# Muon Science Laboratory

## MUSE at J-PARC

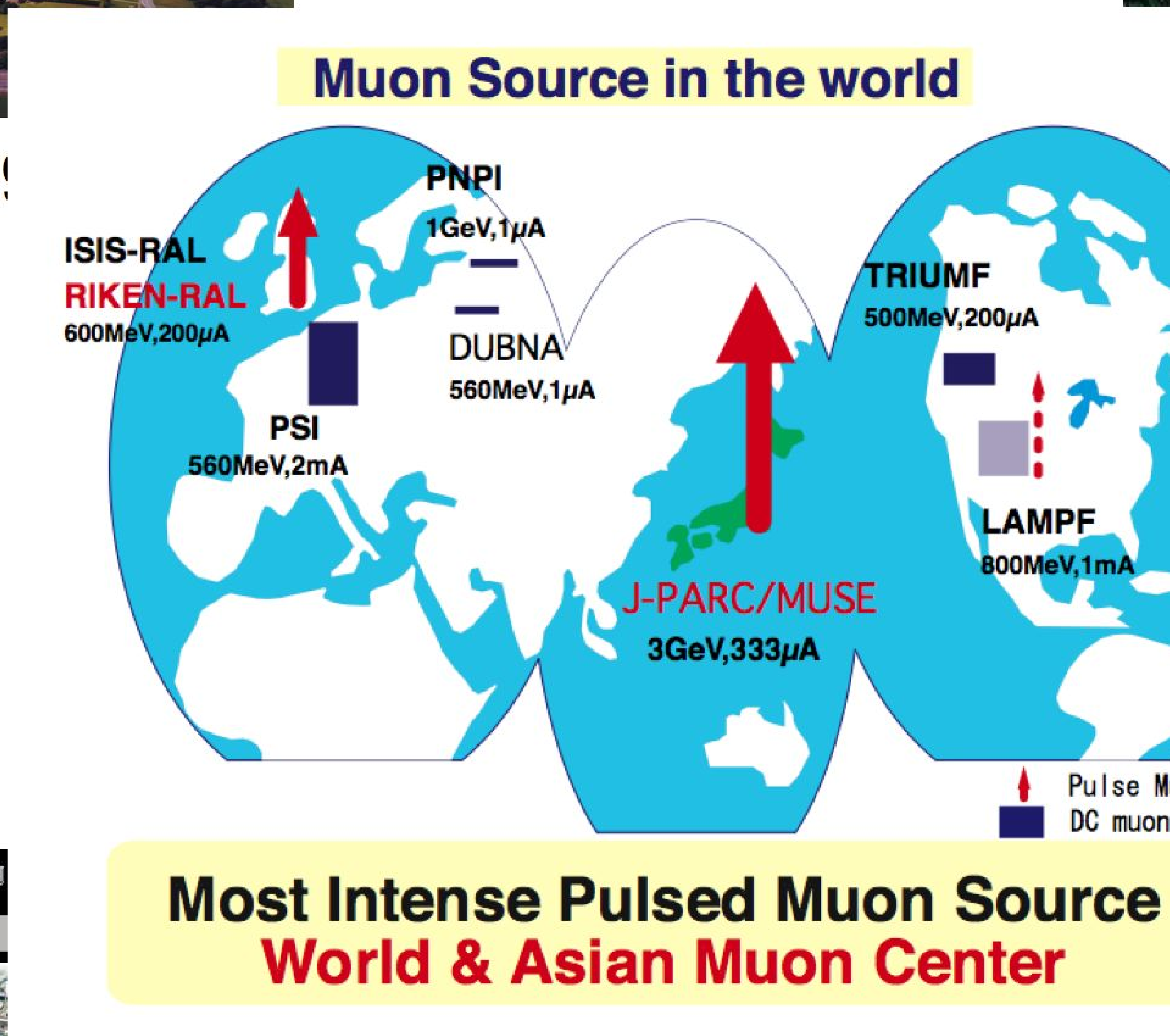
Kusuo Nishiyama
KEK-IMSS-MSL
At Epochal 16.Oct.2008

# Domestic Facility ---> International Facility (best muon facility in the world)

1990/19
ISIS
/RAL

2008

1975
TRIUMF




J-PARC MUSE

PSI
1974

# MSL- past-Last 25Years

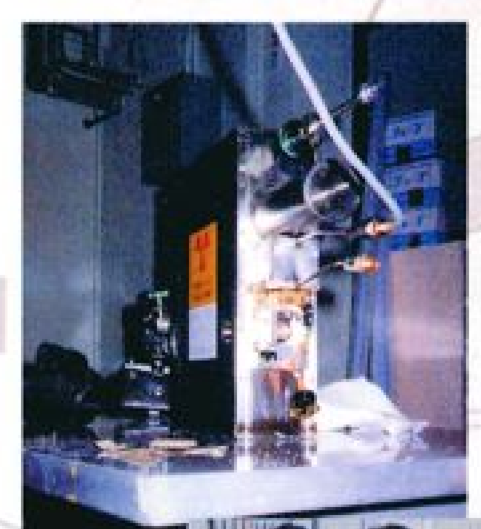
# Muon Science: UT-MSL → KEK-MSL → J-PARC-MUSE

**1980 1985 1990 1995 2000**

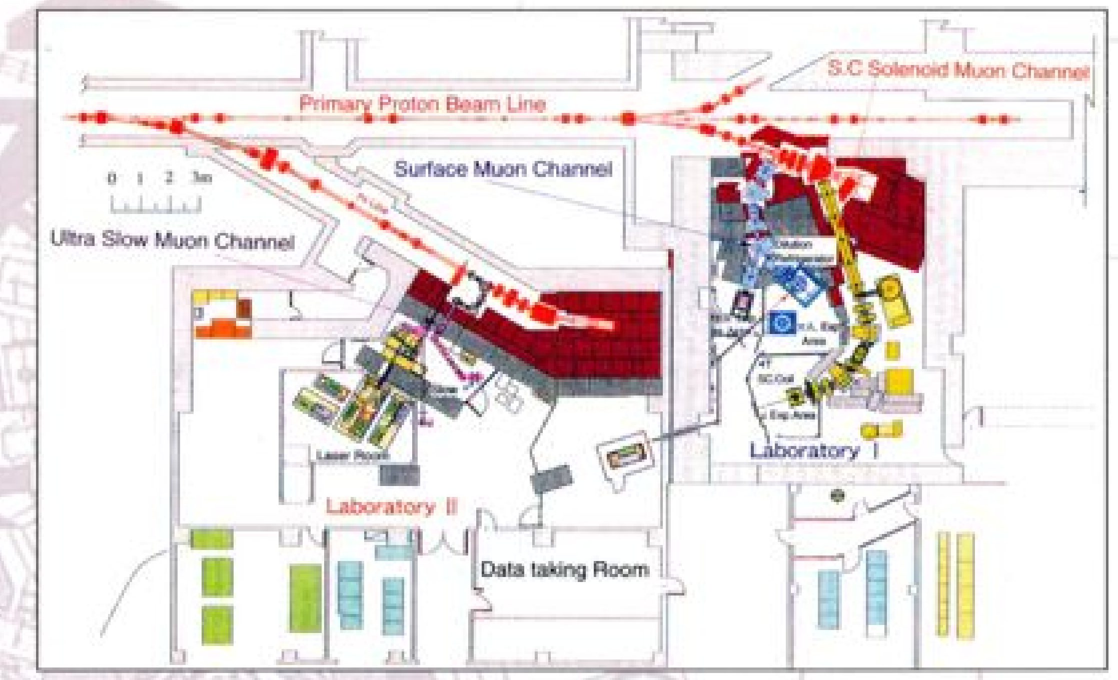
・1980. 7 初ビーム
・1981 πポート
・1982 希釈冷凍機
・1983. 4 下田μSR国際会議
・1984. 2 SHC(μ2)

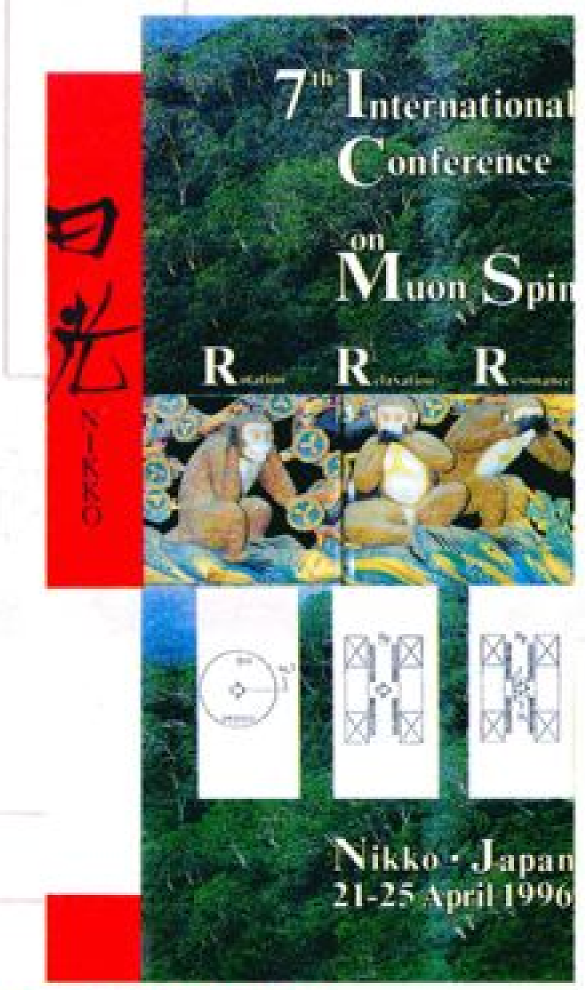
・1980
超伝導ソレノイド
ミュオンチャンネル
μ1 ポート
μ2ポート

・1985 π2チャンネル
π1チャンネル改修
・1986 μCF実験／SCH（μ1）
・1986. 9 μCF国際会議96
・1987 ミュオニウムレーザー共鳴実験
・1988. 4. 1 中間子科学センターに改名
・1988 トライアムフM9Bチャンネル
・1988 μCF実験（D T）
・1989 μ1Eポート



・1991 超低速建屋完成



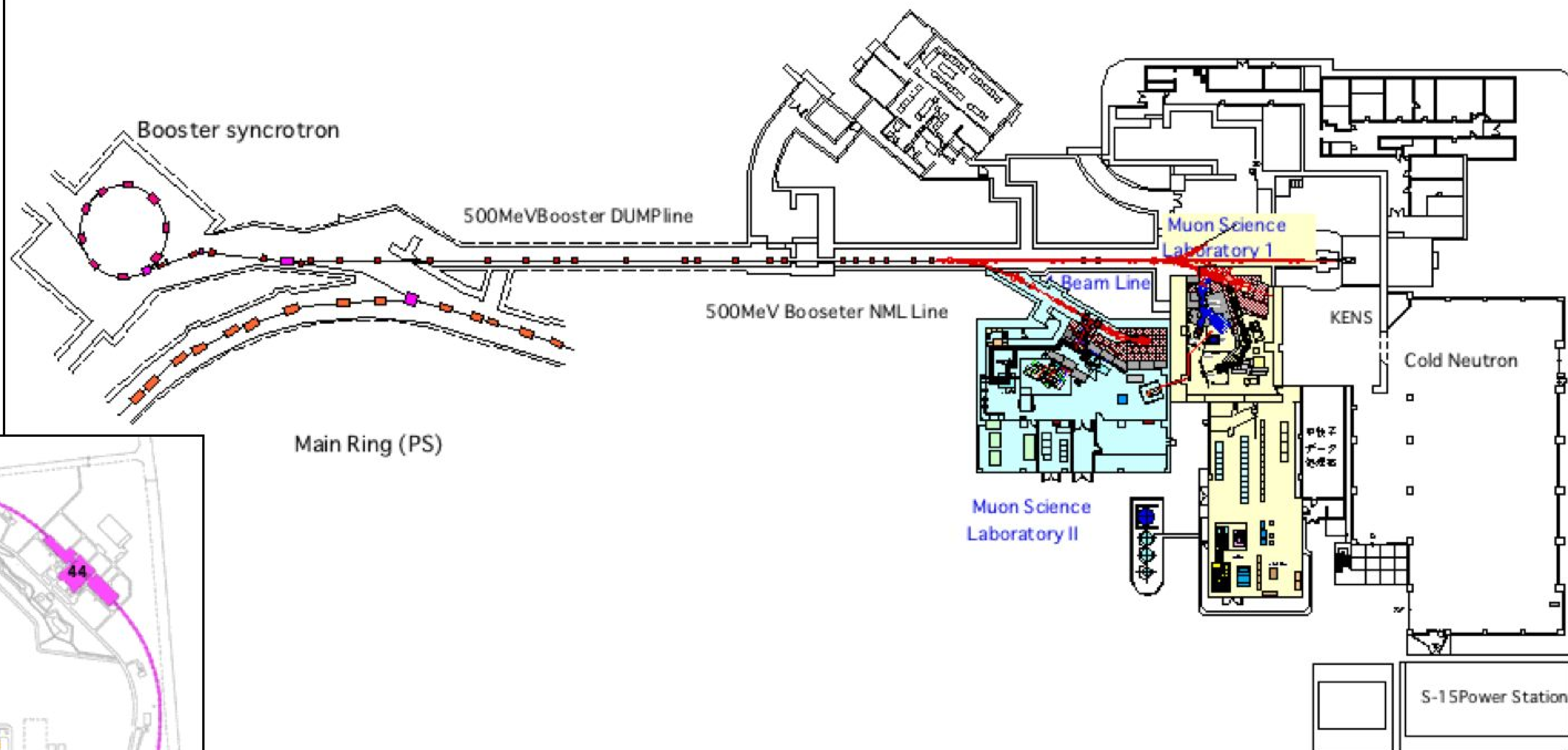




・1994 超低速ミュオン発生
・1995 中間子科学外部評価委員会開催
new 希釈冷凍機（πポート）
・1996 日光μSR国際会議
new SHC（μポート）
・1997. 4 高エネルギー加速器研究機構に移行
中間子科学研究施設（改称）

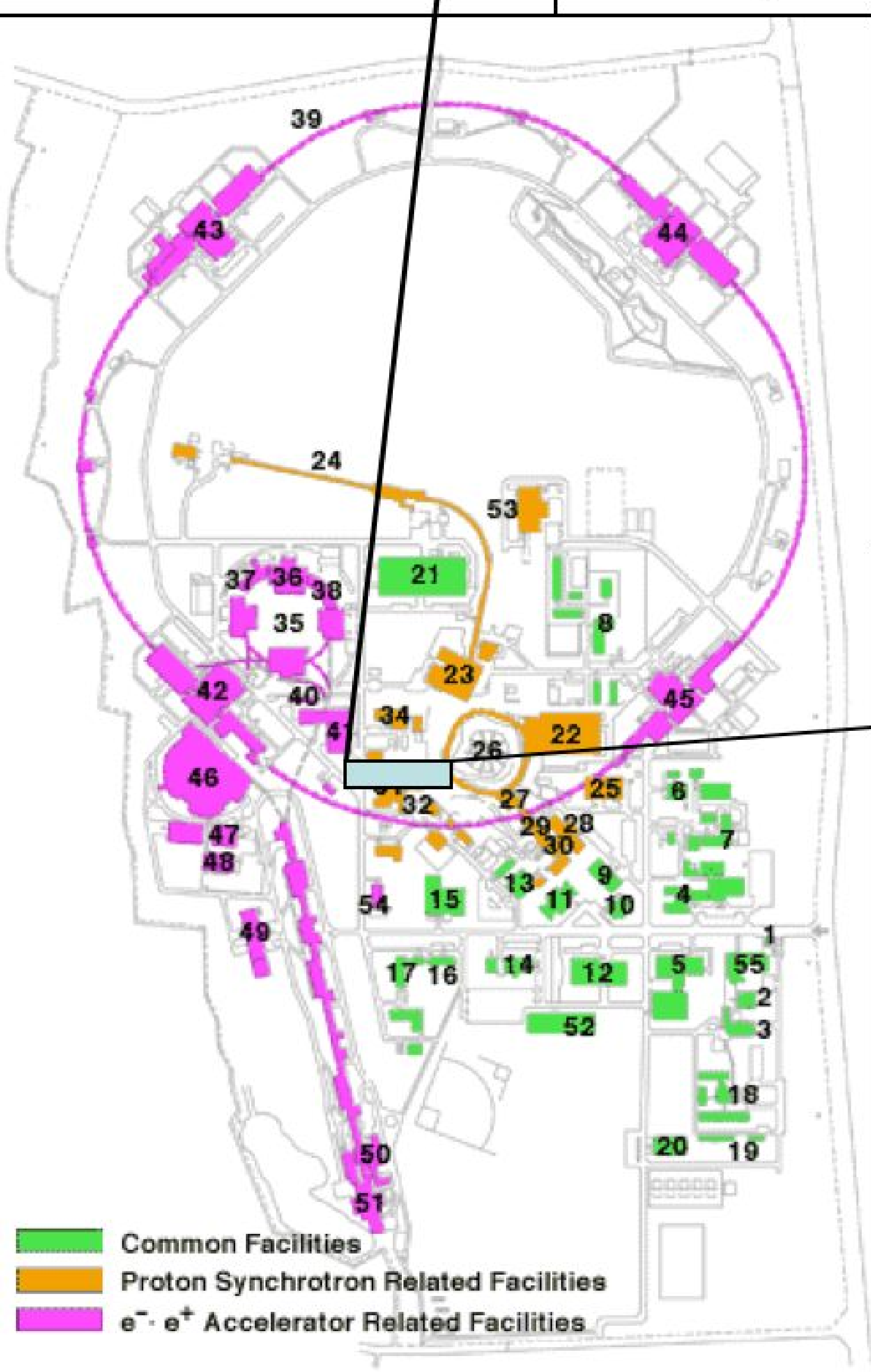
1980 1st muon beam at UT-MSL
1983 Shimoda μSR Int. Conf.
1986 μCF experiment
1987 Muonium Laser resonance Exp.
1994 Ultra Slow Muon production
1996 Nikko μSR Int. Conf.

1997 Reorganization to KEK-MSL
2004 Start construction of J-PARC muon

NML facility（1 ： 7 0 0）
(KEK-MSL, KENS)



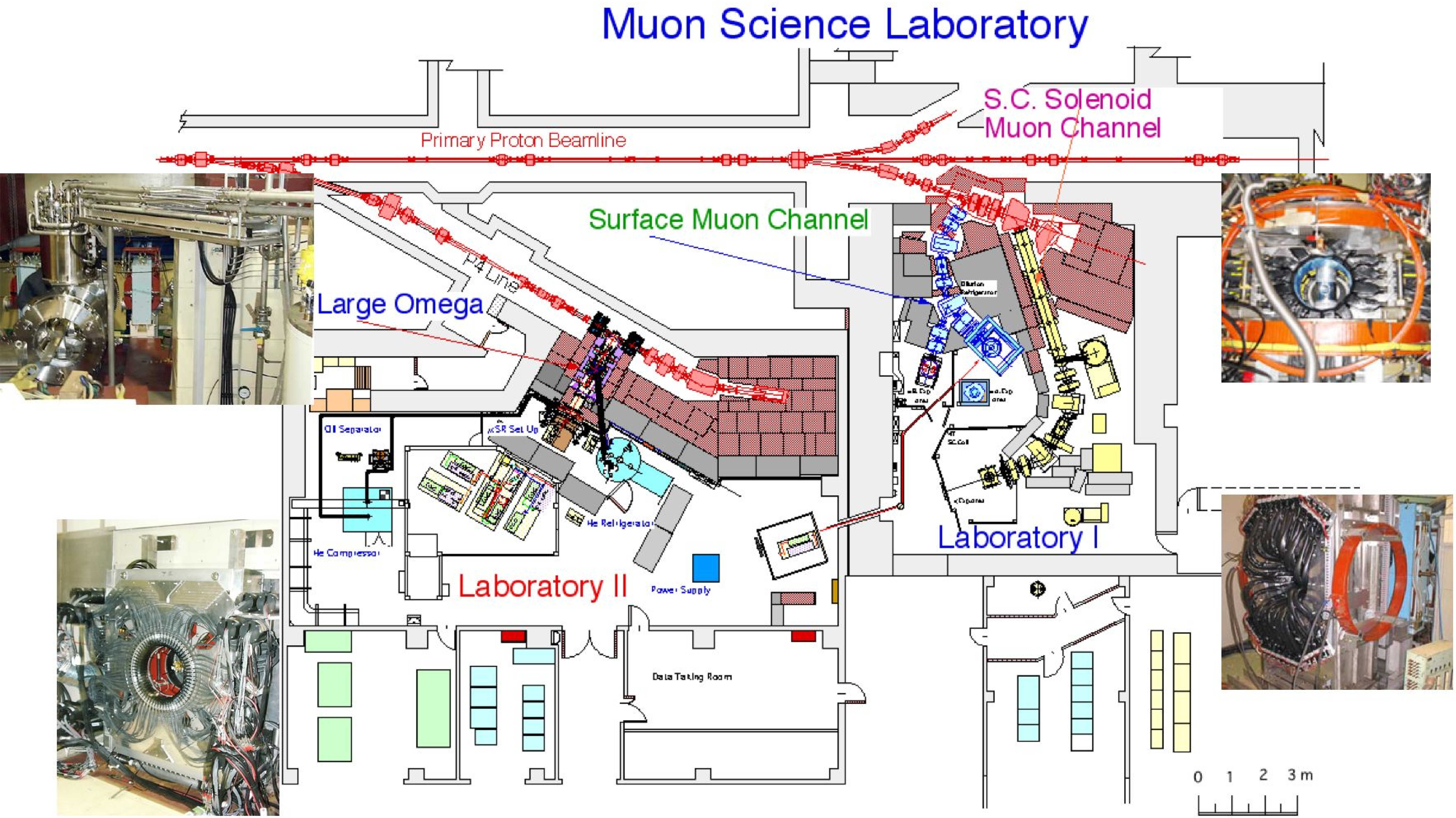

KEK




500Mev
3.2μA-9.6μA
20Hz
50ns

72/80 Pulse 4sec
37/44 Pulse 2.2sec

# KEK-MSL Facility (March 2006)

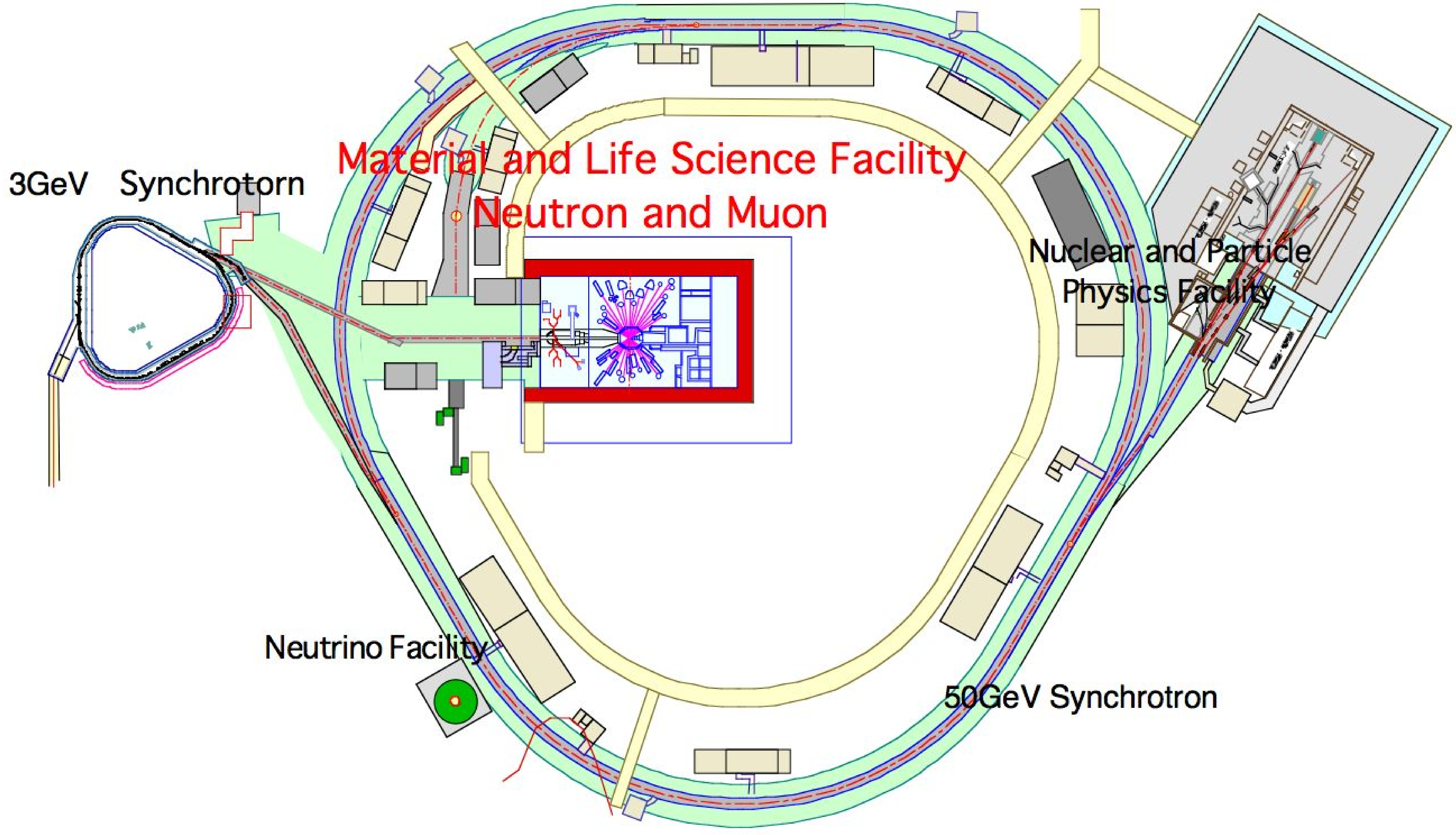



2—Exp. Hall、2—Product. Target、4-Beam line

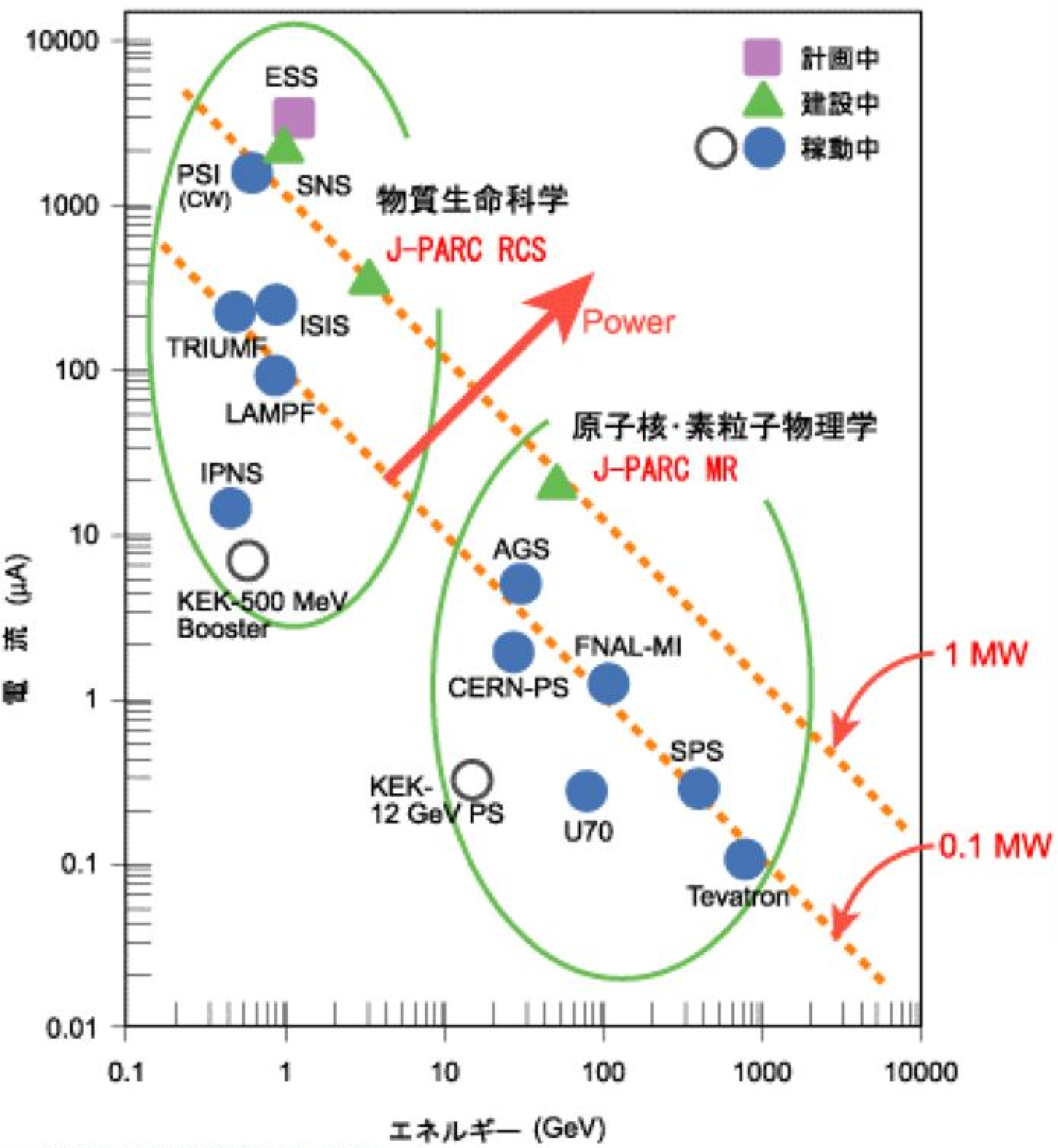
# Instruments and devices operating at the End of the tsukuba-muon Beam

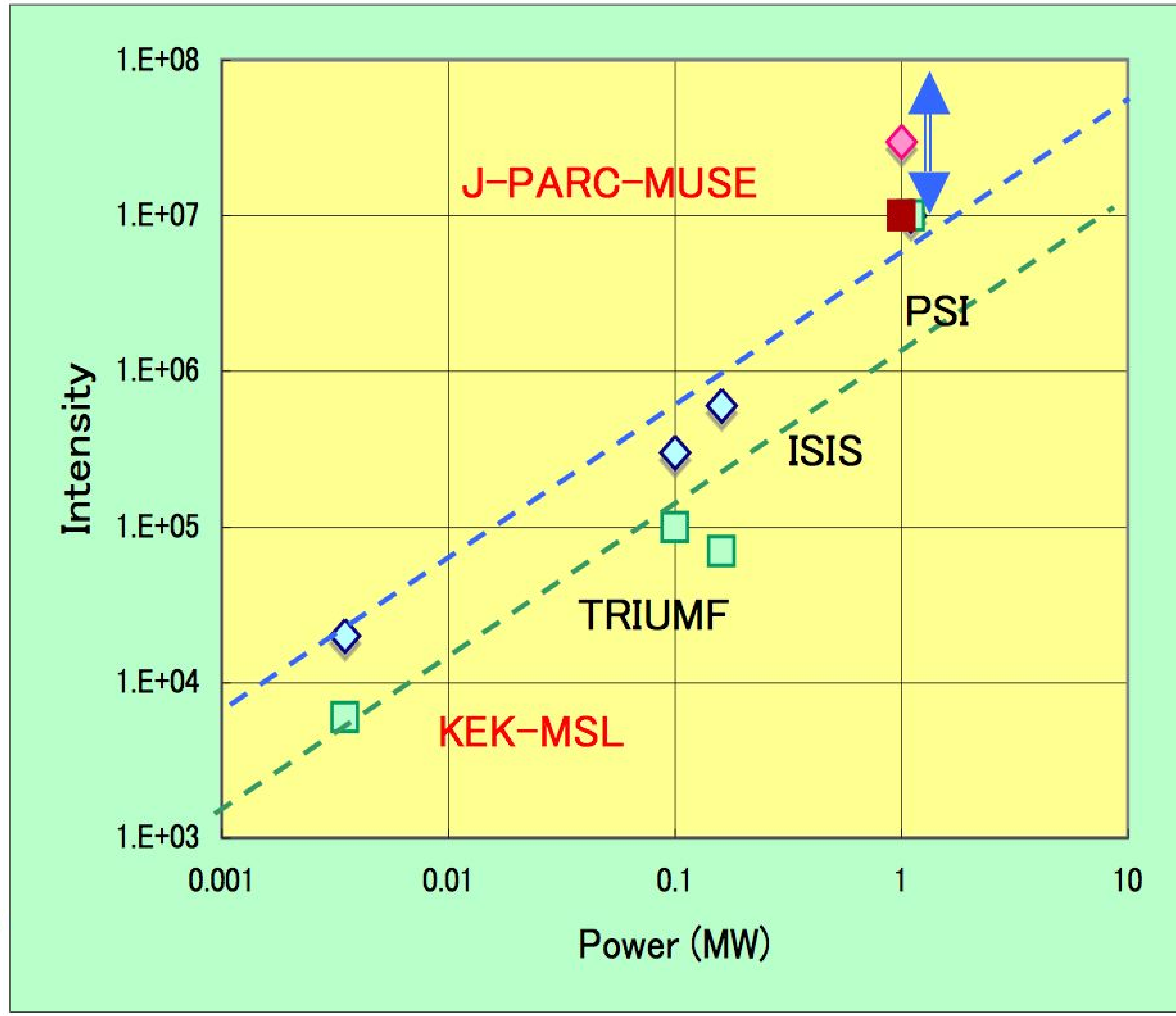
- Sample cooling：
  - Dilution Refrigerator (πA) 20mK-4K, Top Loading (8h exchange time) (πB) 5mK-4K, (24h sample loading)
  - He-flow Cryostat 2-300K
  - （with goniometer）
  - Mini-Cryo. (conduction type) 4-400K
- RH- resonance
  - RF-Resonance (40-60MHz for $\mu^+$, 100-500MHz for $\mu^+\mu^+$ and Mu)
- Light Illumination
  - Laser (TiS) 700nm-900nm 400mJ/pulse
  - UV-flash Lamp
- High Temperature
  - High Temp with IR Lamp 300-1000K
- High Voltage
  - Pos and neg. 10kV variable Bias、with Pulse operation（μs）
  - Detctor system Xray 、gamma ray
  - 7-segmented Si(Li) X-ray-detector
- 3．7T superconducting magnet
- .4T LF coil set up
- 256-segmented Detector system for decay-electron and positron

# Construction at J-PARC MUSE



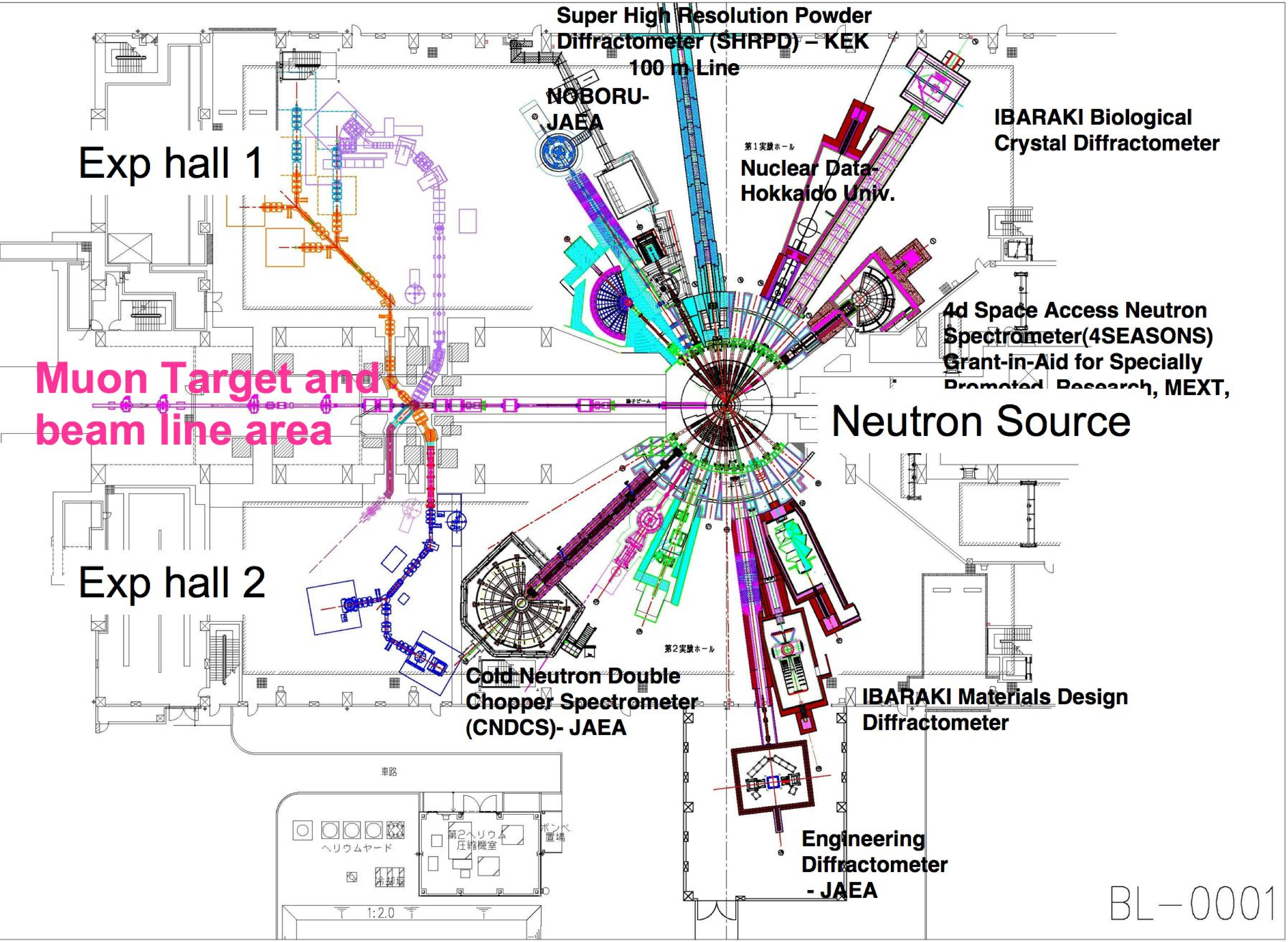
世界の陽子加速器パワーの図



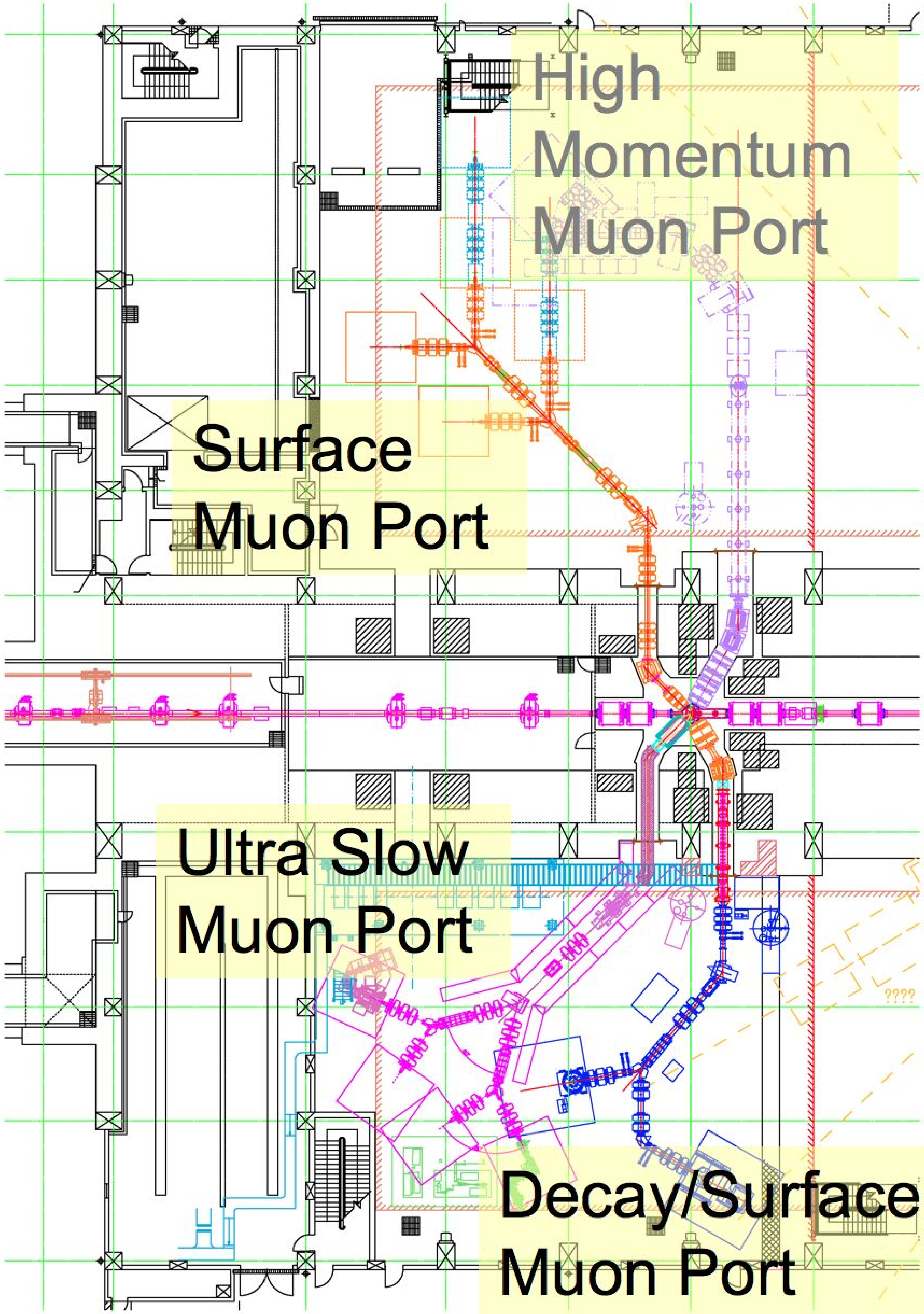




# Basic concept and design

- o Tandem-type target with neutron source
- o Central Tunnel for proton beam line, muon source target and neutron source
- o two experimental area separated by beam tunnels
- o 1st Target with 4-secondary channels
- o Possibility for 2nd muon target


Super High Resolution Powder Diffractometer (SHRPD) – KEK 100 m Line
NOBORU- JAEA
IBARAKI Biological Crystal Diffractometer
Exp hall 1
第１実験ホール
Nuclear Data- Hokkaido Univ.
4d Space Access Neutron Spectrometer(4SEASONS) Grant-in-Aid for Specially Promoted Research, MEXT,
Muon Target and beam line area
Neutron Source
Exp hall 2
第２実験ホール
Cold Neutron Double Chopper Spectrometer (CNDCS)- JAEA
IBARAKI Materials Design Diffractometer
車路
ヘリウムヤード
第2ヘリウム圧縮機室
ボンベ置場
冷却塔
1:2.0
Engineering Diffractometer - JAEA
BL−0001

# Muon Beam available at J-PARC MUSE




1)Decay/Surface Muon Port (Phase 1)

| | Surface Muon ($\mu^+$) | Decay Muon ($\mu^+$,$\mu^-$) |
|---|---|---|
| Beam Energy | **4.1MeV** | **5-50 MeV** |
| Implantation Depth | **~0.2 μm** | **1 mm - ~cm** |
| Energy Distribution | **~15%** | **~15%** |
| Pulse Width | **~100 ns** | **~100 ns** |
| Beam Size | **30 mm x 40 mm** | **70 mm x 70 mm** |
| Intensity | **3 x $10^7$/s** | **$10^{6\text{-}7}$/s** |
| Beam Port | **2** | **2** |

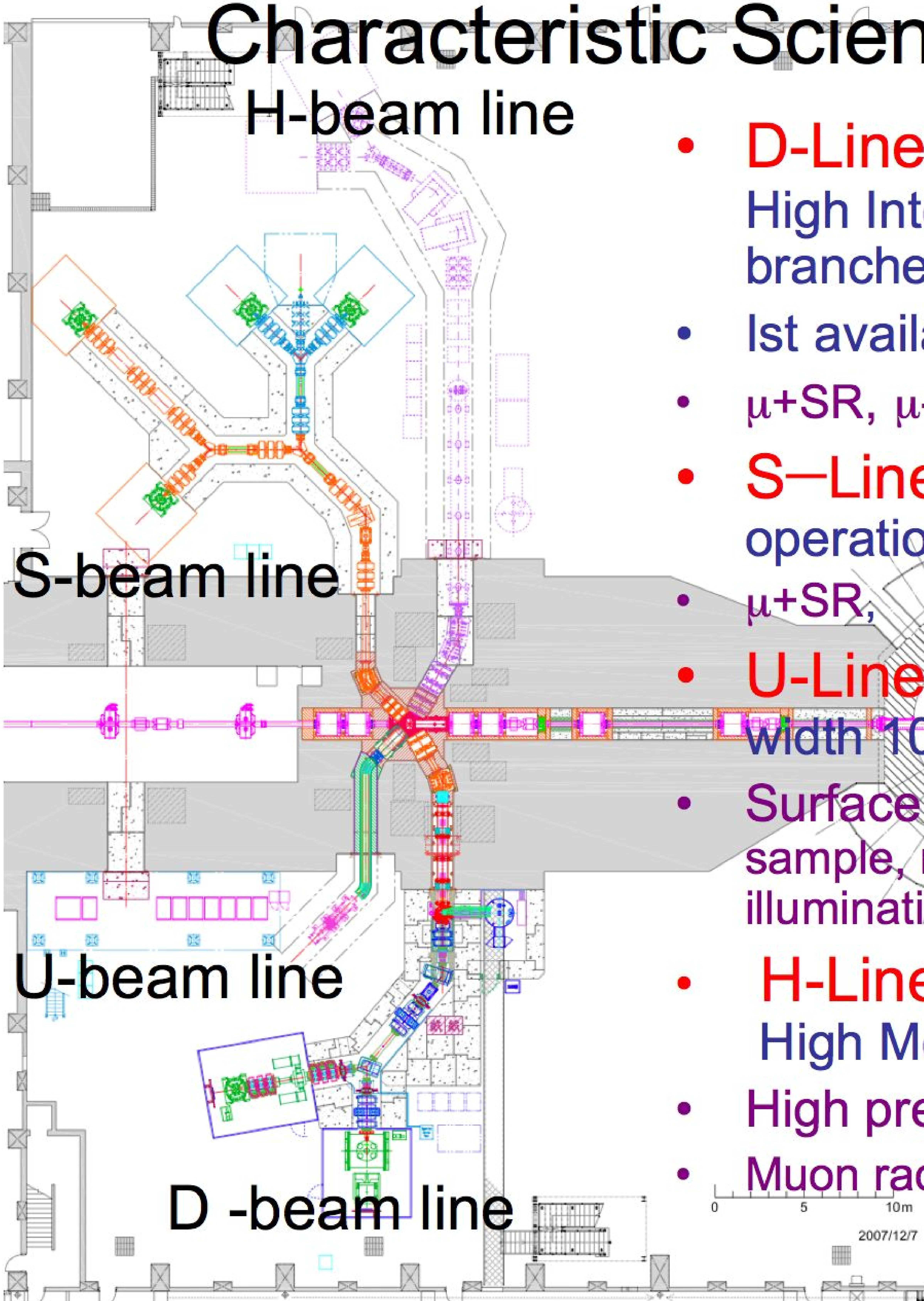
2)Surface Muon Port ( Phase 2)

| | Surface Muon ($\mu^+$) |
|---|---|
| Beam Energy | **4.1MeV** |
| Implantation Depth | **~0.2 μm** |
| Energy Distribution | **~15%** |
| Pulse Width | **~100 ns** |
| Beam Size | **30 mm x 40 mm** |
| Intensity | **$10^{6\text{-}7}$/s** |
| Beam Port | **4** |

3)Ultra Slow Muon ( Phase2)

| | Ultra Slow Muon ($\mu^+$) |
|---|---|
| Beam Energy | **0-30 keV** |
| Implantation Depth | **0 nm - 200 nm** |
| Energy Distribution | **<< 1 %** |
| Pulse Width | **8.3 ns(present) --> ps** |
| Beam Size | **3x4mm(present) --> 1 φ** |
| Intensity | **2-5 x $10^5$/s** |
| Beam Port | **2** |

# Characteristic Sciences at Muon Beam line




- **D-Line:** pos. and neg. muon、E:4Mev-40MeV, High Intensity / simultaneous operation 2 branches by kicker
- Ist available Beam line at Day One
- μ+SR, μ-SR, μCF, muonic atom,
- **S—Line:** pos. Muon、4Mev, simultaneous operation of 4 branch by kicker system
- μ+SR,
- **U-Line:** pos. Muon 、4MeV->1-20KeV,puls width 10ns, beam spot 1-2mm、High luminosity
- Surface science, μ+SR on thin film, with tiny sample, muonium reaction in gas phase, light illumination study on light absorbing surface.
- **H-Line:** pos. and neg. muon 、40-100MeV- High Momentum beam line
- High pressure μ+SR, μ-SR
- Muon radiograph

# construction of J-PARC

- Proton beam line M1／M2 tunnel
- FY2004　MLF-building construction began
  inbetted iron shield, duct for air cooling, basement for power supply yard
- FY2005
  Base plate、Guide shield installation
- FY2006
  Target chamber, proton beam line magnet
- FY2007
  Pillow seal, shield, beam duct  installation
- ＊M2 tunnel（7.17) completion of beam line component
- M2 line Ceiling shield

―――――――――――――――――――――――

- FY2008 construction of 2ndary beam line

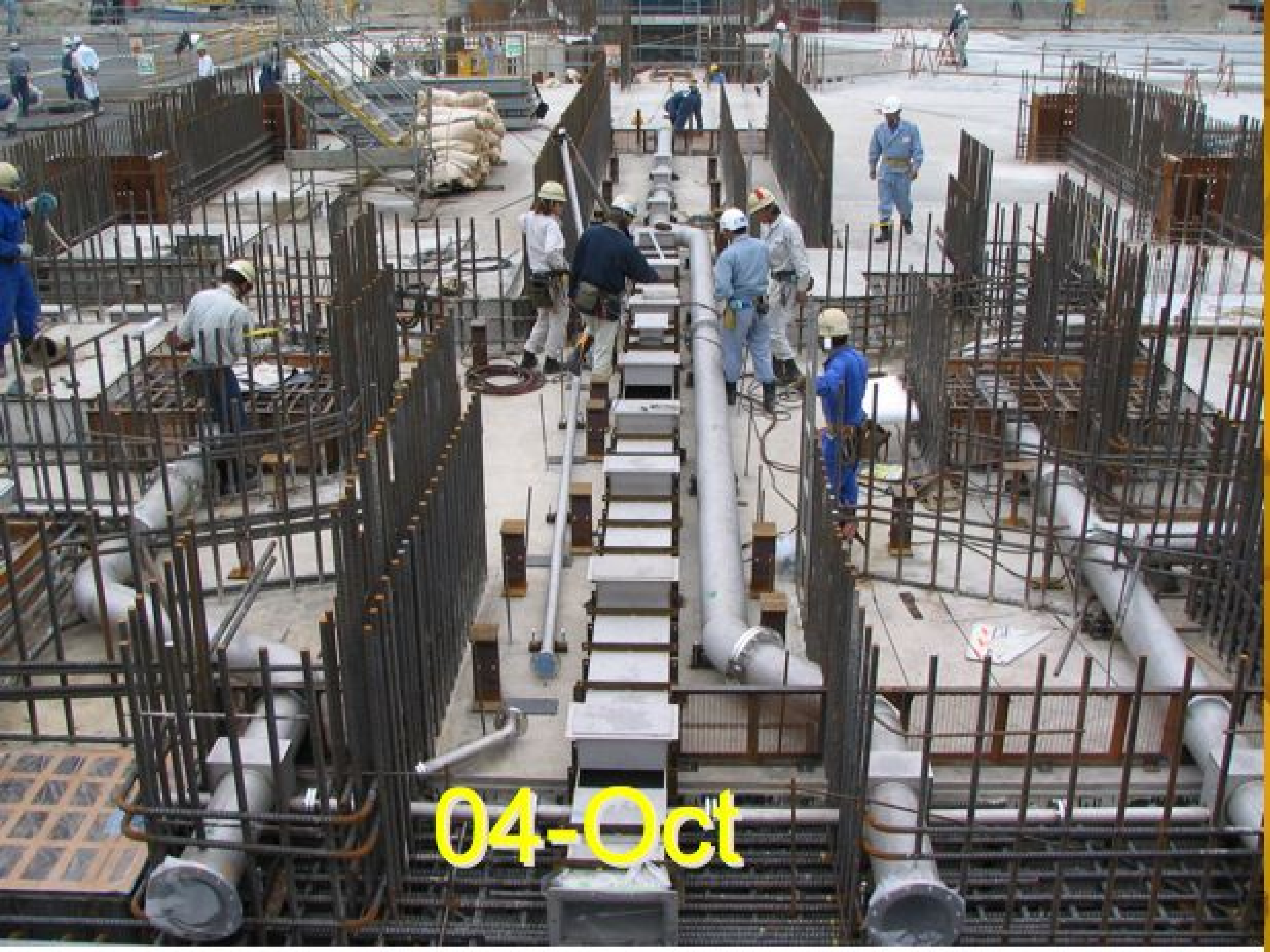
Decay -surface muon beam line

Transport from old facility (superconducting solenoido and cooling system )

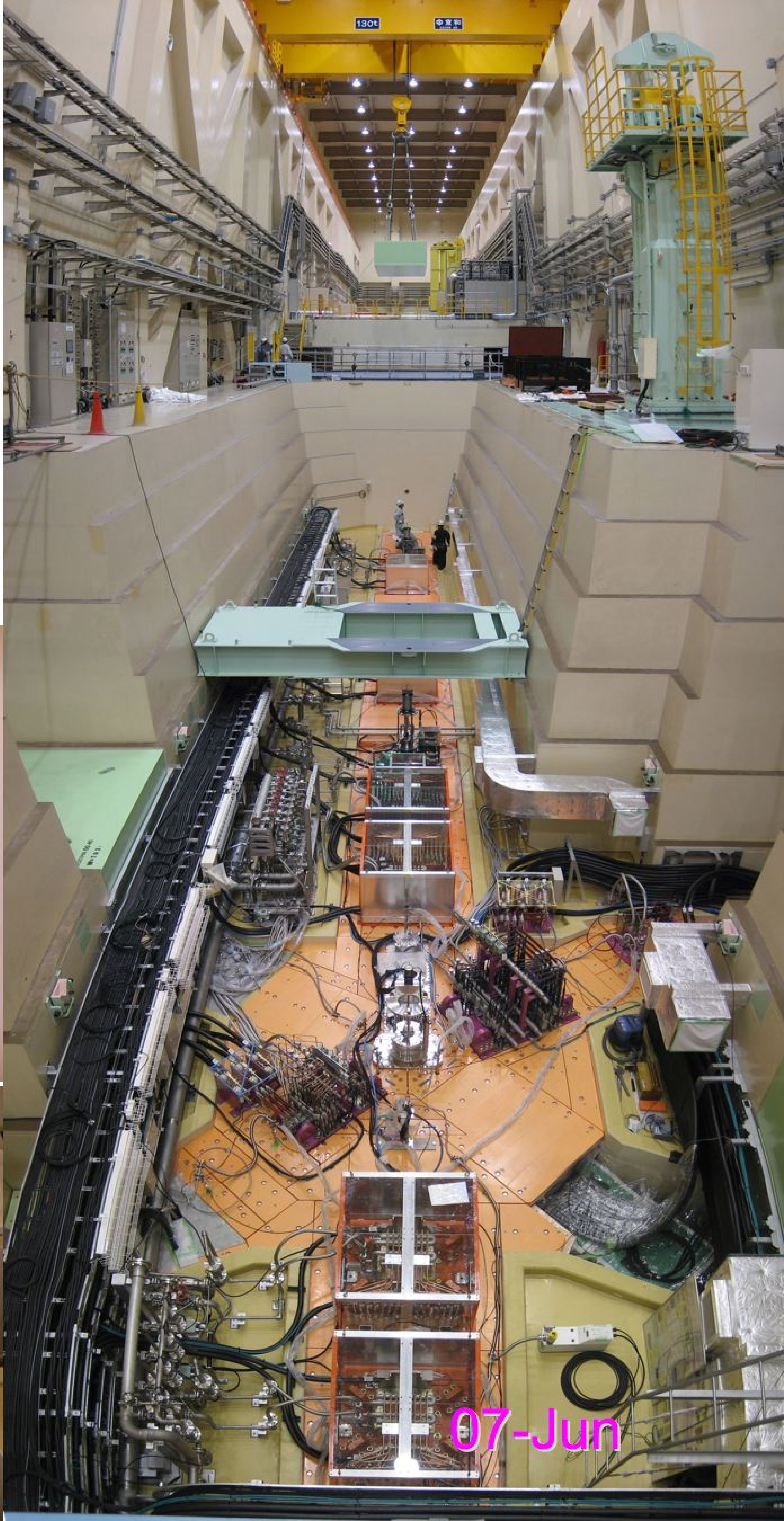
Radiation shield for 2ndary beam line

Magnet and beam duct for Muon Beam line.

Experimental apparatus for general user.


04-Oct


06-May


07-Jun

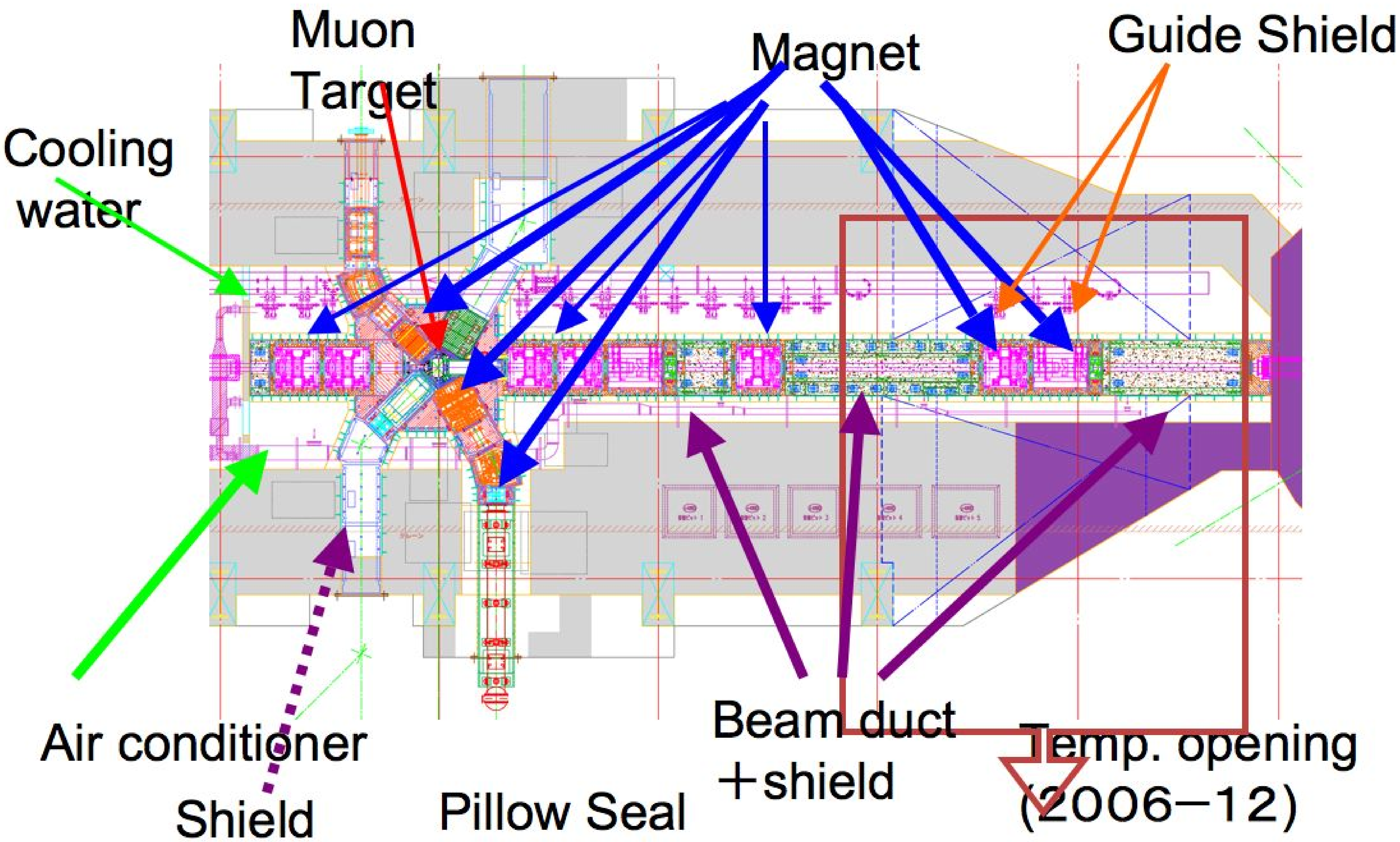

04-Oct


ミラプロ
06-May


05-Sep


06-April

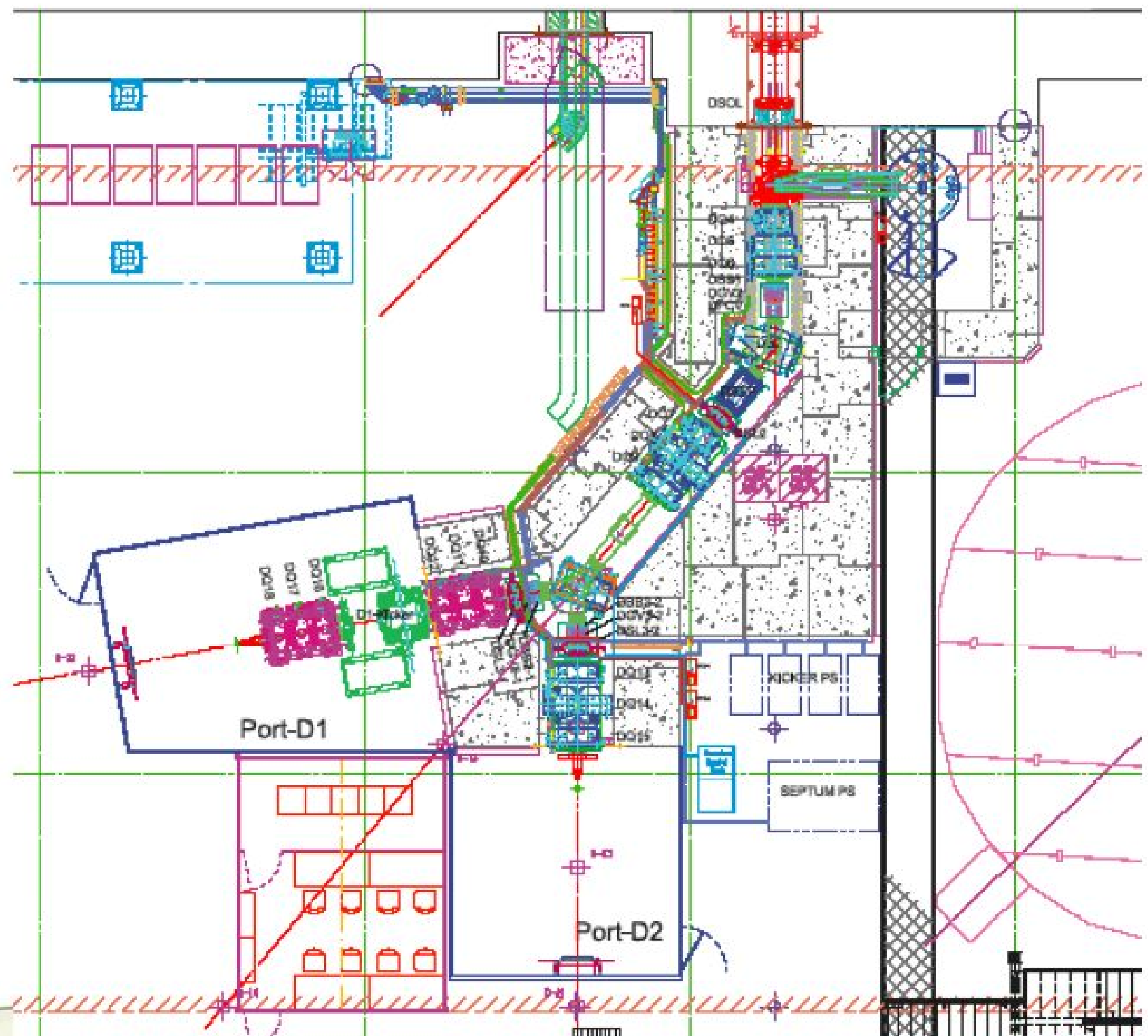
# Construction of muon target and M2 beam line

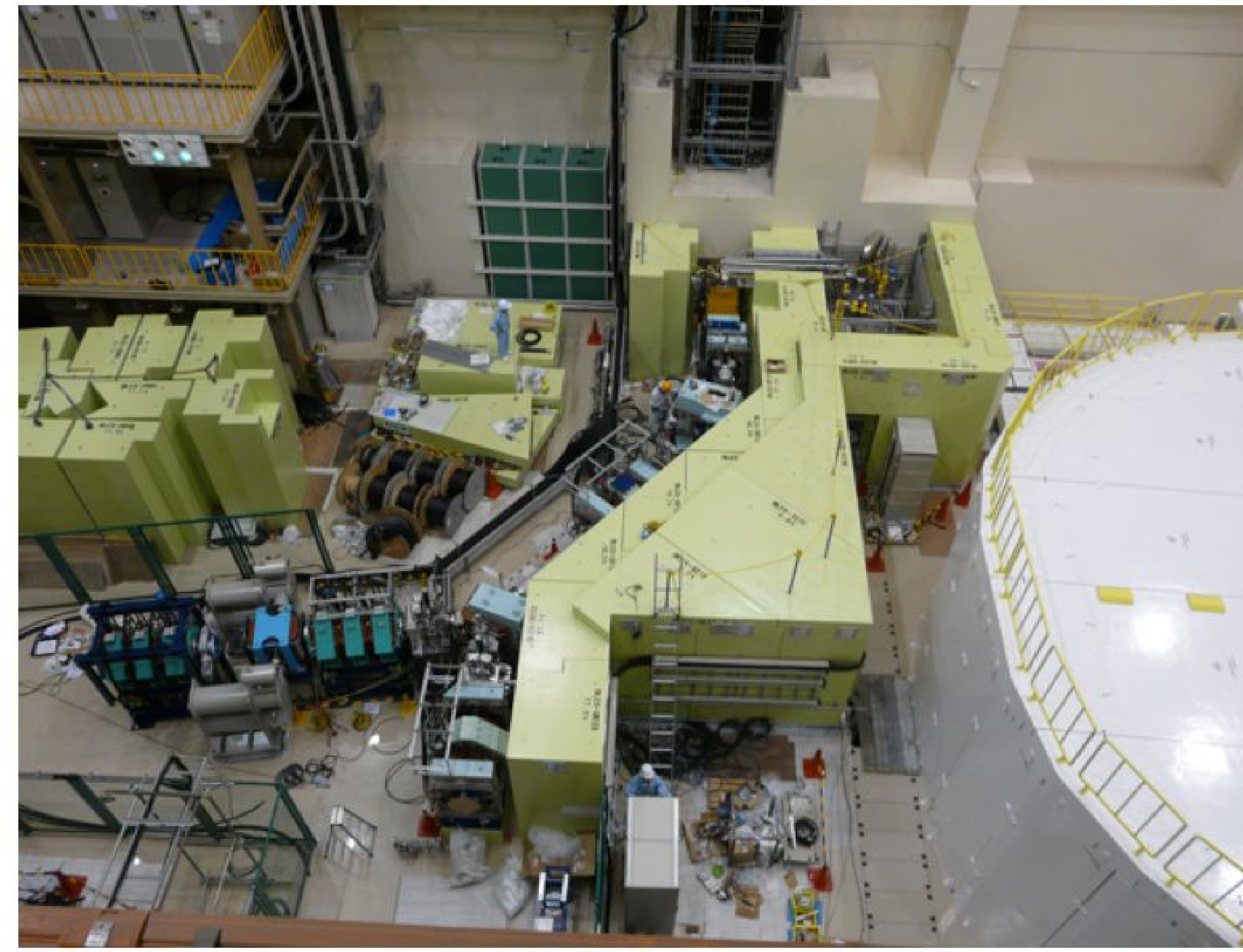



Target cask for remote Handling
(transport to hot cell)

**Installation of Alignment Plates**
**XY +- 0.1mm**
**Precision**
**Level +-0.1 mm**

# Construction of muon beam line (decay/surface)



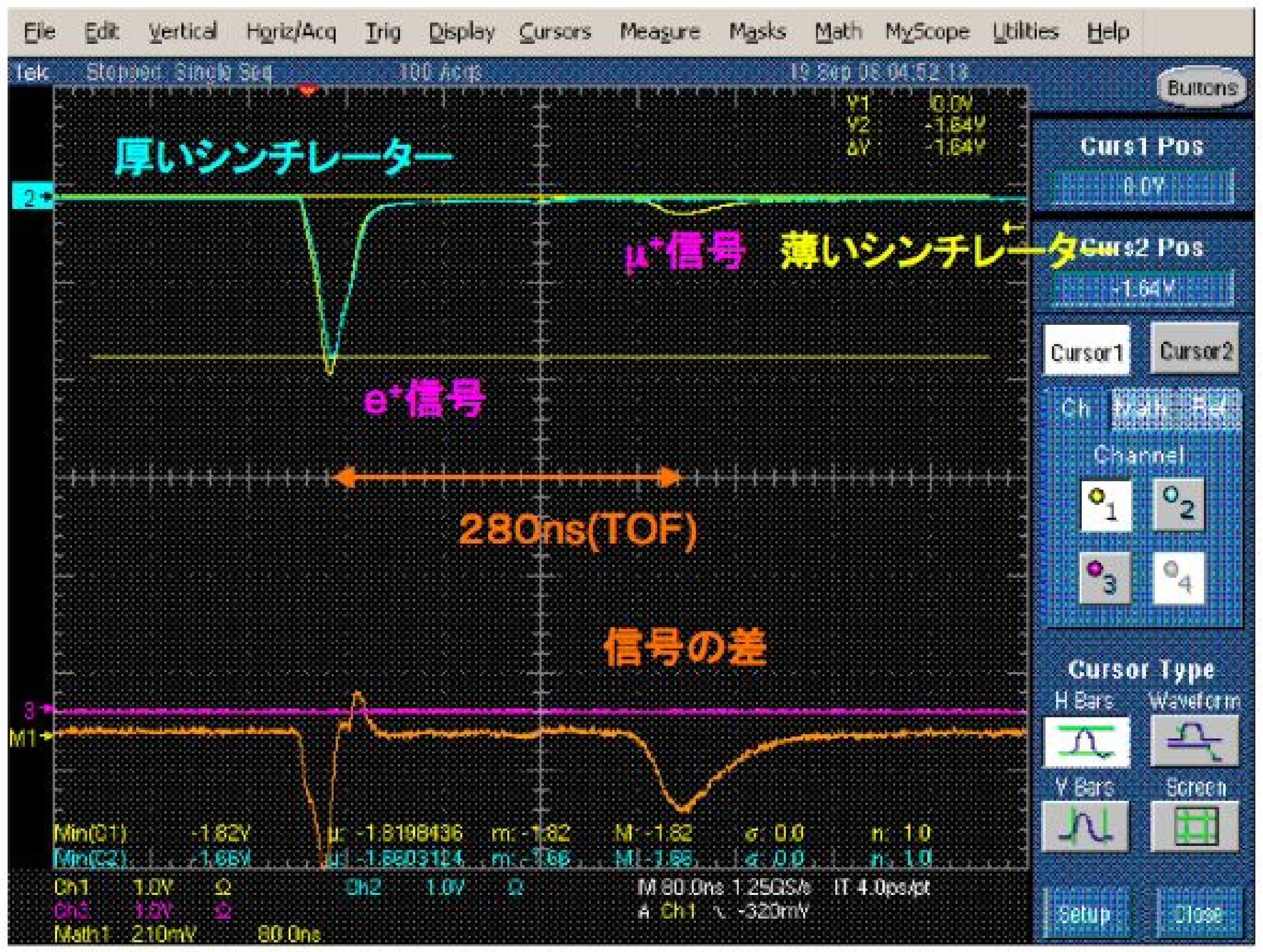



μSR apparatus
highly segmented
128 ch (reuse)

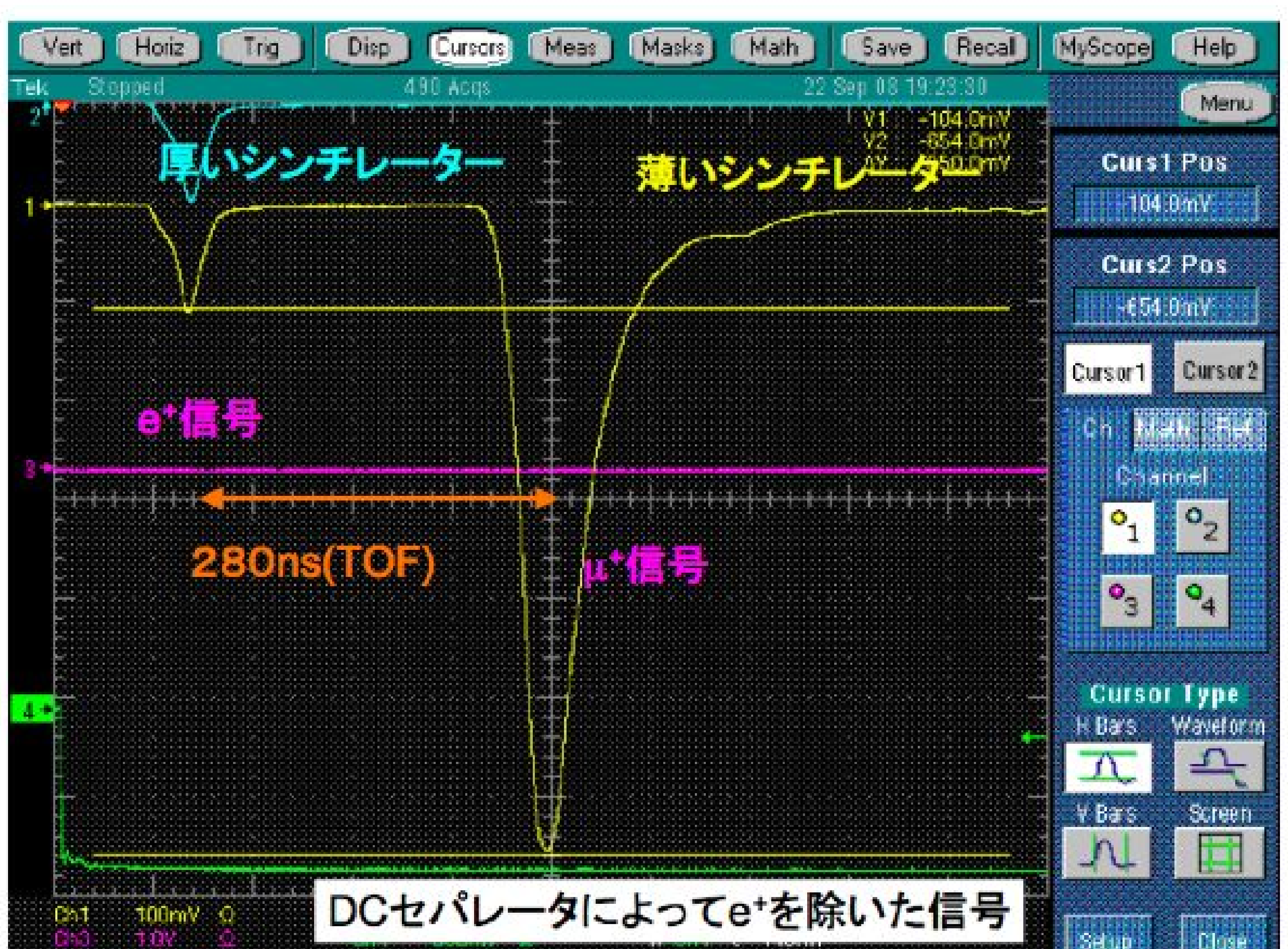
Superconducting solenoid installation (reuse)

# First muon from D1 beam line (4Mev positive muon) on 26.September 2008.

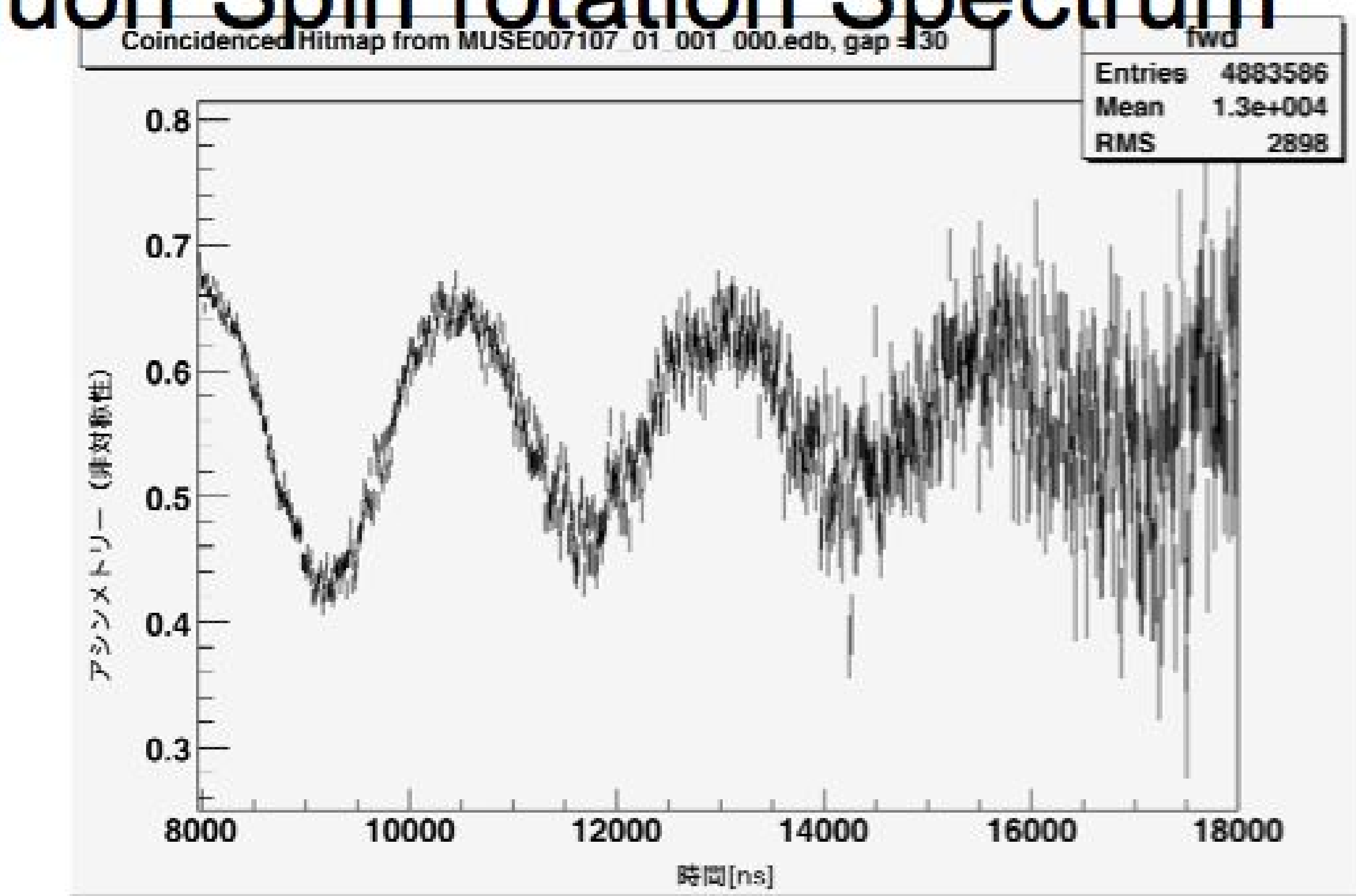
9/19 Proton beam on Muon target



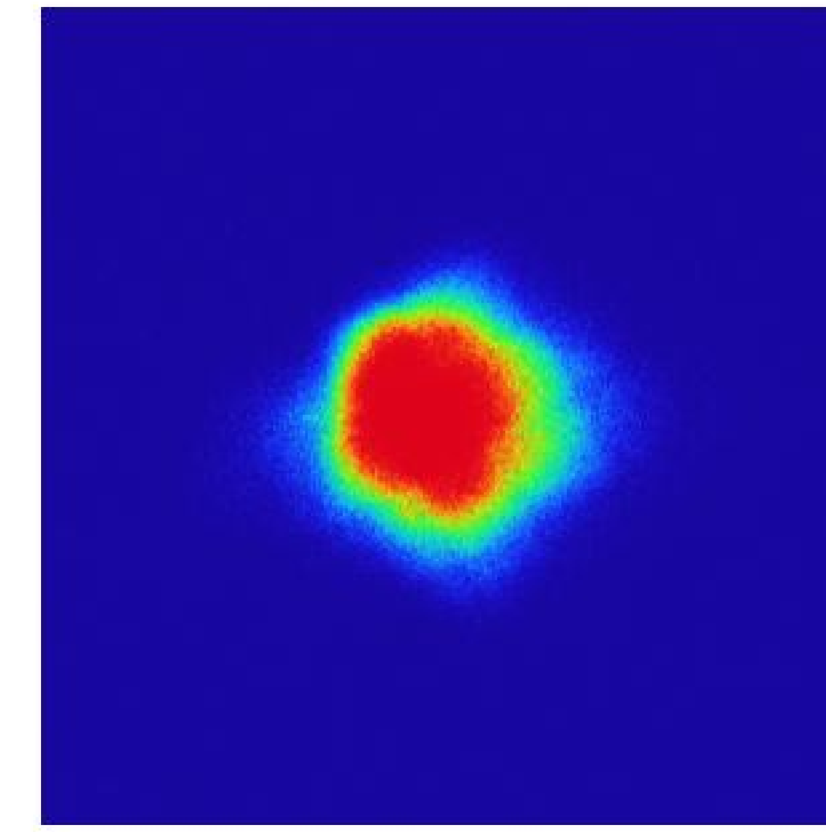

DC separator eliminates positron contamination




Muon Spin rotation Spectrum




Beam profile 35X3mm



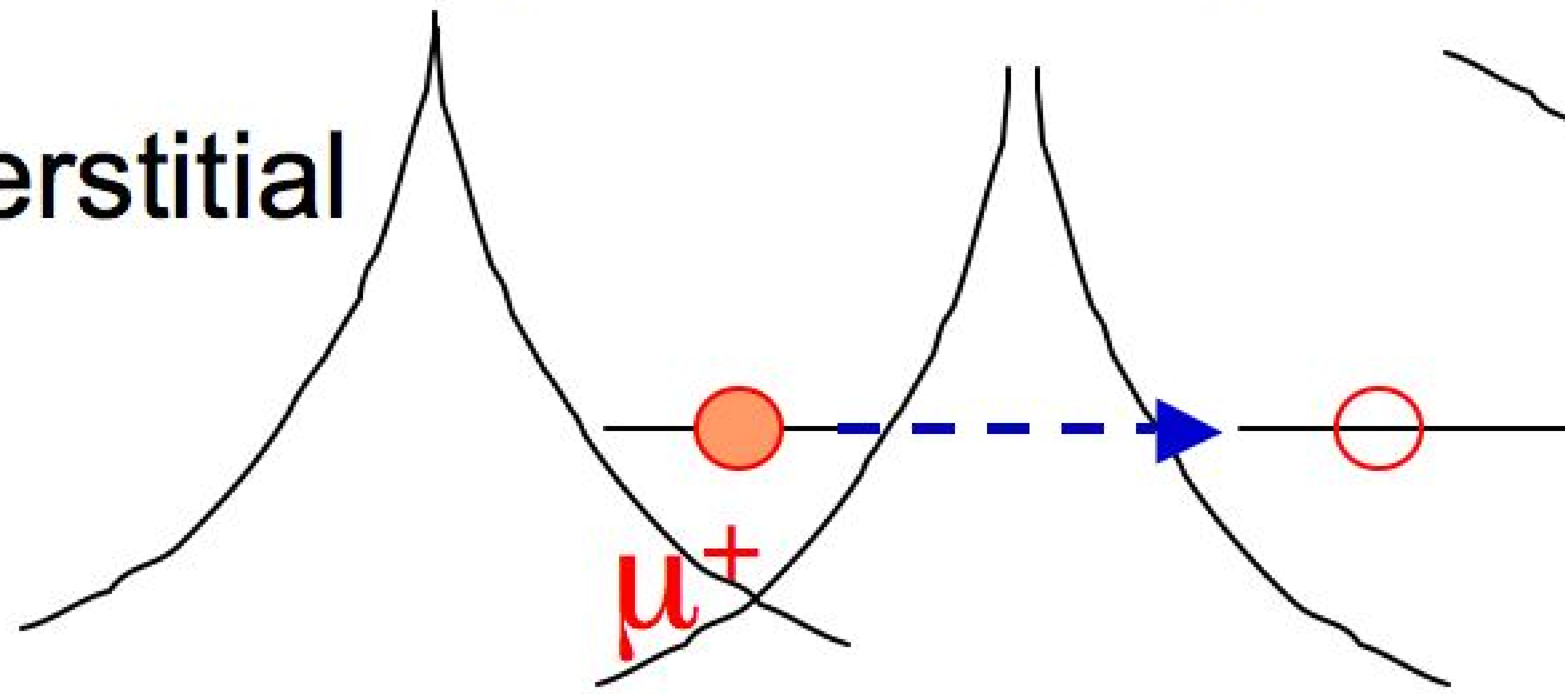

Construction team and muon users celebrate the re-birth of Pulsed muon beam at J-PARC MUSE

# Future of muon science plan at MUSE

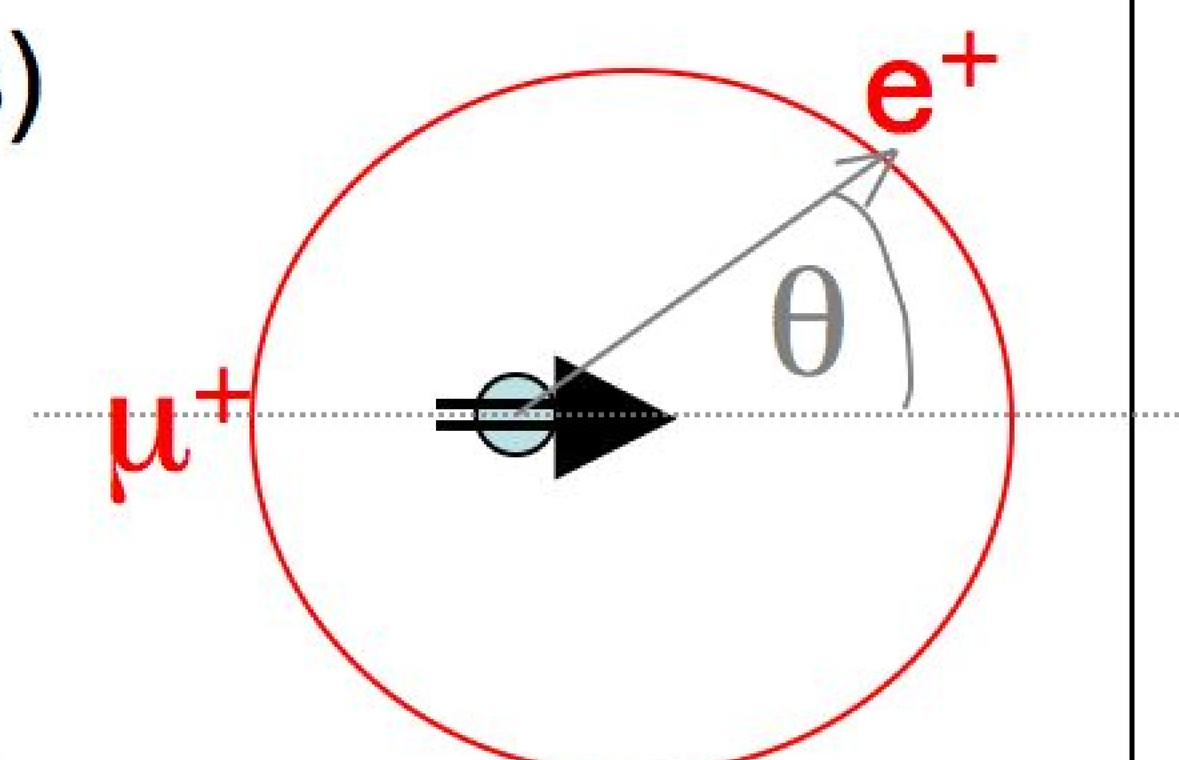
# Sciences explored by muons
# Positive and Negative Muon

## Positive Muon：
## A light Proton（1/9 mass）

Stays interstitial Position.

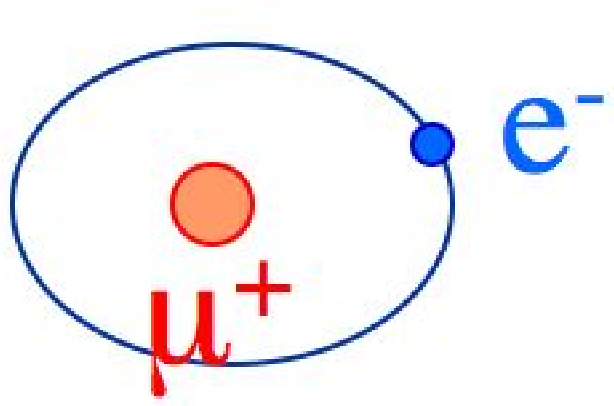



Decay with lifetime（2.2μs）
Its spin perturbed by magnetic field.

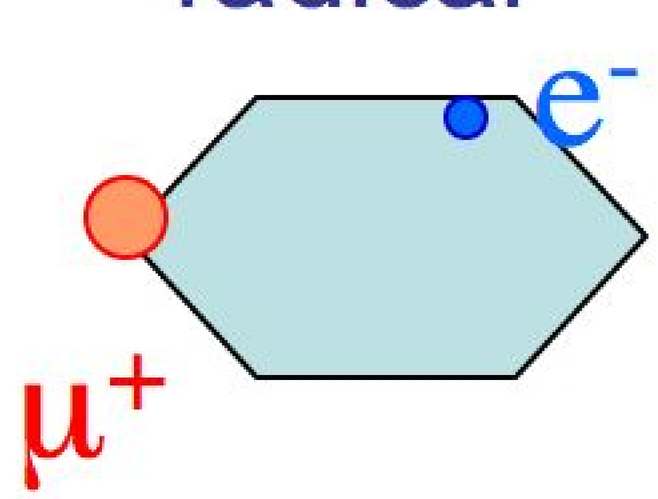


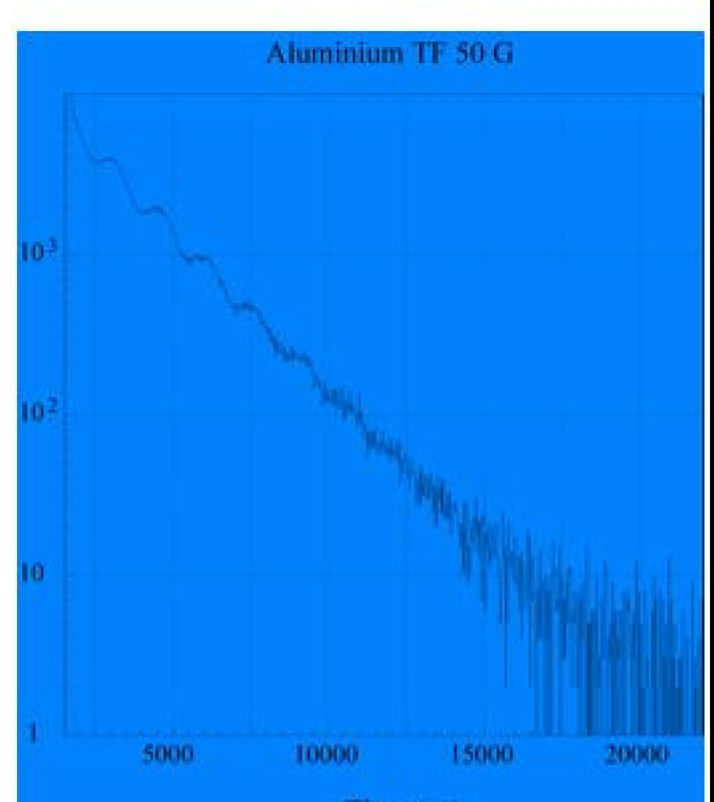

Emit positron preferentially aong the its spin direction

muonium

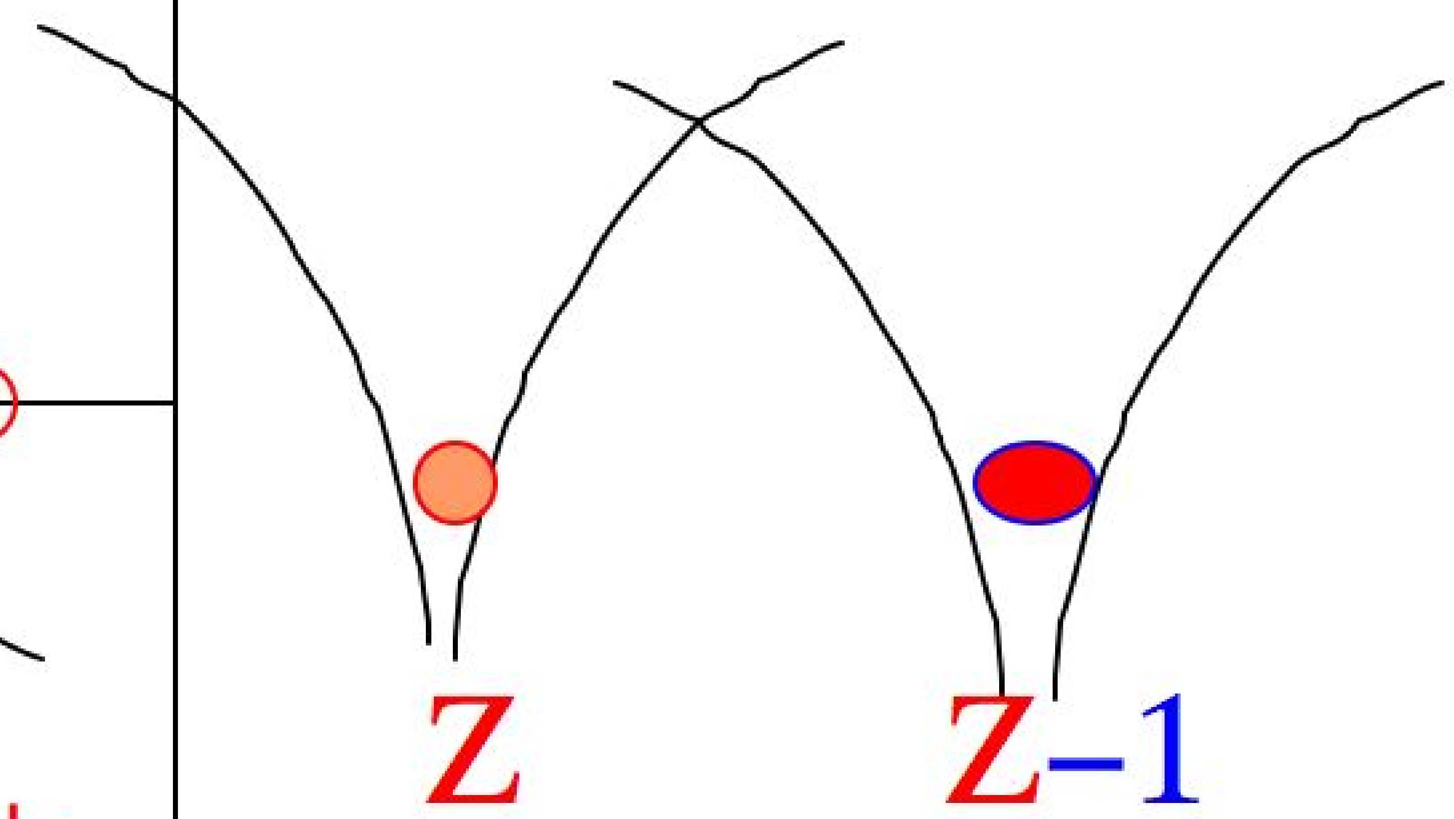



radical

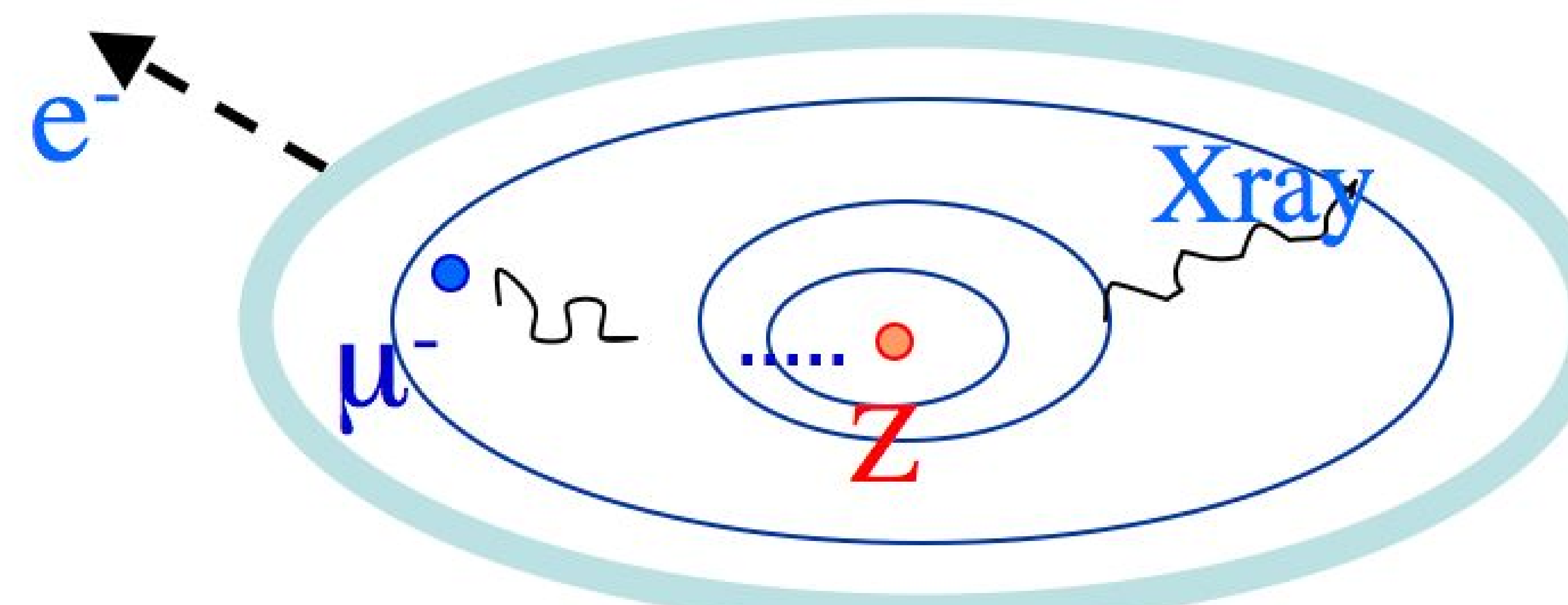



## Negative muon：
## heavy electron（200x mass）




Small orbit of muonic atom orbit -->effective atomic Number (Z-1)




High Energy of muonic Xray
200x (electronic X-ray)

Muonic hydrogen behaves as neutral :
coulomb screening
(muon catalyzed Fusion)

# Positive muon

◎High temperature superconductivity cuprate
◎ μSR study of organic conductor under high pressure
◎ μSR study on 4f, 5f electron system
◎ μSR study on nano-structure
◎ Surface and interface studies of superconductor and magnetic materials with ultra slow muon
◎ Study on Magnetic multilayer with ultra slow muon———

Development
◎ μSR study High pressure
◎ Internal field distribution by RF-resonance High Time resolution by RF
◎ GHZ resonance

◎ Application to industrial study

# Negative muon

$\mu$CF
1) High temp, High Pressure Beam extraction
2) $d\mu^-$、$t\mu^-$—muonicXray $K\alpha, K\beta, K\gamma$ precise measurement 3) $\alpha$–capture precise measurement 4) $(\alpha\mu^-)^+$ Beam extraction 5) Laser resonance

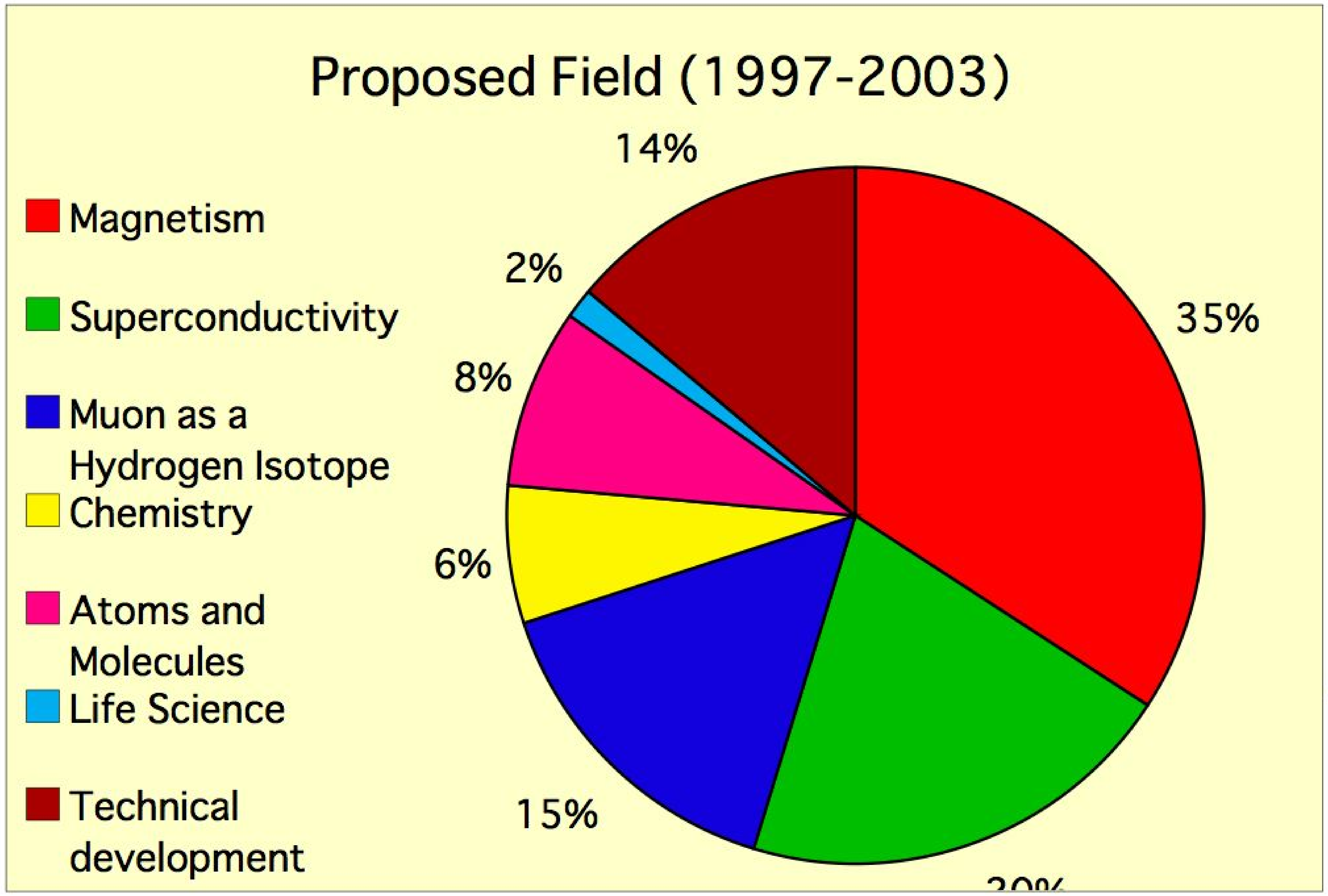
Muonic atom chemistry、chemical reaction、electric state
1) X-r measurement $Z-1+\delta$ 2) Chemical reaction Difference between $\mu^-$Ar, Cl 3) Laser resonance ay

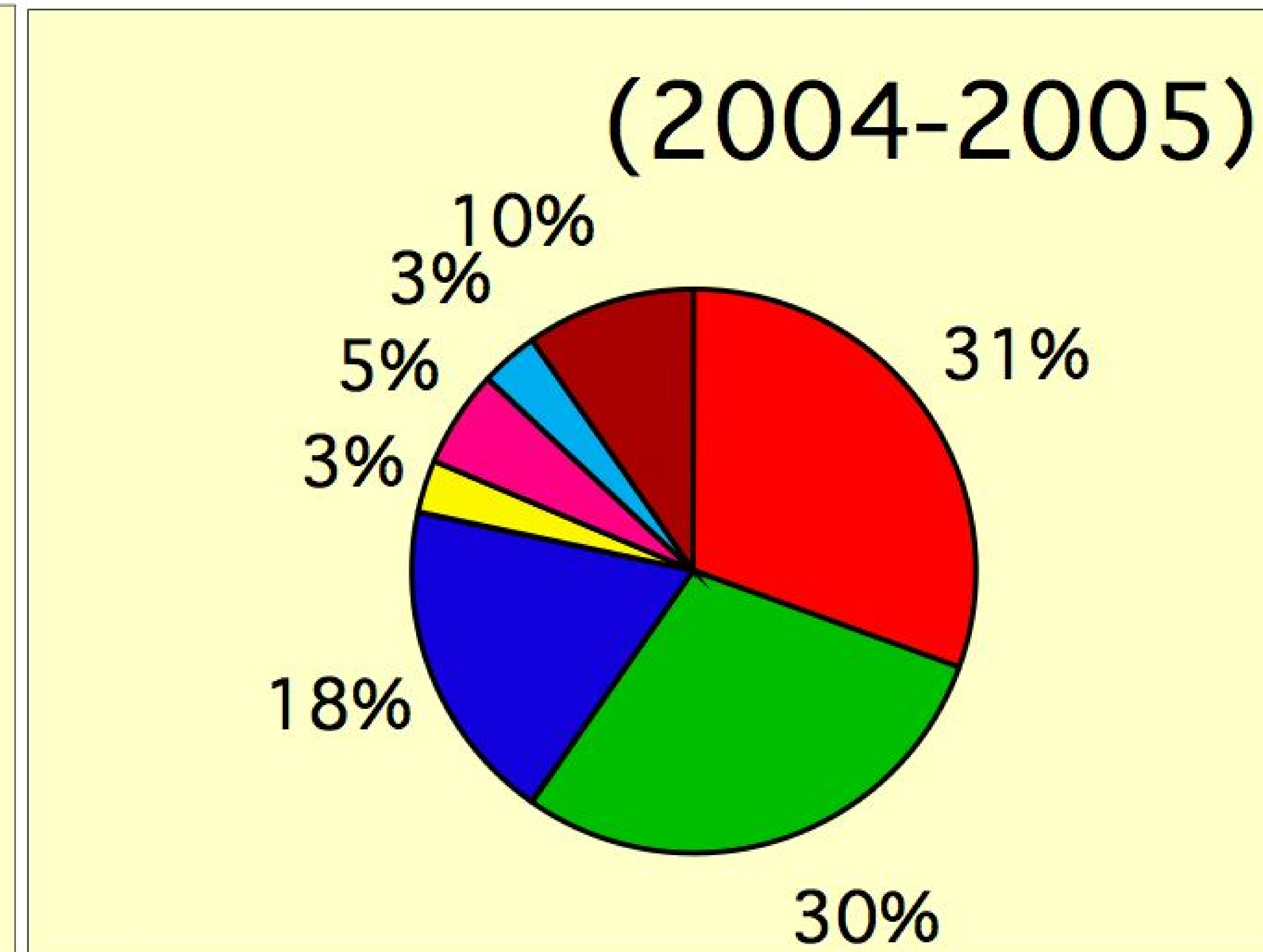
Application Nondestructive 3-dimensional analysis

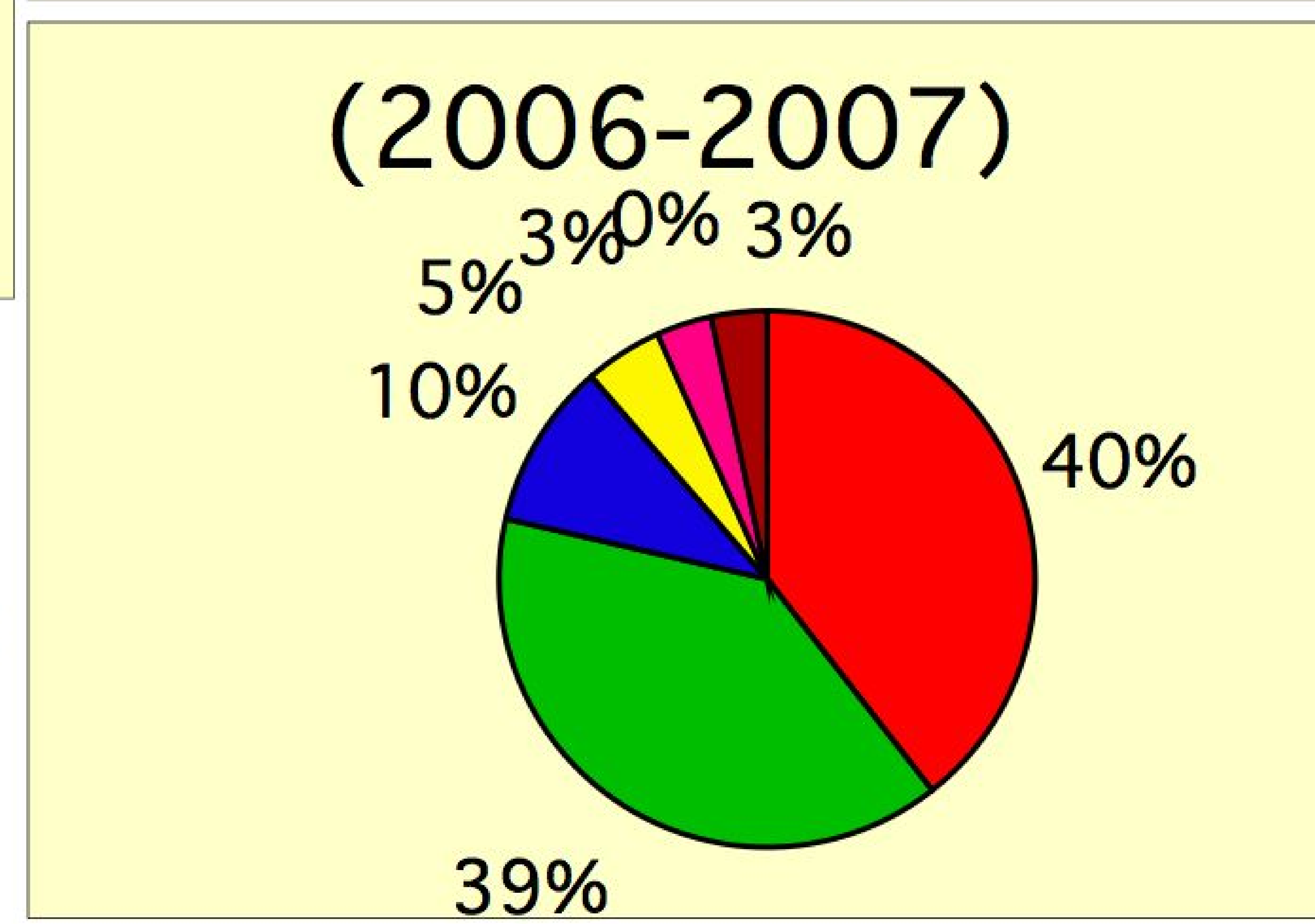
Radioactive muonic atom 1) muonic X-ray
2) charge distribution of Radioactive nuclei
nuclear structure (direct measure of Quadrupole momentm)
Radioactive nuclei in solid hydrogen target (anormalous diffusion $d\mu$)

$\mu$SR with negative muon
1) local hyperfine field at Oxygen site
2) Z−1 impurity electric state and effect in semiconductor Nitrogen atom in ZnO ( using laser)

# Research field of Inter-University Program




Major proposal of Inter-university Research program utilizing oversea facility: Strongly correlated electron systems and Magnetic materials

# Unique Muon Beam in the world （Ultraslow Muon）

4MeV(Rahge1mm)
3cmx3cm beam size
100ns pulse width

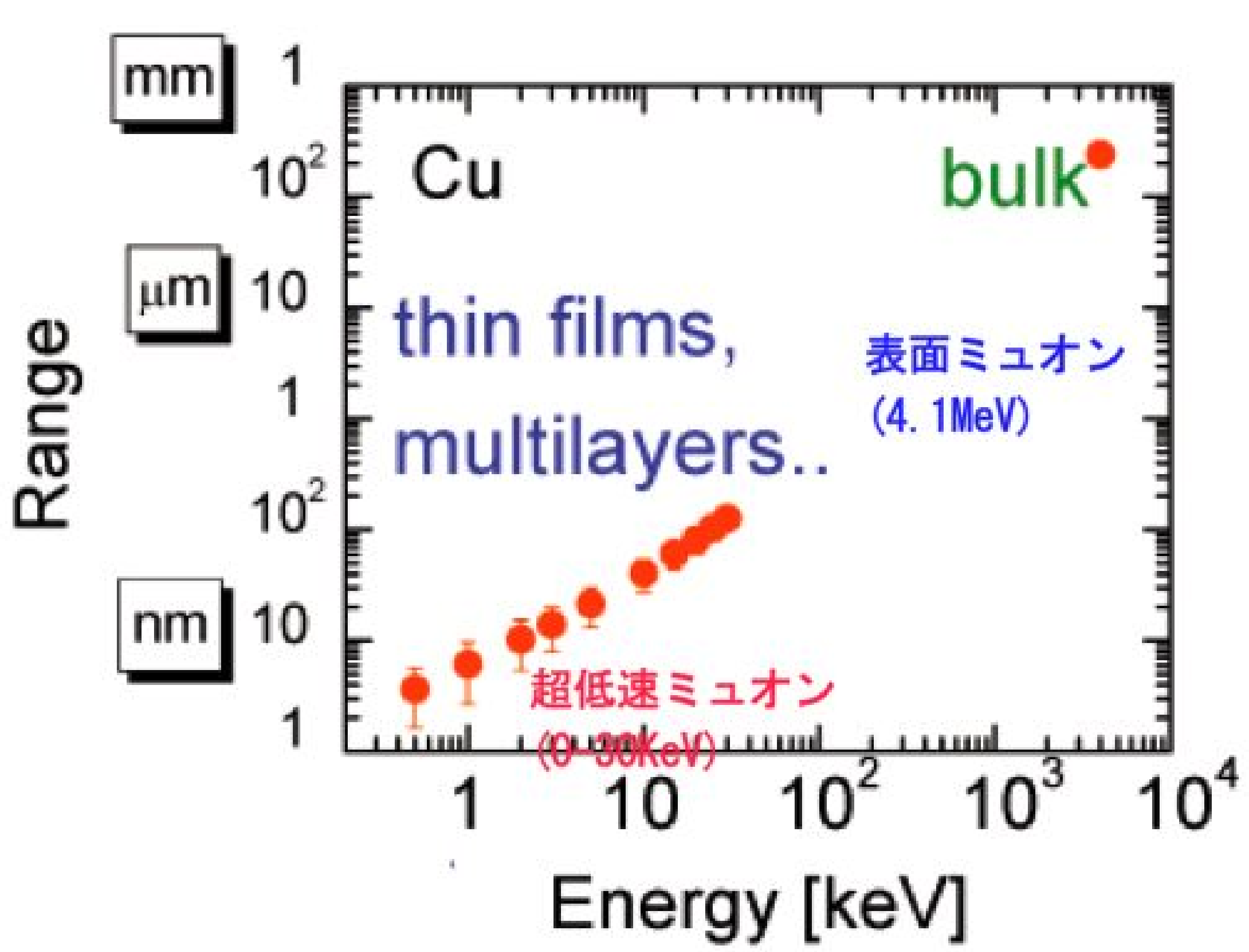
**Magical Moderator**

1~20KeV
(Stopping Range1~nm)
Energy width （〜eV)
Beam spot 1mmx1mm
Pulse width 1ns

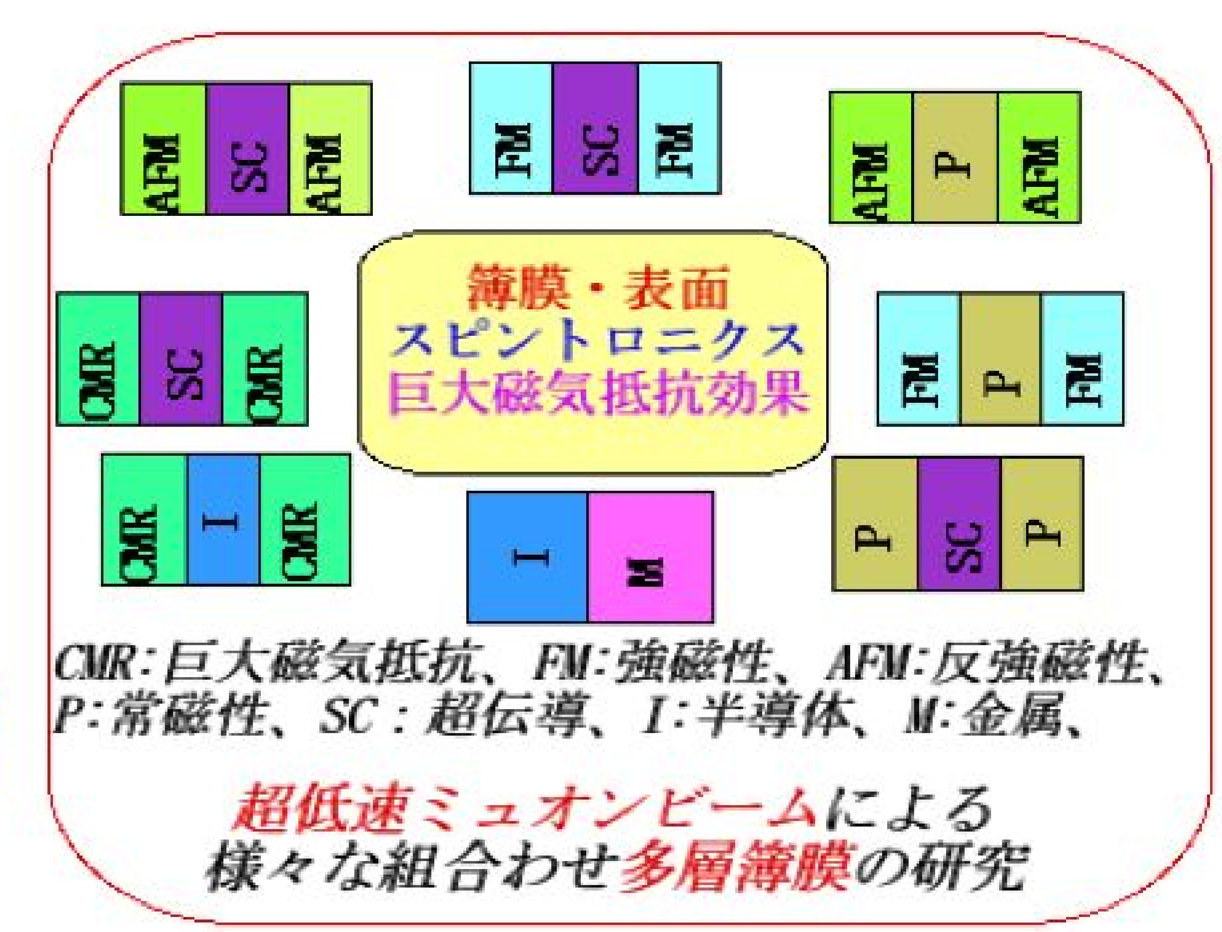
Japanese original technique
Innovation and technique

- ○Discovery of thermal Muonium from hot W
- ○Laser Resonant ionization of Muonium
- ○beam transport of Large acceptance axial focusing

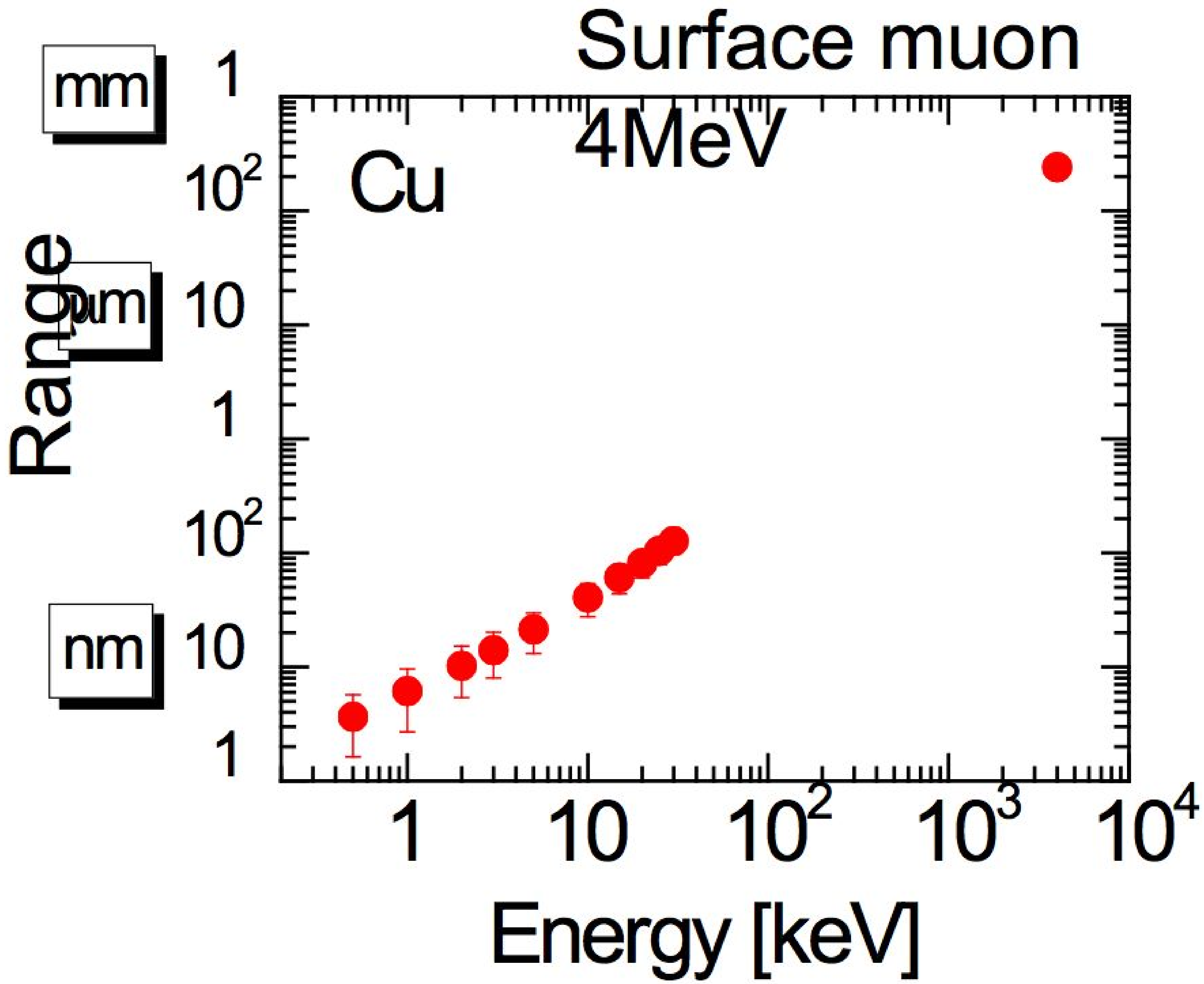
- ○Surface science ／catalytic reaction ／electric state／
- ○Gas phase chemical reaction, kinetics
- ○Small sample（microgram）
- ○High time resolution high field experiment ／ fast transient phenomena




**Muon Science center in the world**



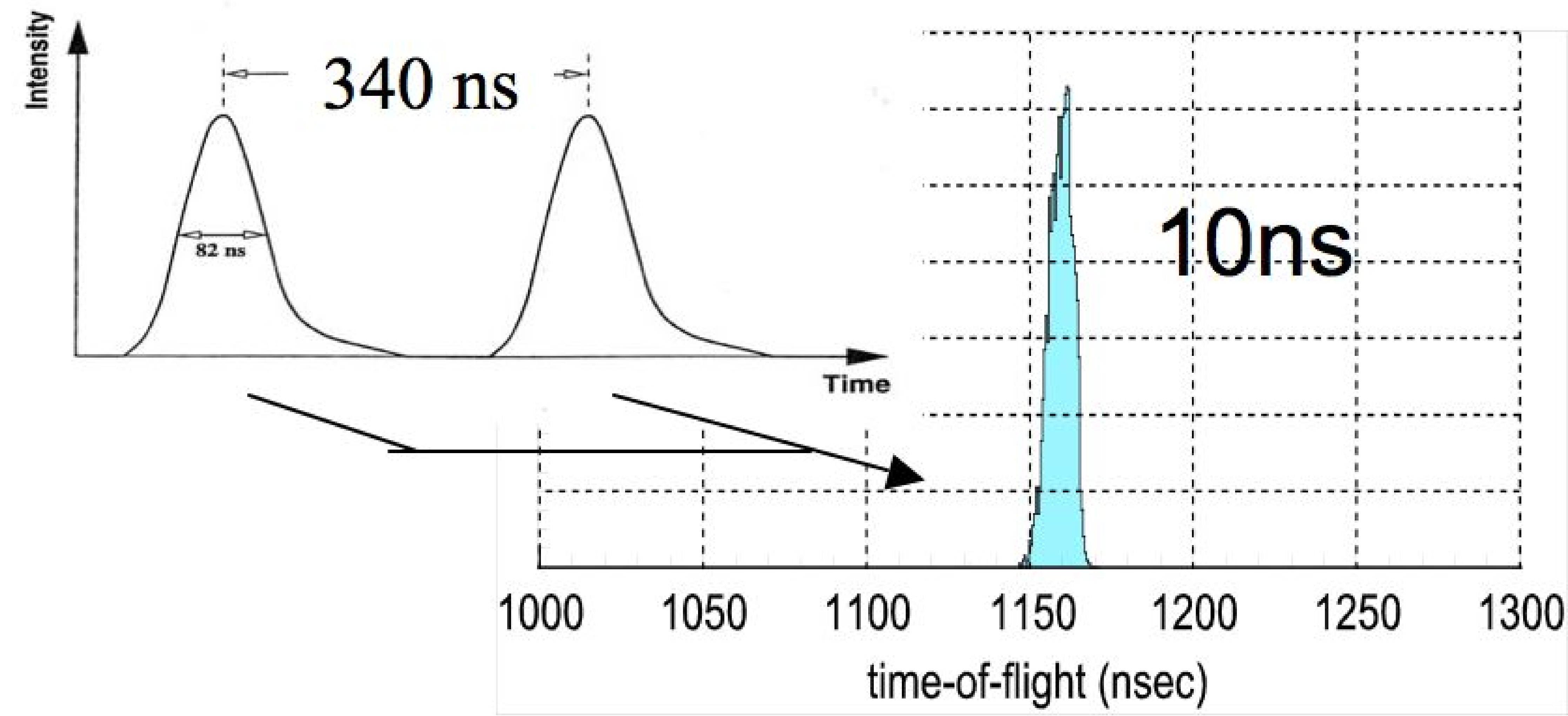
# Ultra Slow muon



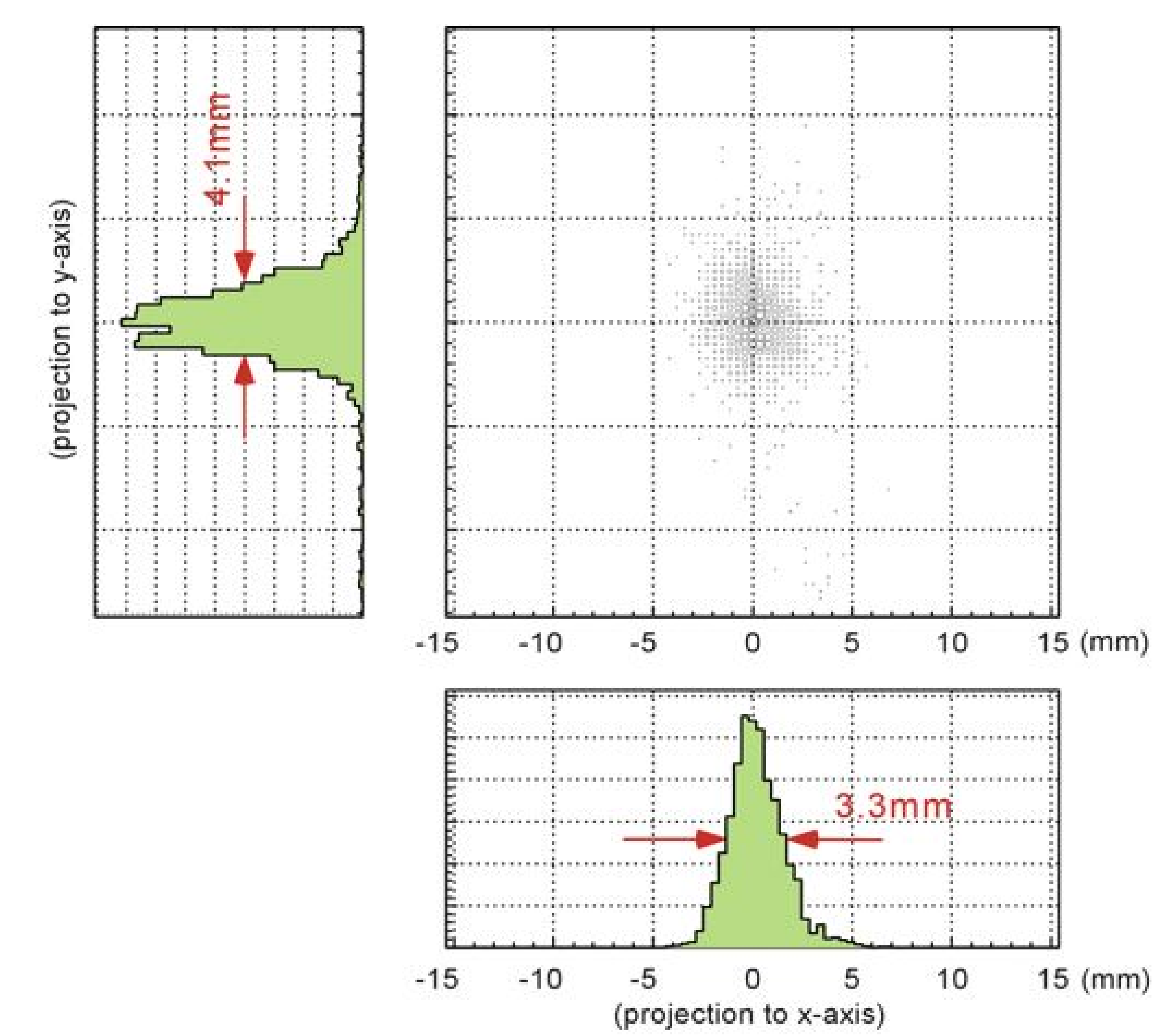

Energy-vs-Range

PSI Slow muon

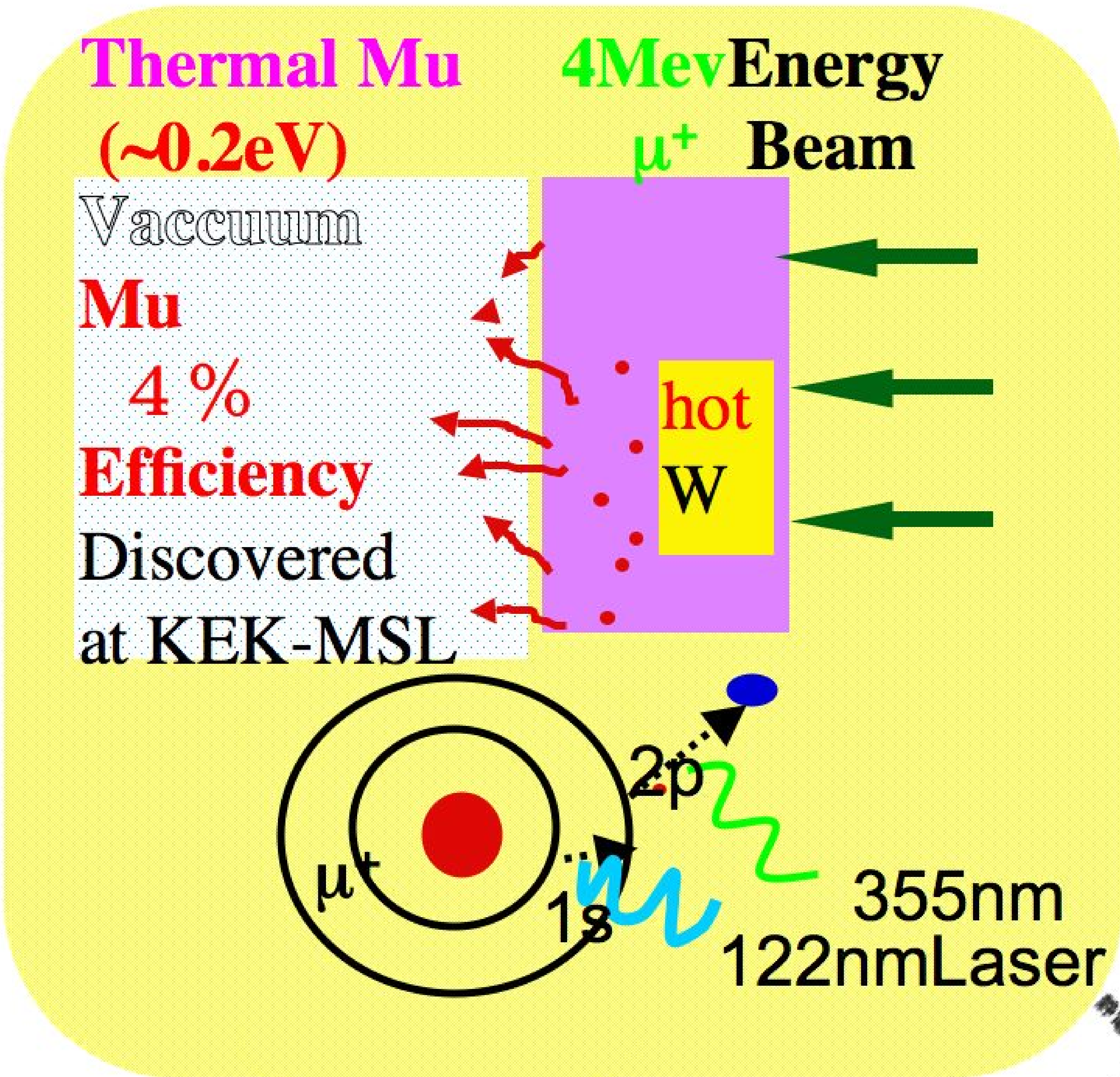
## RIKEN-RAL-KEK/R&D




## Small beam spot



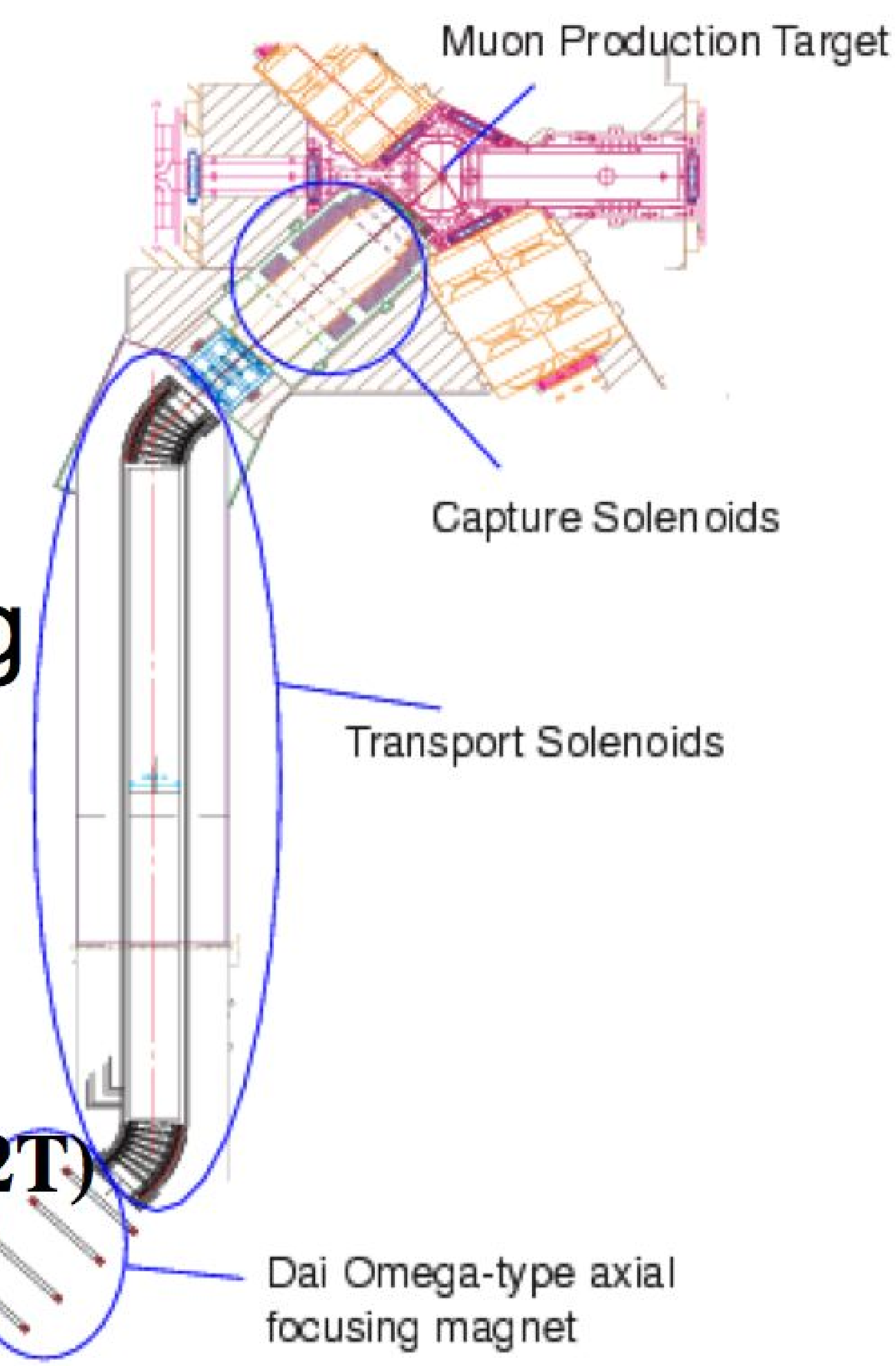
# Ultra slow muon

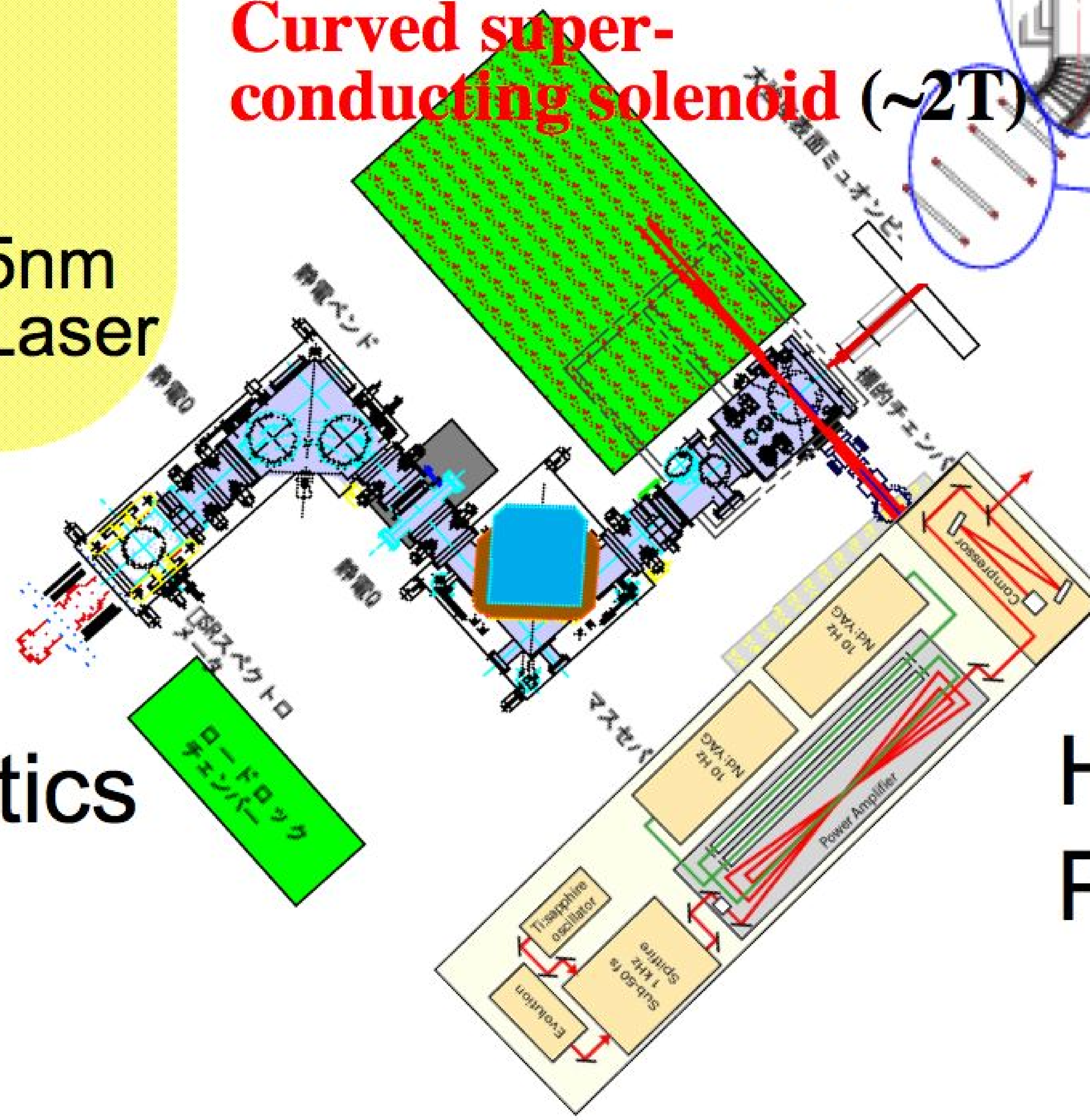



4MeVmuon Transport beam line (superconducting curved solenoid)

**normal solenoid ~ 400mSr (typical magnetic field 0.3T)**

**Curved super-conducting solenoid (~2T)**




Ultra slow muon optics

High power Pulse laser

# Specific feature of $\mu$SR as a material probe "Condensed Matter Research Center"

$\mu$SR is a "local magnetic probe over atomic scale" complementary to other probes neutron/NMR/SR：

in comparison with other such probes:

…with neutron diffraction

1) It can be used without long-range order.
   …applicable to small moment size ／ large unit cell size
2) Small amount of sample would suffice.
3) It responds linearly to the order parameter.

…with nuclear magnetic resonance (NMR)

1) It can be applied to any material regardless of nuclear spin.
2) It is a purely magnetic (S=1/2) probe, leaving less uncertainty of interpretation due to multiplet state.
3) It responds linearly to the order parameter.

…with both neutron/NMR

It has a unique window of time scale inaccessible by those probes.

—Fully complementary to other probes—

# Conclusion

At MUSE variety of sciences will be explored.

Muon Facility consists of
Muon Target and Primary proton beam line
Secondary muon beam line
Spectrometer and instrument

Now 1 muon beam line is available.
(Decay/surface muon beam )

Ultra slow muon beam will be the "most unique beam line in the world and new science will be explored".

Surface muon channel can be used by many users simultaneously.

# Appendix

# Importance of early start of  Phase II

- Surface muon channel
  - many user are expecting as soon as possible
  - possible power user and industrial user can start construct new leg, if funding is available
- Ultra Slow muon line
  - Install front magnet before target environment is highly activated
  - Ultra slow muon beam will be flag ship -unique beam channel
- Sequential construction work is important
  - Restricted manpower (operation +construction)
  - Efficient and effective usage of summer long shut down period

# Ultra slow muon beam -central Project of Phase II

Uniqueness: possible only at J-PARC

Pulsed Laser system+ High Intensity pulsed muon beam

Spec:

- time structure: single short pulse 10ns to sub-ns
- Energy: 30KeV-100eV variable, width <50eV
- Beam spot: few mm
- law background
- Intensity: 10E5/s

Readiness:

- R&D work at KEK-MSL and RIKEN-RAL
  - proofed spec. /achieved intensity-- 20muon/s
- Beam transport R&D by Dai Omega at KEK-MSL-LABII
- Design for superconducting curved solenoid is on the way
- Total beam line design will be finished in FY2007.

# Research of in-Haus staff and collaboration

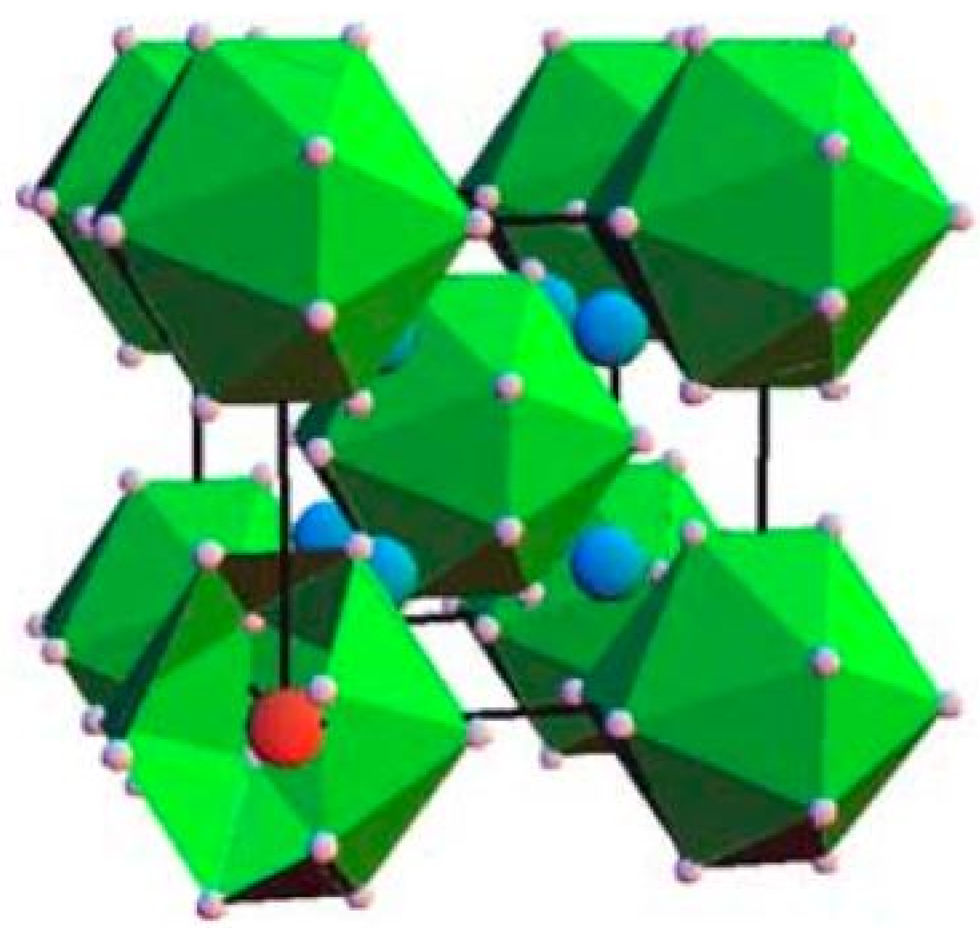
- Strongly correlated electron systems
  - Superconducting state with TRSB
  - High Tc superconductor
  - heavy fermio0n system (f-electron system)
- Magnetism
  - chirality
  - Nano-particle, organic magnetism
- Semiconductor
  - Hydrogen state in the semiconductor
- Others
  - protonic conductor( proton diffusion )
- Atom and molecular physics
  - $\mu$CF with spin controlled hydrogen target
  - muonic atom with unstable nucleus, electric state of muonic X-ray
- Development
  - Production and application of Ultra slow muon
  - surface muon beam with large solid angle acceptance

# Topics 2004–2006

**filled skutterudite PrOs4Sb12**

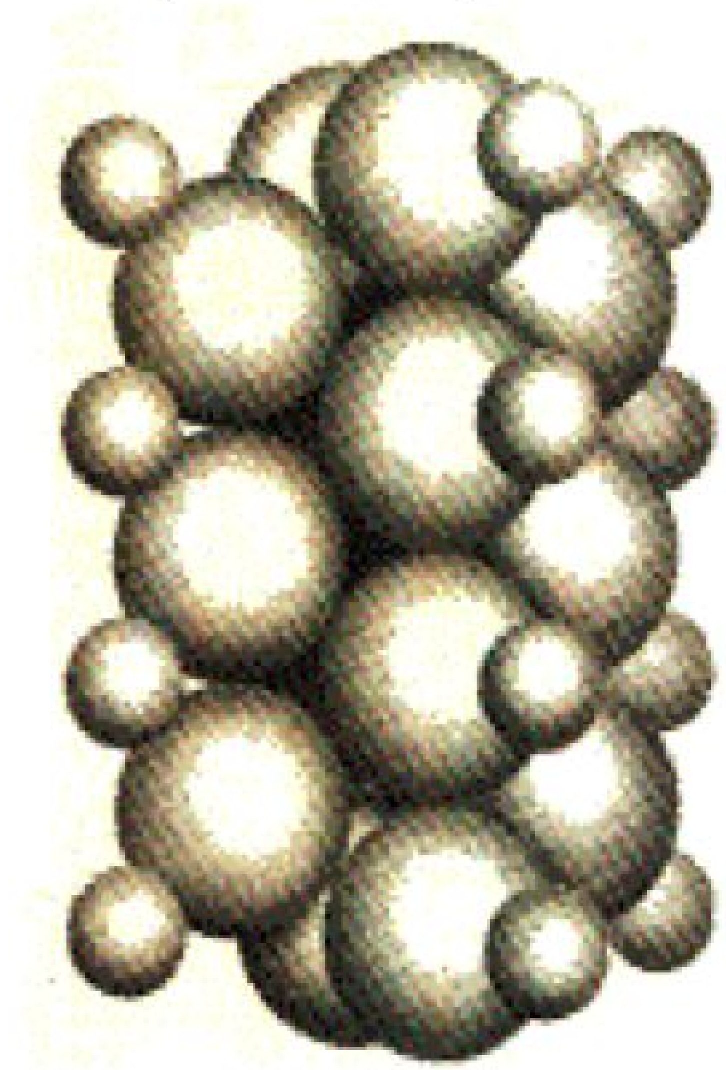
*novel superconducting state with TRSB/ small intrinsic local magnetic field*

*alloying effect* (La, Ru)



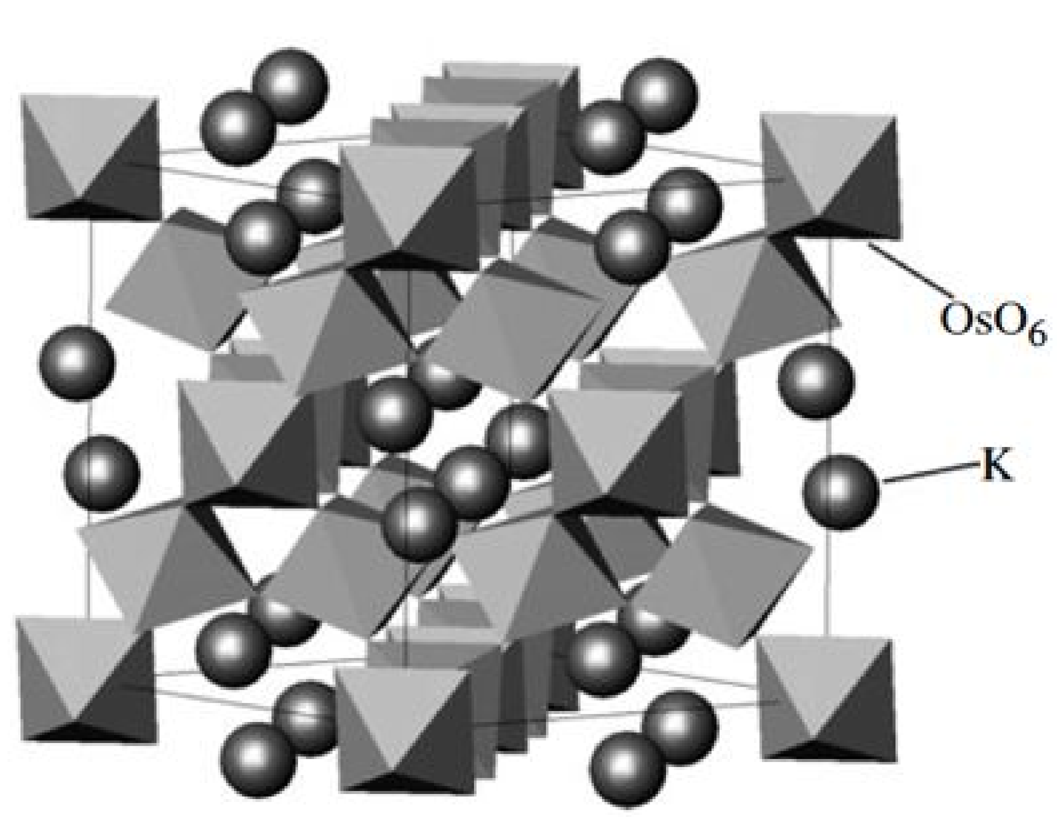
**muonium in**

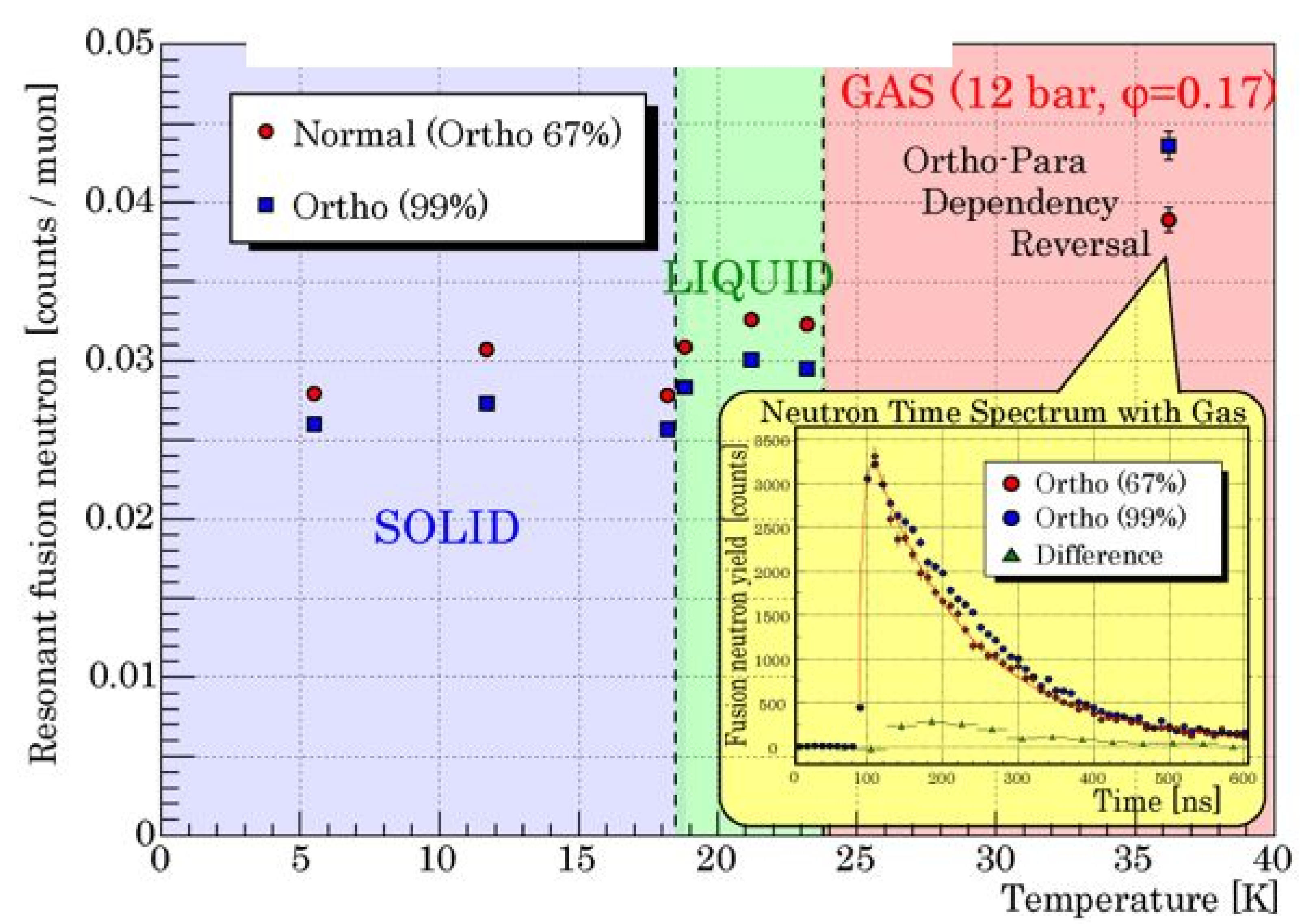
*light hydrogen isotope in ZnO, GaN, TiO2*、



μSR study on b-pyroclore $AOs_2O_6$e (*A*=K, Rb, Cs)-- novel superconducting state

Field dependent relaxation

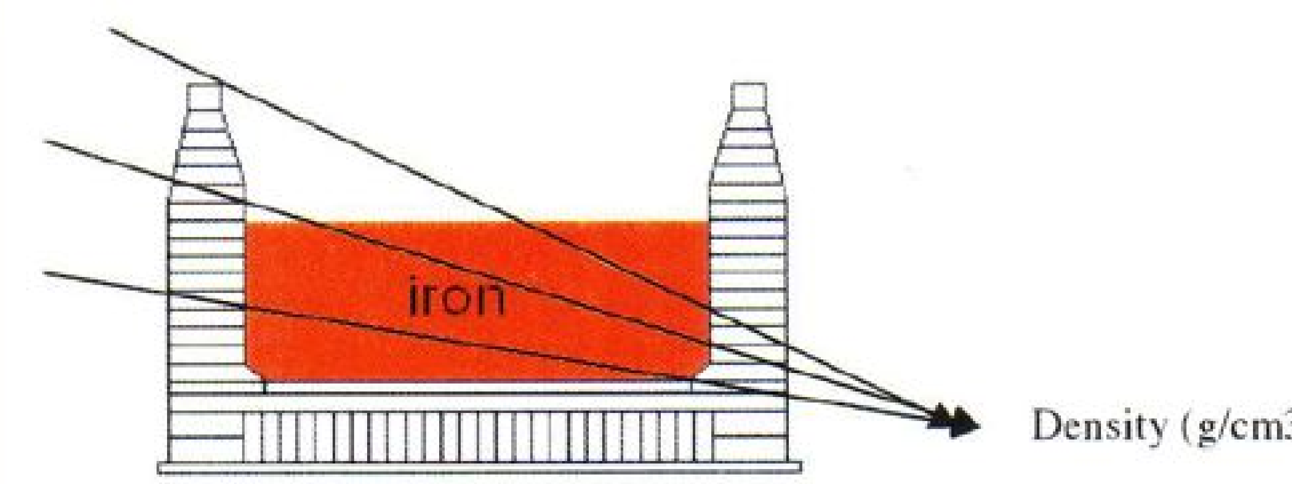



Ortho-para effect of D2 target on μCF

Large Omega cylindric seperator

Furnace



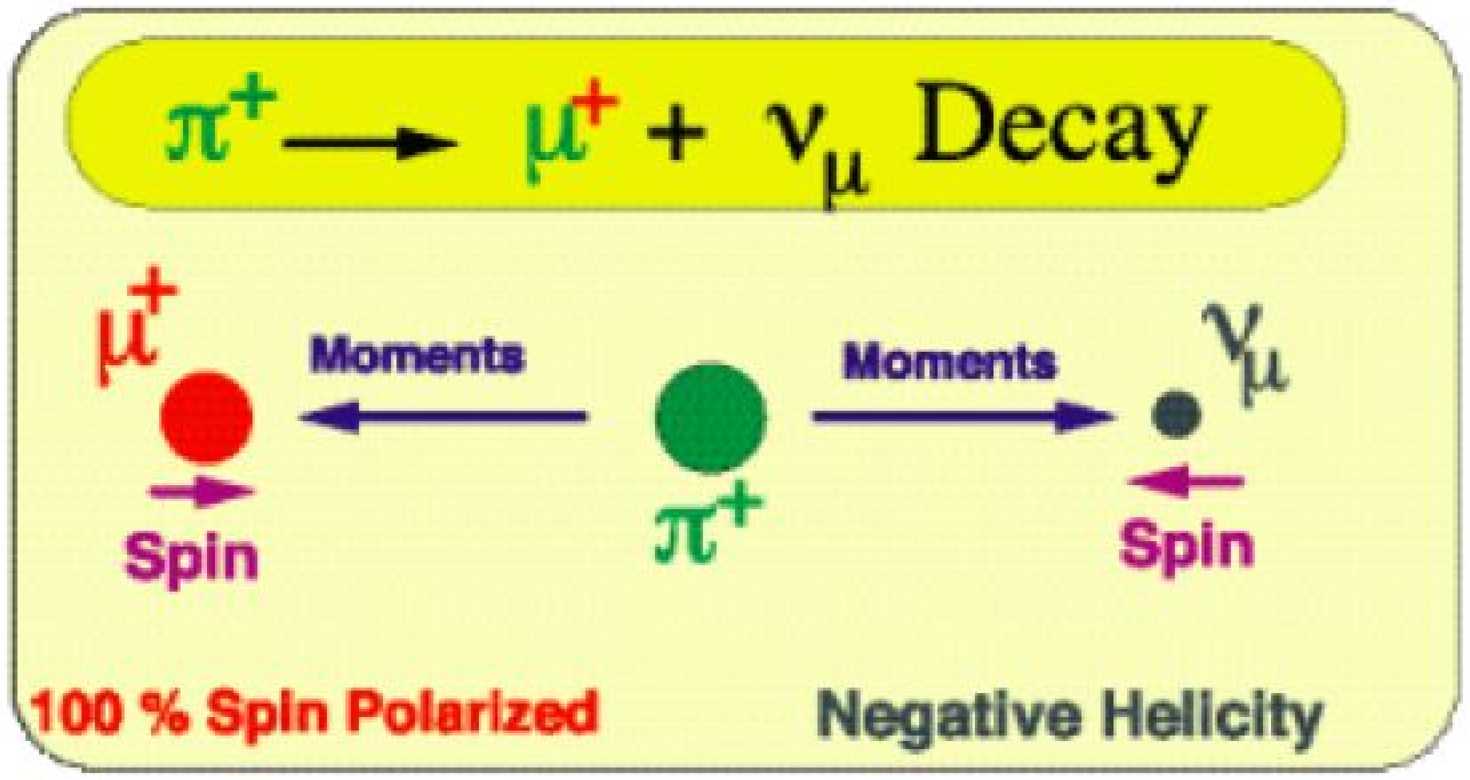

Observation of Furnace state by cosmic ray muon.

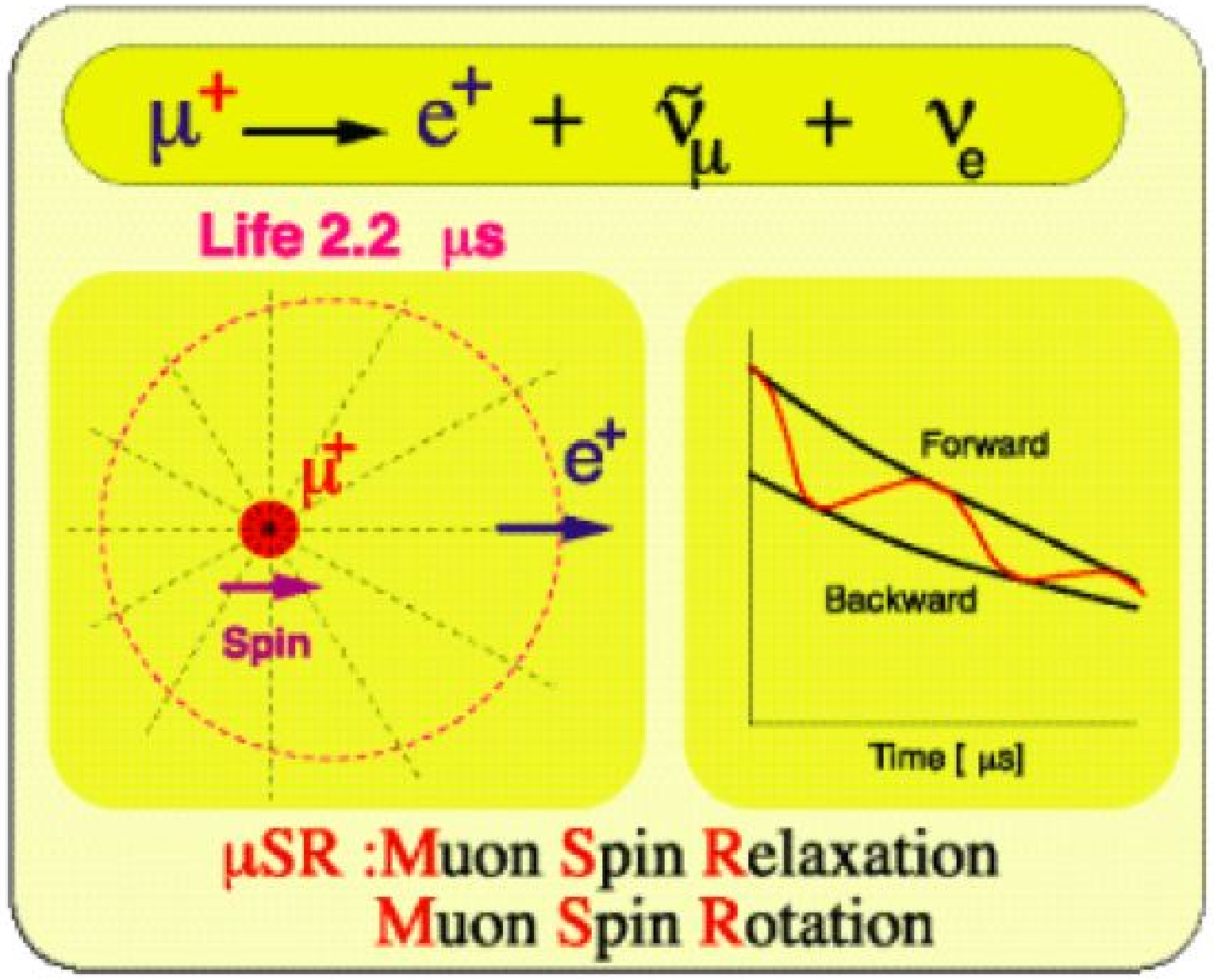
# Development for Future Facility and Experiment (on-going items)

- Vacuum connection (Pillow seal)
- Target development (rotating target for I MW beam)
- Pulsed electric separator/ Deflector
- Beam Channel Automation
- Multi segmented detector
  Position resolving high Time resolution Detector
- High power Short Pulse RF-system

  for RF-μSR technique
- Target environment
  (hydraulic and uni-axial High Pressure, low and high Temperature, High magnetic Field, Laser illumination, Electric High Field)
- DAQ automation

# Variety of Scientific Research Subjects

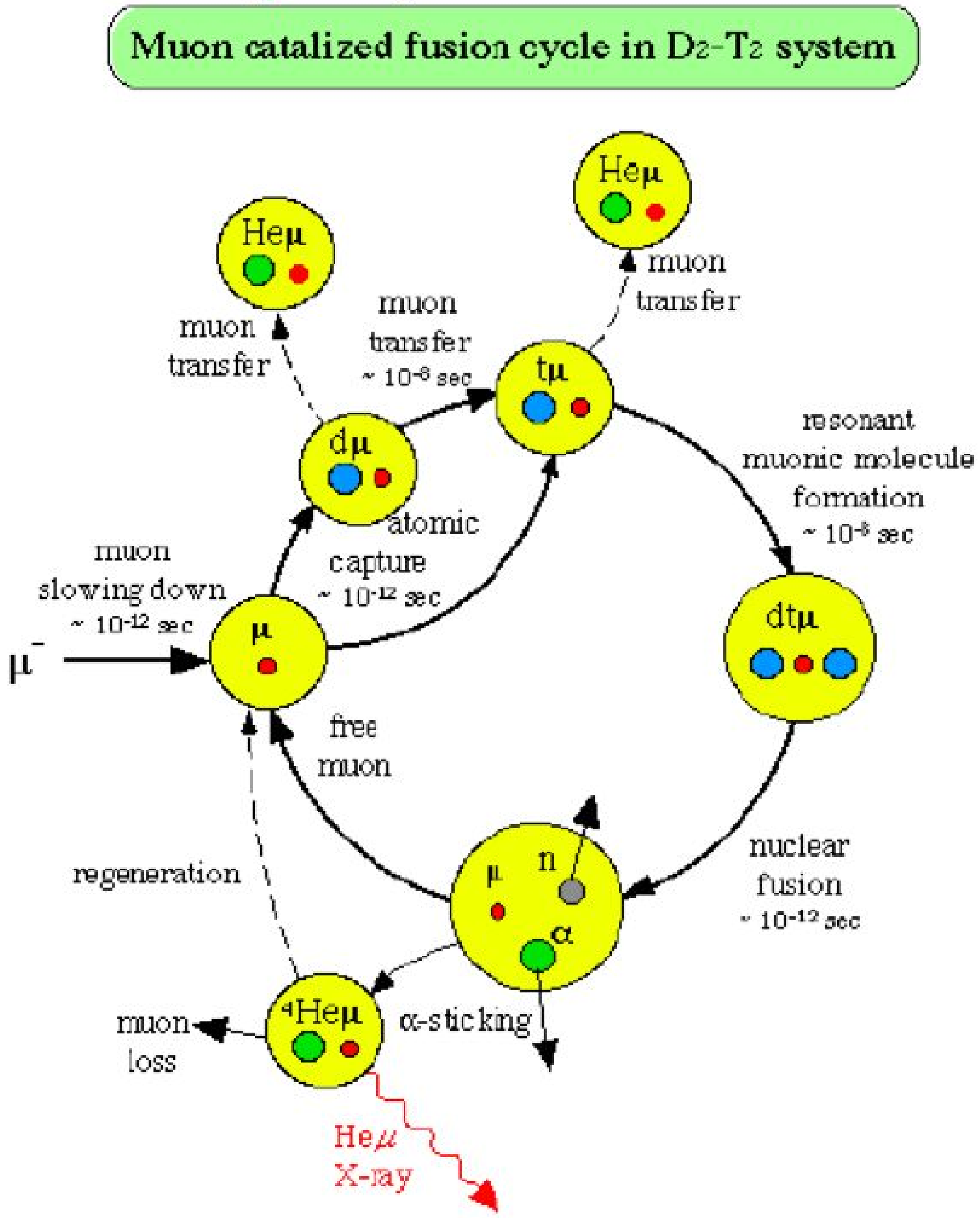



μSR is a "local magnetic probe over atomic scale" complementary to other probes neutron/NMR/SR.

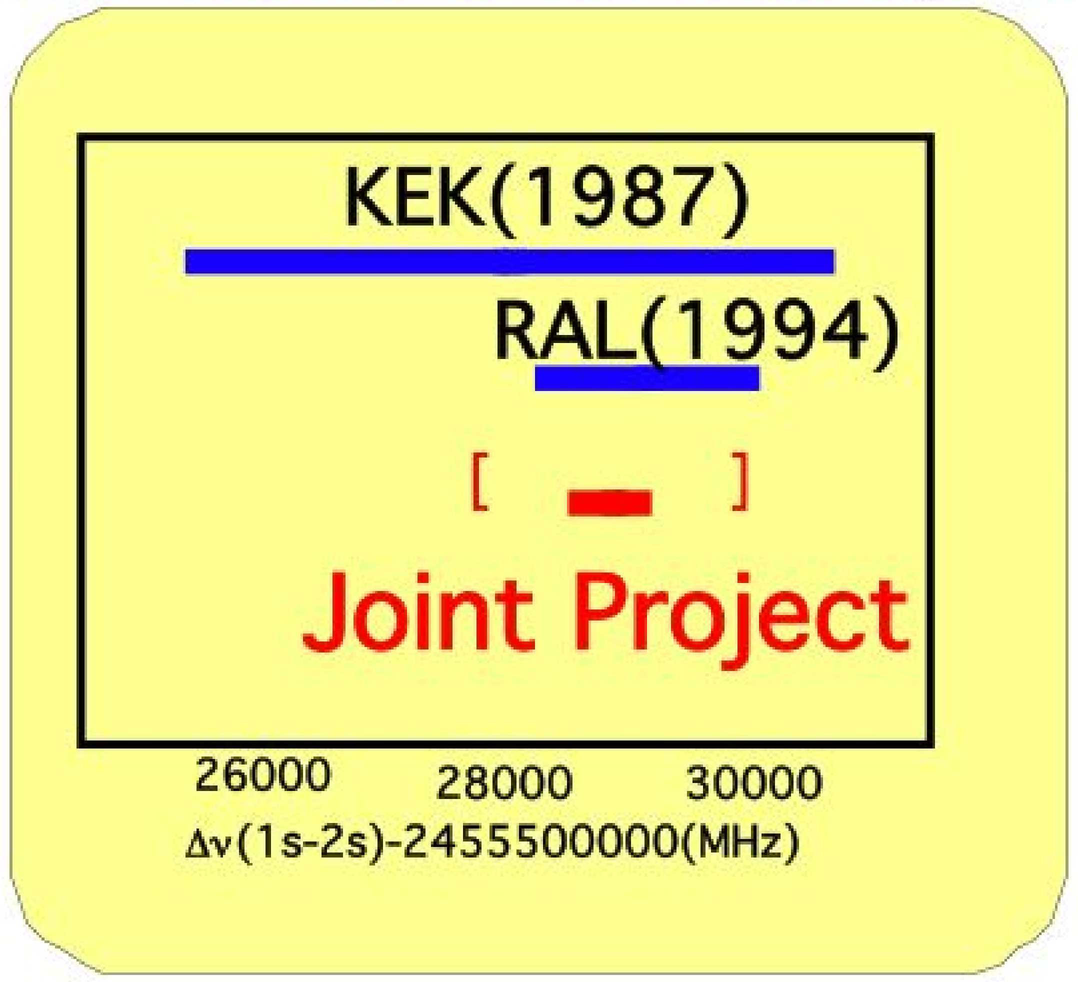
Application:
Magnetism, High Tc superconductor, Hydrogen in semiconductor, Industrial materials (Hydrogen storage, proton conductor, etc)

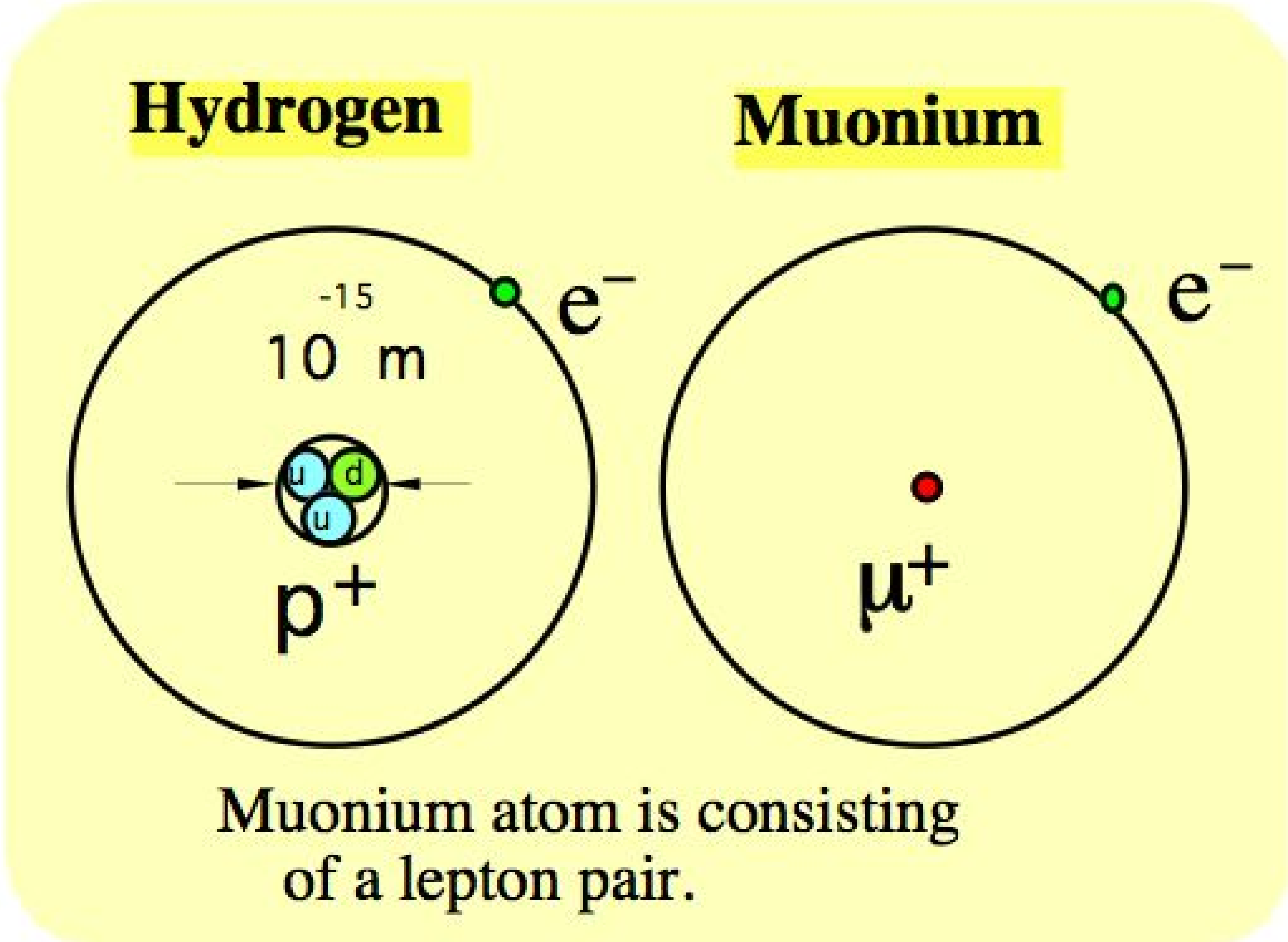
## Muon catalyzed fusion (μCF)




μCF (muon catalyzed fusion) is one of the possible energy production methods. Now 120 dt nuclear fusion occur per muon. To achieve energy break-even(300), various condition can be studied such as high pressure, Temperature, atomic spin state etc.

## Fundamental muon physics



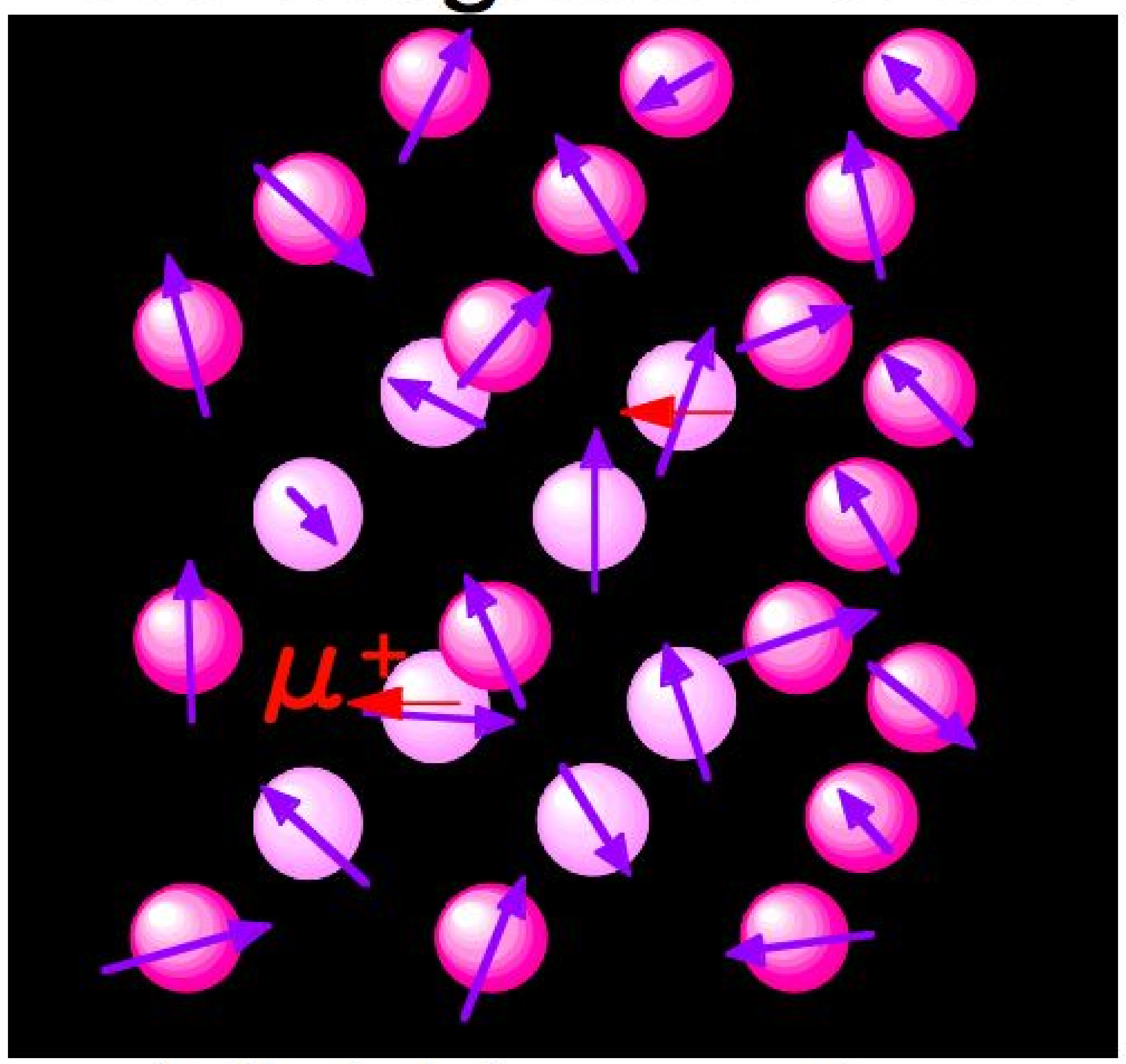

Fundamental muonphysics can be studied by Intense muon beam.: Hydrogen μ- Capture / Mu-anti-Mu Conversion / High Precision Spectroscopy of Mu

The muonium (Mu) consist of positive charged muon and electron can be thought as a ideal object for fundamental physics.

# Magnetic order probed by μSR

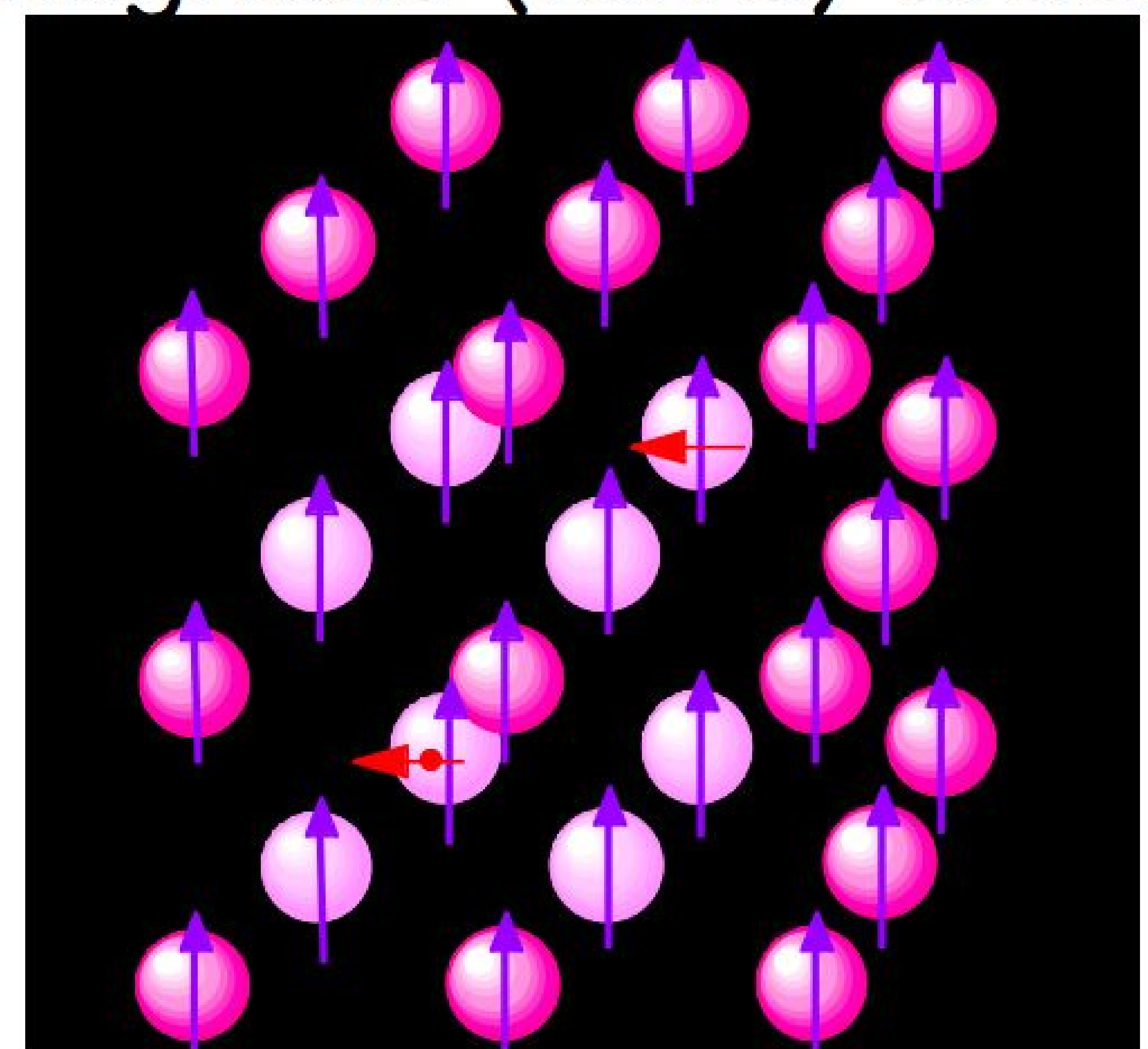
…Muons feel magnetic fields only from the neighboring atoms

No magnetic order

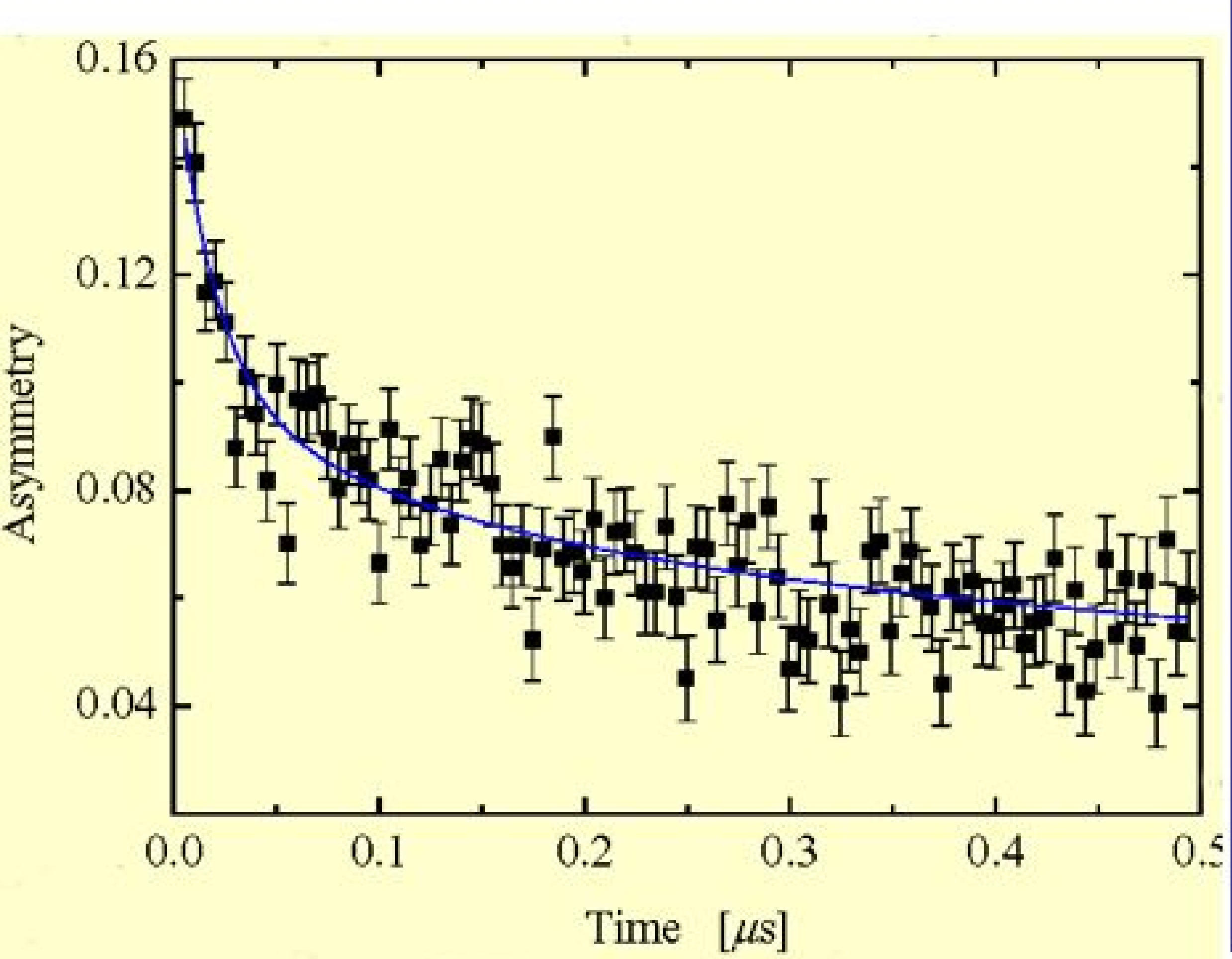


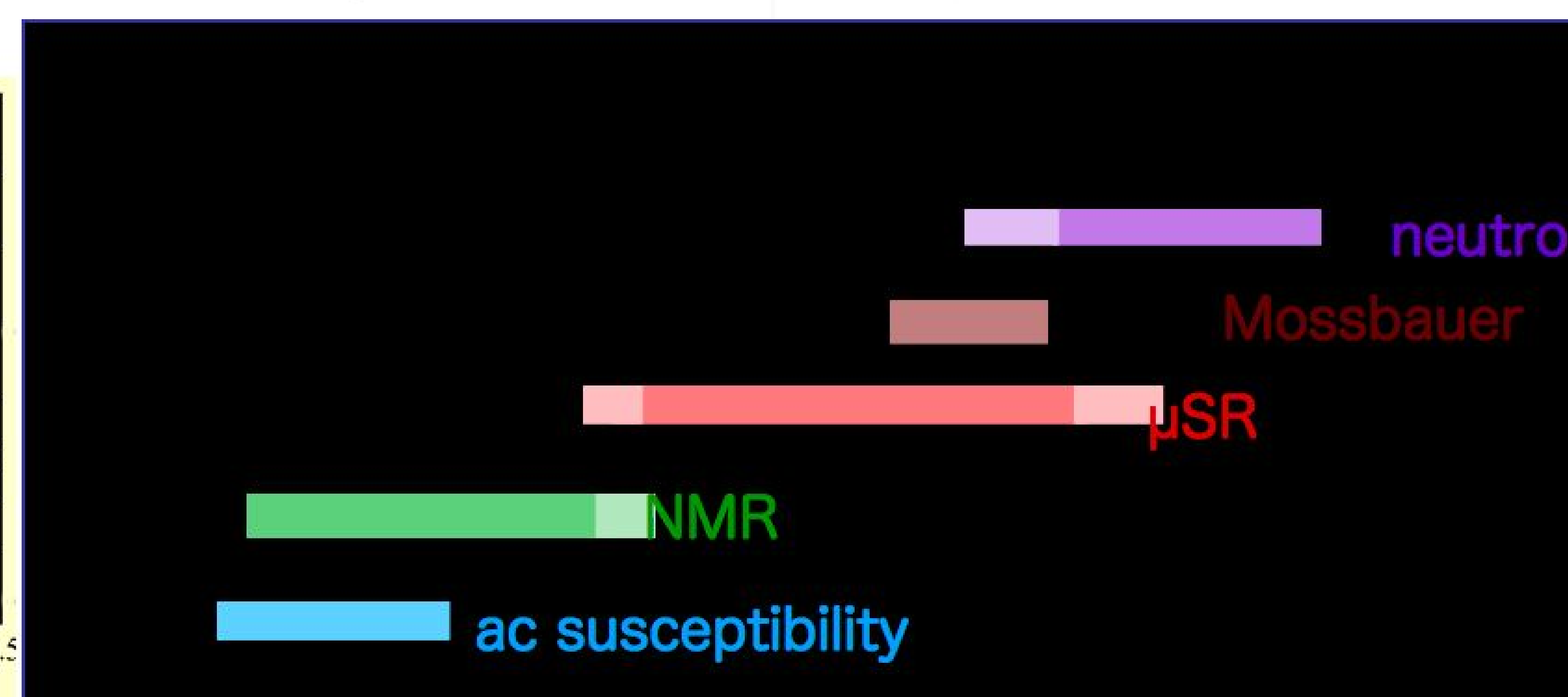

The local field is random at muon sites, which depolarizes muon as time passes by.

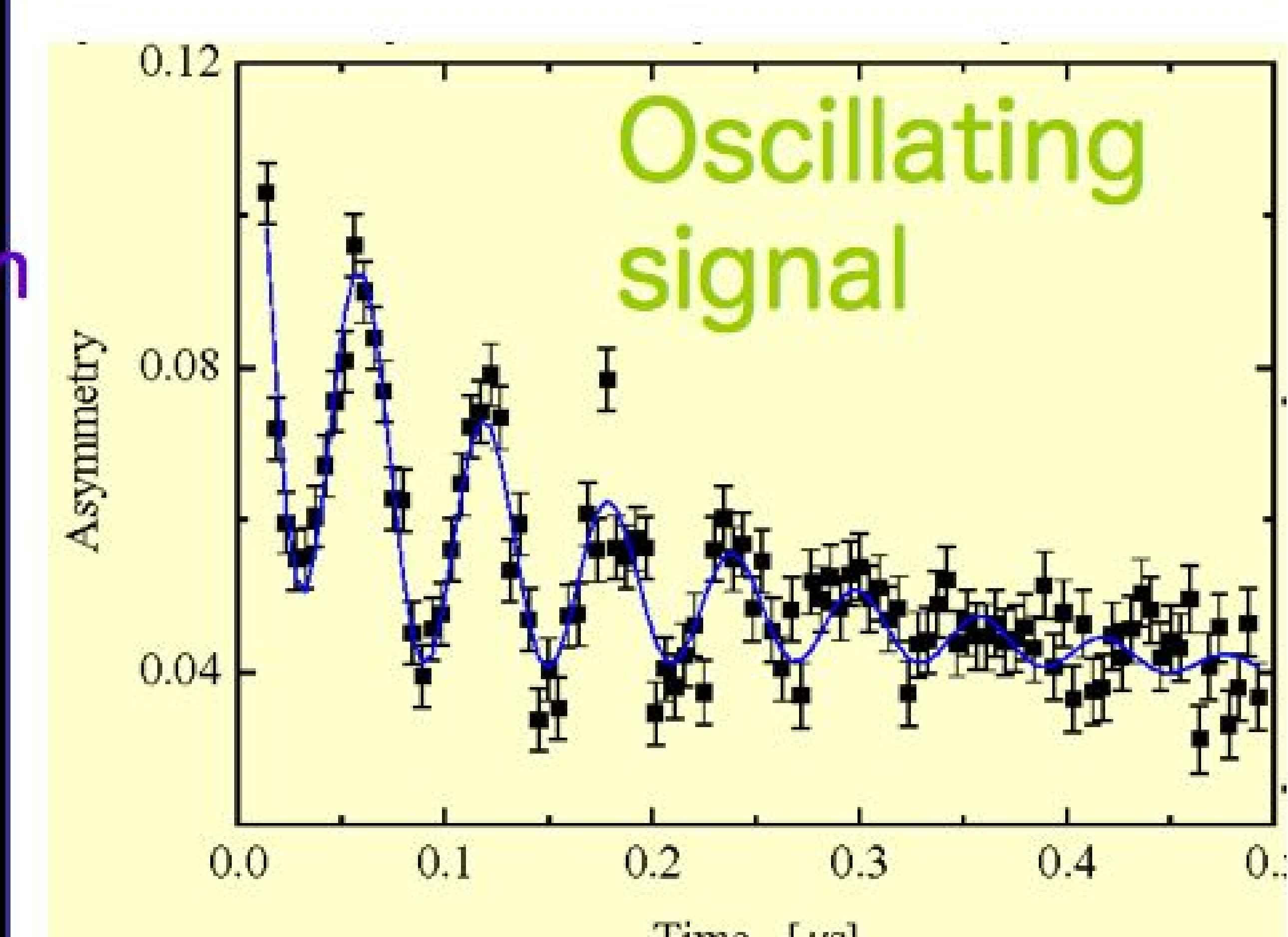
Magnetic (ferro) order



The local field is common through-out muon sites, leading to a spontaneous muon precession.



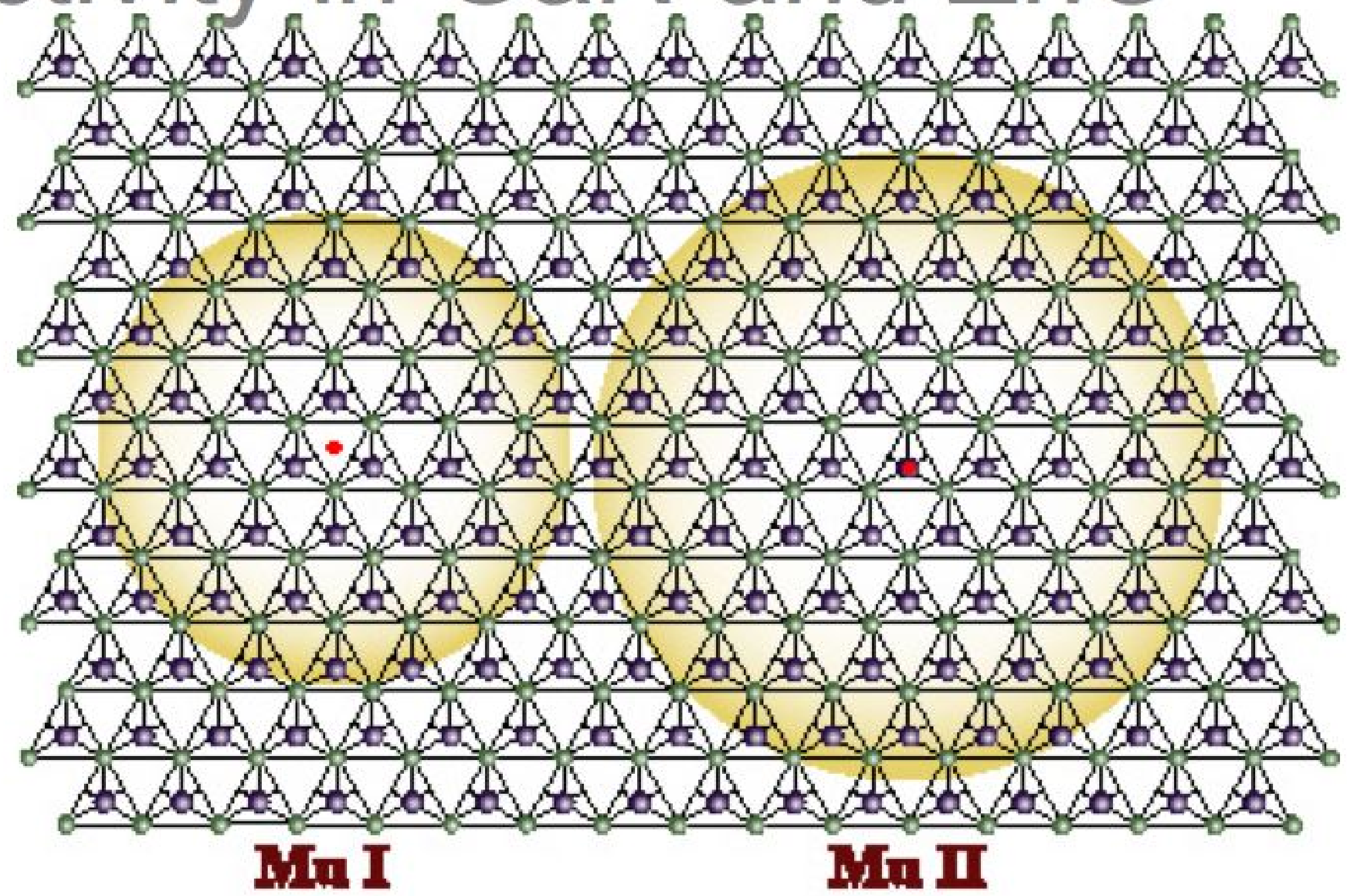
# Semiconductor

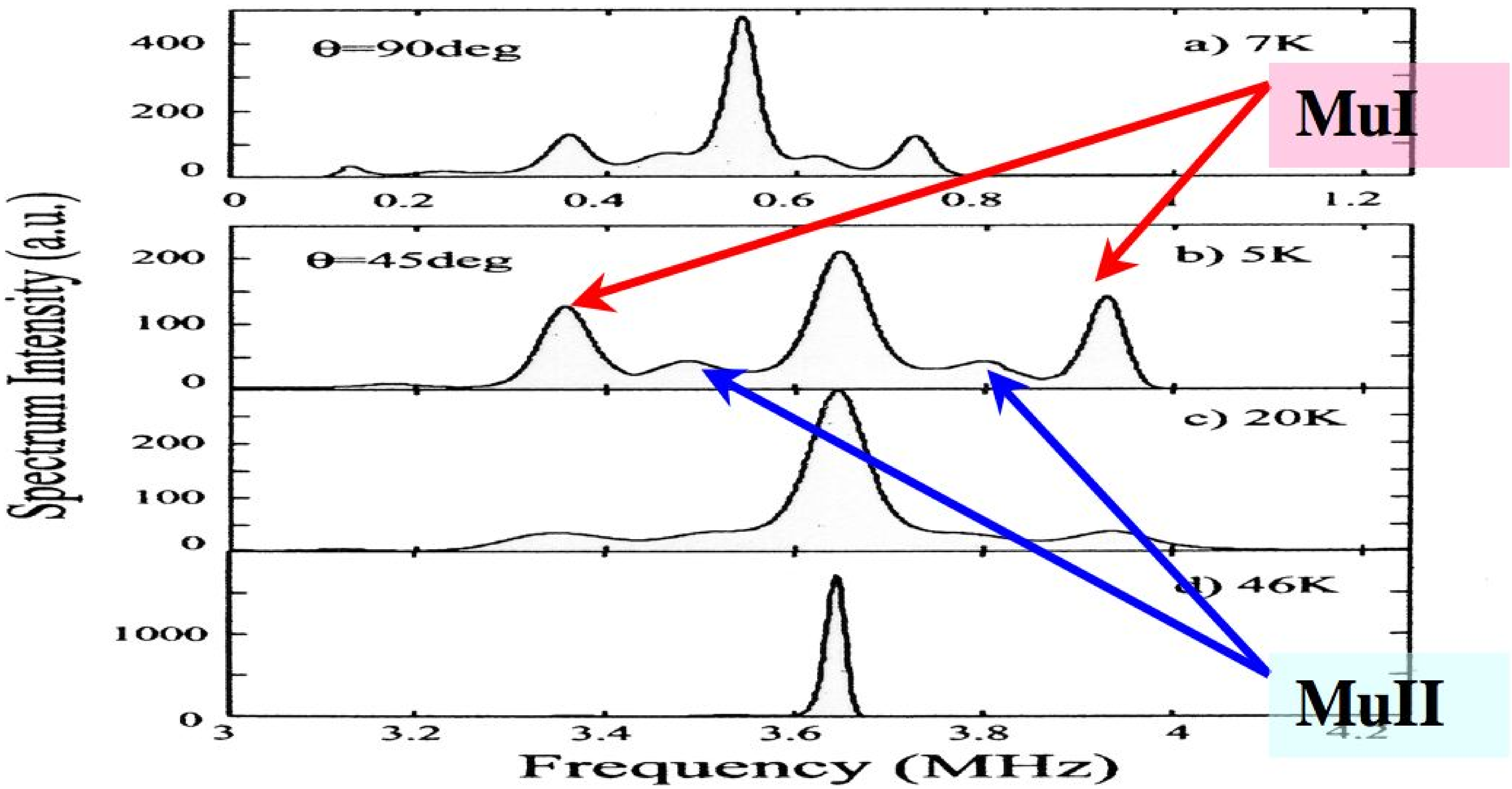
## Discovery of shallow donor hydrogen state in wide gap semiconductor by muon spin rotatio ~ Origin of unintentional *n* type conductivity in GaN and ZnO ~

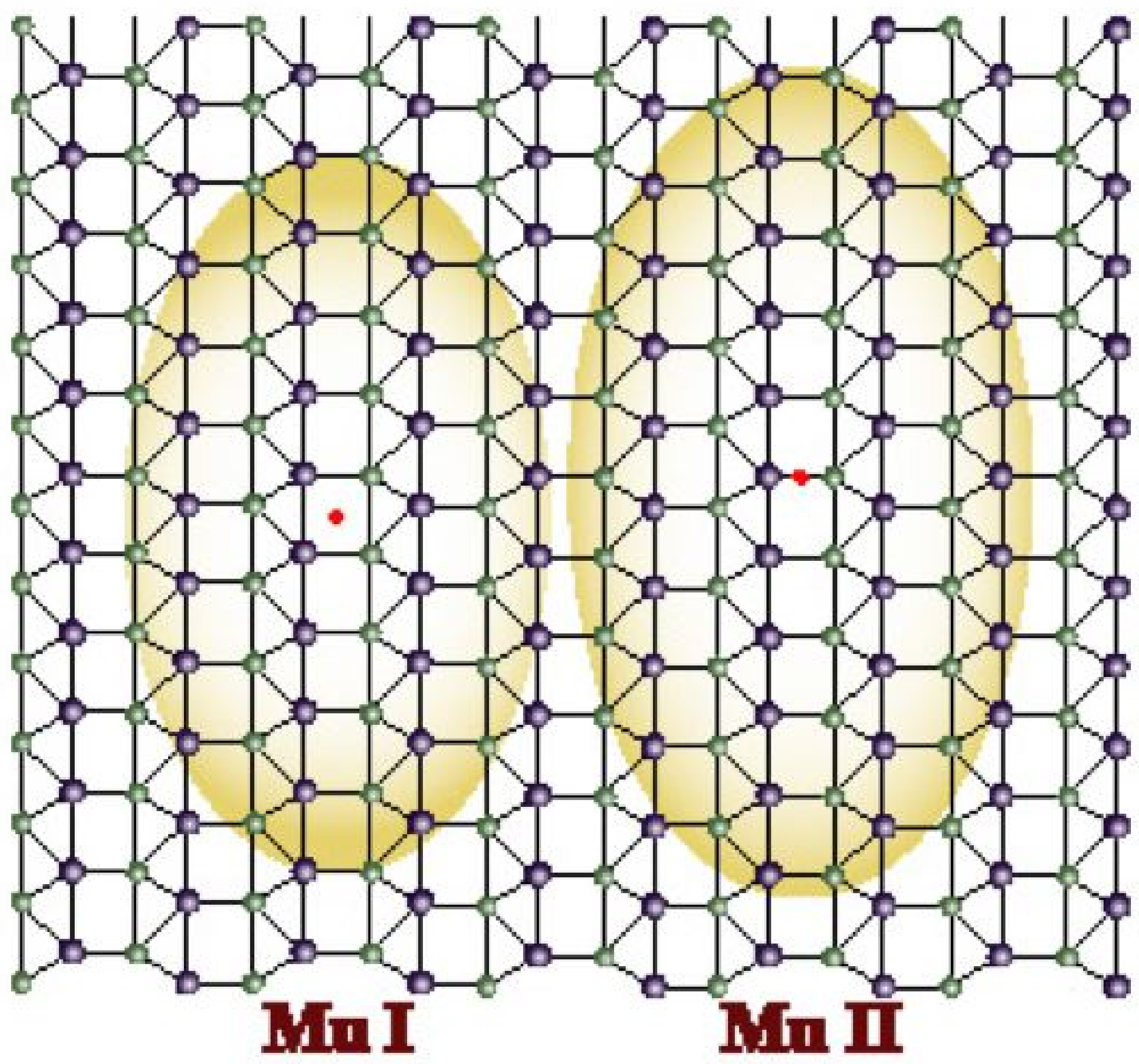
GaN and ZnO important wide gap semiconductor for device application.
Usually always n type
What is the origin of shallow donor? (More than 20 years puzzle)

Muon Spin Rotation Method found the weakly bounded muonium (hydrogen analog), which behaves as a shallow donor.

Hydrogen is the origin of this conductivity in GaN and ZnO!

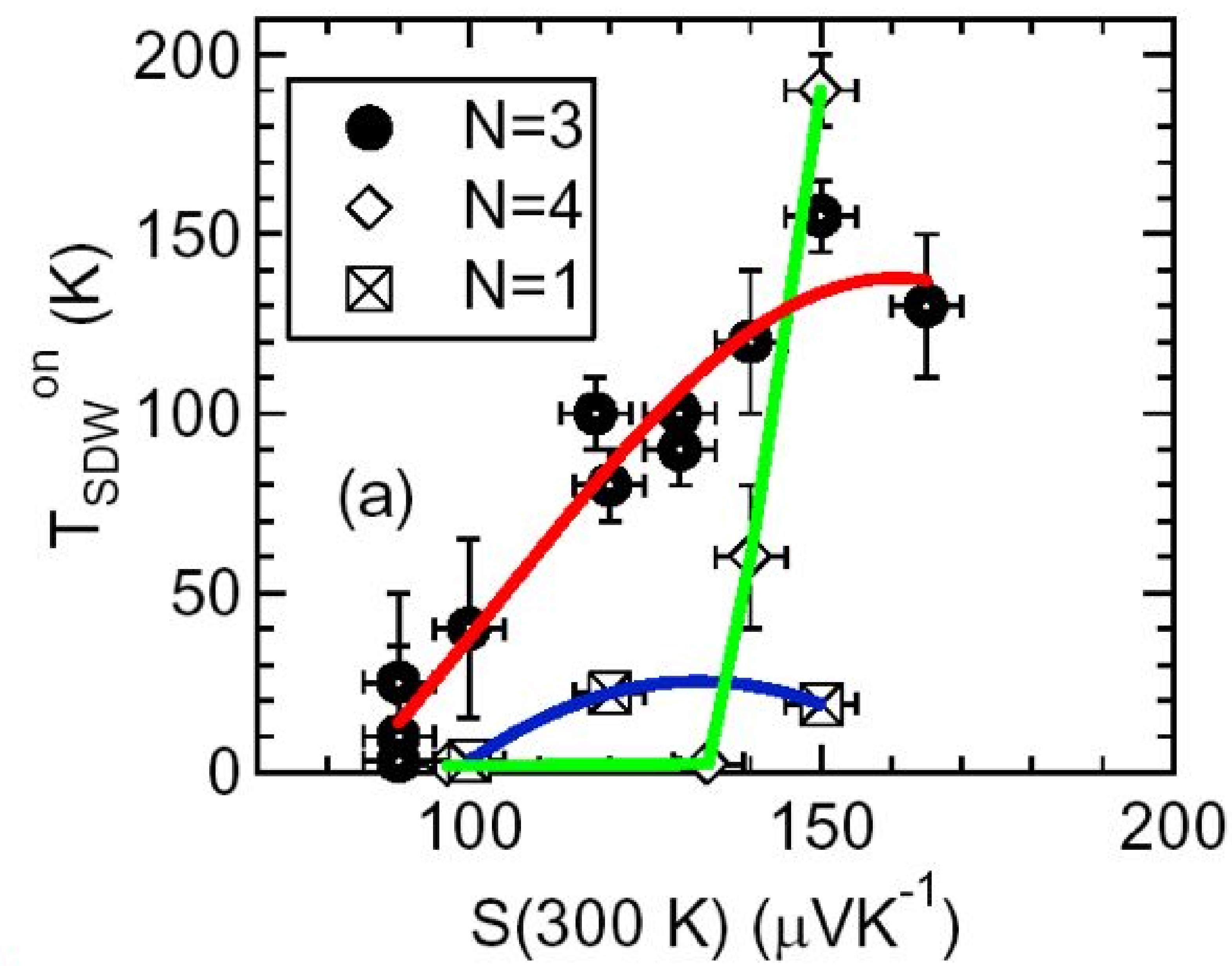



Muonium in ZnO

# Application to the industry
# Basic Research




- **Thermoelectrics** $Na_xCoO_2$
  $[Ca_2CoO_3]_{0.62}[CoO_2]$
  $[Sr_2Bi_2O_4]_x[CoO_2]$
- **Proton Conducting Materials** (nafion)
- **Hydrogen Storage Materials** (Ti-, Mg-, Ca-based alloy)
- **Materials for Li Batteries** ($Li_xCoO_2$, $Li_xNiO_2$, $Li_xMn_2O_4$)

only μSR detected SDW at low-T in cobaltites

mechanism of H adsorption / desorption

$\mu^+$ ($H^+$, $Li^+$) diffusion