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Measurement of the fission cross-section of U-235 relative to n-p scattering from 10 to 70 MeV at CSNS Back-n

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IAEA Headquarters, Vienna, Austria, October 9-13, 2023

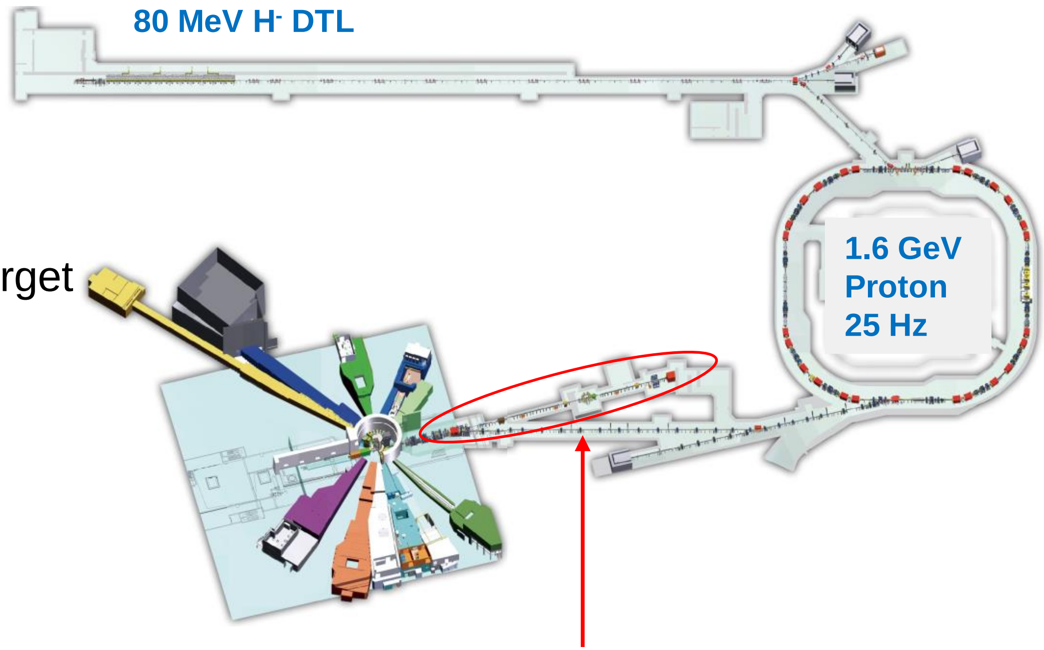
Outline

1. CSNS Back-n facility
2. Experimental setup
3. Analysis and preliminary results
4. Future plan

1. Back-n facility at CSNS

China Spallation Neutron Source (CSNS)

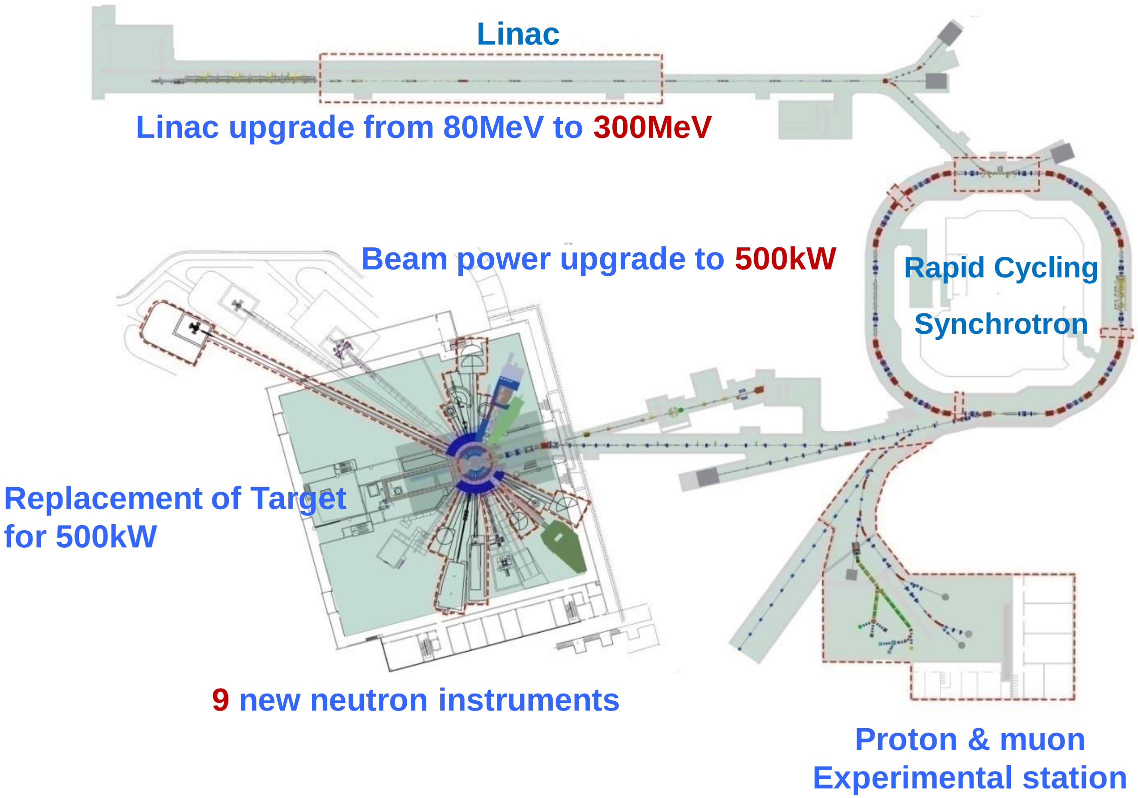
- Started running since 2018
- 1.6 GeV protons bombard tungsten target
- 25 Hz repetition frequency
- Current beam power: ~140 kW
- Double-bunch mode



Back-streaming neutron (Back-n) beamline

1. Back-n facility at CSNS

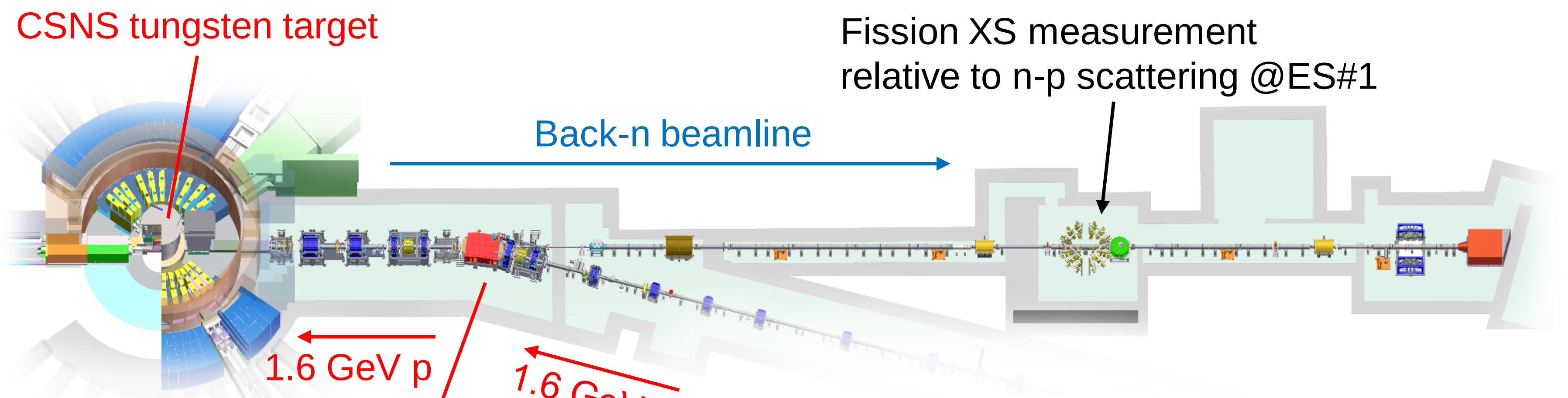
CSNS-II project



- Project Budget: 2.9 BCNY (~377 MEUR)
- Funded by central and Guangdong local government
- Design and R&D completed
- Construction duration: 2023.10~2029.6 (5 years and 9 months)

User operation will be almost unaffected during CSNS II construction

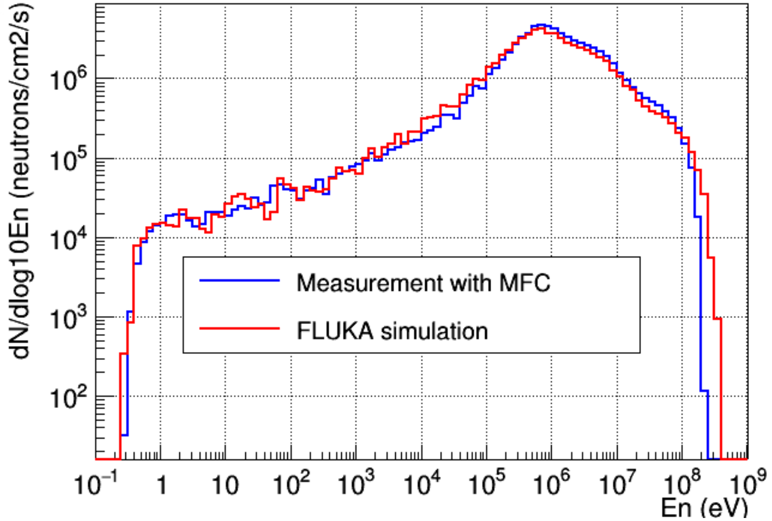
1. Back-n facility at CSNS



1.6 GeV p

Bending magnet

- Time-of-flight (TOF) technique
- Two end stations: ES#1 (~55 m) and ES#2 (~76 m)
- Wide neutron energy range (from 0.3 eV to ~300 MeV)
- Weak γ-flash due to back-streaming design



Yonghao Chen et al., *Eur. Phys. J. A* (2019) 55: 115

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1. CSNS Back-n facility
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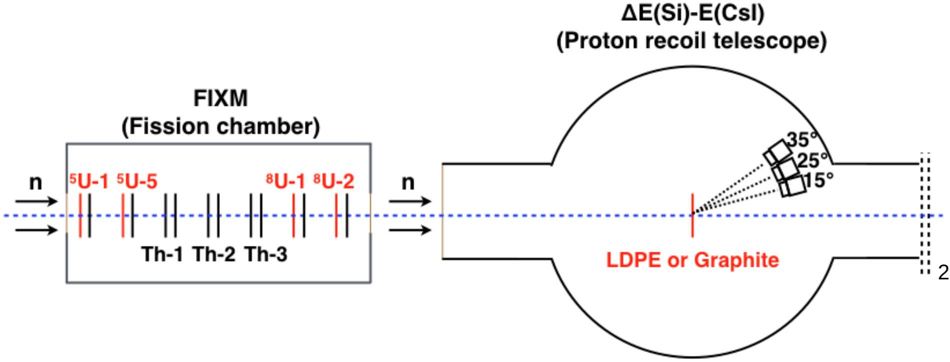
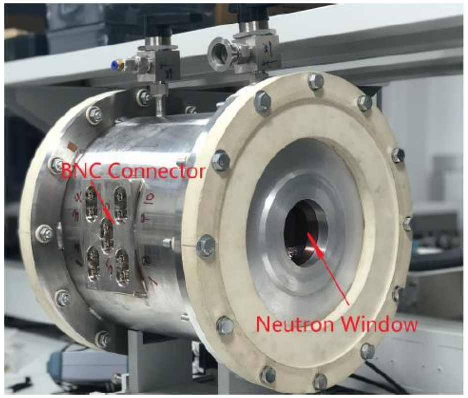
2. Experimental setup

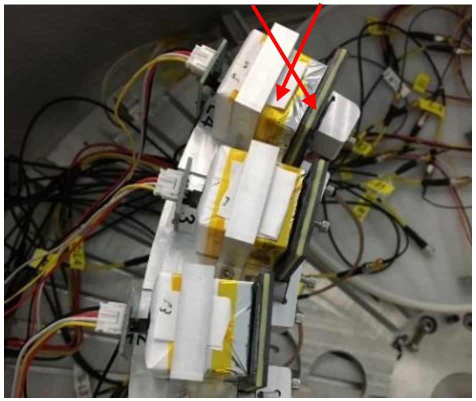
- Setup at Back-n ES#1 with small collimators (beam spot: ~φ18 mm)
- A fission chamber (FIXM) is used for measuring the fission events
- Proton recoil telescope (PRT) is used for measuring the scattering protons



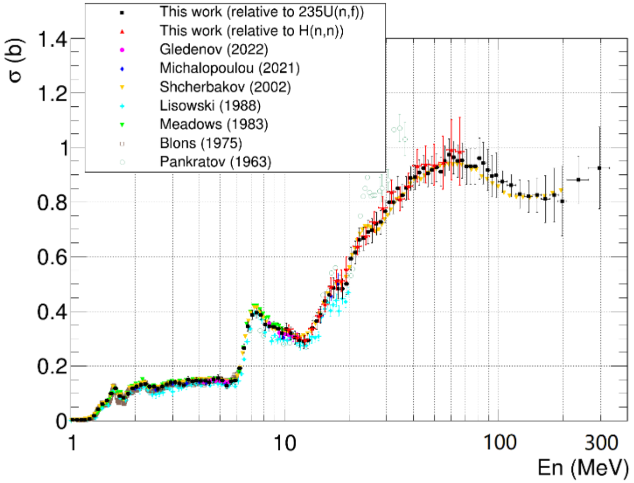
FIXM



PRT: Si+ CsI



^{232}Th(n, f) cross-section measurement in 1-300 MeV (relative to both ^{235}U(n, f) and n-p scattering)

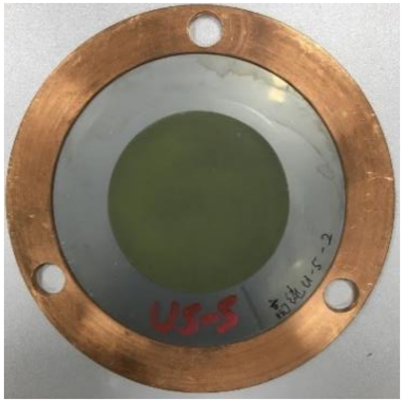


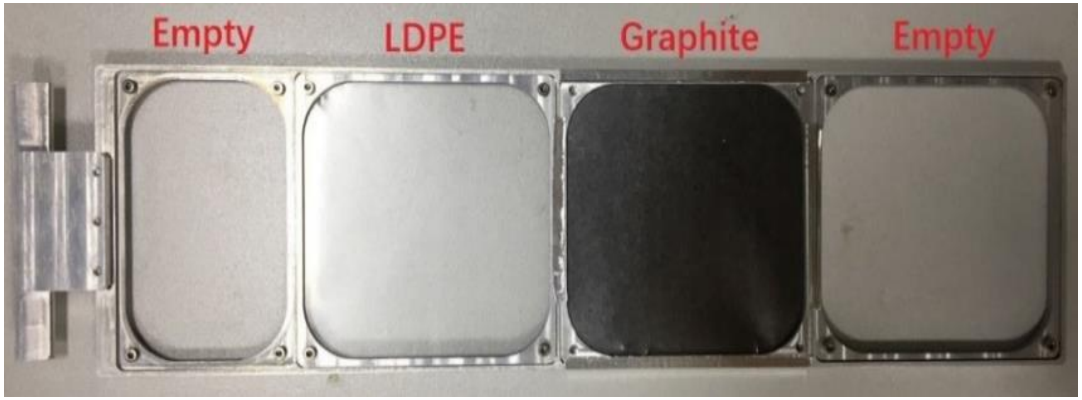
Yonghao Chen et al., *Phys. Lett. B* (2023) 839: 137832)

2. Experimental setup

- Sample details

U5





Sample	Mass (mg)	Size (mm)	Uncertainty
U5	6.319	φ50	0.9%

Sample	Average thickness (mg/cm^2)	Side length (mm)	Uncertainty
LDPE	9.989	77	0.39%
Graphite	8.653	77	0.57%

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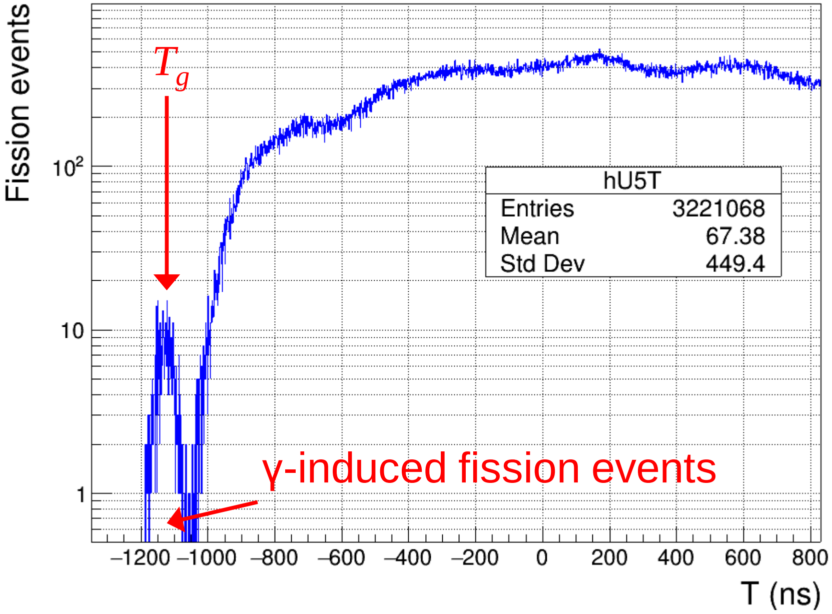
3.1 Analysis of the FIXM

Time-of-flight (TOF) method for determining neutron energy

$$v = \frac{L}{TOF} = \frac{L}{T - T_0}$$

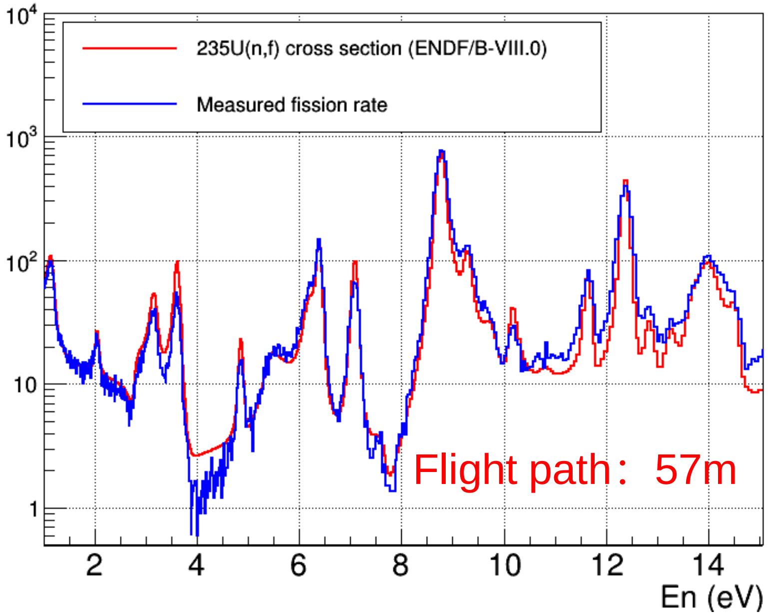
- L is determined by the resonance peaks of ^{235}U sample
- T_0 is determined by the γ-flash events

Time distribution of fission events



γ-induced fission events

Comparison of fission rate and cross section



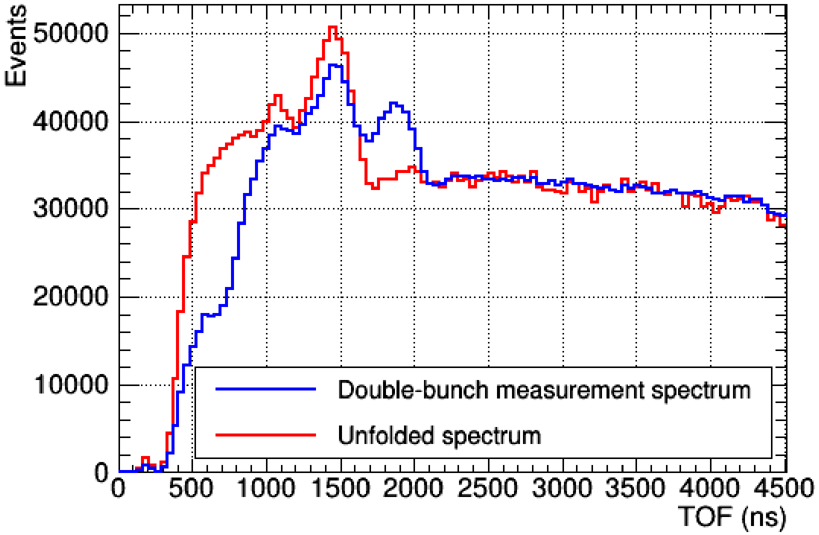
Flight path：57m

3.1 Analysis of the FIXM

- This measurement was campaigned in double-bunch mode: two identical proton bunches with a well-defined interval (410 ns) in each proton pulse
- An iterative algorithm based on Bayes' theorem is developed for unfolding the TOF spectrum (Han Yi et al, *JINST* (2019) **14**: 02011)

$$C_i^{(k+1)} = E_i \frac{C_i^{(k)}}{C_{i-\Delta}^{(k)} + C_i^{(k)}} + E_{i+\Delta} \frac{C_i^{(k)}}{C_i^{(k)} + C_{i+\Delta}^{(k)}}$$

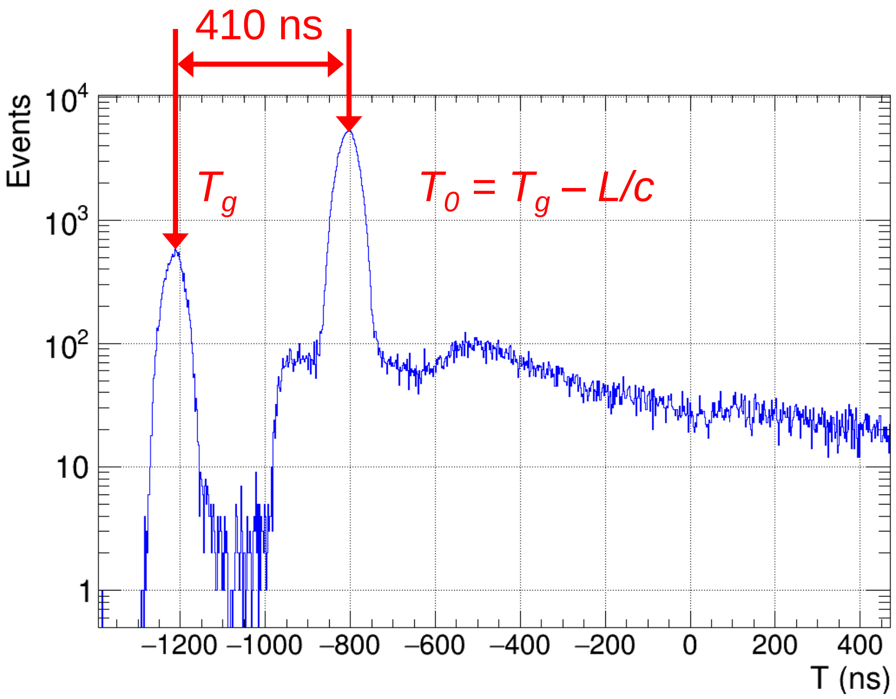
TOF spectrum before and after unfolding



3.2 Analysis of the PRT

TOF method application

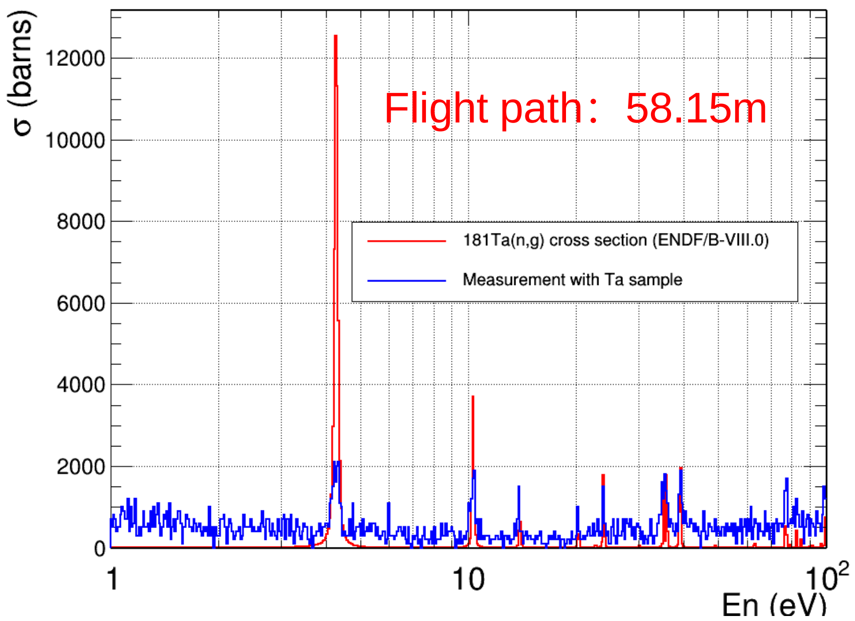
- L is determined by the resonance peaks of ^{181}Ta (n, γ)
- T_0 is determined by the γ-flash events



410 ns

T_g

$T_0 = T_g - L/c$

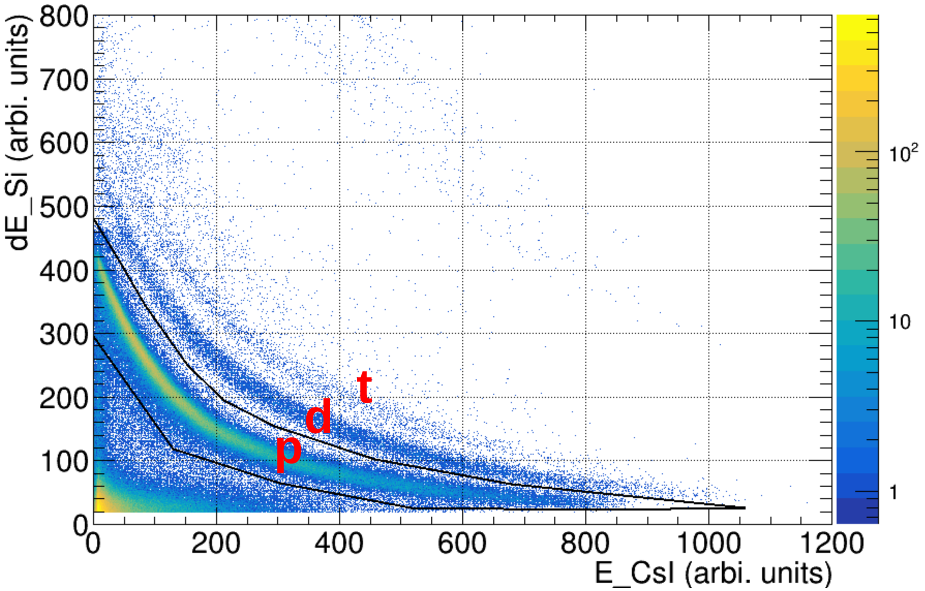


Flight path： 58.15m

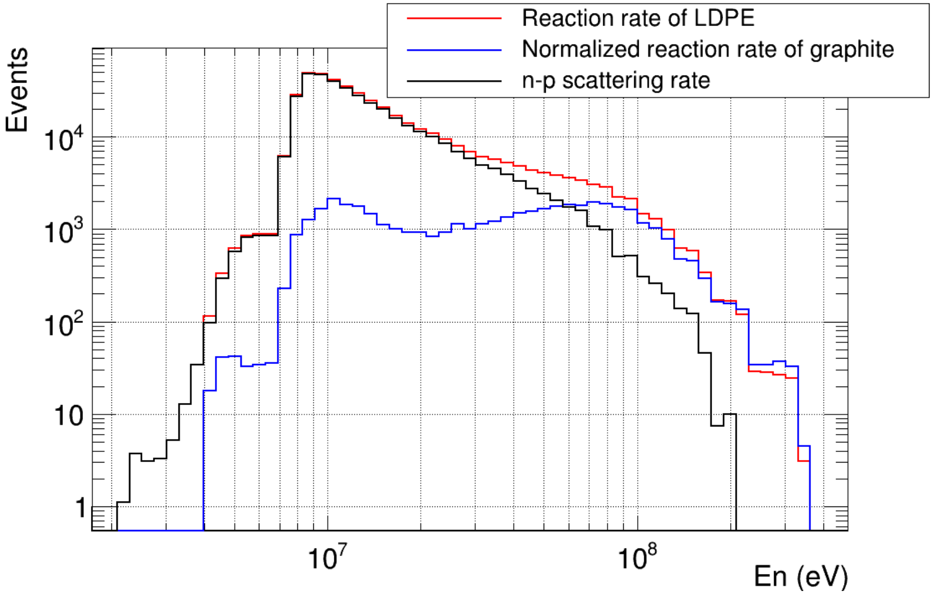
3.2 Analysis of the PRT

- Particle identification by ΔE-E distribution
- A graphite sample with equivalent thickness as LDPE was measured to subtract the contribution from the carbon nuclei

Particle identification



Background subtraction



3.3 Preliminary results

Two approaches (references) were used to determin the ^{235}U(n, f) cross-section

① Use H(n, n) cross-section + simulated efficiency (geometric and angular distribution effects are included in the simulation)

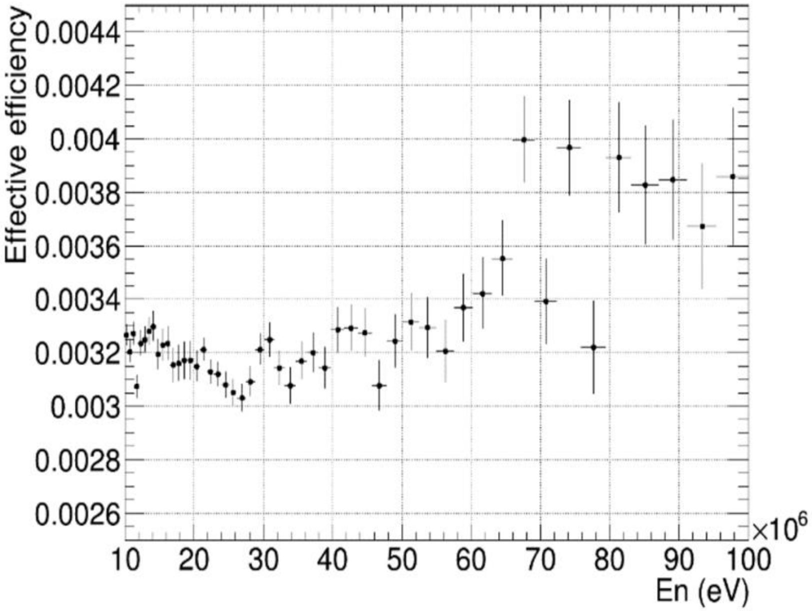
② Use differential H(n, n) cross-section directly

Reference ①

H(n, n) cross section:

- IAEA standards (<20 MeV)
- JEFF-3.1.2 (>20 MeV)

G4 simulation for effective efficiency



Reference ②

Differential H(n, n) cross-section:

- SP07 solution (Arndt) (<20 MeV)
- VL40 solution (Arndt) (>20 MeV)

Thanks to A. Manna and A. D. Carlson for the information of the differential n-p XS data

Transformation:
Coordinate system: center-of-mass -> lab
Emission particle: (n, n) -> (n, p)

$$\frac{\left(\frac{d\sigma_p}{d\Omega_p}\right)}{\left(\frac{d\sigma_{el}}{d\Omega_{c.m.}}\right)} = \frac{4\gamma_0^2}{\left(1+\gamma_0^2 tan^2\Theta_p\right)^2 cos^3\Theta_p}$$

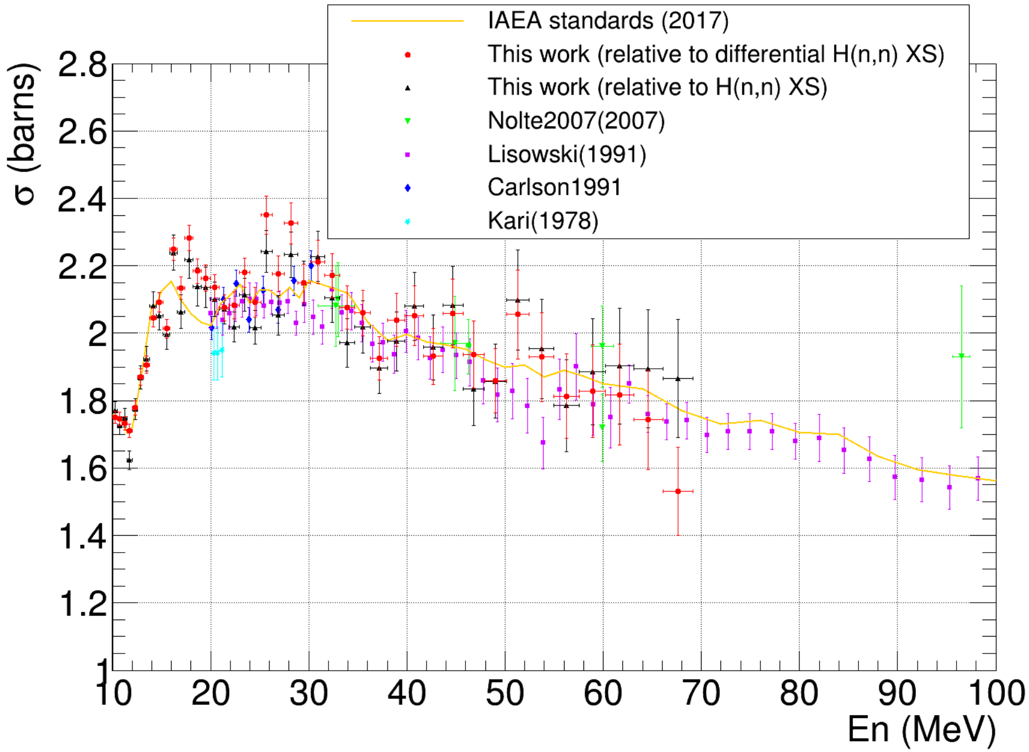
$$\theta_{c.m.} = 180° - arcos\left(\frac{1-\gamma_0^2 tan^2\Theta_p}{1+\gamma_0^2 tan^2\Theta_p}\right)$$

γ_0 – Lorentz factor of the c.m.

3.3 Preliminary results

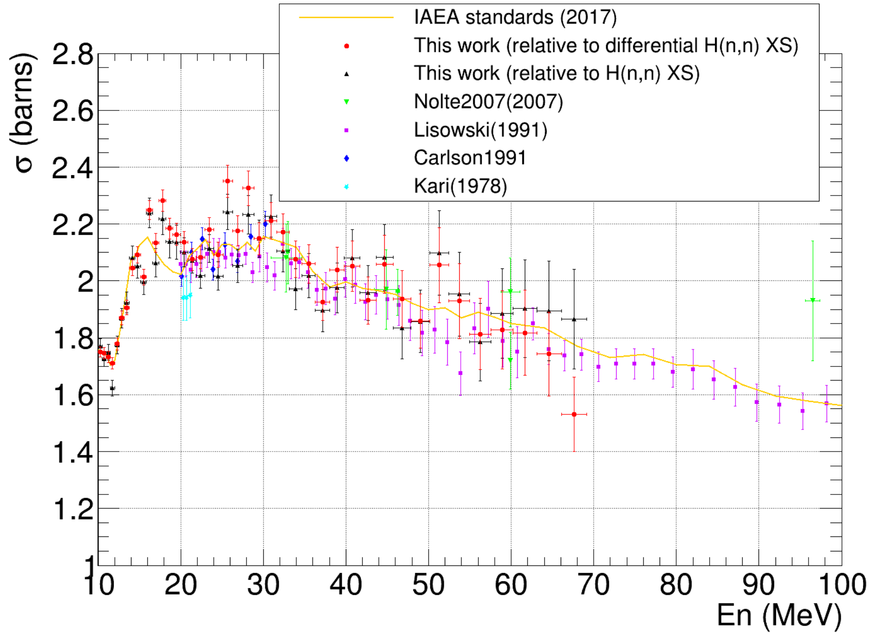
Measured ^{235}U(n, f) cross-section in 10-70 MeV region

- Normalize to the integral value of 10-12 MeV of ^{235}U(n, f) IAEA standards, since the exact sample quantity in the beam map is uncertainly know.
- Only statistical uncertainties are included for the moment
- Two approaches are generally agreeing with each other

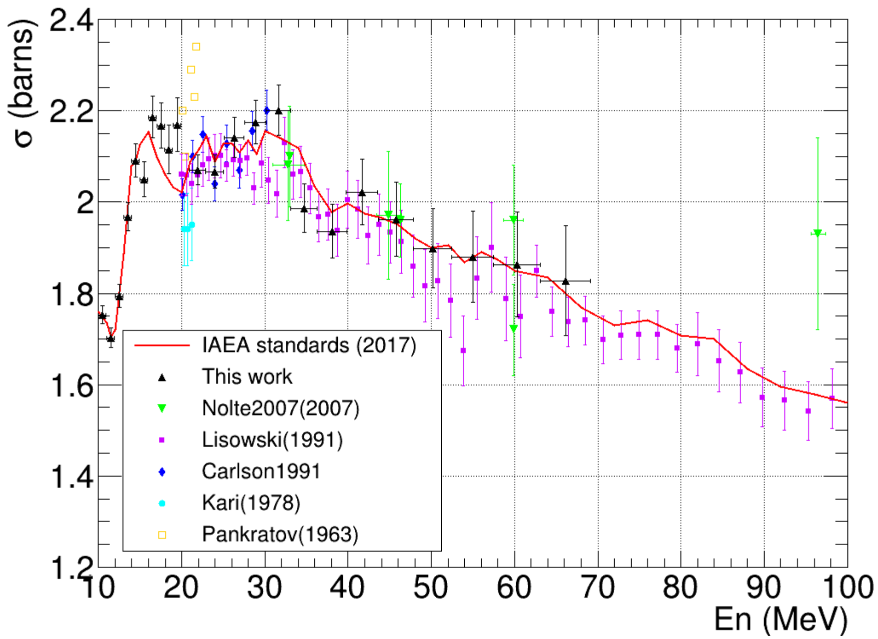


3.3 Preliminary results

Current results (preliminary)



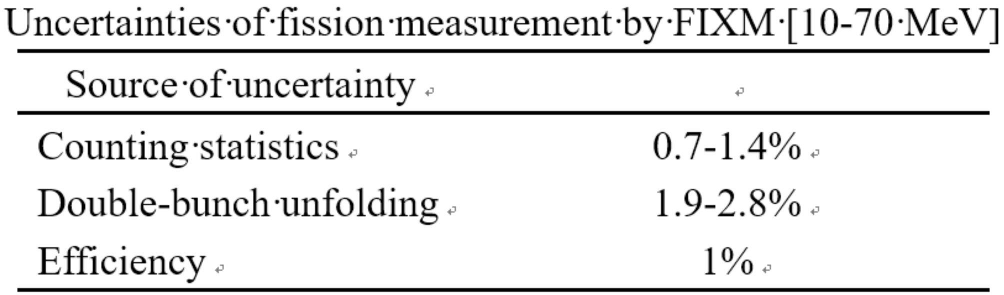
Results of last year



Yonghao Chen et al., EPJ Web of Conf. (2023) **284**: 01013

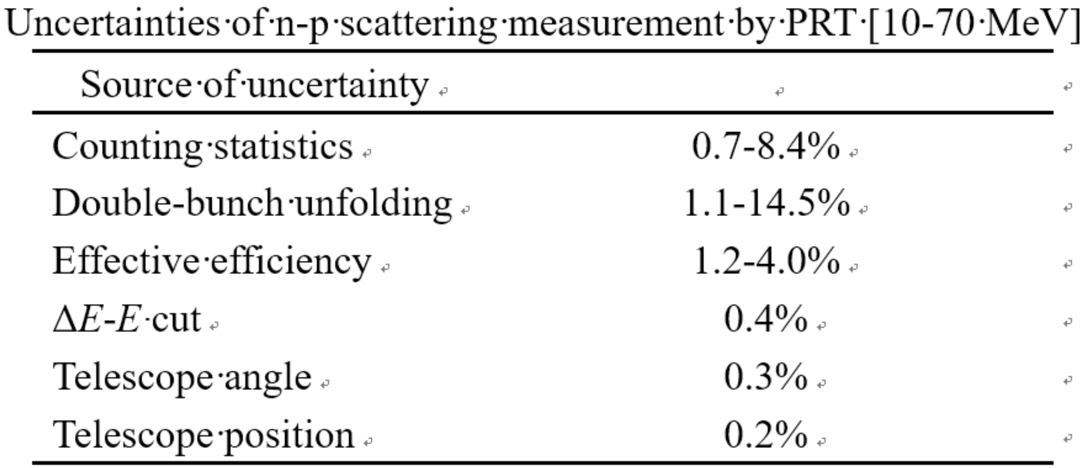
3.3 Preliminary results

- Uncertainty estimation



Uncertainties of fission measurement by FIXM [10-70 MeV]

Source of uncertainty	
Counting statistics	0.7-1.4%
Double-bunch unfolding	1.9-2.8%
Efficiency	1%



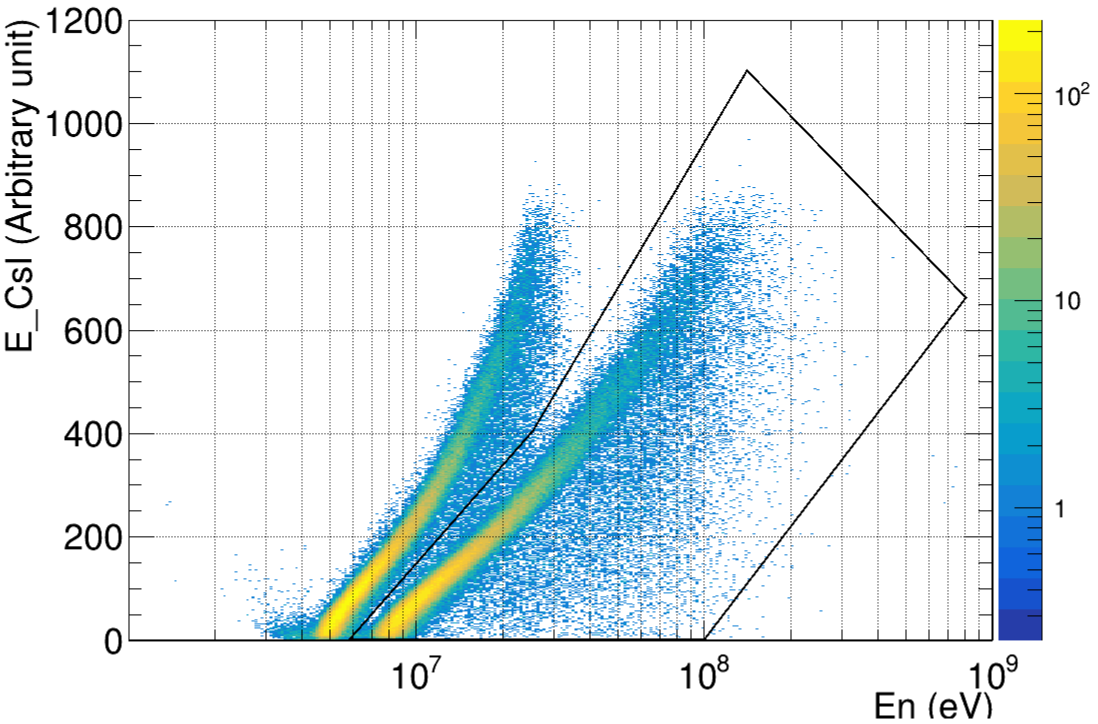
Uncertainties of n-p scattering measurement by PRT [10-70 MeV]

Source of uncertainty	
Counting statistics	0.7-8.4%
Double-bunch unfolding	1.1-14.5%
Effective efficiency	1.2-4.0%
ΔE-E cut	0.4%
Telescope angle	0.3%
Telescope position	0.2%

Uncertainty of double-bunch unfolding is highly depending on the statistics

3.3 Preliminary results

Neutron energy *versus* Amplitude of CsI (proton energy)



Since double-bunch are well separated in n-p scattering measurement, we may try to give up one bunch to save the unfolding process! In this case, the statistics is reduced by half but the unfolding uncertainty is removed as well!

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Future plan

Short-term plan

1. More detailed analysis will be implemented to improve the data quality
   - more dedicated corrections (detection angle spread, intrinsic efficiency, etc.)
   - Systematic uncertainty estimation
   - …

2. Try to extract the ^{235}U(n, f) cross-section in 8-10 MeV region, which is meaningful to the evaluation due to its flat behavior

3. The finalized data should be submitted for publication next year with high priority

Future plan

Long-term plan

1. PRT is foreseen to be upgraded in the future to lower the detection limit
    - 300 μm Si + 2.5 cm CsI → 100 μm Si + 300 μm Si + 2.5 CsI (E)

2. Extending the measurement range relative to n-p scattering by upgrading the PRT and increasing the statistics
    - 10-70 MeV → 7-100 MeV

3. Bunch-merging mode at CSNS/RCS has been proposed for further study
    - CSNS accelerator is generally (most of the time) operated in double-bunch mode
    - Double-bunch unfolding comprise the large part of the systematic uncertainty
    - Current single-bunch mode reduces the half of the CSNS universal neutron flux
    - Bunch-merging is a very good solution since it will provide single-bunch without losing flux!

Future plan

Bunch-merging study @ CSNS/RCS

The newly-installed dual rf system for CSNS-II project makes it possible to perform bunch-merging for single-bunch operation mode

Challenges for bunch-merging in the high intensity RCS

- Strong high-intensity effect → beam dipole oscillation
- Very short merging time → emittance growth

} Beam loss

A fast bunch merging has been proposed

- Desynchronization between the dipole and rf system → increasing the limited merging time
- Optimization/adjustment of the rf phase → compensation of the high-intensity effects

Ref. : Yaoshuo Yuan et al., *Phys. Rev. Accel. Beams* (2023) 26: 024201

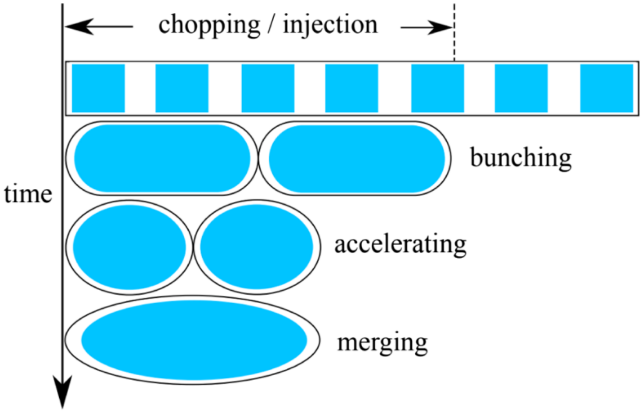
PHYSICAL REVIEW ACCELERATORS AND BEAMS

High-intensity effects on longitudinal bunch merging in hadron synchrotrons

Y. S. Yuan, G. Franchetti, H. Y. Liu, and S. Wang

Phys. Rev. Accel. Beams **26**, 024201 – Published 9 February 2023

The newly-installed magnet alloy rf cavity for the CSNS-II (Sep. 2022)



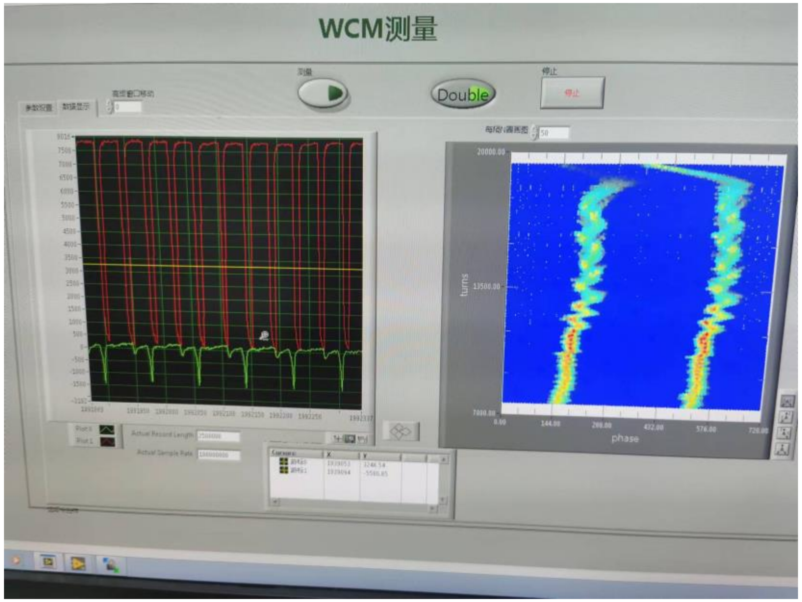
Courtesy of Dr. Yaoshuo Yuan (IHEP CAS)

Future plan

Bunch-merging study @ CSNS/RCS

Experiments of bunch merging has been performed with only one rf cavity

- **Conclusion:** the bunch-merging in the CSNS/RCS works with the Desynchronization method.
- **Problems:** is not enough. In the future, the second rf cavity will be installed to supply sufficient rf voltage for bunch merging.



Experimental results of the bunch merging via the wall current monitor (WCM) in the CSNS/RCS

Thanks!

Courtesy of Dr. Yaoshuo Yuan (IHEP CAS)