Recent progress on developing beam diagnostic for the CSNS Accelerator Upgrade

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On behalf of CSNS Beam Instrumentation Workgroup

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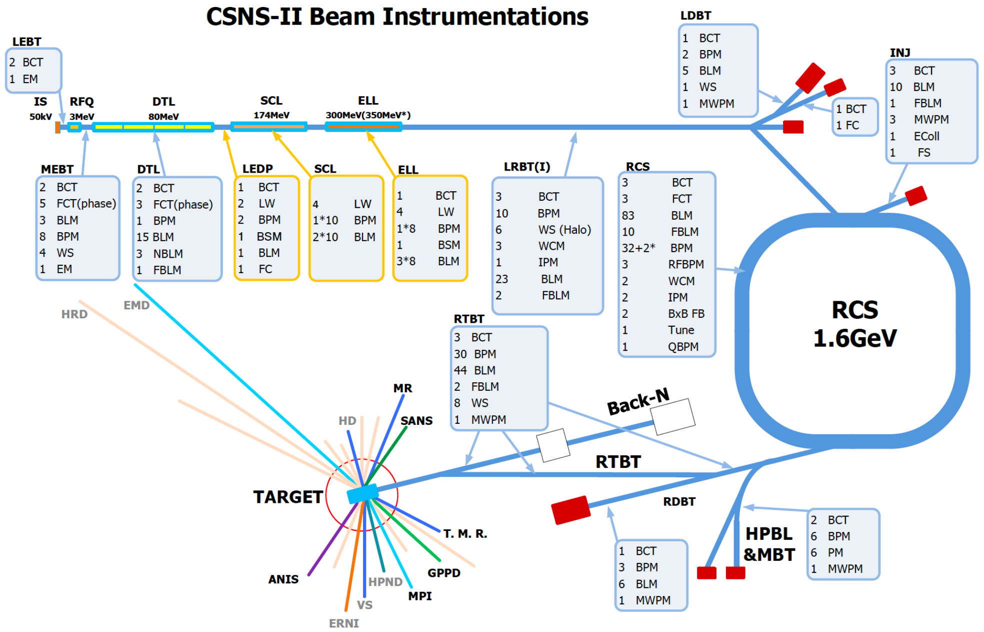
CSNS-II Beam Instrumentation

Work packages

- Essential updates aligning with the front-end and RCS injection upgrades (**2025-2026**)
- Diagnostics for the new superconducting LINAC and understream transport beamlines (**2027-**)
- Tools for the RCS beam monitoring and instability control (**2027-**)
- Instrumentations for the two new proton beamlines (RABT, **2027-**)



About 200+ new instruments (35+ designs) would be developed, installed and commissioned

Highlights

- Renovate the RCS BPM system
- Least-invasive 2D profile
- Reinvent interceptive materials (CNT wire, fluorescence wire, …)
- Transverse damper for the RCS instability

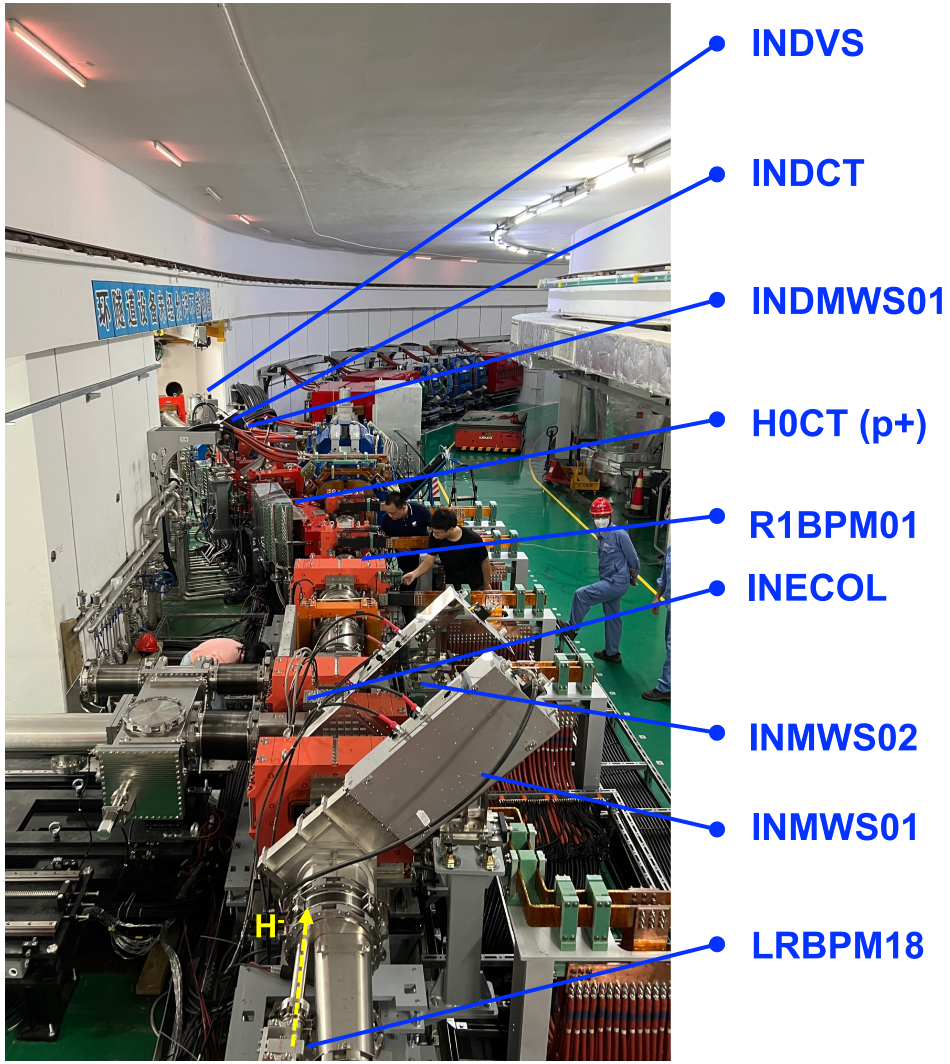
Diagnostics throughtout CSNS-II Accelerator

CSNS-II accelerator will be equipped with ~470 instruments, incorporating ~200 new/restored detectors

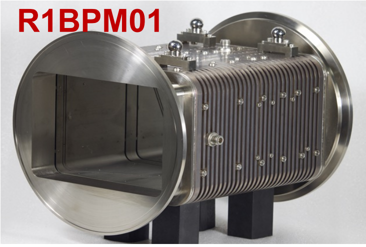
	BCT	FCT	BPM	BLM	WS	LW	MWS	IPM	VS	EMIT	BSM	WCM	FC	Feed back	Tune
Front-end	3		8	3	2					2	1		1		
DTL	3	3	1	18											
SC-LINAC	3		20	63	4	4					2		1		
LRBT	2	2	19	25	4	1				1					
LDBT	2		2	5	1		1						1		
I-Dump	2			4			1		1						
RCS	3	3	35	98			2	2				2		2	2
RTBT		3	30	44	4		1								
RDBT		1	3	6	4		1								
RABT		2	6	8	0		1		1						
Total	8	14	124	274	19	5	7	2	2	3	3	2	3	2	2

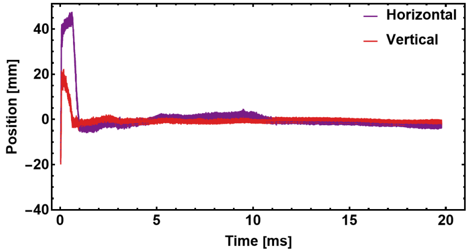
- Upgrade of instruments in RCS injection region (in operation)
- Design of beam instrumentation in the MEBT (installation in 2026)
- Design, prototype of beam instrumentations

Injection Beam Instrument Upgrade

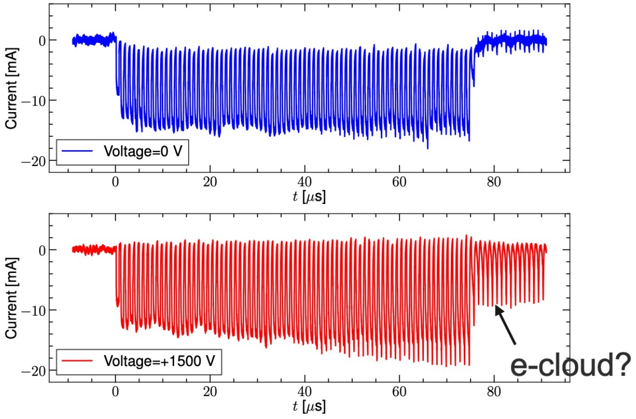


- 9 new detectors are installed this summer
  - LRBPM18：shorted stripline BPM (diam.=50 mm)
  - INMWS01-02、INMWS03：SEM grids (136 ch.)
  - INECOL：stripped electron catcher
  - R1BPM01：rectangular BPM (260 mmx180 mm)
  - H0CT, INDCT：current transformers (10 μA-50 mA)
  - INDVS: screen monitor (Chromox6)
- All the detectors work perfectly as soon as beam enters injection area (Day 1)





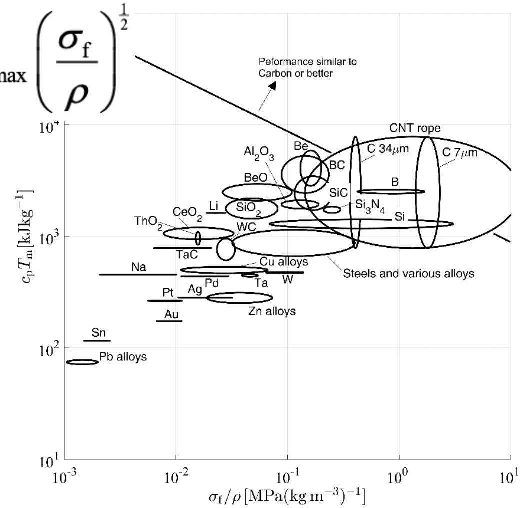
Signal of the stripped e-



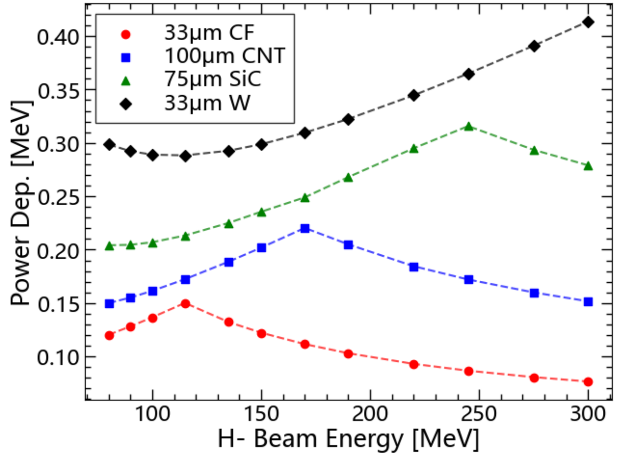
SEM Grids in the RCS Injection Area

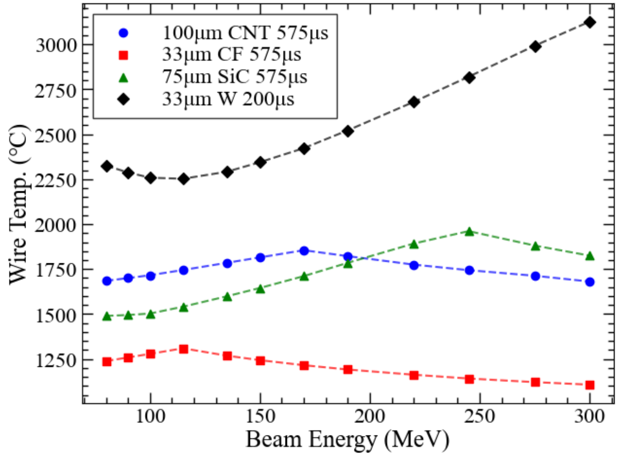
- Requirements & technical challenges
  - Three SEM-grid are required for the RCS injection tuning (H$^-$ beam, 80/300 MeV, 30 mA, 575 μs, σ_{xy}~2.0 mm, single-shot & 1 Hz)
  - The thermal analysis in ANSYS based on G4 simulations suggest that the popular Tungsten and SiC wires might melt/sublimate, while the peak temperature of the carbon fiber (33 μm) is only 1310 ^{o}C
  - For the CF, the SEY is <5%*I_{H-}@>115 MeV, and the mechanical stress & deflection might be serious issues for massive implementation!

$$M = c_p T_{max} \left(\frac{\sigma_f}{\rho}\right)^{\frac{1}{2}}$$



Material	CNT	CF	W	SiC
Diameter(um)	100	33	33	75
Density(g/cm^3)	1.08	1.8	19.35	2.89
Thermal conductivity (W/mK)	350	24	173	340
Tensile Strength(GPa)	1.79	3	1	5.9
Work Temperature (℃)	<2000	<2000	<2000	≥1250
Expected max. temperature (℃)	1855	1310	>3000	1962





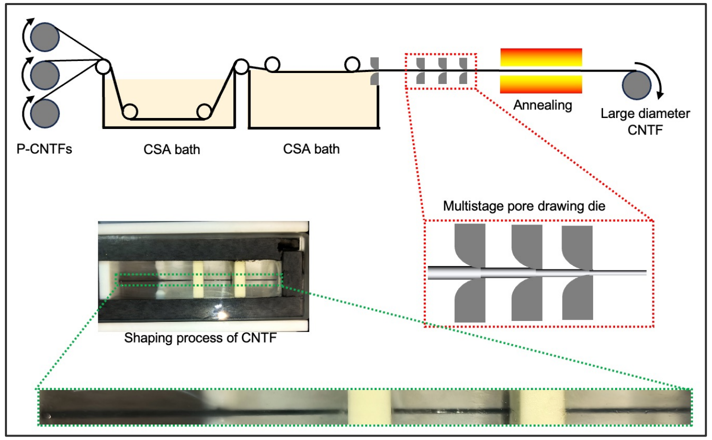
[1] H. Bigland et al., Advanced Engineering Materials (2020)
[2] https://www.specmaterials.com/

SEM Grids in the RCS Injection Area

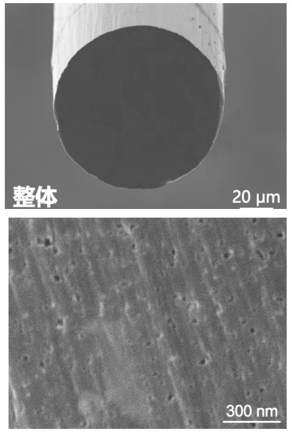
IHEP-SINANO-PKU collaboration

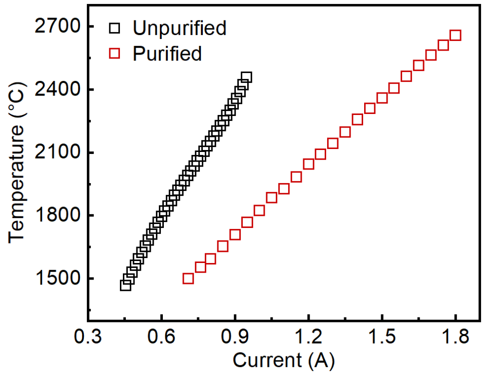
- Large-diameter CNT wire fused by ~30 CNT fiber prepared through CVD method
- Ferrocene ($Fe(C_5H_5)_2$) purified through heating up to 1570 K in vacuum (10^{-5} Pa)

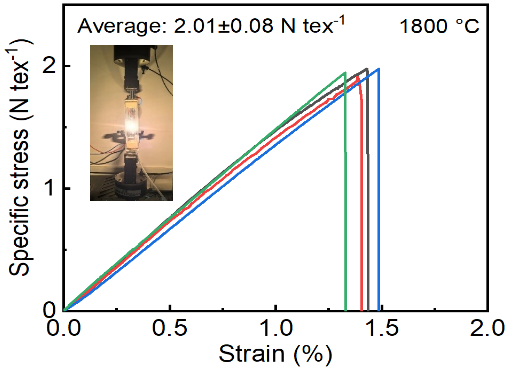
Manufacture of CNT wire



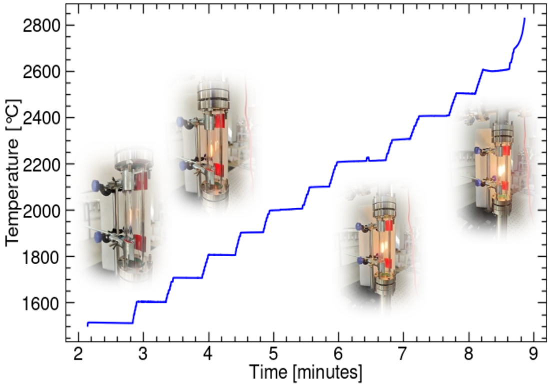
unifomaty~3%

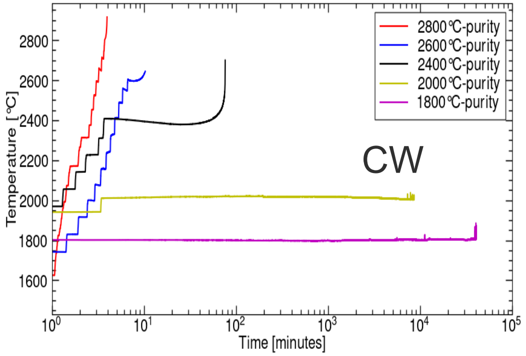


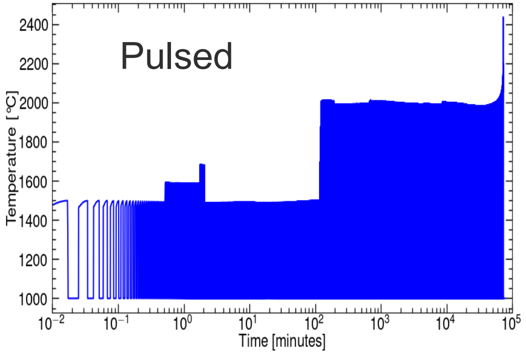




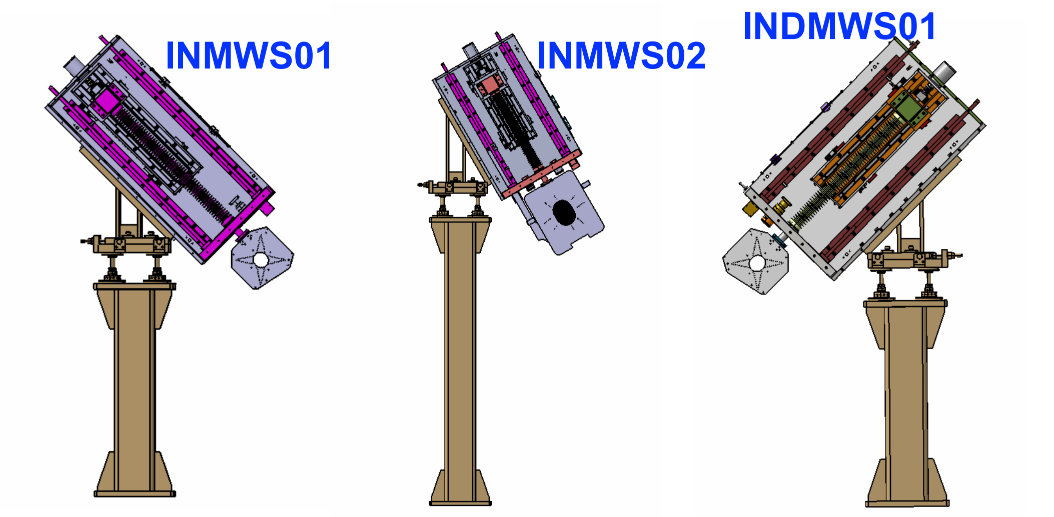
- Thermal heating experiments in lab. show: a max. temperature ~2800 °C; endurance at 2000 K for ~700 h (CW) & >1000 h (1 Hz, duty~0.5)

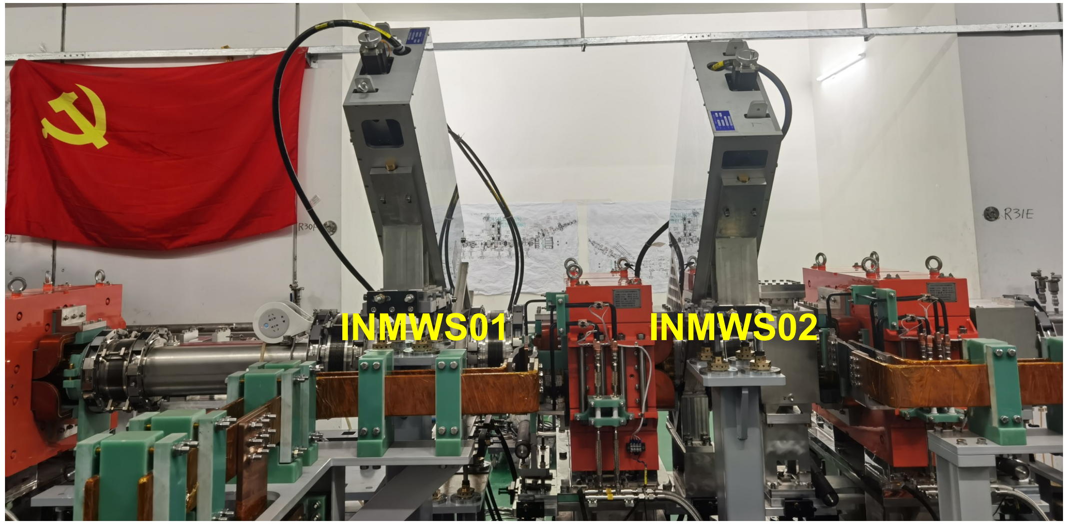




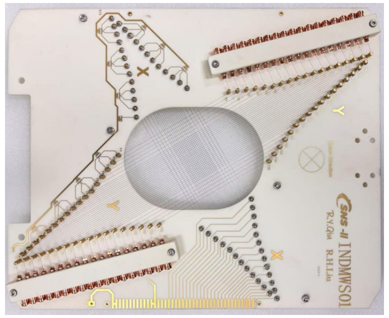


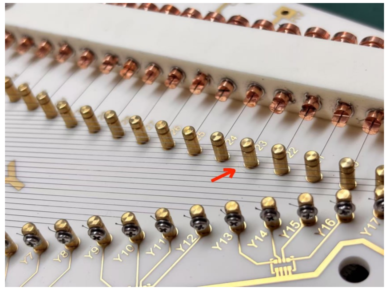
SEM Grids in the RCS Injection Area



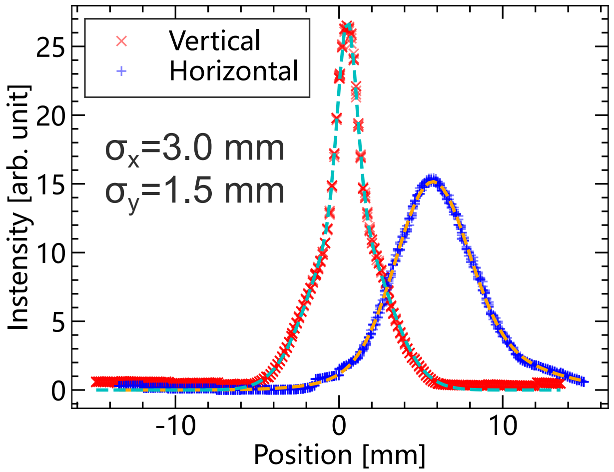


- Three SEM grids with 136 signal CNT wires, a min. wire space of 1.5 mm on a ceramic frame
- Individual biased wires on the other frame (+100V)
- **First massive implementation of large-diameter CNTF to the particles accelerators!**
- DAQ: Linux + NI PXIe+ EPICS IOC (re-use the NI controller and digitizers)





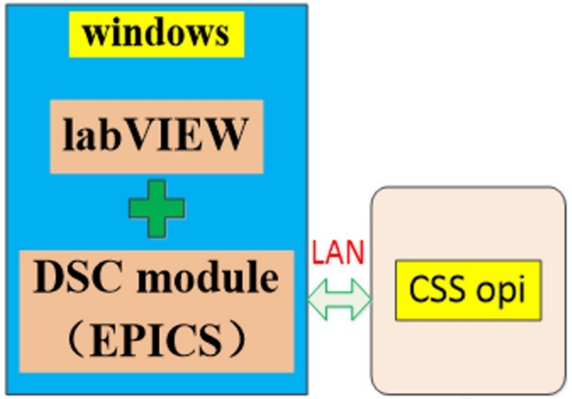
- Capture H^- beam profile on Day 1
- Resolution further improved by scan function (0.15 mm)



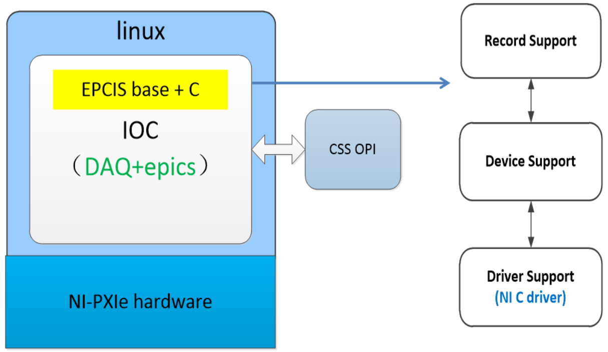
EPICS (linux) + NI PXIe hardware

- Massive implementation of the NI PXIe DAQ modules for the beam instrumentation system (LabView)
- Upgrade to standard EPICS IOC integrated in Linux for the NI modules in operation (~hundred)

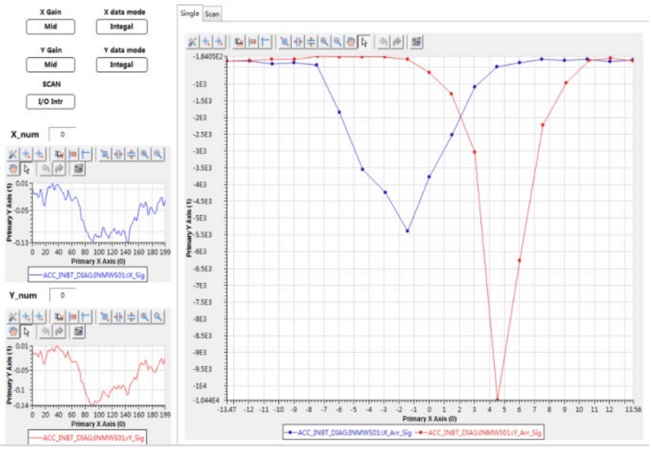
LabView based architecture (v0)



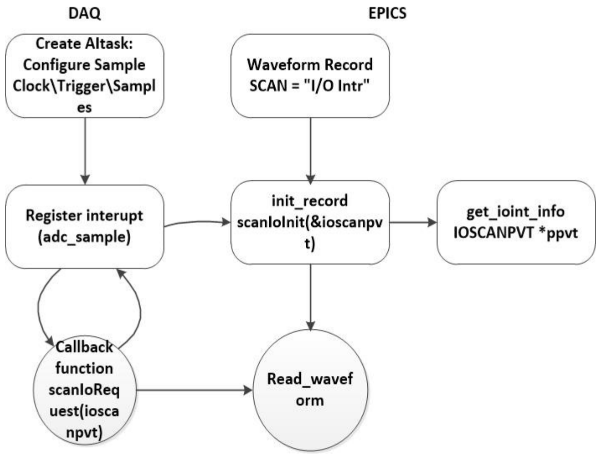
EPICS+C in Linux (v2)



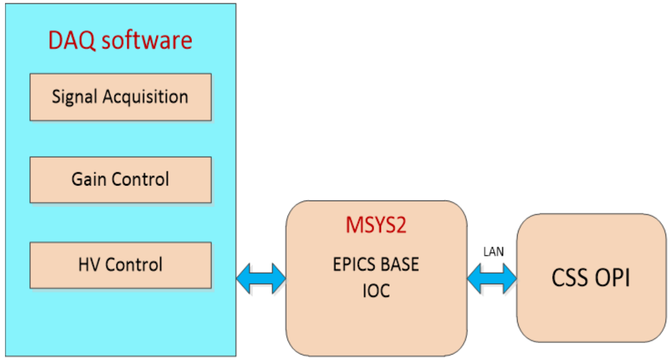
Display with CSS OPI (PXIe-6363 modules, PXIe-1085 chassis)



Architecture of DAQ and IOC



Labview+MYSY2 in Windows (v1)

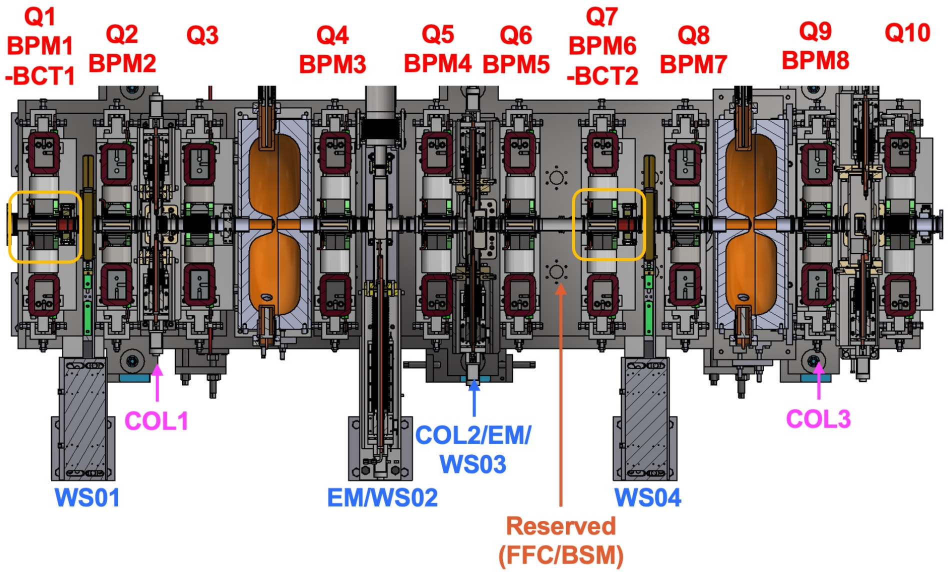


[1] Z. Xu et al., IBIC2025, MOPCO18 (2025)

- Upgrade of instruments in RCS injection region (in operation)
- Design of beam instrumentation in the MEBT (installation in 2026)
- Design, prototype of beam instrumentations

Beam Instrumentation in MEBT

- In accordance with the revision of the MEBT optics and structure, the beam instrumentations are renovated
- 6 individual BPMs, 2 CT-BPMs, 2 individual WSs, 3 FBLM, 1 EM/WS2-COL2/EM/WS03 assembly plus an extra space reserved for the longitudinal diagnostics (FFC vs. BSM)
  - Re-use the current BPM & CT sensor designs and electronics (commercial, Bergoz & Libera)
  - Reduce the transverse dimension of the WS (<0.77 m in hor.), use CNT wires (SNR X10)



	No.	Requirements	Features
BPM	8	Position resolution <0.2%*R phase resolution 0.2º@324 MHz	BPM embedded in quad. poles (8 new BPM+1 LIBERA electronics)
CT	2	Range: 1-50 mA Linearity: ±0.5% Risetime: ≤10 μs	BPM-BCT welded together
EM	1	Max. beam power: 50 mA*20 μs Accuracy: ~10% Min. time-consuming: <10 mins	Slit-wire configuration, integrated with collimator (COL2) and WS02, WS03, 4 wires for beamlet (4X faster)
WS	4	Scan range: ±R Resolution: ≤0.2 mm Positioning repeatability: ≤0.5 mm	d100 μm CNT wire, x&y (new WS01/WS04)

Longitudinal diagnostics at MEBT

- The new CSNS-II MEBT design leaves ~141 mm space (z-direction) for the longitudinal bunch shape diagnostics while the space required by Feschenko-BSM is around ~200 mm
- Information from J-PARC LINAC: the Feschenko-BSM operates NOT often, and the adjacent quad. are powered off during operation (re-match optics); BSM operation by experienced experts
- An alternative scheme based on FFC+EOM techniques has been proposed and demonstrated in lab.

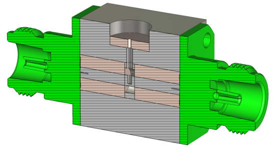
MEBT major beam parameters

Parameter	Value
Beam energy	3 Mev
Beta	0.08
Beam current	1-50 mA
Bunch freq.	324 MHz
Aver. beam size	2-3 mm
Bunch length	50-250 ps

low-β bunch shape diagnostic

GHz sensor

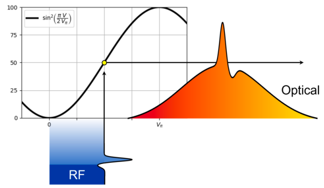
FFC (FNAL idea)



- Round 50 Ω coaxial line
- BW>10 GHz
- Bias voltage (secondary e-)

RF signal distortion

EO modulation



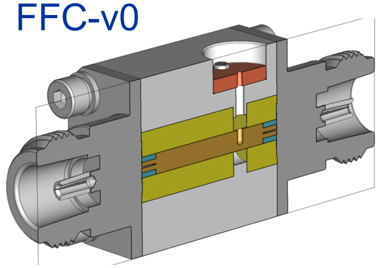
- Mach-Zehnder EO modulator
- Cband CW laser + SMF
- BW~40 GHz (1550 nm laser)
- Atten.: 0.2 dB/km @1550 nm

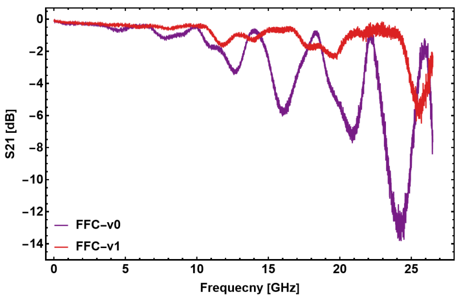
[1] A. Carneiro et al.,Int. J. of Mod. Phys. A, 2019
[2] T. Suwada et al, Scientific Reports (2022); A. Schlogelhofer et al., IBIC2024

Longitudinal diagnostics at MEBT (cont’)

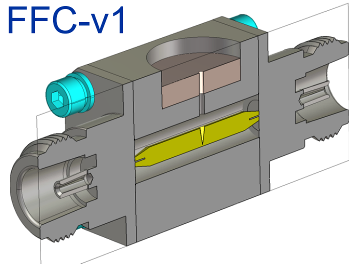
- Two versions of the FFC sensor were prepared this year, and a bandwidth of >20 GHz has been realized
- A 40 GHz telecommunication module using an intensity EO modulator (1550 nm) has been prepared
- For an RF signal with a nominal FWHM of 30 ps, the EO signal (through a 2 km SMF) recorded at a 33 GHz/80 GSPS oscilloscope is ~34 ps (BW~20 GHz, limited by the oscilloscope’s sampling rate)

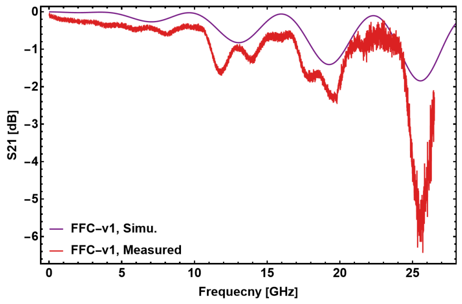
FFC-v0

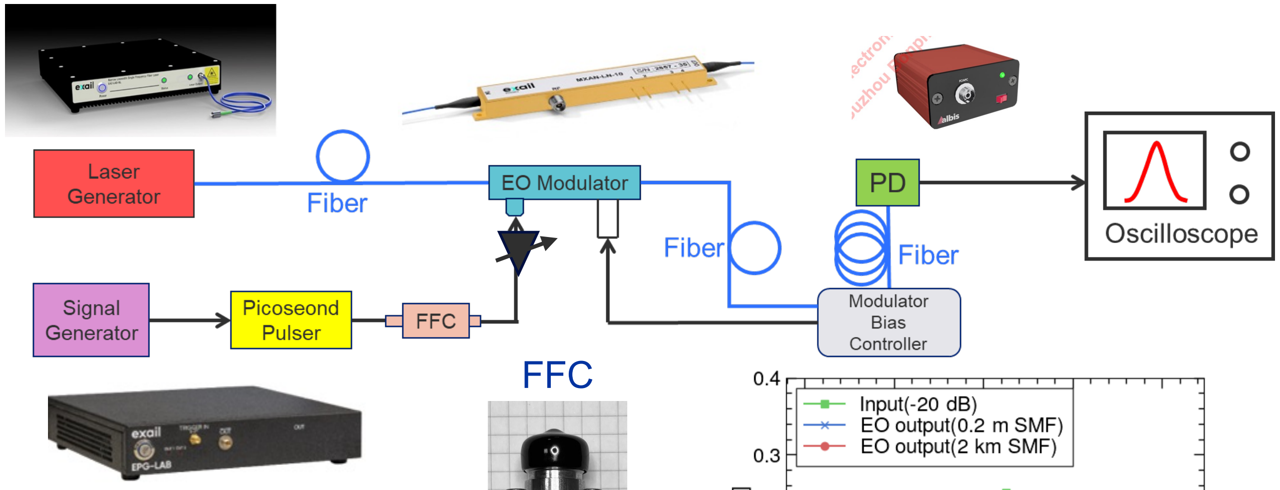




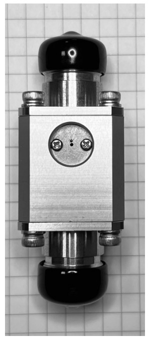
FFC-v1

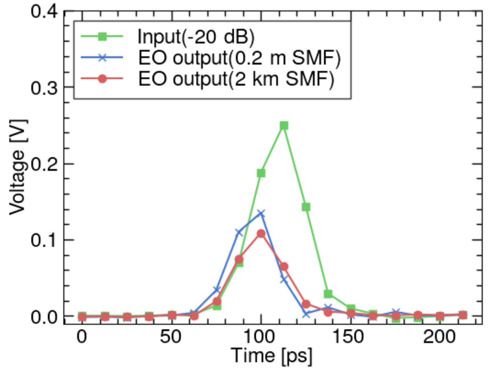






FFC





- Upgrade of instruments in RCS injection region (in operation)
- Design of beam instrumentation in the MEBT (installation in 2026)
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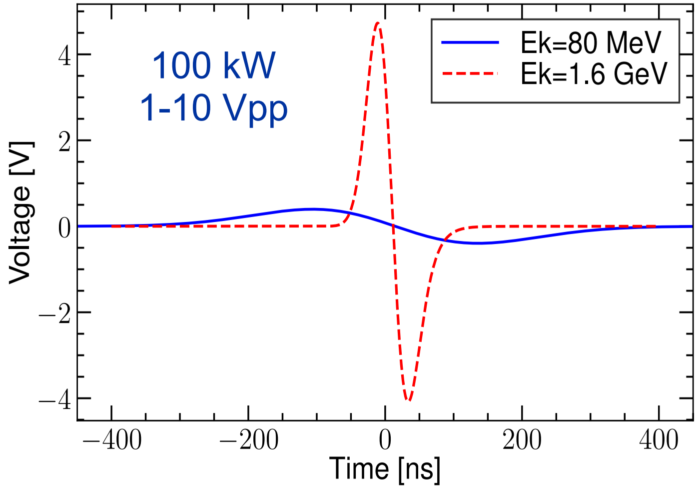
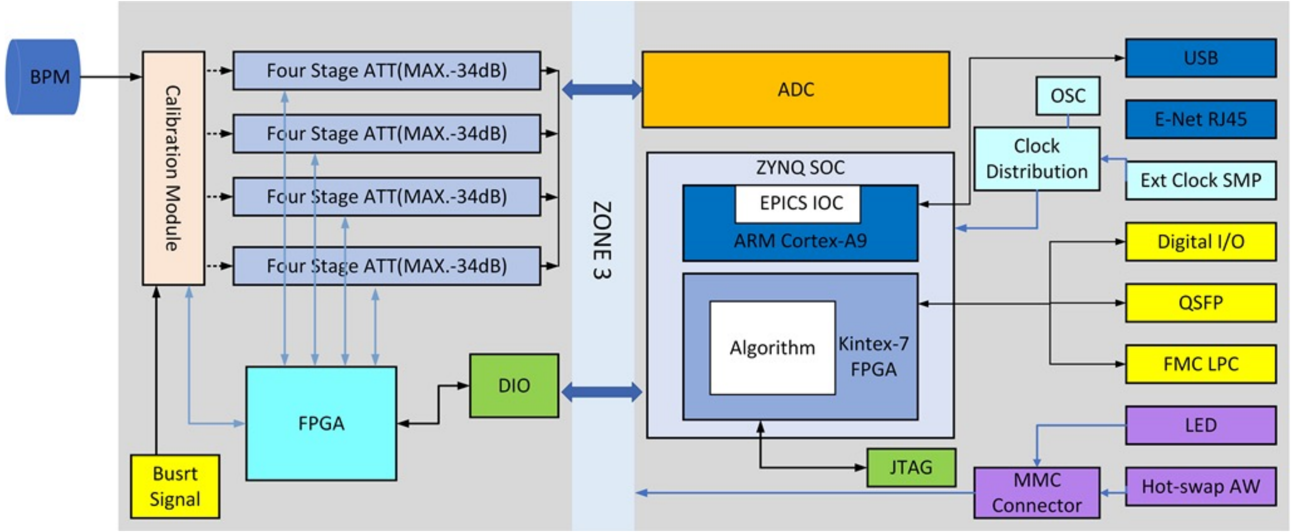
New RCS BPM electronics

- Updated design based upon mTCA.4 system (provided by domestic company)
  - Custom RTM board enables cascaded signal attenuation and transparent gain switch (J-PARC MR experiences)
    - Slow & fast atten./gain switch: ~ms & ~800 ns adapting to commissioning at low and high beam power (20-500 kW), and injection to extraction (0 dB => -34 dB)
    - Digital AMC board used also for the RCS LLRF & Timing system
  - Dedicated AMC board for the trigger and sync. RF window
- Beam position calculation algorithms: Integral, STD

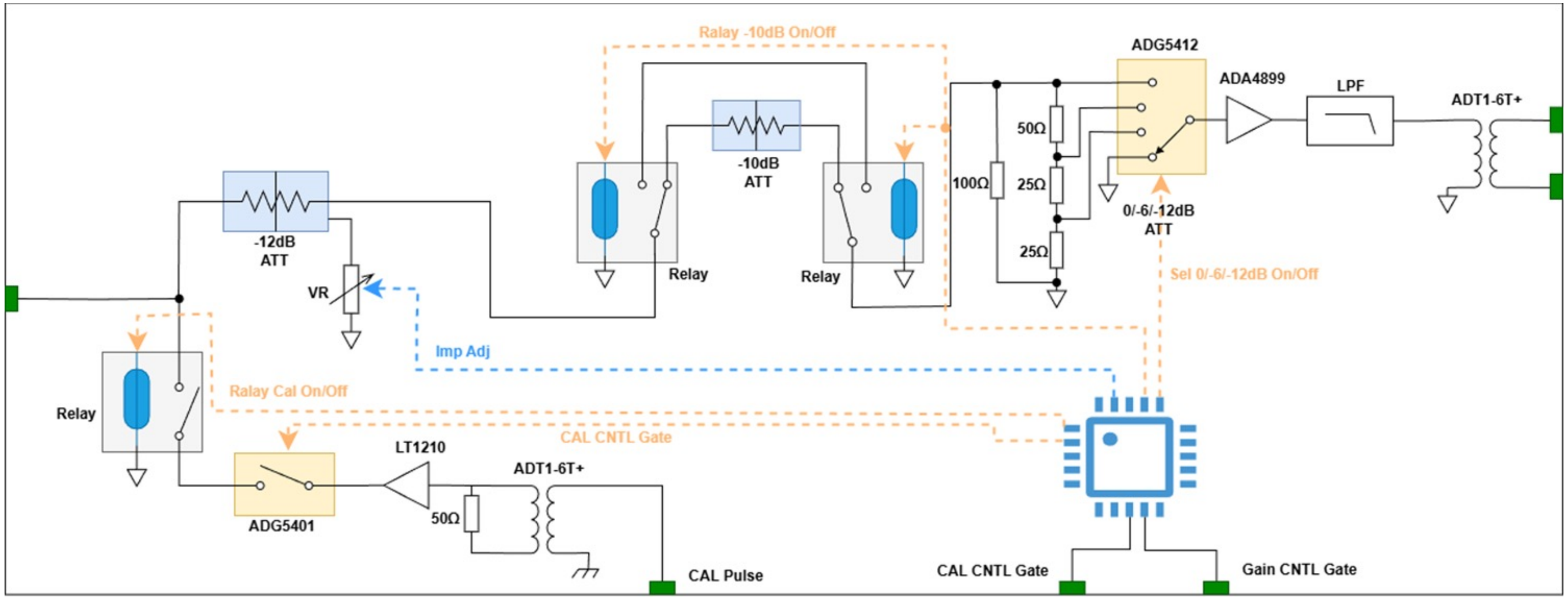


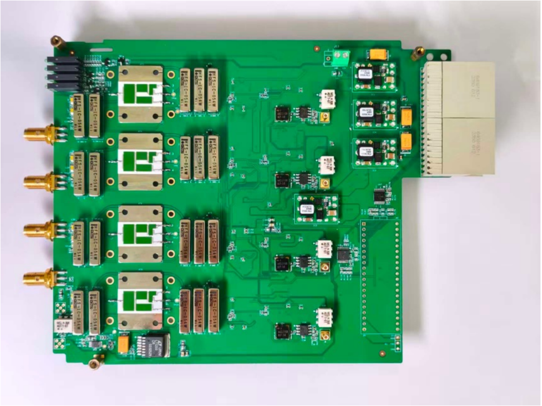


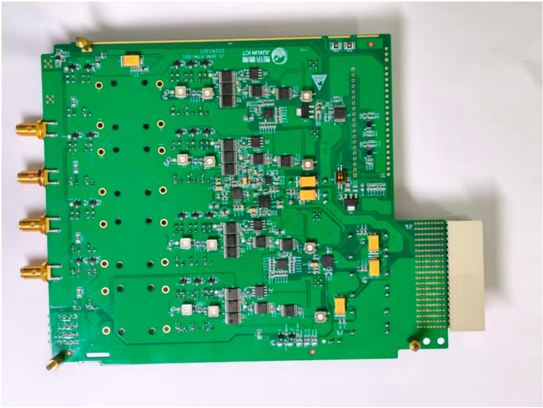
Analog RTM board

- For the all possible beam powers (double-bunch), and the respective signal amplitude ranges from 0.1 V to 50 V for the accelerating beams while the ADC input range is ±2 V

- RF power divider (atten. + impedance matching)
- Three-stage attenuation modules
- Automatic gain calibration to 4 channels





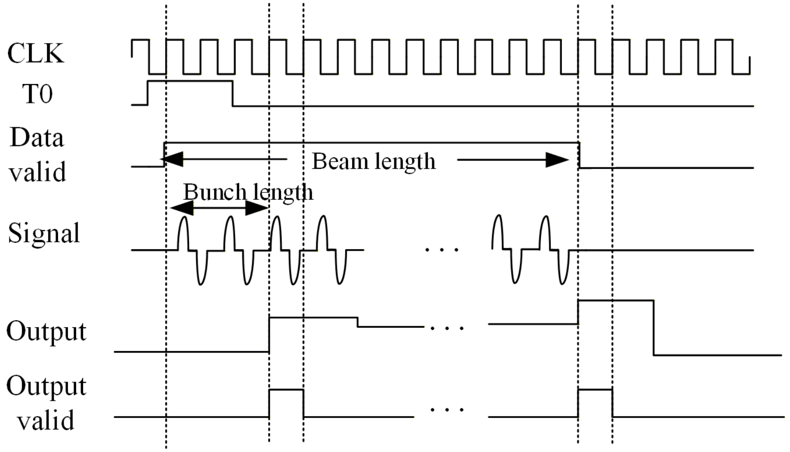


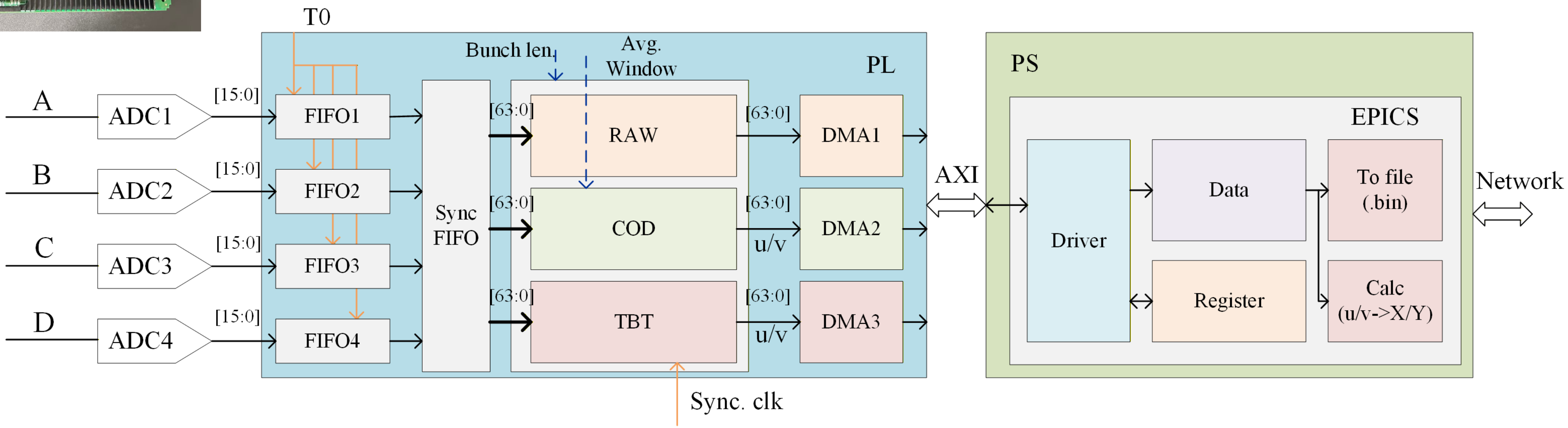
Digital data processing & AMC board

- In-house made AMC boards for data processing and timing (clk. & sync.)

Parameters	New electronics
ADC Sampling rate	125 MHz
ADC resolution	16 bit
Bandwidth	25 MHz
SNR	60 dB
Isolation	60 dB
Signal range	0.1~80 Vpp (60dB)
Timing resolution	1 ns
FPGA platform	Zynq 7000

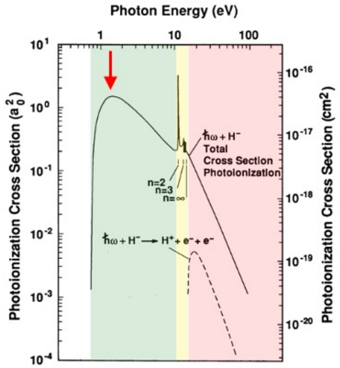
COD calculation w/ STD algorithm

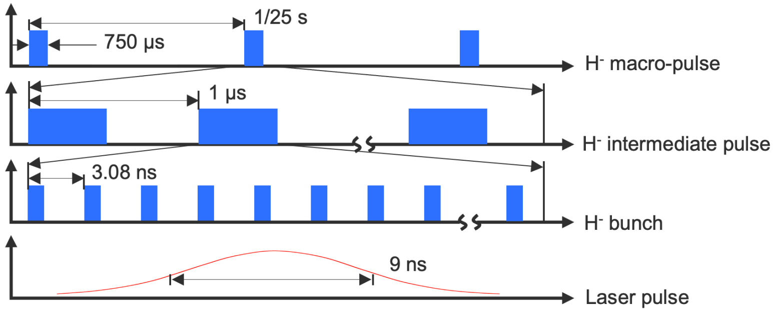


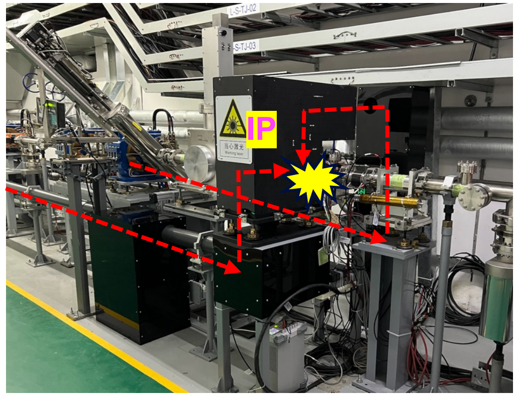


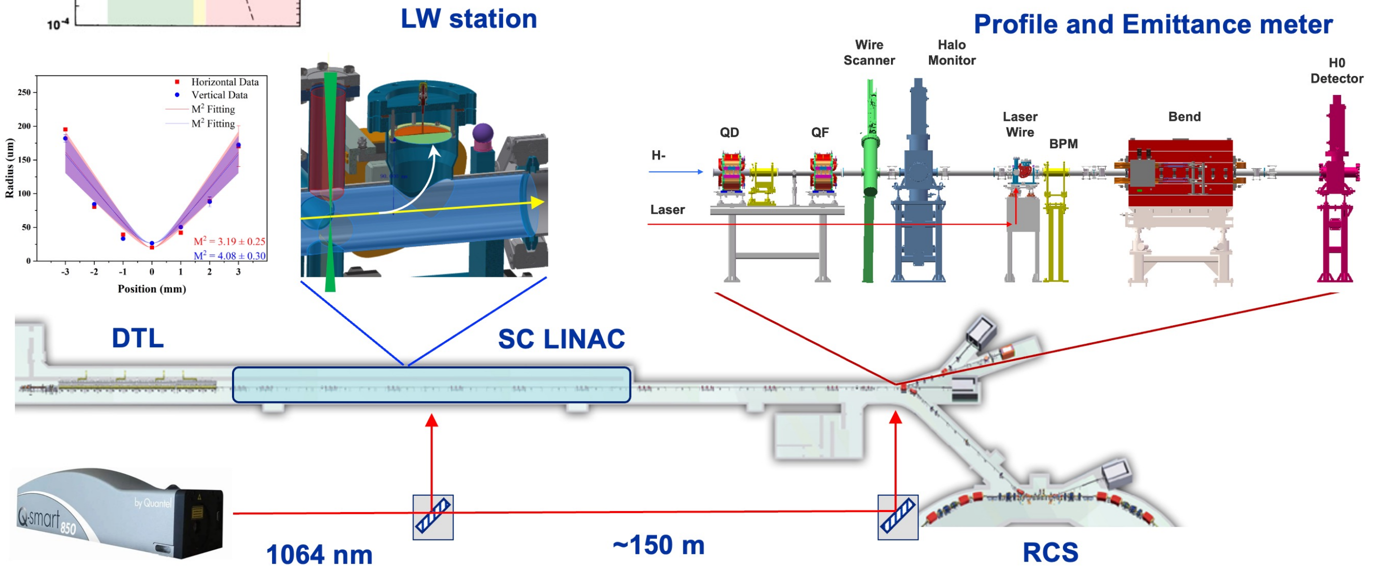
Laser-Wire profile monitor prototype

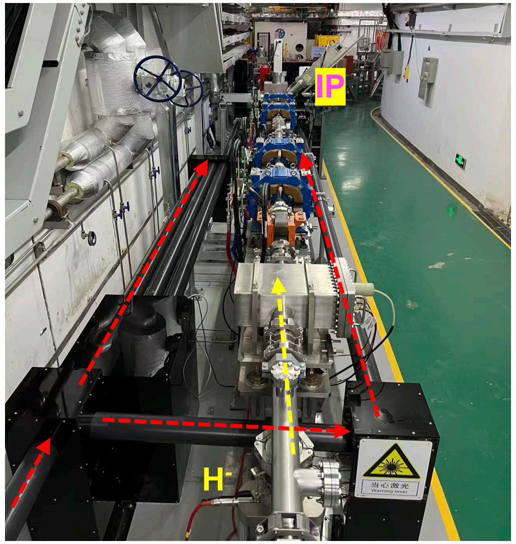
- LW profile monitor: a swiss-knife style non-invasive diagnostic tool for superconducting LINAC
- A prototype of the LW profile monitor/emittance meter was established at the LRBT





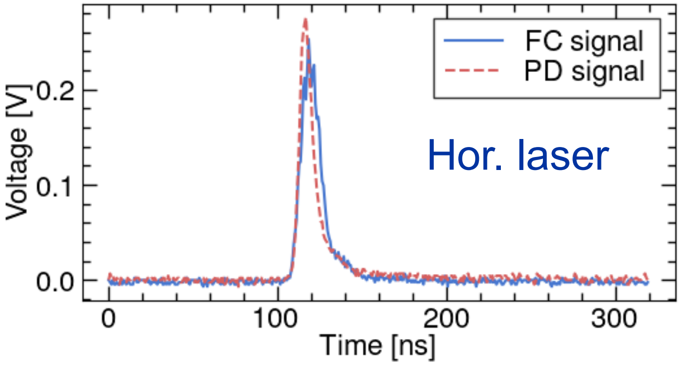


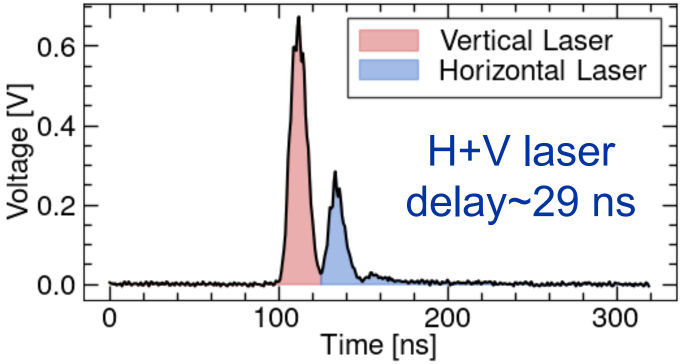


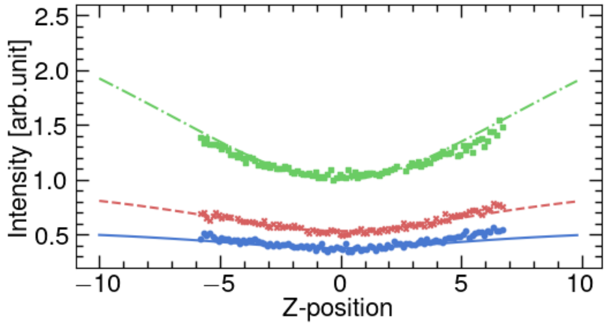


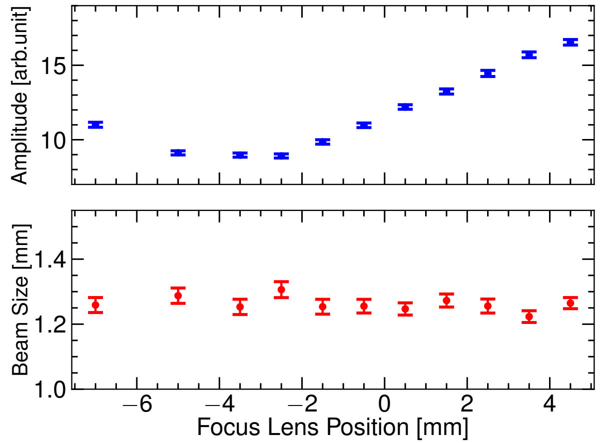
Transverse profile measurements

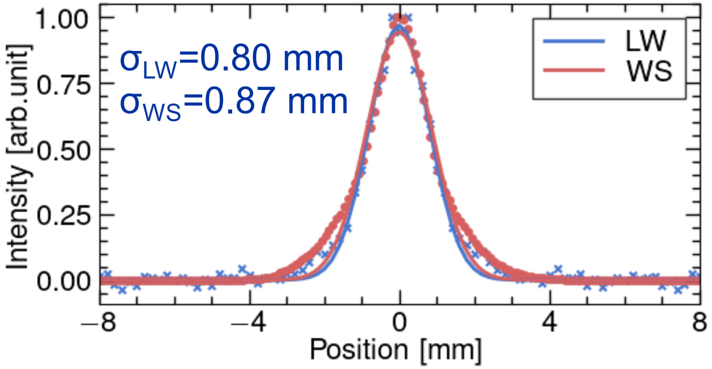
- Commercial Nd:YAG laser: 1064 nm, 900 mJ/pulse (max.), 9 ns pulse width, M^2~2
- About 80 m free-space laser transport (tunnels) with <10 μm pointing stability and M^2<4 nearby LW station
- Horizontal & vertical individual and simultaneous (2X faster, delay line) scans were demonstrated in 2025
- Calibration by an adjacent WS: σ_{LW}=0.80 mm vs. σ_{WS}=0.87 mm => intra-pulse bunch position displacement

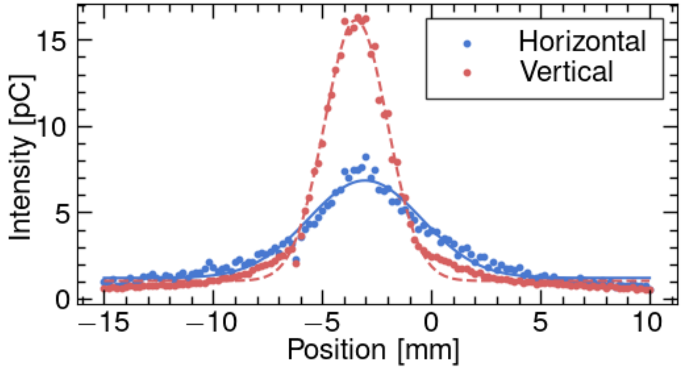








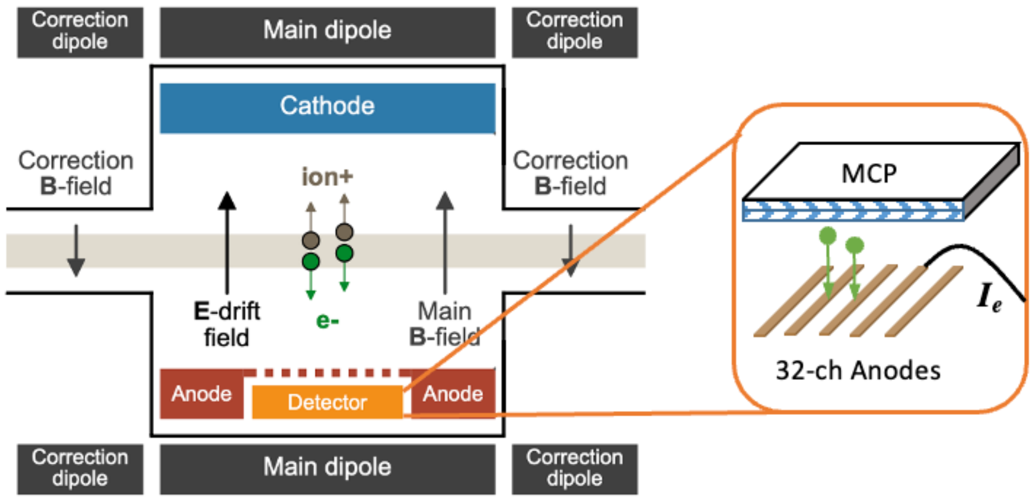




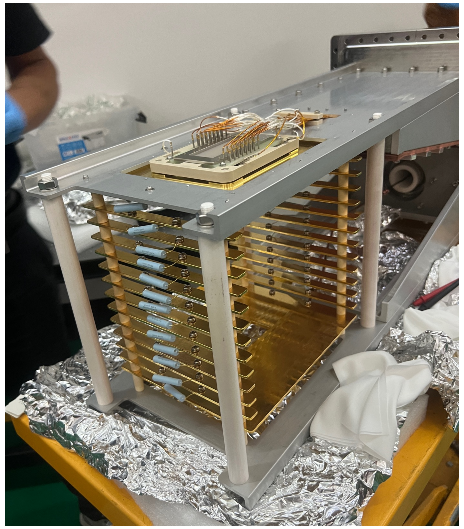
RCS IPM prototype

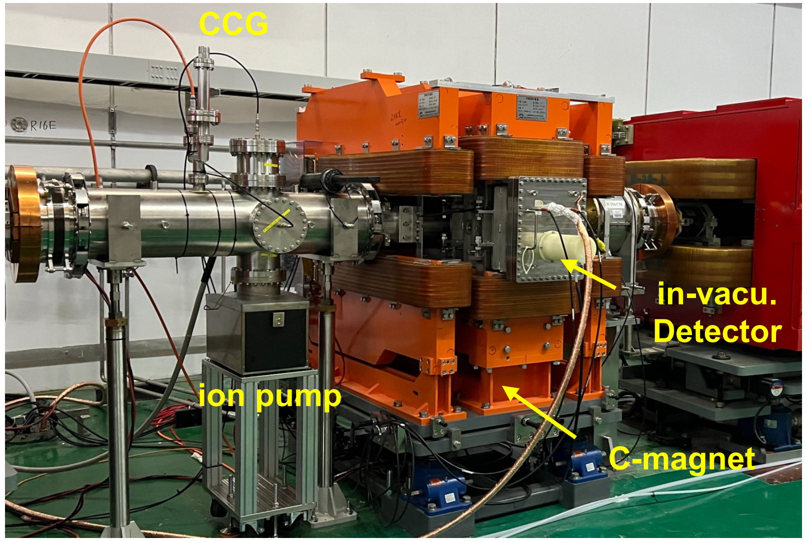
- Two IPMs (H+V) are required to image the RCS beam profile, and emittance in a bunch-by-bunch manner
  - It utilizes beam-induced ionization of residual gas in the beampipe (10^3~10^4 events/passive)
  - The liberated ion+ and e- has ~10 eV energy, and could be separated & accelerated towards the cathode and anode, respectively, by the collection E-field (~100 kV/m, typically)
  - The ion+/e- are then collected on the detector (MCP-anodes, MCP-phosphor, silicon strip/pixel…)
- The prototyping initiative, launched in 2019, was followed by a lengthy commissioning campaign

RCS IPM layout



in-vacuum IPM detector

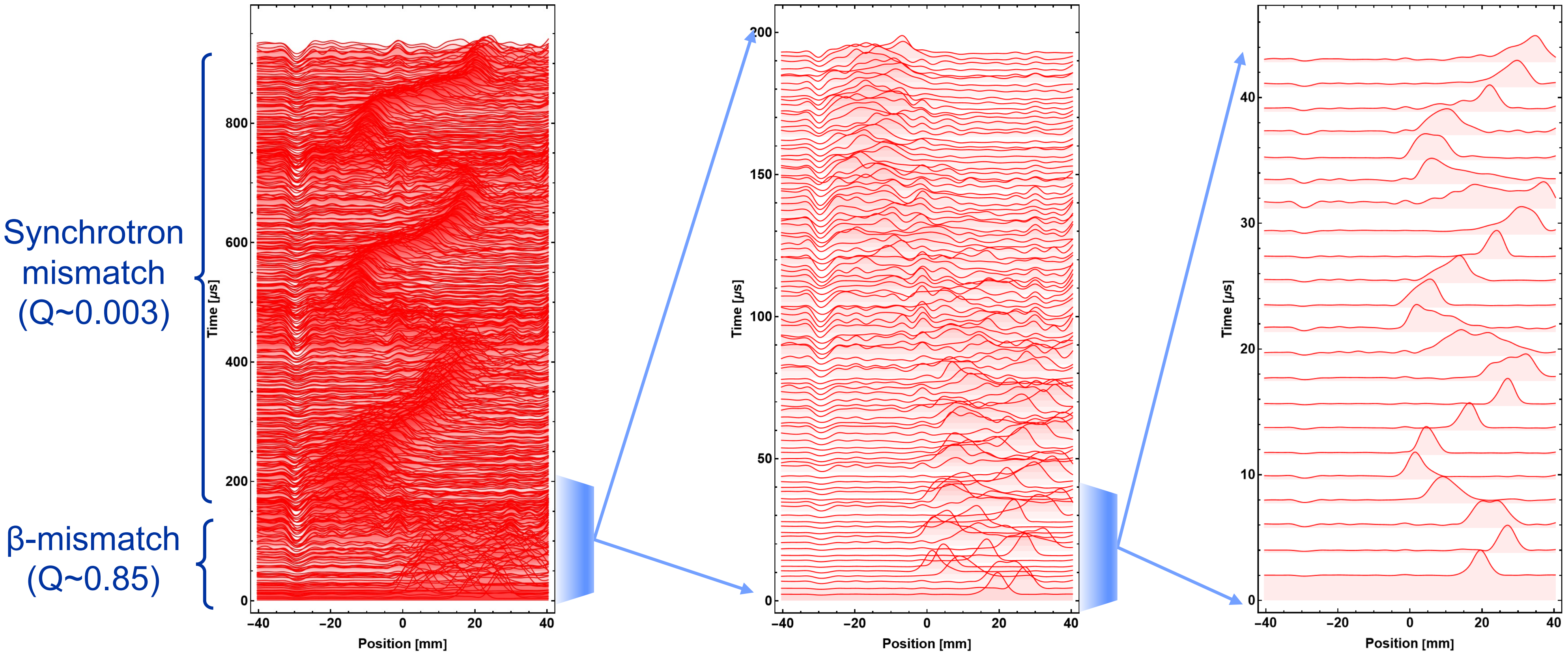




First observations of the RCS injection beam

- The initial commissioning of the IPM detector focus on the ion-mode (w/o B-field)
- The primary beam intensity is limited to <10^{12} ppb => image the early injection proton beam

Observation of injection mismatch (single-turn, 270 ns, 2.5×10^{10}ppb, 19/11/2025)



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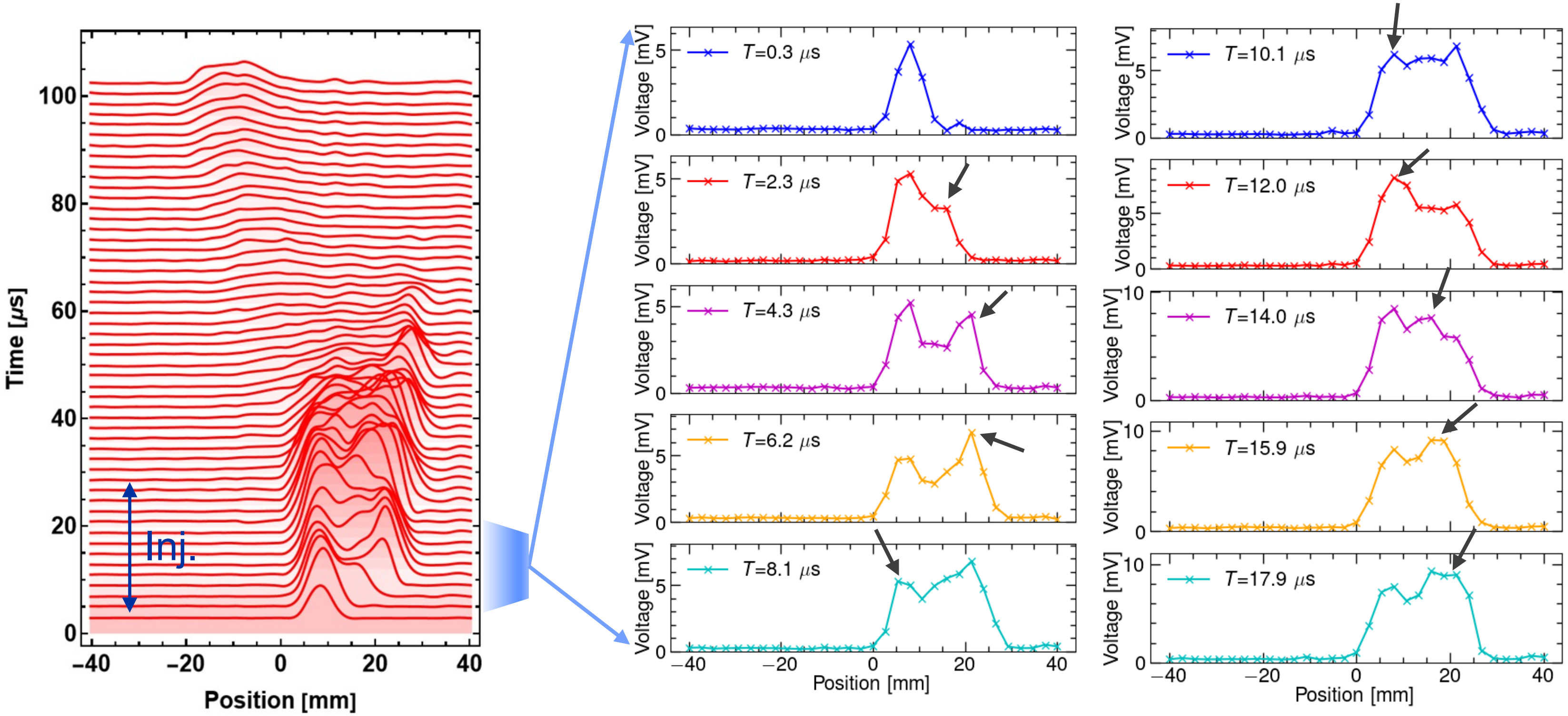
Horizontal injection painting scheme: direct observations

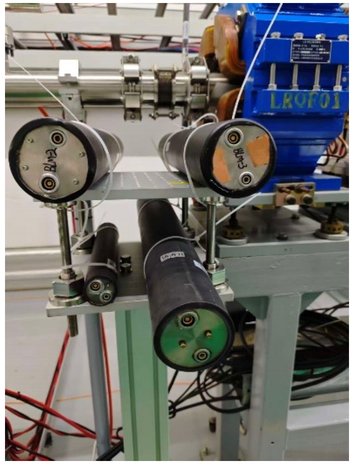


* S. Wang et al., CSNS-II design report; H. Hotchi et al., PRAB 15, 040402 (2012);

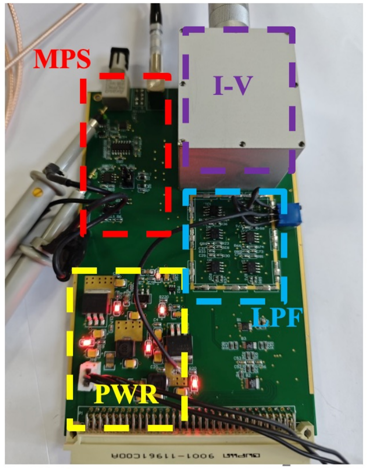
Beam Loss Monitors

- Two types of BLMs are required to localize the loss position and MPS (**damage and quench prevention**)
- Ionization chamber (IC): coaxial IC (70 nC/rad, production) and parallel-plate IC (1800 nC/rad, developing) with response times of 2 μs and 0.3 μs (e- draft time)
  - 1 parallel-plate IC per SC cavity throughout the SC LINAC (abort threshold ~800 nA for >0.01 W/m loss, ESS experiences)
  - Electronics shift from IF converter (CFC) to IV converter; transimpedance amplifier (1 & 100 MΩ, 0.02-20 μA & 0.2-20 nA) + 1 MSPS ADC (20 bit) + FPGA (counter, encoder …)
- New IC and analogue electronics satisfy the design requirements -> further optimization & integration
- Plastic scintillator-PMT: response time ~10 ns (production)

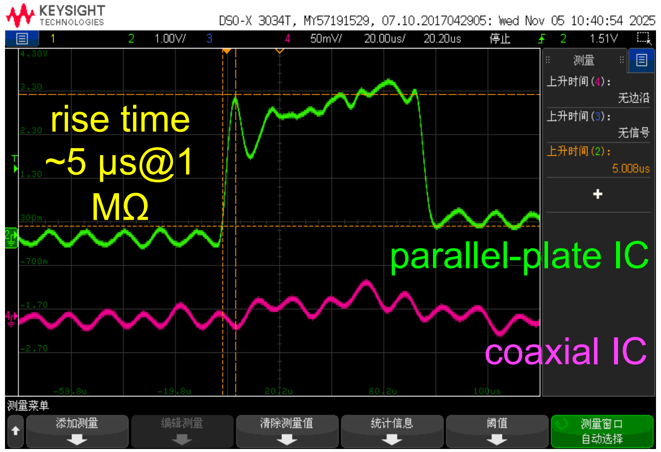
Test at LRBT



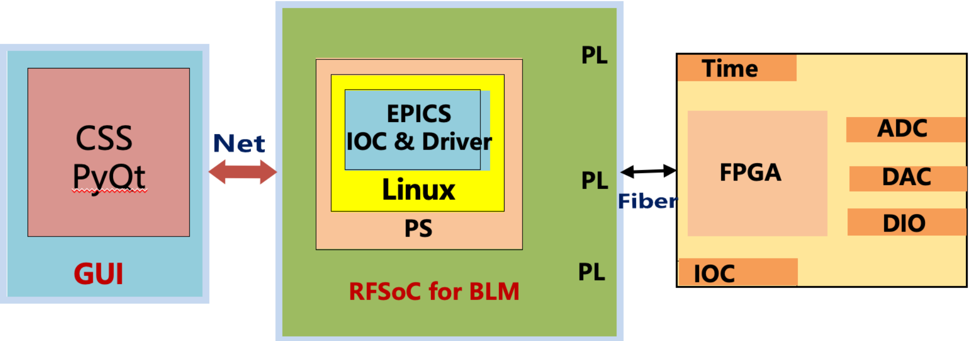
FMC board (v1)



Test at LRBT



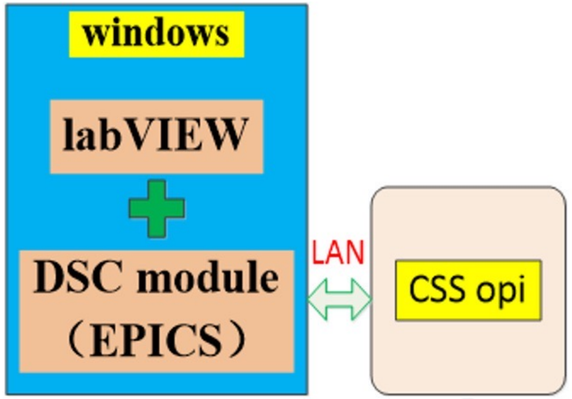
Refurbished BLM Electronics for Superconducting LINAC



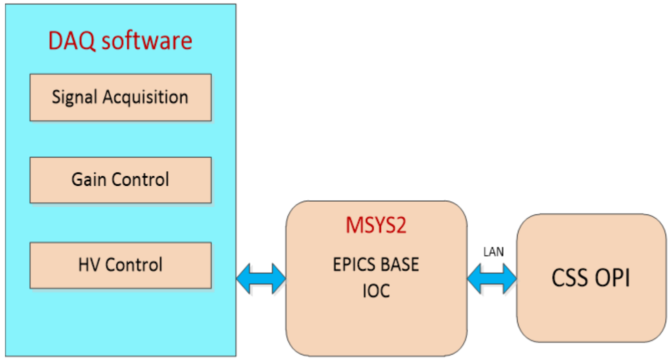
EPICS in CSNS Beam Instrumentation System

2015~2023 (CSNS Phase-I)

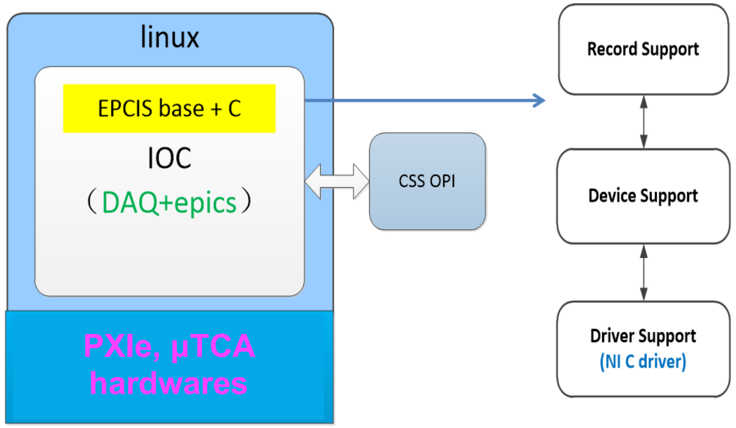
LabView based architecture (v0)



Labview+MYSY2 in Windows (v1)



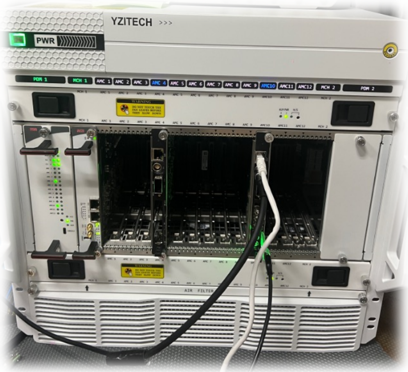
2024-present (CSNS-II)



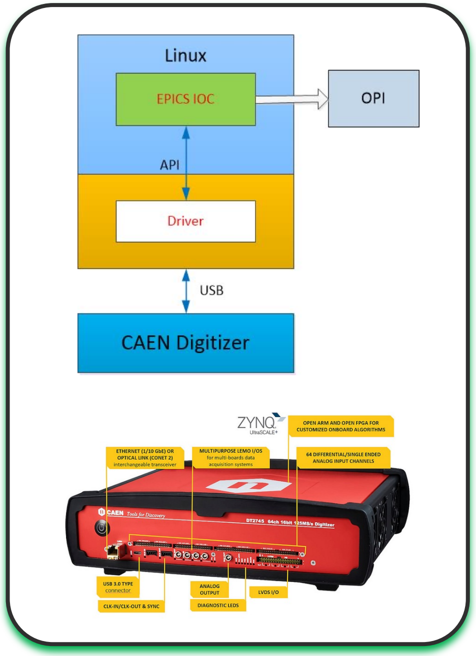
NI PXIe (CT, BLM, WS, ..)

In-house developed PXIe digitizer

µTCA.4 platform BPM



64 ch digitizer for IPMs



Summary

- Many progress made in the development, beam test and production across all tasks
  - Successful instrumentation development for the RCS injection upgrade
  - Design review of the MEBT diagnostics completed, followed by quotation and production
  - Design/prototyping of the BPM electronics, LW and IPM are promising
- Acknowledgements of the internal, domestic and oversea collaborations (SINANO, USTC, PKU, CERN, GSI, KEK, etc.)