Development and beam commissioning of 10-25 MeV superconducting CW proton linac for China ADS project

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On behalf of the project team

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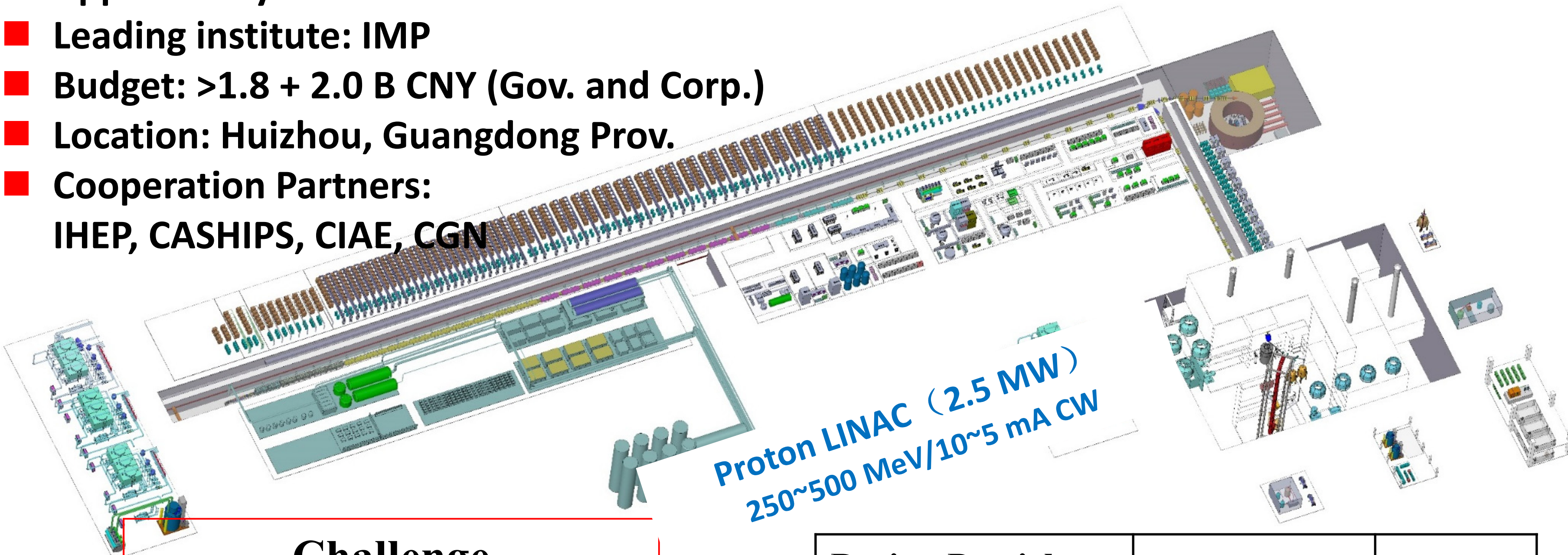
Outline

- Background and brief introduction
- CW RFQ and SRF cavity development
- Commissioning and lessons of CW 10-25 MeV linac
- Summary and conclusion

CiADS Project (2018-2024)

The first demonstration of ADS for nuclear waste transmutation

- Approved by central Gov. in Dec. 2015
- Leading institute: IMP
- Budget: >1.8 + 2.0 B CNY (Gov. and Corp.)
- Location: Huizhou, Guangdong Prov.
- Cooperation Partners:
  IHEP, CASHIPS, CIAE, CGN



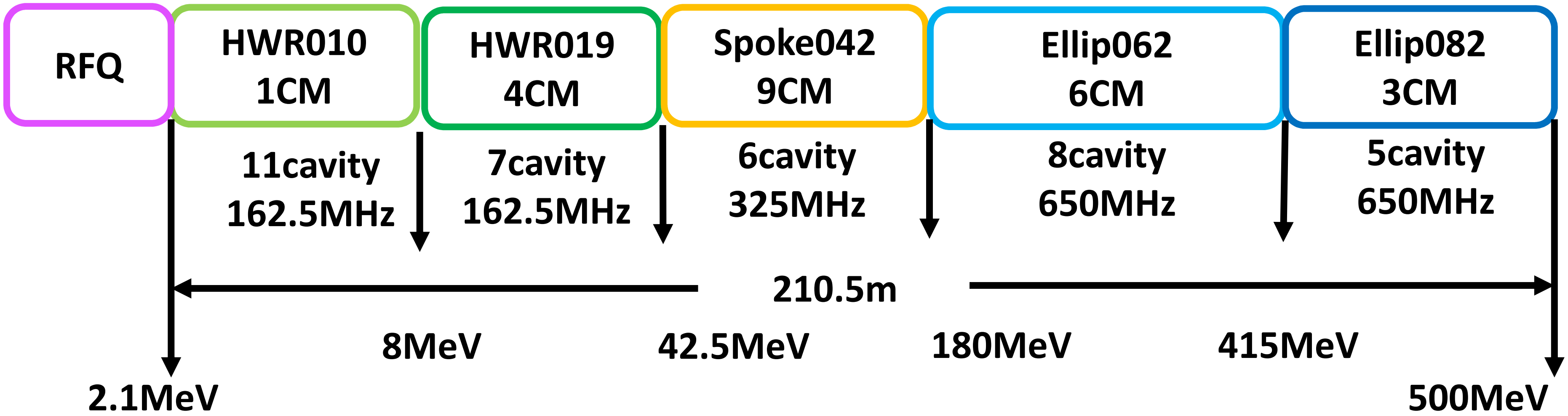
Challenge
-High intensity CW
-Long-term high reliability

Beam trips goal:

<10s,	-
10s～5min,	2500/y
>5min,	300/y

Design Particle	proton	
Energy	500 (250)	MeV
Beam current	5 (10)	mA
Beam power	2.5	MW
Operation mode	CW&Pluse	
Beam loss	＜0.1	W/m
Reactor power	7.5	MWt

General configurations of CiADS Linac

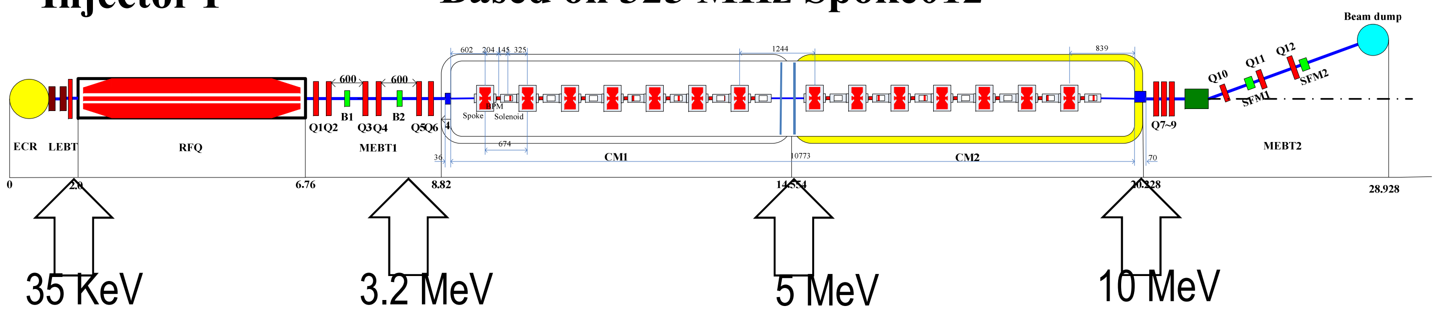


	Unit	HWR010	HWR019	SPOKE042	Ellip062	Ellip082
f	MHz	162.5	162.5	325	650	650
Cavity type		Squeezed	Taper	Double	5 cells	5 cells
V_{max}	MV	1.0	2.5	6.5	13	20
E_p	MV/m	28	32	35	35	35
Q_0	10^9	5.00	5.00	6.00	10.0	10.0
Cavity in CM	Per CM	11/11	4/7	2/6	1/8	0/5
CMs	m/Num.	6.9/1	6.6/4	7.8/9	10.8/6	7.6/3

10MeV injectors – Different technology R&D

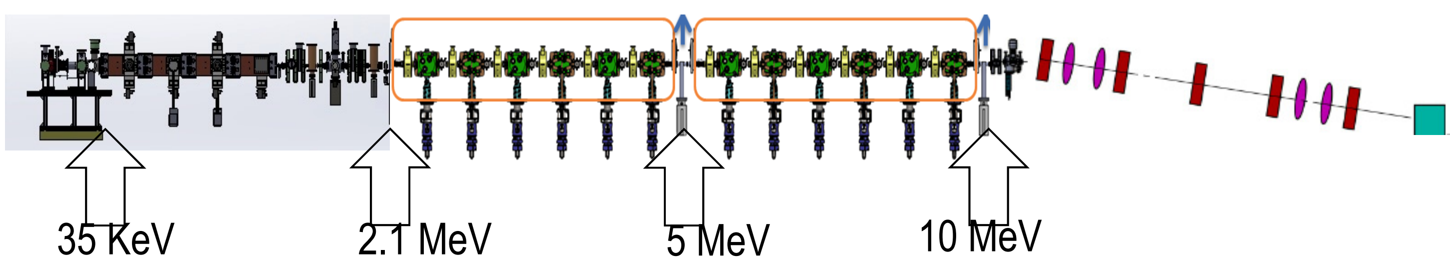
2011-2015

Injector I — **Based on 325 MHz Spoke012** — IHEP/Beijing



F.S. He, TH2A02

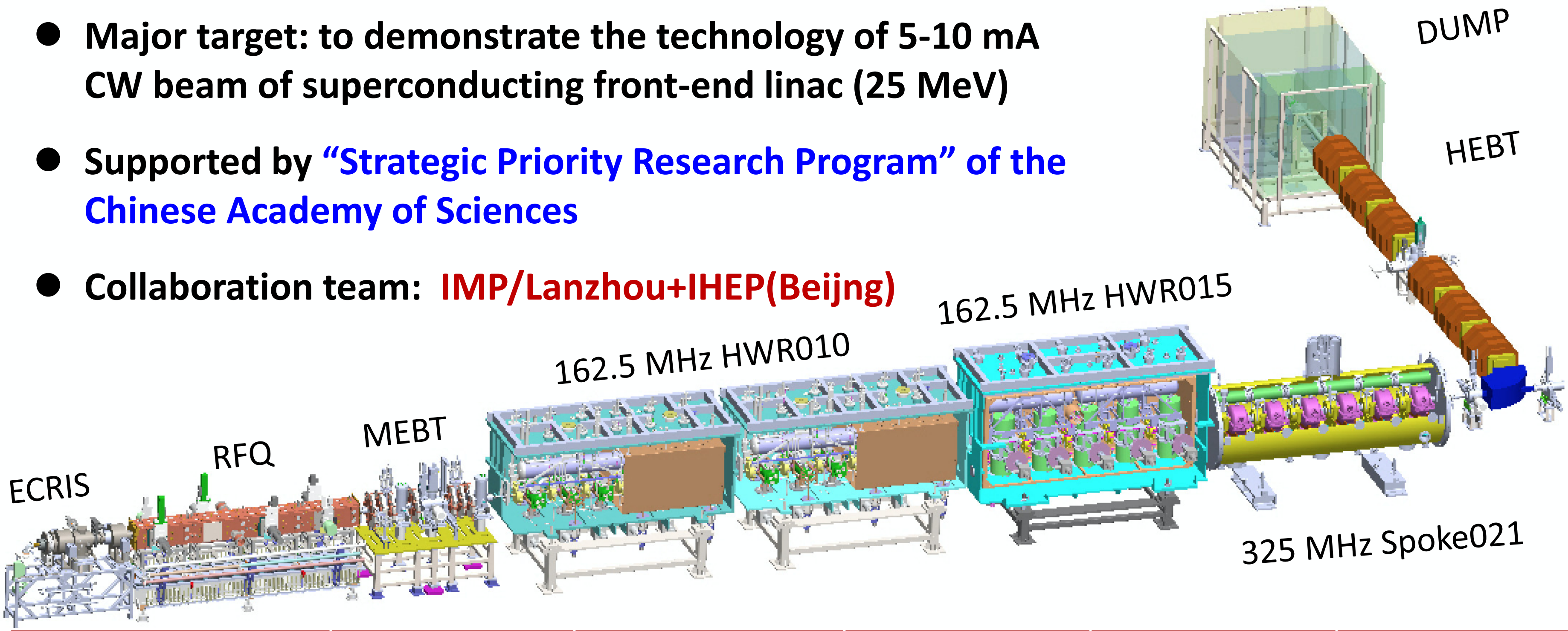
Injector II — **Based on 162.5MHz HWR010** — IMP/Lanzhou



25 MeV ADS Front-end Demo Linac

2015-2017: IMP+IHEP

- **Major target: to demonstrate the technology of 5-10 mA CW beam of superconducting front-end linac (25 MeV)**
- **Supported by “Strategic Priority Research Program” of the Chinese Academy of Sciences**
- **Collaboration team: IMP/Lanzhou+IHEP(Beijng)**



	RFQ/IMP	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
frequency	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
output energy	2.1 MeV	5 MeV	10 MeV	18.5 MeV	25 MeV
cavity type	4-vane	HWR010	HWR010	HWR015	Spoke021
cavity number	1	6	6	5	6

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- **CW RFQ and SRF cavity development**
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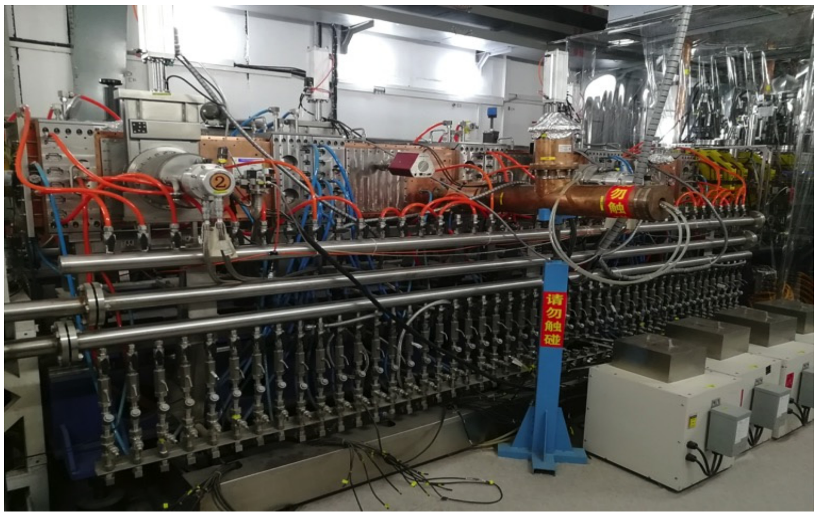
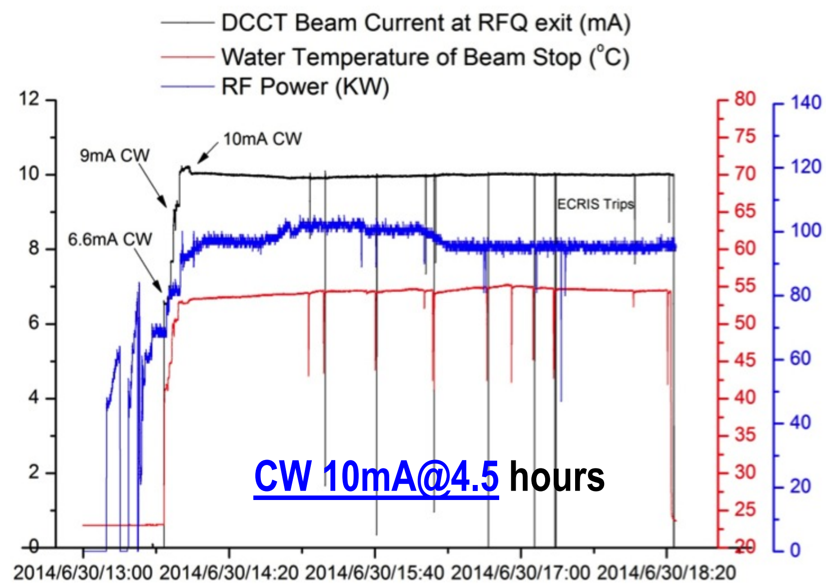
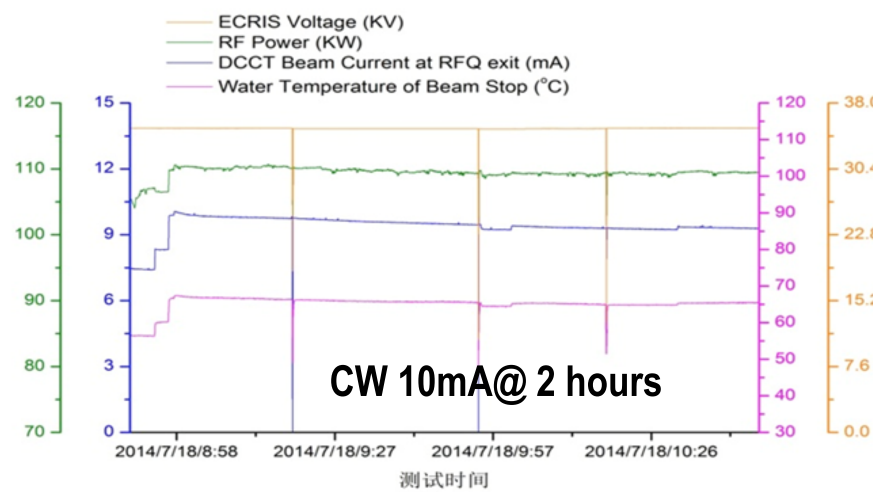
2.1 MeV/162.5 MHz RFQ for C-ADS Injector II







- **The RFQ was designed and built by collaboration with LBNL.**
- **CW proton beam 10 mA/2.1 MeV was reached in 2014.**
- **Total time of CW RF Operation > ~6000 hours (100-110 kW)**
- **Total time of 10 mA CW beam operation < 20 hours**
- **Long-term (weeks) operation with 10 mA CW beam need to be demonstrated.**

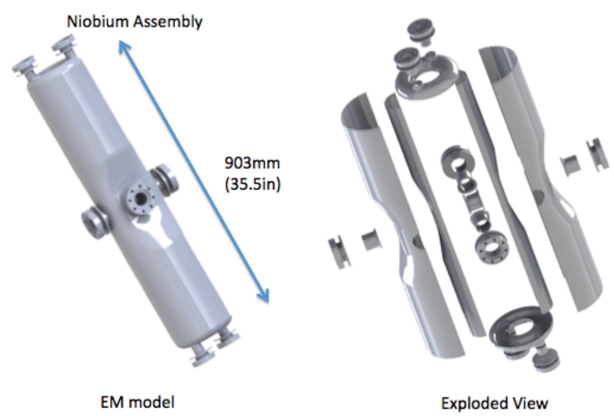
$D^+/H_2^+/He^{2+}$ 3.0 MeV/162.5 MHz RFQ

- A new RFQ dedicated to $D^+/H_2^+/He^{2+}$ 3.0 MeV/CW10-20 mA, 5 m long.
- H_2^+ 7.5 mA pulsed beam was accelerated to 3.09 MeV .
- The RFQ was moved into tunnel and connected with the MEBT and the cryomodules for He^{2+} beam test.
- The RFQ is under CW RF conditioning to reach 125 kW, and then will start He^{2+} CW beam commissioning.

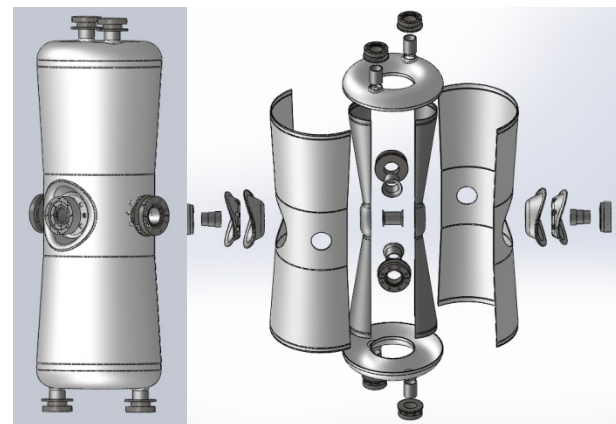
C.X. Li, THPO053

SRF Cavities development for CIADS at IMP

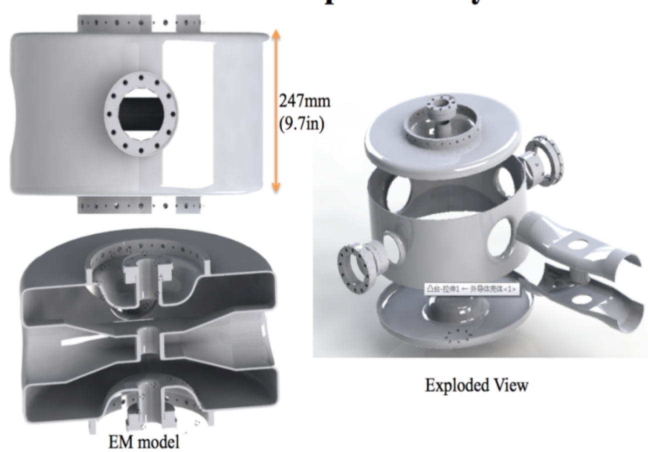
162.5 MHz Half-wave Cavity



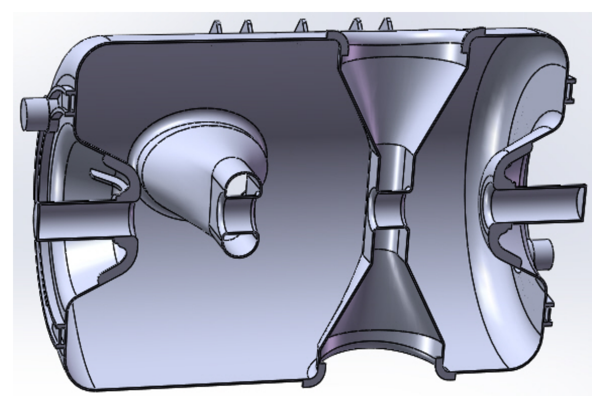
162.5 MHz Taper HWR015



325 MHz Spoke cavity



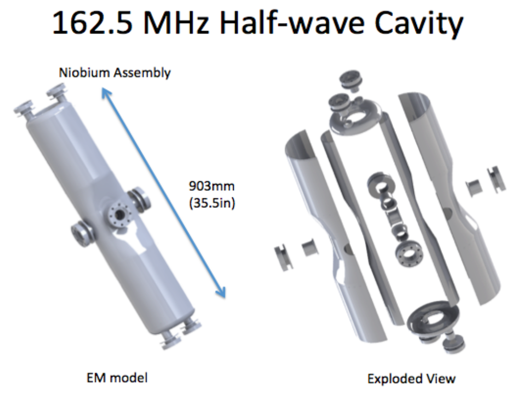
325 MHz Double Spoke052

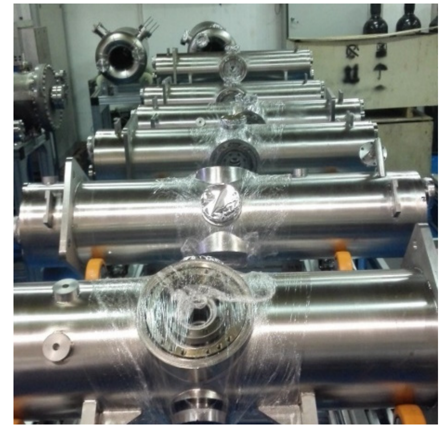


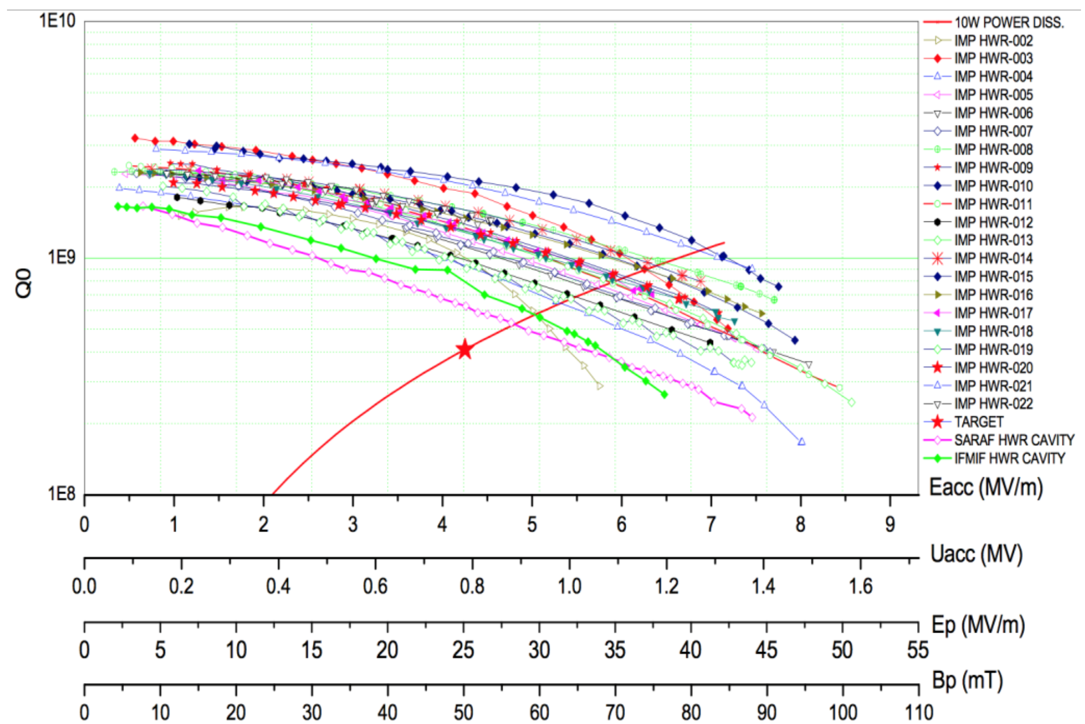
162.5 MHz HWR010 cavity

	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

21 in total, 18 online





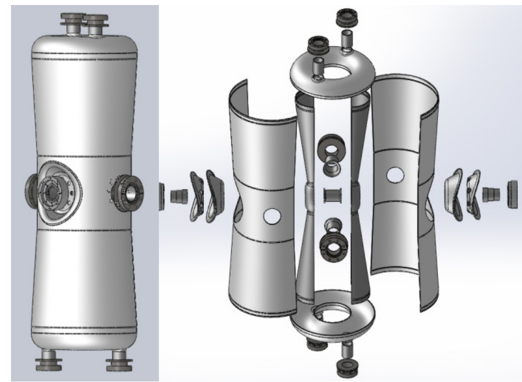


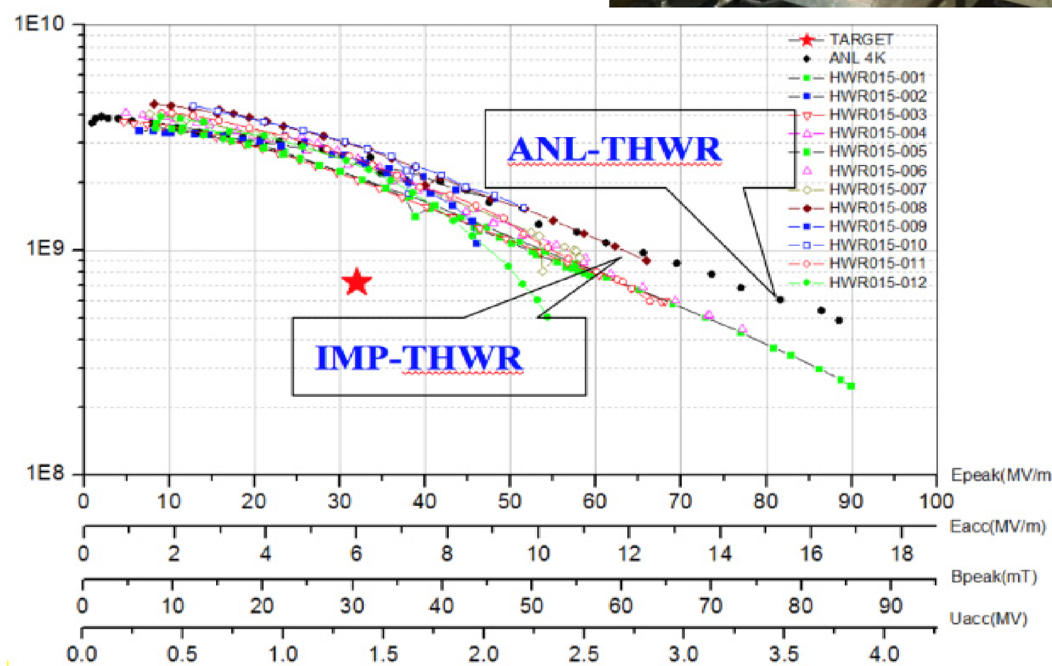
162.5 MHz Taper HWR015 cavity

	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

12 in total, 5 online

162.5 MHz Taper HWR015

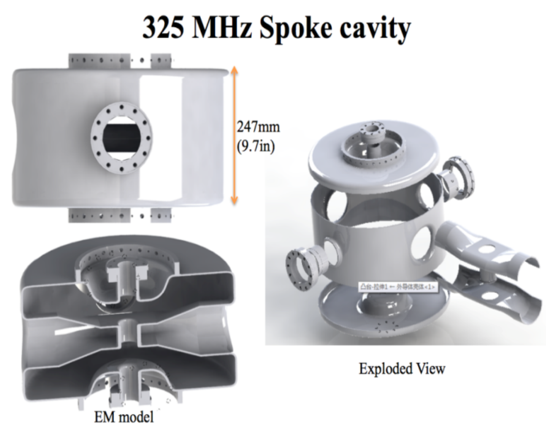


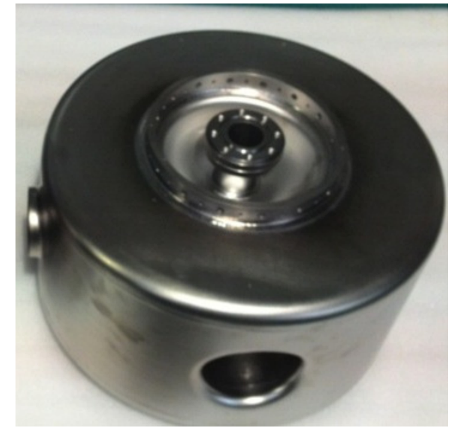


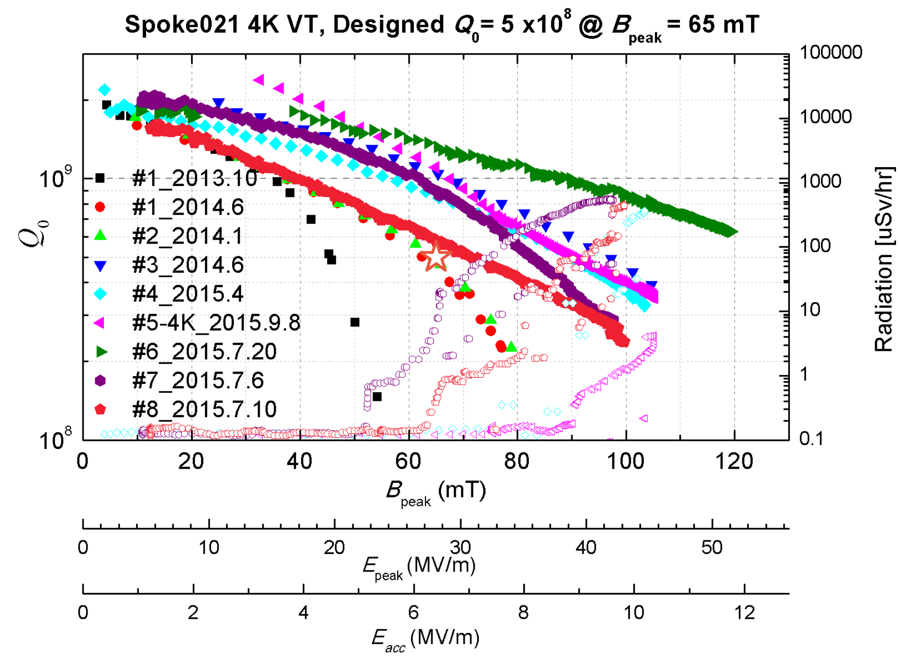
325 MHz Spoke021 cavity (IHEP)

	Spoke021
f (MHz)	325
βopt	0.21
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

12 in total, 6 online (IHEP)







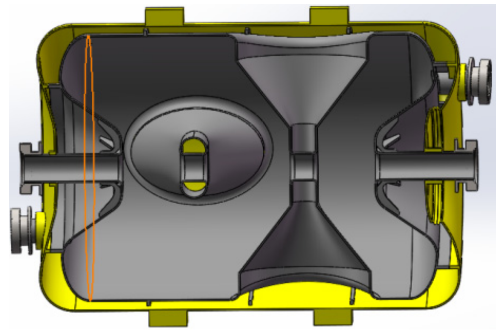
F.S. He, TH2A02

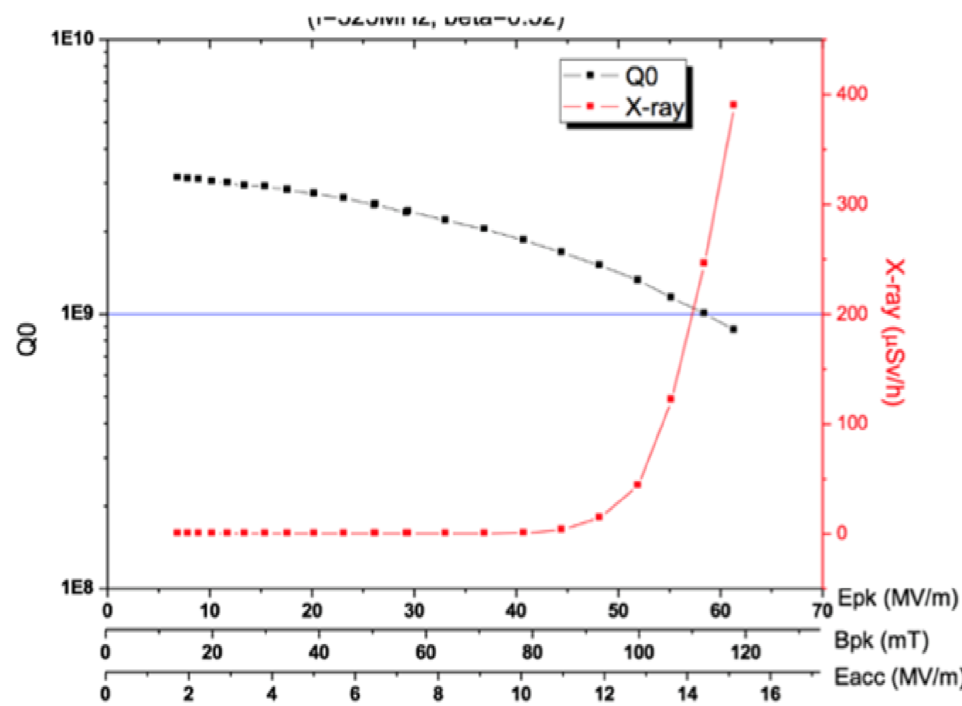
325 MHz Double-Spoke052 cavity

	D-Spoke052
f (MHz)	325
βopt	0.52
Vmax (MV)	6.48
Epeak (MV/m)	35
Bpeak (mT)	70
Eacc(MV/m)	9
Epeak/Eacc	3.98
Bpeak/Eacc (mT/(MV/m))	7.64
G = Rs×Q0 (Ω)	114
R / Q0	499

2 prototypes

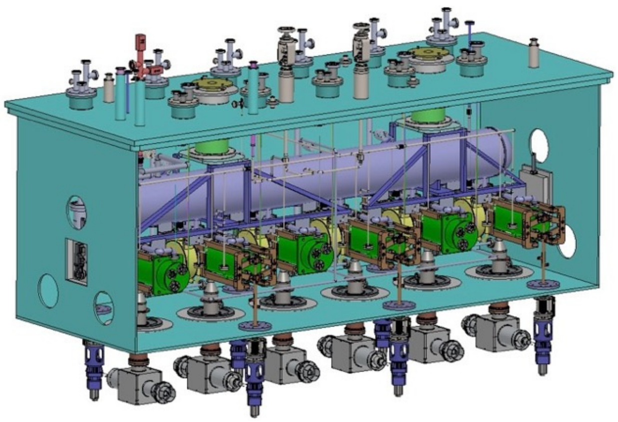
325 MHz Double Spoke052



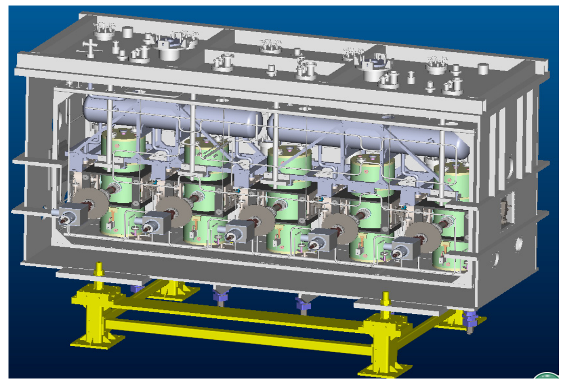


Cryomodules for HWR and Spoke cavities

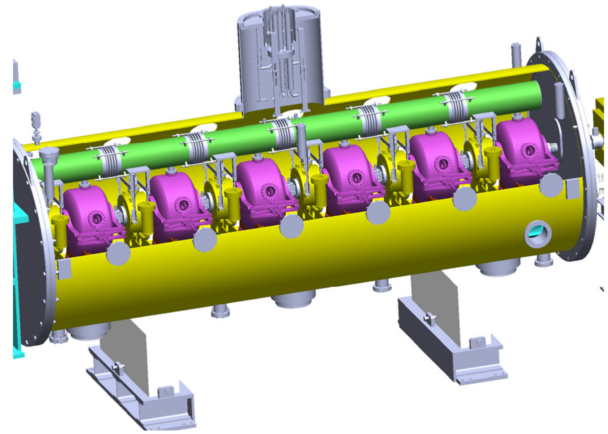
3 CMs HWR010

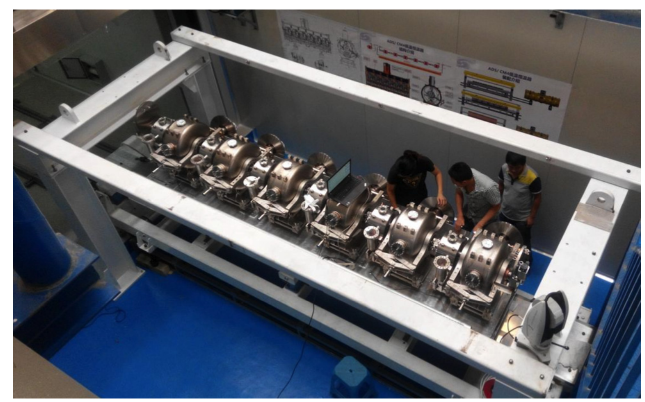


2 CMs HWR015



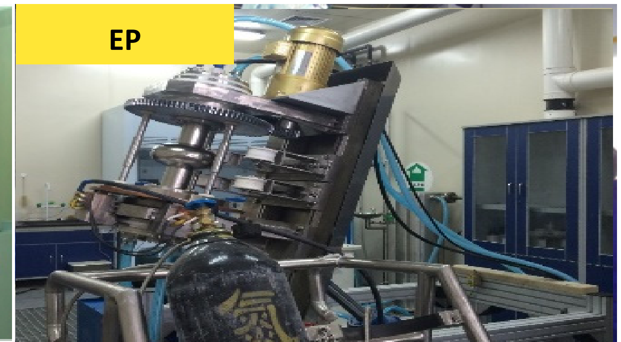
1 CM SPOKE021 (IHEP)

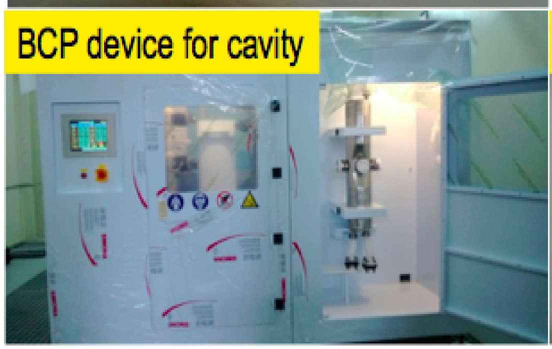


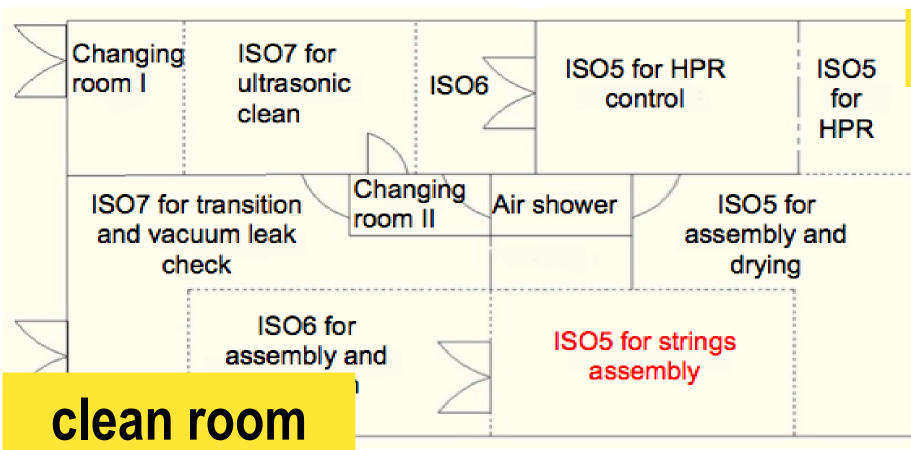


6 CMs have been constructed, and 5 of them operated with CW proton beam.

SRF Infrastructures at IMP







Cryogenic plant of 850 W at 4.2 K at IMP





- 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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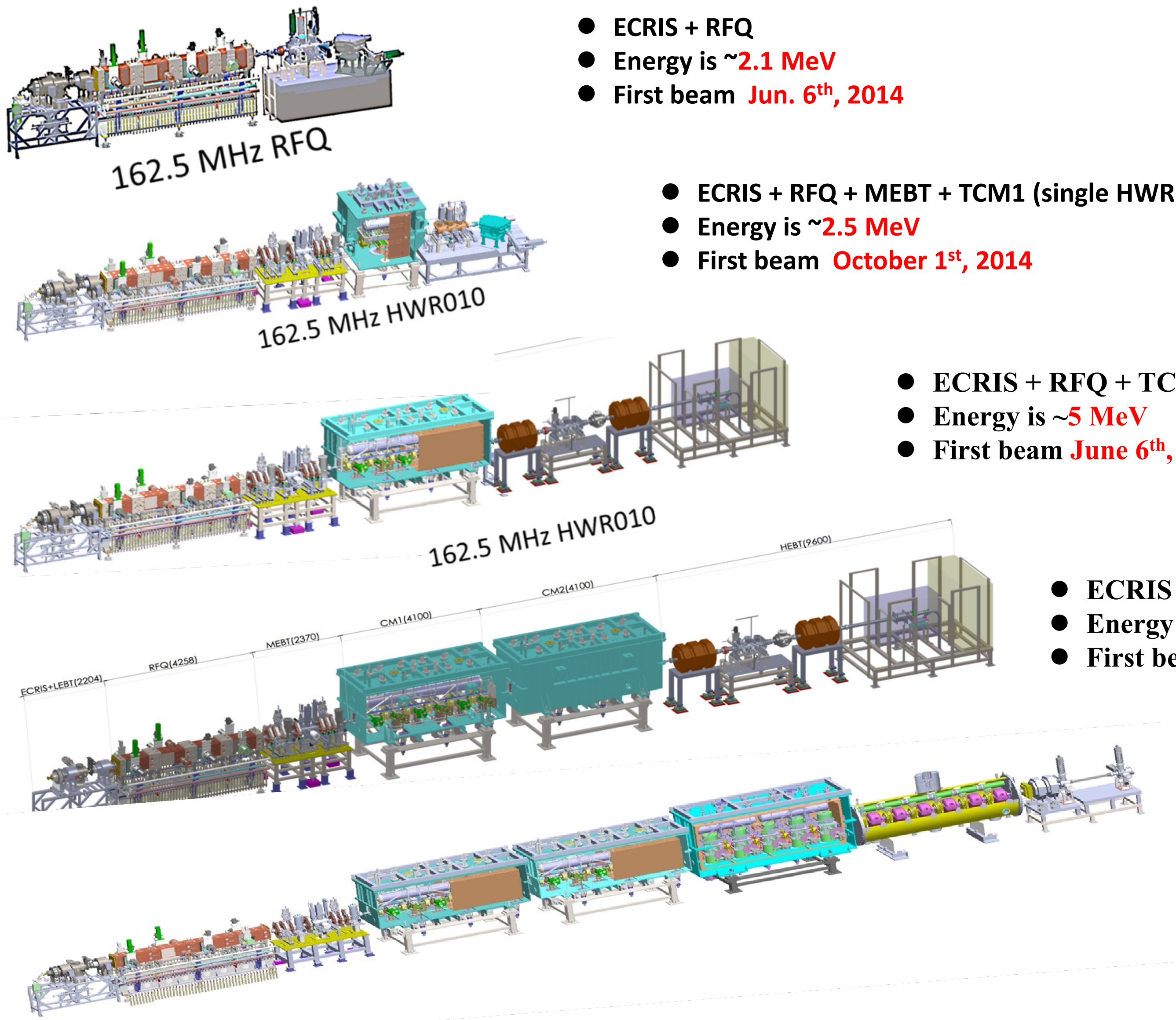
Beam Commissioning since 2014



1

- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014

2

- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~2.5 MeV
- First beam October 1st, 2014

3

- ECRIS + RFQ + TCM6
- Energy is ~5 MeV
- First beam June 6th, 2015

4

- ECRIS + RFQ + CM1 + CM2
- Energy is ~10 MeV
- First beam September 15th, 2016

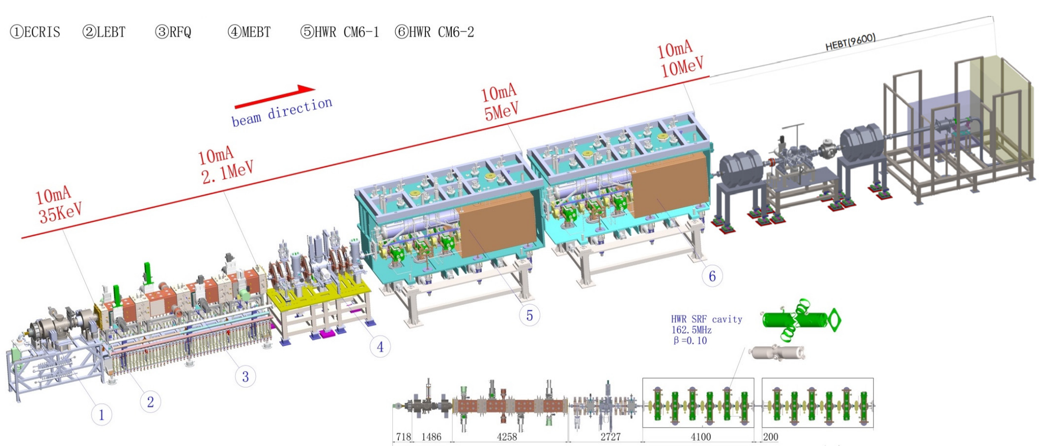
5

- ECRIS + RFQ + CM1 + CM2 + CM3 + CM4
- Energy is ~25 MeV
- First beam May 28th, 2017

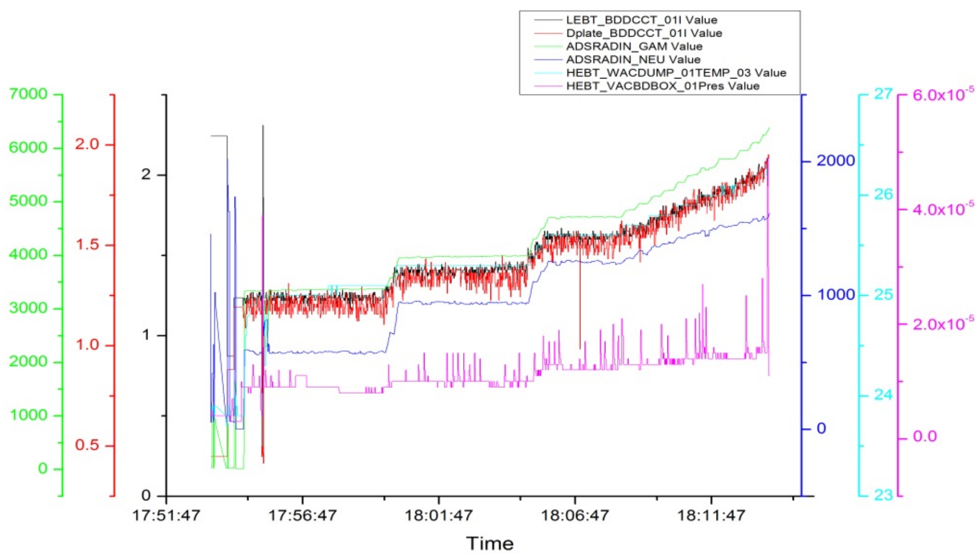
Commissioning procedures of CW proton linac

- **Hardware calibration – To verify the parameters of the key hardwares**
  - RFQ Voltage was calibrated with beam energy spread; BPM offset calibration, cavity phase setting, phase scanning …
- **Beam distribution reconstruction - To match the beam between different section**
  - Lattice initial setting, pulse beam commissioning; Beam emittance and twiss parameters measurements; Trace back to simulate and get new lattice; Initial beam parameters rebuilt and Lattice re-setting; Match tuning for high power,….
- **Beam tuning with CW high power – To ramp the beam power for the whole linac**
  - Always start from pulse beam commissioning, increase pulse-length little bit, and switch to CW with lower intensity.
  - Double-check MPS, ramping mode, beam loss detection system.

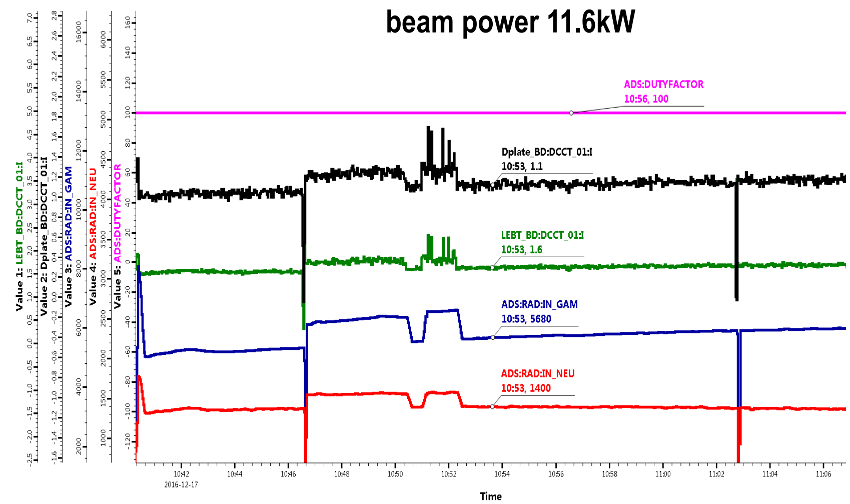
CW proton beam commissioning of 10 MeV



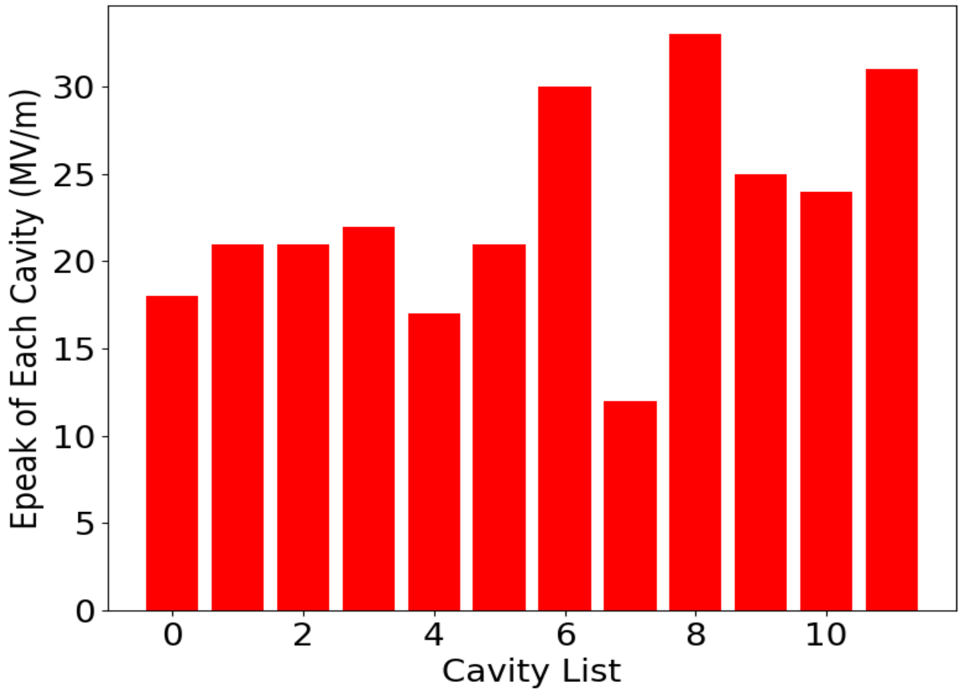
Nov. 27th-28th, 2016, 20 minutes CW beam operation at 1.2 - 2.0 mA

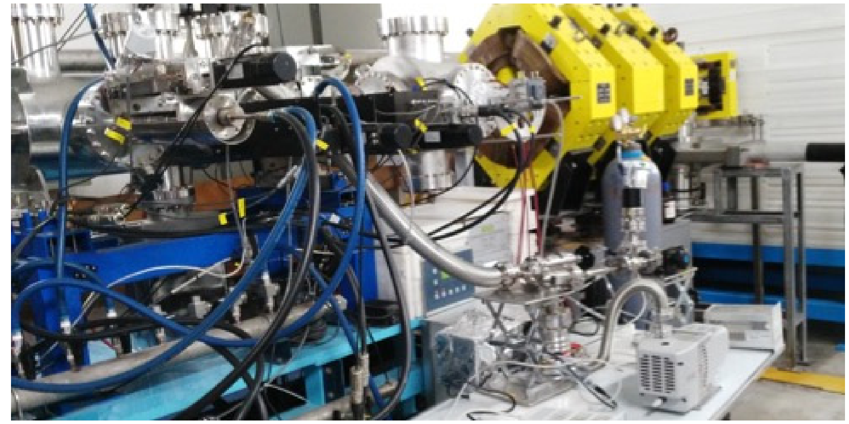


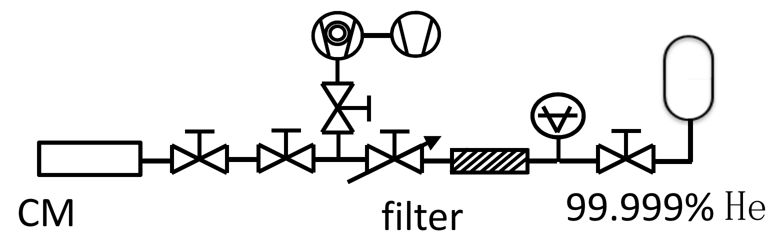
CM1+CM2:Dec.17th,2016;1.15 mA,10.06MeV,CW,~21min
beam power 11.6kW



10 MeV cavity performance and Helium processing





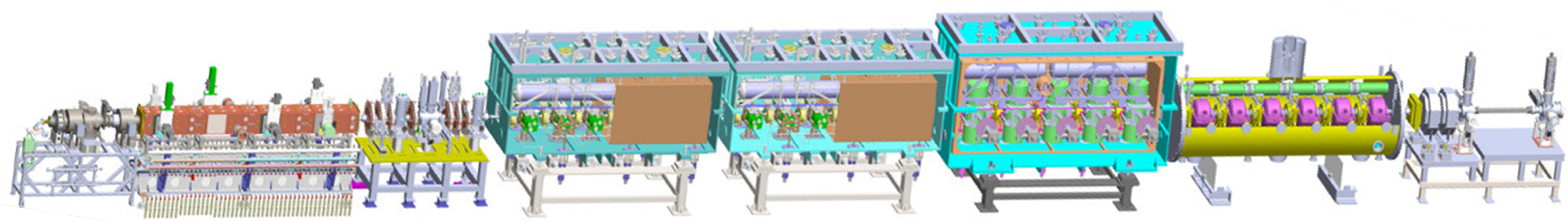


		CM1-1	CM1-2	CM1-3	CM1-4	CM1-5	CM1-6	avg
before	Ep(MV/m)	13.6	12.1	16.2	15.4	11.0	12.1	13.4
after	Ep(MV/m)	**19**	**20.7**	**22.2**	**23.6**	**18.3**	**21.2**	**20.8**
		CM2-1	CM2-2	CM2-3	CM2-4	CM2-5	CM2-6	avg
before	Ep(MV/m)	15.9	15.8	21.3	15.6	18.3	18.3	17.5
after	Ep(MV/m)	**18.8**	**22.7**	**32.2**	**24.9**	**27.9**	**36.1**	**27.1**

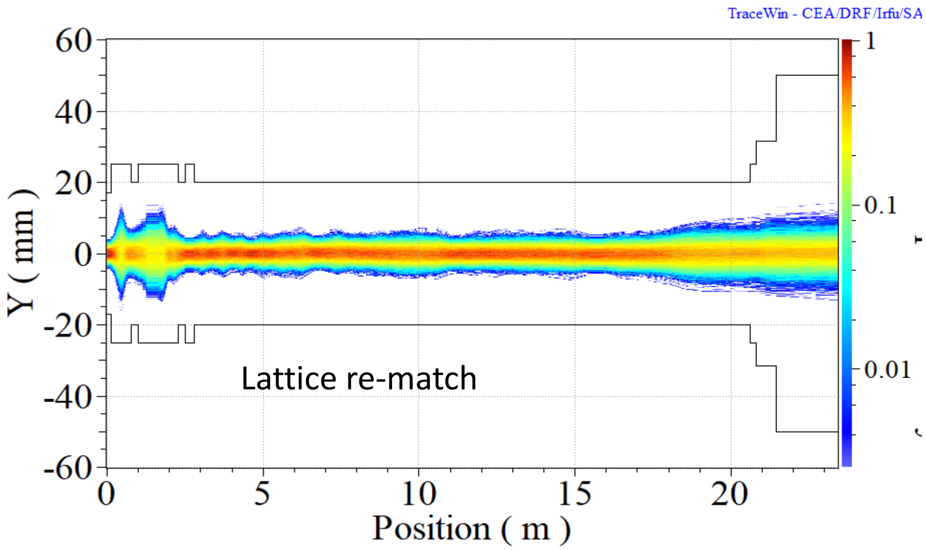
25 MeV CW proton superconducting linac

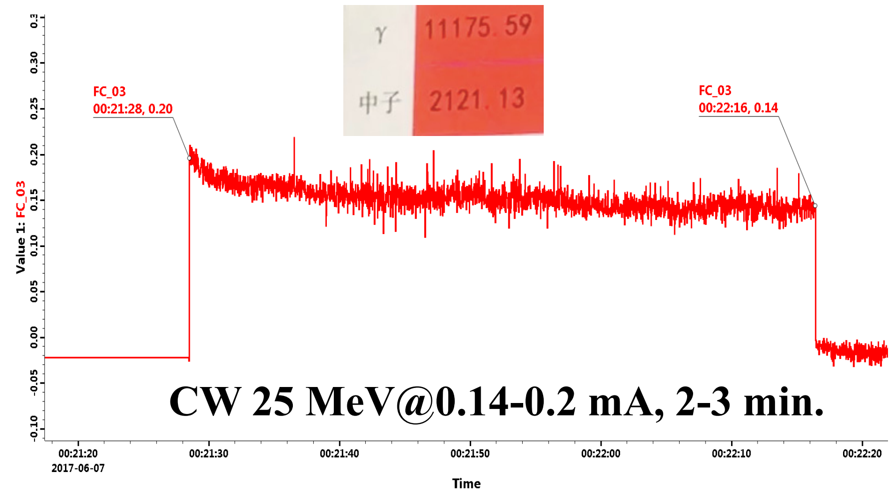
- CM1, CM2 were refurbished in Feb 2017.
- Installation of CM3 and CM4 were completed on May 9th 2017.
- First beam was achieved on May 28th 2017
- The energy was up to 26.2 MeV on June 5th ;
- CW beam with energy 25MeV achieved on June 6th.

	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
Frequency	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
Energy	6 MeV	11 MeV	18.6 MeV	26.2 MeV
Type	HWR010	HWR010	HWR015	Spoke021
Number	6	6	5	6

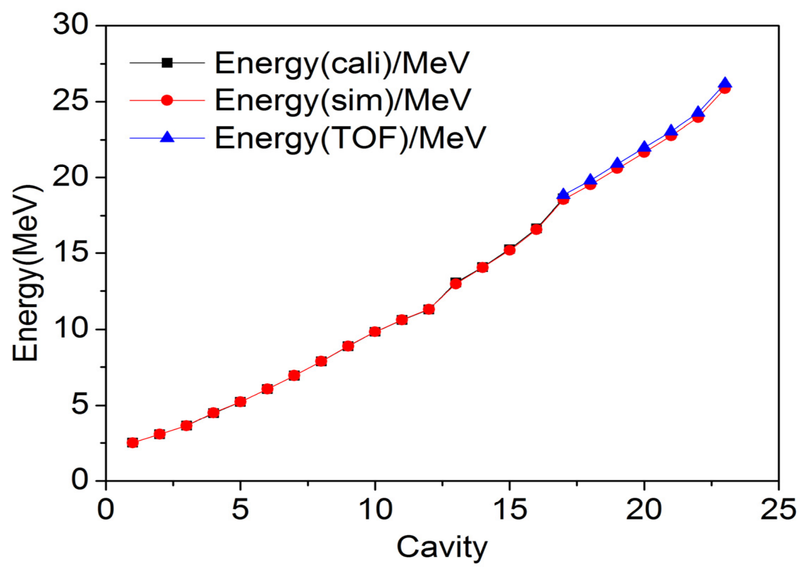


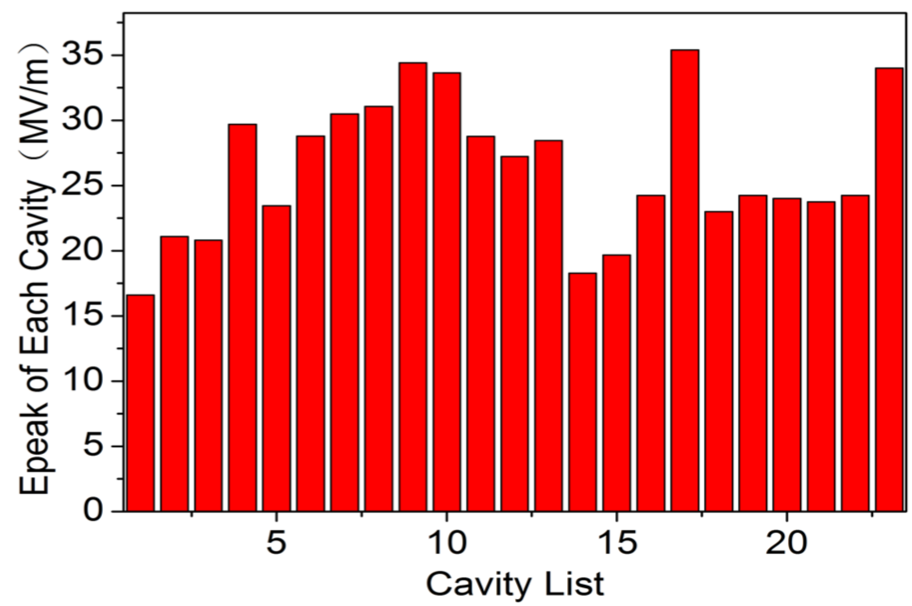
CW Beam Commissioning of 25 MeV



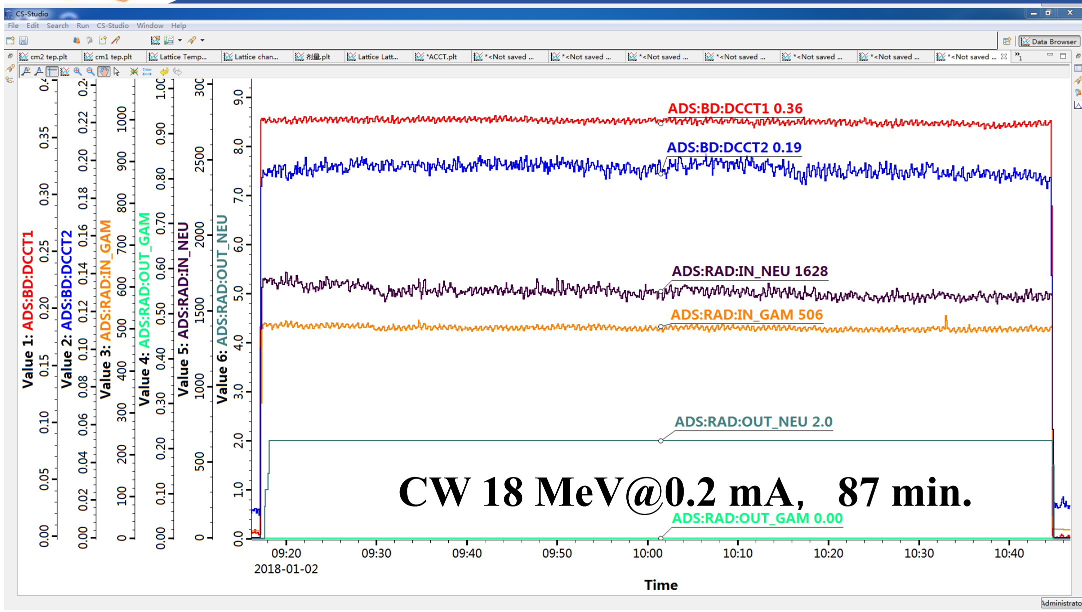


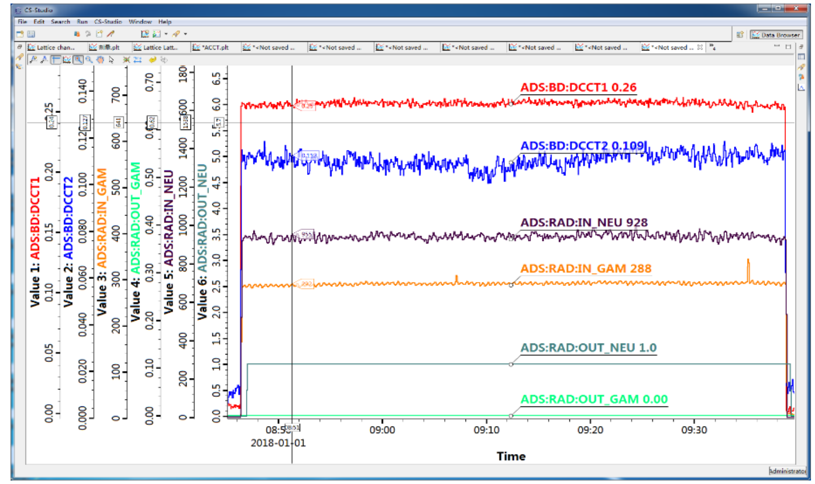
CW 25 MeV@0.14-0.2 mA, 2-3 min.



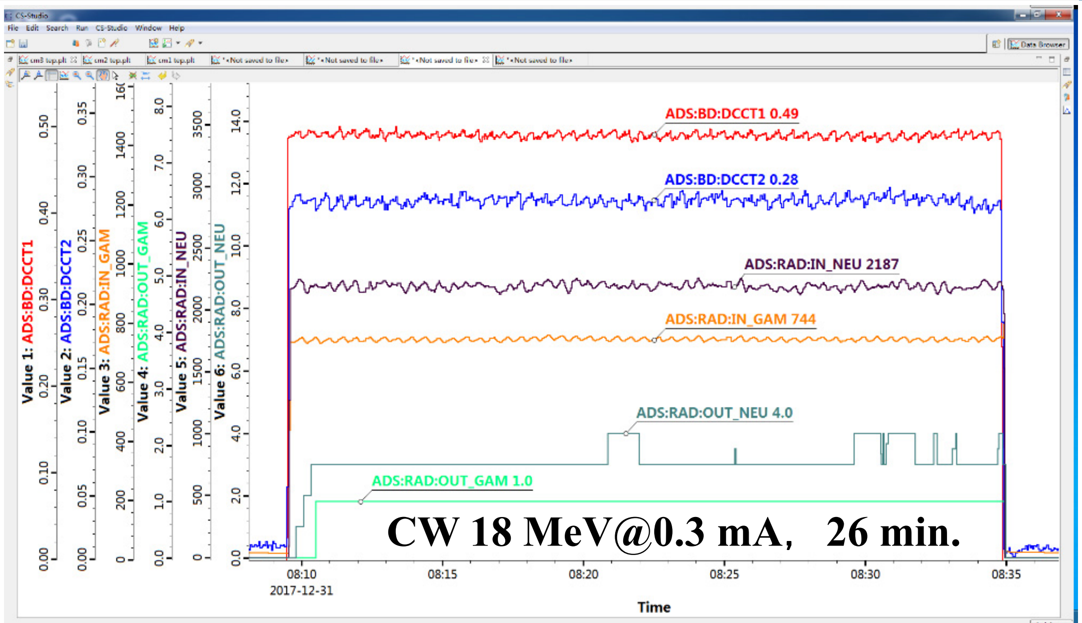


CW Beam Commissioning of 18 MeV



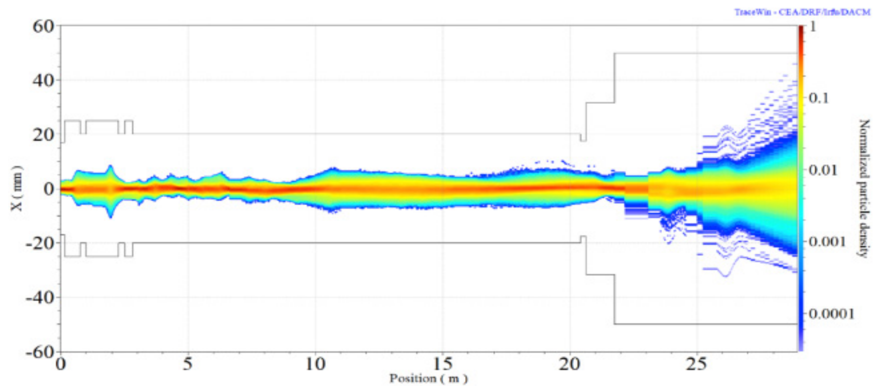


CW 18 MeV@0.1 mA,   52 min.

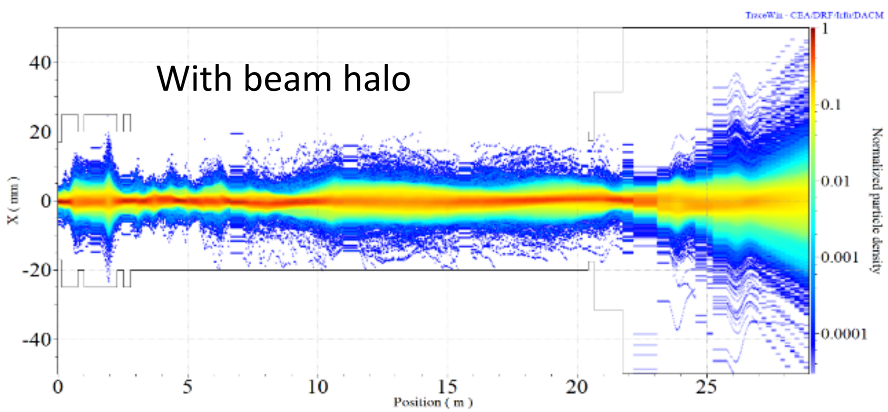


- Main reason of beam trip off is due to phase unlock problem.
- Automatic recovery procedures need to be developed to have a long-term test operation.
- Long term operation with > 1 mA beam will be demonstrated in 2018.

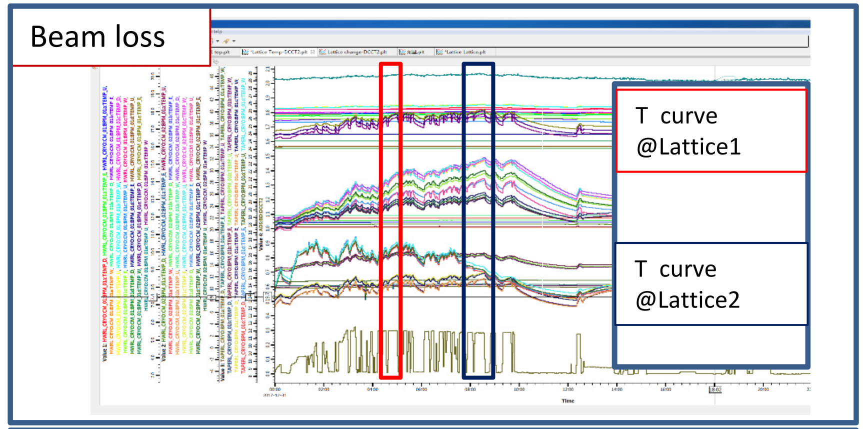
Beam loss and measurement

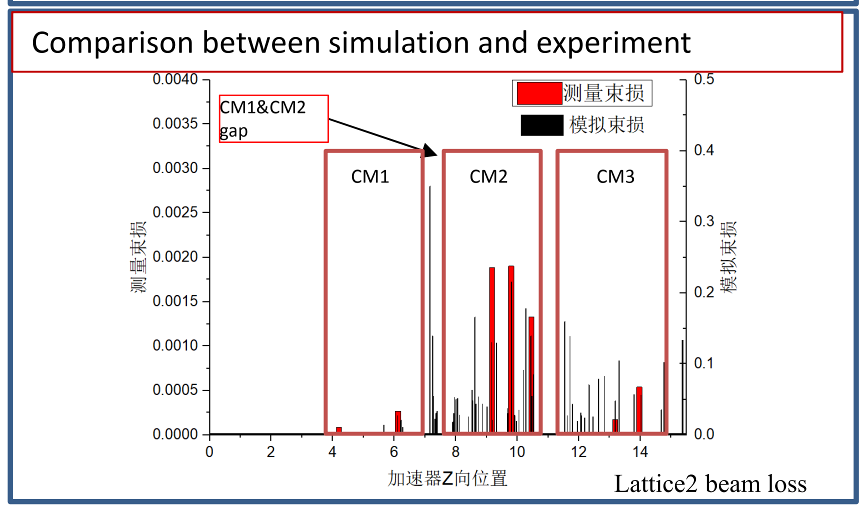


The beam behavior at normal condition



The beam behavior with halo

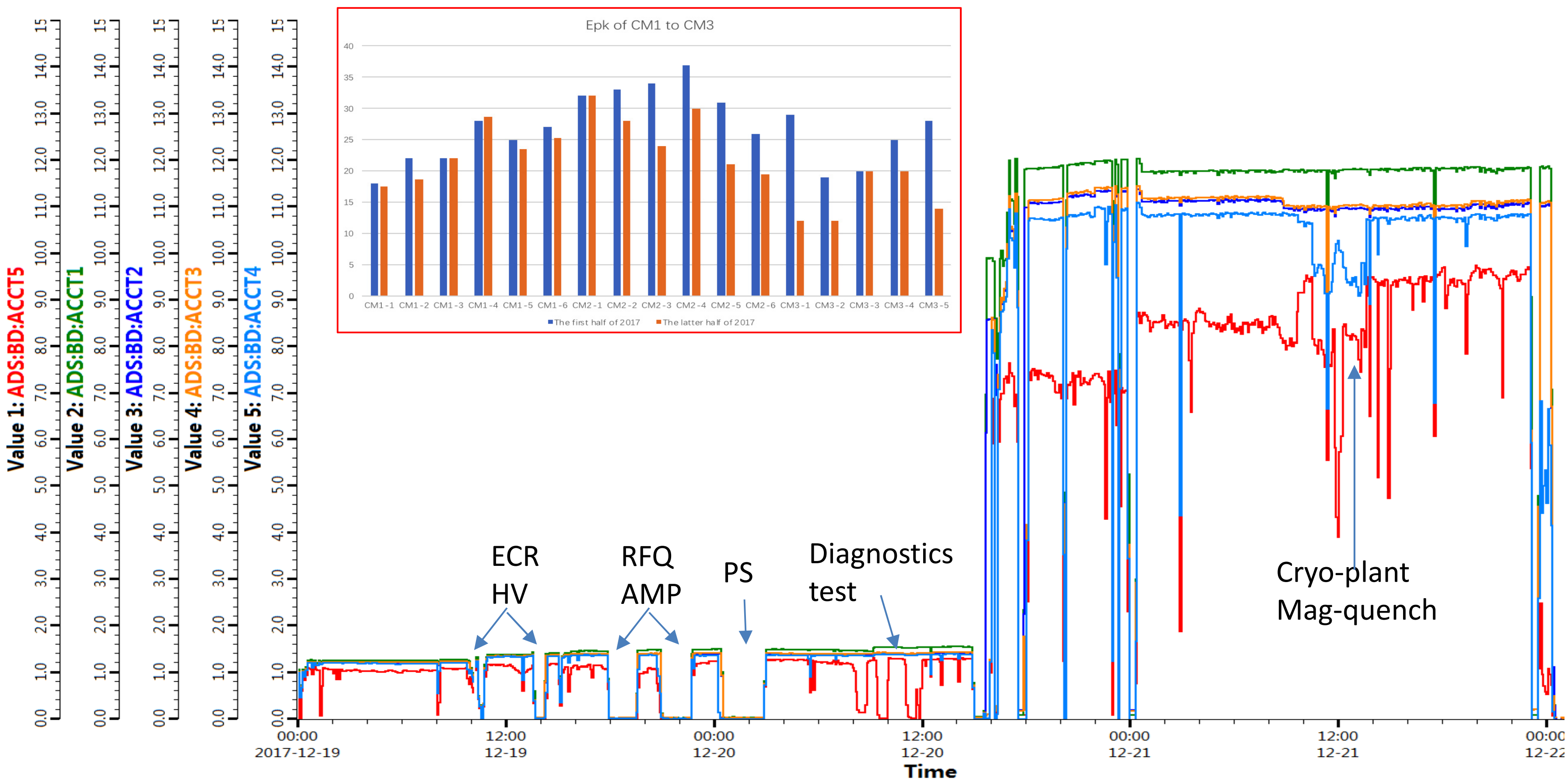




The beam loss detection by the low temperature sensors

Operation Reliability Test

- 2017-12-19-00：00 ~ 2017-12-22-00：00; ~68 hours continuous operation test
- CW RF and Pulse beam
- 18MeV@1mA@1Hz@10uS & 18MeV@10mA@1Hz@10uS
- Long-term stability and reliability challenging! Need to be studied carefully.



Preliminary RAMI analysis

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

Mean time between failure MTBF (min)	Beam trips (10s-5min)	Beam trips (>5min)
111.4	21	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

- Some long time failures (> 5 min), such as HV, AMP, Cryo-plant, PS, have very clear reason, can be avoided in the next stage.
- 10s-5min-trip numbers, root-reasons of the trips from SRF are still under investigation.

Lessons and experiences for CW high power beam test

1. SRF cavity mechanical stability and LLRF control extremely important.

2. MPS is extremely important !!!

- Protection logic, interlock system and action sequences should be clearly defined, reviewed and verified.

- All executive action components, trigger detectors, monitoring and measurement sensors be extremely reliable, or with actively double-parallel protection, and be free of noise.
  Such as those relays, temperature sensors, BPMs, chopper system, vacuum valves, vacuum gauges, LEBT beam stopper…

■ Accident examples:

☐ **2.5 MeV/CW 2.7mA: One vacuum chamber and vacuum valve were damaged by beam**
The RELAY to switch off IS-HV and insert IS-beam stopper, was malfunction due to noise, and the chopper was recovered automatically after 13 s.

☐ **18-25 MeV/CW 0.1-0.3 mA:**
HTS leads of two SC solenoids burned.
Temperature sensors malfunction.

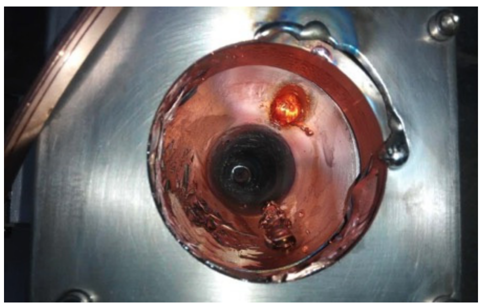
3. Operation regulations and rules important and must be strictly enforced

- Do not bypass any MPS signal until it is well understood.
- Anytime ramping up to high power or switching to CW, double-check MPS or MPS with self-check function . To make sure all sensors and all interlock systems work well and all actions in right sequences.
- Always start commissioning with pulsed beam and low duty factor. Double-check lattice when ramping up to high power.
- Anytime when you would find something improper or strange, stop high power beam without any hesitation.

Lessons and experiences for CW high power beam test

Accident examples:

- **Coupler windows broken and cavities contaminated**
  Interlock signal was bypassed during HWR010 cavity RF conditioning.
- **4.6 MeV/CW 3.9 mA. Beam stopper FC3 damaged with a hole and cooling water leaking out, cavities contaminated.**
  HEBT Beam was off-centered by ~20 mm. The beam bombarding the FC3 wall and damaged. Beam intensity measured by FC3 became unstable, but was ignored.



- **18 MeV/CW 0.3 mA. Fast-response vacuum valve damaged.**
  The beam was ramped to CW from 50% duty factor,
  the beam hitting on the dump and very much outgassing.
  The vacuum gauge triggered the fast valve to close down,
  the beam bombarded the fast valve.

Summary and conclusion

- CW 10 mA proton RFQ, low β SRF cavities such as HWR and Spoke, and relevant cryomodules, have been developed and built successfully as a prototyping program of ADS front-end linac. The average performance of HWR with beam achieved 25 MV/m and one of CMs reached more than 32 MV/m.
- CW proton 10-25 MeV of high power superconducting linac as a demo machine for ADS fron-end linac has been built. The 10 MeV/CW 1-2 mA and 18-25 MeV/CW 0.1-0.3 mA beams have been demonstrated by commissioning of the linac.
- A lot of lessons and experiences have been learned through many CW beam tests and accidents. MPS, LLRF control and beam loss control are extremely important and being improved.
- Long-term reliable and stable operation with CW high beam power is challenging and need to be demonstrated in future.

Beam commissioning summary

LINAC SEGMENTS	FIRST CW BEAM	E (MeV)	CW BEAM (hours)	CW I_{max} (mA)	CW POWER(kW)
RFQ	JUN.21, 2014	2.15	70	11	23
CM1+CM2(6+6HWRS)	SEP.24, 2016	10.2	11	2.7	26
CM1+CM2+CM3+CM4	JUN.6, 2017	25	0.05	0.17	4.25
CM1+CM2+CM3+CM4	DEC.30, 2017	17.5	26.5	0.3	5.24

Thanks for your attention

Thanks for those colleagues

from IHEP, LBNL, Jlab, ANL, SINAP, PKU, THU, MSU,TRIUMF

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Look forward to collaboration