HIAT 2022 | Darmstadt

SIGNAL ESTIMATION AND ANALYSING OF COLD BUTTON BPMS FOR A LOW-BETA HELIUM / PROTON SUPERCONDUCTING LINAC

Yong Zhang

On behalf of BD Group, IMP, CAS

June 30th, 2022, as a remote participation, Lanzhou, China

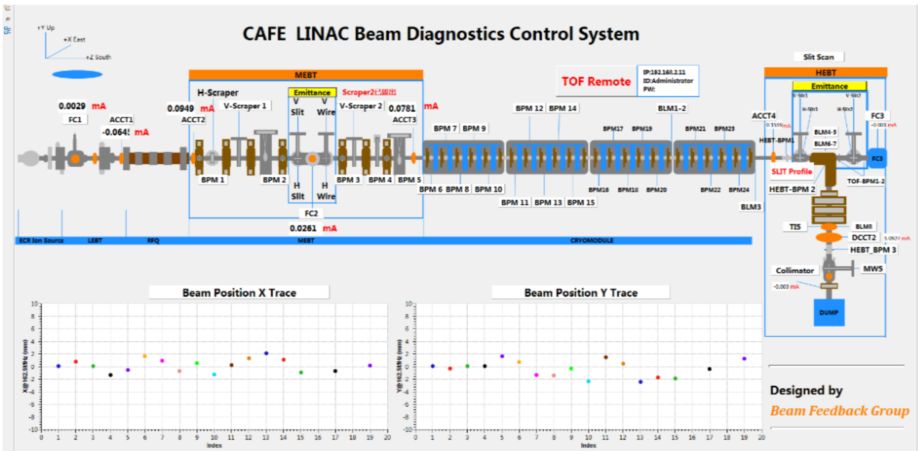
Outlines

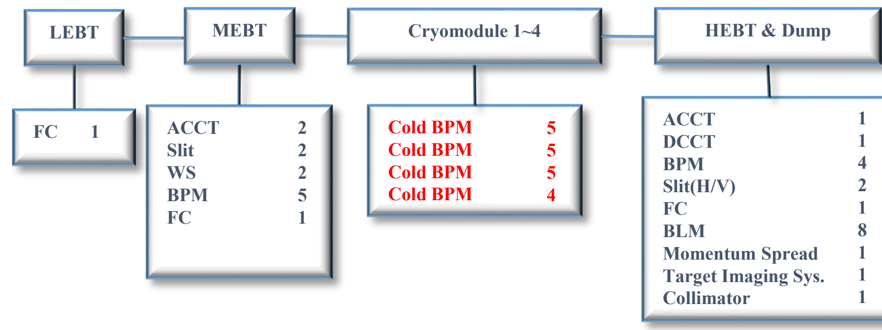
- Beam Diagnostics of a low-β Helium / Proton Superconducting LINAC, CAFe
- Properties of Cold Button BPM in CAFe
- Numerical Model for Estimating the Original Signal of Cold Button BPM
- Analyzing and Comparison between two kinds of Beam commissioning: $^{4}He^{2+}$ / Proton
- Conclusions

Outlines

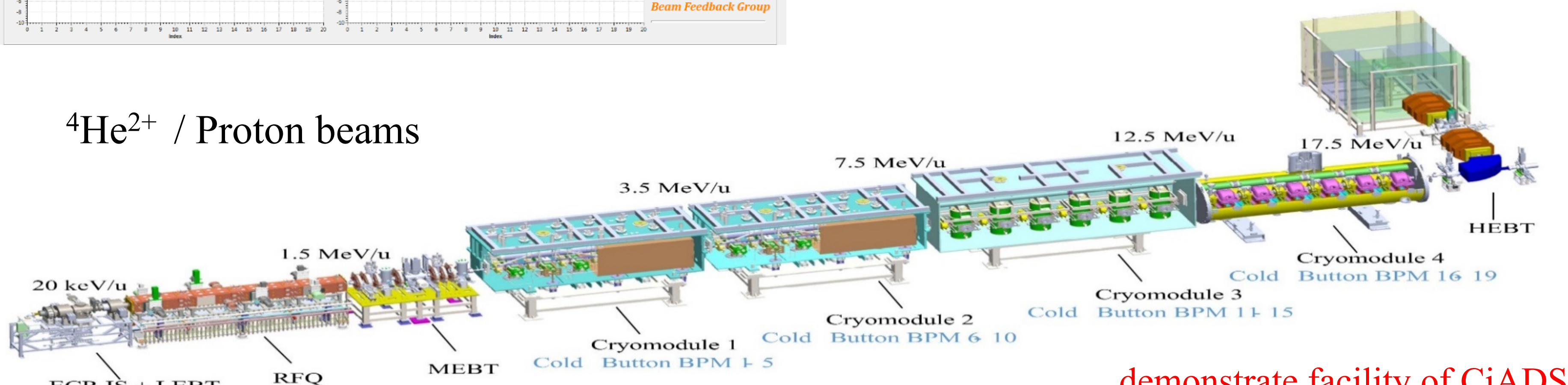
- **Beam Diagnostics of a low-β Helium / Proton Superconducting LINAC, CAFe**

Beam Diagnostics of CAFe



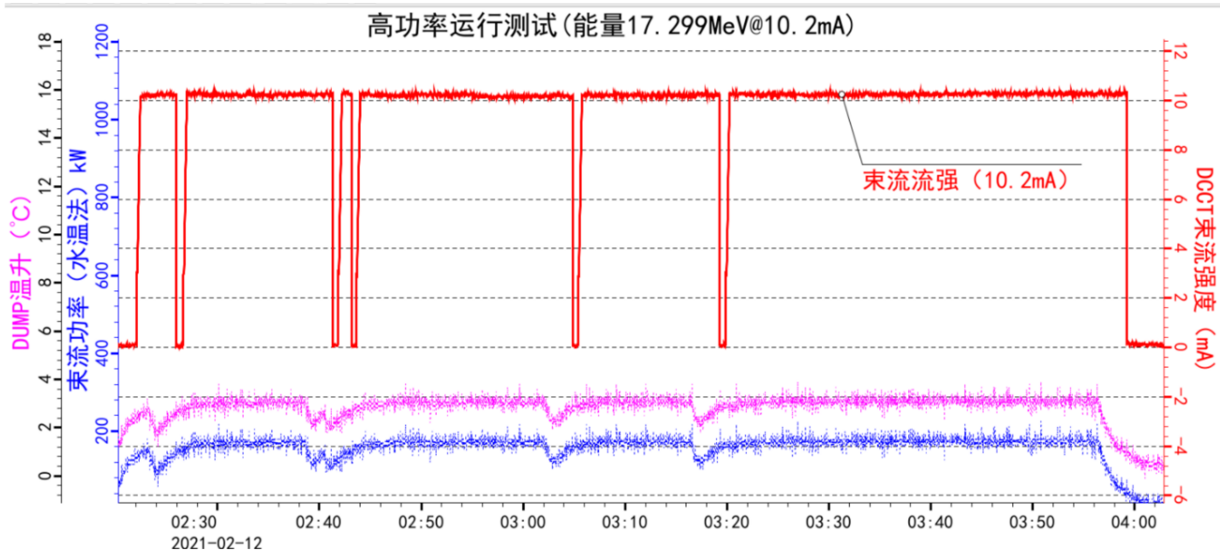


$^{4}He^{2+}$ / Proton beams



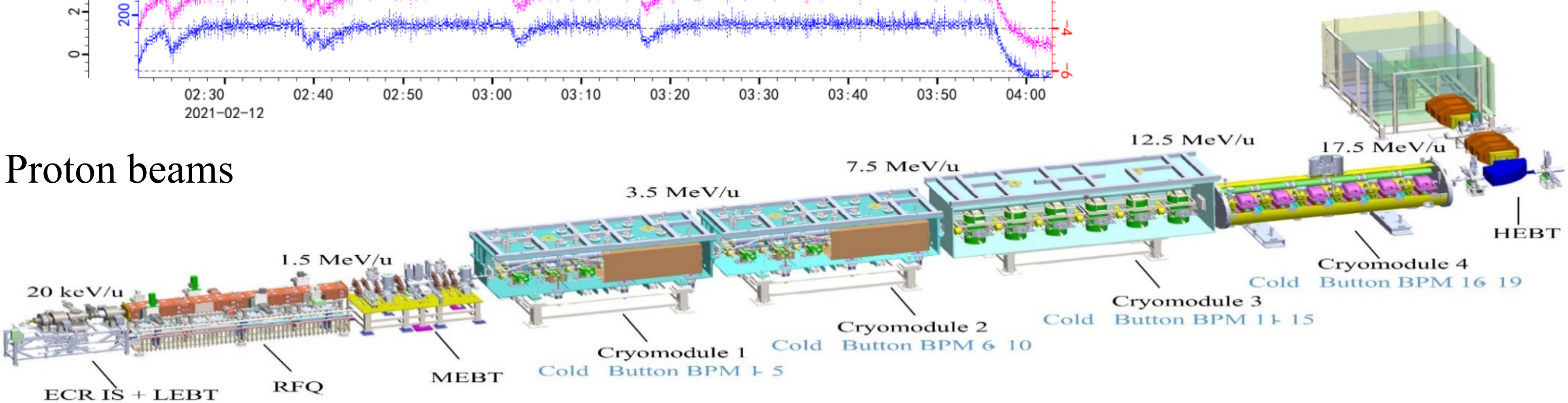
demonstrate facility of CiADS

Beam Diagnostics of CAFe



On January, 2021
> 120 kW, > 100 hours
CW, proton beams

Proton beams

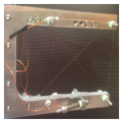


Beam Diagnostics of CAFe

Detectors

CT

WS



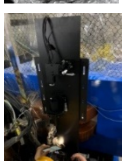
FC

IV convertor

Room BPM

Cold BPM

TIS

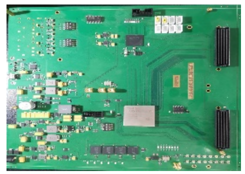


BLM

Electronics

Trig. In/Out

Signal In, 1 MΩ port



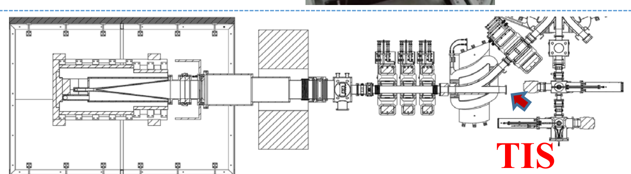
Kintex7 FPGA

Made in-house

6 CH, 1 MΩ
20 MS/s
16 bit

ZYNQ
7020,SoC

Libera Single Pass H
(LSPH)



6 CH, 50 Ω
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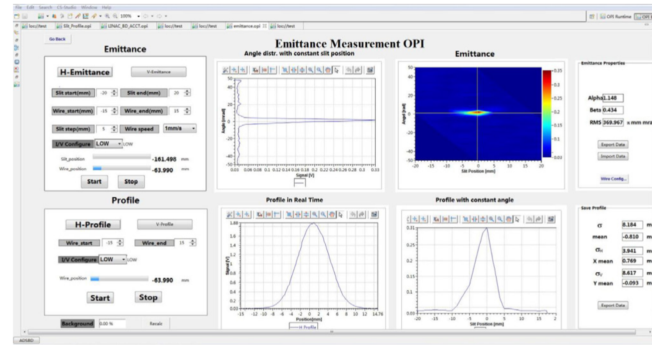
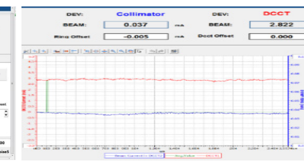
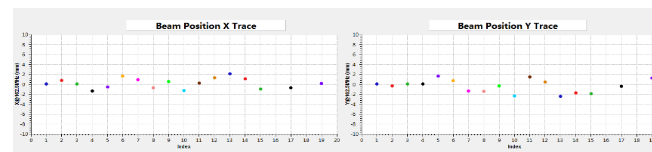
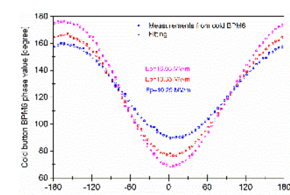
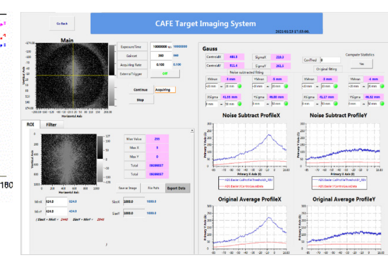
GUI based on EPICS

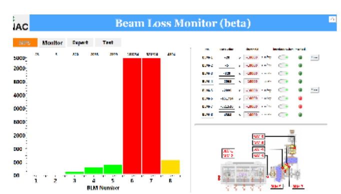


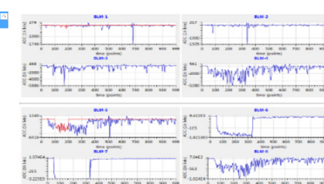












Beam Diagnostics of CAFe

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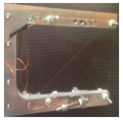

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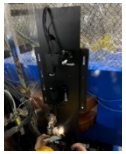
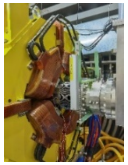
Cold BPM

TIS



BLM



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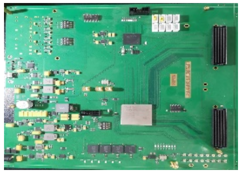

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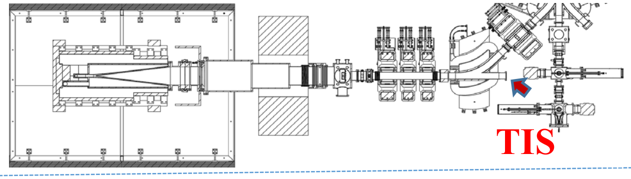

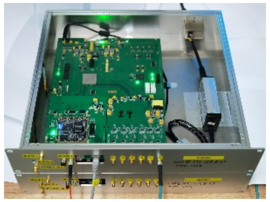

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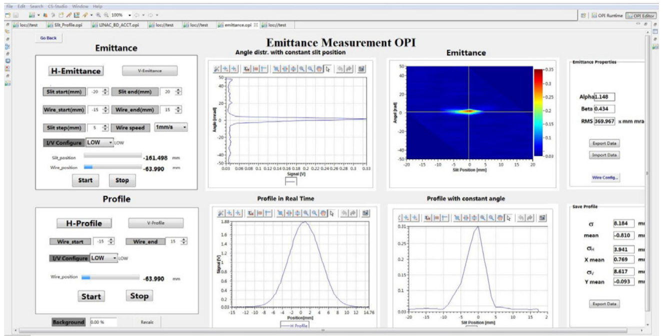
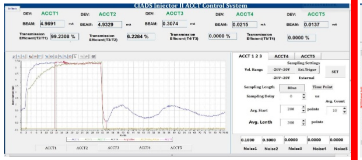
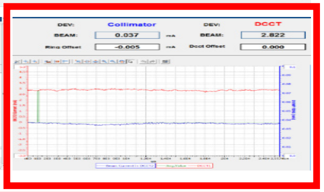
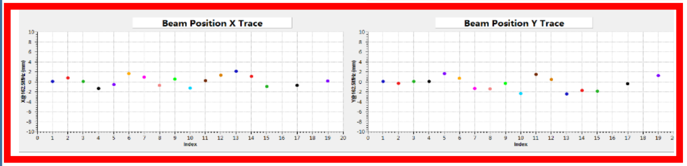
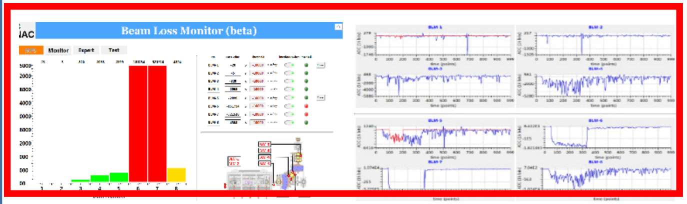








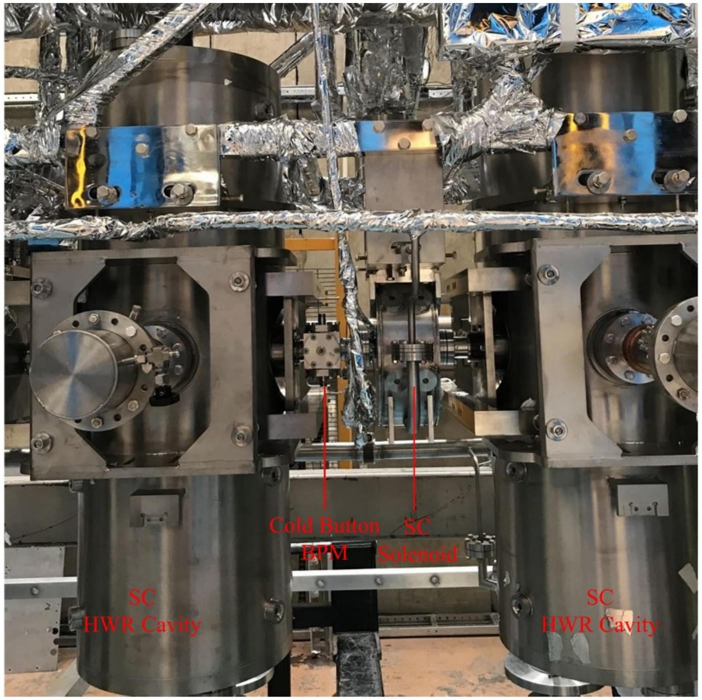
Fast MPS
(Responding time < 10 μs)
for high power proton beams



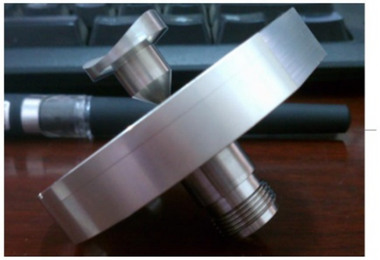
Outlines

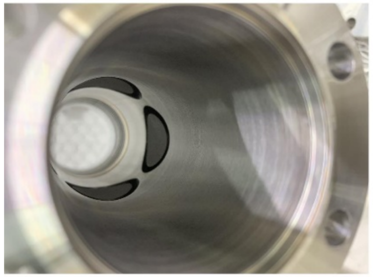
- Beam Diagnostics of a low-β Helium / Proton Superconducting LINAC, CAFe
- **Properties of Cold Button BPM in CAFe**

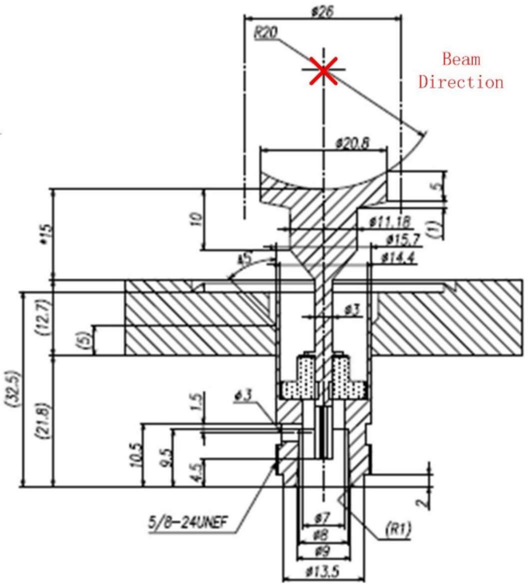
Cold Button BPM Parameters

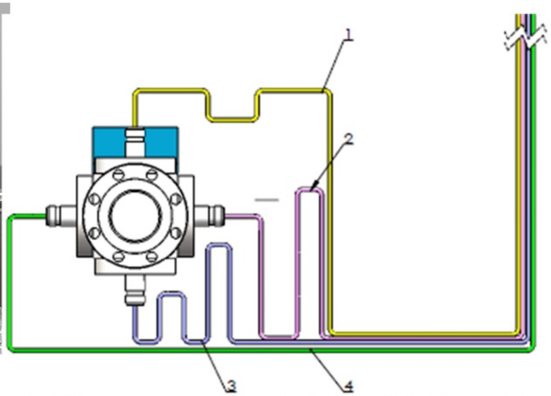


Cold button drawing





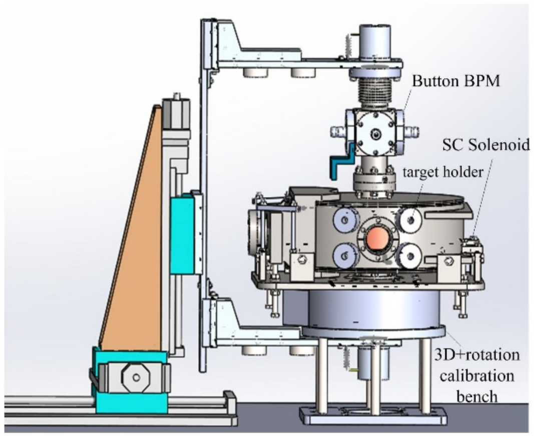




Cold Button BPM

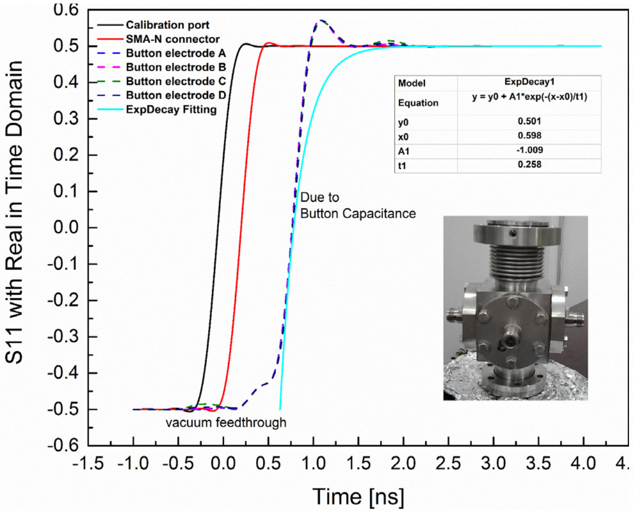
Cold button BPM connected with 4 semi-rigid RF cables

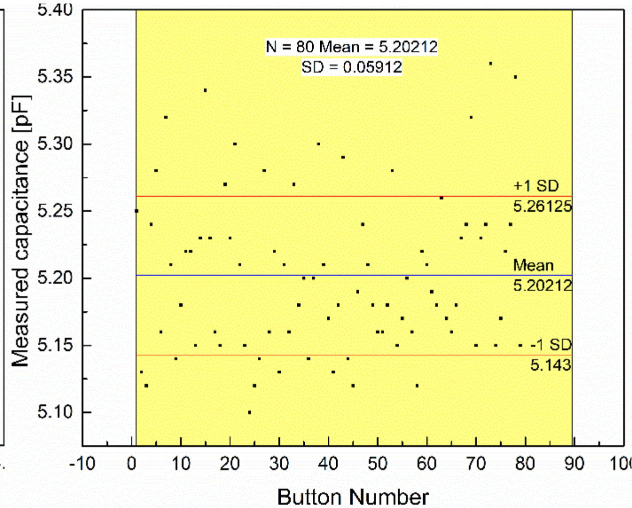
Calibration one cold Button BPM with one SC Solenoid

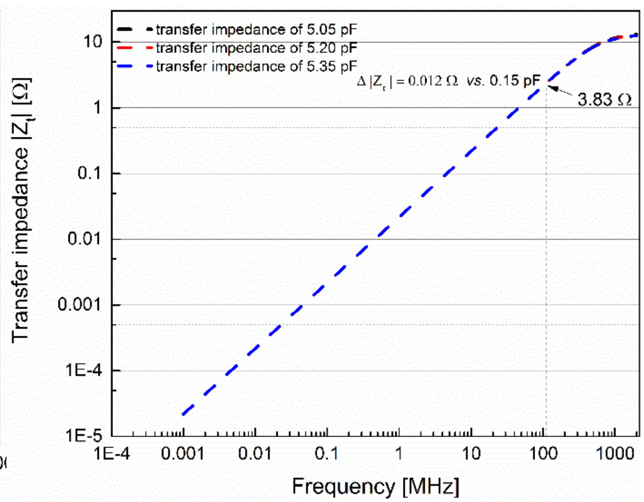


Cold Button BPM Parameters

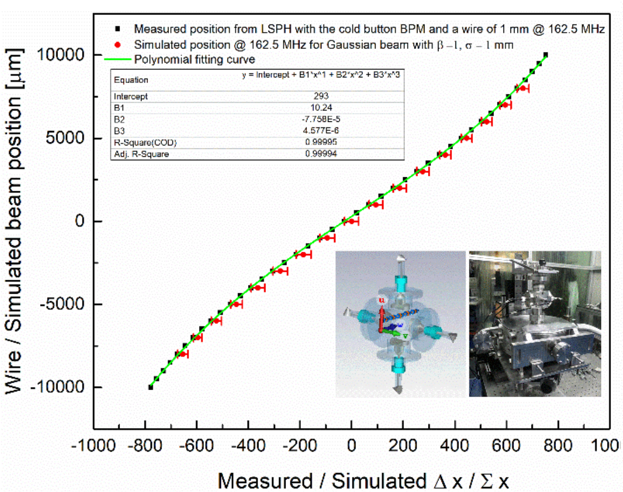
- Capacitance measurements: check the button's consistency and the assembly condition

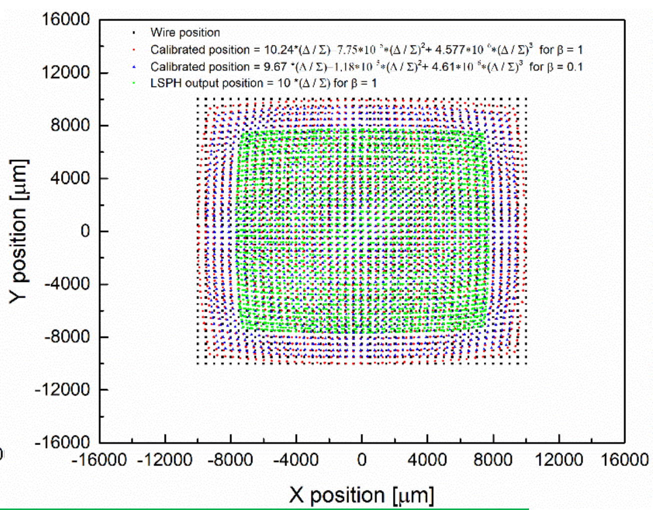


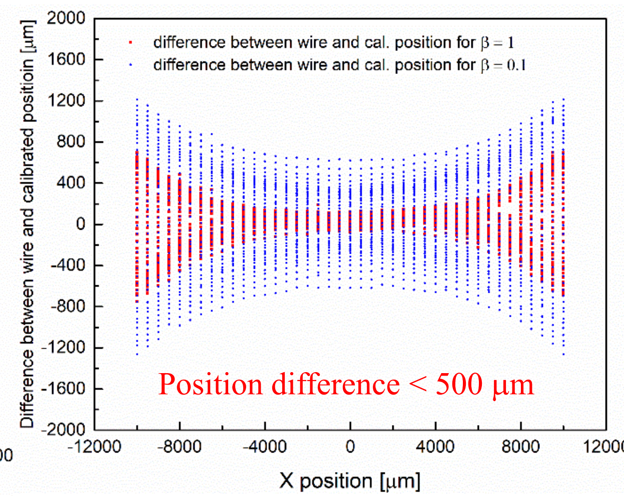




- Simulating the coefficients: for $\beta = 0.1$ proton beams







Fixed offset between the simulated and the calibrated in a linear range

Outlines

- Beam Diagnostics of a low-β Helium / Proton Superconducting LINAC, CAFe
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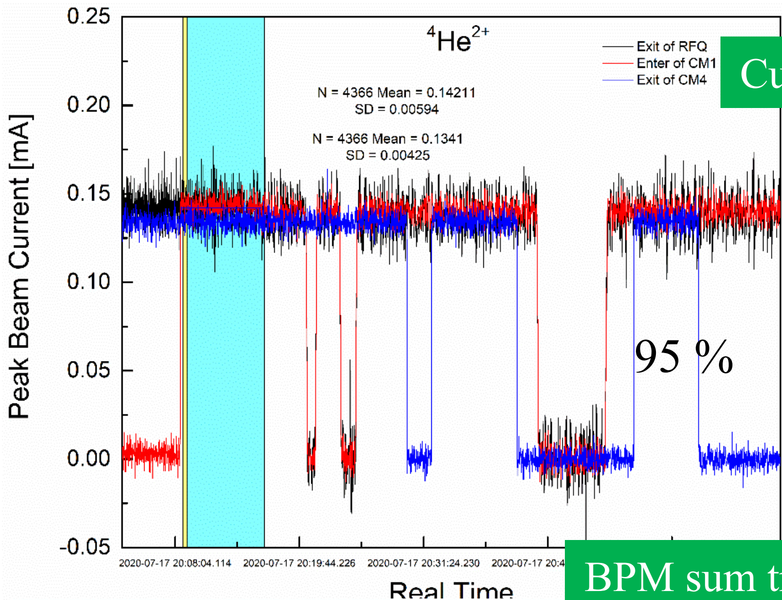
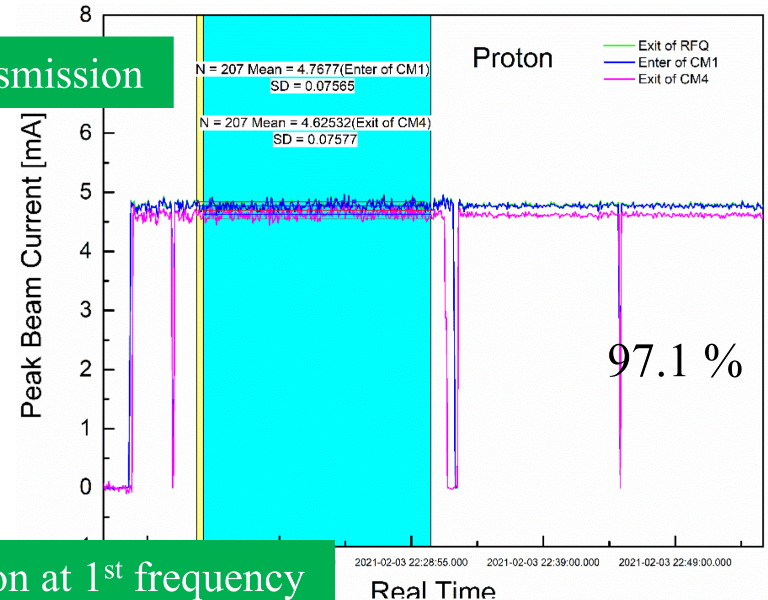
- **Numerical Model for Estimating the Original Signal of Cold Button BPM**

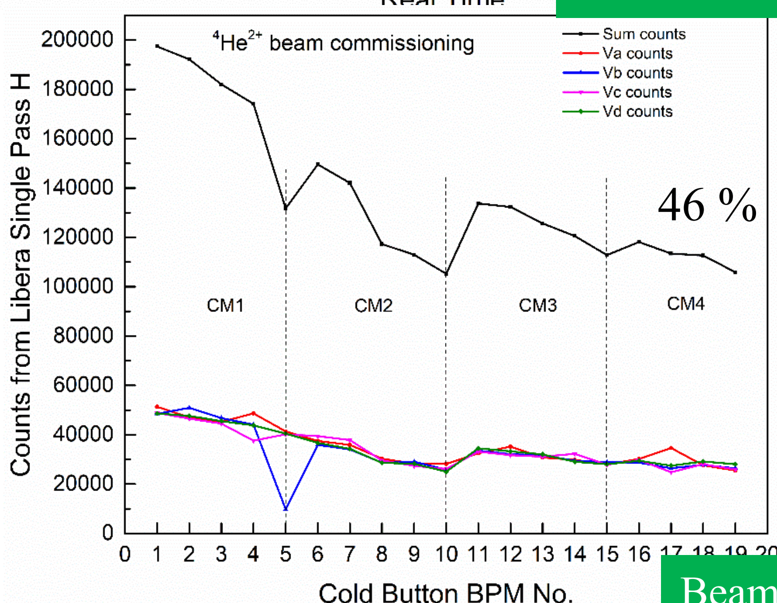
Two kinds of beam commissioning: $^{4}He^{2+}$ / Proton beams

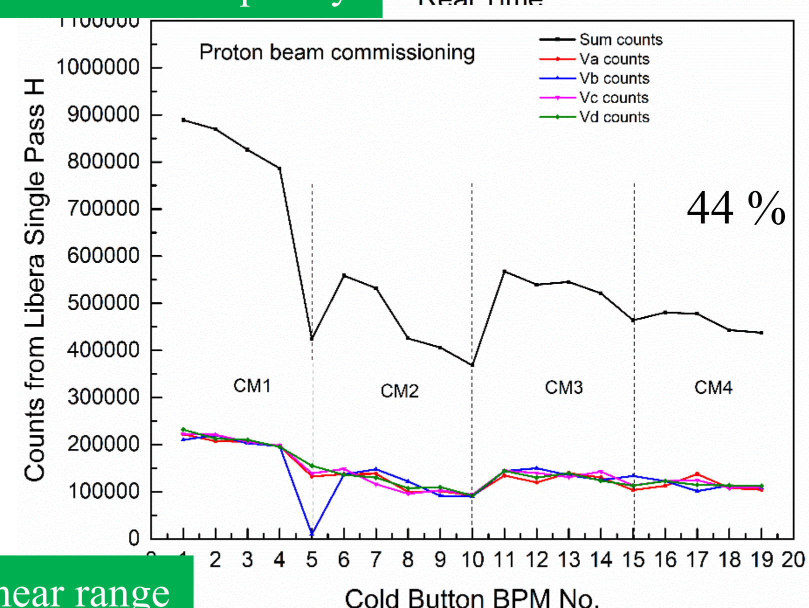
Current transmission





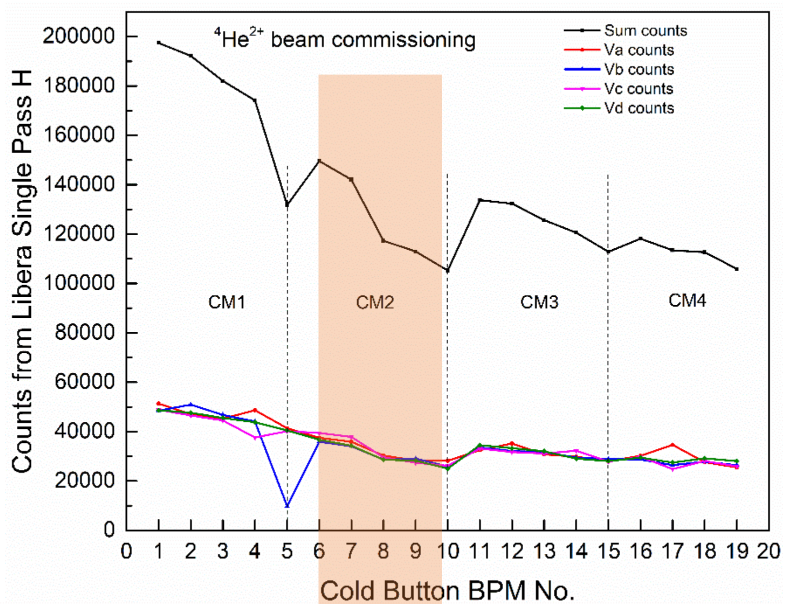
BPM sum transmission at 1st frequency

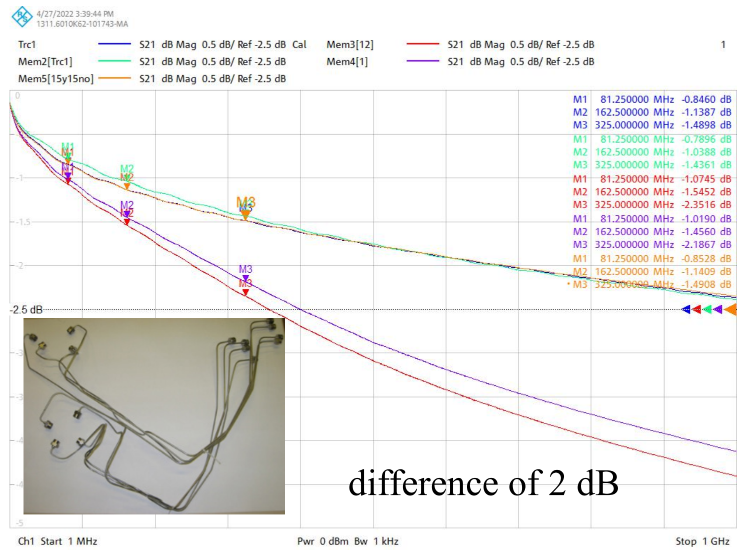




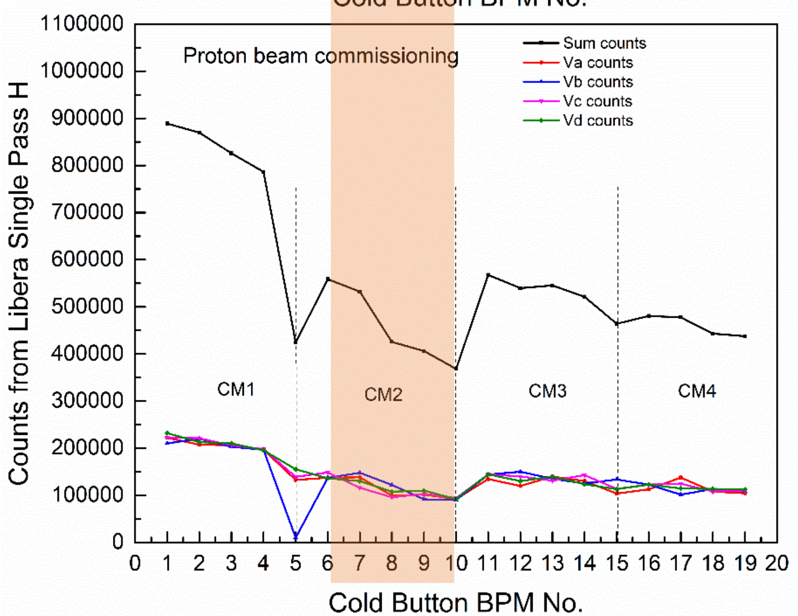
Beam in a linear range

Influence from the different semi-rigid cables





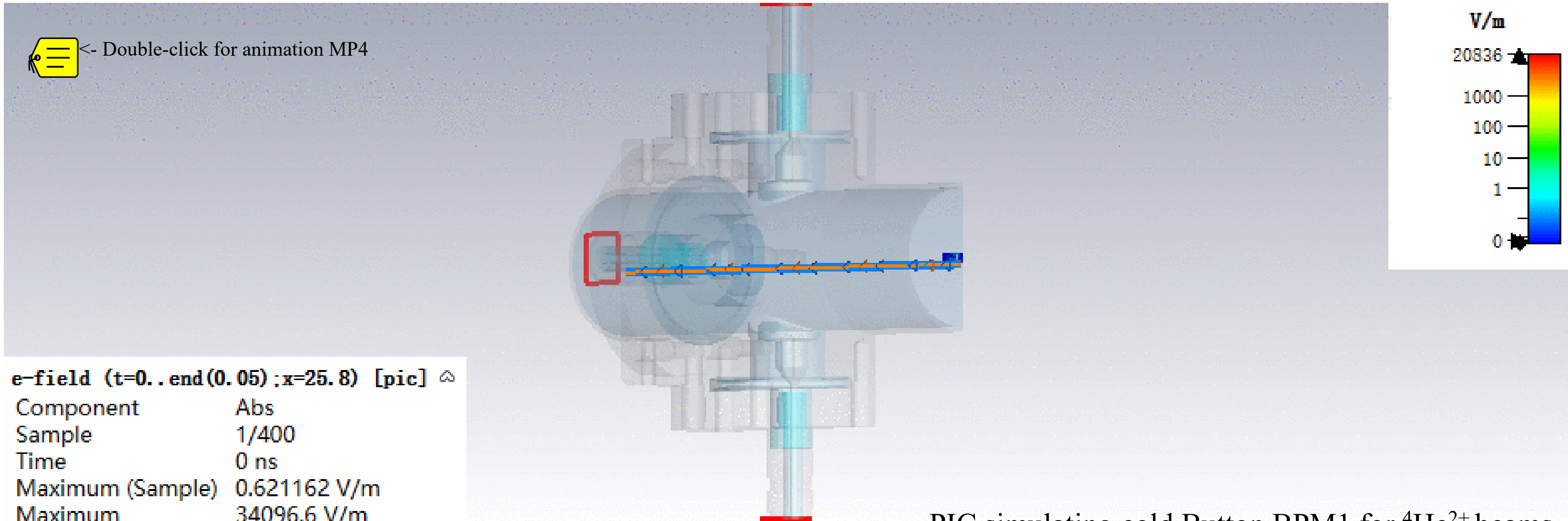
Semi-rigid cables in CM2 is different to others



Beam parameters for cold BPM1 & BPM19

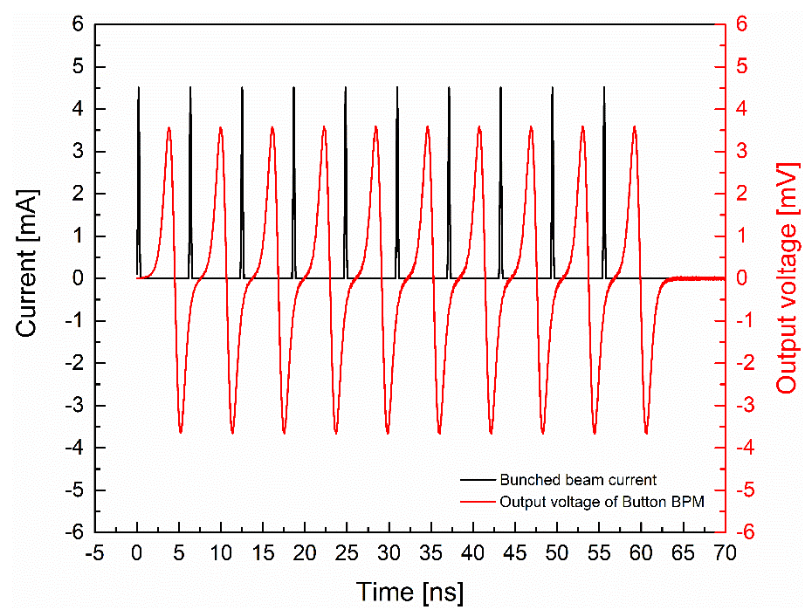
Beam parameters	$^4He^{2+}$		Proton	
	COLD BPM1	COLD BPM19	COLD BPM1	cold BPM19
X_{rms} [mm]	1.66	1.93	1.51	1.31
Y_{rms} [mm]	1.66	2.84	1.42	1.31
Z_{rms} [°]	4.64	3.82	4.3	1.89
Energy [MeV/u]	1.59	6.89	1.78	16.93

3D Simulation for Estimating Button BPM Signal



PIC simulating cold Button BPM1 for $^4He^{2+}$ beams

Parameters	VALUE	UNIT	Descriptions
Particle	$^4He^{2+}$		
Bunch numbers	10		
Beam current	142	μA	
Bunch frequency	162.5	MHz	
Charge	0.94	pC	
Sigma	79.32	ps	rms bunch length
Cutoff length	218.13	ps	half of full bunch length
Offset	218.13	ps	half of full bunch length
Distance	6.153	ns	1/bunch frequency
Kinetic energy	0.0583		
Kinetic spread	0.1%		assuming
Angle spread	0.1	degree	assuming



PIC Solver , Particle Studio, CST

Numerical model 1 : considering low-β effect

A single Gaussian bunch current: $I_b(t) = \frac{eN}{\sqrt{2\pi}\sigma} e^{\left(\frac{-t^2}{2\sigma^2}\right)}$

Multi-bunches current:

- $I_b(t) = \langle I_b \rangle + 2\langle I_b \rangle \sum_{m=1}^{\infty}[A_m \cos(m\omega_0 t)]$

Harmonic amplitude factor:

$$A_m = e^{\left(\frac{-m^2\omega_0^2\sigma^2}{2}\right)}$$

R. E. Shafer, "Beam position Monitoring," p.605 ~ p.606 in Proceedings of the 1992 Accelerator Instrumentation Workshop (Brookhaven National Laboratory), AIP Conference Proceedings, 1992.

Low-β effect on bunch length

$$\sigma_{im} = \sqrt{\sigma^2 + \left(\frac{b}{\sqrt{2}\beta\gamma c}\right)^2} \qquad B_m = e^{\left(\frac{-m^2\omega_0^2\sigma_{im}^2}{2}\right)}$$

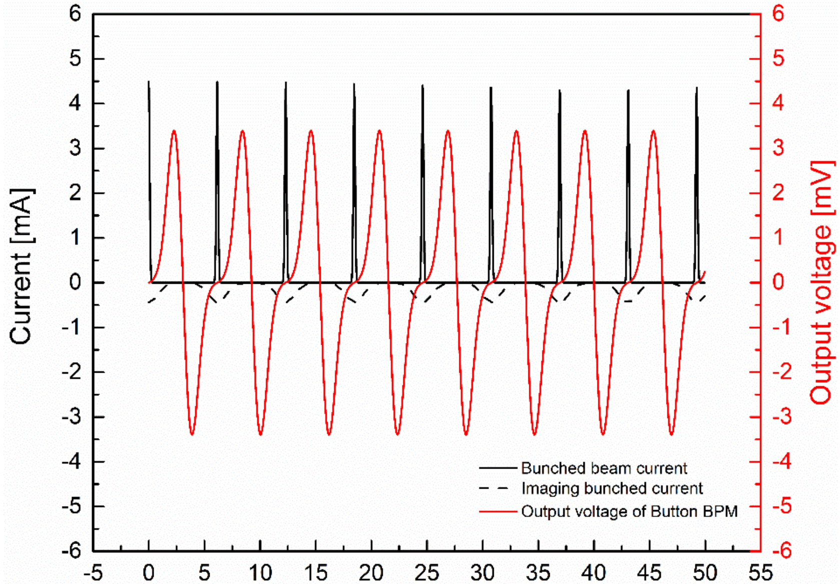
Multi-bunches imaging current:

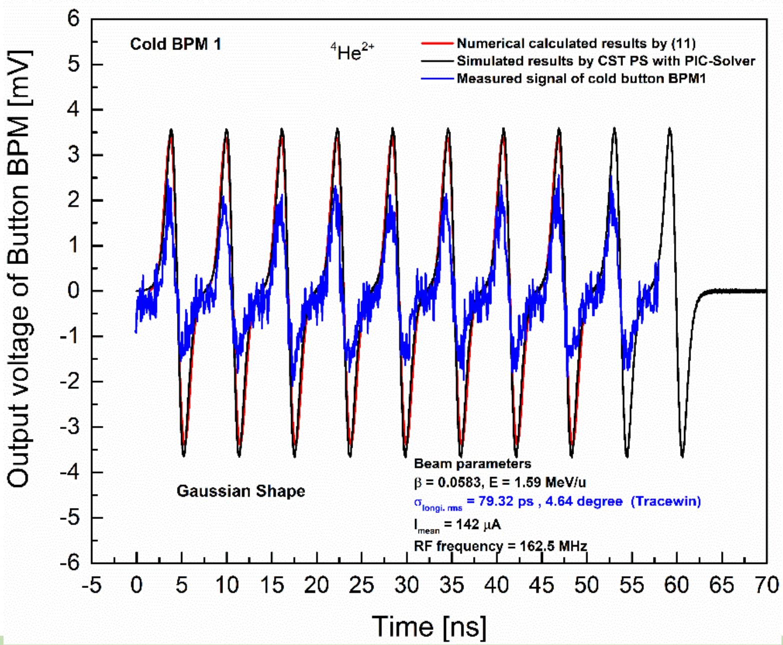
- $I_{im}(t) = -\langle I_b \rangle - 2\langle I_b \rangle \sum_{m=1}^{\infty}[B_m \cos(m\omega_0 t)]$

Button BPM output signal:

$$V_{button}(t) = R\, i_s(t) = \frac{\phi l R}{2\pi\beta c}\frac{dI_{im}(t)}{dt}$$

- $V_{button}(t) = -\langle I_b \rangle \frac{\phi l R}{2\pi\beta c} \sum_{m=1}^{\infty}[e^{\left(\frac{-m^2\omega_0^2\sigma_{im}^2}{2}\right)} (-m\omega_0)\ \sin(m\omega_0 t)],$





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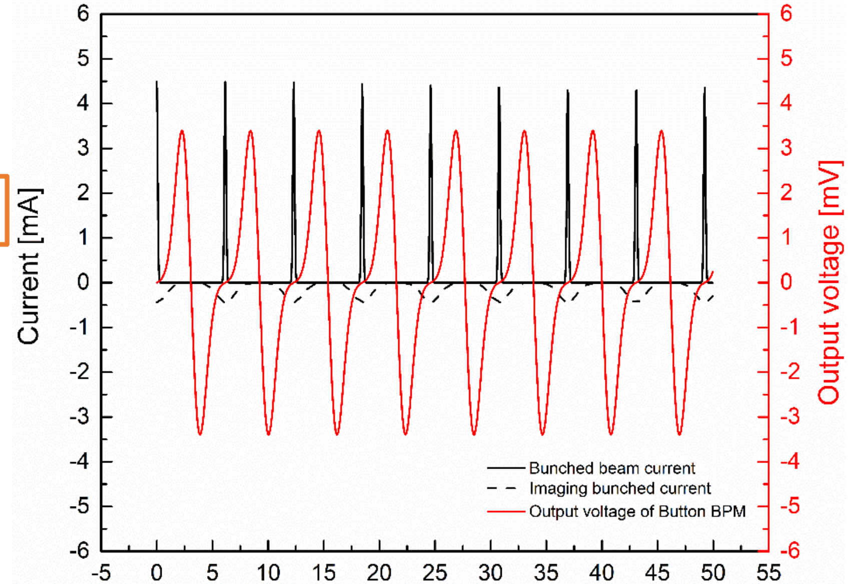
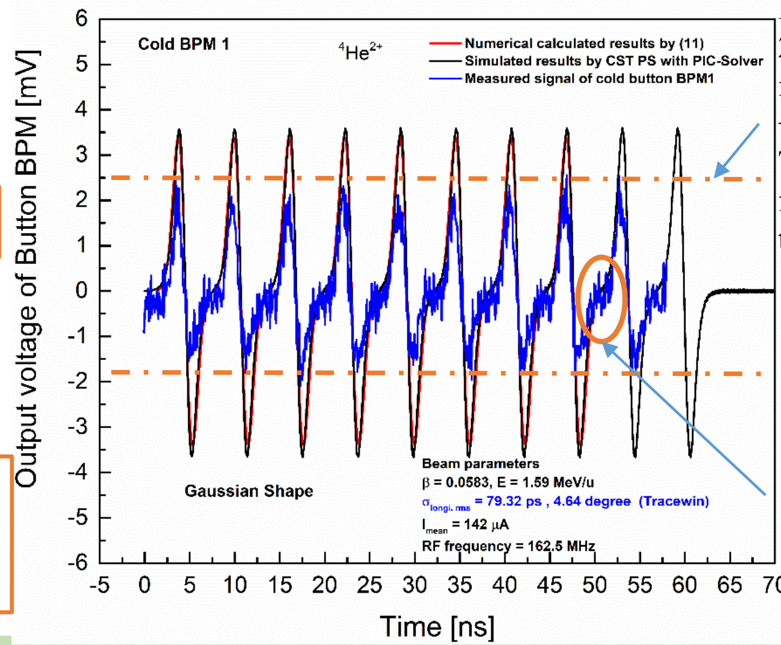




Long cables: 2. 3 semi-rigid in CMs + 30 m TCOM240 from CMs to the oscilloscope

Good match in the expanded length

Numerical model 2 : considering dispersion and attenuation of cables

$$V_{button}(t) = -\langle I_b \rangle \frac{\phi l R}{2\pi\beta c} \sum_{m=1}^{\infty} [e^{\left(\frac{-m^2\omega_0^2\sigma_{im}^2}{2}\right)} (-m\omega_0) \sin(m\omega_0 t)],$$

- $$V_{button}(t) = -\langle I_b \rangle \frac{\phi l R}{2\pi\beta c} \sum_{m=1}^{\infty} \left\{ e^{(-\alpha_m\sqrt{f}z)} e^{\left(\frac{-m^2\omega_0^2\sigma_{im}^2}{2}\right)} (-m\omega_0) \sin\left[m\omega_0\left((t-\tau) - \alpha_m\sqrt{f}\,z\right)\right] \right\}$$

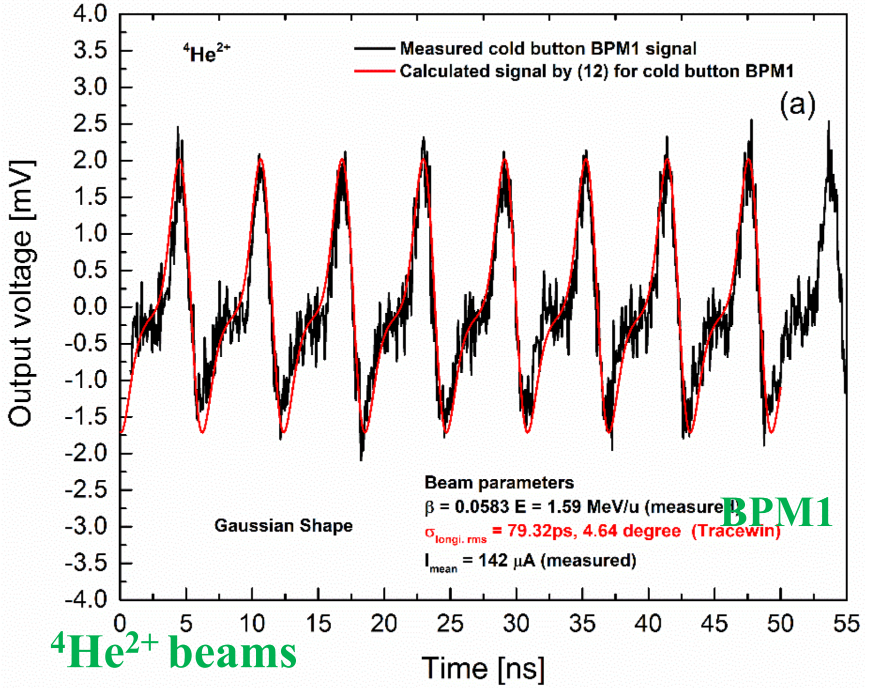
attenuation — low-β expanded — dispersion

TIMES TCOM 240 coaxial cable length 30 m + 2.3 m semi-rigid cable with PTFE

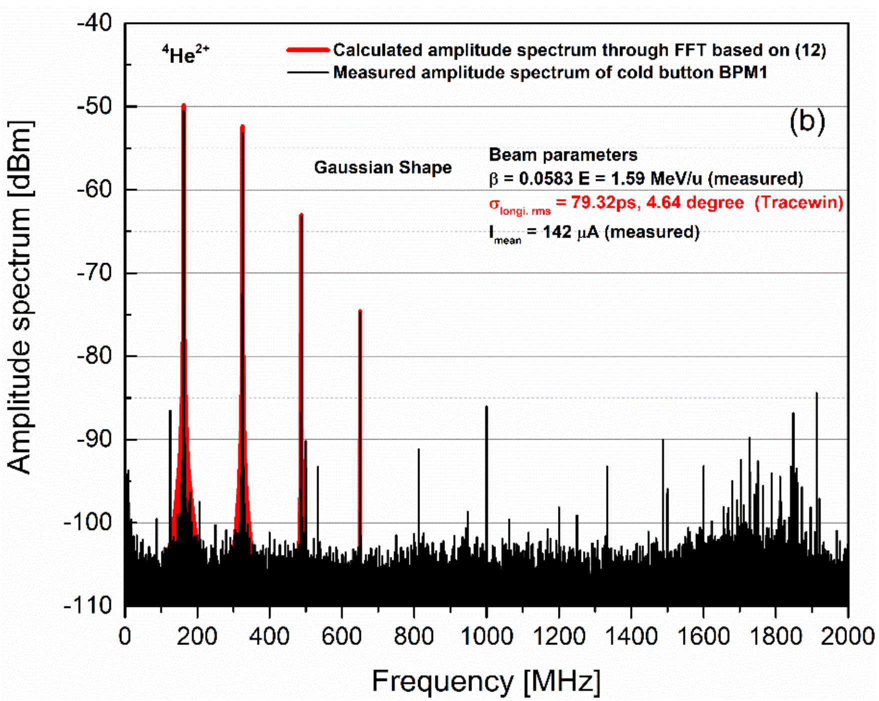
$\alpha_m = (0.229148\sqrt{F\text{MHz}} + 0.000331F\text{MHz})/3\,3/8.6$ neper per meter,

$Z = 33$ m, $\tau = 33 / 0.84 / (3\times10^8) = 131$ ns

R. E. Shafer, "Beam position Monitoring,'' p.626 in Proceedings of the 1992 Accelerator Instrumentation Workshop (Brookhaven National Laboratory), AIP Conference Proceedings, 1992.



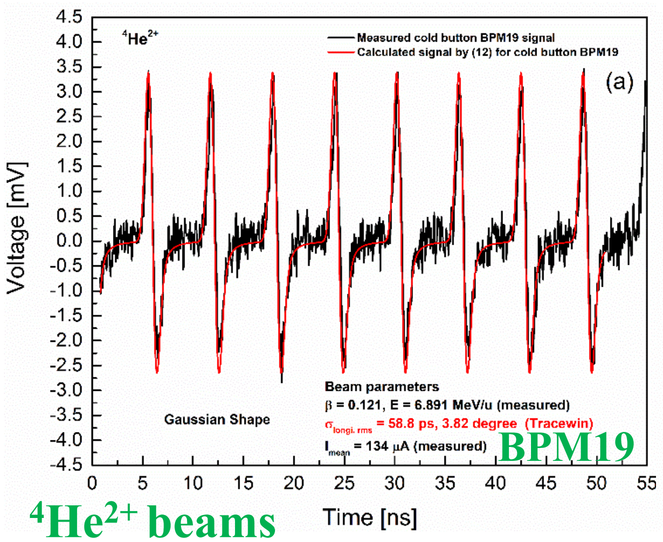
$^4He^{2+}$ beams

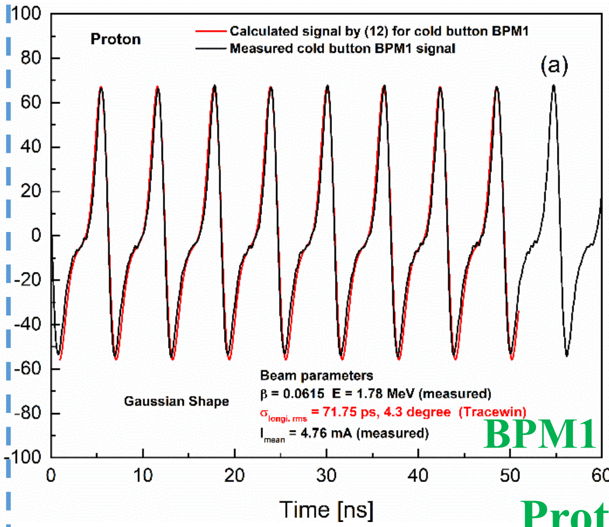


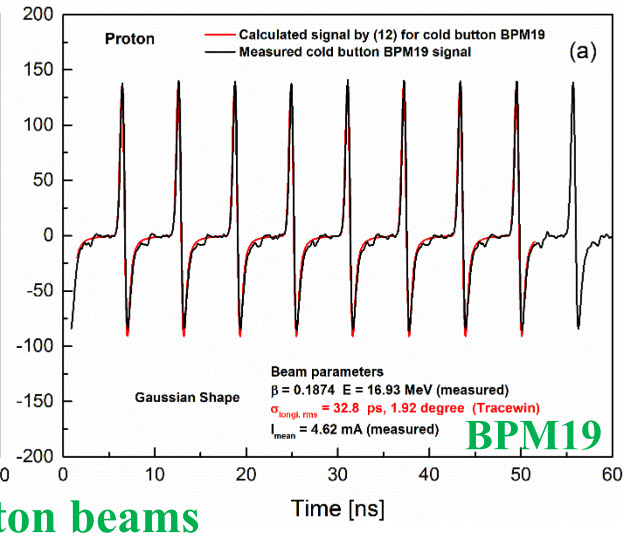
Outlines

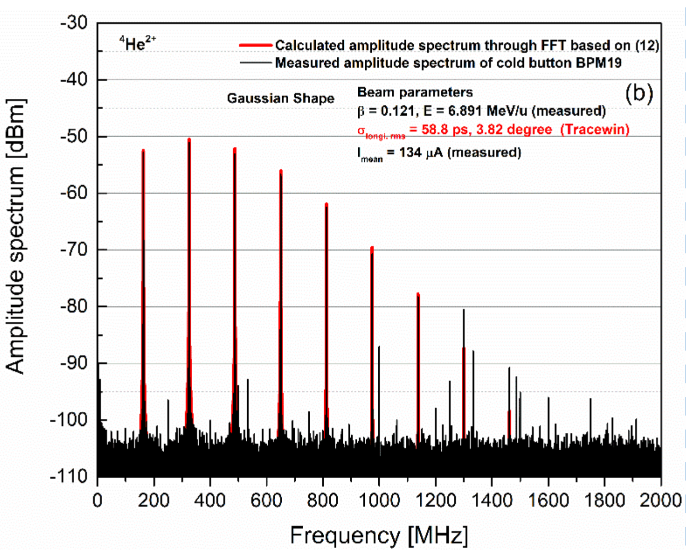
- Beam Diagnostics of a low-β Helium / Proton Superconducting LINAC, CAFe
- Properties of Cold Button BPM in CAFe
- Numerical Model for Estimating the Original Signal of Cold Button BPM
- **Analyzing and Comparison between two kinds of Beam commissioning: $^{4}He^{2+}$ / Proton**
- Conclusions

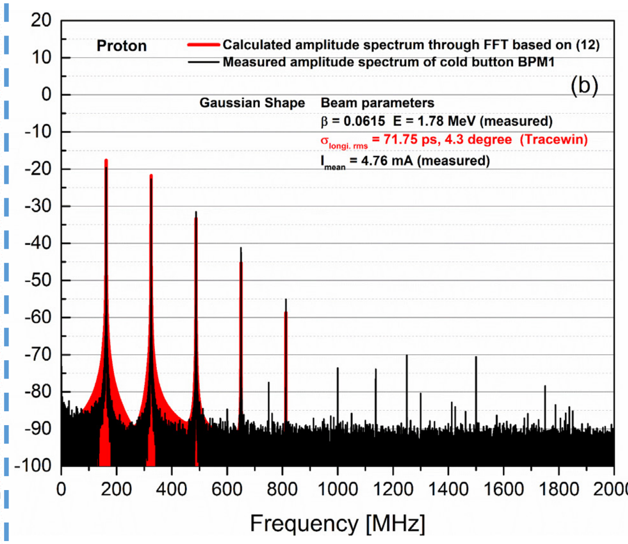
Comparisons between the measured and the numerical for $^4He^{2+}$ / Proton beams

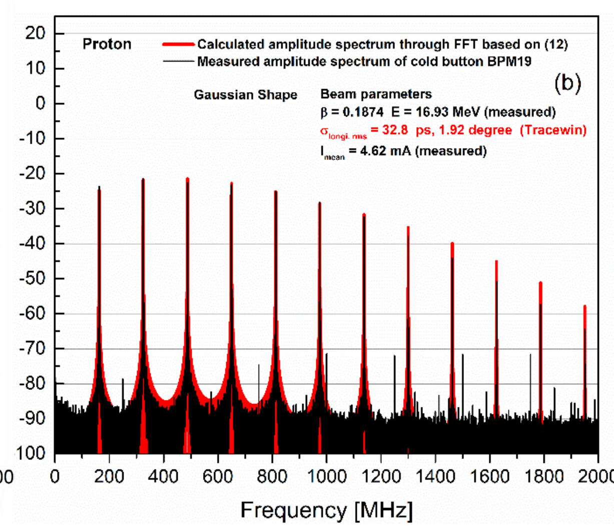








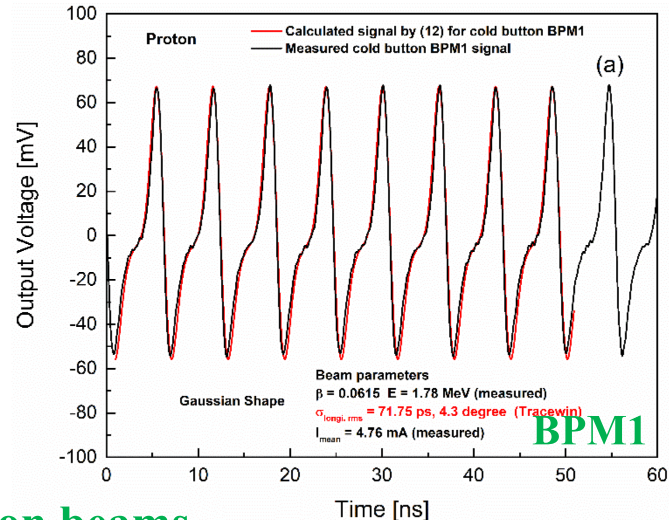


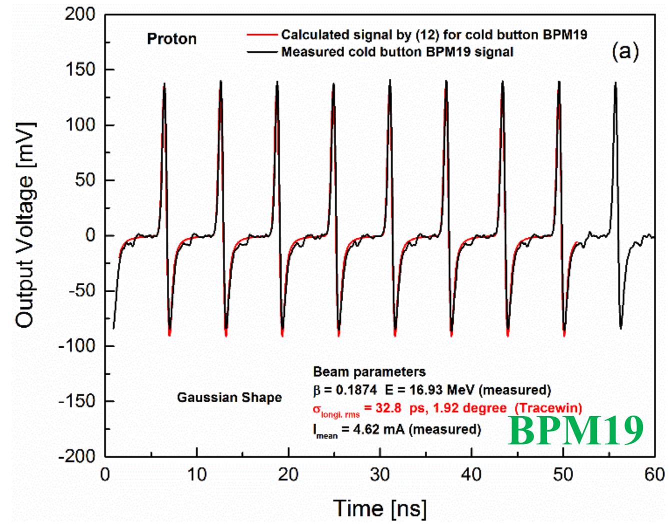


Cold BPM1: entrance of CM1

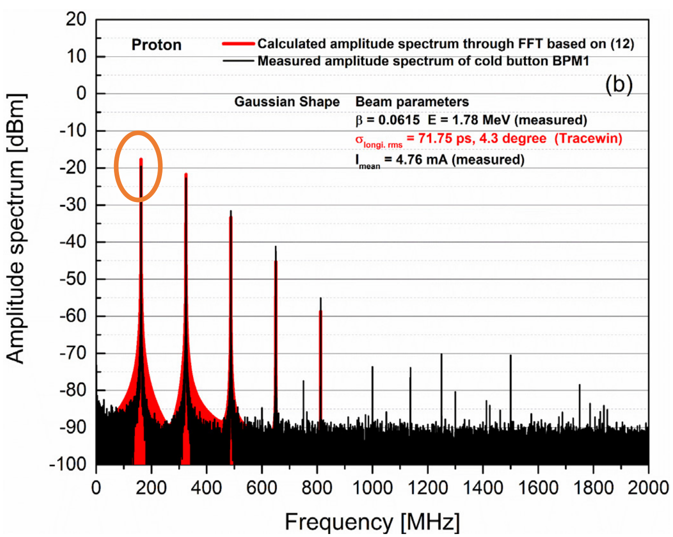
Cold BPM19: exit of CM4

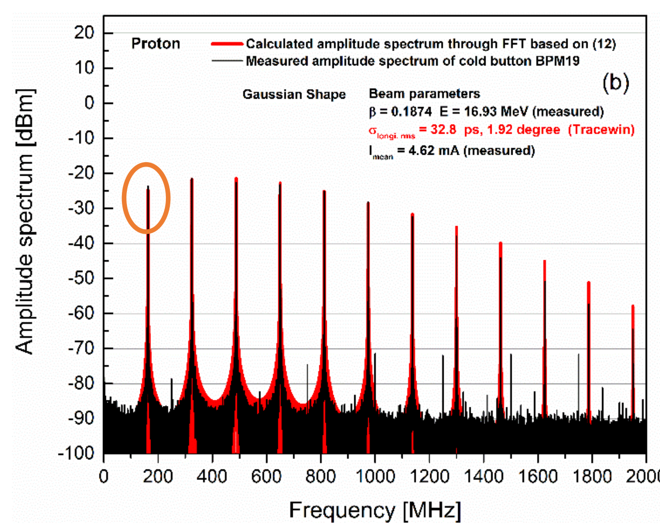
Analyzing of cold Button BPM signal in frequency domain





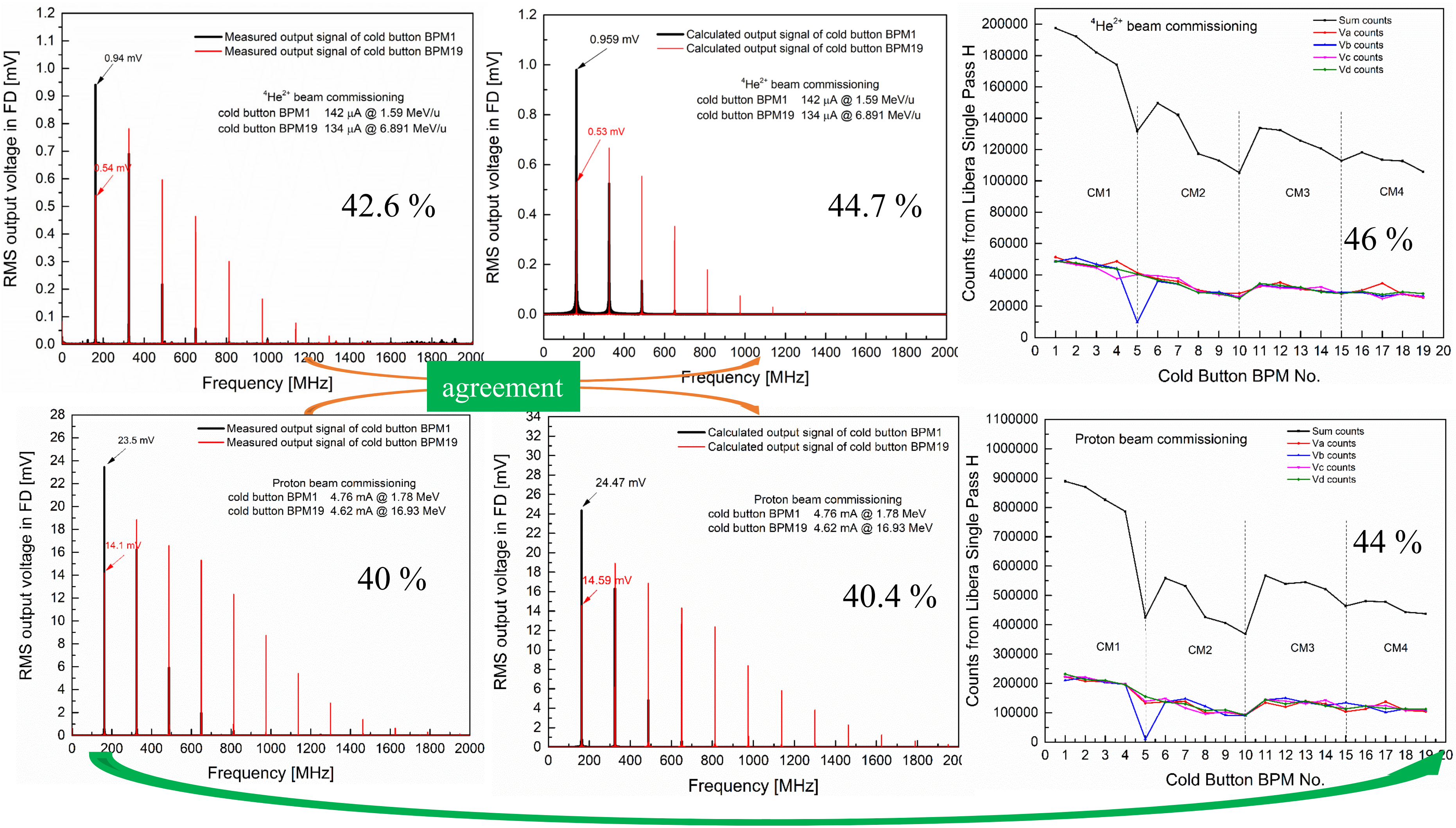
Proton beams





- BPM electronics LSPH: FIR filter bandwidth about 5 MHz, under-sampling of 125 Msps
- Cold BPM Sum values are from LSPH at 1st harmonic frequency of 37.5 MHz or 2nd frequency of 50 MHz
  (162.5-125) (3*125-325)

Analyzing of cold Button BPM signal in frequency domain



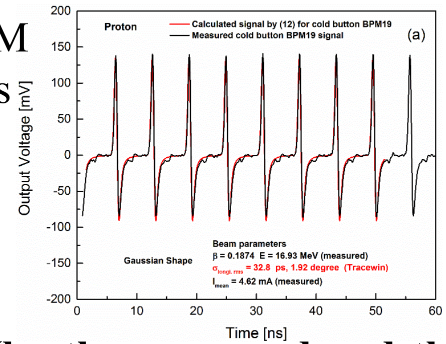
- beam position in a linear range, roughly in the center along CAFe LINAC
- Amplitude spectra become wider, the amplitude at the 1st frequency decreasing with the accelerating
- The decline of BPM sum values from the electronics is not proportional to the ratio of beam current transmission

Conclusions

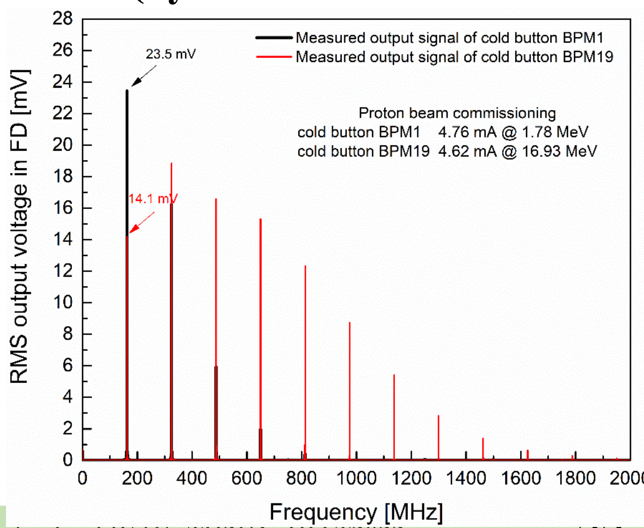
- **BPM original signals are always interesting, specially for high power, low-β ion SC LINAC**
  - In CM, not effective method to measure the beam current and the longitudinal information
  - In low-β CM, no chance to monitor the beam loss, specially in fast method (no thermal detector)

- $$V_{button}(t) = -\langle I_b \rangle \frac{\phi l R}{2\pi\beta c} \sum_{m=1}^{\infty} \left\{ e^{(-\alpha_m \sqrt{f} z)} \, e^{\left(\frac{-m^2 \omega_0^2 \sigma_{im}^2}{2}\right)} (-m\omega_0) \sin\left[m\omega_0 \left((t-\tau) - \alpha_m \sqrt{f} \, z \right) \right] \right\}$$
  - Numerical model is good for estimating the original signal cold Button BPM
  - It consider the influences of low-β effect and long cable transmission issues
  - The imaging bunch length formula could meet Tracewin simulated phase values (in rms) and the measured results

$$\sigma_{im} = \sqrt{\sigma^2 + \left(\frac{b}{\sqrt{2}\beta\gamma c}\right)^2}$$



- **Analyzing the amplitude spectra of cold Button BPM along LINAC (by the measured and the numerical method)**
  - With the beam accelerated, the amplitude spectra of cold Button BPM is widened
  - The amplitude at 1st frequency is decreasing
  - The amplitude at high frequency components is increasing
  - Wide-band sampling of electronics could give a relative reliable information about current, e.g. Spectrum Analyzer
  - Narrow-band digital electronics only give the information at the fixed frequency point, thus the sum values just illustrate whether there are beams or not



Thank you very much for your attention