CSNS

IBIC 2021

Beam Loss Studies at the China Spallation Neutron Source

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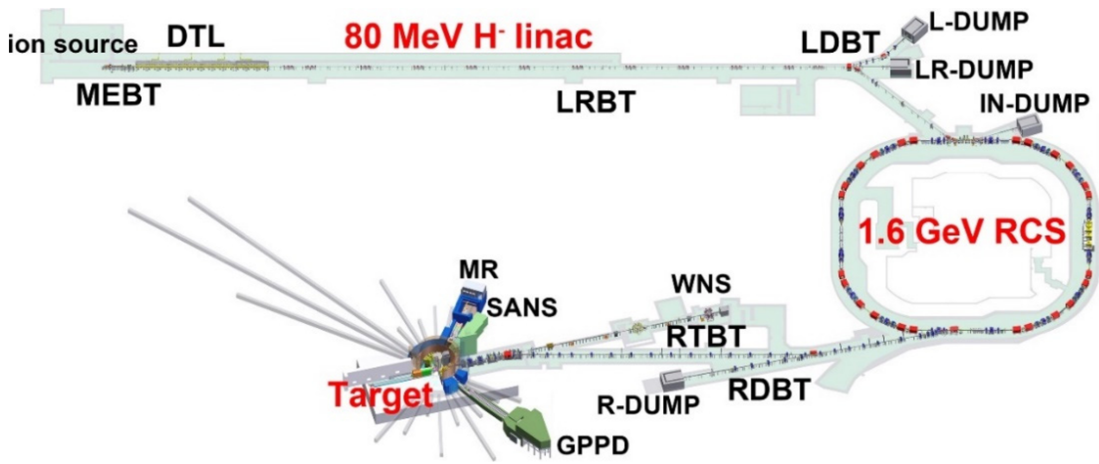
13-19, Sep, 2021

outline

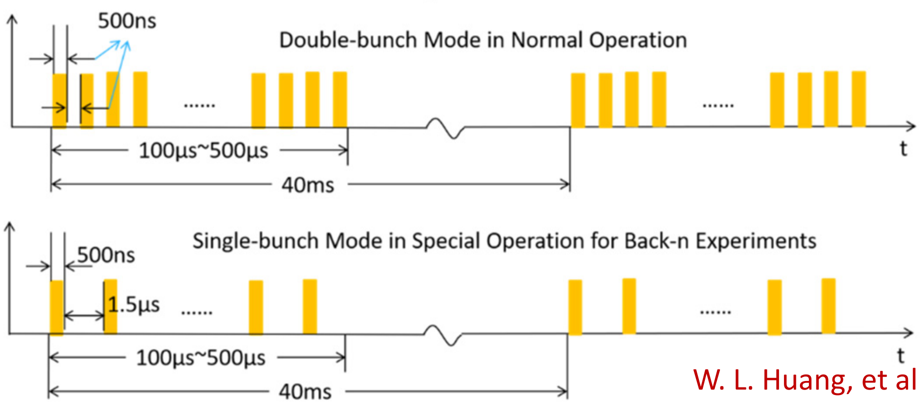
- The CSNS Overview
- The CSNS BLM system
- Monte Carlo simulations and beam experiments

A brief introduction of CSNS



The layout of CSNS

Design parameter	Value
Beam power (kW)	100
Linac energy (MeV)	80
Beam current in the linac (mA)	15
Extraction energy (GeV)	1.6
Proton per pulse	1.56×10^{13}
Repetition rate (Hz)	25
Linac RF frequency (MHz)	324
Target material	Tungsten



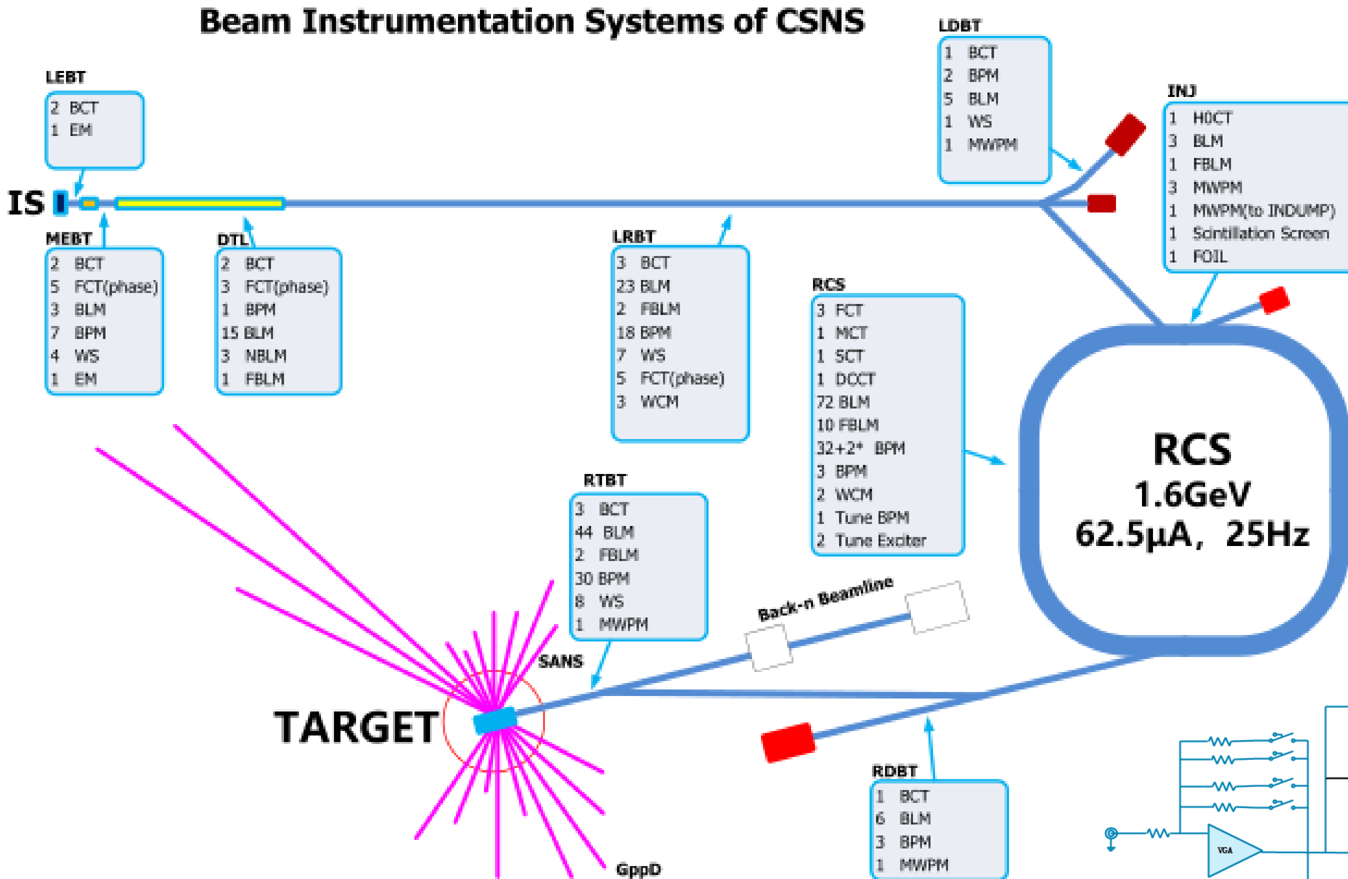
Beam time structures in different modes

A chopping factor of 50% is adopted for user mode in normal operation and 75% for single bunch mode in special operation for the back-n experiments.

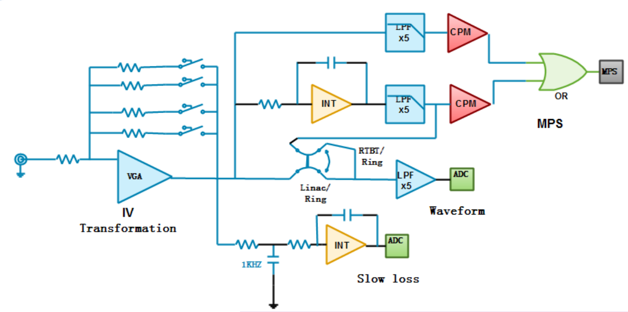
W. L. Huang, et al., A Dual Functional Current Monitor for Stripping Efficiency Measurement in CSNS, IBIC2019, Malmö, Sweden, 96 (2019).

CSNS has achieved its design goal of 100 kW in Feb. 2020.

Beam instruments at CSNS



Beam instruments along the entire beam line at CSNS.



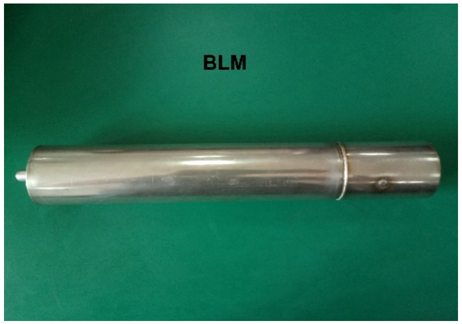
BLM analog electronics

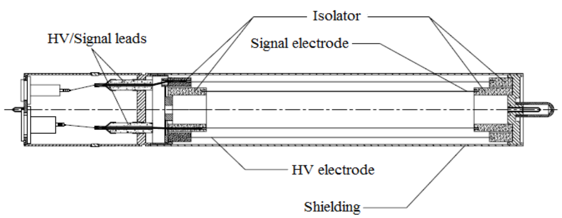
The beam loss detection mainly has two purposes:

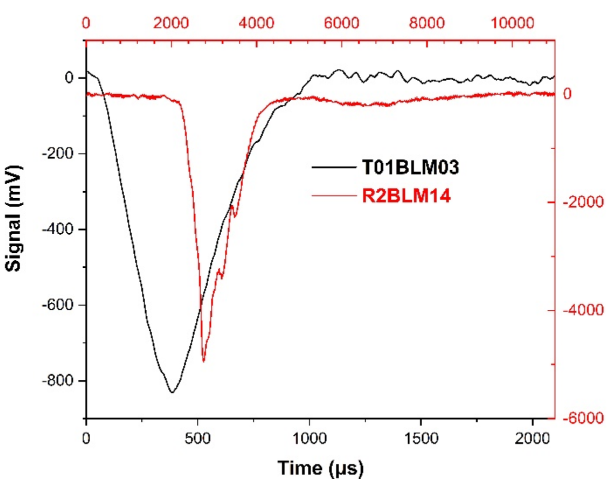
(1) trigger the MPS to shut down the beam or extract it to the dump if the beam loss signal exceeds the threshold.

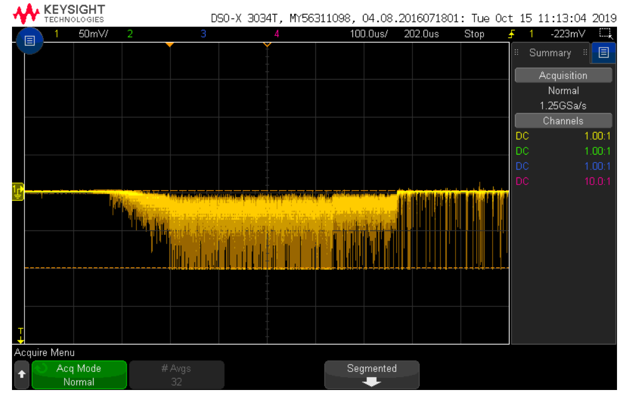
(2) fine tune the accelerator to decrease the beam loss and the consequent induced radioactivity as low as possible.

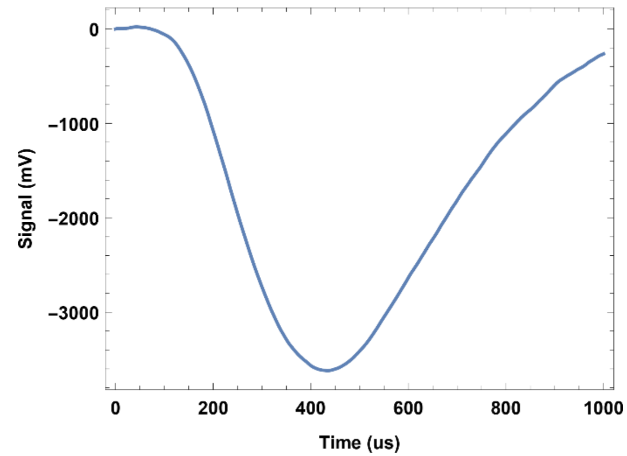
BLM types





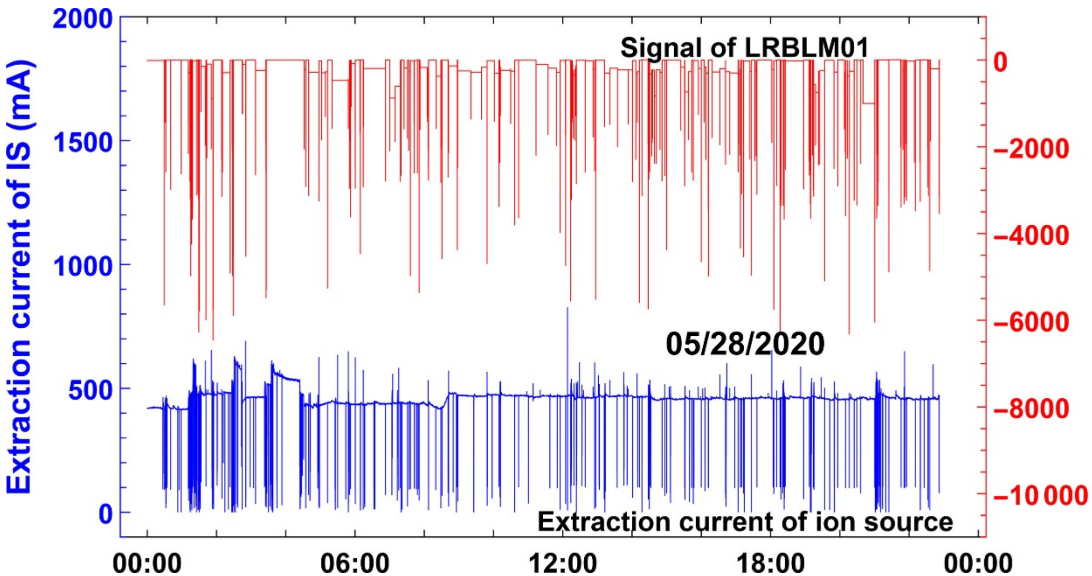




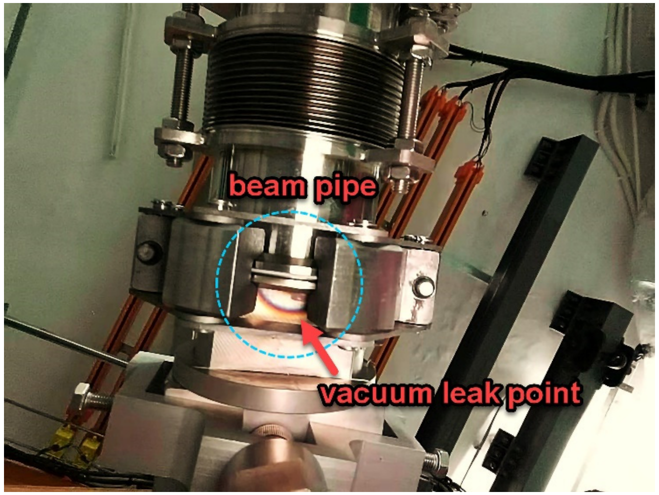


- Ionization-chamber type (Ar/N_2 70:30), 190, the main type, entire beam line
- Plastic-scintillator + PMT, 15, linac, injection & extraction
- Neutron-sensitive IC BLM ($^{10}BF_3$, ^{3}He) + neutron moderator (e.g., HDPE), 5, linac

Experience with beam losses in the CSNS accelerators



Beam losses originated from the sparking of the ion source.

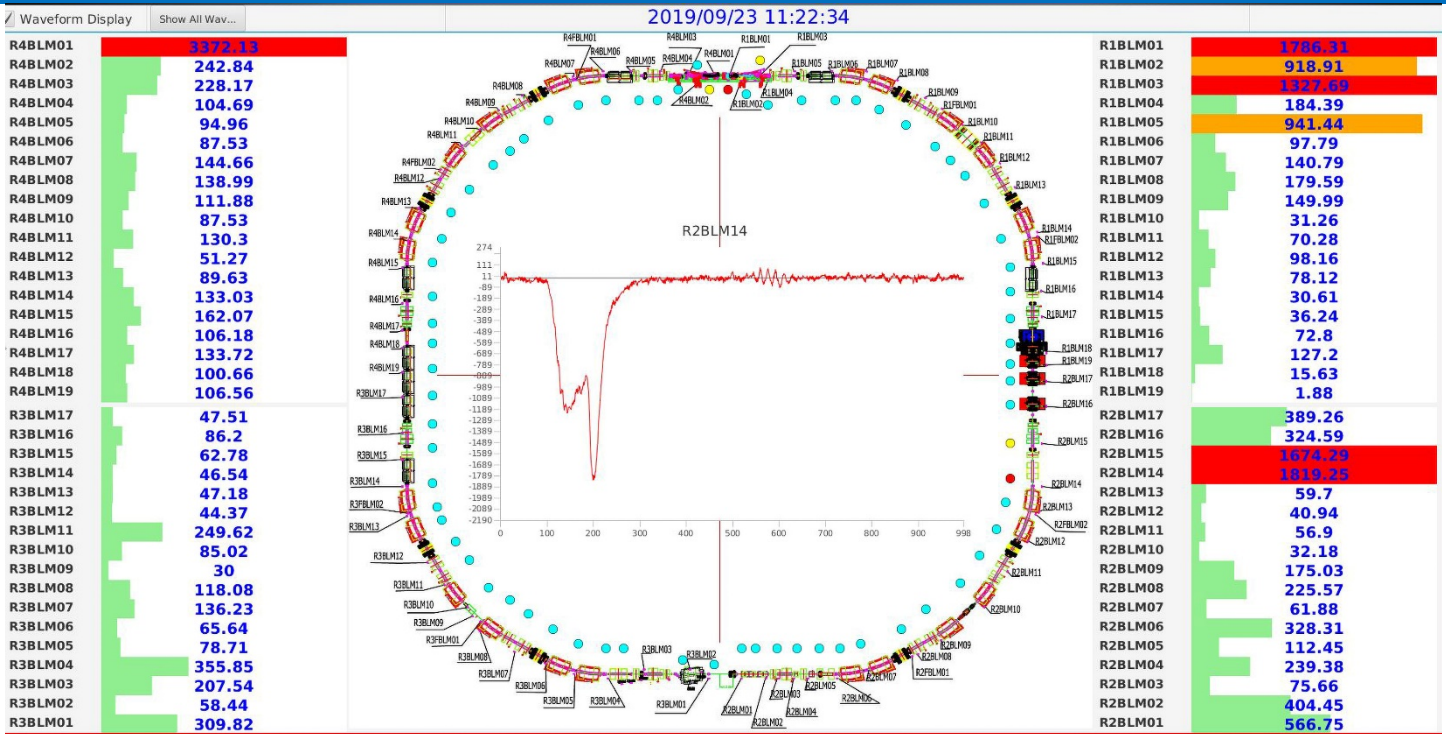


A beam loss event leading to a vacuum leak accident at the CSNS.

- regular loss, e.g., residual gas scattering, beam instability, etc.
- irregular loss, e.g., magnet power supply system, etc.

the detailed summary of beam loss mechanism,
K. Wittenburg, Beam loss monitors, CAS: Course on Beam Diagnostics, Dourdan, France, 2008, p. 249.

The MPS strategy



Display interface of RCS BLM

The MPS strategy in CSNS is to switch off the timing system of the extraction power supply of the ion source to shut down the beam.

Judge the occurrence frequency of the beam loss over-threshold signal.

- A casual over-threshold event will shut down the beam for a second and then the beam is allowed for automatic recovery to normal operation, meanwhile, the MPS will send an alert.
- MPS will trigger the beam interlock system to stop the beam permanently if the beam loss signal exceeds the threshold more than eight times in 10 seconds in the linac or two times in 5 seconds in the RCS, which will require manual recovery.

Monte Carlo Simulations & experiment validations

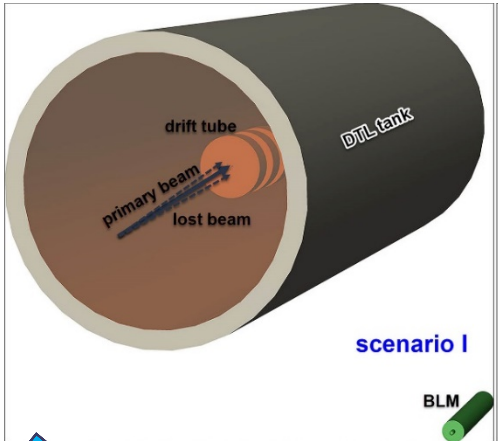
Monte Carlo program:

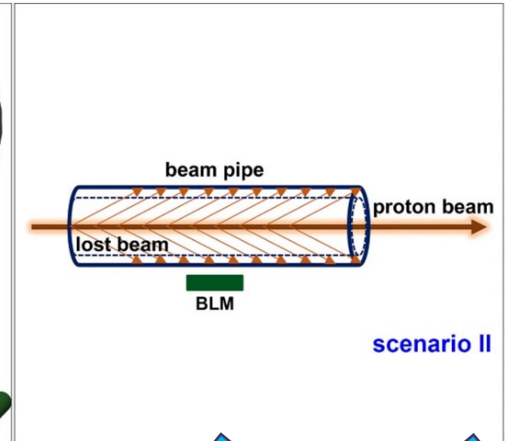
Contents

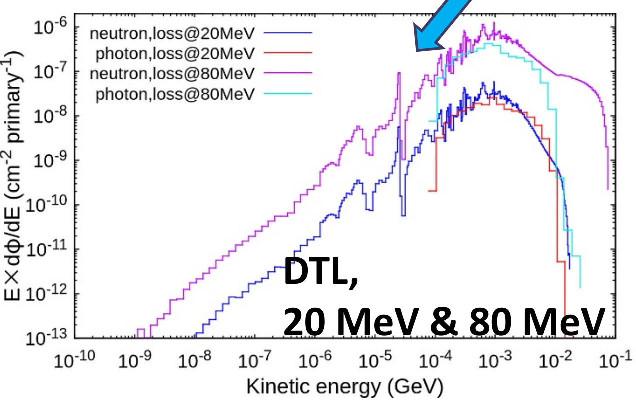
1. Response functions
2. Validation for test and beam-loss experiments
3. BLM responses in the beam-loss induced radiation field
4. Simulations & experiments of beam-loss detection in
   the low-energy section of DTL part of the CSNS

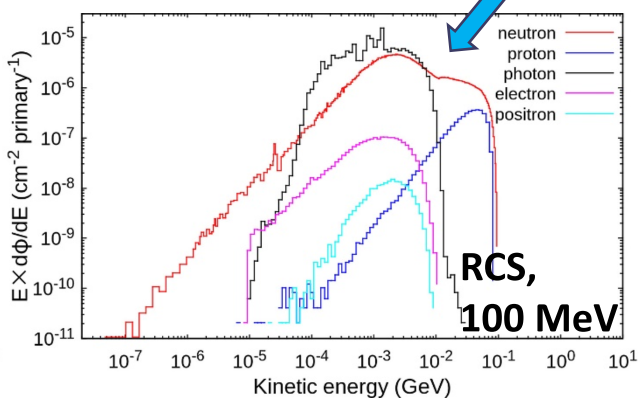
etc…

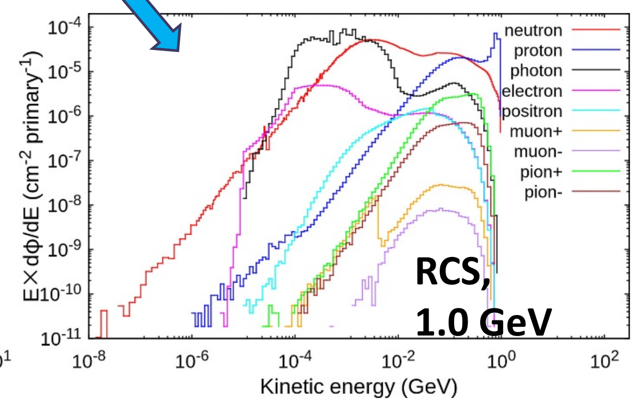
Compositions of secondary radiation fields







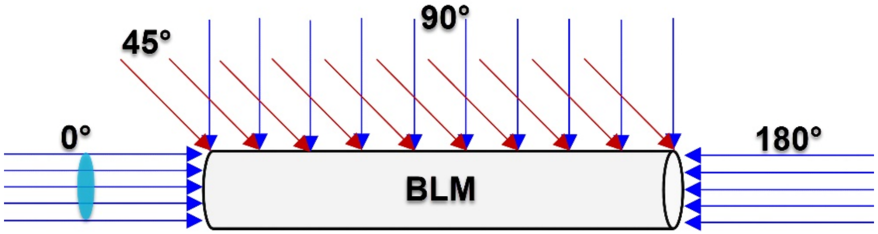




- Loss at a small angle.
- Linac DTL, the main compositions of radiation field are gamma and neutron
- Low-energy of RCS, neutron, gamma, e±, proton; high-energy of RCS, hadronic and electromagnetic cascade start, pions and muons emerges in the radiation field.

Tao Yang, *et al.*, Experimental studies and Monte Carlo simulations for beam loss monitors, PRAB, 24, 032804 (2021).

Response functions

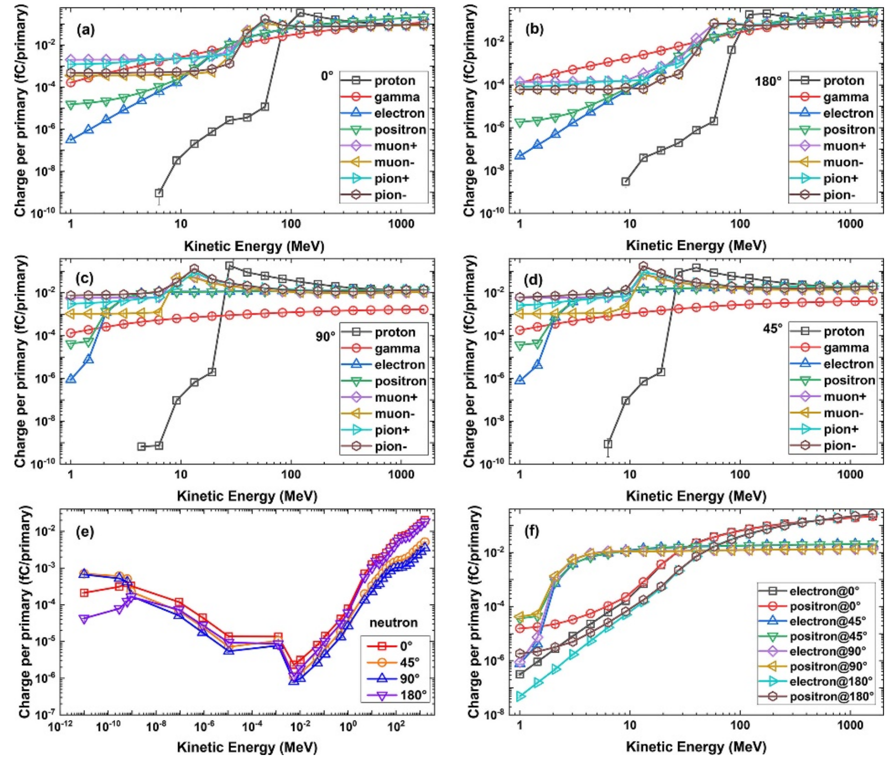


- **Response functions provide the average charge produced in the sensitive volume by the particle traversing the BLM at different energies.**
- **The incident particles are uniformly distributed to traverse the detector at different angles.**
- **Similar results of curve tendency with the LHC BLM except the magnitude.**

- The photon presents a smoother response and a simple increase tendency with the increase of energy.
- Neutron: not so smooth compared with the photon, decrease first and then increase; different energies undergo different. e.g., the small peak @~1.15 keV is caused by the resonance neutron capture in the iron composition of the BLM stainless-steel shell or the electrodes.

Simulated gamma fluence for neutrons traversing the BLM at 90° with energy of 0.95, 1.15 and 1.24 keV.

Neutron energy (keV)	gamma fluence ($cm^{-2}\cdot primary^{-1}$)
0.95	3.94×10^{-7}
1.15	1.61×10^{-5}
1.24	1.37×10^{-6}



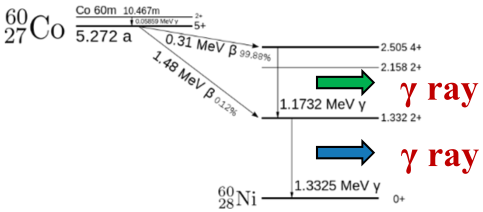
- Response functions of proton, $\pi^{\pm}$ and $\mu^{\pm}$: increases first then decreases, the peak formed in response functions is related to the Bragg peak.
- The electron and positron: a smooth response, for the low energy section, the response difference of $e^{\pm}$ is caused by the effect of electron-positron annihilation.

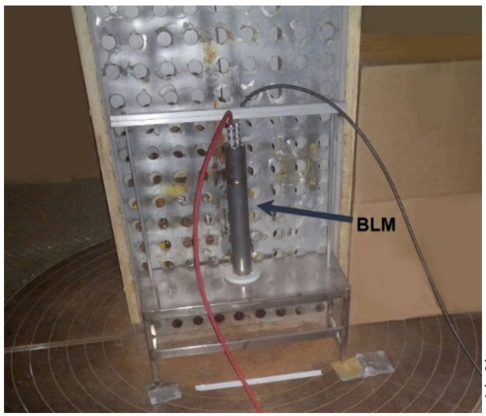
The LHC BLM,

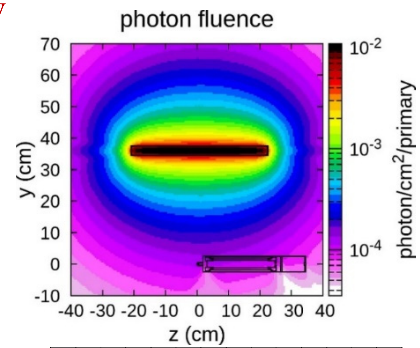
M. Brugger, E. Lebbos, M. Sapinski, and M. Stockner, Response functions of ionization chamber beam loss monitor, Technical Report No. EDMS ID: 1055210, CERN, Geneva, Switzerland, 2010.

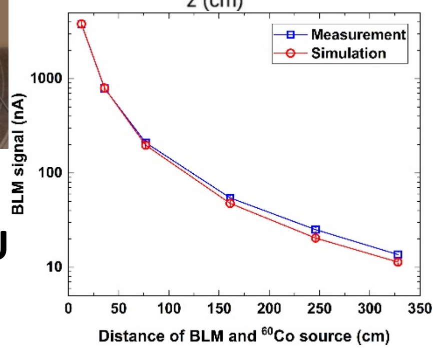
Test in the γ field & mixed field

γ field





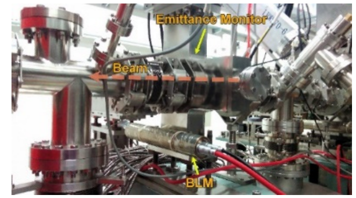


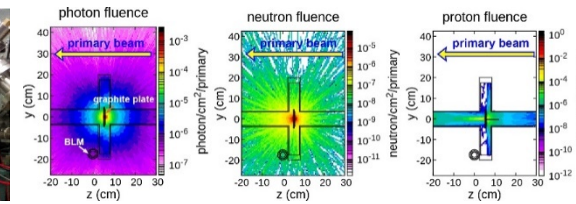


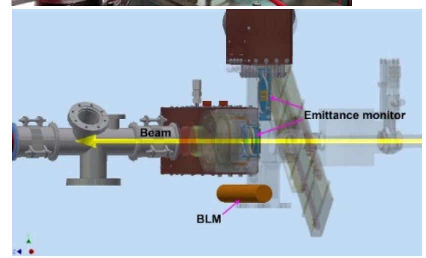
^{60}Co γ-source test @BNU

- activity: 2.92 × 10^{14} Bq
- distance: varing from 13 to 328 cm
- agrees well with simulations

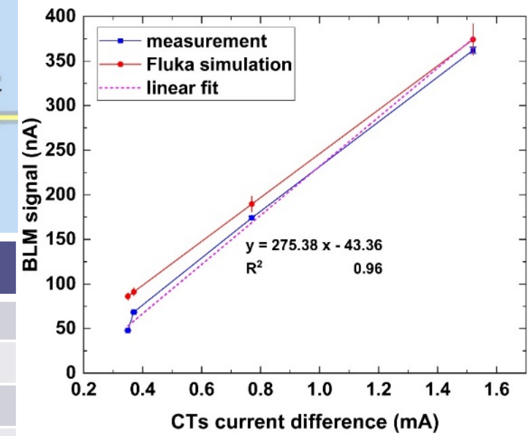
mixed-field







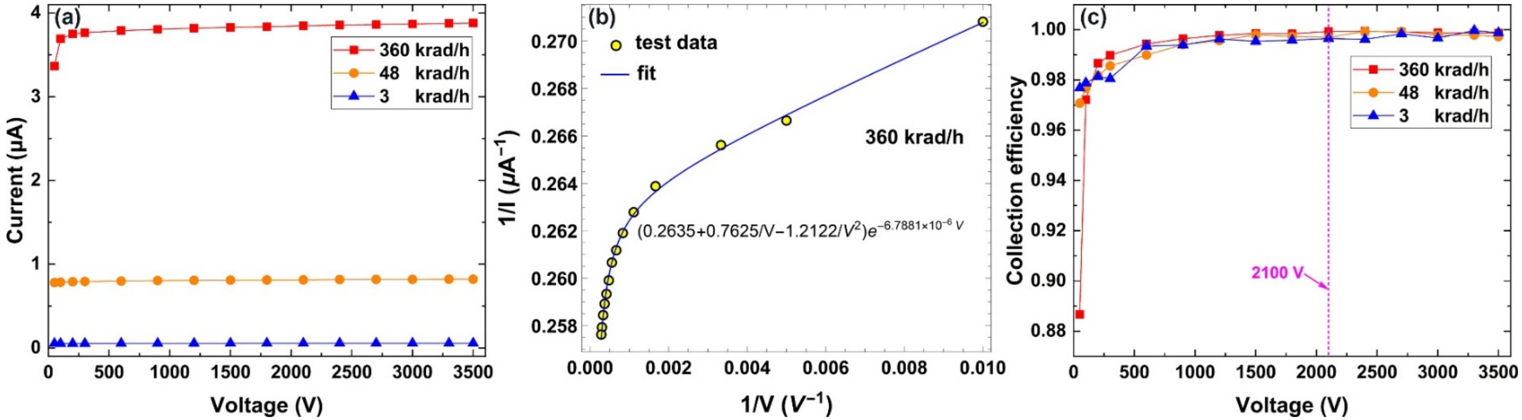
Particle type	Signal contribution
photon	85.15%
neutron	0.057%
electron	14.04%
positron	0.753%



Mixed-field experiment @DTL-1

- H^- beam energy: 21.67 MeV
- Beam loss generated by an emittance monitor
- Beam loss value determined by BCT
- Linear relationship of signal with beam loss

Collection efficiency



- The saturation plateau:~600 to 3500 V for the CSNS BLMs (tested by the radioactive source ^{60}Co).
- Plateau slope is lower than 0.25%/100 V.
- A semi-empirical model proposed by Zankowski: $1/I=\left(1/I_{sat}+\alpha/V+\beta/V^2\right)e^{-\gamma V}$

A recombination model based on the effective length x_0 proposed by Zwaska:

$$x_0=\left(\frac{4\mu\varepsilon_0}{e}\cdot\frac{V^2}{\phi}\right)^{1/4}, \quad f=x_0/d$$

d is the effective electrode separation: $d=\left[(a^2-b^2)\frac{\ln(a/b)}{2}\right]^{1/2}$ for the coaxial cylindrical IC.

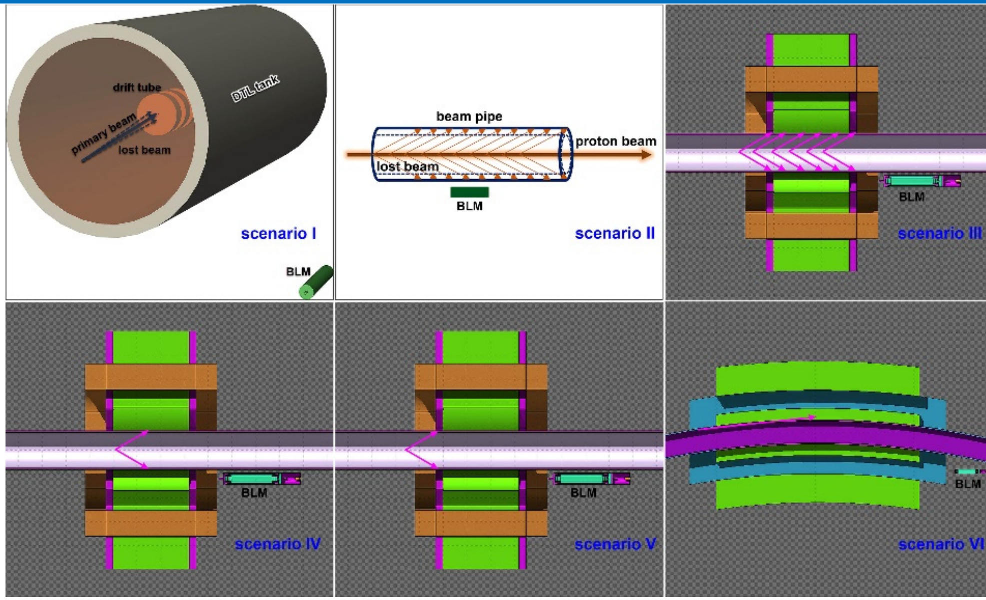
The critical ionization rate at which a dead zone starts to form:

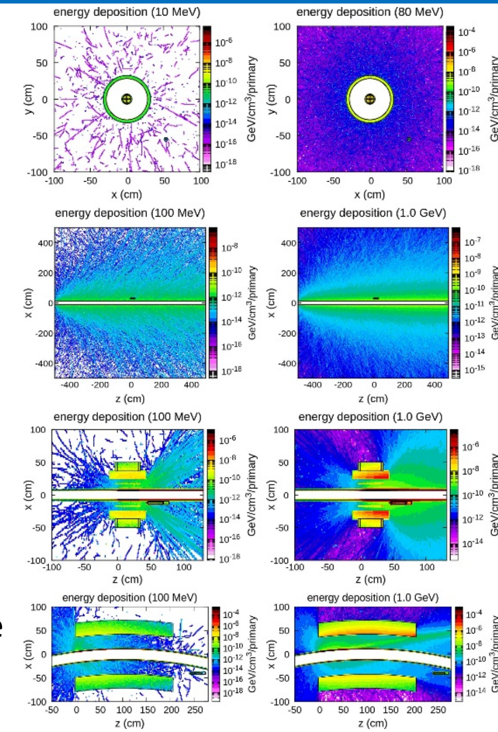
$$\phi_0=\frac{4\mu\varepsilon_0}{e}\cdot\frac{V^2}{d^4}\left[\frac{ions}{cm^3\cdot\mu s}\right]$$

~9.82×10^7 ions/(cm^3·μs), i.e., a charge of 1.73 mC in one second in the sensitive volume of the CSNS BLMs.

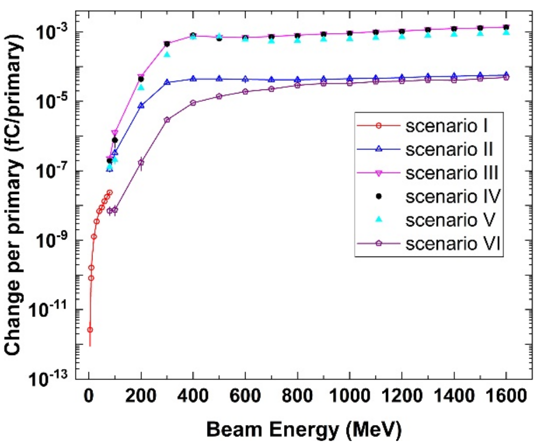
C. Zankowski and E. B. Podgorsak, Determination of saturation charge and collection efficiency for ionization chambers in continuous beams, Medical Physics 25, 6 (1998).
R. B. Zwaska, Accelerator Systems and Instrumentation forthe NuMI Neutrino Beam, Ph.D. thesis, University of Texas at Austin, 2005.

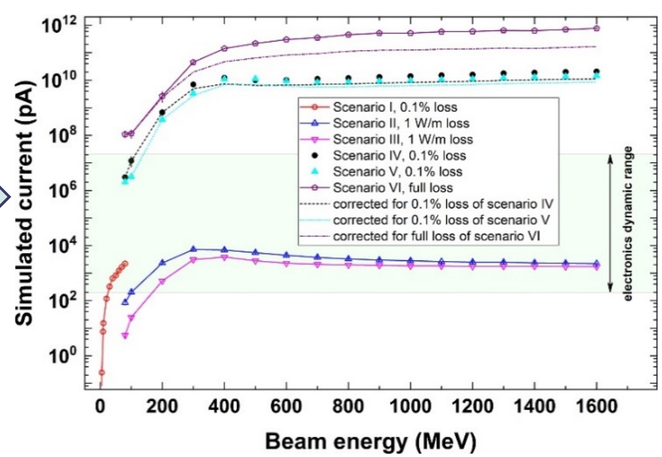
BLM responses with different loss scenarios





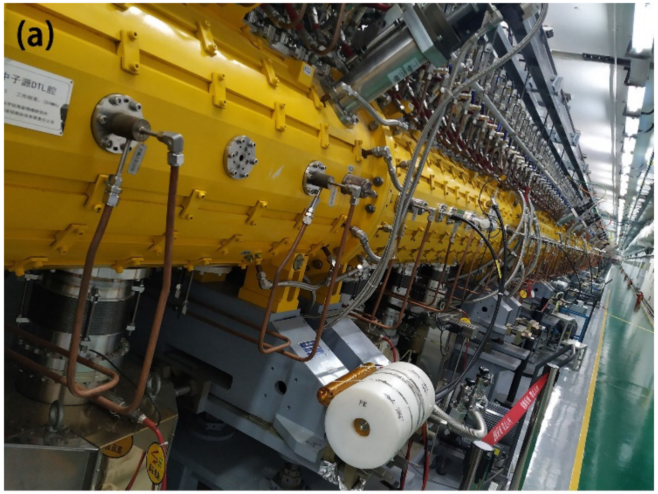
- Scenario I~VI, different loss scenarios from the linac to RCS of the CSNS. Assume losses taking place at the drift tube, beam pipe, the quadrupole, and dipole magnet.
- BLM signal is position sensitive seen from the 2D map.
- Responses of per primary multiplying the loss rate could deduce the macroscopic current.

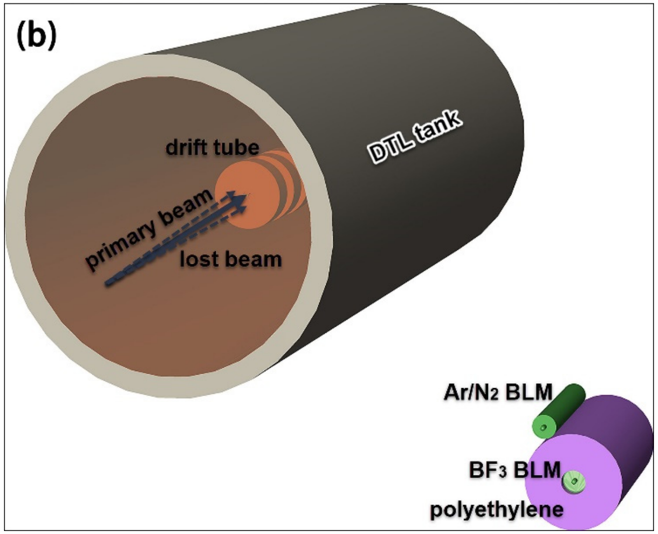




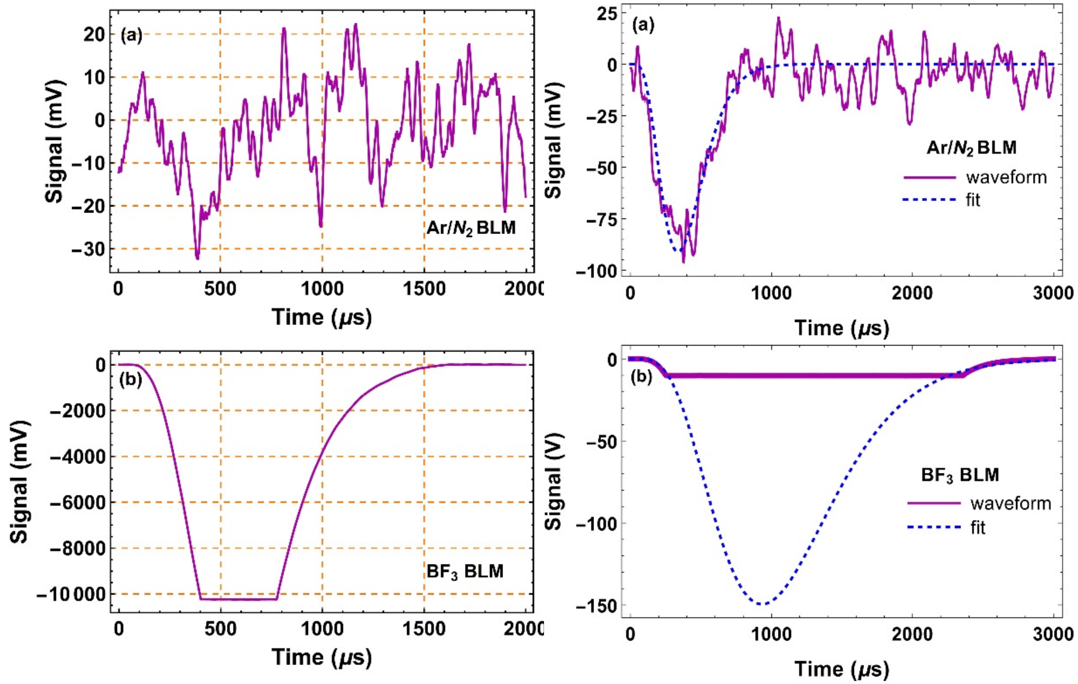
- electronics range of CSNS BLM : 200 pA~20 μA. The simulated current could evaluate the suitability of electronics and supply the essential information for further optimization of electronics.

Beam-losses detection at the low-energy section of the CSNS linac





BLMs placed at the 2/3 length of the DTL-1, the nominal beam energy is about 15 MeV. The thickness of the DTL chamber is 4-cm. The $^{10}BF_3$ (96%-enriched) BLM is enclosed by a 7.5-cm-thick HDPE.

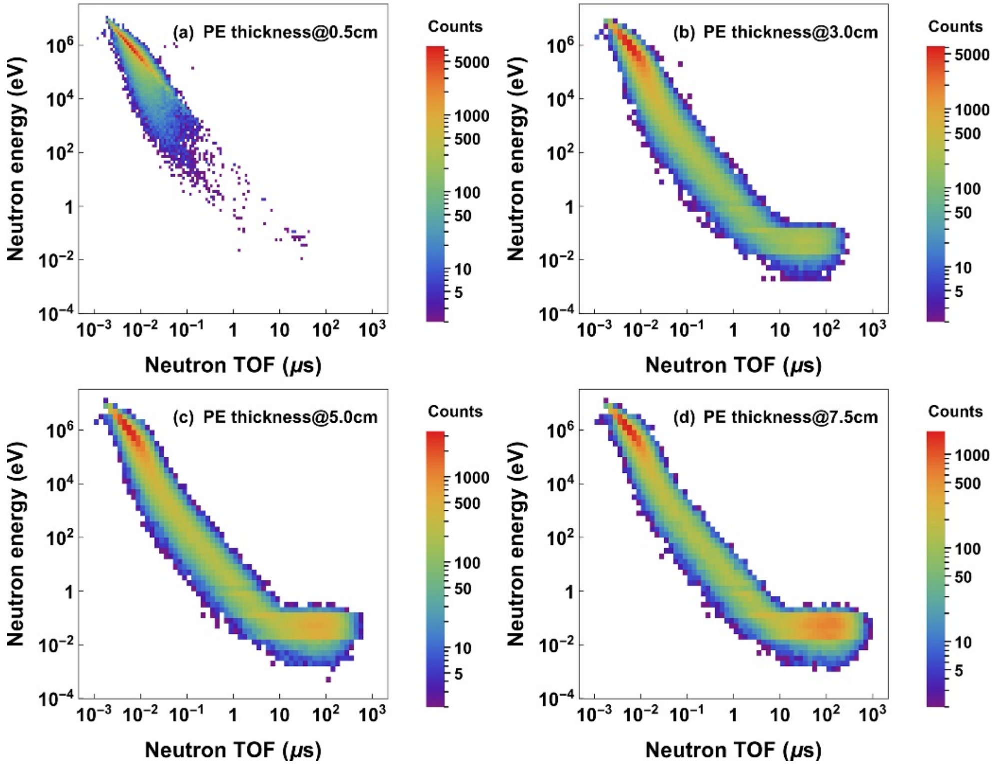


The acquired experimental waveforms of beam loss signal of the BF_3 and Ar/N_2 BLM. Right plot corresponds to a relatively big loss by intentionally mismatching the magnet parameters in a single-shot mode to generate a beam-orbit distortion.

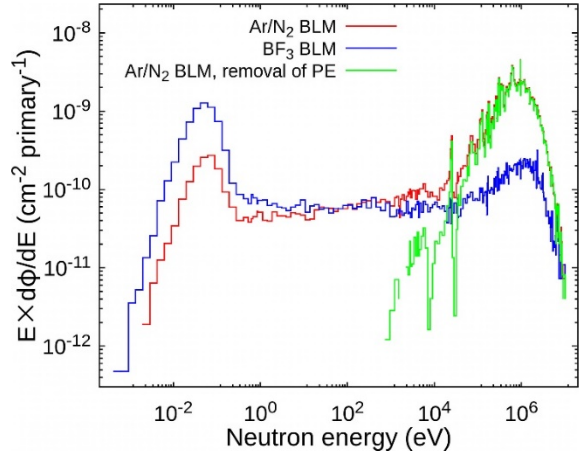
$$\mathrm{n}+{}^{10}B \rightarrow \begin{cases} \alpha+{}^{7}\mathrm{Li}+2.31\ \mathrm{MeV}+\gamma(0.48MeV) & 94\% \\ \alpha+{}^{7}\mathrm{Li}+2.79\ \mathrm{MeV} & 6\% \end{cases}$$

- The simulated energy deposition in the sensitive volume of two BLMs is respectively 0.1335(±2.1%) eV/primary and 1.115×10^{-4}(±7.1%) eV/primary for BF3 and Ar/N_2 monitor. Simulated signal ratio: 1197(±89), experimental: 1642(±27).
- Time delay is ~80 μs, it is caused by the thermalization and migration process of neutrons in the 7.5-cm-thick HDPE.
- Beam loss signal with neutron BLM is high, and instrument is easily assembled.

Beam-losses detection at the low-energy section of the CSNS linac

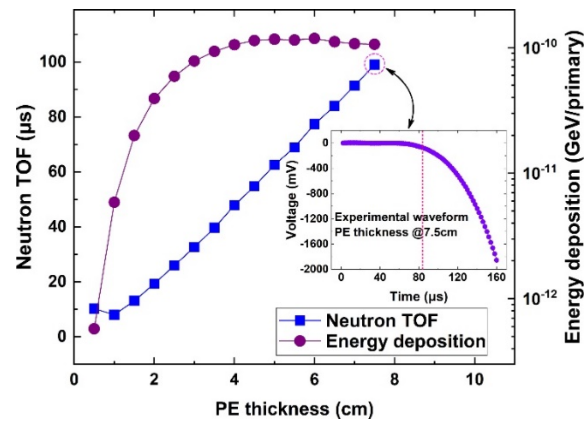


Neutron counts versus the neutron TOF and energy in a 2D histogram.



An apparently higher thermal-neutron peak for the BF_3 BLM. The neutron spectrum of Ar/N_2 BLM is modulated by the backscattered neutrons from the HDPE moderator of BF_3 BLM.

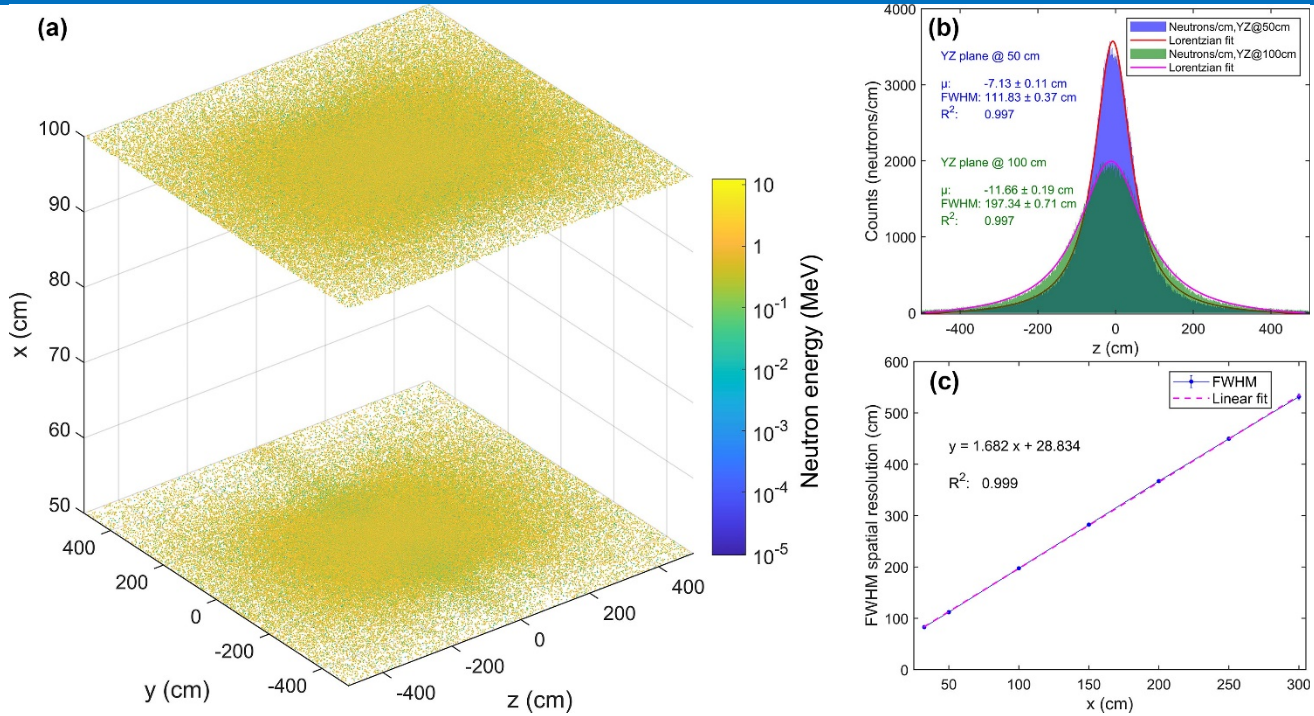
A thermal-neutron zone emerges in the 2D histogram as increasing the PE thickness.



Two competitive mechanisms to determine the final signal: the neutron thermalization, and the neutron shielding effect as increasing the PE thickness.

The average neutron TOF and the corresponding energy deposition versus different PE thicknesses.

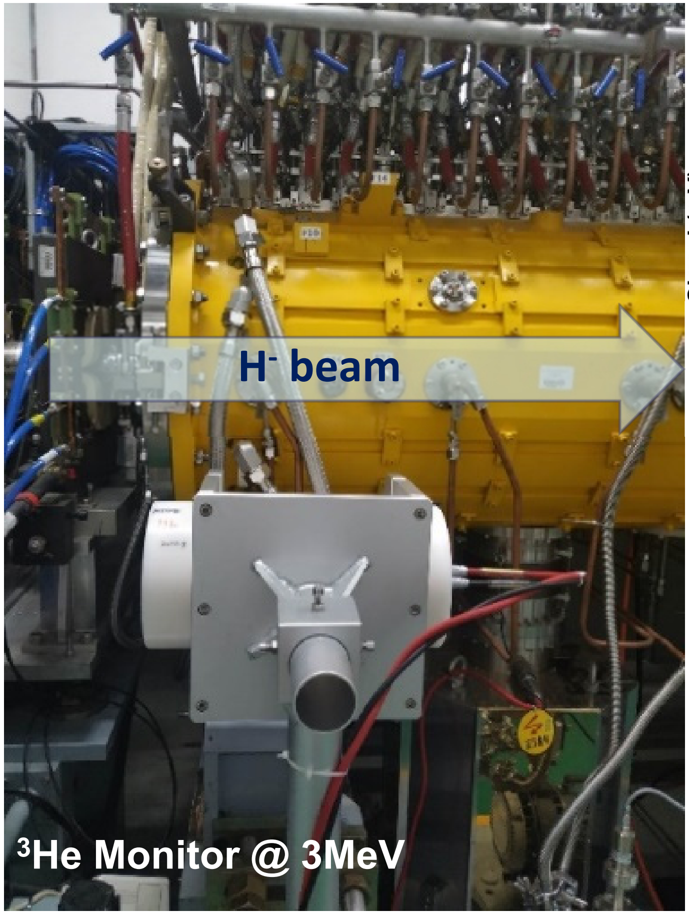
Spatial resolution for the neutron-based beam loss detection



Hit maps of secondary neutrons and the neutron distribution along the z-axis direction.

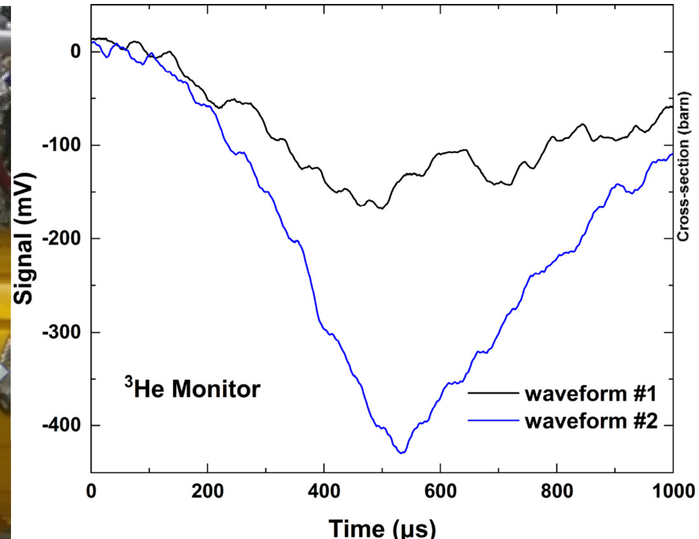
- Multiple scattering of neutrons will lead to an uncertainty for the loss location by the detection of neutrons.
- The recording planes are perpendicular to the *x*-axis (*x*=0 corresponds to the centerline of the DTL tank) with a size of 10×10 m^2. The beam energy is set to be 15 MeV and the loss position is set at *z*=0 with a loss angle of 1 mrad.
- The FWHM is adopted as the spatial resolution. The spatial resolution is respectively 111.83 cm and 197.34 cm for the YZ plane at 50 cm and 100 cm.

Beam-losses detection at the entrance of CSNS DTL (@3 MeV)

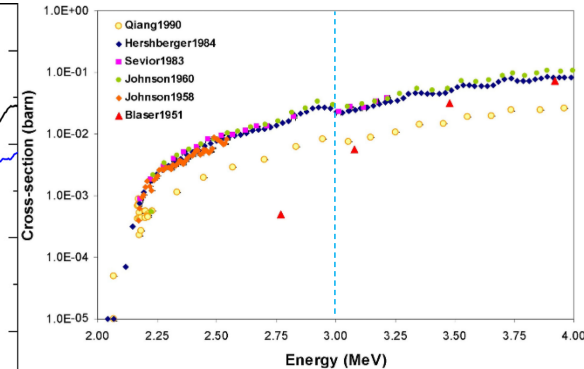


³He BLM installed at the entrance of DTL

For 0.025-eV neutrons, the reaction cross section is respectively 5333 barns for ^{3}He and 3837 barns for ^{10}B.



Waveforms of beam loss



L. Weissman, et al., The use of a commercial copper beam dump for intense MeV proton beams, JINST 6 T03001 (2011).

National Nuclear Data Center homepage, http://www.nndc.bnl.gov/

- Loss @3 MeV. Threshold for ^{65}Cu (p,n)^{65}Zn reaction: ~2.2 MeV, ~20 mb@3MeV, ^{65}Cu natural abundance~31% (rather high!).
- Simulation at such low energy is difficult to get good statistics.
- May be lost at downstream. The scattered neutrons give the signal; it should be investigated, e.g., the phase scan experiment under 3 MeV.

Thanks for your attenti