Bunch-by-Bunch Residual Gas IPM for the CSNS RCS and Gated IPM Development for High Power Operation

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Presented at AFAD2026

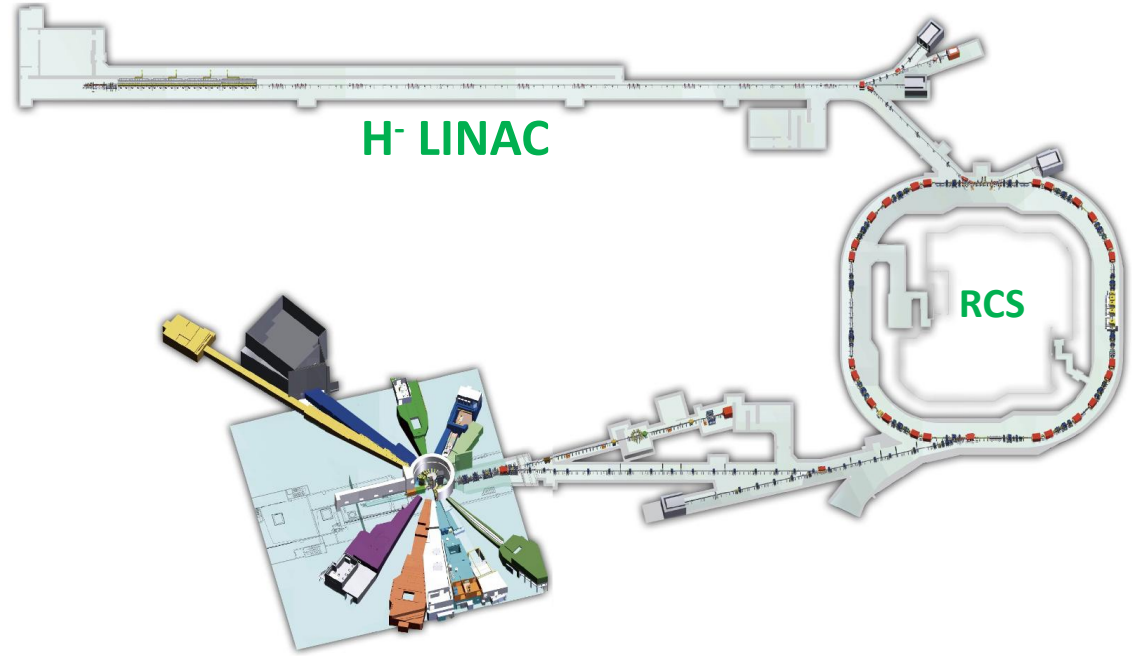
2026-10-15

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China Spallation Neutron Source

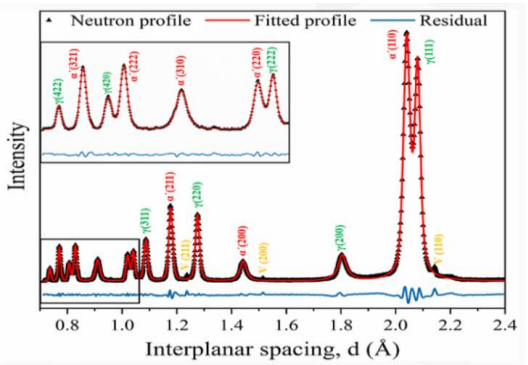
- The 4th pulsed neutron source in the world
  User program started in Oct. 2018
- Three initial instruments (GPPD, MR & SANS) + 8 cooperative instruments
- CSNS-II: beam power ramp up to 500 kW + 9 new neutron instruments, Muon source and proton beamline



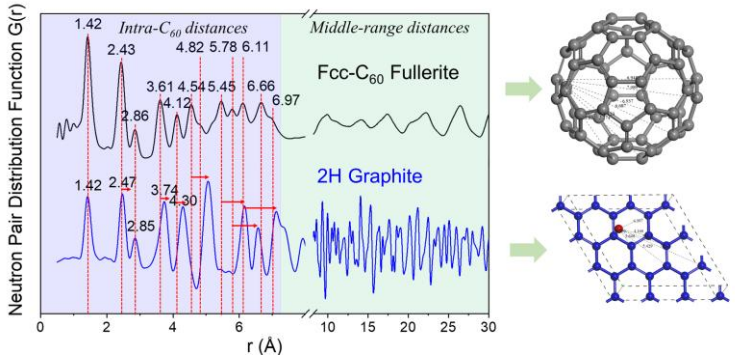
Major machine parameters

Parameter	CSNS	CSNS-II
Beam Power on target [kW]	170	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Macropulse. ave current [mA]	15	50
Macropulse duty factor	1.05	1.5

Liu et. al., Science (2020)



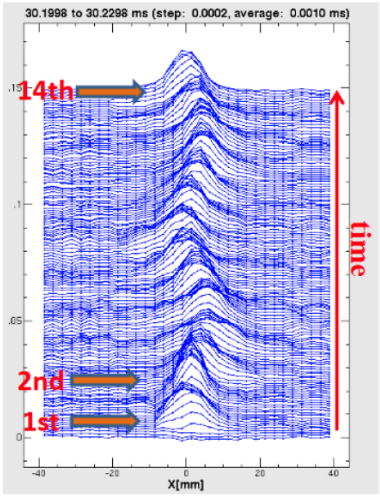
F. Pan et. al., Nature 2023



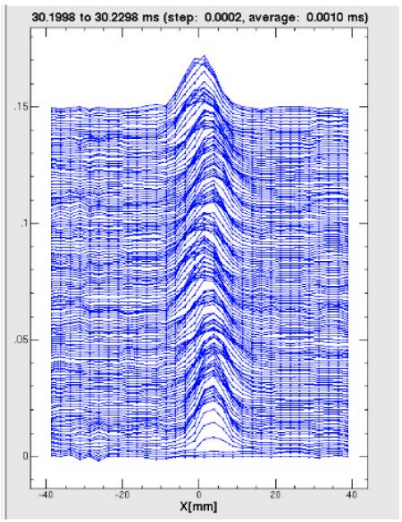
Motivation

- The transverse beam profile of cycling beam is essential for the characterization, commissioning and optimization of a circular accelerator, i.e., booster rings, storage rings and for colliders
- Some applications
  - Continue monitoring of beam size & emittance
  - Diagnostics of beam oscillation at injection/acceleration
  - Bunch by bunch measurement of abnormal beam

Injection matching @ J-PARC RCS
K. Satou et. al.,



Injection miss-match
Q mode + D mode

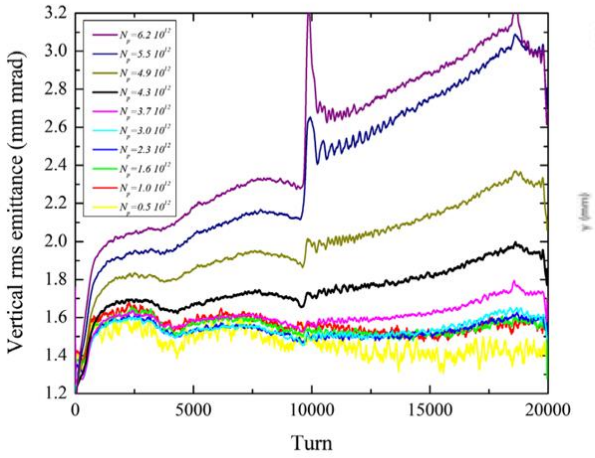


After Q and D mode tuning

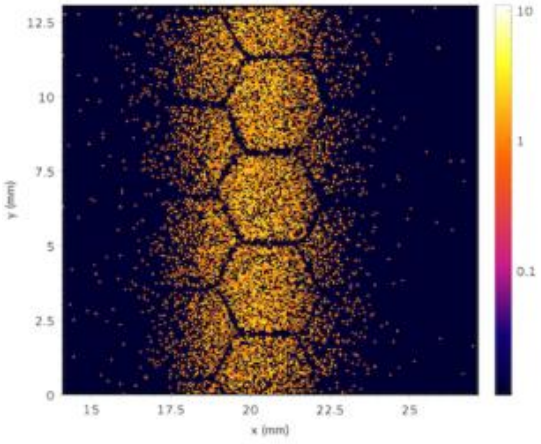
Challenges for time resolved profile monitor for CSNS RCS

- Non invasive: Least perturbation to the cycling beam
- The beam size in the CSNS RCS ranges from 10 to 30 mm (rms)
- The maximum RF frequency in the CSNS RCS is 2.44 MHz.
- Satisfactory spatial and time resolution
  - a spatial resolution of approximately 2.5 mm (≈σ/4)
  - a time resolution of about 205 ns
- Radiation hard, electromagnetic compatibility

Jeff Eldred et al., (2021)



S. Levasseur et al., 2017

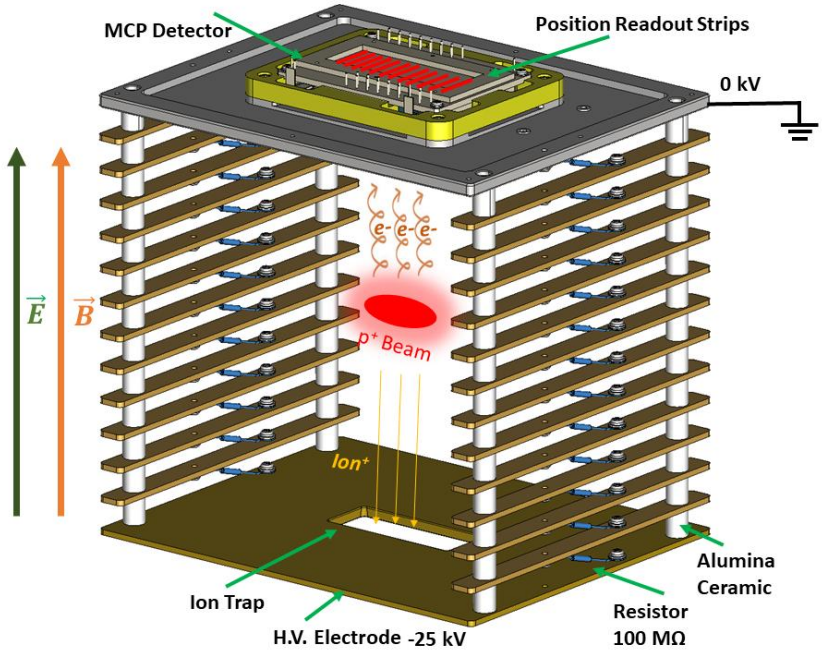


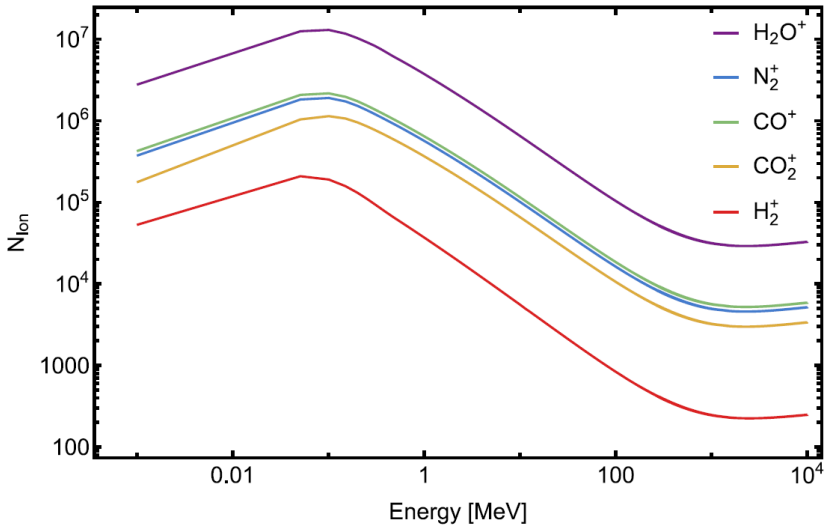
Ionization Profile Monitor

- Utilize beam-induced ionization of residual gas in the beampipe (10^3~10^4 events/passive)

$$N_{\text{ions}} = N_{\text{ppb}}\,\rho\,\frac{\mathrm{d}E}{\mathrm{d}x}\,\frac{1}{W}\,\mathrm{d}Z$$

- 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 population of liberated ion+/e- in a given volume is proportional to the local particle density so that a signal bearing 1D beam distribution information is available

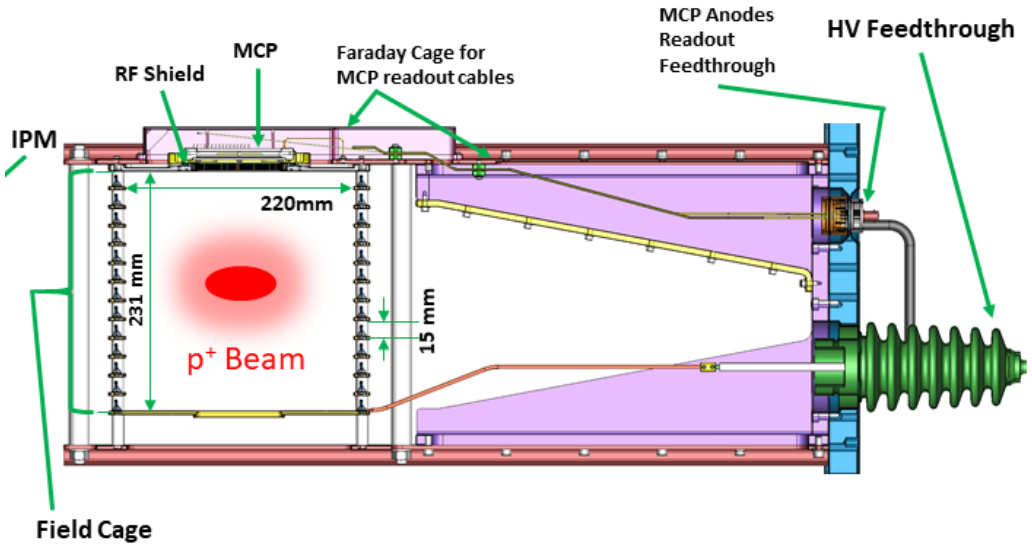


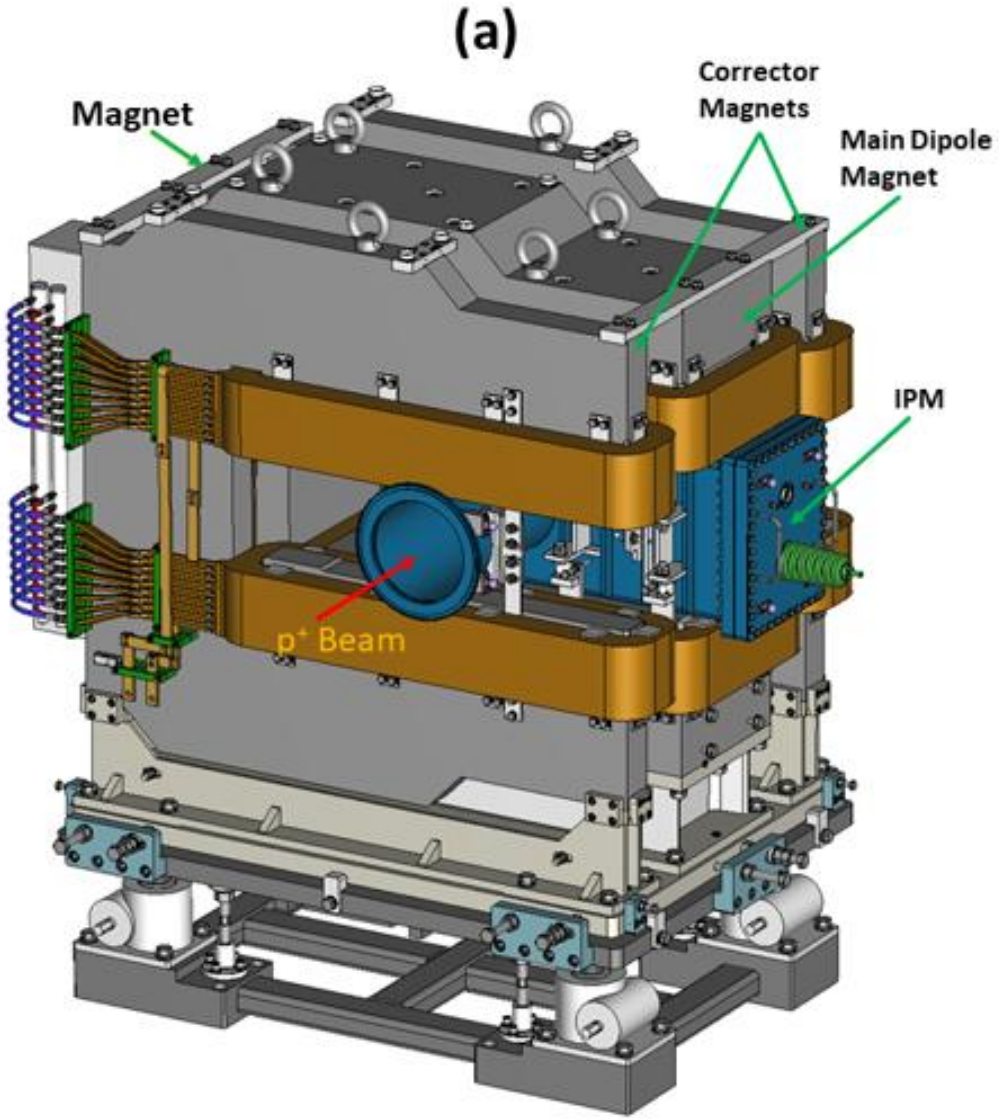


Design of Ionization Profile Monitor

The design of the CSNS IPM

1. Good field cage → Field uniformity ~0.6 %
2. A good in-vacuum Faraday Cage → -42 dB
3. Ion trap prevent SEM→ Efficiency ~70%
4. 32-ch MCP (R_b=25 MΩ, gain>10^6, pitch width = 2.5 mm)
5. CMC to suppress the common mode noise
6. 40-ch digitizer acquires raw signal w/ 125 MSa/s
7. An extra synchronization clk. signal or peak finding to determine the beam passage





Guiding Electric and Magnetic Fields

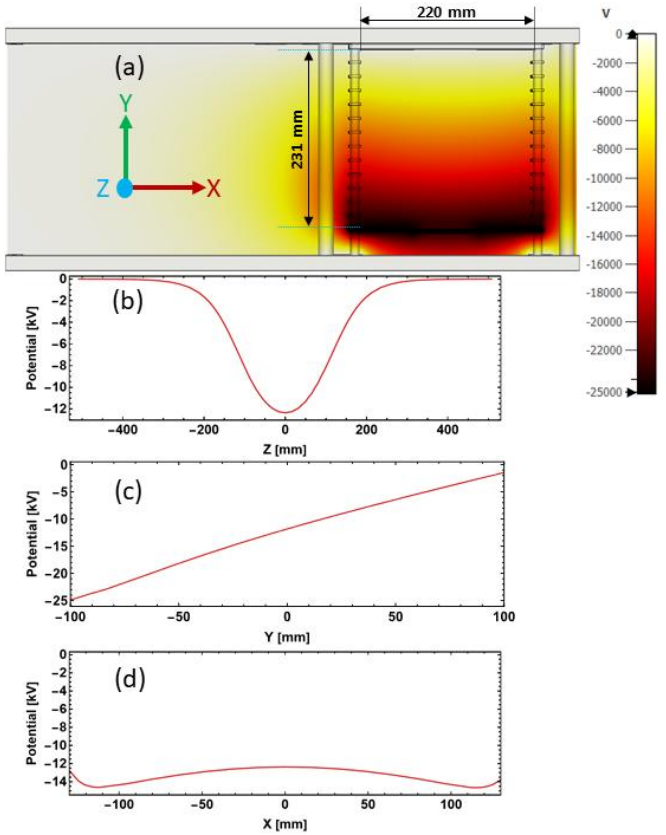
Electric Field

- The IPM field cage consists of 28 electrodes with an aperture of 220 × 231 mm^2
- To generate a uniform electric field to drift secondary charged particles toward the MCP
- Within ±40mm horizontally and ±15mm longitudinally, the IPM electric field uniformity is 0.6% and 4.6%

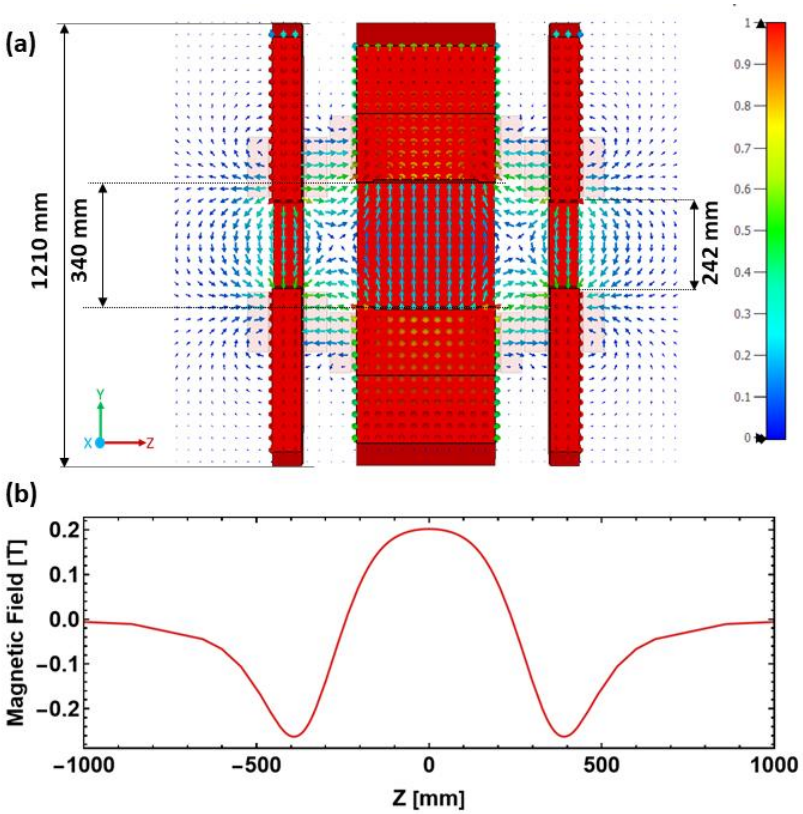
Magnetic Field

- The guiding magnetic field was designed to suppress distortions from the beam's space charge field
- The main C-shape dipole electromagnet features a pole spacing of 300 mm and generates a uniform magnetic field of up to 0.2 T over a good field region of 220mm × 220mm × 50mm with uniformity better than 3%

Electric Field



Magnetic Field



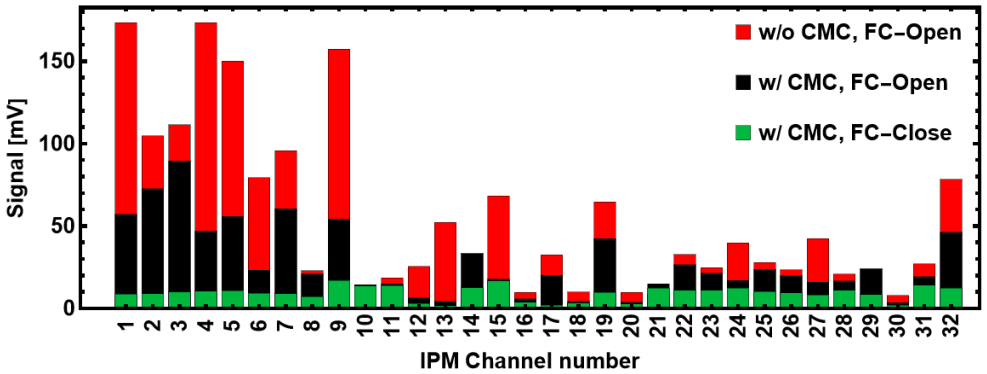
Electromagnetic Compatibility

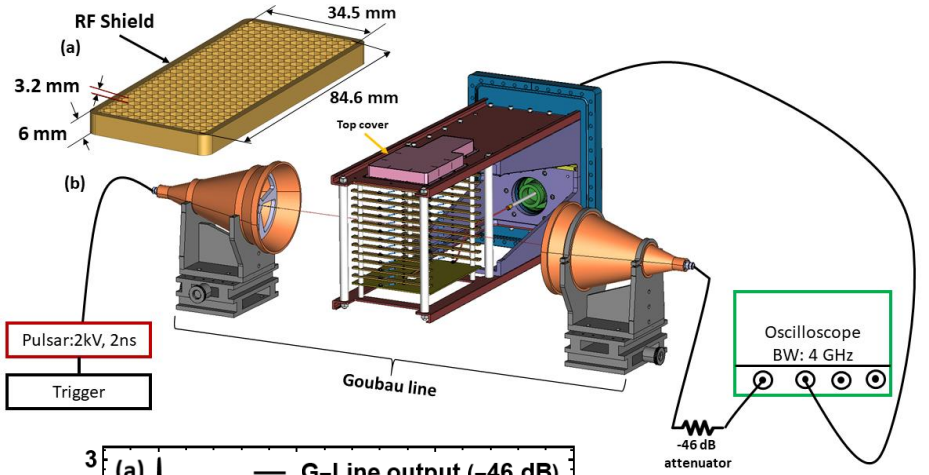
Differential Mode noise

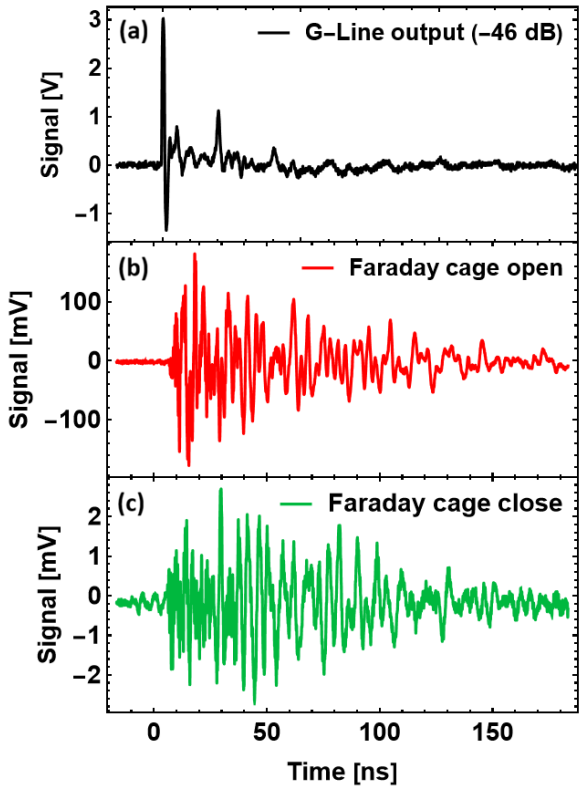
- Prevent the EM field of beam to induce image charge at the MCP anodes
- A good Faraday Cage
  - Gaps filled w/ indium
  - RF-shield w/ 3.2 mm opening
- Lab Tests
  - Setup to mimic beam field (G-line (MHz~2 GHz))
  - Signal source (2 kV, 1 ns)
  - Measurement w/ open and closed Faraday Cage
  - Measured SE = -42 dB

Common Mode Noise

- From accelerator components i.e., magnets, cavities
- Common mode choke was used to prevent this noise

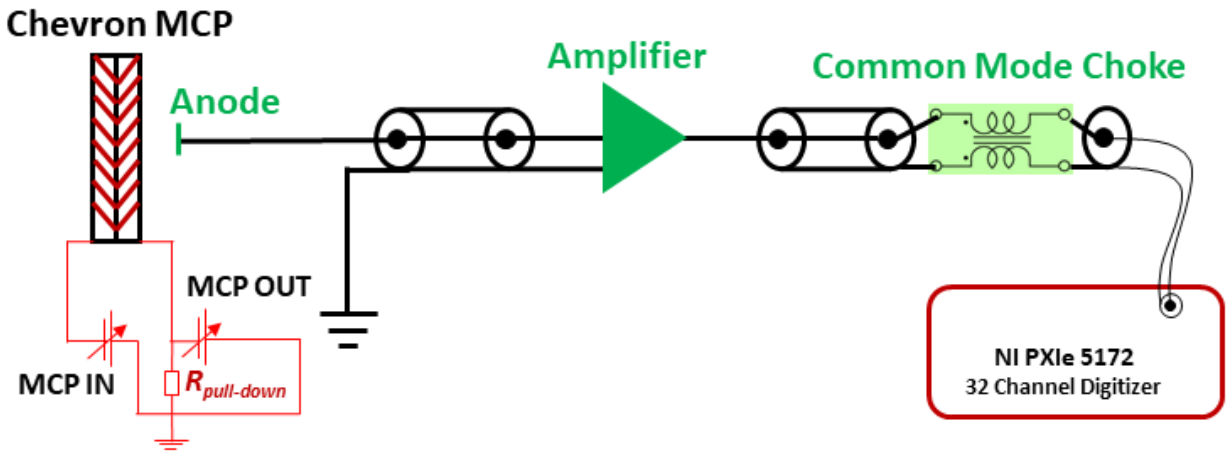




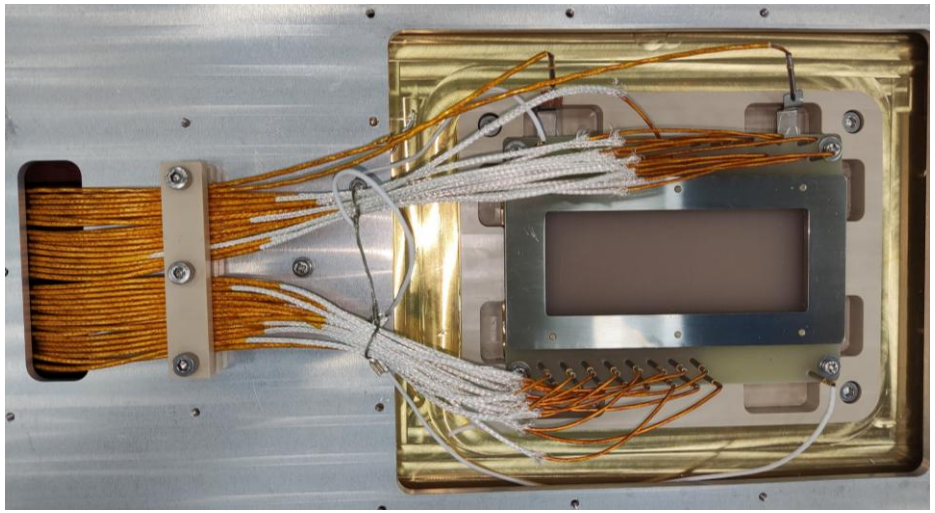


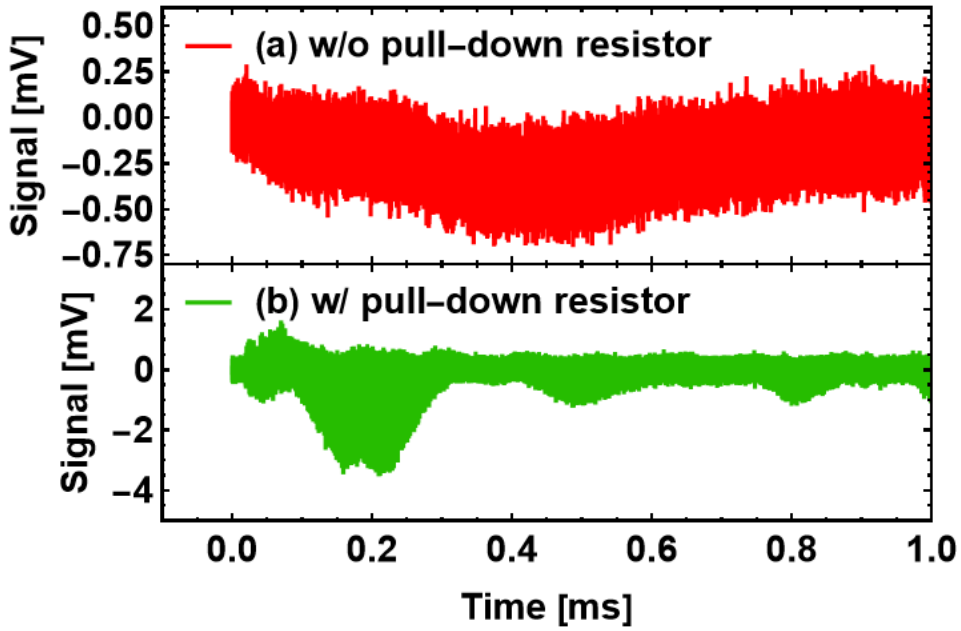
Pre-amplifier Microchannel Plate

- The IPM's MCP is of chevron type and has a resistance of 25 MΩ, which corresponds to a significant current flow from front to back during high gain operation at high particle flux
- A 0.5 MΩ pull-down resistor connected between the MCP-OUT power supply and ground. This resistor prevents voltage overshoot at MCP-OUT and ensures stable operation of the MCP
- This pull-down resistor sinks the current appropriately and maintains a consistent voltage drop across the MCP, and enables a high gain MCP operation



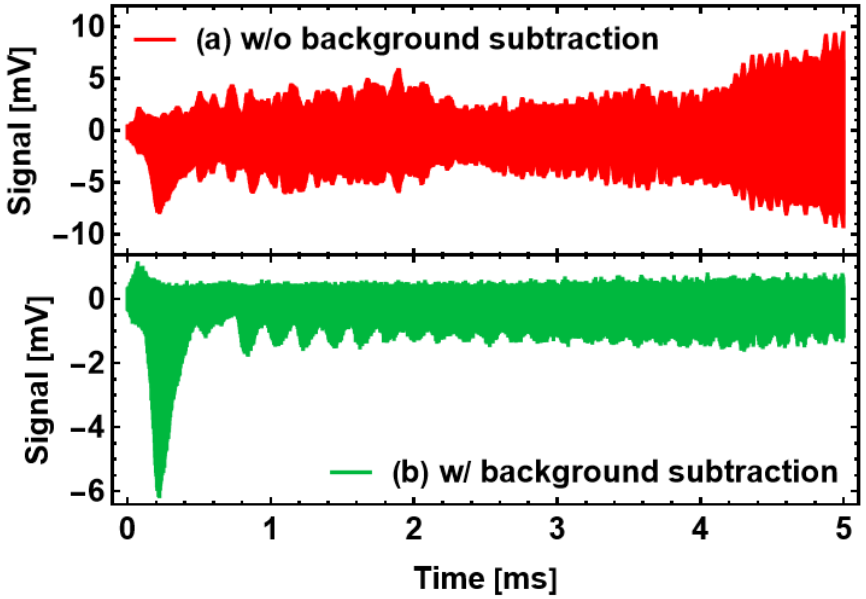
MCP

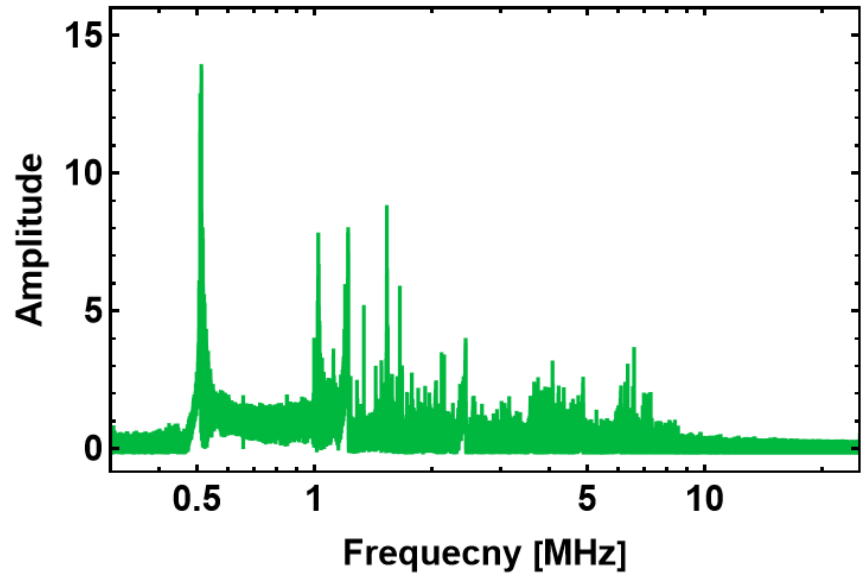




Data Analysis: Background subtraction

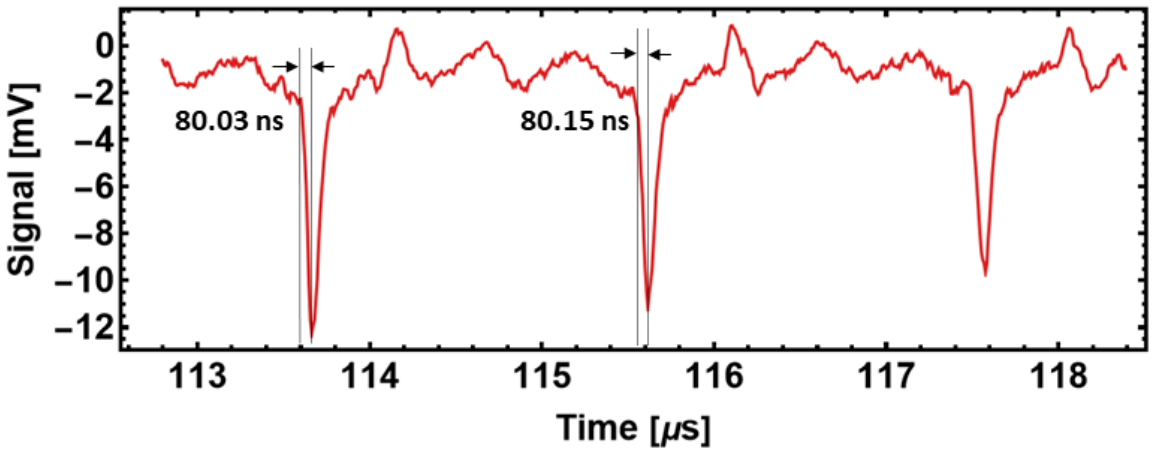
- Despite the measures implemented to suppress beam induced noise on the MCP anodes
  - −20 dB of shielding efficiency was achieved
- To mitigate this issue, a background subtraction technique was employed
- The IPM data from each of the 32 MCP anode strips were collected under two conditions, with the field cage high voltage set to its maximum value of 25 kV and to 0 kV, while maintaining the MCP input high voltage at the operational value of 2 kV in both cases
- The data acquired with the field cage high voltage at 0 kV were used as the background signal and subtracted from the data obtained with the field cage high voltage at 25 kV
- This technique effectively removes the beam induced noise from the MCP anode strips, revealing the true beam signal

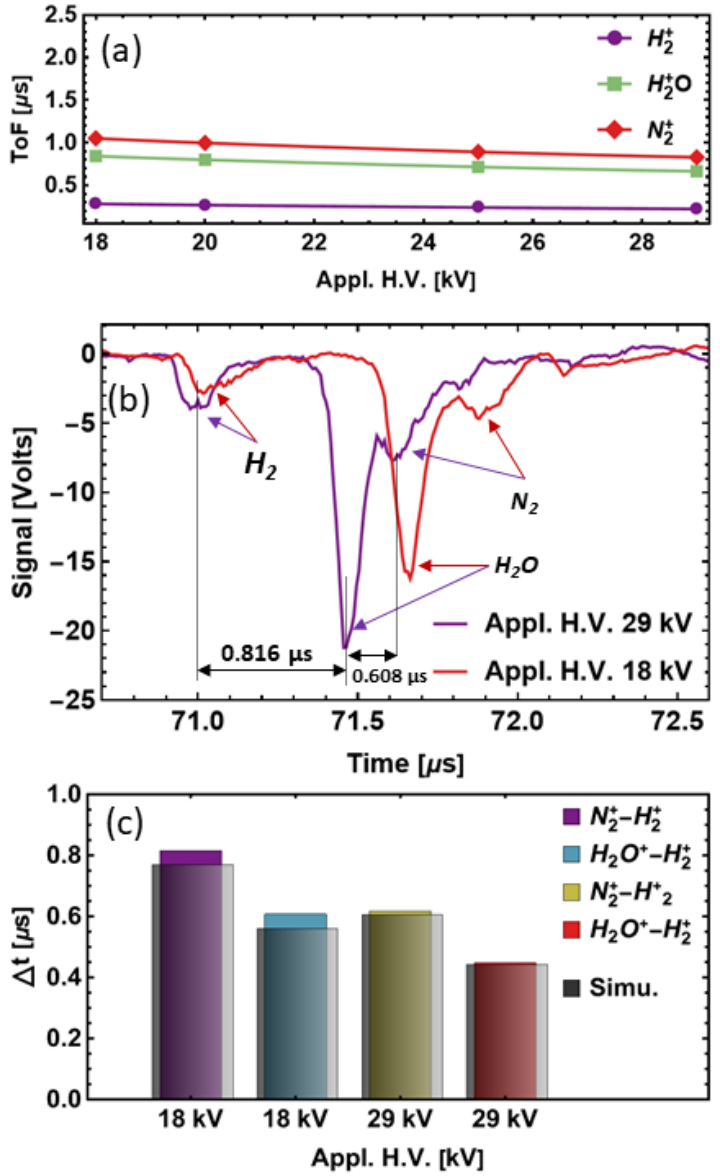




Data Analysis: Gas Species Detection

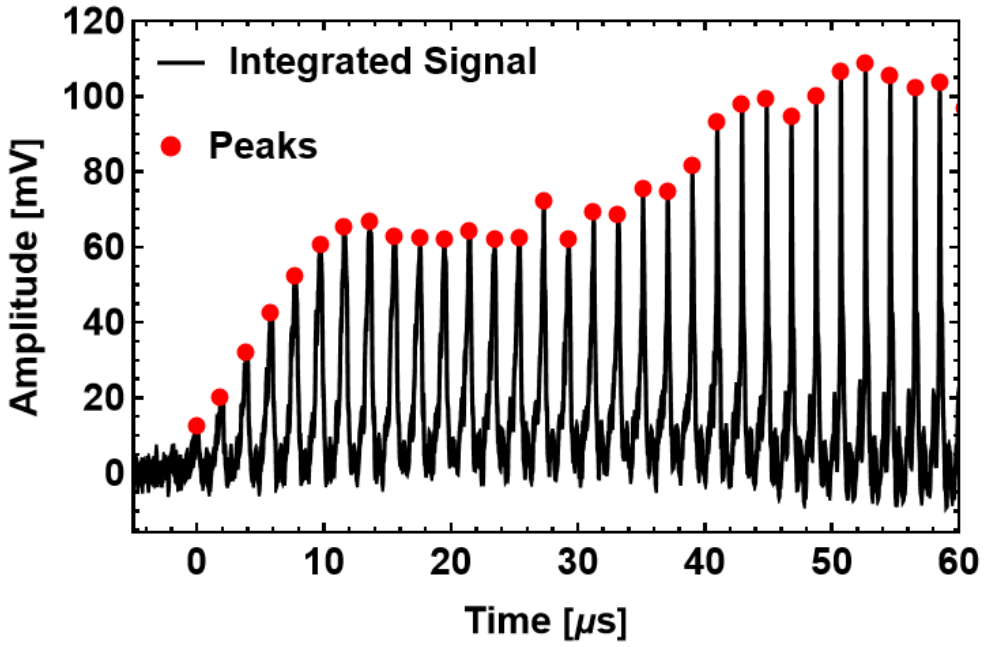
- The vacuum pressure at the IPM location is about 1×10^{-6} Pa and vacuum chamber is unbaked
- The dominant residual gas species in a typical vacuum chamber without
- baking at 1×10^{-6} Pa is water vapor (H_2O)
- The small traces of hydrogen (H_2), carbon monoxide (CO) and nitrogen (N_2) are also present
- The time-of-flight (ToF) of an ion species can be calculated the ion species
- In electron collection mode: The fall time (10%–90%) of the signal is approximately 80 ns, which corresponds to a bandwidth of >4.4 MHz (−3 dB) for the IPM

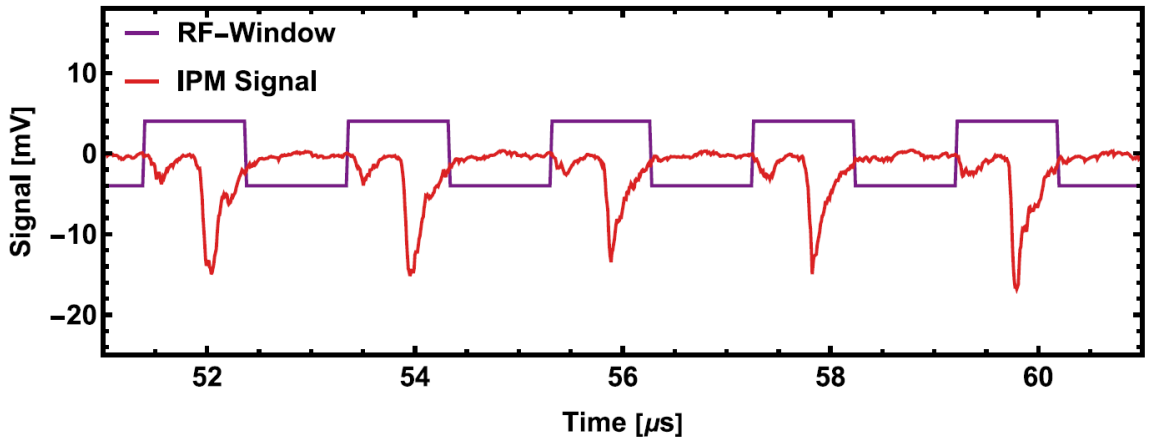




Data Analysis: Time resolved Beam Profile

- In ion-collection mode, the dominant gas species H_2O^+ ions were used to construct the beam profile
- Two methods have been developed to analyze the data from the MCP's 32 channels to extract the bunch-by-bunch signal
- The peak detection approach is based on the integrated signal from all 32 MCP channels
  - Local maxima are identified in the smoothed signal, each corresponding to an individual bunch
  - Although the peak detection algorithm is generally robust, it becomes challenging to correctly identify each bunch in signals with poor signal to noise ratio
- RF-synchronized time windows are employed to reliably extract the bunch-by-bunch signals

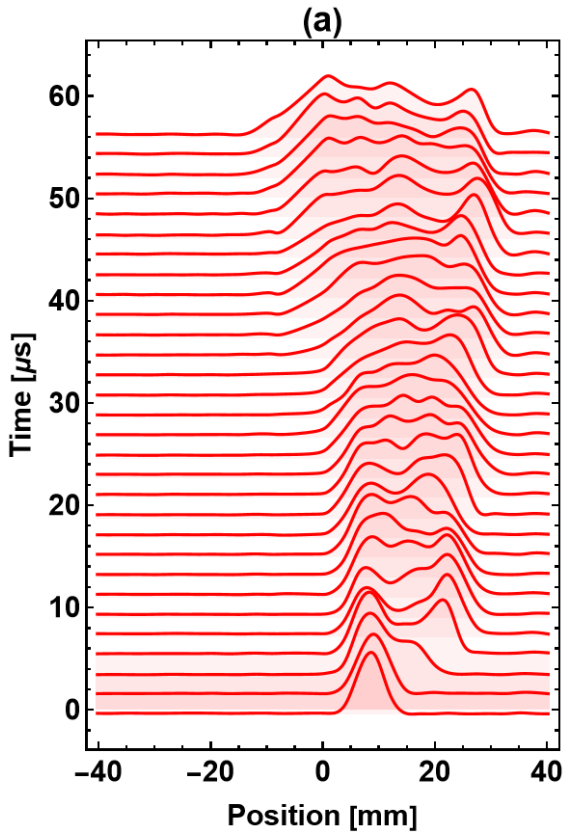




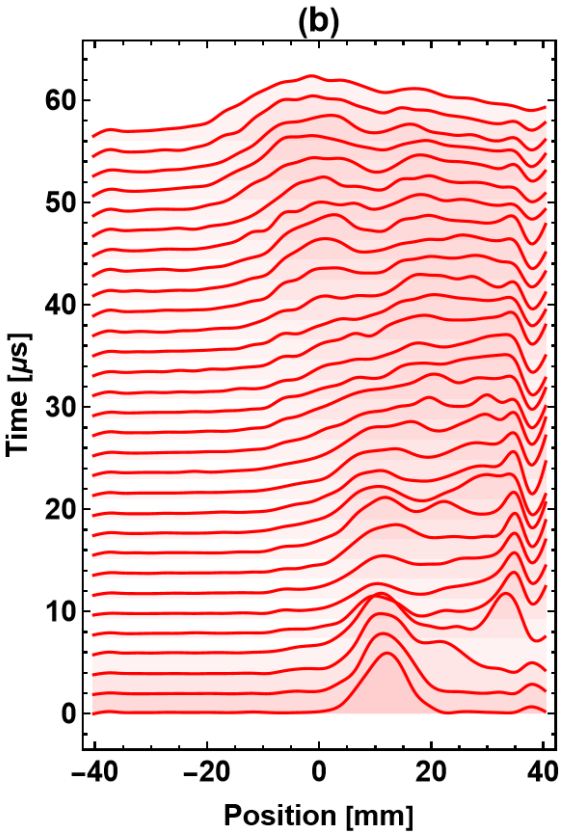
Results: Injection Painting Observation

- Mountain plots of bunch-by-bunch signals from the IPM in ion collection mode were and electron collection mode
- A 30 μs injection pulse containing 15 intermediate pulses was injected into the RCS.
- The injection painting process is clearly visible in the ion collection mode.
- However, in electron collection mode, secondary electron emission from the bottom electrode introduces background signals on the anode strips, resulting in distortion of the measured beam profile

Ion collection mode

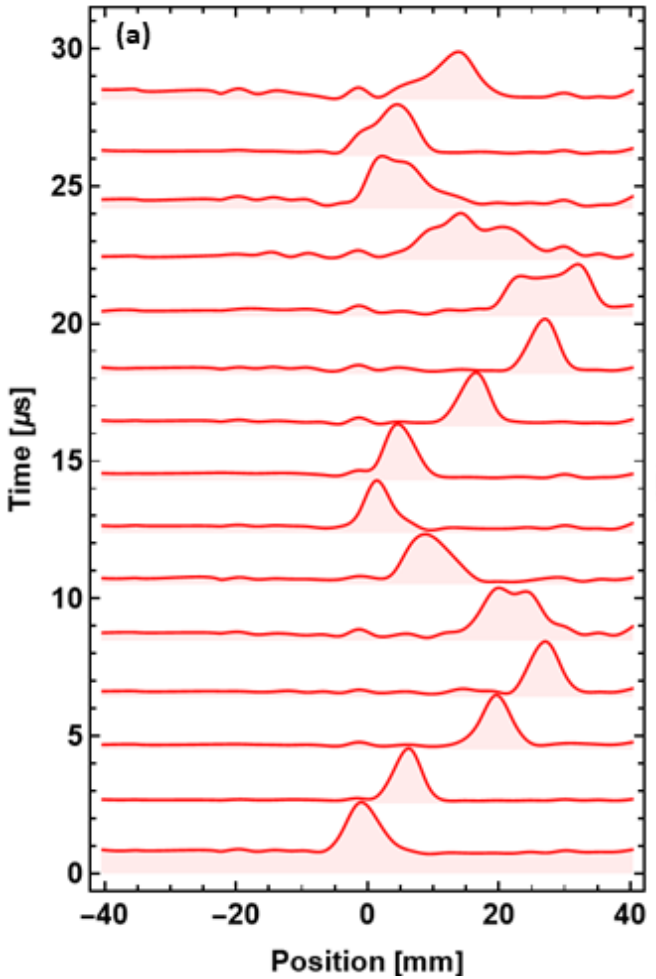


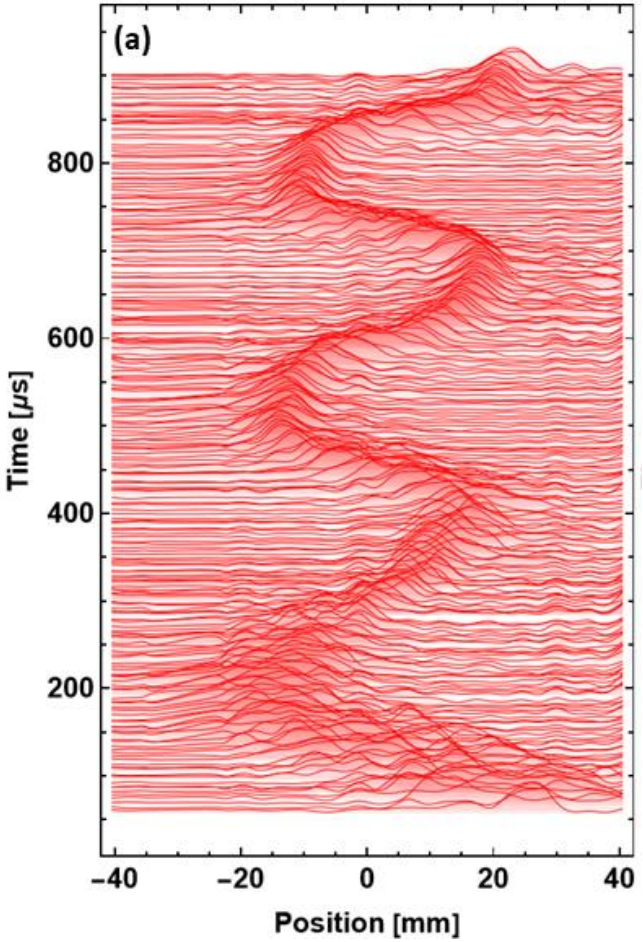
Electron collection mode



Results: Injection mismatch

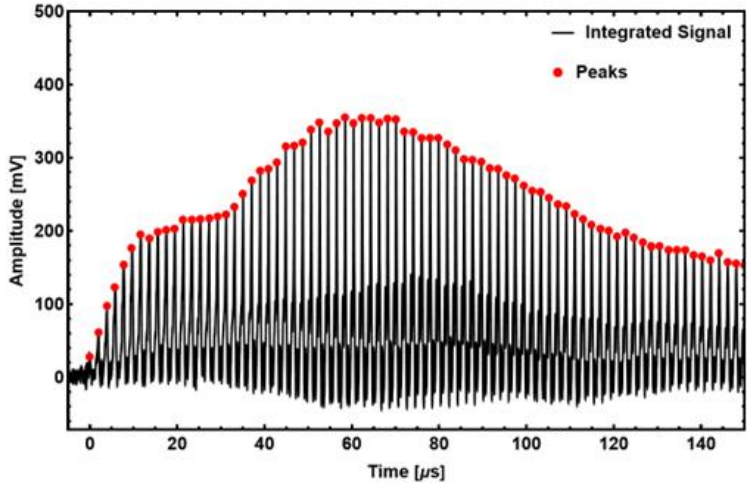
- Bunch-by-bunch horizontal beam profile (mountain plot) for a single 600 ns intermediate pulse injection into the RCS (in ion-collection mode)
- Phase-space mismatch arises from non-optimal injection bump magnet settings.
- Betatron oscillations generated as a consequence of the mismatch
- Beam size variations across turns

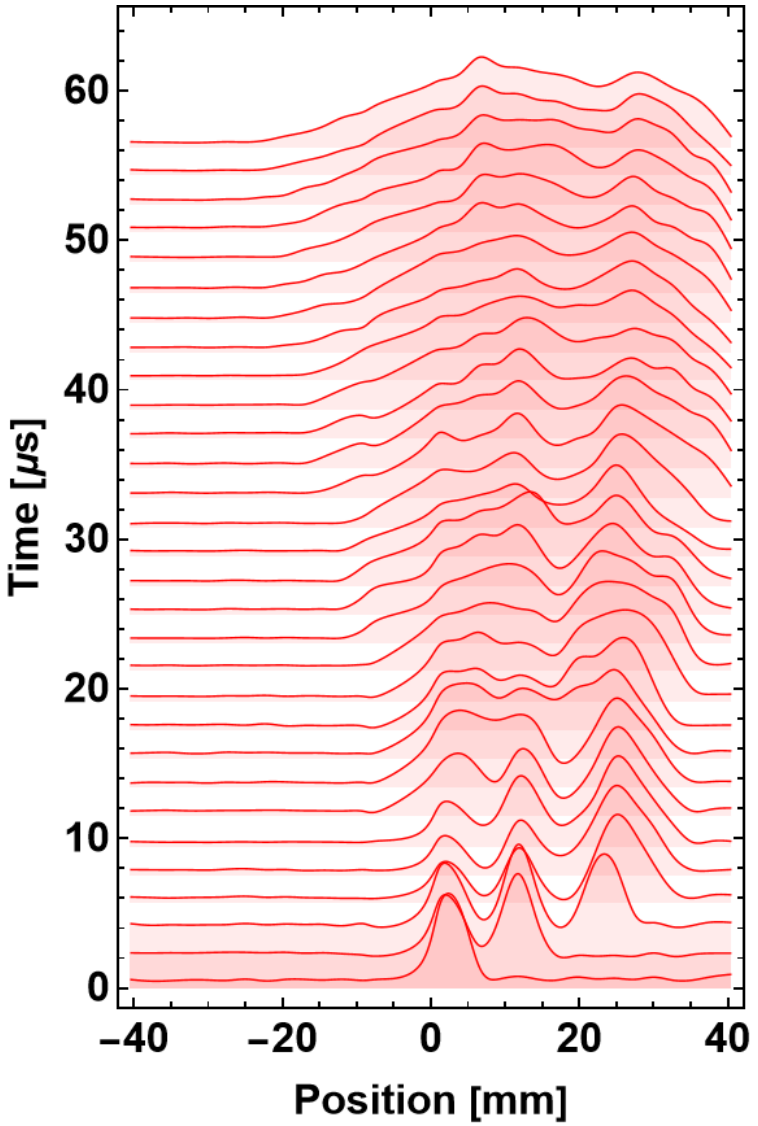




Limitation of IPM: MCP Saturation

- In order to observe the full multi-turn injection painting process a 560 μs long pulse from the linac was injected into the RCS
- MCP saturation during 560 μs long-pulse injection into the RCS has been appeared as a drop in detected signal intensity despite continuously increasing input charge flux from the painting process
- In our setup, the MCP has a 25 MΩ resistance and operated at 1.8 kV bias voltage, yielding a strip current of 72 μ A
- Linear operation is maintained when the output current remains below 10% of the bias current (7.2 μs). With a 50 Ω digitizer input impedance, this corresponds to a saturation voltage of about 360 mV, which is reached at approximately 60 μs
- To mitigate this effect a new gated IPM is under development

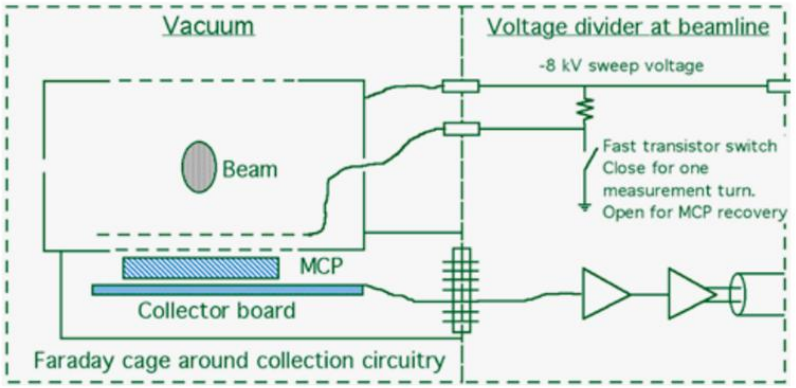




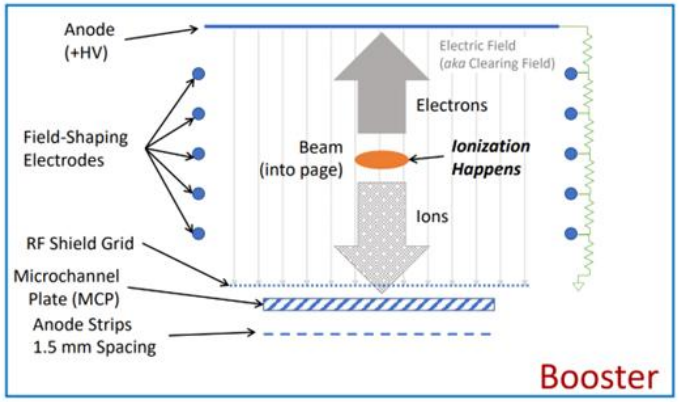
Gated IPM Development

- To solve the MCP saturation, degradation and lifetime issue
  - First solution was proposes in 2005 at BNL
  - Placed a biased grid to control the exposure of secondary particles to MCP
  - Similar scheme was adopted at Fermilab
    - Limit the electric field strength due to arching in bias grid
  - K. Satou proposed and developed a full gated field to solve the issue
- J-PARC style IPM is under development at CSNS to solve MCP saturation

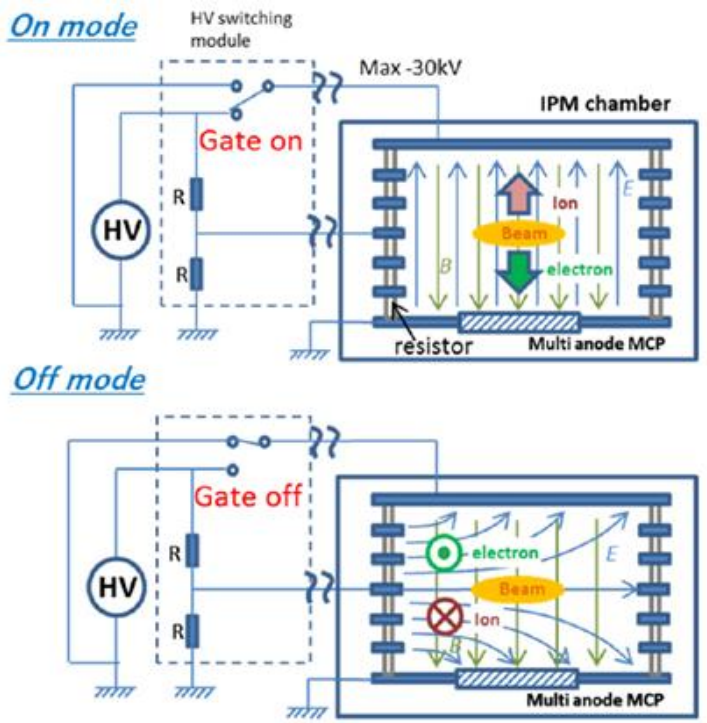
R. Connolly et al., PAC 2005



J. Zagel et al., IBIC2014



K. Satou PASJ2019

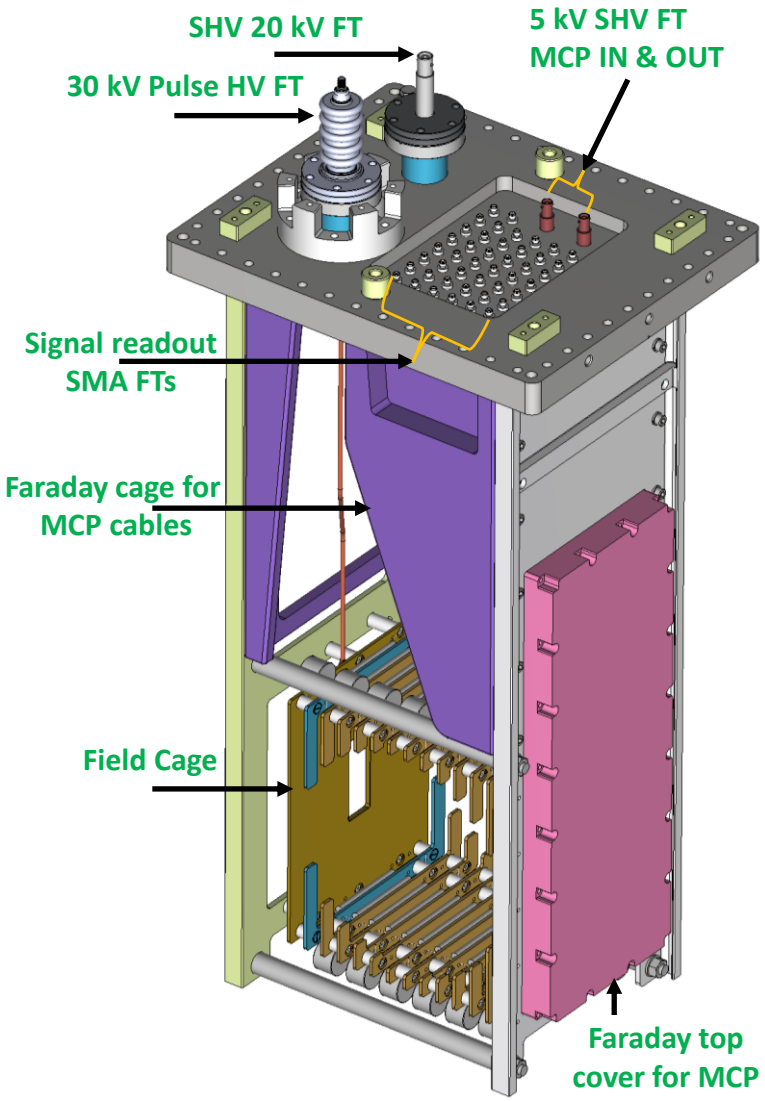


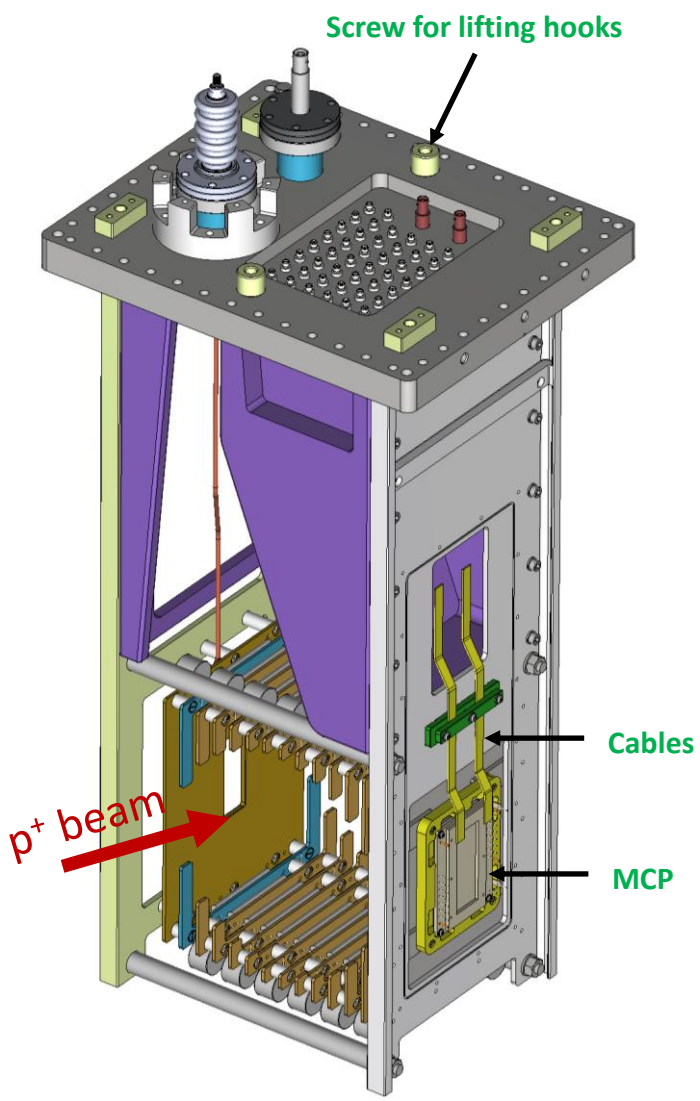
Design of new Gated IPM at CSNS

New vertical gated IPM has designed

Salient feature

- ✓ Good vacuum compatibility: 1×10^{-6} Pa
- ✓ Good EMC: -42 dB
- ✓ Smooth Integration in existing beamline
- ✓ Easy cable access



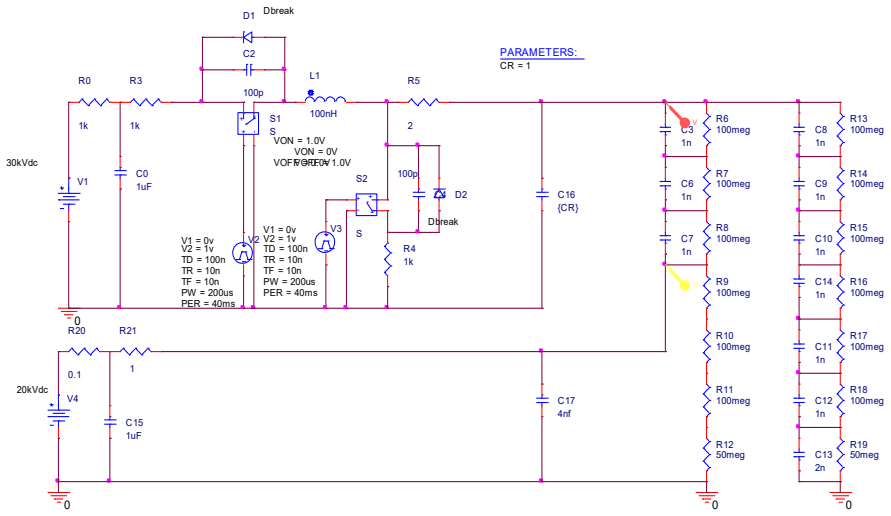


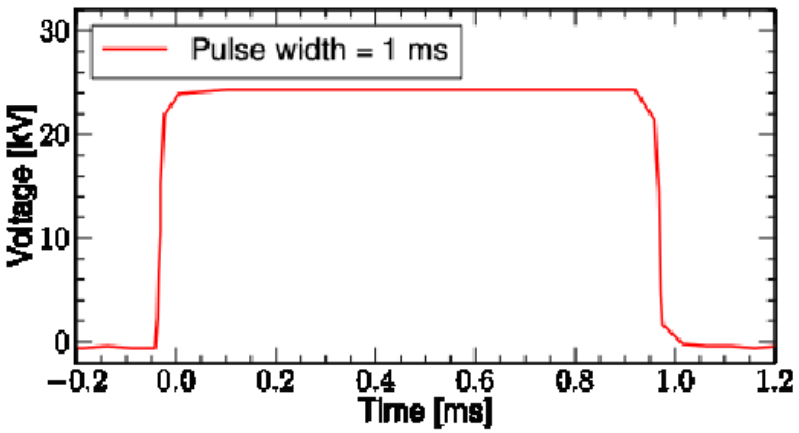
Pulsed H.V Power Supply for Gated IPM

- A new 30 kV/ Pulsed H.V. power supply has been developed for Gated IPM
- H.V. Push and Pull Switch from Behlke (HTS 301-03-GSM) has been used
- The performence of power supply in-lab is satisfactory

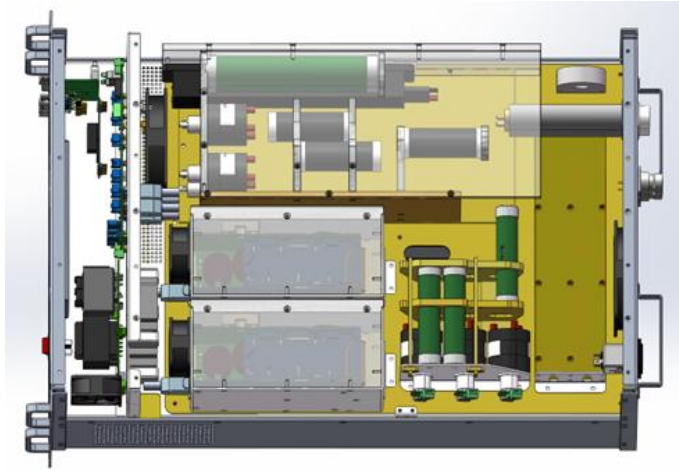
Parameters	Values
Max. output voltage (AC)	±30 kV
Max. output voltage (DC)	±20 kV
Rise/fall time	<10 μs
Turn-on time	0.1-20 ms@1 Hz 0.1-1 ms@25 Hz
Flatness	<0.5%

Design of a pulsed power supply





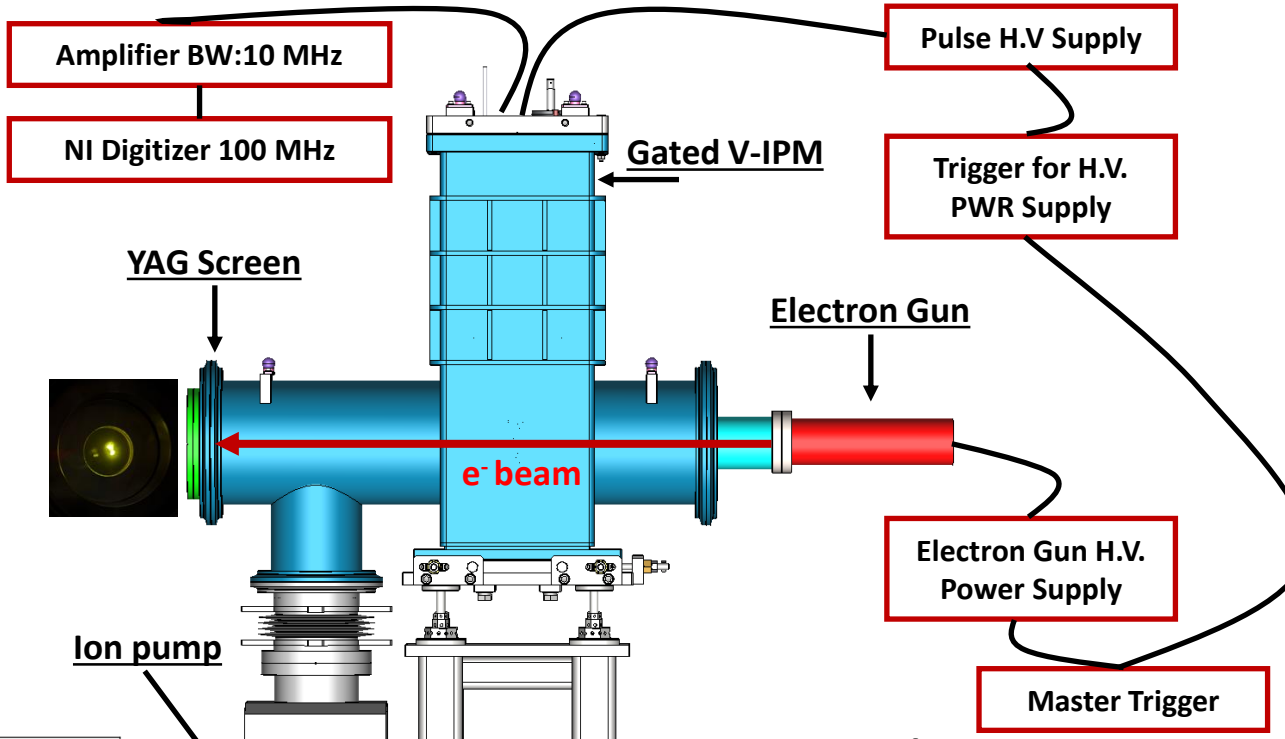


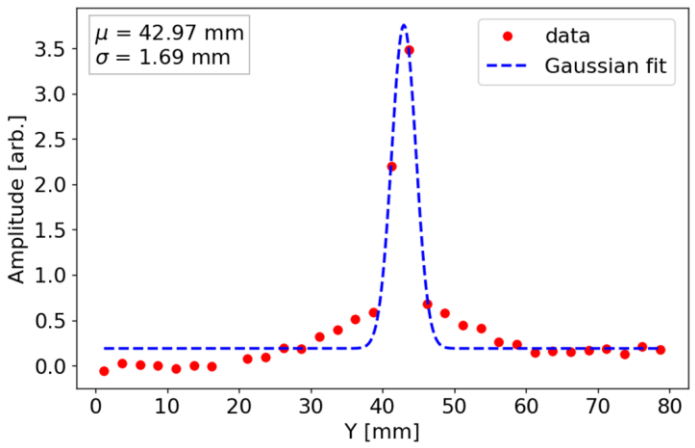


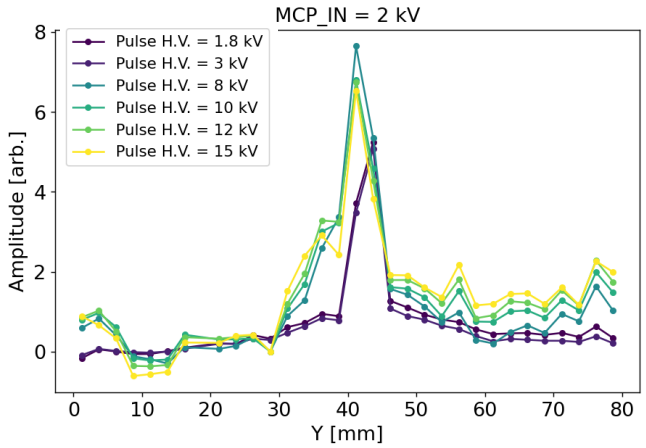
Validation of Gated IPM System

Gated V-IPM test with electron beam

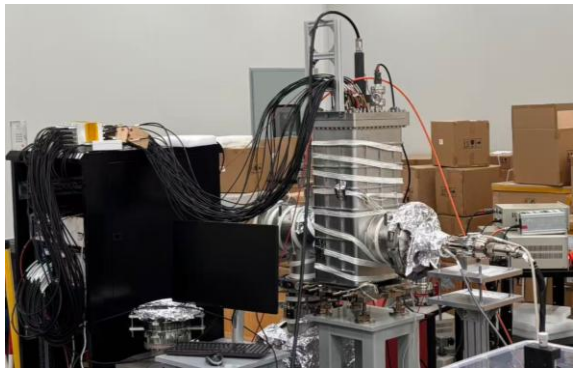
- The electron beam of energy 8 keV/ 10 µA/ 1 ms was generated with the electron
- The beam pass through the Gated V-IPM and ionize the residual gas
- The Gated pulsed electric field of IPM (3kV to 15 kV with 5 ms width) was used to collected the positive ions
- The signal from MCP anodes was successfully detected
- The electron beam profile has been measured
- Due to limited time only proof of principle experiment was performed







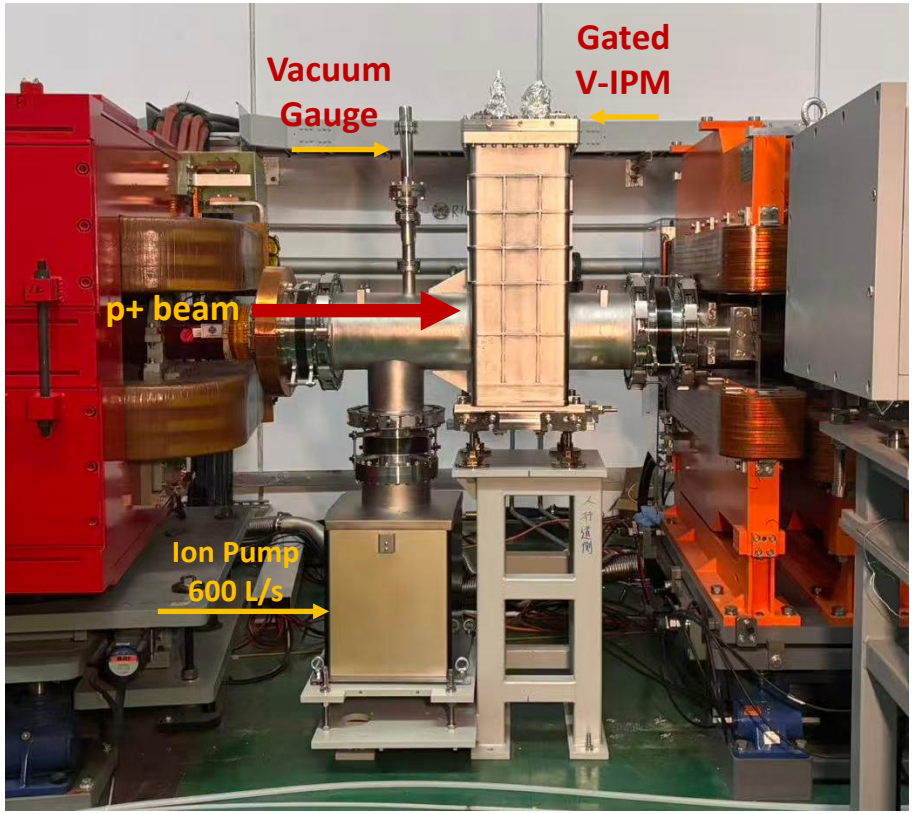
Experimental setup



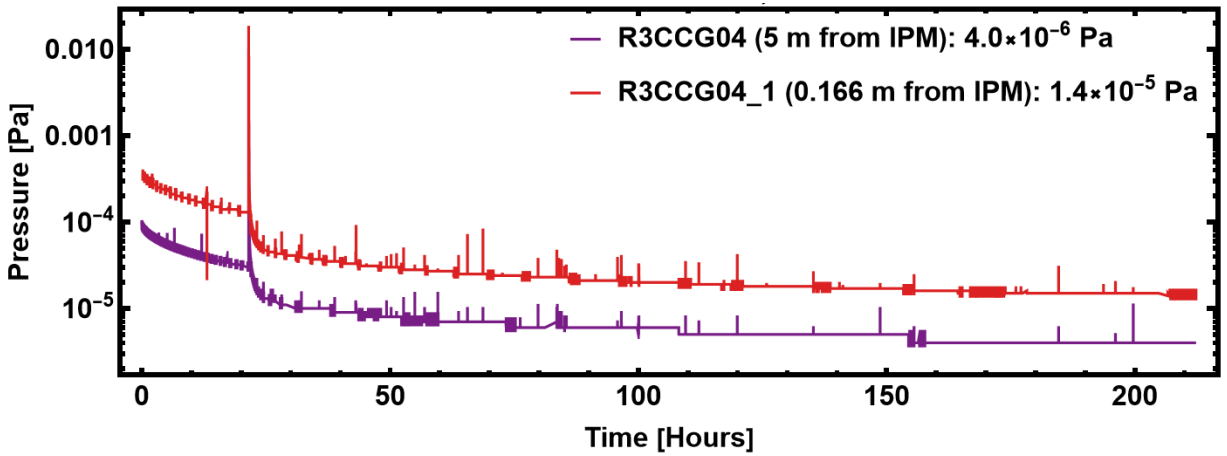
Gated V-IPM Installation in RCS and Vacuum Status

- The Gated V-IPM has been installed in RCS
- Transport and Installation went as planned without any surprise
- The vacuum pumping has been started and vacuum pressure of 1.4×10^{-5} Pa reached in ~200 hours

Gated V-IPM in RCS



Hopefully start commissioning of Gated IPM in this month!!!



Summary

- A fast residual gas IPM has been successfully developed for the CSNS RCS
- A significant advancement in non-destructive, bunch-by-bunch transverse beam profile diagnostics to support the facility's power upgrade
- Through systematic troubleshooting hardware upgrades the IPM achieved reliable and robust performance
- Beam studies demonstrated horizontal bunch-by-bunch profiles in both collection modes
- Single 600 ns intermediate-pulse injections highlighted phase-space mismatches and betatron oscillations,
- These findings establish the IPM as an essential tool for investigating early injection dynamics, mismatches, and beam evolution in the CSNS RCS
- To mitigate MCP saturation and gain degradation from prolonged high-intensity beam exposure, a gated field cage system is under development

For more detail: *M.A. Rehman et al.*, NIMA 1092 (2026) 171809

Thank you very much