International Workshop on μCF and Future Applications
2 July, 2026 @ University of Liverpool

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

μCF Studies in Japan and Moonshot Activities

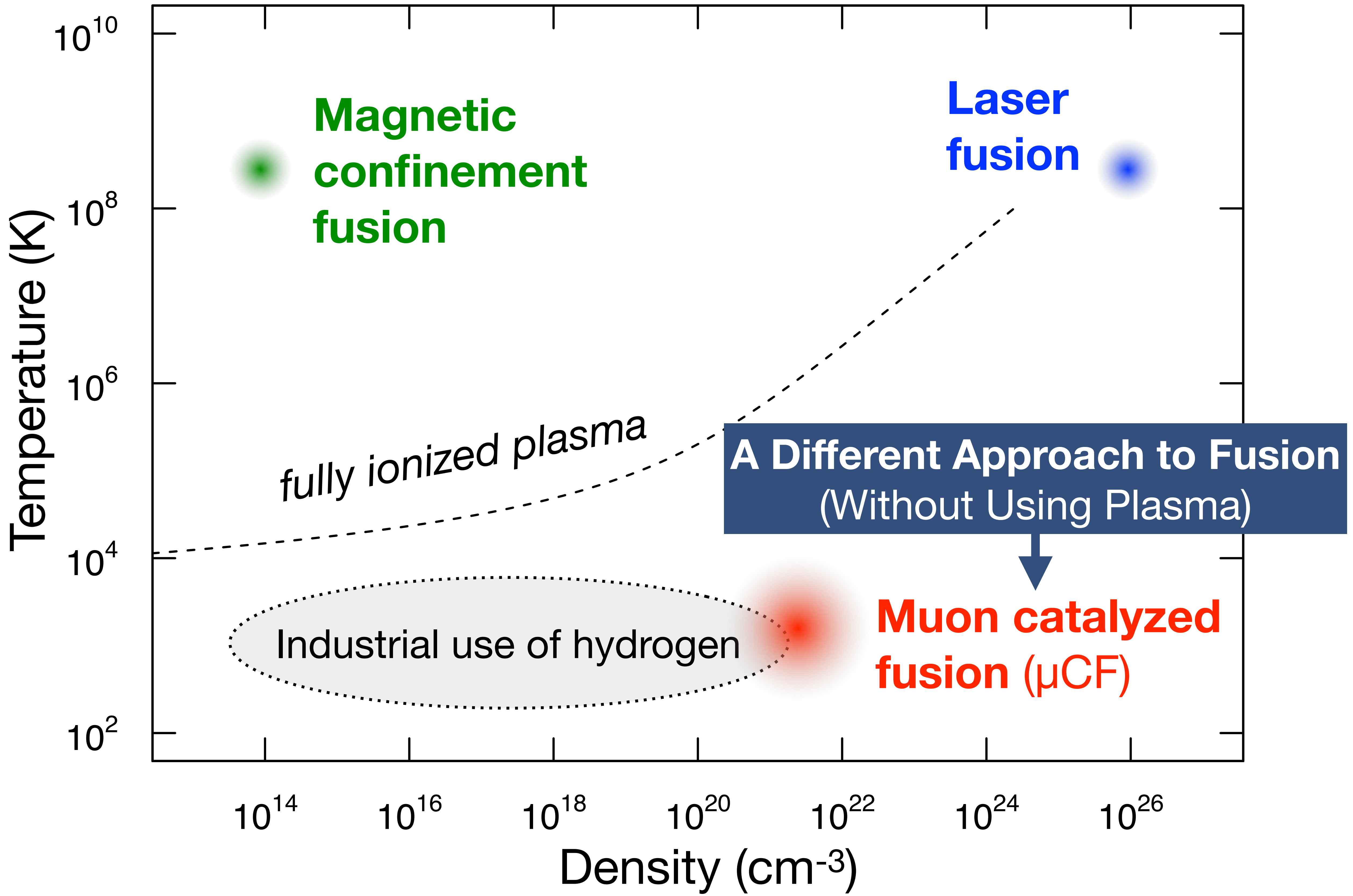
Moonshot Goal 10 : μCF project
PM (Project Manager)

Shinji Okada (Chubu Univ.)

MS10

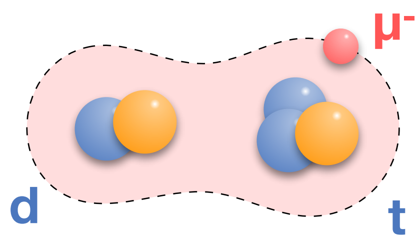
Contents

① What is μCF?

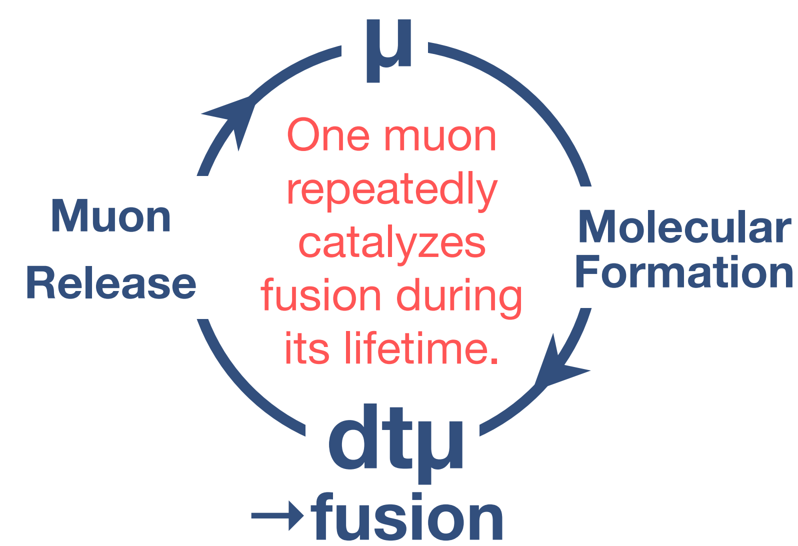

Temperature (K)
10^10
10^8
10^6
10^4
10^2
Magnetic confinement fusion
Laser fusion
fully ionized plasma
A Different Approach to Fusion
(Without Using Plasma)
Industrial use of hydrogen
Muon catalyzed fusion (μCF)
10^14
10^16
10^18
10^20
10^22
10^24
10^26
Density (cm^-3)

Can μCF Become a Practical Energy Source?

Molecular Confinement



A muon brings two nuclei close enough to induce fusion without plasma.



The Key Parameter is the Fusion Cycles per Muon (F)

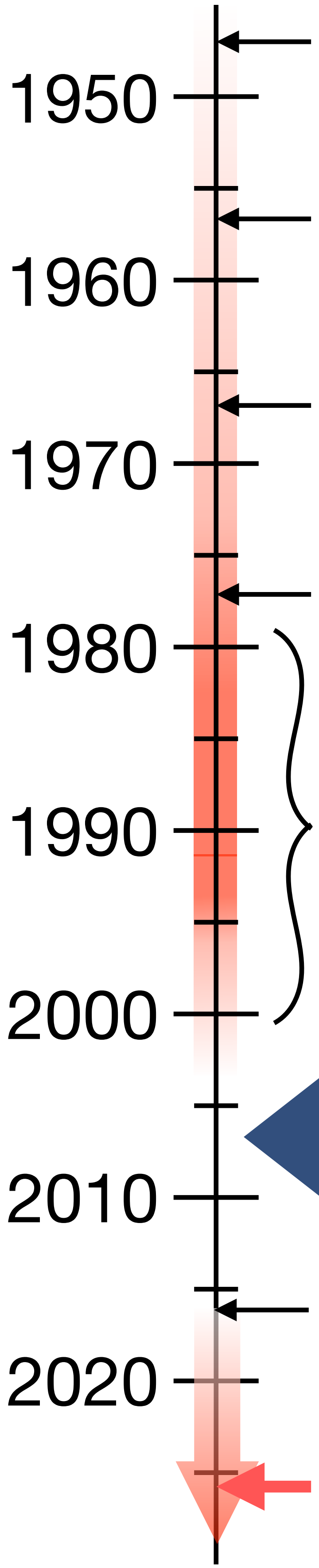
$$\textbf{Energy Gain} = \frac{\textbf{17.6 MeV}/\text{reaction} \times \boxed{\textbf{Fusion Cycles per Muon (F)}}}{\text{Energy Required to Produce One Muon}}$$

~ 5 GeV

F=120~150	F=300	F=1000
Current State-of-the-Art	**Scientific Energy Break-even**	**Economically Viable Region**

including accelerator efficiency

② History of μCF



1947: F.C. Frank proposed the concept of the μCF reaction cycle.

1957: L.W. Alvarez made the first observation of the μCF reaction cycle.

1967: E.A. Vesman developed the theory of resonant molecular formation (**ddμ**).

1977: S.S. Gerstein and L.P. Ponomarev predicted resonant dtμ formation rates.

1980 - 2000: **Major Advances**

→ see Toyoda's talk

Major Facilities:

- ✓ **KEK** (Japan, Tsukuba)
- ✓ **RIKEN-RAL** (UK, Chilton)
- ✓ **LAMPF** (US, Los Alamos)
- ✓ **PSI** (Swiss, Villigen)
- ✓ **TRIUMF** (Canada, Vancouver)
- ✓ **JINR** (Russia, Dubna)

Fusion cycles remained limited to F = 120–150, leading to a temporary decline in μCF research.

2016: Kino et al. revived interest in μCF. (ImPACT Program →KAKENHI)

2026– Present: **Launch of JST Moonshot Goal 10 → Full-scale μCF R&D Program**

③ Recent Scientific Breakthroughs

Why now μCF?

(1) New theoretical understanding

(2) Direct observation of resonant μ-molecular states

(3) Growing international momentum

(4) Launch of Japan's Moonshot Goal 10

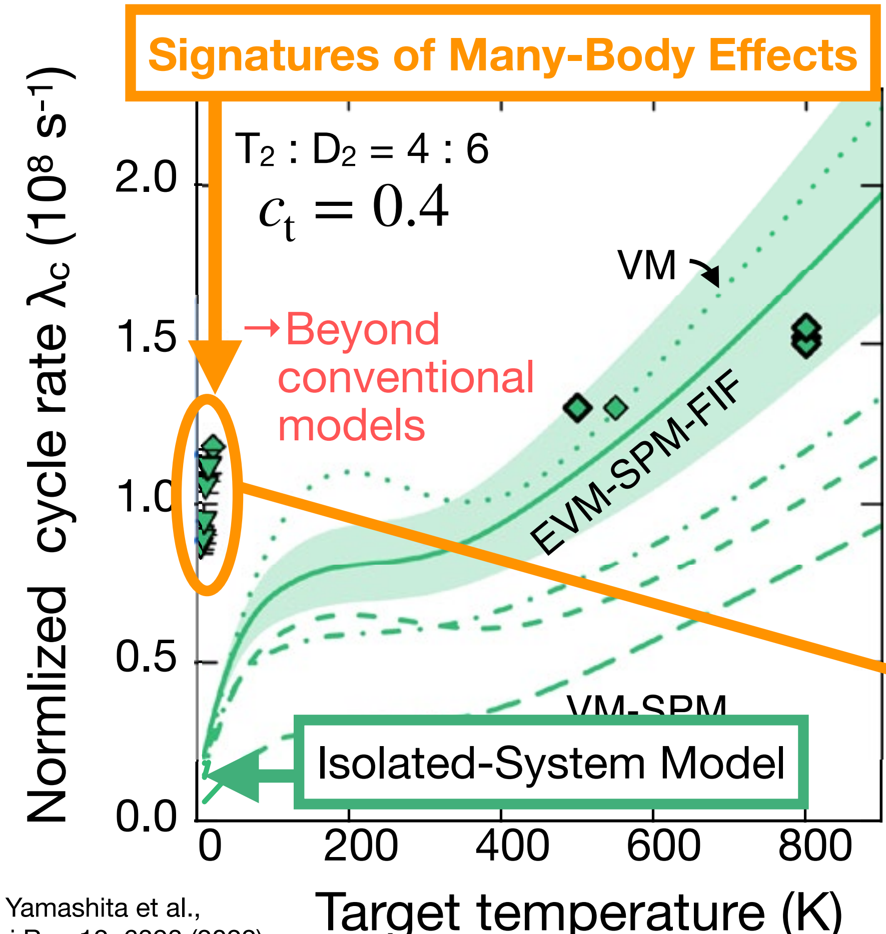
Why μCF Now? (1)

From Understanding to Design

1. Long-standing Challenges

- Many-body effects
- Limitations of the isolated-system approximation

The observed effects arise from condensed-matter structure rather than isolated atomic processes.



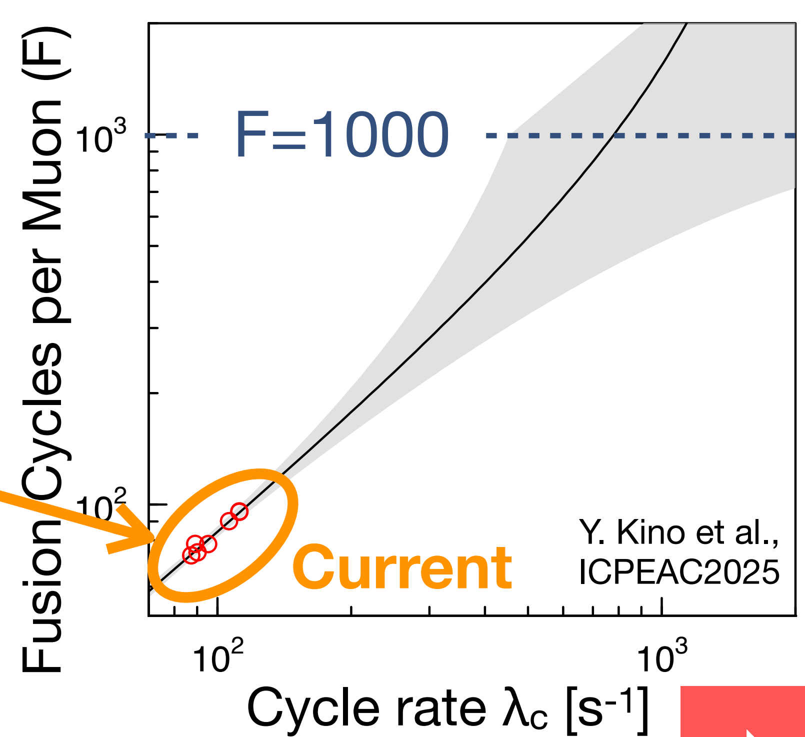
T. Yamashita et al., Sci Rep 12, 6393 (2022)

2. New Design Concepts for Increasing F

1. **Radiation Chemistry** : Enhanced molecular formation in dense clusters
2. **Fast Track** : Utilization of fast reaction pathways
3. **In-Flight Fusion** : Suppression of α–μ sticking

→ **F becomes a controllable design parameter.**

3. Potential



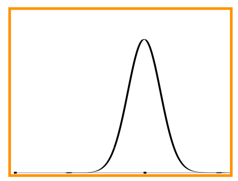
- Current state-of-the-art: F≈150
- Scientific break-even: F≈300
- Theoretical potential: F≈1000

μCF is evolving from understanding to design.

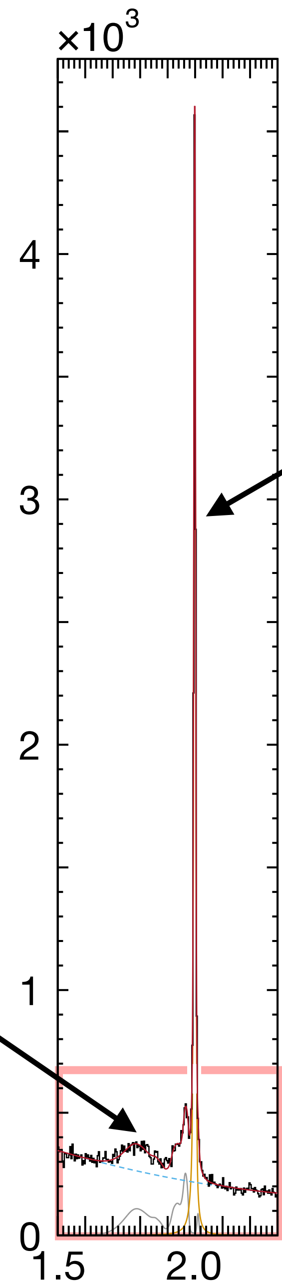
→ see Kino's talk (next)

Why μCF Now? (2)

From Theory to Experimental Verification



Energy resolution with conventional detectors



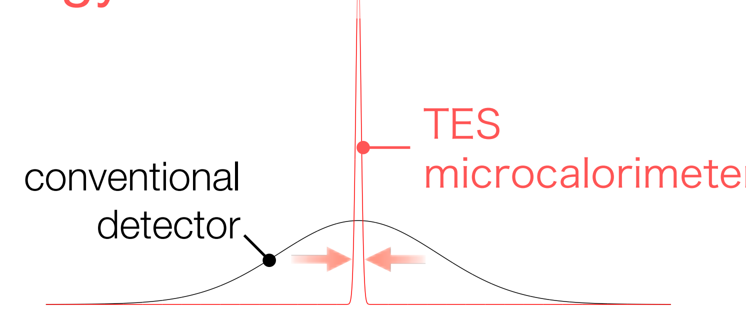
Large peak
from muonic atom (dμ)

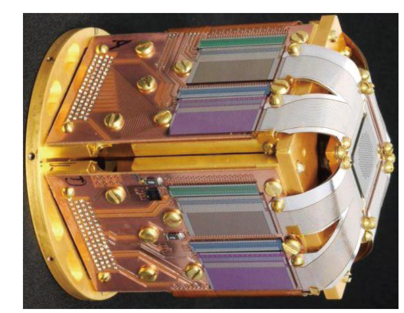
Extended
Structure
from the Muonic
Molecule (ddμ)

High-resolution TES measurement

→ Resolves previously indistinguishable structures

Orders-of-Magnitude Improvement
in Energy Resolution



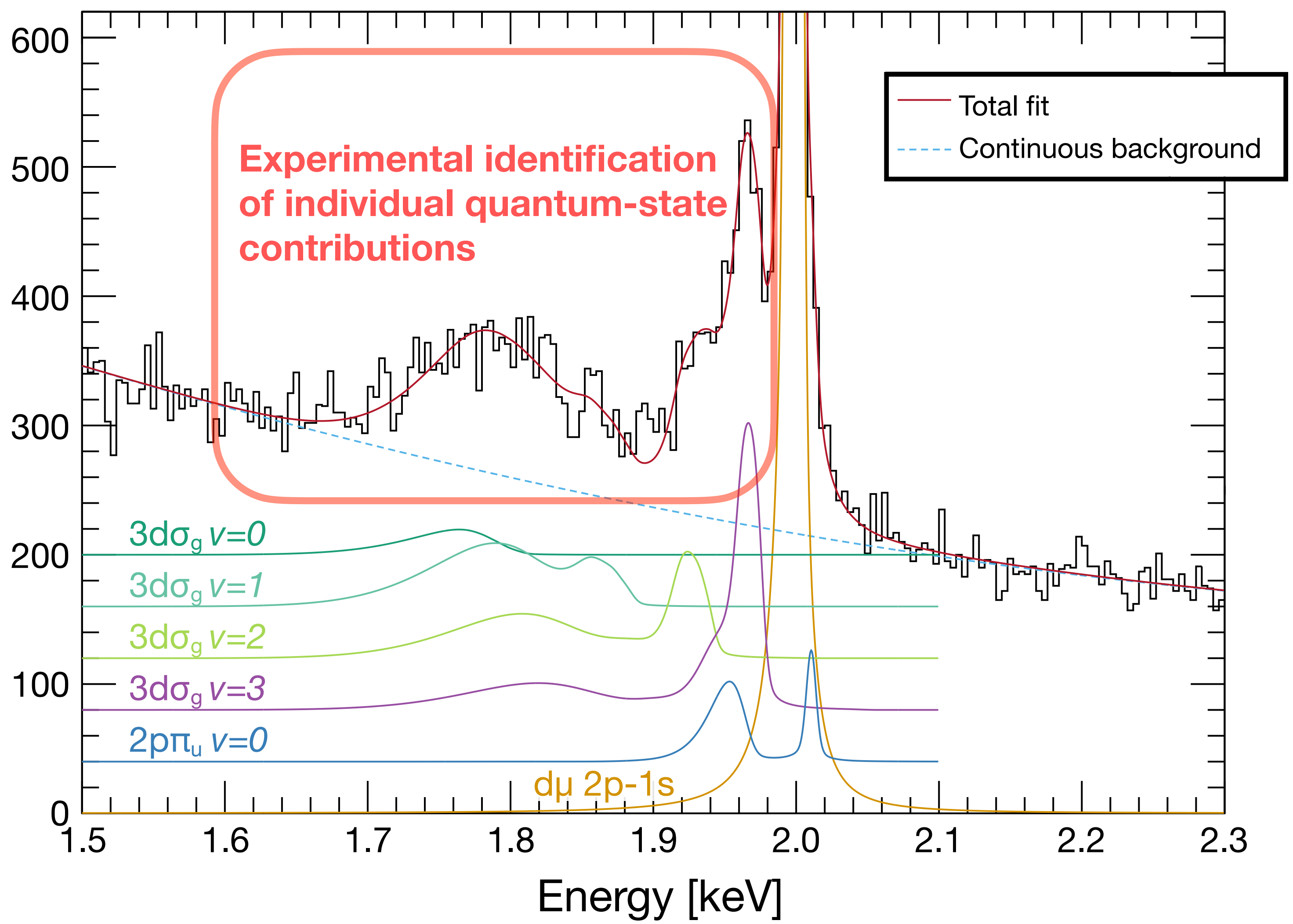


High-Resolution
X-ray Spectroscopy

Why μCF Now? (2)

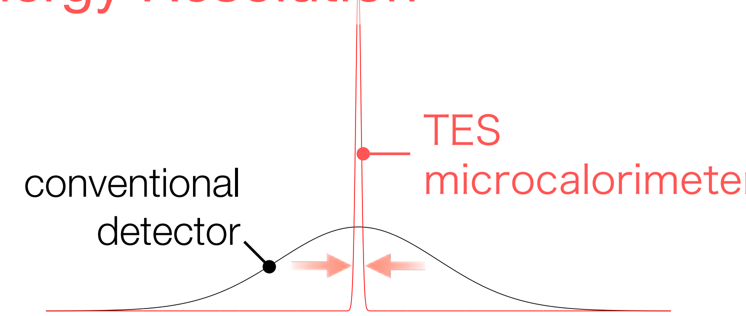
From Theory to Experimental Verification

Direct Observation of Resonant States in Muonic Molecules



Y. Toyama et al., Science Advances 12 eaed3321 (2026).

Orders-of-Magnitude Improvement in Energy Resolution



World's First Direct Observation of Resonant Muonic Molecular States

- ✓ Identification of individual quantum states of ddμ
- ✓ Excellent agreement with theoretical predictions
- ✓ Direct experimental verification of molecular formation processes

μCF can now be understood at the quantum-state level

→ see Toyama's talk

Why μCF Now? (3)

Growing International Momentum

Global Momentum Is Building

- Growing international interest in fusion technologies
- Expansion of muon facilities worldwide

Scientific Opportunities

- Current state-of-the-art: $F \approx 150$
- Scientific break-even: $F \approx 300$
- Long-term goal: $F \approx 1000$ (Adv. μCF)

⇒ **An ideal challenge for JST Moonshot Goal 10**

Muon Facilities Worldwide

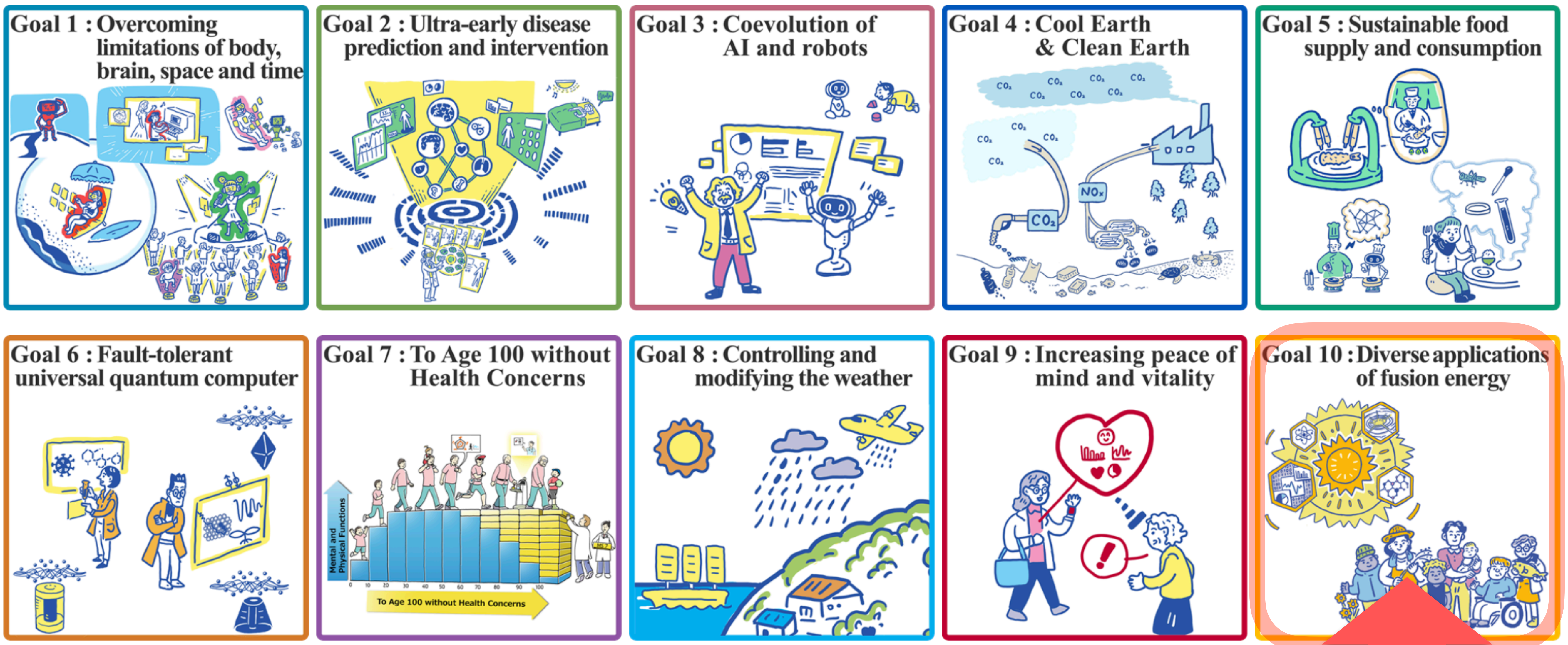
Operating	Japan, Switzerland, Canada, UK
Under construction	China
Planned	USA, Korea

International μCF research is gaining momentum.
Now is the time to pursue Advanced μCF.

④ Japan’s Moonshot R&D Program

10 National Grand Challenges for Society by 2050

AI & Robots



Quantum computer

Controlling weather

Goal 10

Fusion Energy Applications

Moonshot Goal 10 (MS10)

✓ Beyond conventional fusion

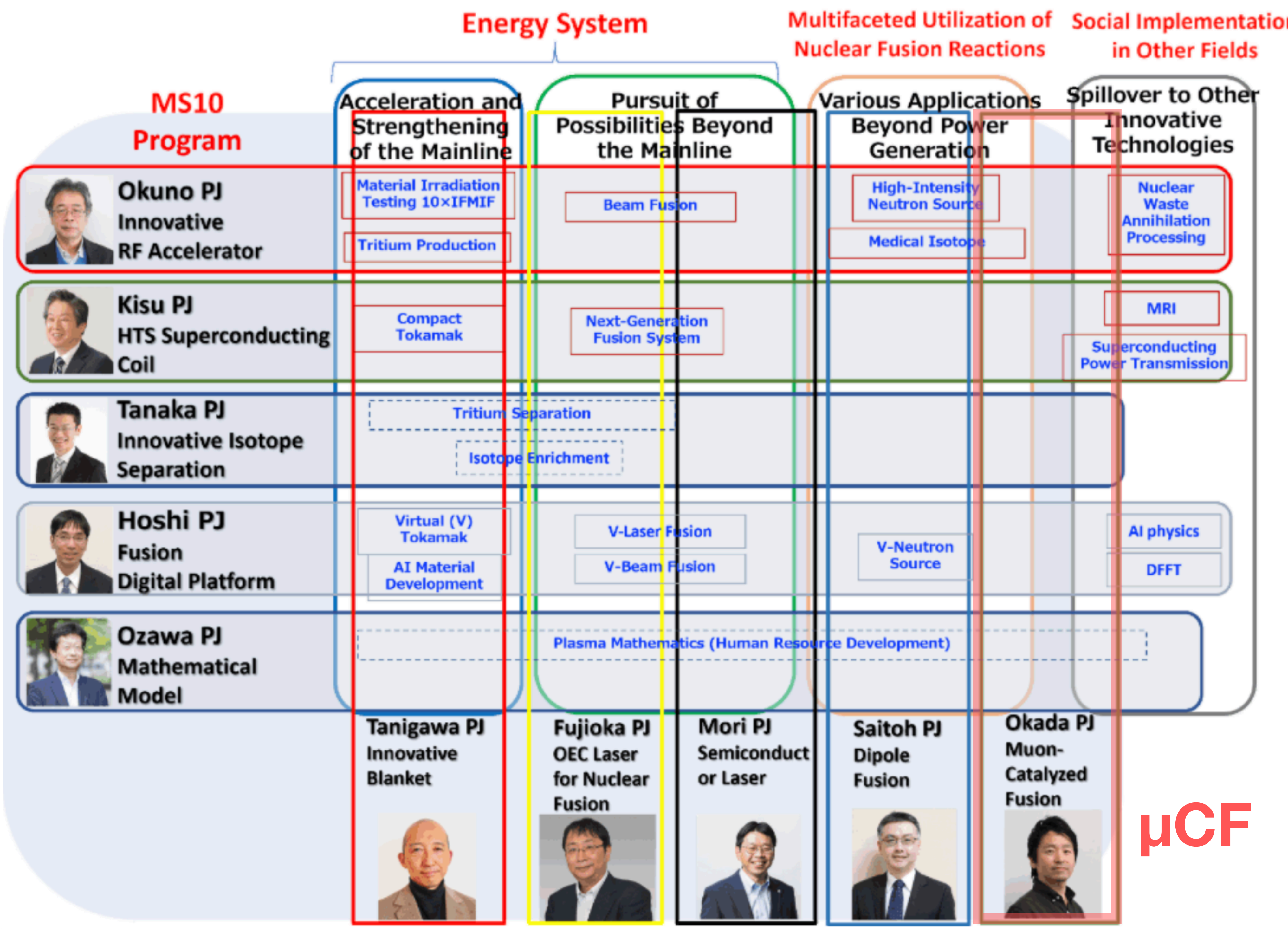
✓ Toward practical implementation

✓ Interdisciplinary innovation

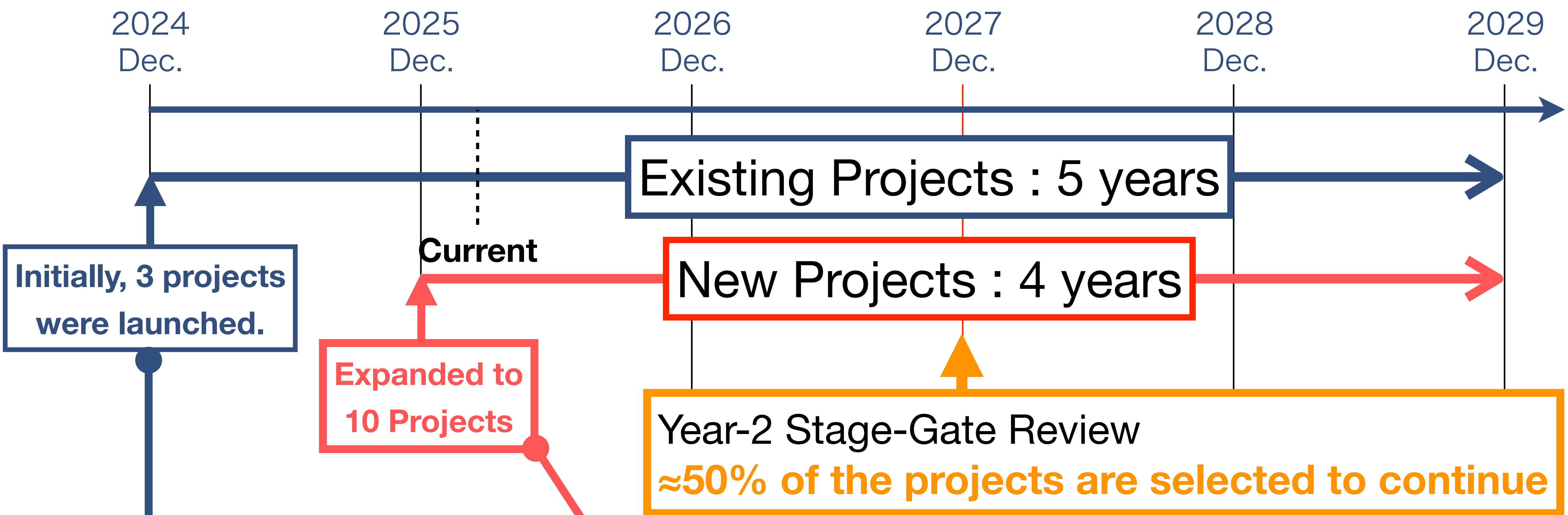
➡ **μCF is one of the novel fusion concepts envisioned in Goal 10.**

Position of μCF Project within Moonshot Goal 10

Moonshot Goal 10 comprises ten research projects spanning the entire fusion landscape —from mainstream technologies to **novel concepts such as μCF**



Schedule & Funding



Inital 3 projects

μCF

New 7 projects

Funding per project

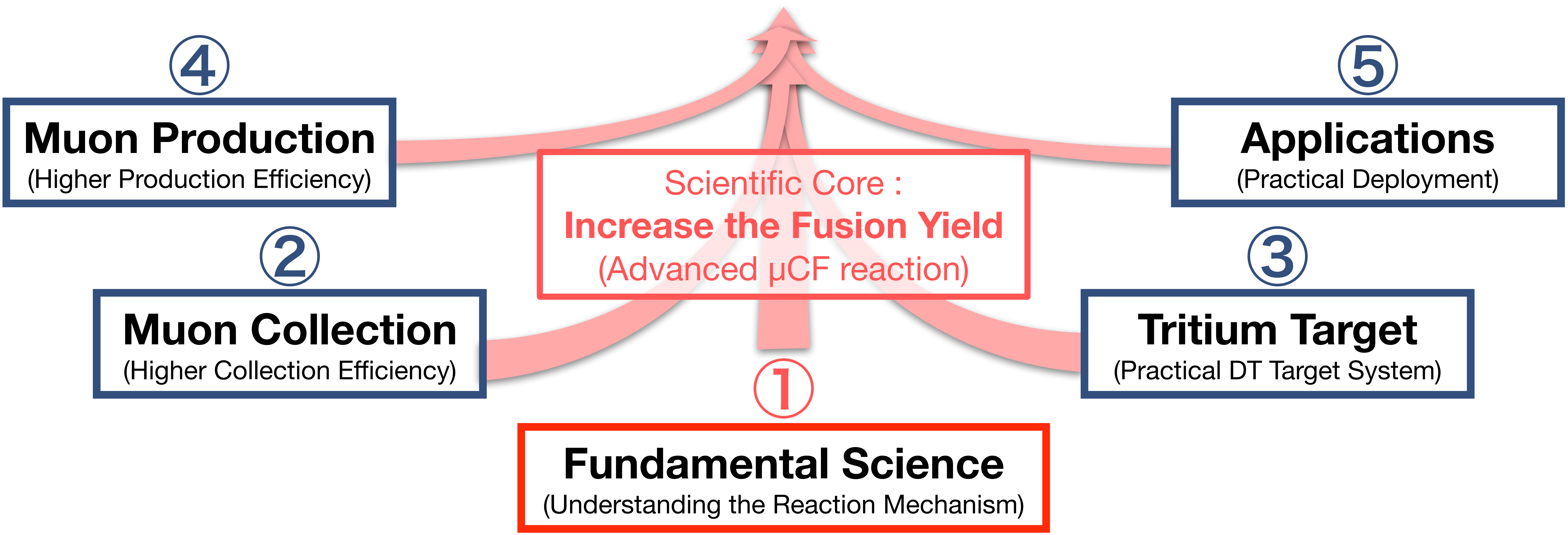
2 years
≤ ¥200M (≈€1.2M)

4 years
≤ ¥2B (≈€12M)

Moonshot μCF : Strategy

Ultimate Goal :

Practical Deployment of Advanced μCF Technology



- ✔ Each challenge is essential for realizing Advanced μCF
- ✔ An interdisciplinary approach is the key to practical implementation

Moonshot μCF : Future Vision

MOONSHOT μCF

2050 **Practical deployment**

DEMO
Technology Demonstration

Deployment of distributed μCF-based energy systems and expansion into a wide range of applications.

2035 (Year 9) **Integrated neutron source**

SYS
System Development

Develop and demonstrate a conceptual system based on Advanced μCF.

2030 (Year 4) **Demonstrate Advanced μCF**

BASE
Fundamental Research

Experimentally validate the Advanced μCF concept and improve target and muon technologies.

2027 (Year2) **Identify Key Conditions for Advanced μCF**

Identify the key factors governing the fusion yield (F) and establish the enabling technologies.

⑤ Current Activities & Collaboration

Project 1：Theory

PI : Yasushi Kino

Quantitative Understanding of the Advanced μCF Reaction Mechanism

- Fast-track and in-flight μCF reaction mechanisms
- Radiation chemistry effects (molecular ions and clusters)
- Identification of key conditions for improving the fusion yield (F)

Project 2：Beam

PI : Satoshi Mihara

Assessment of Beam Capabilities at Domestic and International Muon Facilities

- Beam characterization at J-PARC (MLF/COMET)
- Comparative evaluation with overseas facilities such as RAL, PSI, TRIUMF
- Assessment of achievable beam conditions for Advanced μCF

Advanced μCF

Project 3：Experiment

PI : Shinji Okada

Design of Validation Experiments for Advanced μCF

- Optimization of target and irradiation conditions, including radiation chemistry effects
- Design of TES X-ray and charged-particle detector systems
- Experimental design for post-stage-gate validation experiments

Project 4：Tritium

PI : Koichiro Shimomura

Tritium Handling and Safety Requirements

- Basic design of tritium supply, purification, recovery, and exhaust systems
- Safety requirements for multi-layer protection and interlock systems
- Evaluation based on operational experience at existing facilities

Integrated evaluation of theory, beam, experiment, and tritium technology

Participating Institutions

Project 1：Theory

PI : Yasushi Kino

Quantitative Understanding of the Advanced μCF Reaction Mechanism

- Tohoku University

Project 2：Beam

PI : Satoshi Mihara

Assessment of Beam Capabilities at Domestic and International Muon Facilities

- KEK
- University of Liverpool
- Osaka University

Advanced μCF

Project 3：Experiment

PI : Shinji Okada

Design of Validation Experiments for Advanced μCF

- Chubu University
- Okayama University
- RIKEN
- Rikkyo University
- TMU
- AIST
- KEK

Project 4：Tritium

PI : Koichiro Shimomura

Tritium Handling and Safety Requirements

- KEK
- Toyama University
- Osaka University

→ An Expanding International Collaboration

Summary

Advanced μCF is moving from understanding to design and experimental validation.

Why μCF now?

- ✓ New theory makes F a controllable design parameter
- ✓ TES spectroscopy directly resolves resonant μ-molecular states
- ✓ Global interest and muon-facility capabilities are increasing

Moonshot μCF R&D framework

- ✓ Novel fusion concepts beyond conventional approaches
- ✓ Target path: F ≈ 150 → 300 → 1000
- ✓ An expanding R&D framework built on four integrated core projects

Theory × Beam × Experiment × Tritium

Next step: identify key conditions, validate Advanced μCF, and expand the international collaboration network.

→ Toward Practical Advanced μCF

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