Recent Progress
in
Muon Beam Development
for
Advanced Muon Catalyzed Fusion

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MCF-07, Dubna

K. Nagamine

KEK, RIKEN and UC-Riverside

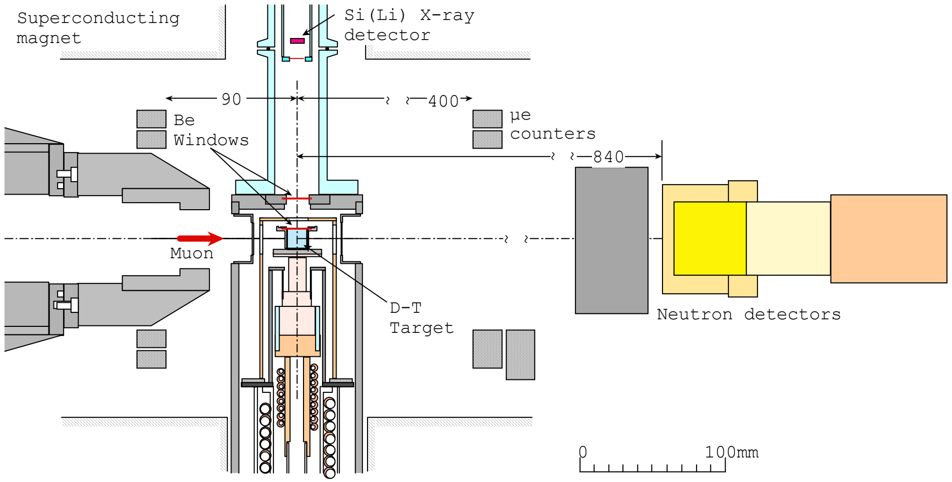
Recent Progress in Muon Beam Development for Advanced Muon Catalyzed Fusion

- Introduction; Need of Advanced Muon Beam for Advanced MCF Experiment
- Recent Progress in Muon Beam Development
- Advanced MCF Experiment In the Near-Future
- Related Experiments
- Summary and Conclusion

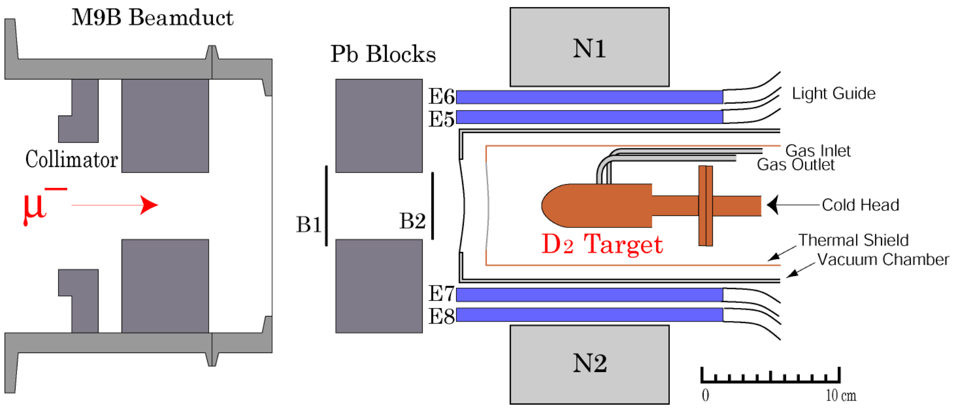
Introduction; Need of Advanced Muon Beam for Advanced MCF Experiment

- Understanding of Various Surprising New MCF Experimental Results;
  Inversion of Ortho-Para Effects in Solid/Liquid versus Gas of D-D and D-T,
  Strange T-Dependence in Regeneration in Solid D-T,
- Need of Extreme Experimental Conditions;
  Higher Density, Higher T →
  Need of Advanced Muon Beam;
  High Energy Micro-Beam

Limitation of the Present MCF Experiments for Further Extreme Conditions



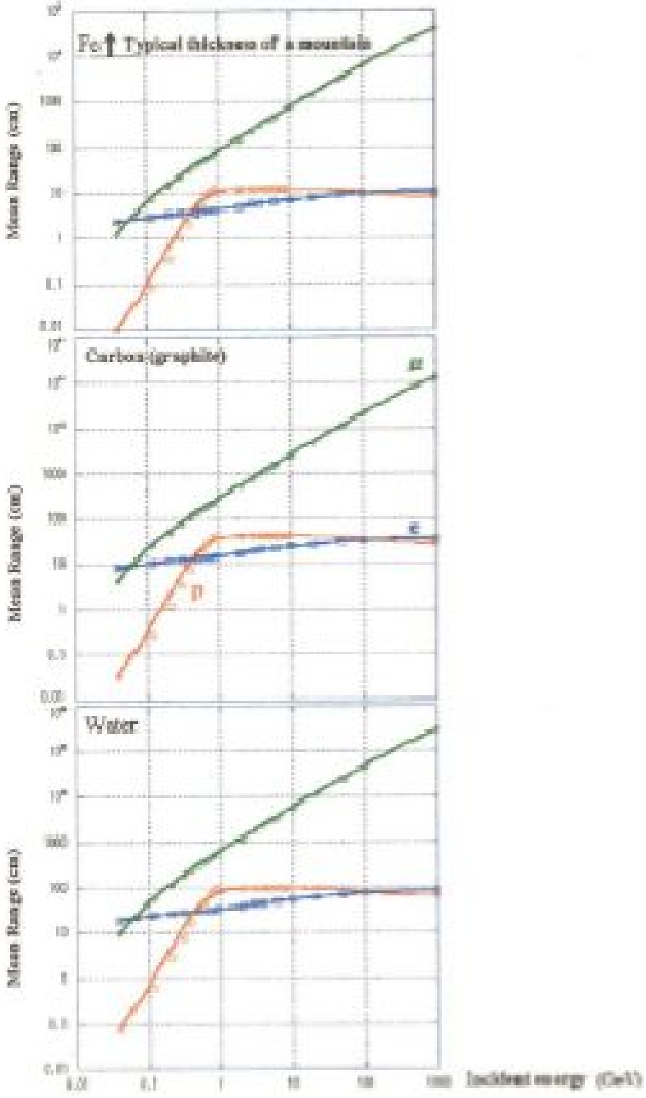
D-T Target at RIKEN-RAL

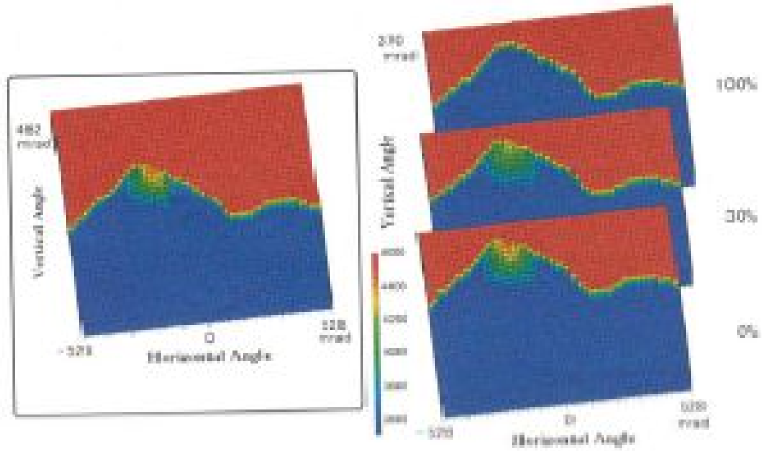


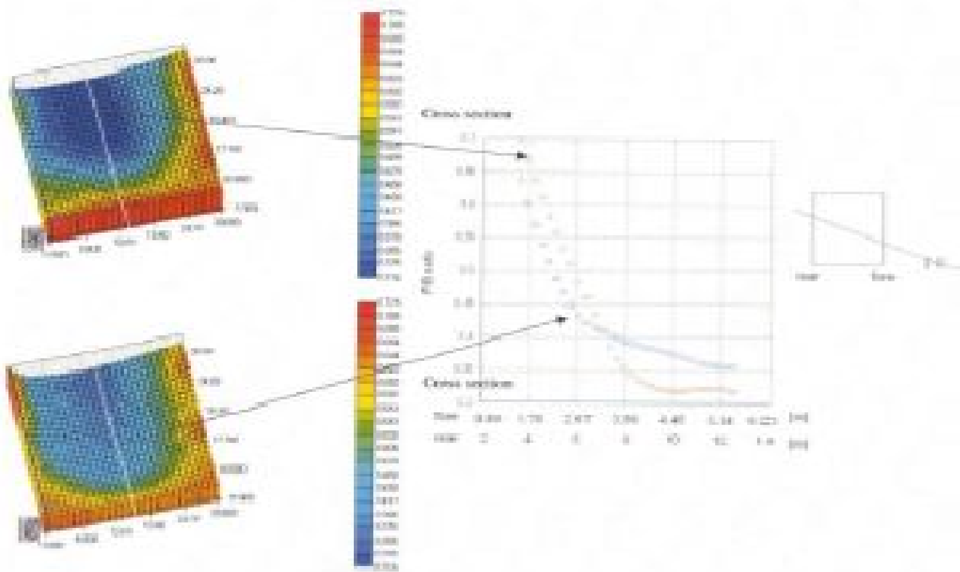
D_2 Target at TRIUMF

- For higher density, pressure and temperature, use of more thicker wall and window materials is inevitable.
- Need of specially prepared negative muon beam is obvious.

High Penetration of High Energy Muon
Cosmic-Ray Muon Radiography of Volcano, Blast Furnace, etc.



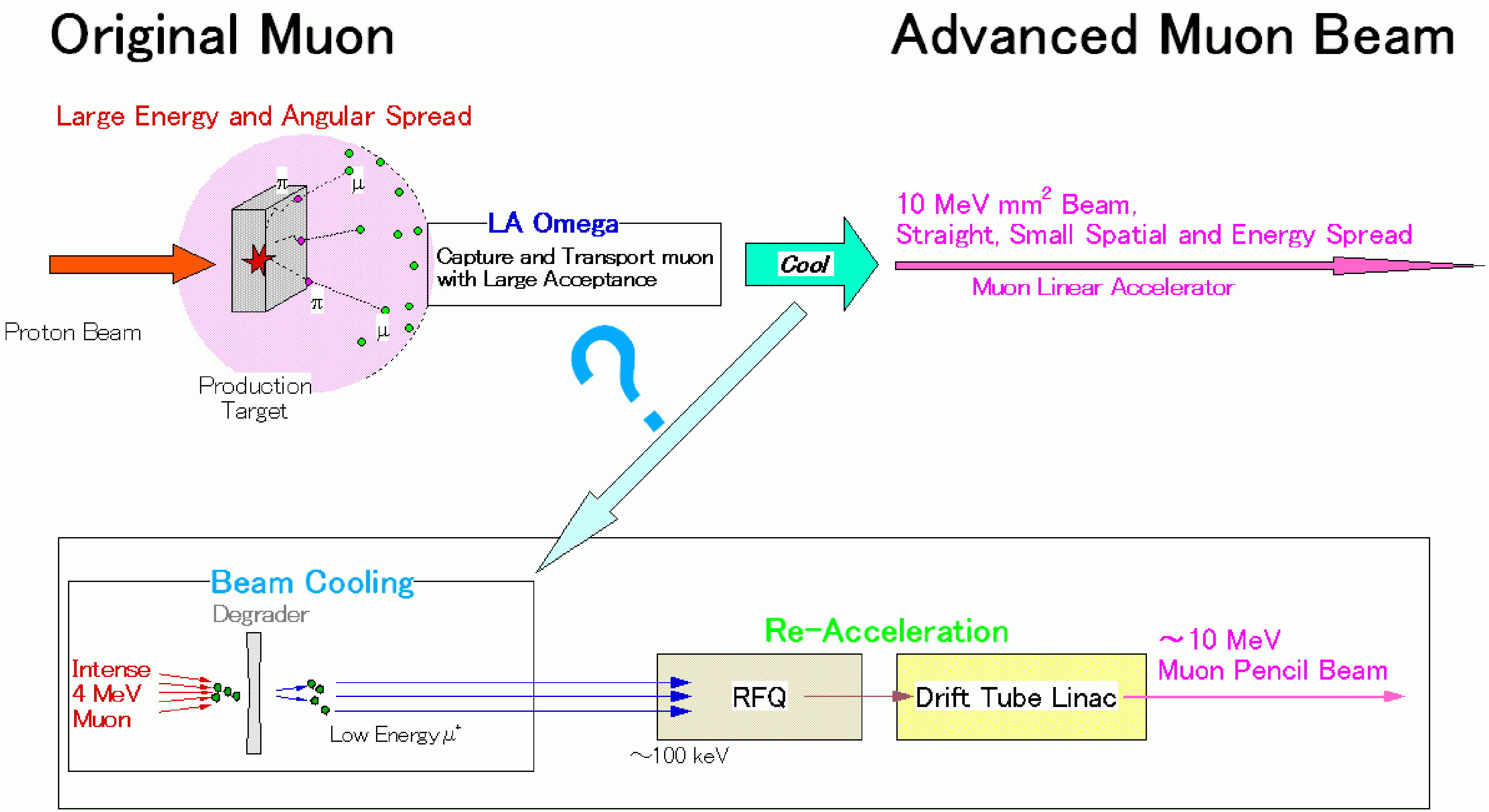




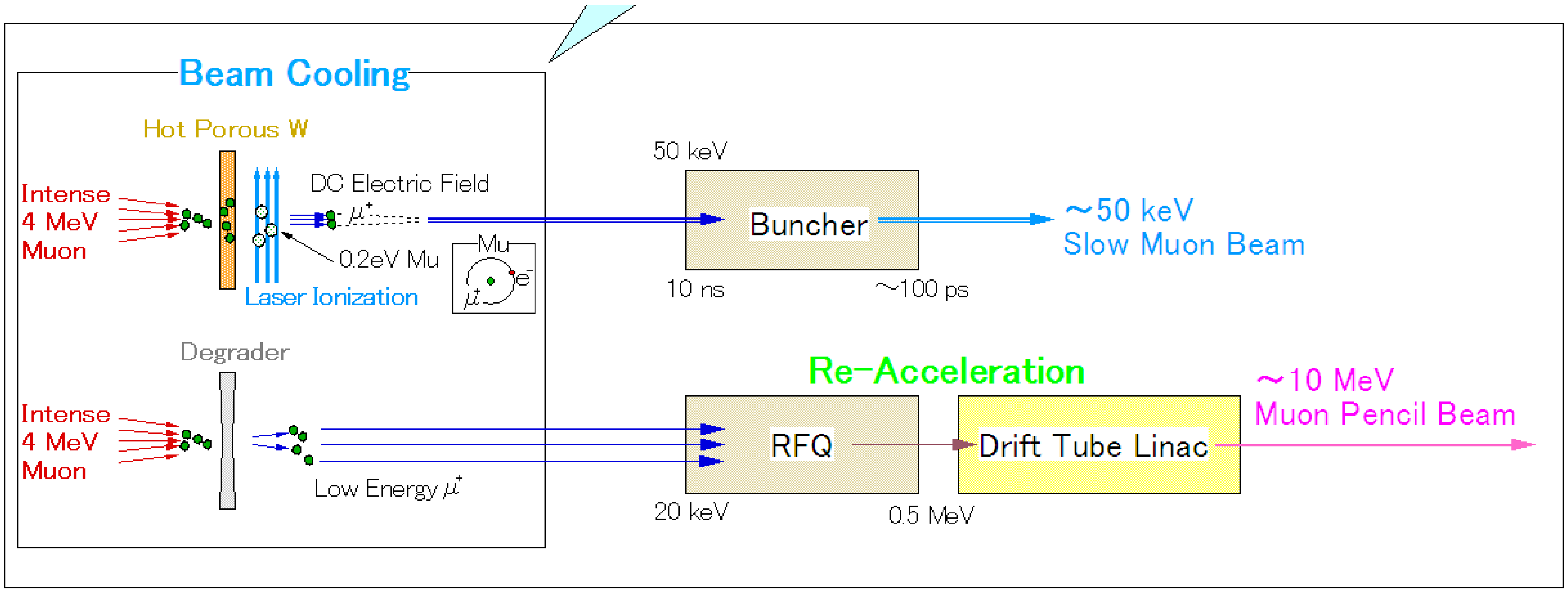
Recent Progress in Muon Beam Development; Generation of High Energy Micro-Beam of Negative Muons

- Large Acceptance Muon Capture,
  Dai-Omega Project at KEK, H. Miyadera
- Finding of Excellent Feature of RFQ,
  Strong Focusing and Acceleration,
  A. Jason and T. Wangler (LANL)
  Effectively Large Energy Acceptance,
  M. Okamura (RIKEN→BNL)

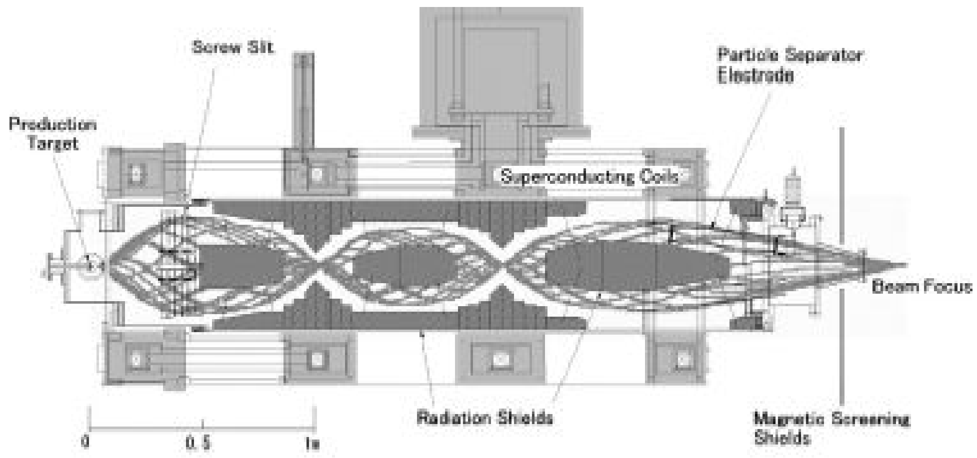
Recent Progress in Muon Beam Development; Generation of High Energy Micro-Beam



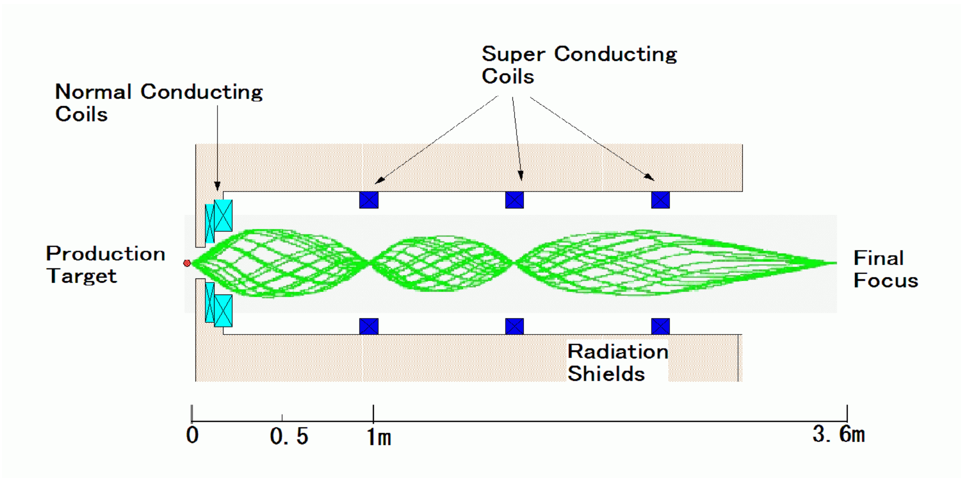
Generation of High Energy Micro-Beam
Original Idea for Positive Muons

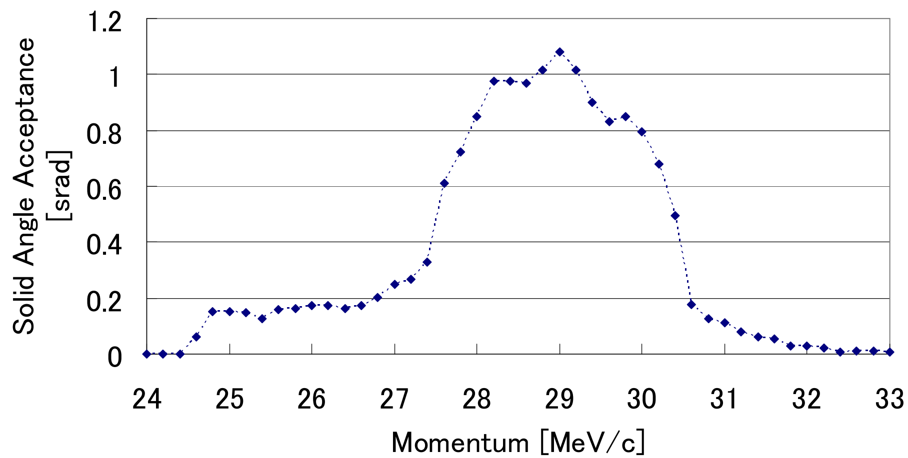


Large Acceptance Muon Capture Realized Dai-Omega Project at KEK

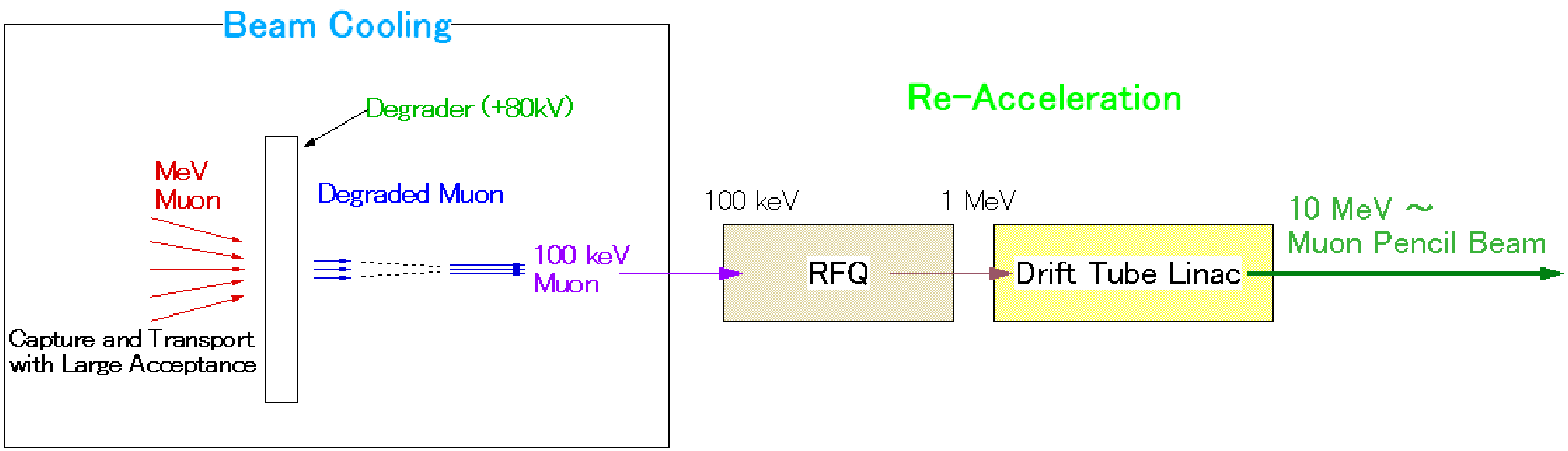


Dai-Omega at KEK
1 Str Solid Angle &
Dispersive Focus





Getting Straight and Sub-mm Size Muon Beam After Dispersive Focus of L.A. Omega



H. Miyadera, A. Jason, T. Wangler, M. Okamura and K. Nagamine, NuFact 06
H. Miyadera, A. Jason and K. Nagamine, PAC 07

COOLING IDEA EMPLOYED

How to Realize Advanced Muon Beam

- Phase Space Volume Conservation
- Need of Acceleration upto MeV

Advantage of RF, compared to DC

Need Beam Bunching, Matching to RF

Efficient Capture to Front-end Accelerator

Previously; Capture + Copper/Pre-Buncher/Buncher + Accelerator

Now; Everything by RFQ

Energy Degrader for 10 keV Muons

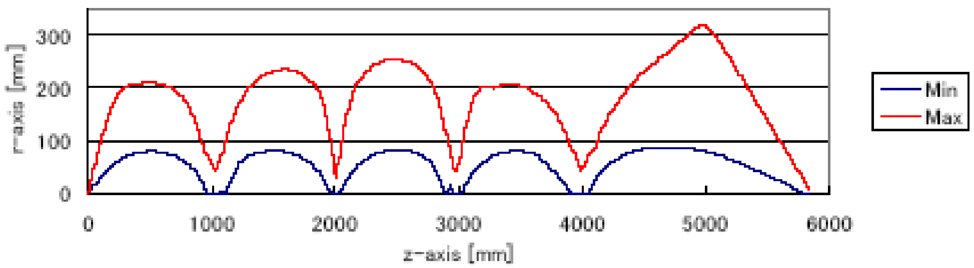
How much fraction can be obained from Surface Muons

- Evaluation (1) by Y. Matuda ;

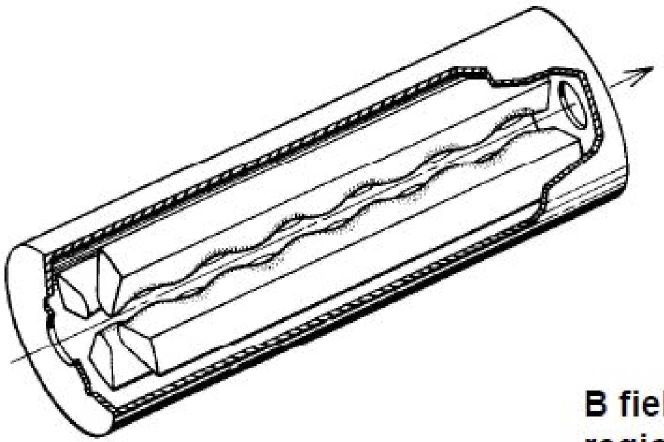
  0.25 % for monochromatic 4 MeV μ incident on Carbon
- Evaluation (2) by H. Miyadera;

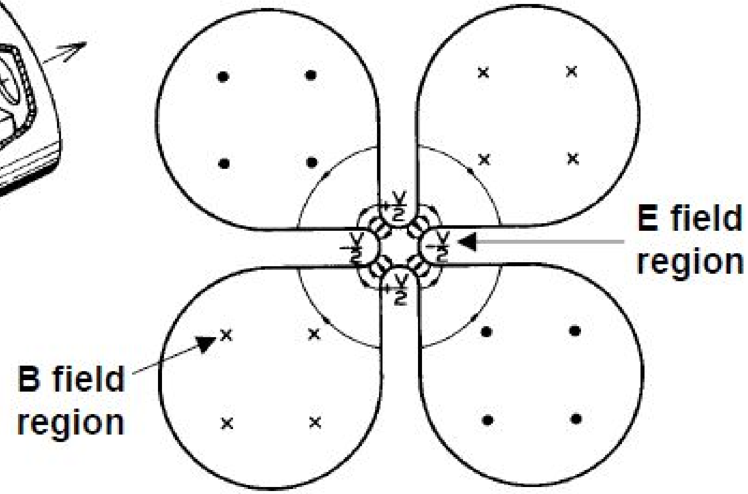
  0.9 %, by MuScat (PSI) for E(μ) = Energy-Loss,

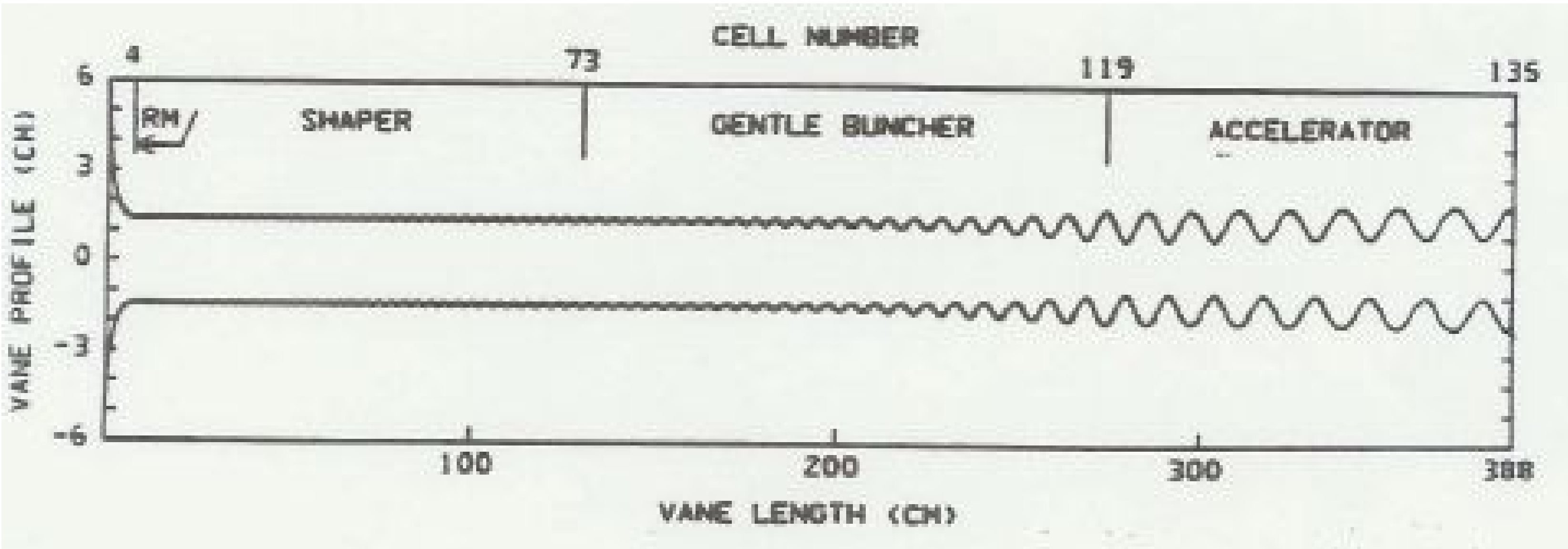
  10 keV/1.2 MeV(Energy Spread after Degrader) = 0.83 %
- Optimistic Value for Wedge Absorber with Dispersive Focus



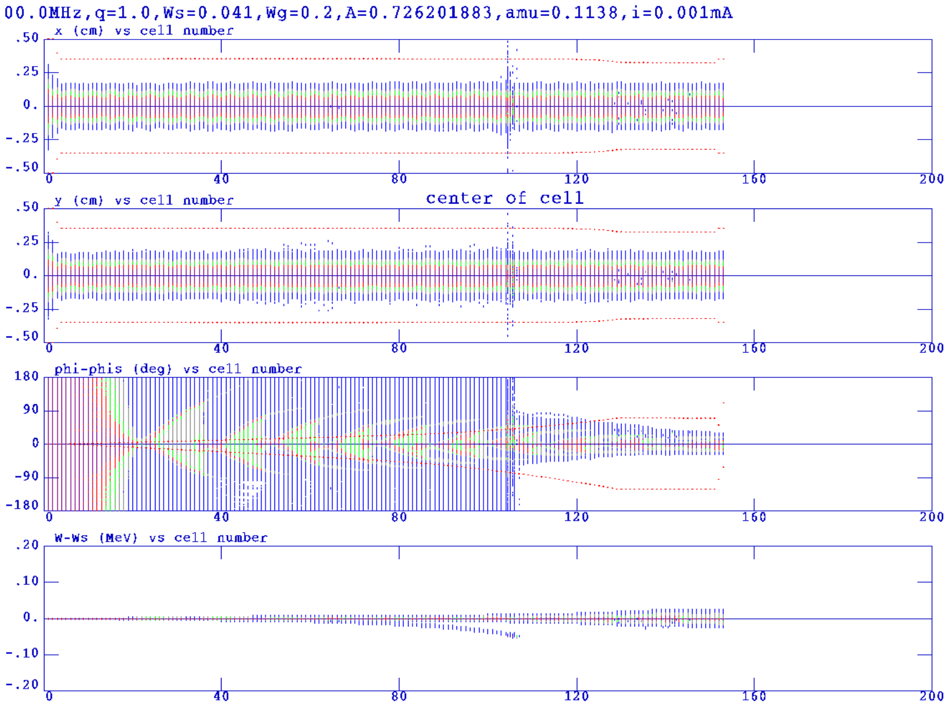
Use of Strong Focussing and Acceleration of RFQ for Degraded Muons



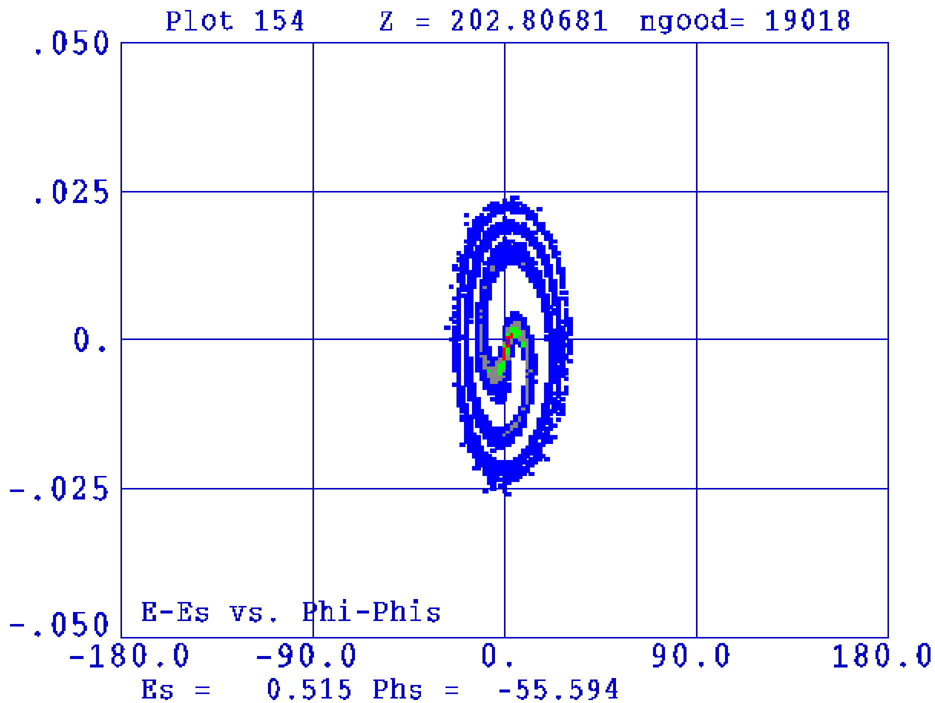




RFQ Performance for Degraded Muons
(1) Beam Trajectory in RFQ

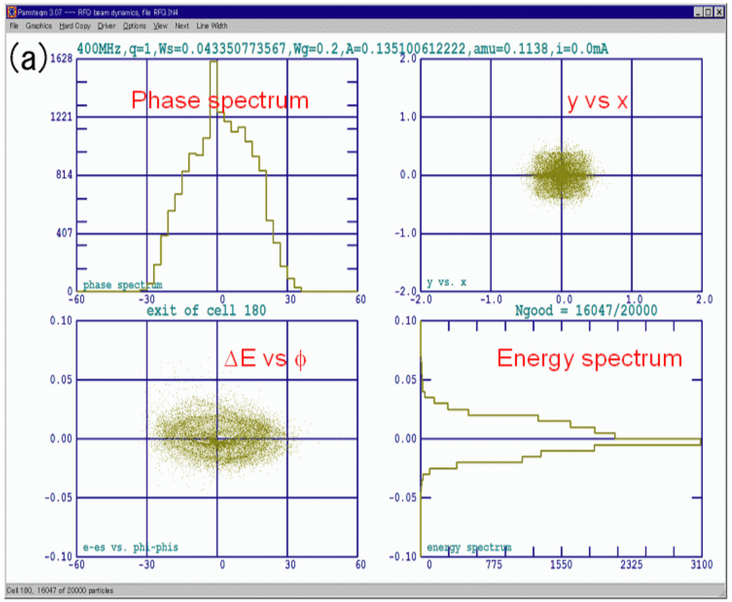


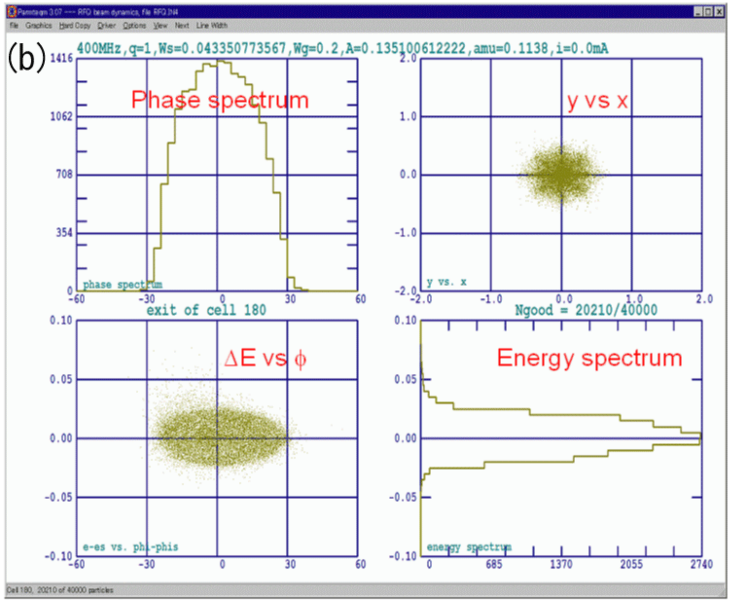
Beam envelopes for the RFQ design in the x, y, phase, and energy dimensions. Respective ordinate units are cm, cm, degrees and MeV. The colors blue to red show gradations in the intensity distribution.



The phase-energy distribution for the RFQ output. Dimensions are in degrees and MeV.

RFQ Performance for Degraded Muons
(2) Features of RFQ Output



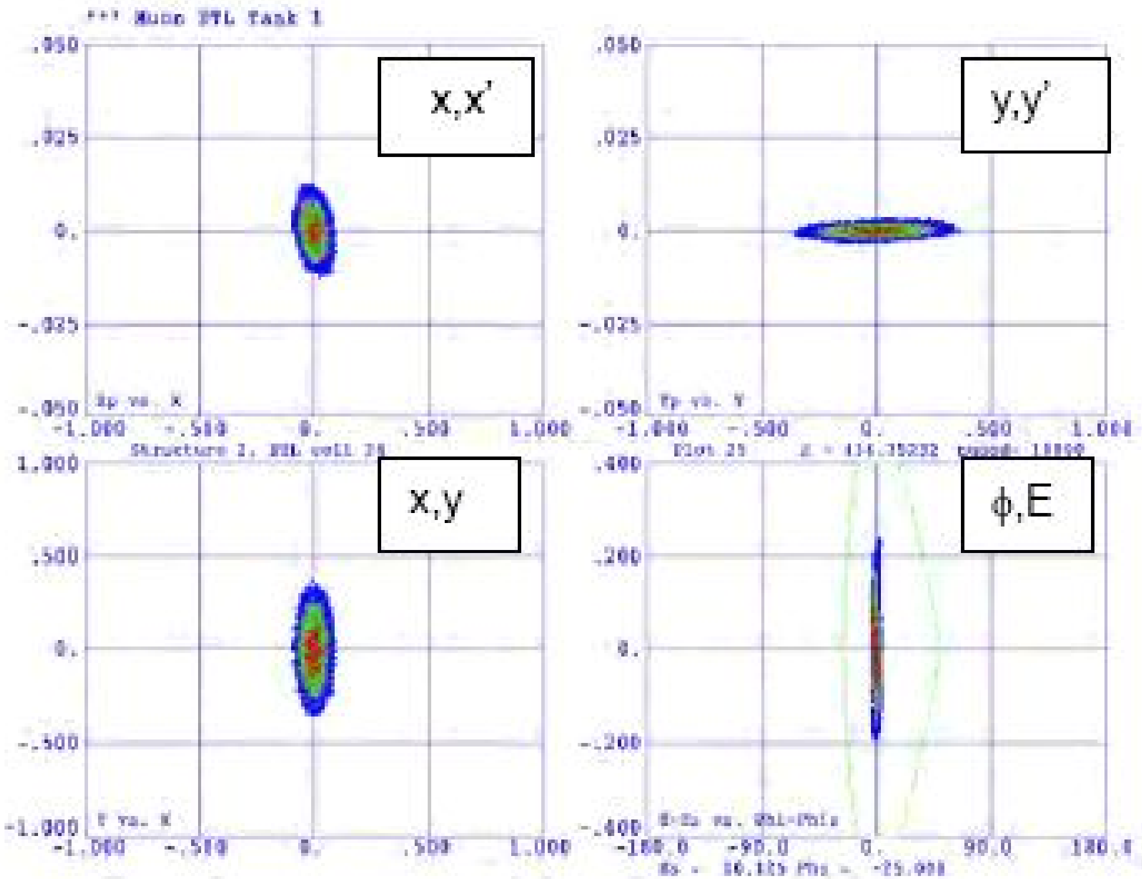


Difference between monochromatic 20 keV and 50 % Width 20 keV

Table 1:Specifications of designed RFQ.

	RFQ-A	RFQ-B	RFQ-C
Frequency [MHz]	400	400	200
Length [m]	2.3	6.5	10.7
Peak Power [kW]	500	3450	5281
Injection Energy [keV]	20	80	100
Ejection Energy [keV]	500	1000	1000
Acceptance [cm rad]	0.03	0.64	1.34
Energy Acceptance [keV]	5	17	45

Performance of 10 MeV DTL after RFQ Realization of Muon Micro-Beam



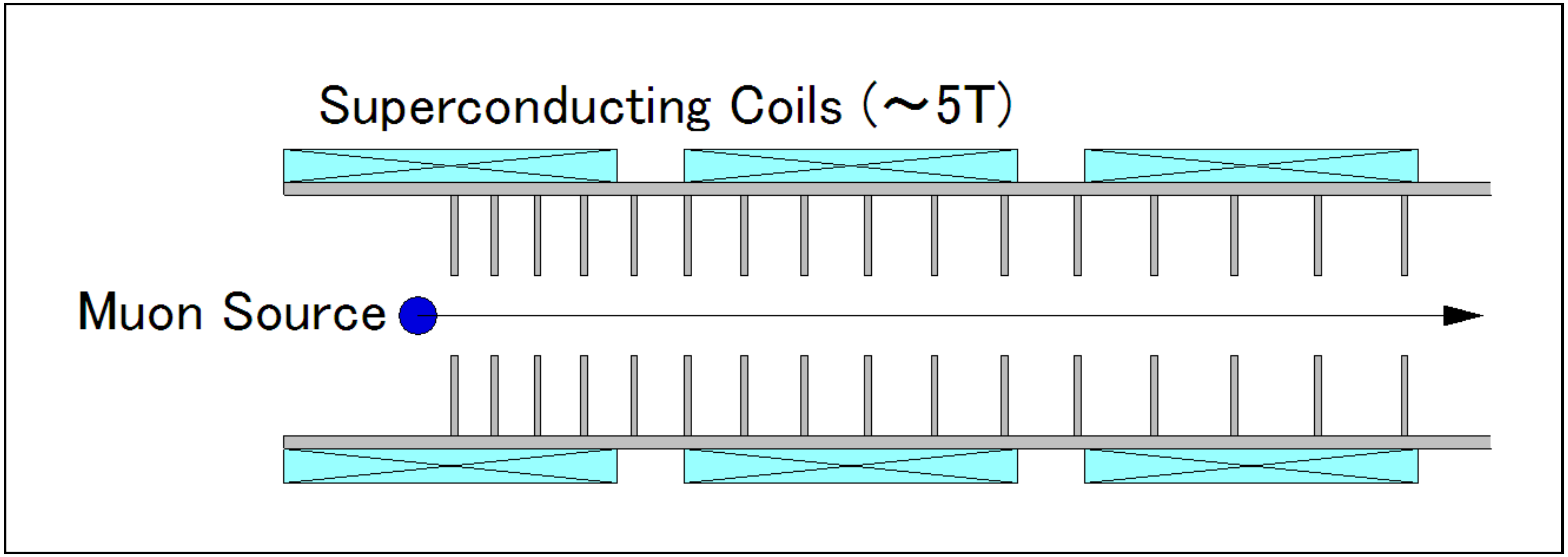
Simulated DTL output distributions in the x, y, x-y, and phase-energy phase planes. Spatial dimensions are in cm and angular dimensions in radians. For the phase-energy plot, the dimensions are in degrees and MeV. The phase-energy plane shows the rf region of stability as a green curve.

Overall Efficiency of the Proposed Advanced Muon Beam

- Capture of cloud and decay negative muons; 5%
- Degraded 20 keV muons; 2%
- RFQ capture; 50%
- DTL Acceleration; 80%

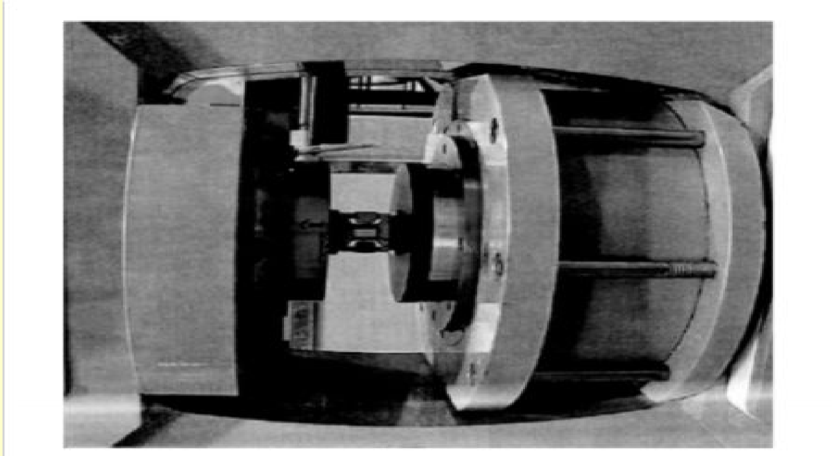
Facility	Proton Beam	Iintensity [/s]	Luminosity [/cm^{2}s]
RIKEN-RAL	800 MeV 200 μA	~10^6	~10^5
J-PARC	3 GeV 333 μA	~3×10^7	~10^5
LA Omega	800 MeV 700 μA	4×10^8	5×10^7
LA Omega+LINAC	800 MeV 700 μA	4×10^6	10^9~

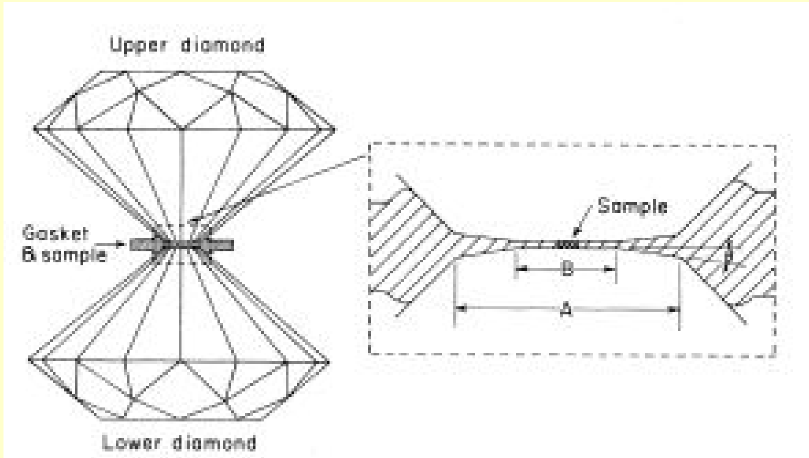
More Advanced Idea
H. Miyadera, LANL Seminar (2007)



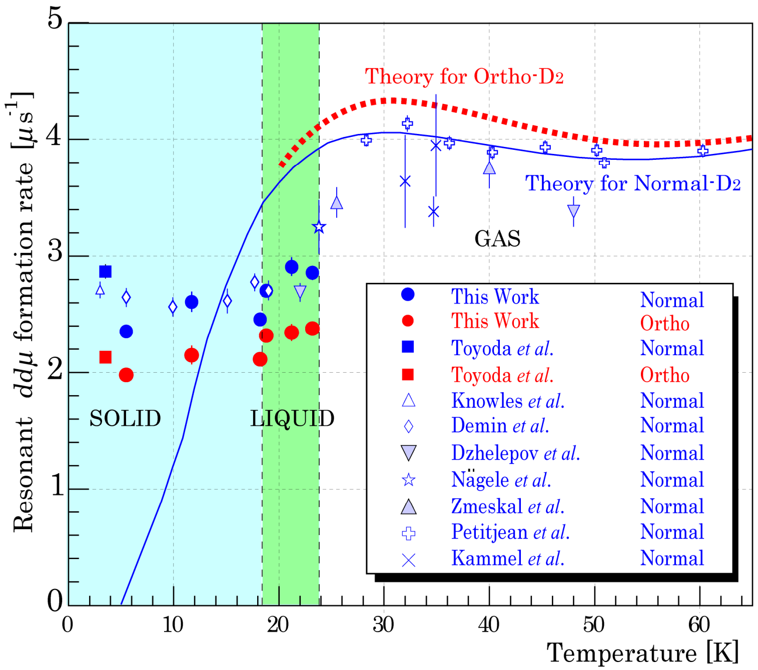
Advanced MuCF Experiment In the Near-Future with Advanced Muon Beam

- MuCF under very high pressure and density
- Use of Muon Micro-Beam through a Narrow Window

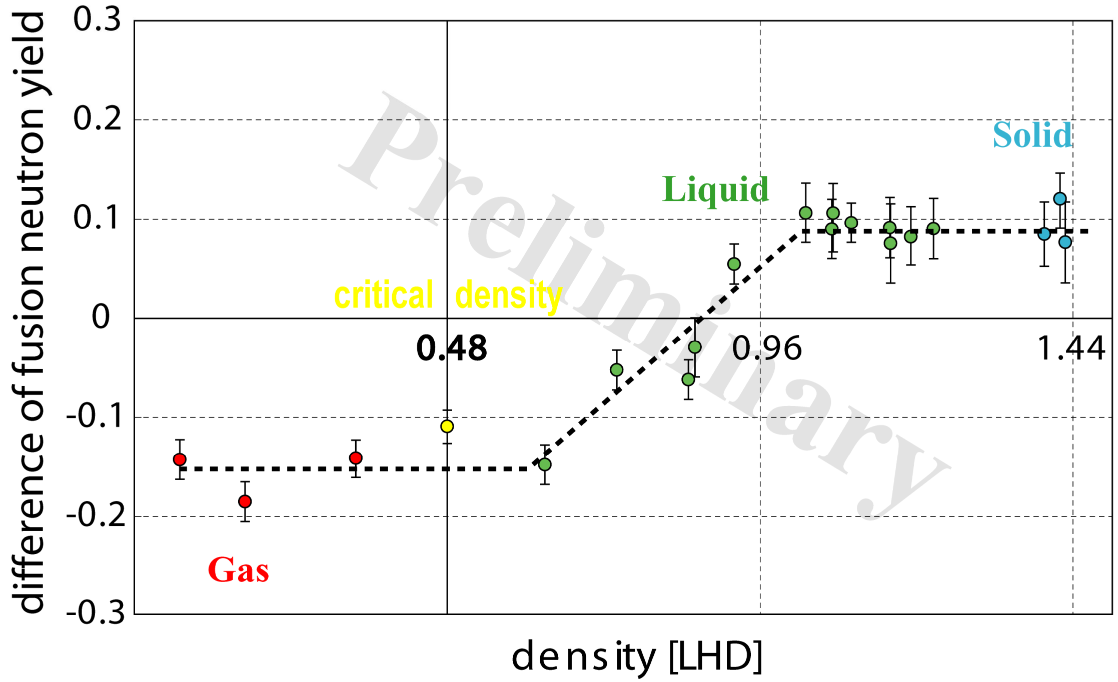




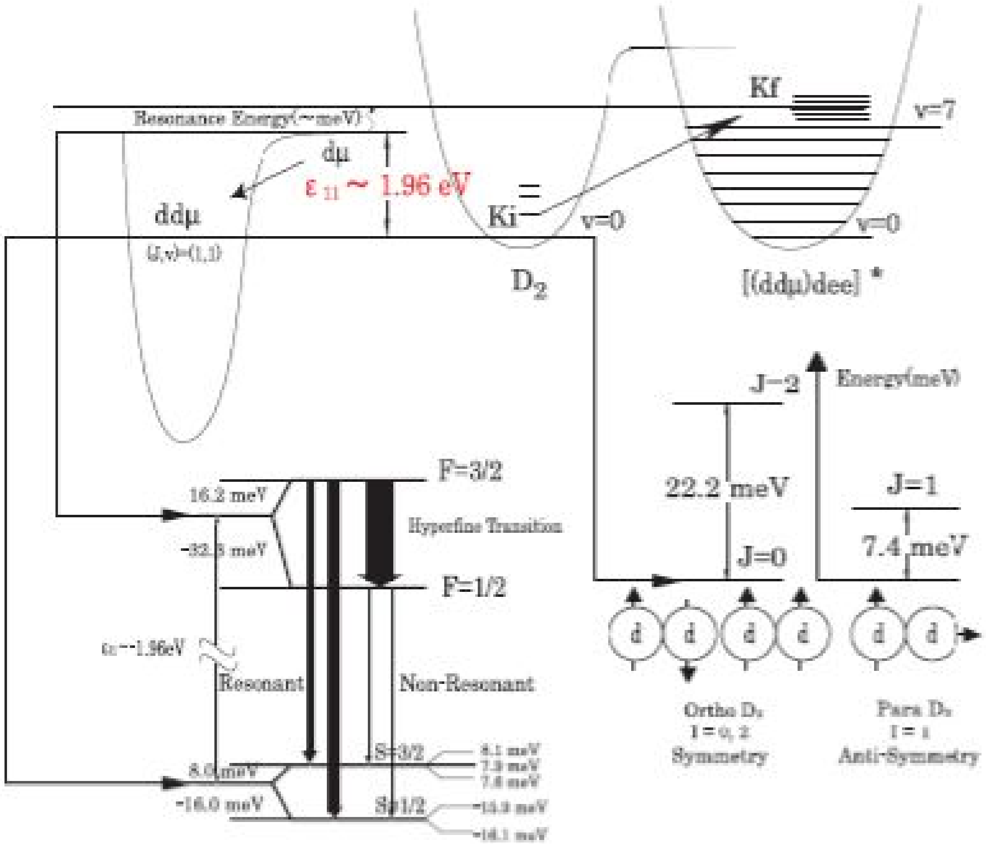
Strange Ortho-Para Effect in DD MCF Reported by H. Imao



Opposite Effect in Solid/Liquid versus Gas and Theory



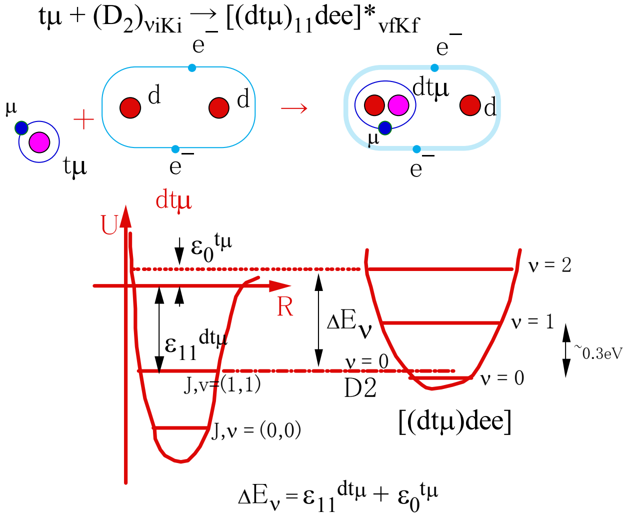
Resonant Molecular Formation of DDμ and Ortho-Para Effect

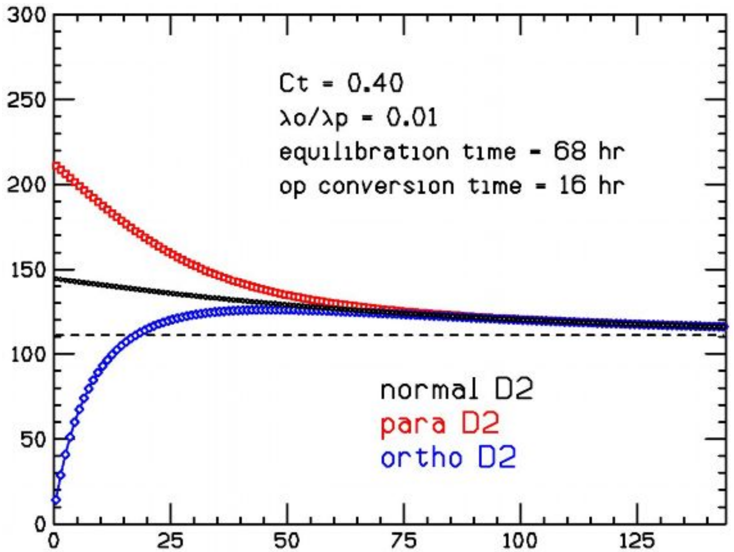


Ortho-Para Effect; The first direct and precise examination of resonance phenomena by energy matching and mis-matching

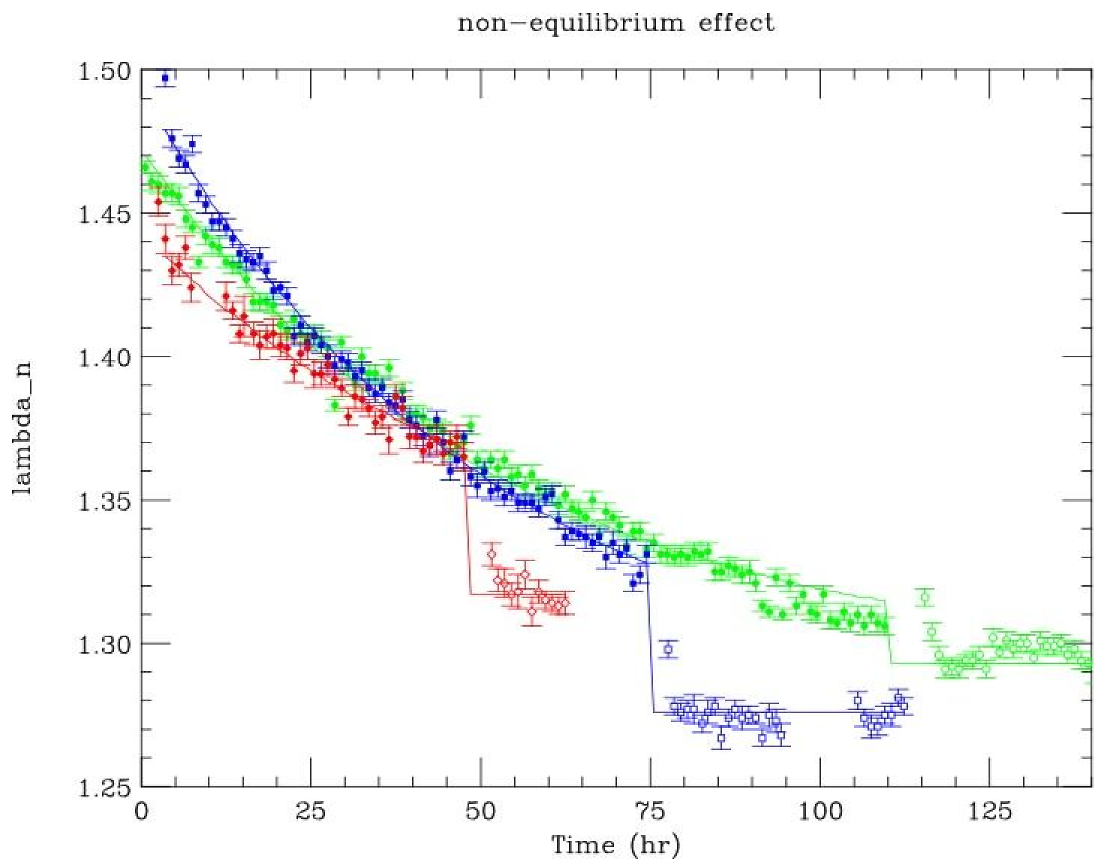
	ϵ_f (meV)	F	K_i	K_f	S
Recent calculation [16, 38]	-0.649	[illegible]	1	0	[illegible]
	-3.325	[illegible]	1	1	[illegible]
	0.8157	[illegible]	0	0	[illegible]
	3.312	[illegible]	1	2	[illegible]
	4.14	[illegible]	0	1	[illegible]
	10.78	[illegible]	0	2	[illegible]
Previous calculation [15]	4.00	[illegible]	0	1	[illegible]
	5.35	[illegible]	1	2	[illegible]
	5.80	[illegible]	2	1	[illegible]
	16.20	[illegible]	1	0	[illegible]
	16.96	[illegible]	3	2	[illegible]
	24.74	[illegible]	4	3	[illegible]

Strange Ortho-Para Effect in DT MCF Reported by K. Ishida

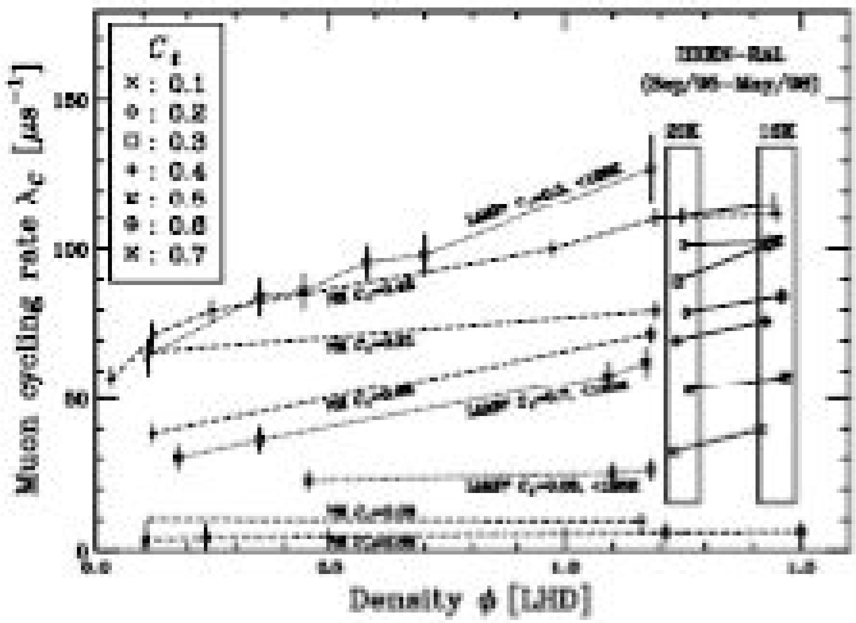


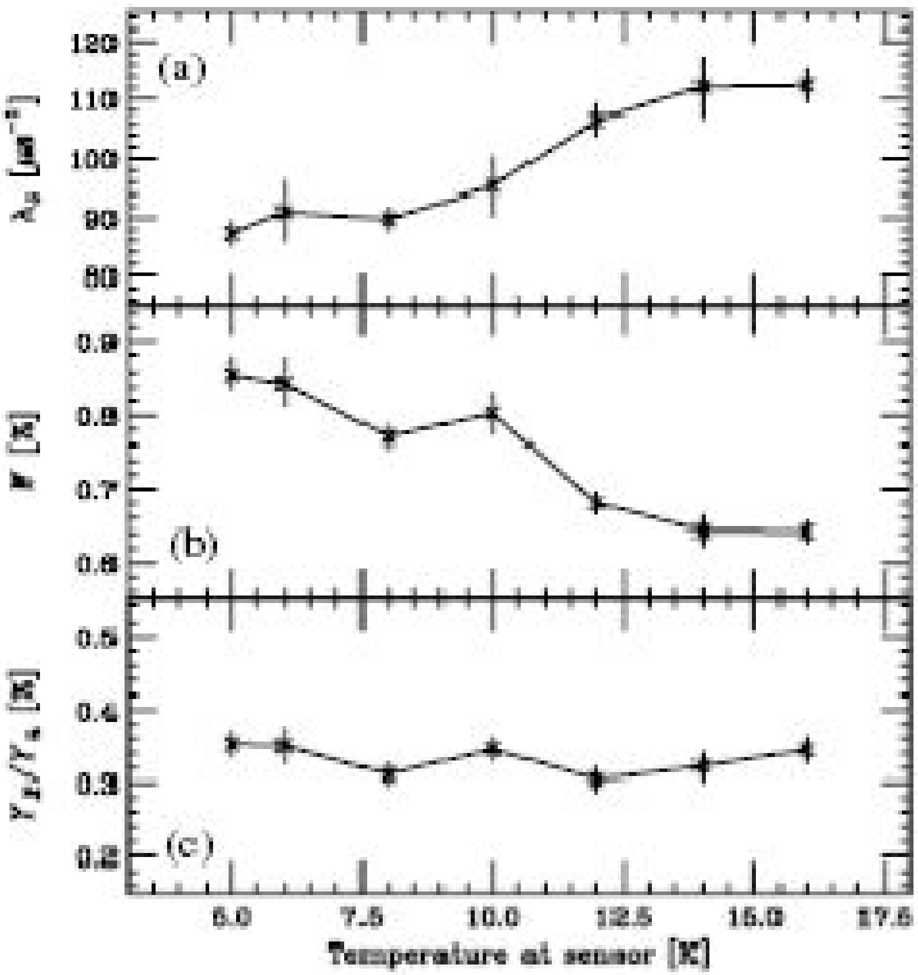


Opposite Effect in Liquid versus Theory



Strange T- or ϕ – Dependence in Regeneration of μHe in DTμ





N. Kawamura et al. PRL 90(2003)043401

Key Factors to understand Condensed Matter Effect on RMF in Liquid and Solid

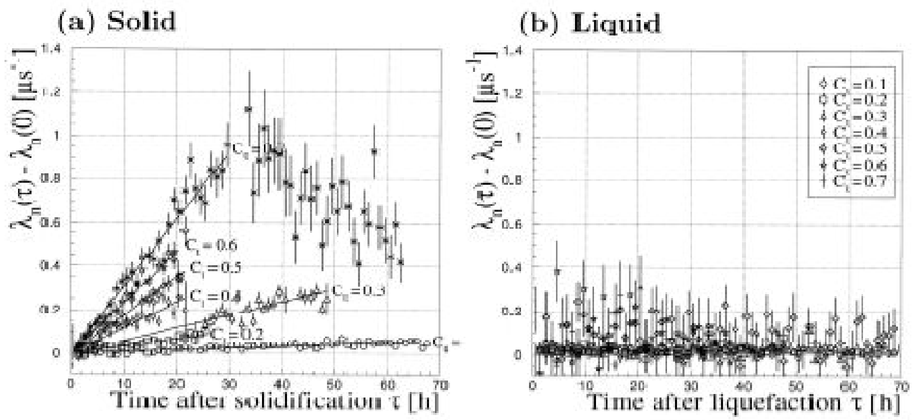
- Intermolecular Correlation before Muon Introduction; Energy and Width of High-lying Level in Liquid/Solid versus Gas
- Intermolecular Correlation between complex muon molecule in the final state
- Molecular Rearrangements due to the Presence of Neutral Charge Defect of Muonic p, d, t.
- Many-Body Collision Effect

Pioneering Works;

A. Adamczak and M.P. Faifman, Phys. Rev. 64(2001)052705.

K. Fukushima, Phys. Rev. A84(1993)4130.

Inter-Molecular Correlation in MuCF Phenomena; He^3 Stability in Liquid and Solid T_2 (1)

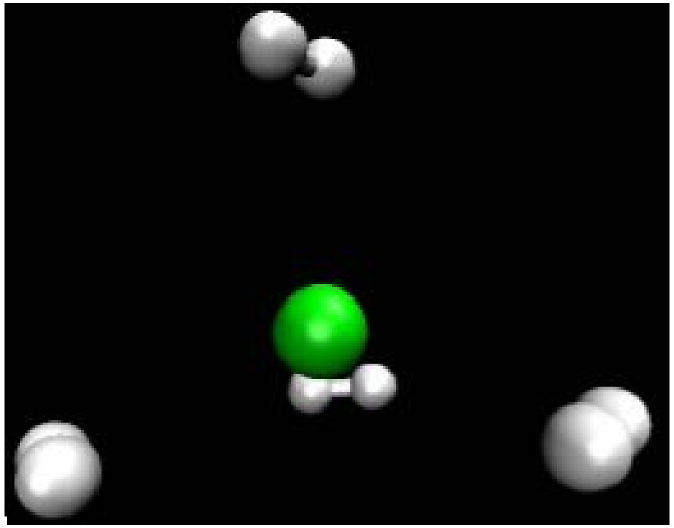


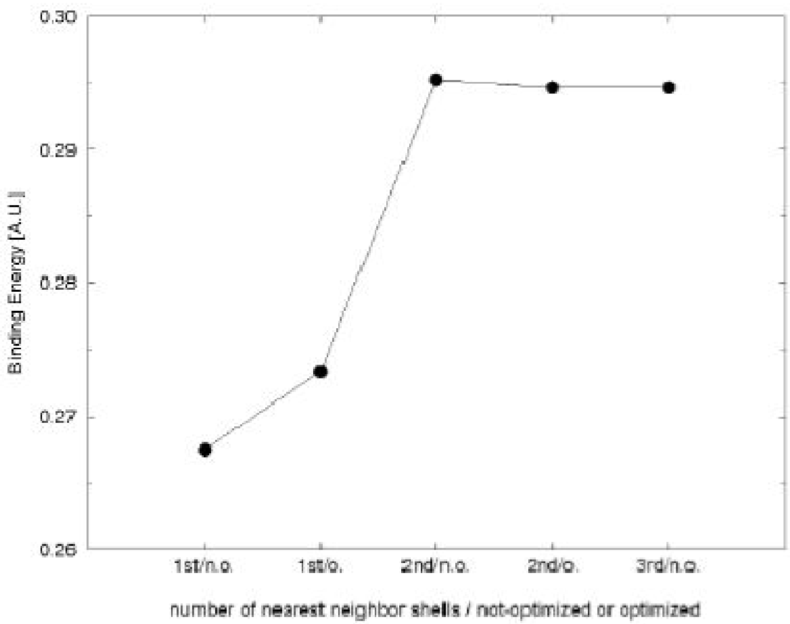
- Detected by t to He Transfer in TT μCF; Complete He Trapping in Solid T_2 and Complete Release in Liquid T_2 *N. Kawamura et al. Phys. Lett. B465(1999)74*

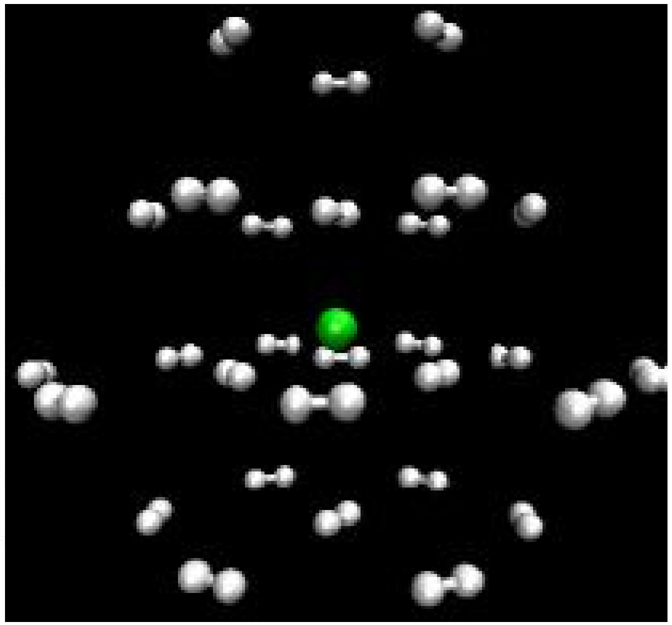
Inter-Molecular Correlation in MuCF Phenomena; He^3 Stability in Liquid and Solid T_2 (2)

Explanation of Increase of Molecular Correlation; n. n. for Liquid and more than second n. for Solid

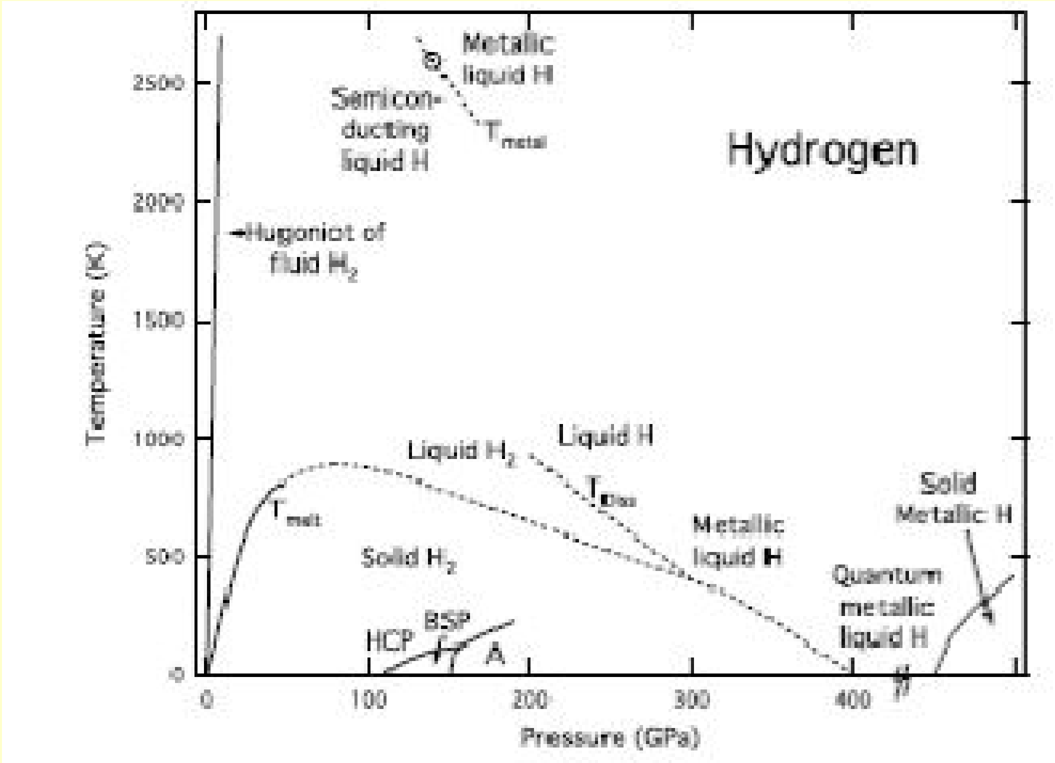
R. Scheicher, T.P. Das et al. Hyperfine Int. 138(2001)431.







Related Subjects; High Density Hydrogen under Very High Pressure



Probing High Density Hydrogen by RMF in MCF

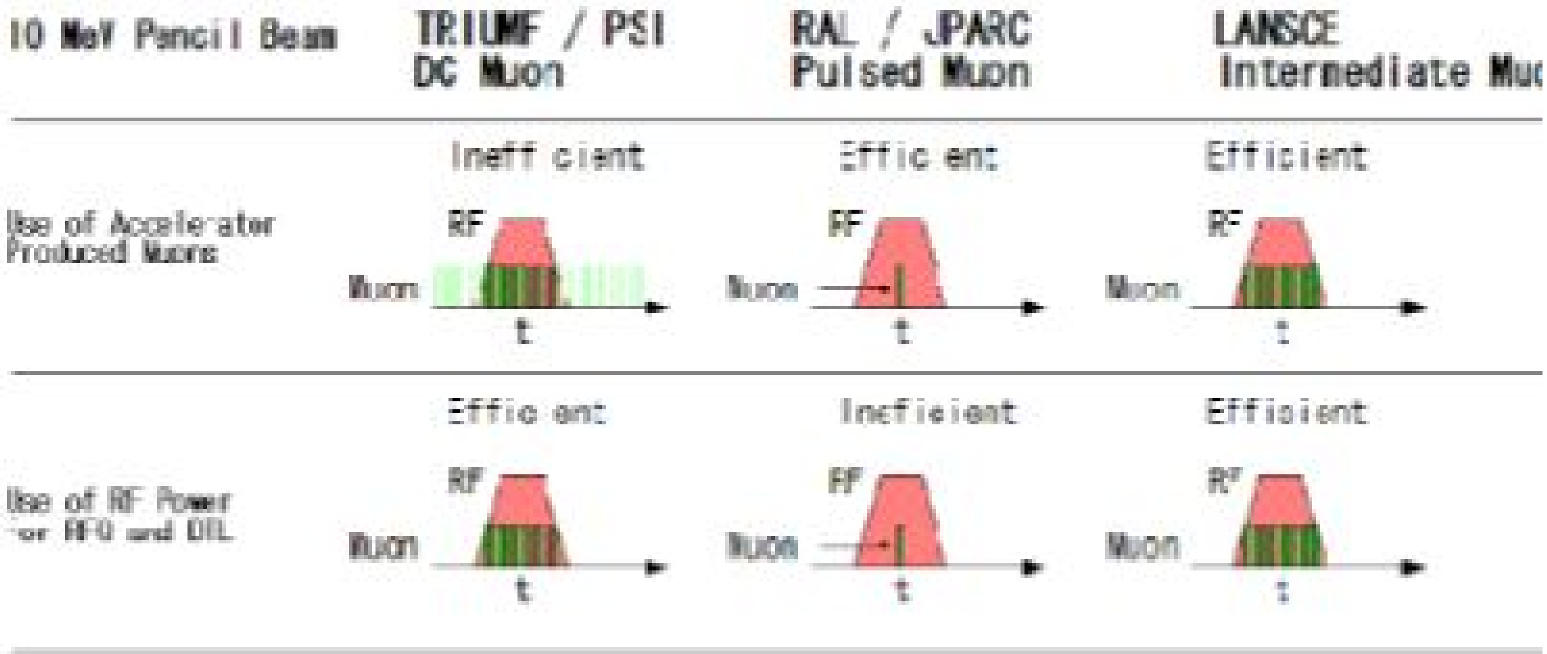
- Probing High Lying Molecular Level
- Monitoring Molecular Dissociation

Summary and Conclusion (1)
Advanced Muon Beam for Advanced MCF

- Muon Micro-Beam becomes available for both Negative and Positive Muons; 10 M$ in 2 years
- MuCF Experiments for High-Density D_2, D-T becomes possible with High-Pressure Cell and with a Narrow Window such as MCF in Plasma
- Resonant Molecular Formation and Regeneration will be studied under Extreme Experimental Conditions
- High-Density Hydrogen Behaviors will be monitored by Using MuCF Phenomena through Celebrated Resonant Molecular Formation

Summary and Conclusion (2)
Future Facility and Advanced Muon Beam

- Good for intense low-duty proton accelerators; J-PARC, LANSCE, etc.
- Future extension to compact muon source
  Life Science, Homeland Security, Industrial Machinery



Congratulation; 30th/40th years Anniversary of Resonant Molecular Formation in MCF

RMF in DD μCF
in 1967

RMF in DT μCF
in 1977