Plan for CiADS Muon Source & Recent R&D Progress

Muon **S**cience and **T**echnology application platform at CiADS (**MuST-CiADS**)

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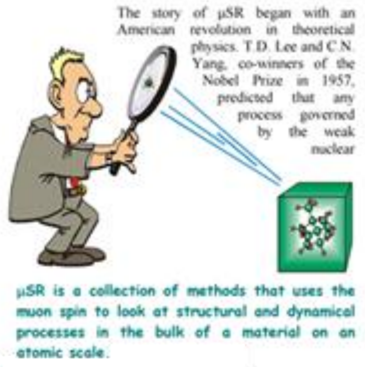
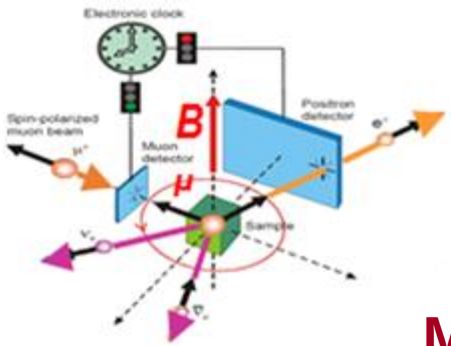
Outline

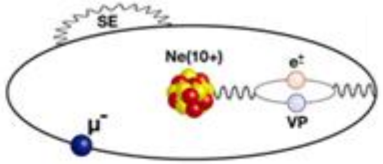
- Motivations
- Plan for CiADS muon source
- Recent R&D progress
- Future key technologies
- Summary

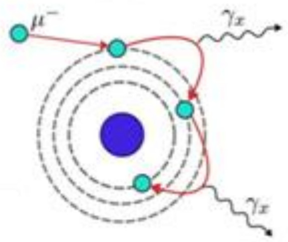
Motivations

Muon source applications

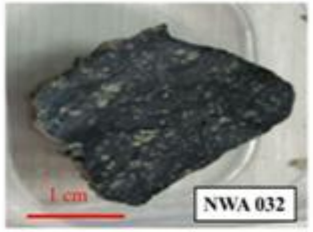








Precision tests of strong-field QED; nuclear structure studies; MIXE Elemental Analysis



Muon applications

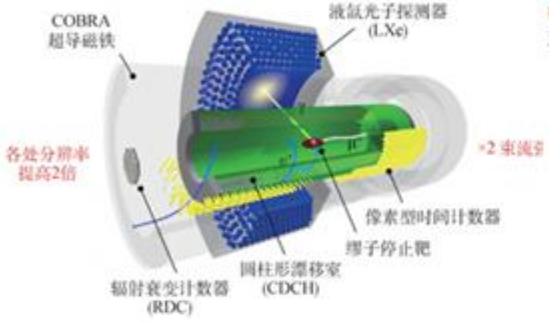
μSR: Magnetic materials; superconductors; semiconductors; battery energy studies; biophysics; chemistry, etc.

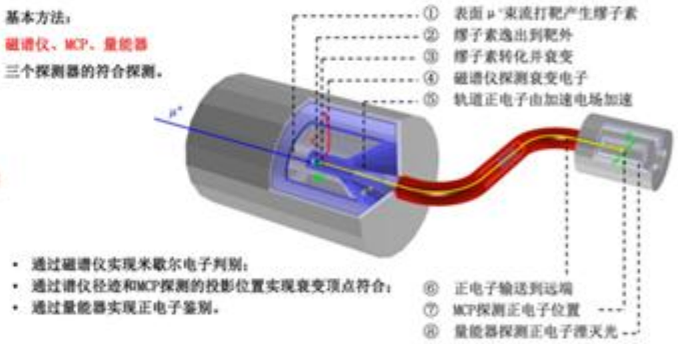
Muonic Atom X-ray Applications: Precision measurements/elemental analysis; catalyzed cold fusion; muon imaging; muonium applications…

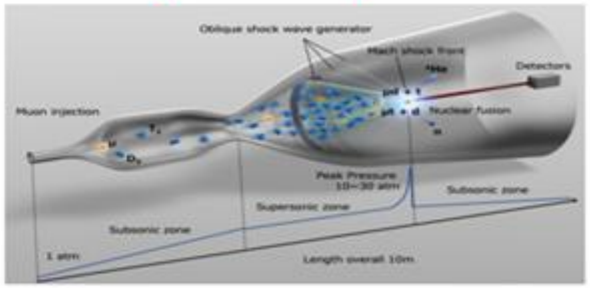
Particle Physics: MEG, Mu3e, Mu2e, MACE, anomalous magnetic moment, electric dipole moment, etc.

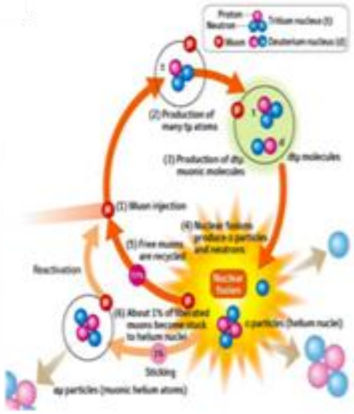
$$d + t \rightarrow \alpha + n + 17.6\,\mathrm{MeV}$$

$$d + t + \mu^- \rightarrow \alpha + n + \mu^- + 17.6\,\mathrm{MeV}$$









Muon source applications in China

Muon research and applications in China

1. Condensed Matter Physics Experiments Based on μSR Technique

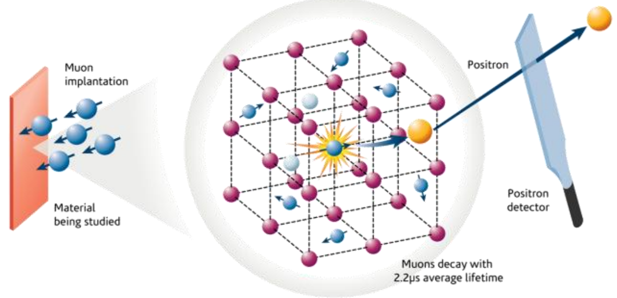
- Superconductivity, semiconductors, magnetic materials, quantum criticality, non-Fermi liquid behavior... (Fudan University, East China Normal University, Institute of Physics CAS, Zhejiang University, USTC, Shanghai Jiao Tong University...)

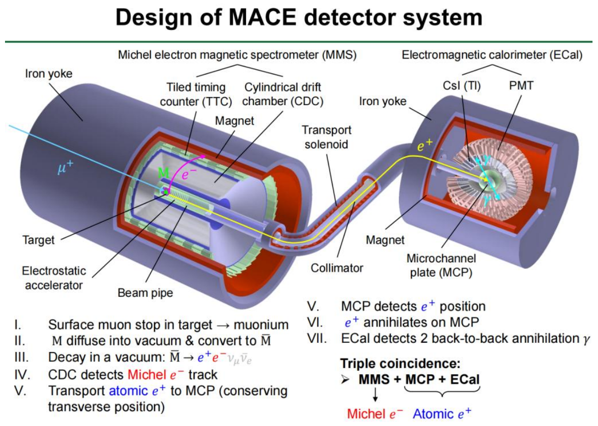
2. High-Precision Muon Physics Experiments

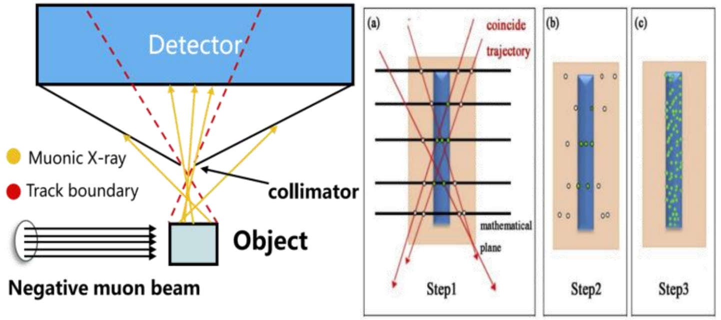
- Chinese deep collaborations in international muon experiments: Mu2e, COMET, g-2/μEDM... (IHEP, Shanghai Jiao Tong University, Sun Yat-sen University, IMP CAS...)
- MACE experimental plan, CDR release (Sun Yat-sen University)

3. Muonic Atom X-Spectroscopy and MIXE Applications

- Muonic X-ray tests of strong-field QED (proposal, SCNT)
- Nuclear structure studies via muonic atom spectroscopy (Central China Normal University)
- Elemental analysis and 3D reconstruction technology using muon-induced X-rays (USTC, University of South China, IMP CAS, etc.)
- ……







Muon facilities in the world

- **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**
  - **Several plans at SNS, SHINE, HIAF and CiADS**

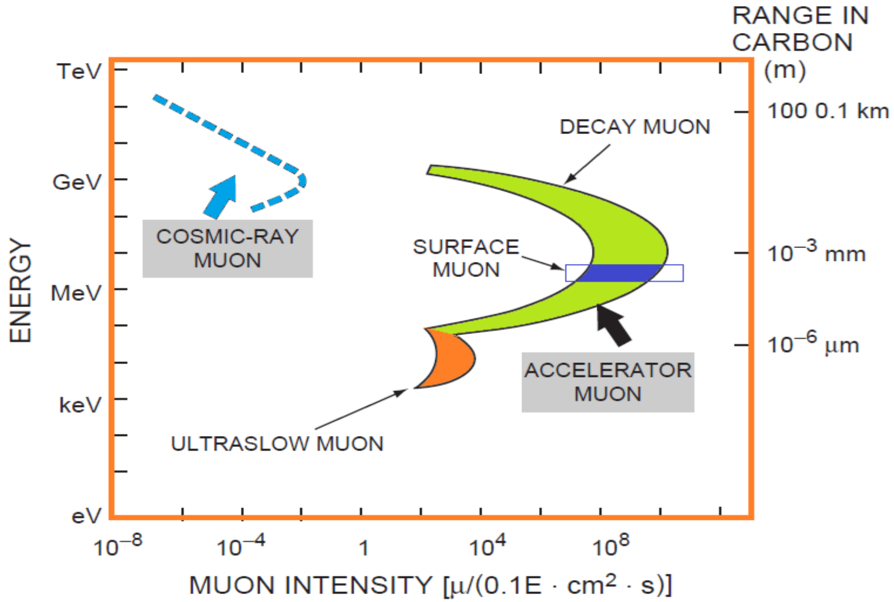
Increasing needs for muon source

- **Beam time allocation (PSI as example):**

  μSR~65% (cover 30%~40% user demand, Swiss users 40%);

  Particle physics + others ~35%

- **Trends:** More beamlines; Super-high intensity (10^9~10^{10}); Application extensions (new ideas, small-scale experiments); New technologies (production, collection/transportation, cooling/acceleration, detection)



- High-Precision Muon Physics Experimental Plans and Requirements

Experiment	Channel	Lab	Precision	Time	Intensity require. (1/s)
MEG-II	$\mu^+ \to e^+\gamma$	PSI	10^{-14}	2024+	10^8
Mu3e-II	$\mu^+ \to e^+e^+e^-$	PSI	10^{-16}	2029+	$>10^9$
COMET-II	$\mu^-N \to e^-N^*$	J-PARC	10^{-17}	2030+	10^{11}
Mu2e-II	$\mu^-N \to e^-N^*$	FNAL	10^{-18}	2030+	10^{11}
MACE	$\mu^+e^- \to \mu^-e^+$	SMOOTH	10^{-14}	2028+	Av10^8/Pk10^9

Muon source development in China

- **Accelerator Infrastructures:**
  - CSNS-I, CSNS-II, CiADS, HIAF, SHINE etc.
- **Long history of Chinese muon source**
  - Early preparation → Diversified proposals → quick R&D
  - **Program/plan list:**

    CSNS muon source ~ 2028

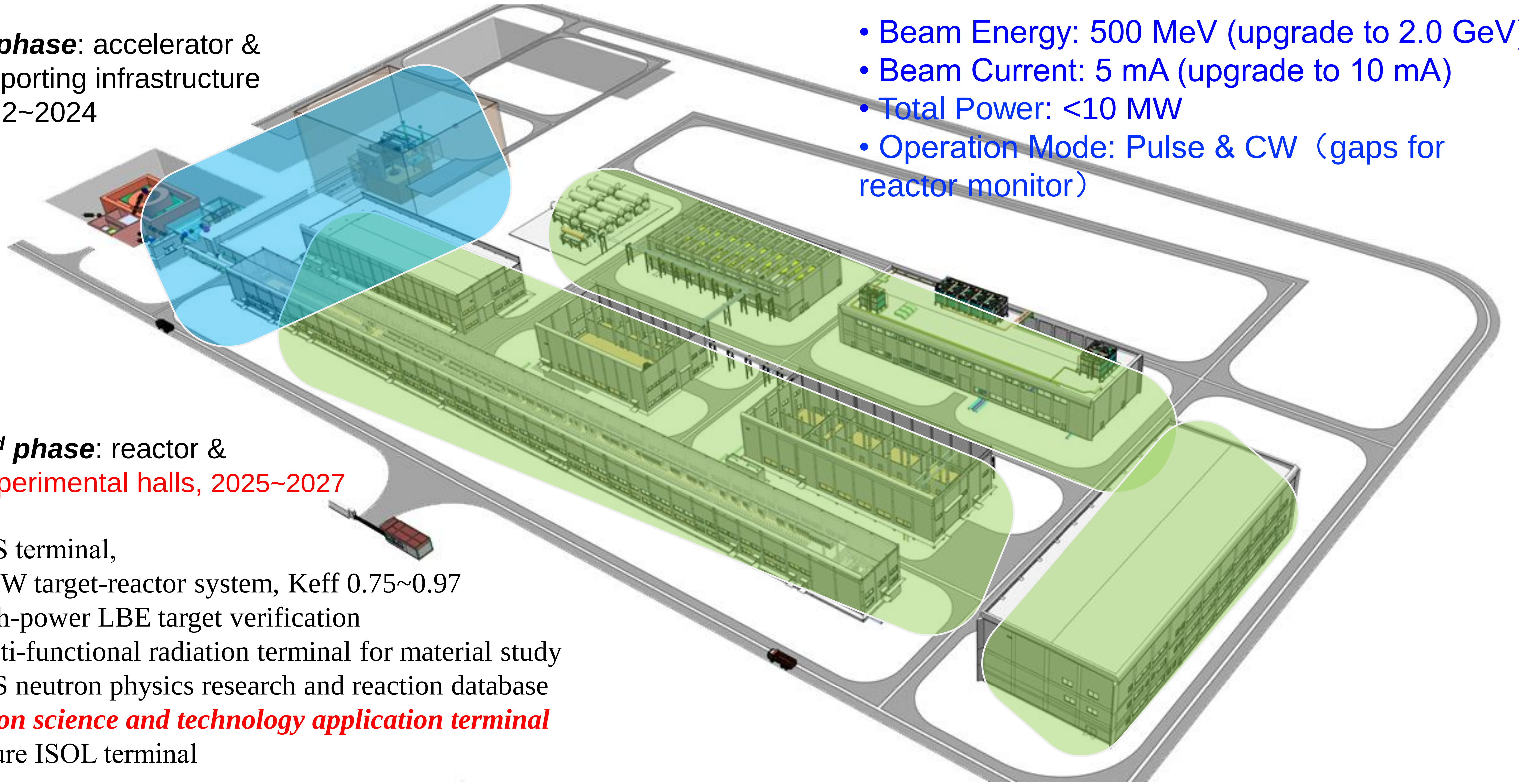
    CiADS muon source ~ 2028?

    HIAF GeV muon beam line ~ 2027?

    SHINE muon source ~ 2030?

Plan for CiADS muon source

CiADS project and design specifications



1st phase: accelerator & supporting infrastructure 2022~2024

2nd phase: reactor & experimental halls, 2025~2027

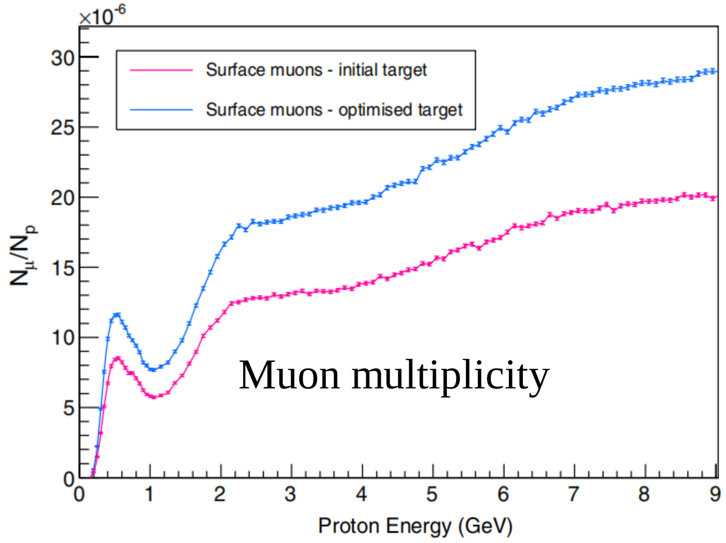
- Beam Energy: 500 MeV (upgrade to 2.0 GeV)
- Beam Current: 5 mA (upgrade to 10 mA)
- Total Power: <10 MW
- Operation Mode: Pulse & CW（gaps for reactor monitor）

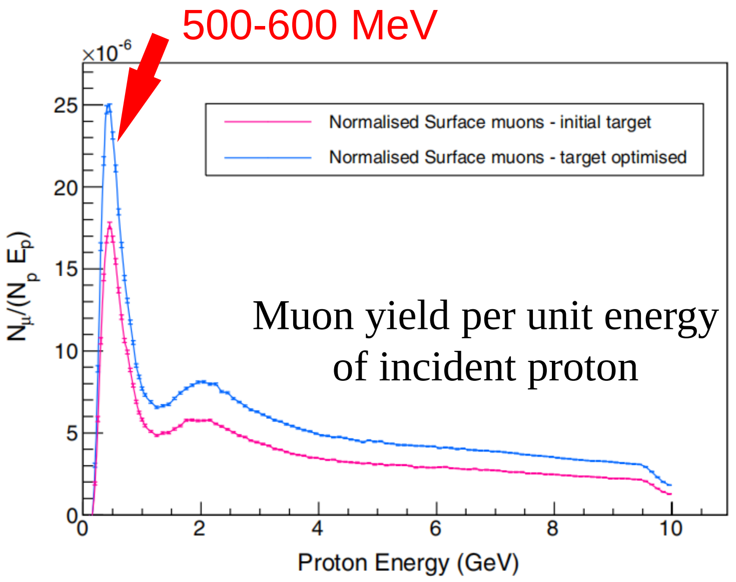
- T1: ADS terminal,
  10MW target-reactor system, Keff 0.75~0.97
- T2: High-power LBE target verification
- T3: Multi-functional radiation terminal for material study
- T4: ADS neutron physics research and reaction database
- ***T5: Muon science and technology application terminal***
- T6: Future ISOL terminal

Role of CiADS muon source and advantages

- **Advantages of CiADS Accelerator**
  - Energy Advantage: 500–600 MeV, ***covering the optimal energy range*** for surface muon sources [A. Bungau et al., PRAB 17, 034701, 2014]
  - Intensity Advantage: 5 mA (***world's highest CW beam***), with theoretical muon intensity capable of surpassing existing facilities [H.-J. Cai et al., PRAB 27, 023703, 2024]
  - Time Structure Advantage: Utilizes a superconducting linac with ***flexible operation modes***, continuous-wave (CW), time-structured operation (e.g., for Mu2e), and high repetition rates (e.g., for MACE)

- **Role and position of CiADS muon source**
  - Global collaboration: high-intensity CW muon source comparable with PSI muon source upgrade
  - Domestic synergy: Complement to the pulsed muon source at CSNS, collectively addressing the domestic needs of muon

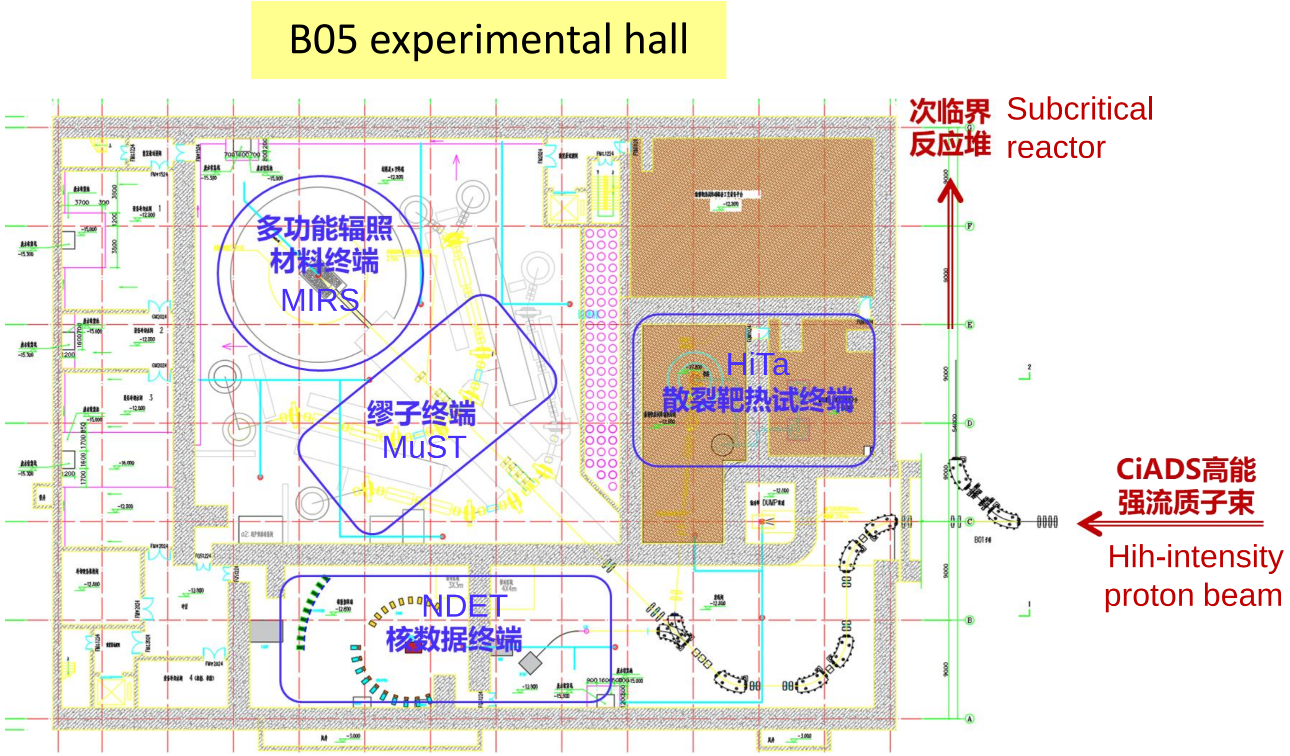


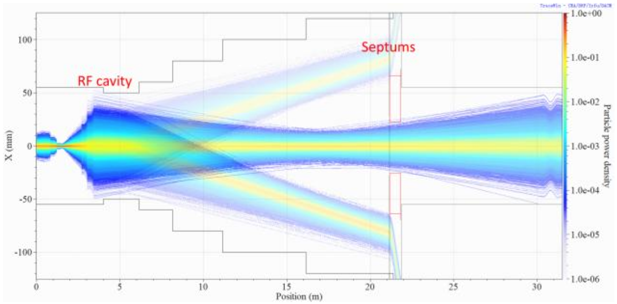


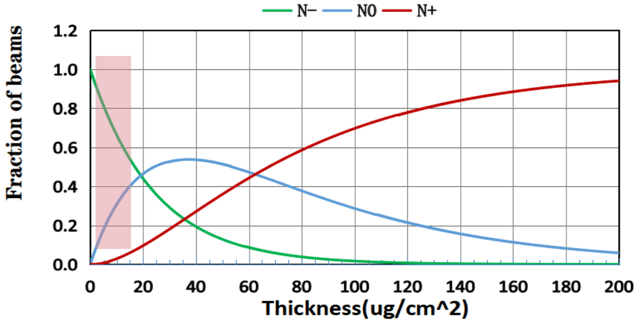
PRAB 17, 034701, 2014

Plan for CiADS muon source

- CiADS reactor
  - A research facility with 3 months of annual operation
- Terminals at B05 experimental hall
  - High-power target testing terminal (HiTa)
  - Nuclear data experiment terminal (NDET)
  - *Muon Science and Technology application terminal (MuST)*
  - Multifunctional Material Irradiation Terminal (MIRS)
- Beam supply modes
  - CiADS Reactor: ~3 months
  - Terminals at B05 Hall : 8–9 months (single or multi-terminal operation)
- Beam-splitting methods
  - RF + Beam-cutting magnet: ISOL vs B05
  - Stripper foil + Bidirectional dipole magnet: HiTa vs NDET vs MuST+MIRS







Plan for CiADS muon source

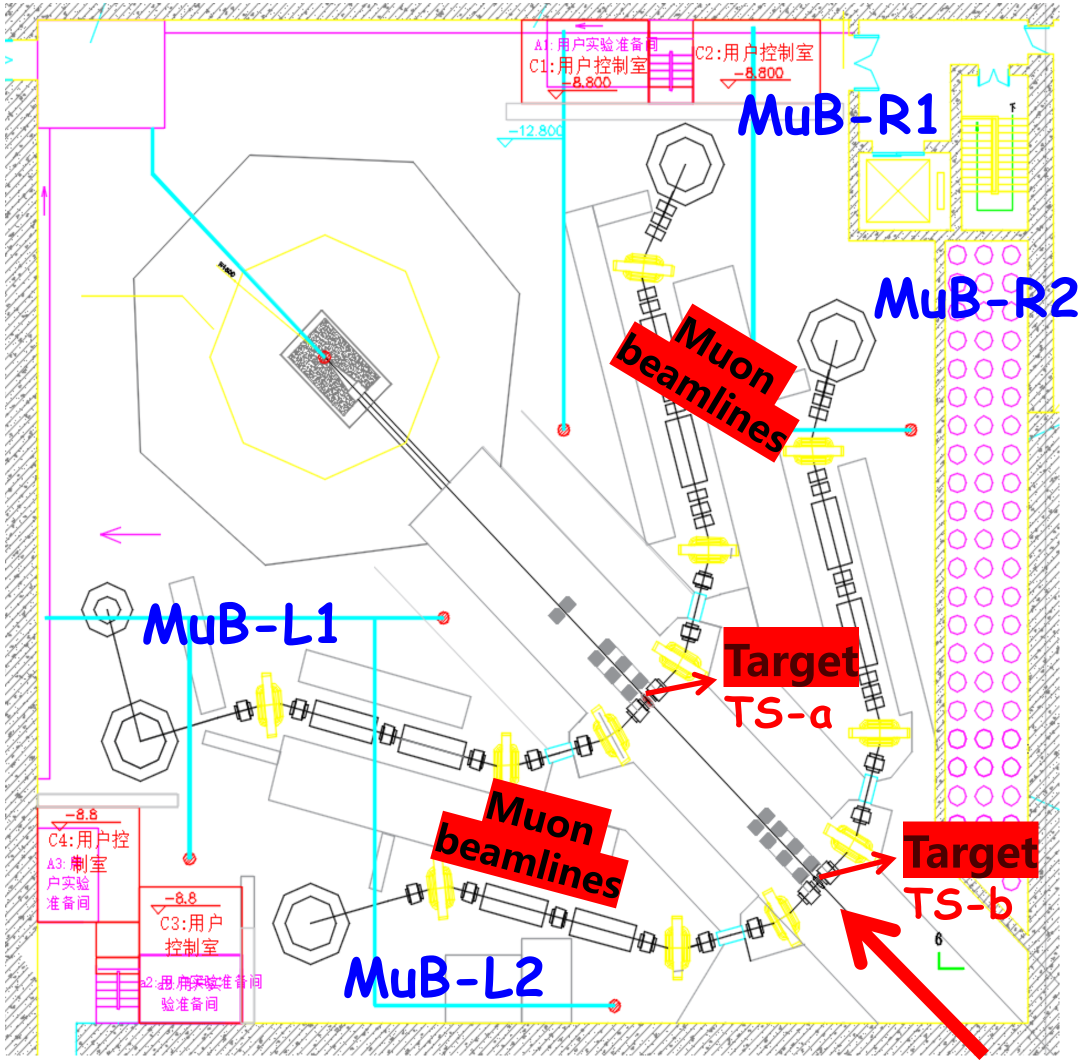
- **Objective:** China's first continuous muon source based on a superconducting linear accelerator beam. Pushing muon intensity up to 1×10^{9} (or even 1×10^{10}) μ/s, in a long run.
- **Construction plan with two phases:**

Phase	Target	Muon type	Main applications
Phase-I 2025~2028	Target Station – a	R1: surface	μSR
		L1: surface/decay/slow	μSR/MIXE/part. phys.
Phase-II 2029~2032	Target Station – b	R2: surface	μSR
		L2: surfcae/decay/slow	μSR/MIXE/part. phys.

- **Overall progress:**

Conceptual design of the target and beamline **largely completed**.

Civil engineering requirements finalized, including: Spatial layout; Water, electricity, gas, and ventilation systems; 4 user control/on-duty rooms; 3 sample preparation rooms.



Recent R&D progress

Muon production target

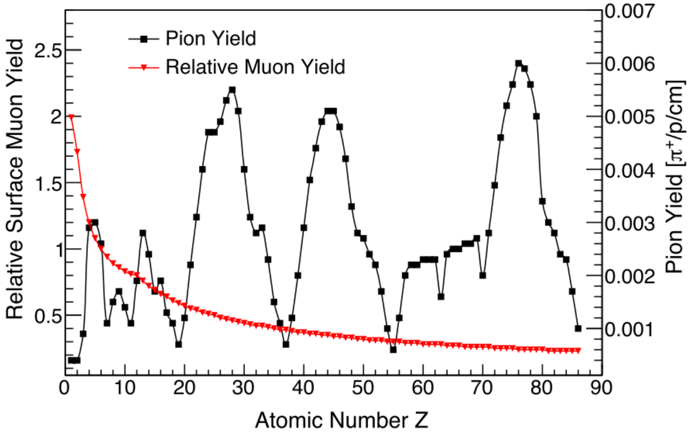
- **Target material**
  - Low-Z material: Be, C, etc.
- **Graphite target**
  - Fixed target: ISIS, RNCP, TRIUMF
  - Rotating target: J-PARC, PSI, RAON

Empirical formula for surface muon yield

$$I^{\mathrm{rel}}_{\mu^+} \propto n\sigma_{\pi^+} \left(\frac{dE}{dx}\right)_{\pi^+} \frac{1}{\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mu^+}} \frac{n_{\mathrm{C}}6}{nZ} l_{\mathrm{C}}$$

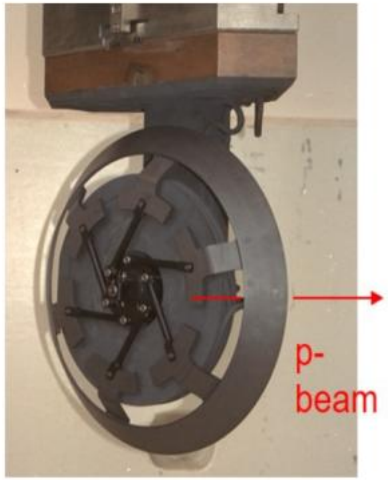
Surface muon yield $\propto Z^{-2/3}$

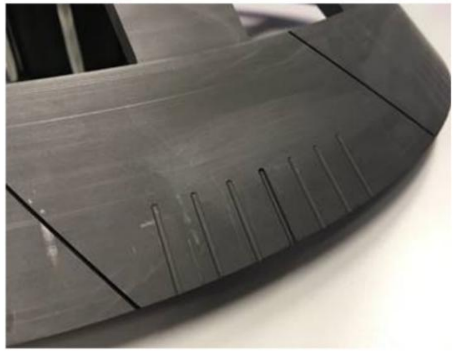
Relative muon yield on different materials



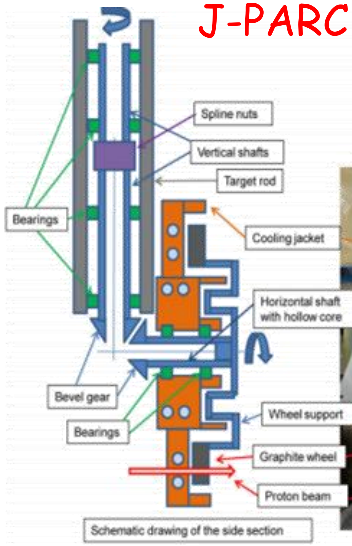
ISIS Moun target

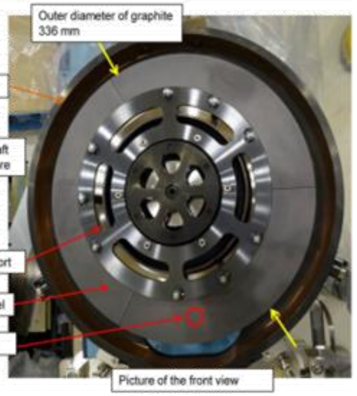
Different target E types from 2002 on of PSI





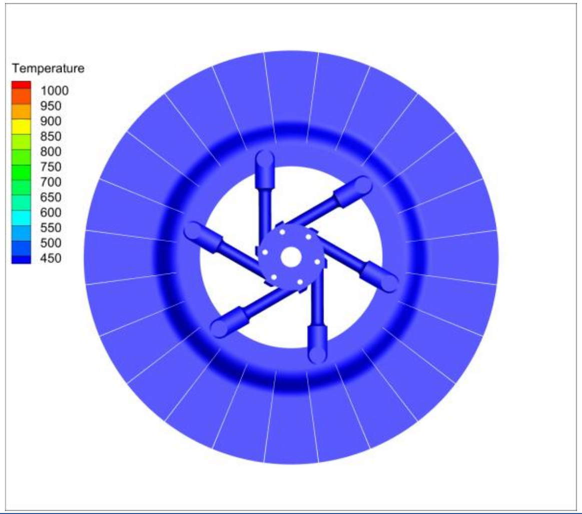
J-PARC Moun target



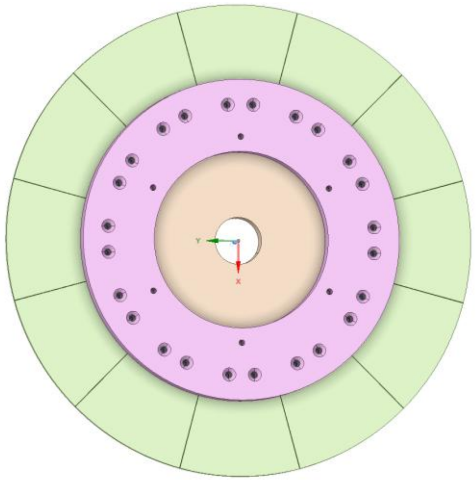


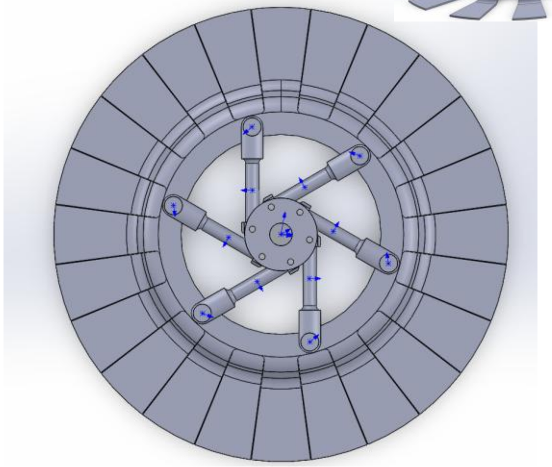
Key parameters for the design

- Beam power of 300kW; ~5KW on target; tilting angle = 10° ; equivalent thickness 2 cm
- Dish-shaped structure; plug-in components; magnetic fluid sealing
- Feasibility: max. temp. ~ 1040 K with considerable safety margin

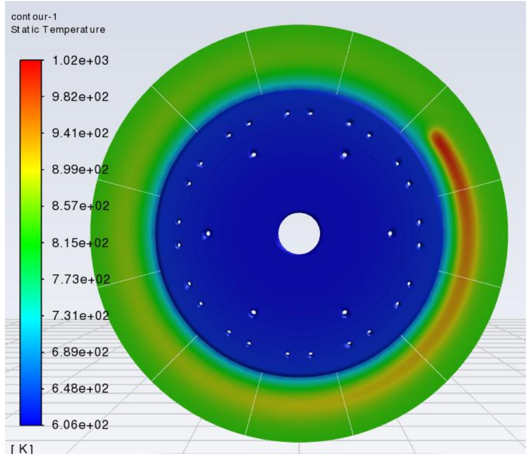


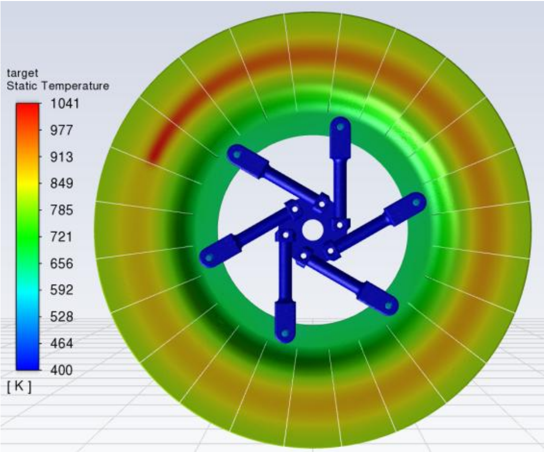
Update of structure design





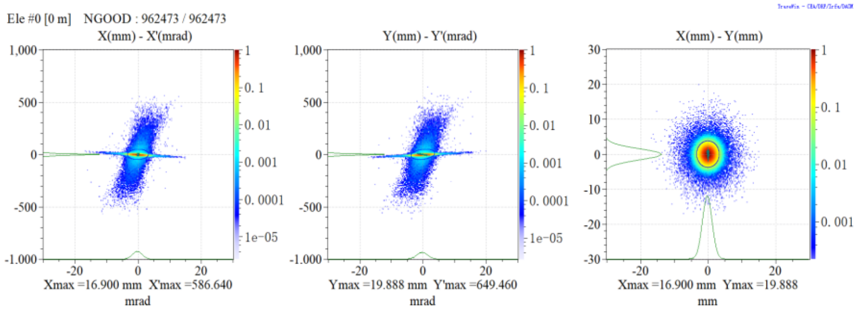
Update of thermal analysis

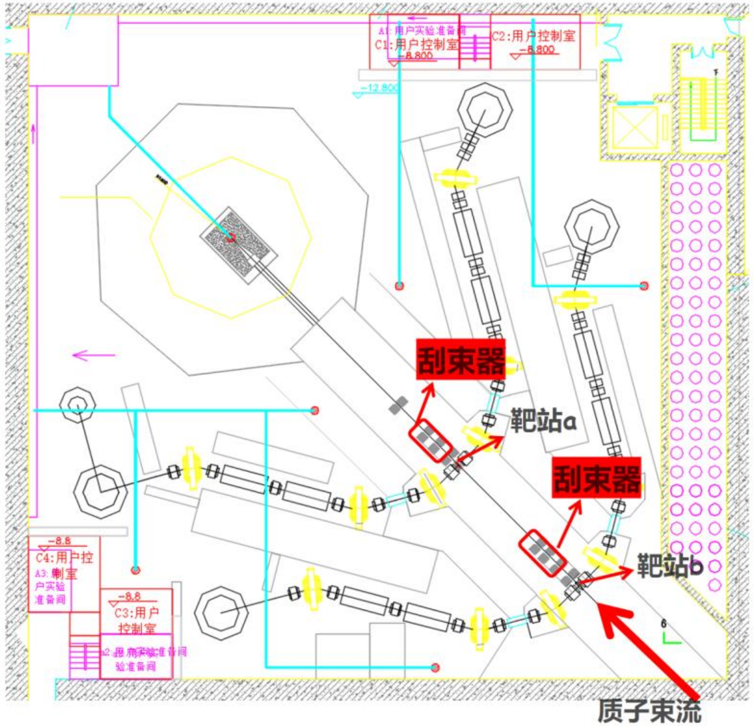




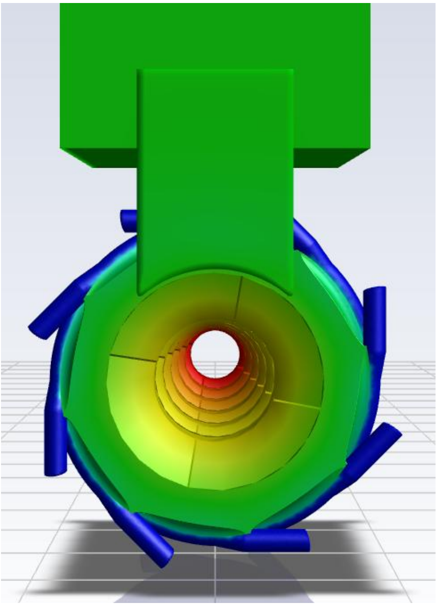
After-target beam trimming

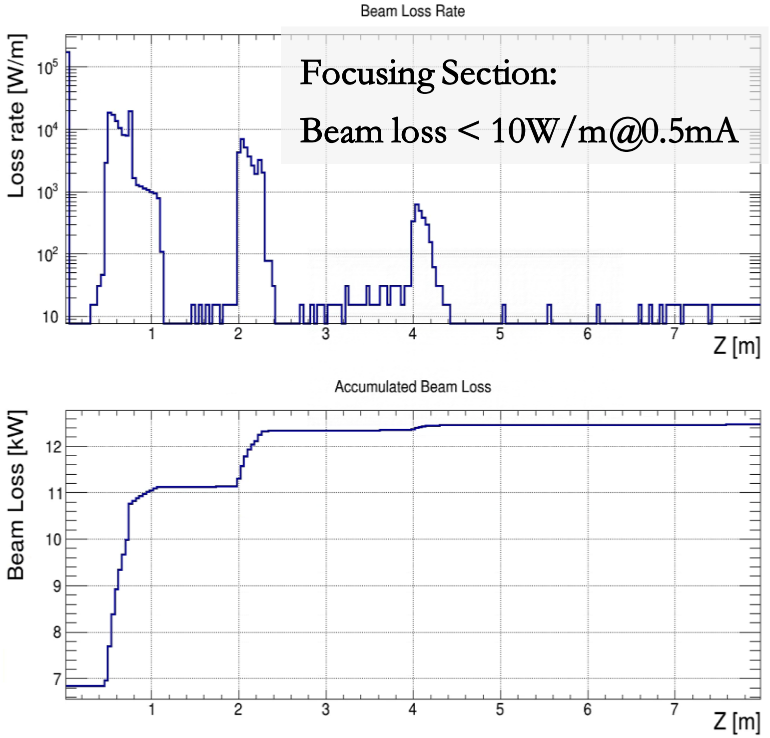
Beam emittance after target >40π·mm·mrad

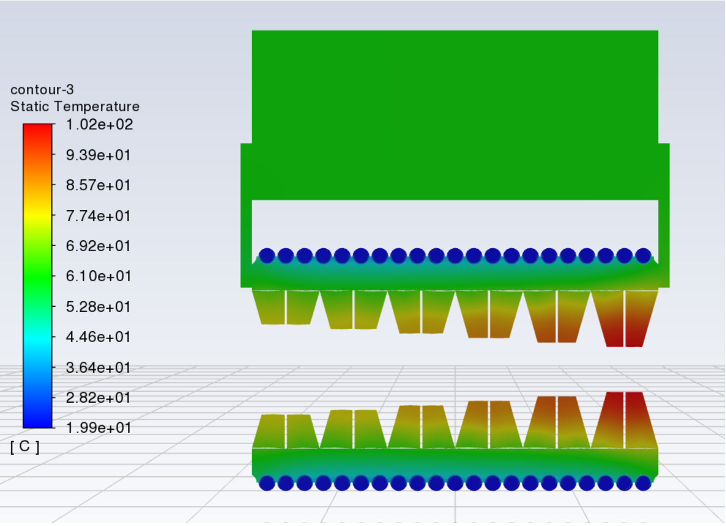




- **Beam Scraper Design:**
  - ~ 5 kW @ 0.5 mA; beam loss <10 W/m
  - Reserved beam scraping capacity to accommodate future power upgrades



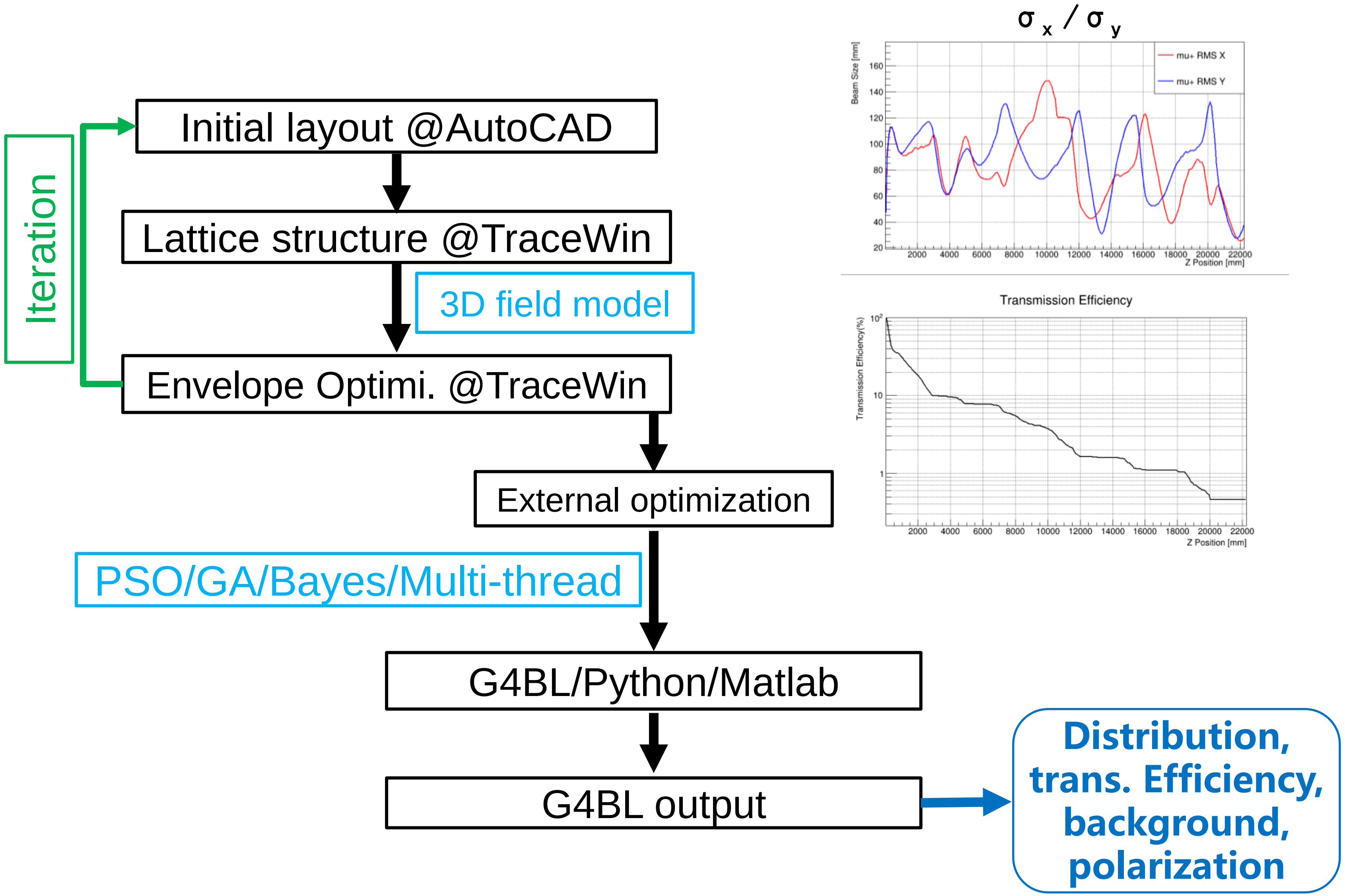




Design and optimization framework

Design methodology

- Based on muon beamline type and terminal objectives, **develop an empirical conceptual layout**
- Conduct preliminary optical design, **establish field models, and perform envelope optimization**
- Execute multi-objective optimization using G4BL and **automated optimization algorithms**

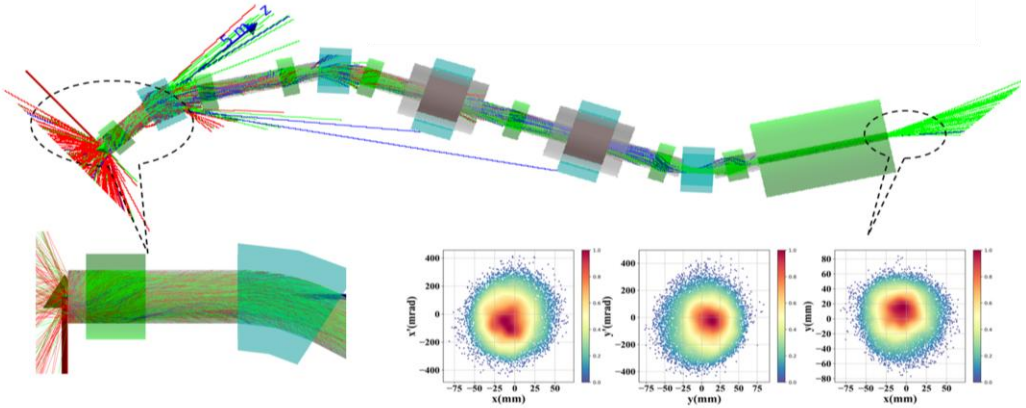


Continuous Improvements:

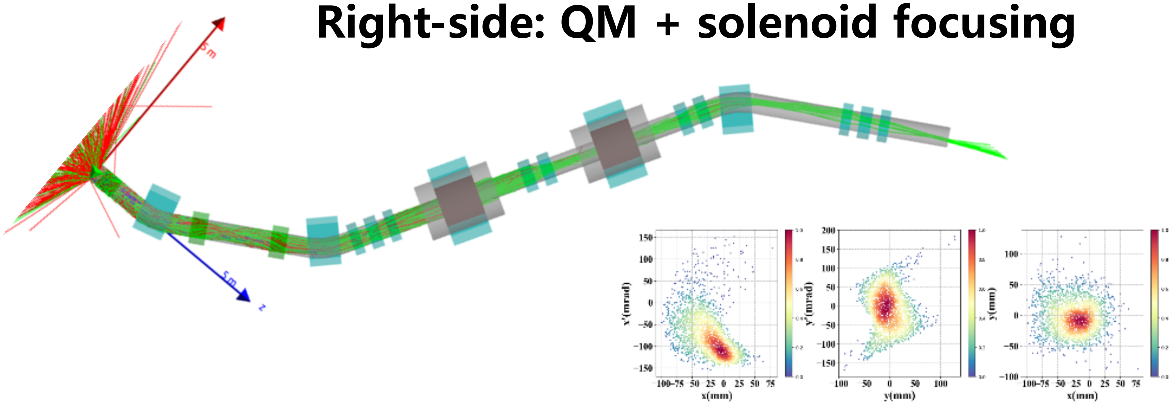
- Multi-objective optimization
- More design flexibility
- Higher computational efficiency
- Improved adaptability of the code

Current results of muon beamline design

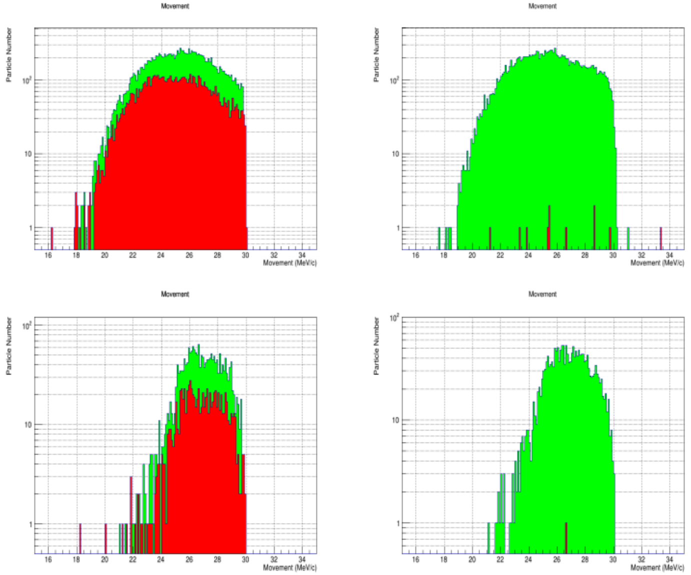
Left-side: Full-solenoid focusing



Right-side: QM + solenoid focusing



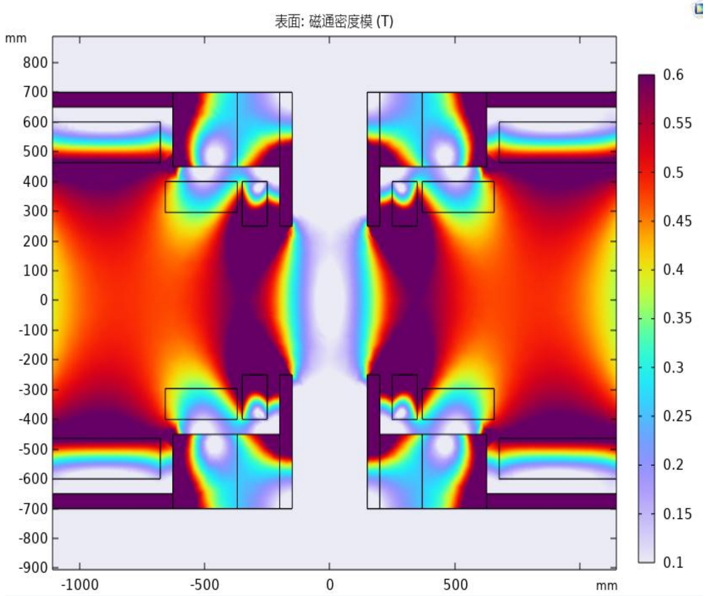
Background separation



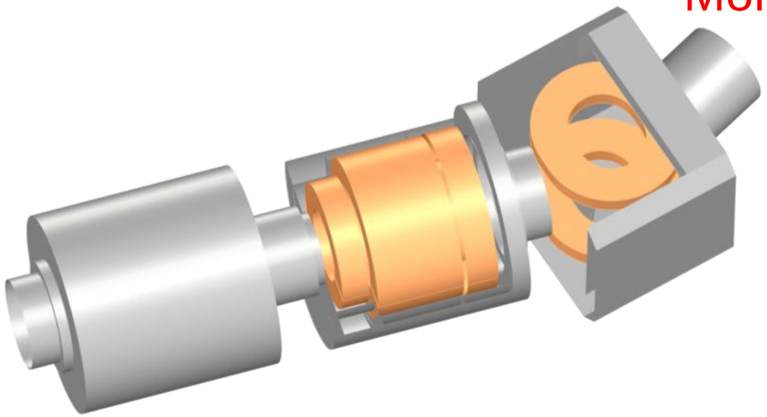
Beam power	Target	Beam line scheme	Intensity μ⁺/s		Spin pol.	background
			Full-range	Φ30mm		
300kW	graphite	Full-solenoid	>5E8	~1E8	~94%	<0.1%
		Mixing	>5E7	~1E7	>99%	
3MW	Lithium jet	Full-solenoid	>1E10	~2E9	~94%	
		Mixing	>1E9	~2E8	>99%	

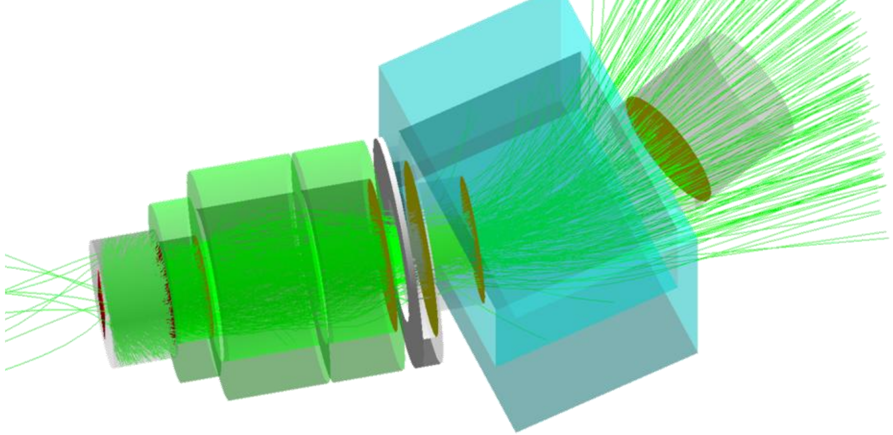
Capture front-end

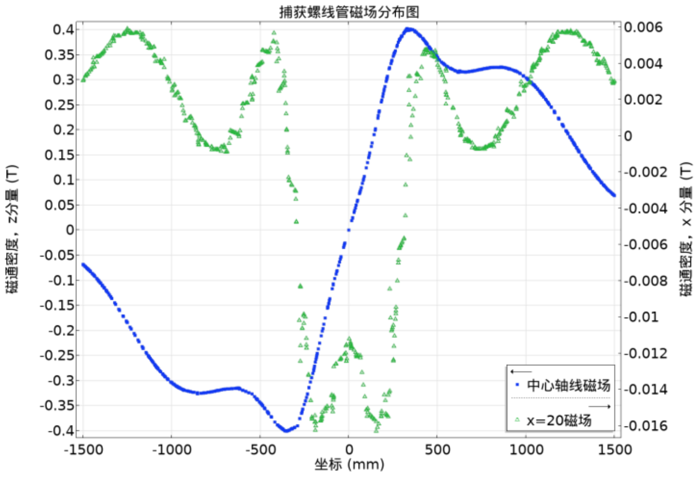
- **Capture Solenoid**
  - **Large aperture**: 400/600 mm, acceptance ~660 mSr
  - **Radiation-resistant**: Magnesium oxide coils
- **Front-End Design**
  - **Optimized design**: Automated optimization based on evolutionary algorithms (front-end efficiency ~20%)
  - **Magnetic shielding**: Target area <0.05 T



More in Gui-Hao LU's talk

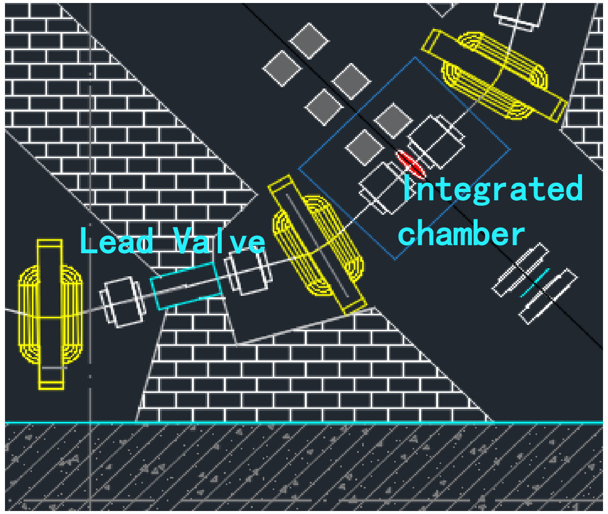


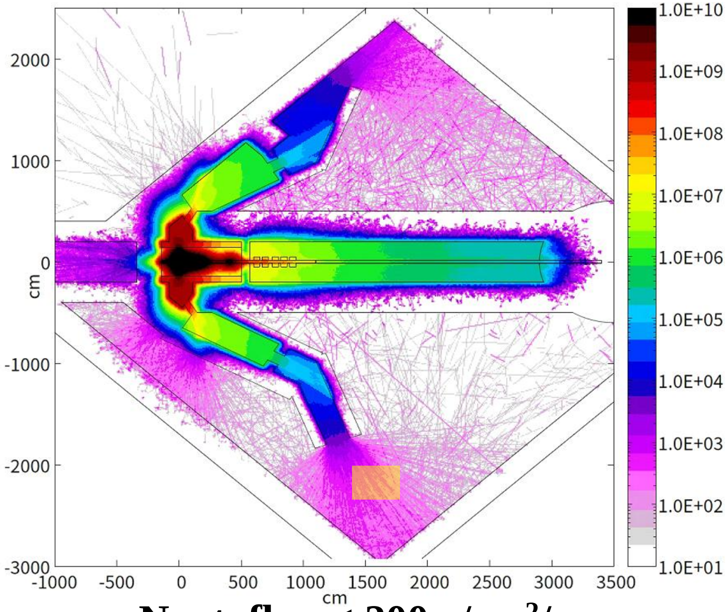




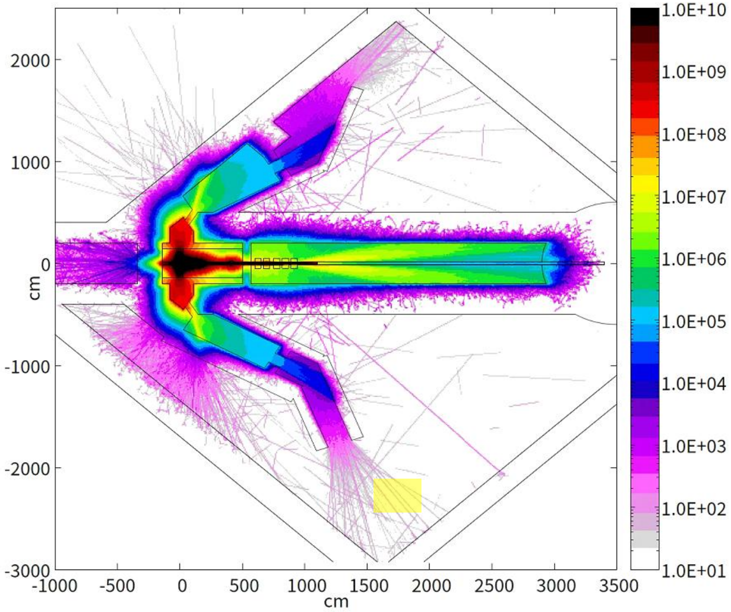
Shielding design

- **Requirements**: Personnel access near the muon beam terminal, reduced signal interference, equipment maintenance, etc.
- **Challenges**: Irregular geometry, large-aperture channels, short beamline
- **Solutions**: Integrated shielding for target/capture solenoid/beam scraper; beamline channel constriction
- **Effectiveness**: Terminal meets requirements for online personnel access

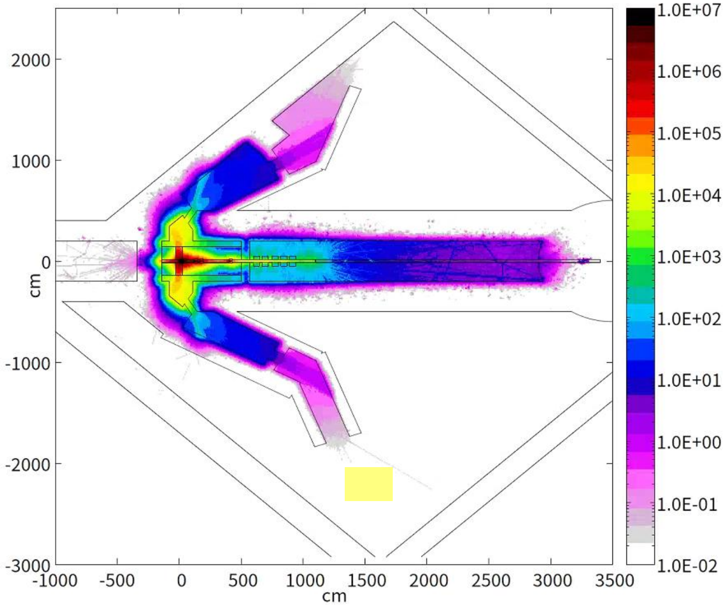




Neut. flux < 200 n/cm^2/s



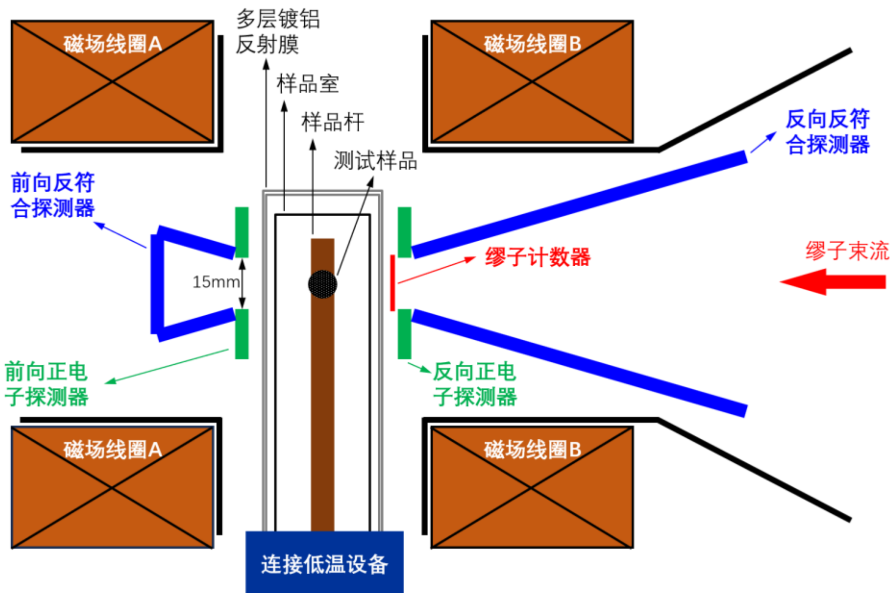
Online equivalent dose rate < 30 μSv/h



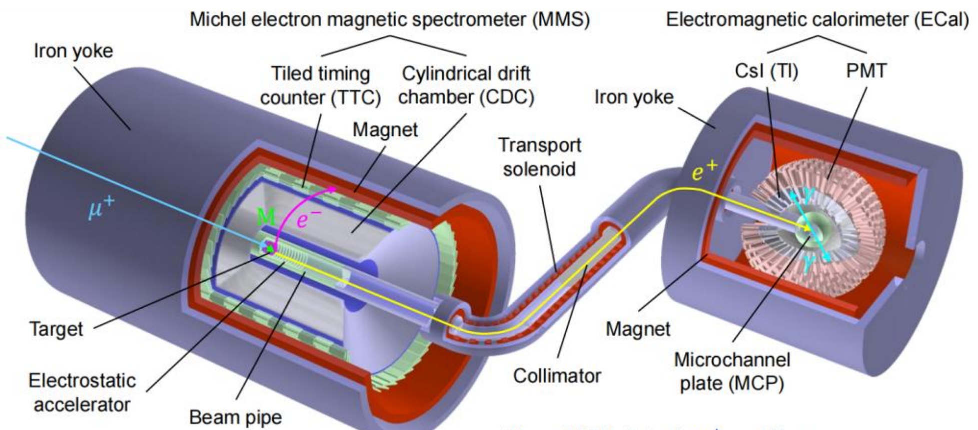
Induced dose rate (3 days after shutdown) < 2 μSv/h

Experiment terminals

- **Possible terminals**
  - MuSR spectrometer
  - Particle physics terminal
  - Atomic-X ray spectroscopy and MIXE terminal



Design of MACE detector system



I. Surface muon stop in target → muonium
II. M diffuse into vacuum & convert to $\bar{\mathrm{M}}$
III. Decay in a vacuum: $\bar{\mathrm{M}} \to e^+e^-\nu_\mu\bar{\nu}_e$
IV. CDC detects Michel e^- track
V. Transport atomic e^+ to MCP (conserving transverse position)
V. MCP detects e^+ position
VI. e^+ annihilates on MCP
VII. ECal detects 2 back-to-back annihilation γ

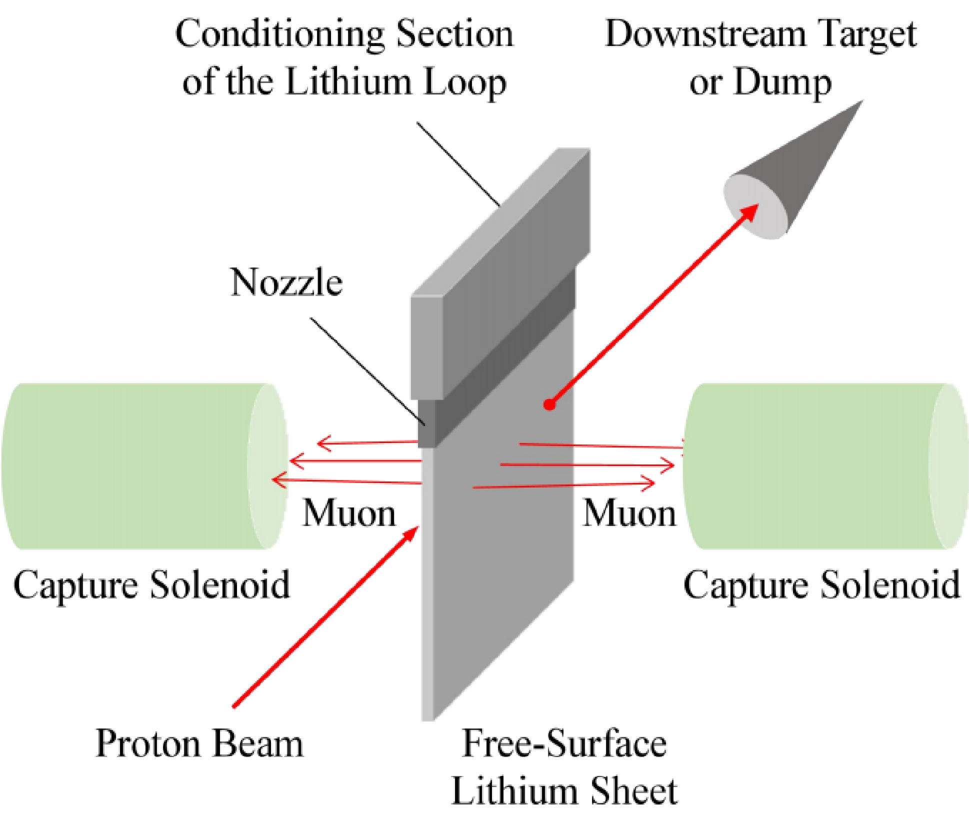
Triple coincidence:
- **MMS + MCP + ECal**

Michel e^- Atomic e^+

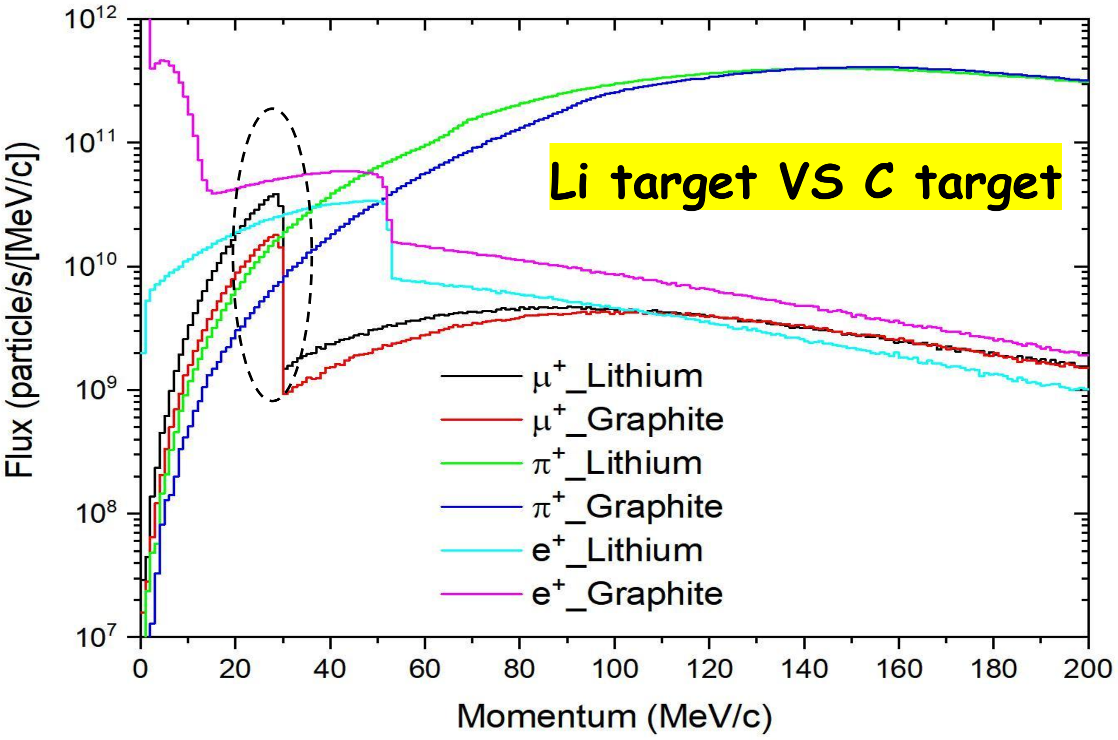
Future key technologies

High-power liquid lithium free-jet target

Lithium jet target configuration



- **Liquid Lithium Jet Target vs. Graphite Rotating Target**
  - Higher surface muon yield
  - Fewer radionuclides, lower positron background
  - No thermal stress issues, no need of frequent replacements, higher power tolerance
  - Theoretically more compact

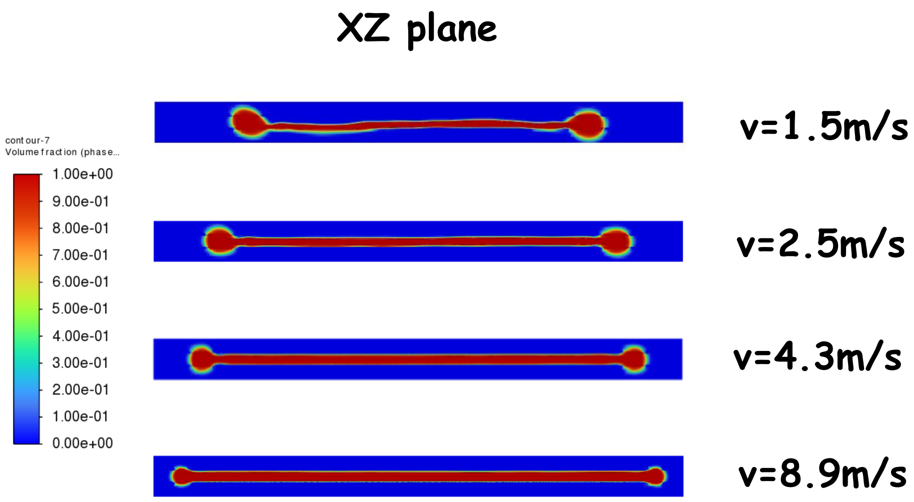


High-power liquid lithium free-jet target

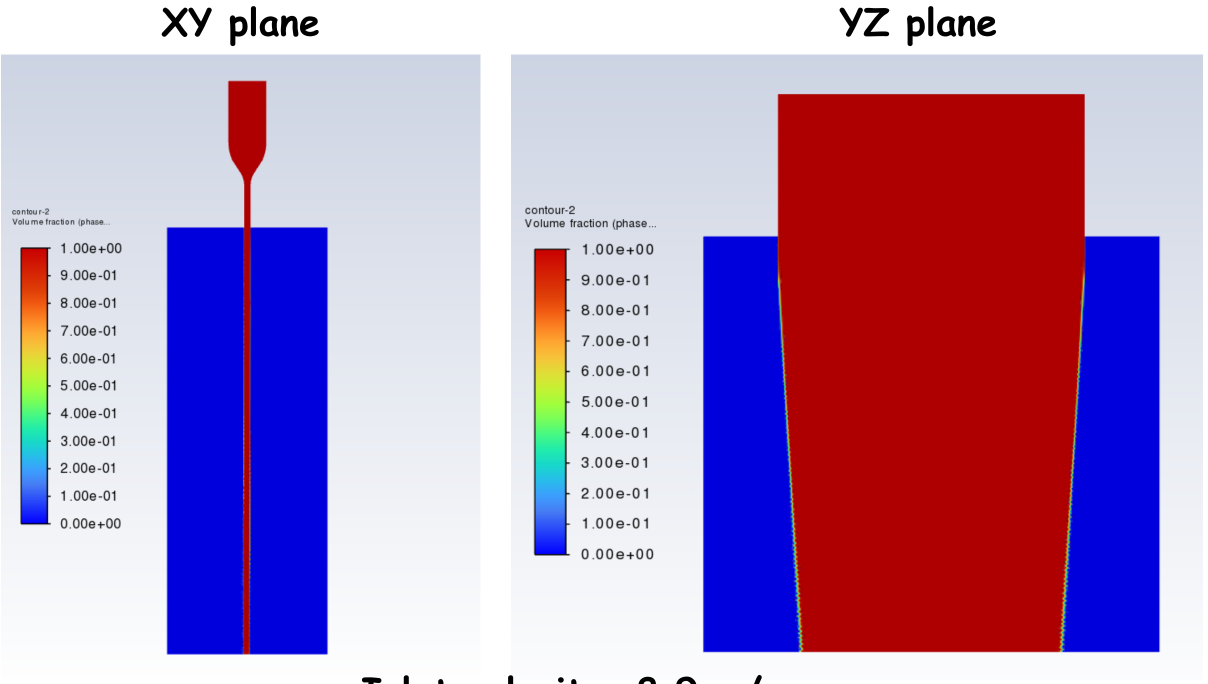
☐ Jet Morphology

- ➢ Higher inlet velocity improves jet morphology
- ➢ Flow velocity of 5–10 m/s meets requirements

Simulation results for different velocities



Horizontal cross-section of jet morphology after 10 cm

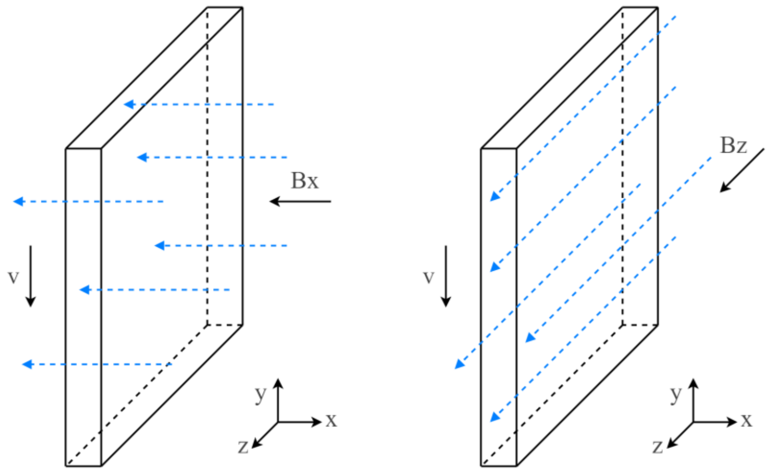


Inlet velocity: 8.9 m/s

High-power liquid lithium free-jet target

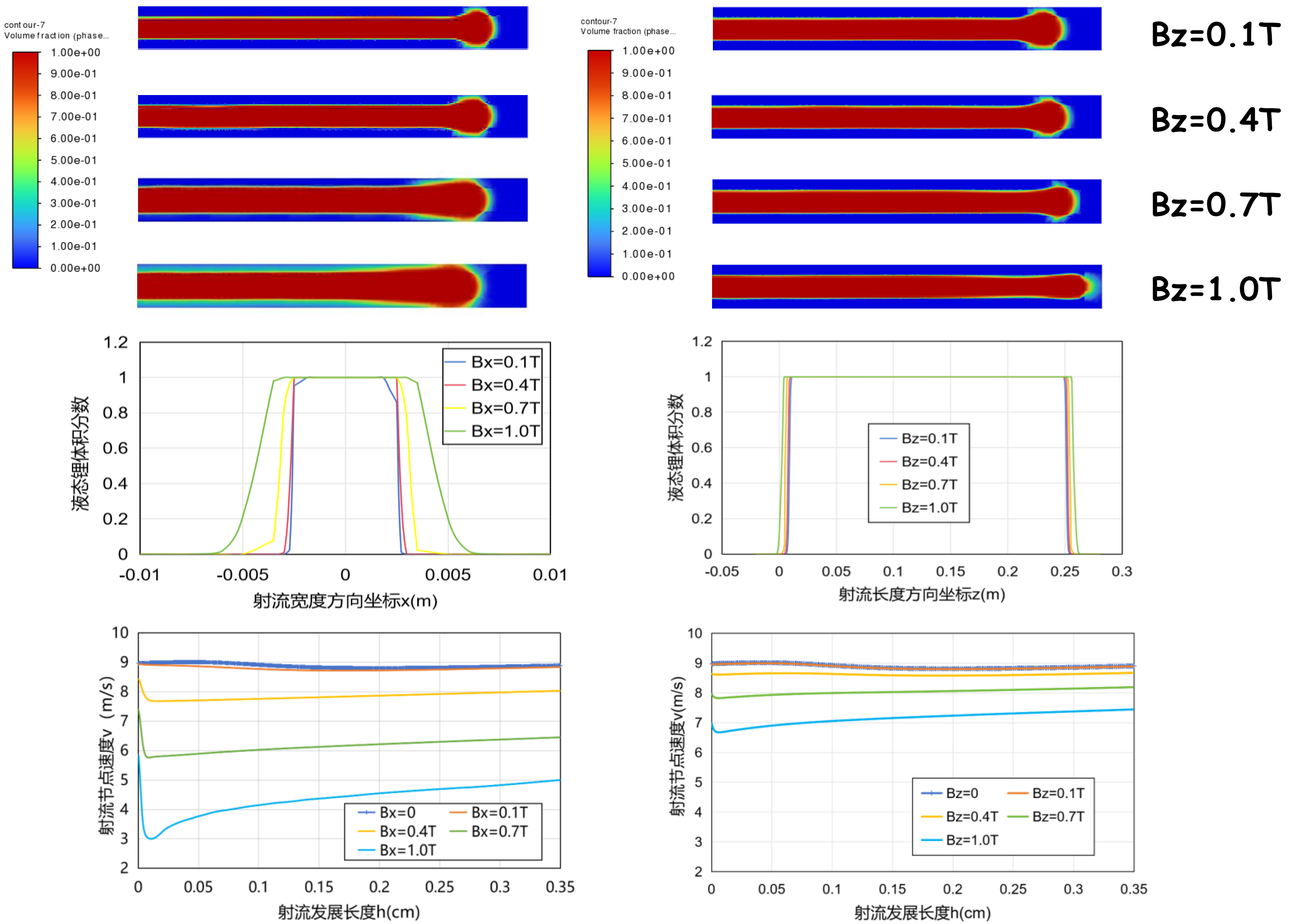
☐ Magnetohydrodynamic Effects

- Magnetic field effects in thickness direction exceed those in length direction
- 0.1 T magnetic field impact is negligible



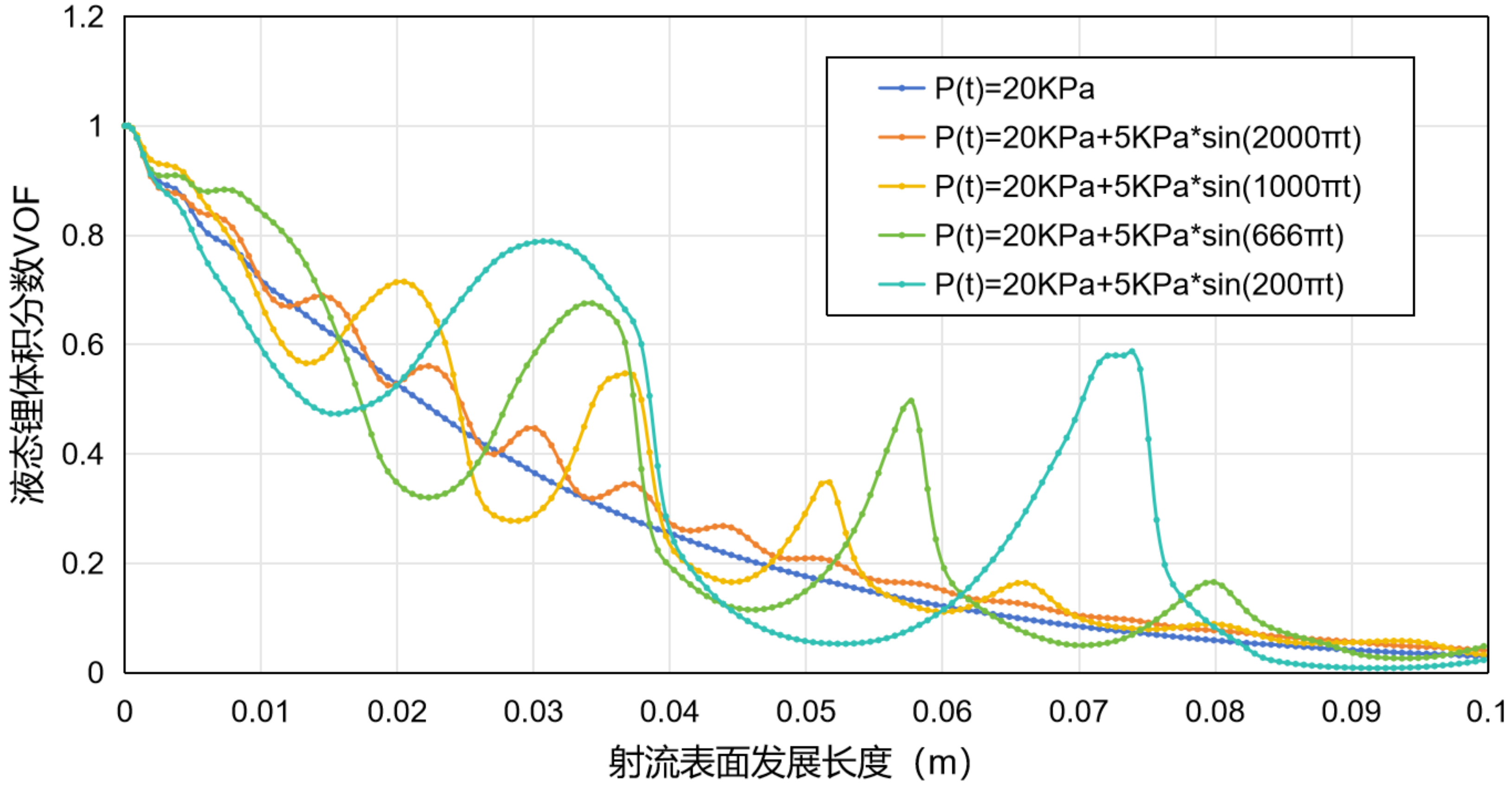
x-direction magnetic field

z-direction magnetic field



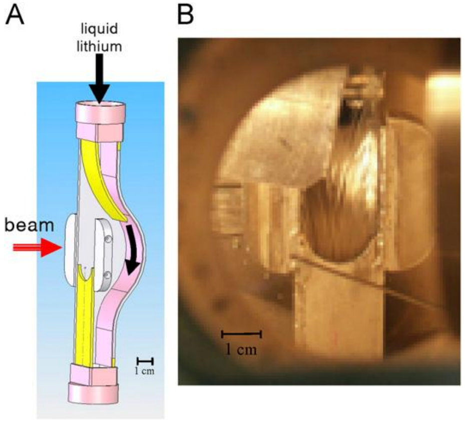
High-power liquid lithium free-jet target

- **Initial Perturbation Effects**
  - Higher frequencies with less surface fluctuation effects
  - Focus on shielding external disturbances below 1000 Hz

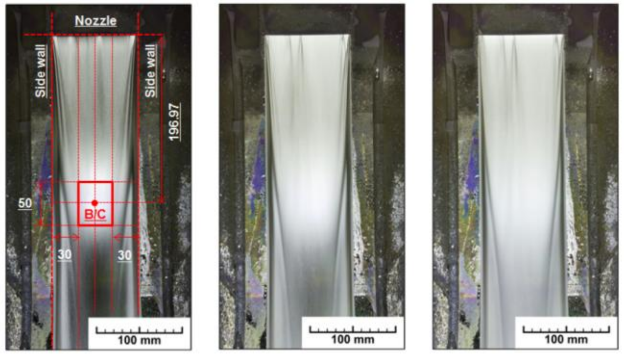


High-power liquid lithium free-jet target

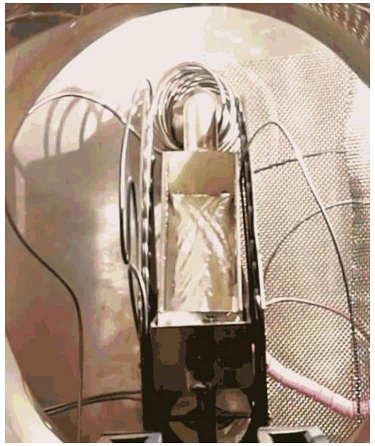
SARAF liquid lithium target



IFMIF liquid lithium target



Collaborate with Sichuan University for experimental tests



Plan of experimental tests

- A windowless liquid lithium jet with backplate support has been successfully applied in compact neutron sources; fully free jets still require experimental validation.
- **Experimental validation**: Jet morphology (free surface fluctuations, external perturbation effects), Magnetohydrodynamic effects.

Summary and outlook

The CiADS superconducting linear accelerator offers the potential for building a continuous muon source with advanced performances.

The conceptual design of CiADS muon source target and beamline is nearly complete. The current plan can provide competitive muon flux for diversified applications.

We warmly welcome collaborations and user feedbacks to push the CiADS muon source forward, to realize our goals in challenging high-precision physics and novel multidisciplinary applications.