Direct Measurement of the Longitudinal Emittance for a Proton Beam at Exit of a RFQ

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on behalf of the BSM-team

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OUTLINE

- **Background of Measured longitudinal emittance in Hadron LINAC**
- **Development of Bunch shape monitor based on Feschenko's style in IMP**
- **Demonstrator of direct measurement of longitudinal emittance**
- **Measured longitudinal emittances in 9 conditions**
- **Conclusions**
- **Acknowledgements**

Background of Measured Longitudinal Emittance in Hadron LINAC

Hadron LINAC beam : single pass, low-β, halo and high power

Matching beam and controlling the loss in hadron LINAC

Indirect method:
cavity voltages
synchronous
phases
BPM signals

Direct method:
BSM+ES

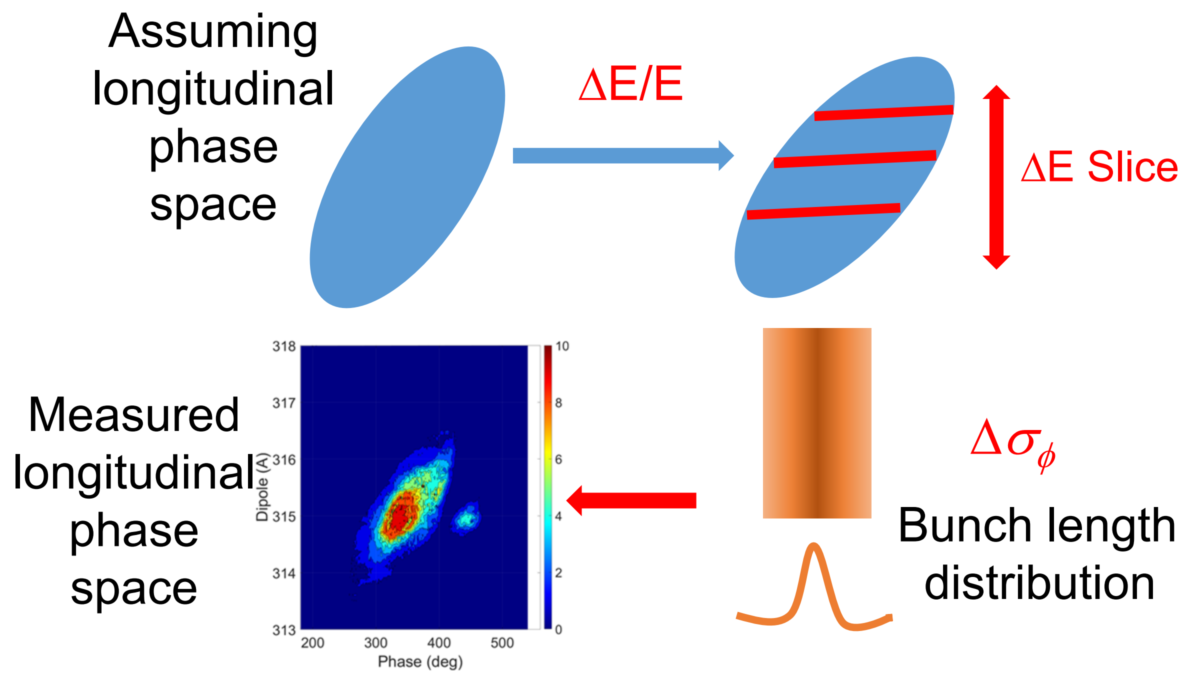
Longitudinal emittance method	LINAC	BEAM ENERGY	MEASURED PARAMETERS	Direct or Indirect metohd	Phase space distribution	Resolution of phase length and energy spread distribution	Publish time
BPM sum	SNS (U.S.A.)	H^- (180 MeV)	Bunch Lengh	indirect	NO	RMS	2013
BPM sum	CPHS (China)	H (3 MeV)	Bunch Lengh	indirect	NO	RMS	2018
BSM	Linac4 (CERN)	H^-	Bunch Lengh	indirect	YES	10 ps	2016
BSM	FRIB (U.S.A.)	Ion	Bunch Lengh	indirect	YES	10 ps	2018
Rutherford spread	SARAF (Israeli)	H	Energy Spread	indirect	YES	20 kV	2009
BEM	SPIRAL2 (France)	Ion	Bunch length	indirect	YES	47 ps	2016
Rutherford spread	GSI (Germany)	Ion	Bunch length, Energy Spread	direct	YES	35 ps , 20 kV	2014
Acceptance	SNS (U.S.A)	H^- (80 MeV)	Acceptance	indirect	YES	RMS	2008
Dipole+BSM		H^- (2.1 MeV)	Energy Spread & Bunch length	direct	YES	10 ps, 0.1%	2018

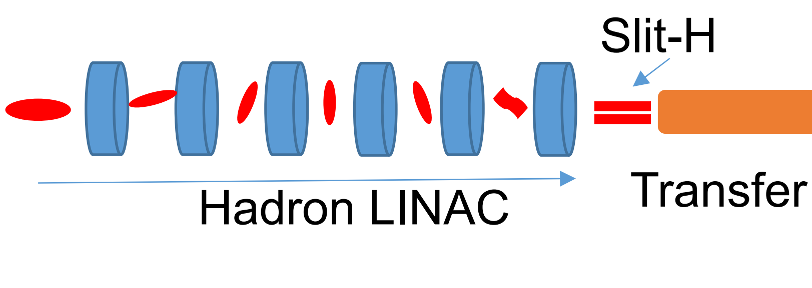
Background of Measured Longitudinal Emittance in Hadron LINAC

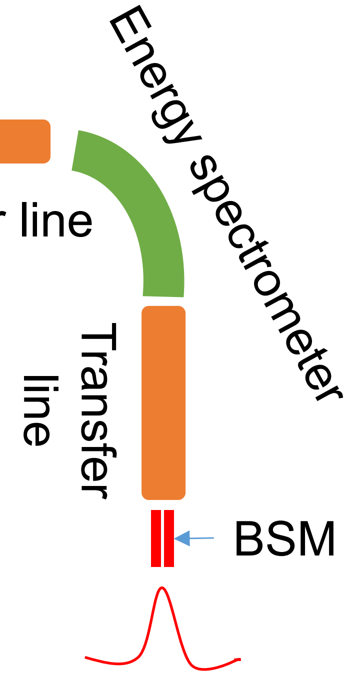
Longitudinal phase space distribution
- Energy spread distribution ΔE
- Bunch length distribution $\Delta\sigma_\phi$

$$\varepsilon_{\sigma E} = \sqrt{\langle \Delta\sigma_\phi \rangle^2 \cdot \langle \Delta E \rangle^2 - \langle \Delta\sigma_\phi \cdot \Delta E \rangle}$$

Resolution is important







- **Developed own BSM**
- **Waist-to-Waist transfer matrix**

Following SNS BTF design, we upgrade the ES resolution by waist to waist

Courtesy of Huan JIA

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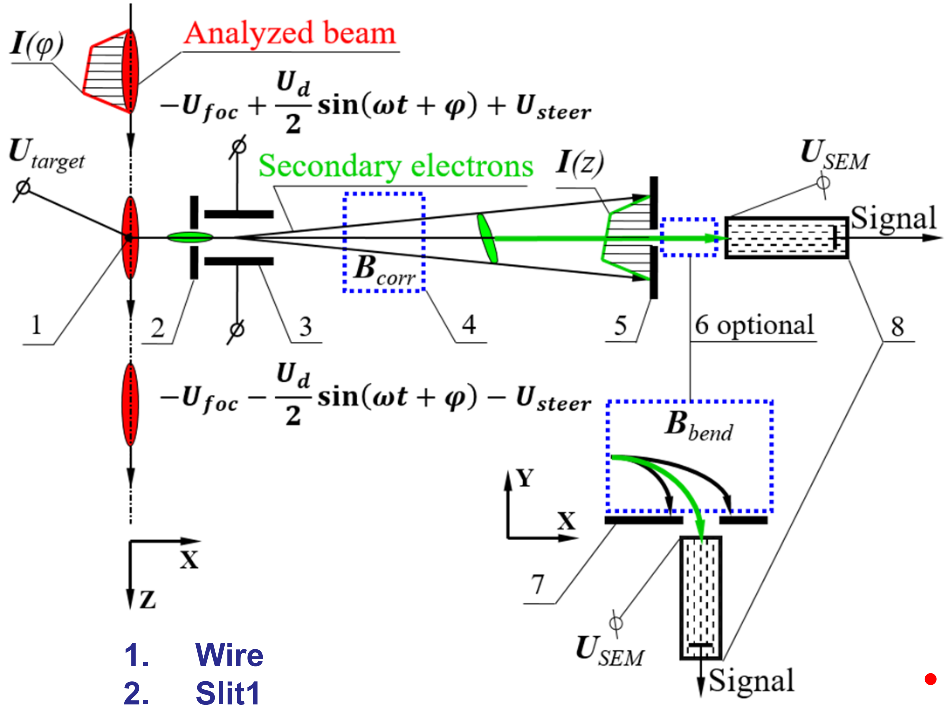
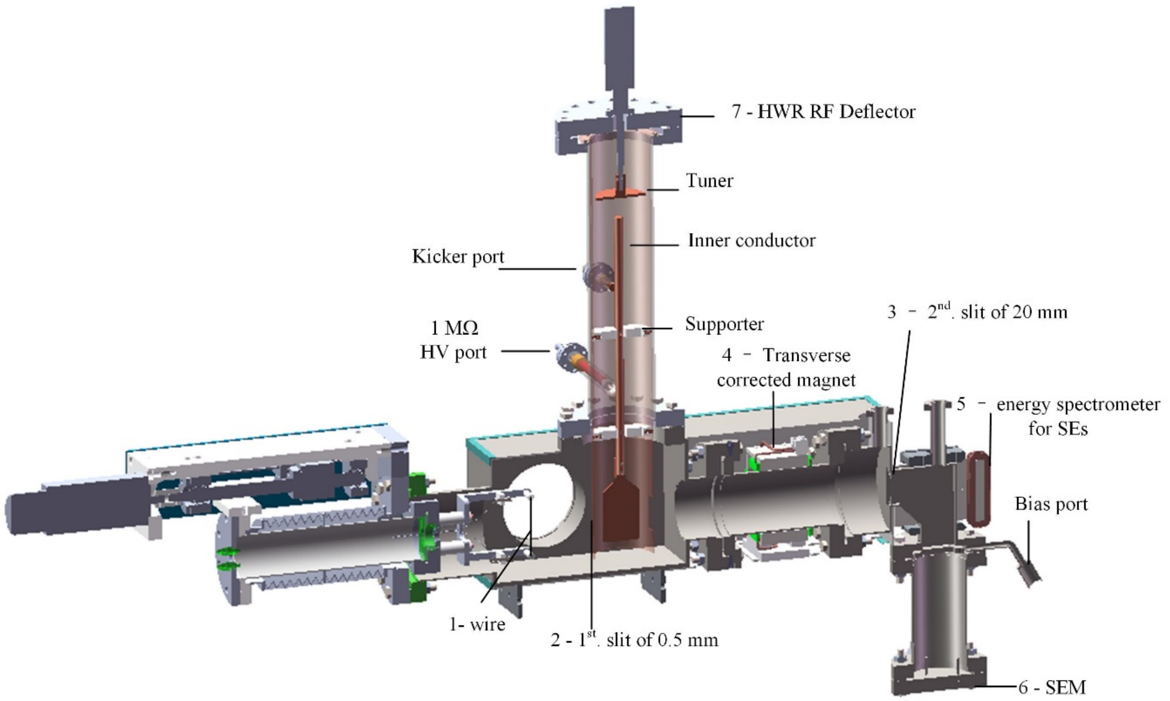
Developed Bunch shape monitor based on Feschenko's style

Operation principle: coherent transformation of a temporal bunch structure into a spatial charge distribution of low SE through a transverse RF-scanning



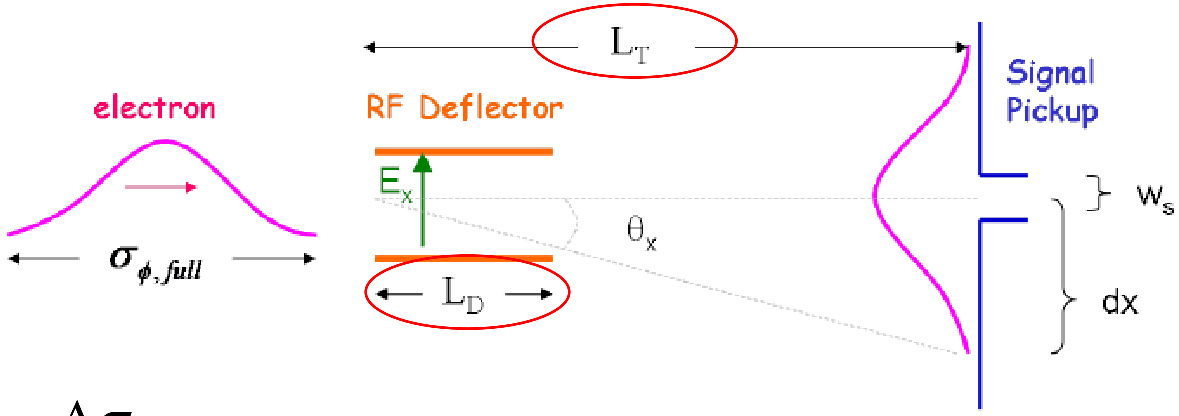
1. **Wire**
2. **Slit1**
3. **RF-Deflector**
4. **Corrected magnet**
5. **Slit2**
6. **Energy spectrometer**
7. **Secondary electron collector**

Cross section view of the developed BSM (HWR @325 MHz)



- **Study the influences of key parameters on the high resolution**
- **How to get a good performance of RF-Deflector**

Analyzing Ld, Ex versus BSM Phase Resolution $\Delta\sigma_\phi / \sigma_{\phi,full}$



$$\frac{\Delta\sigma_\phi}{\sigma_{\phi,full}} = \frac{w_s}{2dx} = \frac{w_s}{2L_T \tan\theta_x} = \frac{w_s}{2L_T\theta_x}$$

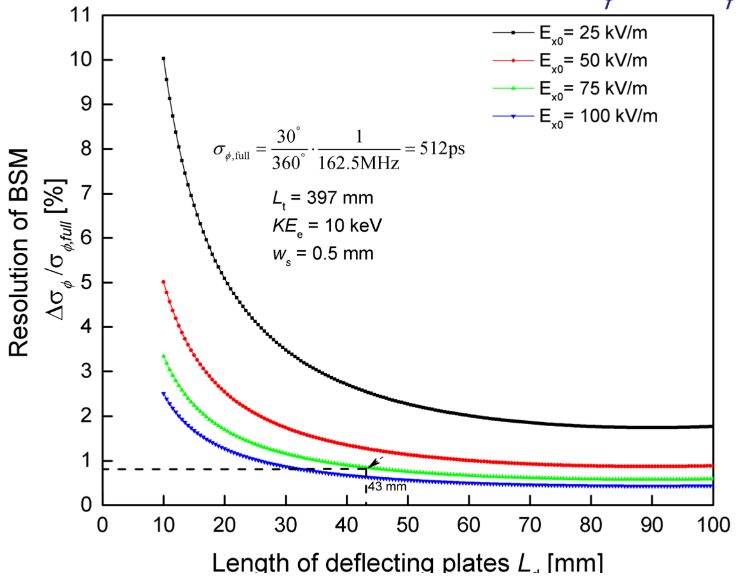
$$\theta_{x,i} = \frac{1}{B\rho}\int_{t_0}^{t_f} E_x(z,t)dt = \frac{1}{B\rho}E_{x0}\int_{t_0}^{t_f}\sin(\omega_{rf}t+\phi_i)dt$$

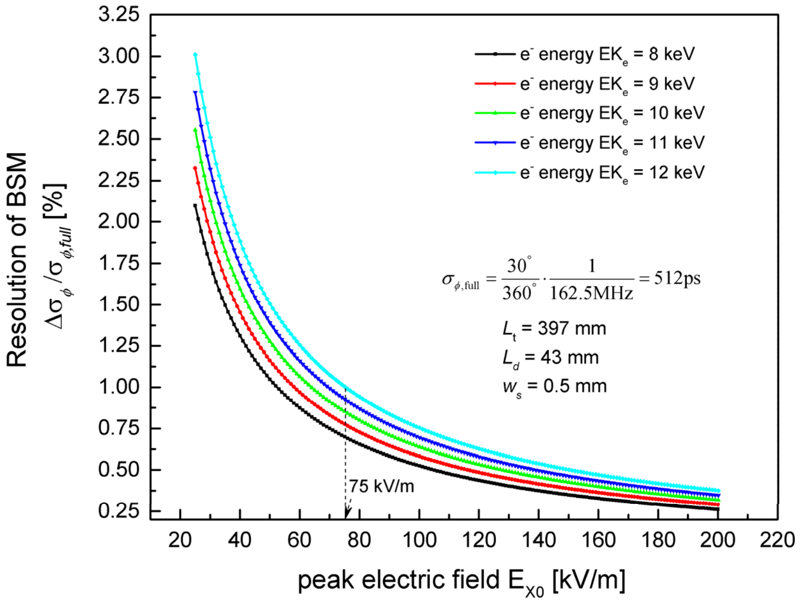
$$\phi_{center} = 0$$

$$\phi_{head/tail} = \pm\frac{\sigma_{\phi,full}}{2}$$

$$\frac{\Delta\sigma_\phi}{\sigma_{\phi,full}} = \frac{w_s}{2L_T\theta_{x,head}} = \frac{w_s \cdot \omega \mathbf{B}\rho}{4L_T \mathbf{E}_{x0}\sin\dfrac{L_D\omega}{2\beta c}\cos\phi_i}$$

courtesy of Wai-Ming Tam thesis





- **Electron energy 8 ~ 12 keV**
- **Full Phase distribution 30 °**
- **Drift length L_T 397 mm**
- **Electrode width L_D 43 mm**
- **E-field 25 ~ 100 kV/m**
- **BSM phase resolution**

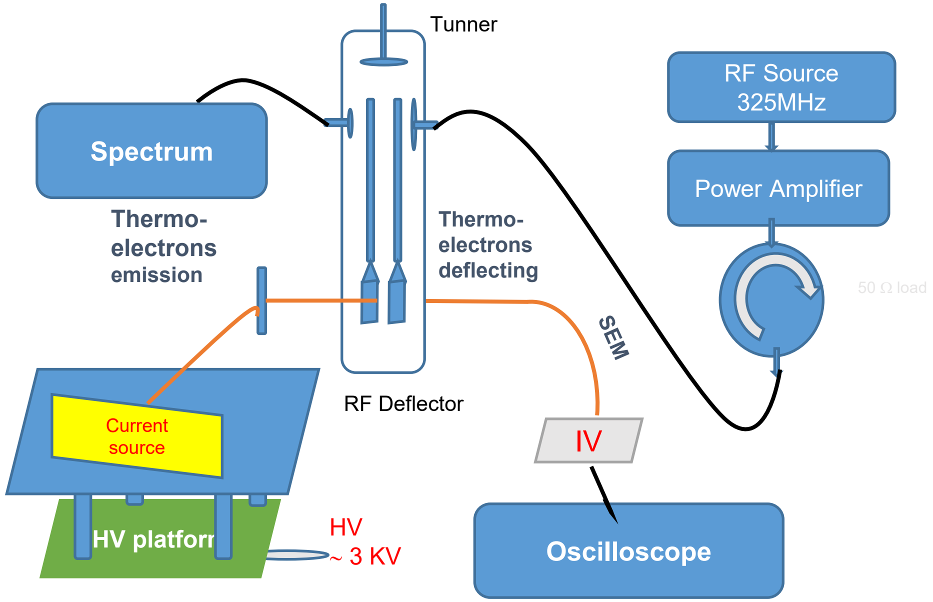
< 1 % of 30 ° @ 162.5 MHz

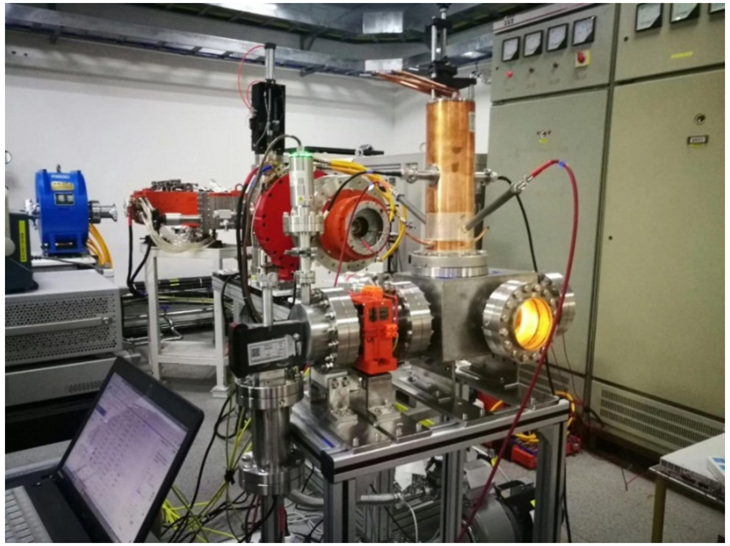
(20 ps / 500 ps @ 162.5 MHz)

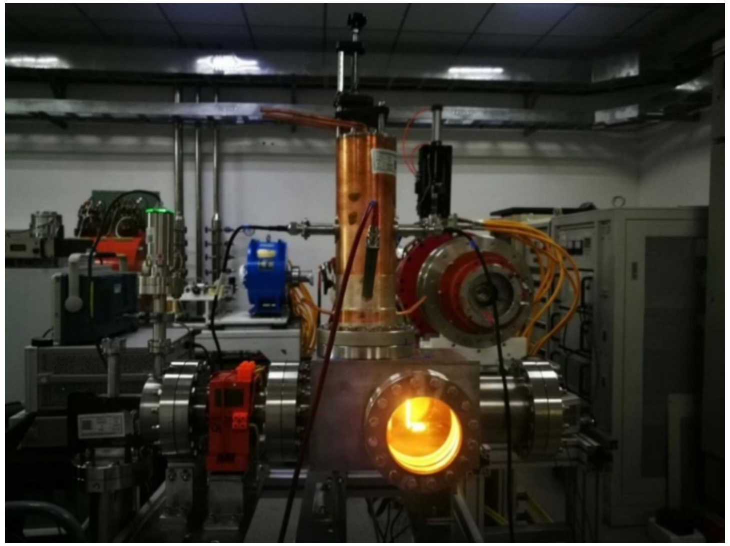
Alignment & mechanic issues

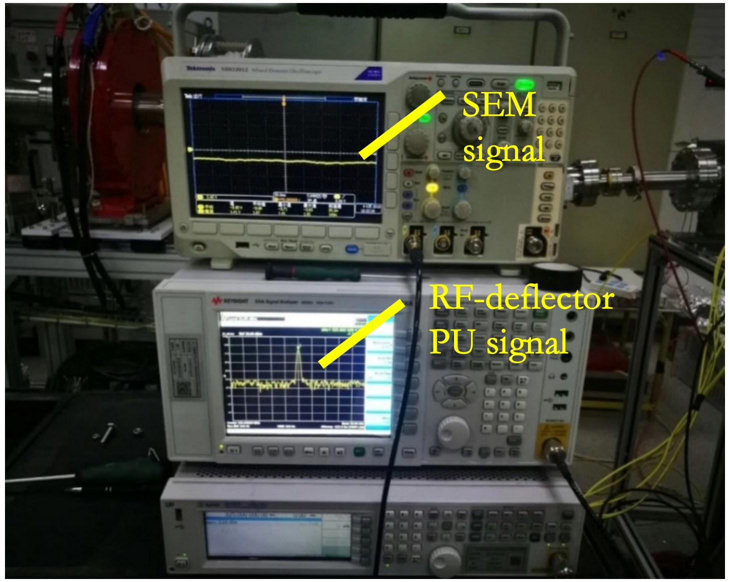
Performance of HWR RF-Deflector- the 1st version BSM

- Off-line test
- Thermal electrons emission
- RF deflector power on
- Check power signal and SEM signal



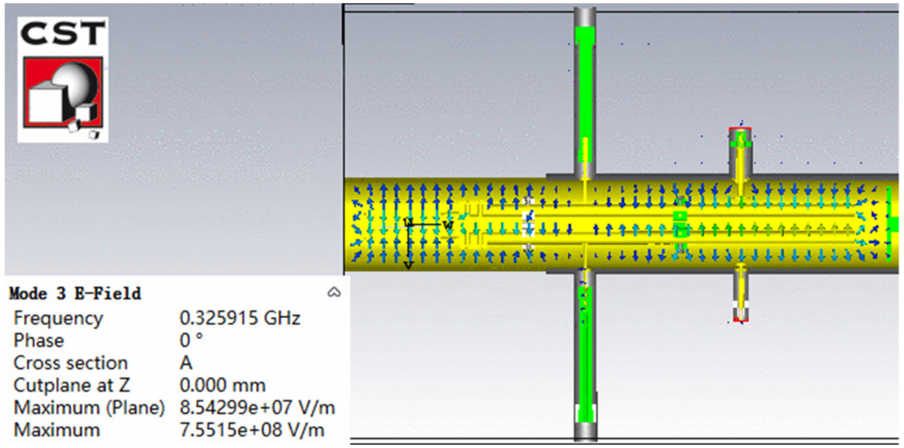


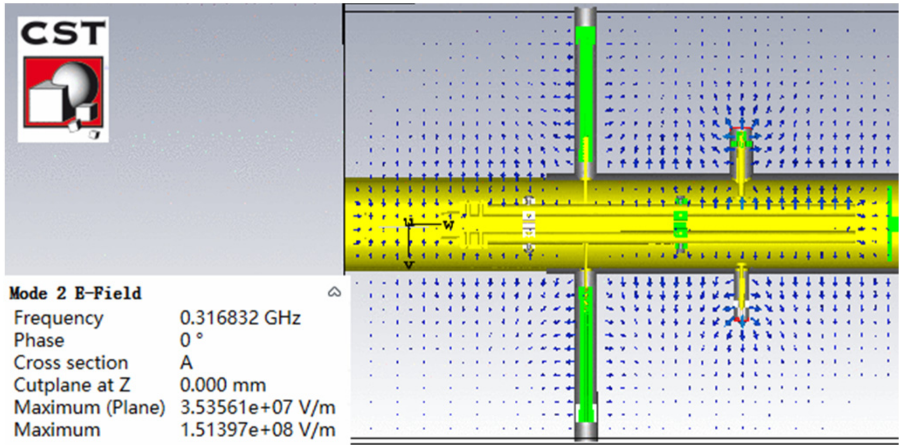


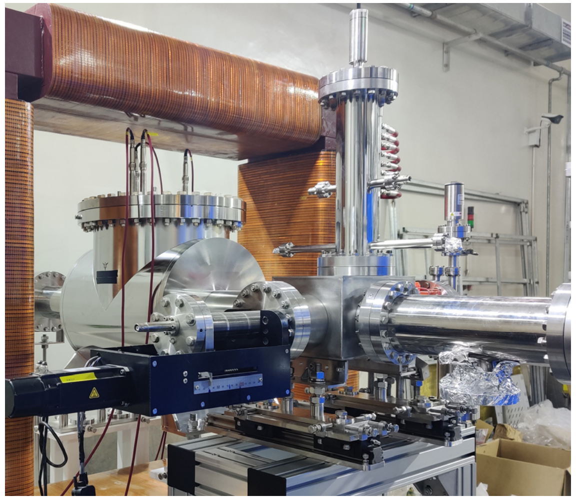


Performance of HWR RF-Deflector- the 2nd version BSM

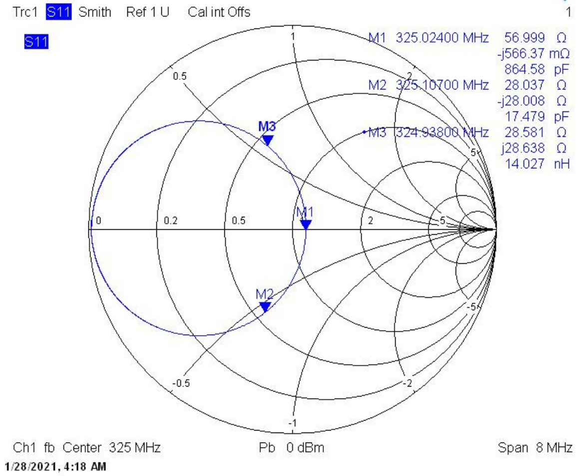
- The improved RF deflector is more stable and easy to tune
- Improving loaded Q value from 300 to 900

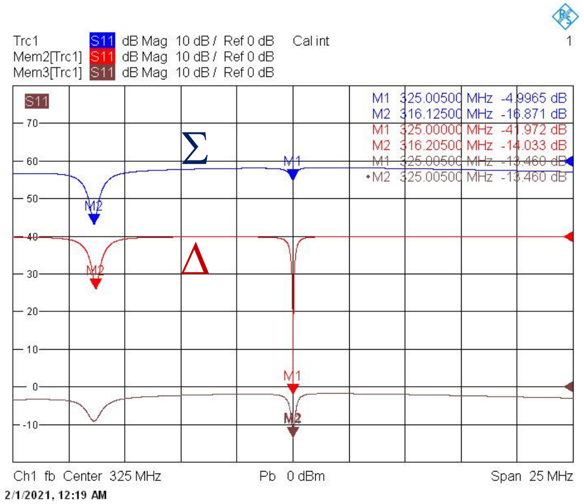




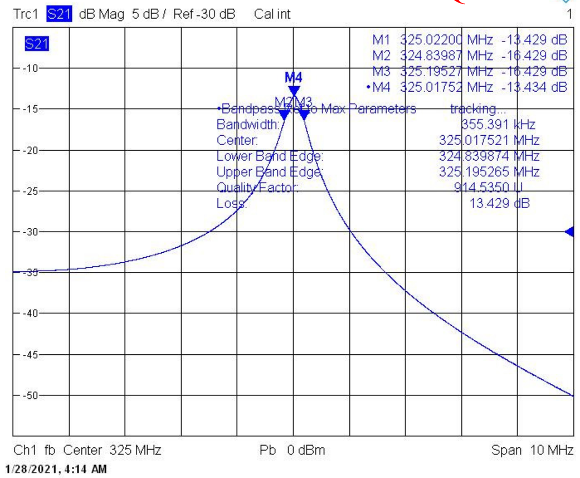


Unloaded Q = 1923



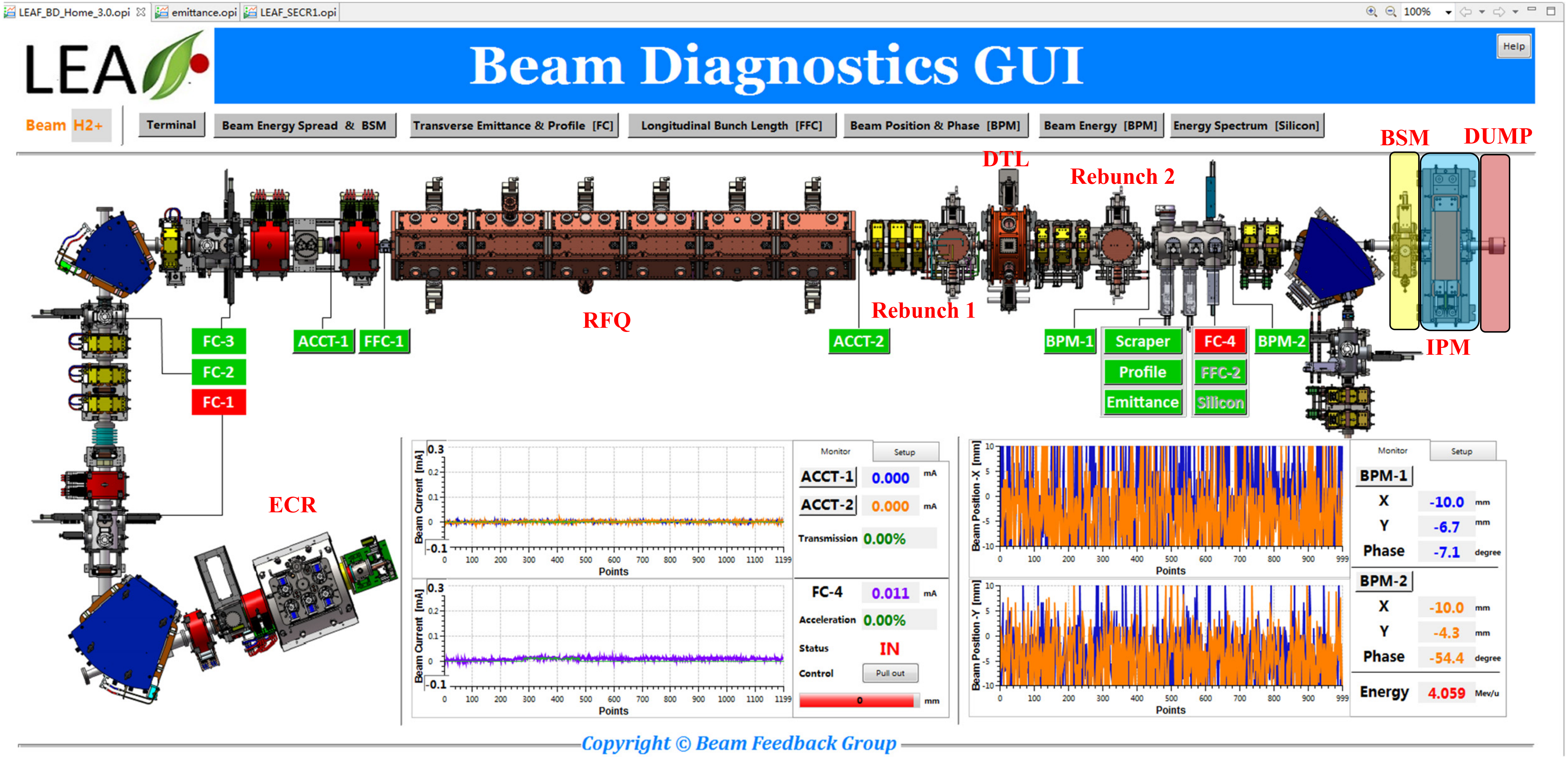


Loaded Q = 914



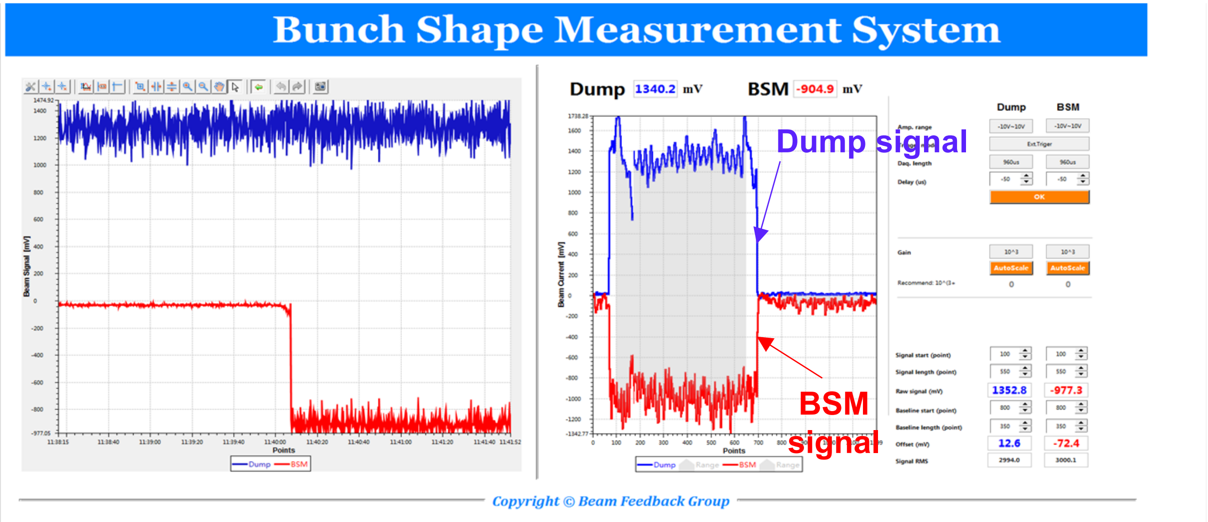
Bunch shape measurements using the 2nd version BSM

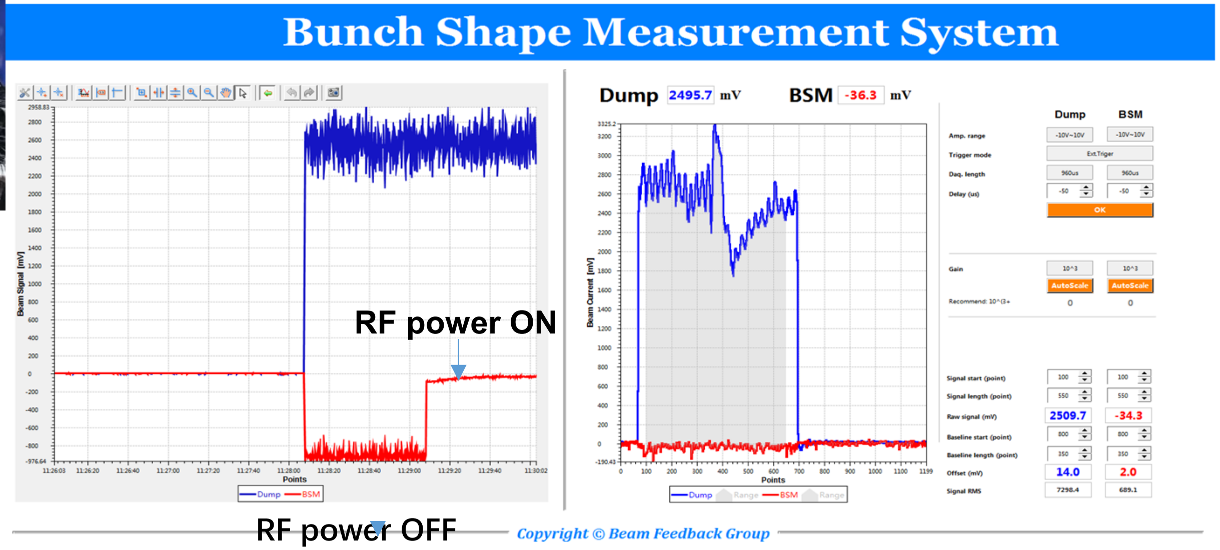
LEAF BD GUI（81.25 MHz, 500 keV/u, 500 euA）



Bunch shape measurements using the 2nd version BSM

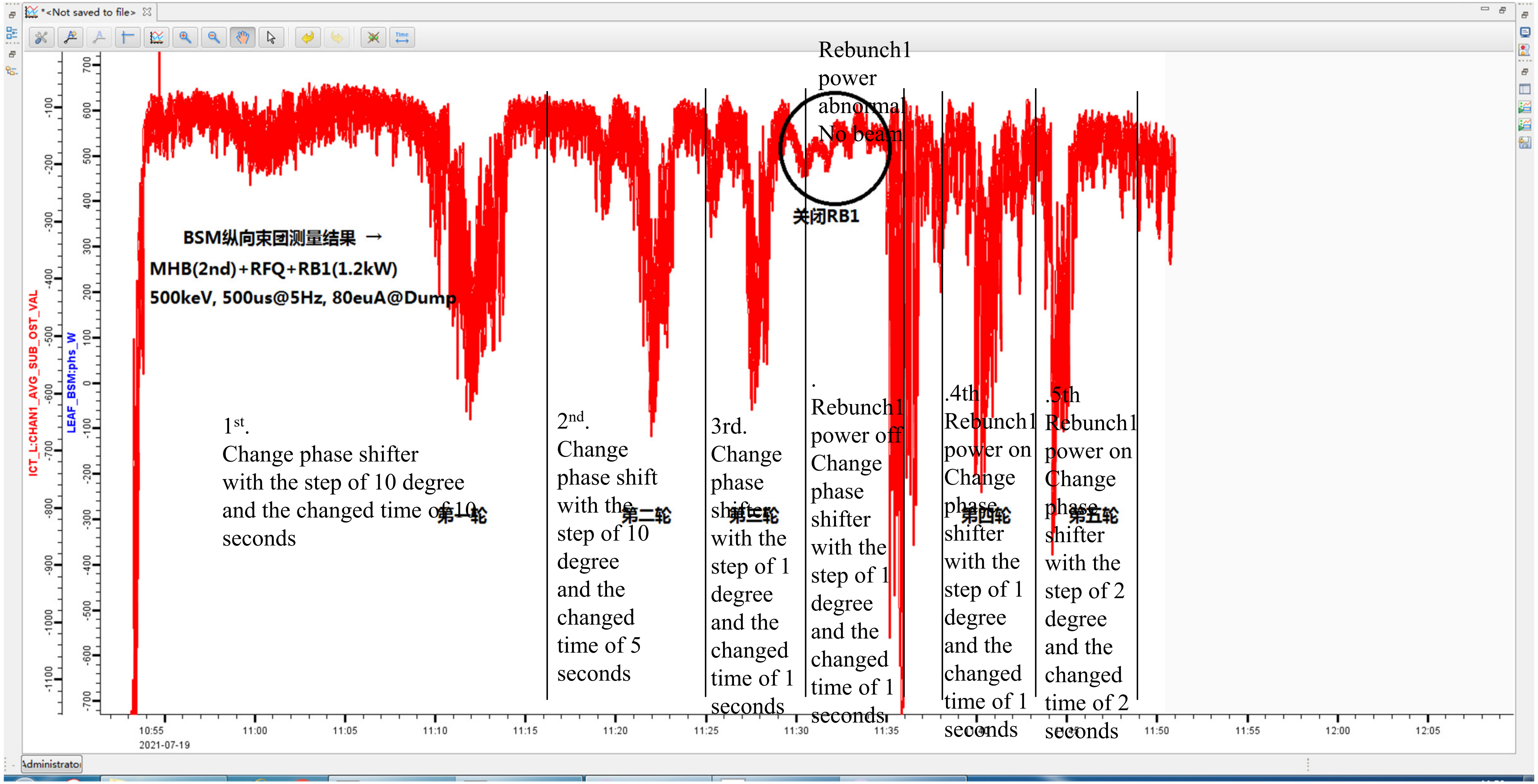
BSM Parameters	
Wire HV	- 6.5 kV
Dipole I	3.75 A
Corrector X I	1 A
Corrector Y I	7.85 A
Collimator bias	- 500 V
Plate 1 bias	- 3500 V
Plate 2 bias	- 3700 V
SEM bias	- 1.4 kV
RF power	10 W





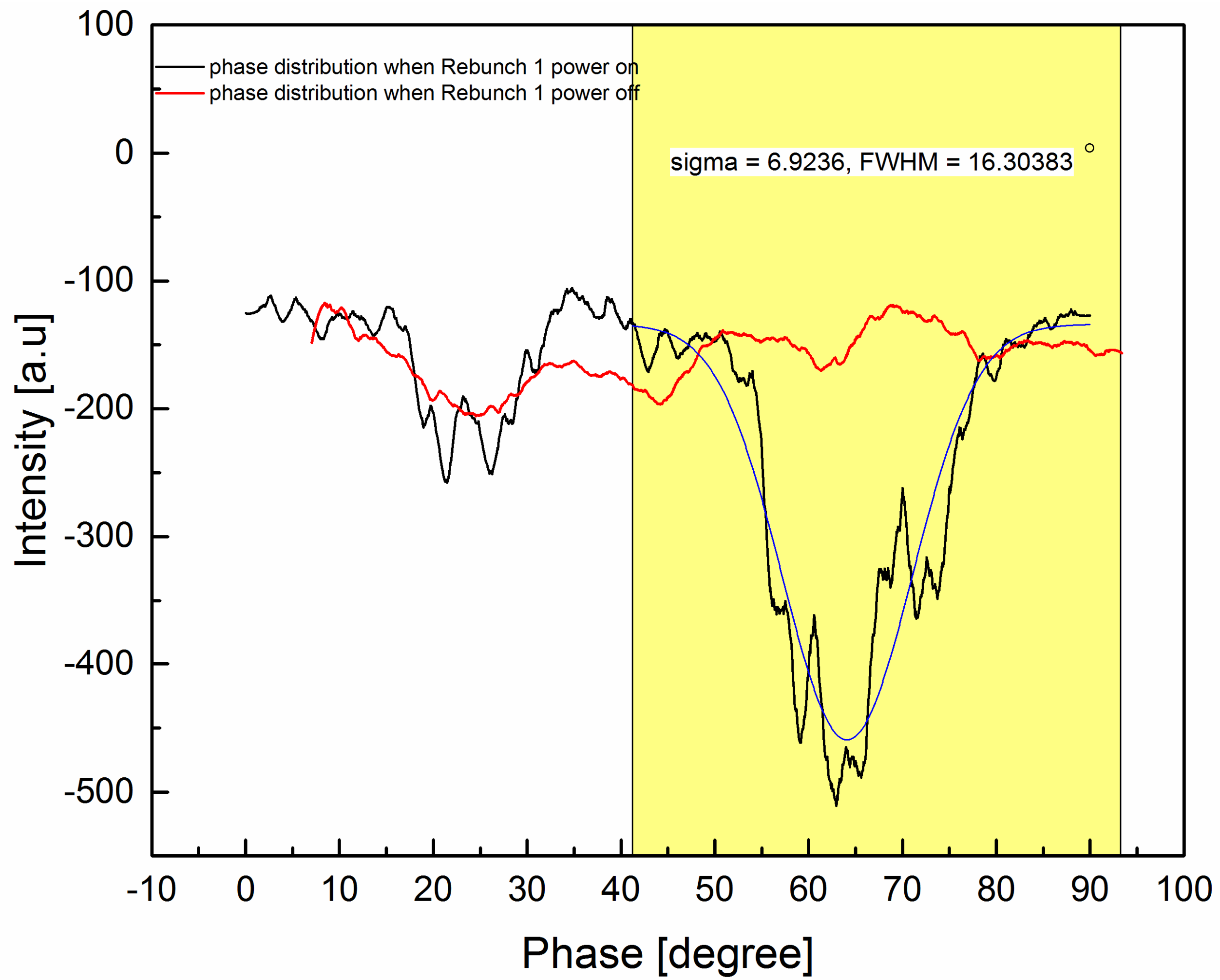
Bunch shape measurements using the 2nd version BSM

By manually sweeping the phase five times, the phase distribution remains consistent

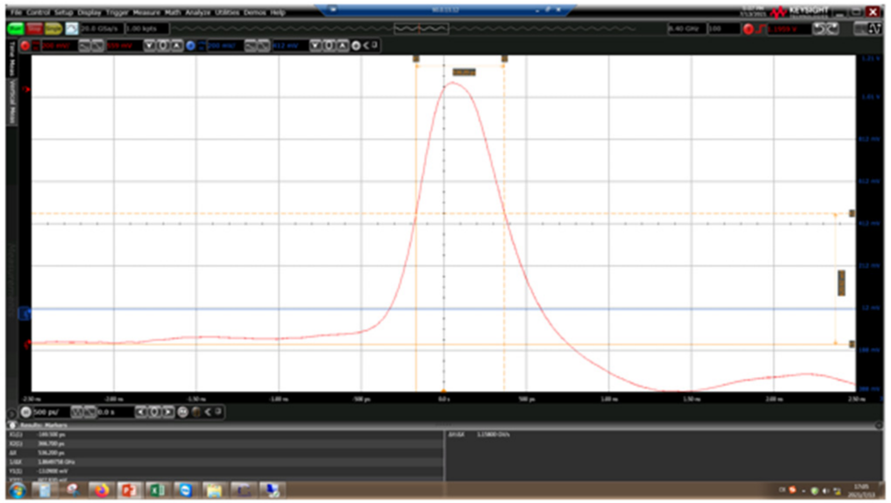


Bunch shape measurements using the 2nd version BSM

Rebuncher power on and off



RB1=0.51kW FWHM=536.2ps



FFC

Measured the phase distribution about 536 ps

BSM

Measured the phase distribution about
547 ps =(16 / 360*12.3 ns)

Keep an agreement

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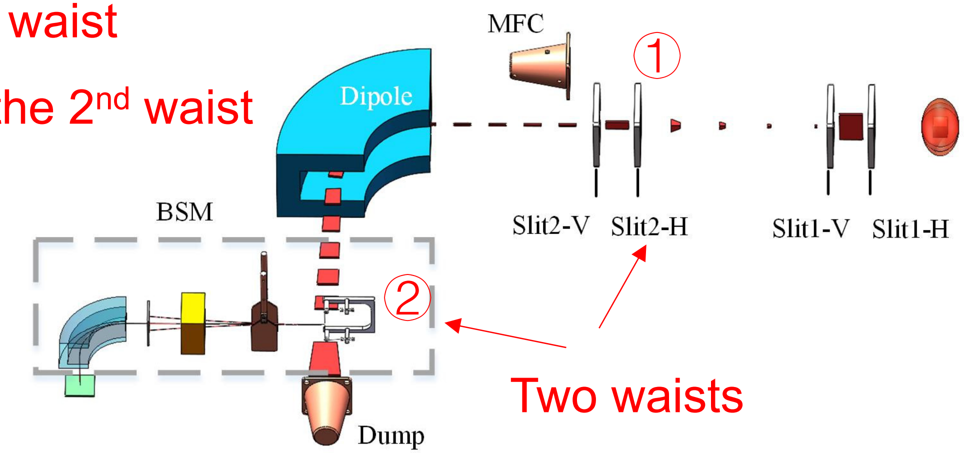
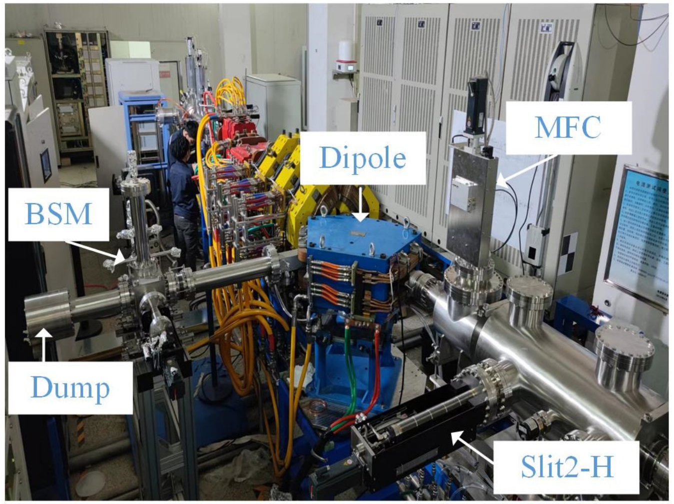
Demonstrator of direct measurement of longitudinal emittance

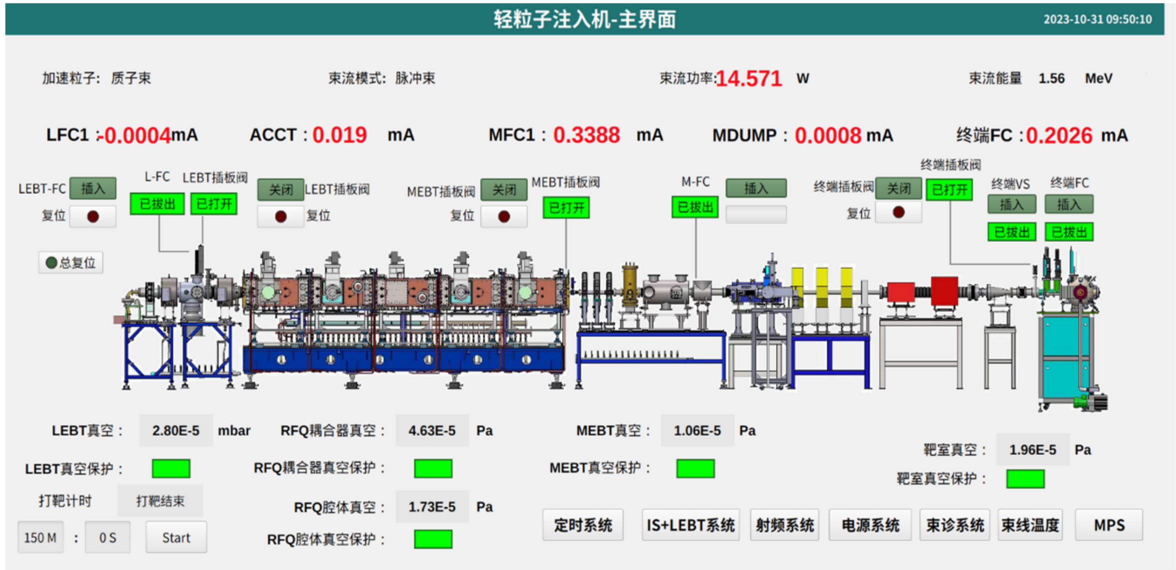
① Slit2-H in the 1st waist

② Wire of BSM in the 2nd waist



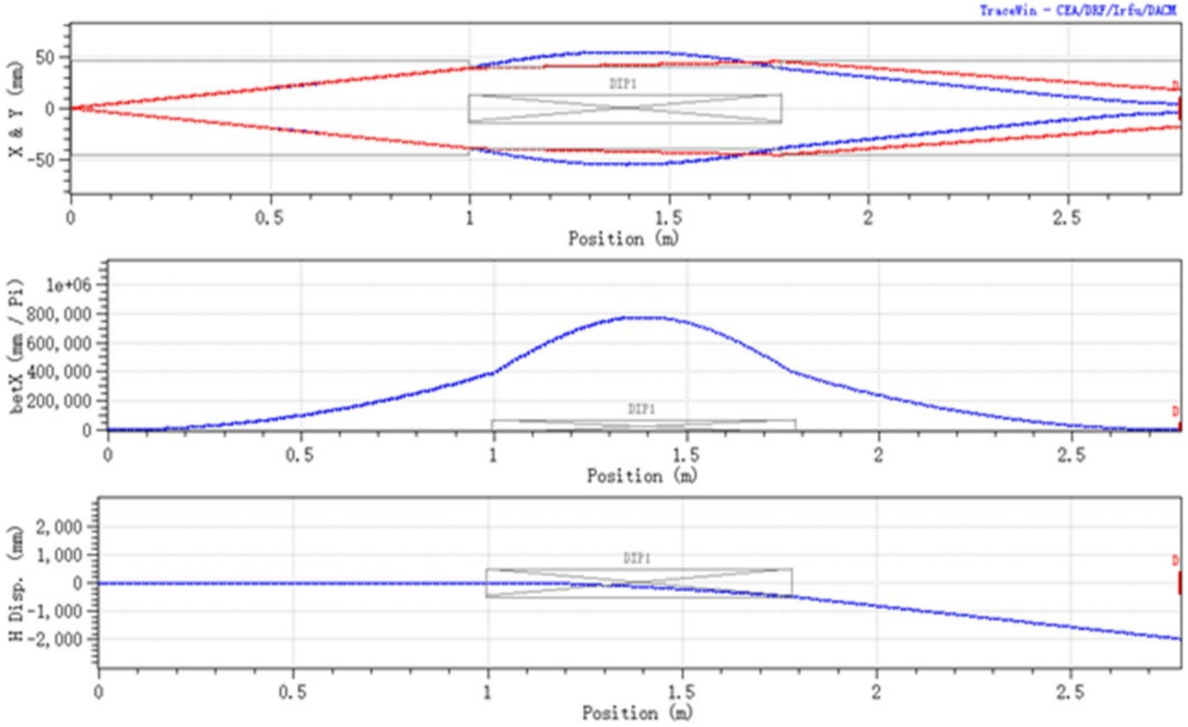


The entrance and exit edge angle of dipole are 26.5 °



Demonstrator of direct measurement of longitudinal emittance

x (m)	-0.99999964	4.8137135e-07	0	0	0	-1.9943421
x' (rad)	-1.5028328	-0.99999964	0	0	0	-1.4985816
y (m)	0	0	-0.70560878	0.4610622	0	0
y' (rad)	0	0	-1.0890423	-0.70560878	0	0
z (m)	1.4985816	1.9943421	0	0	1	2.4858897
dp/p	0	0	0	0	0	1



waist - to - waist transfer matrix

M_{11}= -1, $M_{12} \approx 0$, $M_{16} = D \approx -2$ m, L = 997.17 mm

$$\sigma_{\beta x} = M_{11} \cdot x + M_{12} \cdot x' = M_{11} \cdot x$$

x: Slit2-H width of 0.2 mm at the 1st waist

Resolution of momentum spread Δp / p

$$\delta = \frac{\Delta p}{p} = \frac{\sigma_{\beta x}}{D} = \frac{0.2\text{mm}}{2\text{m}} = 1 \times 10^{-4} = 0.01\%$$

Resolution of BSM $\Delta\sigma_{\phi}$ / $\sigma_{\phi,full}$

- Min. step of phase shifter is 0.7 ° at 325 MHz
- Resolution of BSM is 20 ps / 500 ps (full length)
- Total resolution of BSM is about 1.25 ° / 360 °

Courtesy of Yuanshuai Qin and Duanyang Jia

Procedures of direct measurement of longitudinal emittance

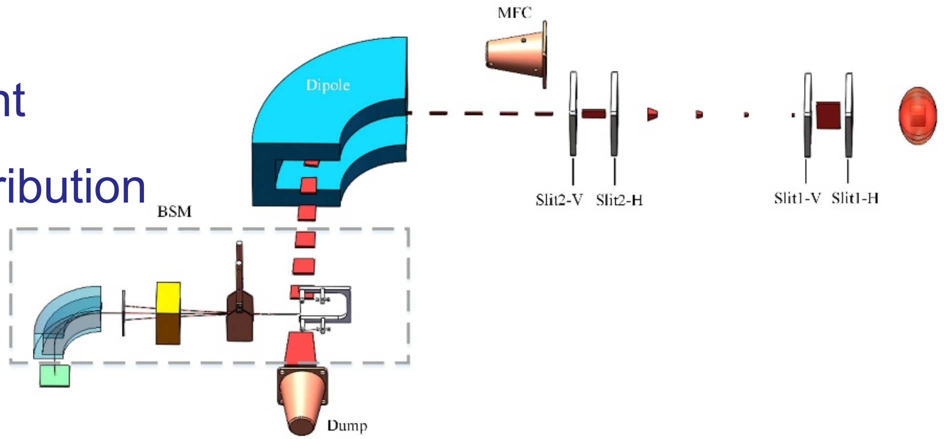
① calibrate the phase and voltage of the buncher in the synchronous

② adjust the corrected magnet to keep beam position and energy constant

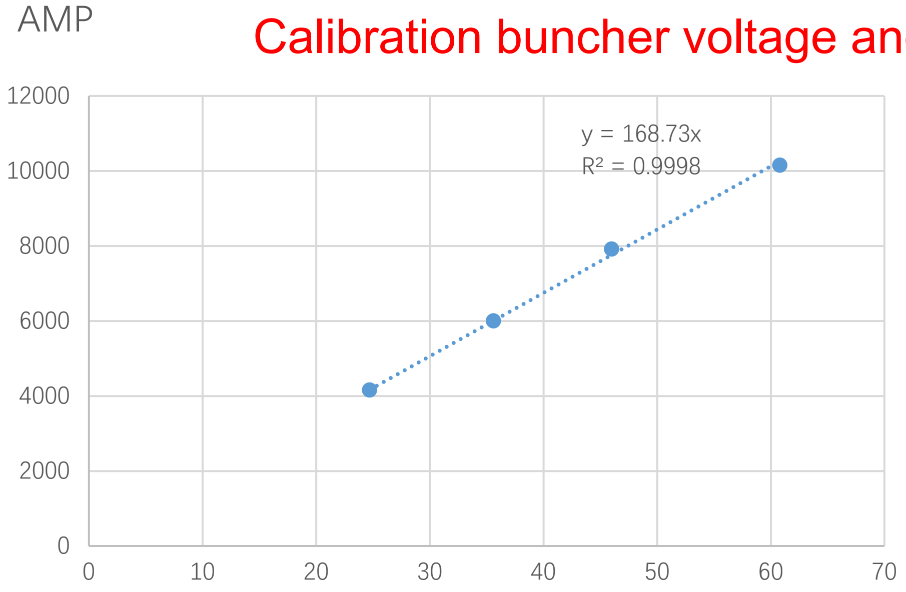
③ use the wire of BSM in the 2st waist to measure the energy spread distribution

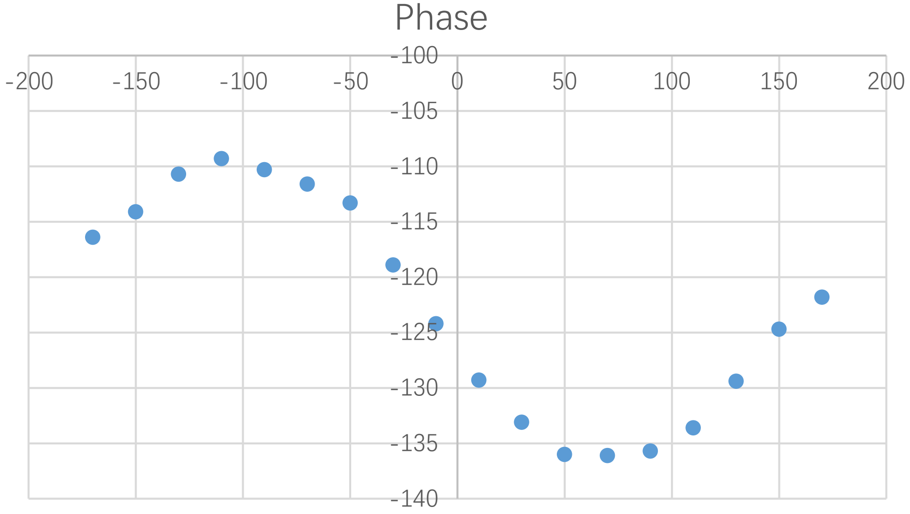
④ get the energy sweeping range and set one dipole current

⑤ scan the phase value of BSM to measure the longitudinal bunch length



Calibration buncher voltage and synchronous phase (by BPM phase value)

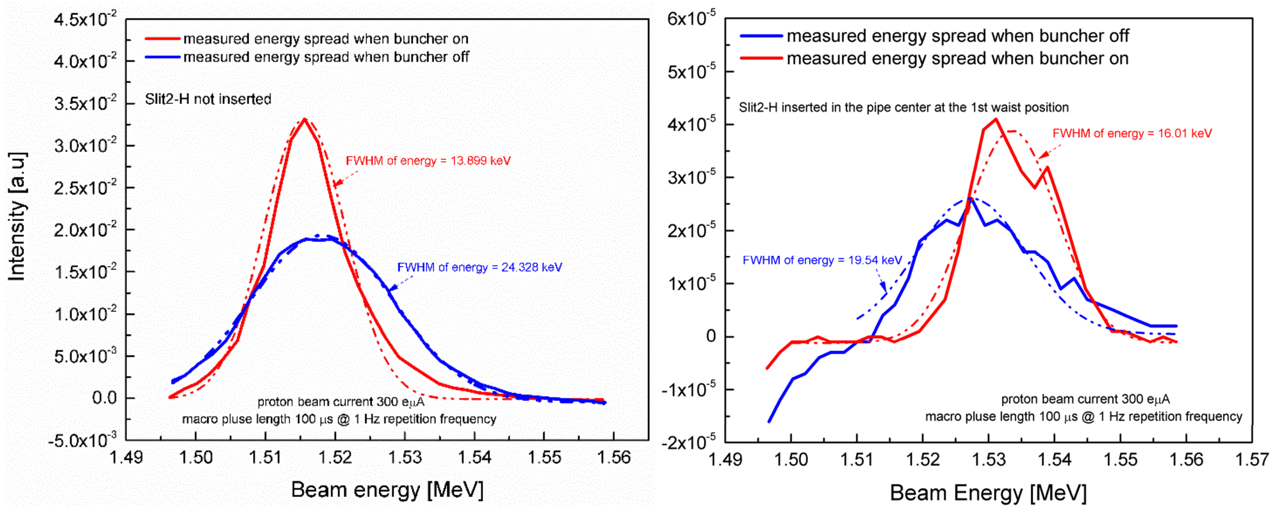




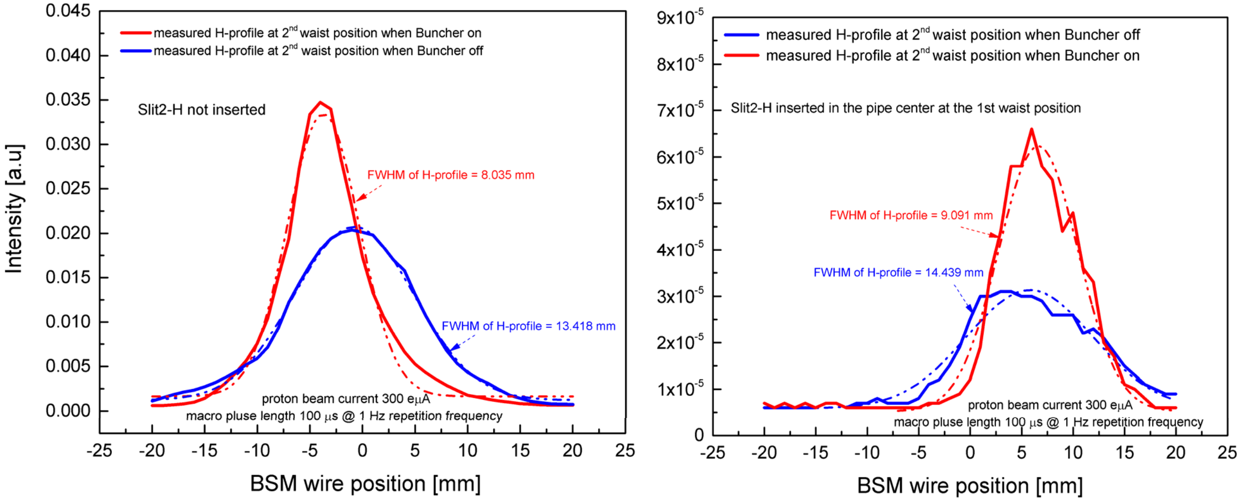
Courtesy of Yuanshuai Qin and Wangsheng Wang

Procedures of direct measurement of longitudinal emittance

Energy spread distribution using BSM wire in center and sweeping dipole



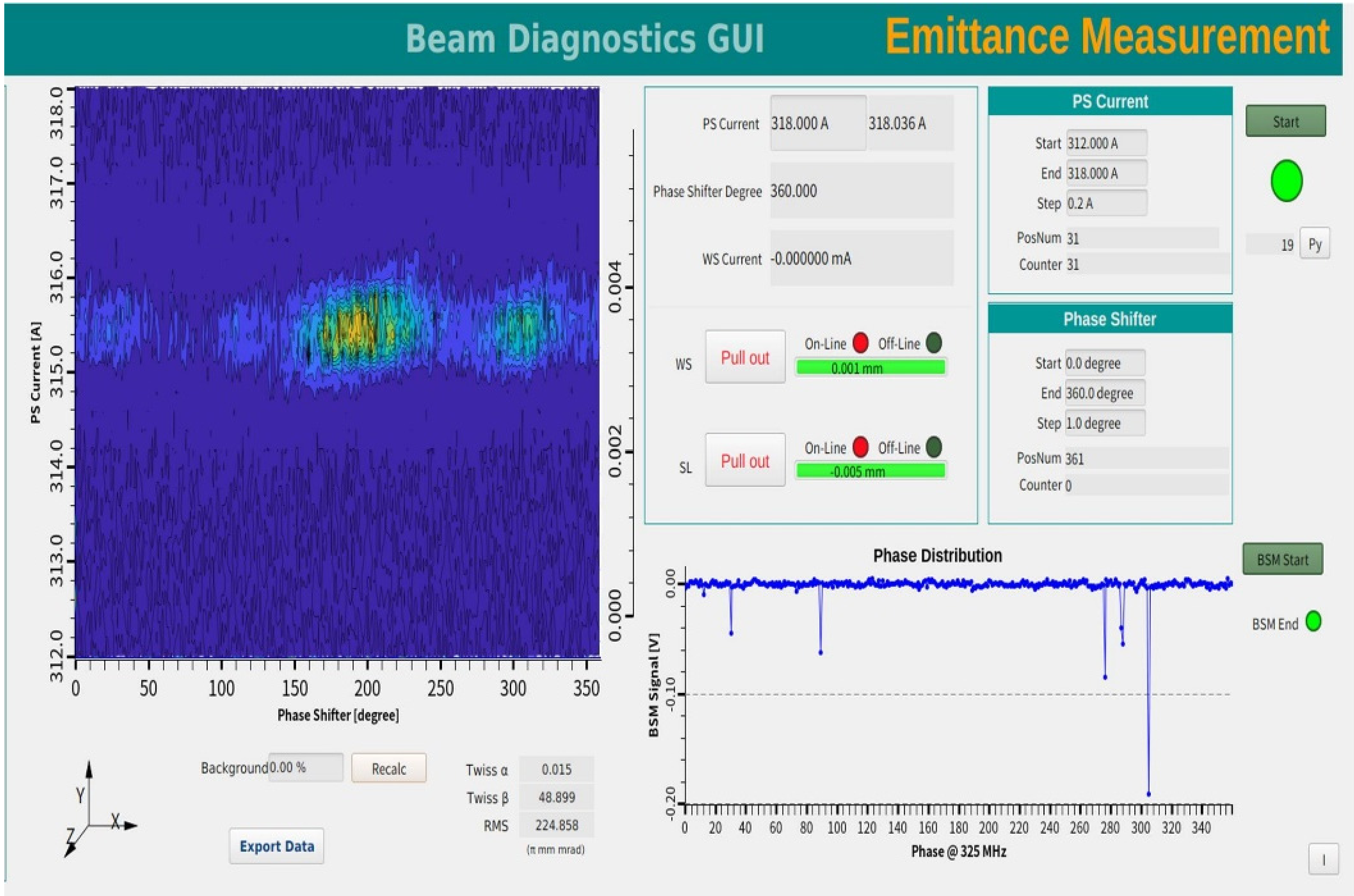
H-profile by sweeping BSM wire when keeping dipole value in center



- Keep beam position and energy constant
- check energy sweeping range

Conditions	H-profile center	FWHM of H-profile	Energy Center	FWHM of ES distri.	Δ w / w
Buncher off, Slit2-H out	-0.86 mm	13.418 mm	1.51839 MeV	24.328 keV	1.602%
Buncher on, Slit2-H out	-3.76 mm	8.035 mm	1.51563 MeV	13.899 keV	0.917%
Buncher off, Slit2-H in	5.69 mm	14.439 mm	1.52731 MeV	19.54 keV	1.279%
Buncher on, Slit2-H in	6.57 mm	9.091 mm	1.53351 MeV	16.01 keV	1.044%

Longitudinal emittance Measurement GUI



- "PS Current" refers to the dipole current setting
- "Phase Shifter" indicates the BSM phase scanning
- "WS" represents the wire of BSM in the center
- "SL" signifies the Slit2-H in the center.

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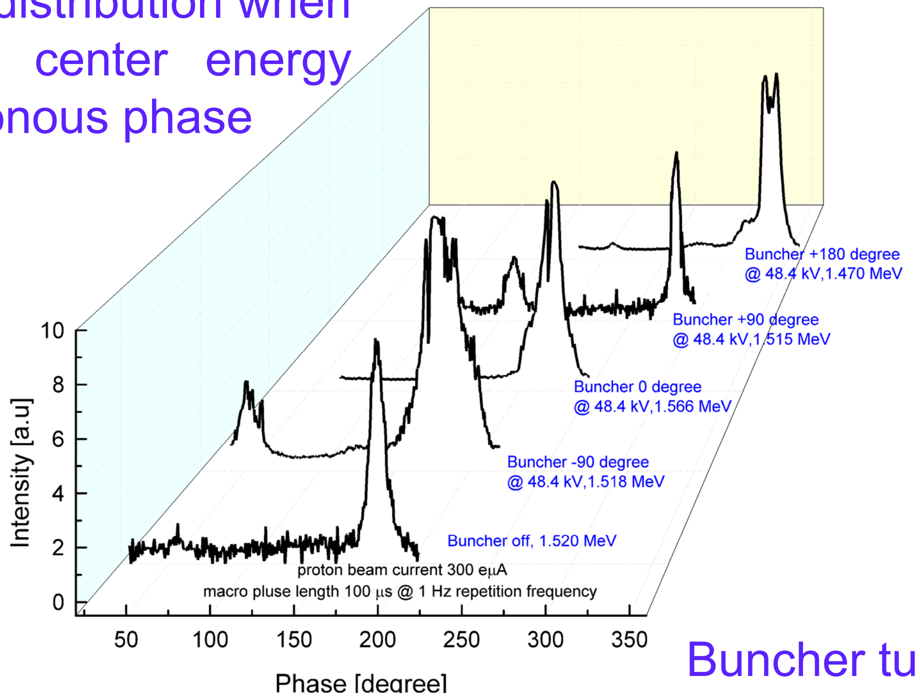
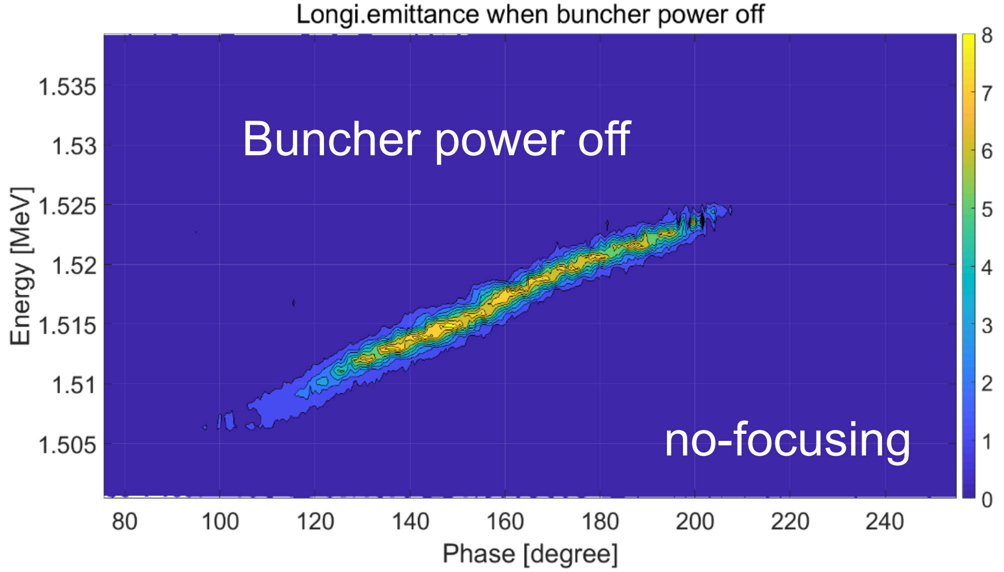
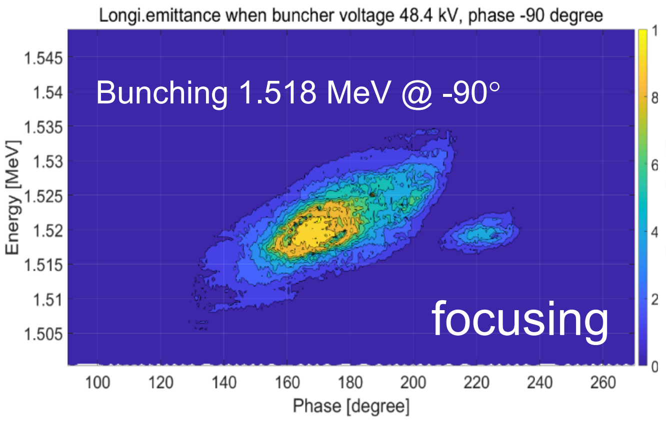
Longitudinal emittances with buncher voltage of 48.4 kV

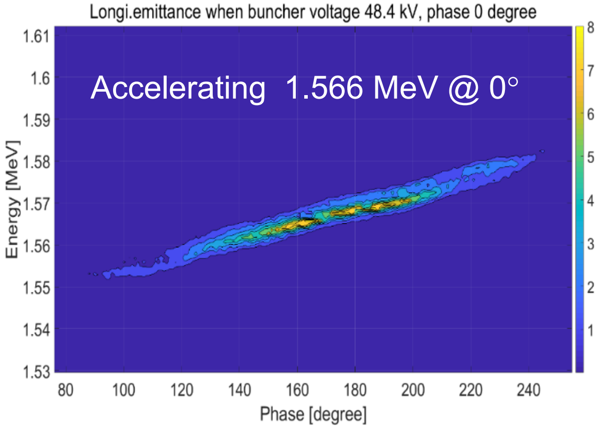
Bunch shape distribution when beam in the center energy with 4 synchronous phase

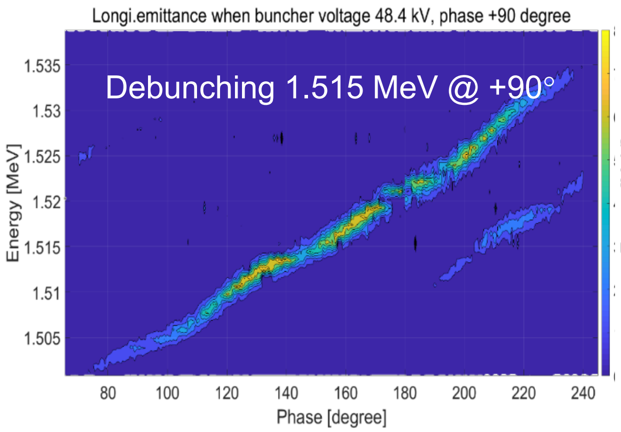


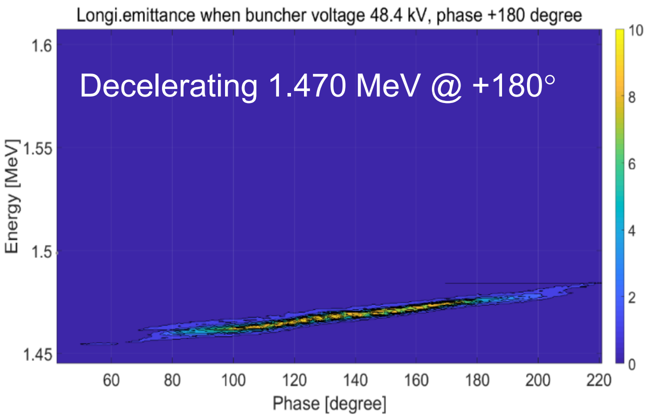


Buncher turned on to 48.4 kV with 4 synchronous phases



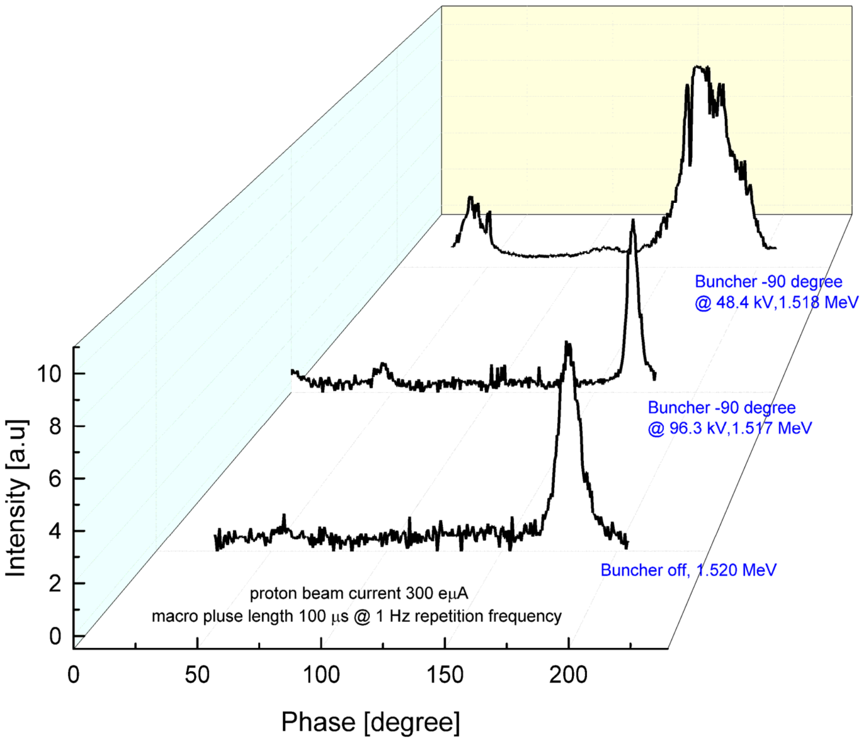


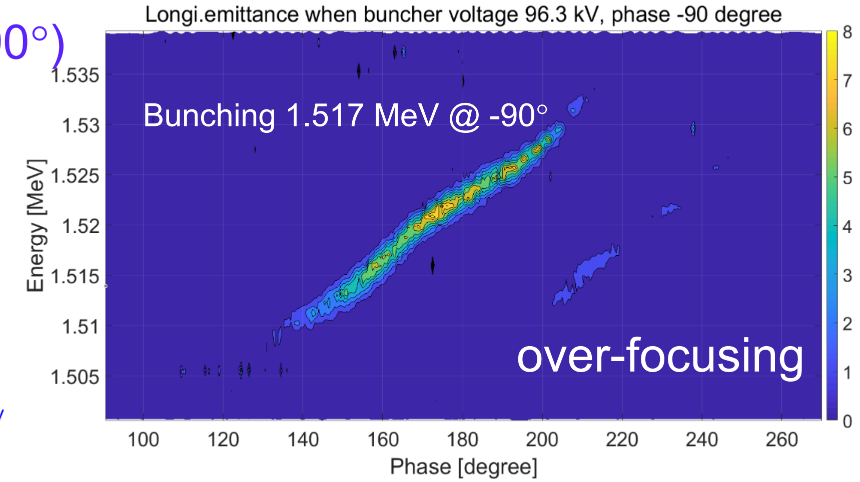


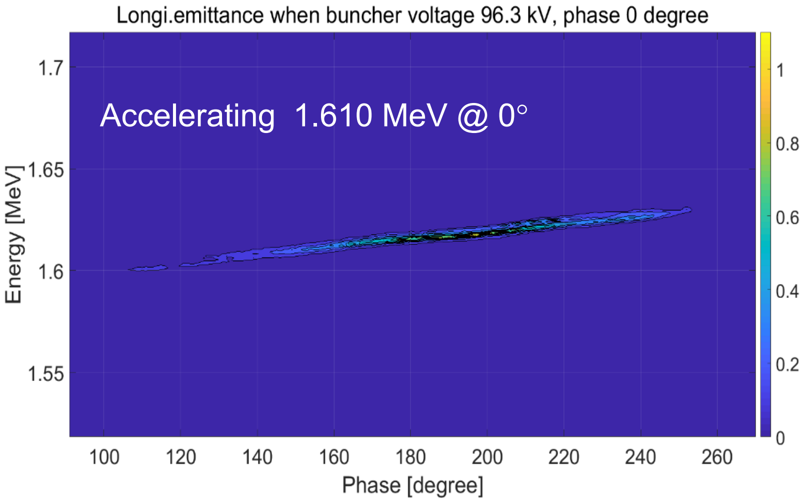


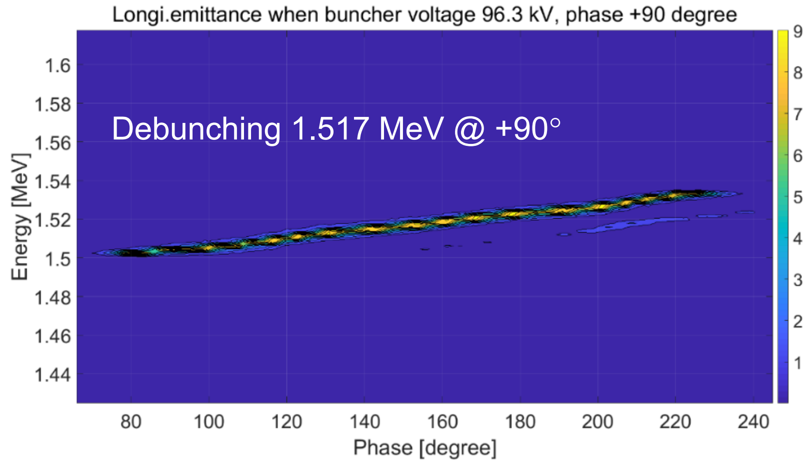
Longitudinal emittances with buncher voltage of 96.3 kV

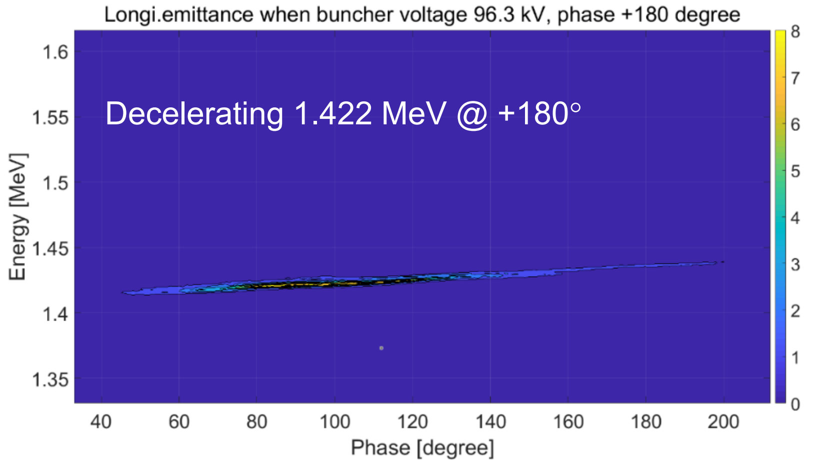
bunch shape distribution
different voltages @ bunching phase (-90°)











Comparisons of Twiss parameters

➢ **Subtracting the background**: variation in longitudinal emittance should not exceed 5% when subtracting background data exceeding 1%

Buncher paramters	Measured results			Simulated results			ε growth	MF
	ε	**α**	**β**	ε	α	β		
	π.mm. mrad	____	**mm / (π.mrad)**	π.mm.mrad	____	mm / (π.mrad)	%	%
Power Off	**0.2995**	**-4.8622**	**10.7768**	0.3709	-2.7287	14.5981	-19	261
48.4 kV @ -90°	**0.8857**	**-1.0586**	**1.8946**	1.703263	-1.3271	4.5917	173	78
48.4 kV @ 90°	**0.6354**	**-6.3765**	**12.1468**	0.8074	-6.3386	26.7958	-21	445
96.3 kV @ -90°	**0.2555**	**-4.7848**	**6.2706**	0.5476	-5.7548	16.5634	-53	191
96.3 kV @ 90°	**1.8203**	**-9.4312**	**16.2801**	1.2391	-10.4577	40.9203	47	150
48.4 kV @ 0°	**0.8994**	**-3.7317**	**7.6373**	0.3699	-2.7216	14.4216	143	250
48.4 kV @ 180°	**0.7002**	**-4.0026**	**10.1502**	0.3725	-2.7817	14.5123	88	184
96.3 kV @ 0°	**0.8984**	**-3.6575**	**7.0327**	0.4002	-2.7957	14.5785	124	268
96.3 kV @ 180°	**0.8511**	**-2.445**	**6.498**	0.4077	-2.8073	14.3978	109	136

Not keep an agreement

- Initial Twiss parameters from the output RFQ not corresponding to the measured beam
- Conduct a benchback simulation using the measured longitudinal emittance and Twiss data to refine the theoretical data

Courtesy of Yuanshuai Qin

Conclusions

- We successfully develop a direct longitudinal emittance platform with high resolution for hadron LINAC
- Nine longitudinal emittance measurements were conducted for two buncher power values at four phase degrees, with the buncher power turned off, in a 1.5 MeV proton MEBT
- Using the waist-to-waist transfer matrix to enhance the resolution of the energy spread distribution
- The impact of transverse emittance on the energy spread is mitigated, now the resolution of ES is 0.07% since the dipole power supply control the minimum step is 0.2 A (0.20 / 320 A full range)
- The developed BSM can achieve a resolution smaller than 20 ps of the full distribution of 500 ps at 162.5 MHz
- Directly measuring the longitudinal emittance, understanding the actual beam phase space distribution, conducting a bench-back simulation using the measured data

IMP longitudinal emittance group

BD group: Ze Du, Lili Li, Jia Yin, Jianjun Su, Hongming Xie, Long Jing, Guangyu Zhu, Zhixue Li, Junxia Wu

Linac physics group: Jia Huan, Yuanshuai Qin, Duanyang Jia, Wangsheng Wang, Weilong Chen, Weipin Dou, Chi Feng, Jie Zeng, Jianqiang Wu

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