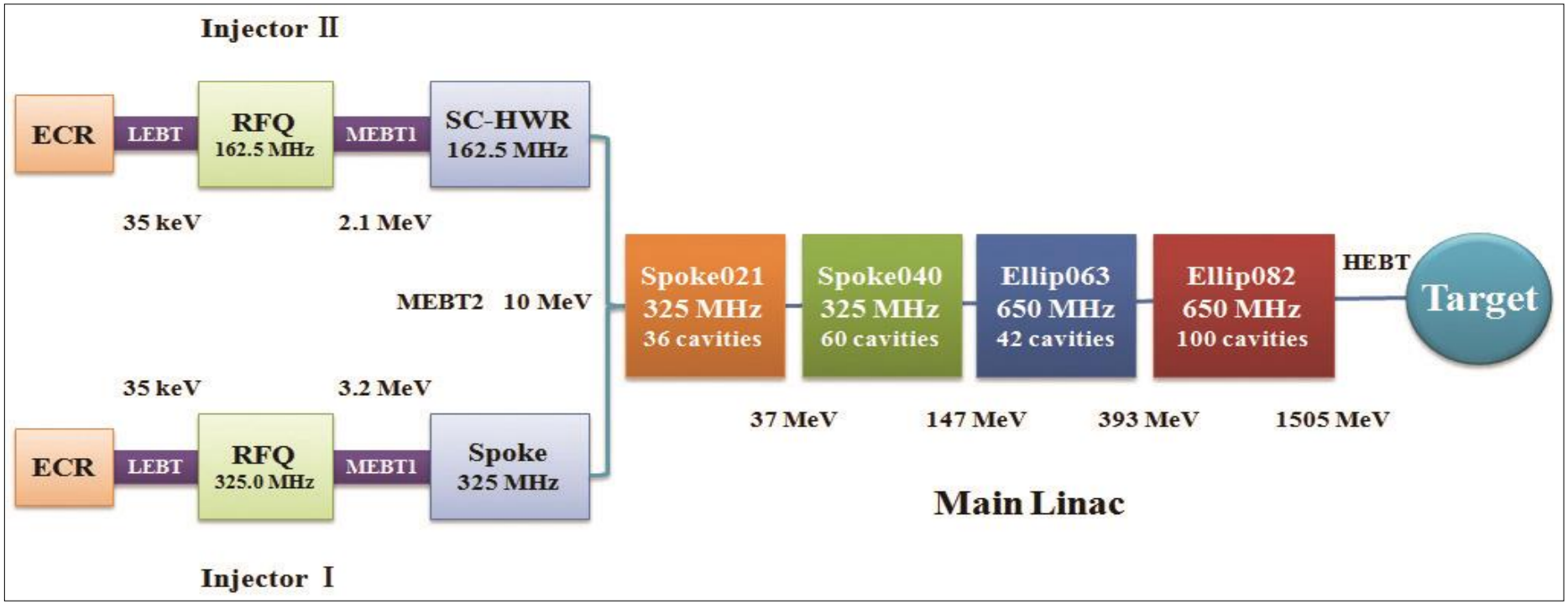
C-ADS Road Map



Y2011-2016, 1.78 B CNY "Strategic Priority Research Program" of CAS, Key technology Development	Y2017-2022, 1.867 B CNY Stage 1: Research Facility (CIADS) (250MeV, 10mA, 10MWt)	Y2030 Stage 2: Demo Facility (CDADS) (1~1.5GeV, 10-25mA, 500MWt)

Layout of C-ADS accelerator

- **Injector (0-10 MeV):** 162.5MHz HWR010 or 325MHz Spoke012.
- **Low β accelerator (10-147 MeV):** 325MHz Spoke021, Spoke040.
- **High β accelerator (147-1500 MeV):** 650 MHz Ellip063, Ellip082.
- **MEBT and HEBT.**

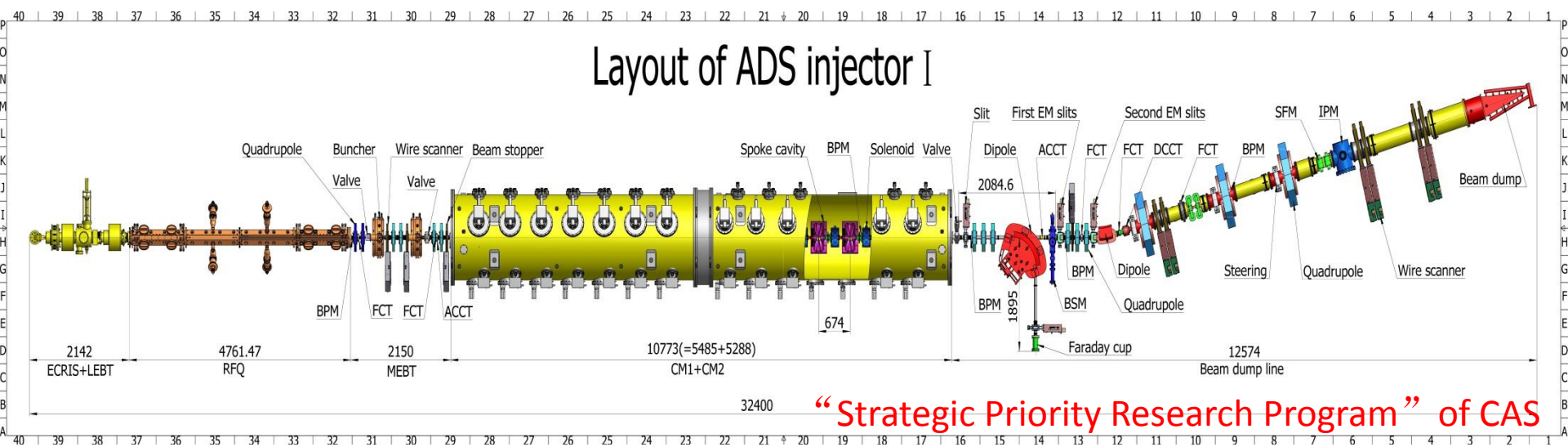


Design of C-ADS Linac

- **Specifications of the required proton beams of C-ADS**

Parameters	Value	Units
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
Frequency	162.5/325/650	MHz
Duty factor	100%	
Beam Loss	<1 (0.3)	W/m
Beam trips/year [4]	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

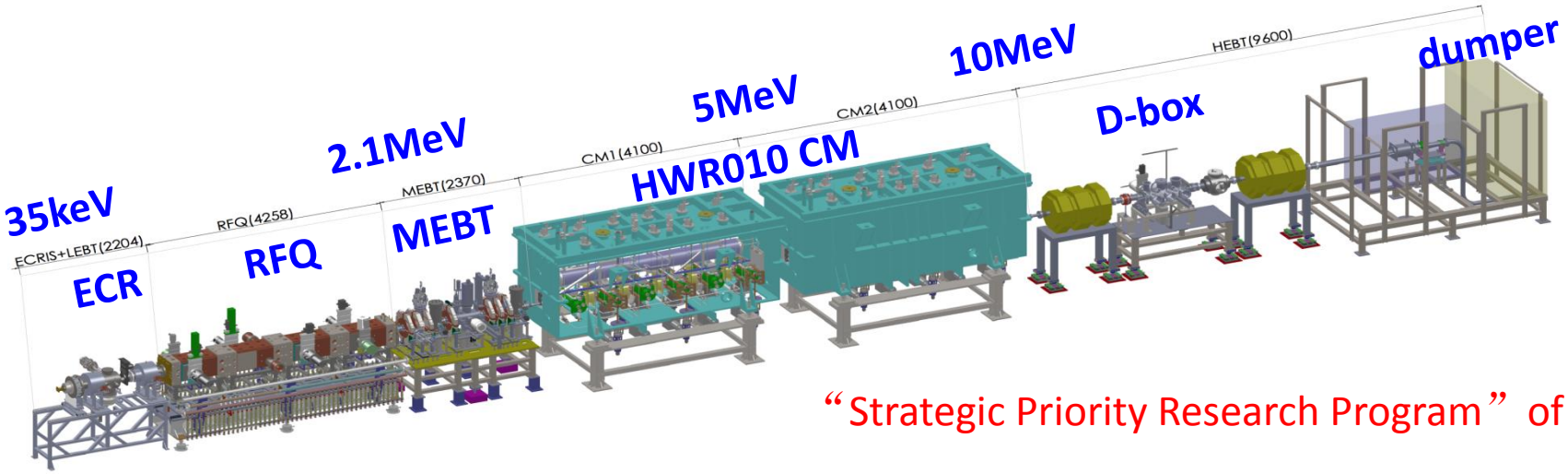
C-ADS Accelerator Injector-I at IHEP



“Strategic Priority Research Program” of CAS

- **RFQ**
  - frequency 325 MHz, 3.2 MeV,
  - RF power 300 kW, 4 couplers
- **SRF Cryomodules**
  - Frequency 325 MHz, 2 K
  - Spoke beta=0.12, Epeak=32.5 MV/m, Vacc =0.84 MV
  - 7 Spokes and 7 solenoids per module

C-ADS accelerator Injector-II at IMP



“Strategic Priority Research Program” of CAS

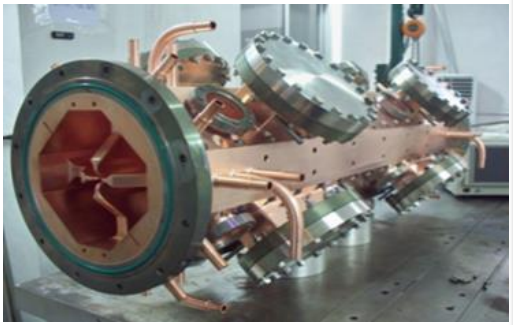
- **RFQ**
  - frequency 162.5 MHz, 2.1 MeV,
  - RF power 100 kW, 2 couplers
- **SRF cryomodules**
  - Frequency 162.5 MHz, 4.5 K
  - HWR beta=0.1, Ep=25 MV/m, Vacc =0.78 MV
  - 6 HWRs and 6 solenoids per module

R&D of Key Accelerator Technologies

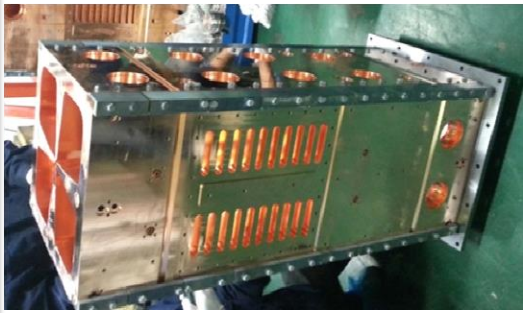
❑ RFQ

Main parameters of RFQs for C-ADS

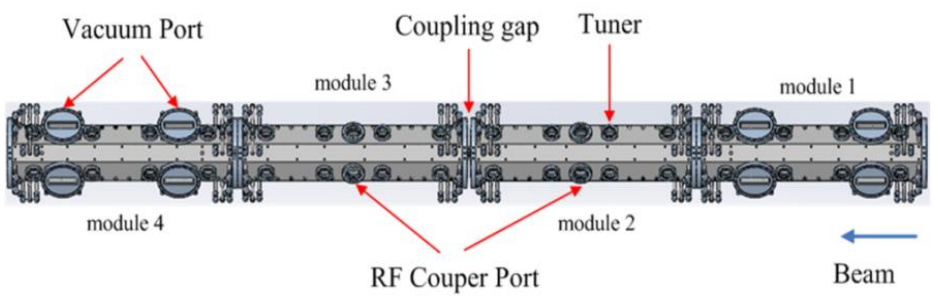
Parameters	RFQ-I	RFQ-II
RF frequency (MHz)	325.0	162.5
RF power (kW)	300	110
Beam current (mA)	10	10
Injection energy (keV)	35	35
Output energy (MeV)	3.2	2.1
Inter-vane voltage (kV)	55	65
Maximum modulation	2	2.3
Beam transition	98.7%	99.5%
εn.rms.t (πmmmrad)	0.2/0.2	0.3/0.3
εn.rms.l(πMeV-deg)	0.06	0.05
Accelerator length(cm)	467.0	420.8

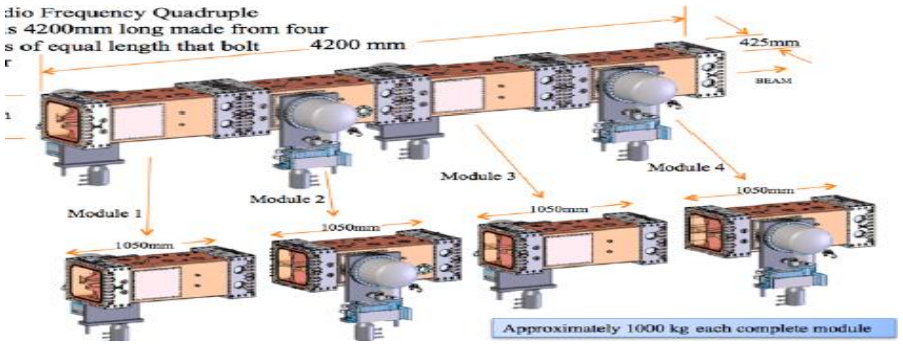


325MHz



162.5MHz





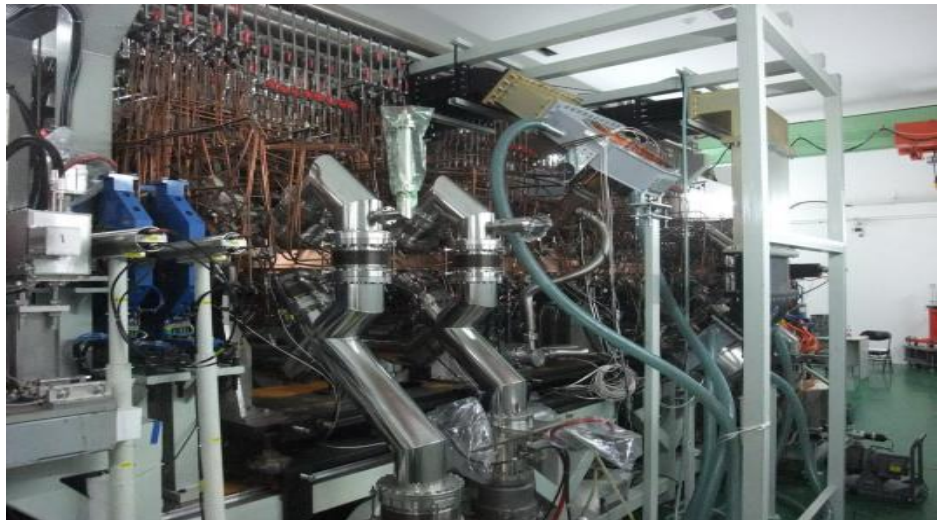
RFQ Commissioning

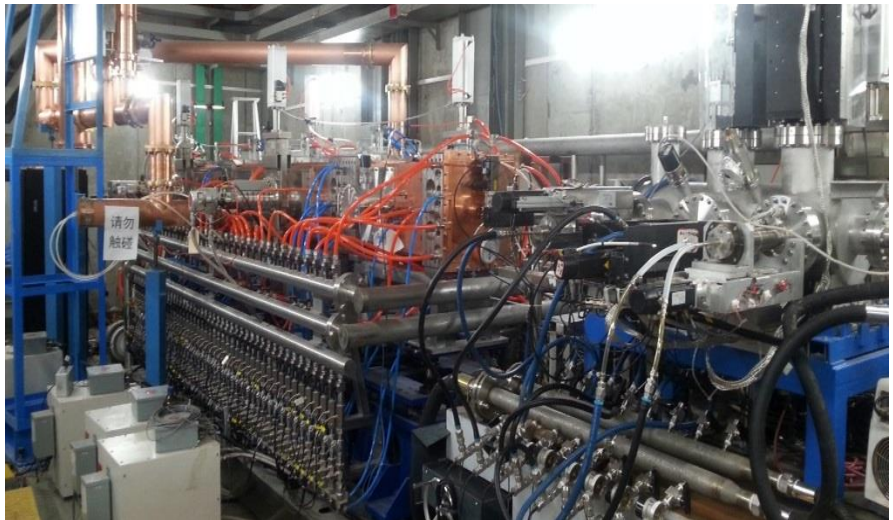
325MHz RFQ

- The maximum duty factor 99.97% (12.5 ms / 79.975 Hz) has reached with 250 kW power.
- The highest power in CW mode was 194 kW.
- The maximum beam duty factor was 90% (18 ms/50 Hz) with 90% transmission rate in 298 kW cavity power and 32 kW beam power.

162.5MHz RFQ

- June 6th, 2014 , the first beam, 2.16 MeV
- June 30th , 10 mA, CW, 21 kW, 4.5 hrs
- July 24th, 18 mA, pulse beam, 37.8 kW, transmission 87%
- Non-trip operation ~220 hrs





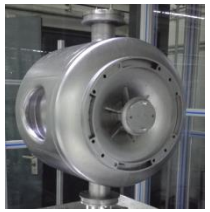
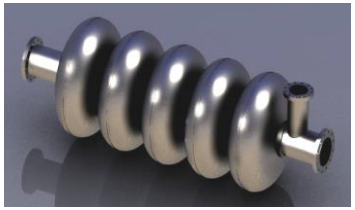
R&D of Key Accelerator Technologies

❑Super conducting cavities

Design specifications and vertical test results of SC cavities for C-ADS

	Spoke012	HWR010	HWR015	Spoke021	Spoke040	Ellip063	Ellip082	Unit
Frequency	325	162.5	162.5	325	325	650	650	MHz
β_0^*	0.14	0.10	0.15	0.24	0.46	0.63	0.82	-
Aperture	35	40	40	50	50	100	100	mm
L_{eff}	0.129	0.185	0.277	0.221	0.424	0.757	0.985	mm
E_{acc} Max	6.5	4.5	6.5	7.5	6.8	13.5	16.0	MV
E_{peak}	32.5	25	32	24/31	25/32	29/38	28/36	MV/m
B_{peak}	46	50	40	50/65	50/65	50/65	50/65	mT
Temp	2	4	4	2	2	2	2	K
P_{loss}	<10	<10	<15.5	<16.8	<6.5	<21	<39	W
E_{acc} Max @VT,4K	13	8.5	12.5	11	11.5	N/A	9	MV/m
Q_0 Max @VT, 4K	1.8	3	3	2	2	N/A	1.7	$\times 10^9$

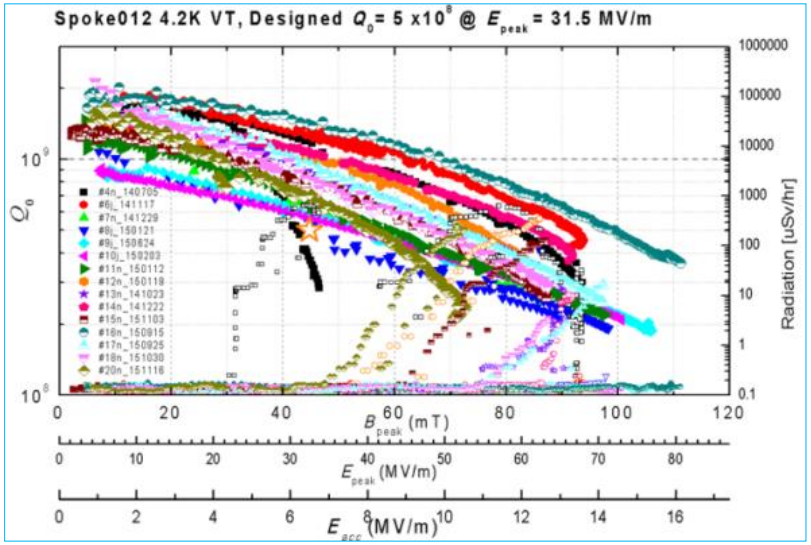


Vertical Test of SC Cavities at IHEP

- **14 Spoke012 for Injector I , 6 Spoke021 for 10-37 MeV.**

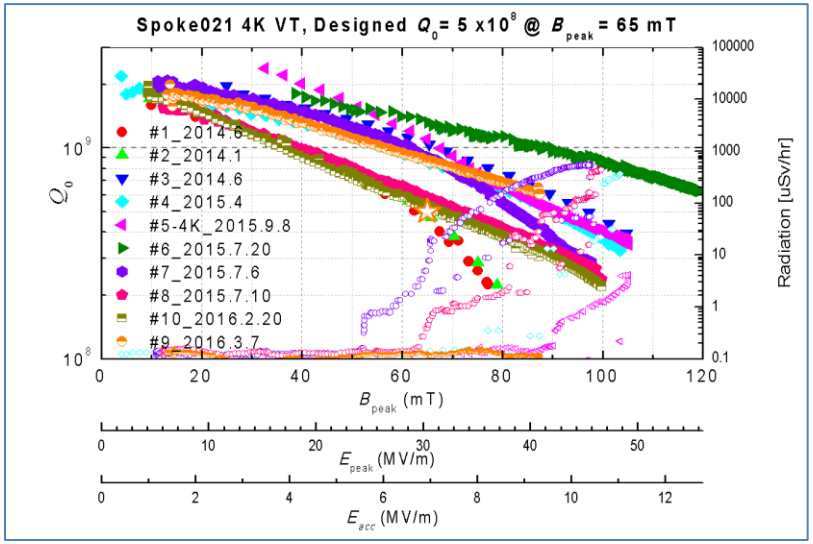
Spoke012	Design	VT
Vacc(MV)	0.84	1.68
Bpeak(mT)	44.9	89.8
Epeak(MV/m)	32.5	65
R/Q(Ω)	150	/
G （Ω）	60	/
Eacc(MV/m)	6.5	13(max)
P(W)(Rs=70nΩ)	5.5	/
βopt	0.14	/
Q0	8.6E8	1.8E9(max)



Target:

Q_0=5e8 @Eacc=6MV/m @4.2K

Spoke021	Design	VT
Vacc(MV)	2.08	3.05
Bpeak(mT)	70.5	103.4
Epeak(MV/m)	33.0	48.4
R/Q(Ω)	191	/
G （Ω）	71	/
Eacc(MV/m)	7.5	11(max)
P(W)(Rs=70nΩ)	22.6	/
βopt	0.24	/
Q0	1.0E9	2E9(max)



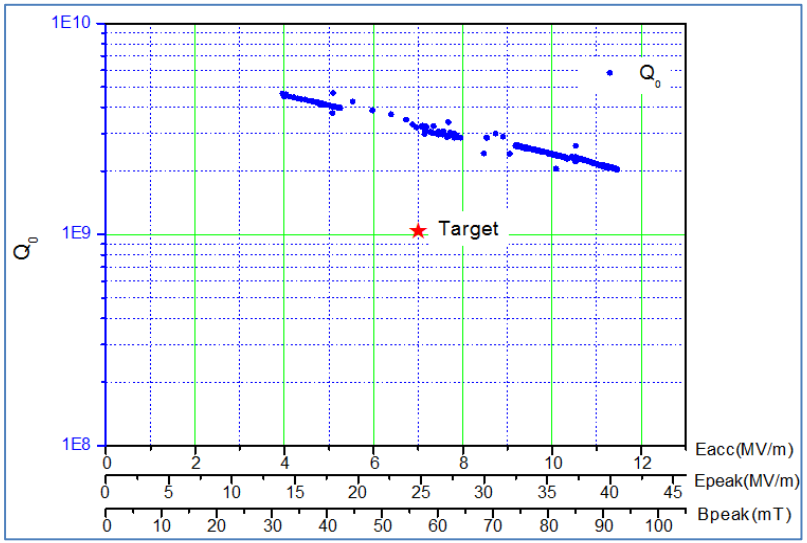
Target:

Q_0=5e8 @Eacc=6.5MV/m @4.2K

Vertical Test of SC Cavities at IHEP

❑ Spoke040 for 37-147 MeV, Ellip.082 for 393-1500 MeV.

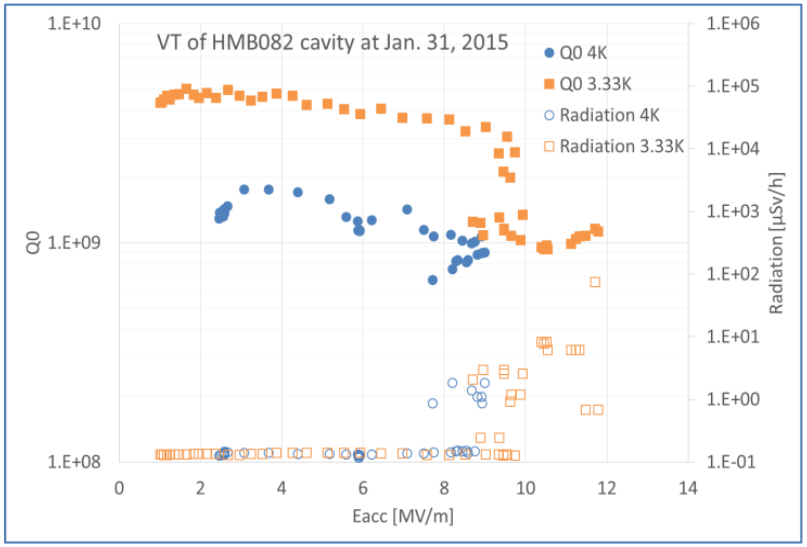
Spoke040	Design	VT
Vacc(MV)	2.88	4.35
Bpeak(mT)	62.3	94.3
Epeak(MV/m)	27.3	41.4
R/Q(Ω)	265	/
G （Ω）	104	/
Eacc(MV/m)	6.8	10.3
P(W)(Rs=70nΩ)	20.9	/
βopt	0.46	/
Q0	1.5E9	2.0E9



Target:

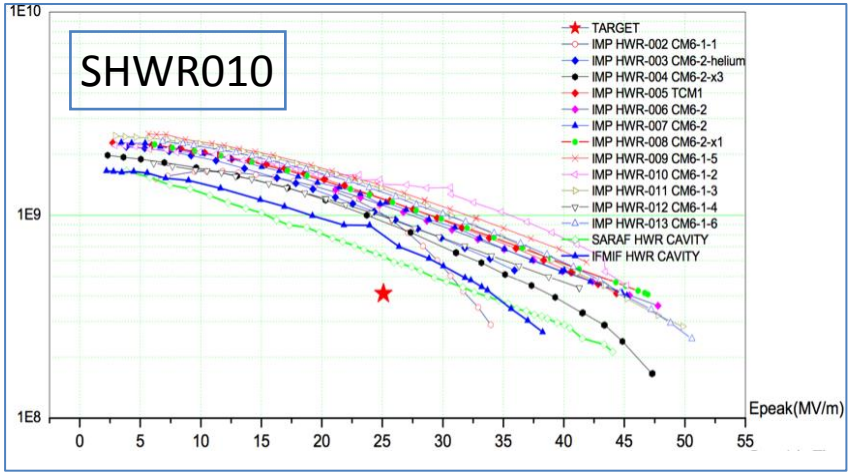
Q_0=1.5e9
@E_{acc}=6.8MV/m
@4.2K

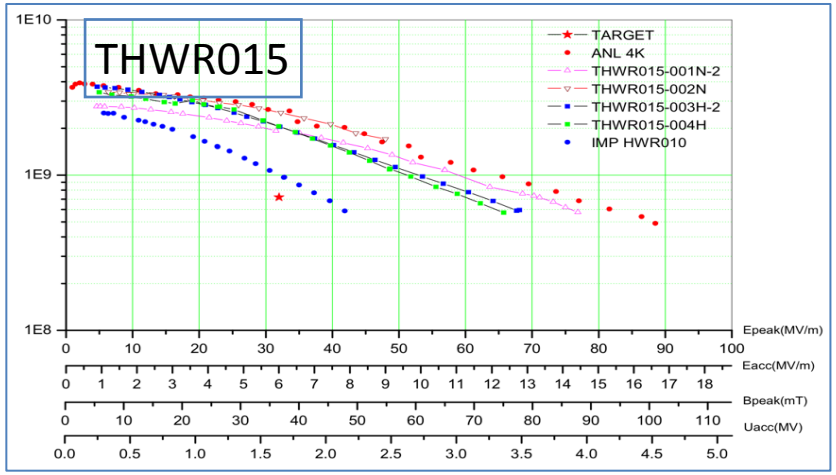
Ellip.082	Design（2K）	VT（4K）
Vacc(MV)	15.12	8.51
Bpeak(mT)	65.6	36.9
Epeak(MV/m)	33.6	18.9
R/Q(Ω)	515	/
G （Ω）	236	/
Eacc(MV/m)	16	9
P(W)(Rs=70nΩ)	*130.6*	/
βopt	0.82	/
Q0	3.4E9	1.7E9



Vertical Test of SC Cavities at IMP

❑ HWR010 & HWR015 for Injector-II





	THWR015	SHWR010
Vacc(MV)	2.25	0.78
Bpeak(mT)	50	50
Epeak(MV/m)	40	25
R/Q(Ω)	286	148
G （Ω）	52	28.5
Eacc(MV/m)	8.25	4.7
P(W)(Rs=70nΩ)	16	10
βopt	0.15	0.10
Q0	7.2E08	4.0E08

SHWR010

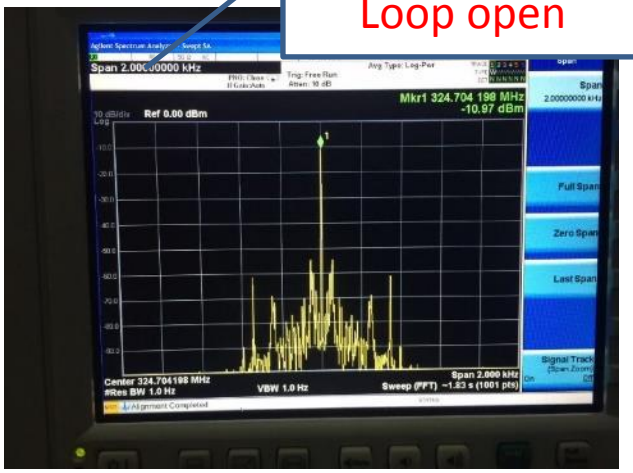
THWR015

Low Level RF systems

❑ mTCA.4 based LLRF system for Spoke Cavities

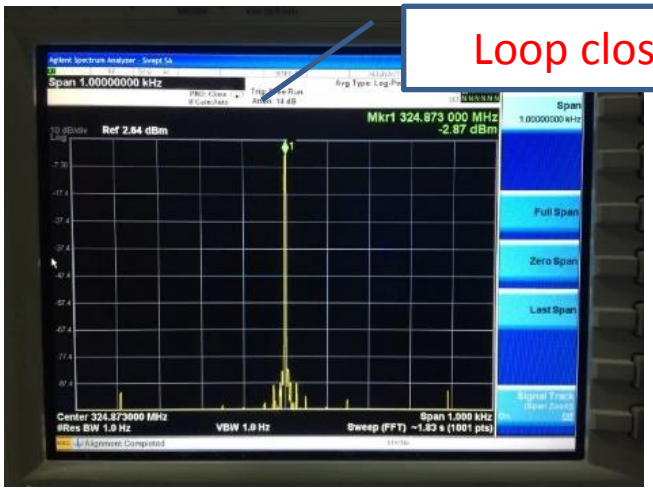
- Amplitude stability long-term with beam on : <0.1% (peak-to-peak);
- Phase stability long-term with beam on after optimization : < 0.3° (peak-to-peak); @325MHz ,~ 80dBc FSDR
- mTCA.4 LLRF system ;
- Pulsed and CW operation mode compatible ;
- Highly integrated control system ;
- fast and easy to recovery from fault ;
- high reliability and repeatability .

Loop open



Cavity Pickup Signal

Loop closed



RF Solid state Amplifier

❑ Several Chinese companies delivered RF SSA for C-ADS R&D

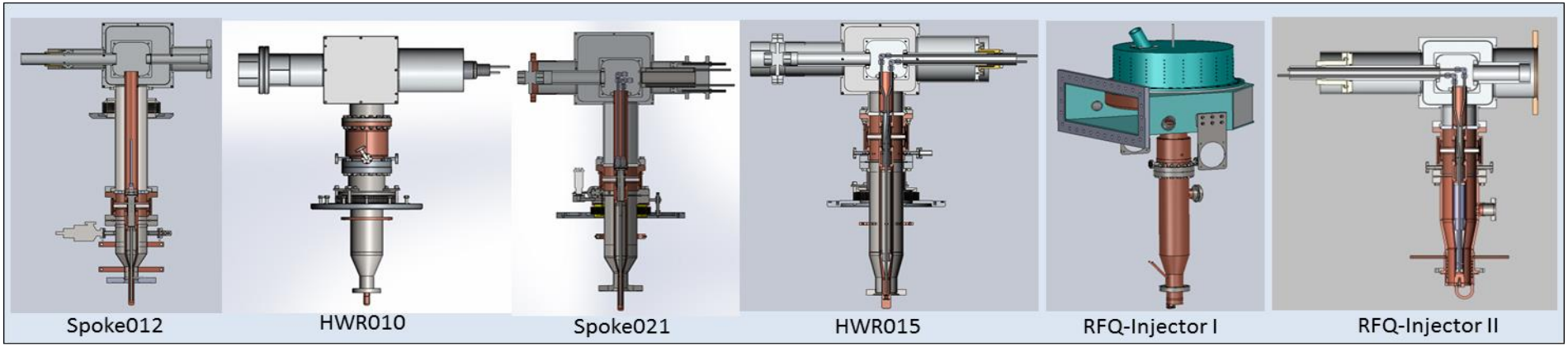
- ❑ Chengdu Weingarten Quartet Digital Radio and Television Equipment Co., Ltd (http://www.ktsf630.com/)
- ❑ Beijing BBEF Science & Technology Co., Ltd (http://www.bbef-tech.com/)
- ❑ East China Research Institute of Electronic Engineering (http://www.cetc38.com.cn/)
- ❑ ……

325MHz 10kW CW

325MHz 25kW CW

High Power Coupler

❑ Developed 6 types couplers for C-ADS



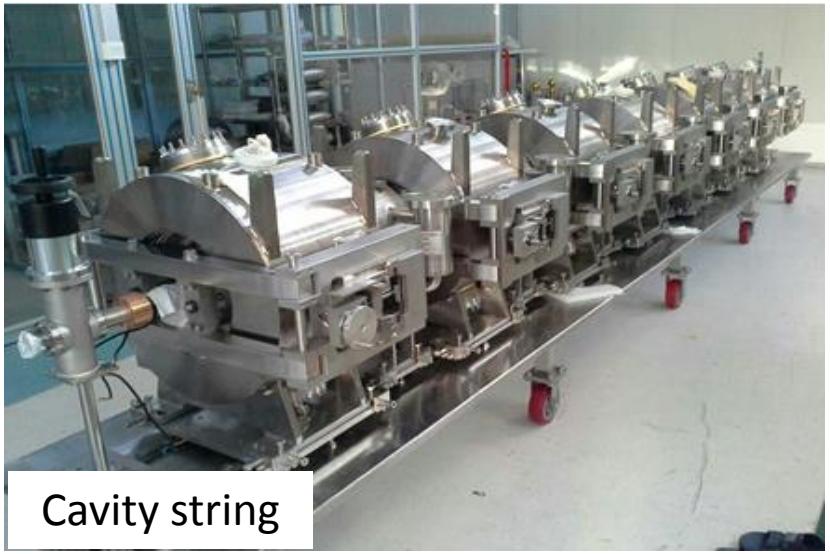
Parameters	Spoke -012	HWR -010	Spoke -021	HWR -015	RFQ (Injector-I)	RFQ (Injector-II)
Frequency (MHz)	325	162.5	325	162.5	325	162.5
RF power (kW)	10,CW	20,CW	25,CW	25,CW	100,CW	100,CW
Qext	7.0E5	7.0E5	8.0E5	6.7E5	/	/
Coaxial line impedance(Ω)	50	50	50	50	50	50
Coaxial OD (mm)	80	40	80	60	48	65
Dynamic losses to 2K (W)	0.5	/	/	/	/	/
Dynamic losses to 4K (W)	3.5	0.18	3.10	1.85	/	/
Dynamic losses to 80K (W)	11.6	14.2	8.1	10.6	/	/
Status	Operate	Operate	Fab.	Fab.	Operate	Operate

Spoke-012 CPL online operation

HWR-010 CPL online operation

Cryomodule for 325MHz Spoke Cavity

- **CM1, CM2 for Injector-I, CM4 for main Linac.**

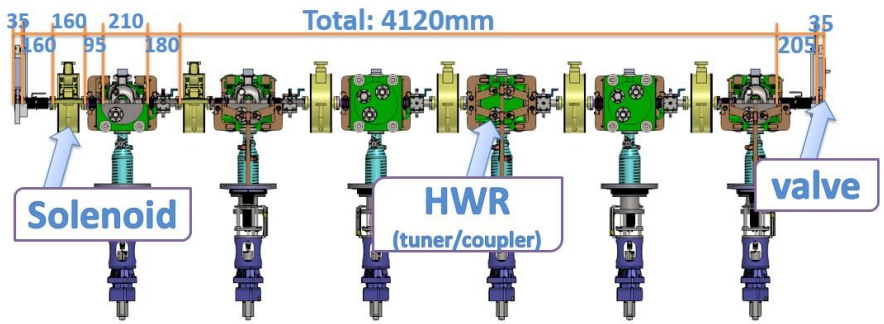

Cavity string

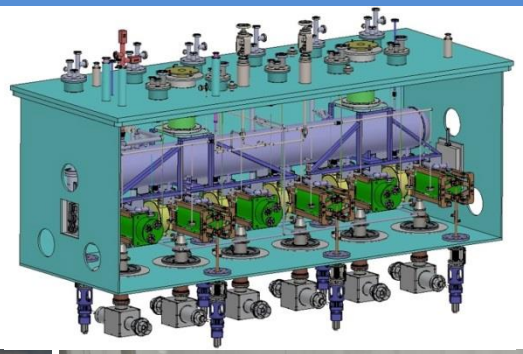

Vacuum vessel

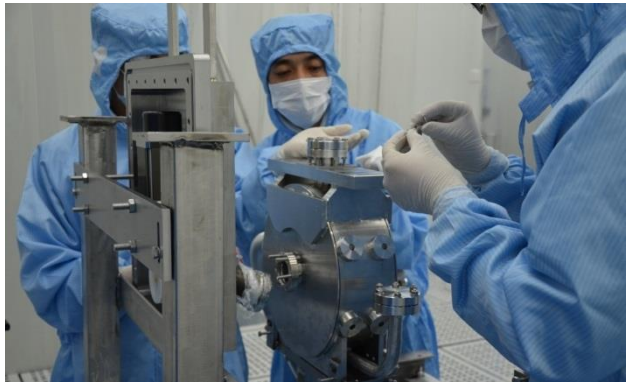

CM1 & CM2


CM4

Assembly of HWR Cryomodule





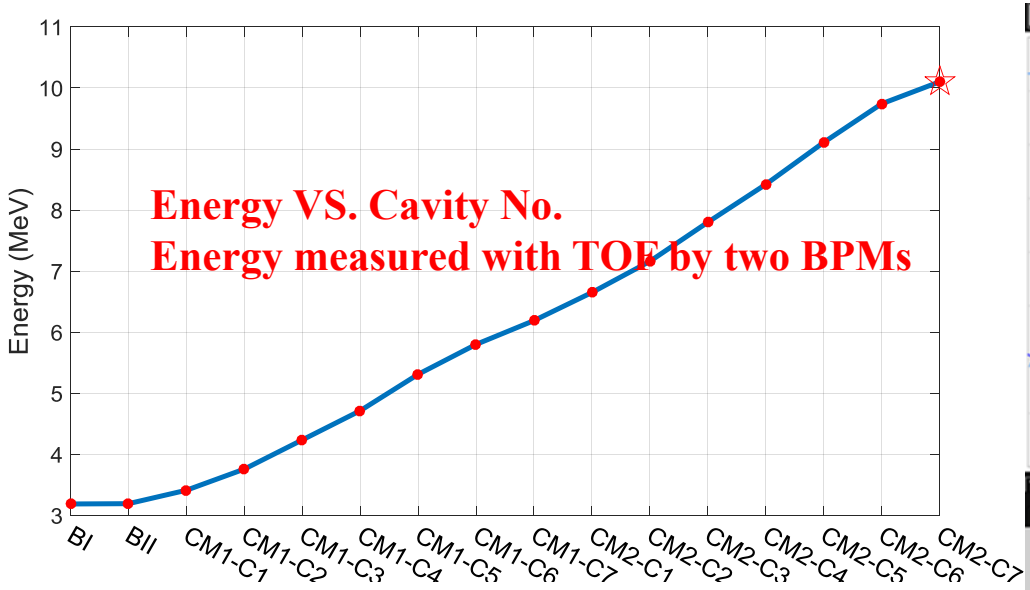


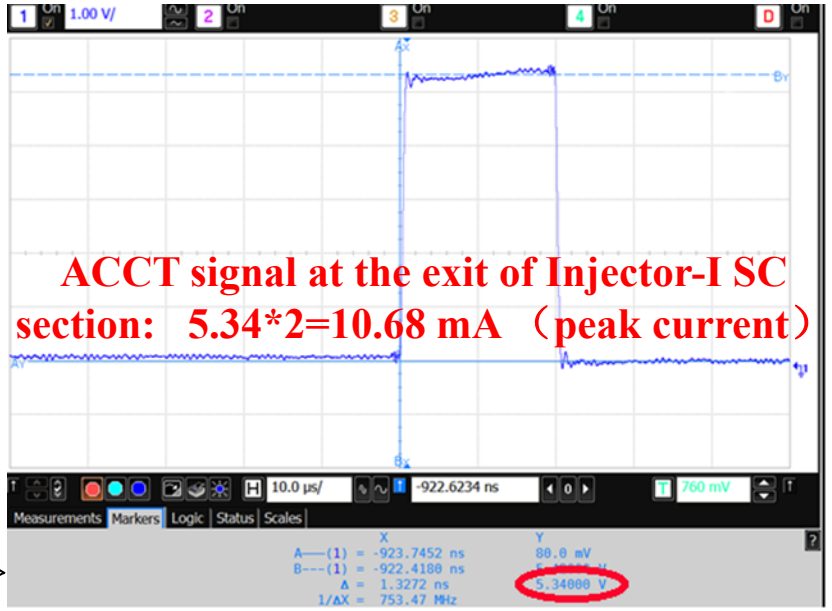
Commissioning of C-ADS Injector I

- Sep. 25th, 2014, The ECR Source+LEBT+RFQ has been commissioned with Max. 90% duty factor beam;
- Oct. 28th , 2015, The CM1 output reached 6MeV with pulsed beam @2K;
- June 15, 2016, The CM2 output reached 10.1MeV/10 mA with 20μs pulsed beam @2K;
- July 2, 2016, The CM2 output reached 10.1MeV/10.6 mA with 20μs pulsed beam @2K， transmission efficiency is 100%.

Commissioning of C-ADS Injector-I

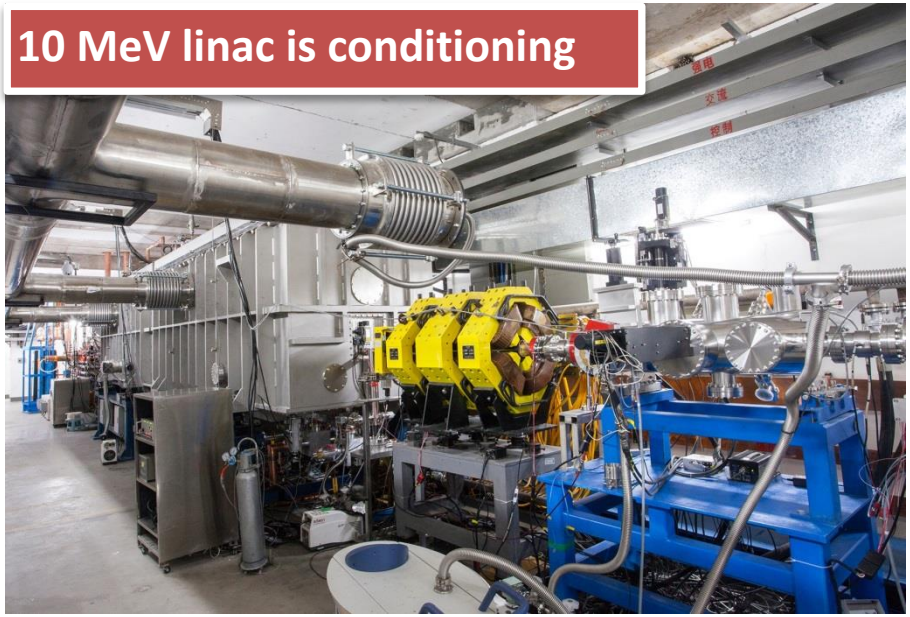
Cav. #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Eacc (MV/m)	3.92	5.44	6.52	5.97	6.96	5.14	5.36	5.68	4.92	6.25	6.14	6.67	6.08	3.59

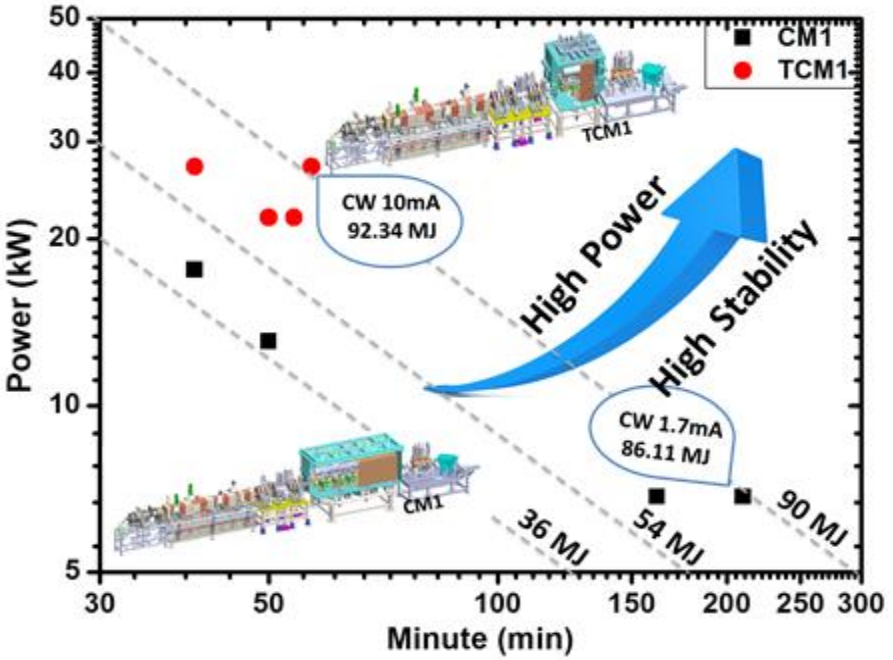




Commissioning of C-ADS Injector-II

❑ Commissioning state at 2014.06.06 - 2016.6.15



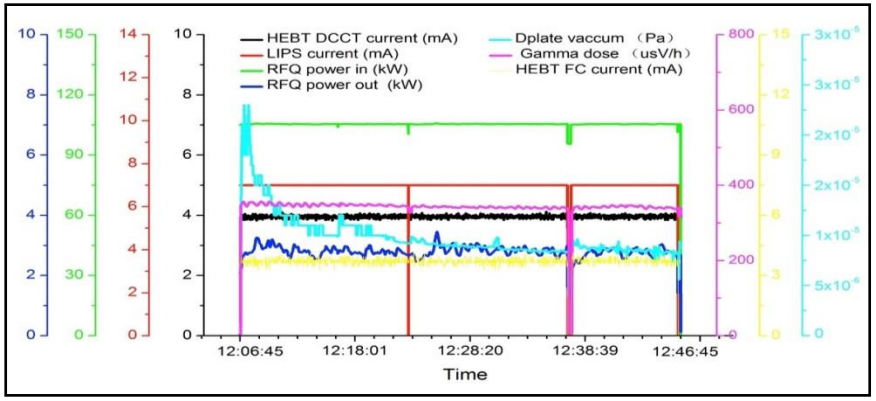


	Accelerator	Beam energy	Beam time	CW	CW @ 10 mA
June, 2015	RFQ	2.1 MeV	1390 h	59 h	10 h
Oct., 2014	TCM1 (1 HWR)	2.5 MeV	208 h	22.5 h	2.5 h
June, 2015	TCM6 (6 HWRs)	5 MeV	400 h	20 h	Imax = 4mA
June, 2016	CM1+CM2 (12 HWRs)	10MeV	Conditioning trouble with couplers		

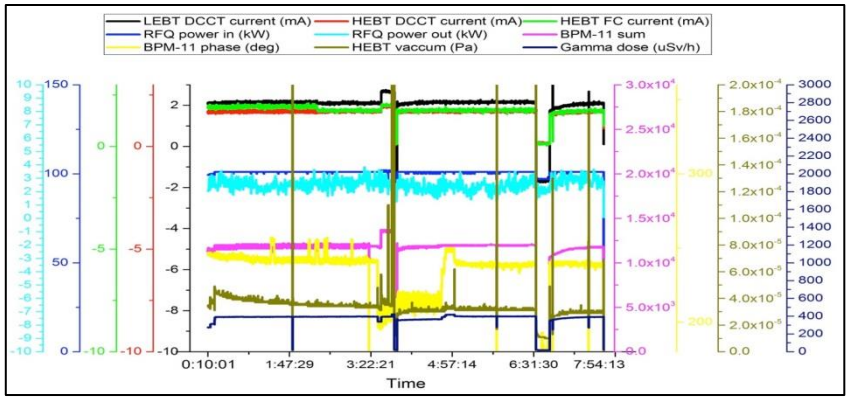
Commissioning of C-ADS Injector-II

❑ Commissioning of 5 MeV

- June 6th, 2015, 5.2 MeV, 10.2 mA, pulse, 100us@1Hz;
- June 24th, 2015, 5.3MeV/2.7mA/CW/14kW;
- Nov. 28, 2015, 4.6MeV/4mA/CW/18kW/40min; CW/3mA/50min;
- **Jan. 2, 2016, 4MeV/1.7mA/CW/6.8kW, 450min.**



History record of 4.6MeV/4mA/CW/40min



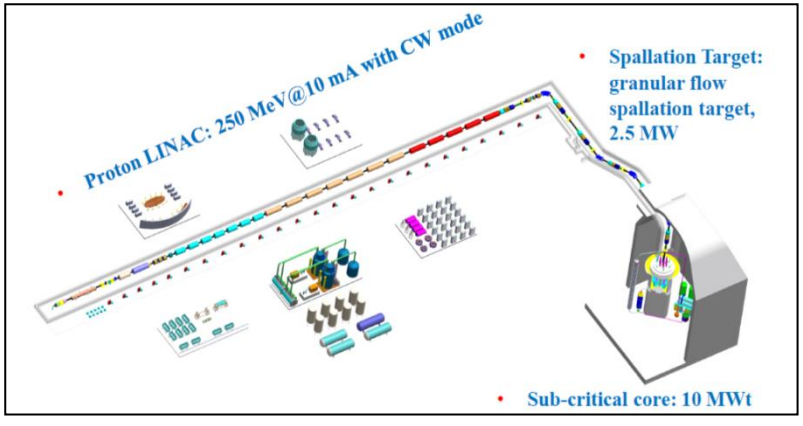
History record of 4MeV/1.7mA/CW/450min

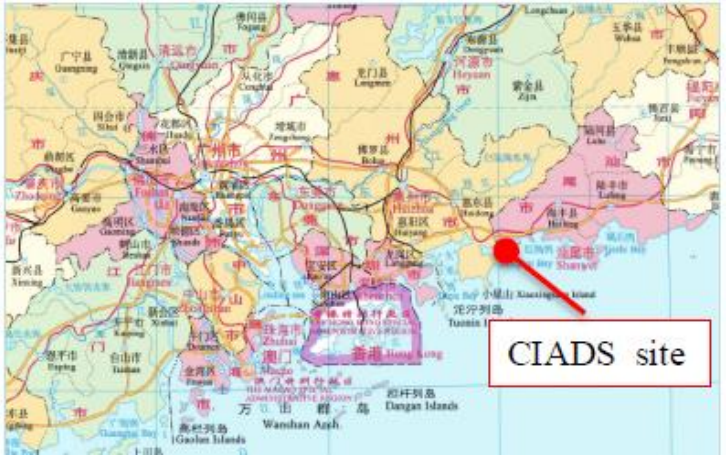
Challenges of C-ADS Injectors

- Operating RFQ in CW mode stably， especially for higher frequency RFQ (325MHz RFQ) ;
- Need to study the instability of SC cavities, especially low beta Spoke cavities (Spoke012 cavities);
- LLRF for heavy beam loading， LLRF controlling mechanism;
- Investigation of the machine reliability and stability， such as compensation of failed SC cavities;
- More research is needed to be done to further understanding the beam performance.

China Initiative Accelerator Driven System

- CIADS Approved by Chinese government in 2015
- Budget: 1.867B CNY, Year 2017-2022,
- Located in Huizhou, Guangdong Province





Conclusion

- A lot of key technologies successfully developed for C-ADS Superconducting linear accelerator during last 5 years;
- Two injectors are successfully integrated for 10MeV energy test;
- Two injectors under commissioning both pulsed beam and CW beam and get preliminary result;
- More research is needed to be done to further understanding the beam performance;
- Investigation of the machine reliability and stability will be done in the future.

Thanks for Your Attention!