MUON CATALYZED FUSION (μCF) FOR ENERGY APPLICATION

300. WE-HERAEUS-SEMINAR

Energie-Forschung

Physikzentrum Bad Honnef

May 26-28, 2003

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Institute of Materials Structure Science
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RIKEN

1. What is Muon and Muon Catalyzed Fusion (μCF)?
2. Present Understanding of μCF Phenomena
3. Future Perspectives for Energy Application

What is a muon ?

Muon is an elementary particle first found in the cosmic ray in 1937. Muon is now produced in large numbers by using accelerators.

	Charge	Spin	Mass	Lifetime
μ^+	+1	1/2	106 MeV (1/9 of Proton)	2.2 μs
μ^-	-1	1/2	106 MeV (207 x Electron)	2.2 μs

Structureless (point-like) particle and interacts mainly electromagnetically with atoms in matters

Pion (π) production by accelerated beam

$p(n) + N \rightarrow \pi^{\pm} + X....$

Muon (μ) production by $\pi\mu$ decay

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

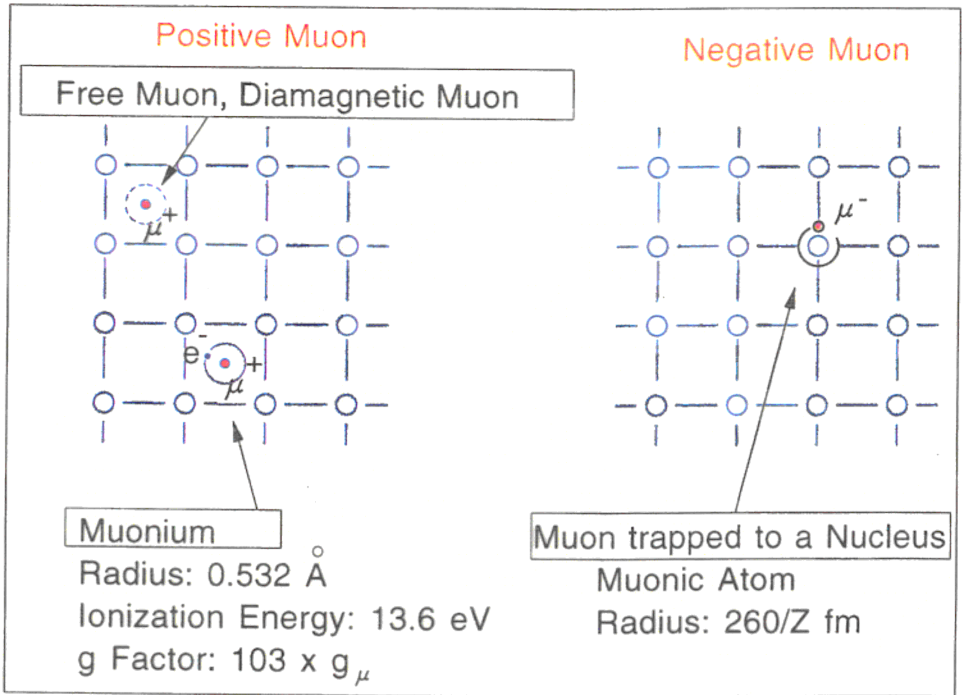
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

(26 ns)

Behavior in Matters

μ^+ "Light proton"

μ^- "Heavy electron"



INTRODUCTION; MUON FOR HUMAN LIFE

Heavy Electron (200 m_e) → Promotion of Cyclic Fusion Reaction → New Atomic Energy

Radioactivity Polarization Phenomena (2.2 μs) → Sensitive Microscopic Magnetic Probe → New Functional Biophysics and Life Science

Heavy Electromagnetic Particle (200 m_{e^-}, 200 m_{e^+}) → Radiography for km-size Substance → Prevention of Nature Disasters

Muon Catalyzed Fusion (μCF)
Clean, Without High Temperature,
Full Controlled

FUSION ENERGY AND MUON

Major Contributors

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G. Eaton (RAL)

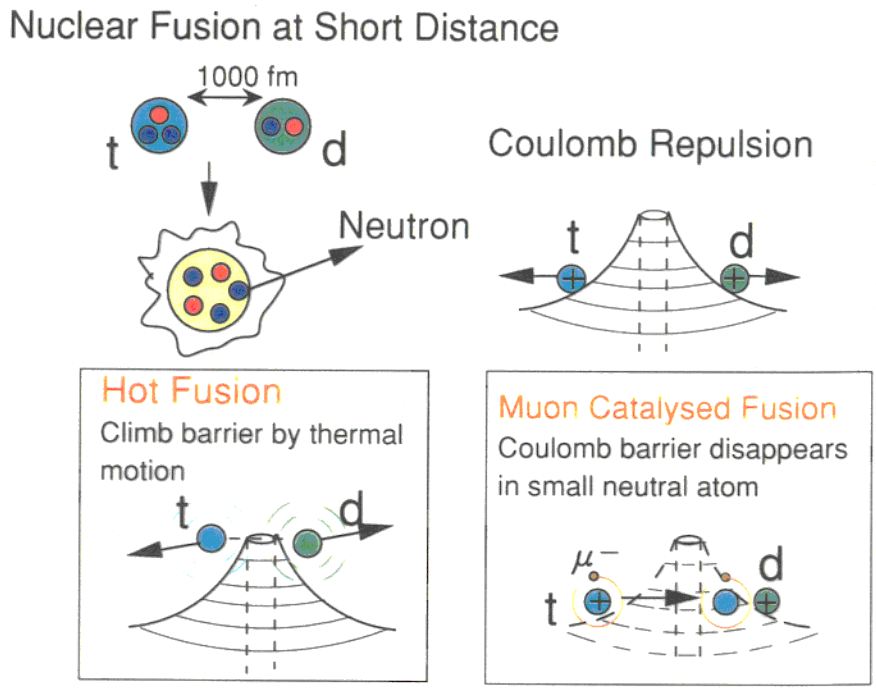
L. I. Ponomarev, M. Faifman, L. Bogdanova (Kurchatov),

J. S. Cohen, M. Leon (LSNL),

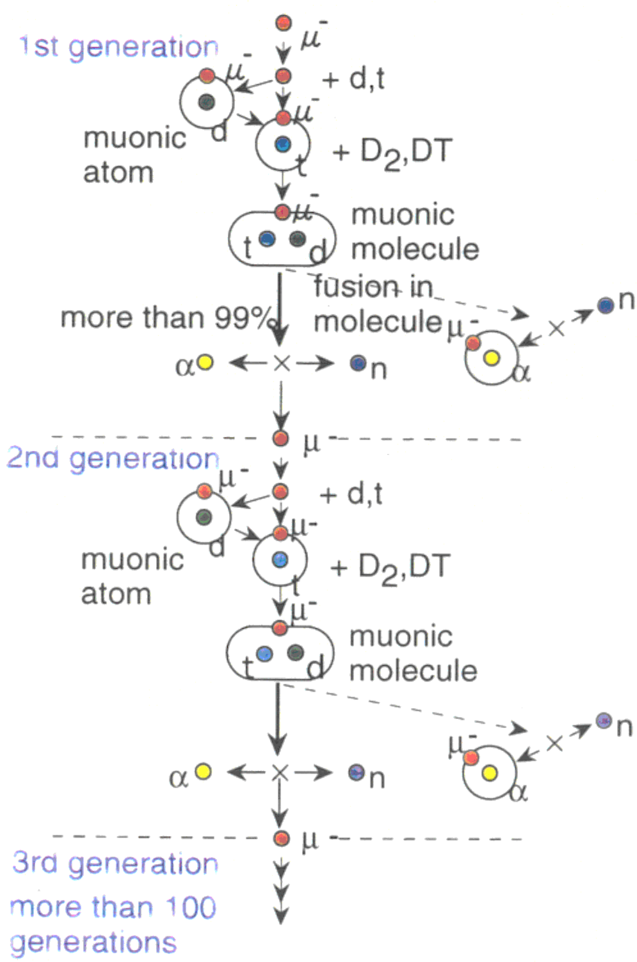
M. Kamimura (Kyushu), T. Koike (KEK)

PRINCIPLE OF μCF

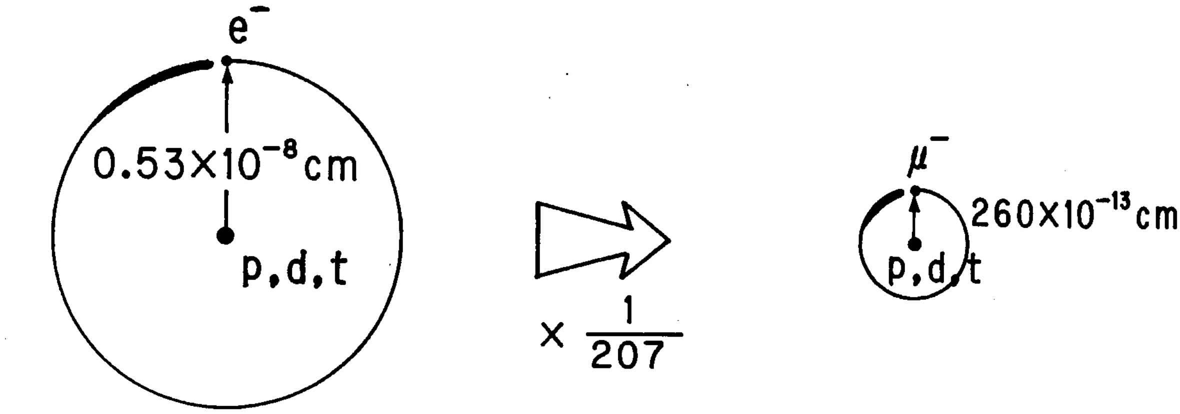
Removal of Coulomb Repulsion



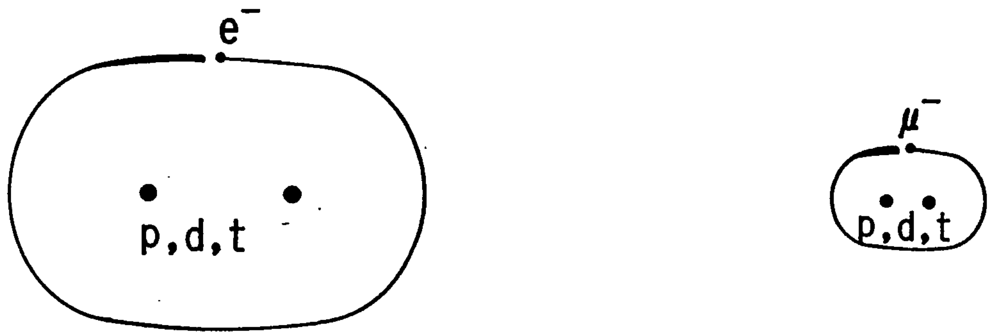
Successive Chain Reaction



MUONIC MOLECULE : BASIC PROPERTIES

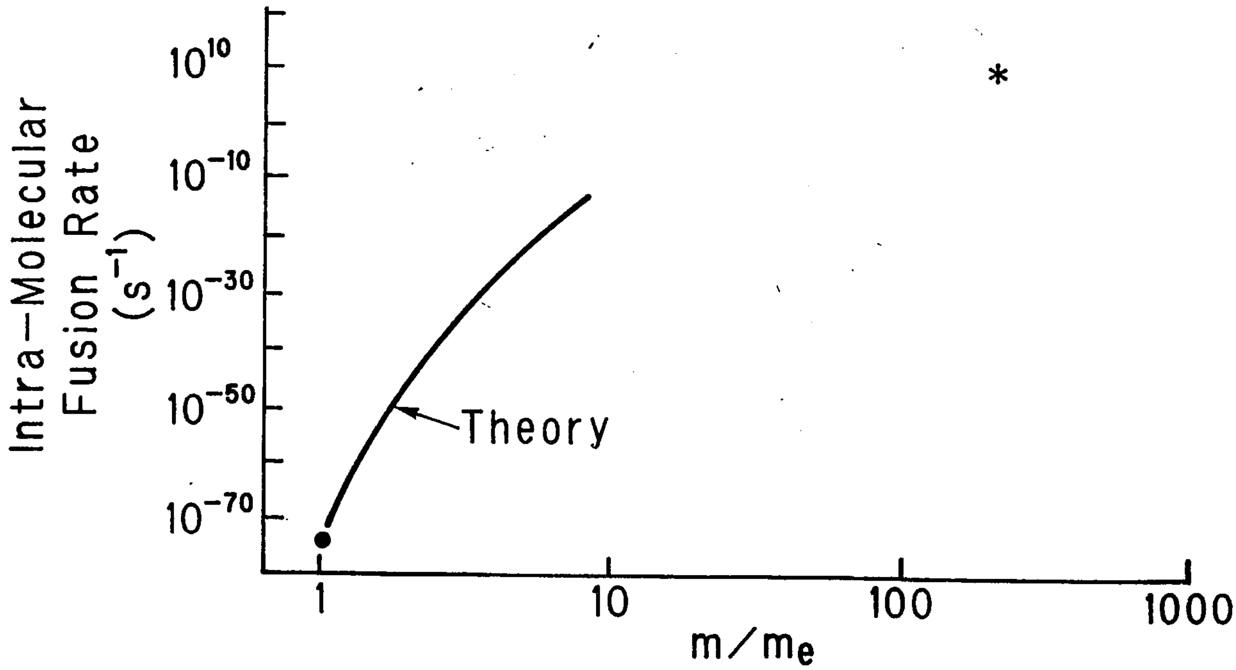


$E_{1s}(pe^-)$: -13.6eV $E_{1s}(p\mu^-)$: -2.8keV



$a_{g.s.}(ppe^-) \simeq 2a_{1s}(pe^-)$: 1×10^{-18}cm $a_{g.s.} \simeq 520\times10^{-13}$cm

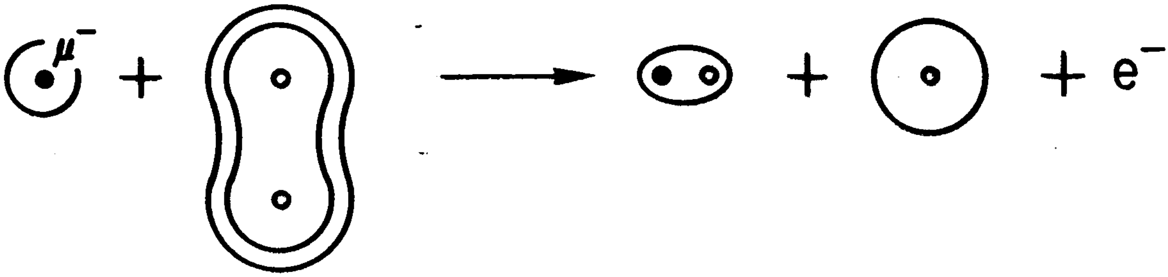
$E_{g.s.}(ppe^-) \simeq \frac{1}{10}E_{1s}(pe^-)$: -1eV $E_{g.s.}(pp\mu^-) \simeq -300$eV



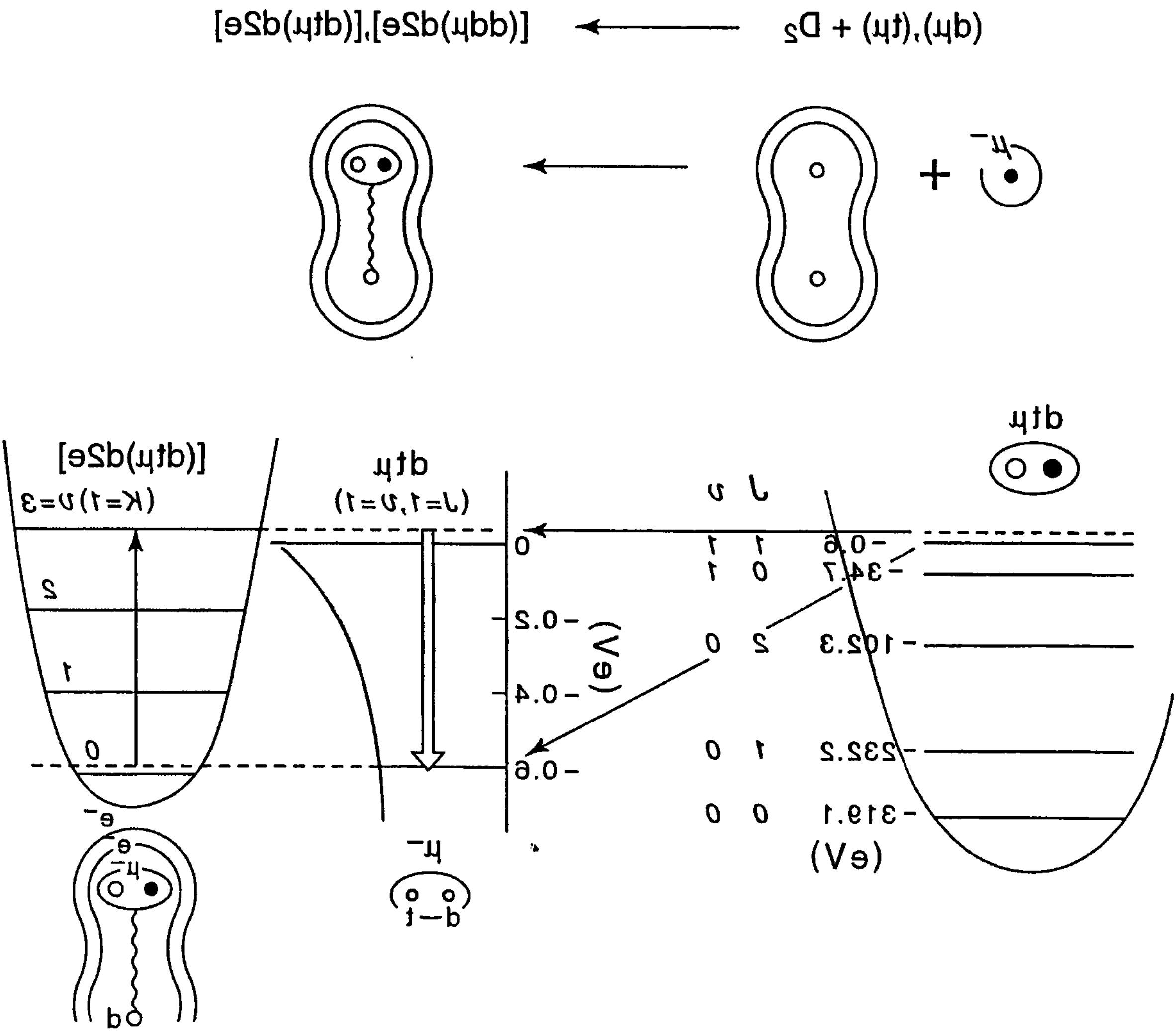
FORMAION OF MUON MOLECULE

Auger Formation $\lambda_{dt\mu} \simeq 10^6 s^{-1}$

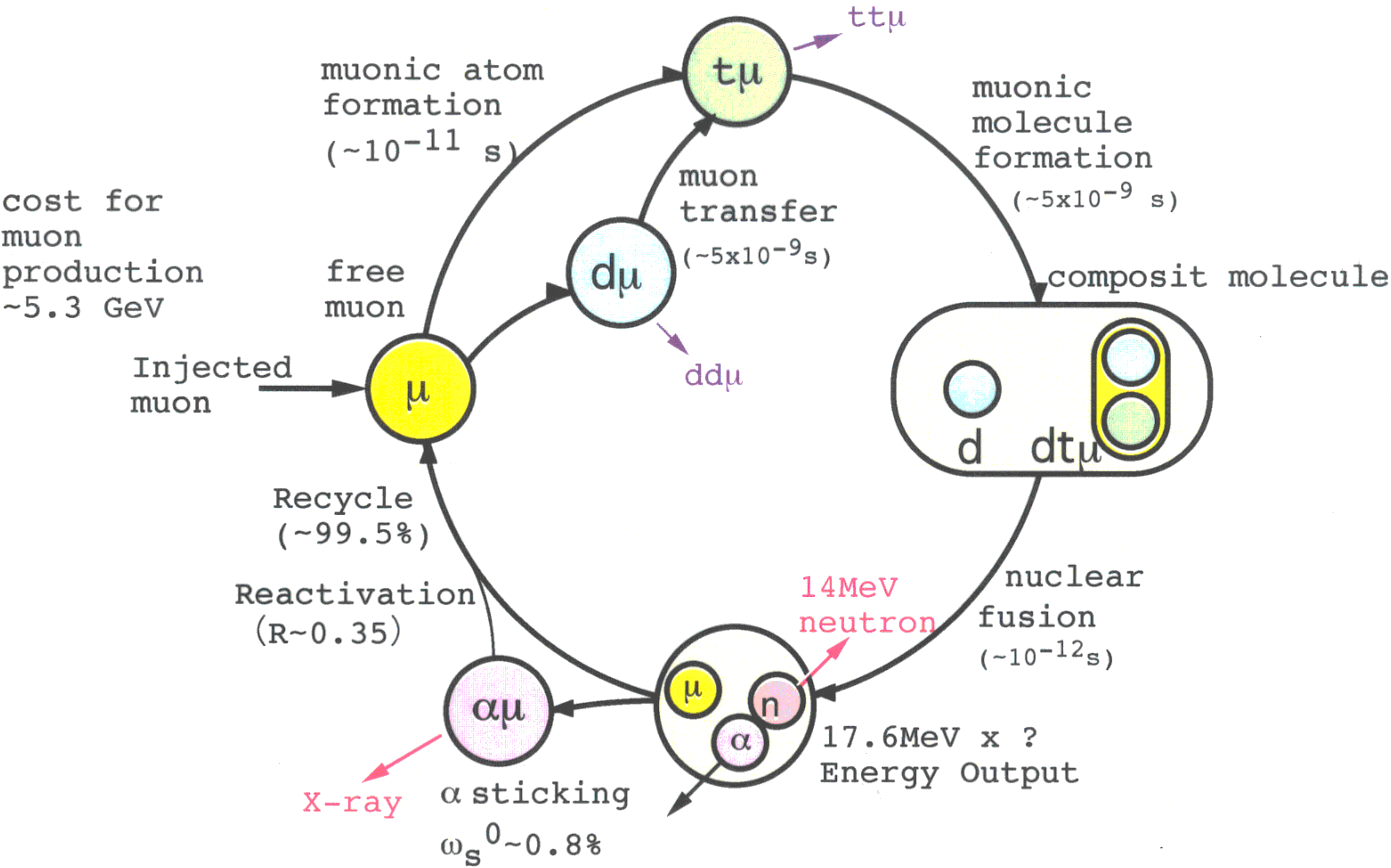
$$(d\mu),(t\mu) + D_2 \longrightarrow (dd\mu),(dt\mu) + (de) + e^-$$



Resonant Formation $\lambda_{dt\mu} \simeq 10^8 \sim 10^9 s^{-1}$



muon catalyzed d-t fusion cycle



PRESENT UNDERSTANDING OF μCF PHENOMENA

1. Typical Experimental Arrangement

   μCF Experiment at RIKEN-RAL

   Realization of "Long-Term" & "Controlled"

   Nuclear Fusion Reaction

   3μW (10^6 Fusion/s) via 160 kW ISIS-RAL
   more than 300 days fusion production

2. Recent Important Discoveries

   N. Kawamura, K. Nagamine et al.
   Phys. Rev. Lett. 90 (2003) 043401-1

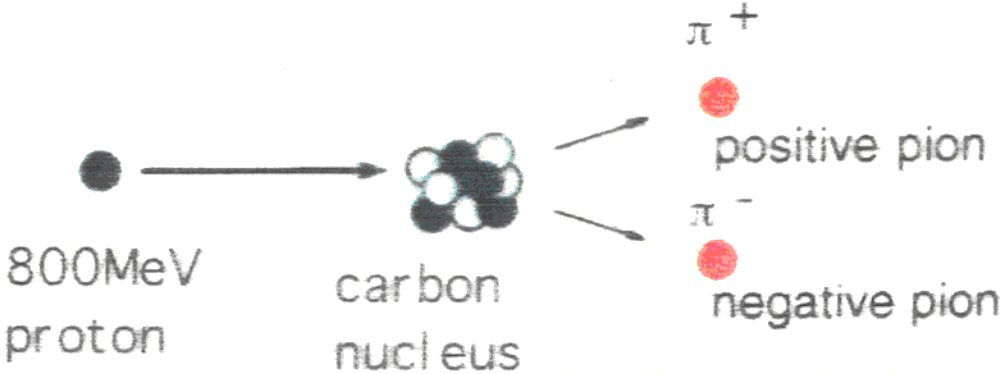
☆Anomalous μ^- Regeneration in Condensed D-T

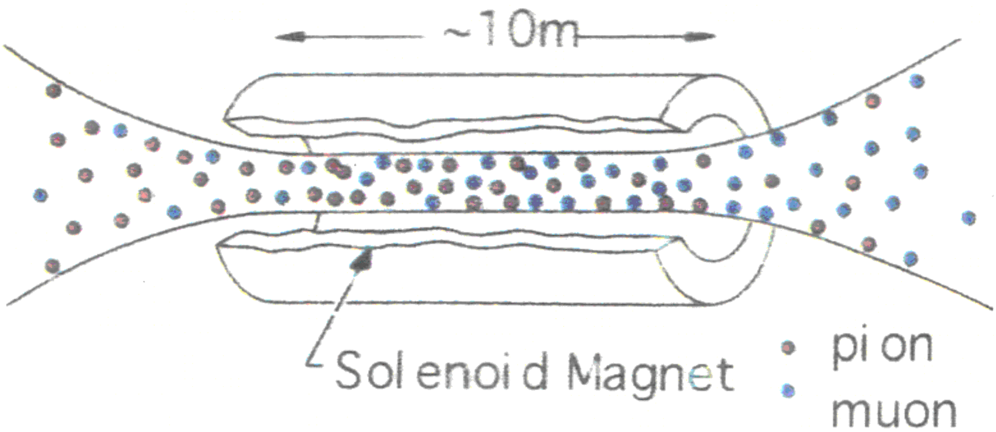
$$Y_n = \frac{\phi\lambda_c}{\lambda_c + \lambda_c W}, \qquad W = \omega_s^0(1 - R) + \text{others}$$

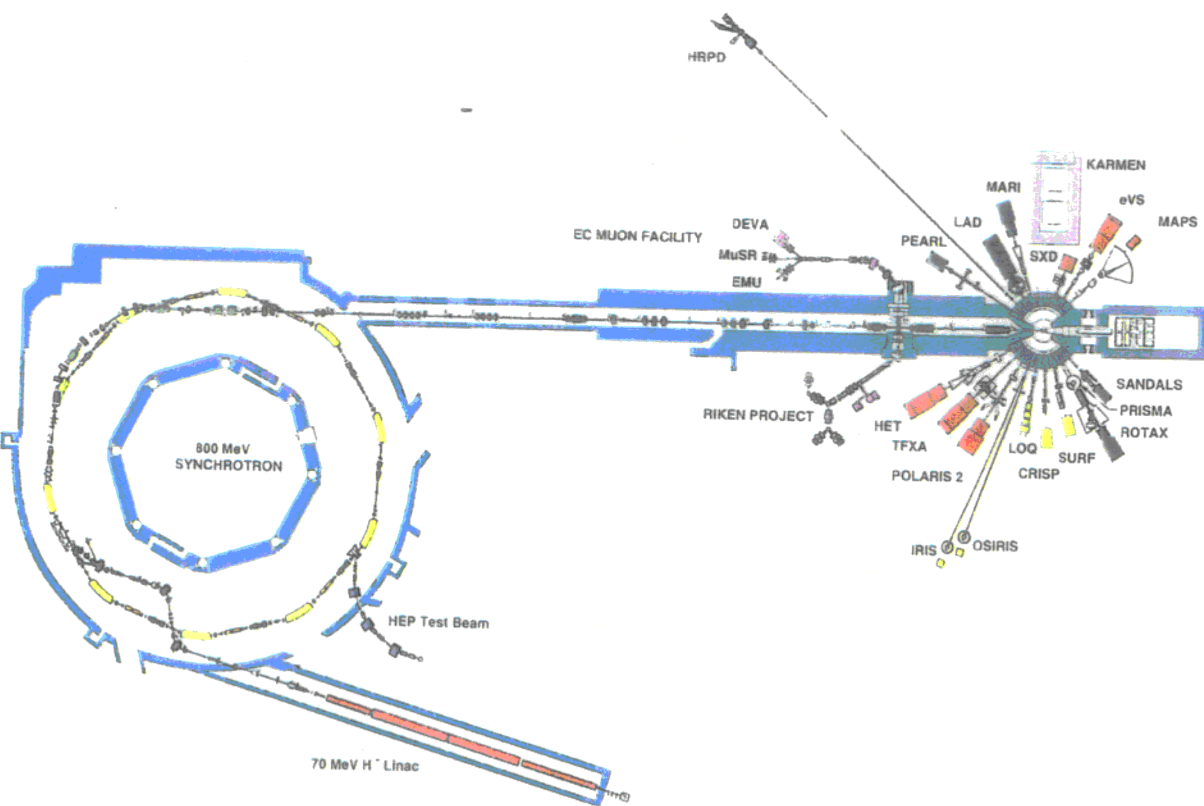
☆Triple Collision Effect in Condensed D-T (upto $\phi = 1.5$)

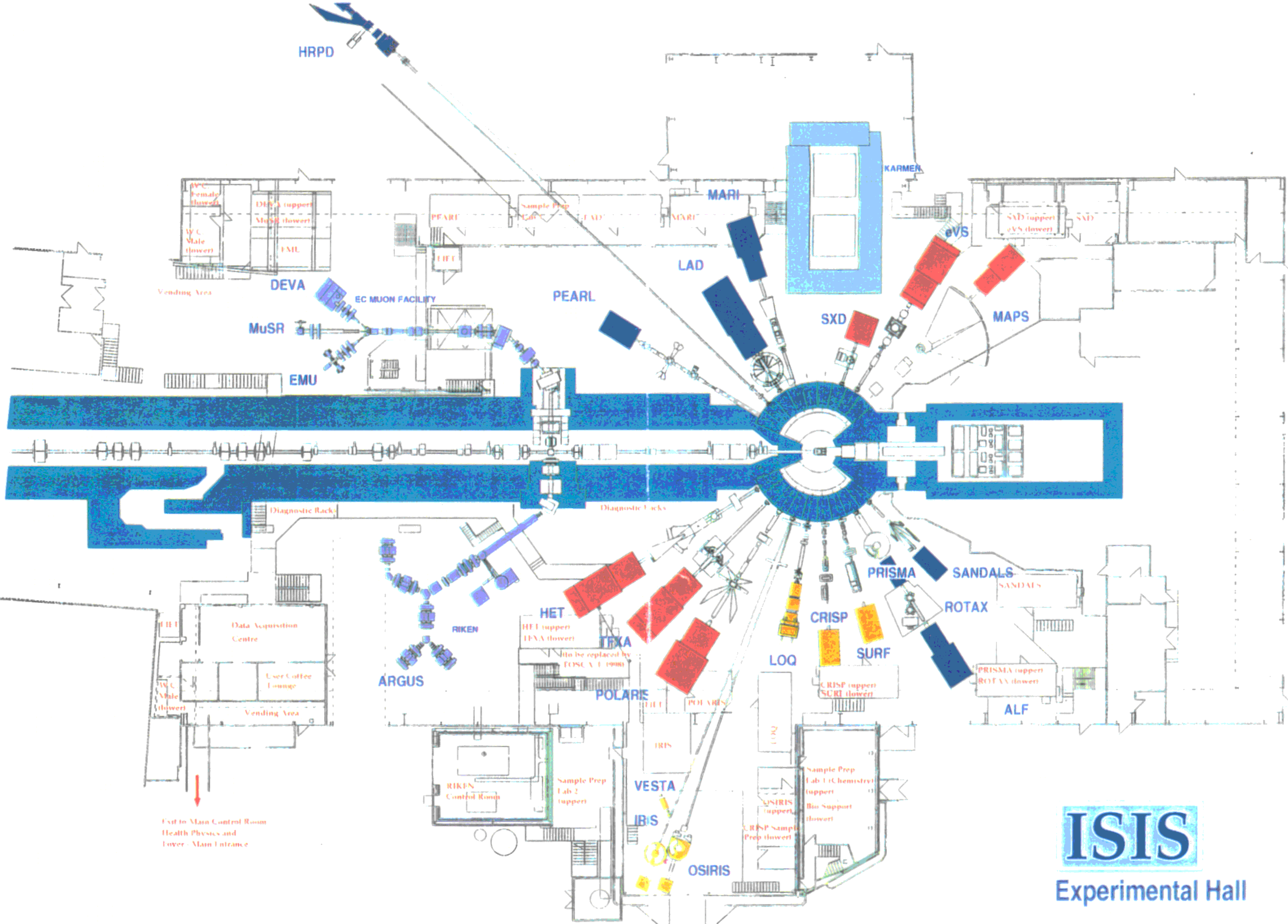
$$\lambda_c(\lambda_{dt\mu\text{-}D_2}) \propto \phi, \qquad \lambda_c^{obs} \propto \phi^2$$

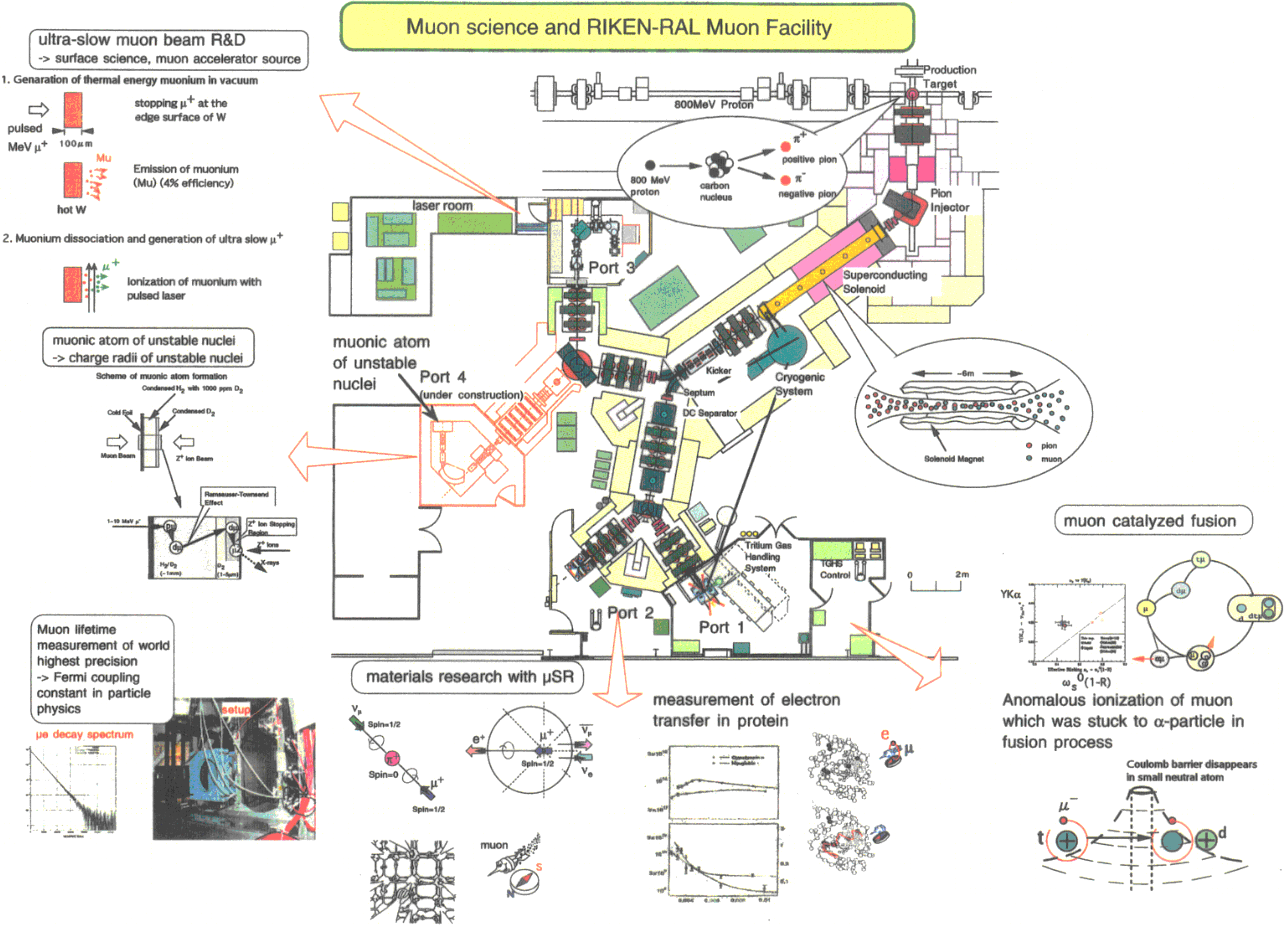
$$t\mu + D_2 + D_2' \rightarrow [\,(dt\mu)d2e\,] + D_2''$$


π +
positive pion
π −
negative pion
800MeV
proton
carbon
nucleus


~10m
Solenoid Magnet
pion
muon


HRPD
KARMEN
MARI
eVS
MAPS
LAD
PEARL
SXD
DEVA
EC MUON FACILITY
MuSR
EMU
800 MeV
SYNCHROTRON
RIKEN PROJECT
HET
TFXA
POLARIS 2
LOQ
SURF
CRISP
SANDALS
PRISMA
ROTAX
IRIS
OSIRIS
HEP Test Beam
70 MeV H⁻ Linac


HRPD
KARMEN
MARI
LAD
PEARL
SXD
eVS
MAPS
DEVA
EC MUON FACILITY
MuSR
EMU
Diagnostic Racks
HET
TFXA
POLARIS
LOQ
CRISP
SURF
PRISMA
SANDALS
ROTAX
ALF
RIKEN
ARGUS
VESTA
IRIS
OSIRIS
Data Acquisition Centre
User Coffee Lounge
Vending Area
RIKEN Control Room
Sample Prep Lab 2 (upper)
PRISMA (upper)
ROTAX (lower)
CRISP (upper)
SURF (lower)
Exit to Main Control Room
Health Physics and
Foyer - Main Entrance
ISIS
Experimental Hall

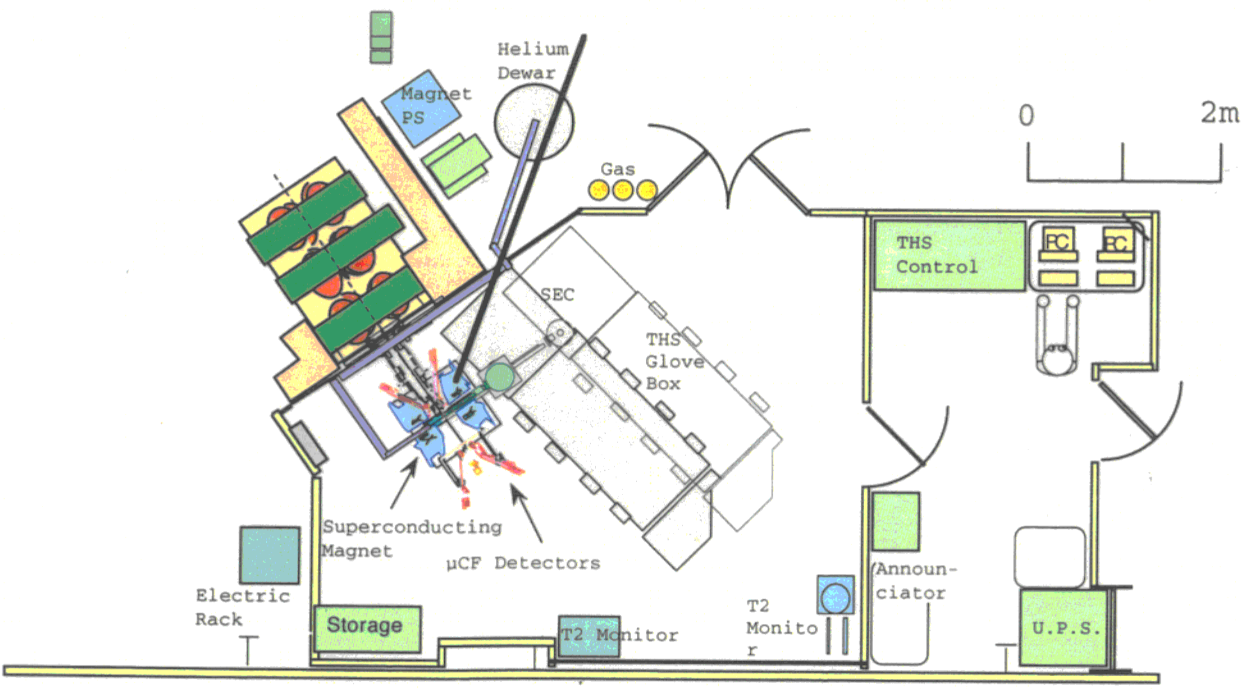

Muon science and RIKEN-RAL Muon Facility
ultra-slow muon beam R&D
-> surface science, muon accelerator source
1. Genaration of thermal energy muonium in vacuum
pulsed MeV μ^+
100 μm
stopping μ^+ at the edge surface of W
Mu
hot W
Emission of muonium (Mu) (4% efficiency)
2. Muonium dissociation and generation of ultra slow μ^+
μ^+
Ionization of muonium with pulsed laser
muonic atom of unstable nuclei
-> charge radii of unstable nuclei
Scheme of muonic atom formation
Cold Foil
Condensed H_2 with 1000 ppm D_2
Condensed D_2
Muon Beam
Z^+ Ion Beam
Ramsauer-Townsend Effect
1–10 MeV μ^-
Z^+ Ion Stopping Region
Z^+ Ions
X-rays
Muon lifetime measurement of world highest precision
-> Fermi coupling constant in particle physics
μe decay spectrum
setup
800MeV Proton
Production Target
800 MeV proton
carbon nucleus
π^+ positive pion
π^- negative pion
Pion Injector
laser room
Port 3
Superconducting Solenoid
~6m
Solenoid Magnet
pion
muon
muonic atom of unstable nuclei
Port 4 (under construction)
Kicker
Septum
DC Separator
Cryogenic System
Tritium Gas Handling System
TGHS Control
0
2m
Port 2
Port 1
materials research with μSR
ν_μ
Spin=1/2
π^+
Spin=0
μ^+
Spin=1/2
e^+
μ^+
Spin=1/2
$\bar{\nu}_\mu$
ν_e
muon
S
N
measurement of electron transfer in protein
e
μ
muon catalyzed fusion
YKα
$\omega_s^0(1-R)$
Anomalous ionization of muon which was stuck to α-particle in fusion process
Coulomb barrier disappears in small neutral atom
μ^-
t
d

μCF EXPRIMENTAL SET-UP

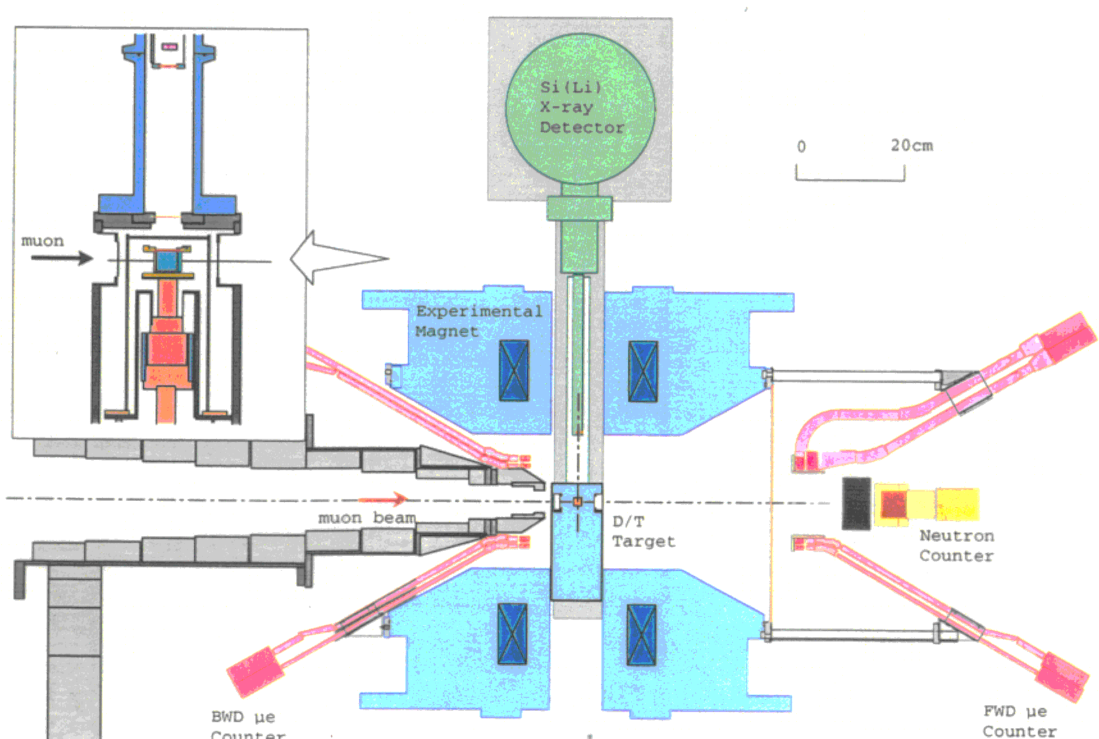
FOR D-T WITH HIGH DENSITY AND HIGH C_T

RIKEN-RAL (1996 — Present)

ϕ: 1.2 ϕ_0 (Liquid), 1.4 ϕ_0 (Solid) (ϕ_0: 4.25×10^{22}/cc)



RIKEN μCF Experimental Port1 Layout

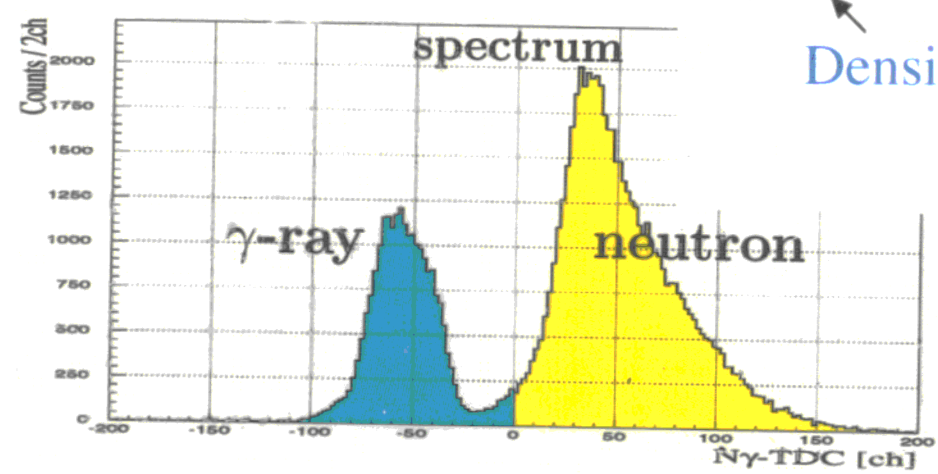


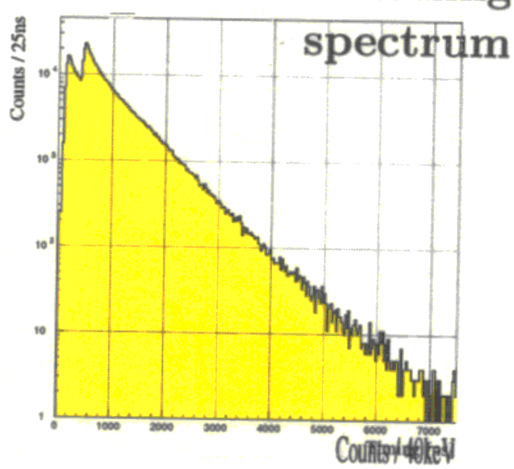
OBSERVATION OF FUSION NEUTRON
FROM μCF IN HIGH ϕ & HIGH C_T D-T

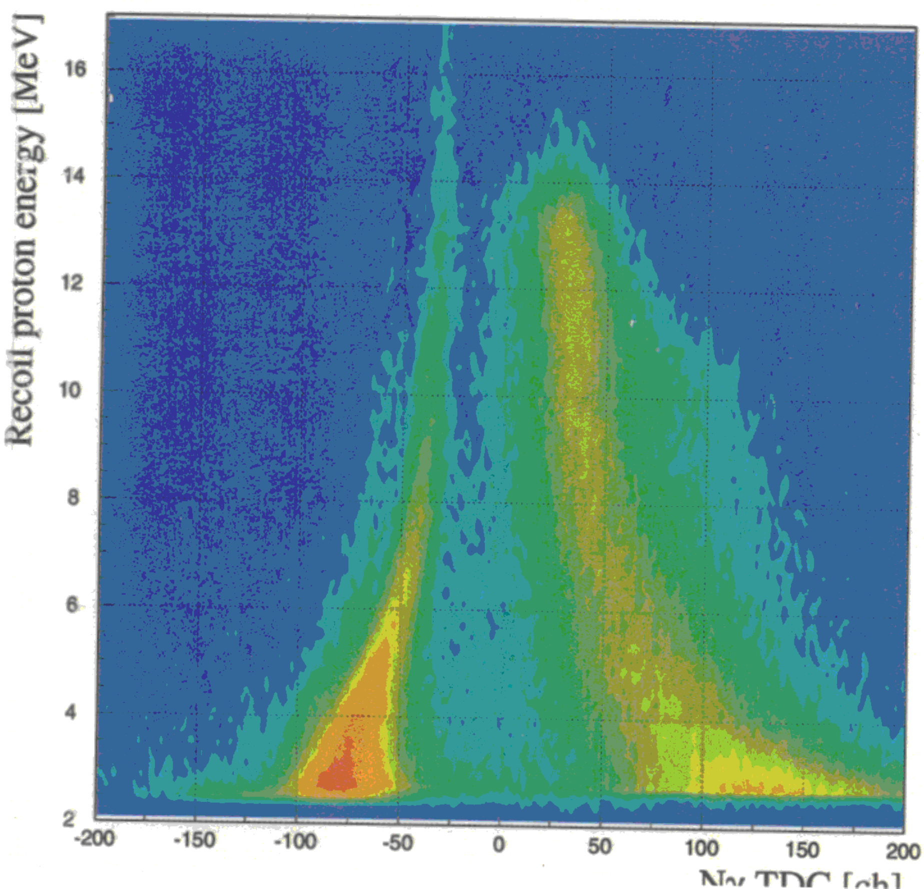
Cycling Rate — Neutron Yield — Disappearance Rate

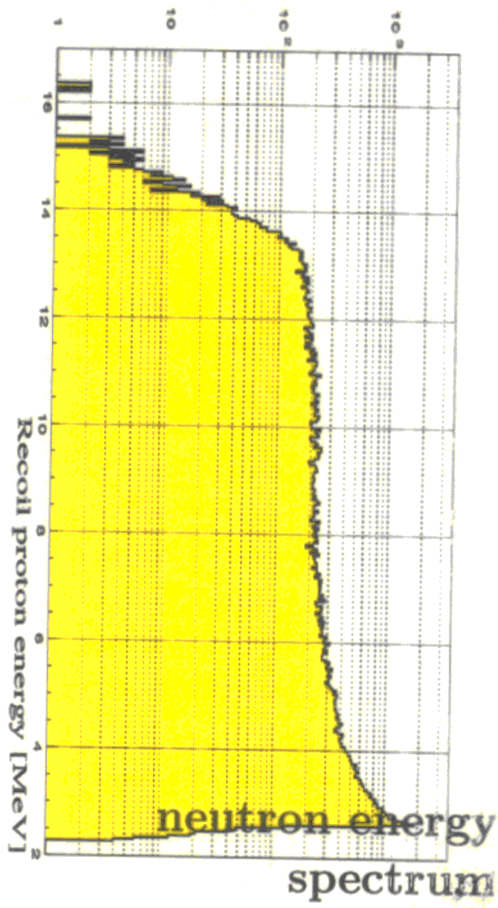
$$\lambda_c = \frac{Y_n \lambda_n}{\phi}$$

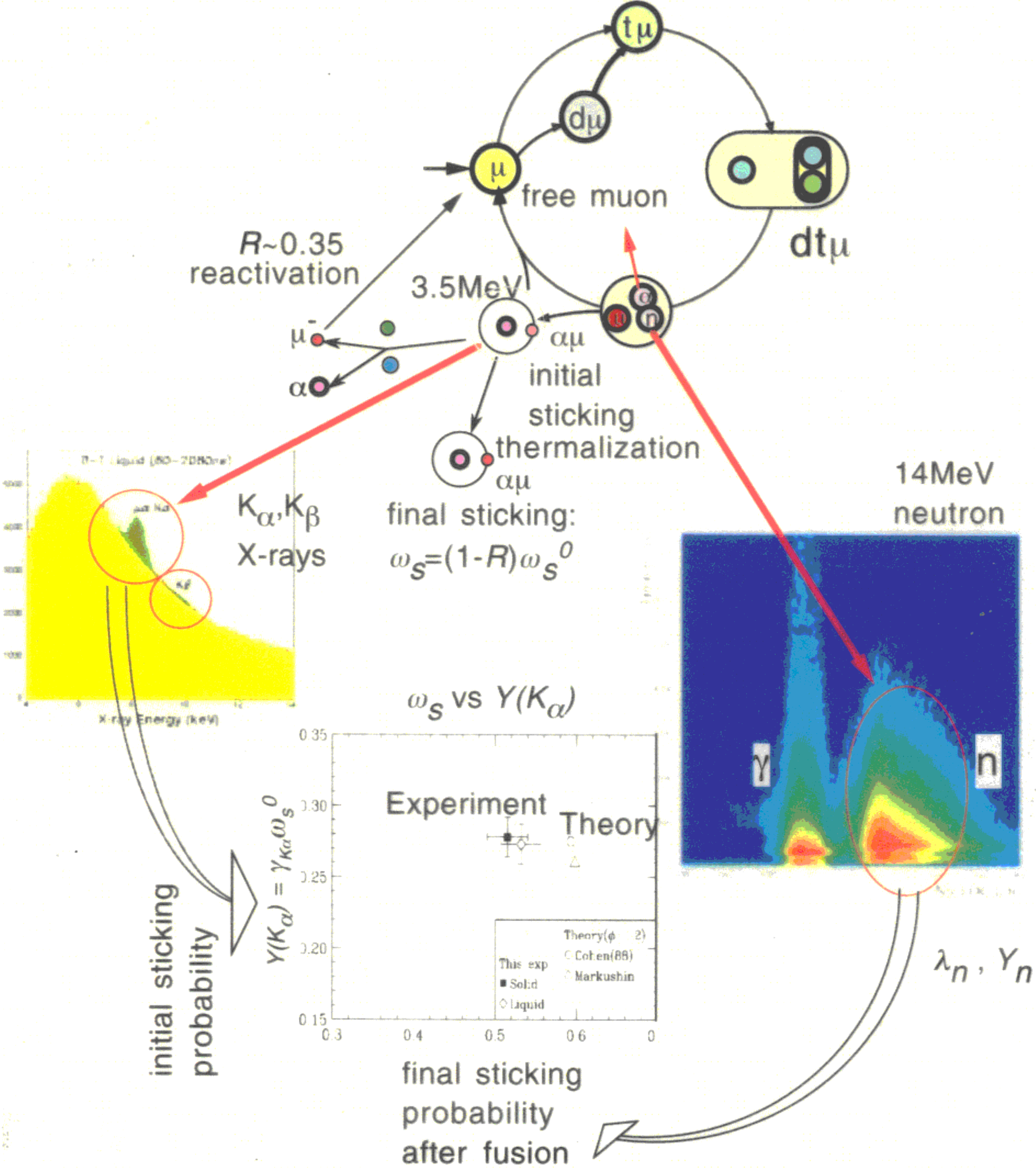
Density



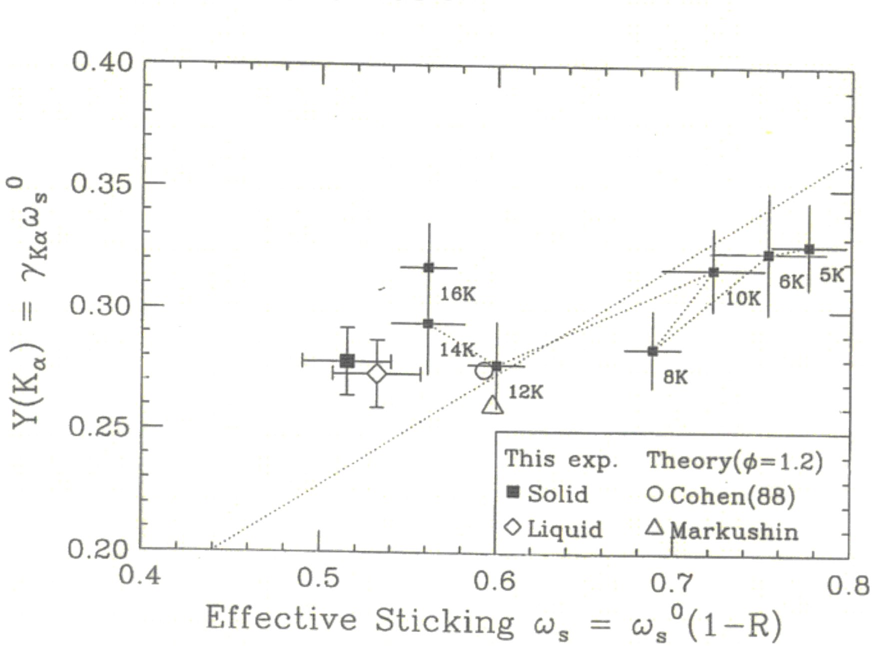








tμ
dμ
μ
free muon
dtμ
R~0.35
reactivation
3.5MeV
μ⁻
α
αμ
initial
sticking
thermalization
αμ
final sticking:
ωs=(1-R)ωs⁰
Kα,Kβ
X-rays
X-ray Energy (keV)
14MeV
neutron
γ
n
λn , Yn
ωs vs Y(Kα)
Experiment
Theory
Y(Kα) = γKαωs⁰
This exp
Solid
Liquid
Cohen(88)
Markushin
initial sticking
probability
final sticking
probability
after fusion



Y(Kα) = γKαωs⁰
Effective Sticking ωs = ωs⁰(1−R)
16K
14K
12K
10K
8K
6K
5K
This exp.
Solid
Liquid
Theory(φ=1.2)
Cohen(88)
Markushin

ORIGIN OF DISCOVERED μCF PHENOMENA IN SOLID (CONDENSED) D-T

→ Understanding → Enhanced Energy Production!

☆ Triple Collision Effect in Condensed D-T

negative resonance defect in $(dt\mu)$ formation

☆ Anomalous $(\alpha\mu)^+$ Ionization & Its T-Dependence

Atomic Process in $(\alpha\mu)^+$

Transition among Metastable States

Radiolysis Effect

Behaviour of Spur

Black Scattering Effect

⇨ Need Exotic Atom/Molecule Theory

In Highly-Correlated Condensed Matter

FUTURE PERSPECTIVES FOR ENERGY APPLICATION

— Muon Catalyzed Fusion (μCF) —

1. Muon Cost & Towards Break-Even
2. Hybrid Reactor & Realistic Energy Application
3. Realization of kW μCF Reactor for Fusion Energy Demonstration
4. 14 MeV Neutron Source & Contribution to Fusion Energy
5. Optimistic μCF Power Plant in the Future

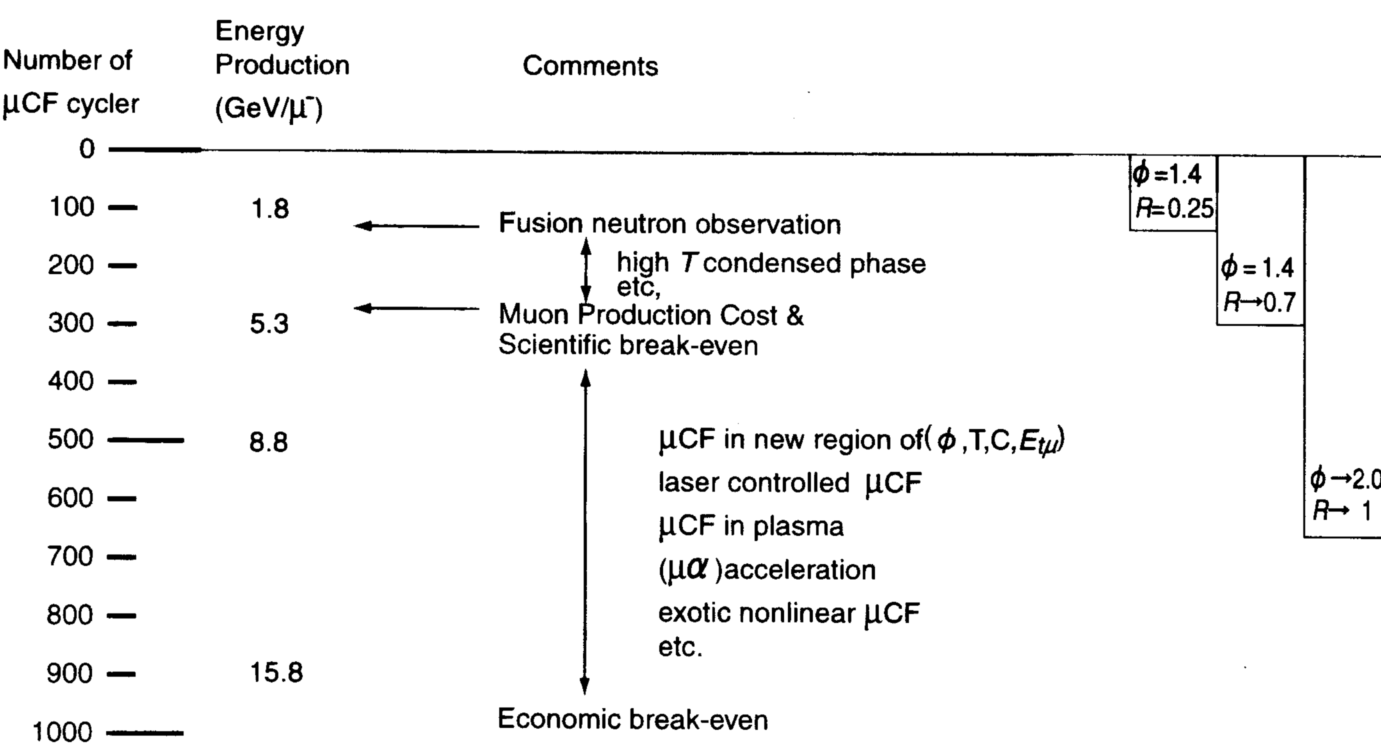
μCF ENERGY SOURCE

Muon Cost

1 GeV d(t) beam on (t, Li, Be) target; 0.25 π^-/1 GeV

Large Scale Superconducting Magnet; 0.75 μ^-/π^-

⇨ 0.20 μ^-/1 GeV and 5 GeV/μ^-



MUON-CATALYSIS and ACCELERATOR-BREEDER HYBRID REACTOR

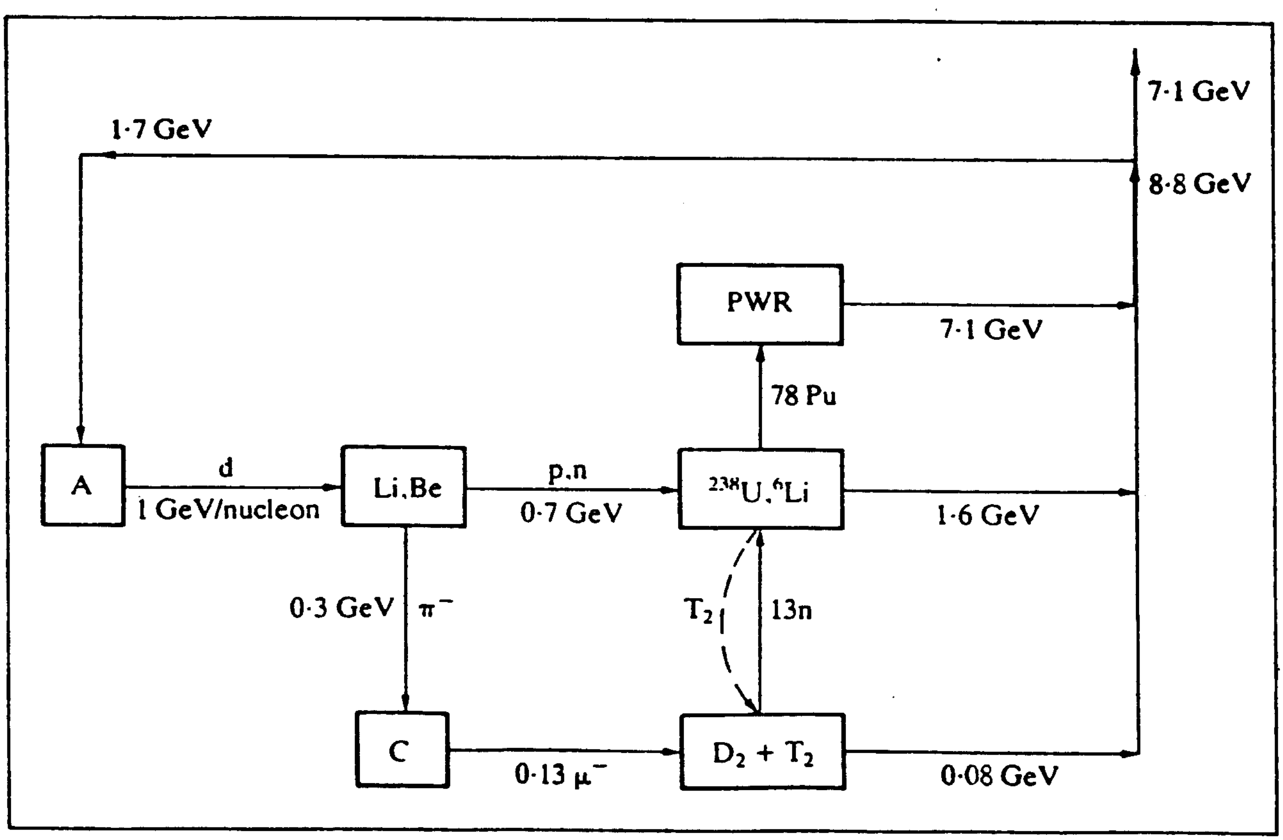
— *Petrov* —

☆Nuclear Reaction of 1 GeV d, t Beam & Li, Be, B, C Nuclei

π^- Production (30%) → μCF Neutron
↓
Rest (70%) → ^{238}U Fission & ^{239}Pu Production
t Production via ^{6}Li

☆Doubling Energy Productivity (4.4 + 4.3(μ) = 8.7 GeV/GeV)

Doubling Fuel Breading (45 + 30(μ) = 87 ^{239}Pu → 7.1 GeV/GeV)
(0.6 + 0.7(μ) = 1.3 t)



REALIZATION OF kW μCF REACTOR;

PUBLIC UNDERSTADING OF FUSION ENERGY

(— ; under construction)

Launching of High Intensity (> MW) Accelerator Project

Neutron Facility

KEK-JAERI (Japan) (n, μ, K, ν)

SNS (USA)

ESS (Europe)

Neutrino Factory

CERN

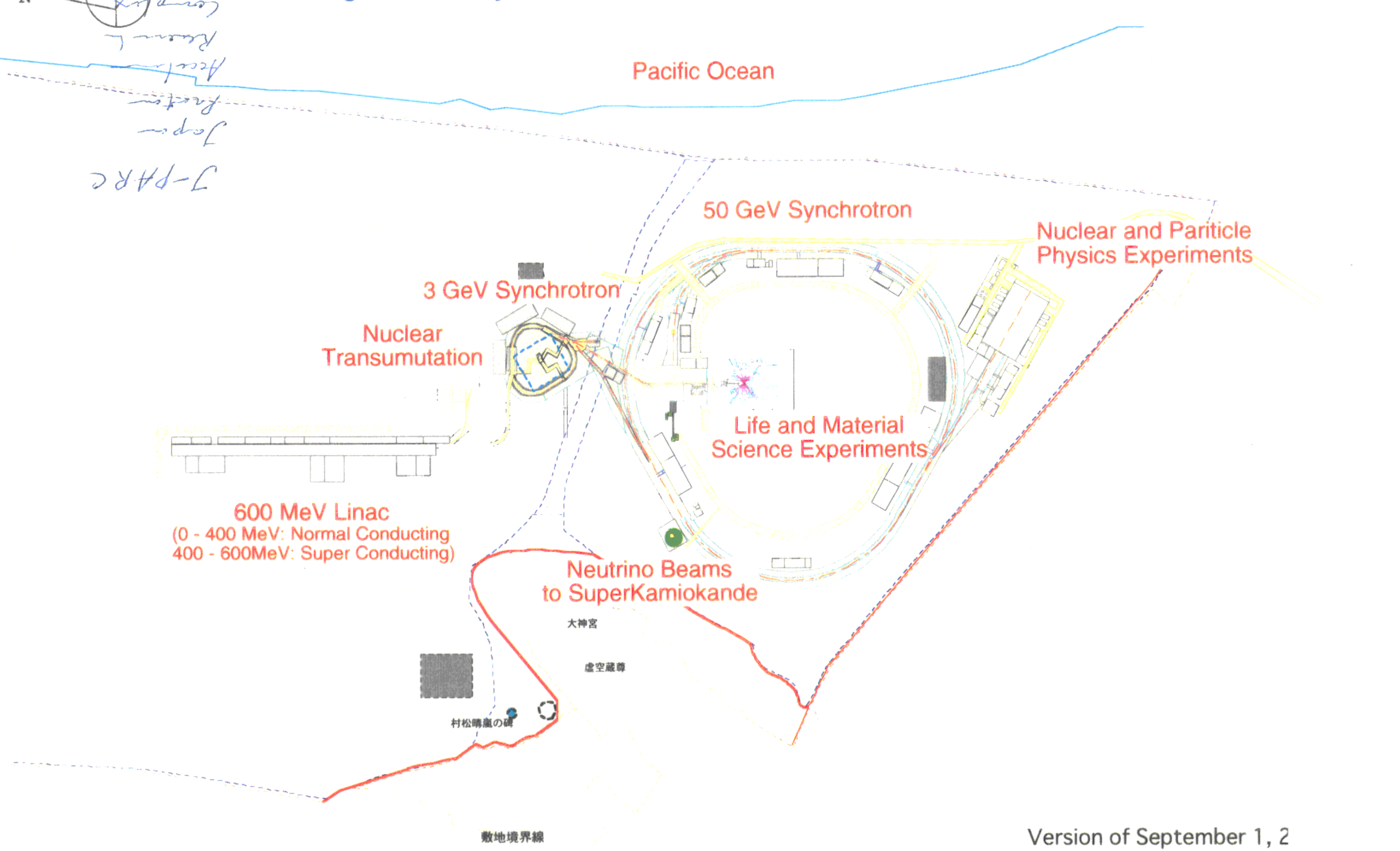
Muon-Colliders

Realization of Large-Solid Angle Muon Production-Channel

Dai Ω at KEK

MECO at BNL

Plan View of High-Intensity Proton Accelerator Complex



J-PARC
Japan Proton Accelerator Research Complex
2007, First Beam

Version of September 1, 2

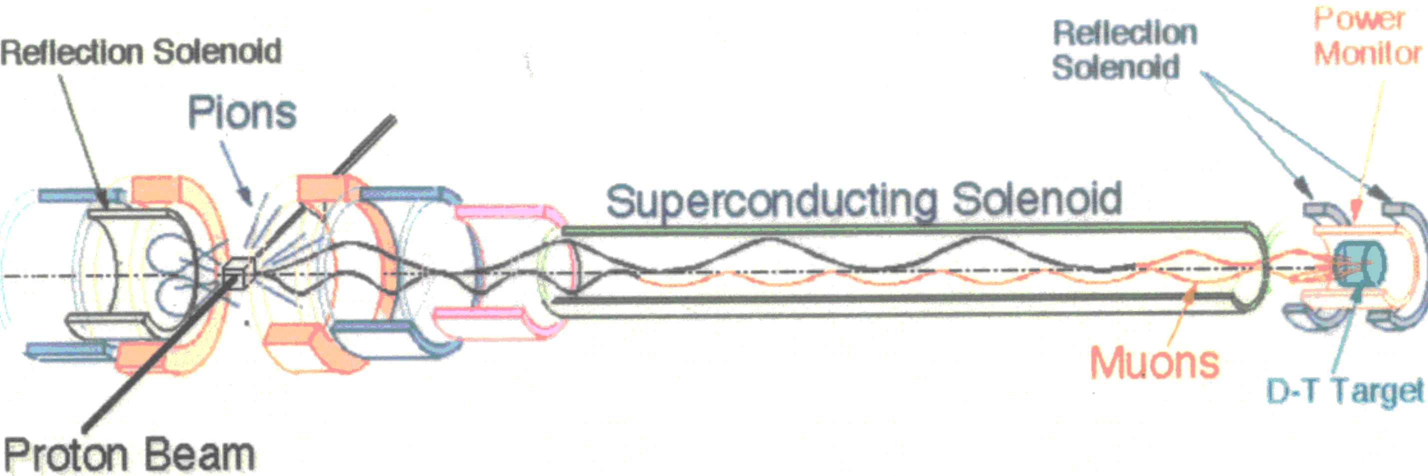
COCEPTUAL DESIGN OF kW μCF REACTOR (October, 2002)

REQUIREMENTS

Assume 150 μCF/μ^-

$\rightarrow 4.22 \times 10^{-10}$ J/μ^-

1 kW $\rightarrow 2.5 \times 10^{12}\ \mu^-/s$



	(SUPER)^2 at ISIS-II K. Ishida et al. ('98)	kW μCF Reactor	Gain Factor
Ip×Ep	60μA×800 MeV	5mA×1 GeV	≅ 100
Target	4 cm, C	4 cm, C	
π^- Total Production	1.2×10^{12} /s	1.2×10^{14} /s	
$\pi^- \rightarrow \mu^-$	0.025	0.025 (1+α)	α : mirror reflection ≅0.10(μCF·INS)
μ^- Stopping in D-T	$3\times10^{10}\times\varepsilon_1$	$3\times10^{12}\times(1+\alpha)\cdot(1+\beta)\cdot\varepsilon_1$	β : mirror reflection

need : $1+\alpha+\beta > \varepsilon_2^{-1}$

14 MeV μCF NEUTRON SOURCE FOR MATERIALS IRRADIATION

– *FNEA-MUCATEX-PSI Collaboration* —

Source Type/ References	Reaction E_{beam}	Acc. Current Beam Power	14-MeV Neutorn Intensity (n/s)	Test Surface (cm^2)	14-MeV Neutron Fluxes ($n/cm^2 \cdot s$)	Damage (dpa/y)	Remarks On E_n
IFMIF (Extrapolated)	d → Li 35 MeV	500 mA 18 MW	5×10^{16}	5×5	5×10^{15} 5×10^{14}	500 50	5 to 32 MeV Strongly divergent
SNS	p → Pb 0.6 GeV	6 mA 3.6 MW	9×10^{17}	45	2×10^{16} (all energies)	320	En < 14 MeV (+ high-energy tail)
Muon-catalyzed fusion neutron source (A) $X_c = 100$	d → Li 1.6 MeV 0-deg geometry	10 mA 16 MW 1 mA 1.6 MW	1×10^{17} 2×10^{15}	9400 (5 T) $R\times L = 30\times20$ 2000 (10 T) $R\times L = 10\times30$	1×10^{15} 1×10^{12}	1 0.1	14 MeV
Muon-catalyzed fusion neutron source (B) $X_c = 100$	d → Li 1.5 MeV 180-deg geometry	12 mA 18 MW	0.5 to 1×10^{17}	2000 (5 T) $R\times L = 8\times40$ 800 (10 T) $R\times L = 5\times25$	2.5 to 5×10^{15} 1×10^{14}	2.5 to 5 10	14 MeV

OPTIMISTIC μCF PLANT

— *Possibility of Future Directions* —

μCF in Inertially Confined D-T Pellet

$\phi = 10.0$, $T \geq$ R. T.

☆ $\lambda_c \rightarrow 1000 \times 10^6\ s^{-1}$ ($\lambda_c \propto \phi$)

☆ $R \rightarrow 1$ (high ϕ, high T)

Both Expected from Recent RIKEN-RAL Data

N. Kawamura, K. Nagamine et al.
Phys. Rev. Lett. 90 (2003) 043401-1

$Y_n \rightarrow 6600/\mu^-$

Power Output from 10 MW Accelerator

(15 MW electric power)

→ *175 MW* *(75 MW electric power)*

PRESENT STATUTS

— Muon Catalyzed Fusion (μCF) —

1. Development of μCF Towards New Atomic Energy

    a. Need Further Fundamental Understandings

    λ_C (T, φ)? , R(T)? , etc.

    b. Close to Break-Even

    c. Close to Realization of Hybrid Reactor

    d. Close to Realization of 14 MeV Neutron Source

2. Contribution to Fusion Energy

    ☆ Quick Realization of 1 kW μCF Reactor
    for Public Demonstration of Fusion Energy

    50 ~ 100 M$ for J-PARC

CONCLUSION

— Optionen in Entwicklung —
— Aufwand an Forschung, Kosten, Zeit —

1. Realization of Dedicated MW Accelerator for μCF & ≥ 0.1 MW Power Generation

    FFAG

    Full Pion Capture

    Full Muon Production & Use

    100g D-T Target

2.

1 MW FFAG (1 GeV × 1 mA)	*300 M$*
Muon Generator	*100 M$*
D-T Target & Power Monitor	*100 M$*

3. Completion in 5 years after Successful Funding

CONCLUSION

— *Potenziale im Verbund* —

1. Development of μCF Towards New Atomic Energy

   a. Close to Break-Even
   b. Need further fundamental Understandings
   c. Close to kW Power Generation
   d. Close to Realization of Hybrid Reactor

2. Contribution to Fusion Energy

☆ Materials Development for 1st wall of Fusion Reactor
  14 MeV Neutron Irradiation Facility
    10^{14} $n/cm^2/s$ with 2 GeV × 12 mA d Beam

☆ Tritium Production Facility
  Blanket Performance Test
  > 50 g T Production/Year/1 MW μCF

☆ Plasma Instability Studies
  μCF Ignition of Plasma Facility

☆ Quick Realization of 1 kW μCF Reactor
for Public Demonstration of Fusion Energy