Recent Progress in Muon Beam Development for Advanced Muon Catalyzed Fusion

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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

- 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

Original Muon

Large Energy and Angular Spread

LA Omega
Capture and Transport muon with Large Acceptance

Advanced Muon Beam

10 MeV mm² Beam, Straight, Small Spatial and Energy Spread
Muon Linear Accelerator

Beam Cooling

Degradar:

Intense 4 MeV Muon

Low Energy μ⁻

Re-Acceleration

RFQ

Drift Tube Linac

~10 MeV Muon Pencil 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 obtained from Surface Muons

• Evaluation (1) by Y. Matuda;
  0.25 % for monochromatic 4 MeV $\mu$ incident on Carbon

• Evaluation (2) by H. Miyadera;
  0.9 %, by MuScat (PSI) for $E(\mu) = $ Energy-Loss,
  10 keV/1.2 MeV(Energy Spread after Degrader) = 0.83 %

• Optimistic Value for Wedge Absorber with Dispersive Focus

![Graph showing energy degrader performance](image)
Use of Strong Focussing and Acceleration of RFQ for Degraded Muons

[Diagram of RFQ and field regions]
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

Table 1: Specifications of designed RFQ.

<table>
<thead>
<tr>
<th></th>
<th>RFQ-A</th>
<th>RFQ-B</th>
<th>RFQ-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>400</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Length [m]</td>
<td>2.3</td>
<td>6.5</td>
<td>10.7</td>
</tr>
<tr>
<td>Peak Power [kW]</td>
<td>500</td>
<td>3450</td>
<td>5281</td>
</tr>
<tr>
<td>Injection Energy [keV]</td>
<td>20</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Ejection Energy [keV]</td>
<td>500</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Acceptance [cm rad]</td>
<td>0.03</td>
<td>0.64</td>
<td>1.34</td>
</tr>
<tr>
<td>Energy Acceptance [keV]</td>
<td>5</td>
<td>17</td>
<td>45</td>
</tr>
</tbody>
</table>
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%

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton Beam</th>
<th>lintensity [s]</th>
<th>Luminosity [cm²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIKEN-RAL</td>
<td>800 MeV 200 μA</td>
<td>~10⁶</td>
<td>~10⁵</td>
</tr>
<tr>
<td>J-PARC</td>
<td>3 GeV 333 μA</td>
<td>~3 x 10⁷</td>
<td>~10⁵</td>
</tr>
<tr>
<td>LA Cmega</td>
<td>800 MeV 700 μA</td>
<td>4 x 10⁸</td>
<td>5 x 10⁷</td>
</tr>
<tr>
<td>LA Cmega+LINAC</td>
<td>800 MeV 700 μA</td>
<td>4 x 10⁶</td>
<td>10⁹~</td>
</tr>
</tbody>
</table>
More Advanced Idea
H. Miyadera, LANL Seminar (2007)

Superconducting Coils (~5T)

Muon Source
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 DD$_\mu$ and Ortho-Para Effect

Ortho-Para Effect; The first direct and precise examination of resonance phenomena by energy matching and mis-matching
Strange Ortho-Para Effect in DT MCF
Reported by K. Ishida

Opposite Effect in Liquid versus Theory

\[ t\mu + (D_2)_{\nu\kappa i} \rightarrow [(d\mu)_{11}\text{dee}]^* \nu K_f \]

\[ \Delta E_v = \varepsilon_{11} d\mu + \varepsilon_{0} d\mu \]

\[ C_t = 0.40 \]

\[ \lambda_\sigma/\lambda_\rho = 0.01 \]

Equilibration time - 68 hr
Conversion time - 16 hr

Non-equilibrium effect
Strange T- or \( \phi \) – Dependence in Regeneration of \( \mu \text{He} \) in DT\( \mu \)

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;
Inter-Molecular Correlation in MuCF Phenomena; He$^3$ Stability in Liquid and Solid T$_2$ (1)

- Detected by t to He Transfer in TT $\mu$CF; Complete He Trapping in Solid T$_2$ and Complete Release in Liquid T$_2$

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

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 $\mu$CF in 1967

RMF in DT $\mu$CF in 1977