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
Institute of High Energy Physics Chinese Academy of Sciences

Beam diagnostics for CW and pulsed proton superconducting linac

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Outline

- Review beam diagnostics for CW and pulsed proton superconducting linac
- Beam diagnostics developed for CADS 10-25 MeV CW proton linac
  - Beam current
  - Position, phase
  - Transverse profile, emittance
  - Energy spread
  - Longitudinal bunch shape
- Lessons, challenges and improvements

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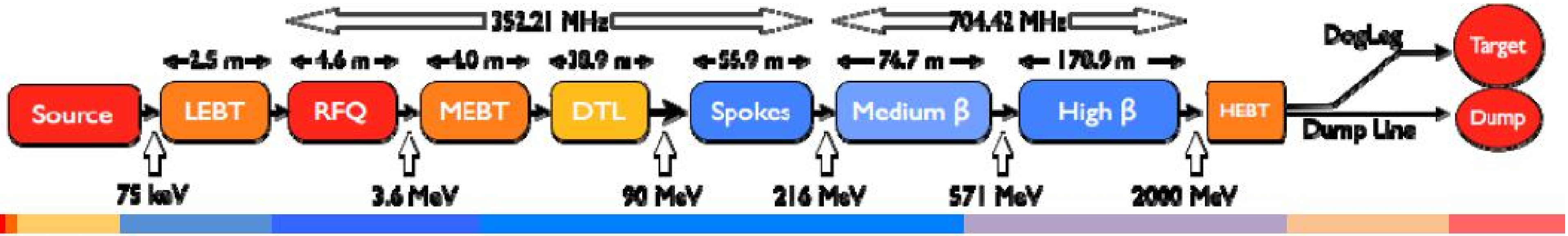
Hadron Superconducting Linac Worldwide

	Beam	Energy (MeV/u)	Start Energy of SC Section （MeV/u）	frequency （MHz）	Ipeak （emA）	Imean （emA）	Operation mode	Status
SNS	H^-, H^+	1000	186	402.5	38	1.6	pulsed	Operation
PIP-II	H^-, H^+	800	2.1	162.5	5	1	Pulsed/CW	Construction
ESS	H^+	2000	90	352.2	62.5	2.5	pulsed	Construction
IFMIF	D^+	40	5	175	125	125	CW	Construction
SARAF	H^+, D^+	40	1.5	176	5	5	CW	Operation
CADS	H^+	25	2.1/3.2	162.5/325	10	10	CW	Operation
ATLAS	H^+, ions	20	0.3	60.625	0.01	0.001	Pulsed/CW	Operation
SPIRAL2	H^+, D^+, ions	33/20/15/8.5	0.75	88.0525	5/5/1	5/5/1	CW	Construction
ROAN	$H^+ \sim {}^{238}U$	600/200	0.5	81.25	0.66/0.008	0.66/0.008	CW	Construction
FRIB	$H^+ \sim {}^{238}U$	200	0.5	81.25	0.7	0.7	CW	Construction
……								

Beam instruments for the proton SCL

- **Beam current:** Toroid, WCM, Faraday cup, EIDs
- **Beam position and phase:** Warm and cold BPMs
- **Beam transverse profile:** scrapers, wire scanner, grid, IPM, BIF, imaging, e-beam scanner
- **Beam transverse emittance:** Slit-grid, Allison, pepper-pot, phase space scans
- **Beam energy:** TOF
- **Energy spread:** Magnetic spectrometer, Rutherford scattering, Schottky signal, Doppler system
- **Longitudinal bunch shape:** BSM-INR Feschenko, FFC, BEM-SPIRAL2,
- **Beam loss:** Halo ring, ion chamber, scintillator-based detector, diamond/silicon detector, thermometer, neutron detector

ESS linac beam instruments



System	LEBT	RFQ	MEBT	DTL	Spk	MBL	HBL	HEBT	A2T	DumpL	TOTAL
Position	0	0	7	15	14	9	21	16	12	4	98
Ionization profile	0	0	0	0	1	3	1	0	0	0	5
Fluorescence profile	1	0	2	0	0	0	0	0	1	0	4
Ionization chamber	0	0	0	5	52	36	84	49	37	6	269
Neutron detector	0	0	5	11	14	4	0	1	0	0	35
Wire scanner	0	0	3	0	3	3	1	3	1	0	14
Bunch Shape	0	0	1	0	1	1	0	0	0	0	3
Faraday cup	1	0	1	2	0	0	0	0	0	0	4
Current monitor	1	1	4	5	0	1	1	2	3	2	20
Emittance	1	0	1	0	0	0	0	0	0	0	2
Aperture monitor	0	0	0	0	0	0	0	0	3	1	4
Doppler	1	0	0	0	0	0	0	0	0	0	1
Multi-wire grid	0	0	0	0	0	0	0	0	1	0	1

Tom shea, IBIC2017 mo2ab2

FRIB driver linac diagnostics

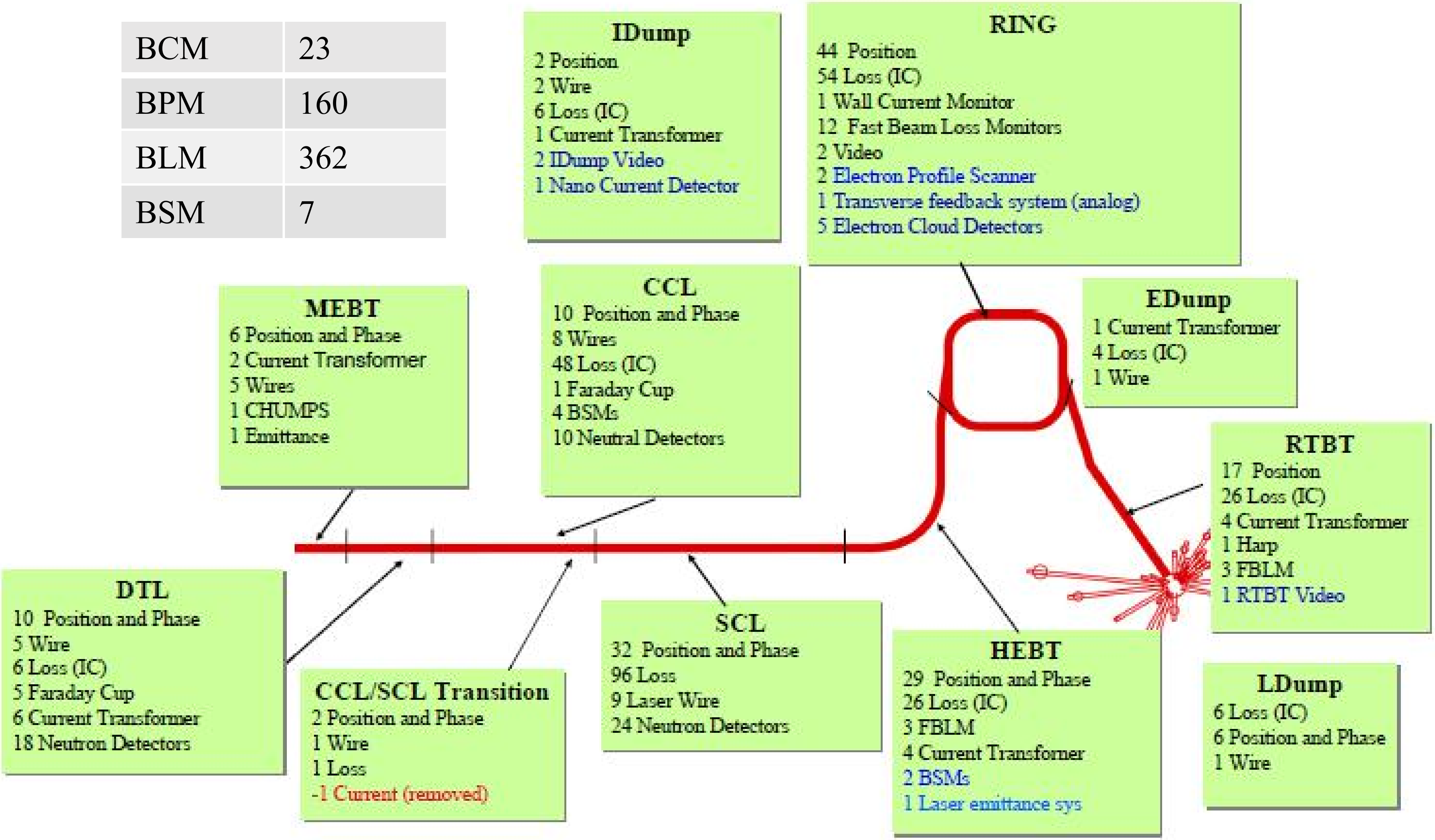
Accelerator Systems - Diagnostics	TOTAL	FE	LS1	FS1	LS2	FS2	LS3	BDS
Beam Position Monitor	**150**	4	39 + 20	18	24	12	20	13
Beam Current Monitor (ACCT)	**12**	3		5		2		2
Beam Loss Monitor – Halo Monitor Ring	**17**		17	8	24	4	13	
Beam Loss Monitor - Ion Chamber	**47**			8		12	15	12
Beam Loss Monitor - Neutron Detector	**24**	1	9	1	12		1	
Beam Loss Monitor – Fast Thermometry System	**240**		192		48			
Profile Monitor (Lg., Sm. Flapper)	**42**	7L/4S/3F	2S	4L/7S		2L/2S	4S	2L/5S
Bunch Shape Monitor	**1**			1				
Allison Emittance Scanner (2 axis)	**2**	2						
Pepper pot emittance meter	**1**	1						
Faraday Cup	**7**	7						
Fast Faraday Cup	**2**	2						
Viewer Plate	**5**	5						
Selecting Slits System - 300 W	**5**	5 axes						
Collimating Apertures - 100 W	**2**	2						
Intensity Reducing Screen System	**2**	2						

559 total diagnostic devices

J.Wei, et al., IBIC2017 mo1ab1

SNS beam instruments

BCM	23
BPM	160
BLM	362
BSM	7



A.Aleksandrov, DIPAC09 MOPD21

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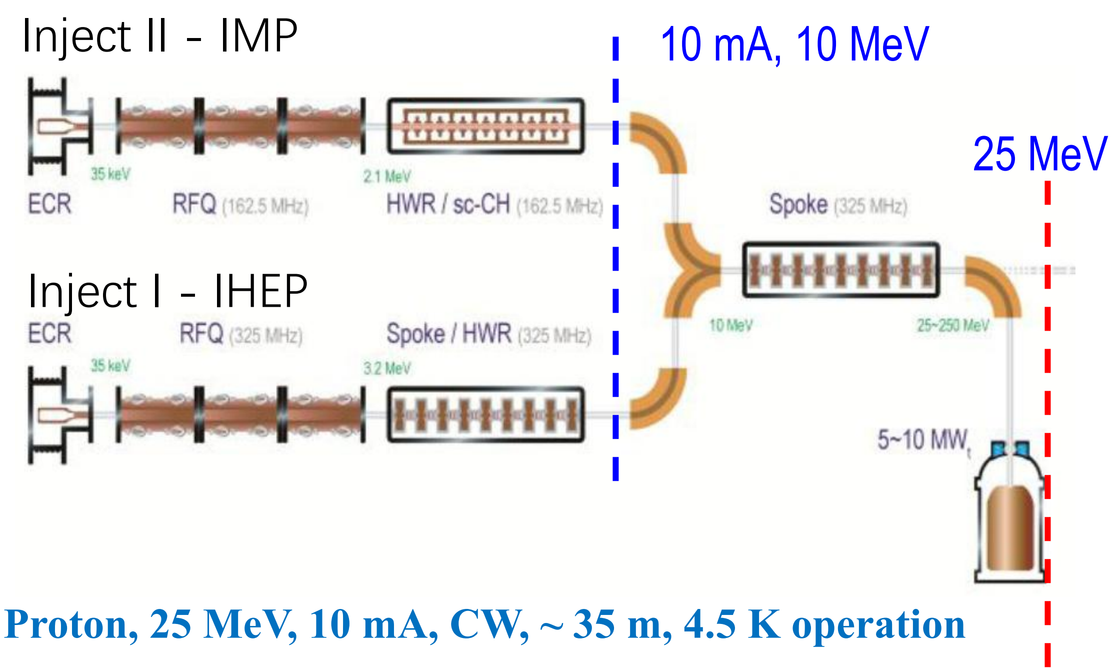
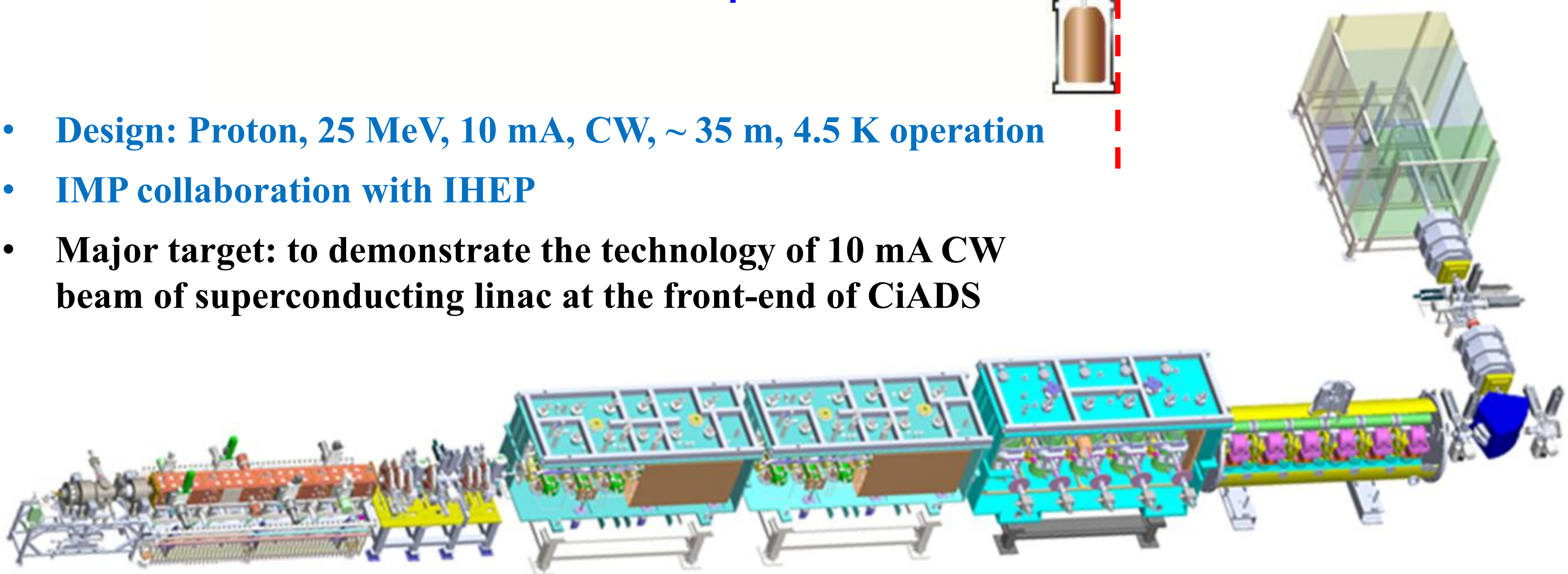
Chinese ADS(CADS) project



- **Design: Proton, 25 MeV, 10 mA, CW, ~ 35 m, 4.5 K operation**
- **IMP collaboration with IHEP**
- **Major target: to demonstrate the technology of 10 mA CW beam of superconducting linac at the front-end of CiADS**



Beam instruments on CADS

RFQ

LEBT — MEBT — Cryomodule 1,2,3, 4 — HEBT

LEBT

Wire Scanner	1
DCCT	1
ACCT	1

MEBT

ACCT	2
BPM	5
Scaper	3
Wire Scanner	3
Slit	2
Emittance	2
FFC	1
FC	1

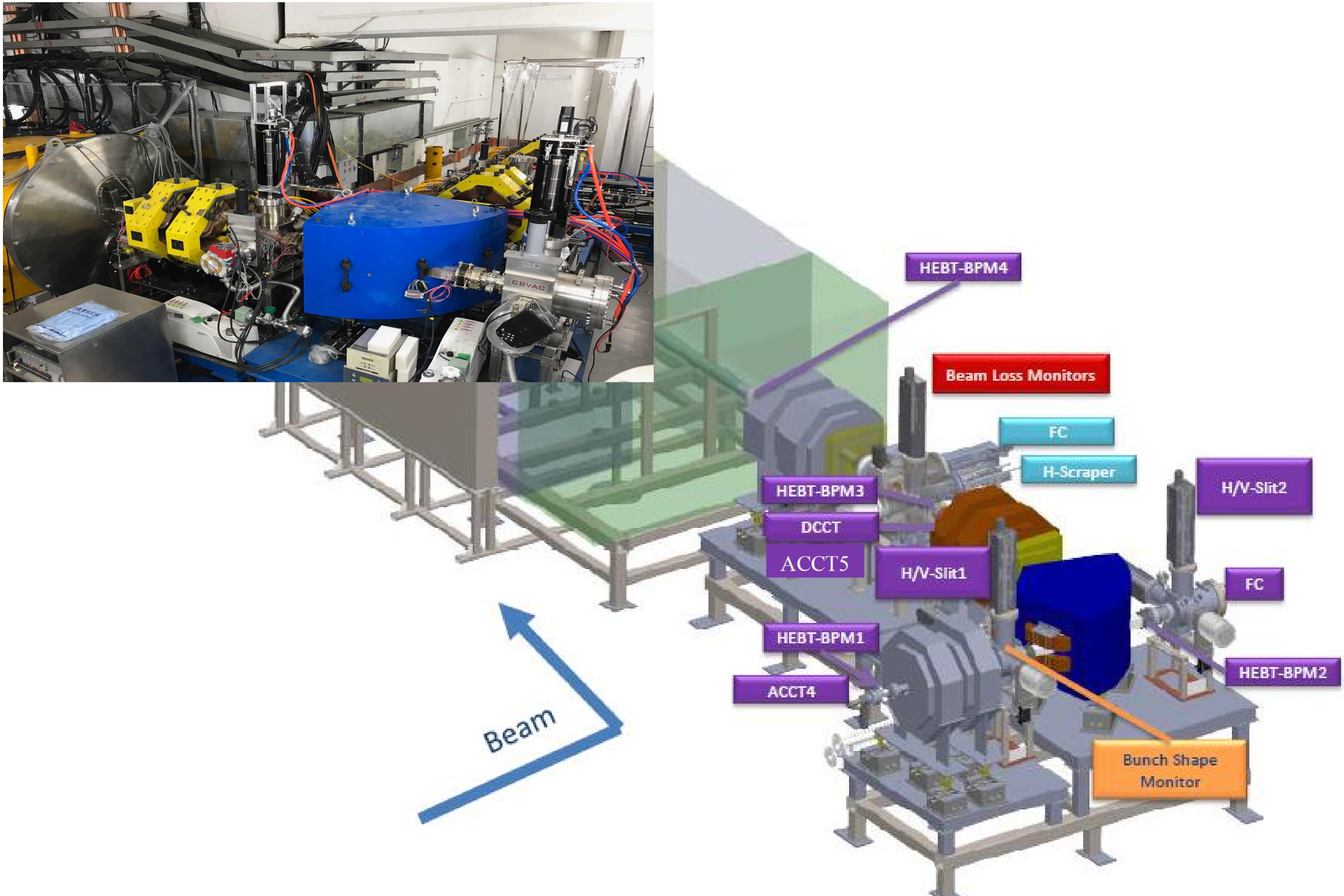
Cryomodule 1,2,3, 4

Cold BPM	5
Cold BPM	5
Cold BPM	5
Cold BPM	5

HEBT

ACCT	2
DCCT	1
BPM	4
Slit(H/V)	2
FC	1
Scraper(H)	3
Momentum Spread	1

HEBT Beam instruments on CADS



Beam Current Measurement

Detector

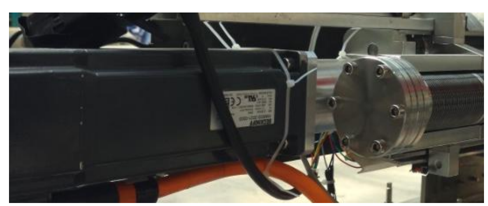
- ACCT for short Pulsed beam
- DCCT for long pulsed/CW beam
- Faraday Cup (beam dump)



Data acquisition: PCI 6712

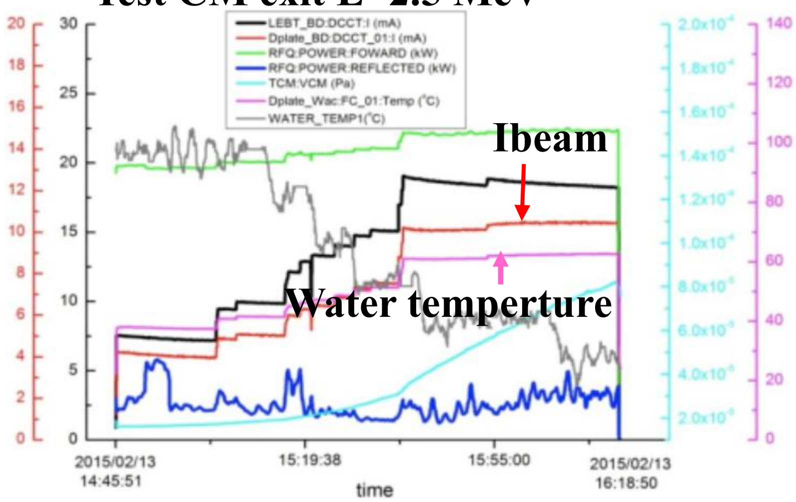
- Channel：4 Channels / Board；
- Input Impedance：1MΩ / 20pF；
- Sampling Frequency：60 MS/s；
- AD resolution: 12 bit,
- DC accuracy: 0.2 %；
- Sampling Length：16 MS
- Sampling Delay：±16 MS
- Trigger mode: internal, external
- Range：±100 mV、±200 mV、±500 mV、±1 V、±2 V、±4 V、±10 V、±20 V
- Bandwidth：0 ~ 20 MHz (-3 dB)；
- DI/DO: 16

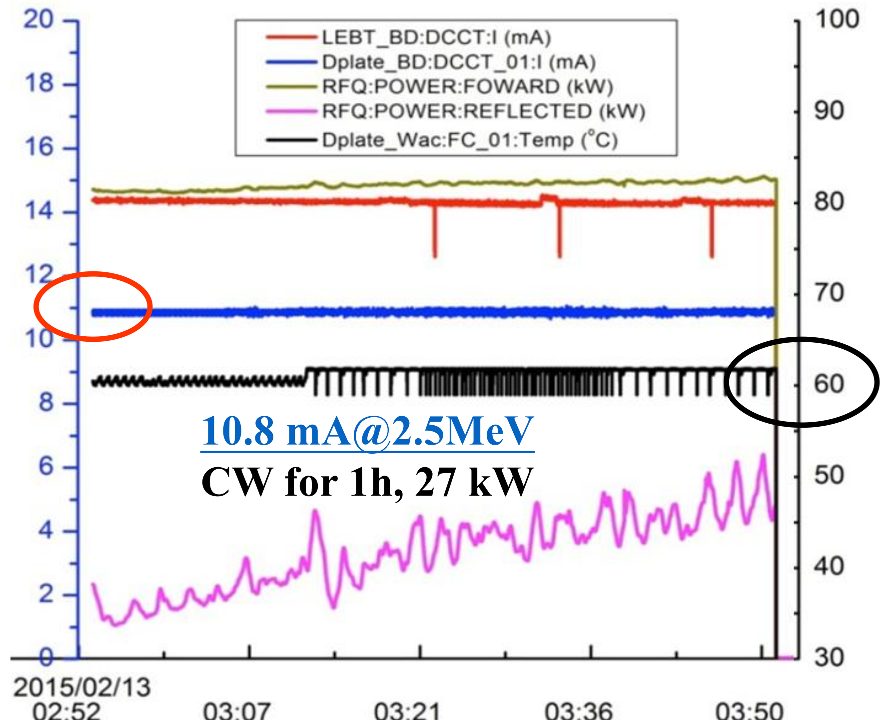
Motion Control: Servo-Motor@EtherCAT

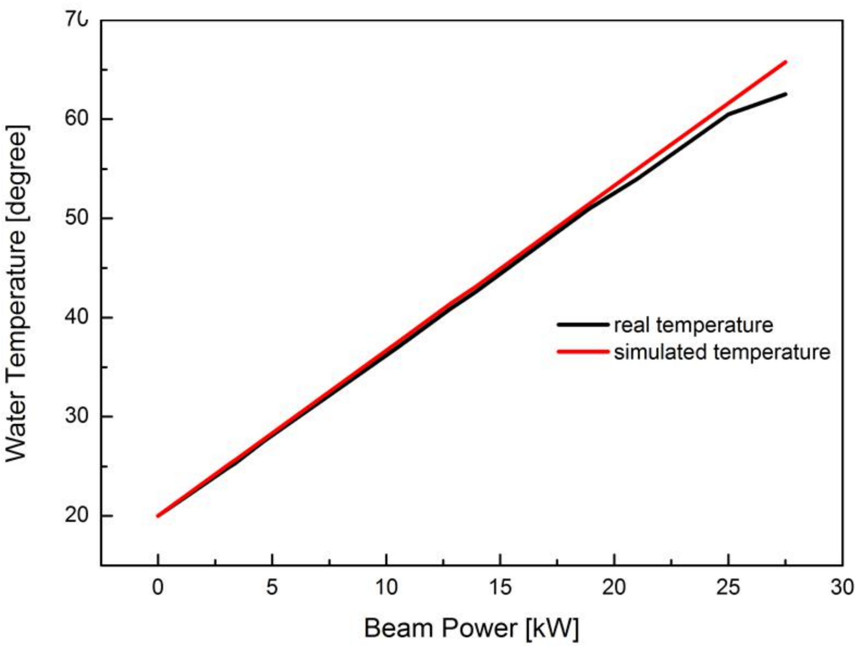



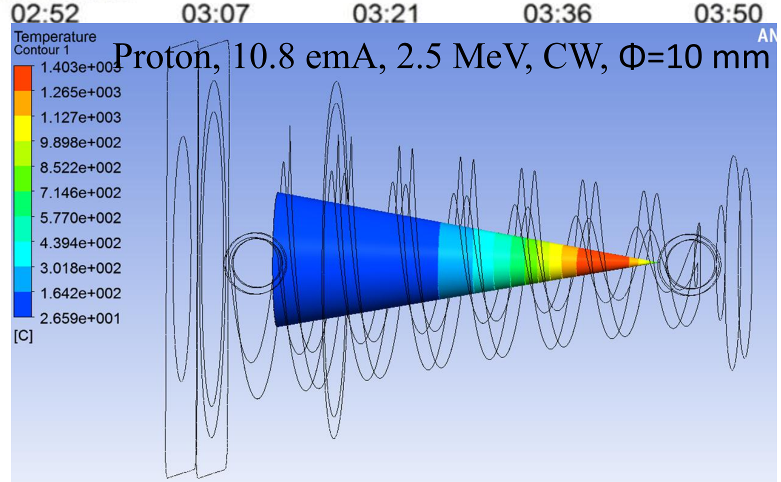
Beam Current Measurement

Test CM exit E=2.5 MeV



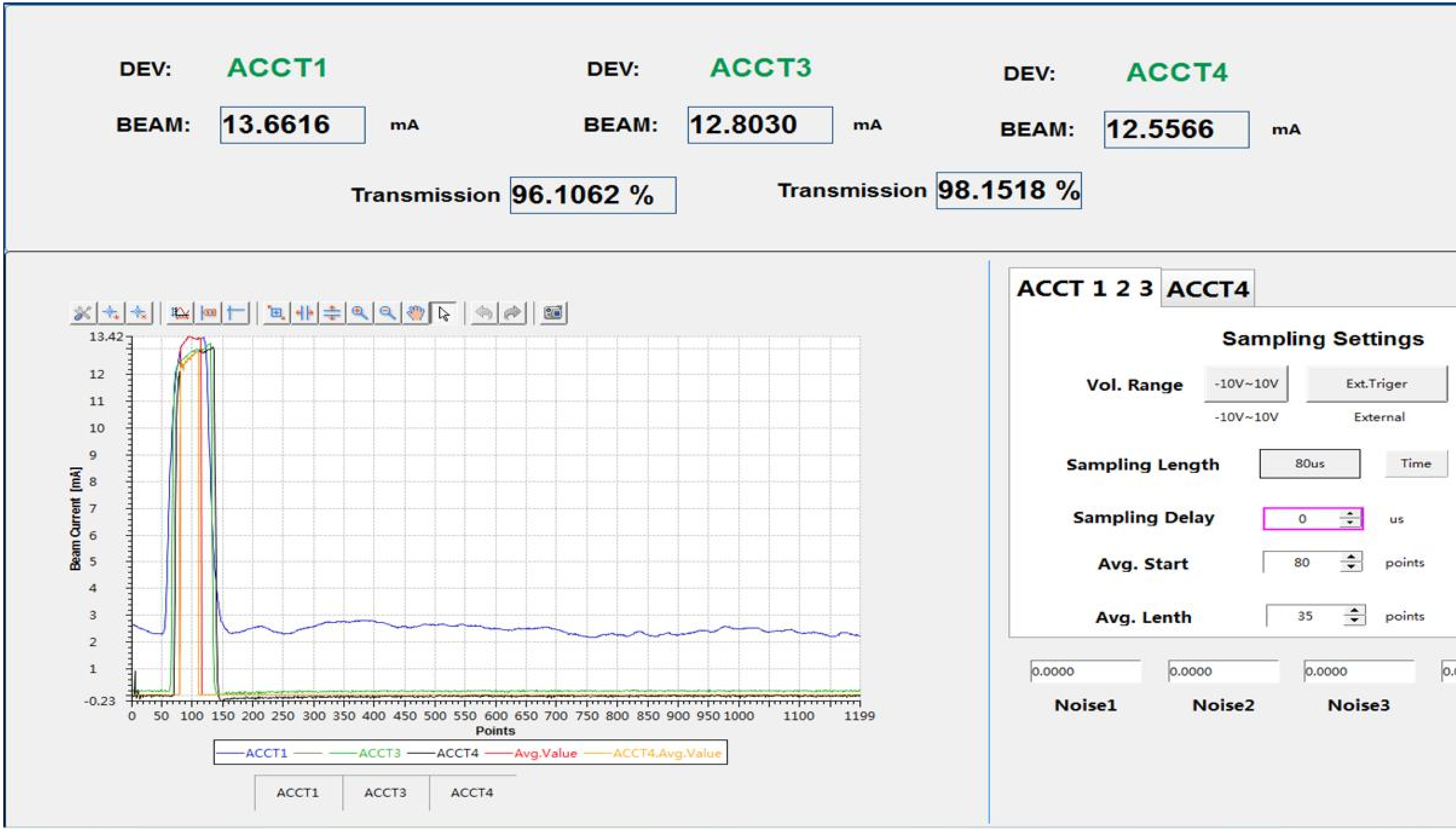






Beam Current Measurement

E=25 MeV

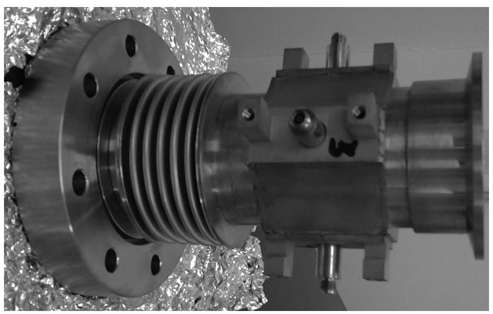


Position, Phase and Energy Measurements

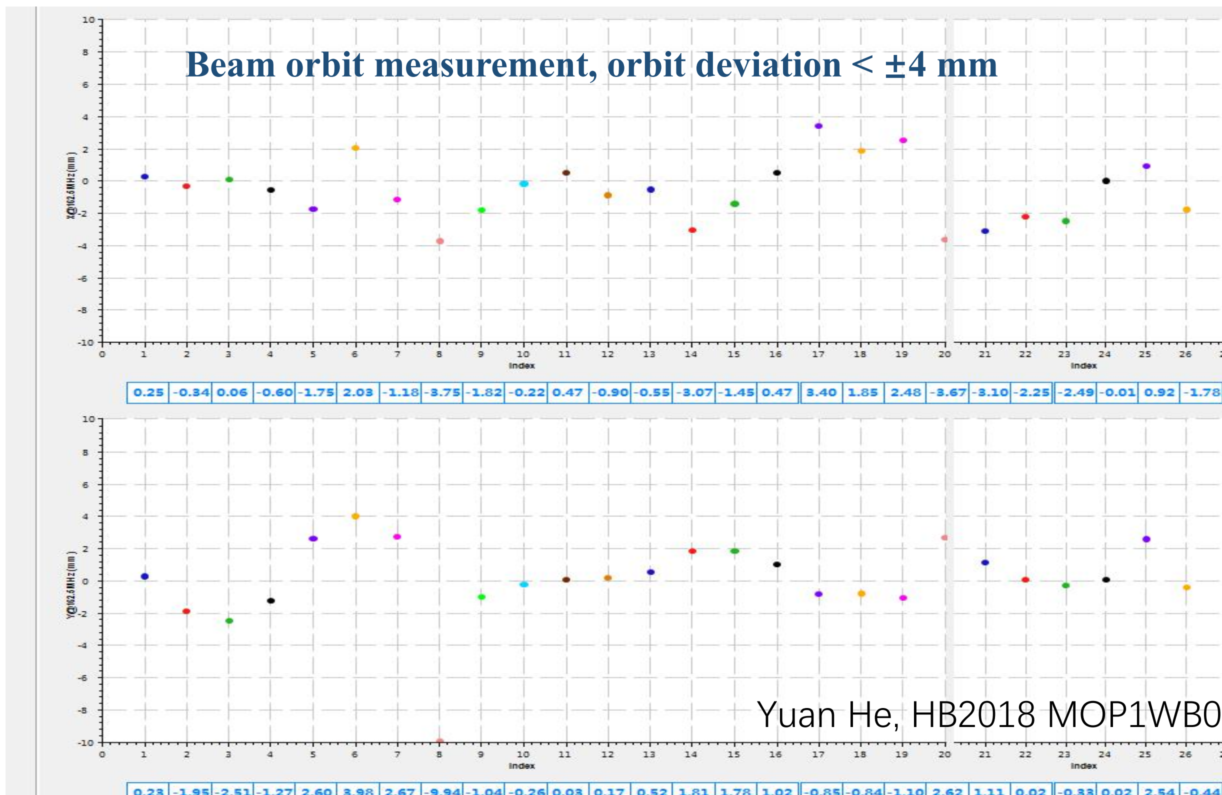
Stripline

- Output: X, Y, Sum, phase @ f1 and f2
- Interlock signal: adc, position, sum, and phase
- Interlock response time: < 6 μs

Capacitive-Warm BPM

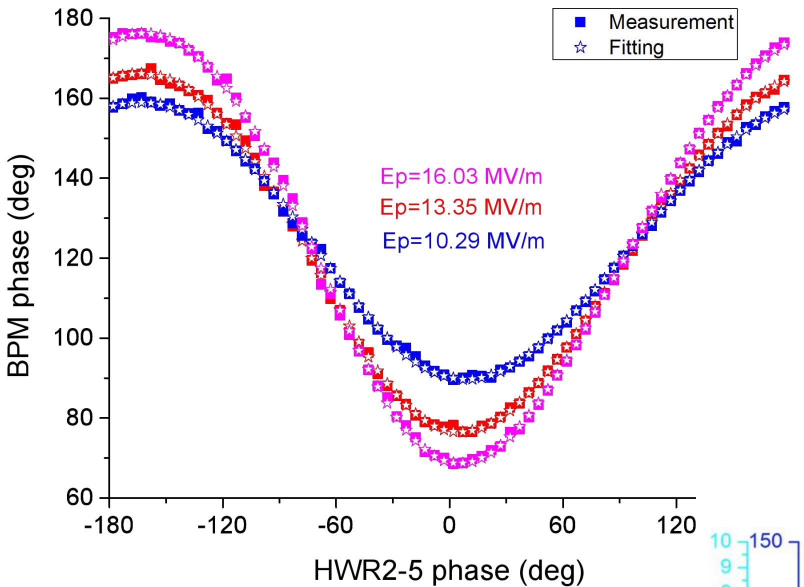


Button – Cold BPM



Yuan He, HB2018 MOP1WB01

Position, Phase and Energy Measurements

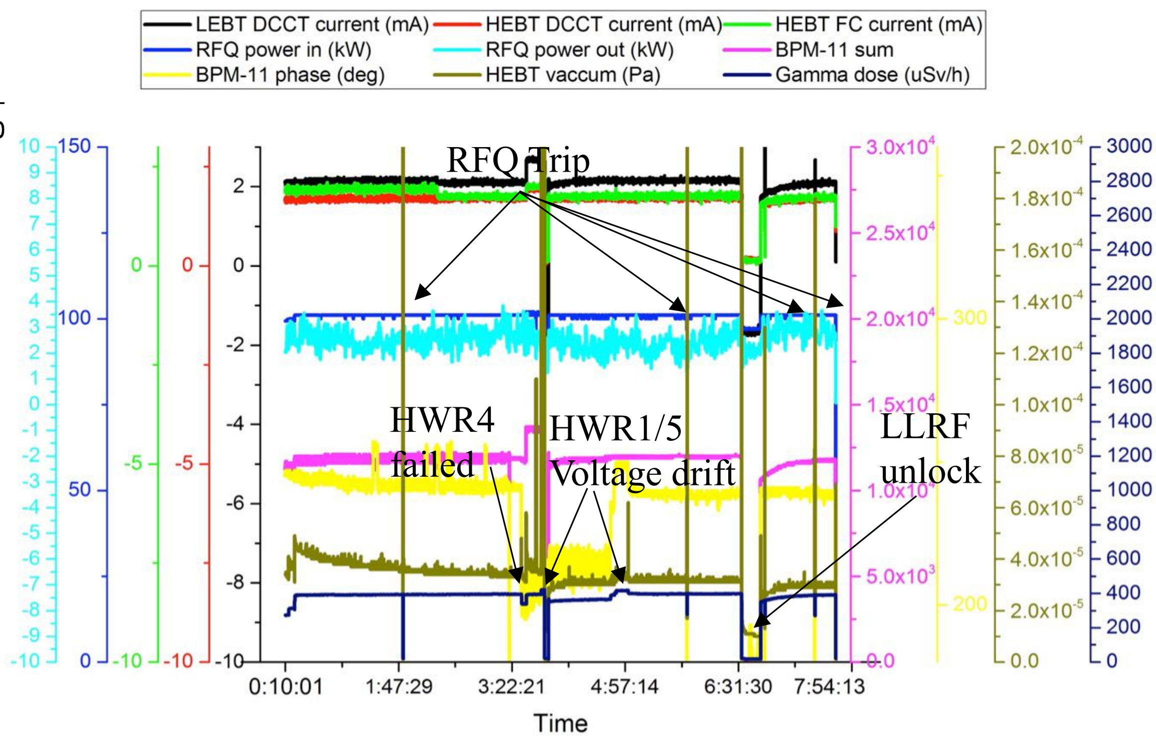


HWR cavity	ΔE (MeV,TOF)	ΔE (MeV,Phase)
CM1-2	0.16	0.15
CM1-4	0.203	0.206
CM2-2	0.117	0.12
CM2-3	0.095	0.105
CM2-4	0.325	0.312

Phase measurement

- Accurate phase measurement
- Good agreement with simulation
- Reliable for the interlock system

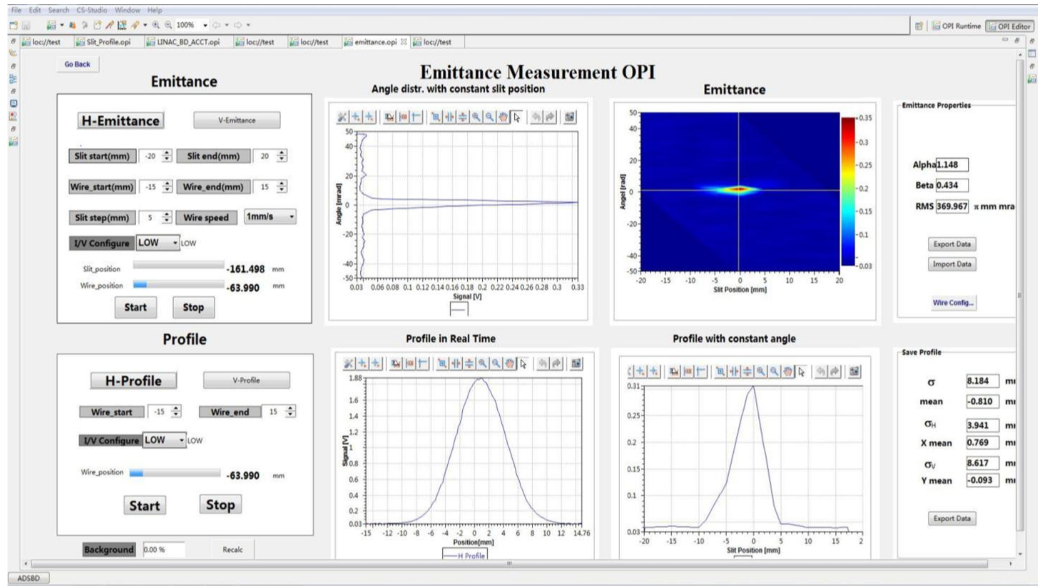
Jan. 2th, 2016, ～2emA, 4.0 MeV, CW, 7.5 hours

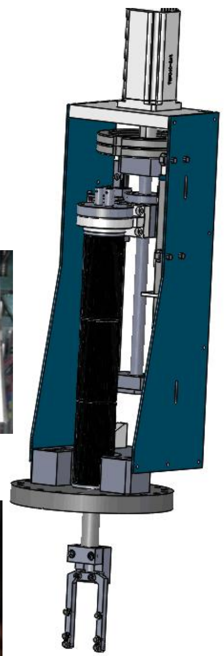


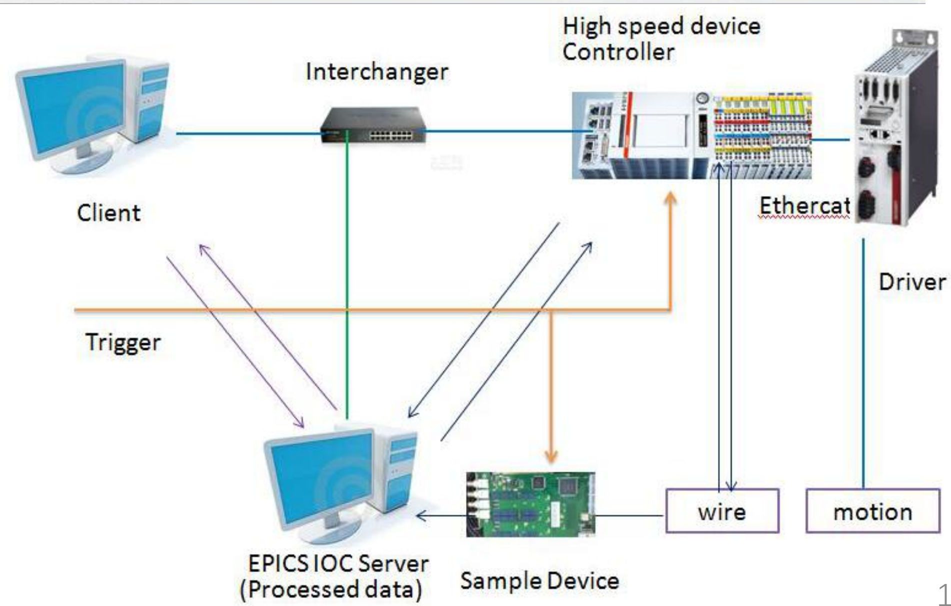
Huan Jia, HB2016, TUPM8Y01

Transvers Profile, Emittance Measurements

- **Profile:** Wire / scraper+FC
- **Emittance:** Wire + Slit / slit+slit+FC
- Max Sampling rate :60 MS/s
- Precise :12 bit
- Storage :16 M
- Absolute position accuracy (sensor): 0.5 mm
- Position resolution: 0.01 mm



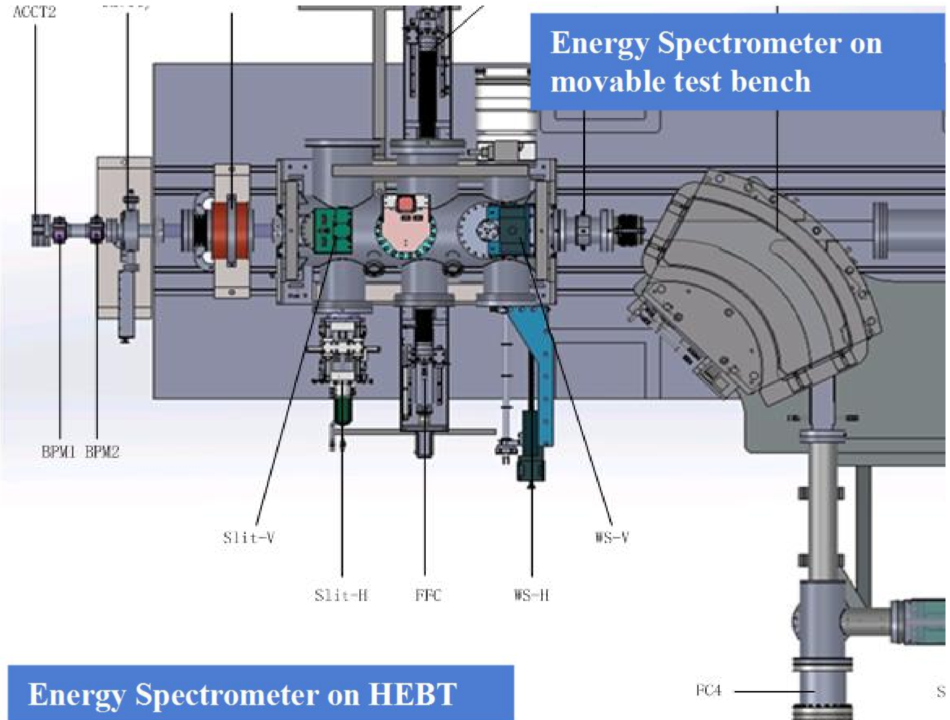




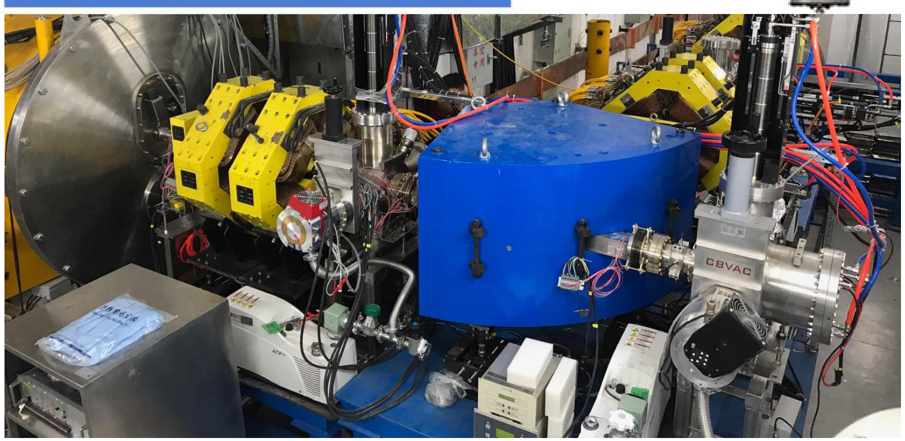
Energy, Momentum Spread Measurements

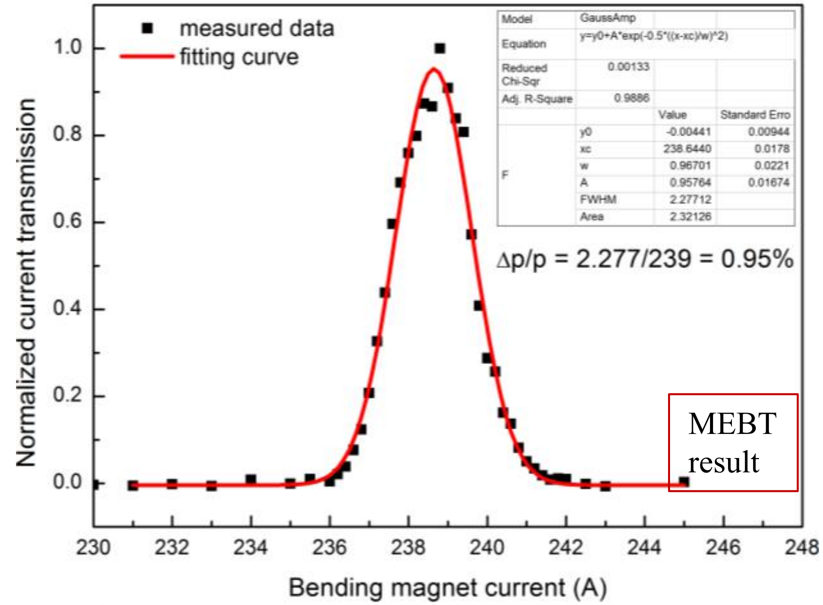
Magnetic Spectrometer

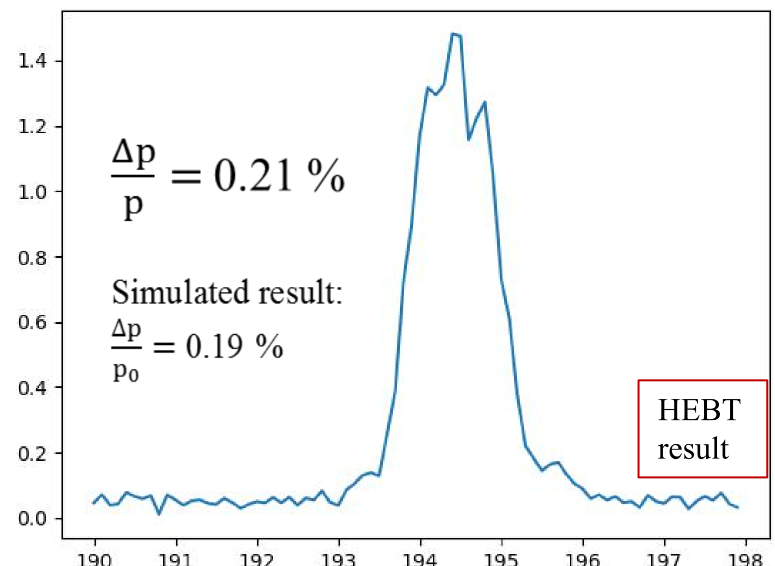
Energy Spectrometer on movable test bench



Energy Spectrometer on HEBT

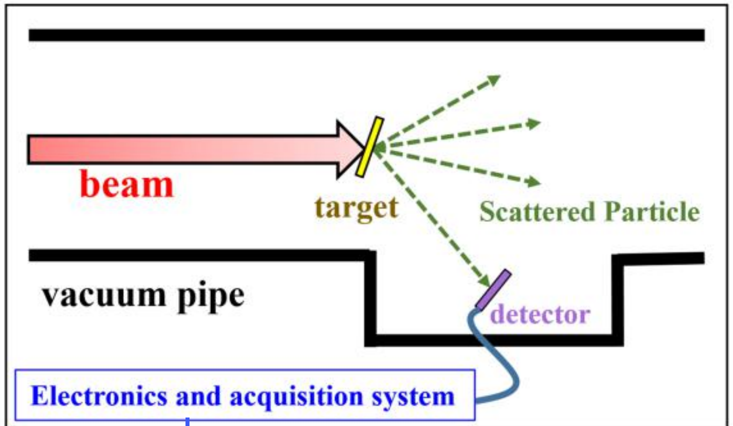


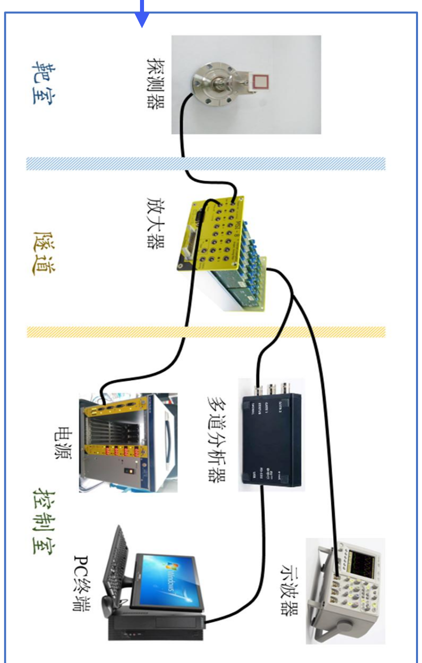


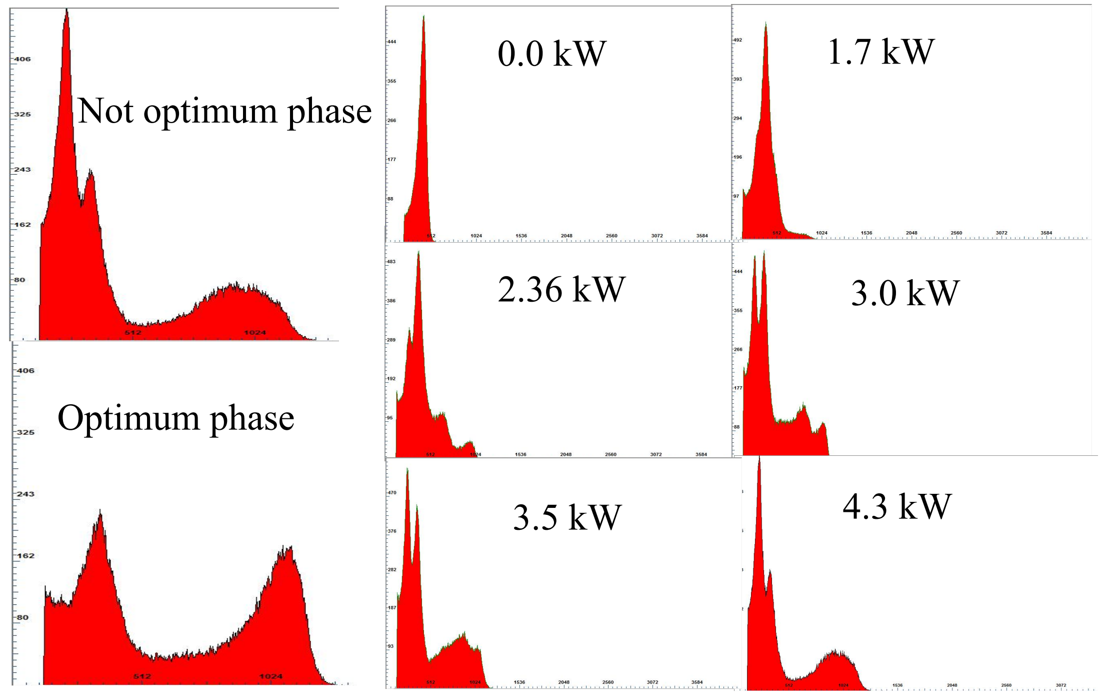


Energy, Momentum Spread Measurements

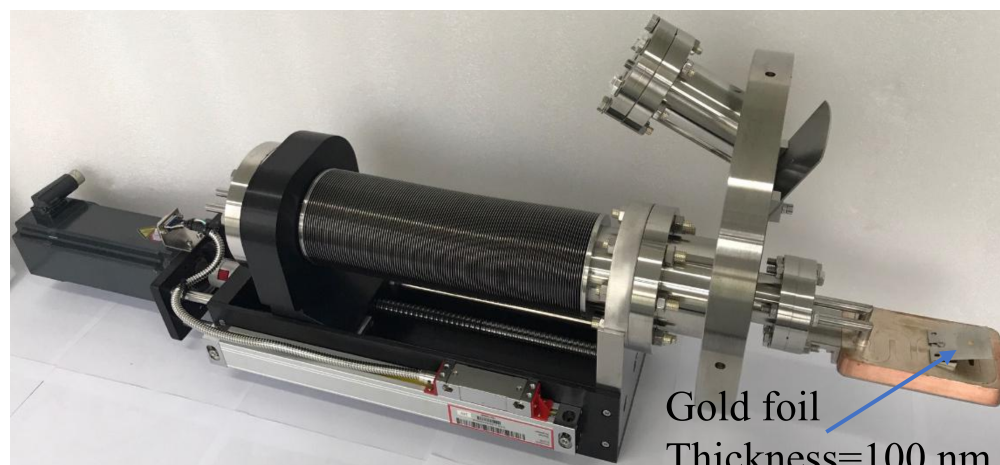
Rutherford scattering





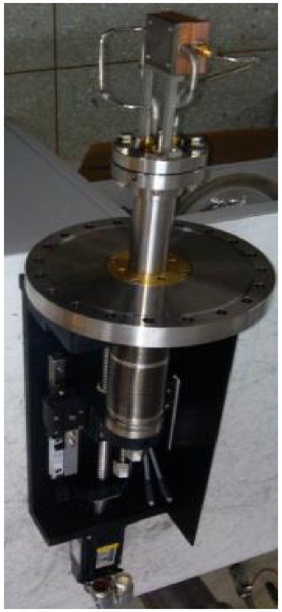


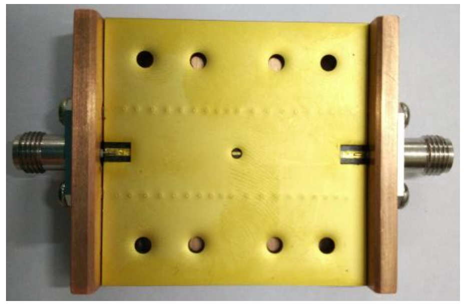
PIN Detector

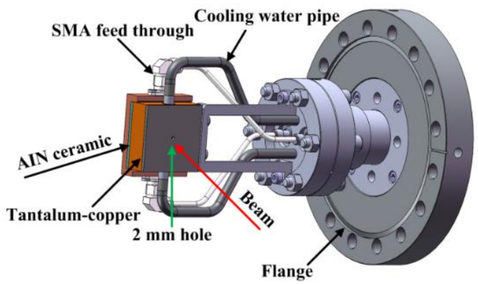


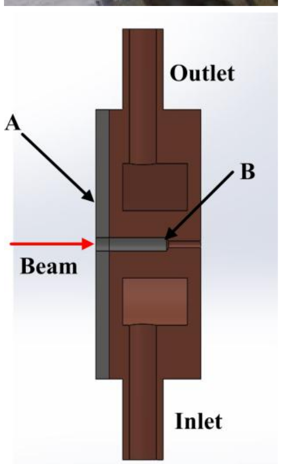
Longitudinal Bunch shape measurements

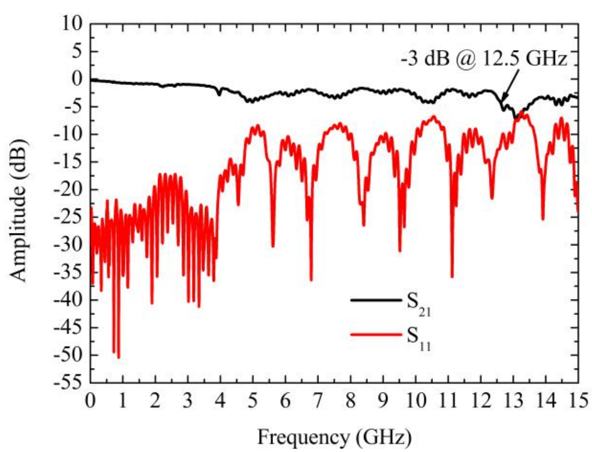
- **Fast Faraday Cup (FFC): stripline structure with 50 ohm**











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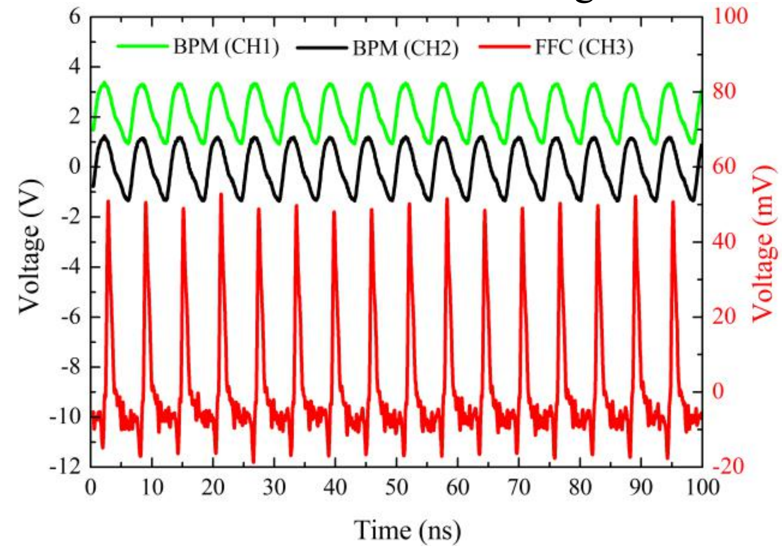
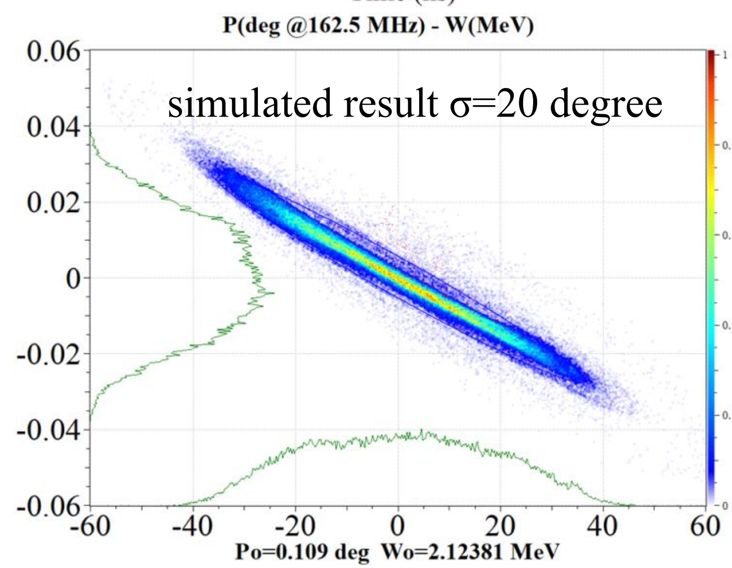
Measurement result σ=22 degree



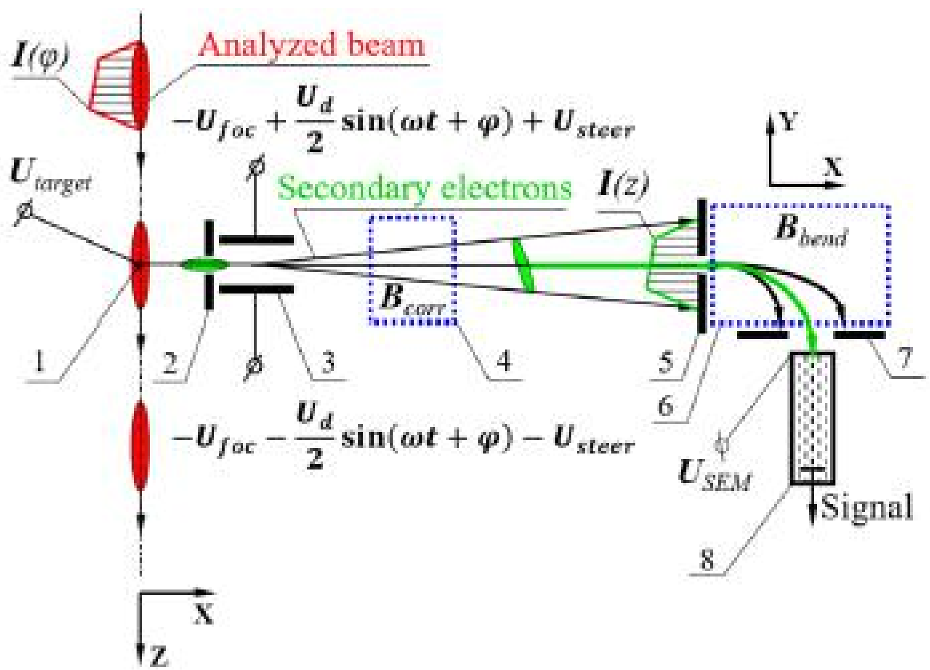


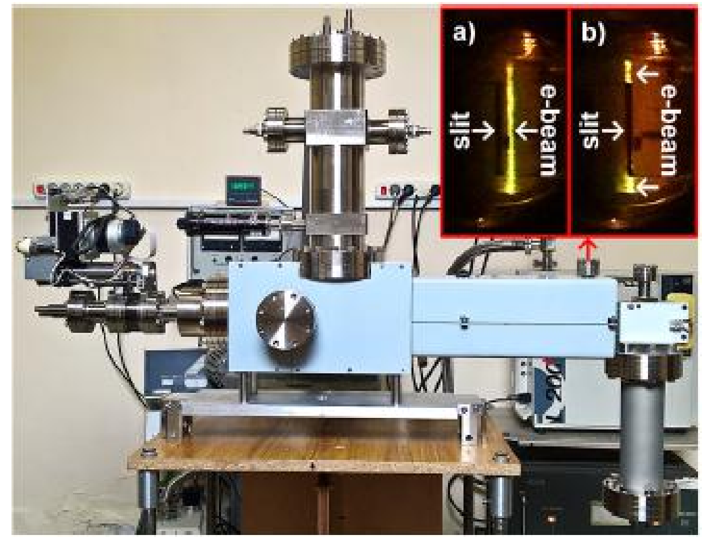
Longitudinal Bunch shape measurements

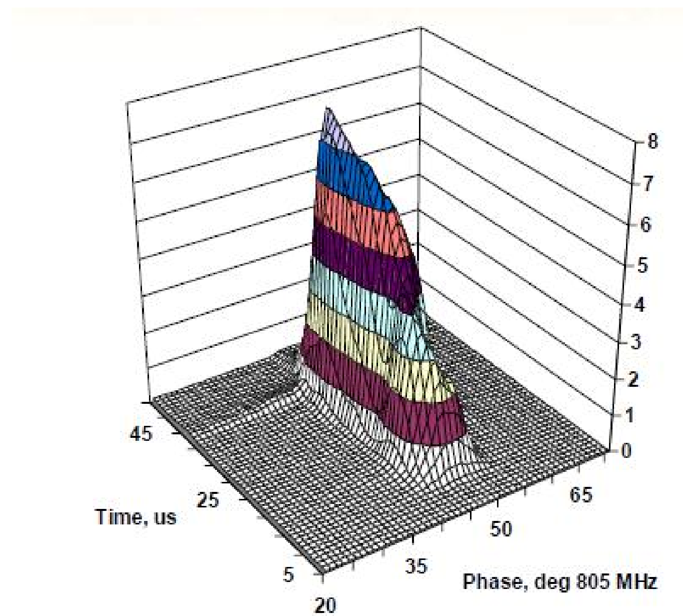
- **Secondary electron emission (INR)**

Resolution: 6 ps

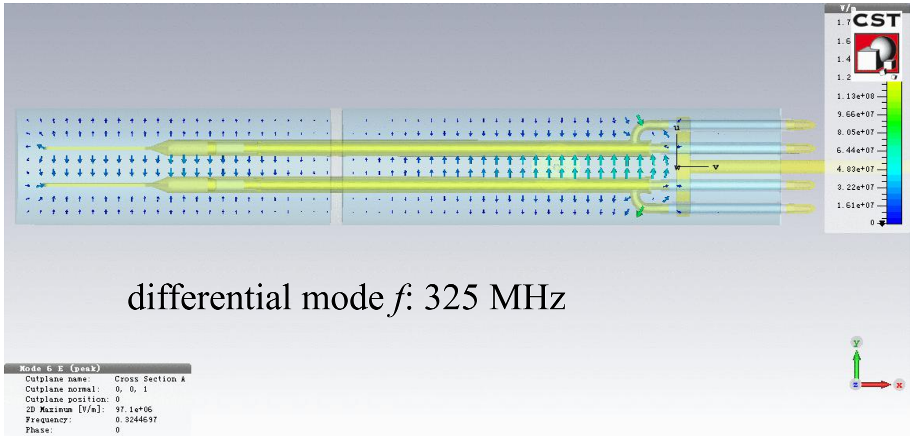
User: CERN Linac 4/3/2, FAIR GSI, FRIB MSU, ESS ERIC, SNS, DSEY H^- LINAC, J-PARC, LANSCE, SSC ……

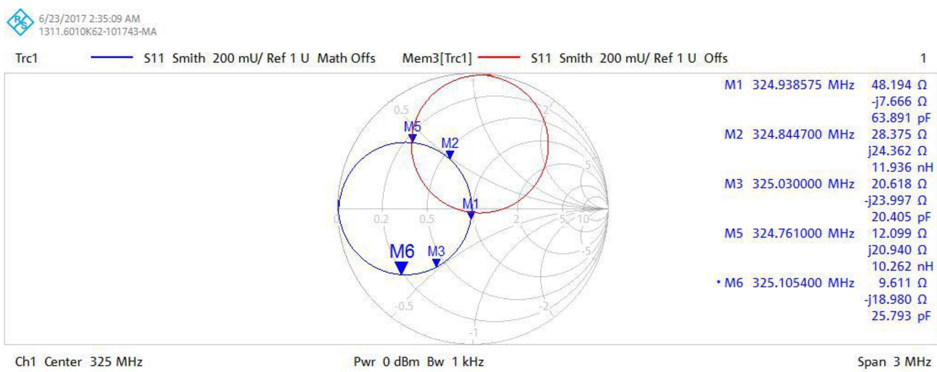


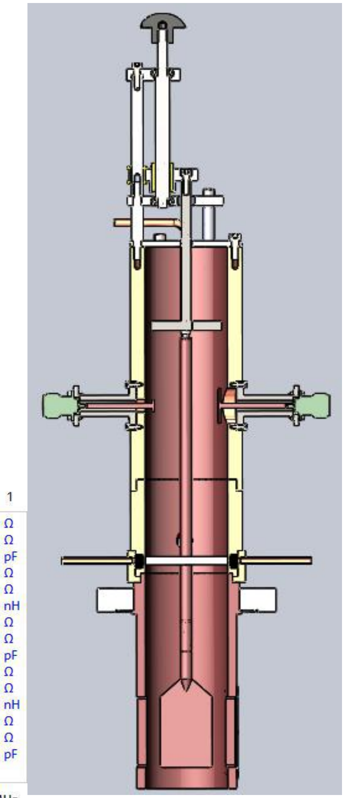


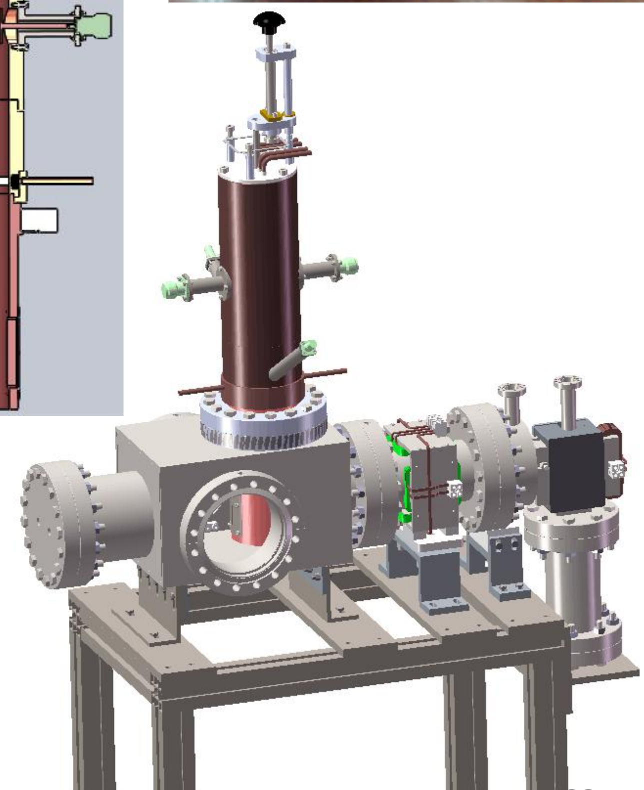


Longitudinal Bunch shape measurements









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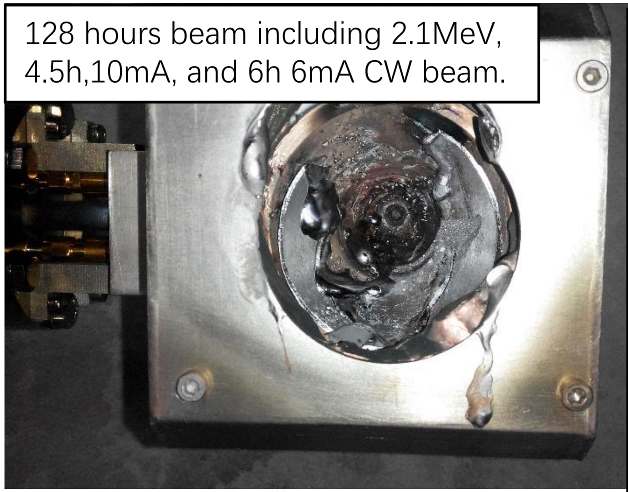
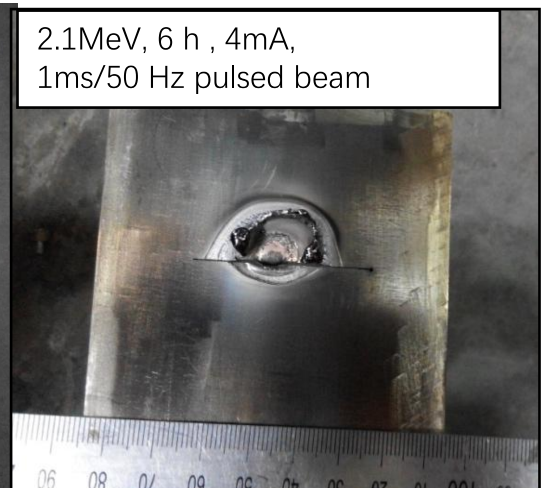
Challenges and lessons

Lesson learnt: for high current long pulsed/CW linac beam, beam can melt everything or drill a hole everywhere if something is wrong, except the beam dump at the right position.

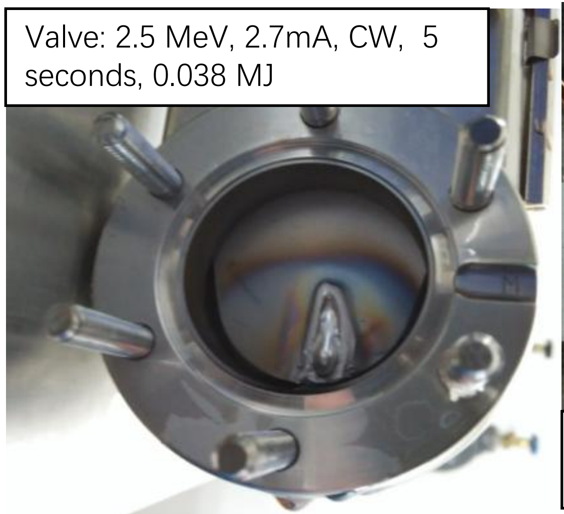


128 hours beam including 2.1MeV, 4.5h,10mA, and 6h 6mA CW beam.

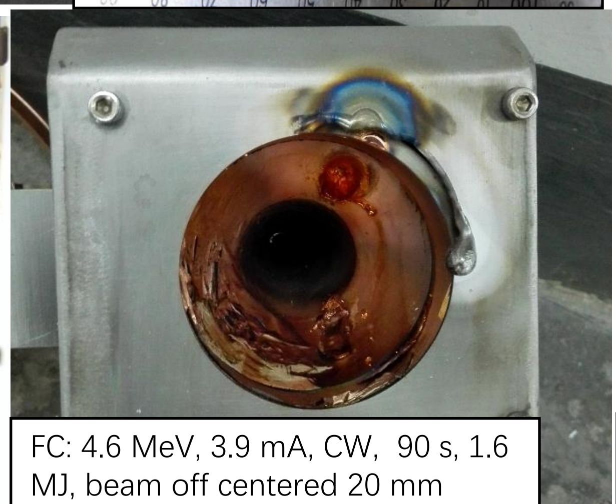


2.1MeV, 6 h , 4mA,
1ms/50 Hz pulsed beam

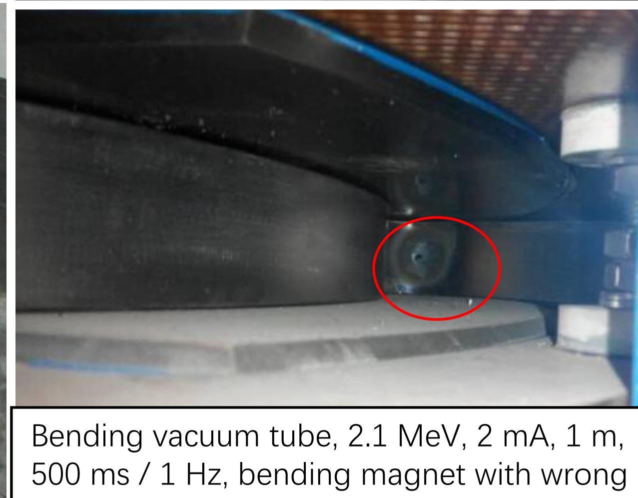
Tungsten wire broken many times



Valve: 2.5 MeV, 2.7mA, CW, 5 seconds, 0.038 MJ



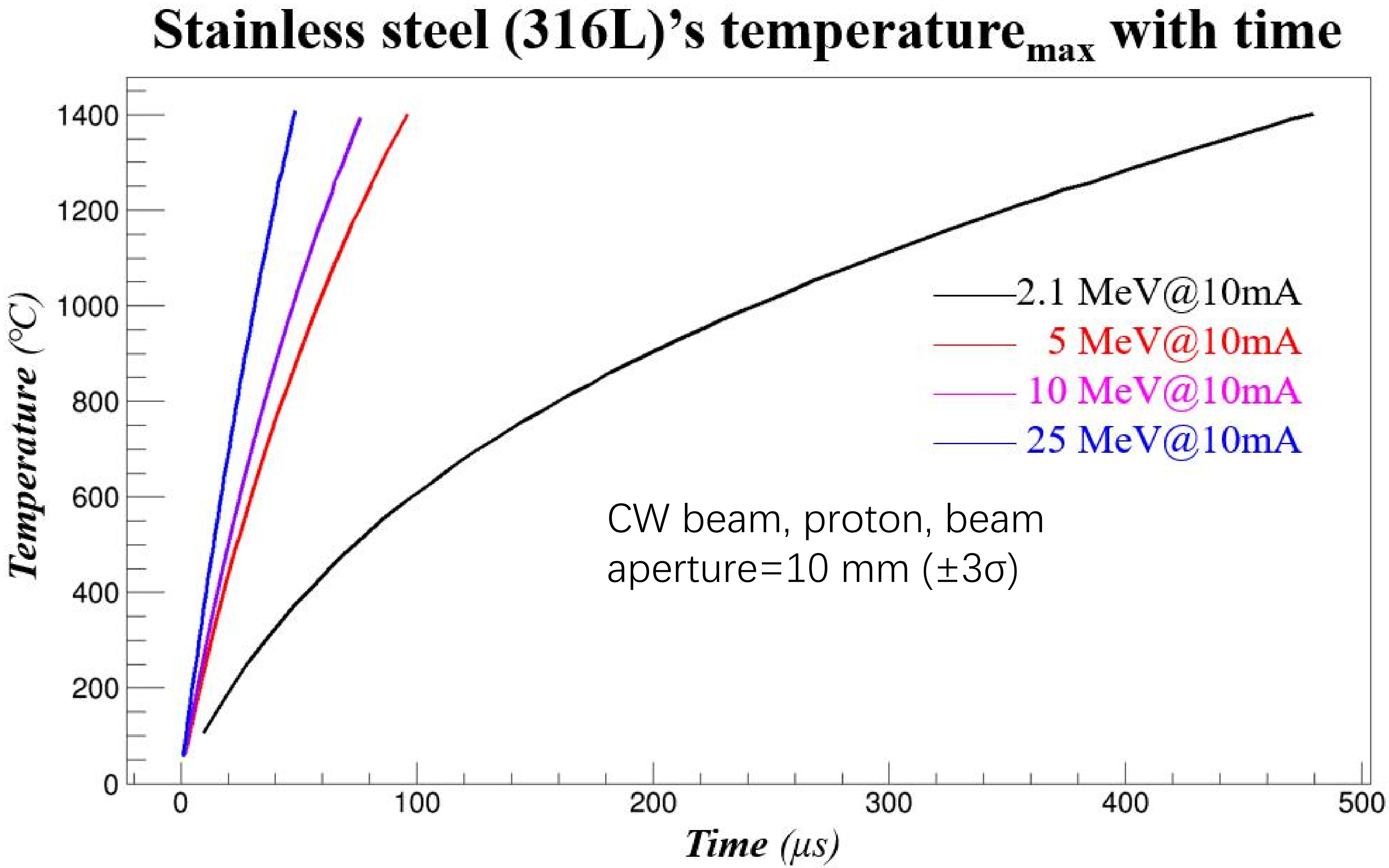
FC: 4.6 MeV, 3.9 mA, CW, 90 s, 1.6 MJ, beam off centered 20 mm



Bending vacuum tube, 2.1 MeV, 2 mA, 1 m, 500 ms / 1 Hz, bending magnet with wrong set

Challenges and lessons

Lesson learnt: for high current CW/long pulsed linac beam, beam can melt everything or drill a hole everywhere if something is wrong, except the beam dump at the right position.



Challenges and lessons

Lesson learnt: for high current CW/long pulsed linac beam, beam can melt everything or drill a hole everywhere if something is wrong, except the beam dump at the right position.

⇩

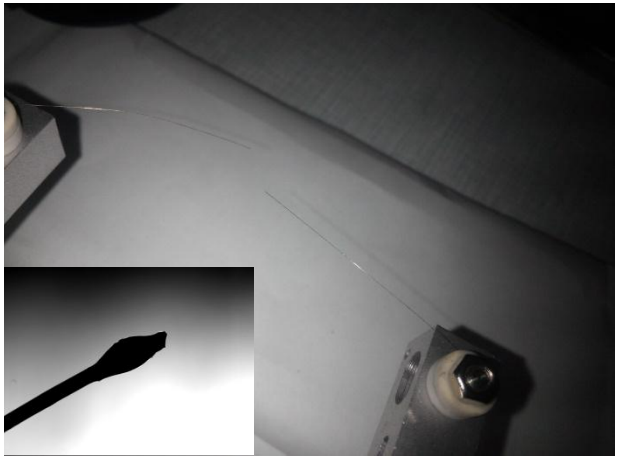
- **Importance of beam loss monitoring and machine protection system!!**
- High average beam power needs minimally invasive diagnostics
- Diagnostics and instrumentation must be fully integrated with timing and machine protection system.

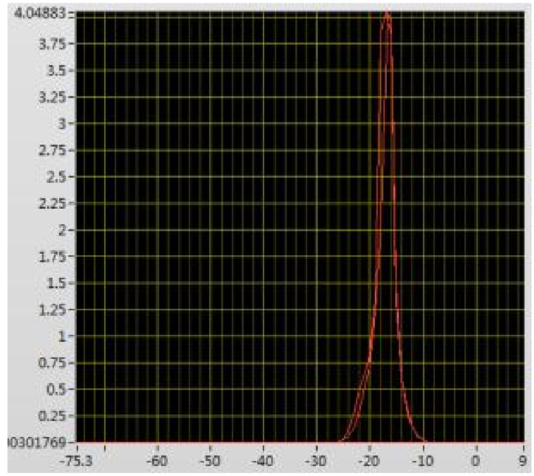
Challenges and lessons

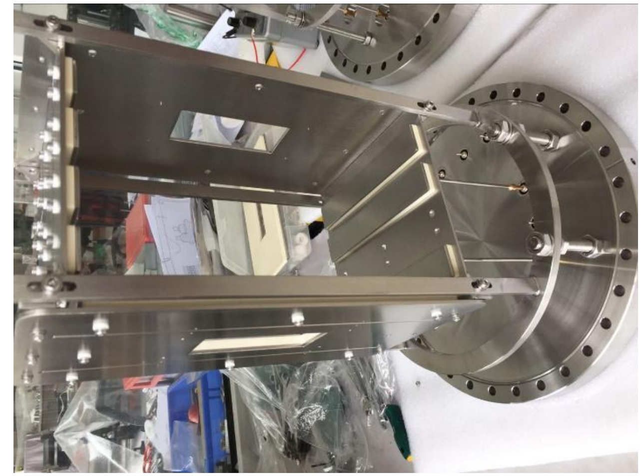
Beam instruments challenges for high power long pulsed/CW beam:

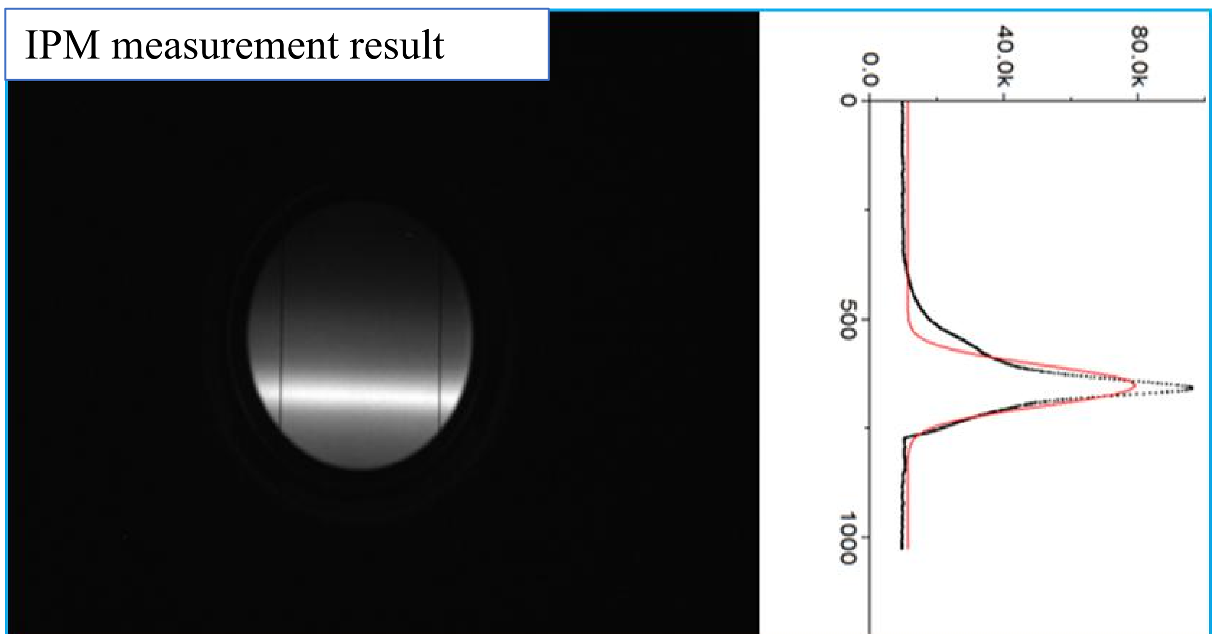
- **Big challenge for invasive diagnostics**
- **Beam loss monitoring for low energy intense beam**
  - Low detection sensitivity on low-energy beam
  - Short range, high power concentration
- **Beam halo measurement for high power beam in CW machine**
  - Significant fraction
  - Must be understood to prevent slow degradation of superconducting RF cavities under long term "slow" beam loss conditions
- **Errant beam diagnostics (SNS):** sudden beam loss caused by off-normal beam pulse or pulses
  - Damage the SCL cavities: beam hitting rf cavity surface desorbs gas and creates an environment for arcing / discharge
  - Super Conducting Linac (SCL) cavity performance degrades over time

Challenges and lessons – invasive diagnostics

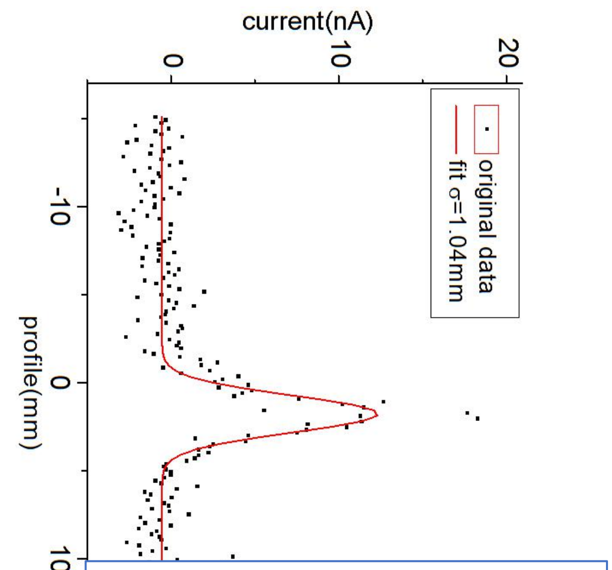






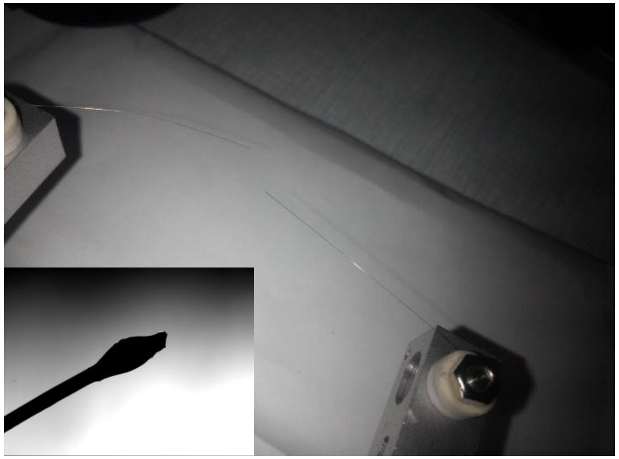


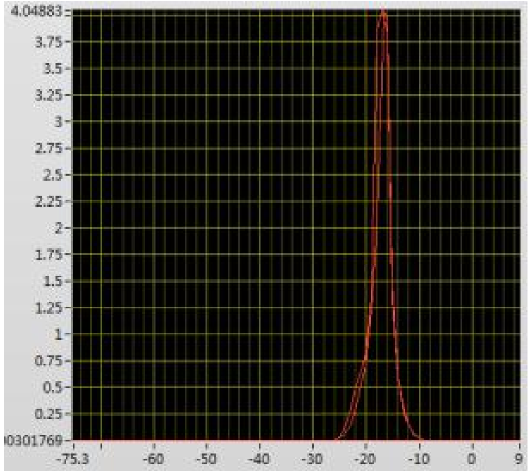
IPM measurement result

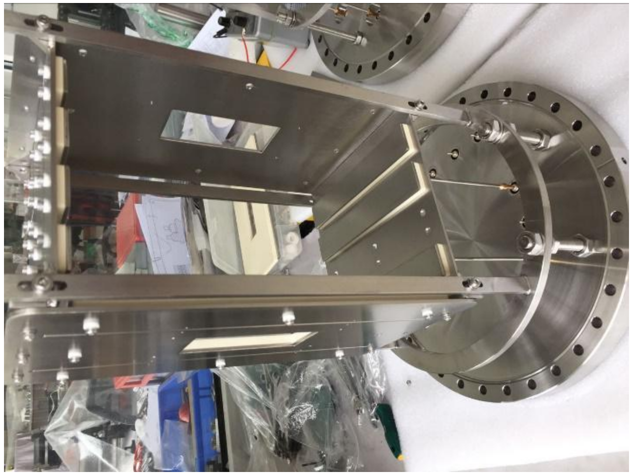


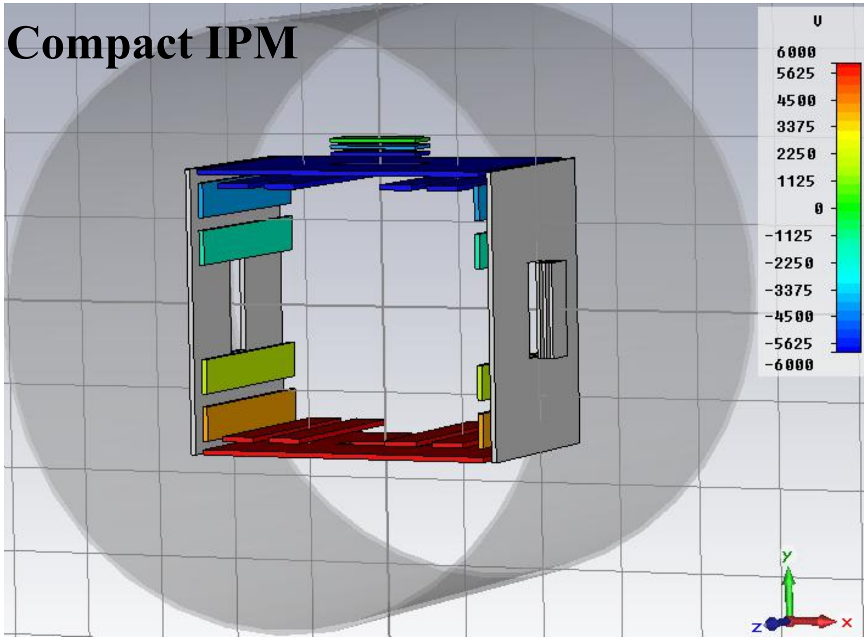
Wire scanner measurement result

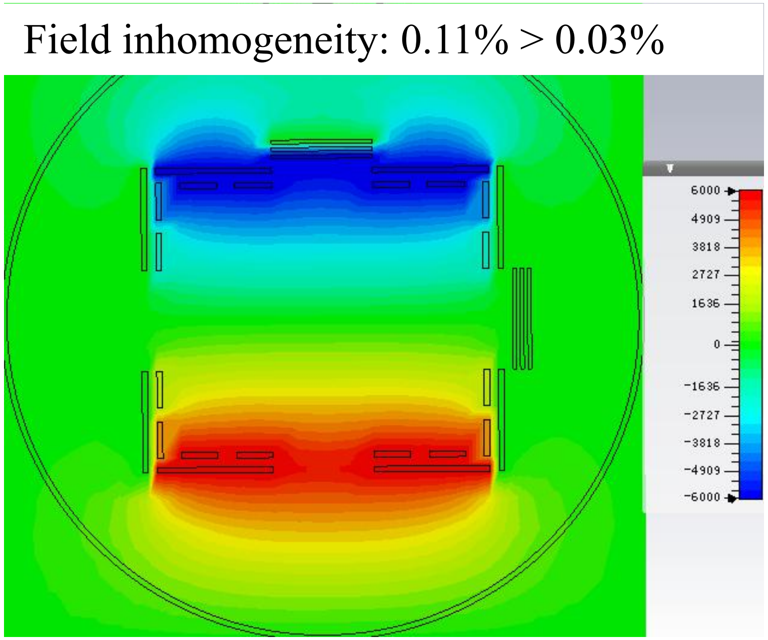
lessons and improvements – IPM



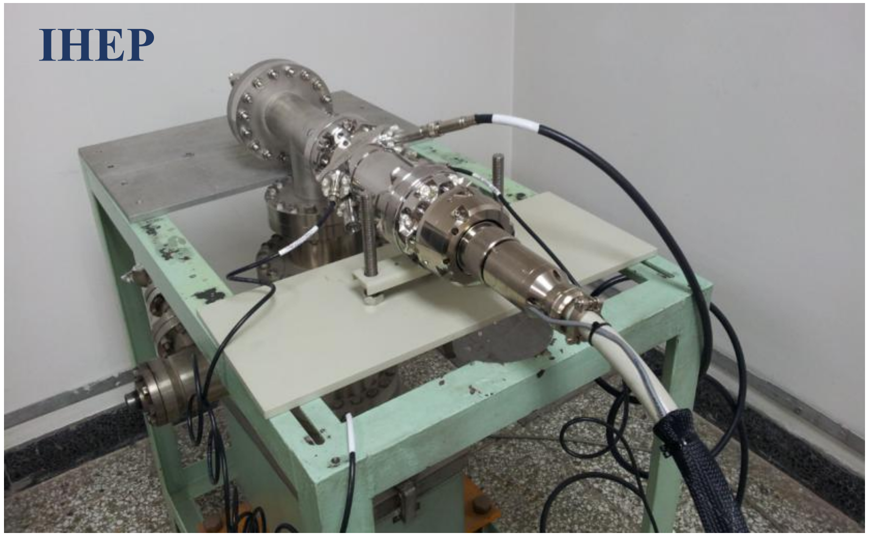


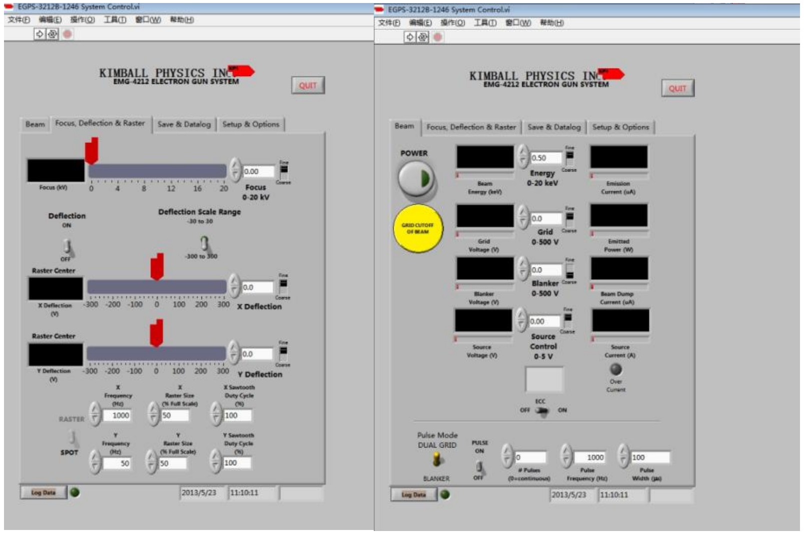






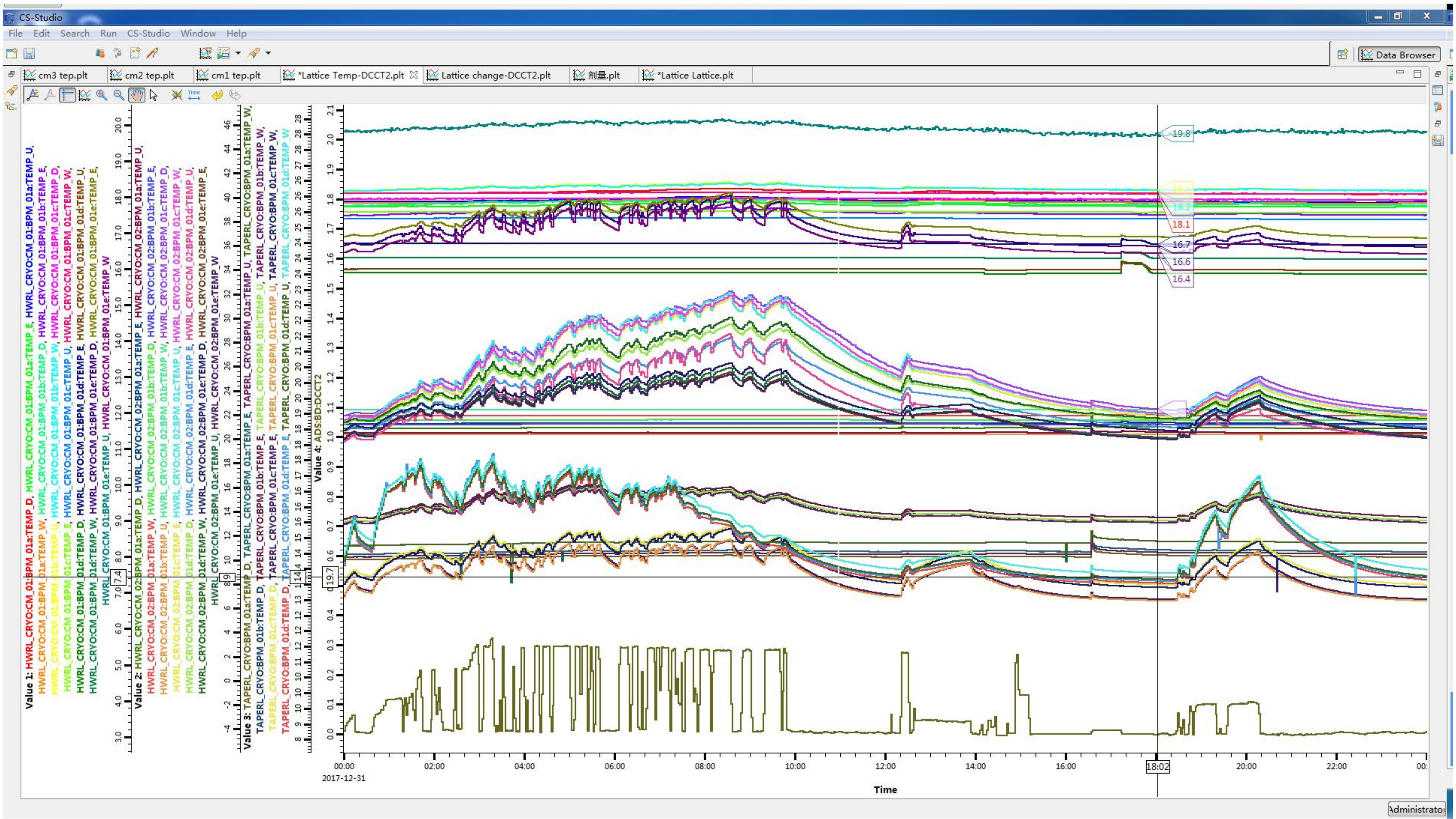
lessons and improvements – E-beam scanner





Lessons and improvement - Beam loss monitoring

- Thermometer



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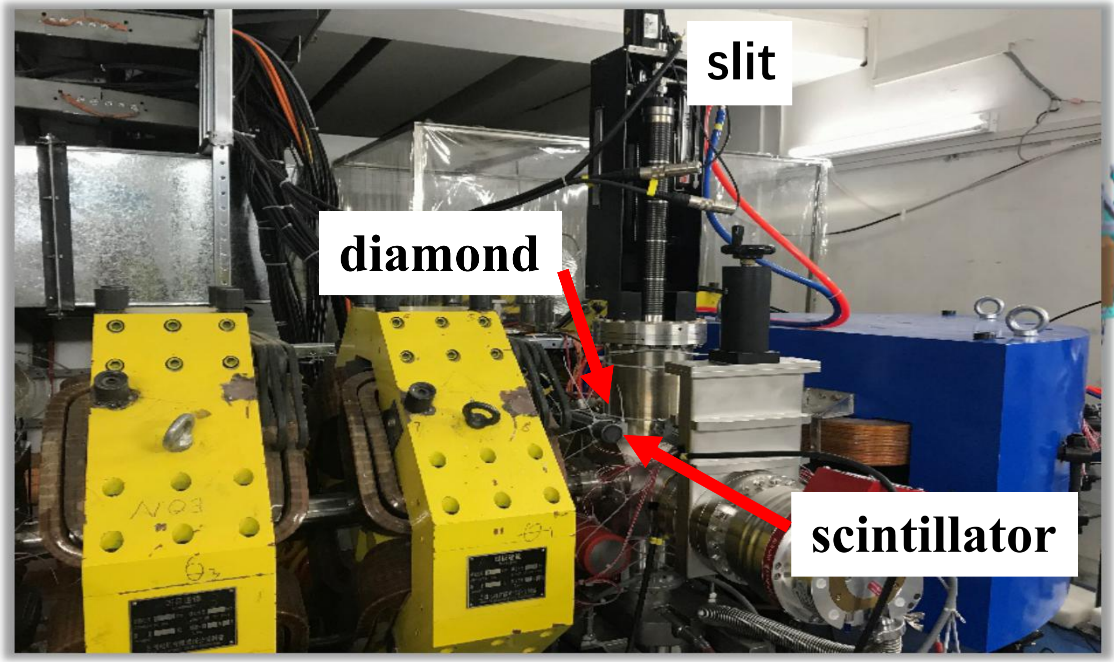
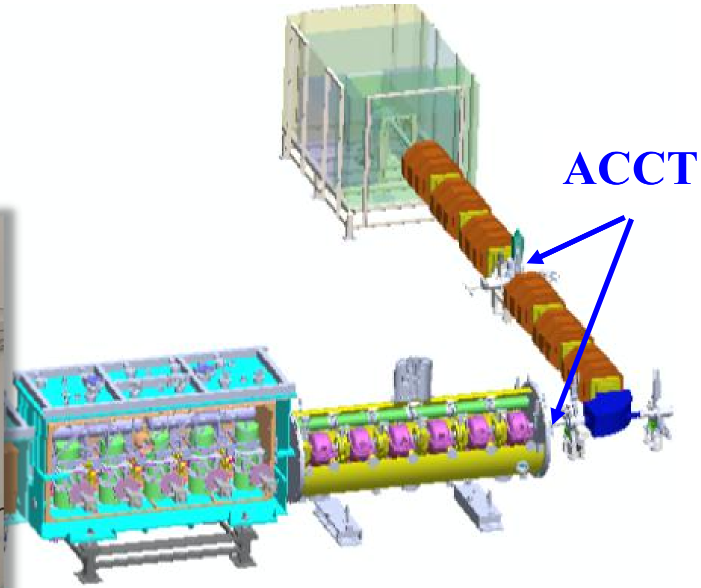
Lessons and improvement - Beam loss monitoring

- Beam loss monitoring experiment for low energy beam at 18.3 MeV
- Beam: proton (pulse length10μs)
- Energy: 18.3 MeV
- Intensity: 1 emA
- Detector: scintillator and diamond
- Comparison with difference ACCTs

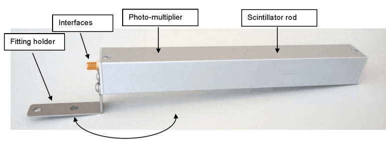
HEBT





Lessons and improvement - Beam loss monitoring

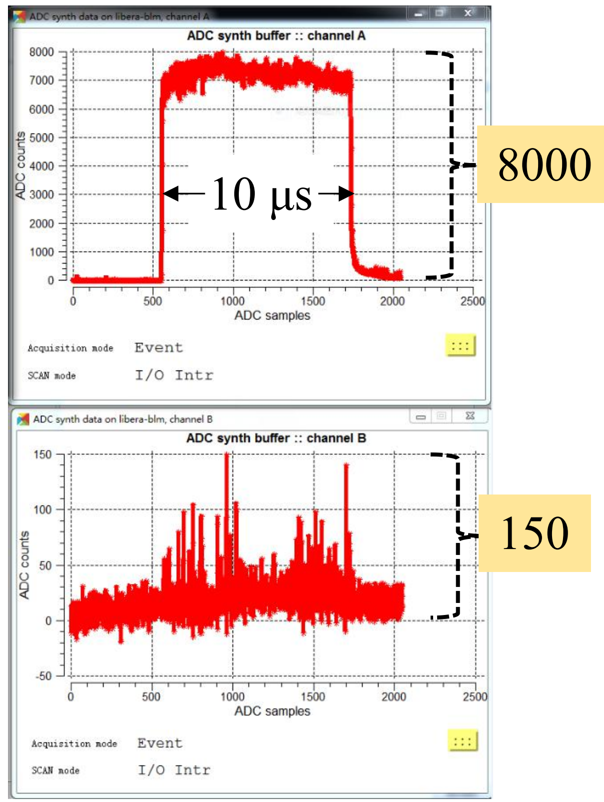
- **Beam loss monitoring experiment for low energy beam at 18.3 MeV**



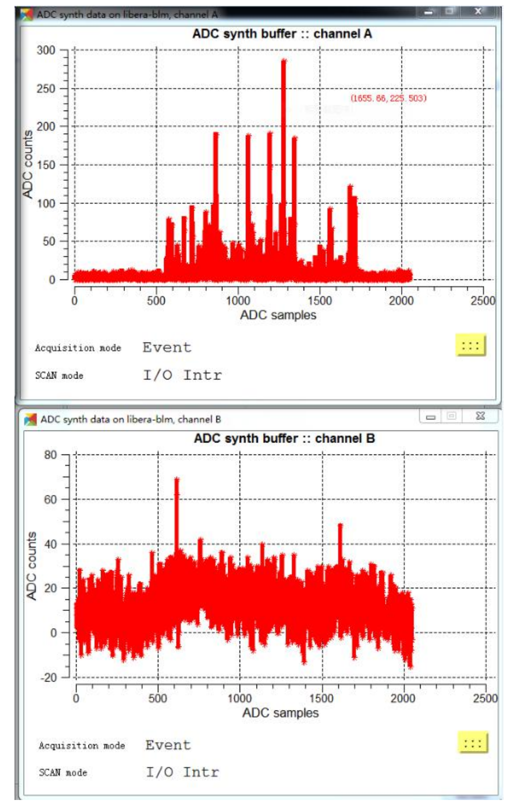
BLD-**scintillator**

BLD-**diamond**

Slit inserted



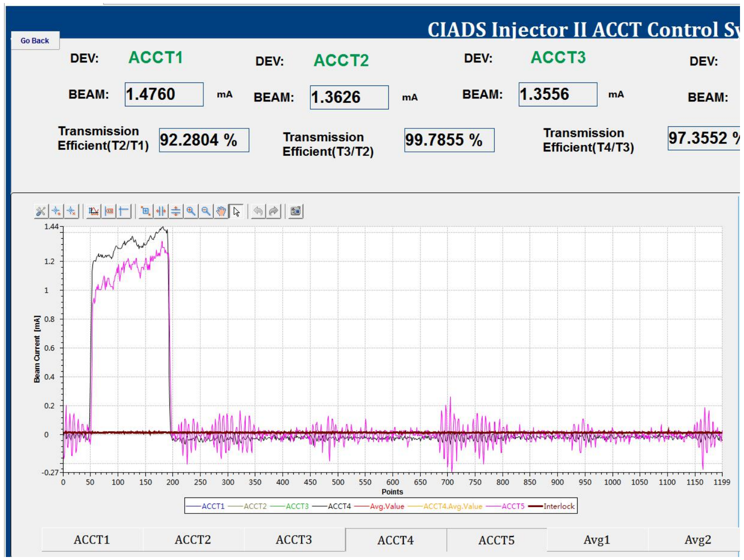
Slit outside

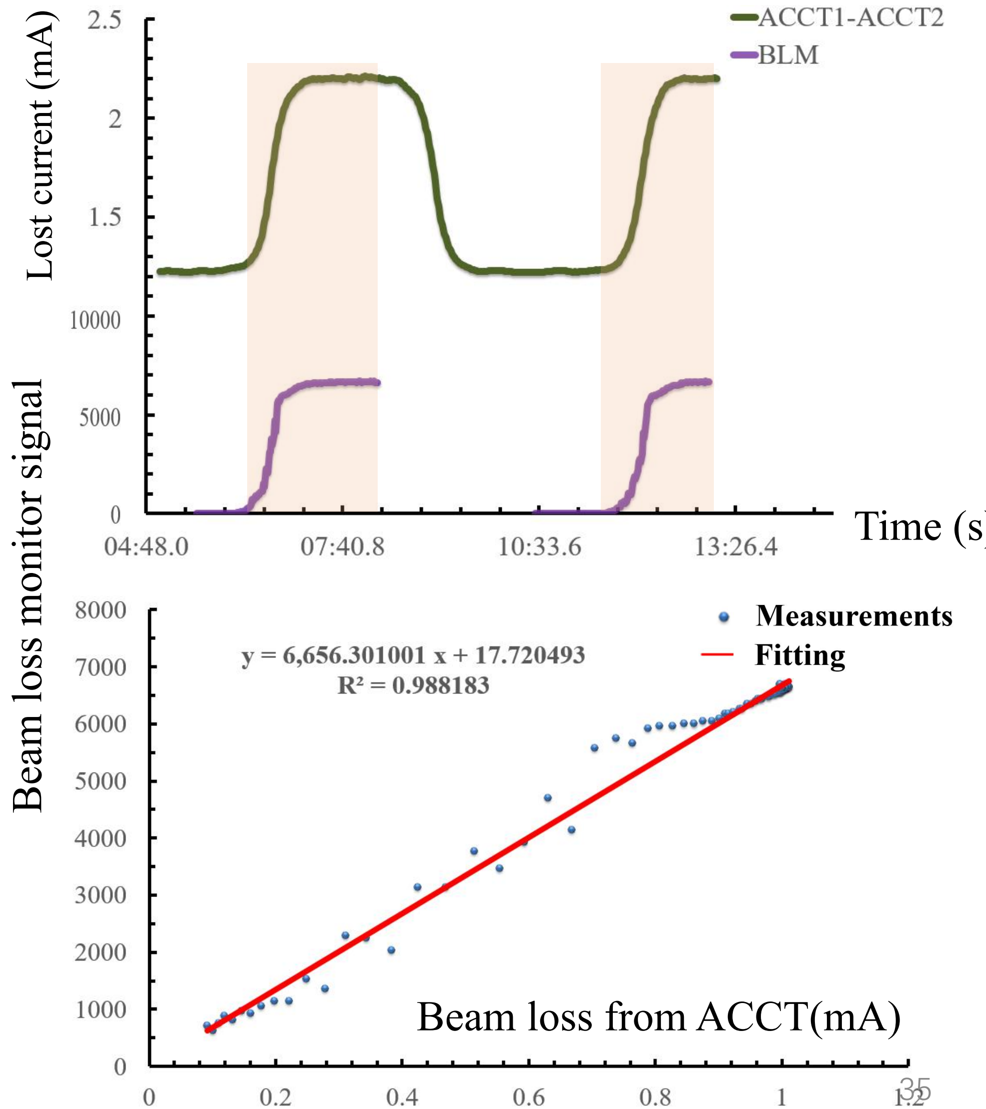


Conclusion: scintillator is much more sensitive than diamond detector (10 mm*10 mm)

Lessons and improvement - Beam loss monitoring

- **Beam loss monitoring experiment for low energy beam at 18.3 MeV**

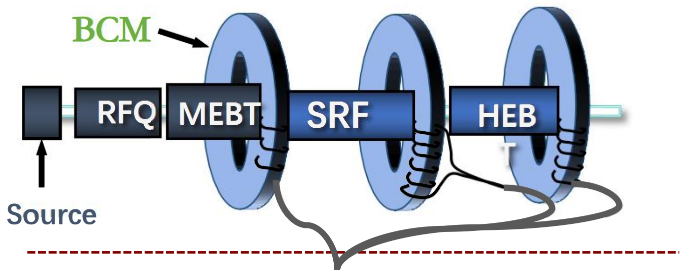


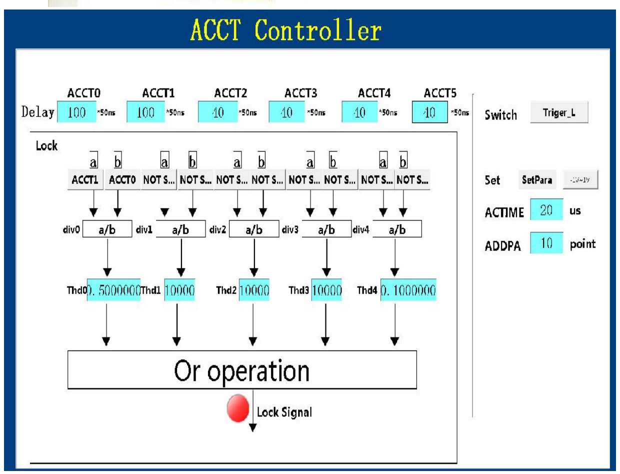


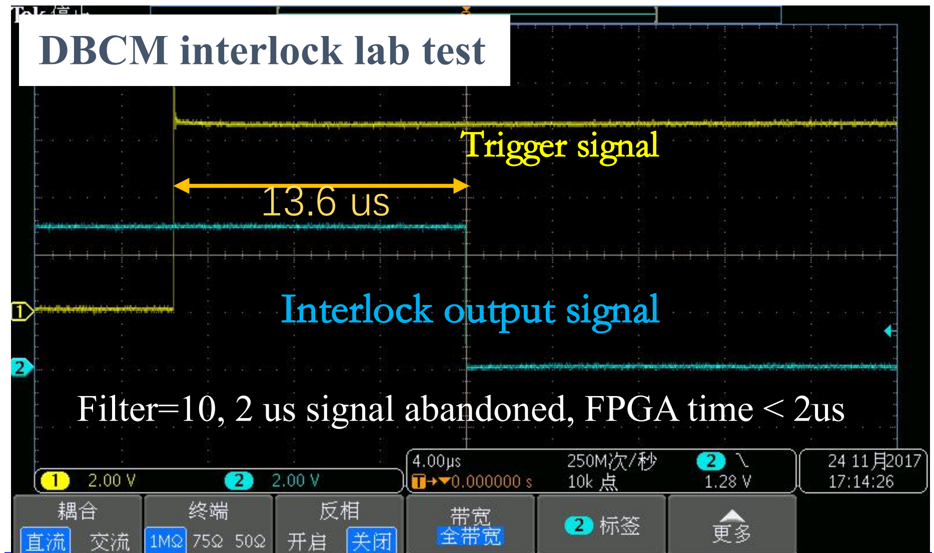
- There is a linear relationship between BLM's signal and beam loss at 18.3 MeV.
- The scintillator BLM is very sensitive for proton beam loss at 18.3 MeV.

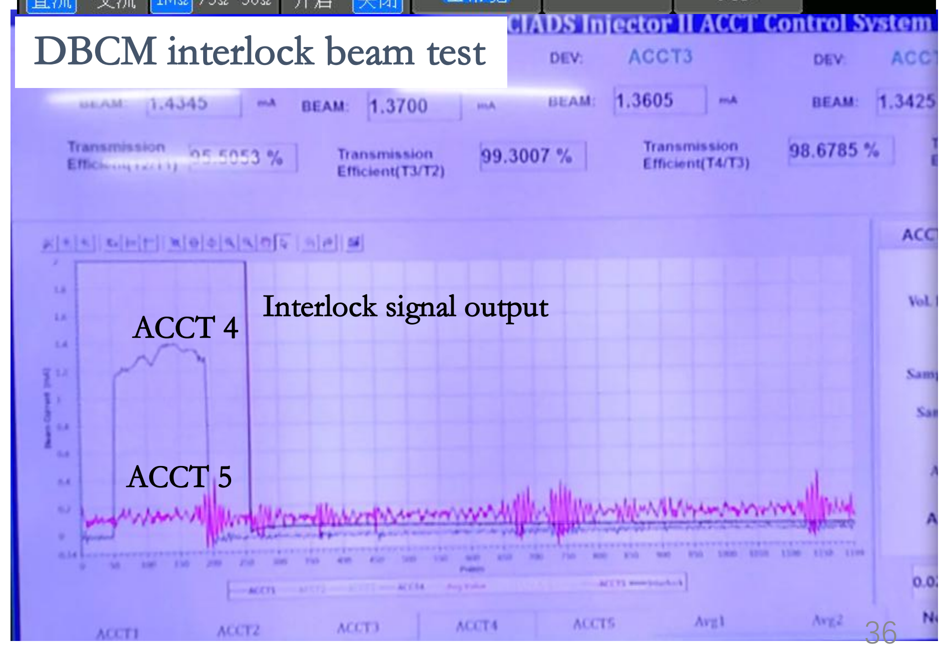
Lessons and improvement – Errant beam measurement

- DBCM development









Lessons and improvement – Errant beam measurement

- **DBPM development**

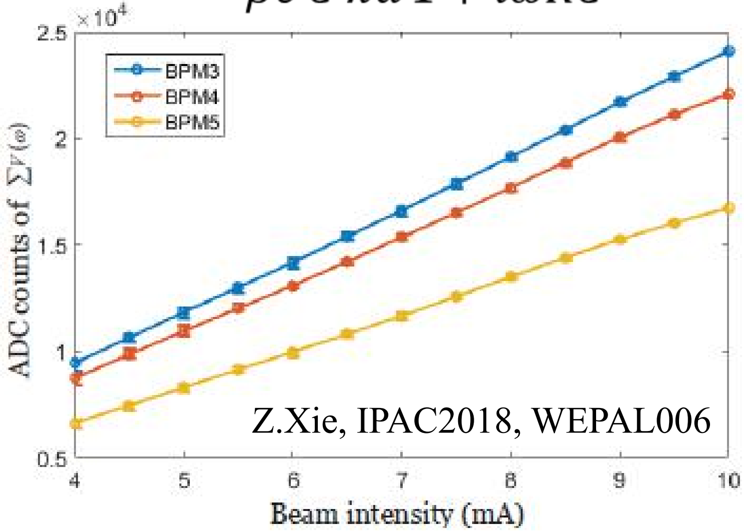
$$U_{im} = \frac{1}{\beta c}\frac{1}{C}\frac{A}{\pi a}\frac{i\omega RC}{1+i\omega RC} I_{beam}$$

$$I_b(t) = \frac{eN}{\sqrt{2\pi}\sigma} exp\left(\frac{-t^2}{2\sigma^2}\right)$$

$$I_b(m\omega_o) = \frac{2eN}{T} exp\left(\frac{-(m\omega_o\sigma)^2}{2}\right)$$

R.E.Shafer

$$i_w = \frac{-I_b(t)}{2\pi a}\left[\frac{a^2-r^2}{a^2+r^2-2arcos(\emptyset_w-\theta)}\right]$$



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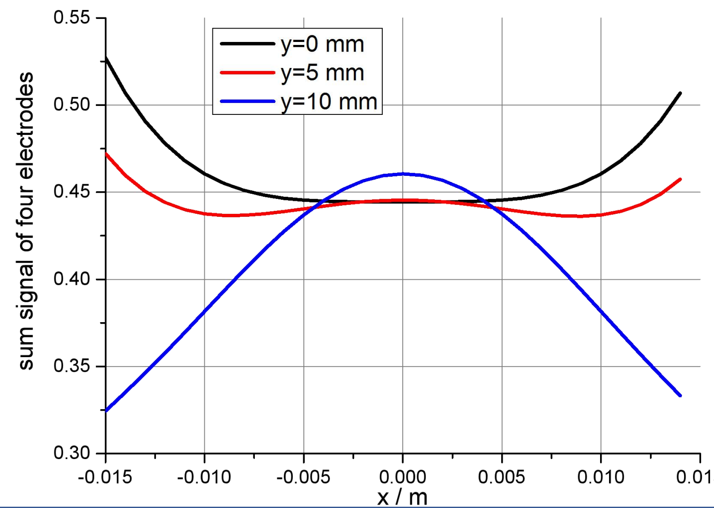
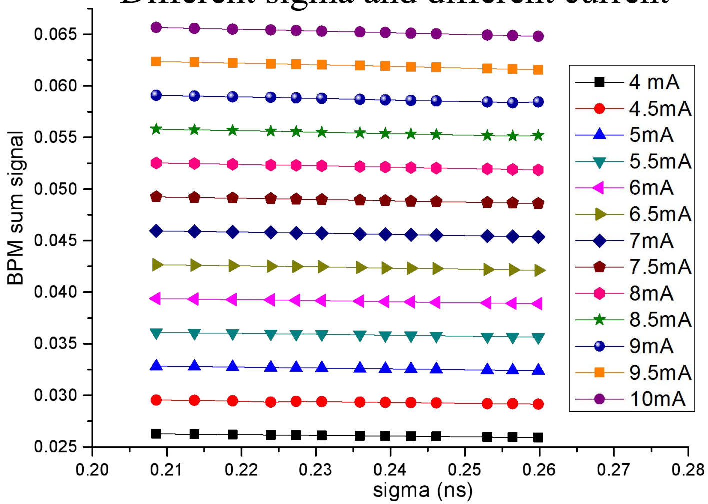
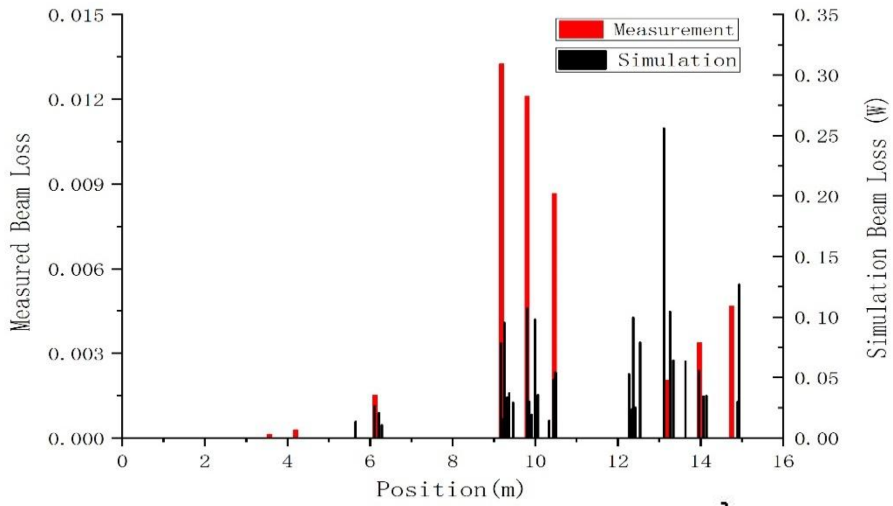


Different sigma and different current



- **Bunch length**
- **Beam position**
- **BPM characters**
- **Beam velocity**
- **Electronics gain**
- **……**

Lessons and improvement – beam halo measurement



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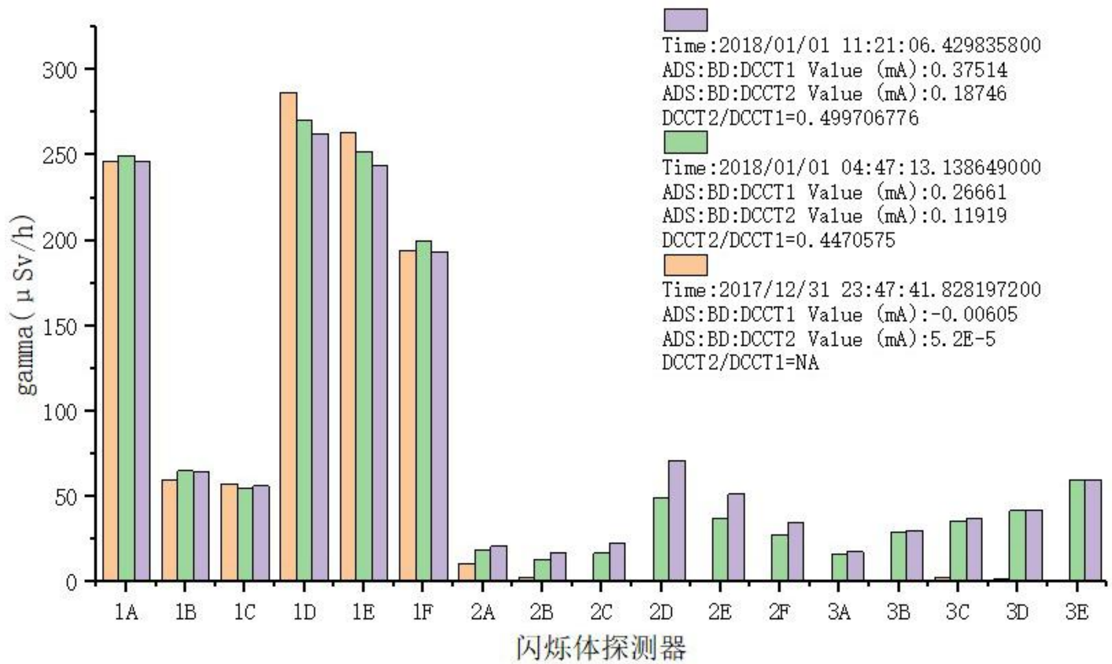
The beam loss is defined as the sum of four quadrant temperature raising per unit time at a certain temperature probe:

- Scintillator was used for each SC cavity calibration.
- During beam Commissioning, it is found that Scintillator can give out the beam loss at each SC cavity.



Summary

- CADS 10-25 MeV proton linac have been constructed
  - Diagnostics are well developed
  - Beam commissioning: nearly all beam parameters have been measured except the longitudinal emittance (FFC less resolution)
- The work planned to do
  - DBPM
  - BSM (high resolutoin)
  - Beam loss detection, especially inside CM
  - More beam time for the beam instruments test
  - High reliability, availability, ……

Acknowledgments to Linac 2018 committee, my colleague Huan Jia ……

Thank you for your attention !

Any comments welcomed!