Muon Microscopes

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(KEK IMSS)

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   Transmission Muon Microscopy
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   Scanning positive Muon Microscopy
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TμM:
Transmission Muon Microscopy

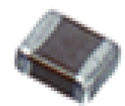
It visualizes Electromagnetic Fields
in thick specimen

Our Goals by Visualizing Ele/Mag-field

- **Our modern civilization is constructed on Electromagnetism.**
  Computer / Semiconductor / Communication dev. / EV / Rader / …

- **Power Devices: Power/RF Tr, Capacitor, Magnet, Battery, Piezo, …**

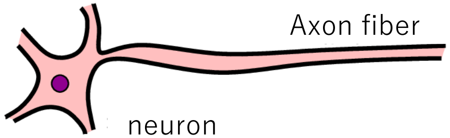




Ultrasonic Medical Dev.

  Making them **higher voltage / higher speed / higher efficiency**
  contributes to **industrial benefits** and **SDGs** of our society
  by realizing smarter EV / power grid / comm. networks / radar …

- **Visualization of EM-field** in devices makes them higher performance.
  eg.：Specifying field concentration ⇄ design of relaxation → Higher voltage dev.

- **Brain / Nerves system uses network of action potential to process our thinking, emotion or consciousness**

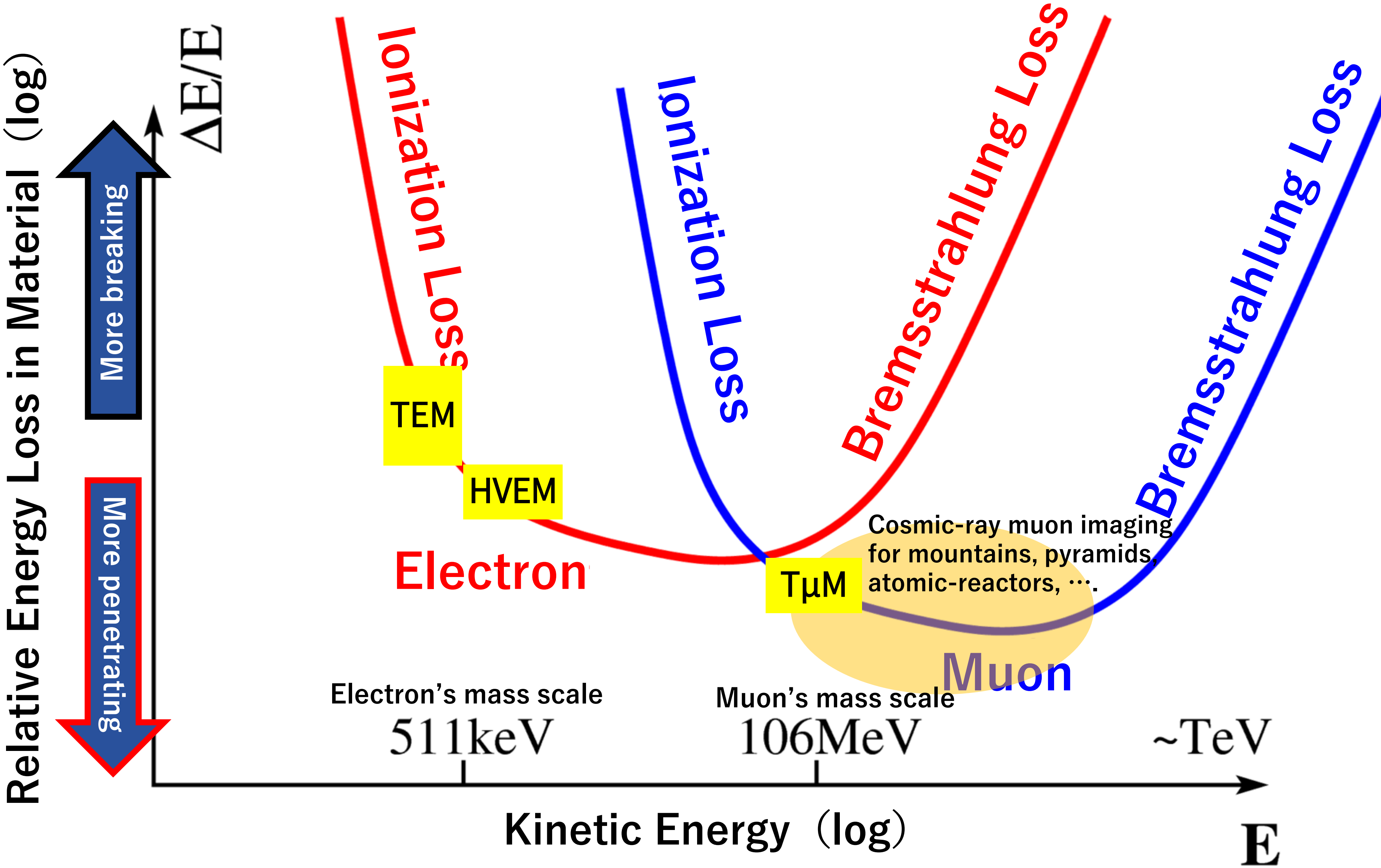
Visualization of EM-field in bulk object is quite important subject in wide fields including industry and life science.

Muon can visualize EM-fields in objects

- Muon is **charged particle ➡ Sensitivity both E and B field**
- **The highest material permeability** by acceleration
- **Mass production** by accelerator
- **High resolution** and **high sensitivity** by beam-cooling
- **Magnification of Image / Visualization of EM field** by Electron Microscopy Technologies
- **High resolutional Image-detection** by Direct-detecting CMOS Image Sensors for Electron Microscopy

Combining accelerator technology and electron microscopy one allows us it

Penetration-capability of e and μ



Transmission Electron Microscopy (TEM)

It visualizes EM-field by highest resolution:

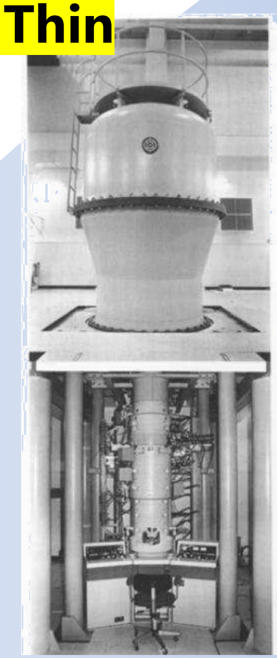
Methods：Lorentz Microscopy, Electron Holography、Phase-Contrast TEM

Targets：Transistor(Rau), Mag-field among atoms(Shibata),

Membrane Potential for liposome (Sigworth), …

Specimen should be **Ultra-Thin**
（depending on beam energy）

200 kV cryo-TEM



1 MV HVEM @ NIPS

World Highest
3 MV HVEM @ Osaka U.

Observable Thickness	～200 nm	～1　µm	～3 µm

Recent Topics : HVEM by RF-Accelerators

Recently, linear accelerators are applied into HV-TEMs.


nature > research highlights > article

a natureresearc ournal

nature
International journal of science

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This high-voltage transmission electron microscope is much smaller than earlier models, which can take up an entire two-storey building. Credit: Yukinori Nagatani/NIPS

PHYSICS · 18 OCTOBER 2019

How to improve a huge super-resolution microscope: shrink it

Physicists redesign an enormous and costly imaging device to make it smaller and cheaper.

NIPS 500kV Linac TEM by Y.N. [PRL123(15)2019]

Osaka U. 3MV RF-Gun TEM by J. Yang [Microscopy, 291-295 (2018)]

Concept of Transmission Muon Microscopy (TμM)

- **Properties of electron and muon are very similar.**
- **Accelerator-generated muon can be higher luminance.**
- **Accelerated muon has strong penetration capability to materials**

By employing muons instead of electrons in TEM, Ele/Mag-fields in thick object are visualized.

Essence of the Transmission Muon Microscopy (TμM)

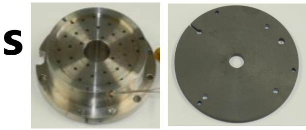
Comparing with present methods

	Mag-field	Ele-field	Penetration Power	Versatility of specimen
muon (TμM)	**○**	**○**	**○ 10μm～cm**	**Widely acceptable**
electron (TEM)	○	○	× 100s nm～a few μm	should be Ultra-thin
neutron	○	×	○ a few cm	Widely acceptable except for B, Gd, Cd, ….
Circular polarized X-ray	△indirect	×	△ 10μm	should has X-ray magnetic circular dichroism.
Optical Kerr scope	△indirect	△indirect	transparent or surface	Limited to transparent magnetic or nonlinear optical materials.
Ca-Imaging fluorescence microscope	×	△indirect	transparent life-tissue	Ca density measurement in life.

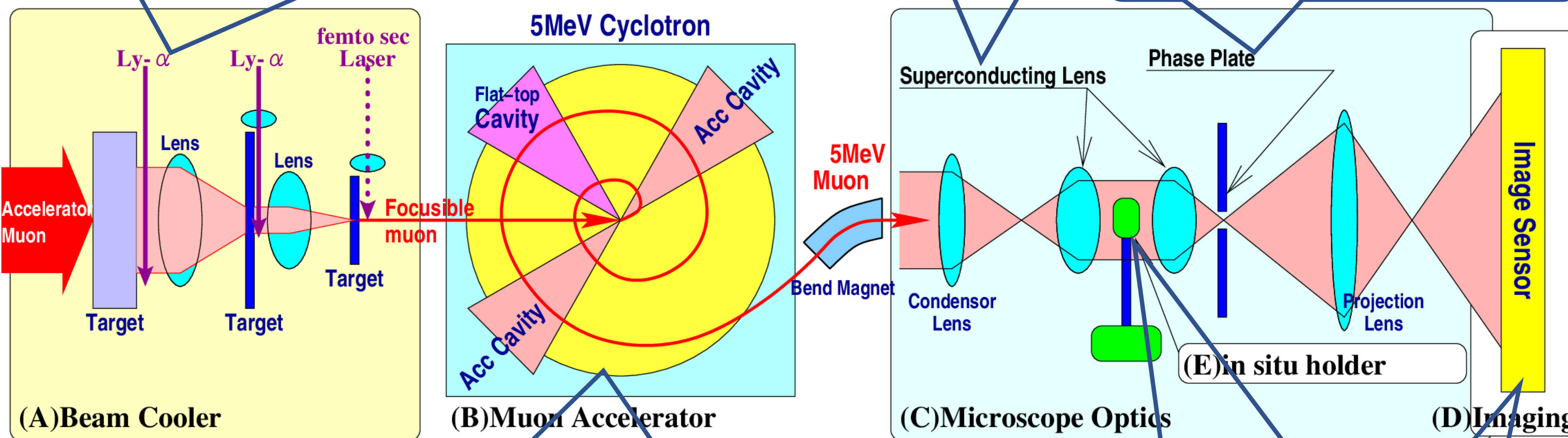
Phase 1: 5MeV TμM

Muon Beam Cooling
- 4-step cooling system is planed
- The first step has been already working
- The steps are increased step by step
- The final step uses femto-sec laser

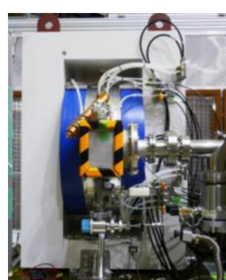
Superconducting Object Lens
focuses accelerated μ-beam



Lorentz / Phase-contrast optics for muon



5 MeV Muon Cyclotron
- AVF-type, Flat-top RF accel.
- $\Delta E / E \sim 10^{-5}$ (goal)
- Time to accel. < 1 μsec
- Already been installed at MLF!

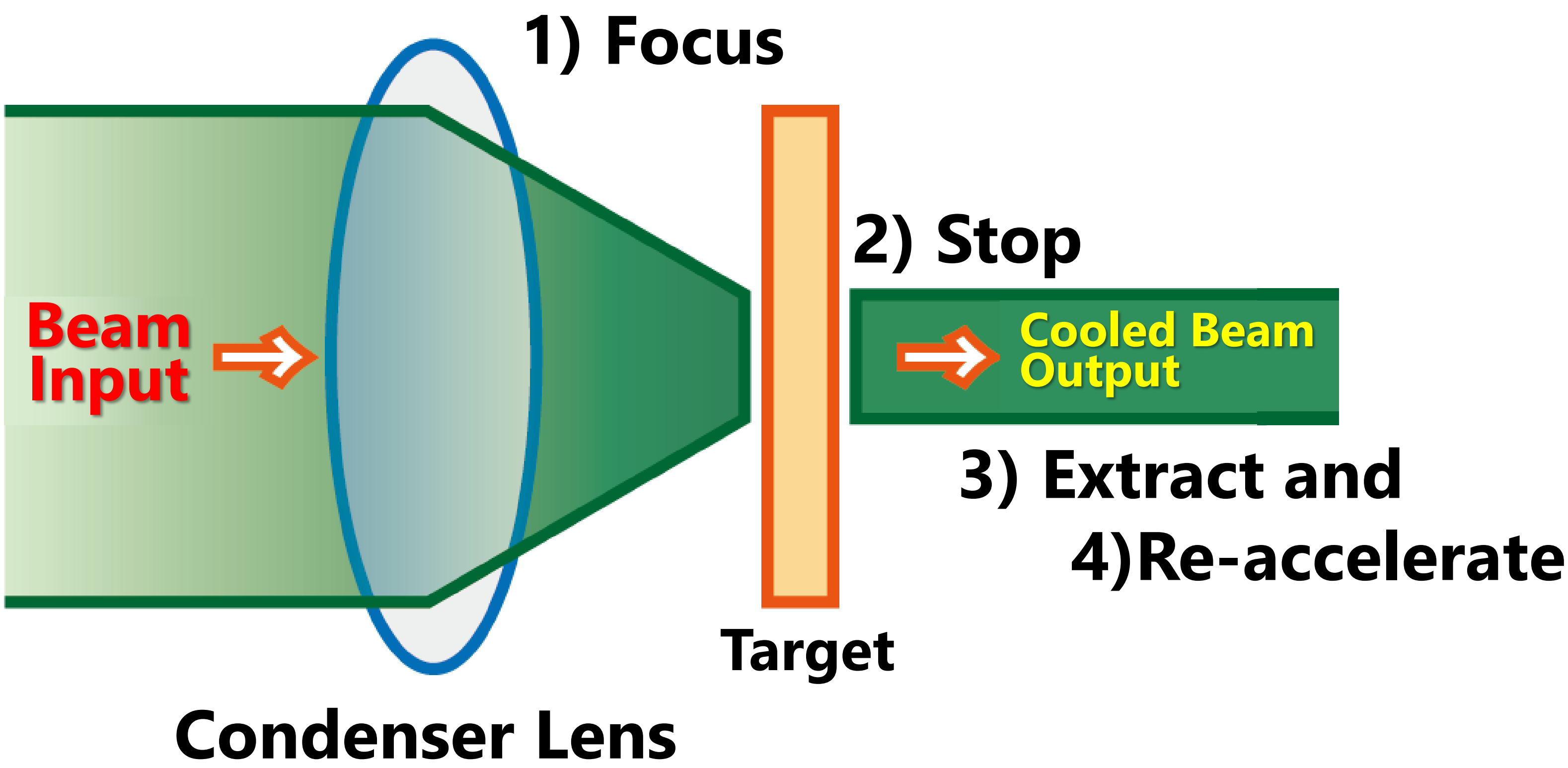


In situ specimen holder for Power-device / Life

CMOS Image Sensor for TEM is employed

Digital Camera Sensor has been checked.

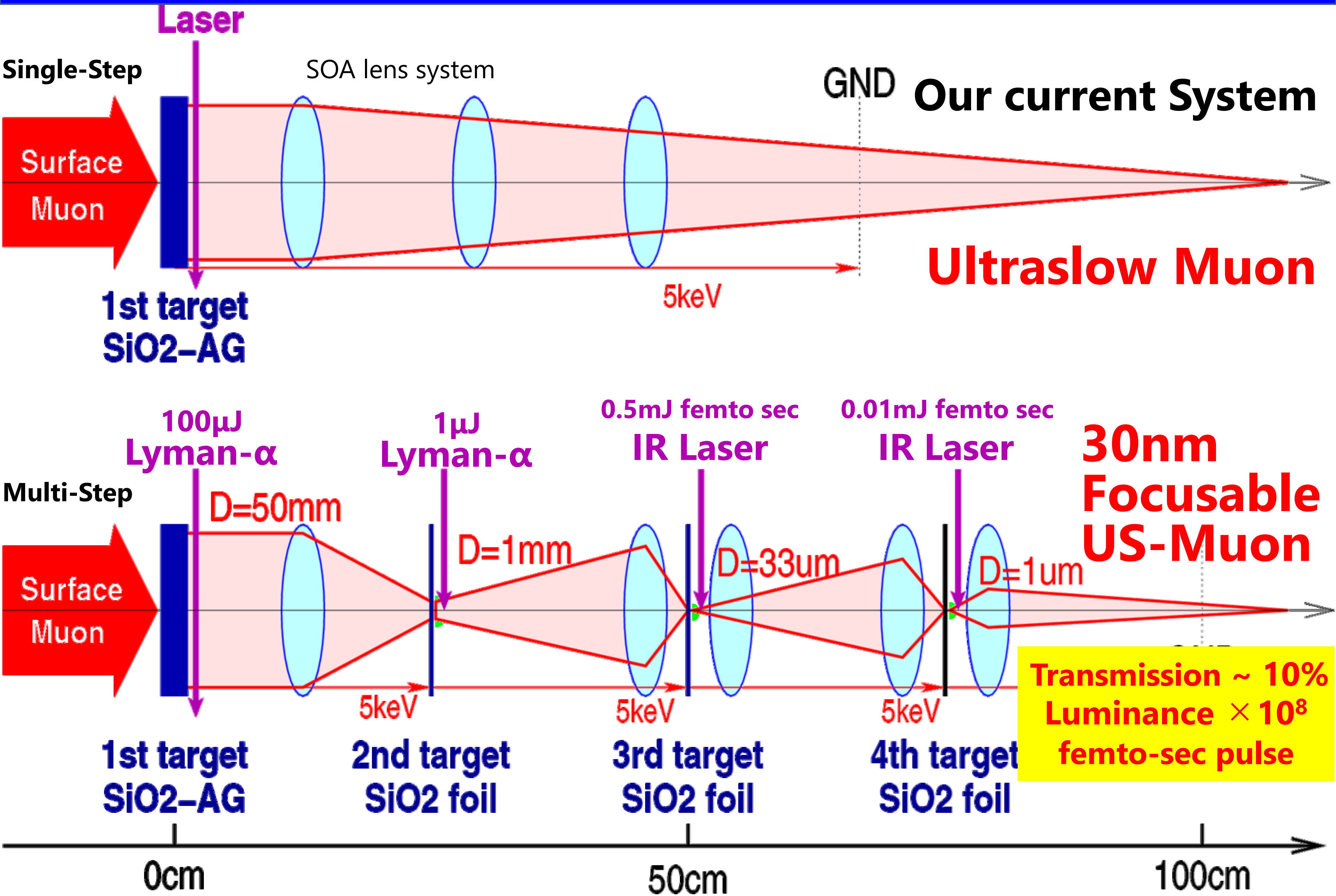
Essence of the Beam Cooling



- Momentum distribution is cleared by stopping.
- Volume in phase space (emittance) is shrunken down. = Beam-Cooling

- Iteration of this process can cool the beam down much more.

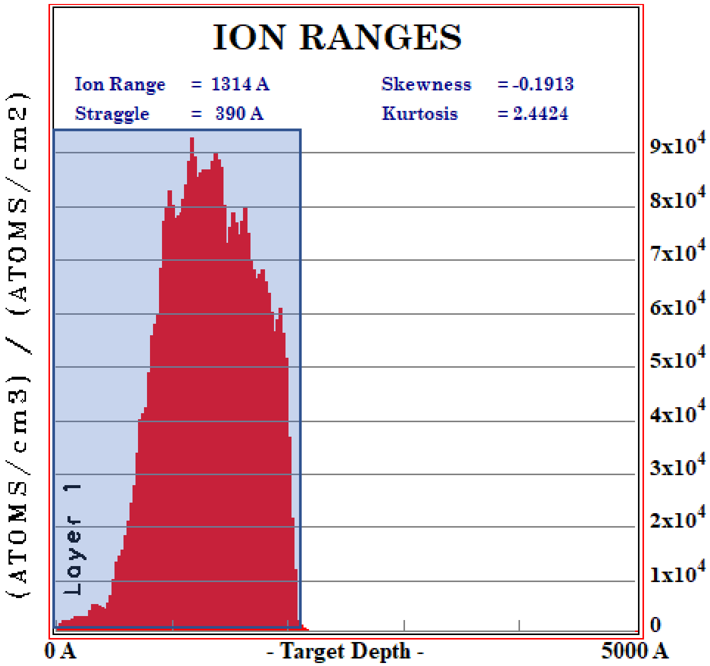
Single-step / Multi-step Beam Cooling

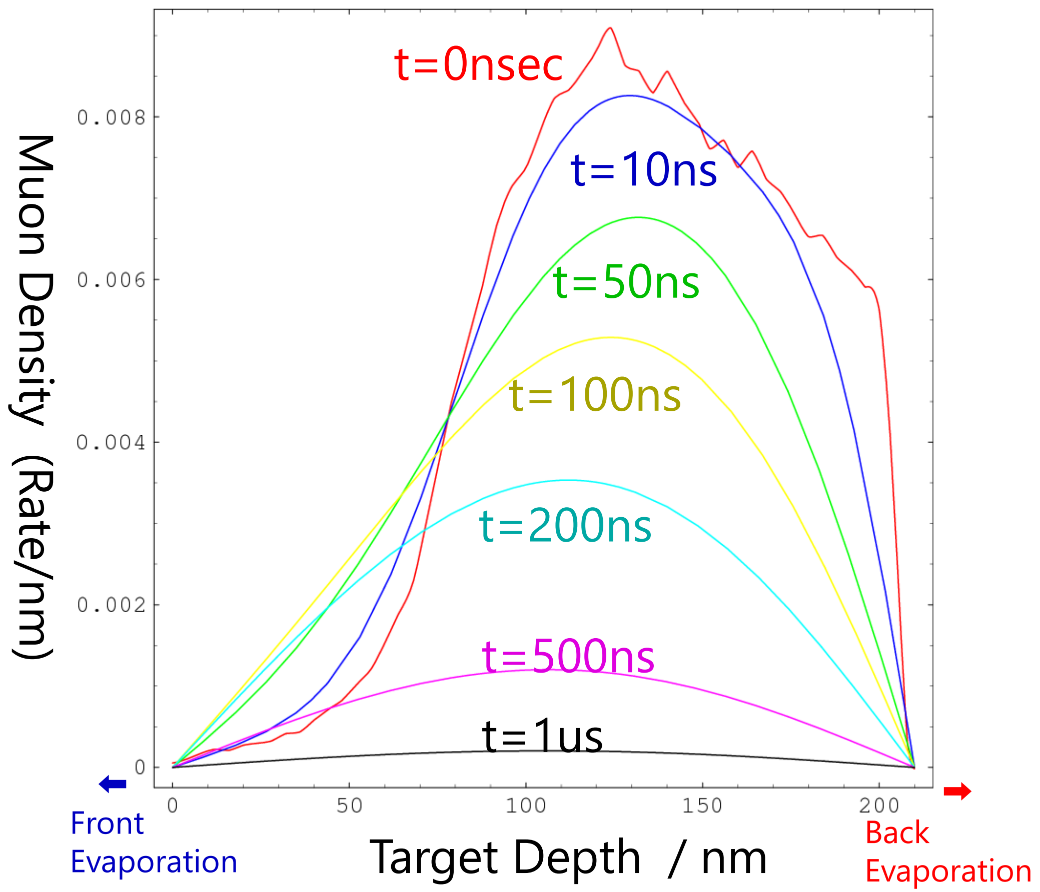


Diffusion in the thin target

Diffusions of Mu in mesoporous silica are evaluated

t=210nm, ρ=1.1g/cm^3, D=1.6×10^{-4}cm^2/sec＝16 nm^2/nsec.





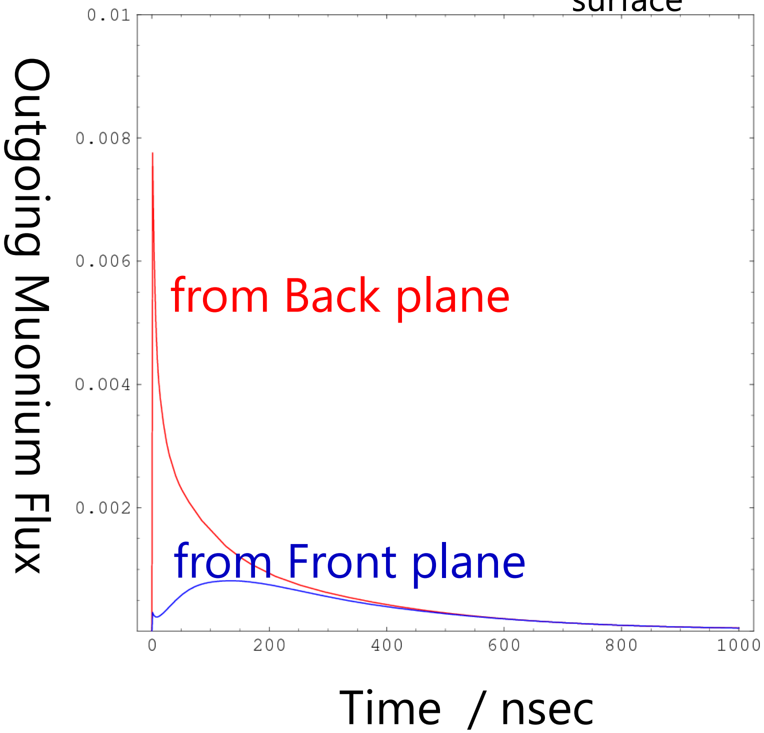
SRIM Simulation
➡ Diffusion Equation Analysis

Mu-distribution : f(t,x),

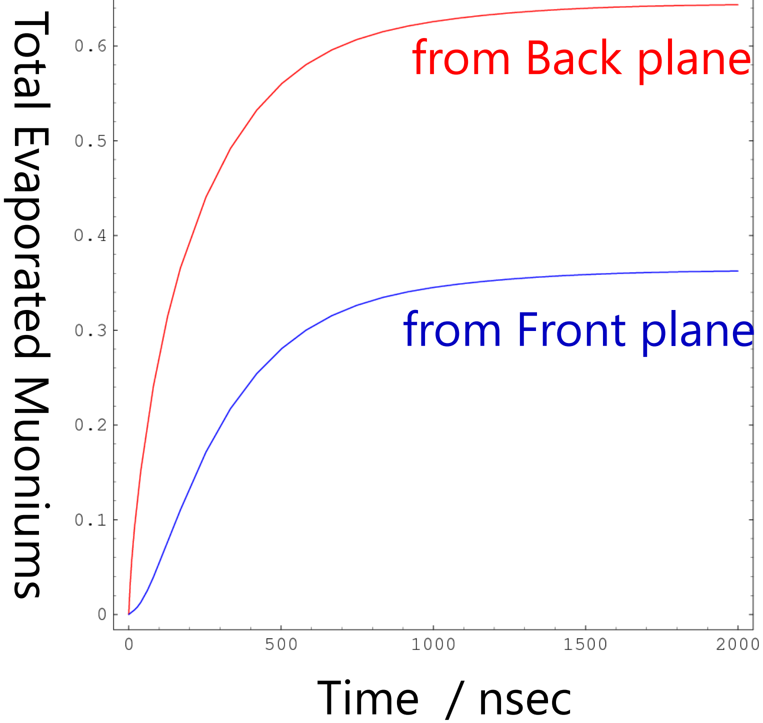
Eq: df/dt=D△f,　BC: f(t, $_{\text{surface}}$) =0, f(0,x)={SRIM-Result}.

Mu-Evaporation from the target

Mu-Flux : $F=-D\nabla f_{surface}$



Total Ratio : $R(T) = \int_0^T dt\, f(t, _{surface})$



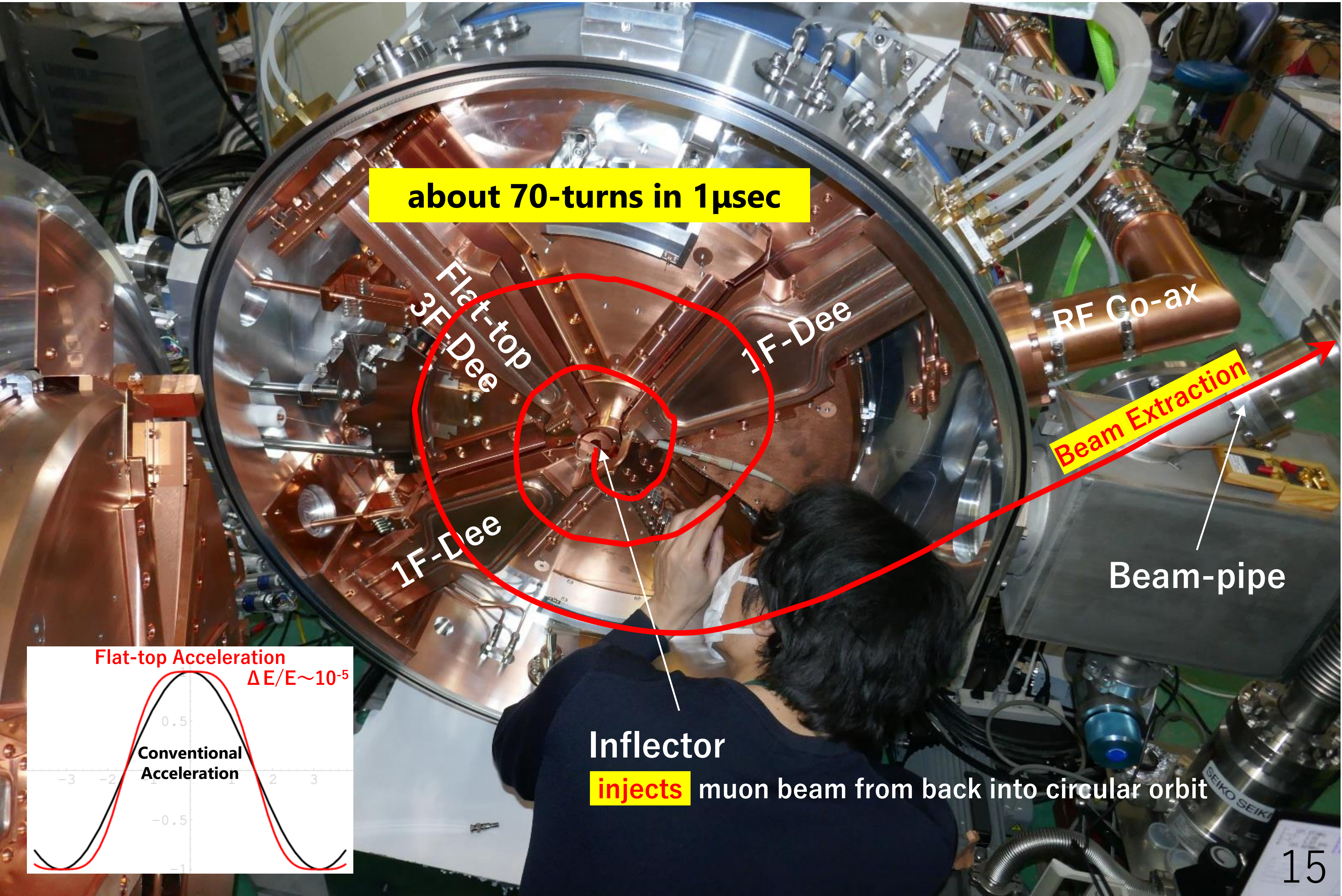
Muoniums are evaporated

～60% from back plane and ～30% from front plane.

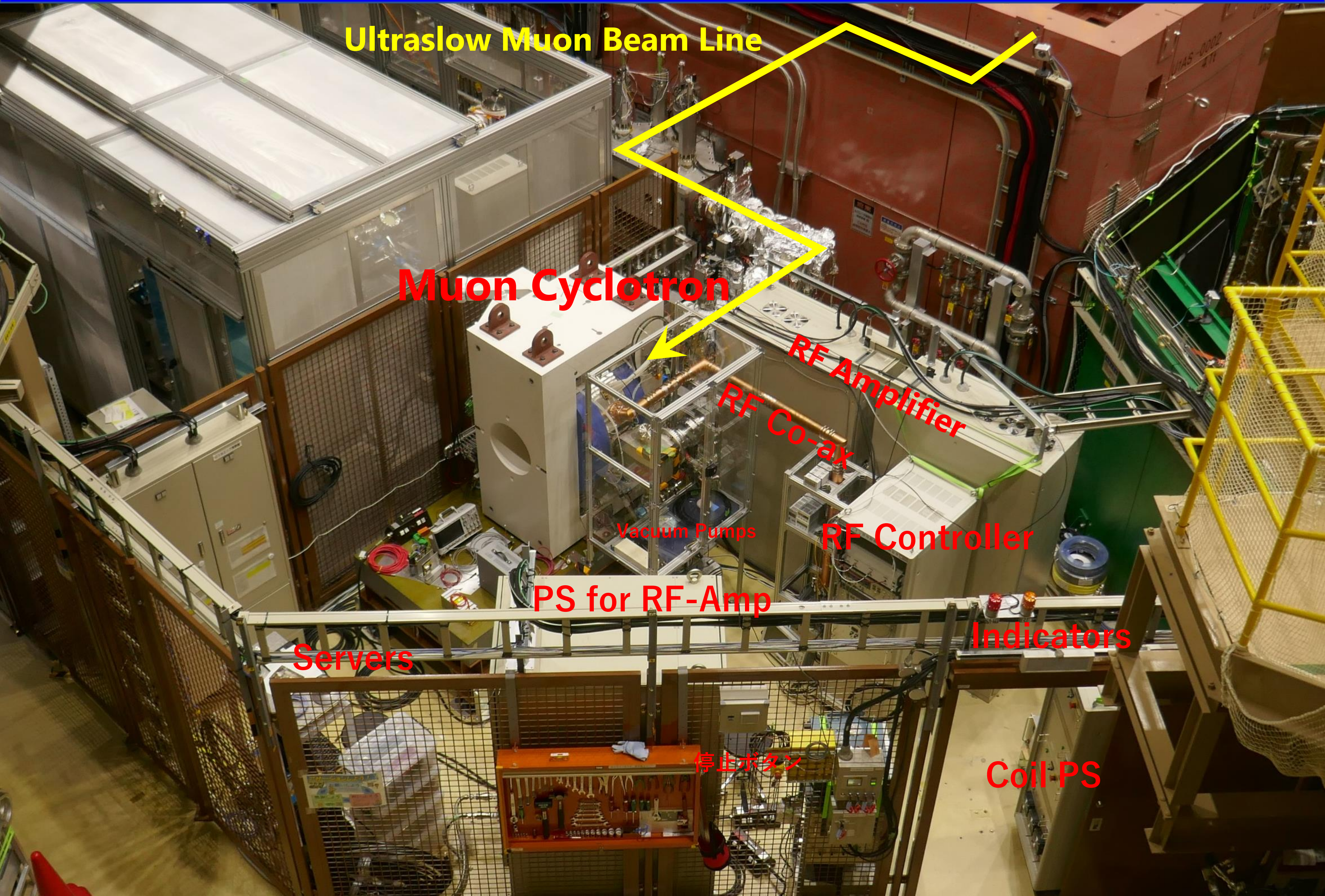
Rate for passing thorough additional 3steps ～ >10%.

The 3 steps-cooler improves $\times 10^8$ Luminance for US-Muon beam.

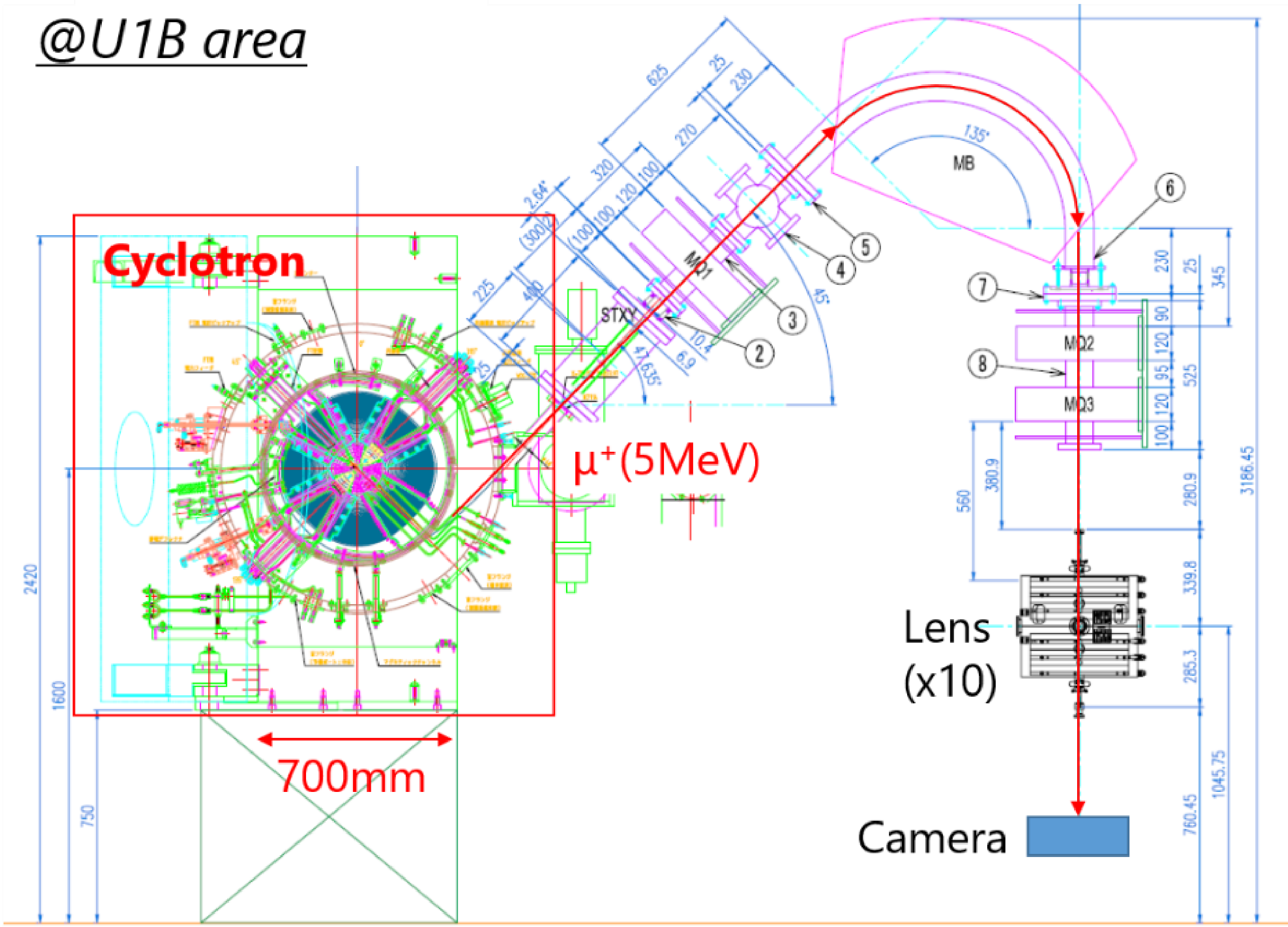
5MeV Muon Cyclotron



Cyclotron installed in U1B area MLF/J-PARC



5MeV TμM：Cyclotron + Main Column of TμM

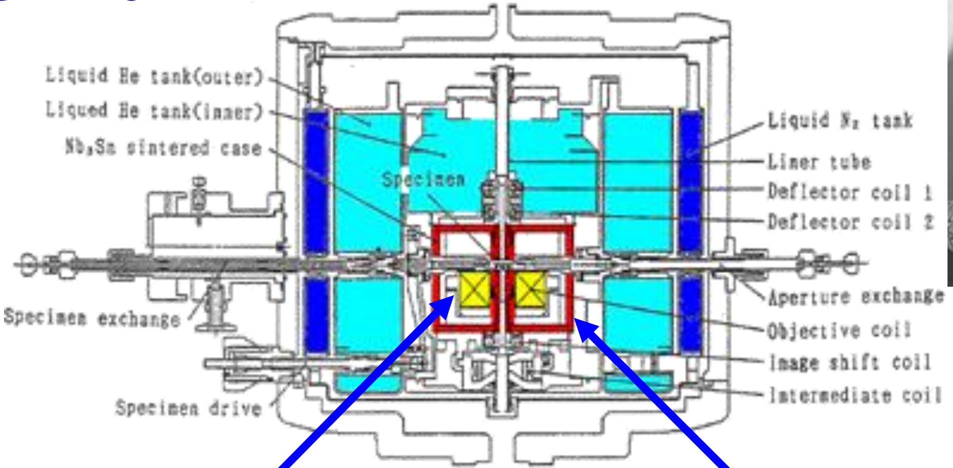


Accelerated muon beam is vertically injected into TμM column.
This is the design for prototype. It's resolution is ～1μm.

R&D of lenses for TμM

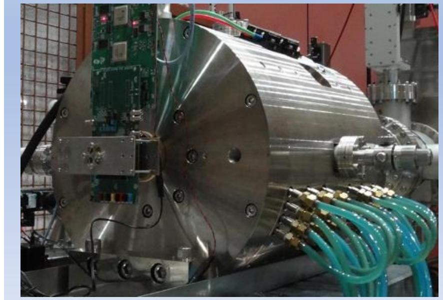
Superconducting Object Lens

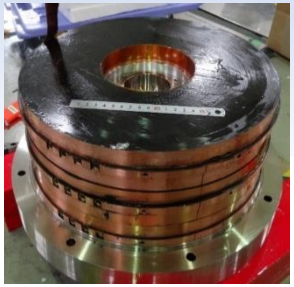
Developed by I. Dietrich



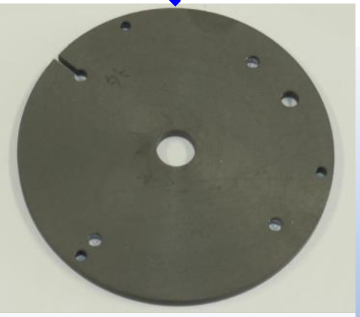
Transfer from JEOL to KEK

Normal Conductor Lens



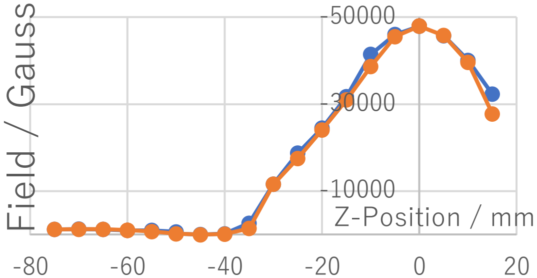


Superconducting Coil
with persistent current SW



Meissner Shield
for field convergence

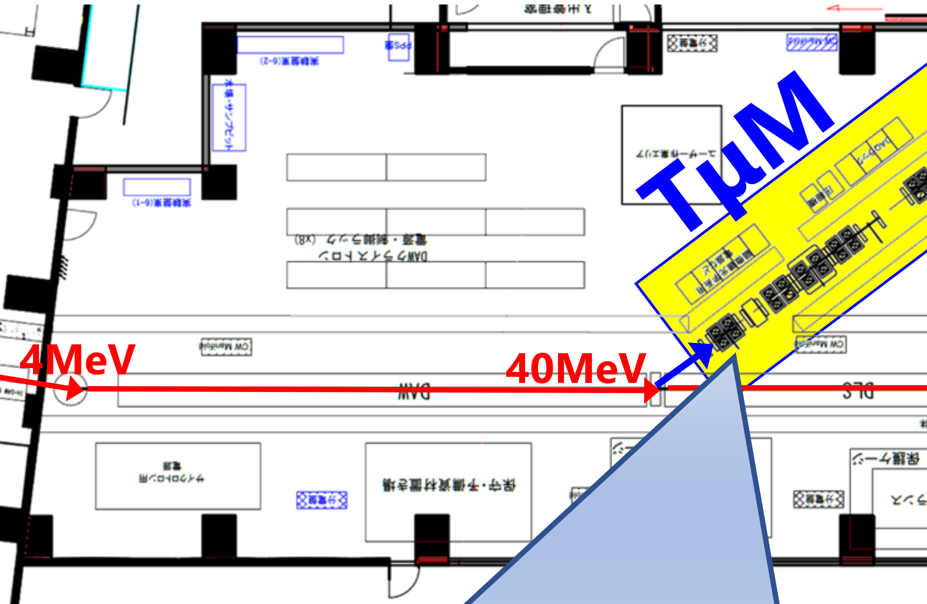
Magnetic field is guided to be focused by Meissner shields rather than pole-piece / yoke.



40MeV TμM becomes 8～9m Length by scaling design of TEMs.

Phase 2: 40MeV TμM

At the H2 extension building, max synergy with the g-2/EDM experiment



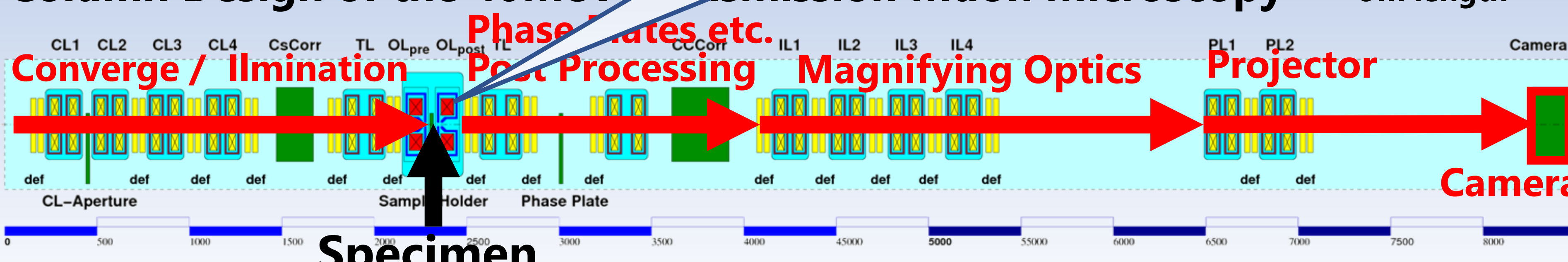
Superconducting Lenses are employed

Superconducting Coil
with persistent current SW

Meissner Shield
for field convergence

Magnetic field is guided to be focused by Meissner shields rather than pole-piece / yoke.

Column Design of the 40MeV Transmission Muon Microscopy ～9m length



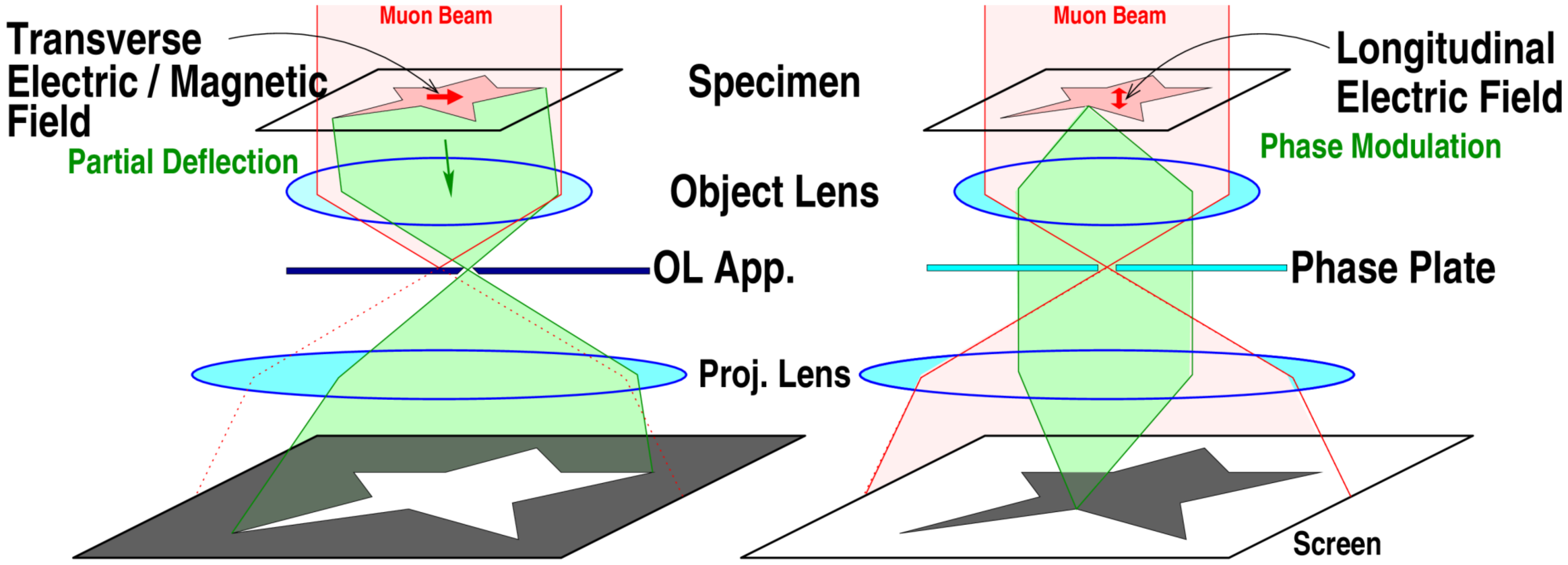
Visualization of Electromagnetic Fields

Lorentz Method

visualizes distribution of beam deflection:

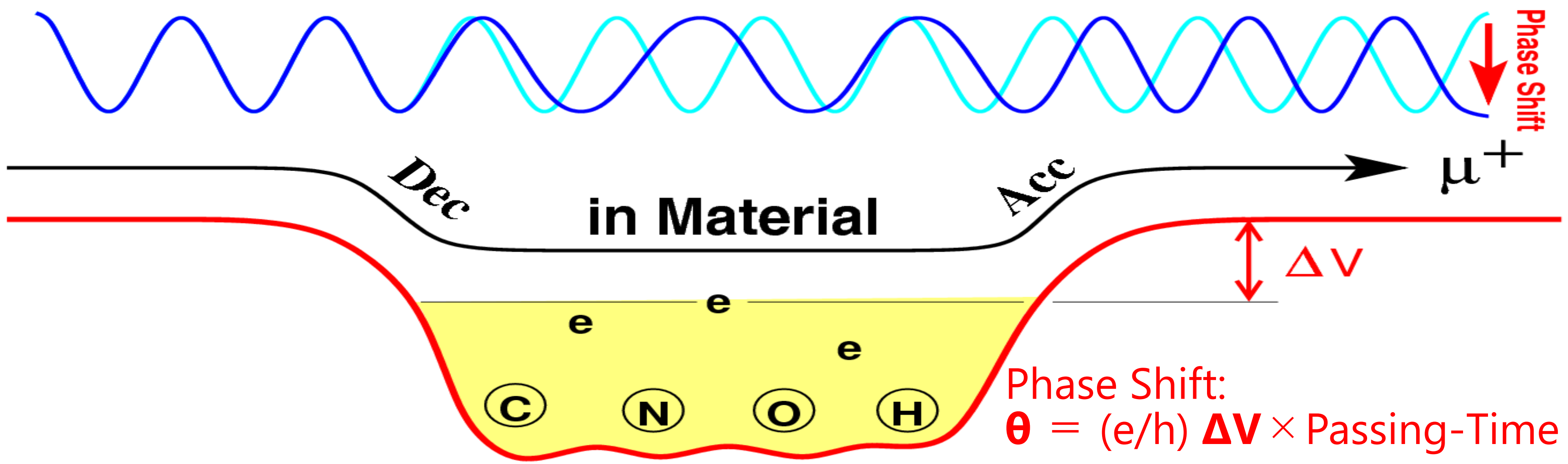
Zernike Method

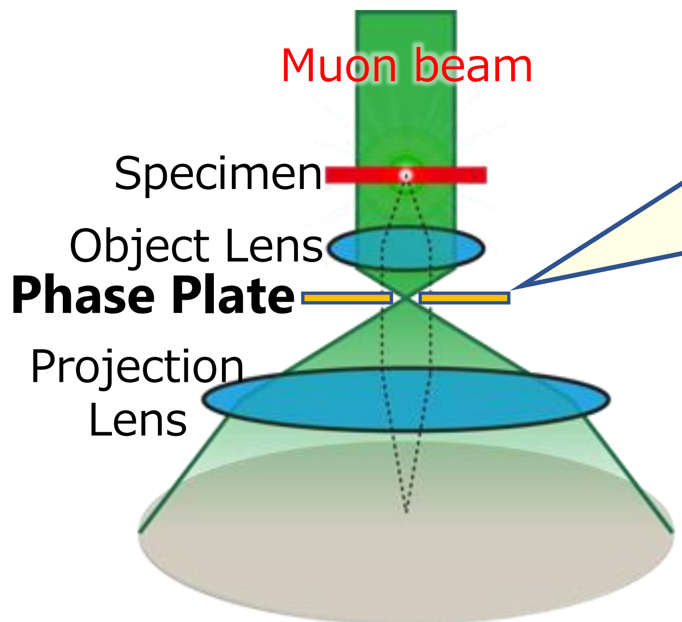
visualizes electrostatic potentials:

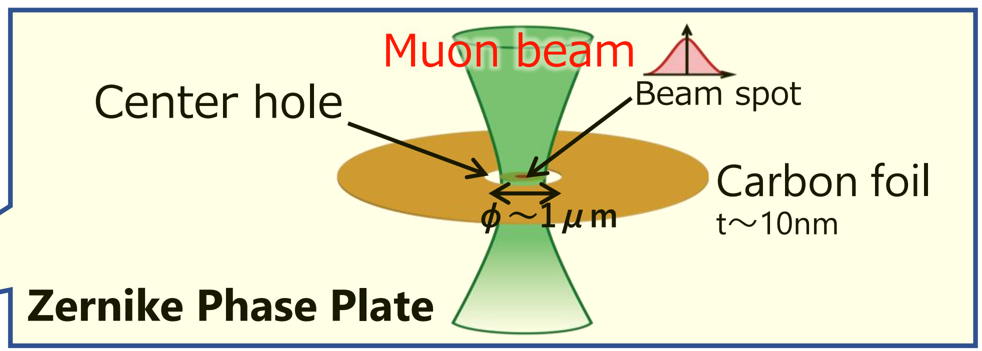


TμM can visualize electromagnetic field in a bulk specimen.
The 3D distribution is also obtained by Computed Tomography.

Visualization of Elec-Potential by Phase-Contrast







$$I(x) = \left\| e^{i\theta(x)} \right\|^2 = \mathbf{1}, \qquad \textbf{...No Contrast}$$

Insertion of the Zernike Phase Plate

$$I_{ZPP}(x) = \frac{1}{2}\left\| 1 + e^{i\theta(x)} \times e^{i\pi/2} \right\|^2 = \frac{1}{2} - \frac{1}{2}\sin \boldsymbol{\theta}(x).$$

Phase-shift is converted into Contrast

Test of muon imaging by CMOS Image Sensor

- CMOS Image Sensors for TEM are too expensive for test (>100k$).
- We have tested imaging-capability of commercial digital camera (3k$) Nikon Z7II.

Specification：

Sensor	Color CMOS Sensor, Nikon FX format
Size	35.9×23.9 mm
Pixels	8256×5504、 43 μm× 43 μm

There are several objects which disturb incoming muons on the sensor:

vibration plate for dust-cleaning, low pass filter, Infra red filter, glass window, and color filter.

Set-up of the test

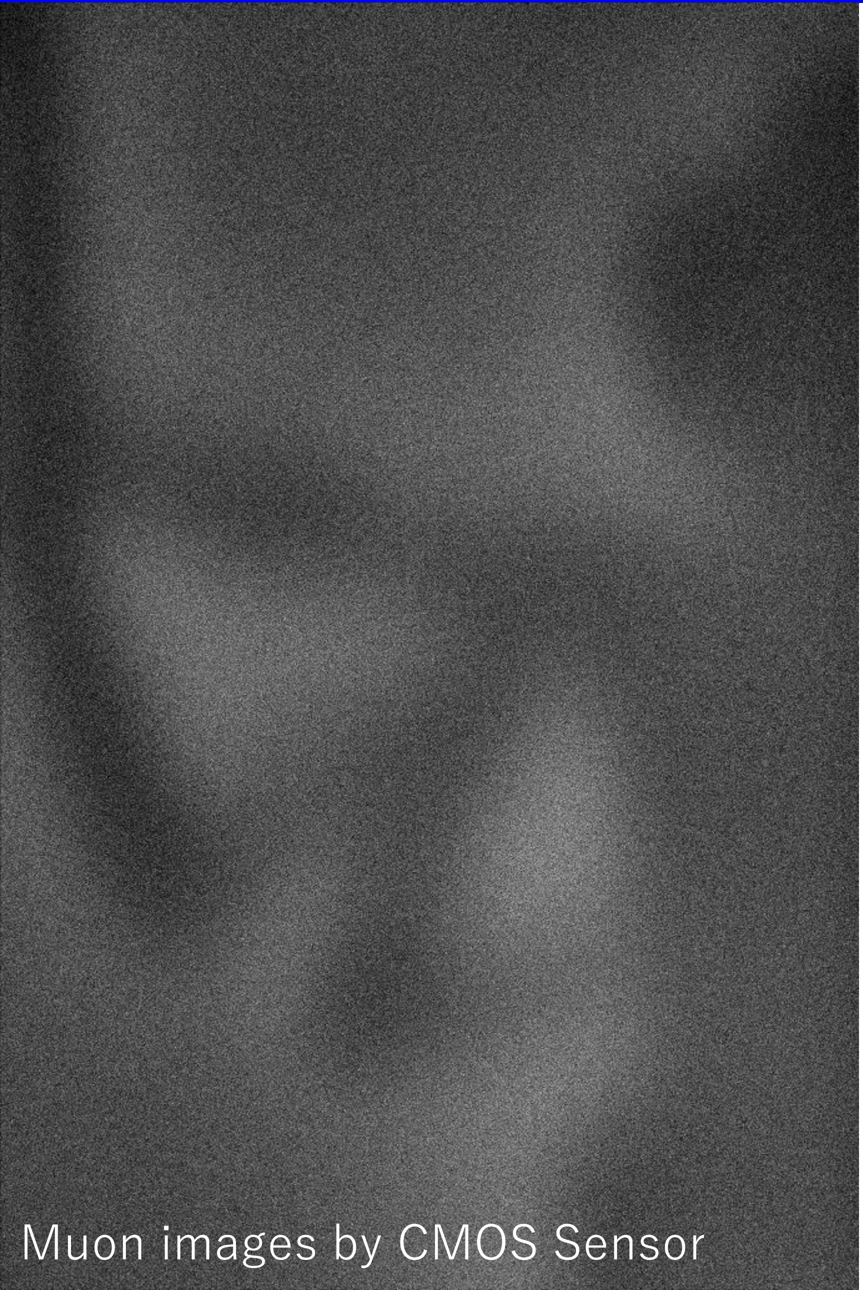
Muon Beam

Camera

Muon beam is directly projected into the sensor without any fluorescent screen

Rotating Stage

Detected Images



Muon images by CMOS Sensor

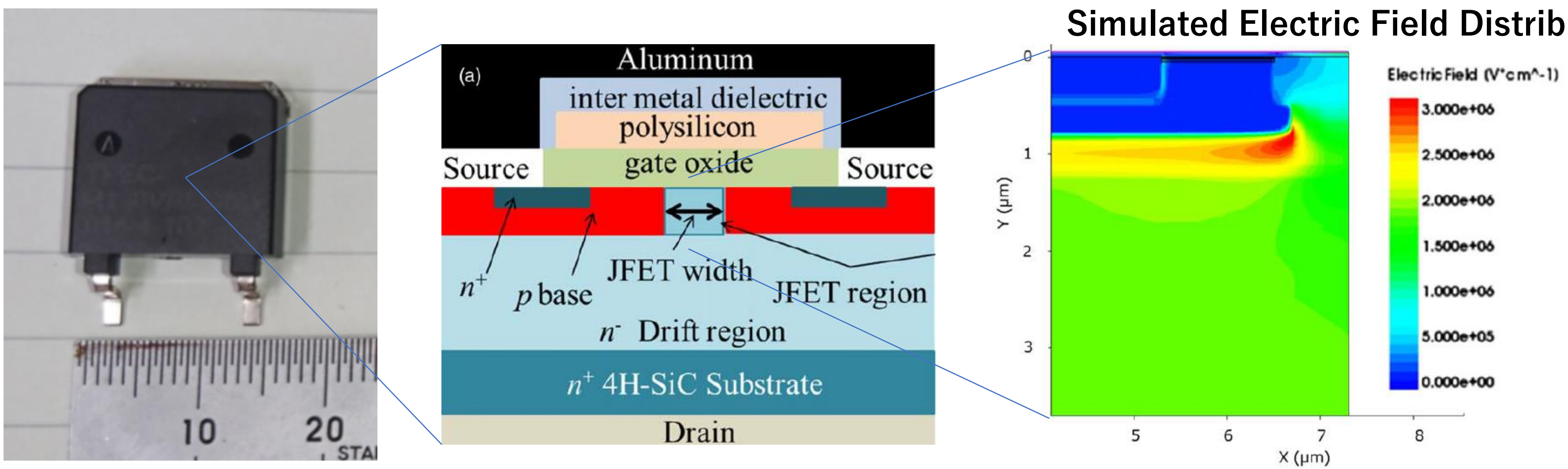
Muon images by fluorescent screen

- RESULT：
  CMOS image sensor can detect positive muons as images.

- **We can detect each projected muon, namely, muon-counting.**
  ➡ Super-resolution is available.
  ➡ Spatial resolution can be ＜ 30 μ m.

Elec-field in High Voltage Transistor (AIST)

- AIST Power Electric Group developed **14kV SiC MOS FET**。
  （Highest commercial device is 3.3kV）

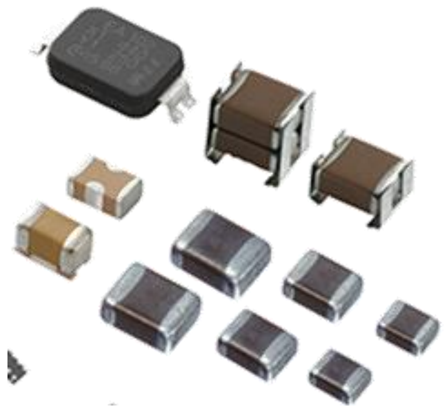


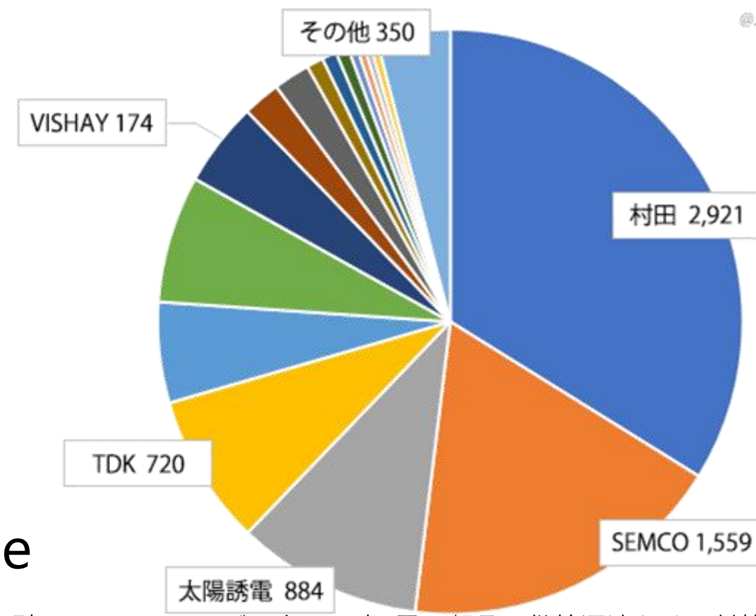
- By finding points of **electric field concentration** and **break-down**,
  we can develop more high-voltage devices. ➡ down-sizing, energy-saving.
- Efficient **Electric Vehicles**, **Power-Grids** ➡SDGs。
- Applicable for any power devices not only SiC but also **GaN**, **Ga_2O_3**.
- By GHz Stroboscopic imaging, **RF fields** are also visualized
  ➡Speed up the **communication network**, Higher performance **Rader**…

For High Performance Electric Devices

2017 MLCC Market Shares，Wold：￥8,617億

● **Ceramic Condenser**（MLCC）





引用：J-Chipユーザー会2018年 電子部品の供給逼迫とその対策

Higher dielectric strength in unit volume is essential for market competition.

$$E = (C/2) \times V^2$$

TμM visualizes the field concentration and break-down phenomena.

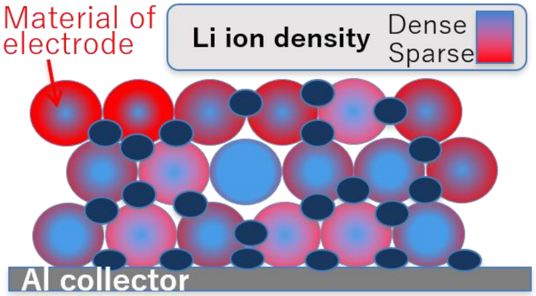
➡ It helps to develop higher performance condensers.

● Motor, transformer, generator → EV, Power Grid,

● Piezo, ultrasonic devices → Medical、Non-destructive inspection.

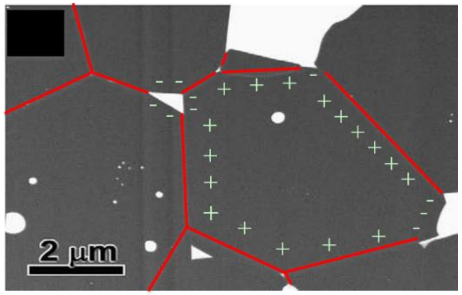
Applications for Material / Engineering Fields

- **Electromagnetic fields in Semiconductor Devices.**
  IC, LSI, Memory, RF semiconductor devices,
  Reverse engineering of packaged devices.



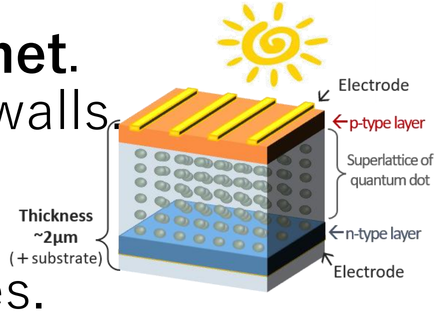
- **Electromagnetic field in Li ion Battery.**
  Visualization of inside during (dis)charging.

- **Electric fields in Piezo Devices**
  Ultrasonic transmitter, US-motor, US-actuator.

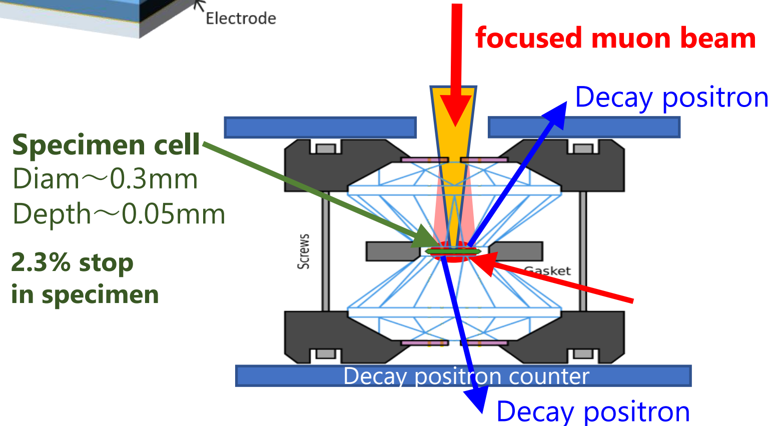


- **Magnetic field in permanent magnet.**
  Visualization of grains and domain walls.

- **Electric field in Quantum dots.**
  Solar cell, display, plasmonic devices.

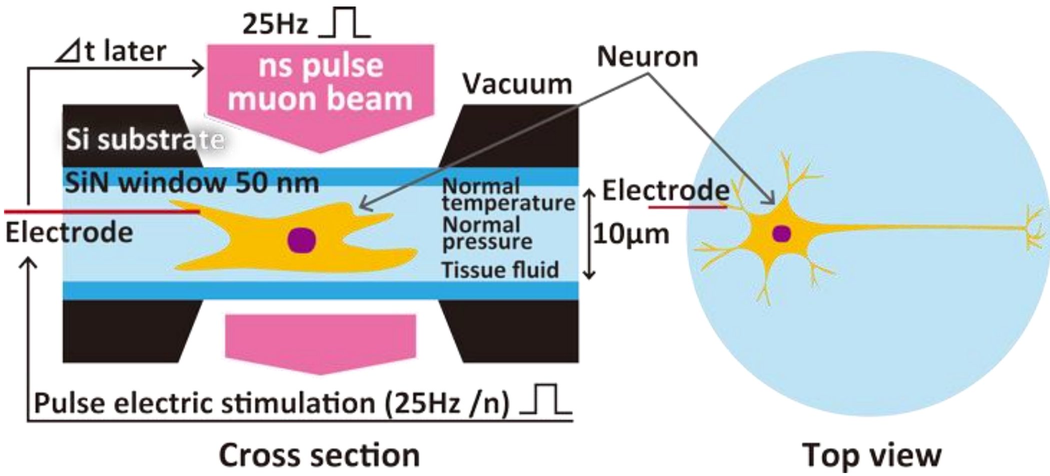


- **μSR in a diamond anvil cell**
  for room temperature Superconductors
  like CH_8S. (Planed at Phase-2 at H-line)



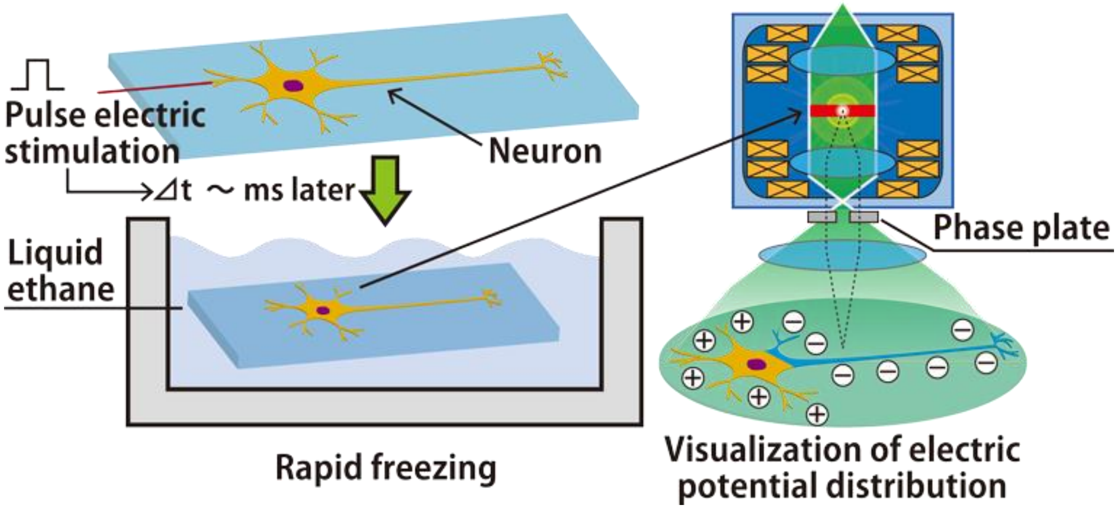
Functional Visualization of Neurons by TμM

Stroboscopic Visualization of Action-Potential Propagation in Living Neurons in Environmental Cell



- Visualization of living neurons/networks.
- Live cells/organs in an environmental cell. in bio-liquid at room temp and pressure with windows.
- Electric pulse stimulation is synchronized with the muon pulse.
- Timing delayed Δt is scanned.

3D Tomography of Action-Potential in Neurons frozen just after an electrical stimulation

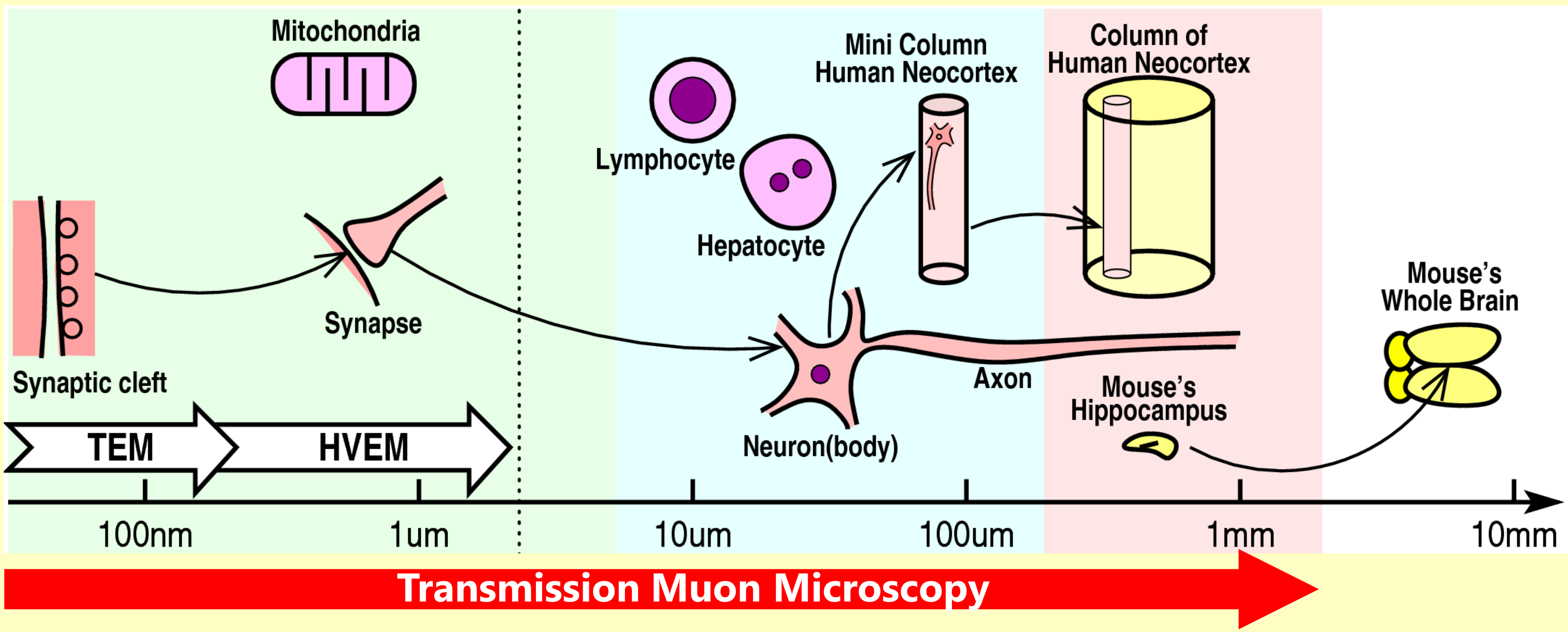


- The neuron are cultured on the electric microscope grid.
- Freezing rapidly with liquid ethane just after an electric pulse stimulation to a neuron..)
- TμM with cryo-holder and stage.
- 3D measurement by the tomography of phase contrast.

Functional Visualization of Neurons by TμM

Our Goal in Life Science：

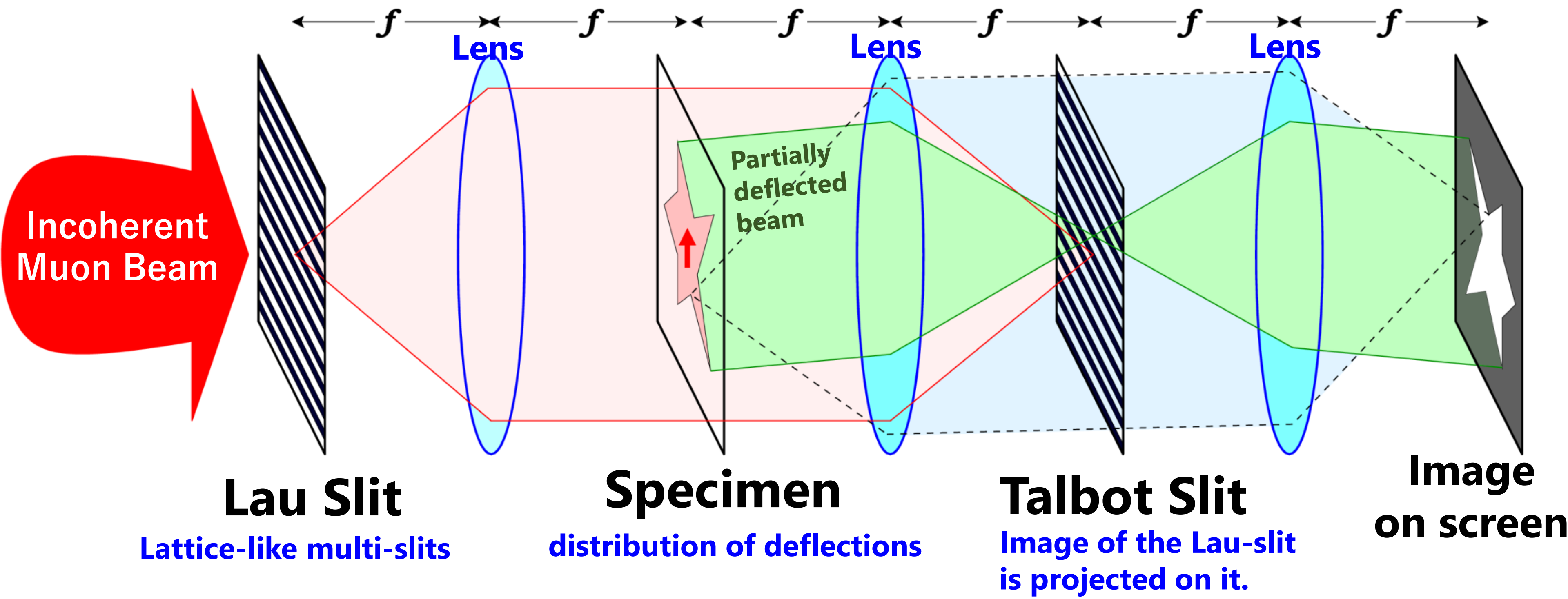
Integrated / unified understanding among multi-layers: synaptic level / neuron level / network level / organ level.



TμM becomes really important method for brain / bio sciences.

Phase-X: EM-Fields Imaging for Industrial Use

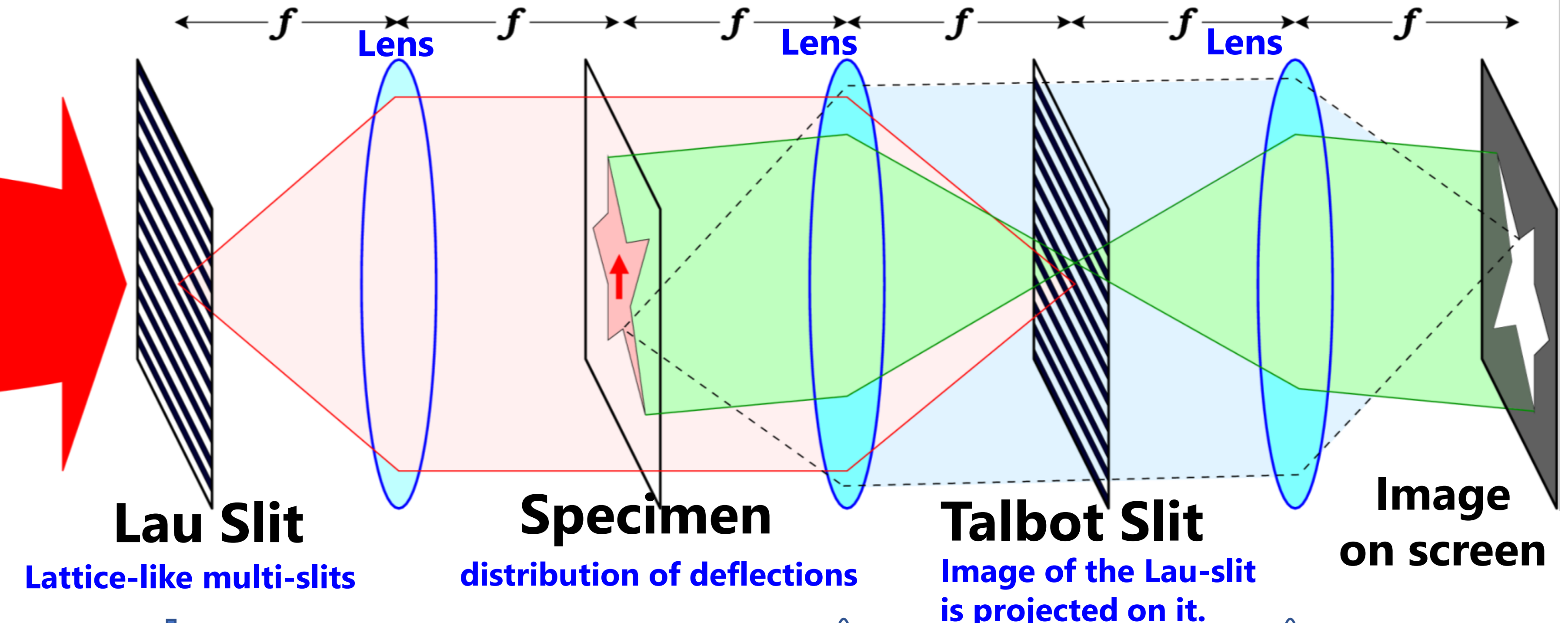
Visualizing distribution of beam-deflection by specimen.
It uses accelerator-generated muon beam directly:

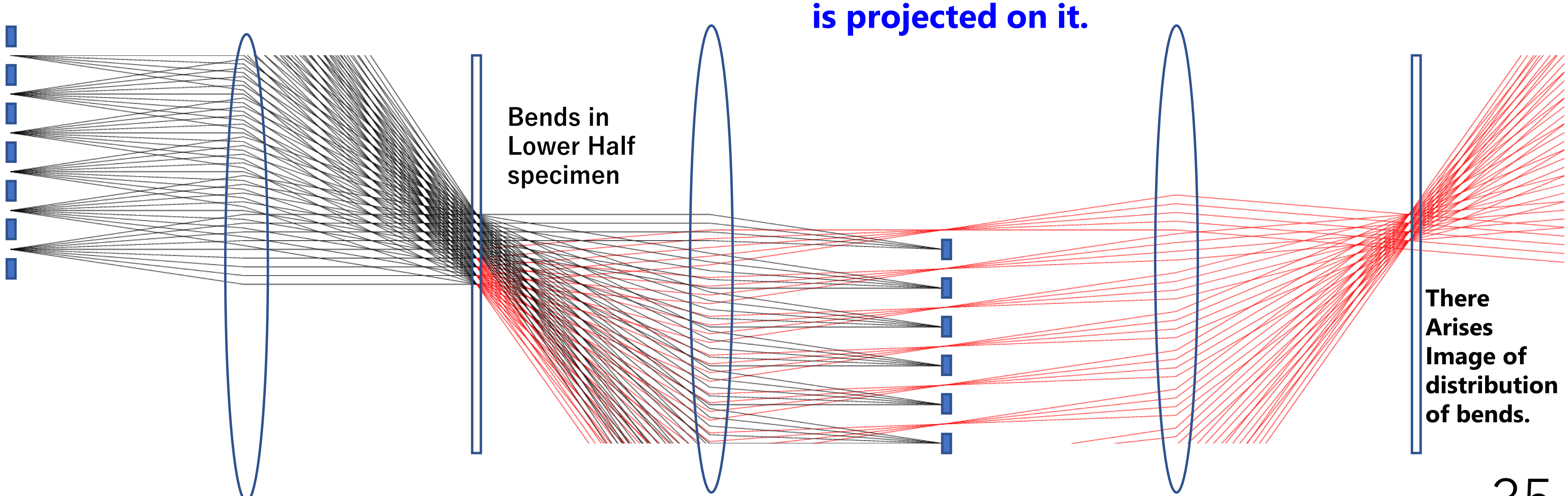


- **Beam cooling and re-acceleration is not required.**
- **While resolution is limited ～ 3um, cm object can be observed**

Work of the Method

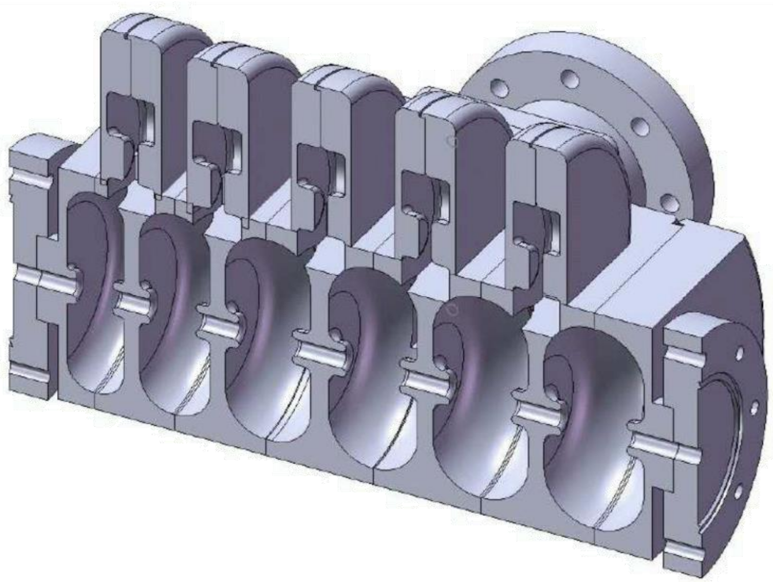
Lorentz-like and Talbot-Lau-like

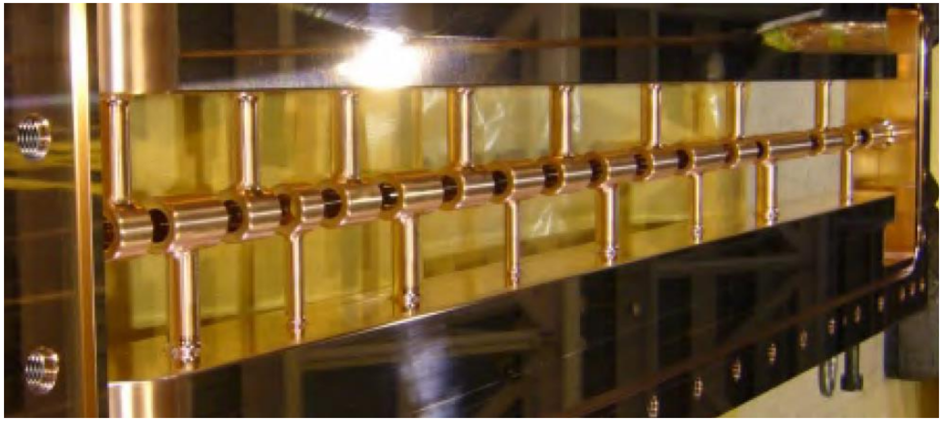




For High Performance Accelerator (TITech Hayashizaki)

- **Particle Accelerator** uses **strong RF field** in resonant cavity.

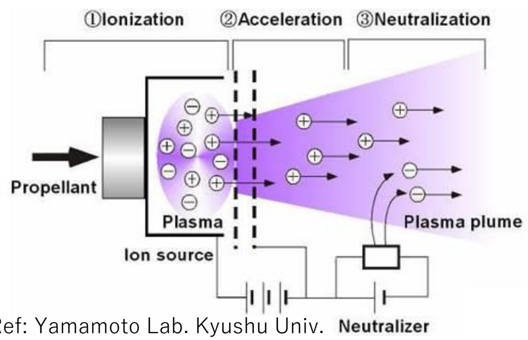




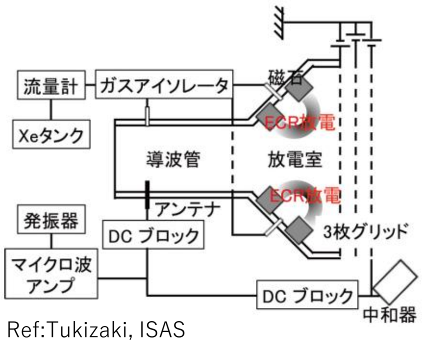
- Higher RF field makes smaller and higher accelerator （～100MV/m）, **Electric break-down** of high RF field limits the highest acceleration.
- Physics of the electric break-down in high RF field is unknown.
- Muon can visualize **the EM field in working accelerators**.
- **RF break-down** and **transitional phenomena** are visualized
  ➡ Developing the ultra high performance accelerator.

For High Performance Propulsion System in Aerospace

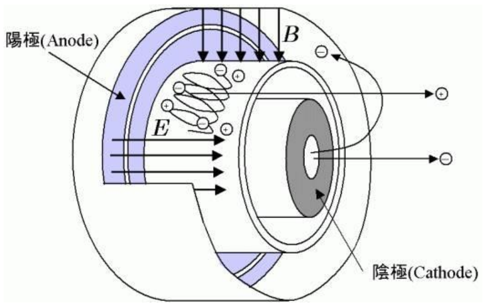
● **Ion engine / Hall thruster**： generate plasma-jet by electricity.



Ref: Yamamoto Lab. Kyushu Univ.



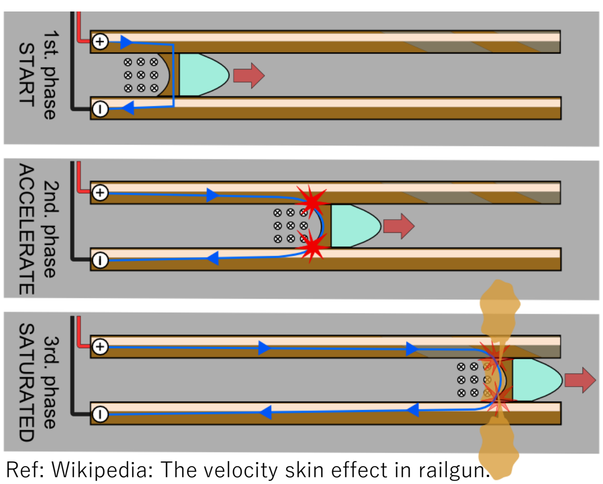
Ref:Tukizaki, ISAS



Ref:Nakanishi, Tohoku Univ.

Complex interactions among EM/RF field and ions/electrons.
Space-charge effect limits the thrust.
➡ Measurement of **4D EM field** makes **more efficient** and **more thrust**.

● **Rail-gun**：An acceleration system by Lorentz force.



Ref: Wikipedia: The velocity skin effect in railgun.

At high velocity（～7km/sec）, **velocity skin effect** limits the highest velocity.
Current concentration ➡ plasma generation ➡ dissipation➡ velocity limit.

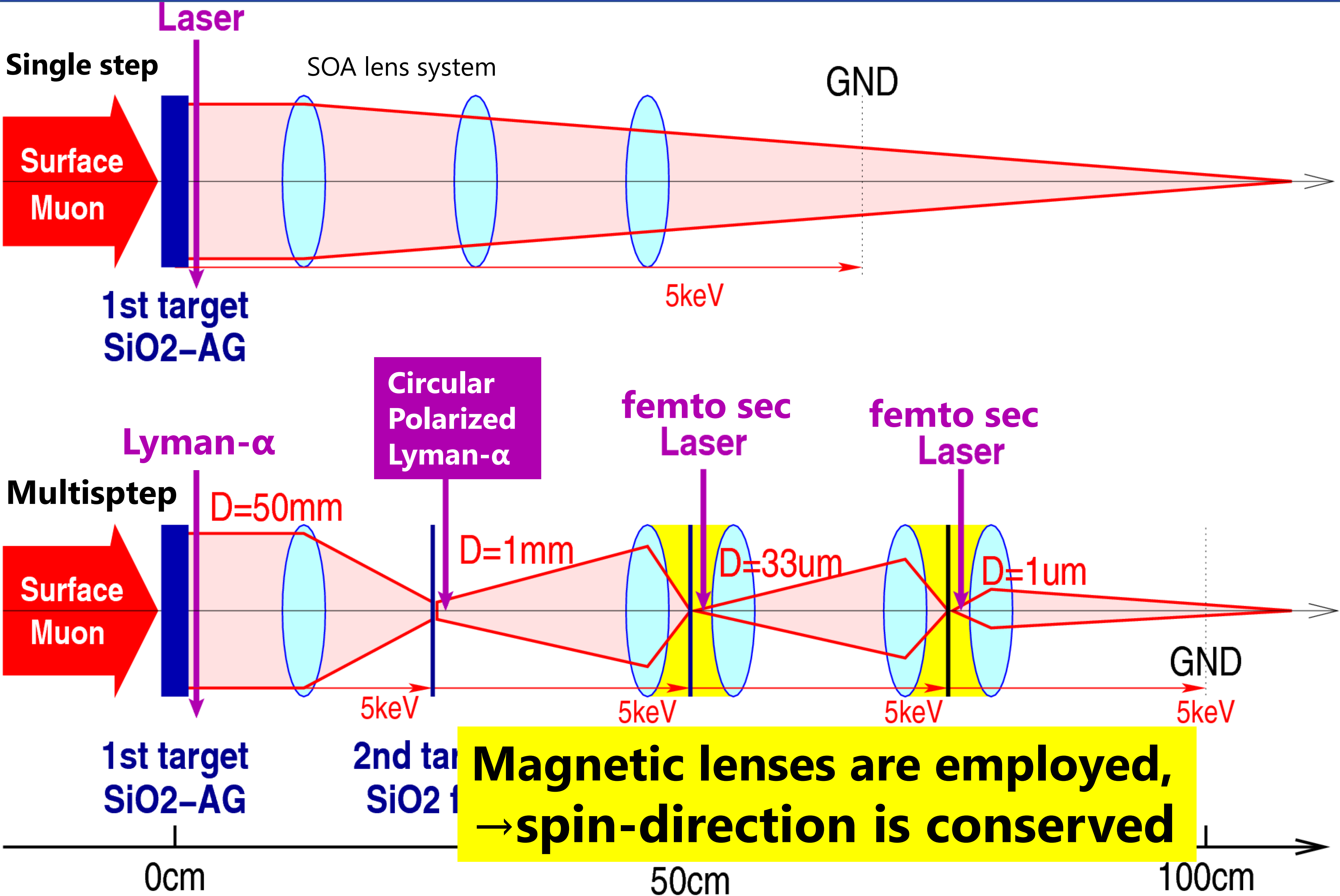
Muon visualizes the Lorentz force directly!

4D visualization of velocity skin effect makes design of **higher velocity Rail-gun**.

$S\mu^{+}M$:
Scanning positive-muon Microscopy

Nano-resolutional **2D/3D mapping** of **μSR spectroscopy** on/in specimens

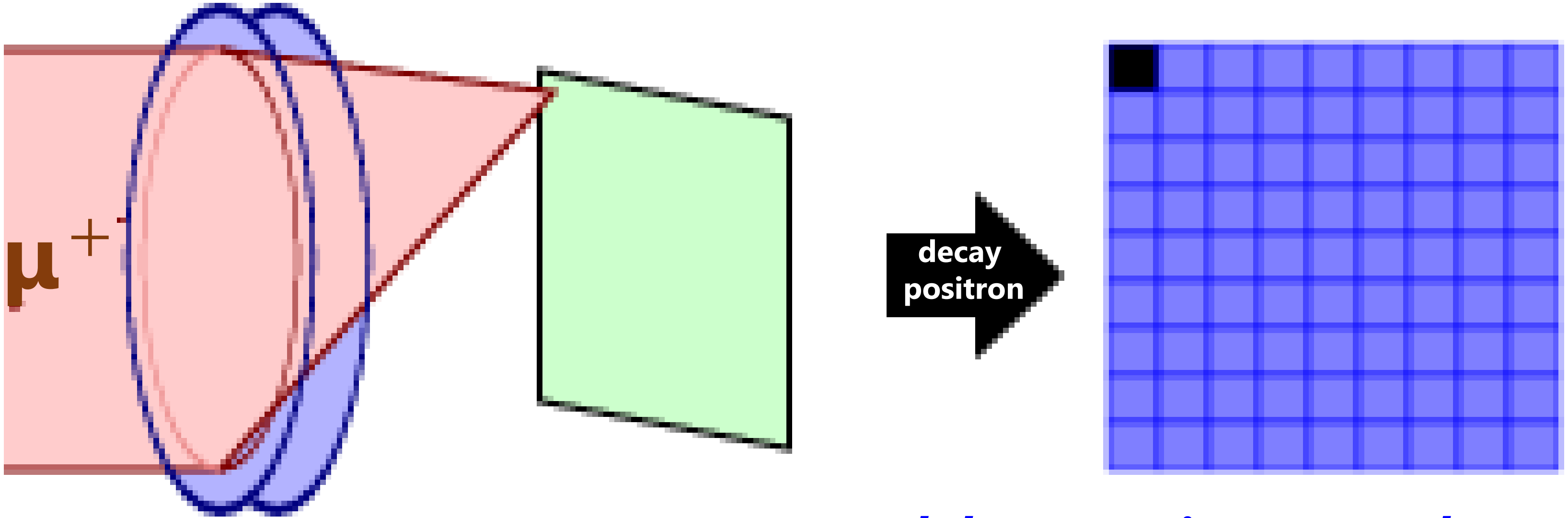
Muon spin polarization maintained Cooling



Magnetic lenses are employed,
→spin-direction is conserved

Scanning positive Muon Microscopy: Sμ^+M

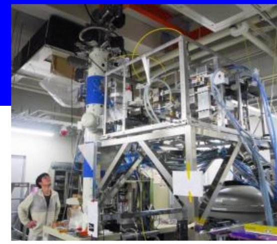
Specimen is Scanned by focused μ^+ beams,



and decay positrons are detected for μSR Spectroscopy

It works as a Scanning μSR Microscope:
μSR Spectrum is obtained point by point!
3-dim mapping of magnetic field and its fluctuation, density of Fermi surface, state of hydrogen, and etc., in Nano/Micro Resolutions.

Members

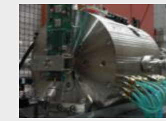


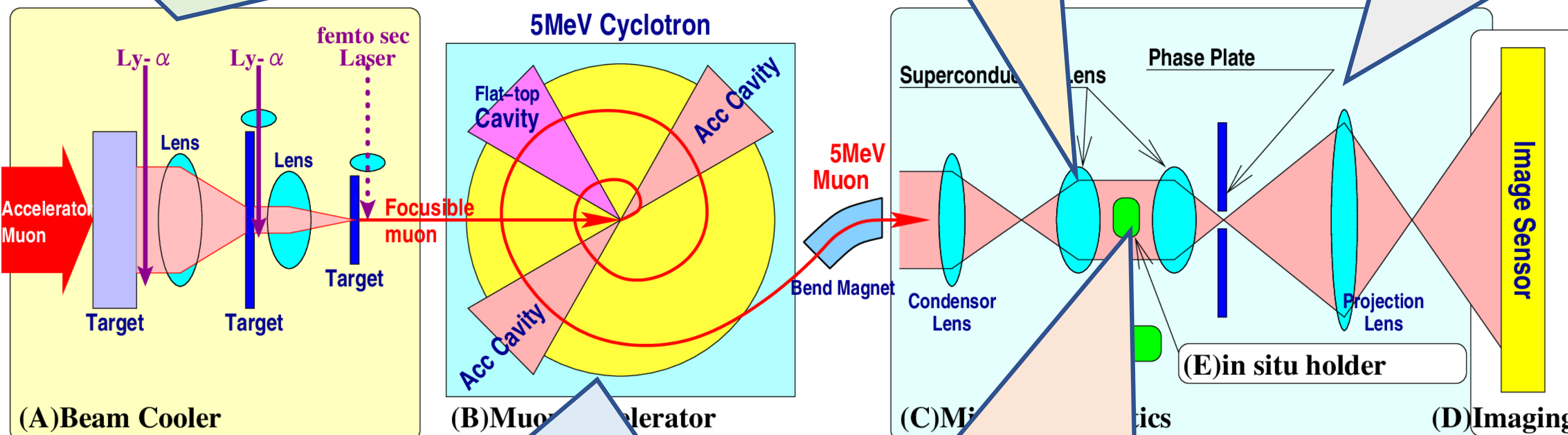
Direction： Y.N （KEK、Fusion of Microscopies and Accelerators）

Superconducting Lens：
Kenicih Sasaki
（KEK Cryo-G、SC-Magnets）

Laser Devices：
Yu Ohishi （KEK、Lyman-α Devices）、
Shinki Nakamura （Ibaraki U.、Yb:YAG Laser）

Optics：
Y.N.





Cyclotron and Beamlines：
Junichi Ohnishi （Riken、Cyclotron）、
Takayuki Yamazaki （KEK、Beamline Develop.）、
Akira Goto （Riken/KEK、Cyclotron）

Power Devices：
Hiroshi Sato （AIST、MOSFET）

Life Sciences：
N. Usuda, M. Fukazawa (Fujita Med. U, Brain),
K. Jokura, K. Kame (Shinshu U. Med.),
K. Muratra (NIPS, TEM), **T. Senda** (KEK, TEM/X-ray)

Beamline Management：Koichiro Shimomura （KEK）

*印は研究協力者

Collaboration and Partners

- **KEK**
  - Muon group: Y. N., T. Yamazaki, P. Strasser, S. Kanda, S. Nishimura, S. Matoba, Y. Ikedo, T. Yuasa, N. Kawamura, Y. Ohishi, A. D. Pant, M. Tampo, S. Doiuchi, A. Goto, K. Shimomura, Y. Miyake.
  - g-2/EDM group: T. Mibe et.al. (g-2/EDM collaboration)
  - Accelerator facility: Toshikazu Adachi, H. Someya, M. Yoshida.
  - Cryogenic group: T. Ogitsu, K. Sasaki, N. Kurosawa.
- **RIKEN** J. Ohnishi, Taihei Adachi.
- **Tokyo I.Tech** T. Sannomiya, N. Hayashizaki.
- **AIST** H. Sato, T. Kuroiwa, K. Sakamoto, F. Kato.
- **NIPS** K. Murata.
- **Industry** (Sumiotmo HI) K. Kumada, S. Kusuoka, K. Onda, Y. Tsutsui. (JEOL) M. Iwatsuki, (Terabase) Y. Arai.

Summary

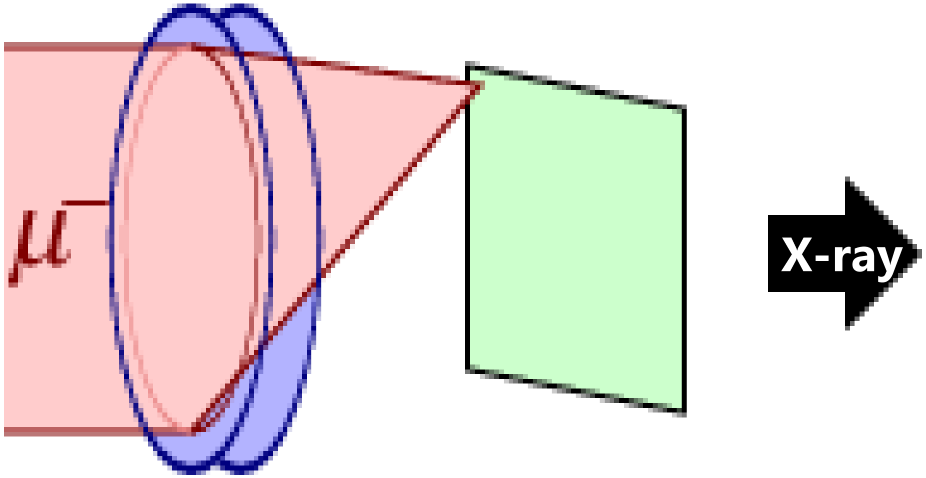
- TμM clarifies how our brain works,
  by **functional imaging of macroscopic neural systems** in nanometer resolution.
- **Visualization of electromagnetic fields in bulk object** is
  widely applicable to material science and engineering fields,
  so our modern material civilization is depending on electromagnetism.

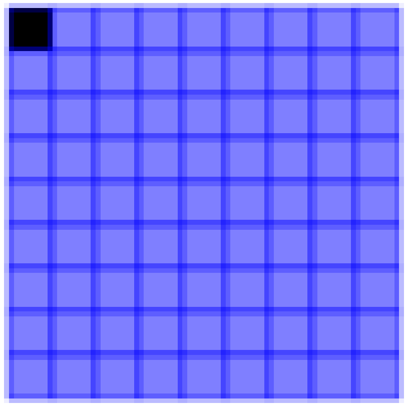
$S\mu^-M$:
Scanning negative-muon Microscopy

2D/3D mapping of **elements**
in µm-resolution

Goal of Sμ⁻M

Specimen is scanned by focused μ⁻ beam





Muonic X-ray analysis

- **2D/3D mapping of elements, isotopes and chemical situations.**
- High sensitivity for light elements
  ➡ **Applicable to Life** consisting from C, N, O.

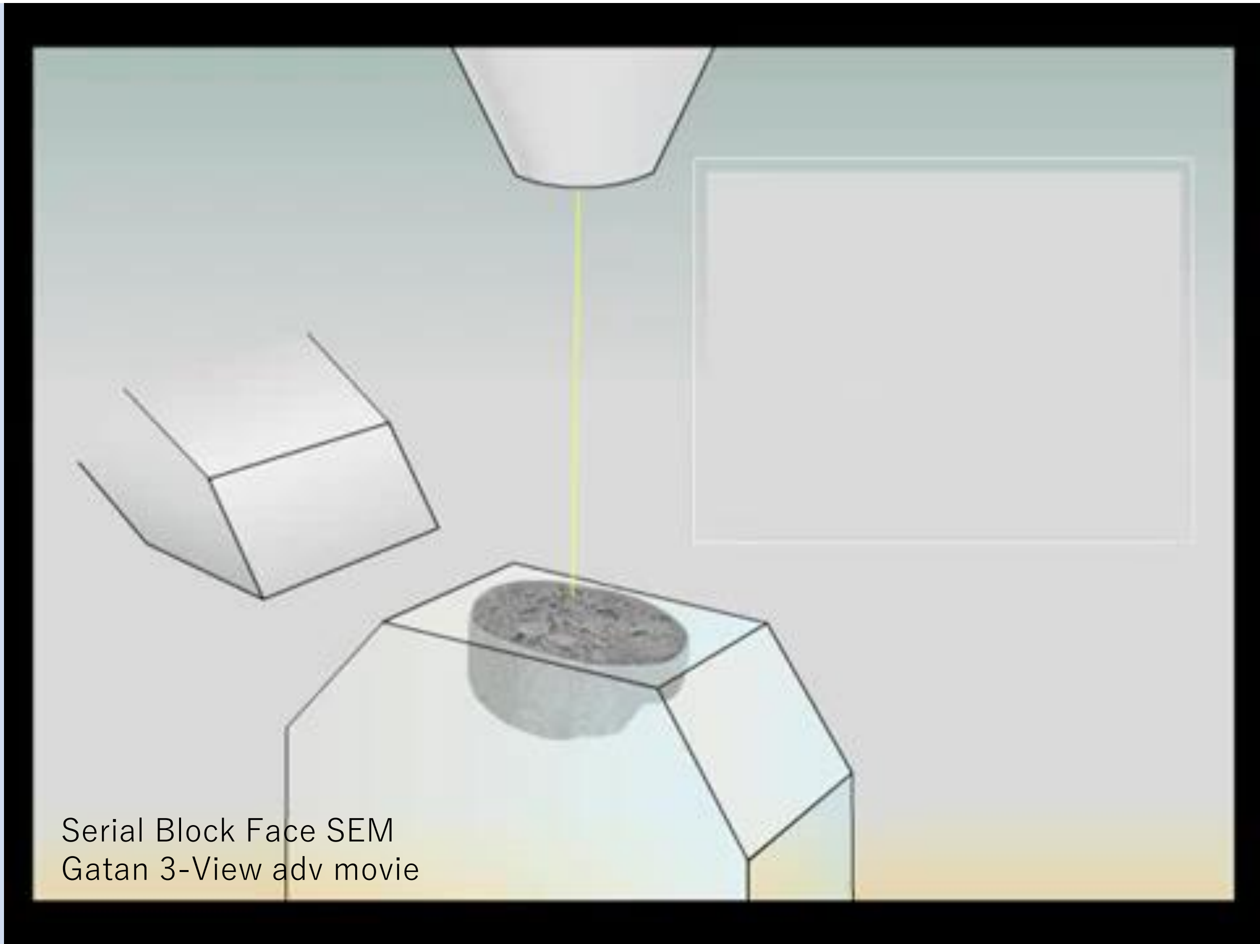
Application： 3D elemental map of Life

Comprehensive 3-dimensional mapping of elements/isotopes for life/tissues.

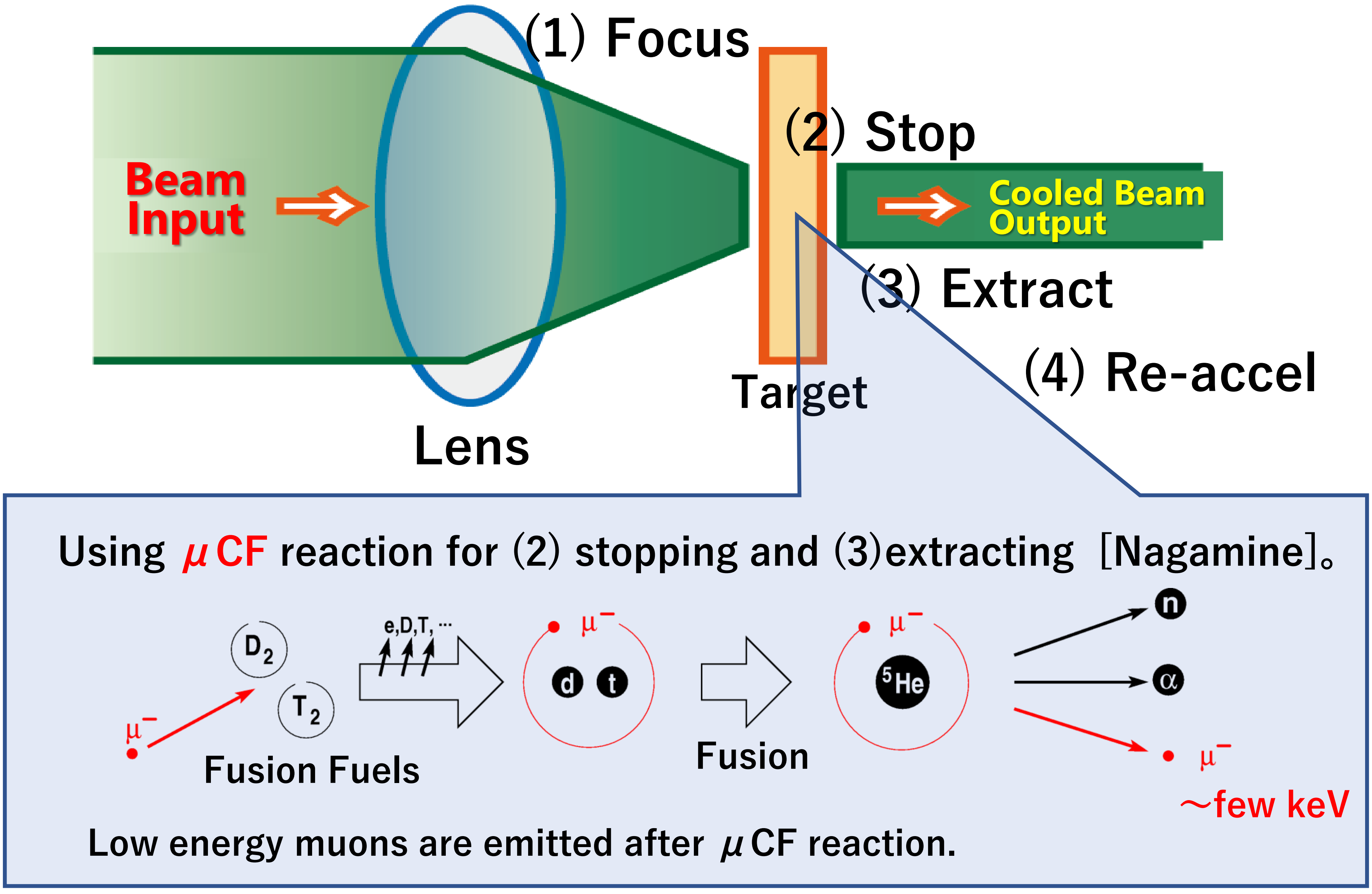
➡New generation of the life-informatics

1. Rapid freezing
2. Taking elemental images serially with cutting the frozen tissue.
3. 3-dimensional elemental map is obtained in μm resolution.

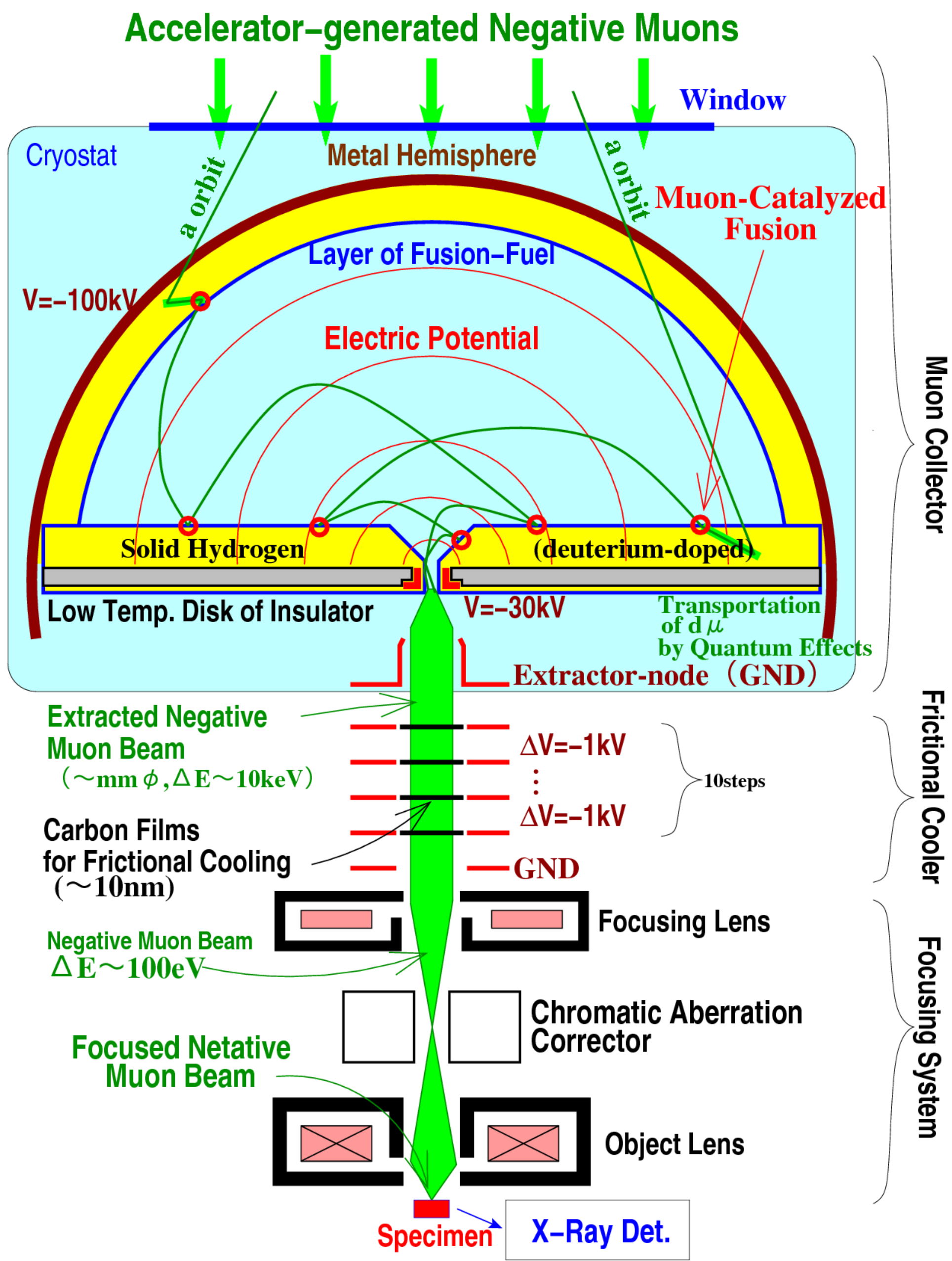
This method is a destructive measurement.



Beam Cooling of negative muon



Generation of Focused neg. Muon Beam.



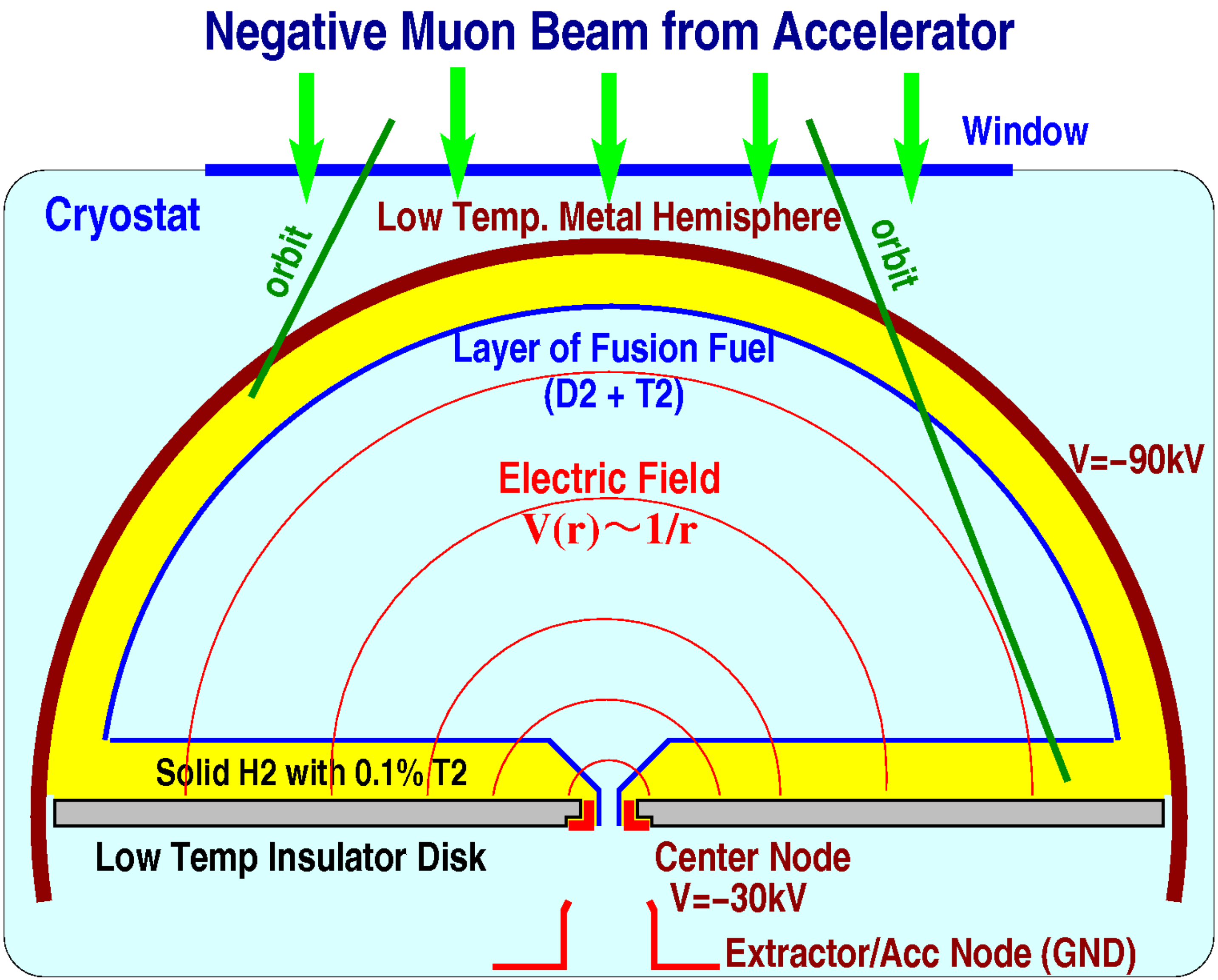
1) **Muon Catalyzed Fusion (μCF)** is applied to the beam-cooling. Captured muon into atom is dissociated with low energy ~ 10keV after μCF .

2) Accelerator muon is captured by solid H2 with mm-thickness. pμ is converted into dμ, and dμ diffuses in mm-range by **Ramsauer–Townsend effect**.

3) μCF on thin DT-layer on solid H2 dissociates the muon. The muon is transported into center by E-field.

4) Muon beam is extracted, is cooled frictionally, and is focused on specimen.

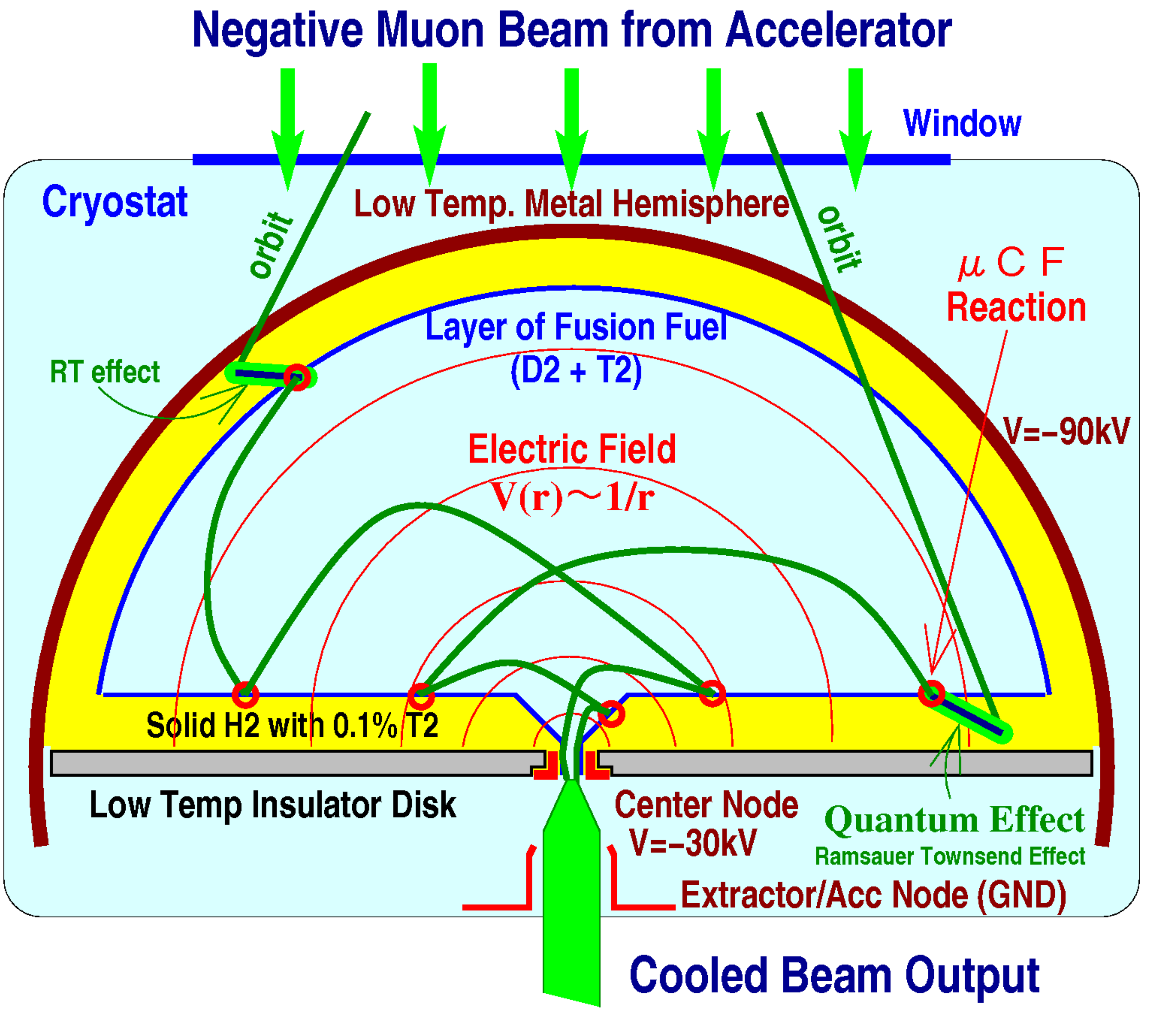
Negative Muon Collector



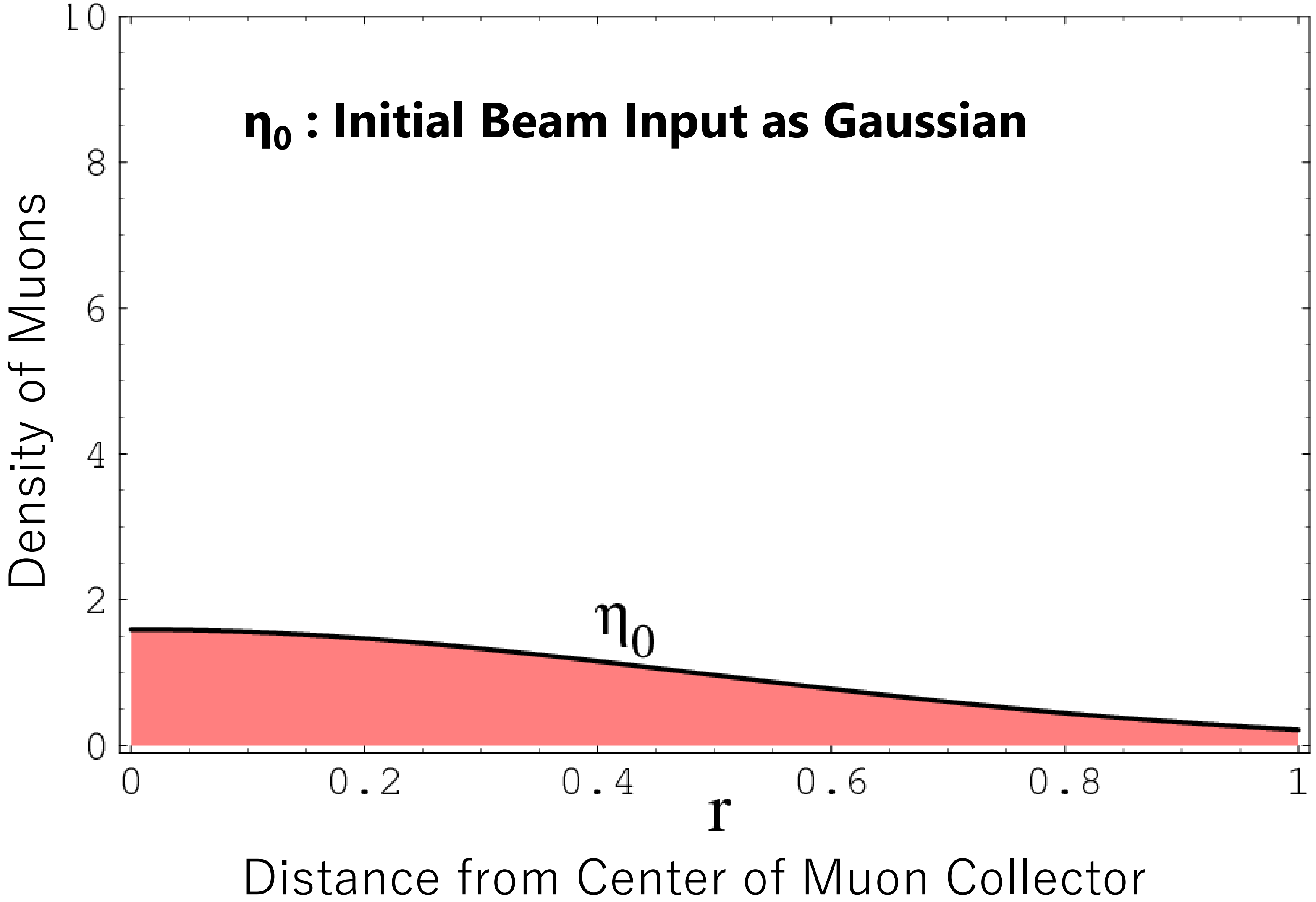
Use of Ramsauer Townsend Effect

- Solid H2 Layer : 1mm : 99.9% $\mathbf{H_2}$ + 0.1% $\mathbf{T_2}$,
  Solid DT Layer : 1μm : 70% $\mathbf{D_2}$ + 30% $\mathbf{T_2}$.
- Injected μ^- stops at Solid H2 Layer ➡ pμ is formed.
- Isotope exchange: pμ + t → tμ + p
  tμ obtains kinetic energy around E～40eV.
- Thermally tμ relaxes into sub meV.
  At the way, its scattering cross section becomes almost zero at E～1eV by Ramsauer Townsend effect.
- Finally, **tμ diffuses in sub mm range**.

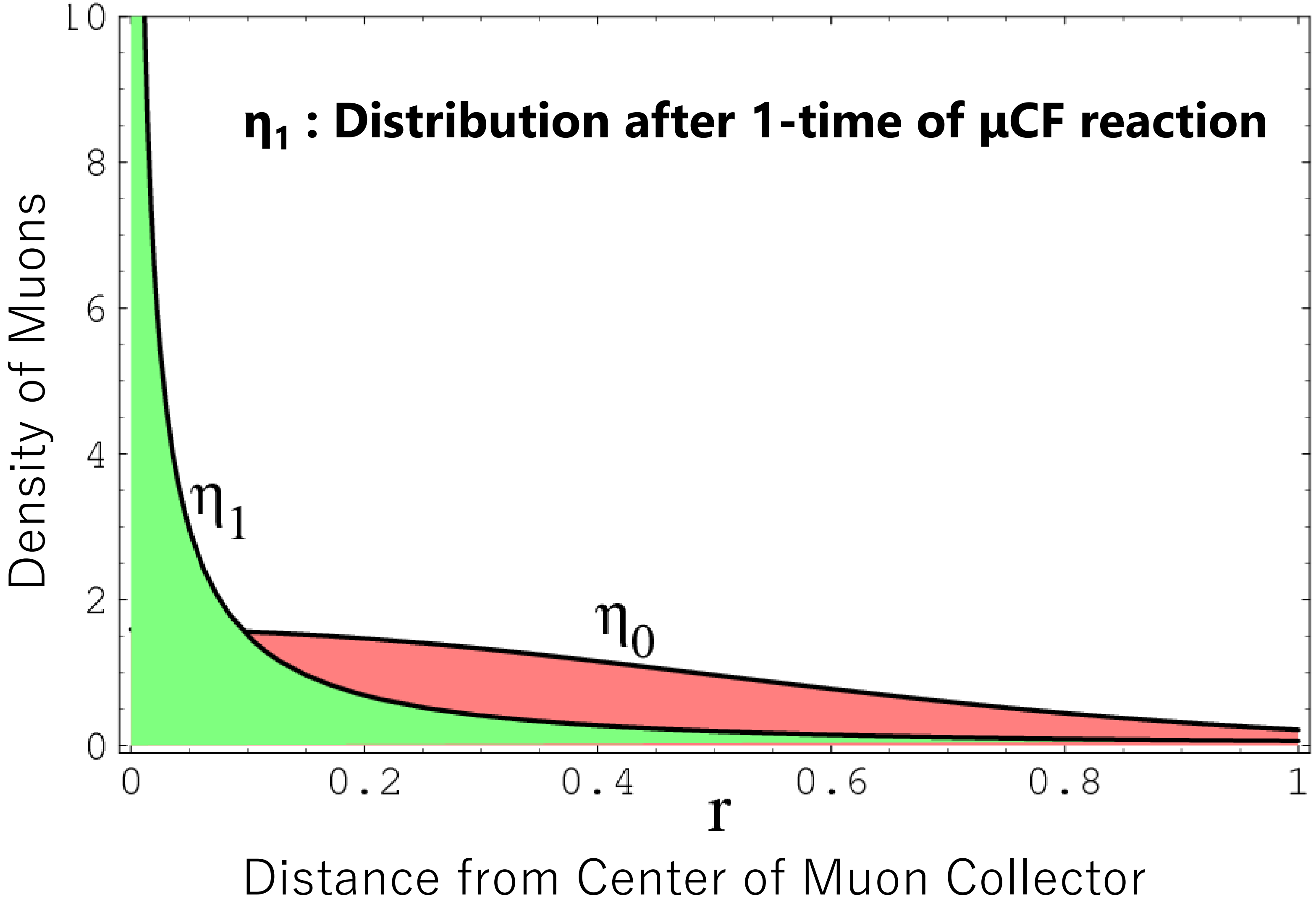
Negative Muon Collector



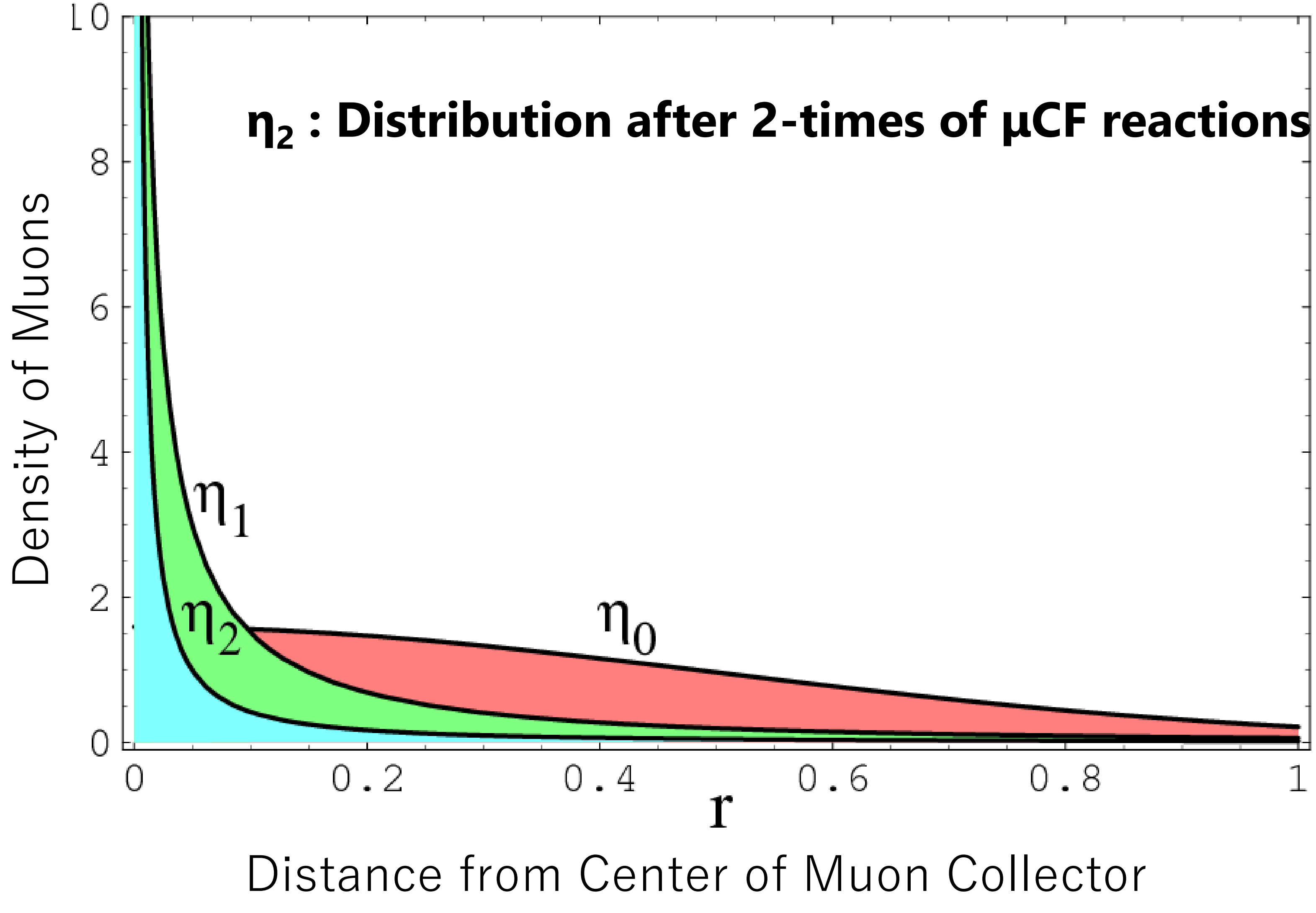
Simulation of Muon Collector



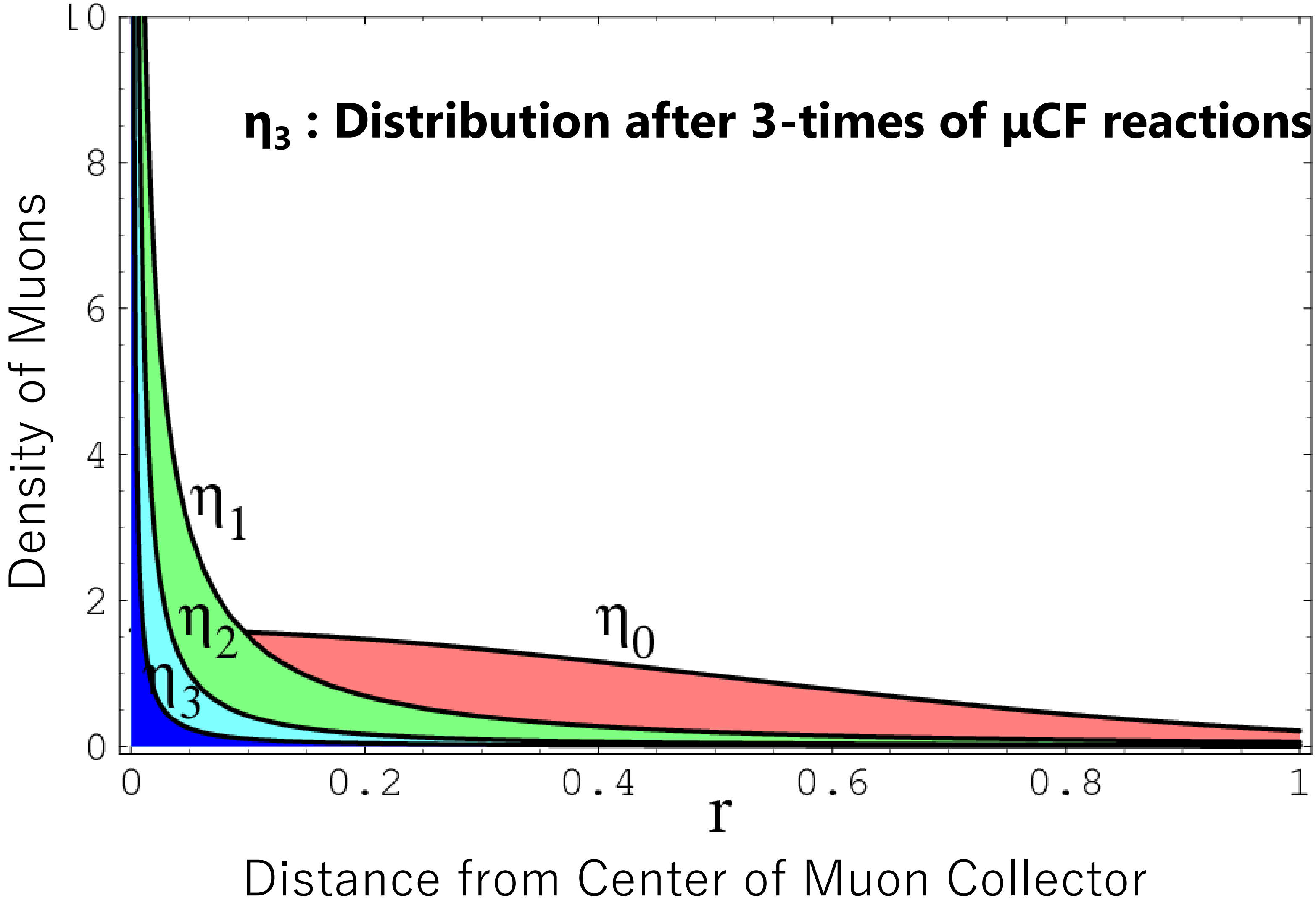
Simulation of Muon Collector



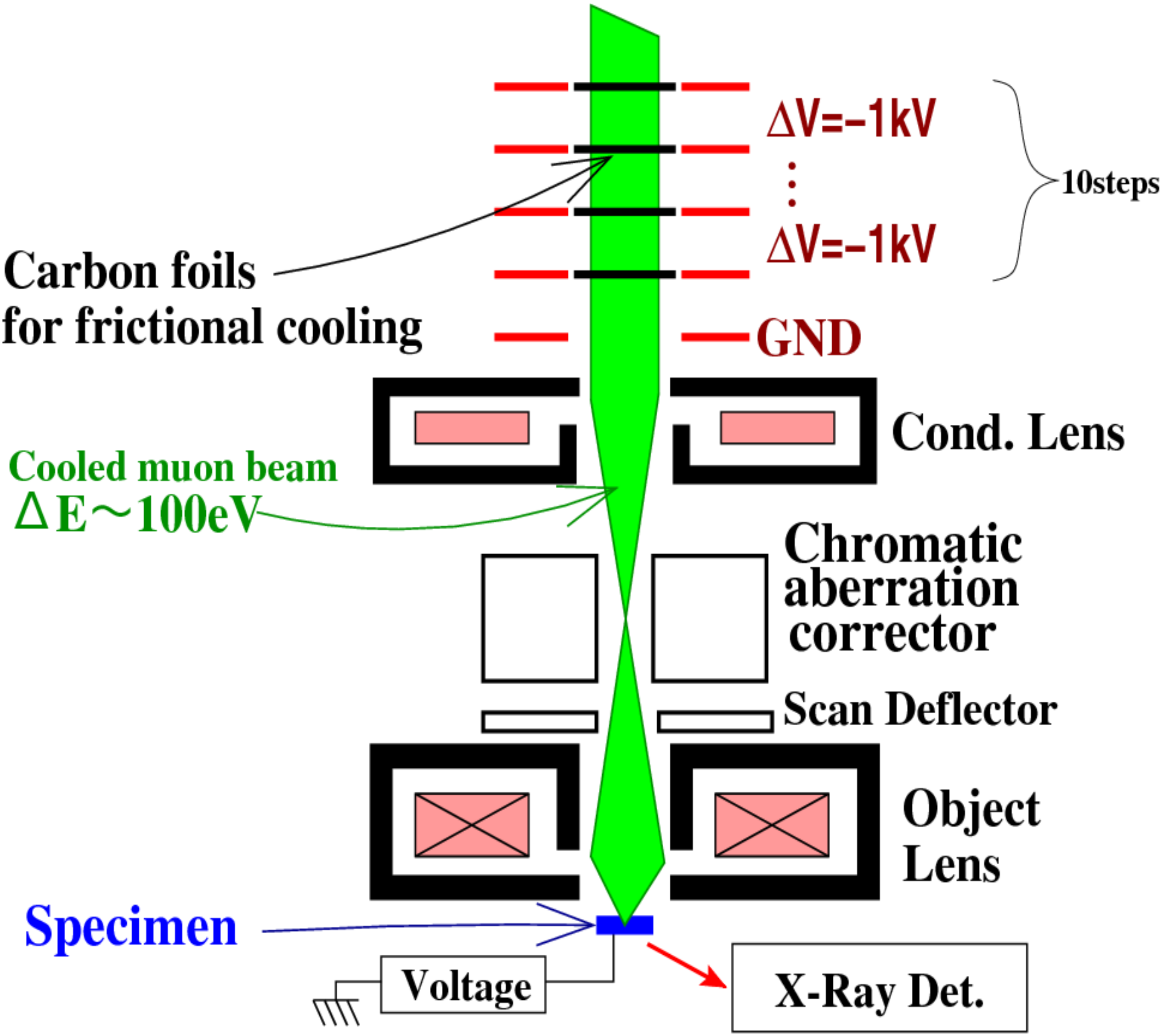
Simulation of Muon Collector



Simulation of Muon Collector



Parts of Cooler, Converge, Scan and Detection



- Frictional Cooling using carbon foils of 10nm thickness.
- Object Lens assisted by Chromatic Aberration Collector focuses beam into 10um diameter.
- XY-Scan, and retarding voltage scan.
- Detect X-ray Spectrum

3D mapping of Elements, Isotope and Chem.Props

Expected Performance

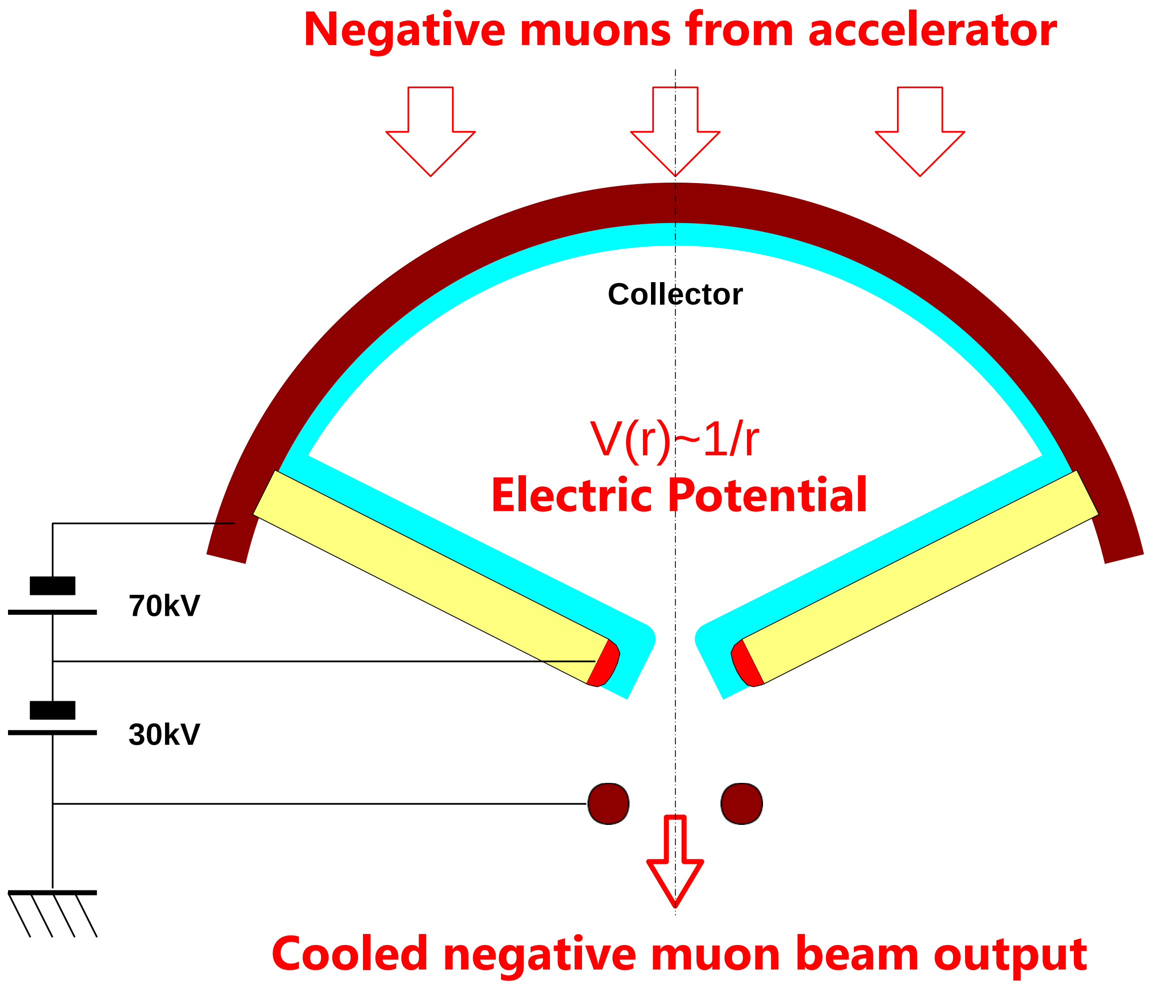
The Sμ^-M expected to have resolution <10μm, when Tritium is used. DD-fusion is less performance.

	DD-Fusion　Only D	**DT-Fusion　using T**
Re-emission rate of μ	2.0%	85.3%
Available # of μCF cycle	Only 1 step	More than 10 steps
Diameter of extracted μ beam	10mm	<0.1mm
Diameter of focused μ beam	**1mm**	**<10μm**
Beam strength of μ	～1/sec	>30/sec

⇒ Luminance Ratio (DT/DD) = 100 × 100 × 30

Use of Tritium is essential.

Optimization of the neg μ collector

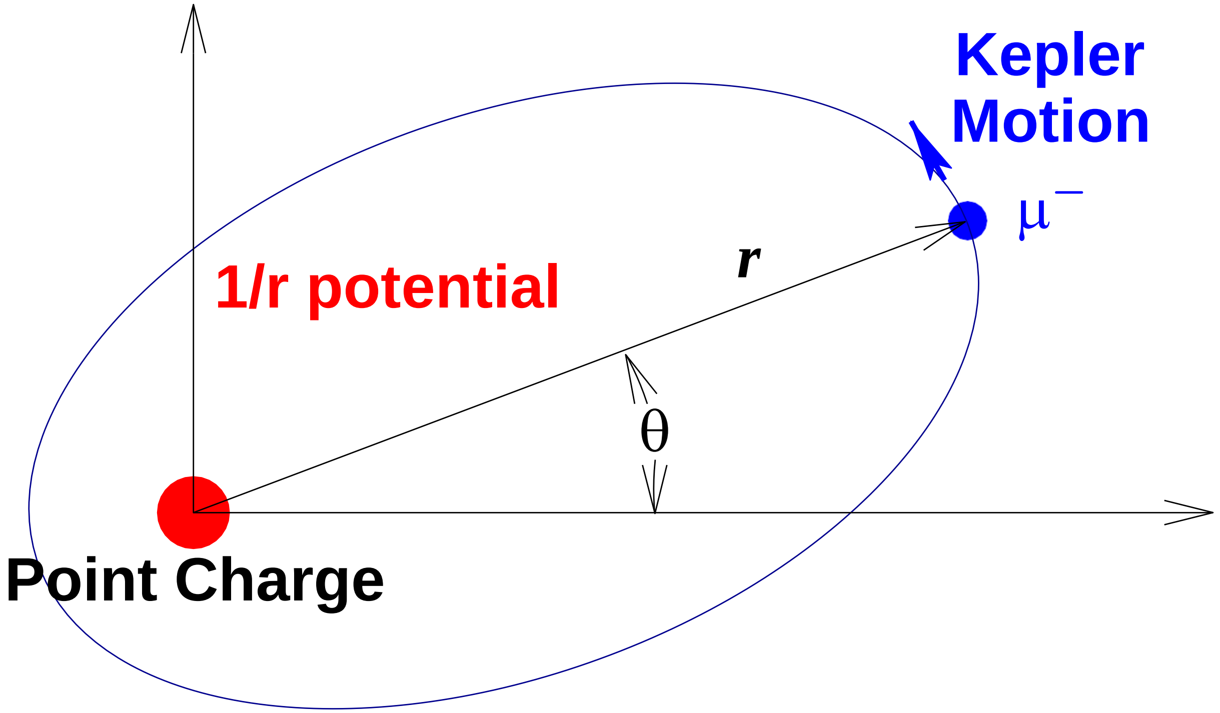


- We search **the most efficient design to collect μ^-** by electric potential **V(r)～1/r**. For generalization, conical form of the collector is assumed.

Orbits under (-1/r) potential : Kepler Motion

- **Lagrangian:**

$$L = \frac{m}{2}(\dot{r}^2 + r^2\dot{\theta}^2) + V(r), \quad V(r) = -\frac{e\,V_s\,r_s}{r} \qquad (1)$$



- **Eq of Motion:**

$$\ddot{r} = \frac{m^2}{l^2}\frac{1}{r^3} - \frac{eV_s r_s}{m}\frac{1}{r^2}, \tag{2}$$

constant：$l = mr^2\dot{\theta}$　　：angular momentum.

- **General Solution （Eliptic curve）：**

$$r = \frac{r_c}{1+\varepsilon\cos(\theta+\alpha)}. \tag{3}$$

ε: eccentricity, α: phase、r_c: radius of circlar-motion

$$r_c = \frac{l^2}{eV_s r_s m}. \tag{4}$$

- **A positive parameter depending on initial condition**
  (initial position r_1, projection angle β_1, velocity v_1)
  is introduced:

$$Q := \frac{\frac{1}{2} m {v_1}^2}{-V(r_1)} \tag{5}$$

When $Q < 1$, the orbit closes.

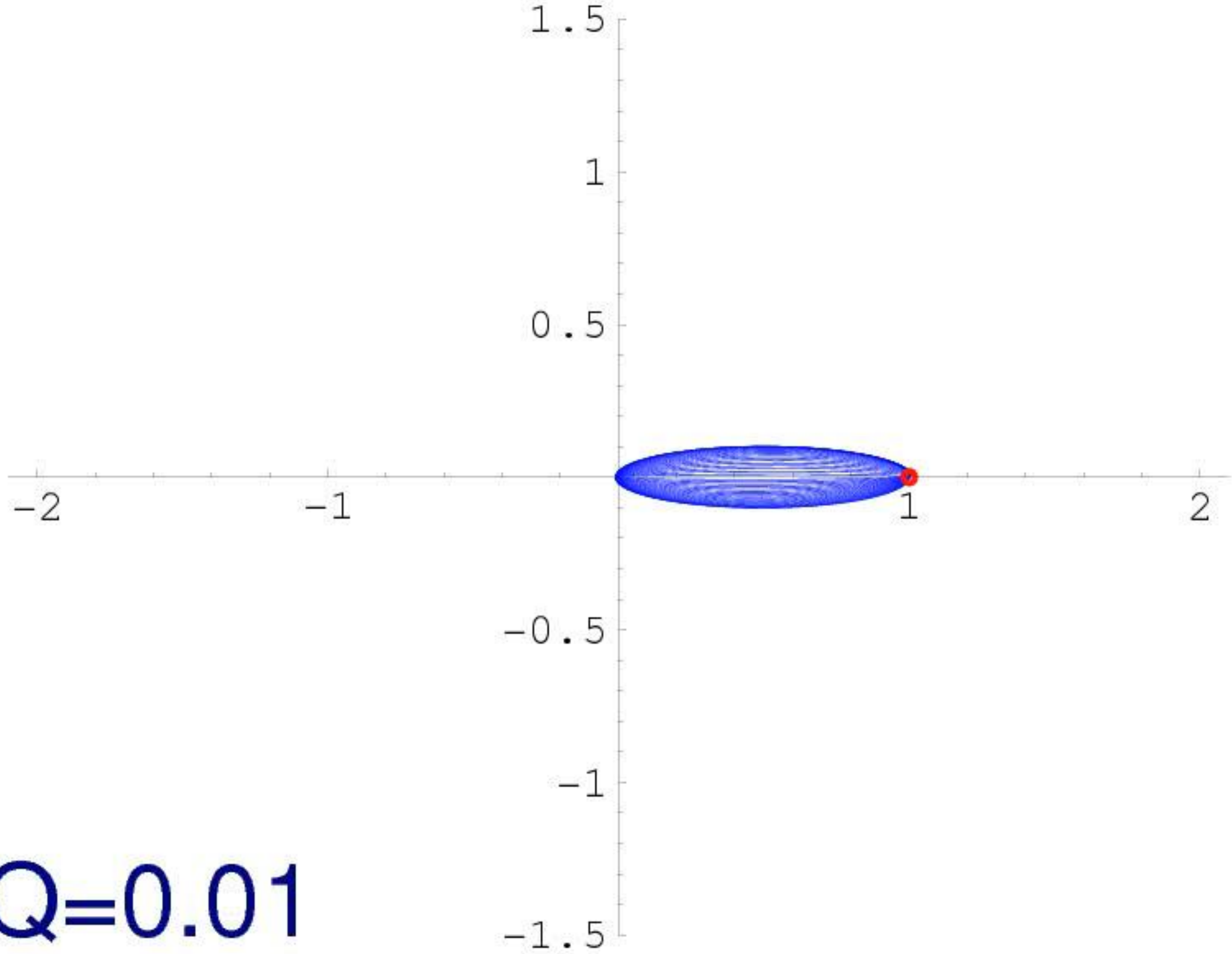
Q and β determin the motion：

$$\frac{r_c}{r_1} = 2Q\cos^2\beta_1, \tag{6}$$

$$\varepsilon = \sqrt{1 + 4(Q-1)Q\cos^2\beta_1} \tag{7}$$

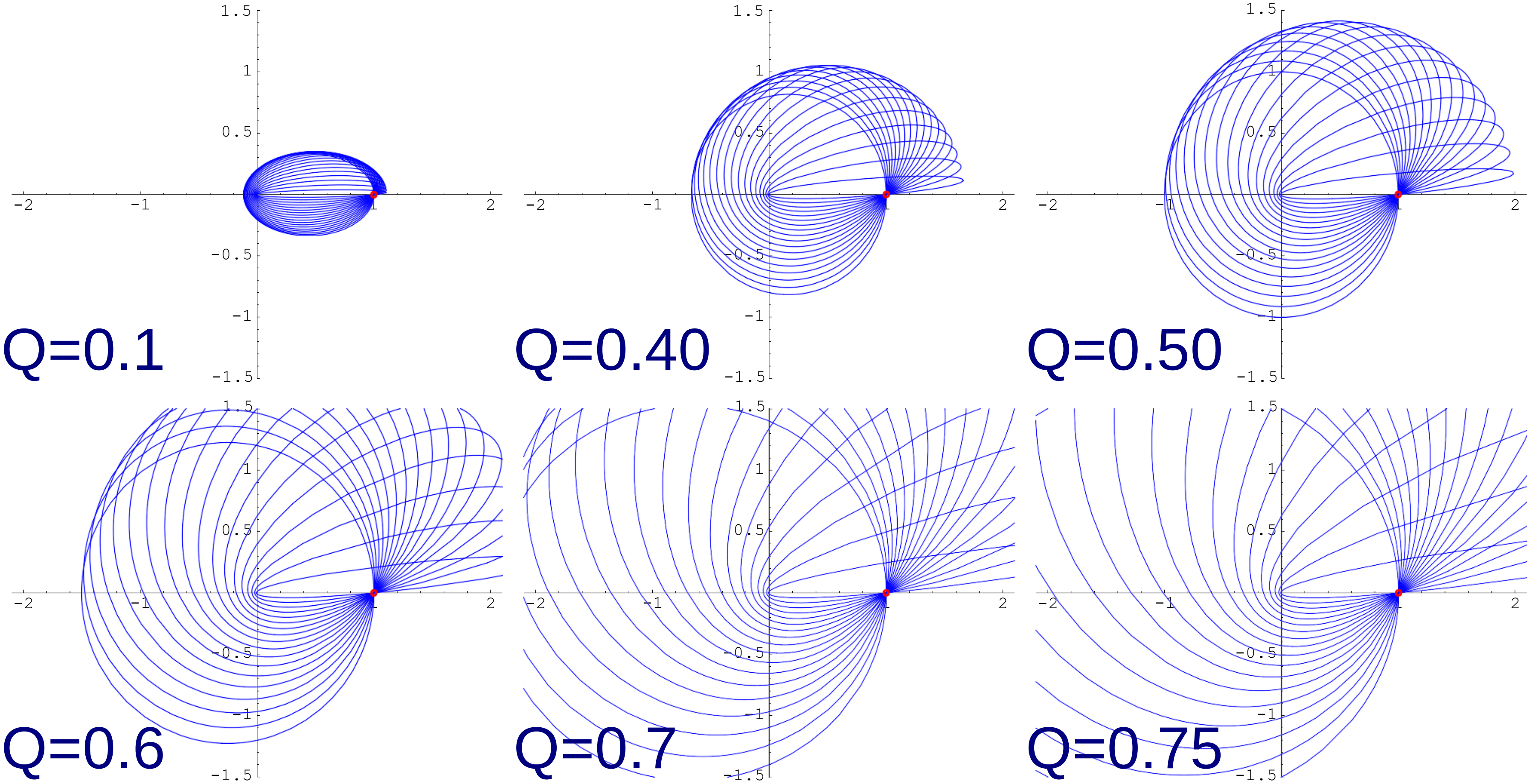
$$\alpha = \arg\left[\, \sin\beta_1\cos\beta_1 + i\left(\cos^2\beta_1 - \frac{1}{2Q}\right)\right] \tag{8}$$

Orbits for projection angles β_1

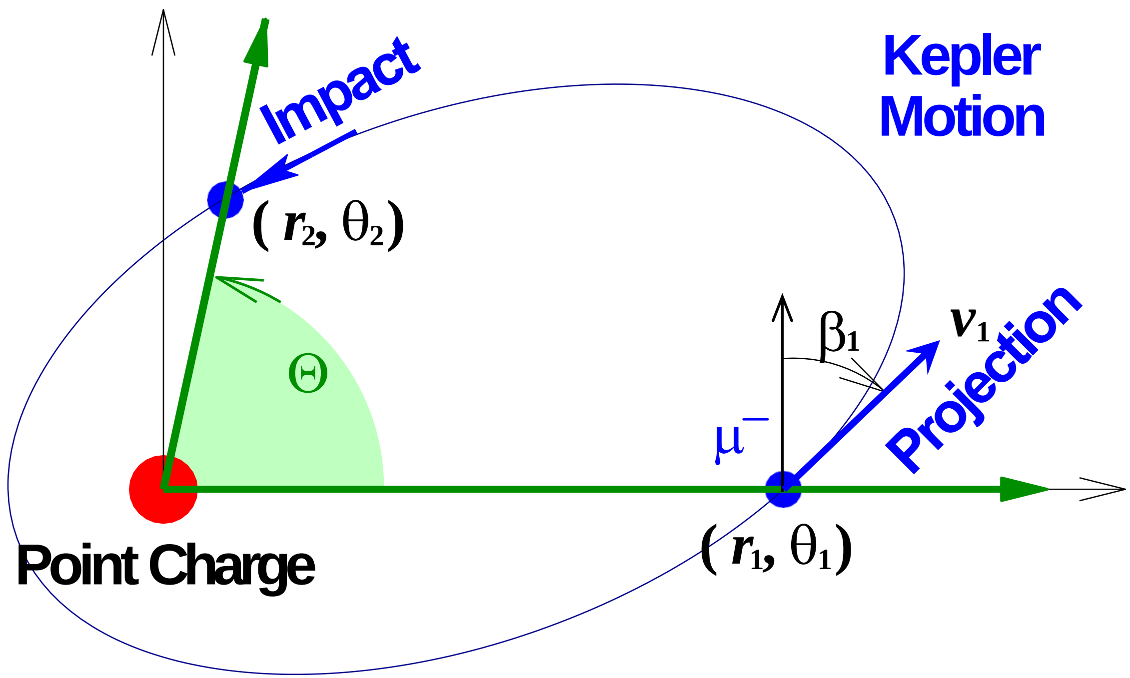


Q=0.01

Orbits for several Q



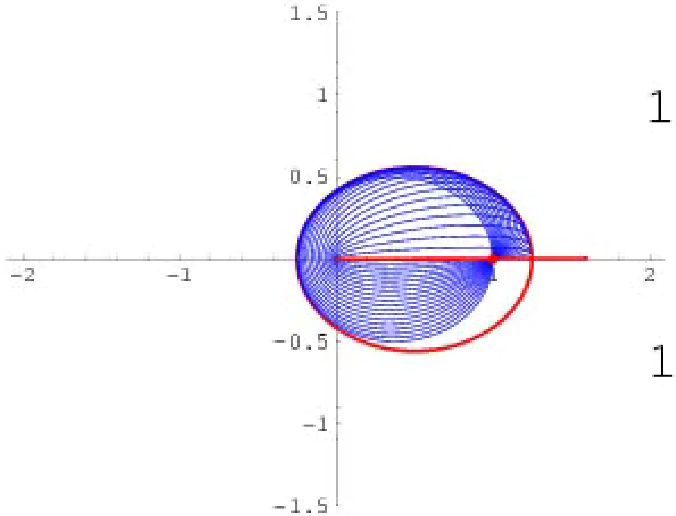
Impact point on counter side of fan



- By the motion from projection-point（$\theta_1 = 0$）to impact-point（$\theta_2 = \Theta$）, radius changes as $r_1 \rightarrow r_2 = R \times r_1$, where R is mag/shrinking ratio.
- When distribution of projection-angle is fixed, the point splitting function (PSP) is obtained.

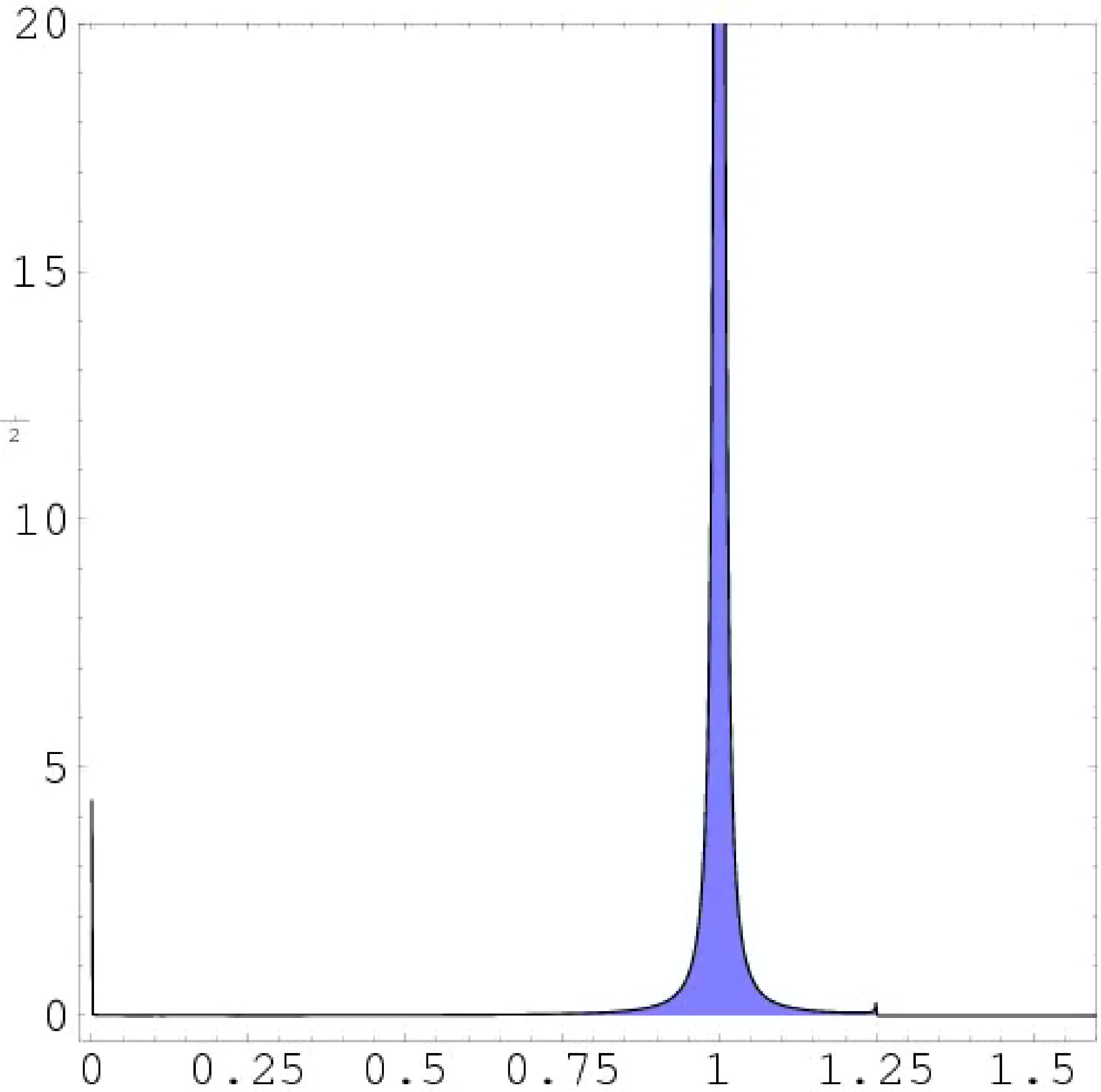
Distribution of Impact Points depending on Fan-angle

Projection-Angle-Distribution is assumed to be uniform.



$$Q = 0.2,$$

$$\Theta = 0.001\pi.$$



PSF is analytically derived for uniform-angle projection

$$
\begin{aligned}
n(R)^2 \quad = \quad & \Bigg[+2R(\cos\Theta - R)\Big\{ +\sqrt{1+\cos\Theta}(-Q+R+\cos\Theta(Q-1)R) \\
& \quad +\sqrt{2Q/R+\cos\Theta*(Q-1)^2+(Q-1)(Q+1)}(\cos\Theta*R-1) \\
& \quad \Big\}/(1-2\cos\Theta R+R^2) \\
& \quad +\Big\{ -2*(\cos\Theta-1)*R+Q(2\cos\Theta R-1)\Big\}\sqrt{(1+\cos\Theta)} \\
& \quad +\Big\{ +((\cos\Theta-1)+(\cos\Theta+1)Q^2)(2\cos\Theta R-1) \\
& \quad\quad +Q(-1/R+5\cos\Theta-4\cos\Theta^2 R) \\
& \quad \Big\}/\sqrt{2Q/R+\cos\Theta(Q-1)^2+(Q-1)(Q+1)} \Bigg]^2 \\
& \times \Bigg[+Q^2(1-2\cos\Theta R+R^2)^2/(1-\cos\Theta) \\
& \quad -R^2\Big\{ +\sqrt{1+\cos\Theta}(-Q+R+\cos\Theta(Q-1)R) \\
& \quad\quad +\sqrt{2Q/R+\cos\Theta(Q-1)^2+(Q-1)(Q+1)}(\cos\Theta R-1)\Big\}^2 \Bigg]^{-2} \times \frac{1}{\pi} \qquad (9)
\end{aligned}
$$

- PSF ($n(R)$) depending on fan-angle Θ :

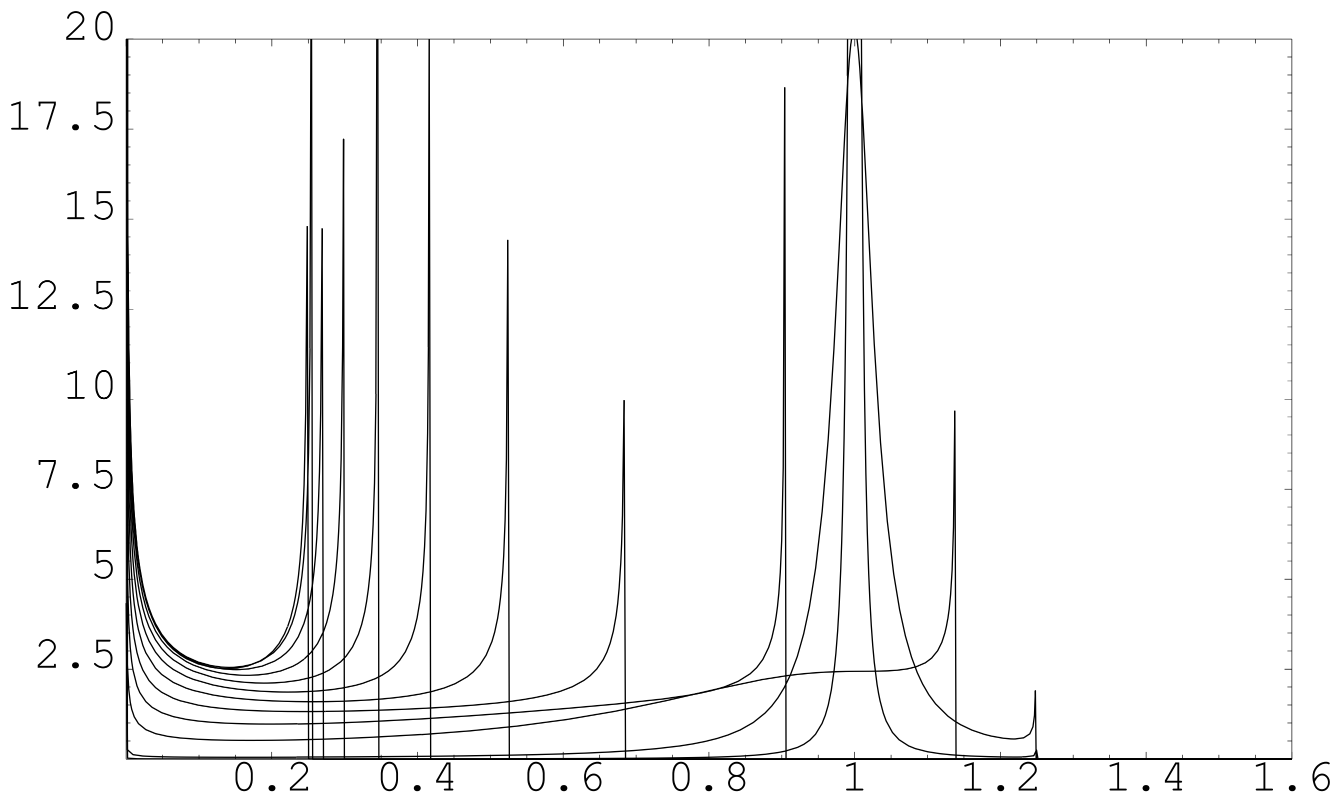


FIG: $Q = 0.2$, $\Theta/\pi = 0.001, 0.01, 0.1, 0.2, 0.3, \cdots, 1.0$

- **When Θ = π, PSF becomes simple form：**

$$n(R,Q) = \begin{cases} \dfrac{1}{\pi}\left[(1+R)\sqrt{(1-Q)R(R_{\text{sing}}-R)}\right]^{-1} & (R \le R_{\text{sing}}) \\ 0 & (R > R_{\text{sing}}) \end{cases}$$

$$R_{\text{sing}} = Q/(1-Q)$$

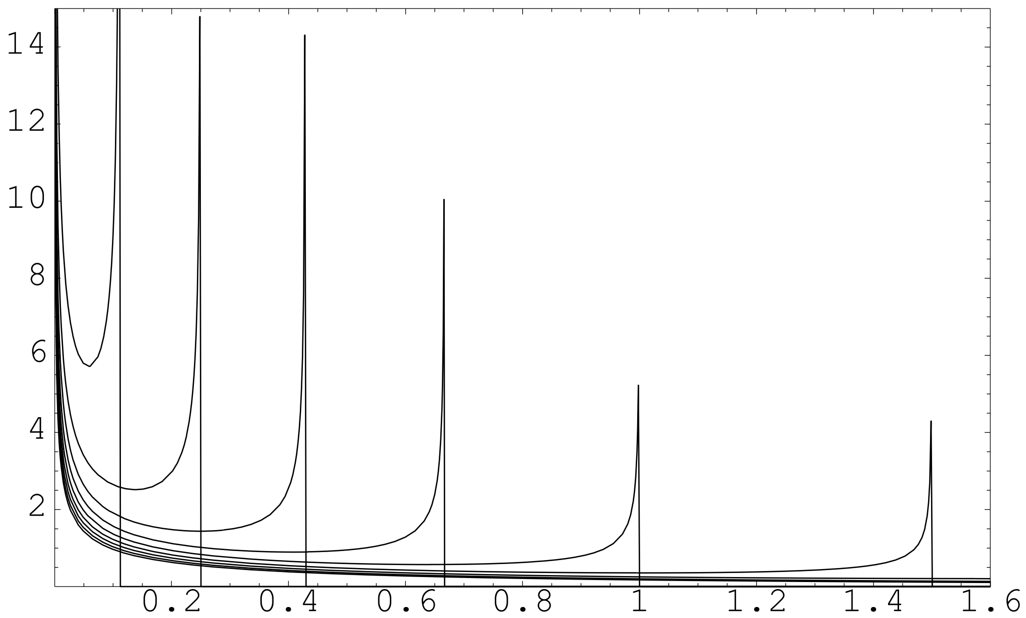


FIG: PSF for $Q = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$, $\Theta = \pi$.

Average and deviation of mag-rate R

is defined by giving distribution of projection-angle ρ(β) **:**

$$\langle R \rangle := \int_{-\pi/2}^{\pi/2} d\beta\, \rho(\beta) R(Q, \Theta, \beta), \qquad (10)$$

$$R^2 := \int_{-\pi/2}^{\pi/2} d\beta\, \rho(\beta) R^2(Q, \Theta, \beta), \qquad (11)$$

$$\sigma^2 := R^2 - \langle R \rangle^2. \qquad (12)$$

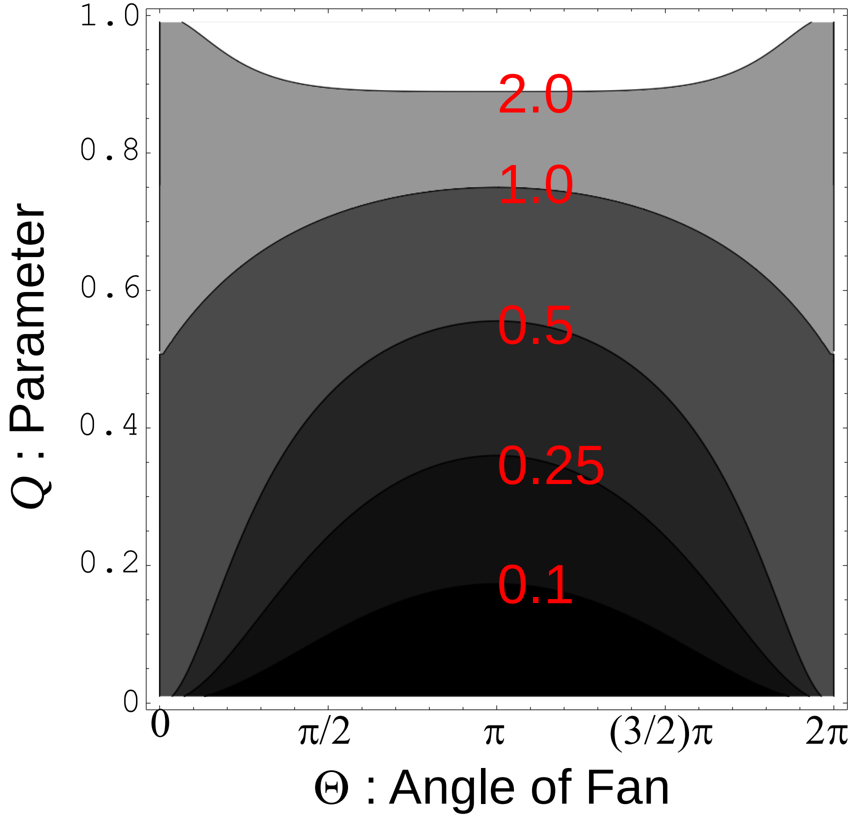
Here we will assume uniform distribution:

$$\rho(\beta) \sim \text{constant}$$

Average of Mag-rate R

$$\langle R \rangle = \cos\Theta + (Q + (Q-1)\cos\Theta)\sqrt{\frac{\cos\Theta - 1}{Q^2 - 1 + (Q-1)^2\cos\Theta}},$$

Distribution of $\langle R \rangle$

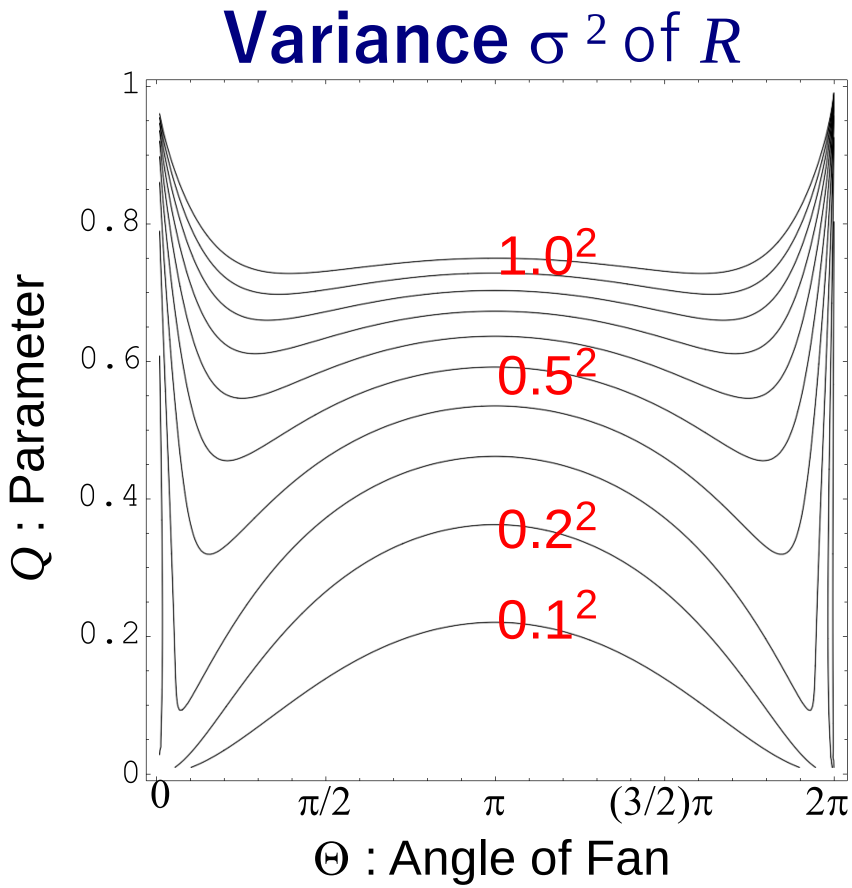


When $\langle R \rangle \leq 1$,
$\langle R \rangle$ is minimized at $\Theta = \pi$.

Variance of mag-rate R

$$\langle R^2 \rangle = \cos 2\Theta + Q^2 \frac{-2Q\cos\Theta + \frac{1}{2}(3+\cos 2\Theta)}{(-Q^2+q^2)^{3/2}} - \frac{q\cos(2\Theta)}{(-Q^2+q^2)^{1/2}}$$

(New parameter: $q := 1 + (Q-1)\cos\Theta$.)



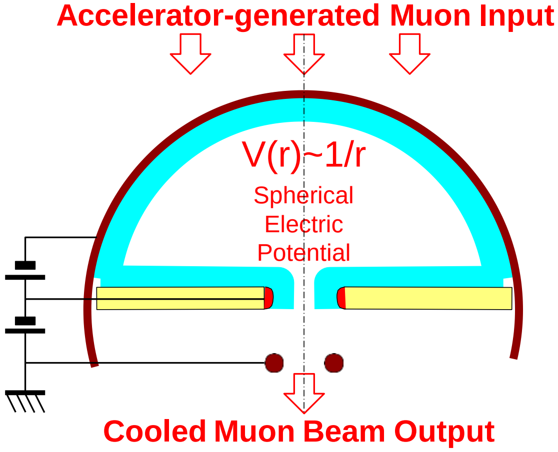
σ^2 is also minimize when $\Theta = \pi$, except for $Q \sim 0$

Optimized fan/cone-angle

Theorem1:
For 2-dim, the fan-angle is optimized by $\Theta = \pi$.

Theorem2:
For 3-dim, the cone-angle is optimized by $\Theta = \pi$.
Disk Shape

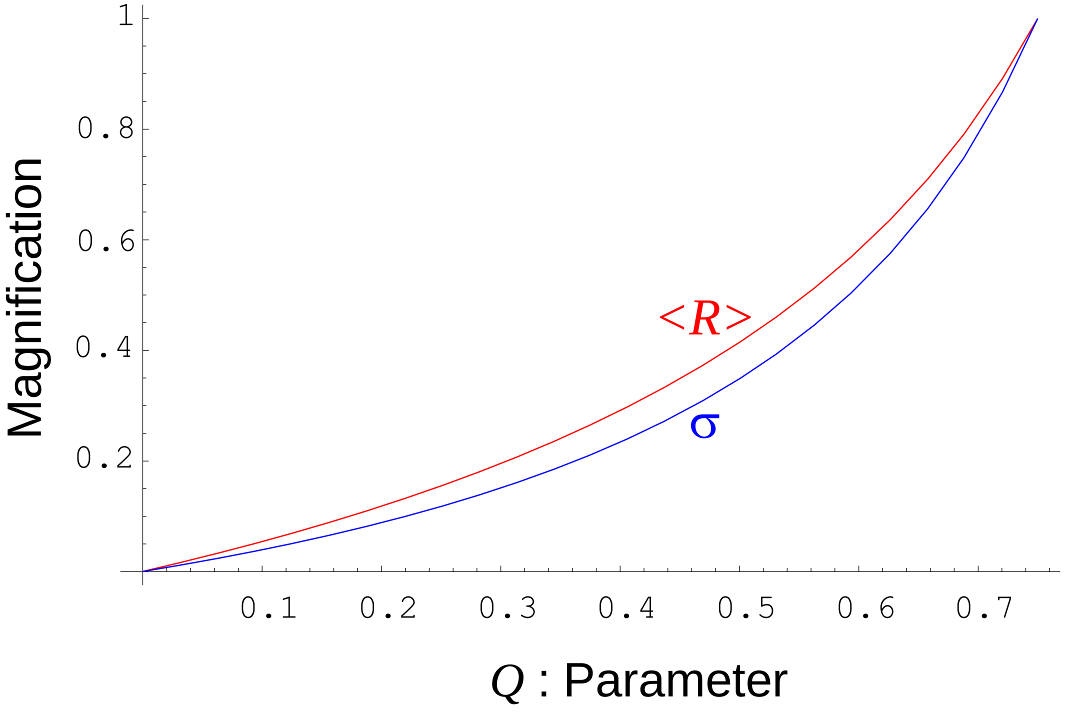
Shape of muon collector is optimized by disk-form rather than cone.



Ave. and Variance of Mag-rate of Disk Collector

$$\langle R \rangle = (1-Q)^{-1/2} - 1, \quad (13)$$

$$\sqrt{\sigma^2} = \langle R \rangle \times \frac{1}{\sqrt{2}} (1-Q)^{-1/4}. \quad (14)$$



Average $\langle R \rangle$ and variance $\sqrt{\sigma^2}$
of the magnification-rate R

Multistep cooling by Muon Collector

- Initial distribution $\eta_0(r)$ is given by accelerator

- By re-emission of muon by μCF reaction, the distribution is developed as a generation:

$$\eta_0 \to \eta_1 \to \eta_2 \to \eta_3 \to \cdots \to \eta_n \to \cdots.$$

- Relation of generation：

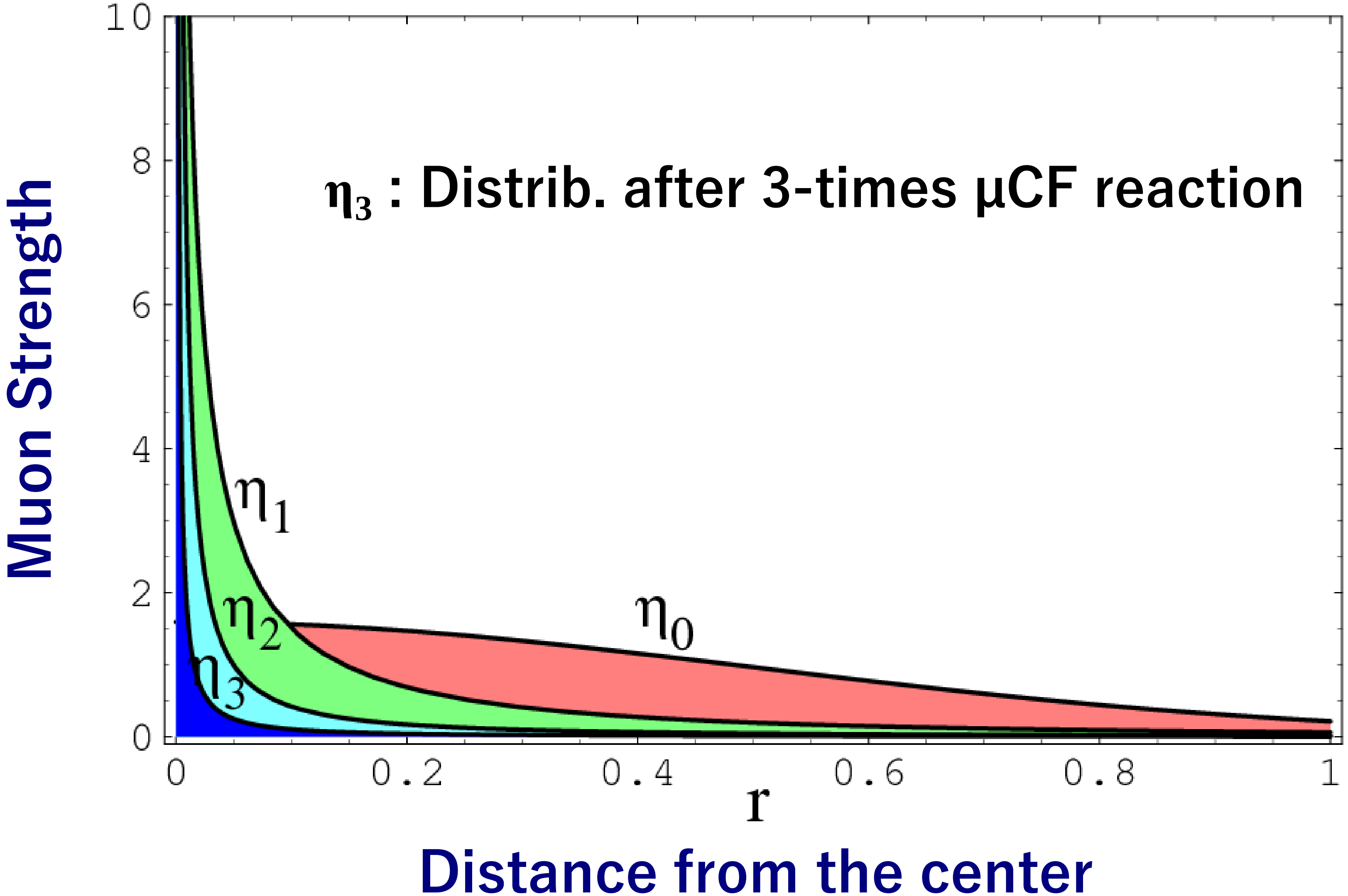
$$\eta_{n+1}(r) = \int_0^\infty d\tilde{r}\, K(r,\tilde{r}) \times \eta_n(\tilde{r}), \qquad (15)$$

The integral-kernel depending on position r is derived from the PSP:

$$K(r,\tilde{r}) := \frac{1}{\tilde{r}} n \left[\frac{1}{\tilde{r}}, Q(\tilde{r})\right]. \qquad (16)$$

Evolution of the Generation

Gauss distribution $\sigma = 1/2$, $Q(\sigma) = 1$ is assumed as initial input.



Mag-Rate： Applying Volt. vs re-emission Energy

Re-emission energy ～ 2 keV

EV-ratio ＝ Re-emission energy ／ Applying Voltage

	Generation of μCF Reactions				
EV-ratio	0	1	2	3	4
10%	1	0.12	1.4×10^{-3}	2.0×10^{-7}	4.0×10^{-15}
50%	1	0.41	5.1×10^{-2}	6.6×10^{-4}	1.1×10^{-7}
60%	1	0.58	1.4×10^{-1}	6.2×10^{-3}	1.1×10^{-5}
70%	1	0.83	4.5×10^{-1}	9.2×10^{-2}	3.1×10^{-3}
75%	1	1	1	1	1

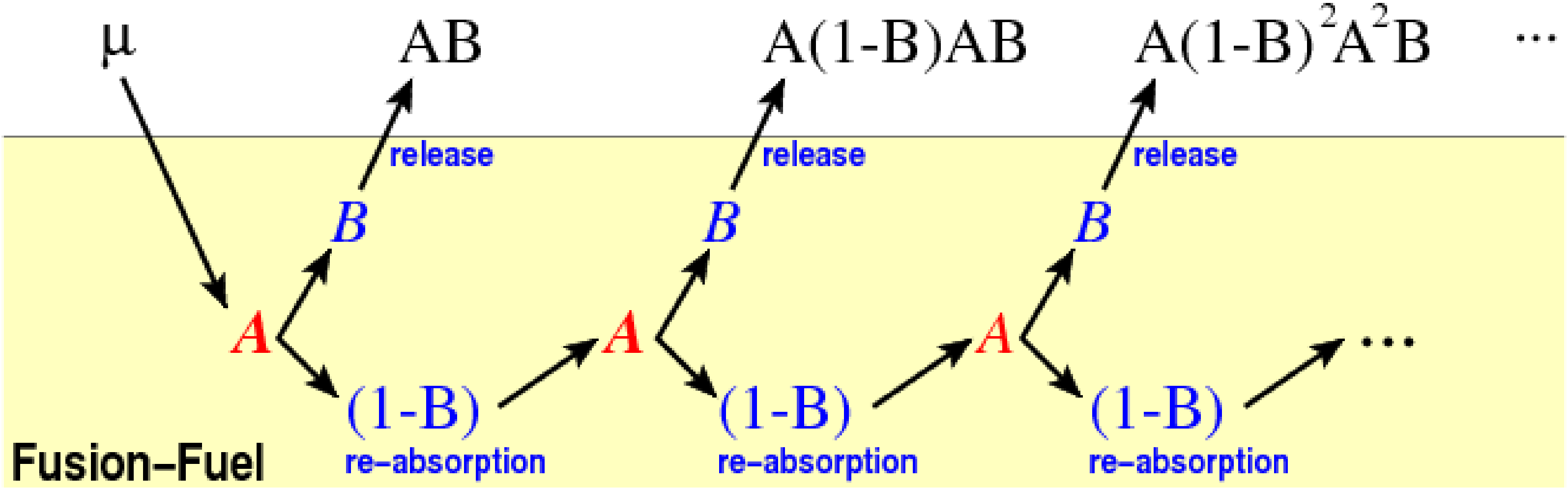
- We have assumed ideal potential $V(r) = C/r$.
- Mag rate becomes 1/1000 by applying 10kV with 4～5 μCF generation.
- Possible generation is up to 10. (1-time makes 15% loss, 4-times make 50% loss)

Rate of the re-emission after slow muon impacts (Okutsu)

A:	Re-emission rate from D or T	**A_{DD}=0.16, A_{DT}=0.98,**
B:	Posibility of releasing to front side	～0.1、
(1-B):	Posibility of recapturing by D or T	～0.9

(Calculated by inpact E=8V, project E=3keV)

Sum of releasing probability by multiple μCF reaction：

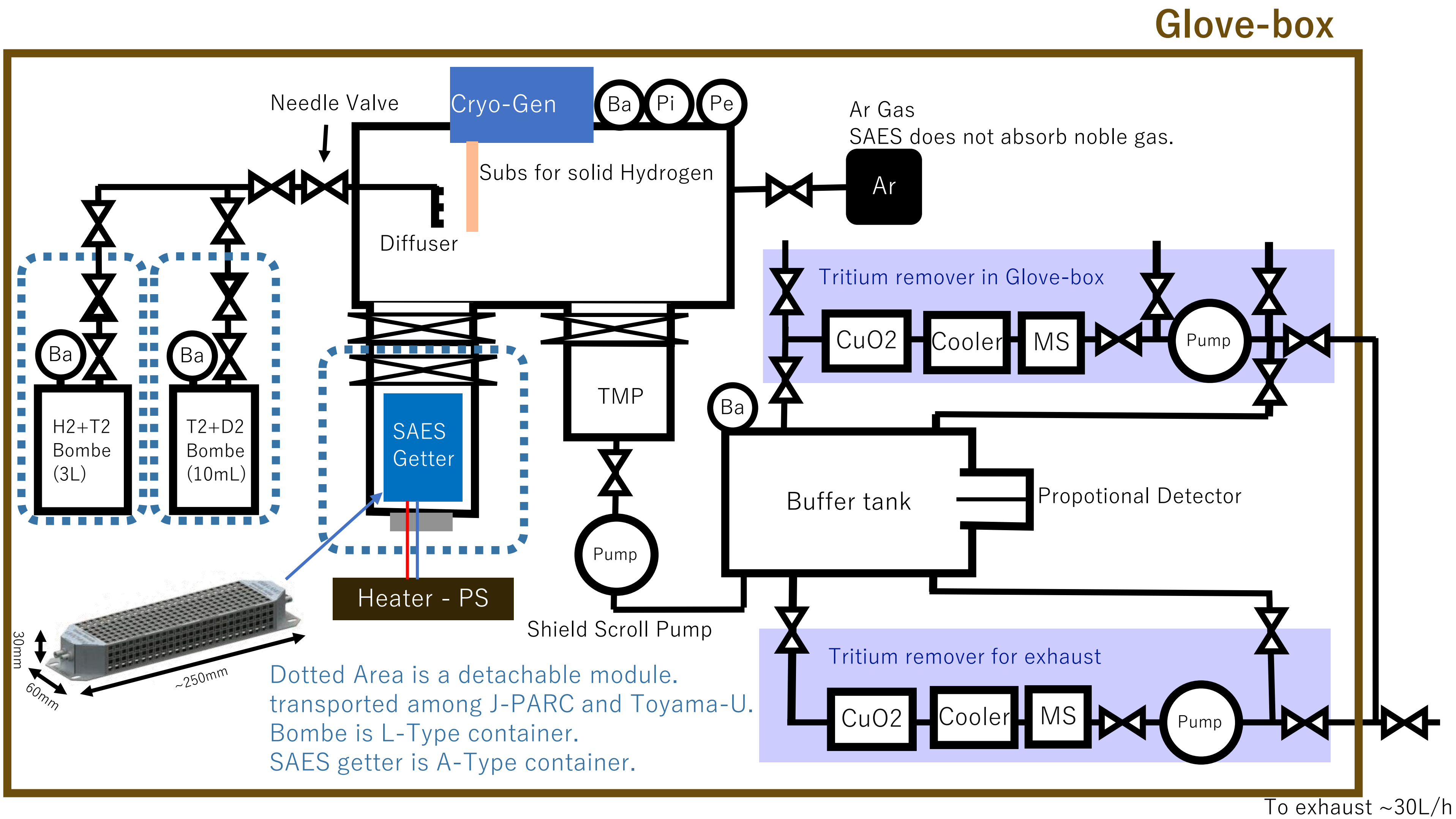


$$C = AB + A(1-B)^1A^1B + A(1-B)^2A^2B + A(1-B)^3A^3B + \cdots$$
$$= AB\,\Sigma_{n=0,\infty}(1-B)^nA^n$$
$$= AB/(1-(1-B)A)$$

DD-reaction： 2.0% ··· μCF generation is only 1-time.
DT-reaction： 85.3% ··· μCF generations can be 10-times.

Almost same result by Montecarlo Calculation.

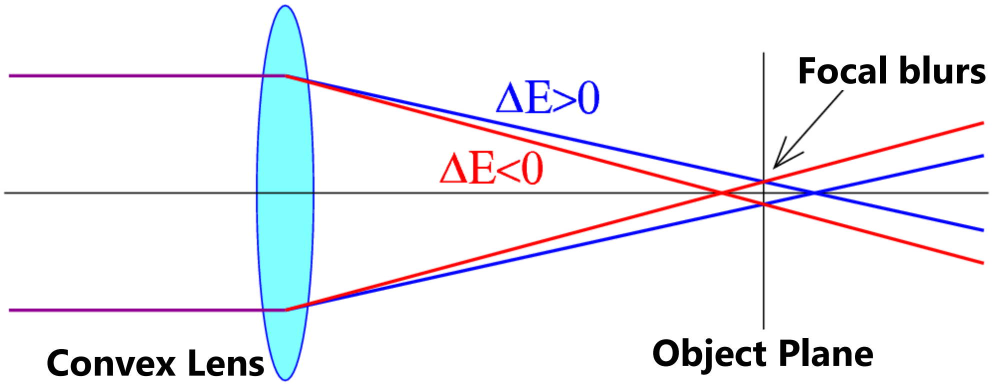
Design of Tritium Handing collaborating with Toyama U.



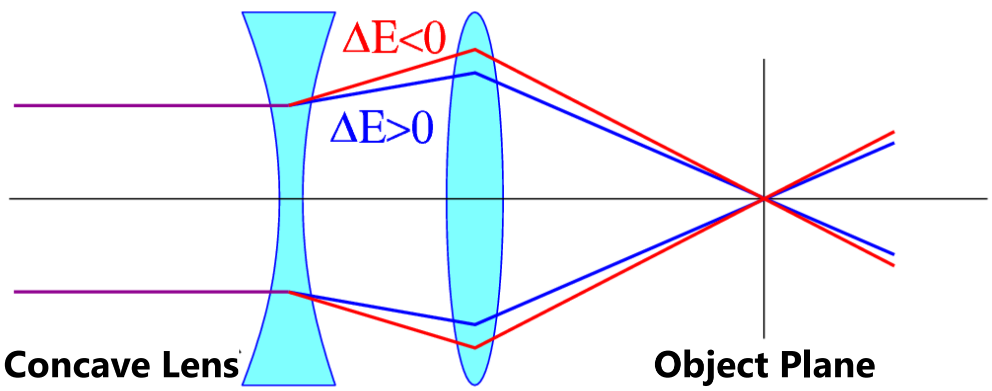
Designed by Hatano, Hara (Toyama U.), and Natori (KEK).

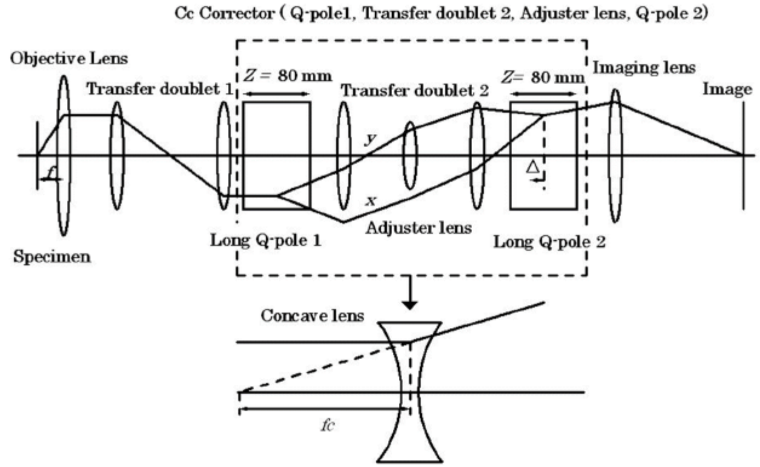
Beam Focusing by Aberration Corrector

- There is ΔE ~ 1 keV even for beam-cooling.
- Chromatic aberration of conversion-lens blurs the focal point.



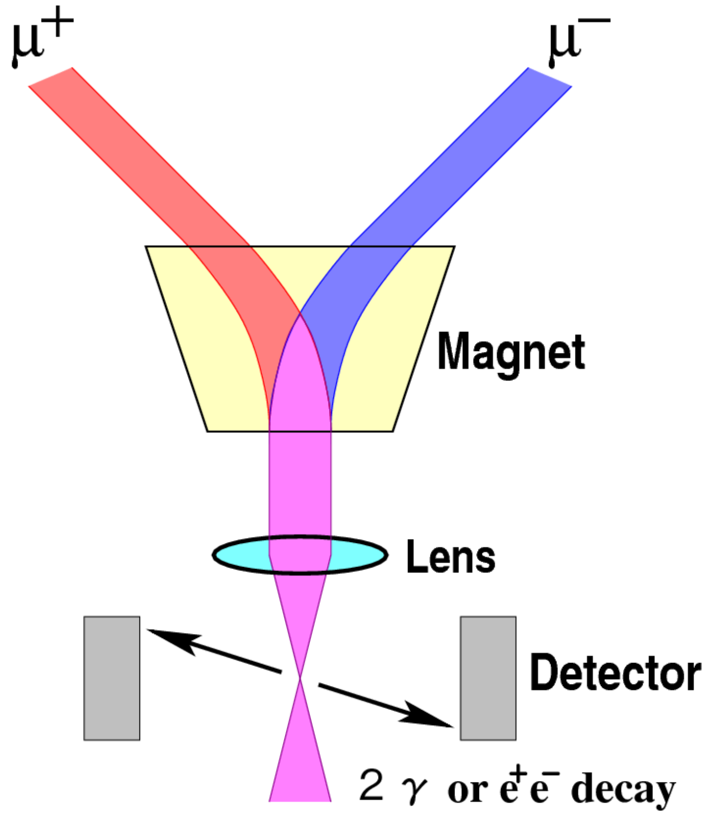
- **Chromatic aberration corrector solves the problem.** Hosokawa Corrector





The other Applications of the Focused μ⁻

- **Generation of True Muonium $\mu^+ \mu^-$ and spectroscopy**



- **Beam source for Muon Collider (${\mu^+}\rightarrow\leftarrow{\mu^-}$)**
- **Soft-error evaluator for IC/LSI by focused μ^-**