Beam Commissioning activities 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
- Summary

Brief introduction of C-ADS SC Linac

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

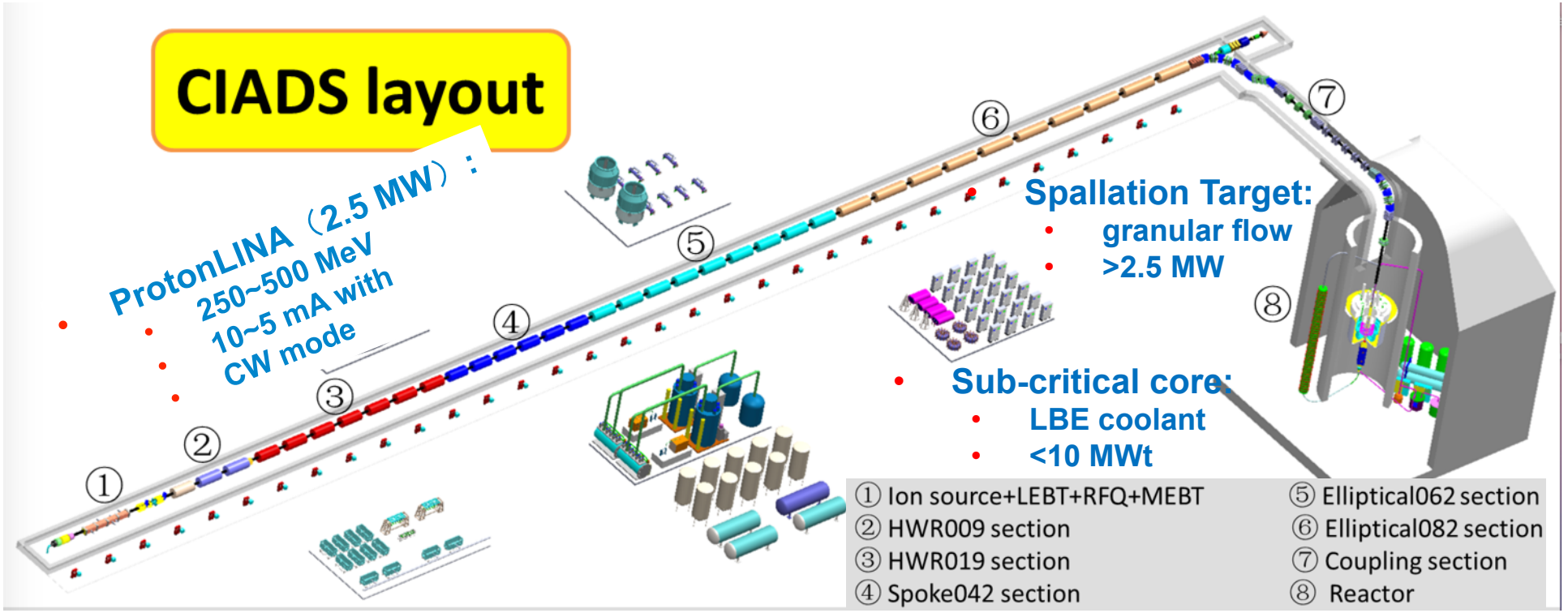
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

中国科学院高能物理研究所 中广核 CGN

Hefei Institutes of Physical Science
Chinese Academy of Sciences

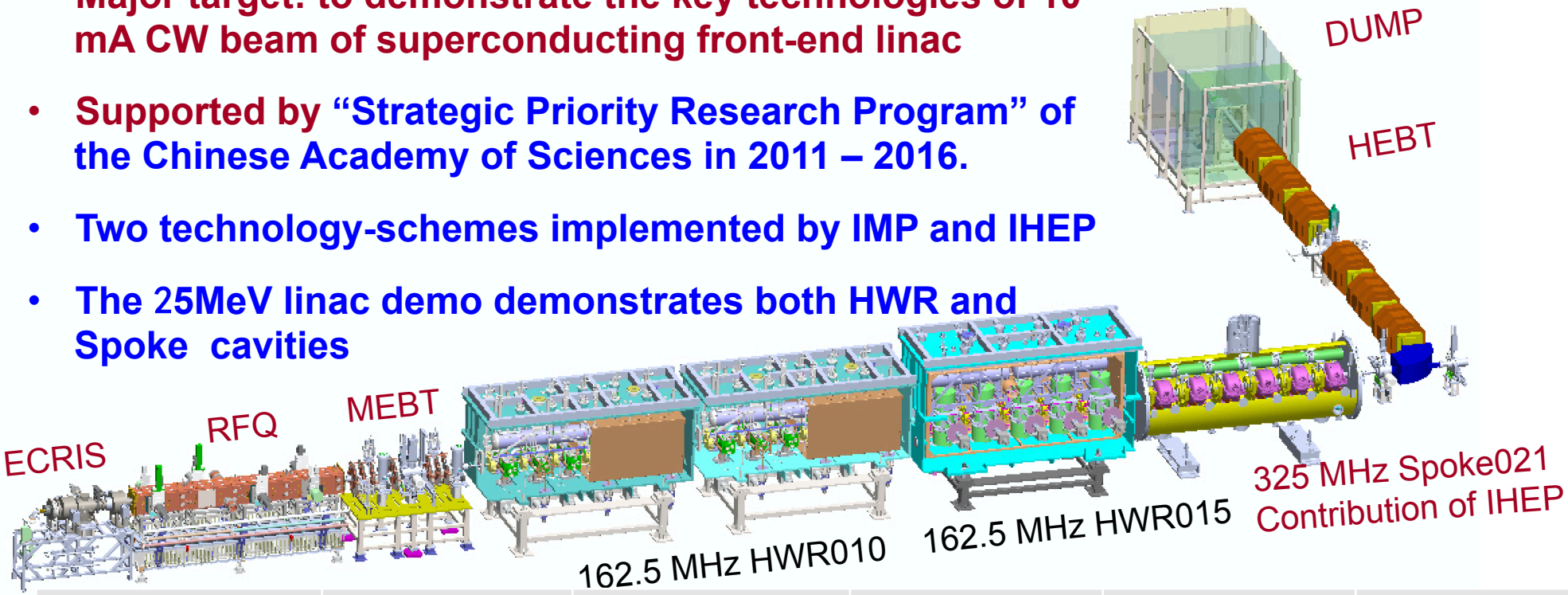
CIAE 中国原子能科学研究院

CIADS layout



Brief introduction of C-ADS SC Linac

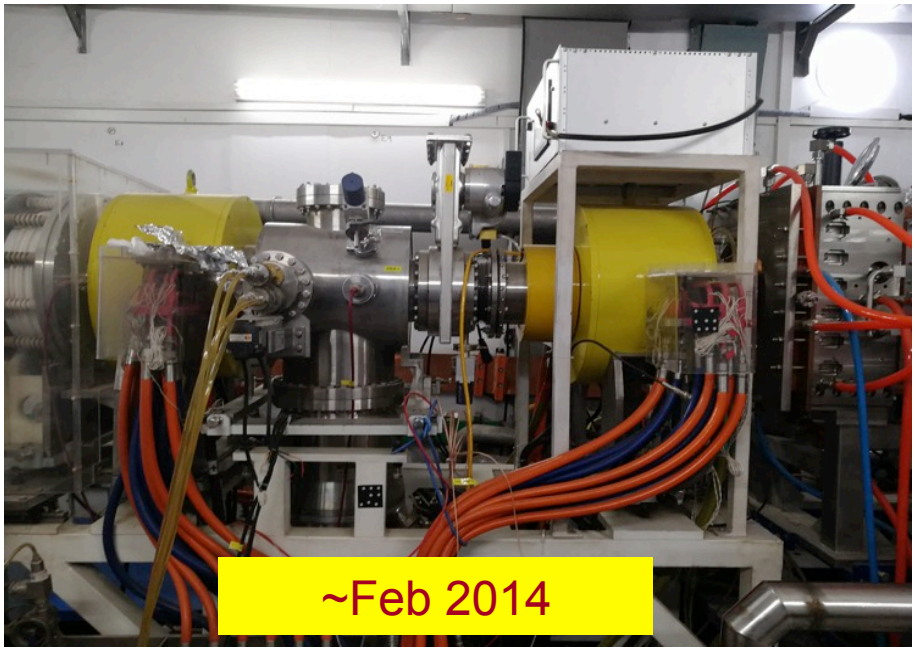
- **Major target: to demonstrate the key technologies of 10 mA CW beam of superconducting front-end linac**
- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences in 2011 – 2016.**
- **Two technology-schemes implemented by IMP and IHEP**
- **The 25MeV linac demo demonstrates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

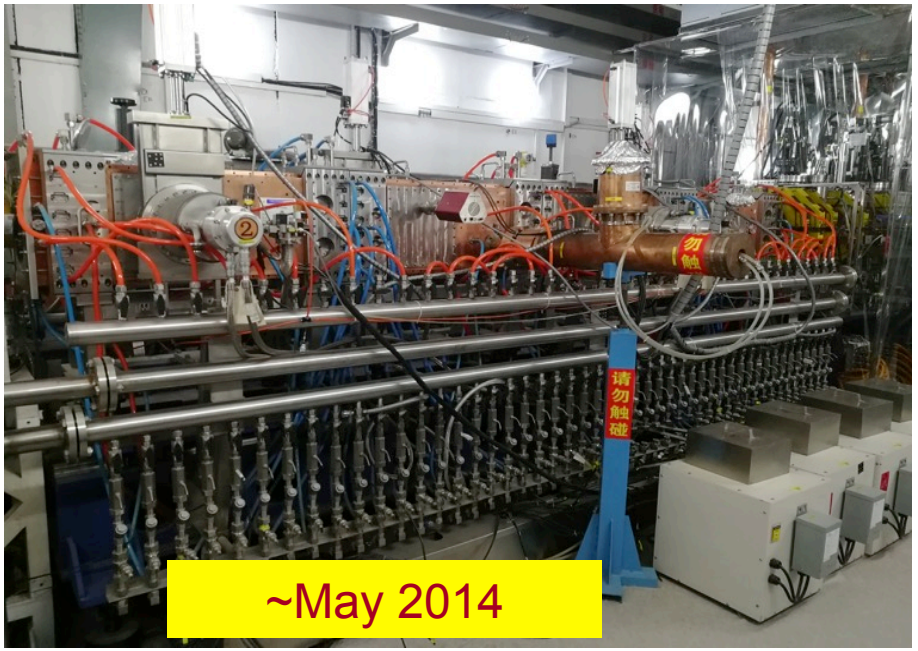


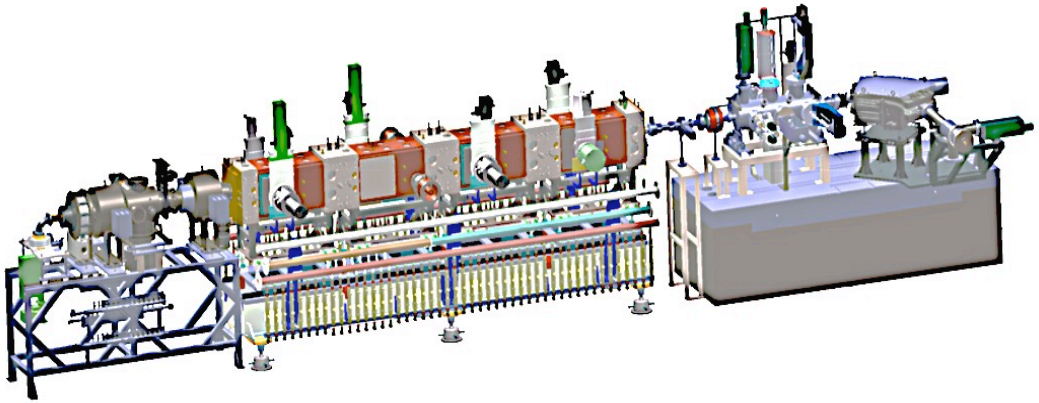
	RFQ/IMP	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
frequency	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
output energy	2.1 MeV	5 MeV	9 MeV	17 MeV	25 MeV
cavity type	4-vane	HWR010	HWR010	HWR015	Spoke021
cavity number	1	6	6	5	6

Brief introduction of C-ADS SC Linac

Phase1: ECR + LEBT + RFQ + DP



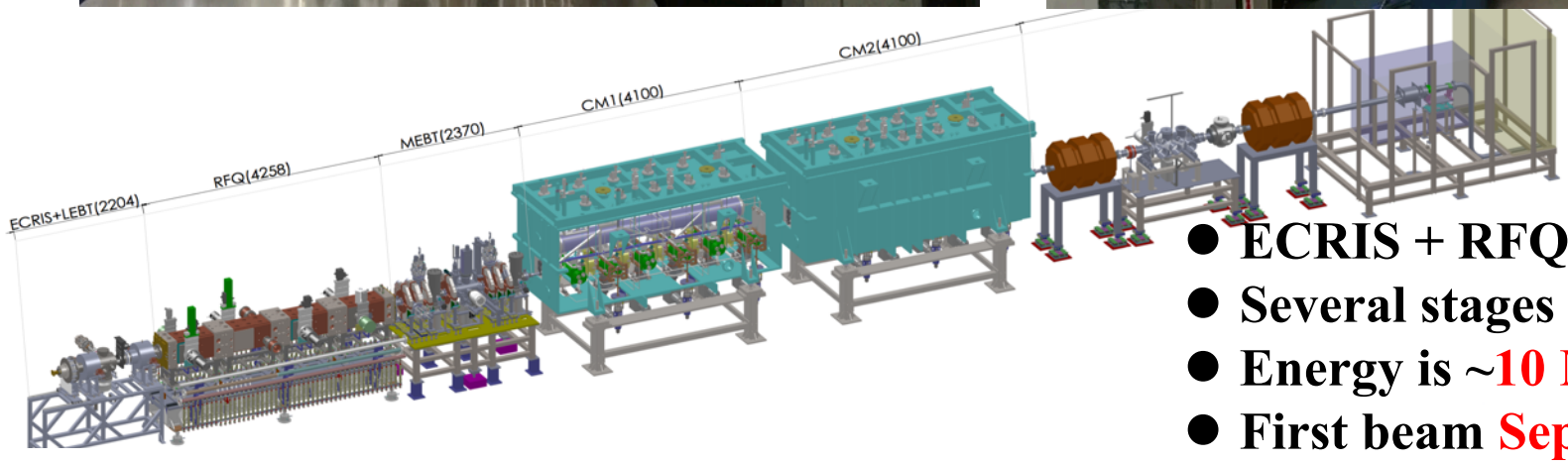




- ECR + LEBT + RFQ
- Energy is ~2.15 MeV
- First beam June 6th, 2014

Brief introduction of C-ADS SC Linac

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

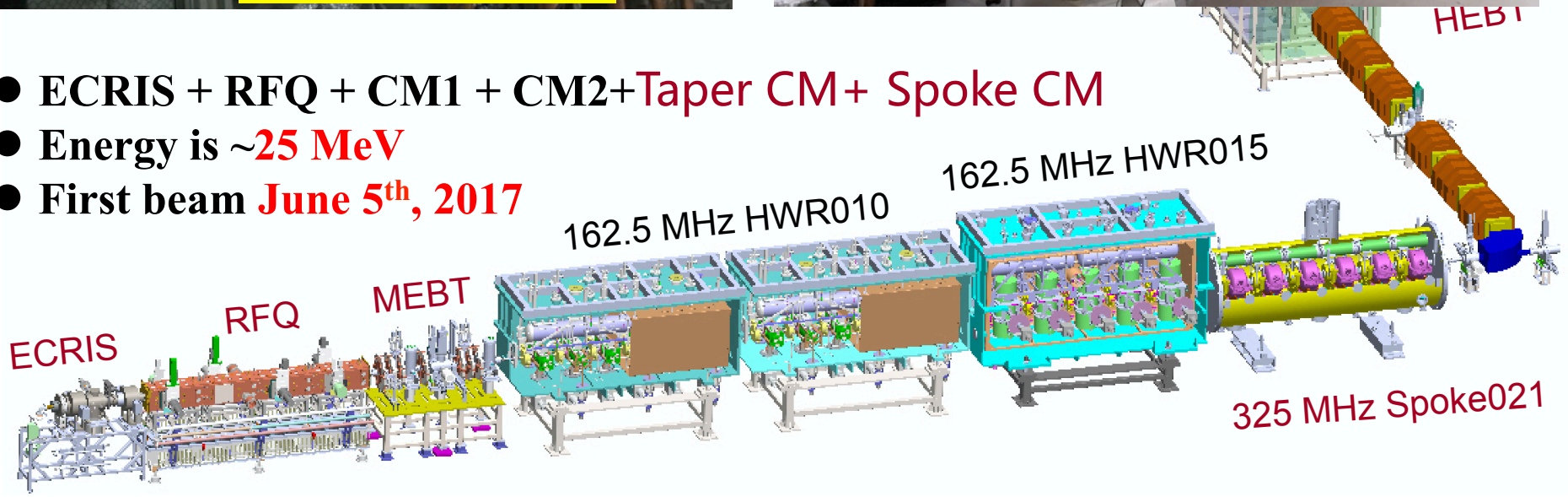


- ECRIS + RFQ + CM1 + CM2
- Several stages in the two years
- Energy is ~10 MeV
- First beam September 15th, 2016

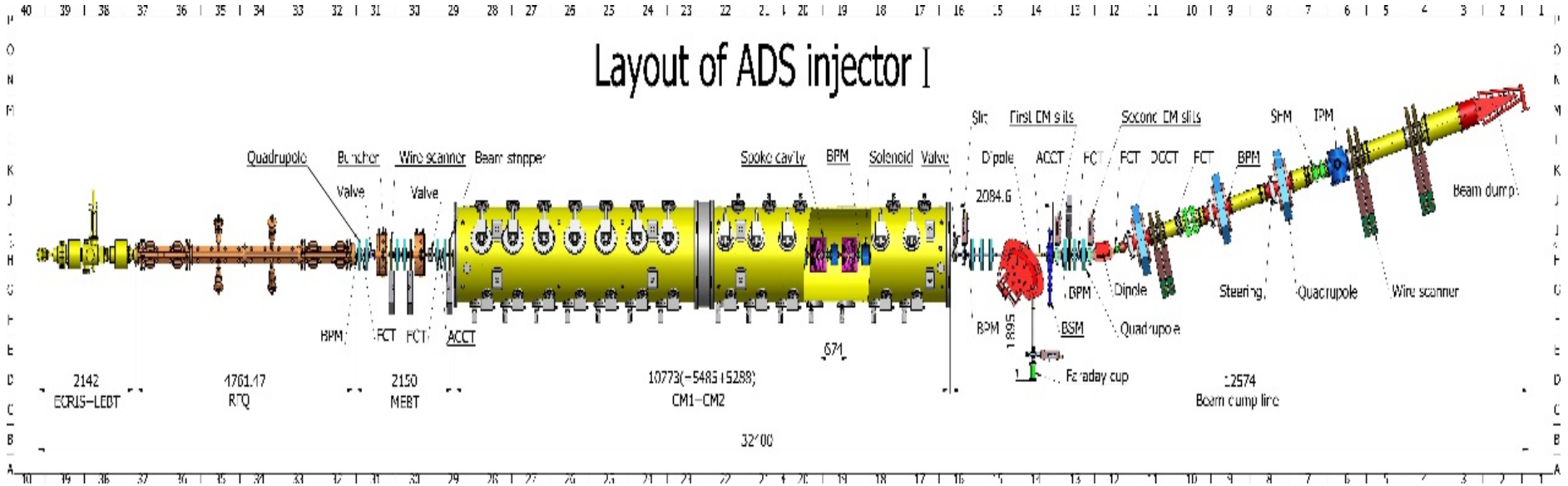
Brief introduction of C-ADS SC Linac

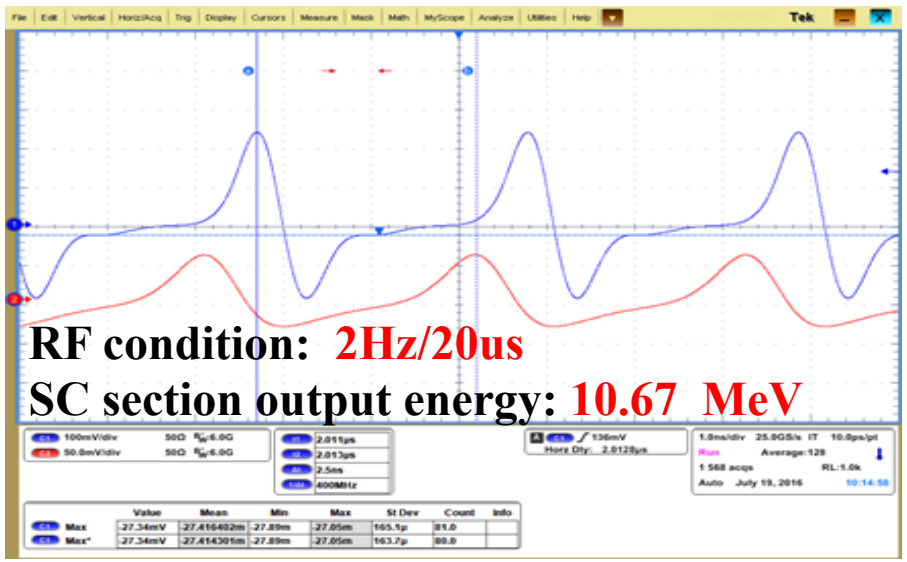
Phase3: ECR+LEBT+RFQ+2×HWR_CM+Taper CM+ Spoke CM+HEBT

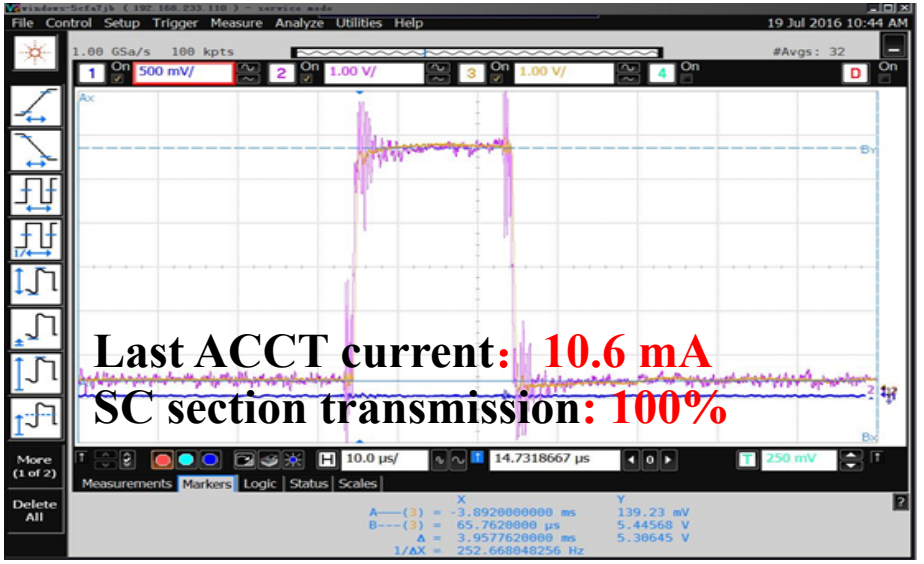
- **ECRIS + RFQ + CM1 + CM2+Taper CM+ Spoke CM**
- **Energy is ~25 MeV**
- **First beam June 5th, 2017**



Brief introduction of C-ADS SC Linac







Outline

- Brief introduction of C-ADS superconducting Linac demo
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Commissioning procedures of Linac

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

Commissioning procedures of Linac

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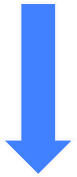
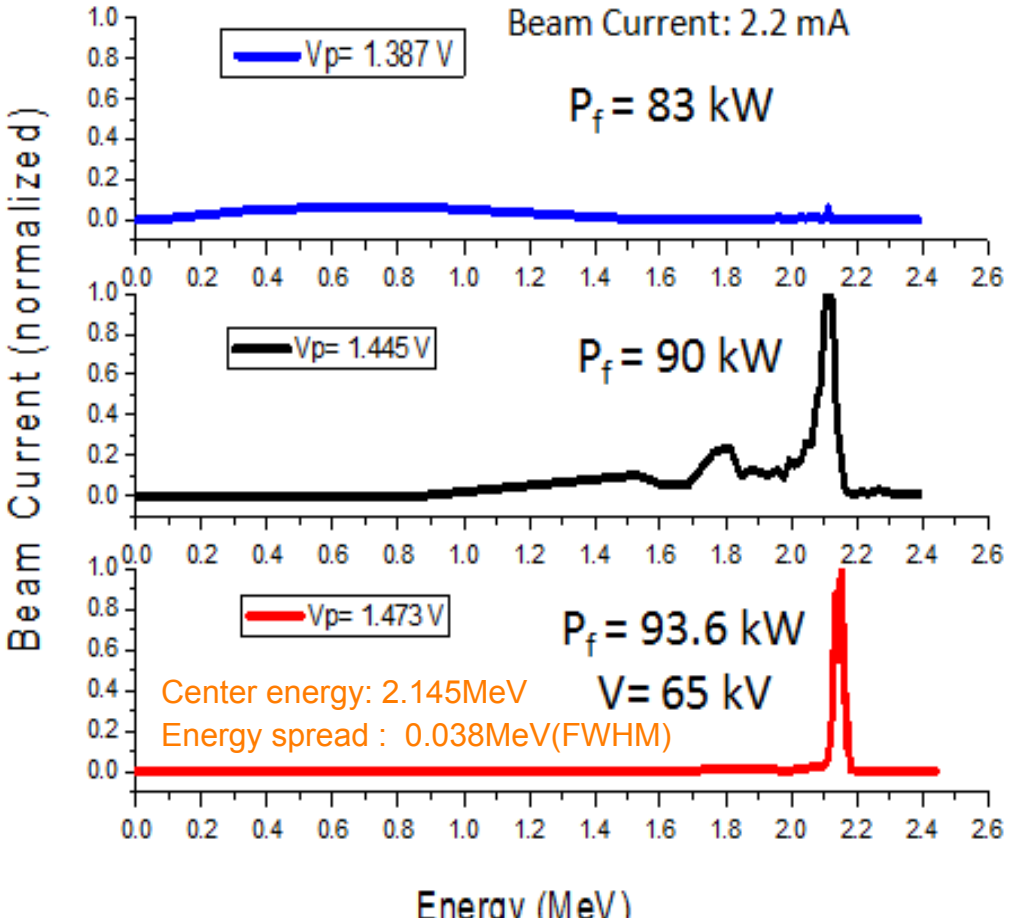
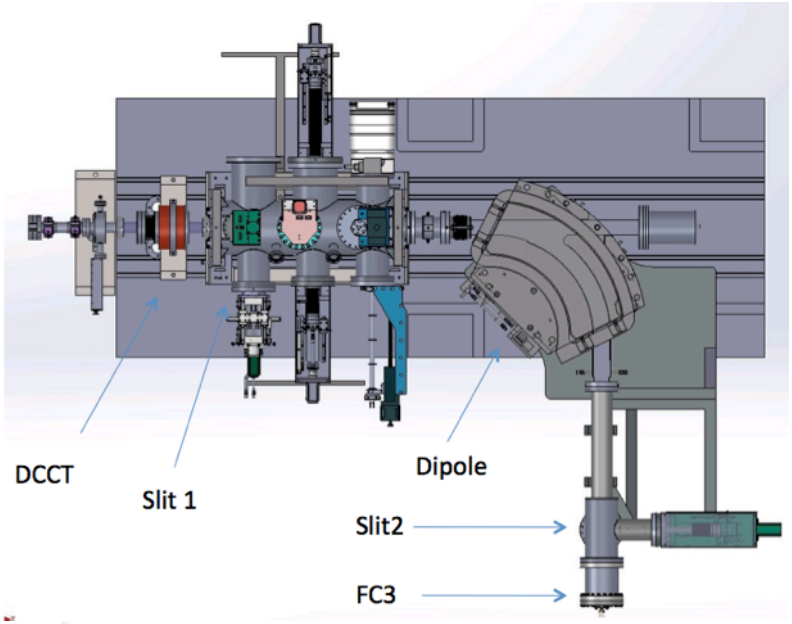
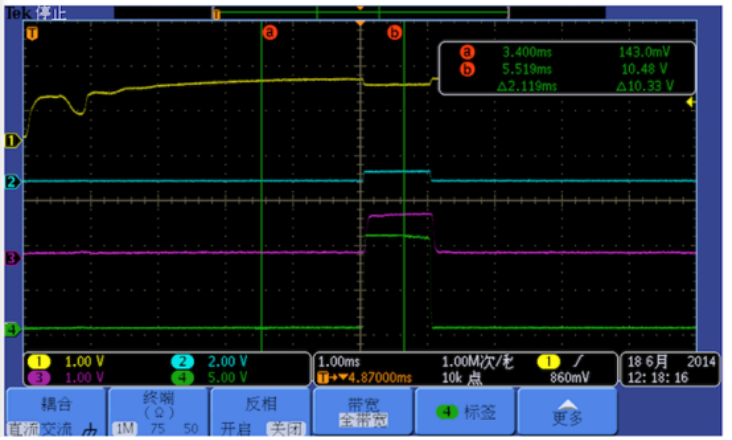


- Hardware calibration – To verify the parameter of the key hardware
  - The verification of hardware array, calibration of BPM offset, phase scan et al
- Beam distribution reconstruction – To match the beam between different section
  - The emittance measurement, lattice setting, matching et al
- Beam 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





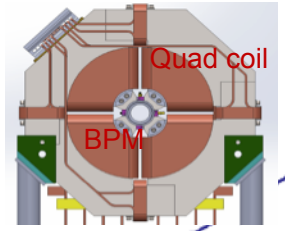


RFQ Voltage calibrated with energy spread, more precise than transmission.

Commissioning procedures of Linac

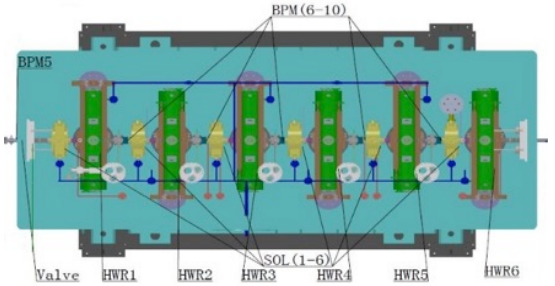
Hardware calibration

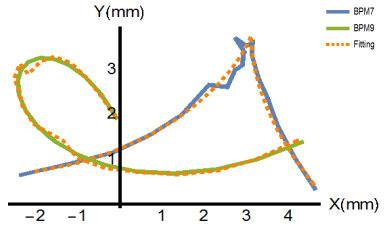
Normal-T BPMs @ BT

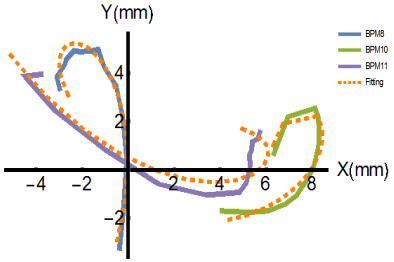


- The special structure
- The 'null comparison' method

Cold BPMs@SC Linac

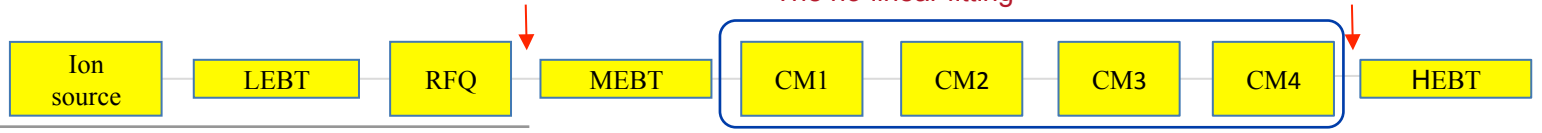






$$\begin{pmatrix} X_0 \\ X_0' \\ Y_0 \\ Y_0' \end{pmatrix} = M^{-1} \cdot \begin{pmatrix} X_1^{(1)} \\ X_1^{(2)} \\ \cdots \\ Y_1^{(1)} \\ Y_1^{(2)} \\ \cdots \end{pmatrix}$$

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

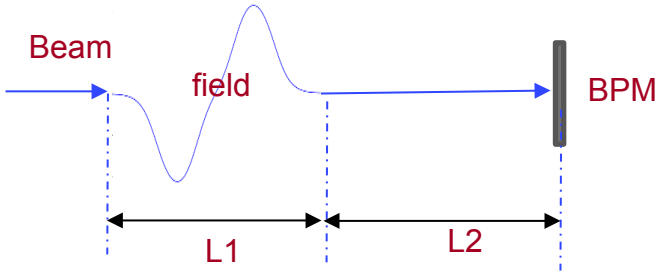


BPM	X (mm)	Y (mm)
BPM1	0.449	0.559
BPM2	-0.026	0.432
BPM3	0.063	-0.325
BPM4	0.434	0.158

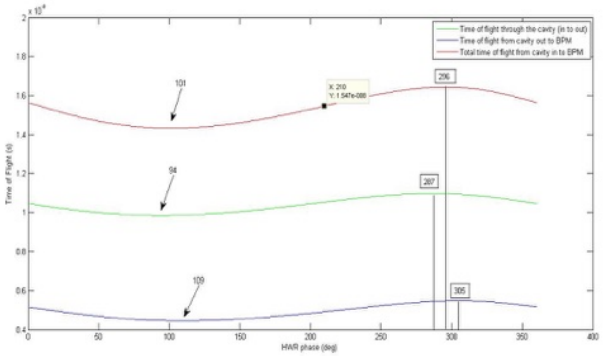
The calibration results of Cold BPMs

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

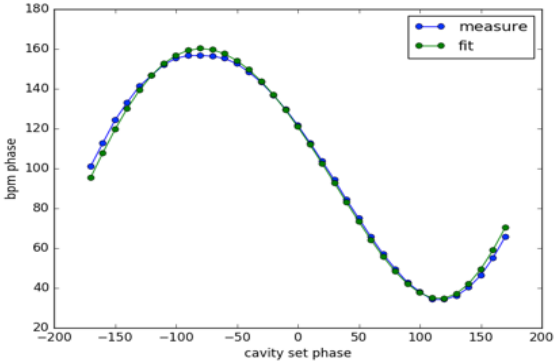
Hardware calibration



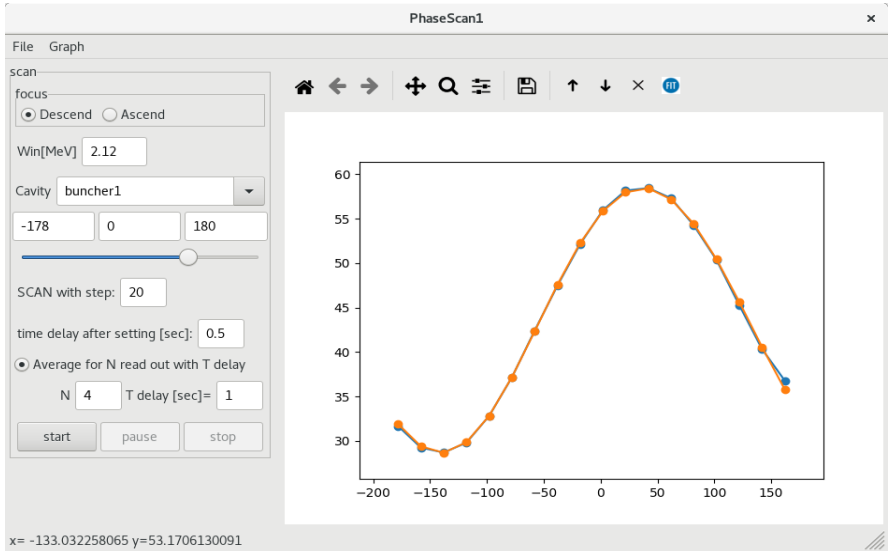
The physical model of phase scanning



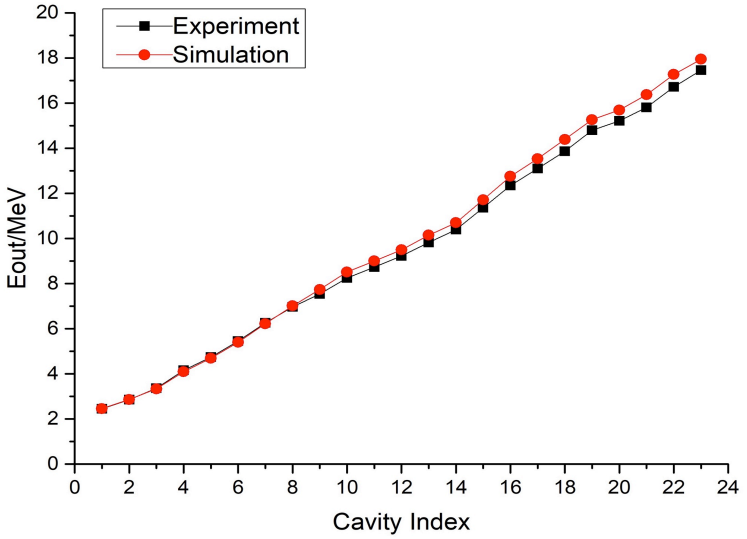
The BPM phase VS RF phase



The fitted phase scanning curve

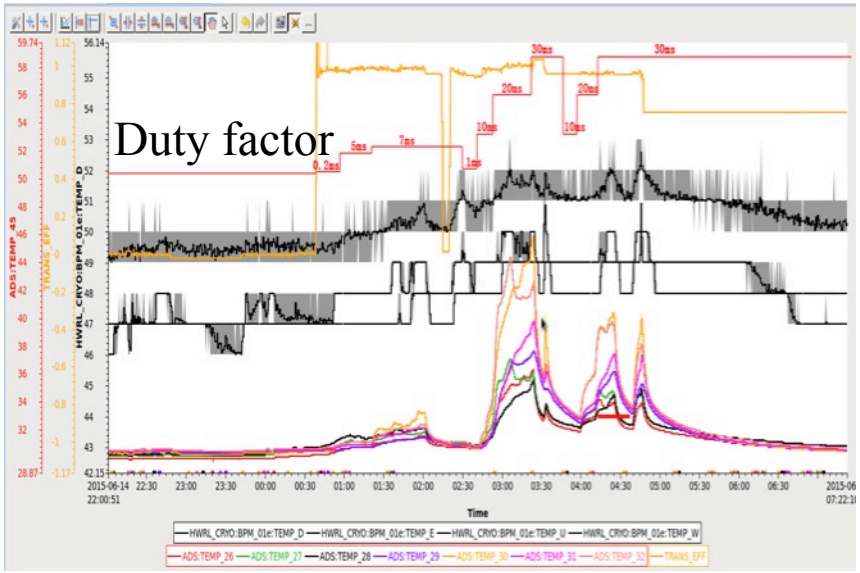


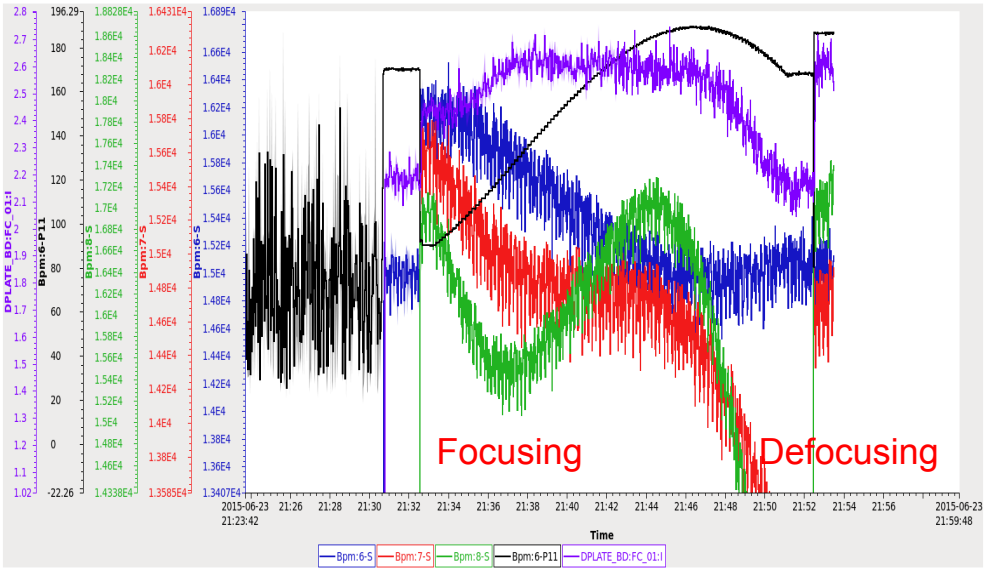
The developed phase scanning APP



The comparison between simulation and experiment

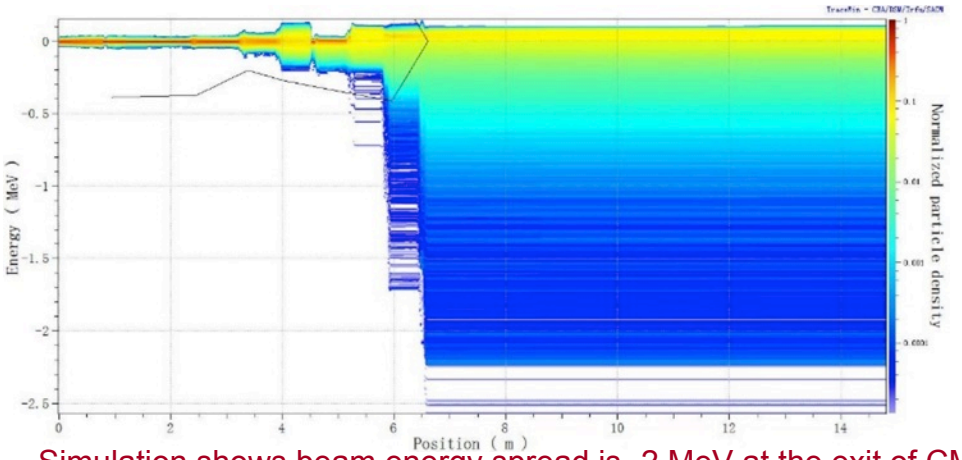
Hardware calibration





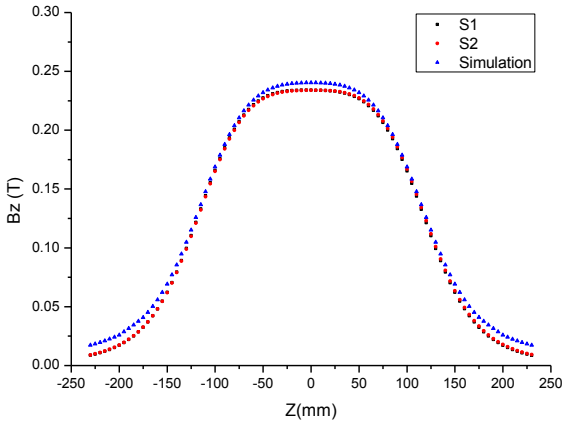
HWR2, rising edge is the focusing edge, opposite to other cavities.

- 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.

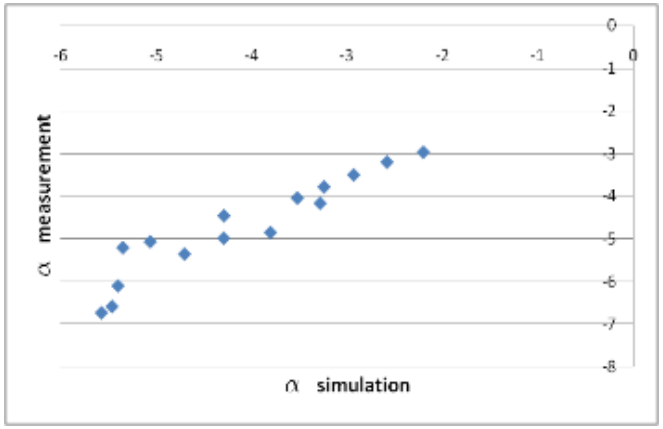


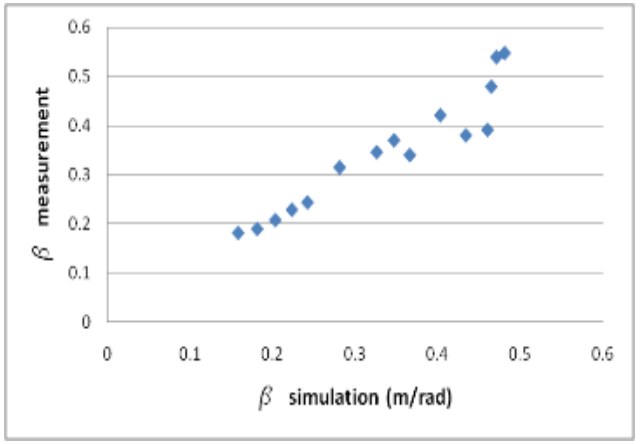
Simulation shows beam energy spread is -2 MeV at the exit of CM

Beam distribution reconstruction

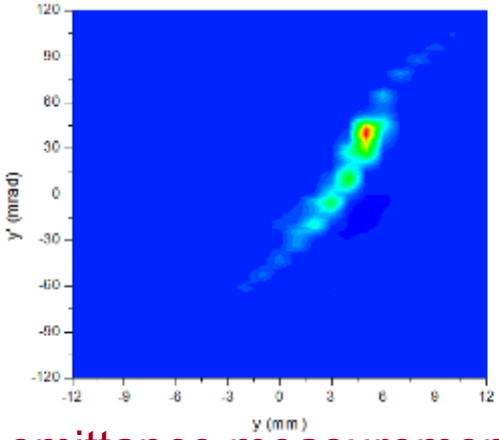


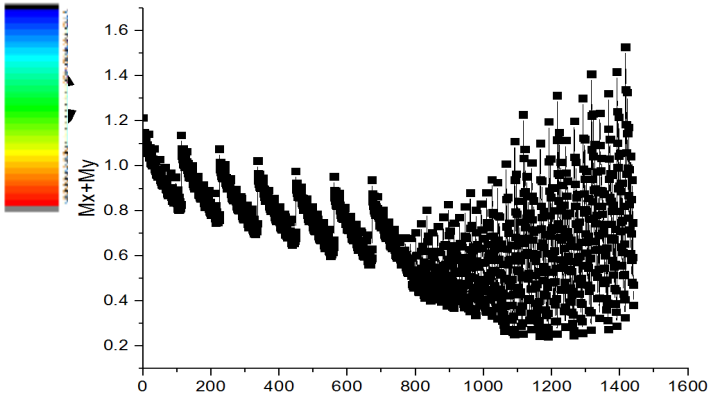
solenoid field measurement





TWISS parameters measurement and simulation



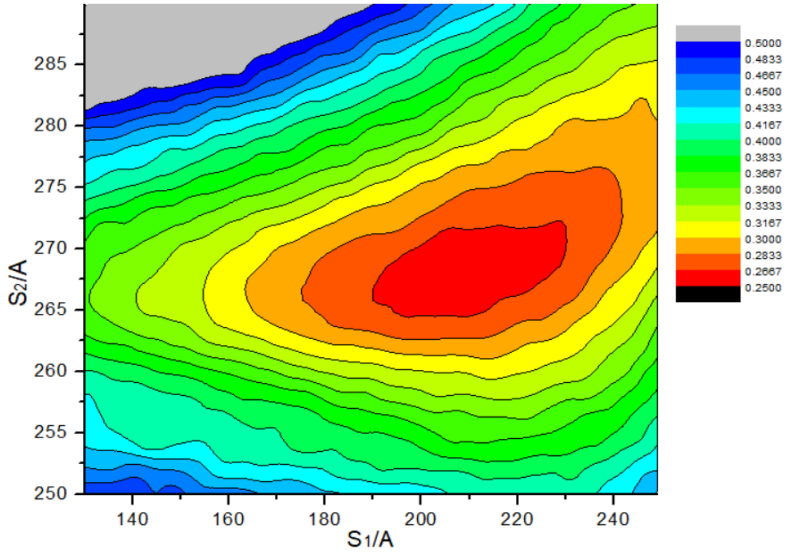


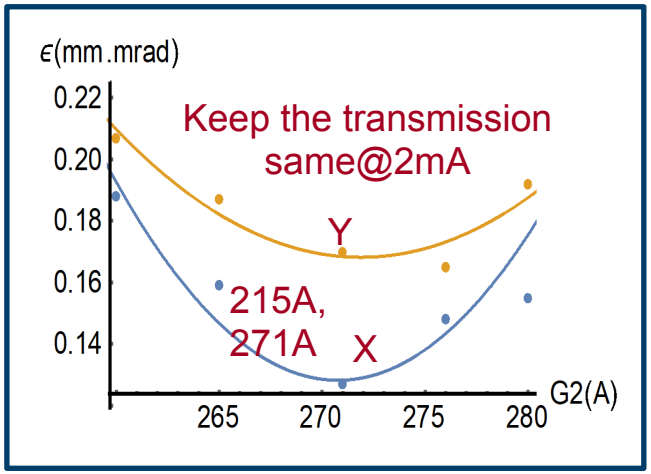
emittance measurement at LEBT

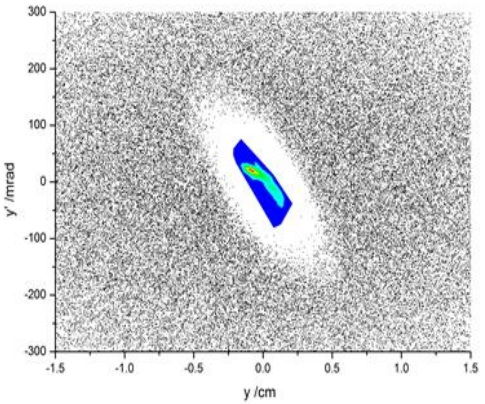
Parameters	value	unit
ε	0.13	πmmmrad
α	0.26	
β	0.3	m/rad
SSC factor	0.9	

Commissioning procedures of Linac

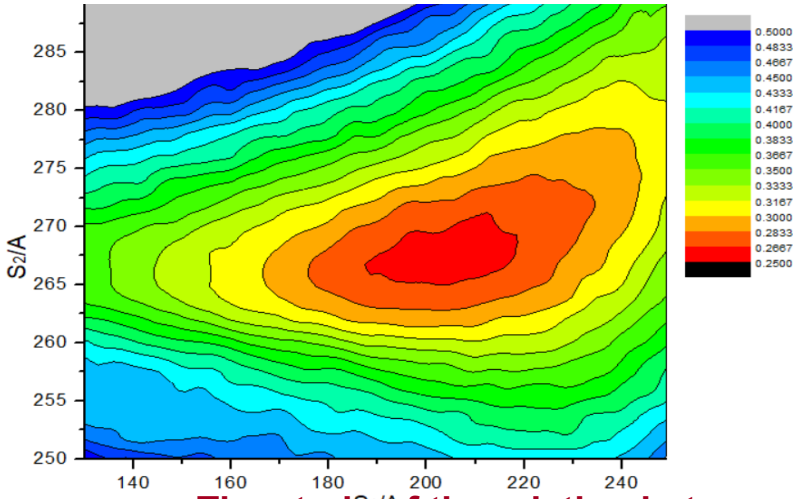
Beam matching from LEBT to RFQ

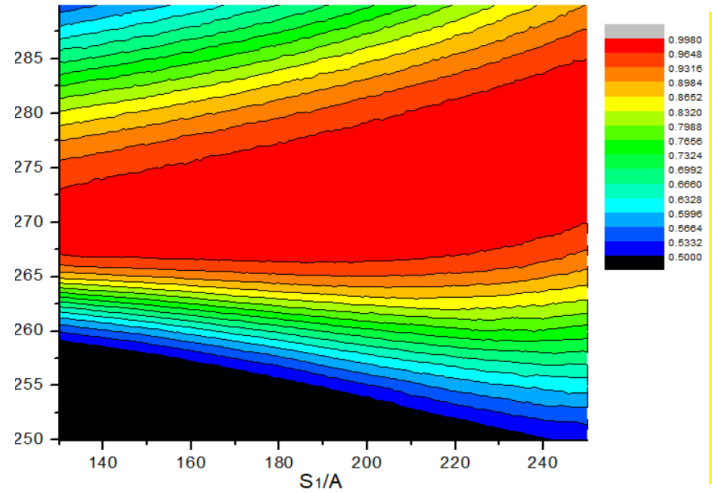






Beam emittance VS acceptance of RFQ



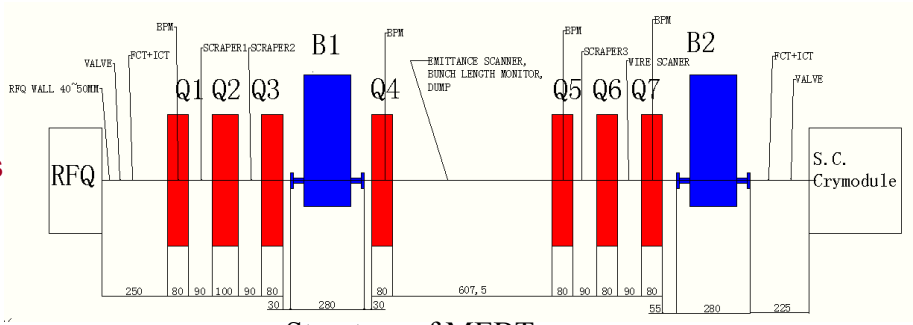


The study of the relation between transmission and emittance

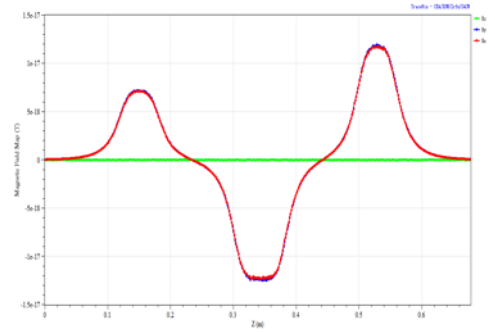
Maximum transmission is not enough, matching tuning should be considered for the high beam power linac!

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

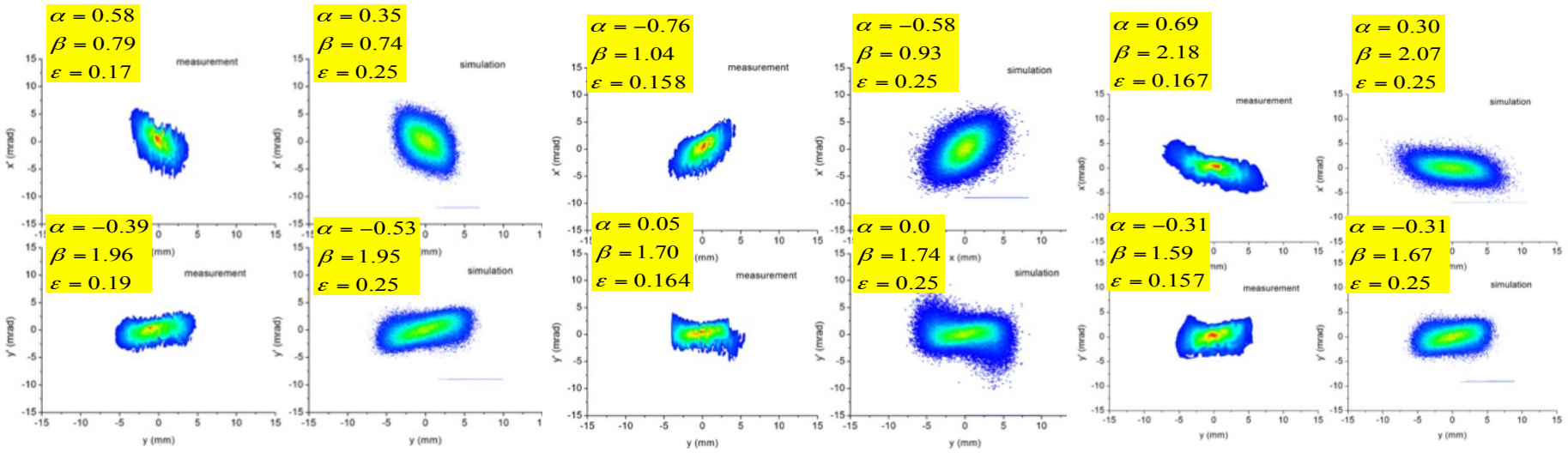


Structure of MEBT



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



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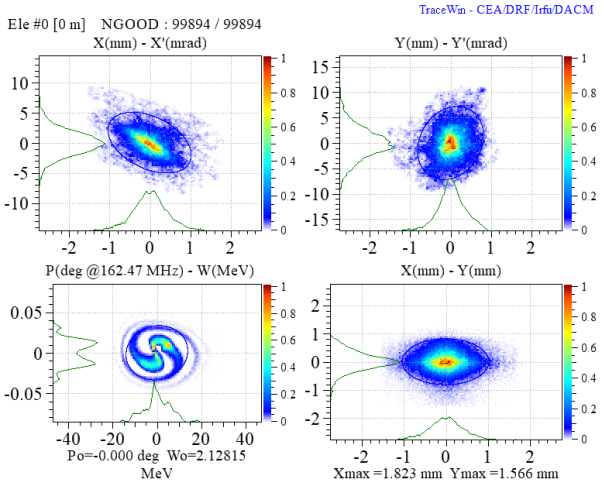
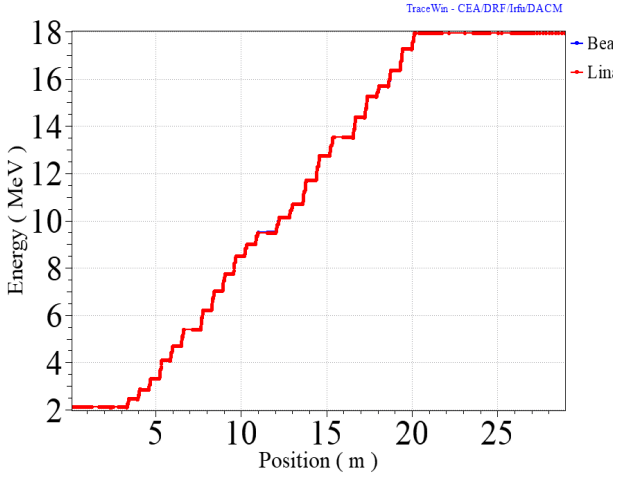
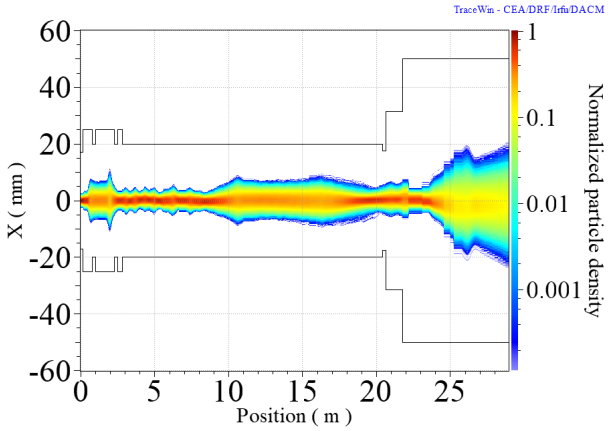


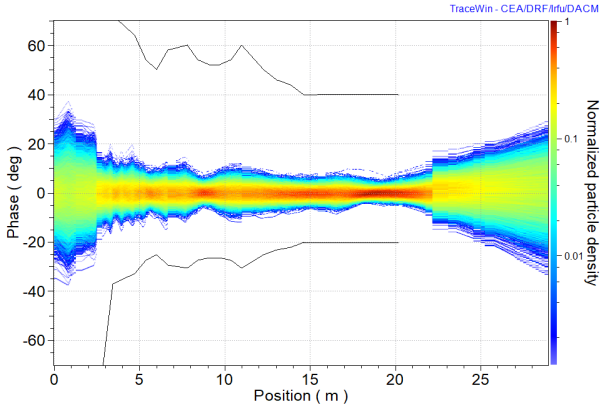
The reconstructed beam distribution at the exit of RFQ



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			

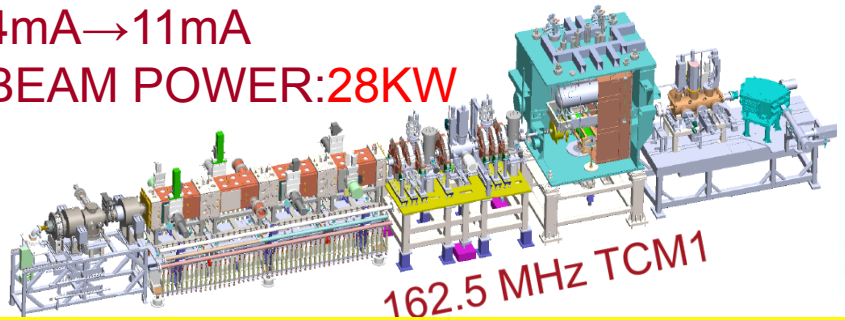
	Cavity_Nb	Cavity Epk	Beam Epk	Phase	Solenoid_Nb	Current (A)
CM1	1	18.00	16.57	-36	1	94.65
	2	18.00	17.68	-34	2	99.28
	3	20.09	18.87	-32	3	102.36
	4	27.00	27.52	-27	4	109.82
	5	22.44	21.19	-25	5	91.56
	6	24.74	25.40	-29	6	113.63
CM2	1	29.94	30.38	-30	1	103.09
	2	28.64	28.75	-27	2	93.57
	3	30.00	26.50	-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

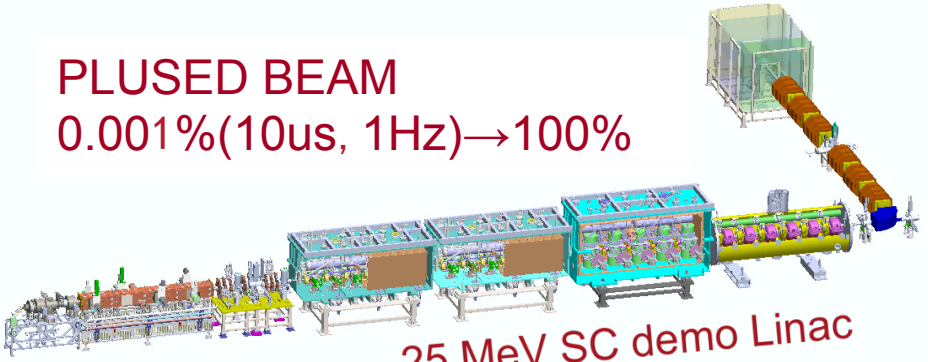
Commissioning procedures of Linac

Multi-particles step

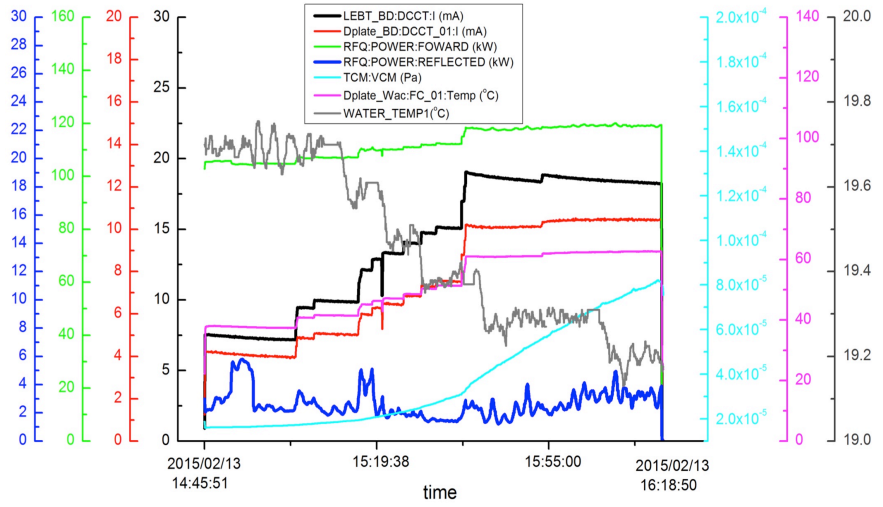
CW BEAM
4mA→11mA
BEAM POWER:28KW

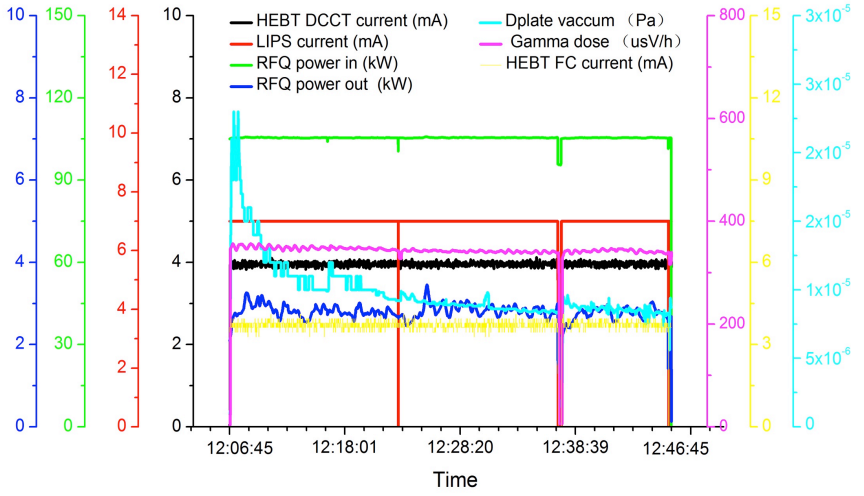


PLUSED BEAM
0.001%(10us, 1Hz)→100%

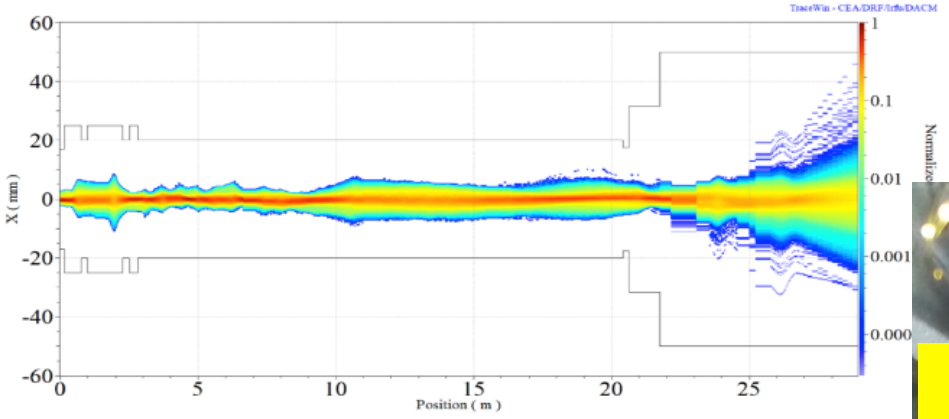


The comprehensive monitoring system including vacuum, temperature, beam current et al has been built to guarantee the power ramping process

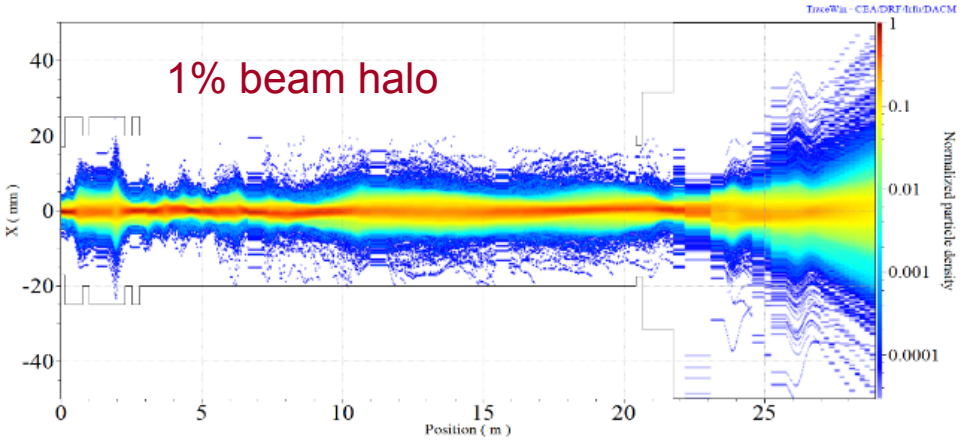




Beam tuning with high power

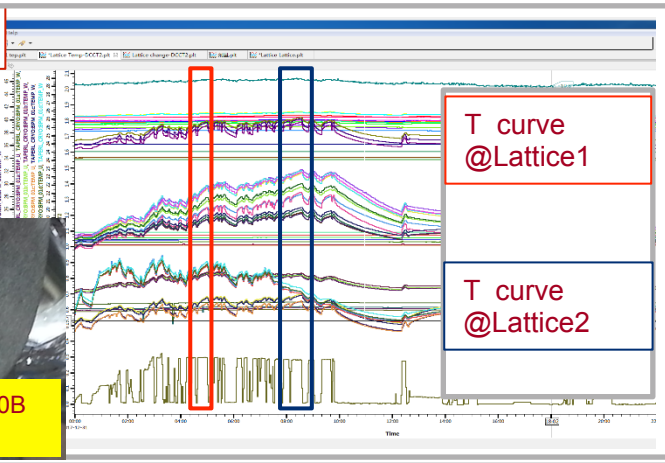


The beam behavior at normal condition

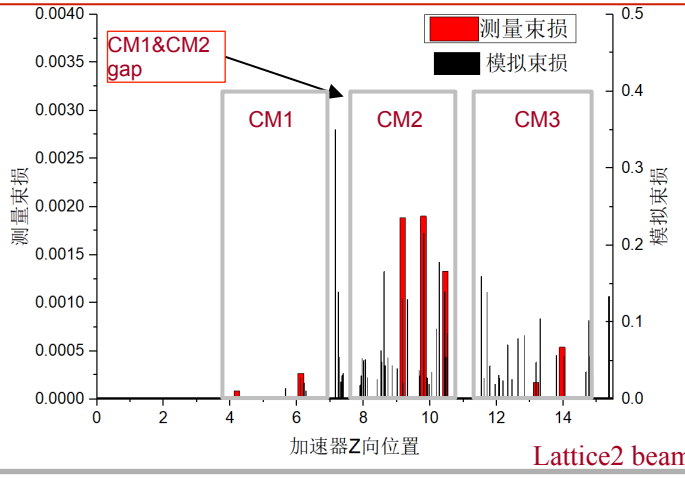


The beam behavior of the beam with beam halo

Beam loss



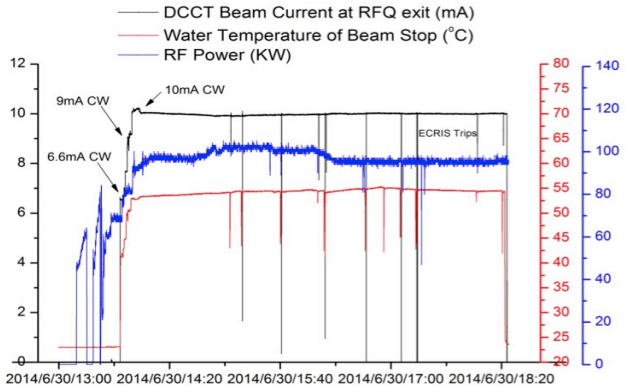
Comparison between simulation and experiment



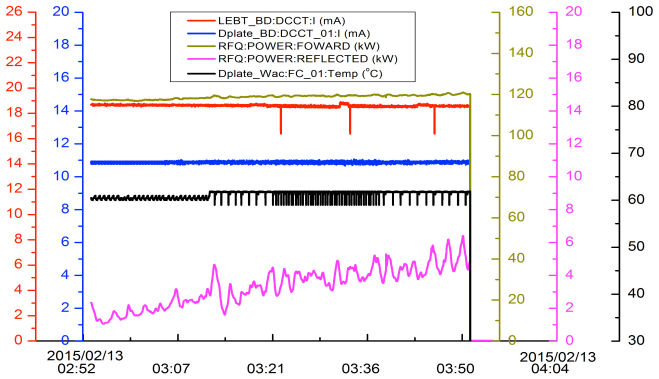
The beam loss detection by the low temperature sensors

Commissioning procedures of Linac

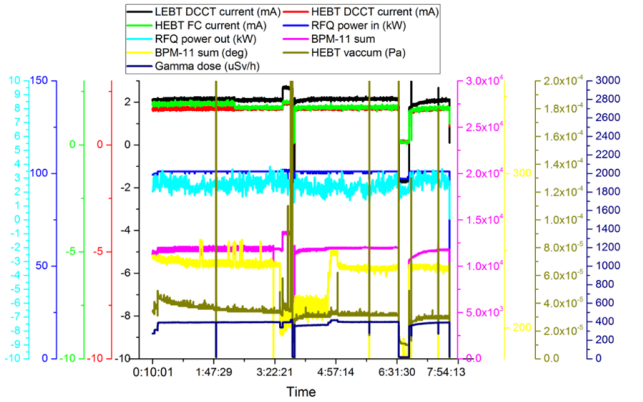
Beam tuning with high power



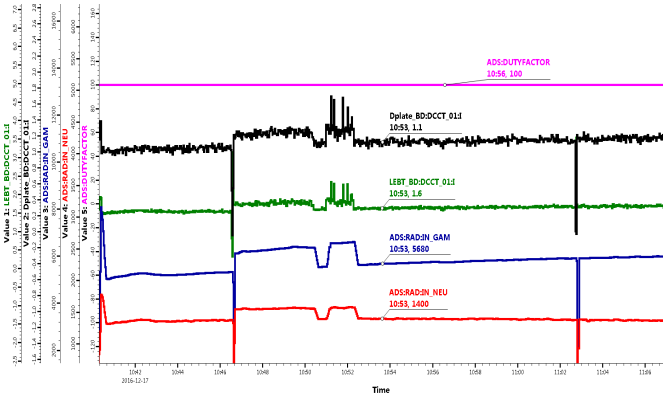
RFQ:Jun.30th,2014;10mA,2.15MeV,CW, max of lasting time:265min,beam power 21.5kW.



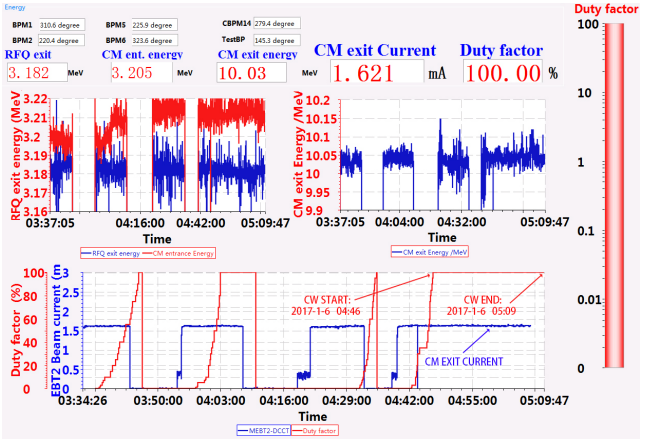
TCM1:Feb.13th,2015;~11mA,2.55MeV,CW, 60min,beam power 28kW.



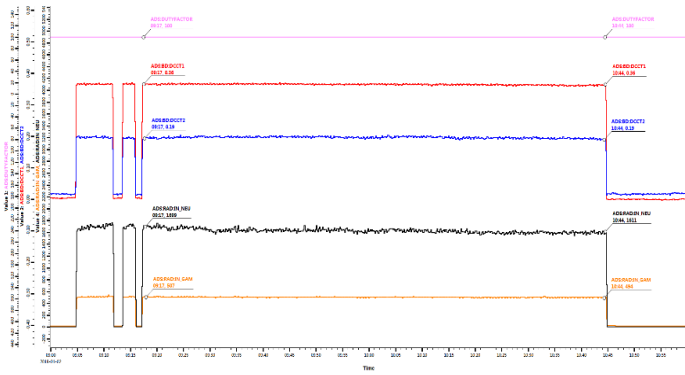
CM1:Jan.3rd,2016;1.7mA,4.02MeV,CW, max of lasting time:210min,beam power 6.8kW.



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



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



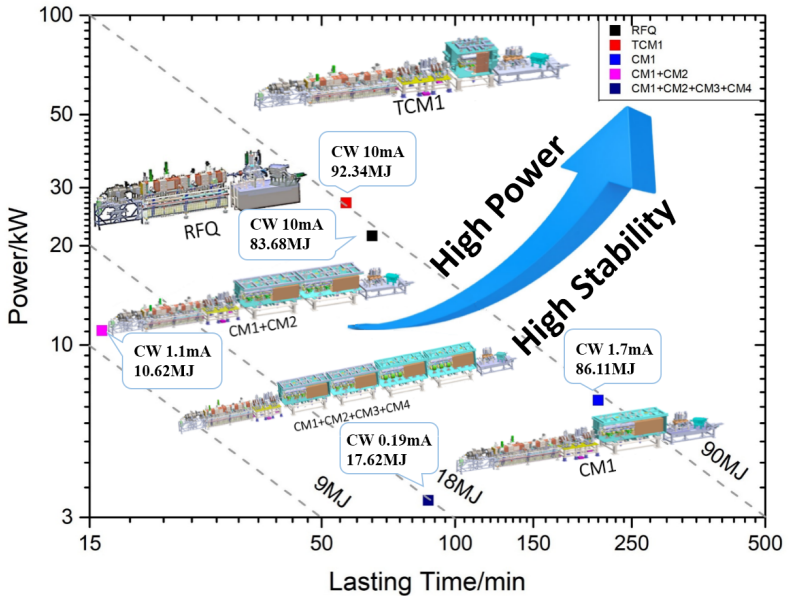
CM1+CM2+CM3+CM4:Jan.2nd,2018;0.293mA,18MeV, CW, max of lasting time:87min,beam power 5kW.

Outline

- Brief introduction of C-ADS superconducting Linac demo
- Commissioning procedures of CW SC Linac demo
- Summary

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

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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!