Beam Commissioning of the ADS CW SRF Linac Demo

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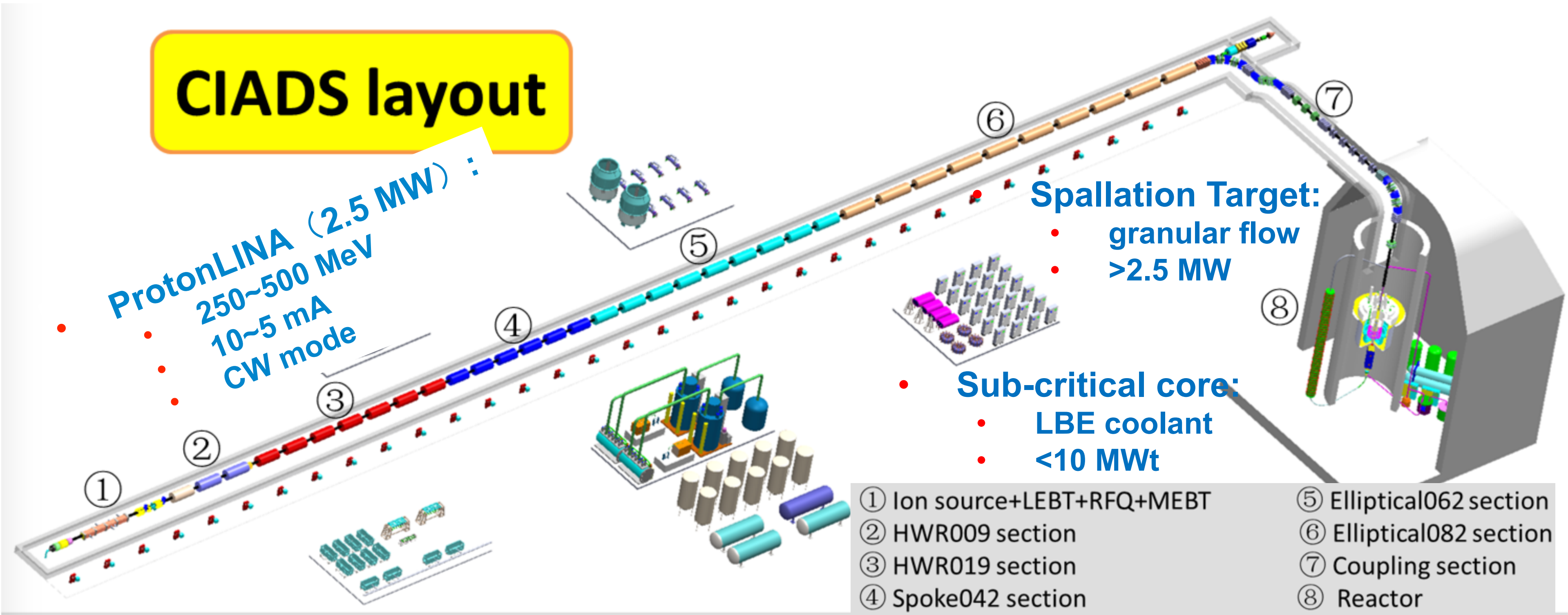
Outline

- Brief introduction of C-ADS superconducting Linac demo
- Commissioning procedures of CW SC Linac demo
- Some lessons and experience of the commissioning
- Summary and Acknowledgements

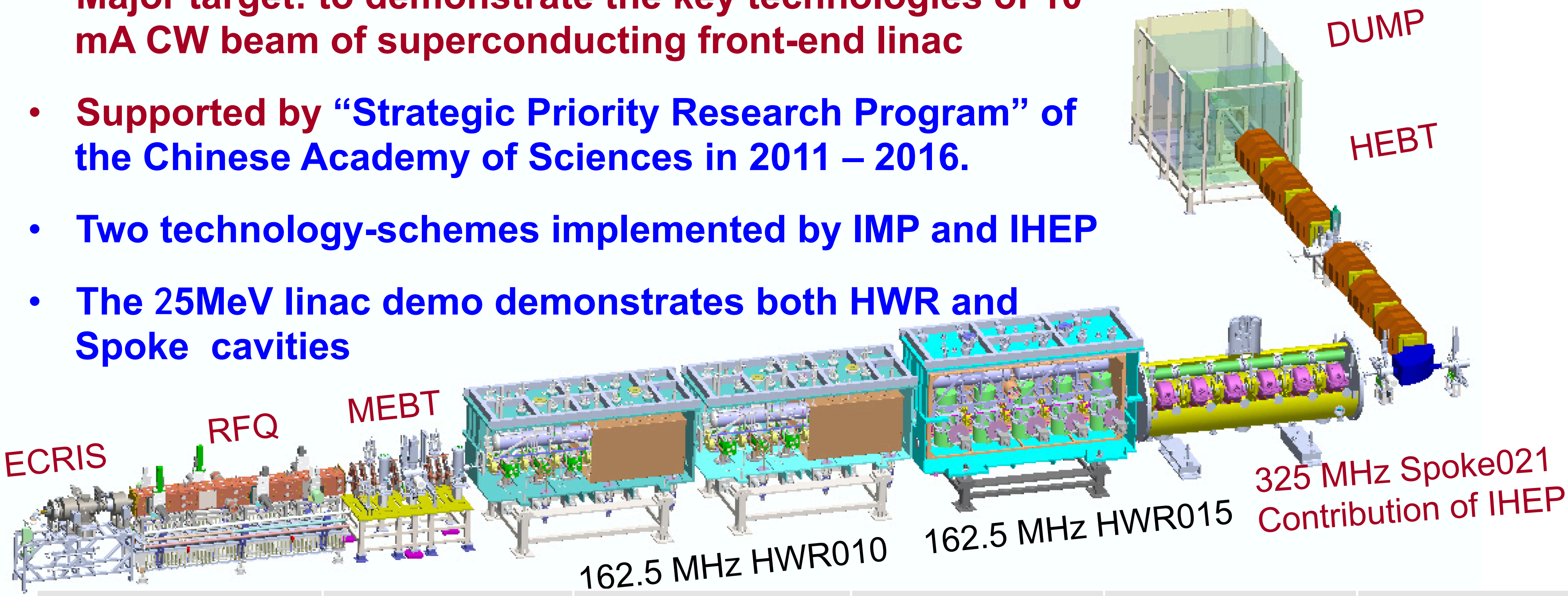
China initiative Accelerator Driven System (CiADS)

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



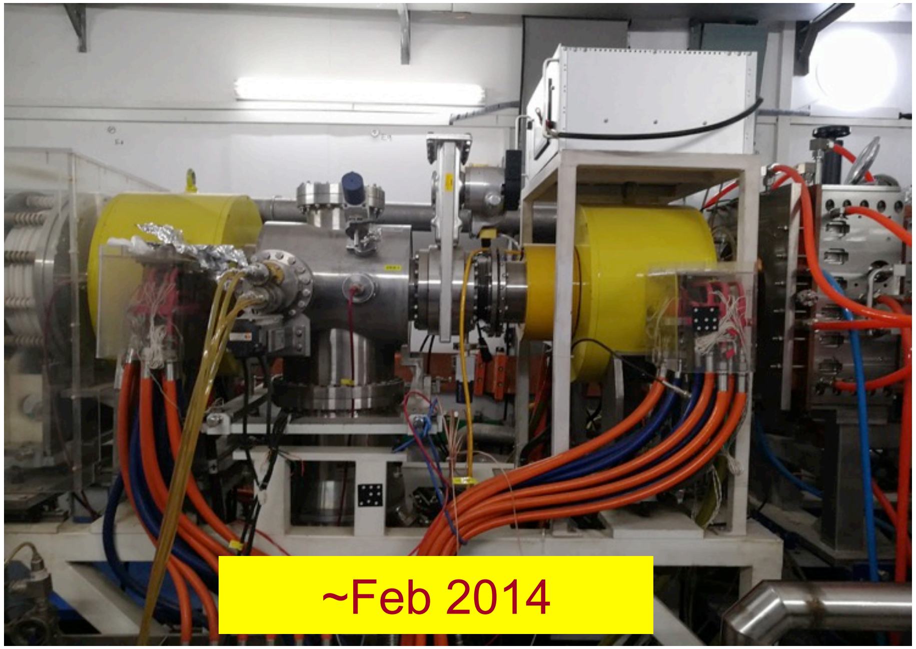
Brief introduction of C-ADS SC Linac

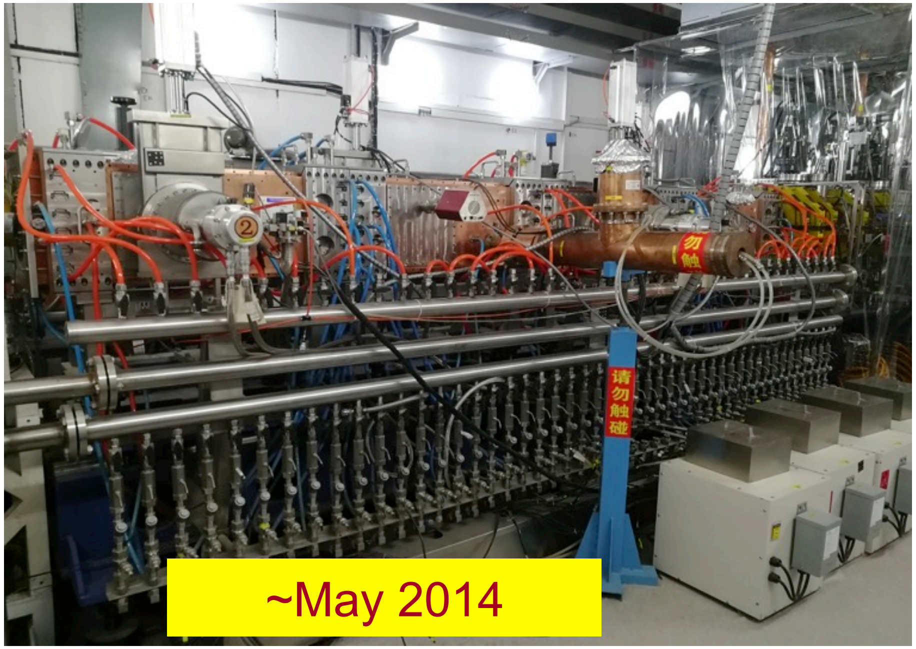
- **Major target: to demonstrate the key technologies of 10 mA CW beam of superconducting front-end linac**
- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences in 2011 – 2016.**
- **Two technology-schemes implemented by IMP and IHEP**
- **The 25MeV linac demo demonstrates both HWR and Spoke cavities**

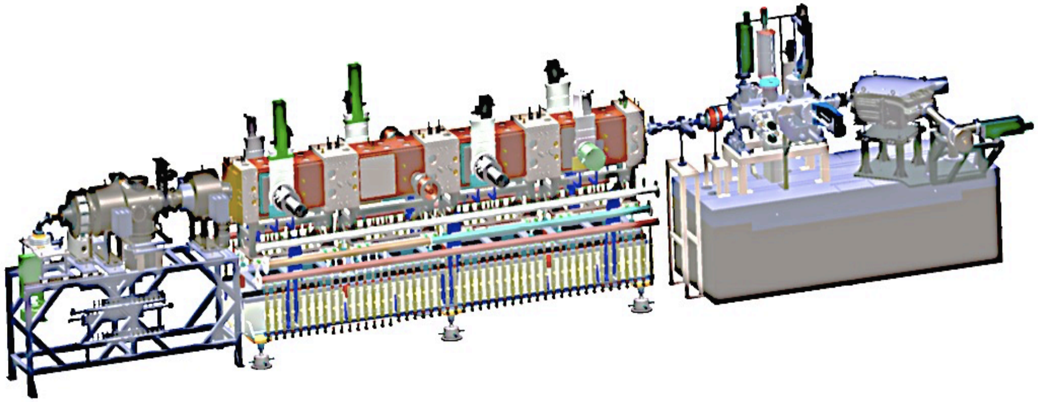


	RFQ/IMP	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
frequency	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
output energy	2.1 MeV	5 MeV	9 MeV	17 MeV	25 MeV
cavity type	4-vane	HWR010	HWR010	HWR015	Spoke021
cavity number	1	6	6	5	6

Phase1: ECR + LEBT + RFQ + DP



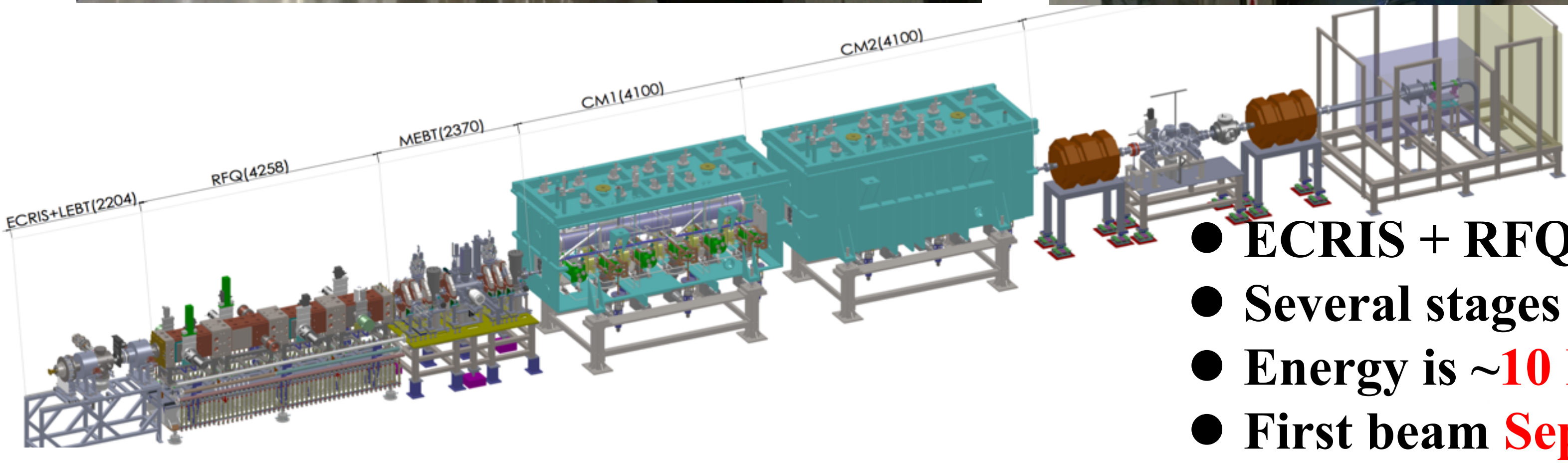




- ECR + LEBT + RFQ
- Energy is **~2.15 MeV**
- First beam **June 6th, 2014**

Brief introduction of C-ADS SC Linac

Phase2: ECR + LEBT + RFQ + 2×HWR_CM + DP

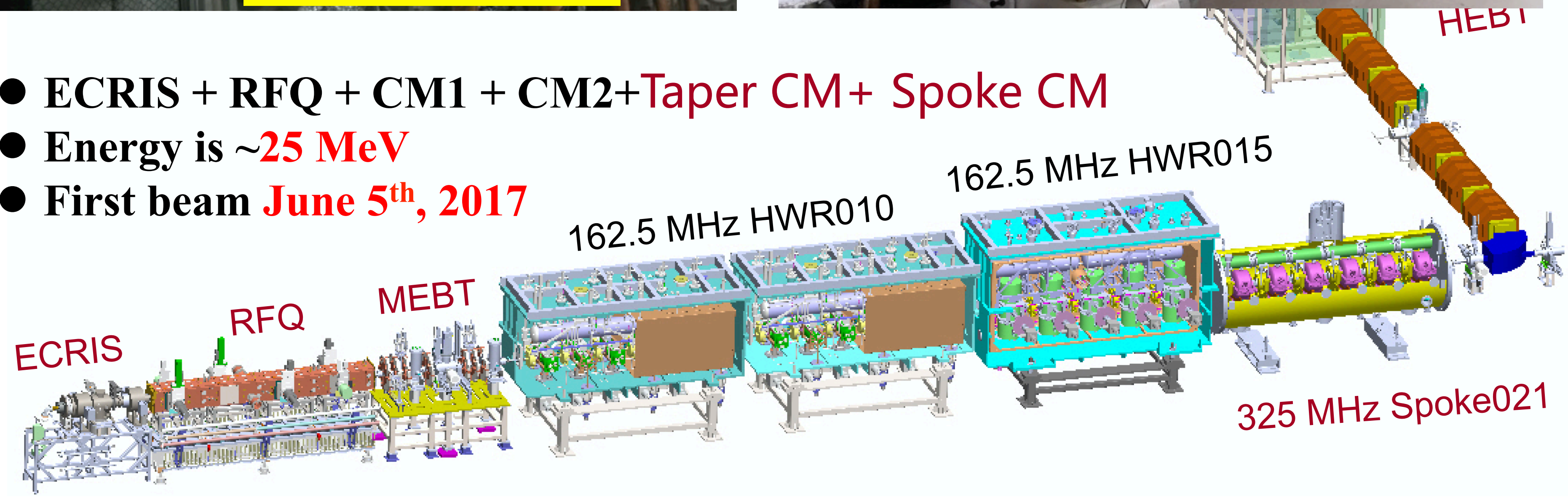


- **ECRIS + RFQ + CM1 + CM2**
- **Several stages in the two years**
- **Energy is ~10 MeV**
- **First beam September 15th, 2016**

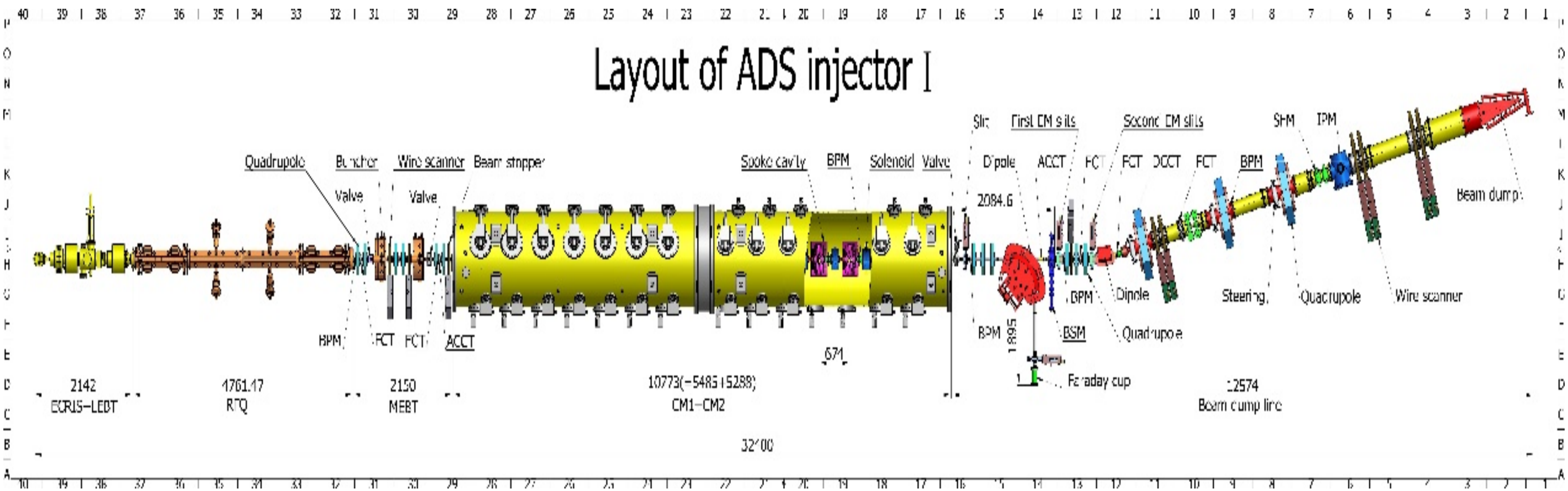
Brief introduction of C-ADS SC Linac

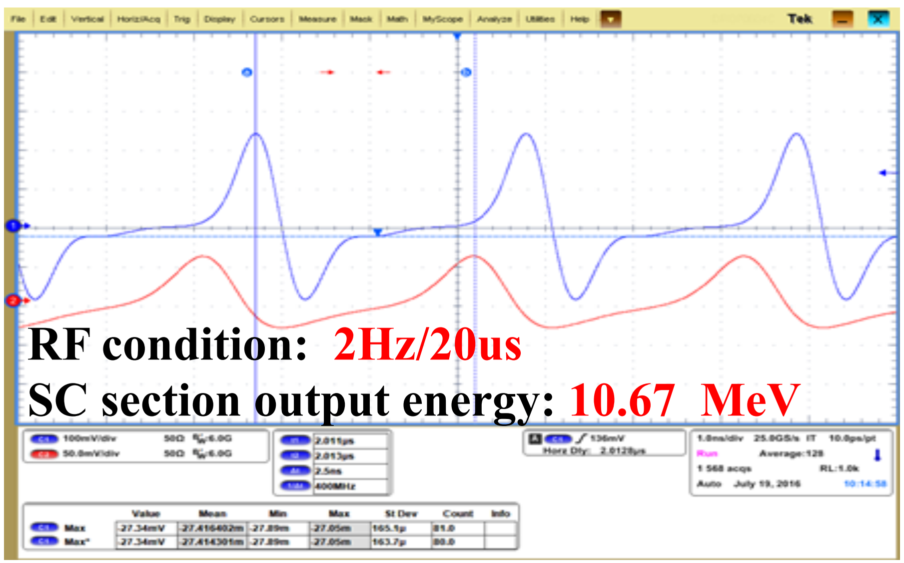
Phase3: ECR+LEBT+RFQ+2×HWR_CM+Taper CM+ Spoke CM+HEBT

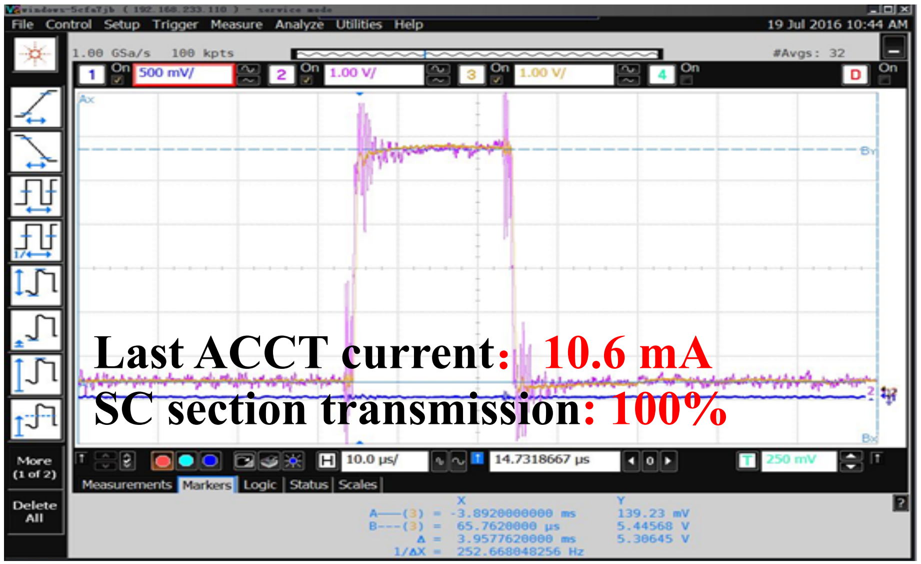
- **ECRIS + RFQ + CM1 + CM2+**Taper CM+ Spoke CM
- **Energy is ~25 MeV**
- **First beam June 5th, 2017**



Brief introduction of C-ADS SC Linac







Outline

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- Commissioning procedures of CW superconducting Linac
- Some lessons and experience of the commission
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Challenge of the CW SC Linac for ADS

- **First of world to demonstrate the 10 mA, CW beam, at the low-energy superconducting Linac**
- Highest CW beam power of 2.5 MW for CIADS
- Only SARAF demonstrated 2.1 mA, 2 MeV proton beam before

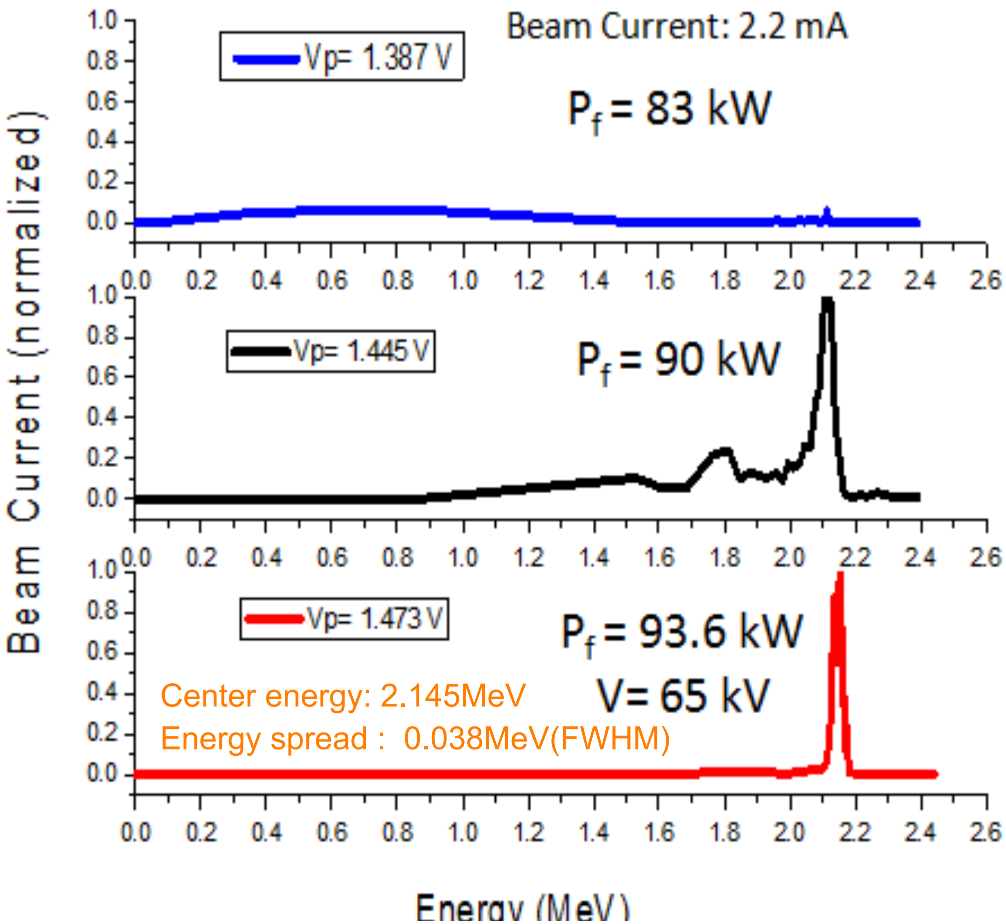
Challenge of the CW SC Linac for ADS

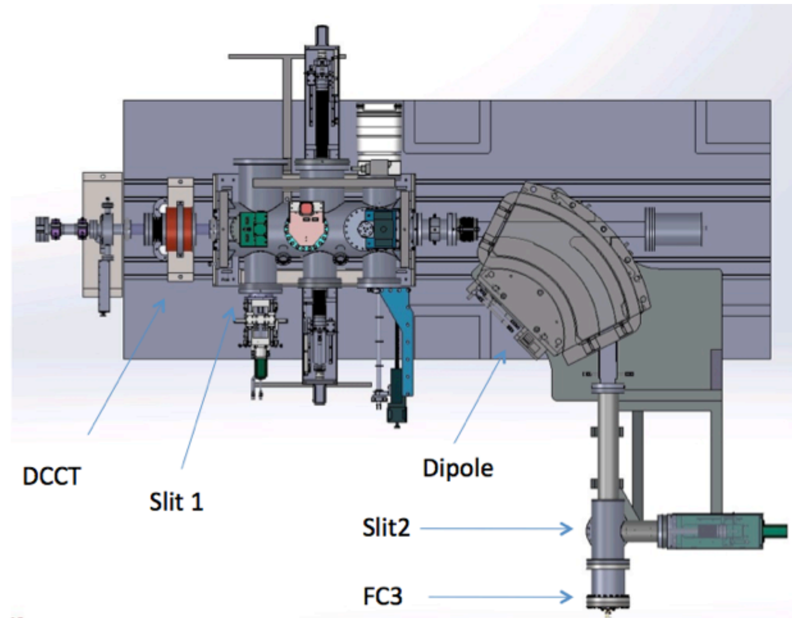
- **First of world to demonstrate the 10 mA, CW beam, at the low-energy superconducting Linac**
- Highest CW beam power of 2.5 MW, 5mA/CW@500MeV for CIADS
- Only SARAF demonstrated 2.1 mA, 2 MeV proton beam before

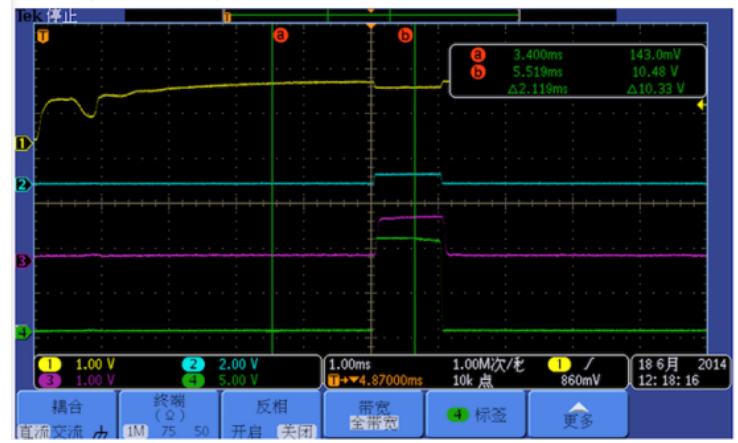
↓

- Hardware calibration－To verify the parameter of the key hardware
  - The verification of hardware array, calibration of BPM offset, phase scan et al
- Beam distribution reconstruction－ To match the beam between different section
  - The emittance measurement, lattice setting, matching et al
- Beam tuning with high power－To ramp the beam power for the whole linac
  - BBA, MPS, ramping mode, beam loss detection system et al

Hardware calibration





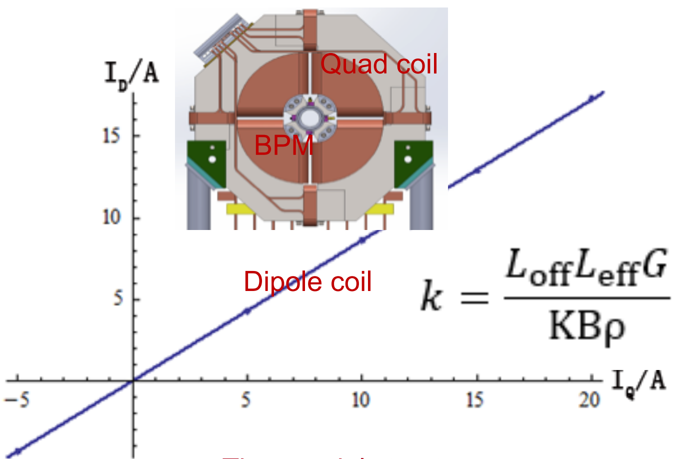


RFQ Voltage calibrated with energy spread, more precise than transmission.

Commissioning procedures of Linac

Hardware calibration

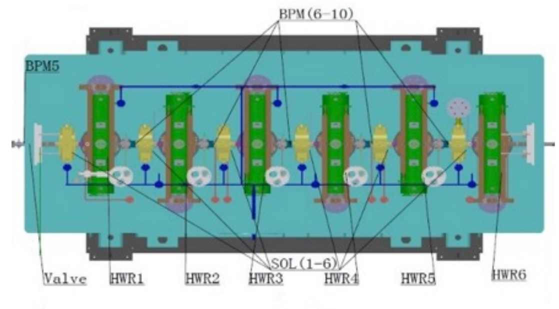
Normal-T BPMs @ BT

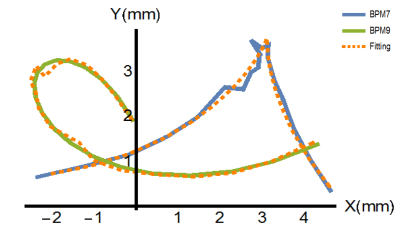


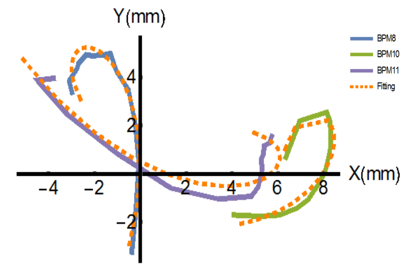
$$k = \frac{L_{off} L_{eff} G}{KB\rho}$$

- The special structure
- The ‘null comparison’ method

Cold BPMs@SC Linac

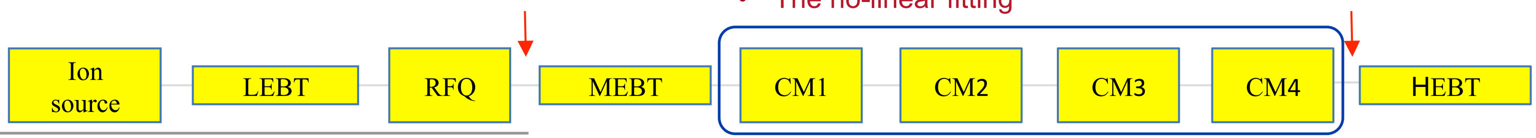






$$\begin{pmatrix} X_0 \\ X_0' \\ Y_0 \\ Y_0' \end{pmatrix} = M^{-1} \cdot \begin{pmatrix} X_1^{(1)} \\ X_1^{(2)} \\ \cdots \\ Y_1^{(1)} \\ Y_1^{(2)} \\ \cdots \end{pmatrix}$$

- The coupling effect between X and Y
- The no-linear fitting

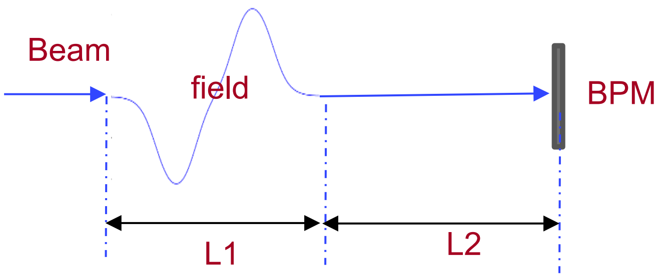


BPM	X (mm)	Y (mm)
BPM1	0.449	0.559
BPM2	-0.026	0.432
BPM3	0.063	-0.325
BPM4	0.434	0.158

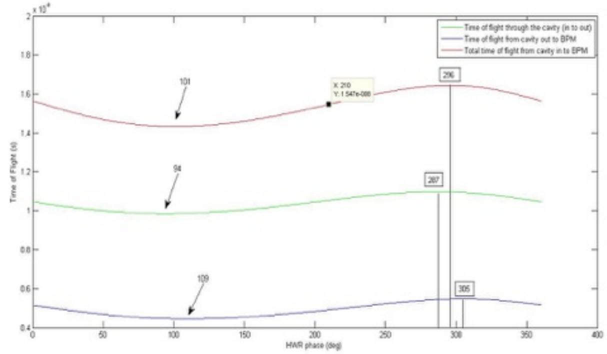
The calibration results of Cold BPMs

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

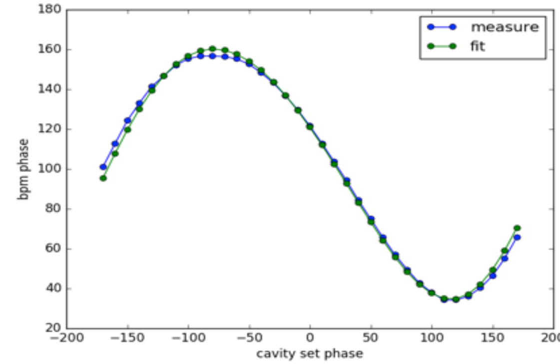
Hardware calibration



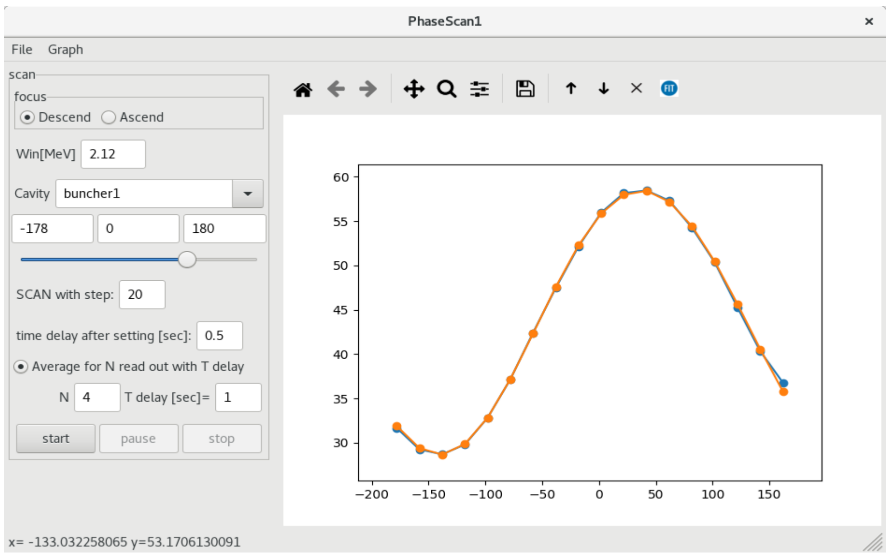
The physical model of phase scanning



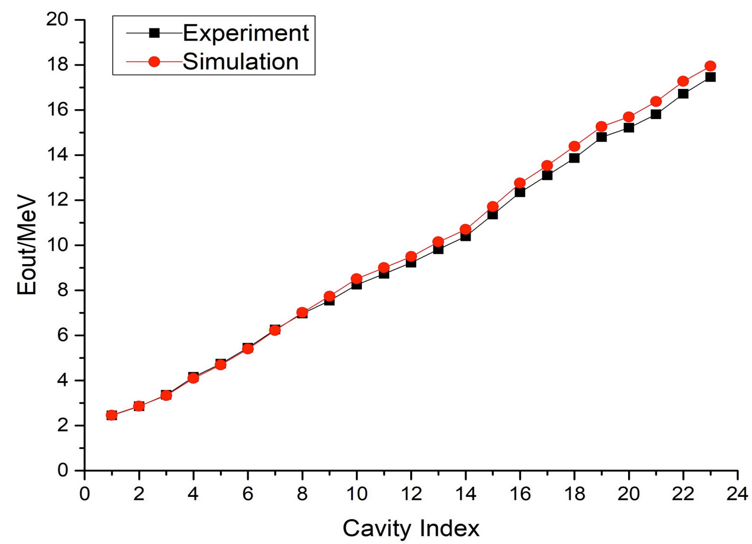
The BPM phase VS RF phase



The fitted phase scanning curve



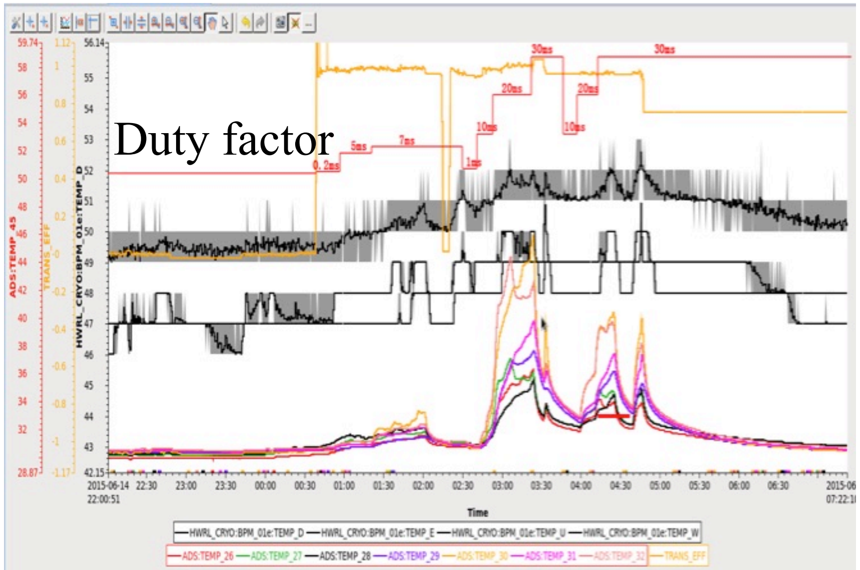
The developed phase scanning APP

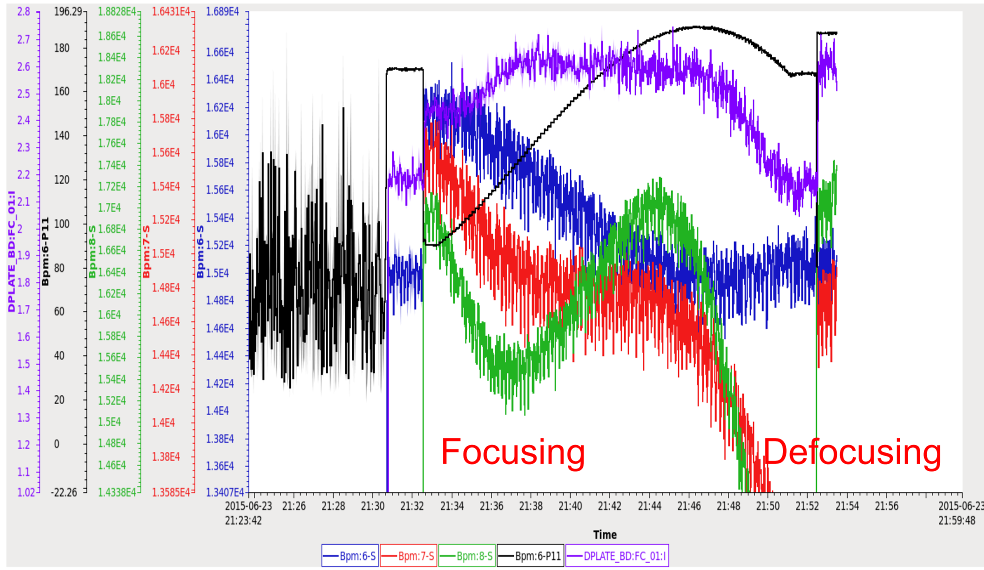


The comparison between simulation and experiment

Commissioning procedures of Linac

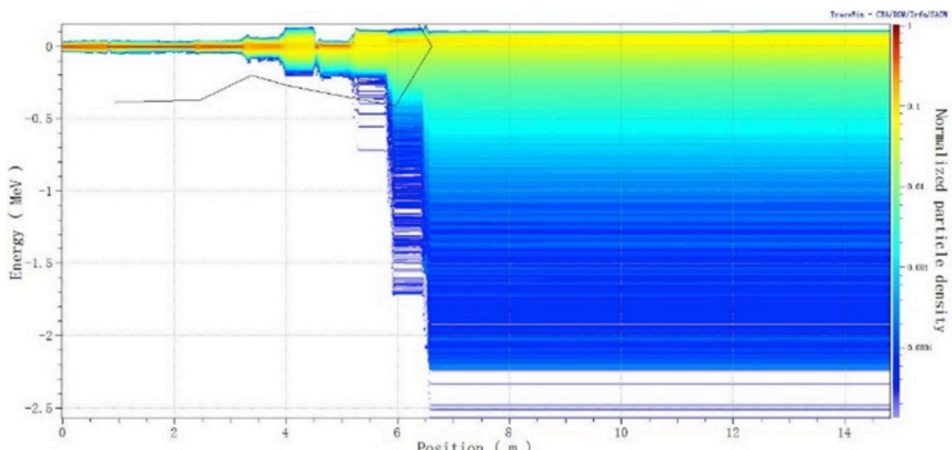
Hardware calibration





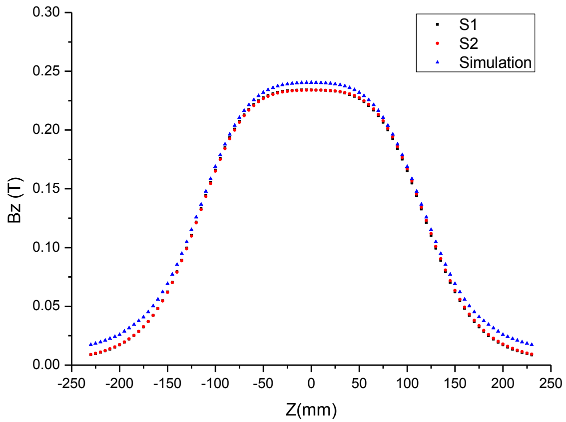
HWR2, rising edge is the focusing edge, opposite to other cavities.

- All HWRs phase are set to -20 deg. But HWR2 and HWR5 are actually 20 deg due to the wrong phase sign of LLRF. This causes beam loss, measured by the temperature sensors on the tube at the end of CM and in HEBT during beam power ramping by increasing duty factor.

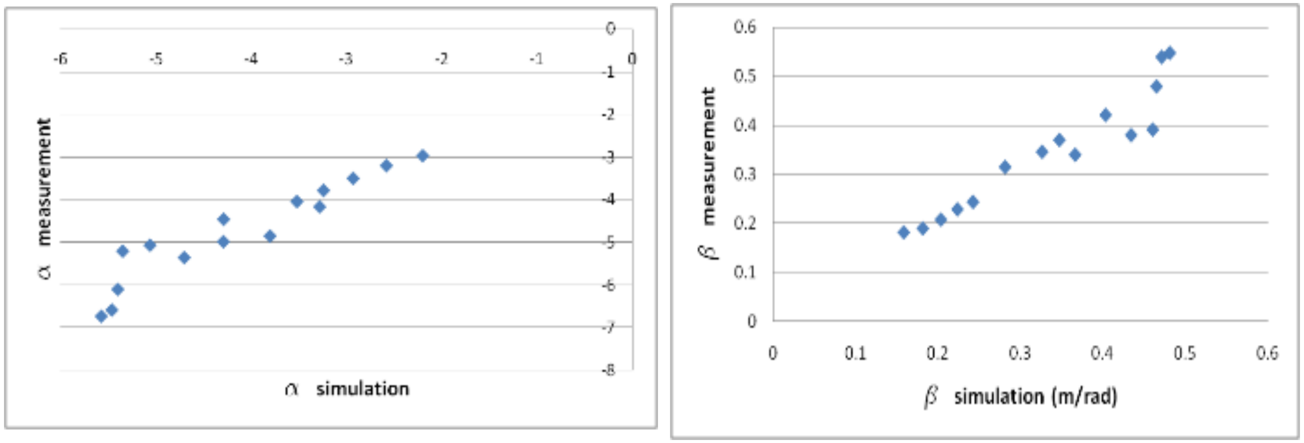


Simulation shows beam energy spread is -2 MeV at the exit of CM

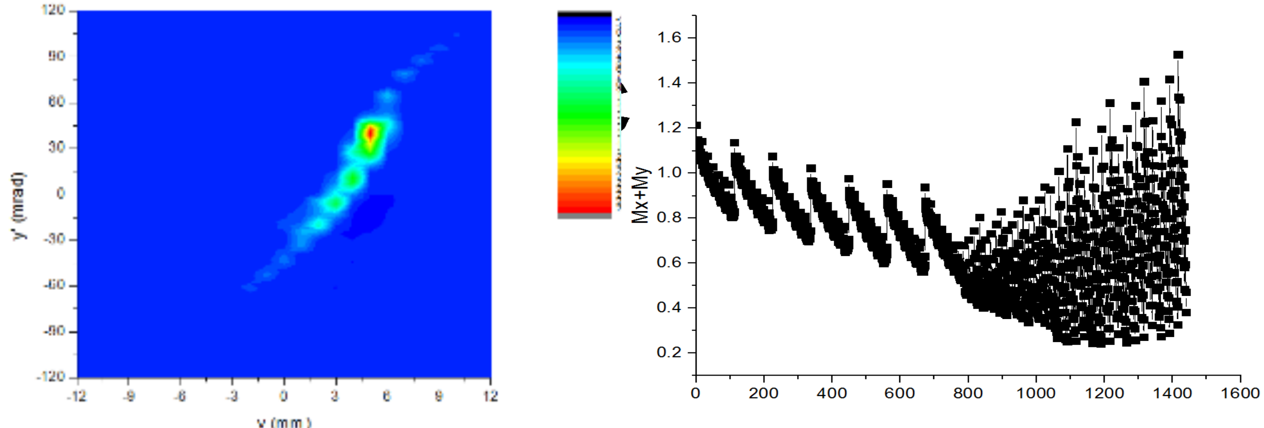
Beam distribution reconstruction



solenoid field measurement



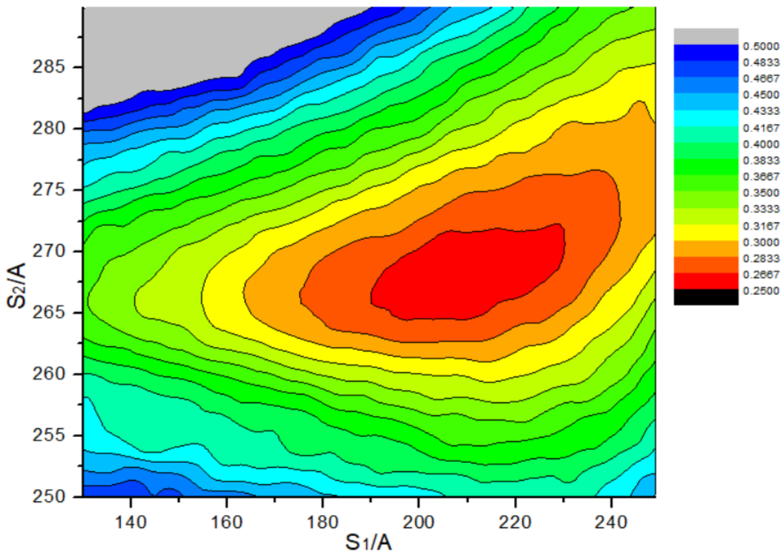
TWISS parameters measurement and simulation

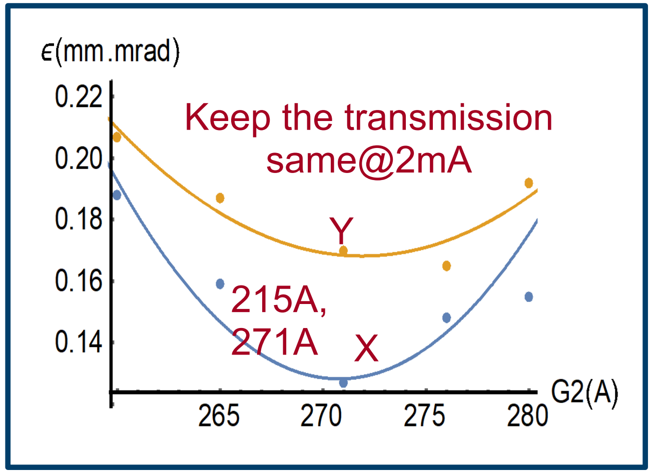


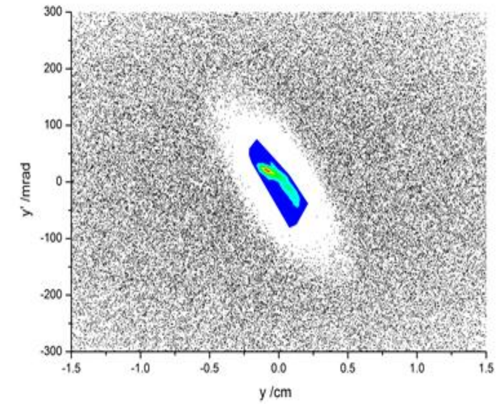
Parameters	value	unit
ε	0.13	πmmmrad
α	0.26	
β	0.3	m/rad
SSC factor	0.9	

emittance measurement at LEBT

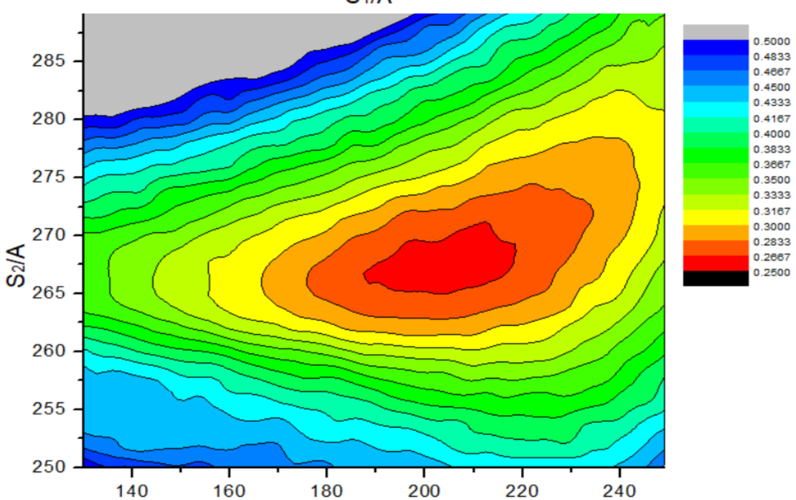
Beam matching from LEBT to RFQ

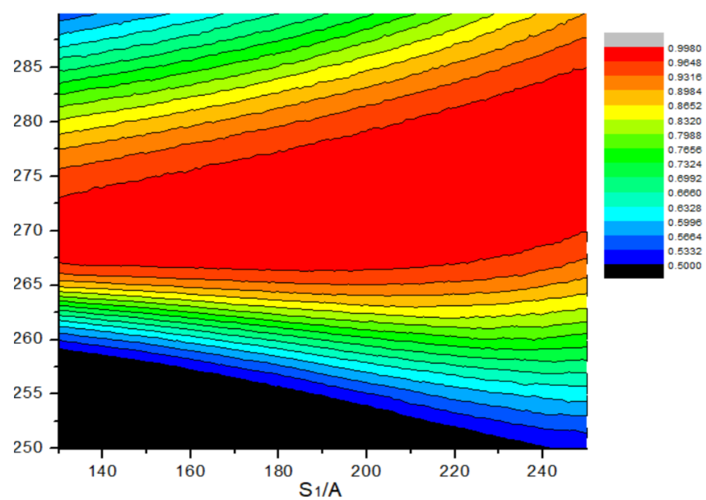






Beam emittance VS acceptance of RFQ

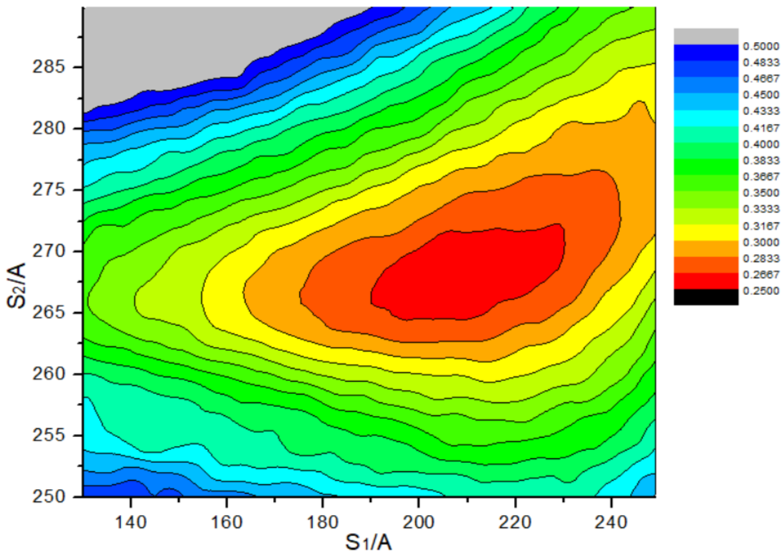


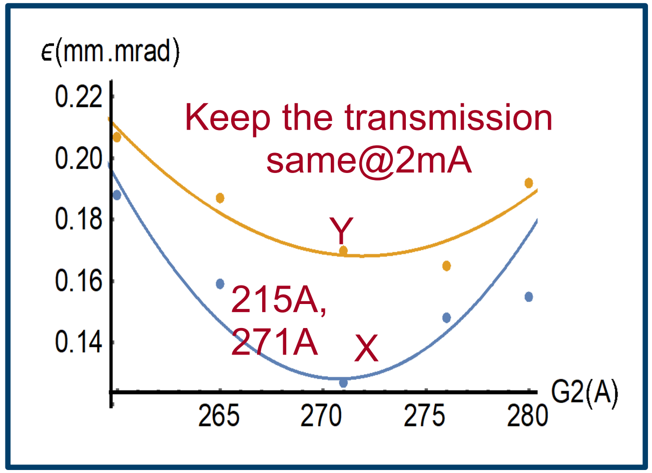


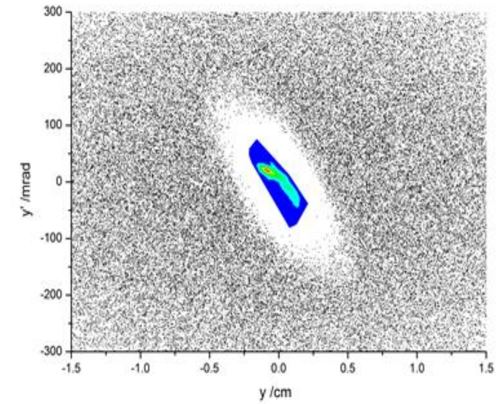
The study of the relation between transmission and emittance

Commissioning procedures of Linac

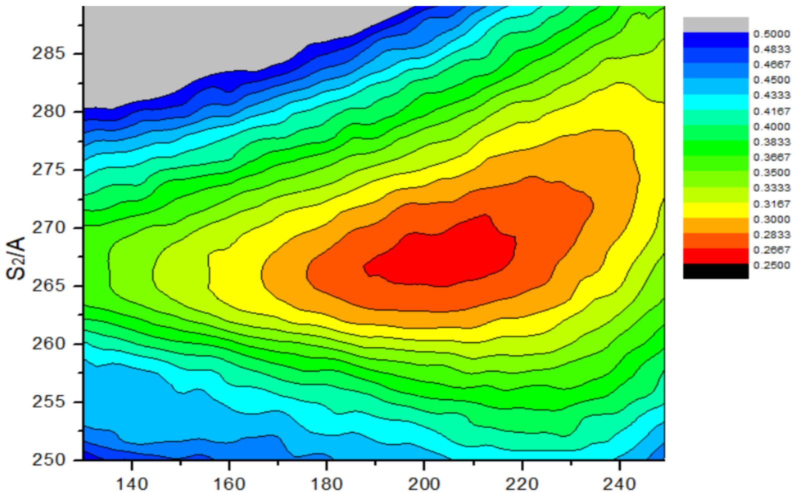
Beam matching from LEBT to RFQ

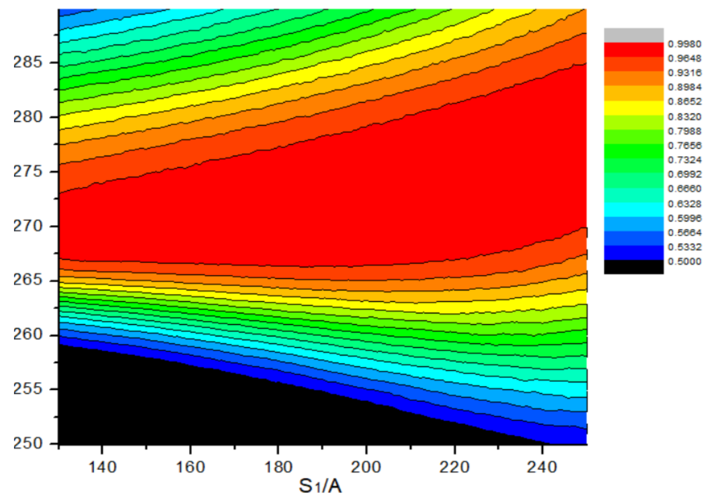






Beam emittance VS acceptance of RFQ



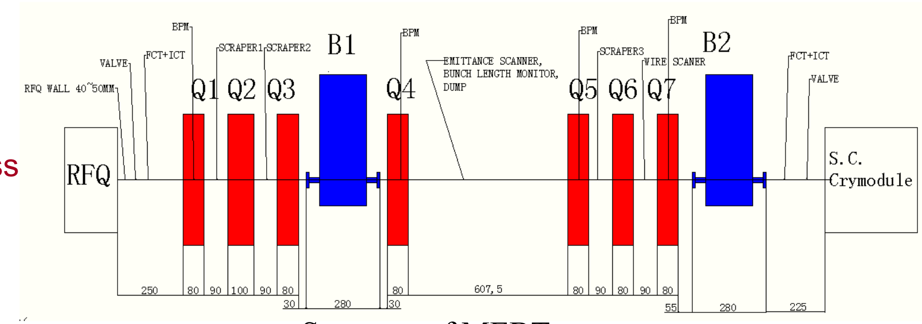


The study of the relation between transmission and emittance

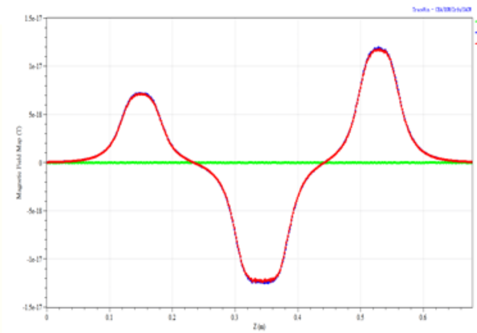
Maximum transmission is not enough, matching tuning should be considered for the high beam power linac!

Beam distribution reconstruction

- Scan Q1-3 for several measurements
- The fringe field overlap
- Trace back to get the exit twiss parameter of RFQ which agrees with the design of Parmteq
- Initial beam is re-built

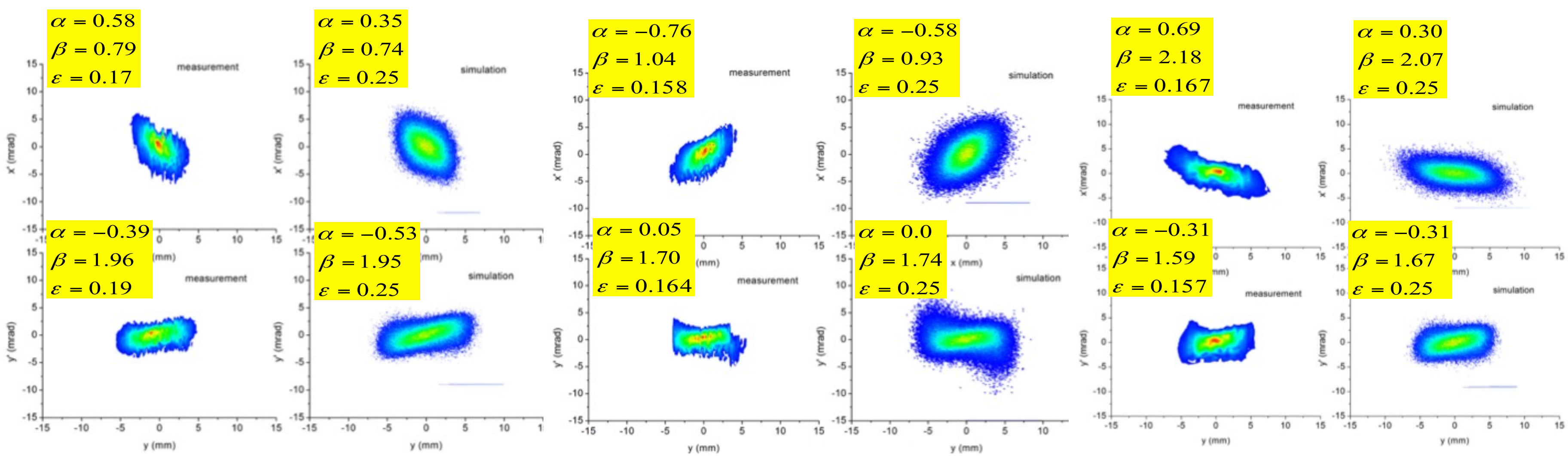


Structure of MEBT

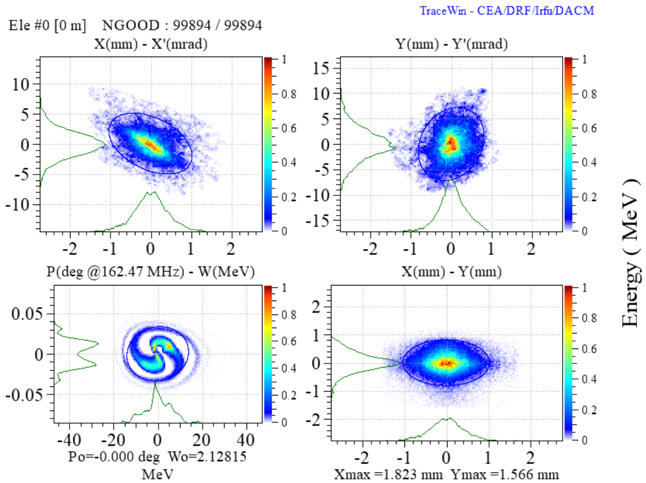


Overlap model of Q1-3

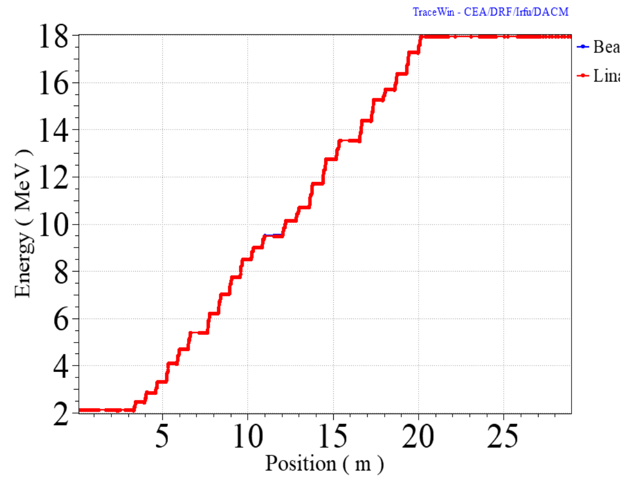
	α_x	β_x (m/rad)	α_y	β_y (m/rad)	Mismatch factor H/V
Measurement	0.3	0.25	-0.11	0.12	0.078/0.005
Parmteq simul (design)	0.46	0.27	-0.10	0.12	reference



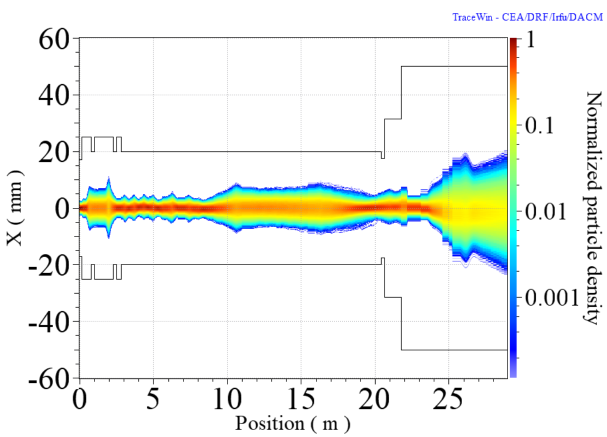
Beam distribution reconstruction



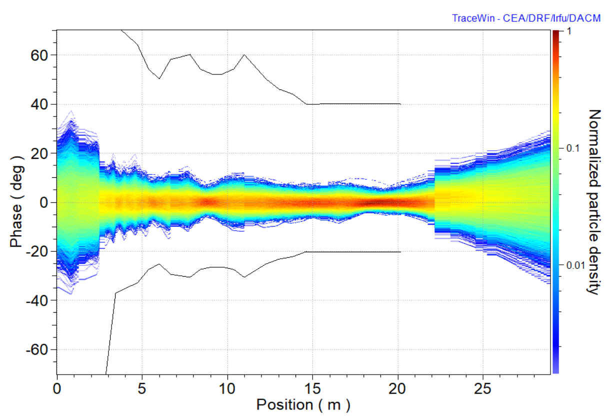
The reconstructed beam distribution at the exit of RFQ



The beam energy along the Linac



The transverse density along the linac



The longitudinal density along the linac

2017.12.20 (162.47MHz) 1mA@CW Lattice

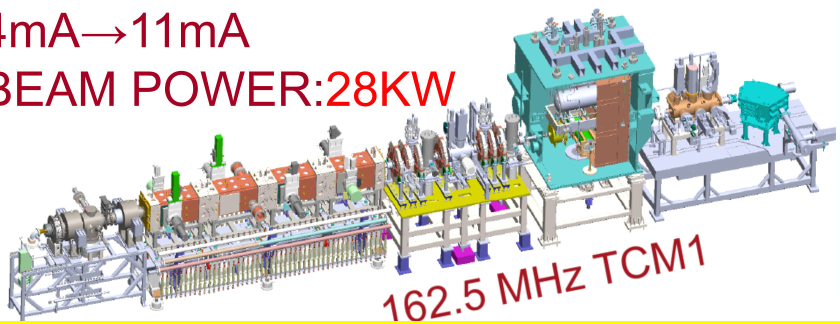
	Quad_Nb	Current (A)			Quad_Nb	Current (A)
MEBT	Q1	79.77		HEBT	Q1	60.00
	Q2	-96.15			Q2	-50.00
	Q3	80.03			Q3	60.00
	Q5	-65.84			Q4	-10.00
	Q6	101.92			Q5	45.00
	Q7	-49.65			Q6	-40.00
Buncher	Buncer_Nb	voltage(KV)	Phase			
	B1	61.00	-90.00			
	B2	103.50	-90.00			
	Cavity_Nb	Cavity_Epk	Beam Epk	Phase	Solenoid_Nb	Current (A)
CM1	1	18.00	16.57	-36	1	94.65
	2	18.00	17.68	-34	2	99.28
	3	20.09	18.87	-32	3	102.36
	4	27.00	27.52	-27	4	109.82
	5	22.44	21.19	-25	5	91.56
	6	24.74	25.40	-29	6	113.63
CM2	1	29.94	30.38	-30	1	103.09
	2	28.64	28.75	-27	2	93.57
	3	30.00	26.50	-26	3	79.30
	4	30.00	28.72	-26	4	71.37
	5	22.14	18.79	-27	5	15.86
	6	18.00	19.66	-30	6	88.02
CM3	1	12.00	12.05	-25	1	36.48
	2	12.00	10.06	-23	2	44.41
	3	20.00	18.34	-22	3	49.96
	4	20.07	18.58	-20	4	49.96
	5	13.95	13.96	-20	5	49.96
CM4	1	28.00	22.79	-20	1	150.12
	2	28.00	22.31	-20	2	138.57
	3	14.00	10.76	-20	3	120.09
	4	20.00	16.55	-20	4	127.02
	5	28.00	21.39	-20	5	150.12
	6	28.00	15.80	-20	6	151.27

The lattice based on the real machine condition

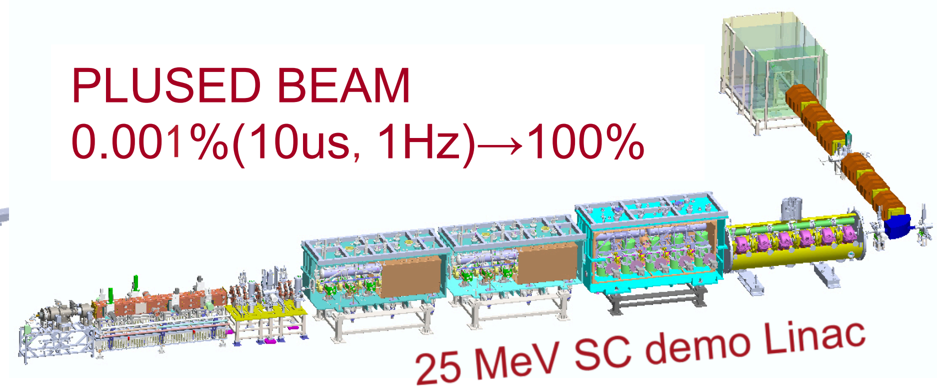
Commissioning procedures of Linac

Multi-particles step

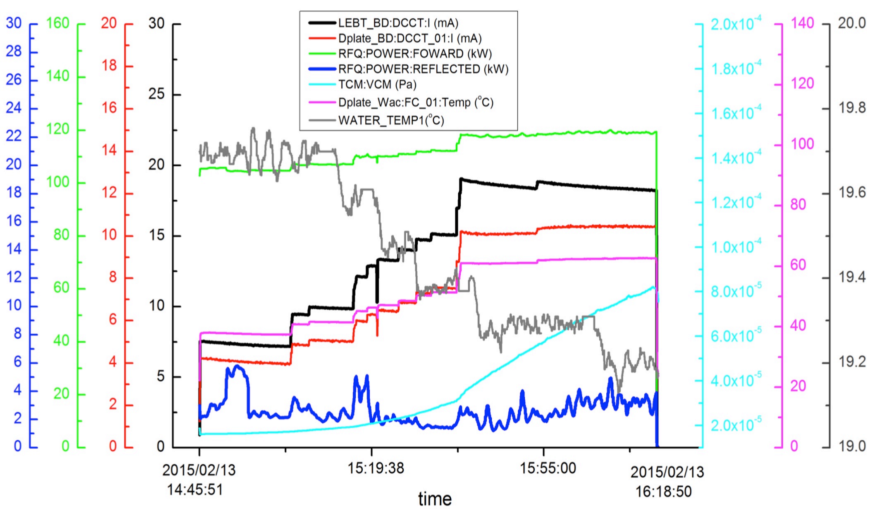
CW BEAM
4mA→11mA
BEAM POWER:28KW

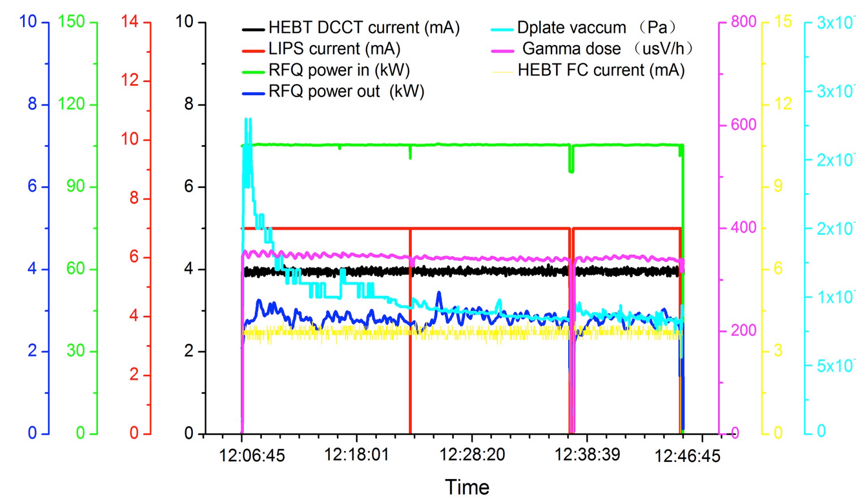


PLUSED BEAM
0.001%(10us, 1Hz)→100%



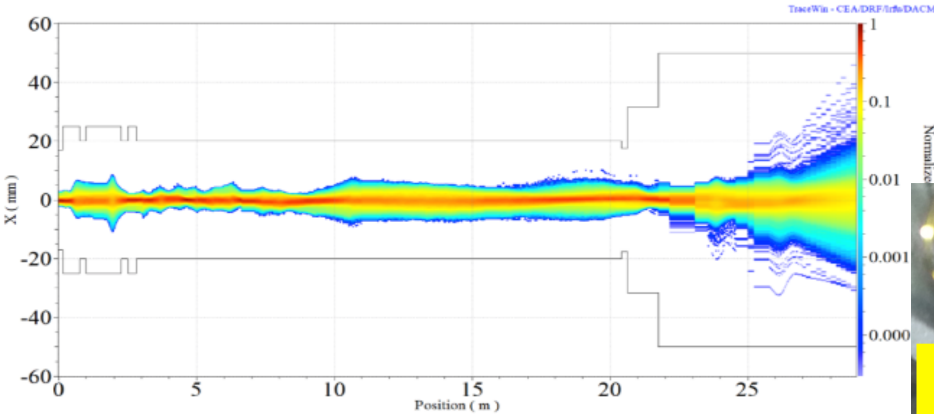
The comprehensive monitoring system including vacuum, temperature, beam current et al has been built to guarantee the power ramping process



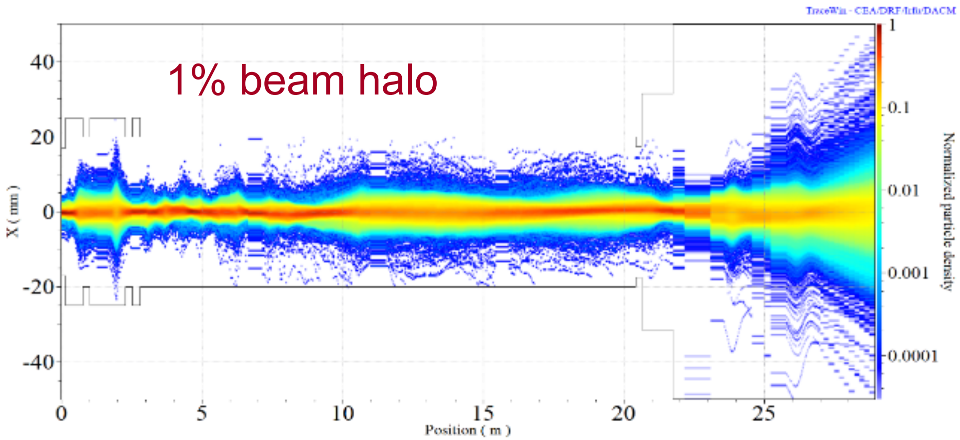


Commissioning procedures of Linac

Beam tuning with high power

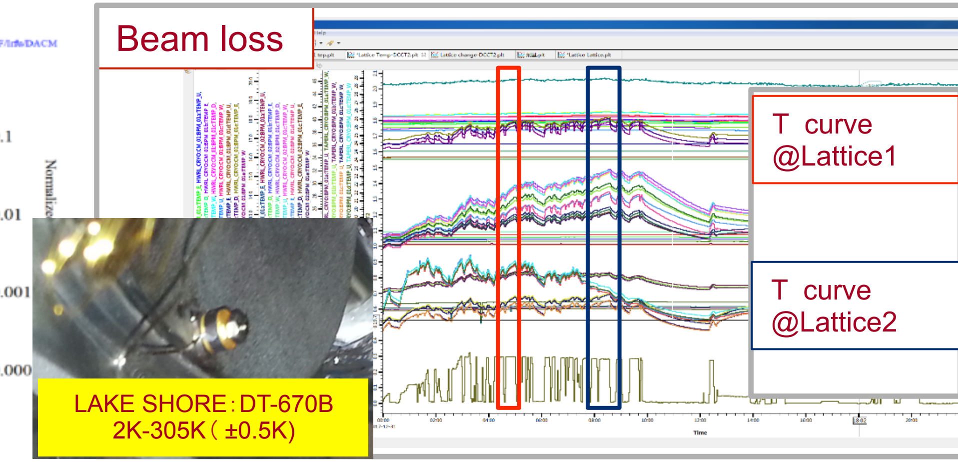


The beam behavior at normal condition

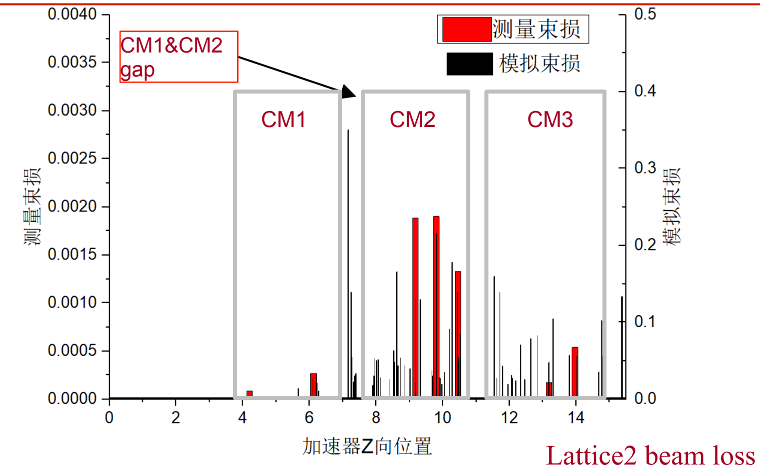


The beam behavior of the beam with beam halo

Beam loss



Comparison between simulation and experiment

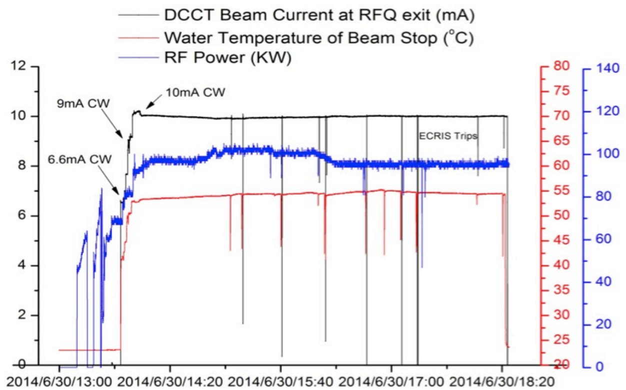


Lattice2 beam loss

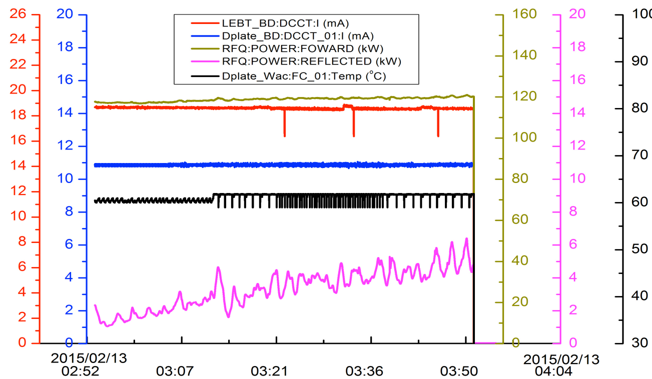
The beam loss detection by the low temperature sensors

Commissioning procedures of Linac

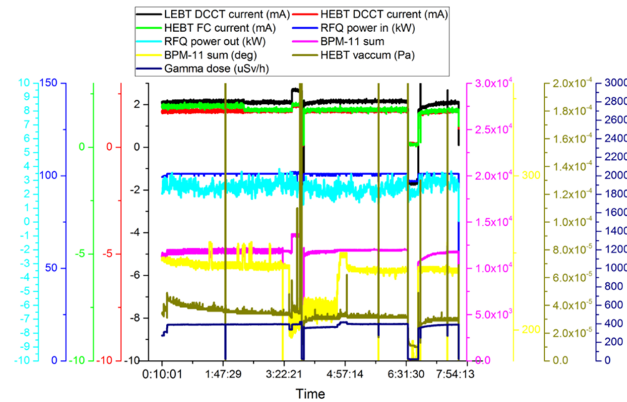
Beam tuning with high power



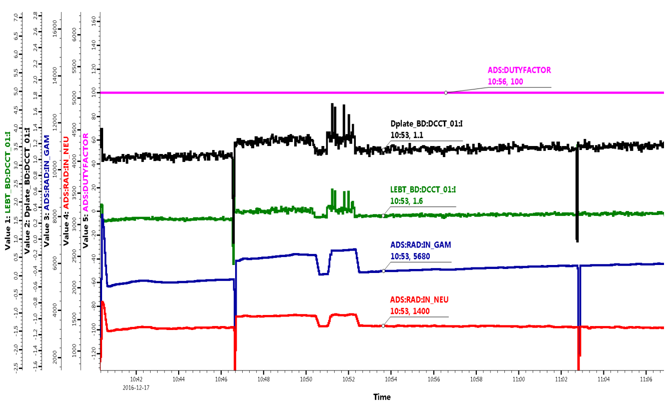
RFQ:Jun.30th,2014;10mA,2.15MeV,CW,
max of lasting time:265min,beam power 21.5kW.



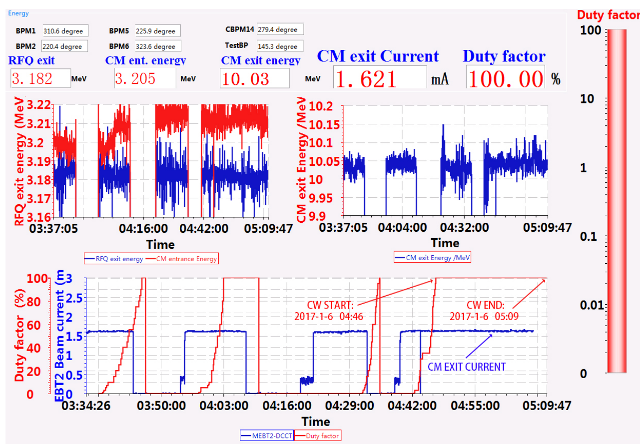
TCM1:Feb.13th,2015;~11mA,2.55MeV,CW,
60min,beam power 28kW.



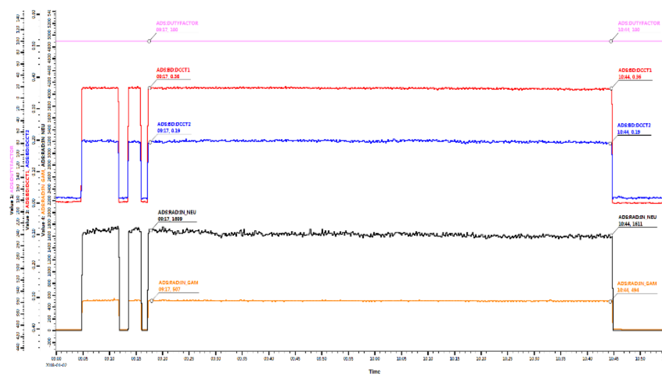
CM1:Jan.3rd,2016;1.7mA,4.02MeV,CW,
max of lasting time:210min,beam power 6.8kW.



CM1+CM2:Dec.17th,2016;1.156mA,
10.061MeV,CW,~21min, beam power 11.6kW@ Injector II



<u>23 min (</u>10.03MeV/1.62mA) @1.6mA
@Injector I

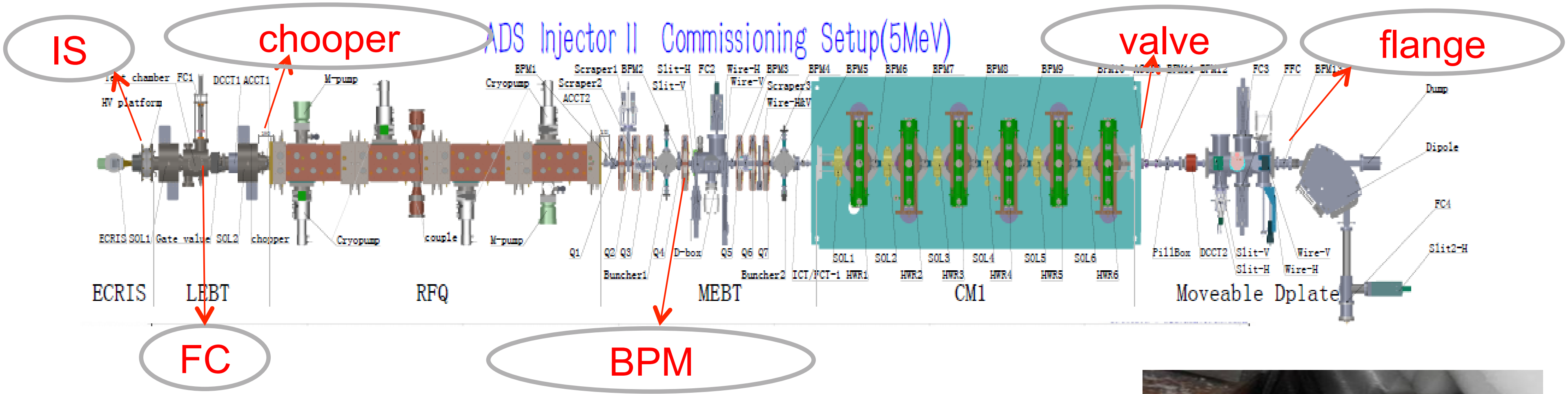


CM1+CM2+CM3+CM4:Jan.2nd,2018;0.293mA,18MeV,
CW, max of lasting time:87min,beam power 5kW.

Outline

- Brief introduction of C-ADS superconducting Linac
- Commissioning procedures of CW superconducting Linac
- Some lessons and experience of the commission
- Summary and Acknowledgements

lessons and experiences

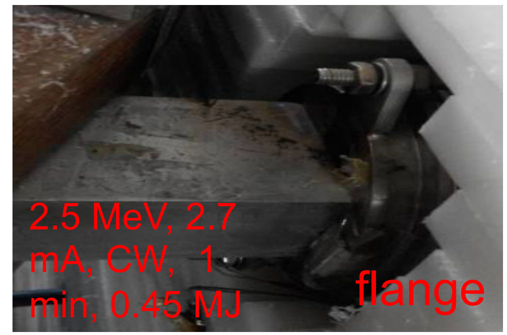


Date： June 29th 2015

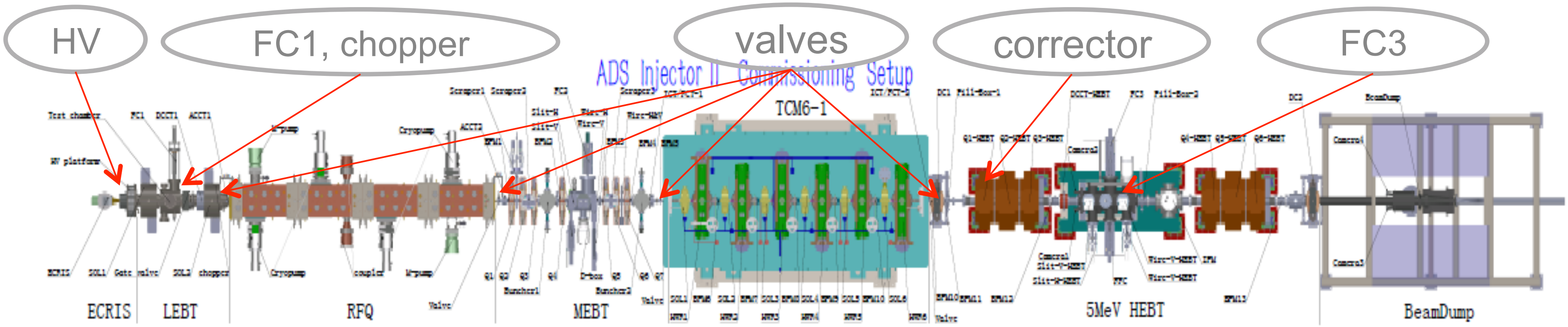
Beam state：2.5 MeV，2.7mA，CW，1 min

Procedure:

- Two paths are defined to do beam interlock, chopper and HV-IS&FC.
- Interlock threshold value of BPM was 1.0 volts, relatively lower. The RELAY to shutdown HV-IS and FC was disabled by triggers due to noise.
- Chopper can be recover automatically after 13 s.
- CW beam recovered after 13 s, and damaged the bellow the bending magnet. Vacuum interlock triggered valves and FC at LEBT. They are the actions of MPS.
- Valve was inserted, but 1 s later than FC was inserted.
- Secondary accident is the valve damage and the CM leak.

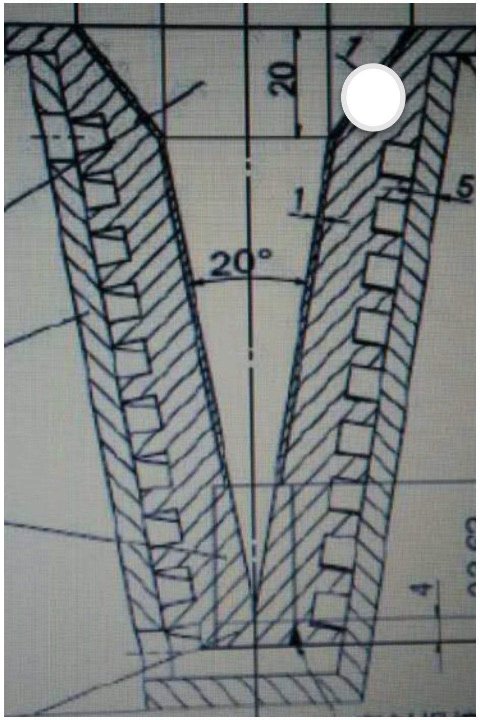


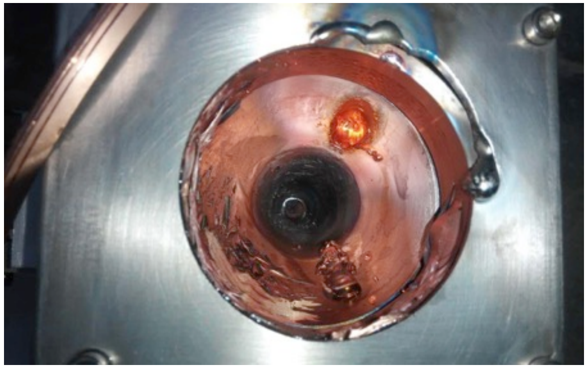
lessons and experiences



Dec. 4th 2015, 4.6 MeV, 3.9 mA, 18 kW, CW beam, 90s

- FC3 was a stopper, because 30 kW beam from RFQ was stopped before.
- The current of FC3 became unstable, but was ignored.
- Beam was off-centered by ~20 mm. It drilled a hole in FC3. MPS was triggered by the vacuum.
- CM1 was degraded. It was removed from tunnel to refurbish.



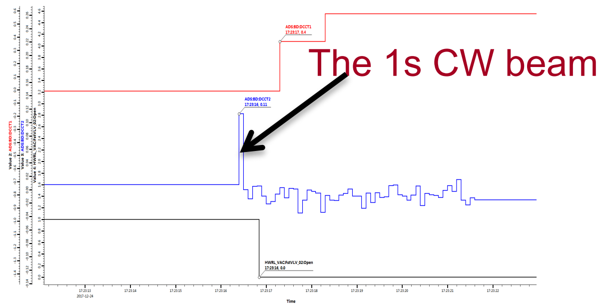


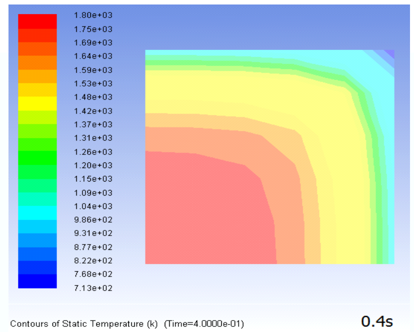
lessons and experiences

Date: Dec 24th 2017

18 MeV, 0.3 mA, 5kW, CW beam, 1s

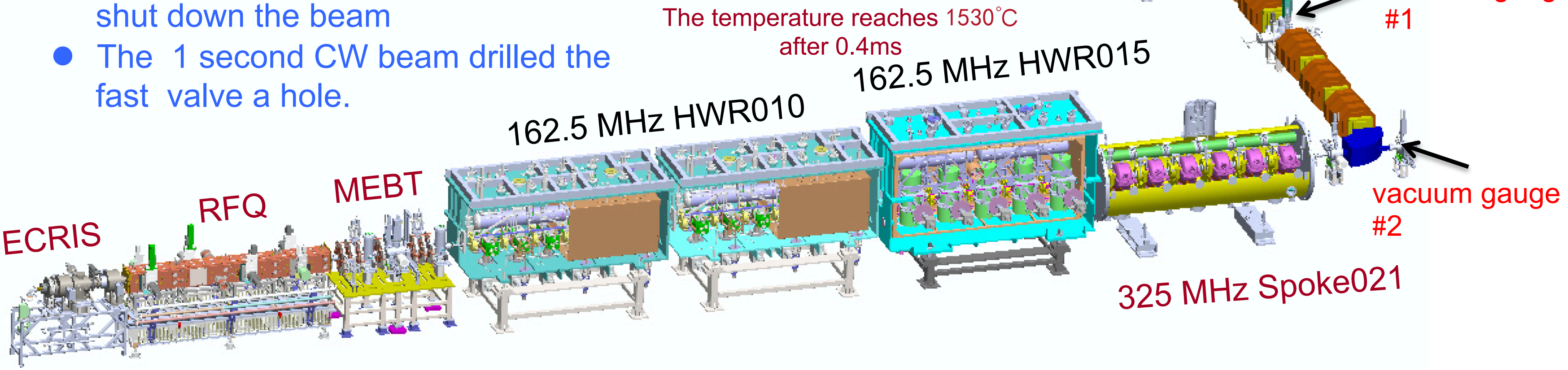
- The beam was ramped to CW after 50% duty factor
- At almost same, the vacuum at HEBT increases rapidly caused by the beam hitting on the beam dump.
- The vacuum gauge near the beam dump triage the fast valve for it is much close to the beam dump.
- After round 1 second, the other vacuum gauge near the bend magnet shut down the beam
- The 1 second CW beam drilled the fast valve a hole.





The temperature reaches 1530°C after 0.4ms


The broken fast valve



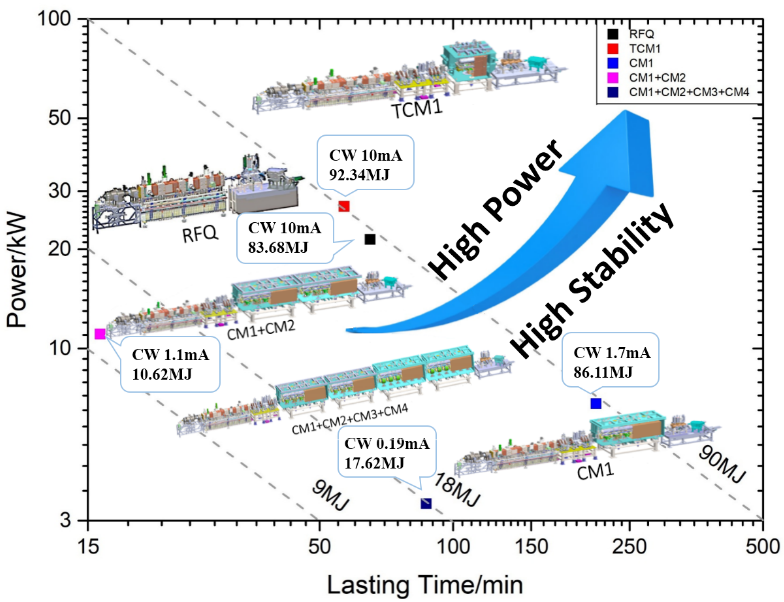
lessons and experiences

Lessons

- MPS, MPS, MPS …….
  1. Self-check function of MPS is important. To make sure every action is in order in advance.
  2. All trigger levels of detector in MPS should be defined carefully, and be free of noise, such as vacuum gauges, BPMs
  3. The executive component MUST be reliable.
  4. Do not bypass any MPS signal until it is well understood.
- The protection logic
  1. Interlock system itself should not recover beam until be reset manually, such as chopper.
  2. Action sequences of inserting devices should be clearly defined to minimize the damage of machine.
- Some other lessons
  1. Operation regulations
  2. Direction signal of beam on the FC/DUMP/target is important, for example, an optical camera system is very important at beginning stage.
  3. Double check lattice during beam power ramping up.
  4. Stop high power beam to analyze any abnormal or strange phenomena.
  5. ……

Summary

ACCELERATOR SEGMENTS	FIRST CW BEAM	MAX (MEV)	BEAM TIME (HOURS)	CW BEAM (HOURS)	CW CURRENT(MA)	CW POWER(KW)
RFQ	JUN.21, 2014	2.15	2036	70	11	23
TCM1(1HWR)	NOV.24, 2014	2.55	208	22.5	11	28
CM1(6HWRS)	JUN.24, 2015	5.3	400	20	4	21
CM1+CM2(6+6HWRS)	SEP.24, 2016	10.2	327	11	2.7	26
CM1+CM2+CM3+CM4	JUN.6, 2017	25	134.6	0.05	0.17	4.25
CM1+CM2+CM3+CM4	DEC.30, 2017	17.493	198.8	26.5	0.3	5.24



- The 25MeV SC demo facility has been built and run with proton beam successfully.
- Tens of kilowatt CW beam achieved in the SC front-end of Chinese ADS.
- The tuning procedures of high power CW beam has been demonstrated successfully.
- The dumper and radiation shielding is a limit for tuning higher power beam.
- Beam loss, higher power and operation stability will be the key issues to be demonstrated in the future.

Acknowledgements

Thanks for the help

LBNL: Derun Li’s RFQ team

J-Lab: Tom Powers, Bob Rimmer, Haipeng Wang ……

TRIUMF: Bob Laxdual, Ken Feng, Qiwen Zheng ……

ANL: Peter Ostroumov, Brahim Mustapha ……

FNAL: Sergei Nagaitsev, ……

MSU/FRIB: Xiaoyu Wu, Jie Wei, Qiang Zhao, ……

SNS/ORNL: Michael Plum, John Mammosser, John Galambos ……

SINAP: Zhengtang Zhao, Jianfei Liu, Li Wang ……

IHEP, HIT, PKU, THU, RIKEN, CEA/Saclay, IPN/Orsay, IAP ……

Looking forward more collaboration for the coming CiADS project!