MIP 2024, Peking University, 20th Apr. 2024

Toward A High-intensity Muon Source at CiADS

Han-Jie Cai, Yuanshuai Qin, Huan Jia, Jianwei Niu,
Zhilv Zhang, Yuan He

Institute of Modern Physics, Chinese Academy of Sciences

Outlines

- The CiADS Linac for Muon Source
- Lithium Target for Muon Source
- The Plan and the Conceptual Design
- Summary

How many muon sources do we need?

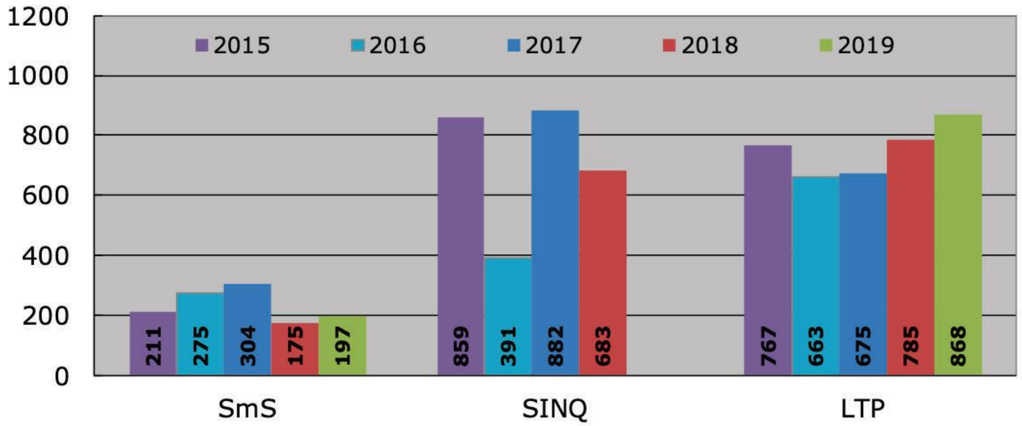
- **Muon Facilities**
  - **5 existing muon sources, 2 pulsed ones and 3 CW ones**
  - **4 muon beam lines for dedicated muon experiments**

- **Future Facilities**
  - **Upgrade project (HiMB) at PSI**
  - **CSNS and ROAN muon source are under construction**
  - **Plans at SNS, SHINE and CiADS**

- **So, will there be too many muon sources?**

How many muon sources do we need?

User statistics for the SINQ neutron source and SμS muon source at PSI



from "IMPACT Conceptual Design Report"

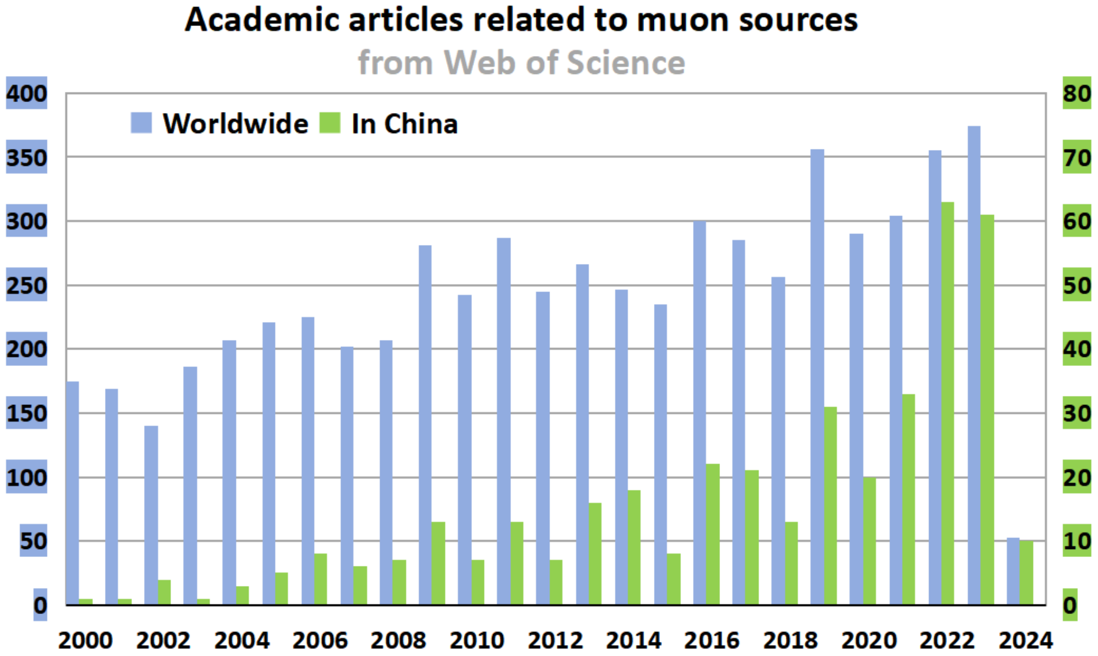
■ **Requirement of muon beam time**

- At PSI, about 65% of the beam time is used by an average of 230 μSR users every year, the rest being used by the particle physics community.
- For μSR, the instruments are 2 ~ 3 times oversubscribed at ISIS and PSI.

from "Science Case for the new High-Intensity Muon Beams HIMB at PSI" and Adrian Hillier

■ **R&D interest in the muon source topic**

- According to Web of Science, the R&D interest in muon source topic increased by twice in the last twenty years.
- In China, the number of academic articles related to muon sources has dramatically increased from just one or two articles per year to over 60 annually.

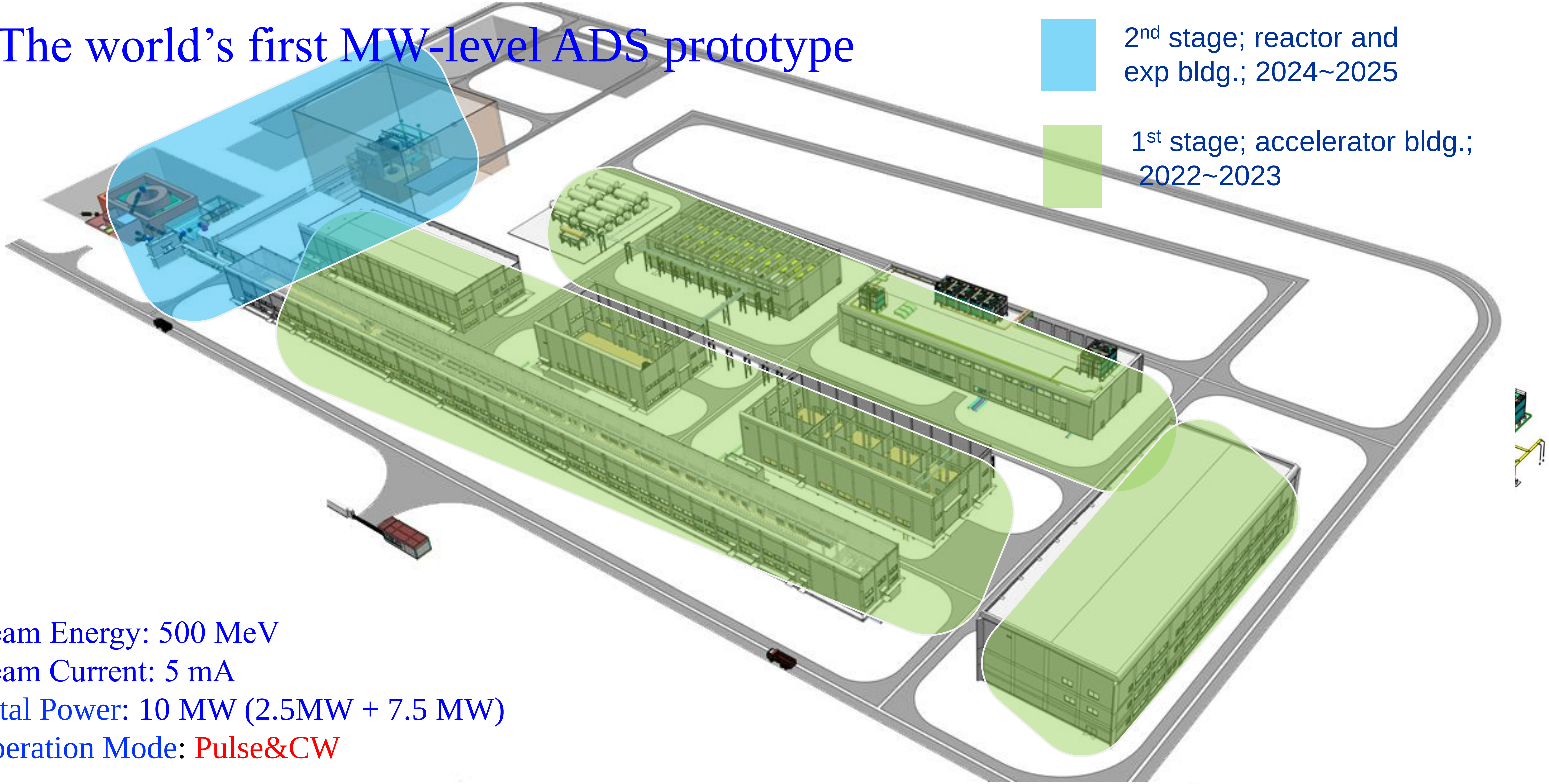


The CiADS Project

- **Approved in Dec. 2015, Ground broke in August 2018, Officially started in July 2021**
- **Leading institute: IMP**
- **Budget: ~4 B CNY (Gov. 1.8B + CNNC 1.0 B + Local Gov. 1.2 B)**
- **Location: Huizhou, Guangdong Prov.**

CiADS Project

The world's first MW-level ADS prototype



- Beam Energy: 500 MeV
- Beam Current: 5 mA
- Total Power: 10 MW (2.5MW + 7.5 MW)
- Operation Mode: Pulse&CW

Timetable of the CiADS Linac (2025 ~ 2030)

2025 ~ 2026年

25 kW:
500MeV & 50μA

- Construction
- Commissioning

2026 ~ 2027年

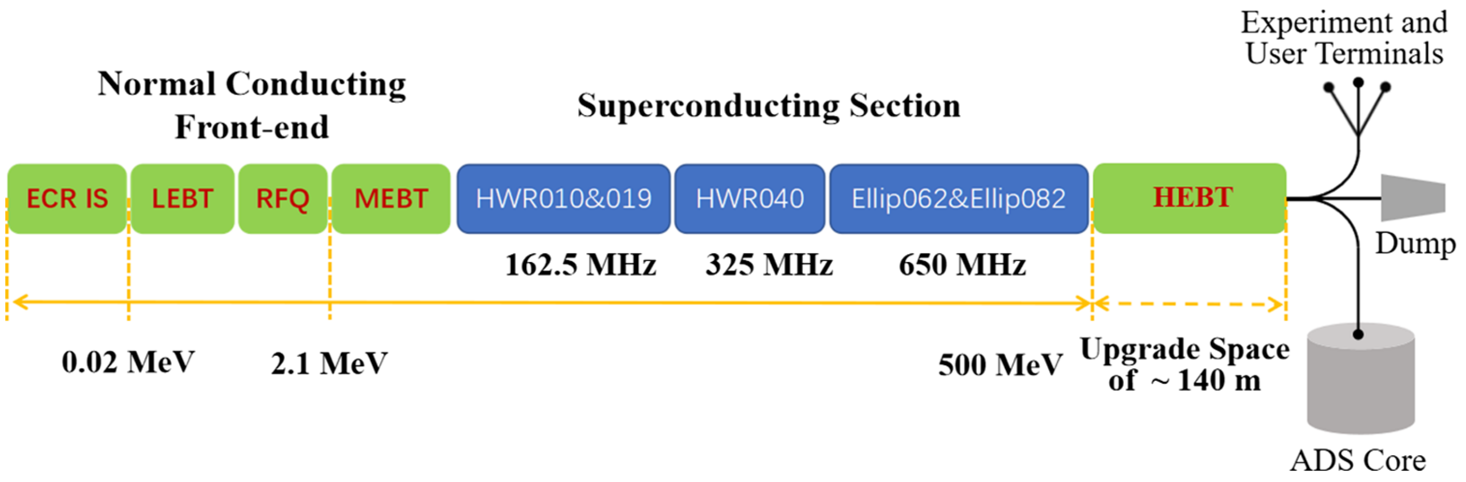
250 kW:
500MeV & 500μA

- Accelerator stability study
- Beam to the subcritical core and the terminals

2027~2030年

2.5 MW:
500MeV & 5mA

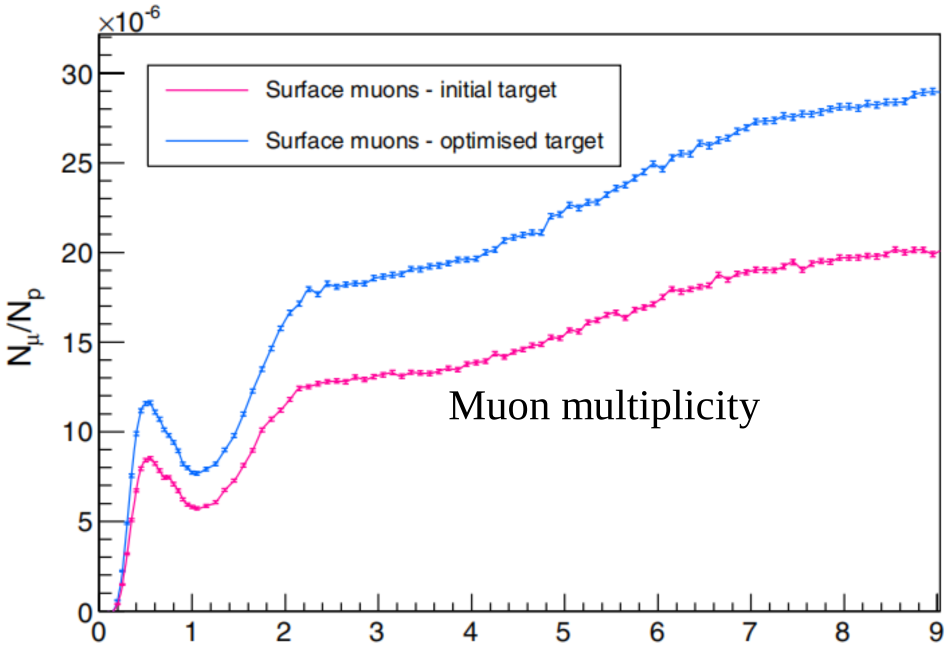
- 2.5MW Commissioning
- Normal operation with 2.5 MW beam

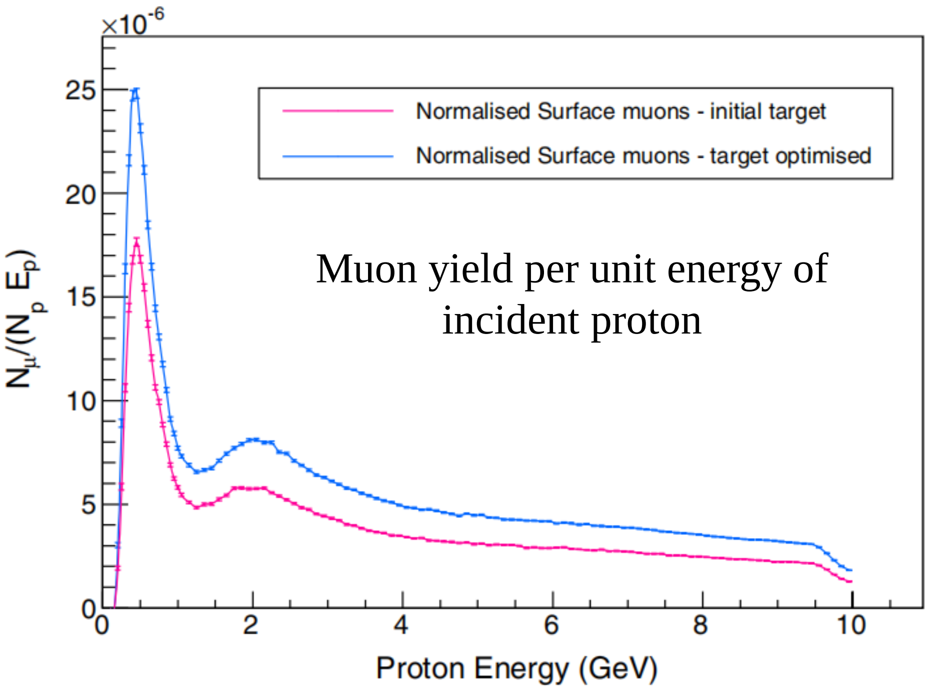


- The space for upgrading the linac to an energy of 1.5 GeV has been reserved.
- The upgrade to 600 MeV before 2027 is now under consideration.

Features of the CiADS Proton Beam for Muon

- The beam energy of 500 MeV is quite efficient in surface muon production for its high beam utilization rate in a surface muon production target which is usually has a limited length. (A. Bungau et al, PRAB 17, 034701, 2014)
- Unprecedented proton beam current of 5 mA will provide opportunities for new muon intensity record

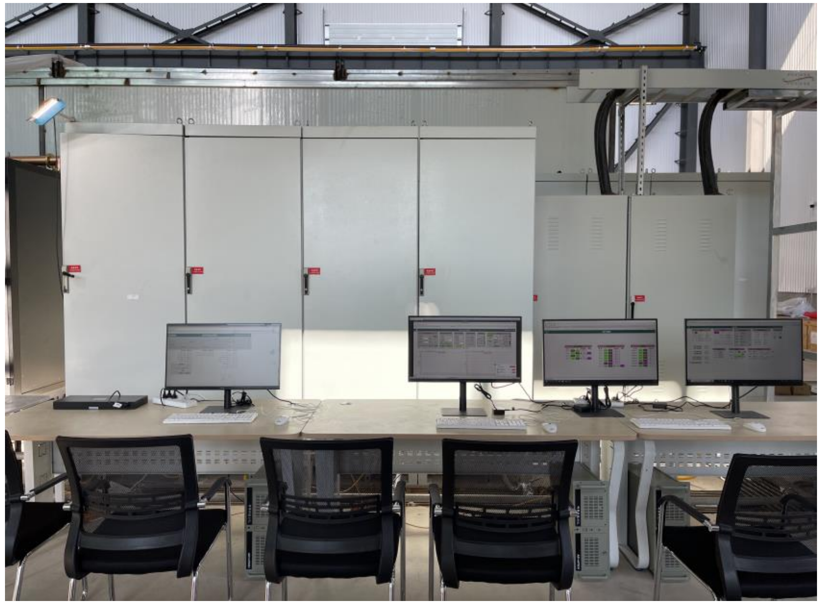


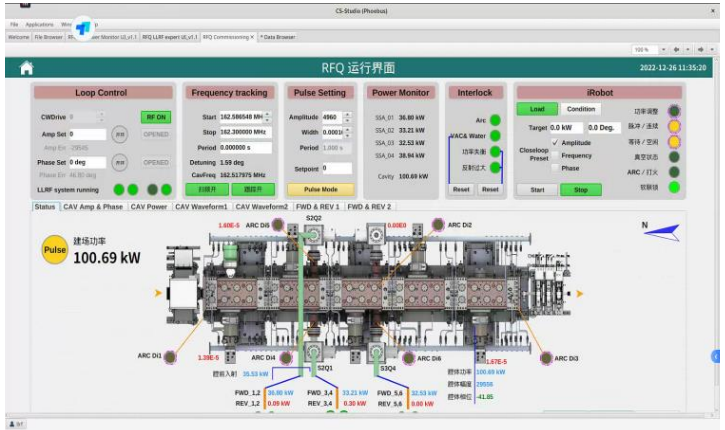


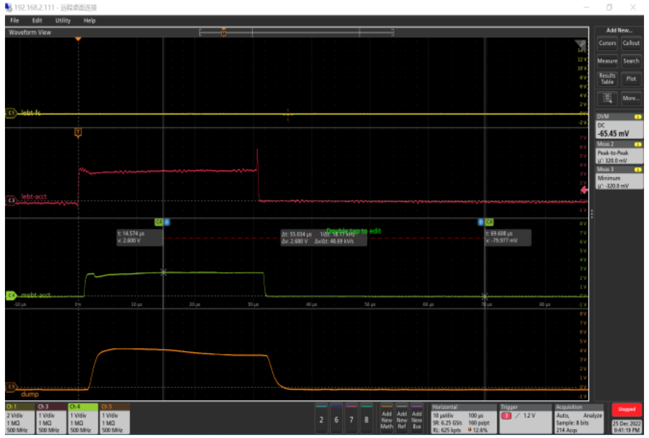
A. Bungau et al, *PRAB 17, 034701, 2014*

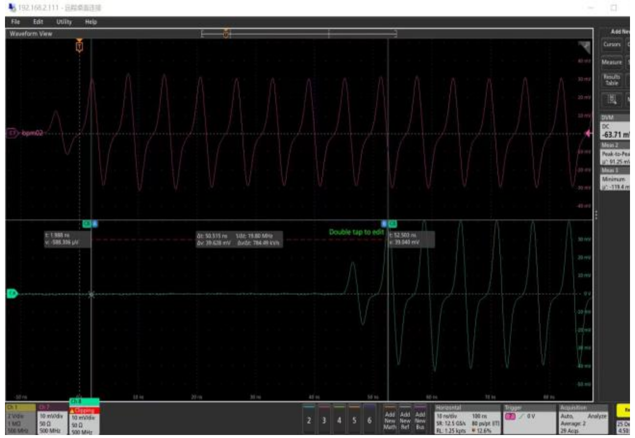
Progress of the Linac

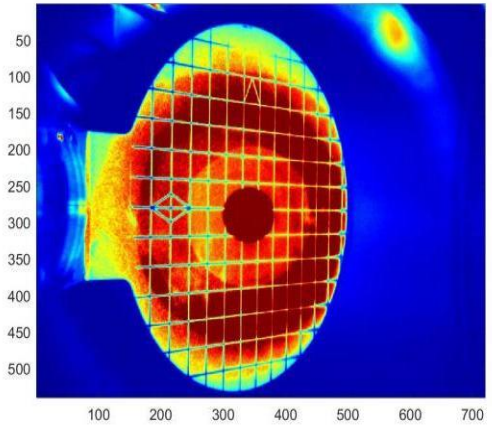
- **Normal conducting front end, beam commissioning @ 5.2mA, 2.18MeV**











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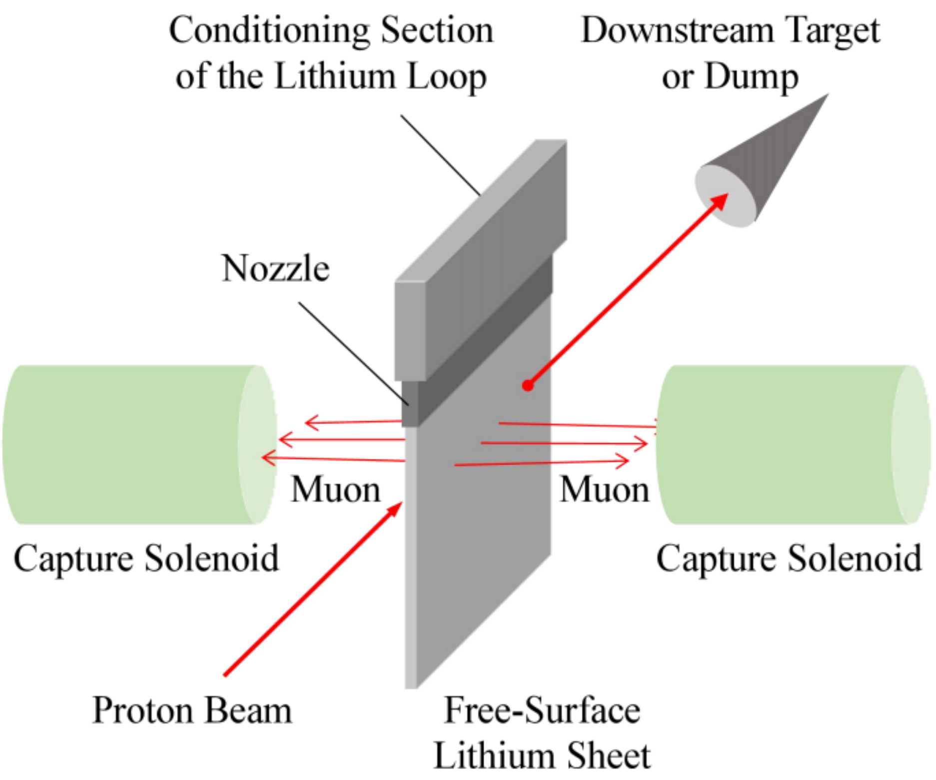
Conceptual Solution of the Production Target



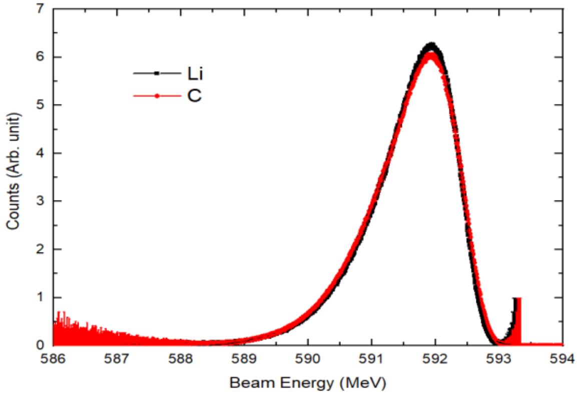
- Pressured liquid lithium flows through the conditioning section of a lithium loop and finally forms a sheet-shaped jet out of the narrow nozzle.
- The proton beam is collimated to hit the lithium jet under a small angle
- Surface muons produced in lithium escape from either side of the sheet, entering the capture field of the solenoids.

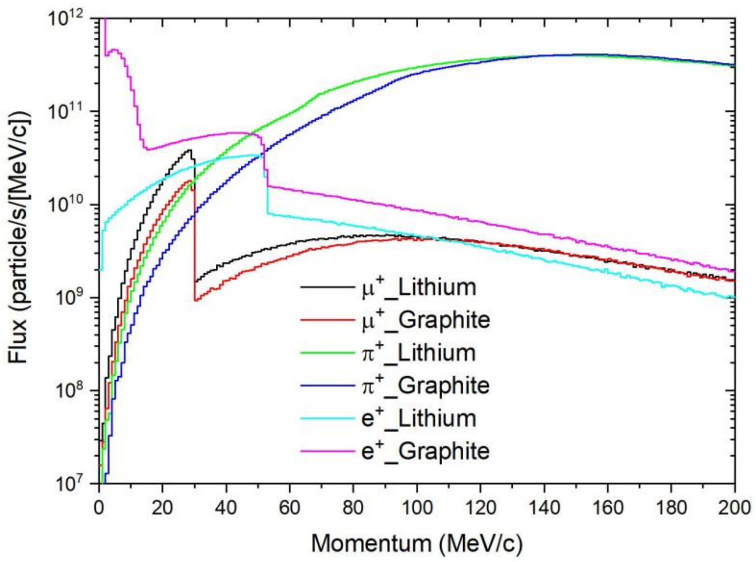
Conceptual Solution of the Production Target

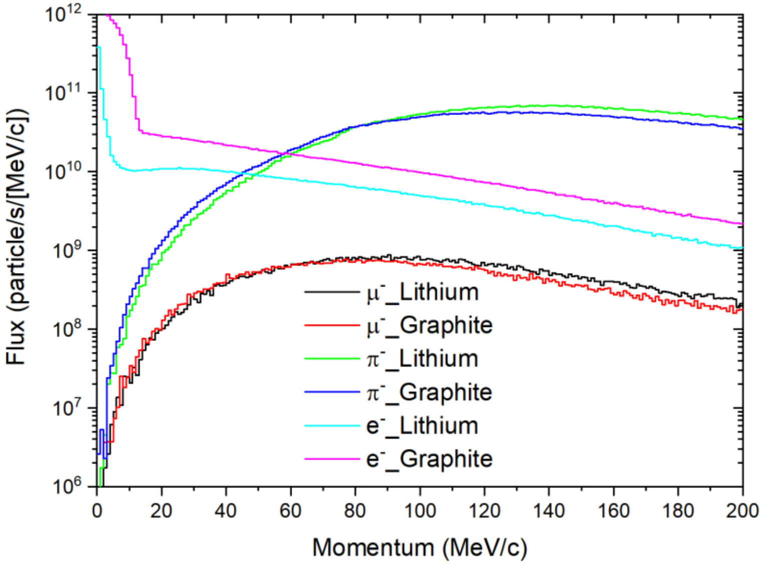
- **Higher muon rate & lower backgrounds**
  - With an identical proton beam consumption rate. the yields of μ^+ and π^+ is higher for lithium target, especially in the momentum range from 0 to 100 MeV/c. The surface muon will be double.
  - The substantial backgrounds from positrons and electrons are about one order of magnitude lower, which will make the background separation requirements less challenging.

7.8-cm lithium Vs 2-cm graphite

	2-cm graphite	7.8-cm lithium	Unit
$I_{\text{det 1}}$	0.57	1.22	10^{-5} μ^+/p
$\varepsilon_x(1\sigma)/\varepsilon_y(1\sigma)$	506/548	767/571	π cm mrad
Polz	66.8	66.9	%



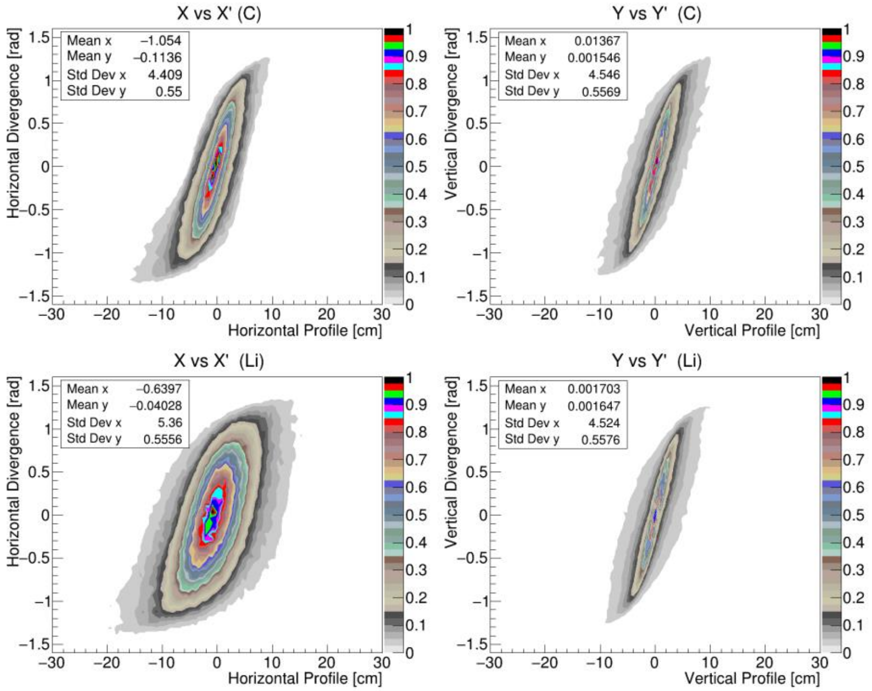




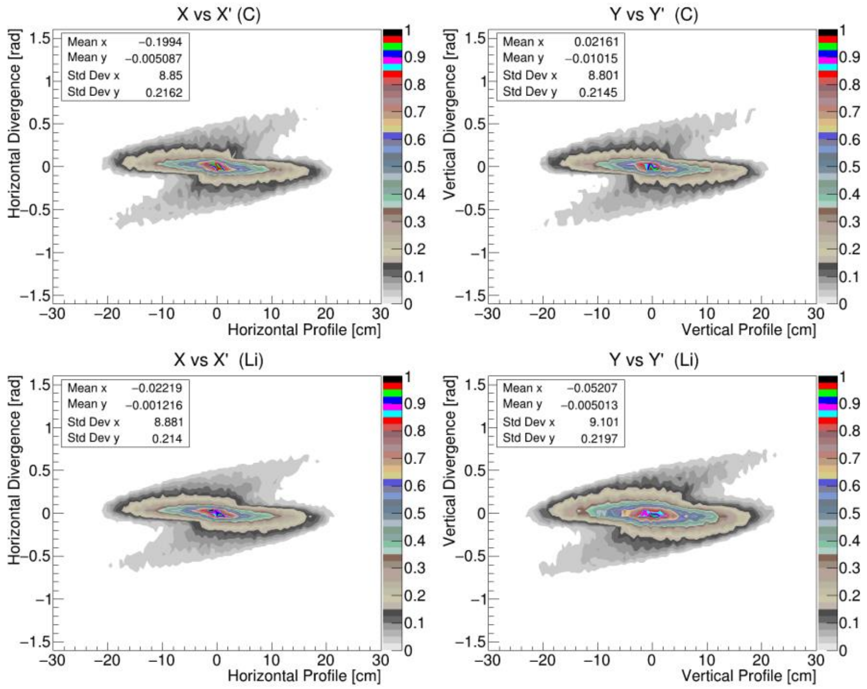
Emittance

- The emittance at the Li target surface is apparently larger due to the target length
- The distributions in phase space after the capture solenoids become almost the same.

Before capture solenoid

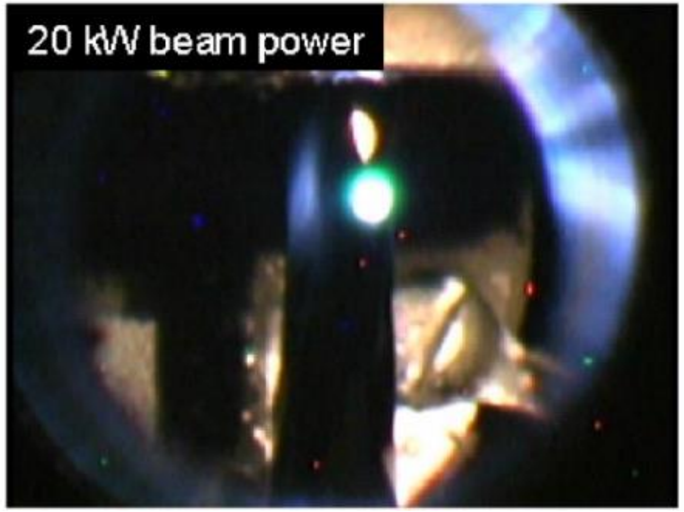


After capture solenoid

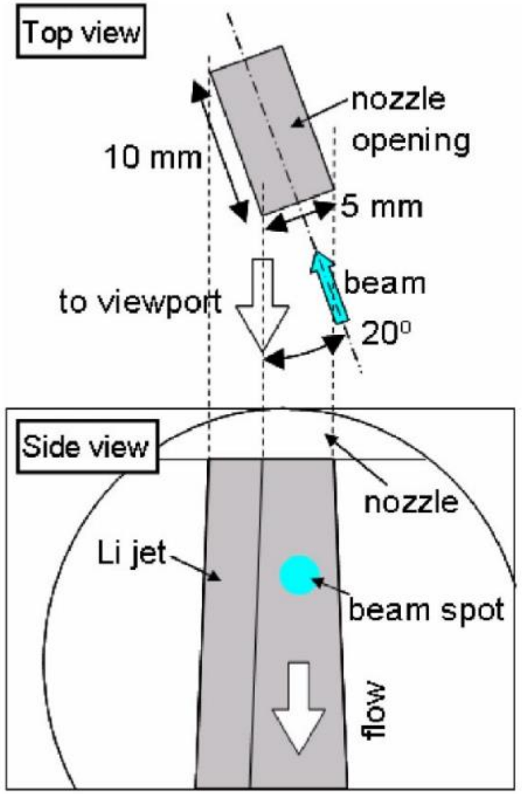


Feasibility of the Lithium Jet Target

- At ANL, experiments were conducted by Nolen et al.
- The free-surface lithium jet flowing at 1.8 m/s operates stably.
- With a beam energy deposition up to 20 kW, no disruption or excess vaporization was observed.

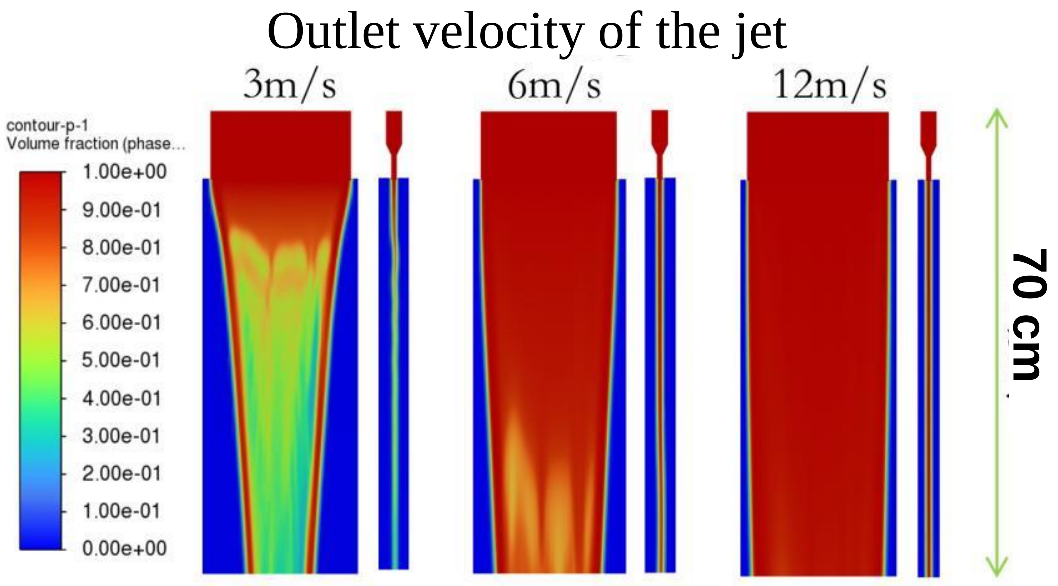


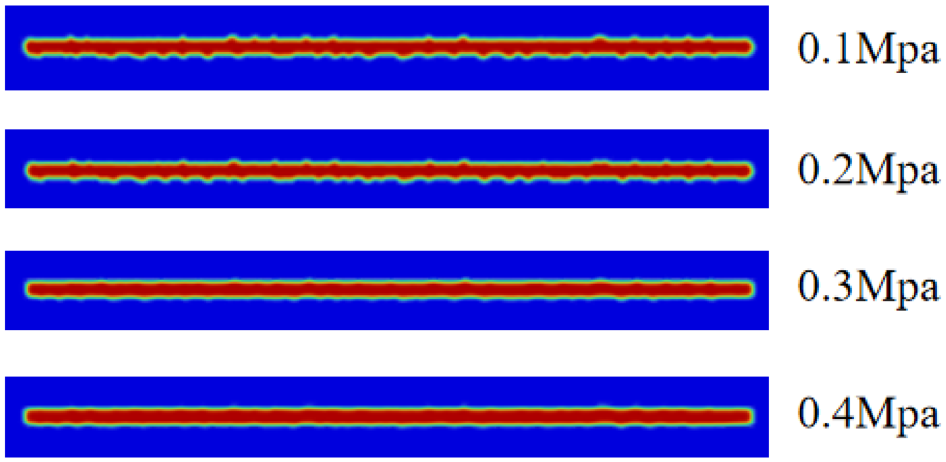
J.A. Nolen et al.,*Rev. Sci. Instrum*. 76, 073501 (2005)



Feasibility of the Lithium Jet Target

- Stable jet can be obtained in the target area when the nozzle outlet jet velocity is 12m/s.
- When the inlet pressure increases from 0.1 MPa to 0.4 MPa, we observed a significant reduction in the amplitude of the free surface waves.





Volume fraction of lithium

See the poster by Jianwei Niu, No20, Simulation study of the liquid lithium target for the CiADS muon source

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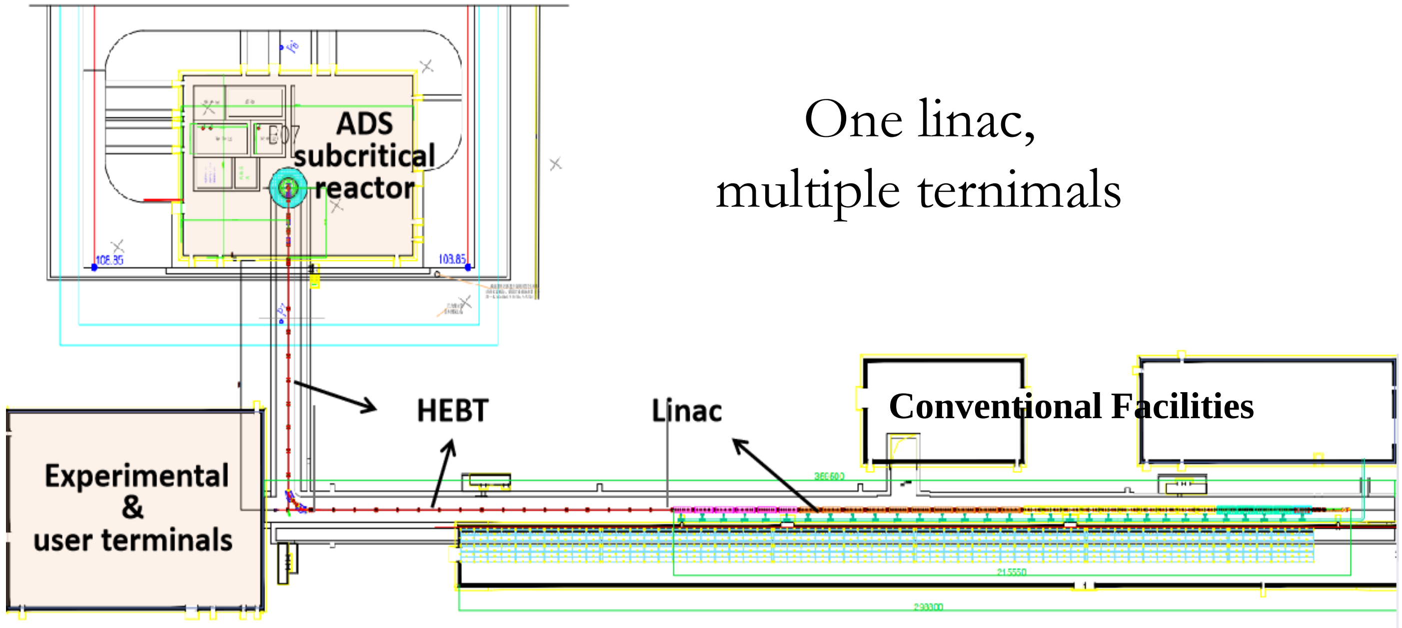
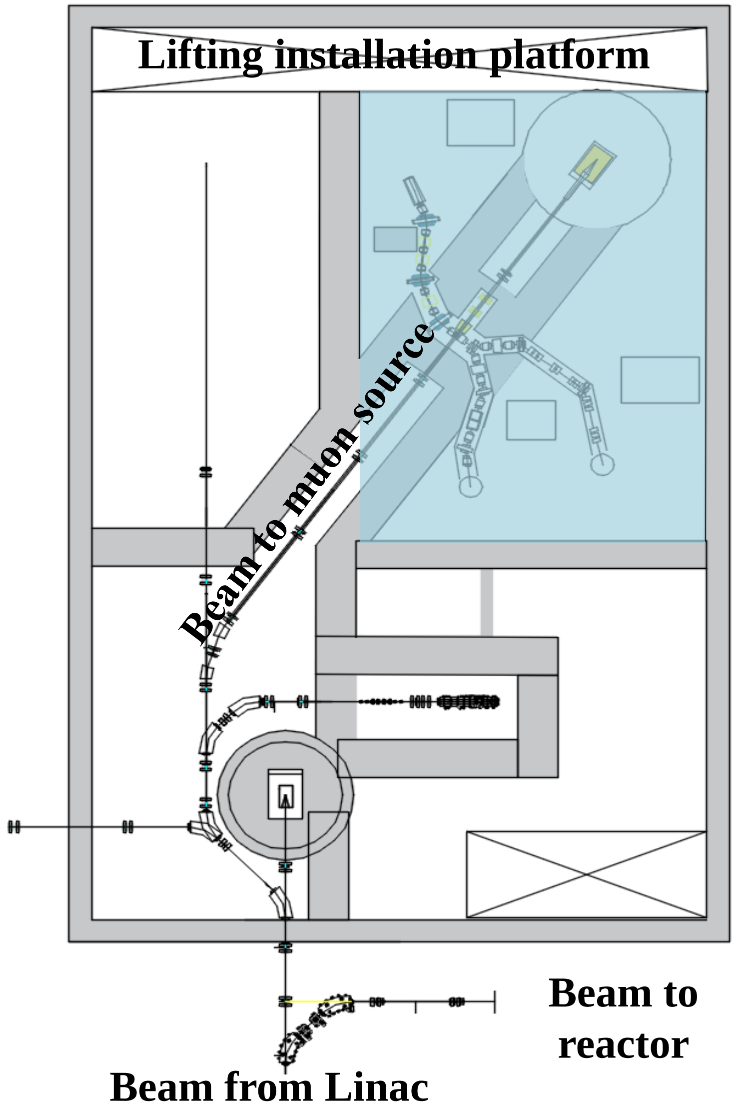
Availability of the CW Muon Source

- The subcritical reactor is designed to operate for 3 months/year.
- The muon target station is upstream the material irradiation station, both of them are schemed to operate with high beam-time occupancy.

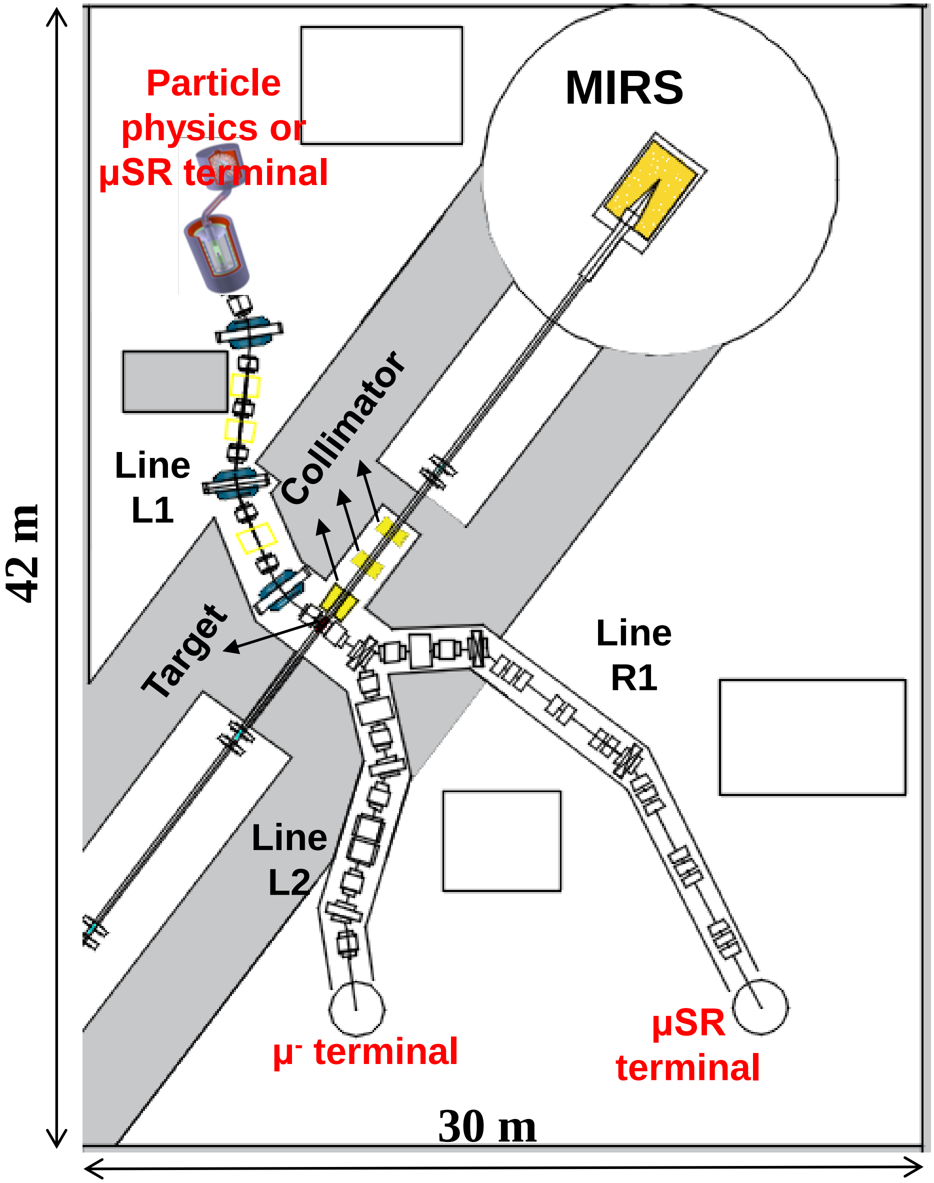


One linac,
multiple ternimals



Conceptual Layout of the Muon Source

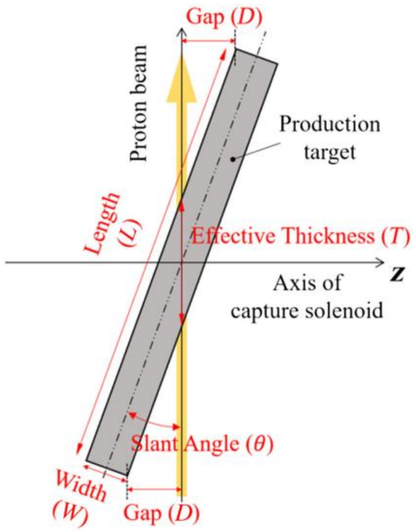
- An area of >1200 m^2 is available for muon source together with the material irradiation station
- One production target, 2 large aperture capture solenoids, which are mechanically mirror symmetric, supporting 3 muon beam lines (2 μ^+ & 1 μ^-) to work simultaneously
- The beamlines feature two or three dipoles of moderate deflection angles to obstruct any direct line-of-sight from the experimental areas onto the production target
- Surface muon and the decay muons up to 80 MeV/c can be provided at the L1 line. Low energy muon beam is planned to be developed at either L1 or R1 line
- Available space for each terminal is ~50 m^2

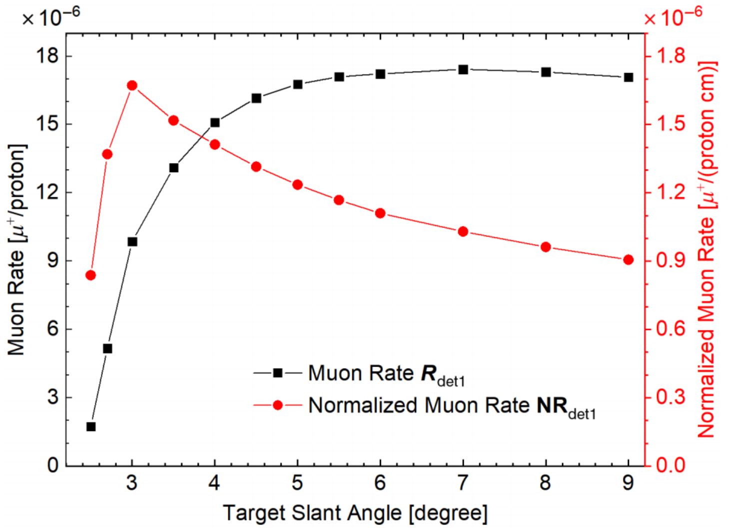


Courtesy of Prof. Jian Tang for the diagram of the MACE spectrometer

Conceptual Design of the Capture Part

- **Optimization of the target geometry configuration**
  - The slanted geometry is used for a higher muon rate
  - The target width and slanted angle have been optimizated. With a width of 5 mm a slant angle of 3.5 degree, the effective thickness is about 8 cm





- **A more compact capture part**
  - The rate after the solenoid increases by 50%, the emittances in both the horizontal and vertical planes decrease by around 15%

Aperture 50 cm	Distance between target and coil 30 cm	20 cm	10 cm	Unit
$R_{\mathrm{det}\,2}$	2.97	3.74	4.45	$10^{-6}\ \mu^+/\mathrm{p}$
$\varepsilon_x(1\sigma)/\varepsilon_y(1\sigma)$	603/629	561/587	526/544	π cm mrad
Polz	93.2	94.6	95.5	%

Aperture 40 cm	Distance between target and coil 30 cm	20 cm	10 cm	Unit
$R_{\mathrm{det}\,2}$	2.21	2.89	3.78	$10^{-6}\ \mu^+/\mathrm{p}$
$\varepsilon_x(1\sigma)/\varepsilon_y(1\sigma)$	407/431	379/405	368/384	π cm mrad
Polz	93.2	94.7	95.9	%

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 023403 (2024)

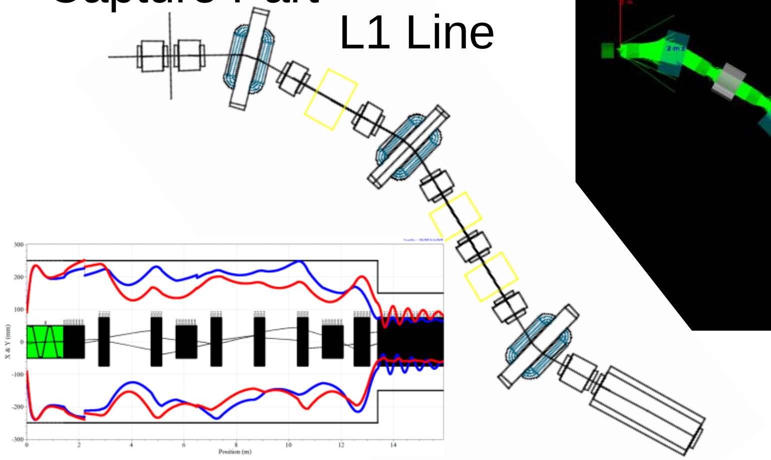
Towards a high-intensity muon source

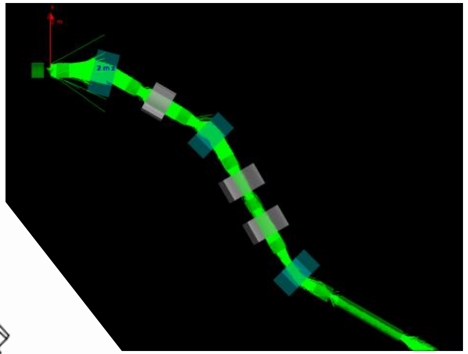
Han-Jie Cai,[1,2] Yuan He,[1,2,*] Shuhui Liu,[1,2] Huan Jia,[1,2] Yuanshuai Qin,[1] Zhijun Wang,[1,2] Fengfeng Wang,[1,2] Lixia Zhao,[1] Neng Pu,[1] Jianwei Niu,[1,2,3] Liangwen Chen,[1,2] Zhiyu Sun,[1,2] Hongwei Zhao,[1,2] and Wenlong Zhan[1,2,4]

[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*School of Nuclear Science and Technology, University of the Chinese Academy of Sciences, Beijing 100049, China*
[3]*Lanzhou University, Lanzhou 730000, China*
[4]*Chinese Academy of Sciences, Beijing 100864, China*

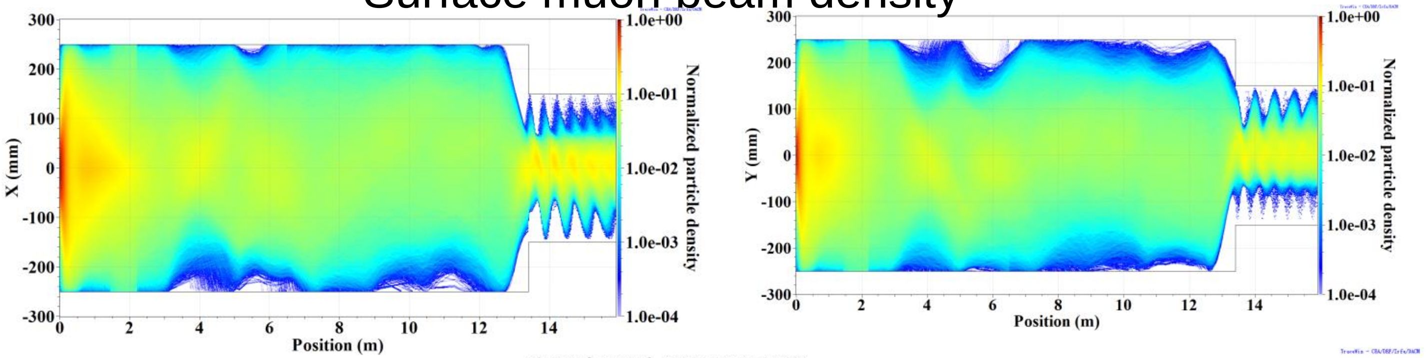
(Received 4 September 2023; accepted 12 February 2024; published 27 February 2024)

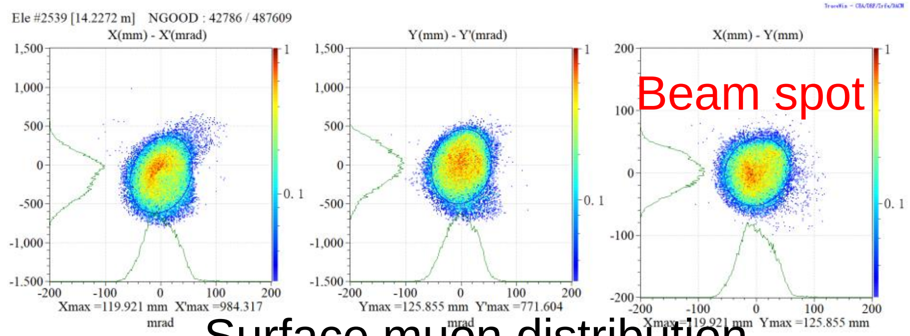
Conceptual Design of the Muon Beam Line



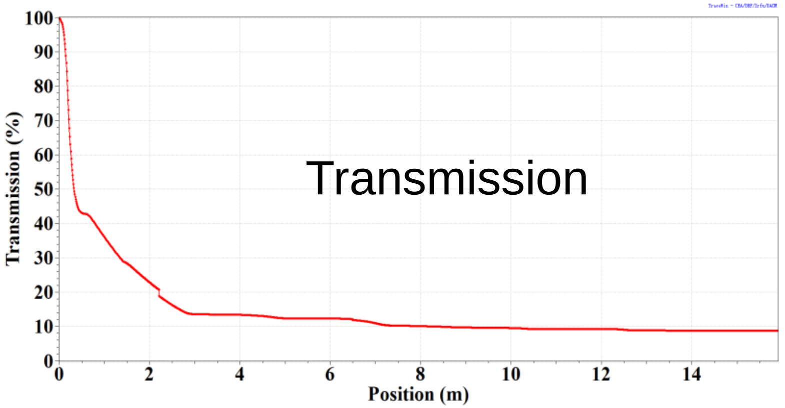


Surface muon beam density





Surface muon distribution

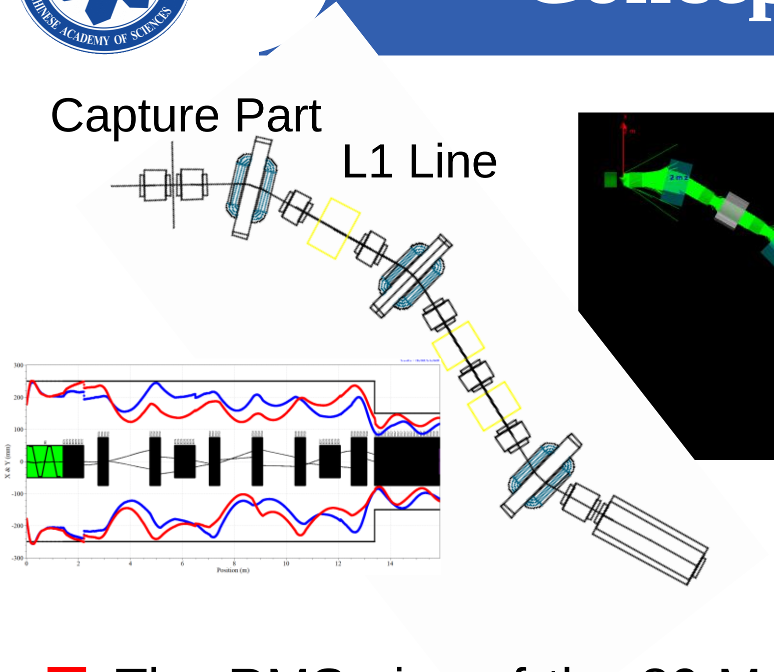


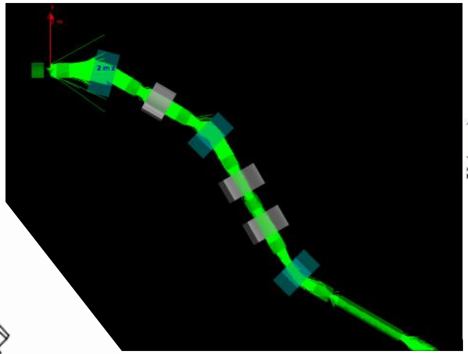
- The L1 beam line is planned to provide high-intensity surface muons as well as decay muons. Solenoid-based design to make the beam line compact and to achieve high transmission efficiency
- The RMS size of the surface muon beam is ~27 mm (Gaussian-like). A transmission efficiency of ~9% can be achieved with three deflections.
- The rate of surface muon beam will be up to 3.7E10 μ^+/s with a 5-mA proton beam

Conceptual Design of the Muon Beam Line

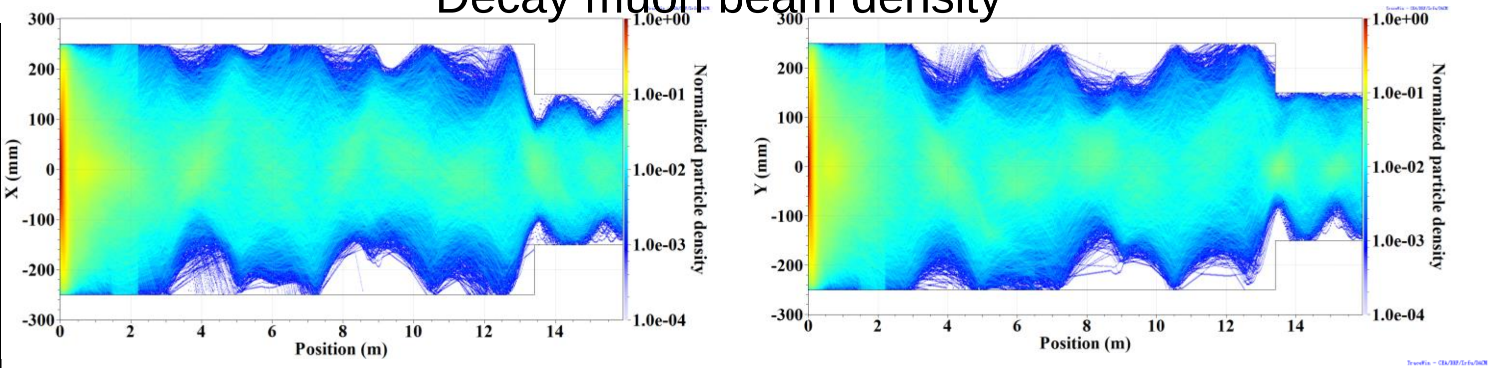
Capture Part

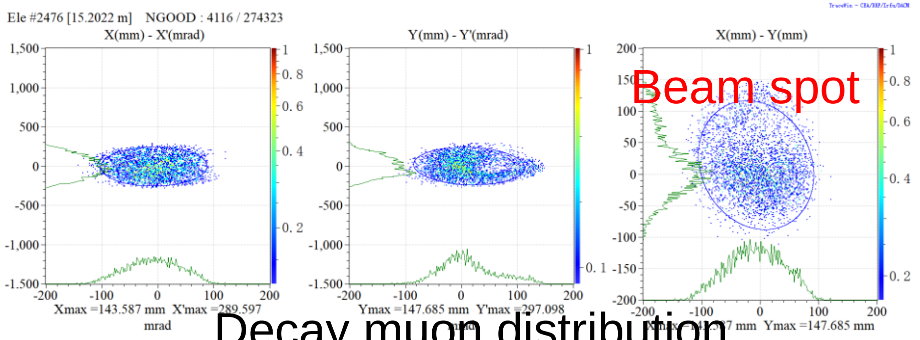
L1 Line





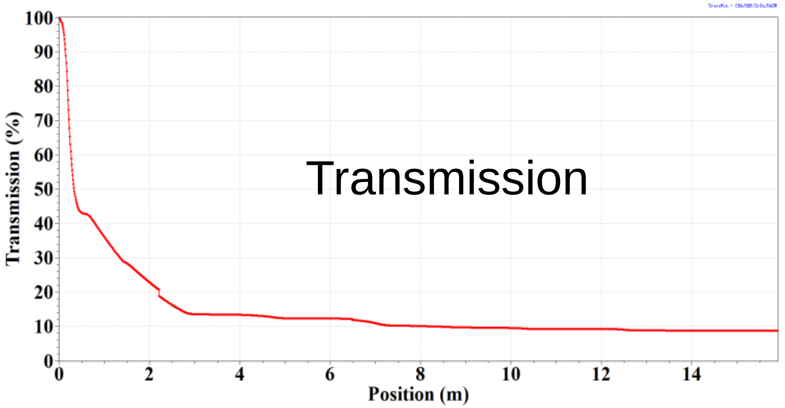
Decay muon beam density





Beam spot

Decay muon distribution



Transmission

- The RMS size of the 80-MeV/c decay muon beam is about 47 mm (Gaissian-like) and the transmission efficiency of is ~1.5%
- Despite the relatively low efficiency and the large beam size, with a 5-mA proton beam, the rate of the 80-MeV/c muon beam is still as high as 3.6E9 μ^{+}/s
- The possibility for the transport of higher energy decay muons is under consideration

Plan of the CiADS Muon Source

2024 ~ 2026年 — **R&D**
- Conceptual and engineering design
- key technologies verification

2027 ~ 2028年 — **Construction**
- Manufacture and installation of one muon beam line
- Commissioning and pilot operation under 0.5mA proton beam

2029~2032年 — **Operation & Upgrade**
- User operation
- Construction of 2 more lines
- Upgrade to 5mA proton beam on target

		Surface muon (1/s)	Low energy muon (1/s)	Decay muon (1/s)
Phase I 0.5mA	C target	1.5E9	1.8E5	1.5E8
	Li target	4E9	5E5	4E8
Phase II 5mA		4E10	5E6	4E9

- Both rotation graphite target and lithium jet target are under consideration in the Phase I
- In Phase II, tandem production targets is planned to support more muon beam lines

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Summary

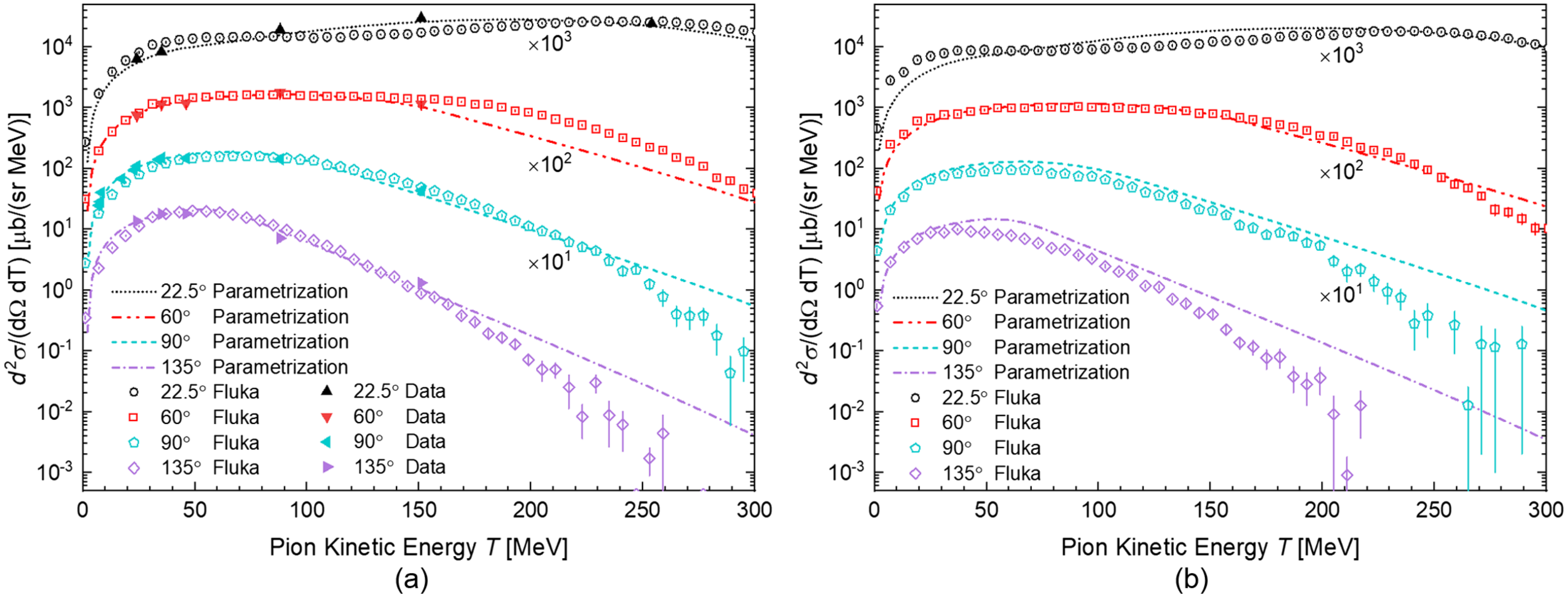
- The intense CW beam provided by CiADS Linac can be used to drive a high-intensity muon source. The plan is to start with an initial project with a moderate beam power of 300 kW driving one muon beam line, and to upgrade it afterward.
- We believe the unprecedented muon intensity will enable new experiments with considerable discovery potential and unique sensitivities in particle physics, condensed matter physics, and materials science.
- The R&D efforts for a muon source at CiADS shall benefit from and make contributions to the community. Any advice for the muon source and the application terminals are warming welcome.

Thanks for your attention!

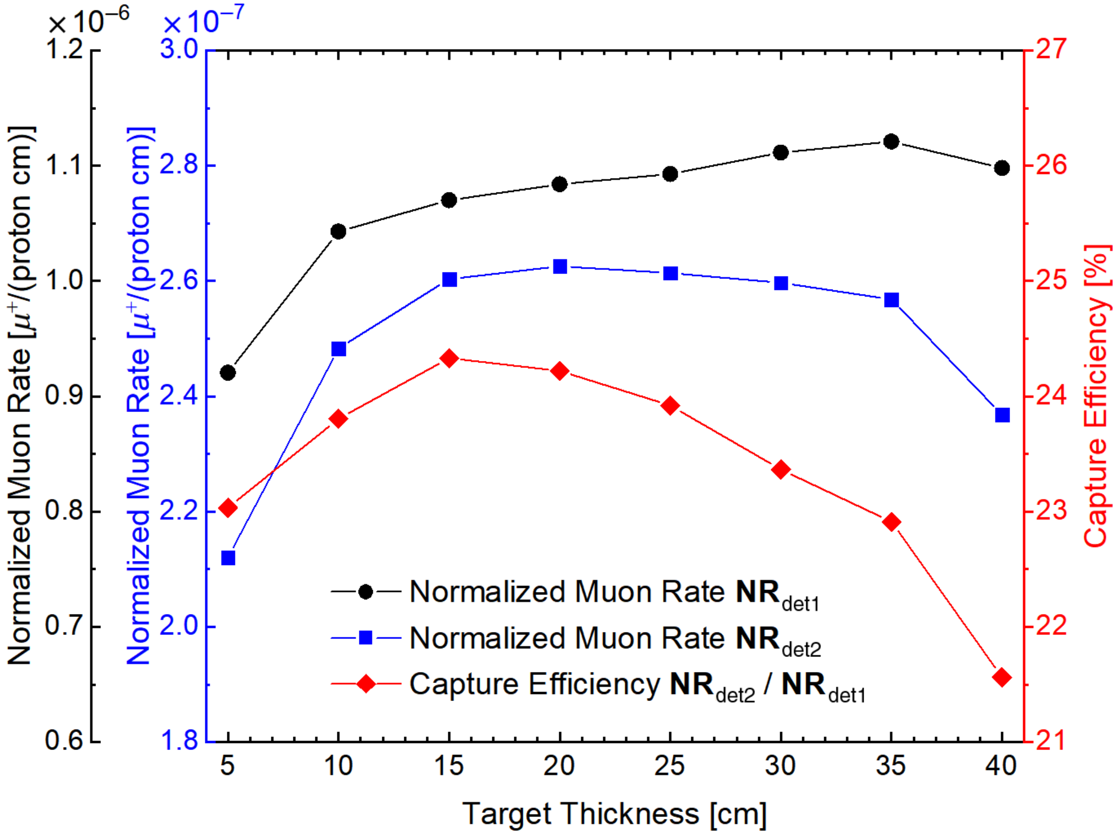
Welcome Collaborations !

Backup

Prodution Cross Section of Pi+ for Li and C



Capture efficiency varies with target length



Polarity of the two capture solenoids