

Measurement of Neutron Electric Dipole Moment (J-PARC P33)

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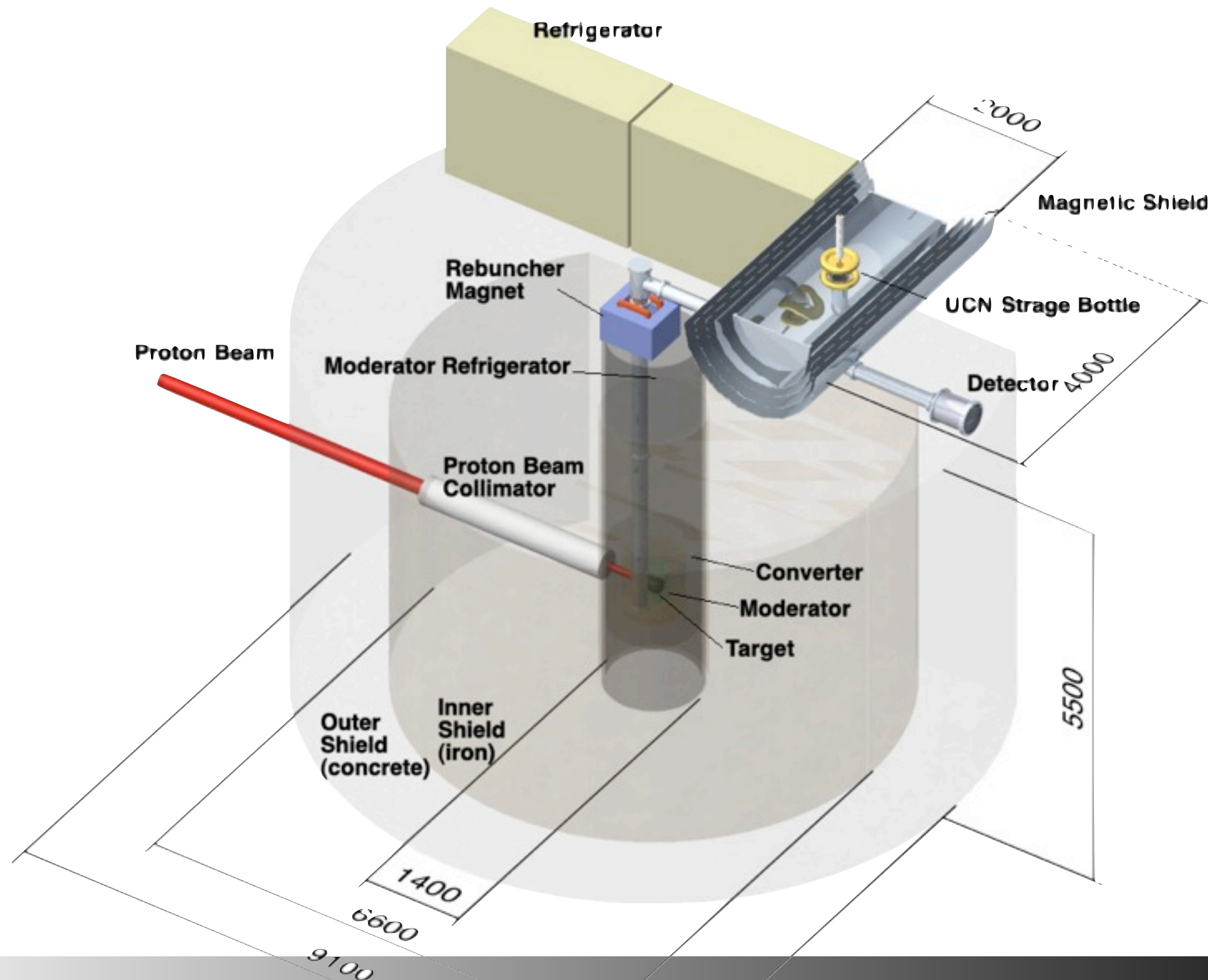
Haruhiko FUNAHASHI	Osaka Electro-Communication Univ.
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- 2010 Jan. 15 : 9th J-PARC PAC Meeting



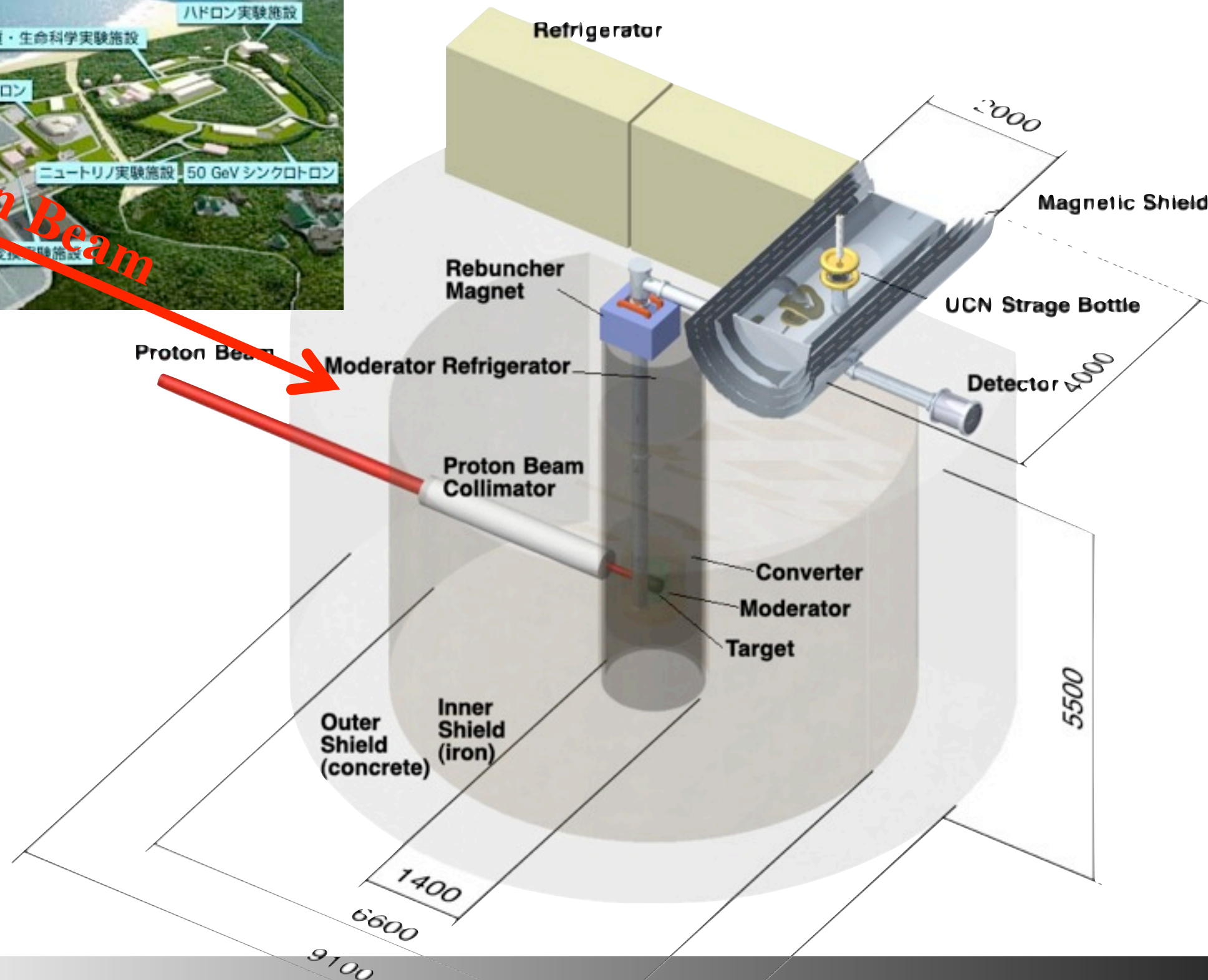
J-PARC P33: J-PARC UCN for $|d_n| < 10^{-27}$ e cm

for the study of new physics with the improved experimental accuracy by the optically controlled transport of pulsed ultracold neutrons to the measurement cell.



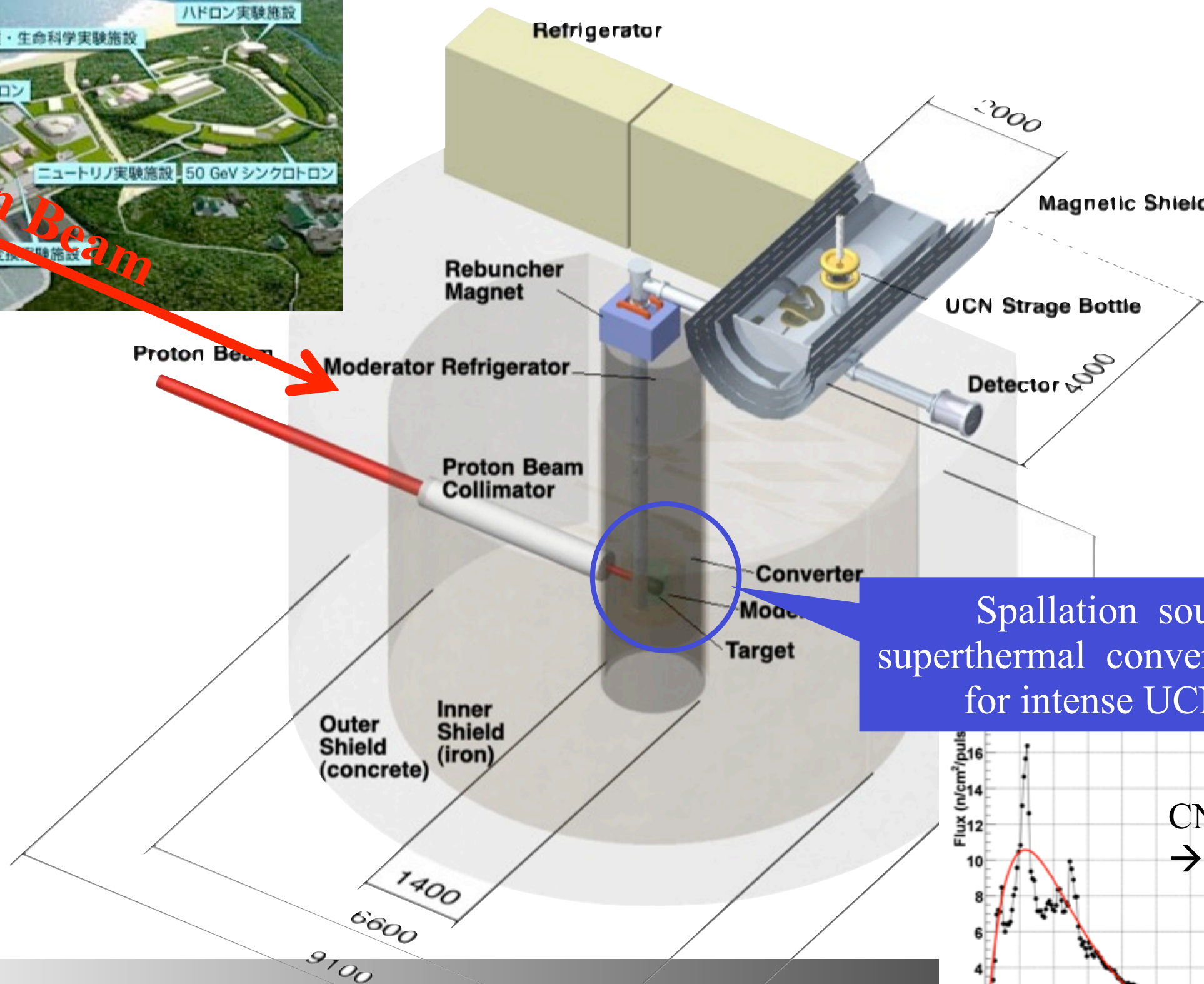
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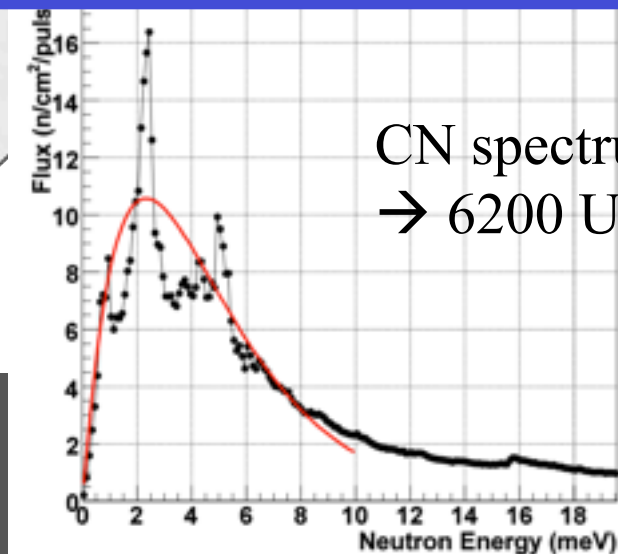


J-PARC P33: J-PARC UCN for $|d_n| < 10^{-27}$ e cm

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Spallation source and superthermal converter using sD2 for intense UCN source

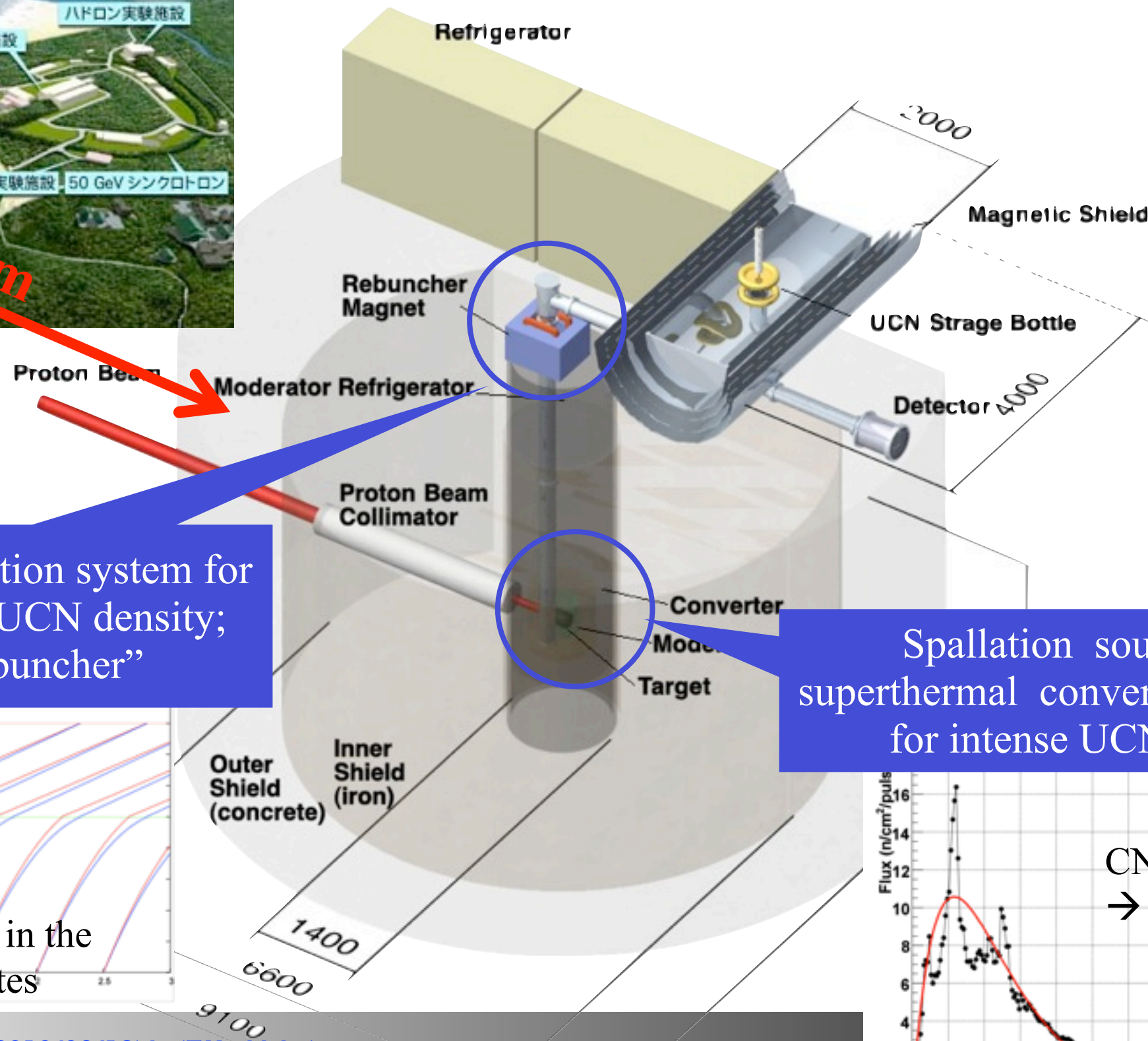


CN spectrum
→ 6200 UCN/cm³



J-PARC P33: J-PARC UCN for $|d_n| < 10^{-27}$ e cm

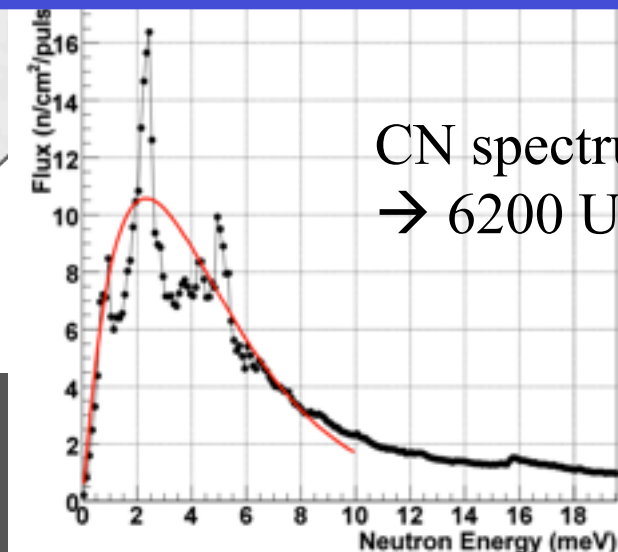
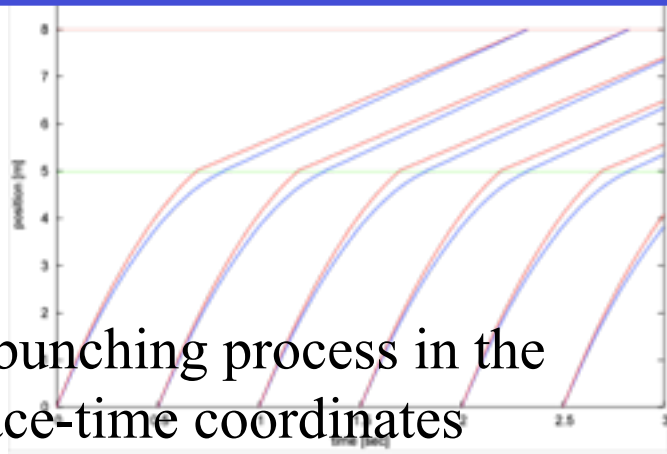
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Novel transportation system for preserving the UCN density; called “rebuncher”

Spallation source and superthermal converter using sD2 for intense UCN source

Rebunching process in the space-time coordinates



CN spectrum
→ 6200 UCN/cm³

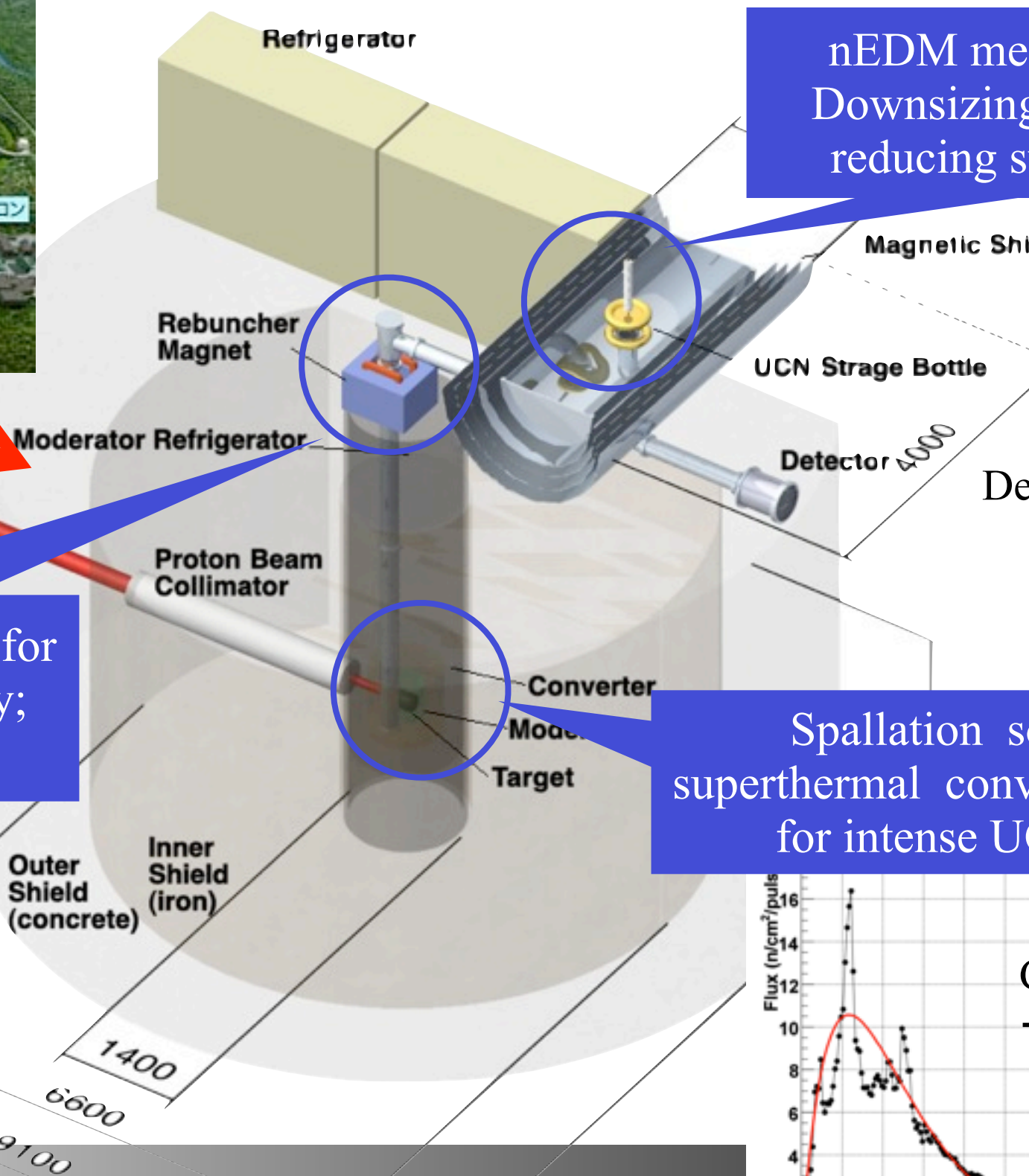
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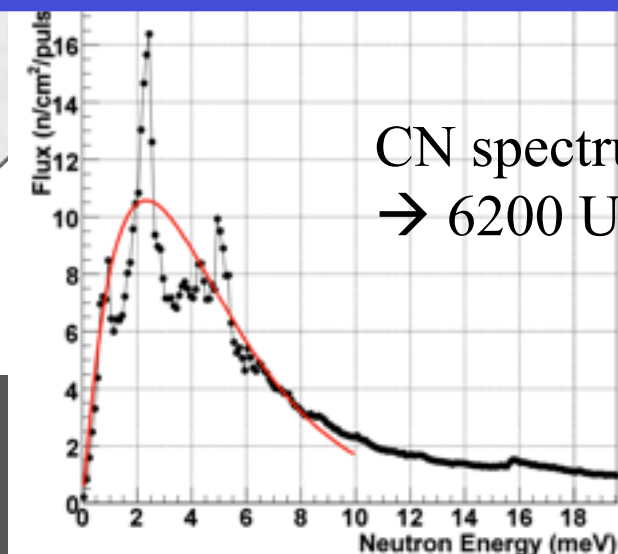


nEDM measurement cell.
Downsizing the volume for reducing systematic error



Deuterated Polystyrene

Spallation source and superthermal converter using sD2 for intense UCN source

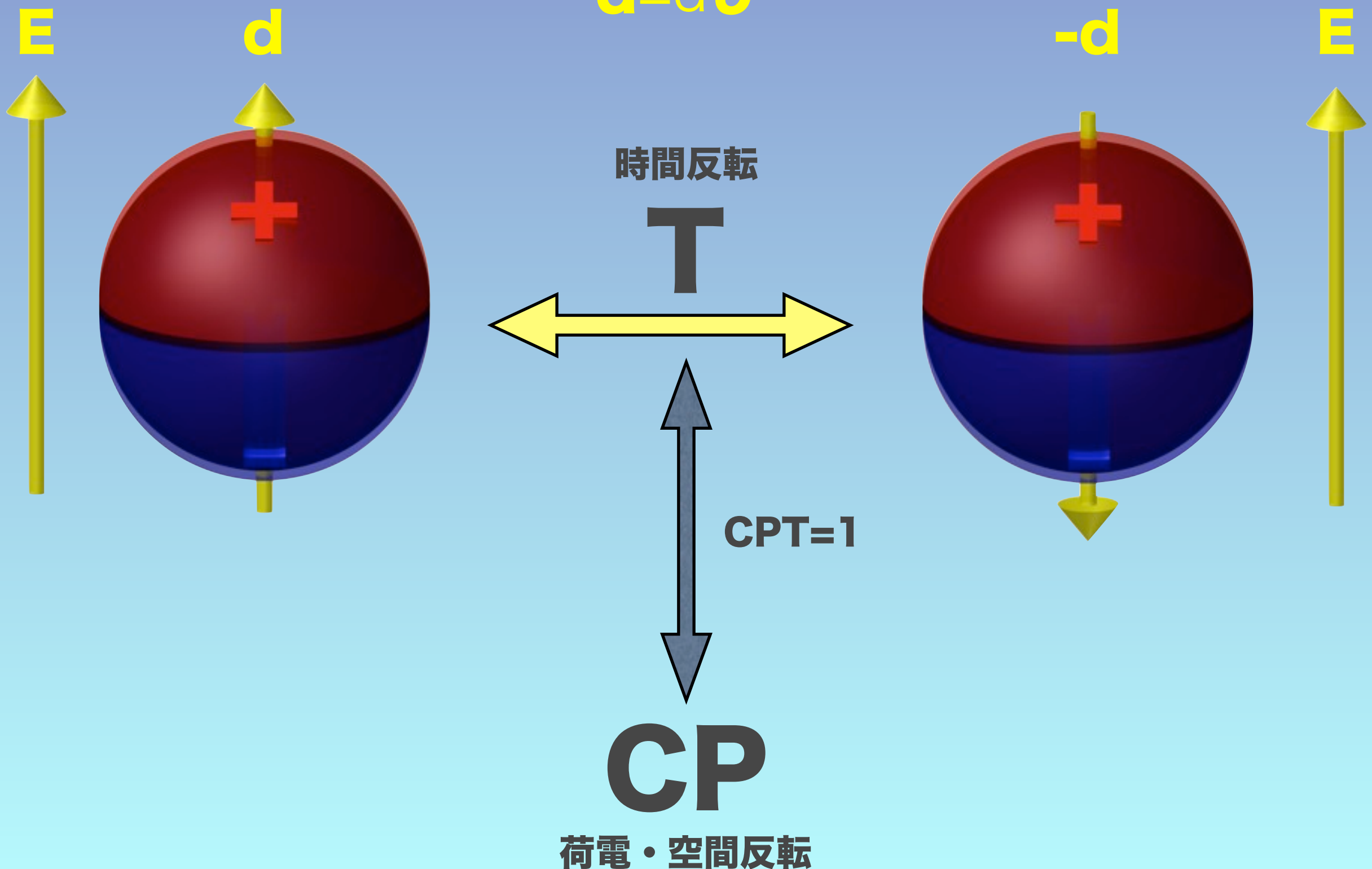


CN spectrum
→ 6200 UCN/cm³

電気双極子能率

EDM: Electric Dipole Moment

$$\mathbf{d} = d \boldsymbol{\sigma}$$



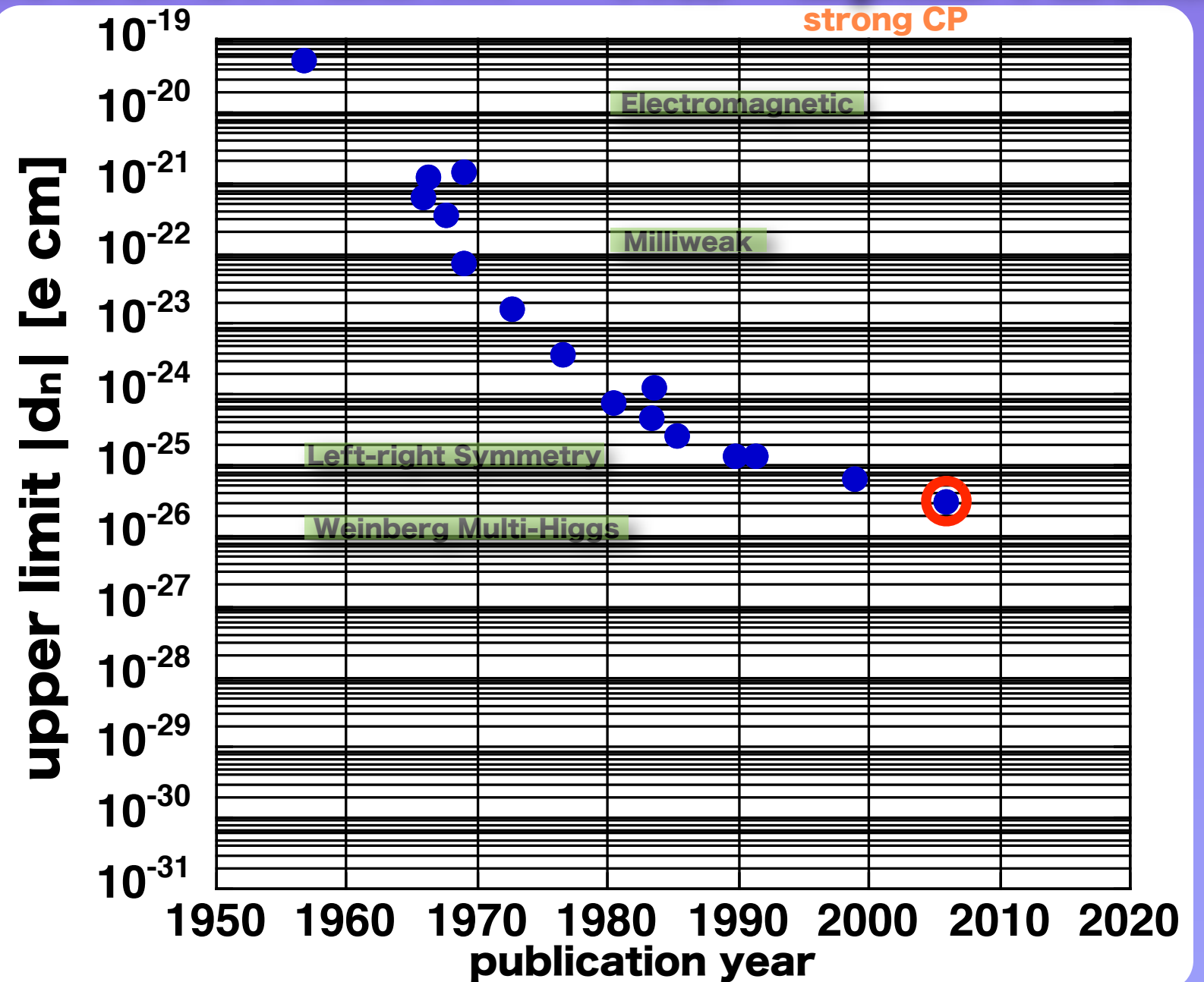
Electric Dipole Moment



neutron EDM

$$\hbar\omega = 2\mu_n B + 2d_n E$$

strong CP



$$|d_n| < 2.9 \times 10^{-26} \text{ e cm} \quad (90\% \text{ C.L.})$$

Baker et al., PRL97 (2006)131801

Electric Dipole Moment

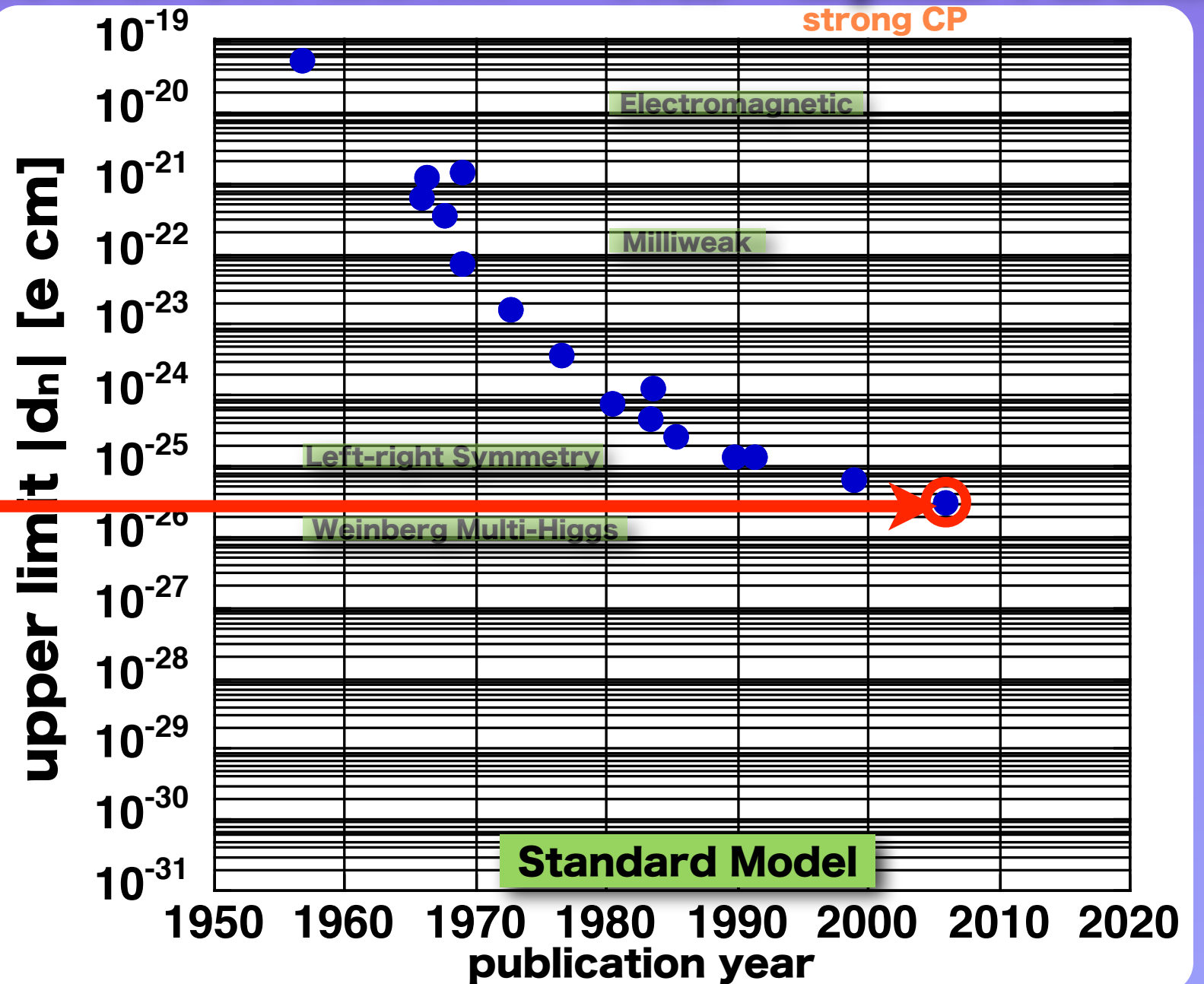
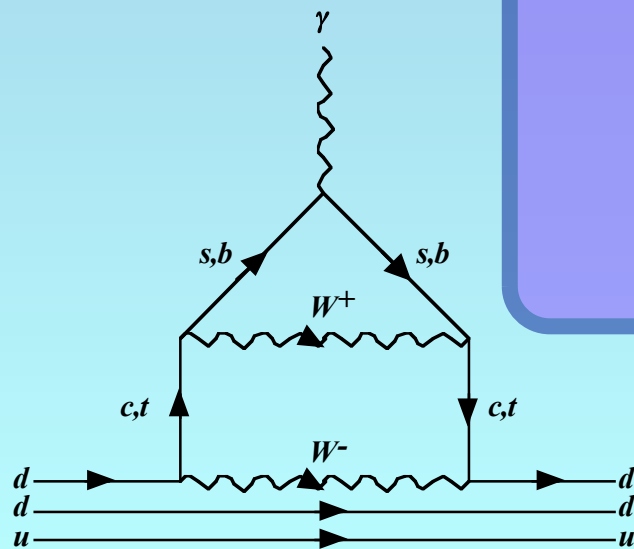
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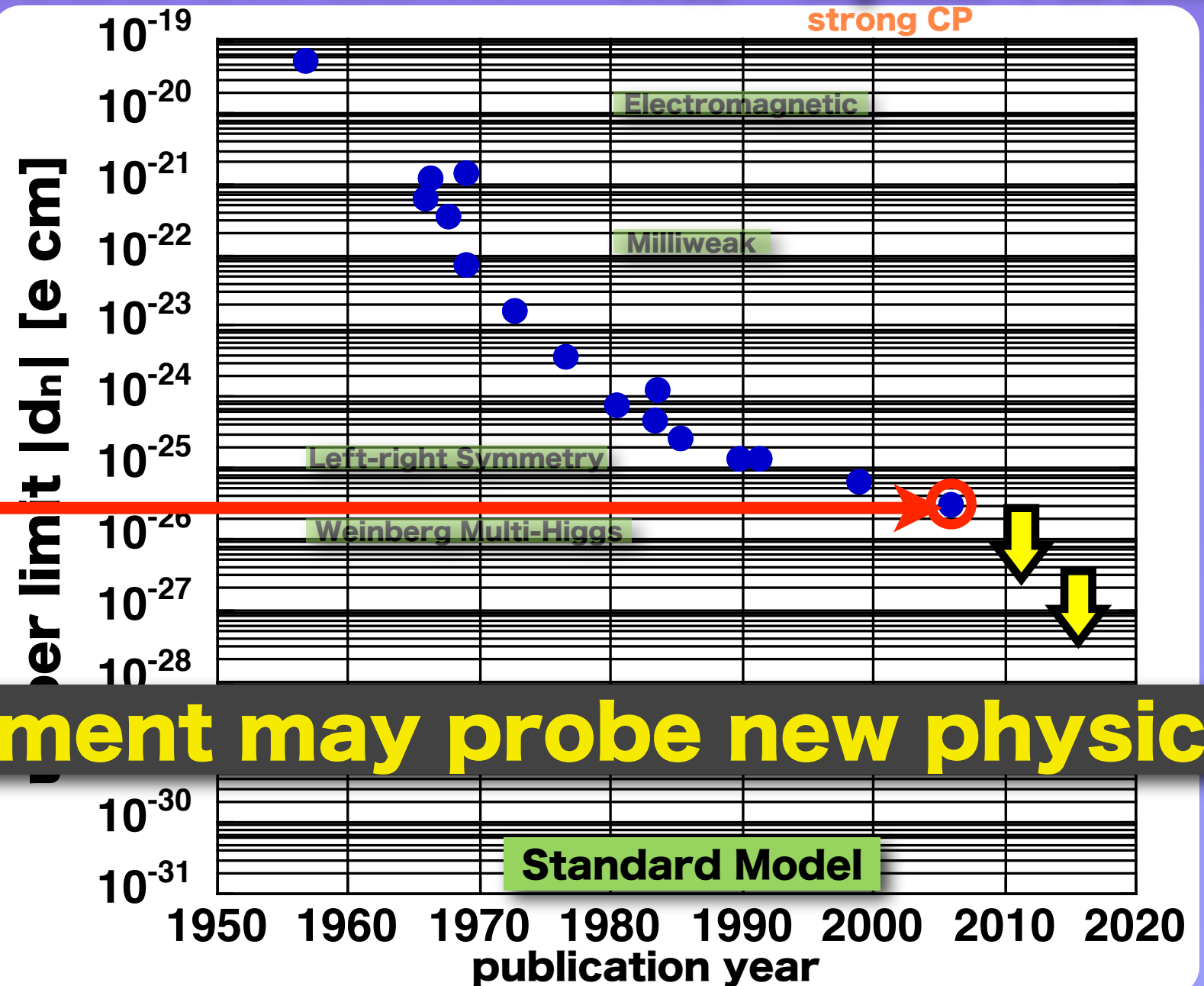
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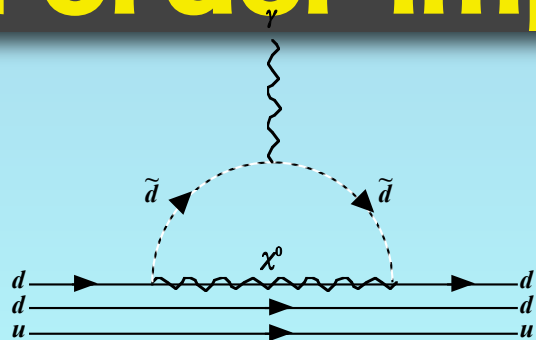
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1-2 order improvement may probe new physics

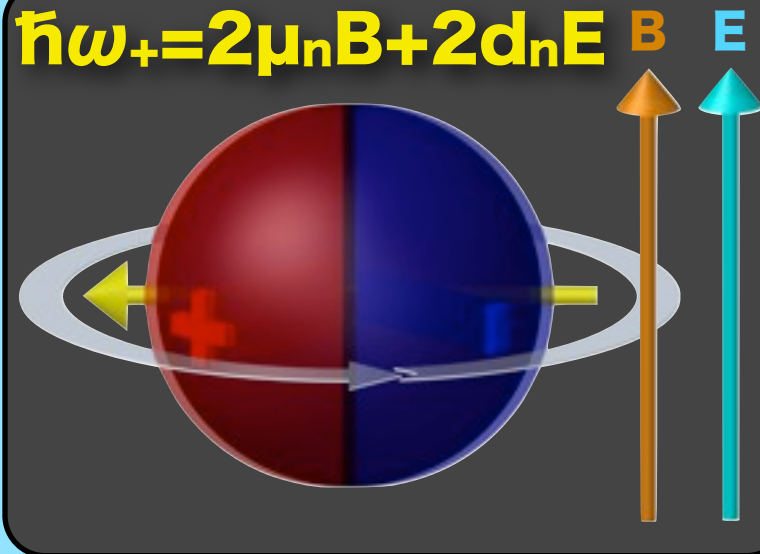


One of Precision Frontiers

Measurement Procedure

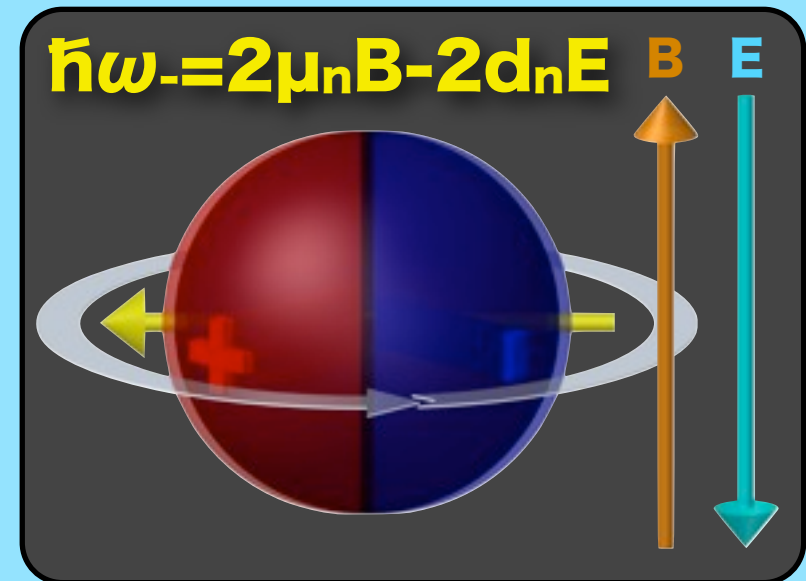
search for the phase change when the electric field is reversed

$$\frac{\omega_{\pm}}{2\pi} = \underbrace{3 \times 10^1 \frac{B}{1 \mu T}}_{\text{magnetic}} \pm \underbrace{5 \times 10^{-8} \frac{d_n}{10^{-26} \text{ e cm}} \frac{E}{10 \text{ kV/cm}}}_{\text{electric}}$$

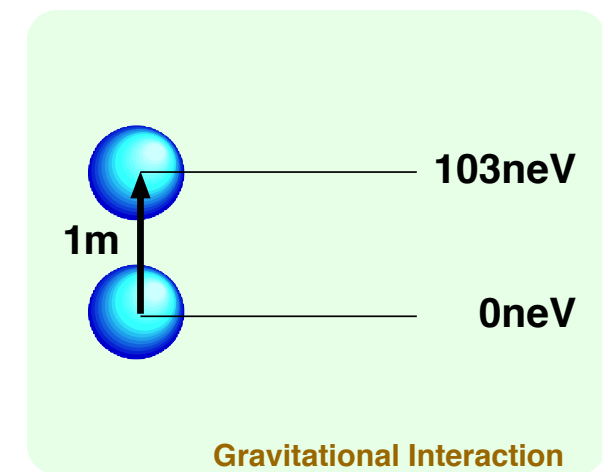
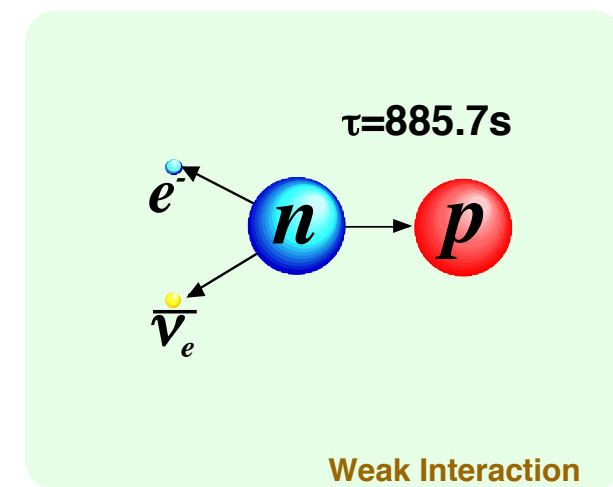
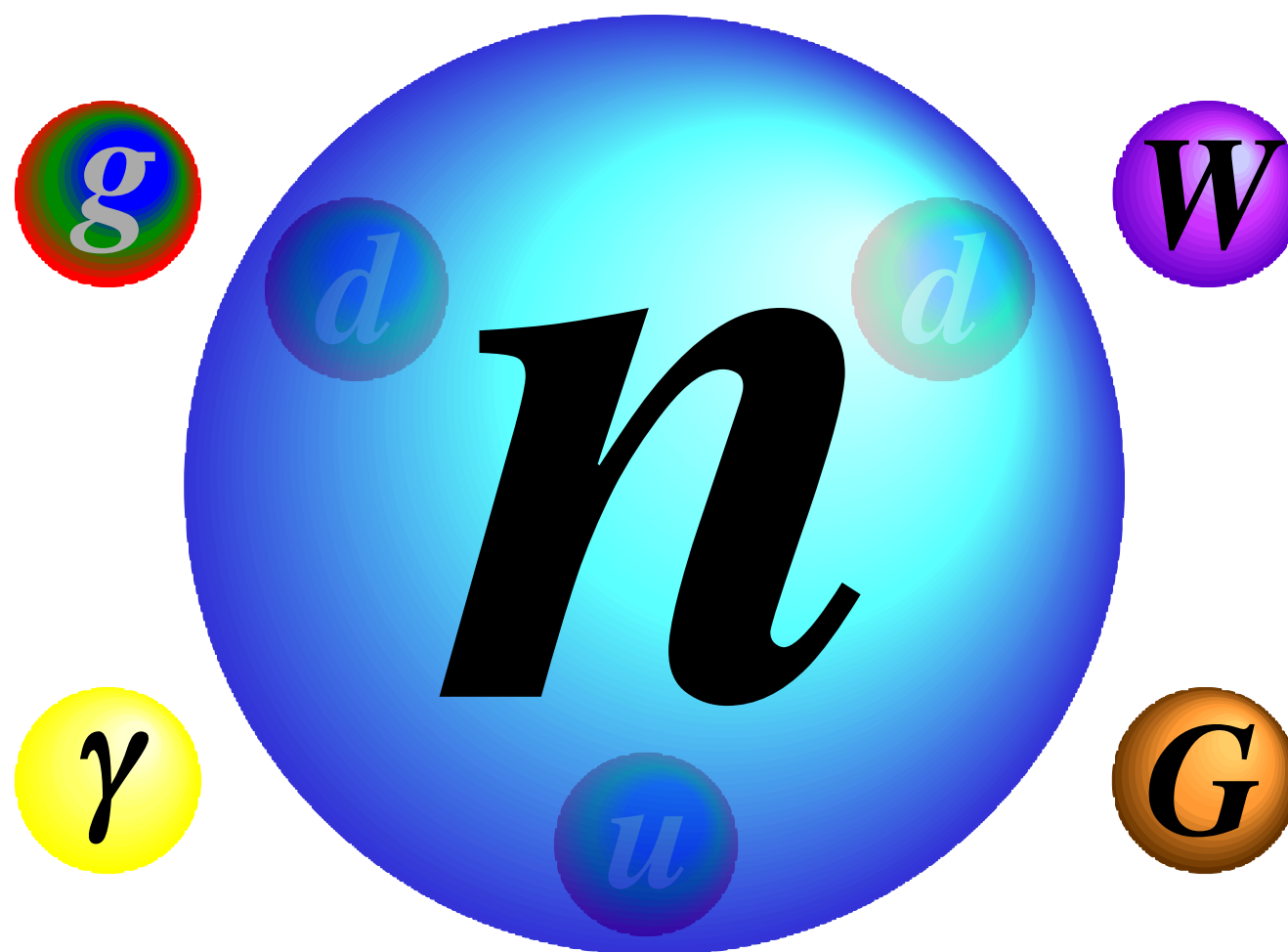
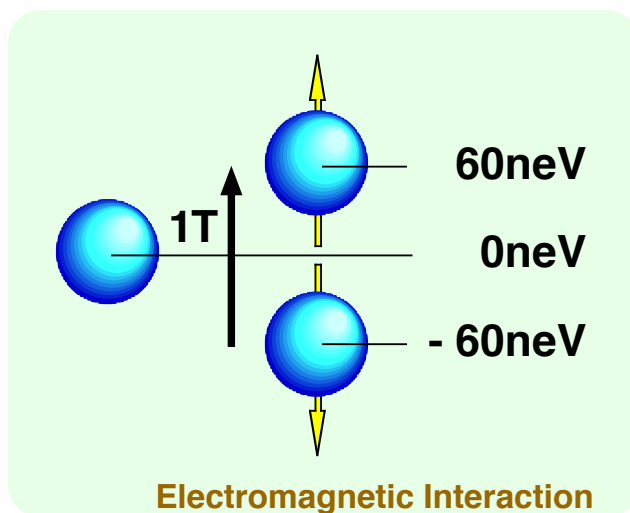
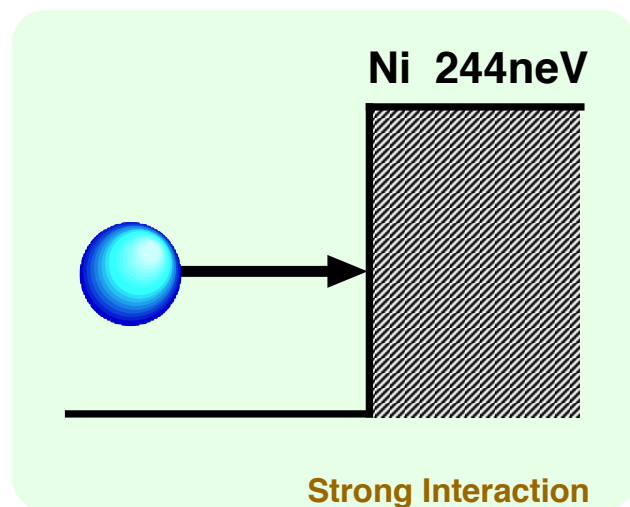


$$\Delta\phi = \int (\omega_+ - \omega_-) dt = \frac{2d_n E T}{\hbar}$$

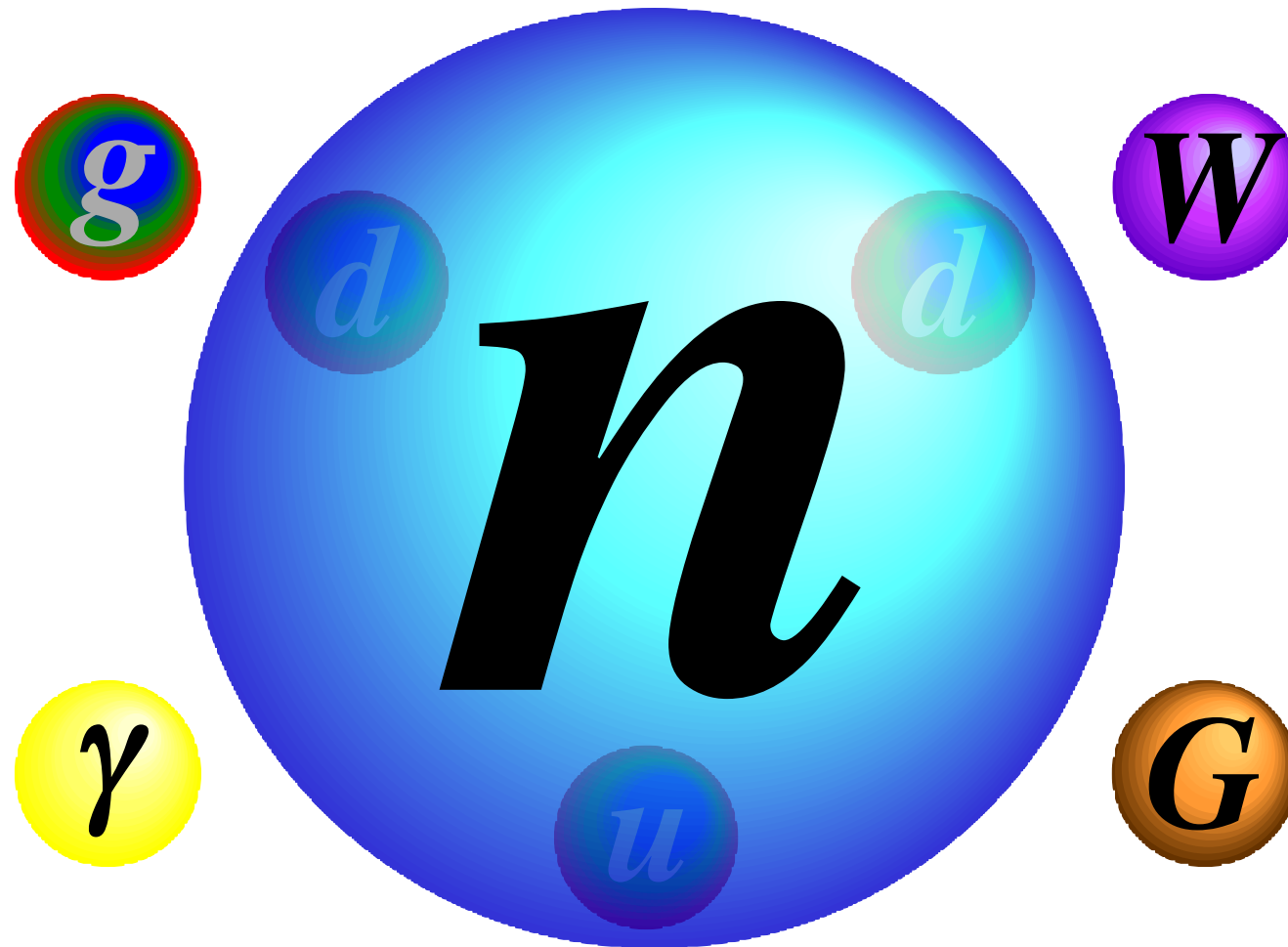
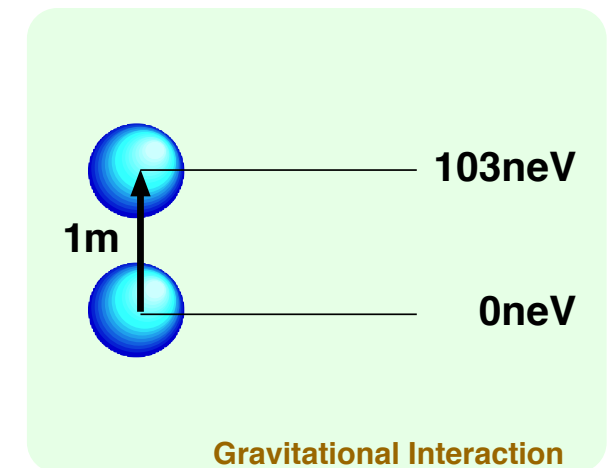
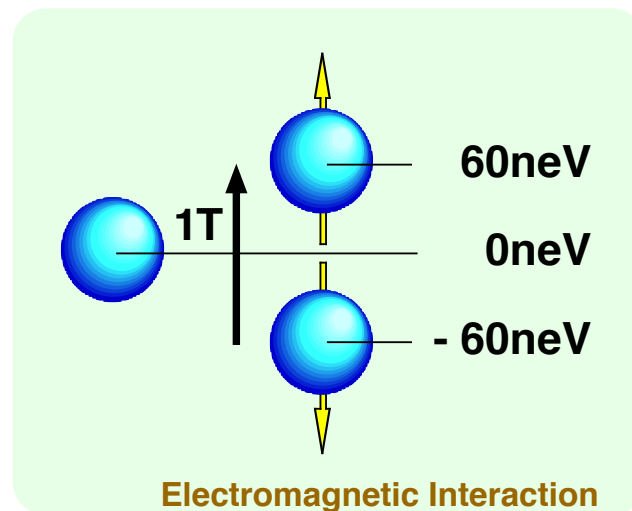
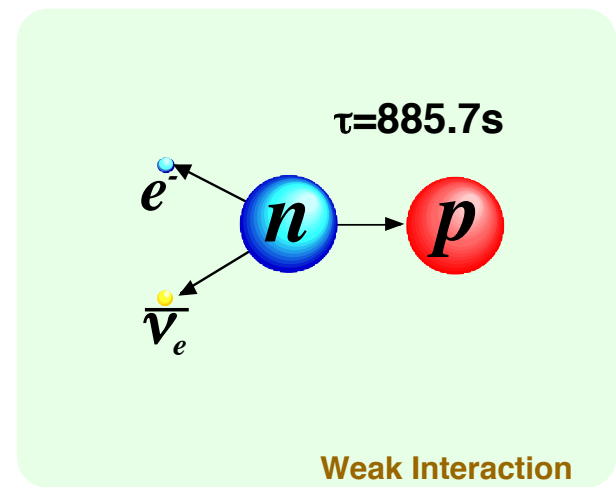
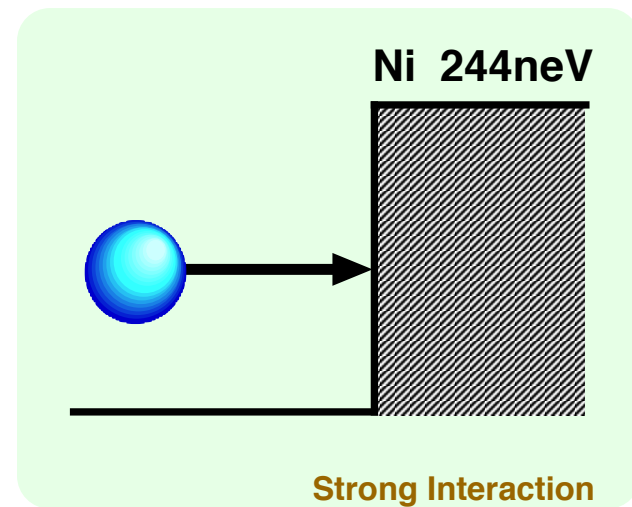
$$\Delta d_n = \frac{\hbar/2}{E T N^{1/2}}$$



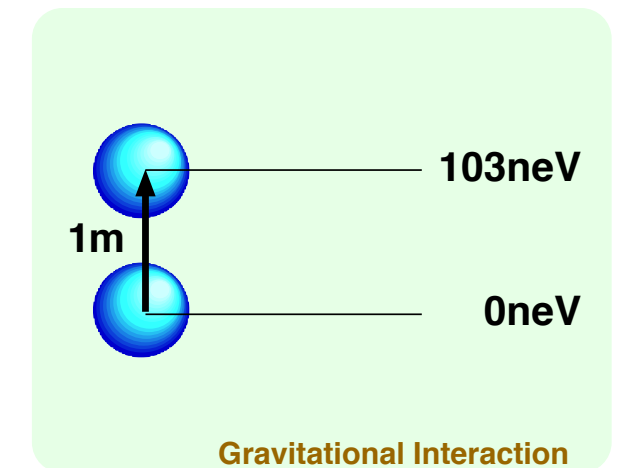
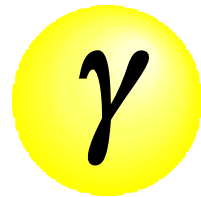
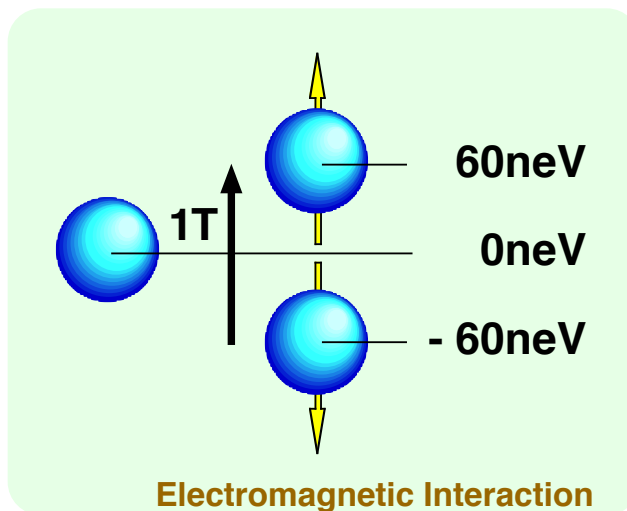
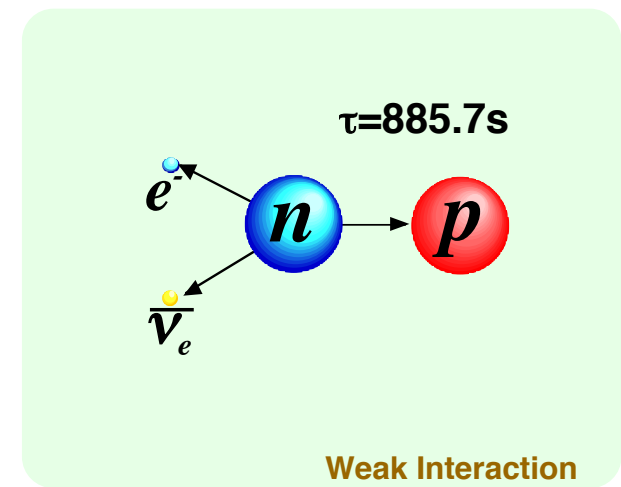
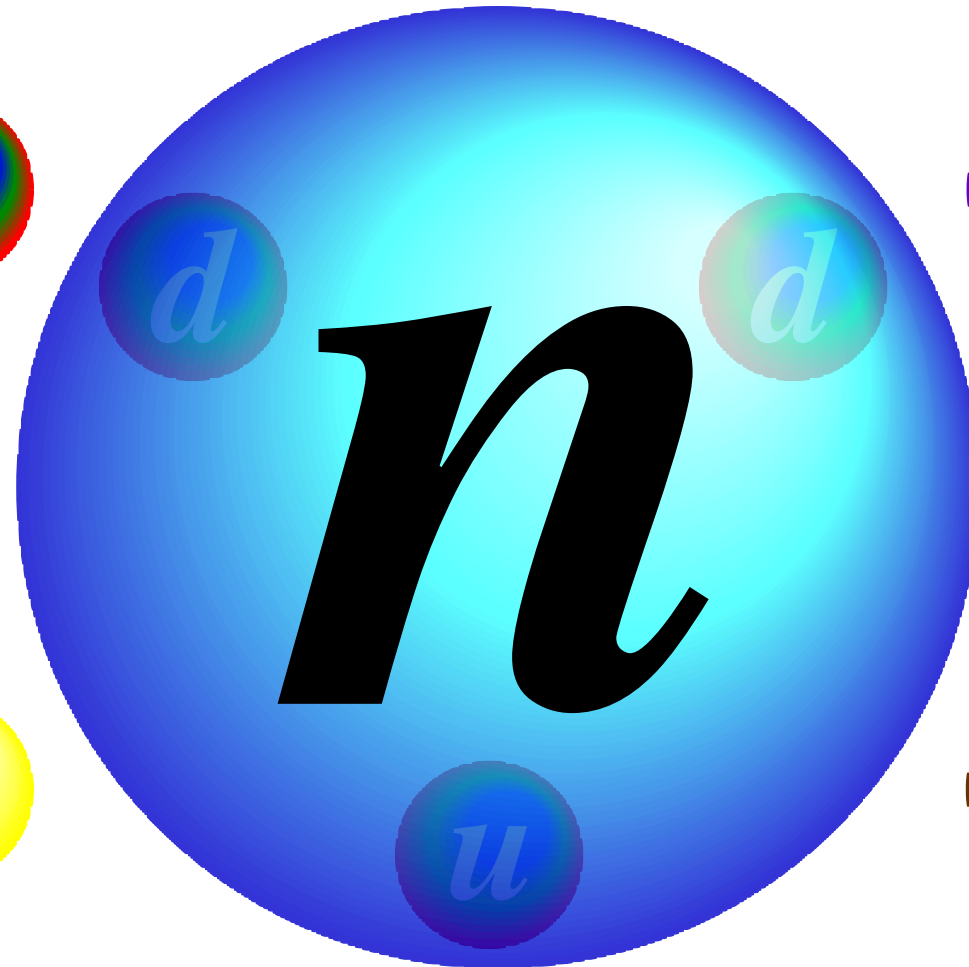
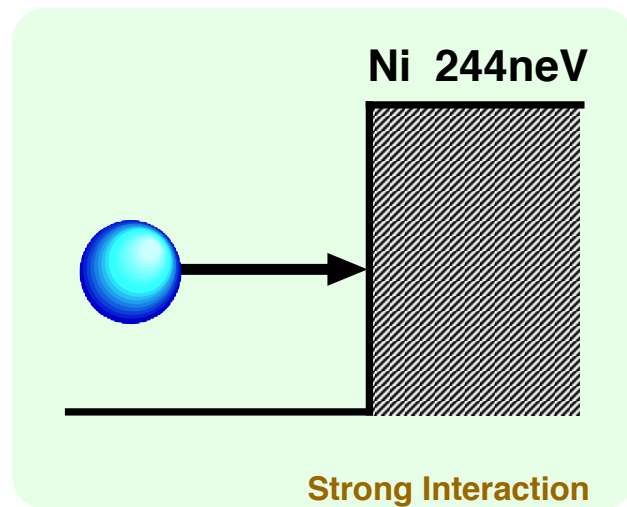
Confined Ultracold Neutron Spin Precession Freq.



250neV 7m/s

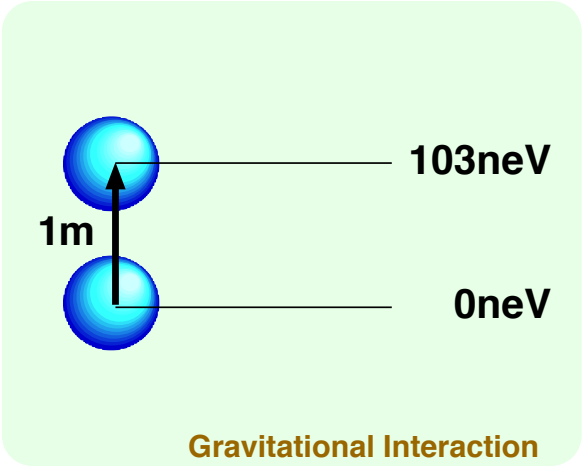
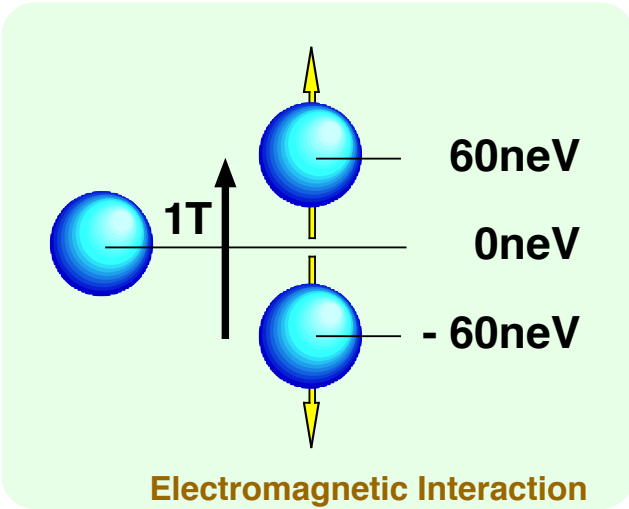
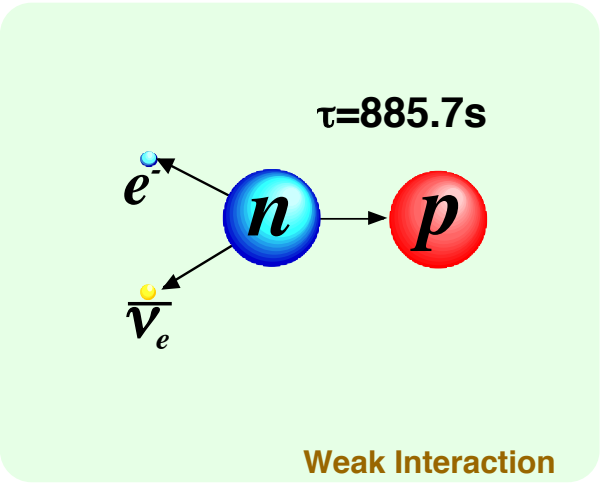
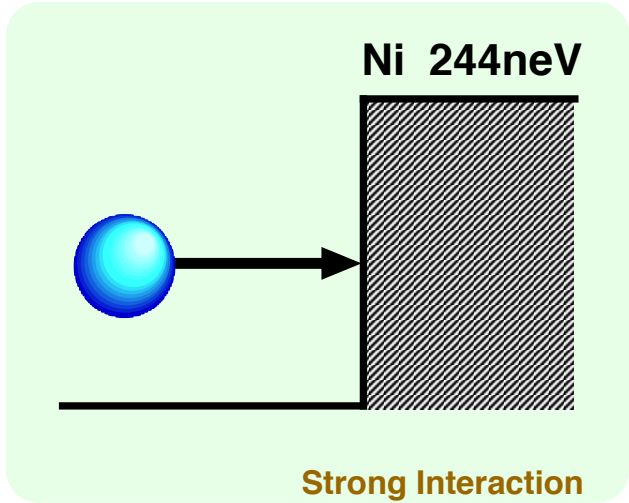


250neV 7m/s



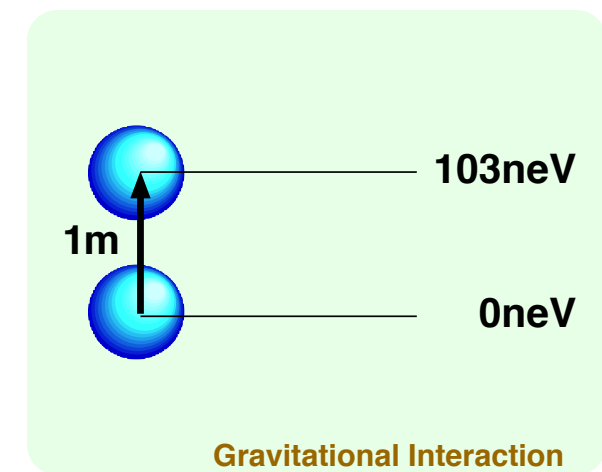
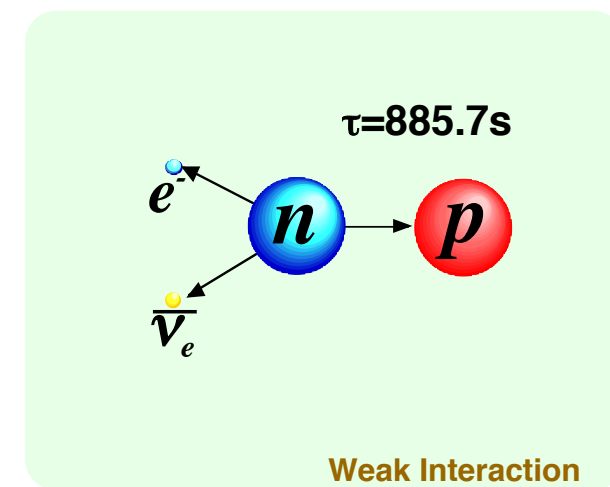
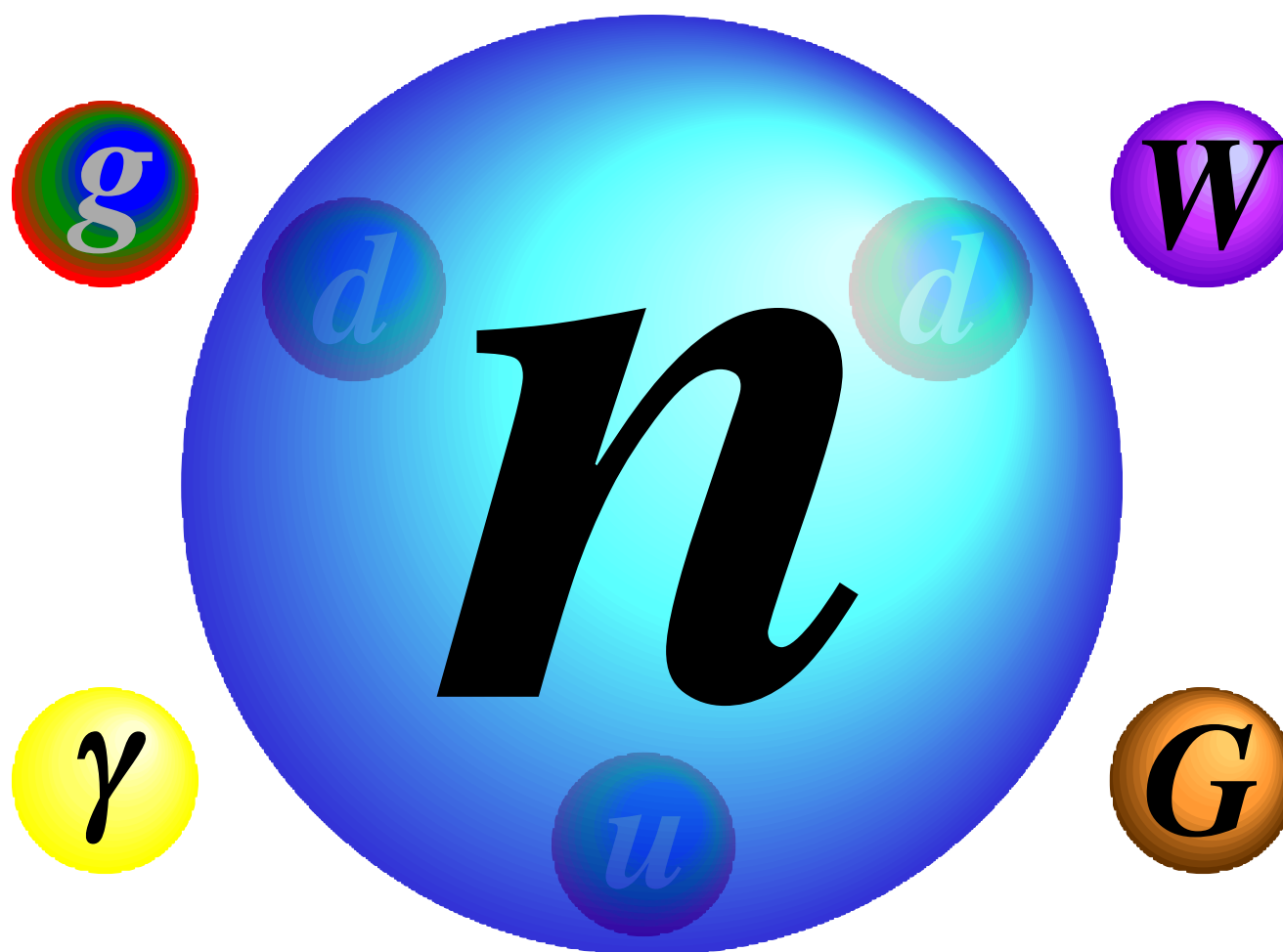
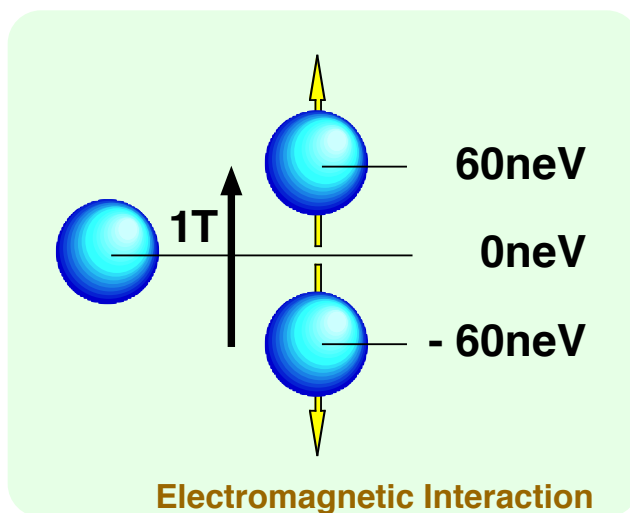
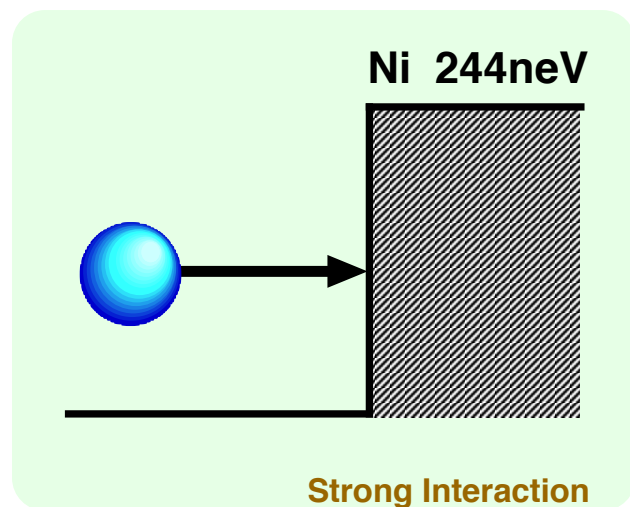
Ultracold Neutron (UCN)

250neV 7m/s



1 20neV/T

1 00neV/m



Neutron Fundamental Physics

TRIUMF: He-II UCN Source
UCN-EDM
Lifetime, Decay Correlations

NIST:
Lifetime, Decay Correlations
EDM in crystal field

PSI: D₂ UCN Source
UCN-EDM
Lifetime, Decay Correlations

LANL: D₂ UCN Source
UCN Decay Correlations
R&D for SNS-EDM

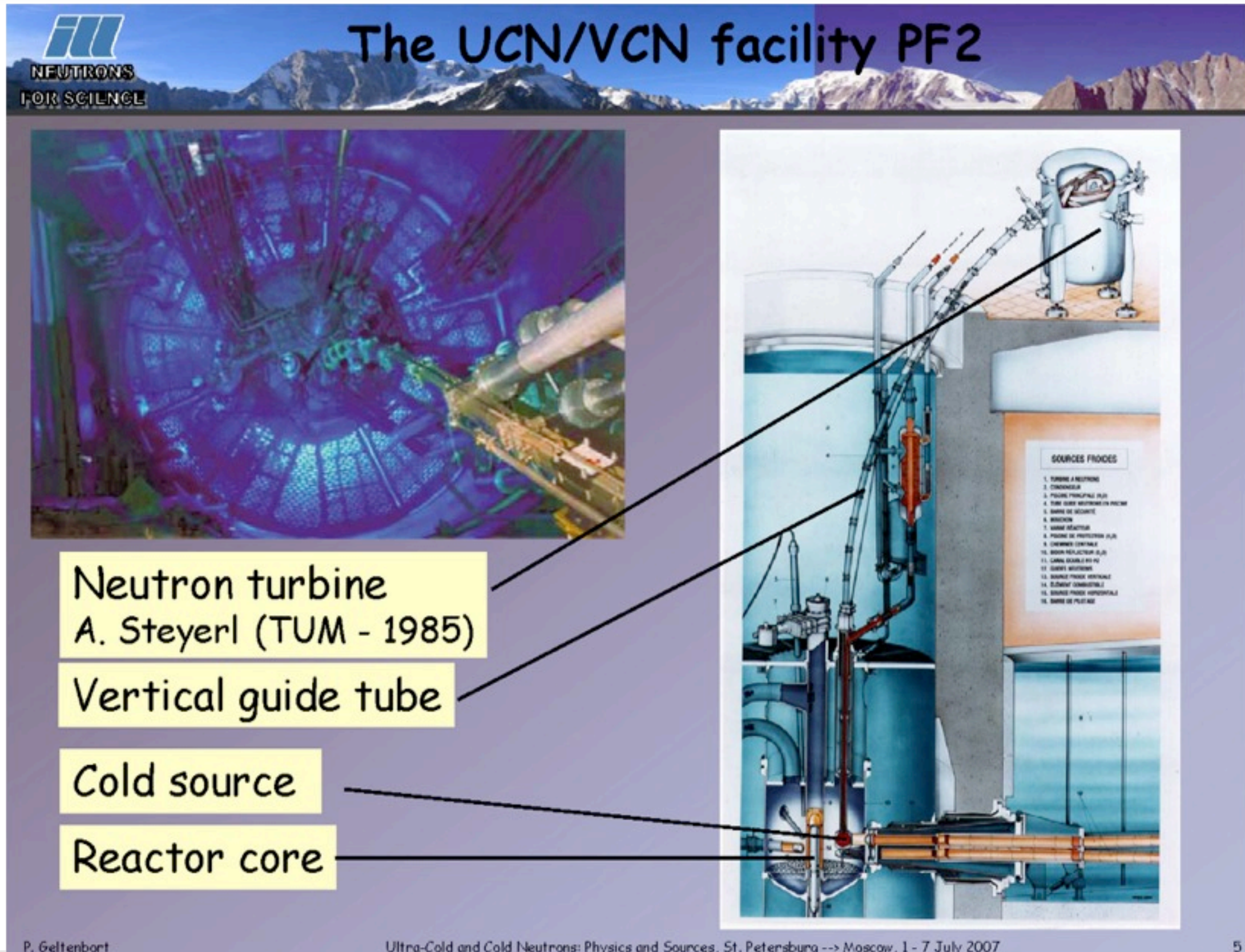
SNS:
Hadronic-weak Interacton
Lifetime, Decay Correlations
UCN-EDM(measurement in production volume)

ILL: Turbine UCN Source
EDM
Lifetime
Decay Correlations
He-II UCN Source
UCN-EDM
(measurement in production volume)

existing UCN facilities - ILL / LANL / Mainz $I \sim 10^1$
UCN facilities in construction - PSI / SNS / TUM $\sim >10^3$
UCN facilities planned - J-PARC / TRIUMF / NCSU

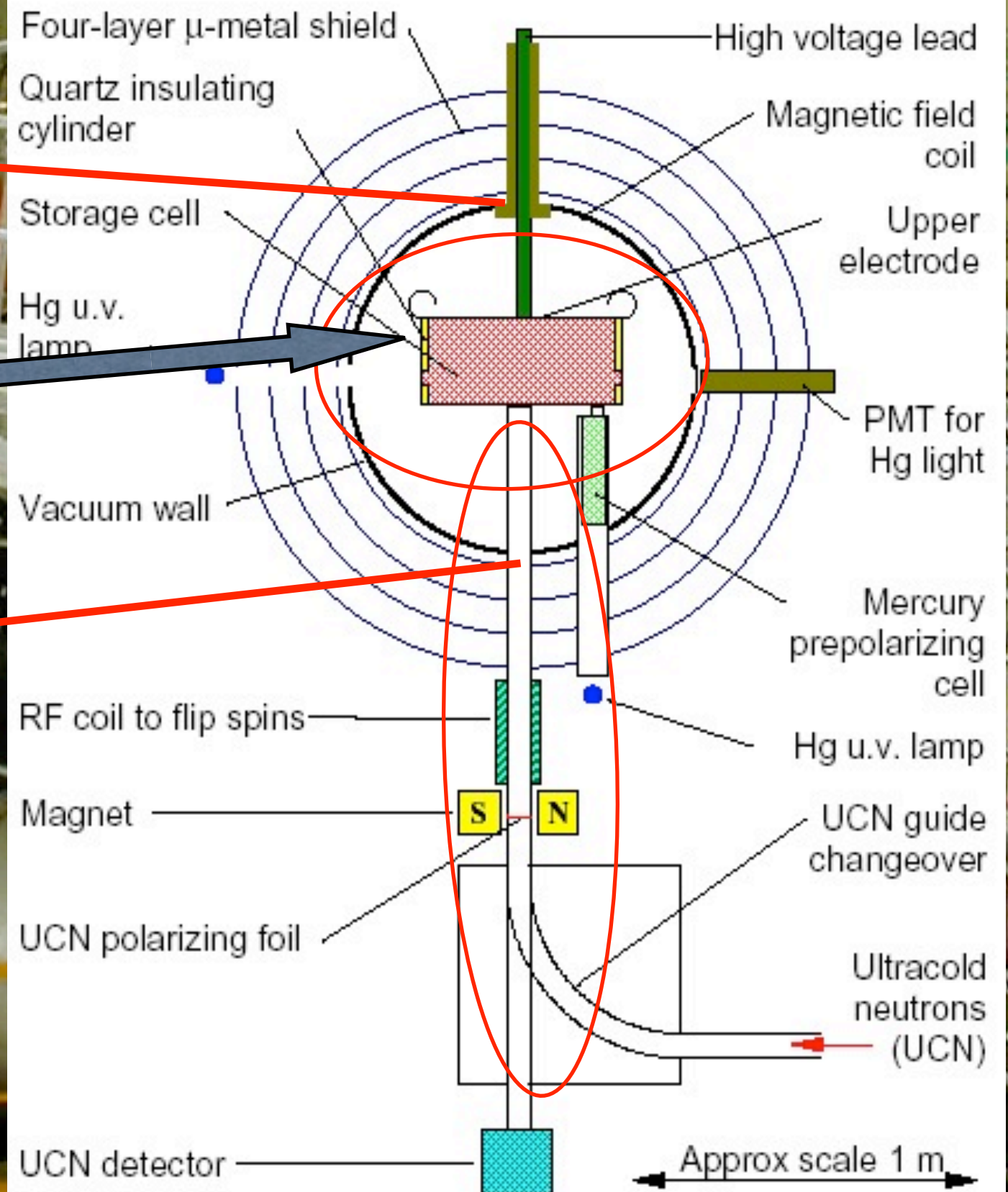
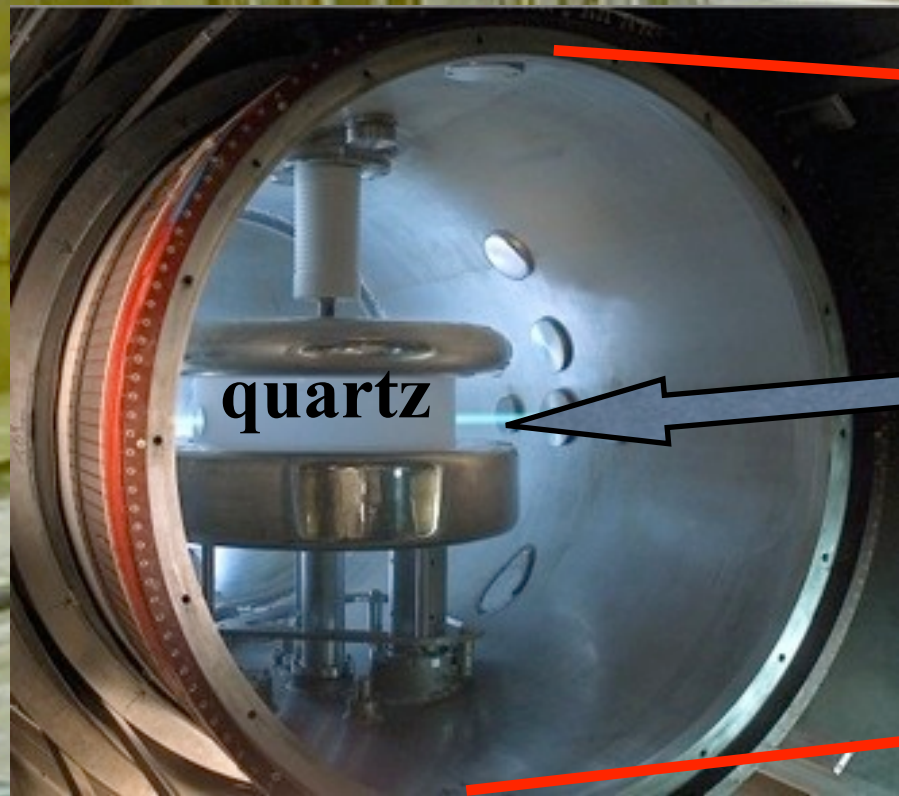
ILL-UCN ($\sim 10 \text{ UCN/cm}^3$)

gravity+mechanical turbine

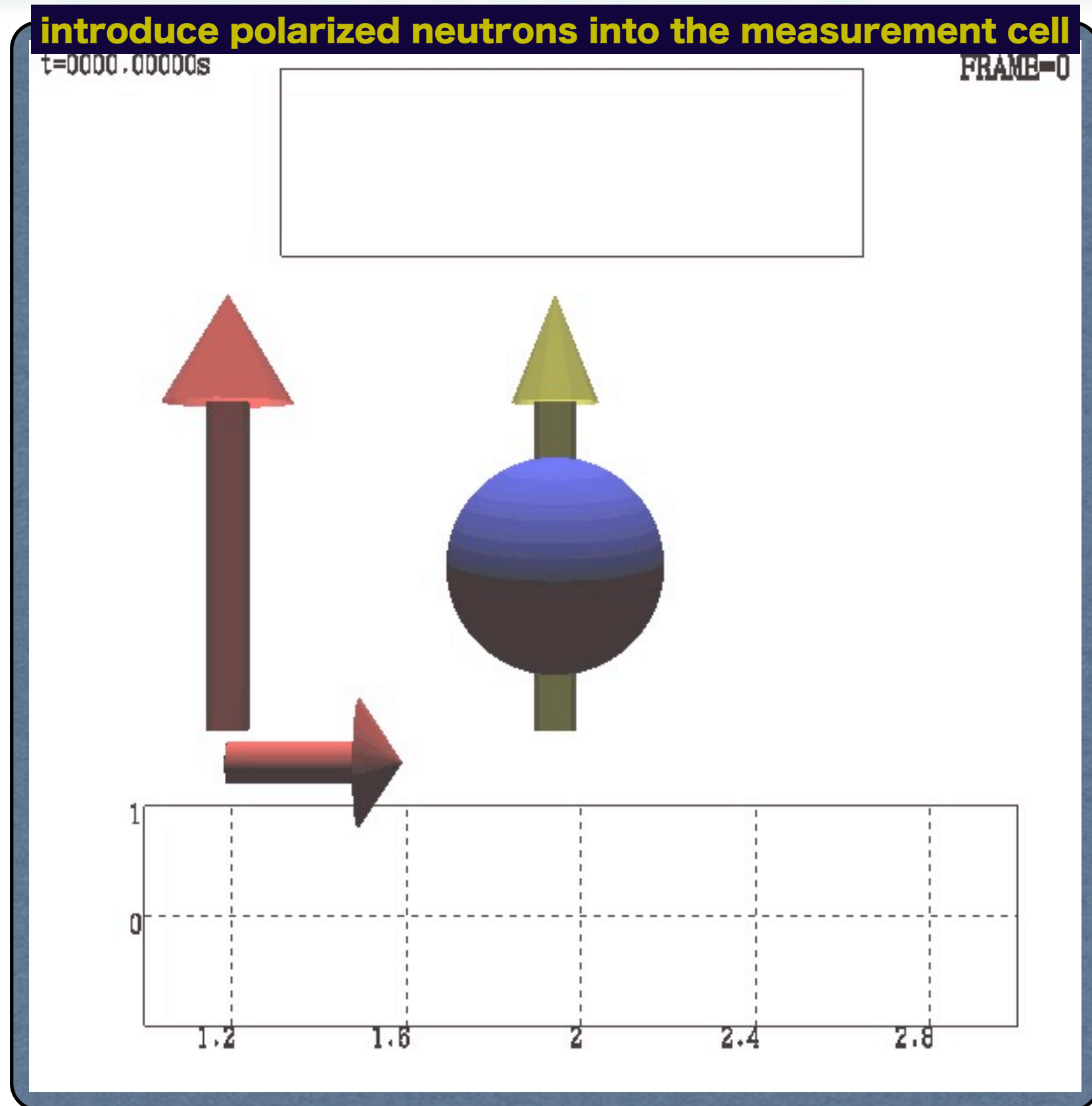


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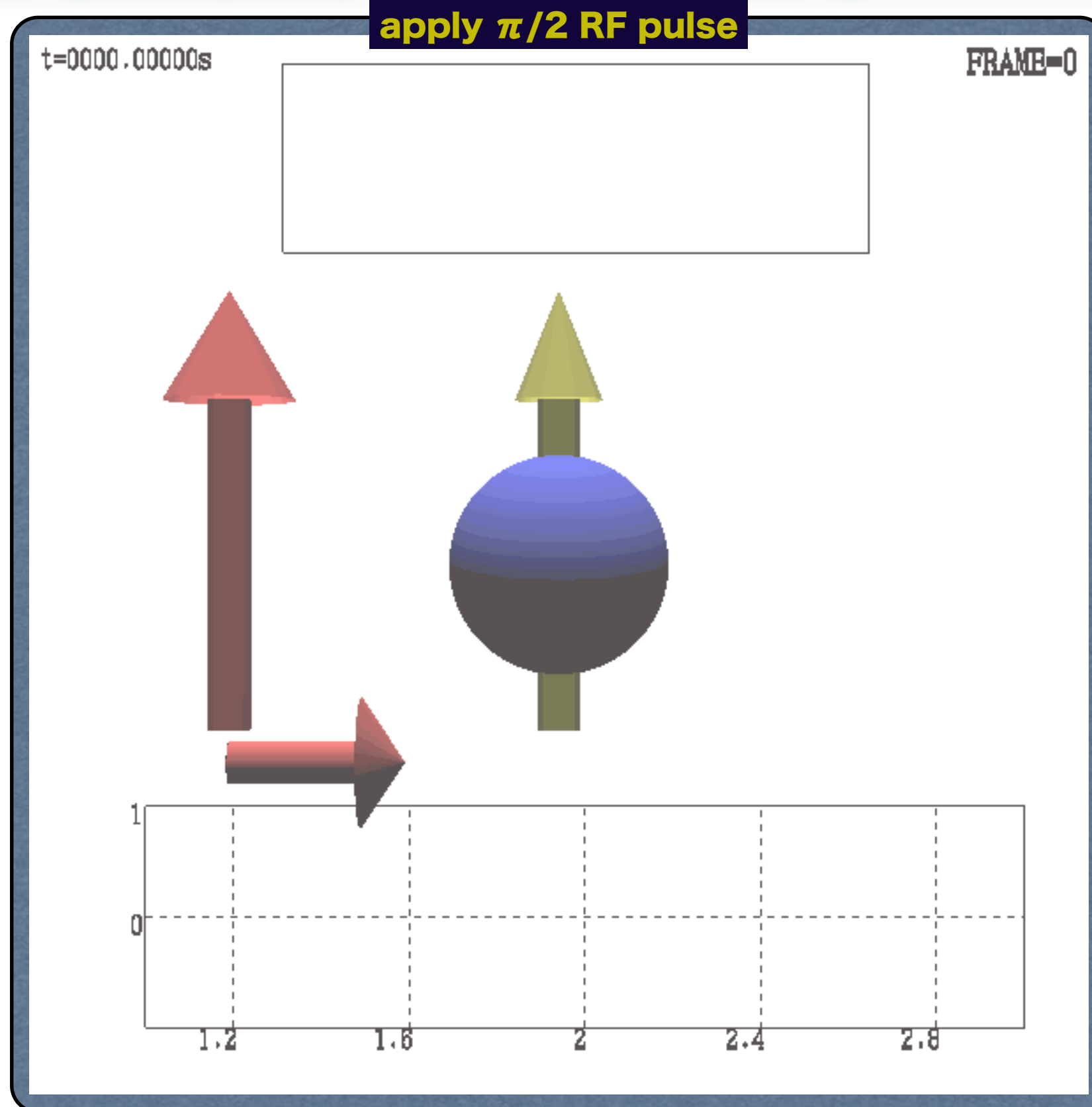
ILL EDM Measurement



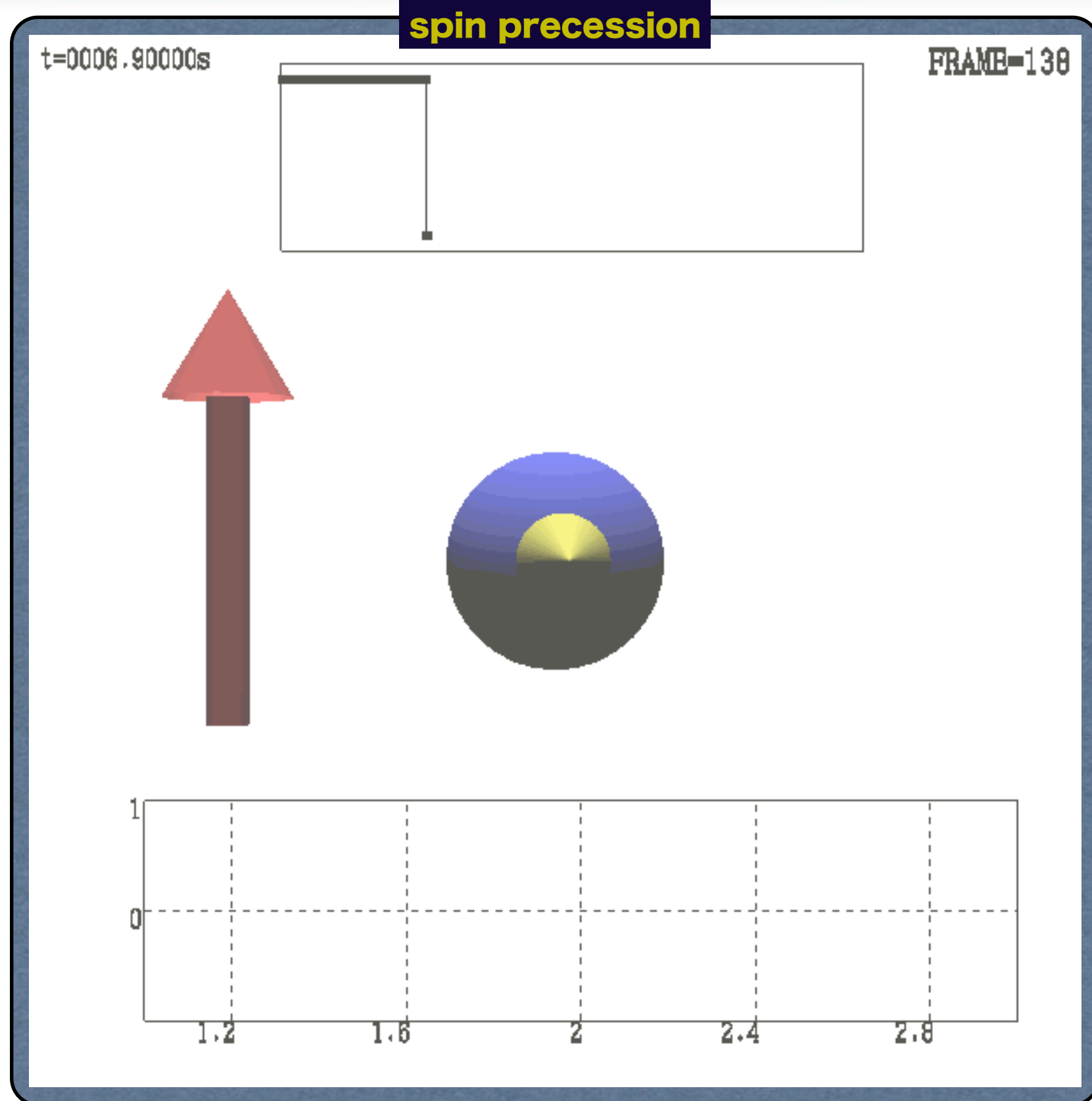
Measurement Procedure



Measurement Procedure



Measurement Procedure

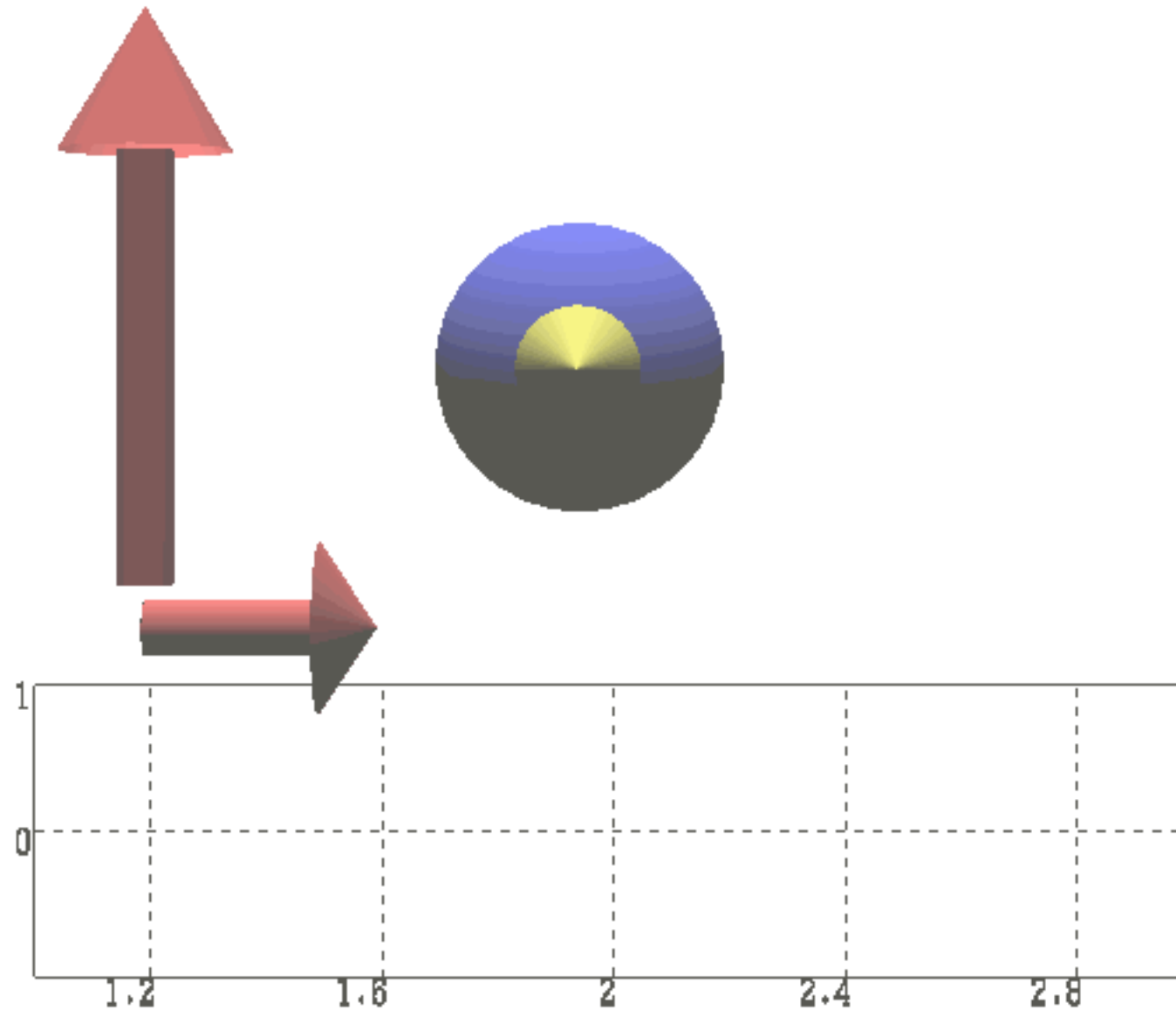
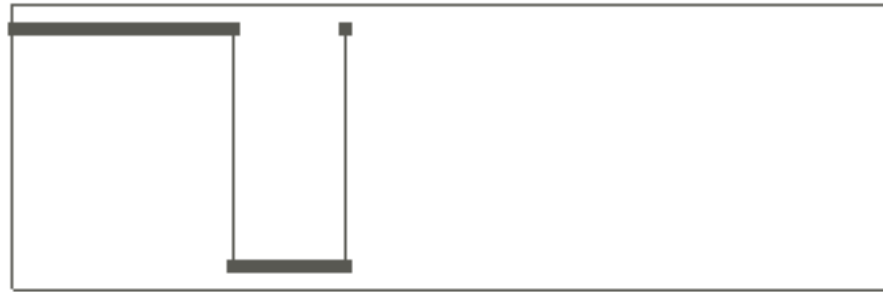


Measurement Procedure

apply another $\pi/2$ RF pulse and measure the polarization

t=0010.30000s

FRAME-206

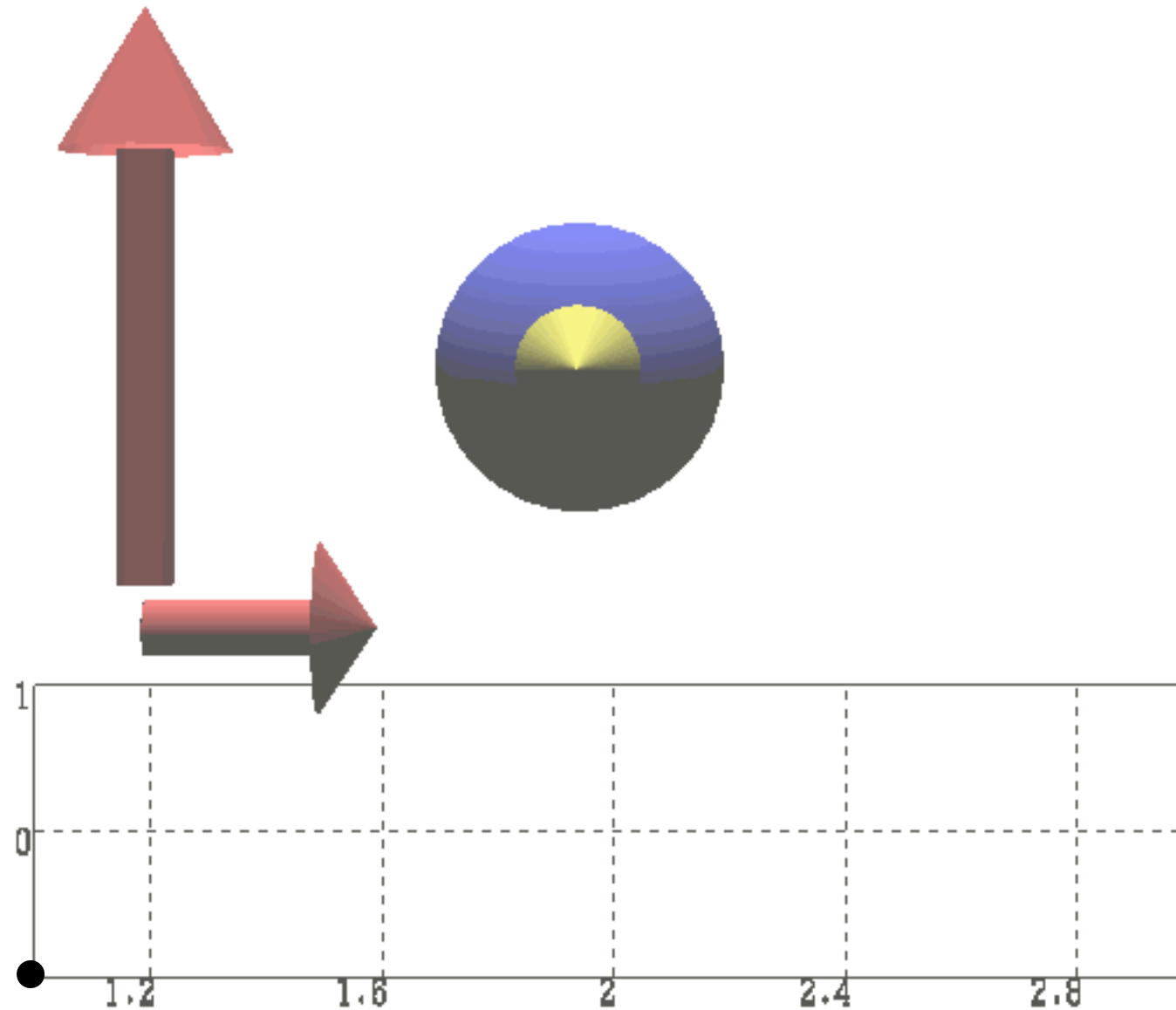
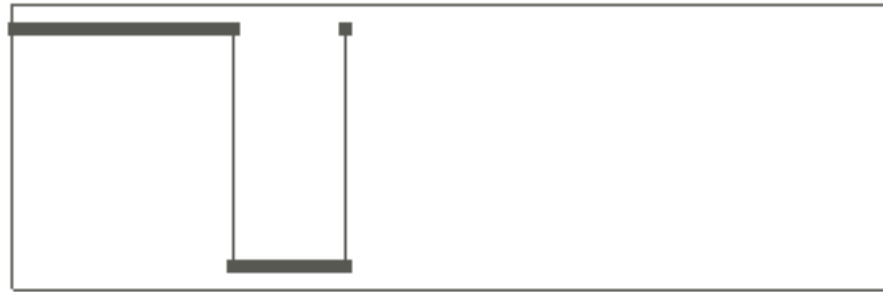


Measurement Procedure

apply another $\pi/2$ RF pulse and measure the polarization

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FRAME-206

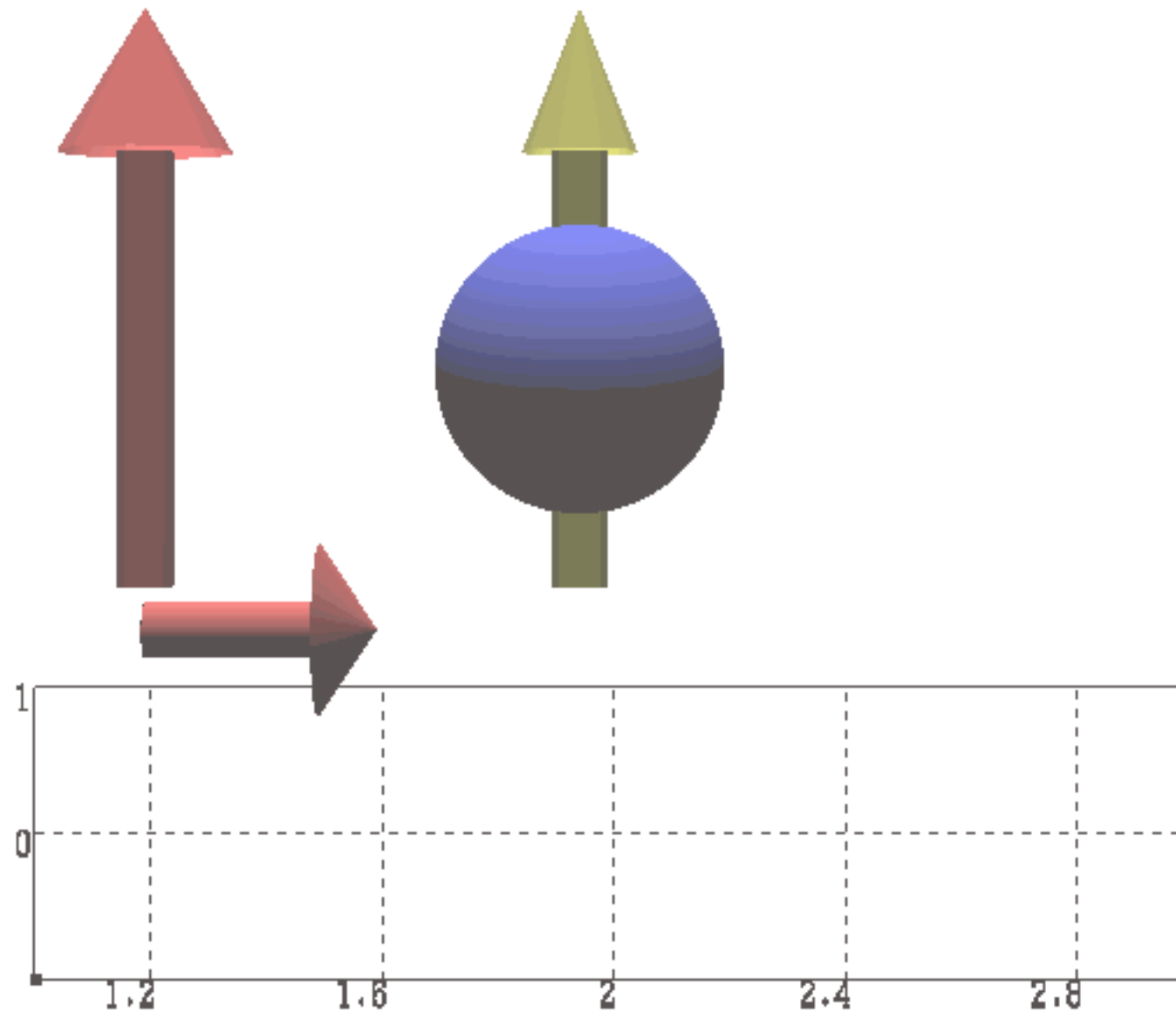


Measurement Procedure

same sequence with different precession time

t=0000.00000s

FRAME=412

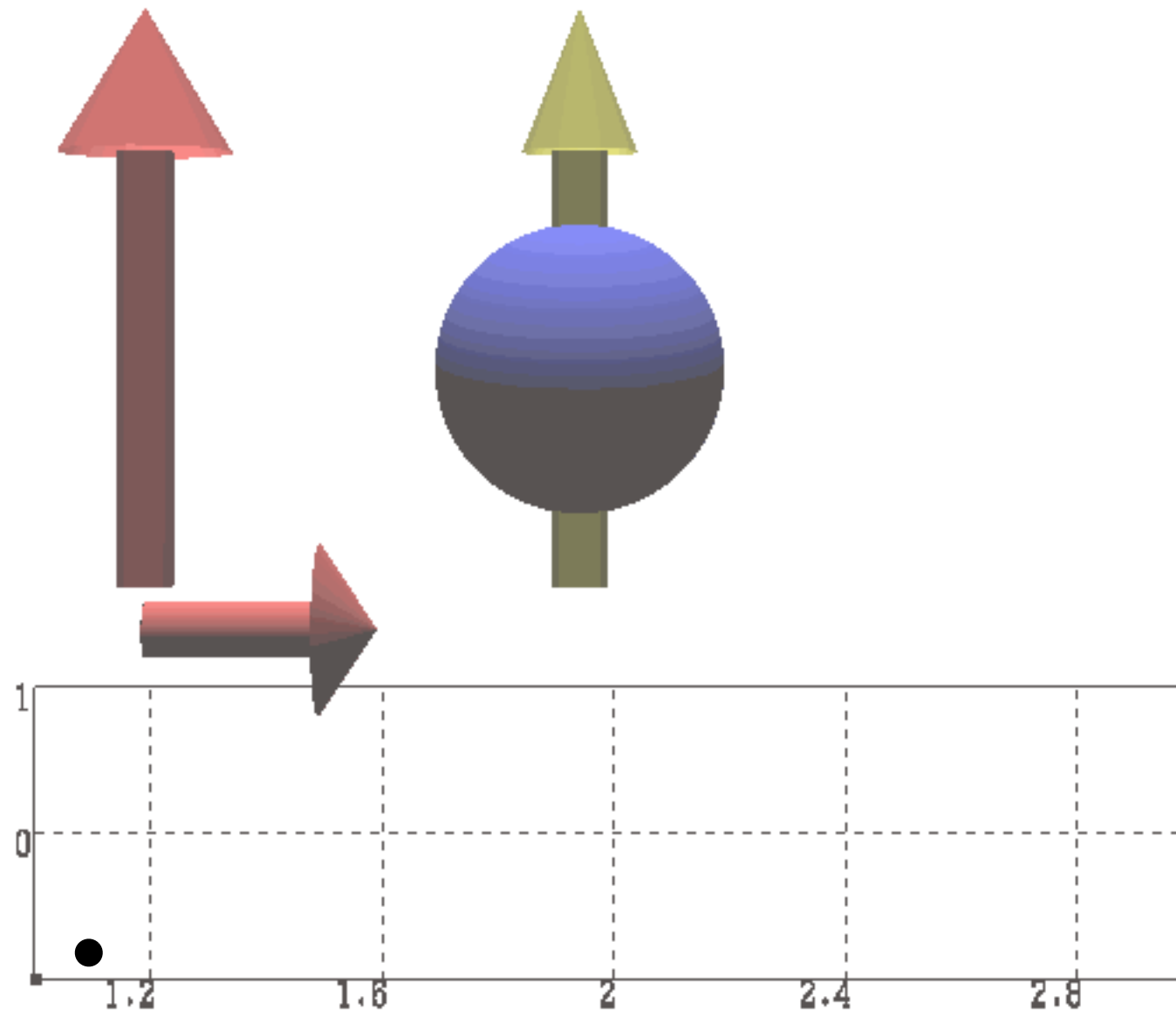


Measurement Procedure

same sequence with different precession time

t=0000.00000s

FRAME=412

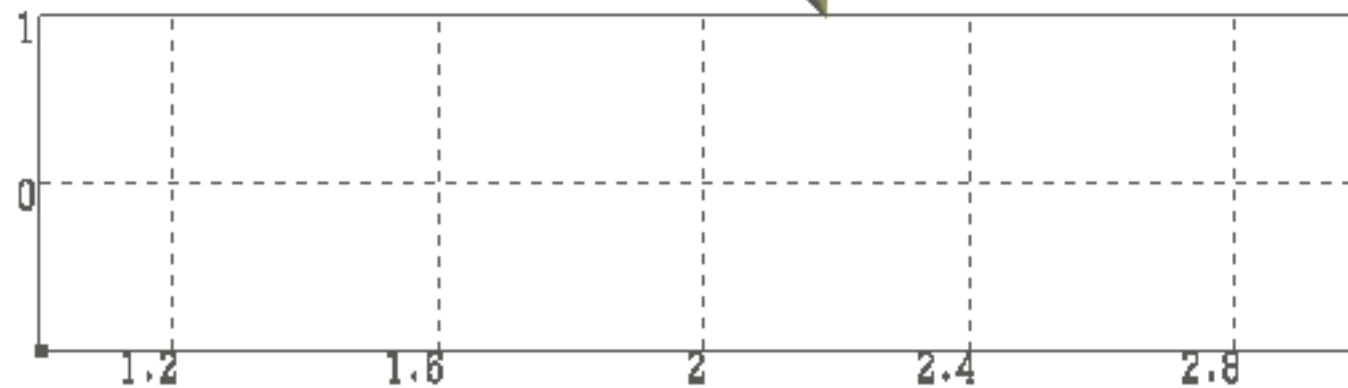
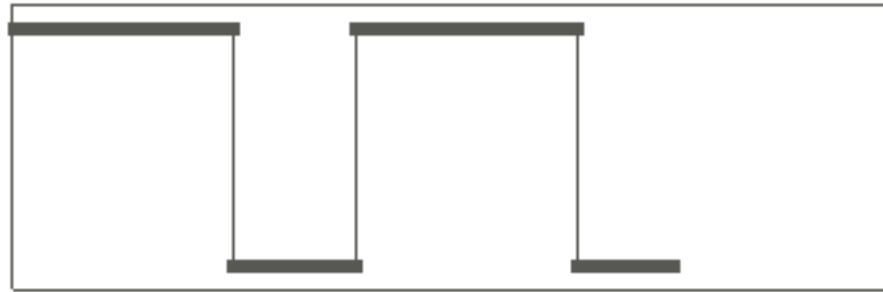


Measurement Procedure

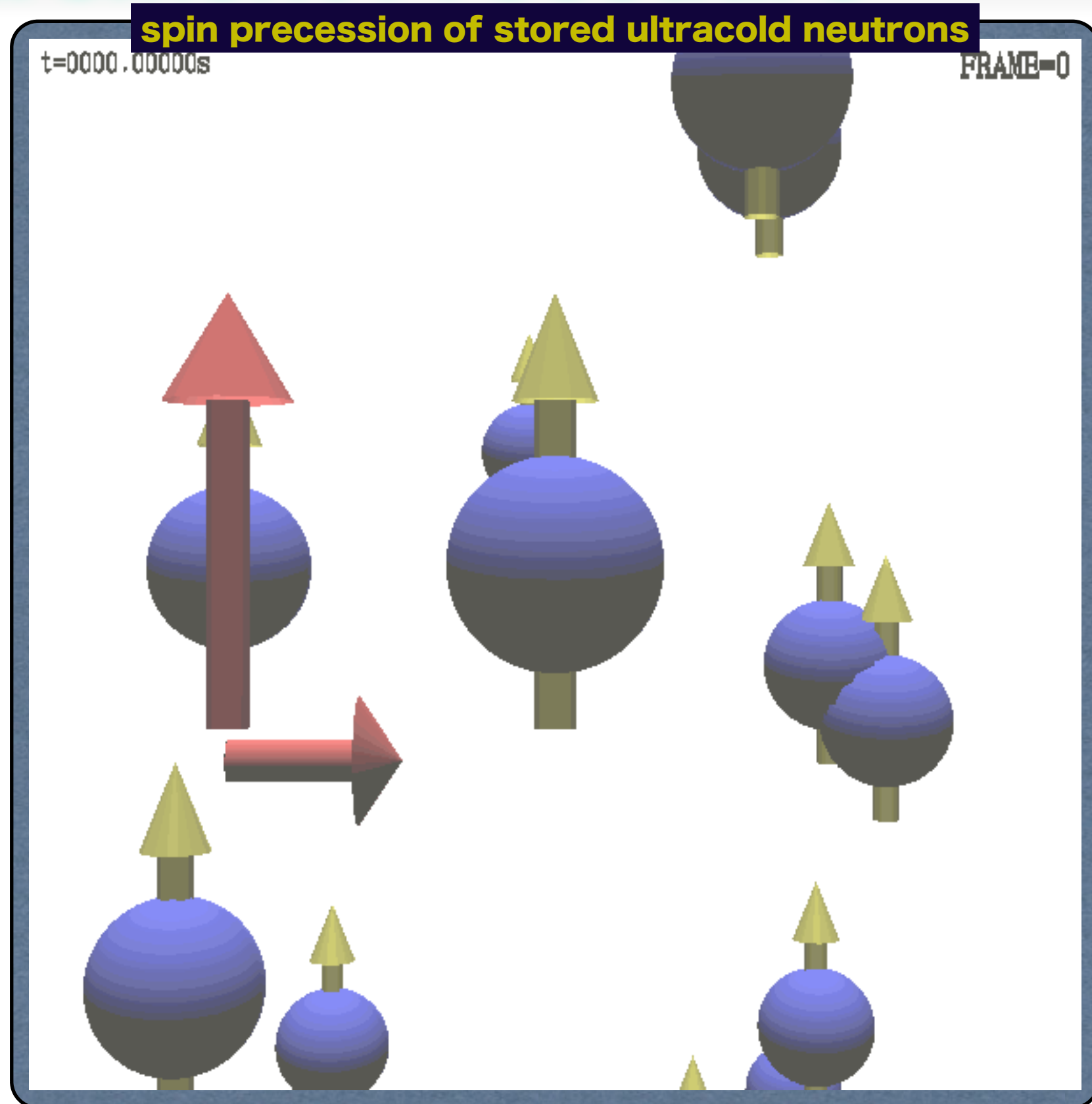
repeat the sequence to calibrate the resonance location

t=0020.50000s

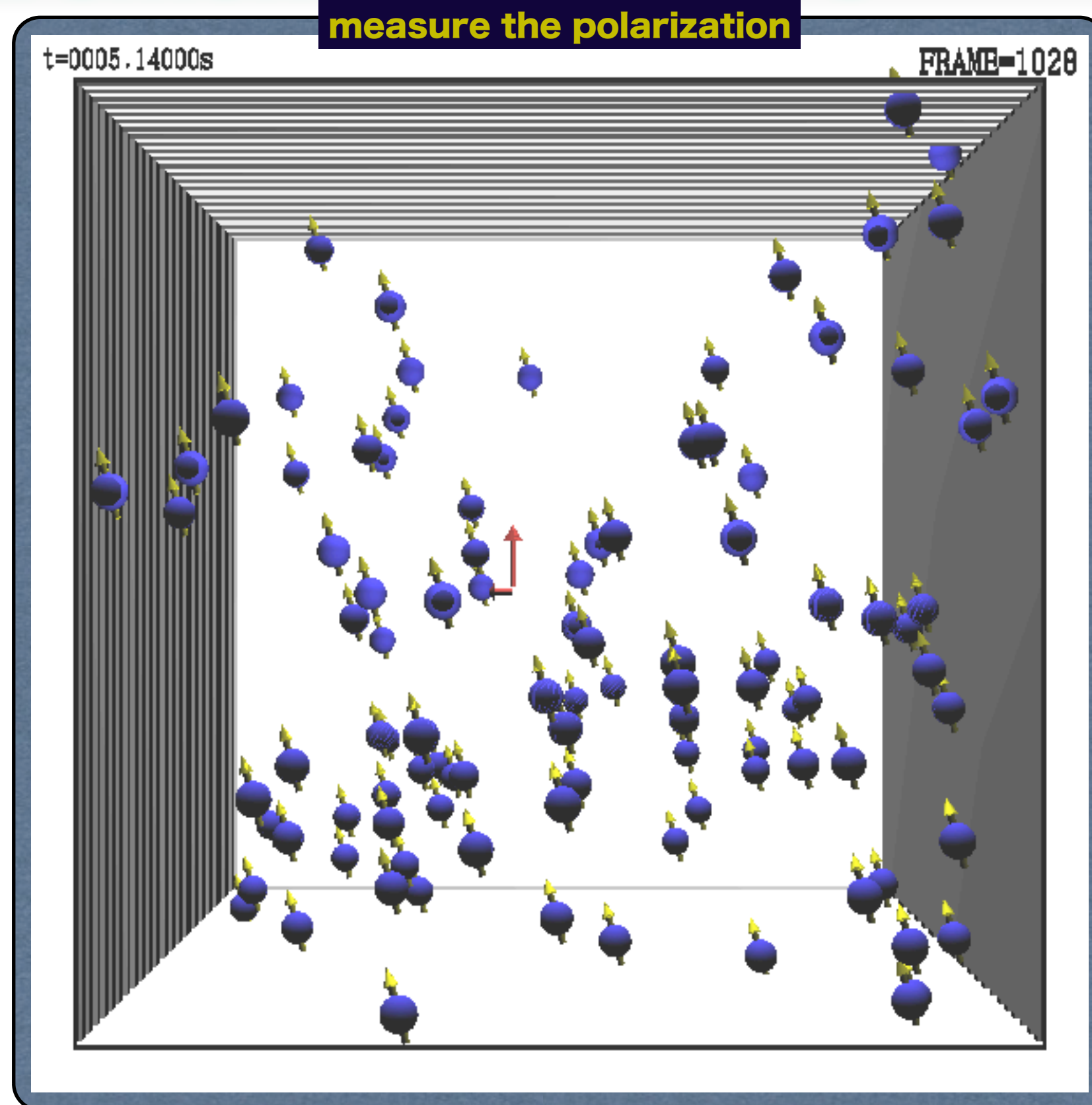
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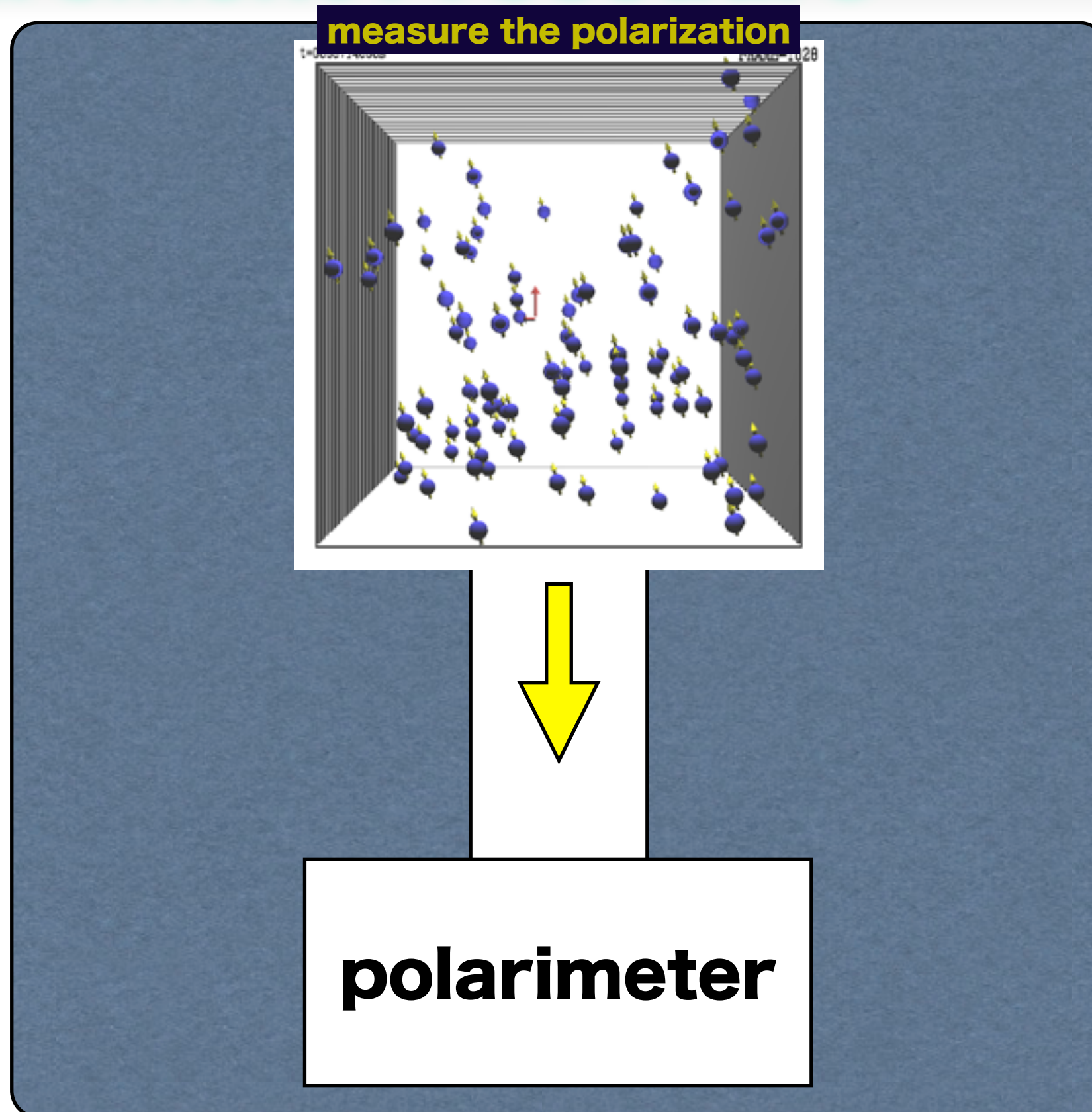
Measurement Procedure



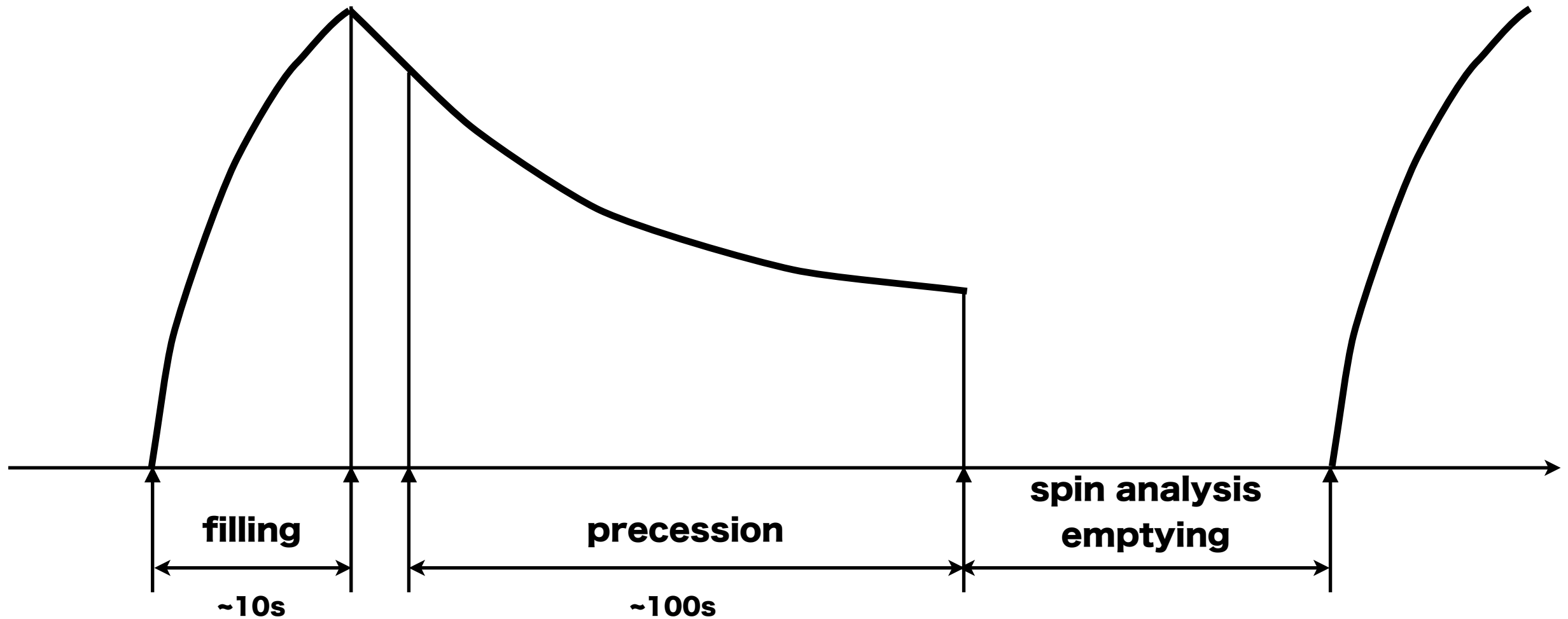
Measurement Procedure



Measurement Procedure



Measurement Procedure



Statistical Errors

$$\Delta d_n = \frac{\hbar/2}{ET N^{1/2}} \quad (\text{is minimum at } T=2\tau \text{ (storage lifetime)})$$

L: measurement cell size (volume= L^3)

large L $N \propto L^3$
 wall reflection rate $\propto L^{-1}$

$v_{\max}$: maximum velocity of stored UCN

large $v_{\max}$ $N \propto v_{\max}^3$
 reflection loss $\propto v^{3-r}$

ρ_0 : UCN spatial density for $|v_{\max}|=7\text{m/s}$

large ρ_0 $N \propto \rho_0$

longer T decreases the repetition rate of measurement cycle

larger storage volume faster UCN

denser UCN

$$(\Delta d_n)_{\text{stat}} \propto L^{-2} v_{\max}^{-(r+3)/2} \rho_0^{-1/2}$$



Statistical Errors

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Systematic Errors

	Effect	Correction	$(\Delta d_n)_{\text{syst}}$	dependence
(1)	Door cavity dipole	-5.6	2.0	$\propto R^2 H$
(2)	Other dipole fields	0.0	6.0	$\propto R^2 H$
(3)	Quadrupole difference	-1.3	2.0	$\propto R^2 H$
(4)	$v \times E$ (translational)	0.0	0.03	
(5)	$v \times E$ (rotational)	0.0	1.00	$\propto R$
(6)	Second-order $v \times E$	0.0	0.02	$\propto v^2$
(7)	ν_{Hg} light shift (geo phase)	3.5	0.8	$\propto R^2$
(8)	ν_{Hg} light shift (direct)	0.0	0.2	
(9)	Uncompensated B drift	0.0	2.6	$\propto H$
(10)	Hg atom EDM	0.02	0.06	
(11)	Electric forces	0.0	0.4	$\propto (R^2 H)^{1/3}$
(12)	Leakage currents	0.0	0.1	$\propto H/R$
(13)	ac fields	0.0	0.01	
	Total	-3.4	7.2	

$\propto V$

$\propto V_{\text{max}}$

$\propto R, H, V^{1/3}$

smaller storage volume

slower UCN



Statistics

Systematics

larger storage volume

smaller storage volume

faster UCN

slower UCN

denser UCN



Statistics Systematics

larger storage volume

smaller storage volume

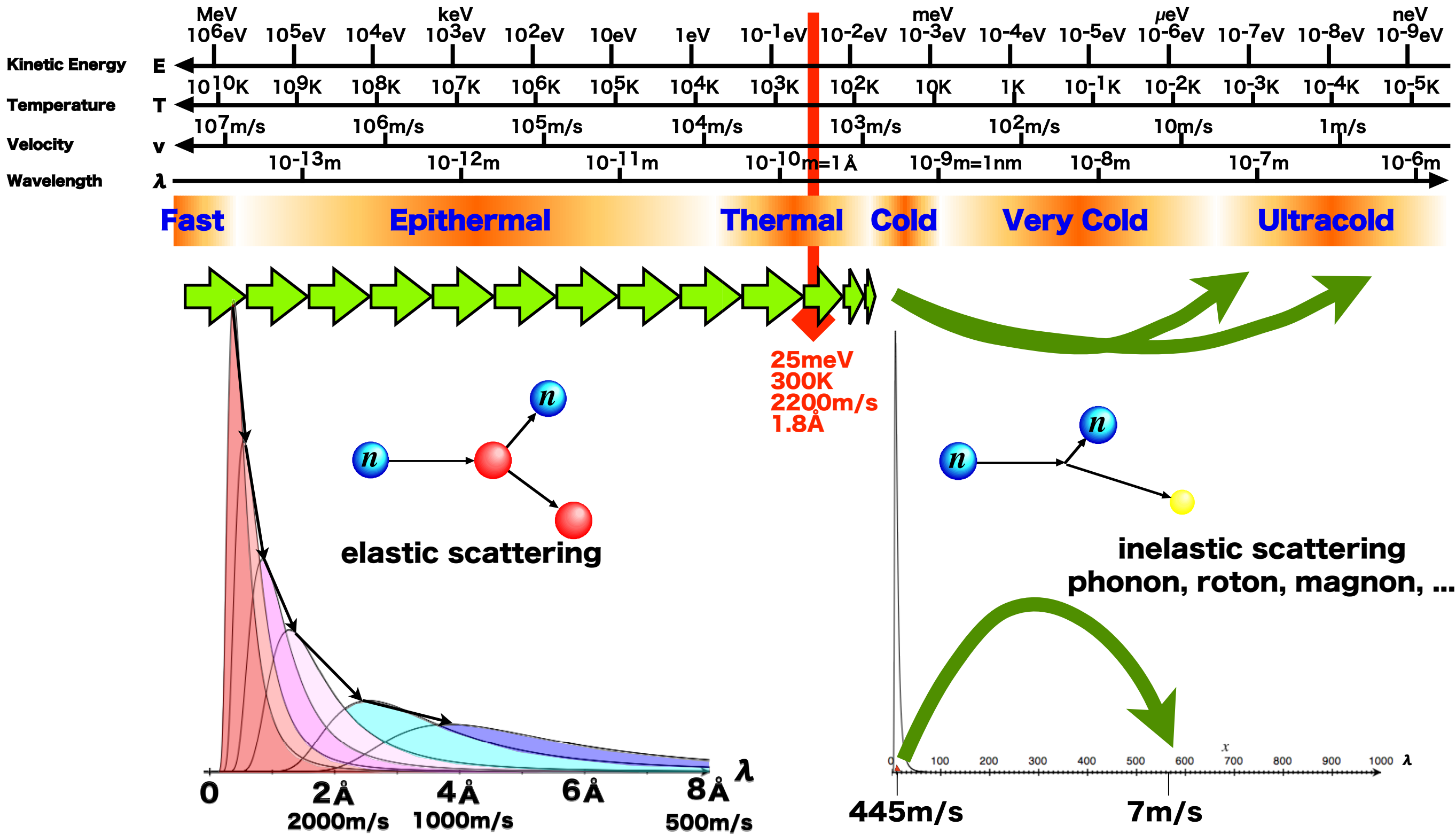
faster UCN

slower UCN

denser UCN



Superthermal UCN Production



Superthermal UCN Converters

C.-Y.Liu, Dissertation, Princeton Univ. (2002)

converter	He-II	Solid ortho-D ₂	α -O ₂
interaction	phonon	phonon	magnon?
converter temperature	0.7K	5K	2K
optimal neutron temperature	9K	29K	12K
production rate (30K neutrons)	$90 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$	$1300 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$	$\sim 1000 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$
ideal lifetime (no wall loss, no upscattering)	886 s	146 ms	489 ms

$$\rho_{\text{UCN}} = 10^{-11} \Phi_0$$

(thermal moderator)



Superthermal UCN Converters

C.-Y.Liu, Dissertation, Princeton Univ. (2002)

converter	He-II	Solid ortho-D ₂	α -O ₂
interaction	phonon	phonon	magnon?
converter temperature	0.7K	5K	2K
optimal neutron temperature	9K	29K	12K
production rate (30K neutrons)	$90 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$	$1300 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$	$\sim 1000 \times 10^{-11} \Phi_0 \text{ cm}^{-3} \text{ s}^{-1}$
ideal lifetime (no wall loss, no upscattering)	886 s	146 ms	489 ms

low loss

large production rate

$$\rho_{\text{UCN}} = 10^{-11} \Phi_0$$

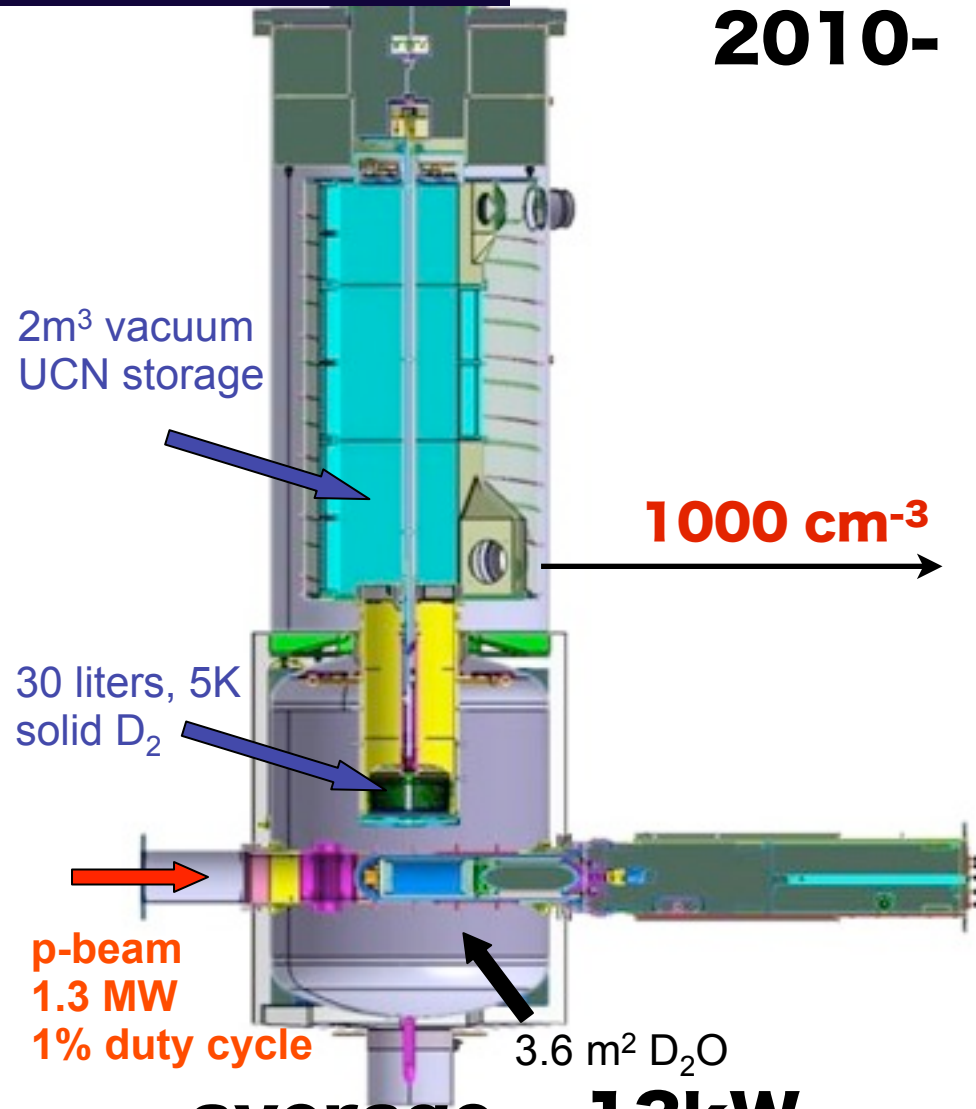
(thermal moderator)



UCN Sources (Accelerator+Spallation)

PSI

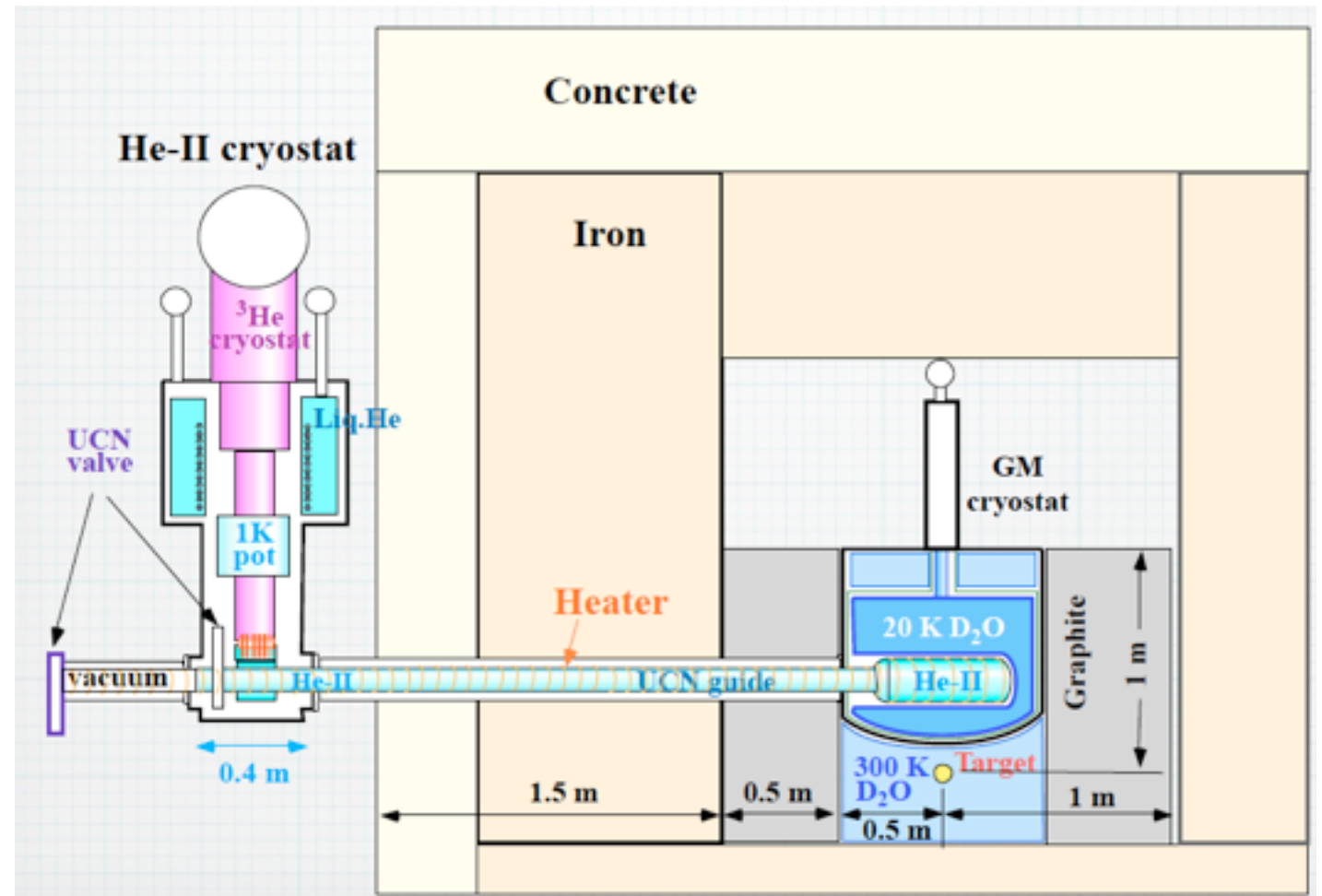
high power
2010-



average = 13kW
max. peak power = 1.3MW

TRIUMF

low loss
2013-?



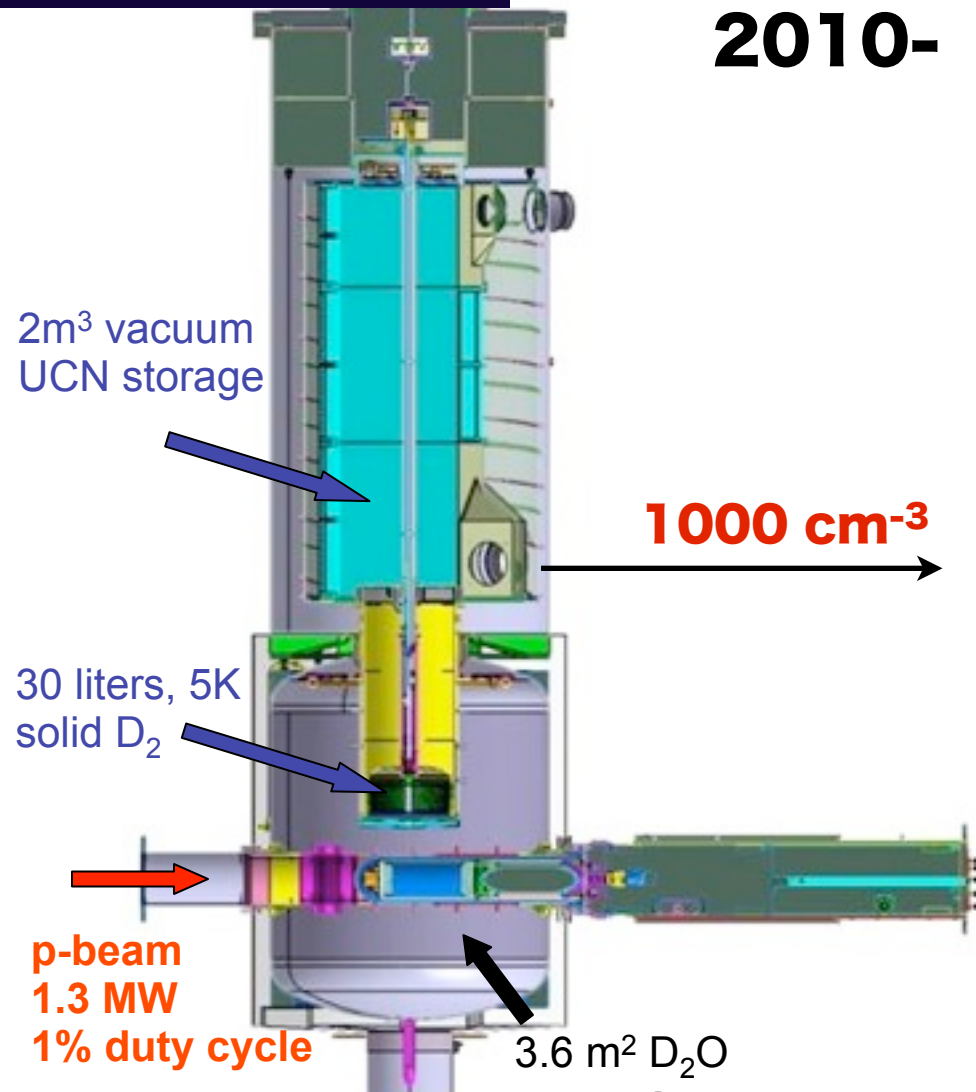
average=20kW
max. peak power = 200kW



UCN Sources (Accelerator+Spallation)

PSI

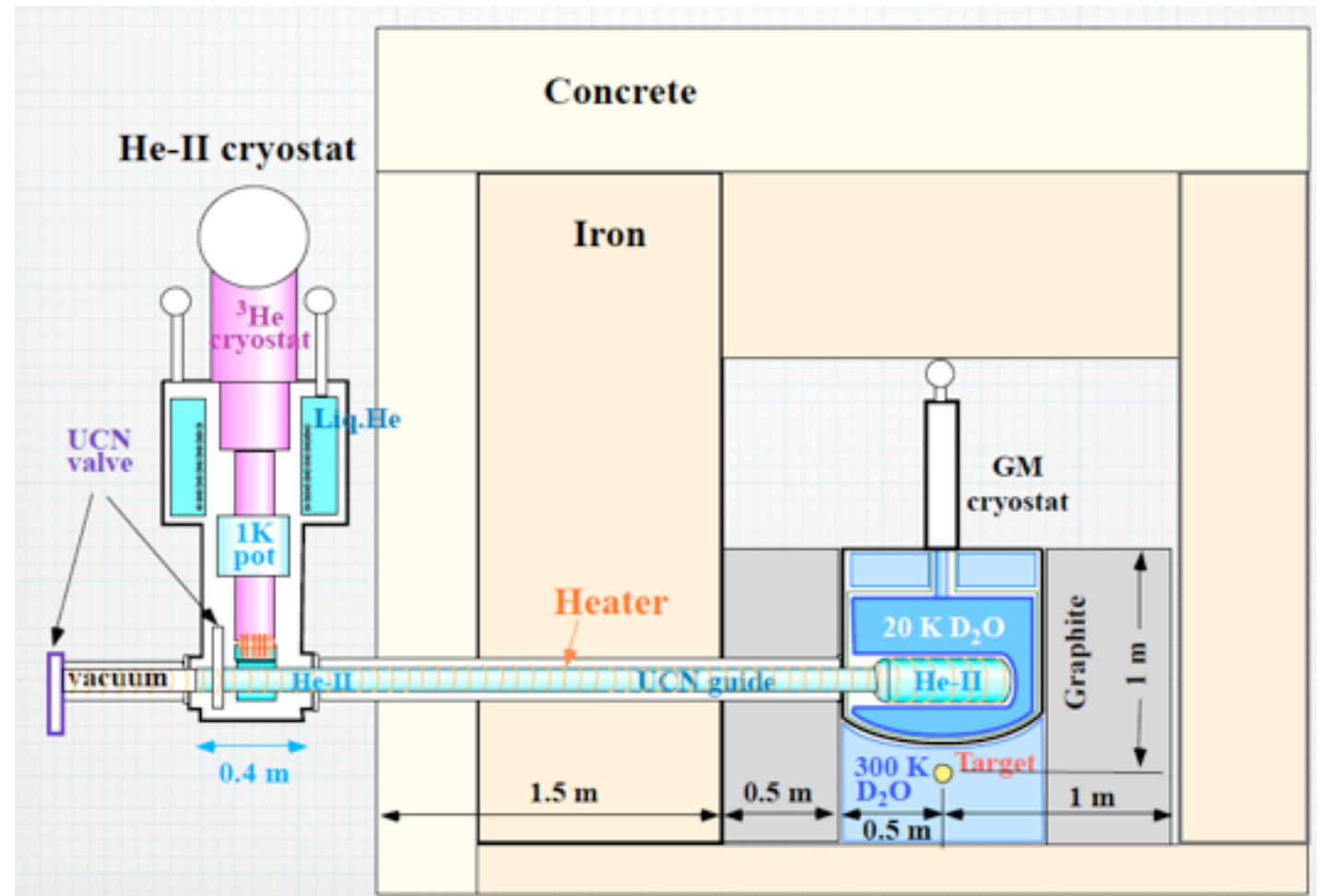
high power
2010-



average = 13kW
max. peak power = 1.3MW

TRIUMF

low loss
2013-?



average=20kW
max. peak power = 200kW

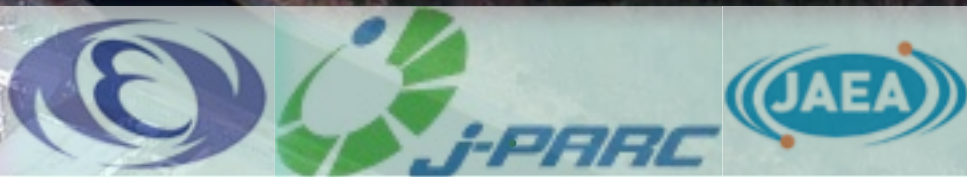
J-PARC P33

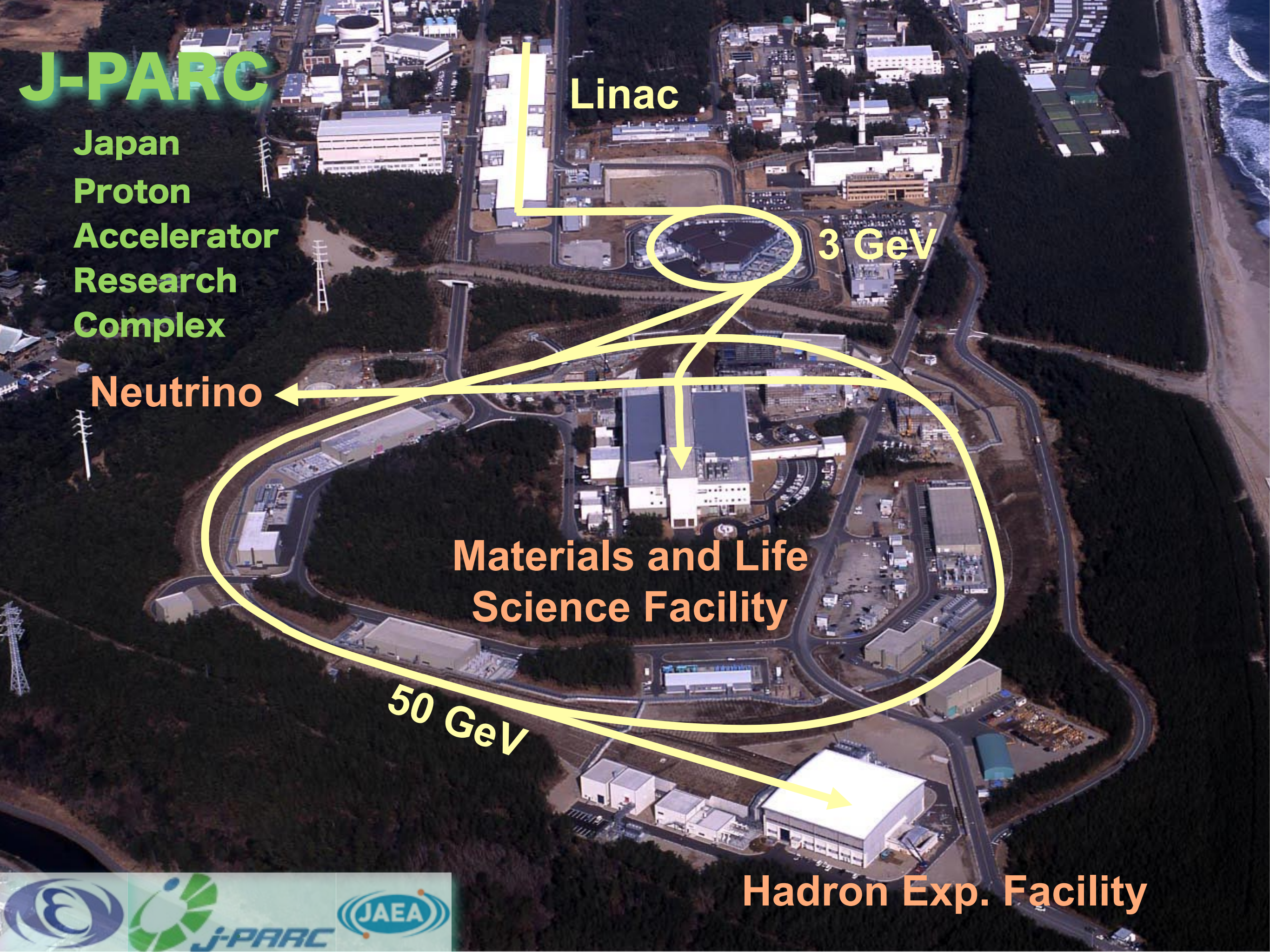
instantaneous power + transport optics

average = 2kW
max. peak power = 20MW

J-PARC

Japan
Proton
Accelerator
Research
Complex





J-PARC

**Japan
Proton
Accelerator
Research
Complex**

Linac

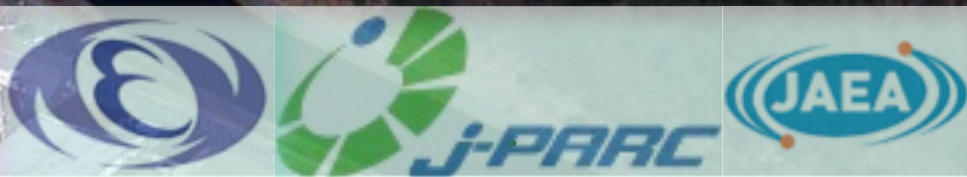
3 GeV

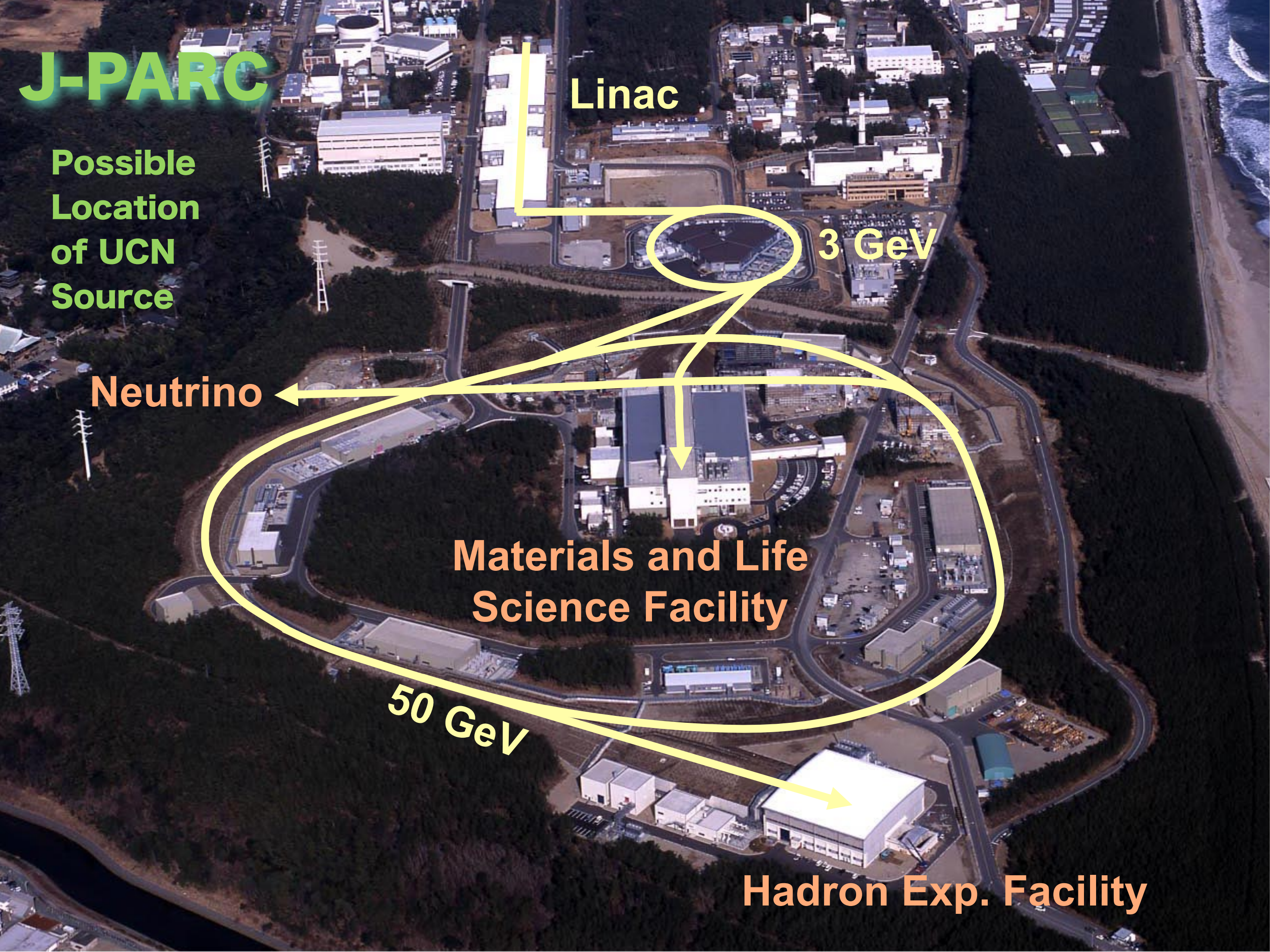
Neutrino

**Materials and Life
Science Facility**

50 GeV

Hadron Exp. Facility





J-PARC

Possible
Location
of UCN
Source

Linac

3 GeV

Neutrino

**Materials and Life
Science Facility**

50 GeV

Hadron Exp. Facility

J-PARC

Possible
Location
of UCN
Source

Linac

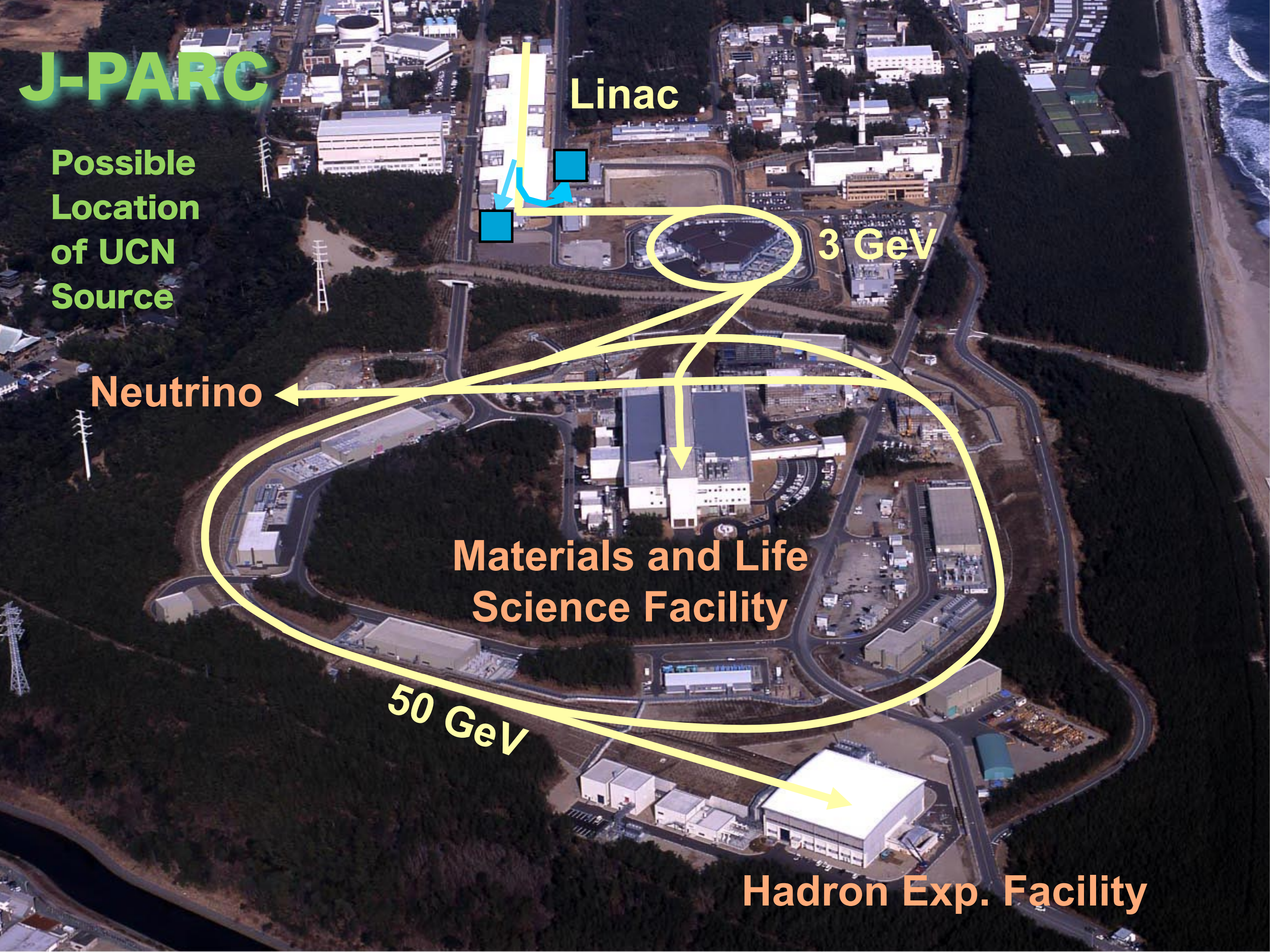
3 GeV

Neutrino

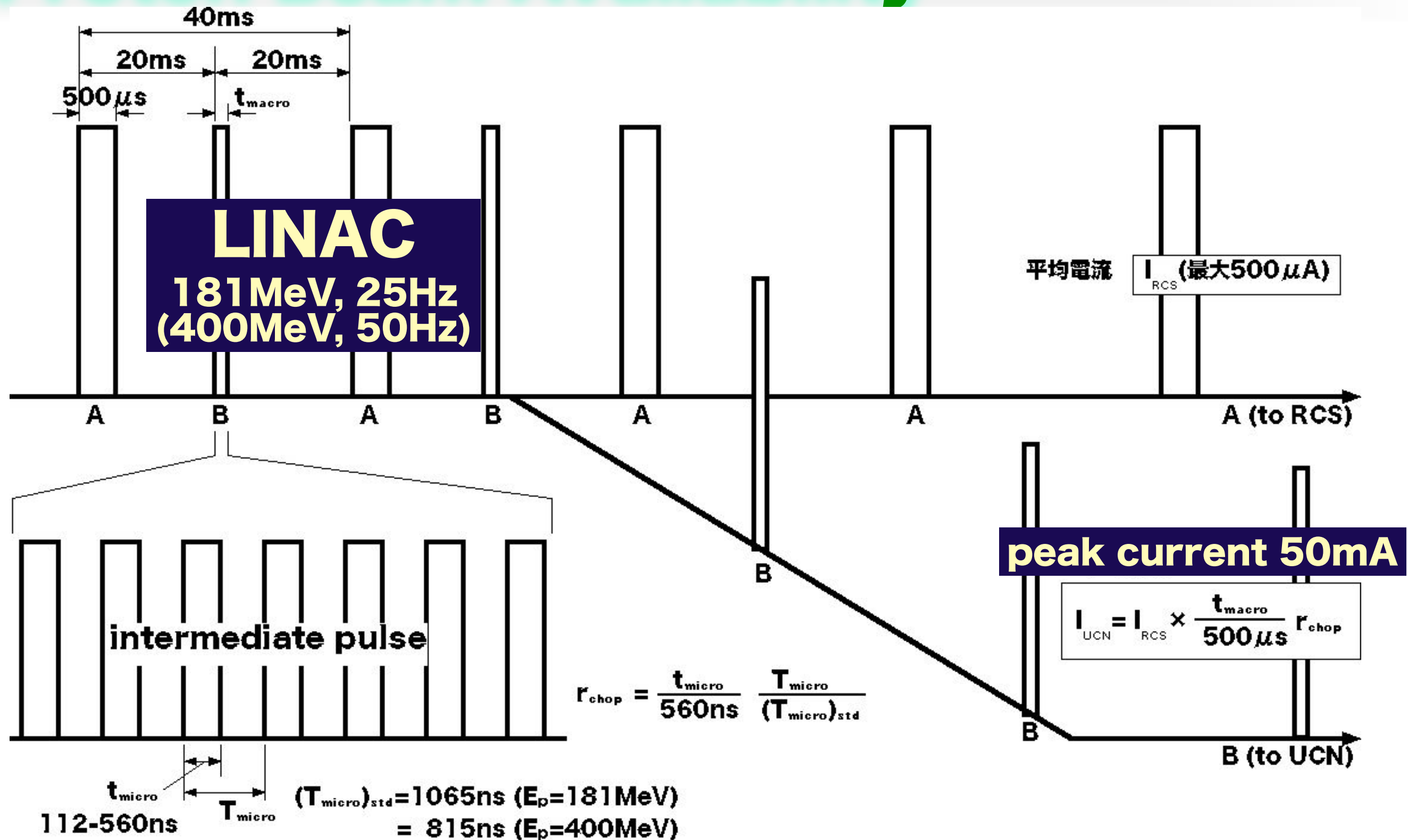
Materials and Life
Science Facility

50 GeV

Hadron Exp. Facility



Proton Beam Availability



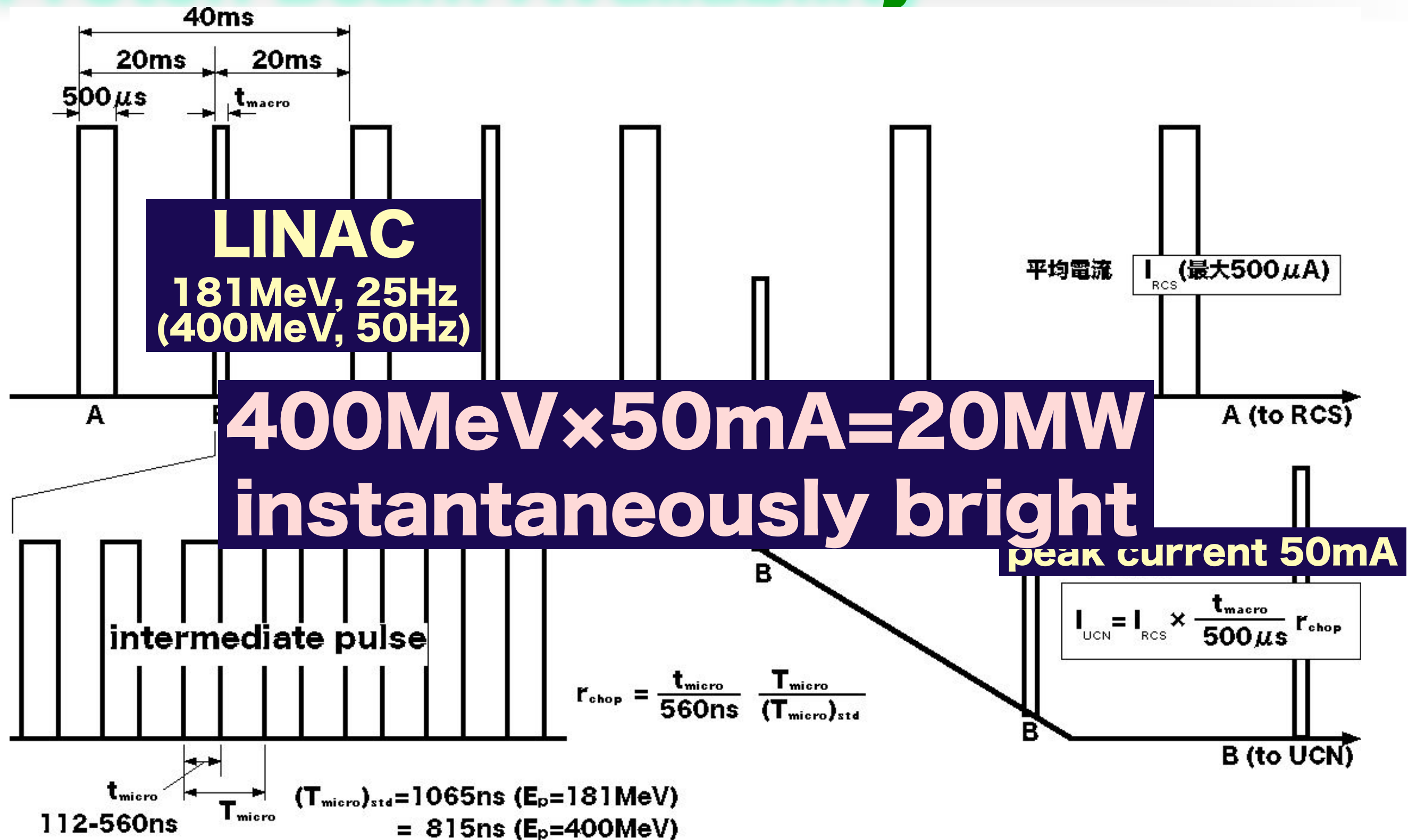
**maximum 250kW (400MeV) is available
for 2nd Target Station, Nuclear Transmutation and UCN**

Date(2010/06/12) by (T. Itoh)

Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))

Conf(将来計画検討小委員会) At(Tokyo)

Proton Beam Availability



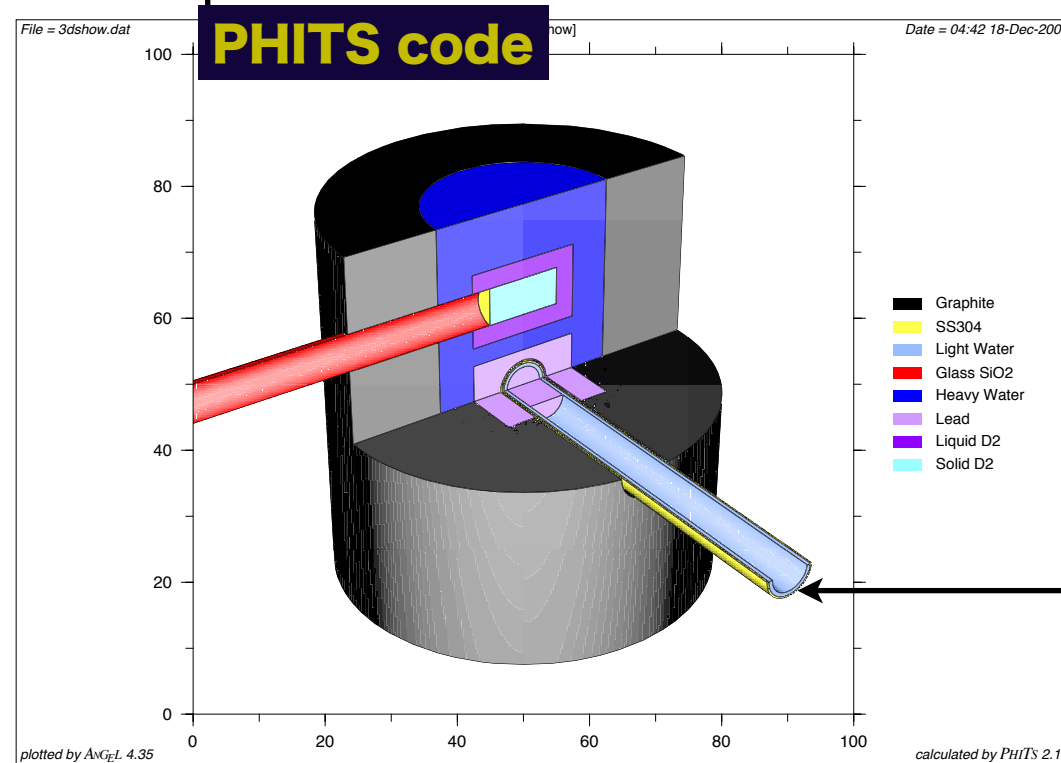
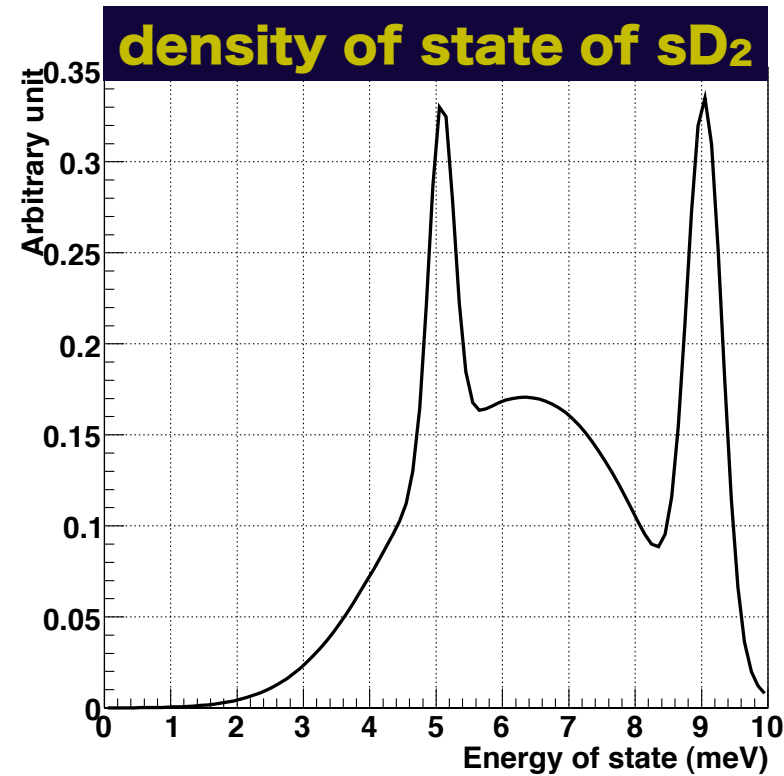
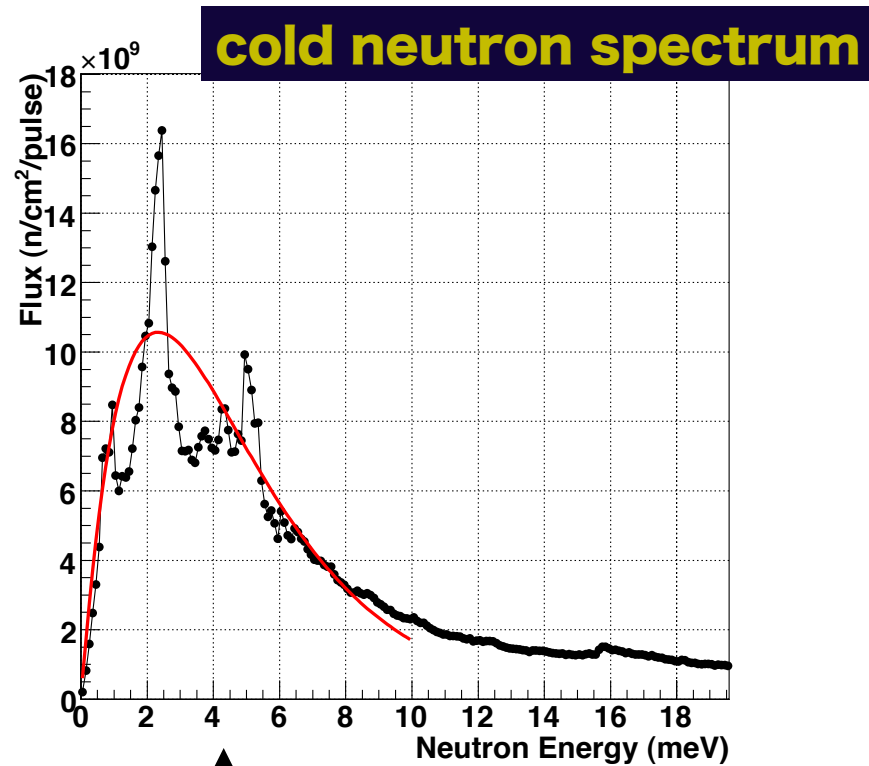
**maximum 250kW (400MeV) is available
for 2nd Target Station, Nuclear Transmutation and UCN**

Date(2010/06/12) by (T. Hosokawa)

Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))

Conf(将来計画検討小委員会) At(Tokyo)

Solid D₂ Converter



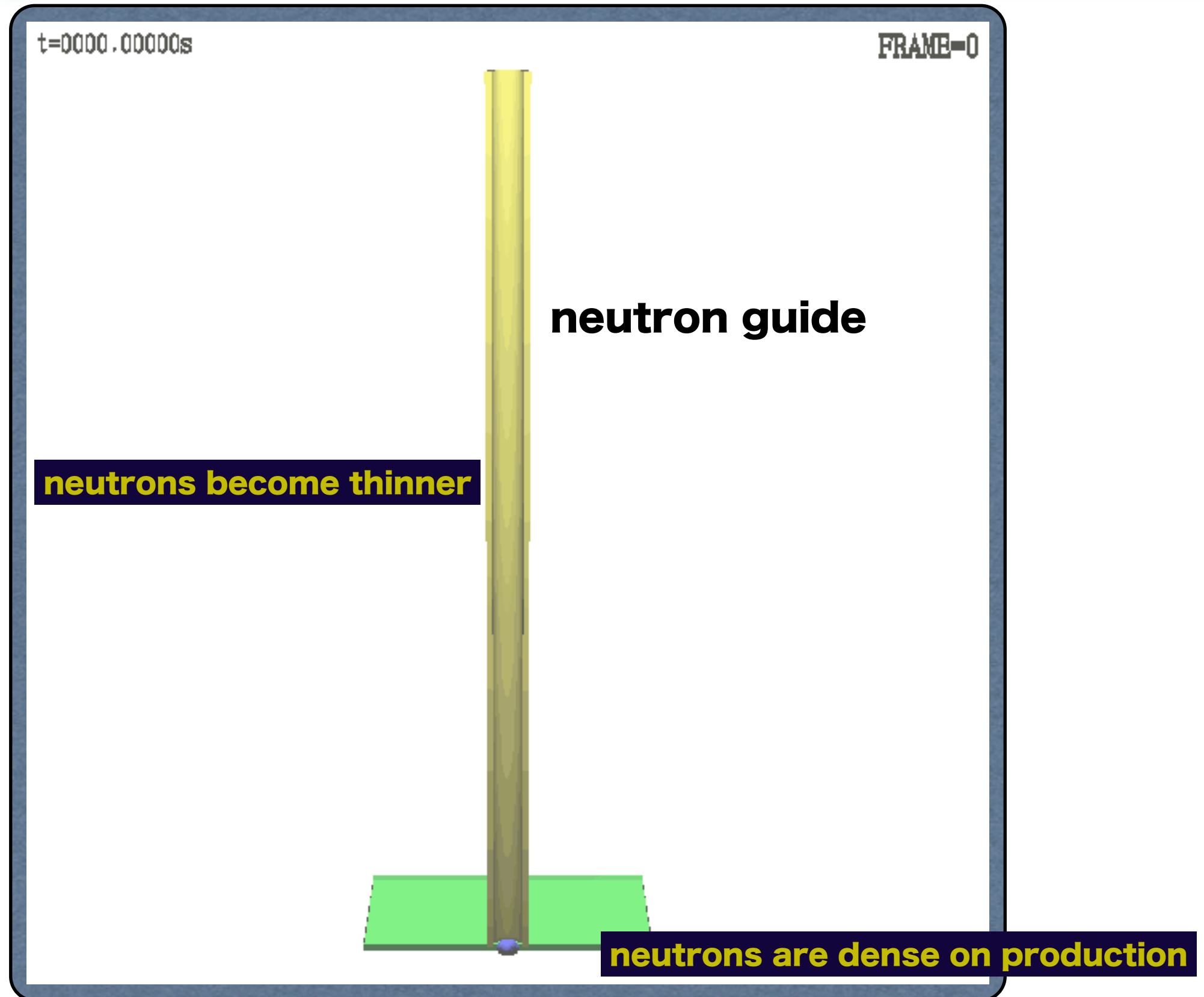
UCN density in the converter

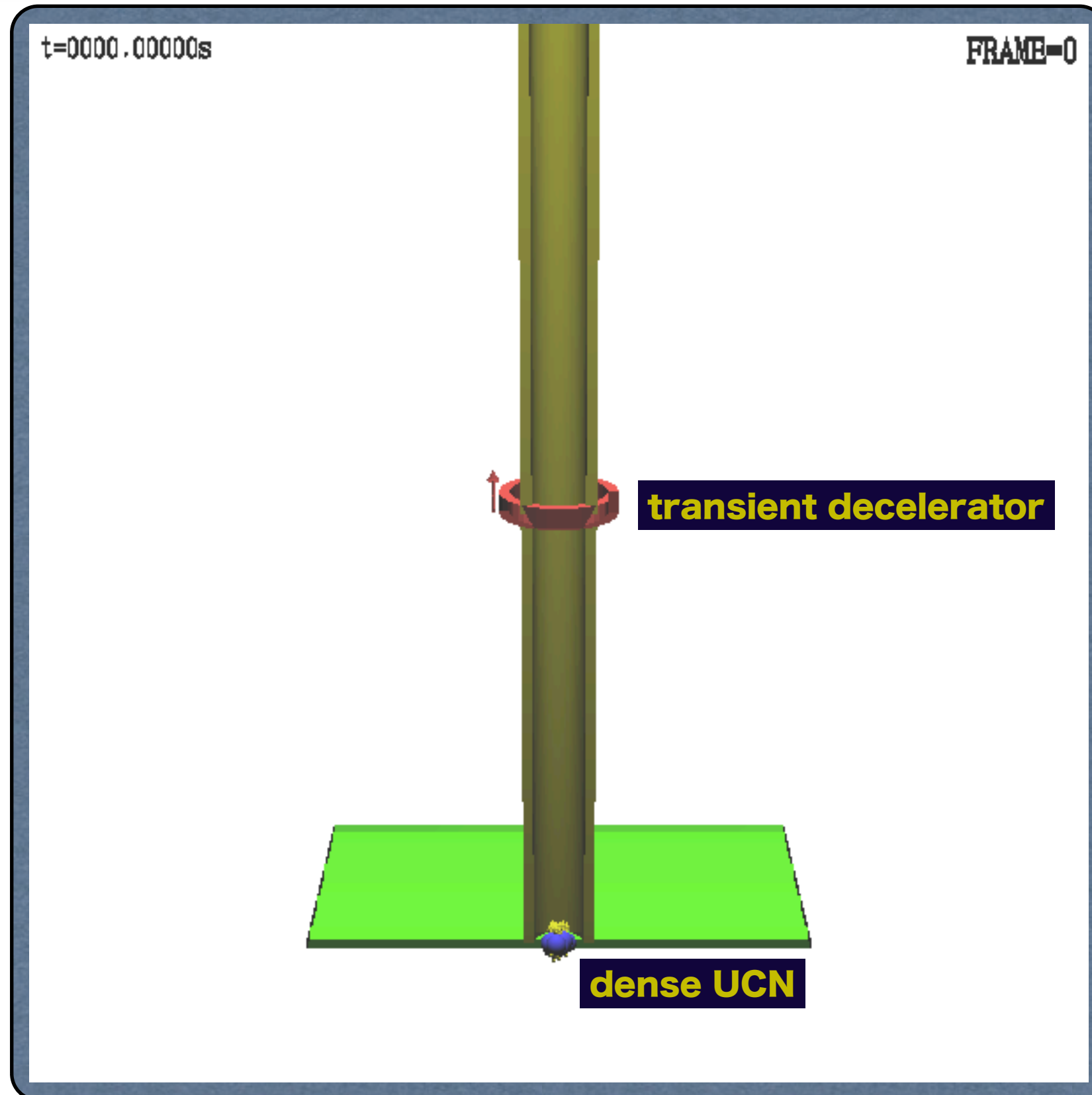
6200 cm⁻³ pulse⁻¹

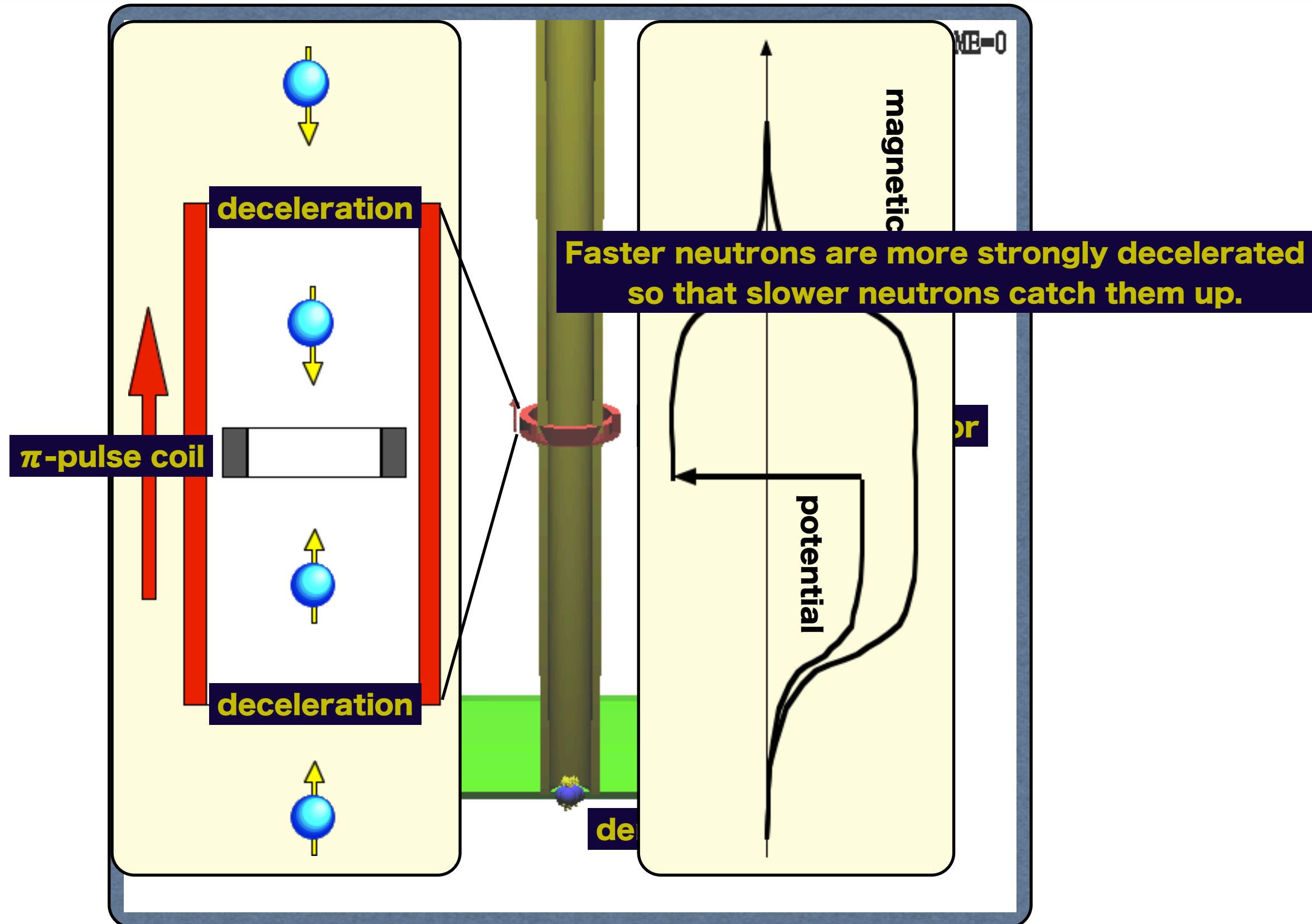
J-PARC LINAC

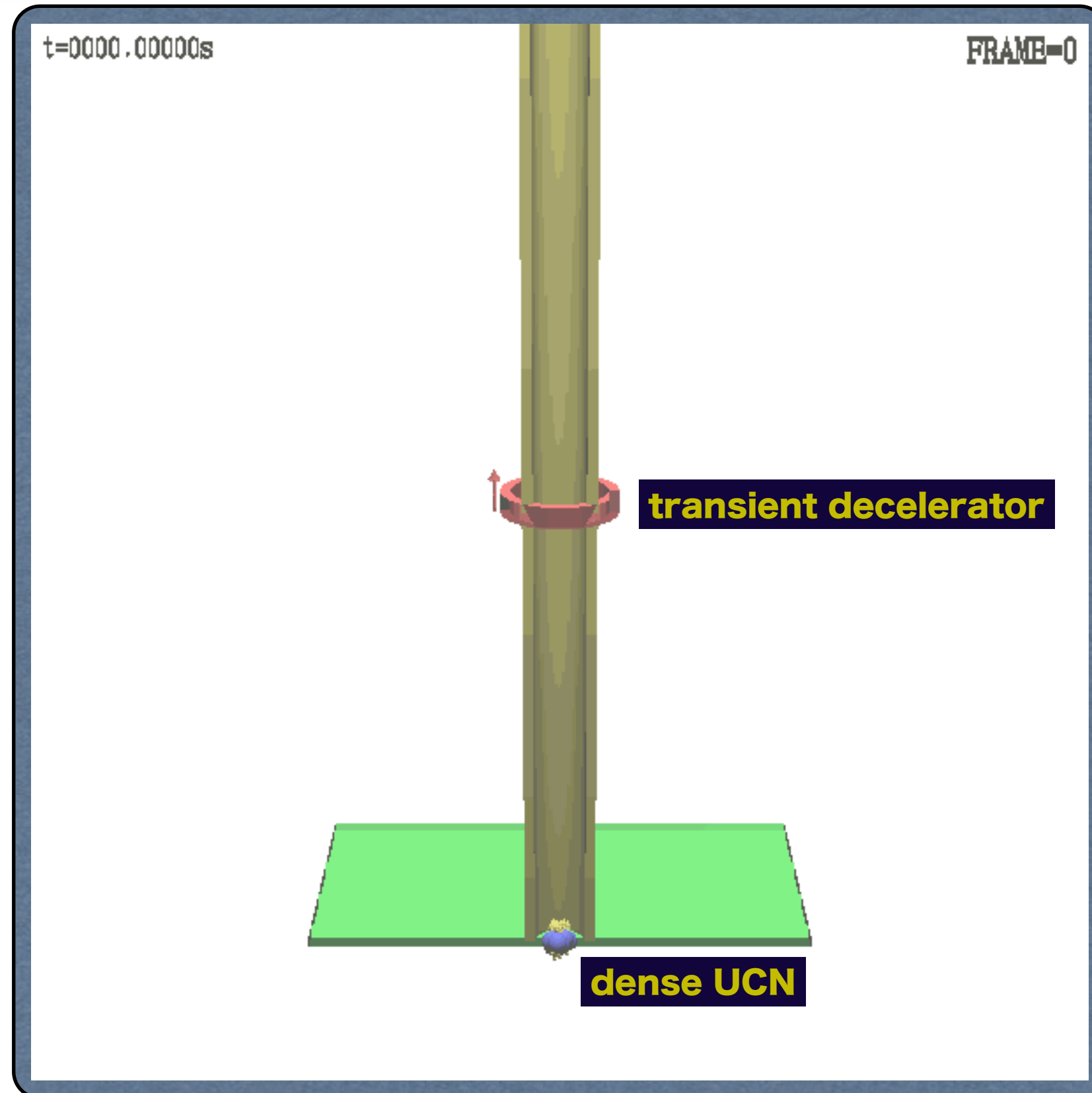
proton 400MeV
t_{pulse}=0.5ms I_{peak}=50mA
(10 kJ pulse⁻¹)

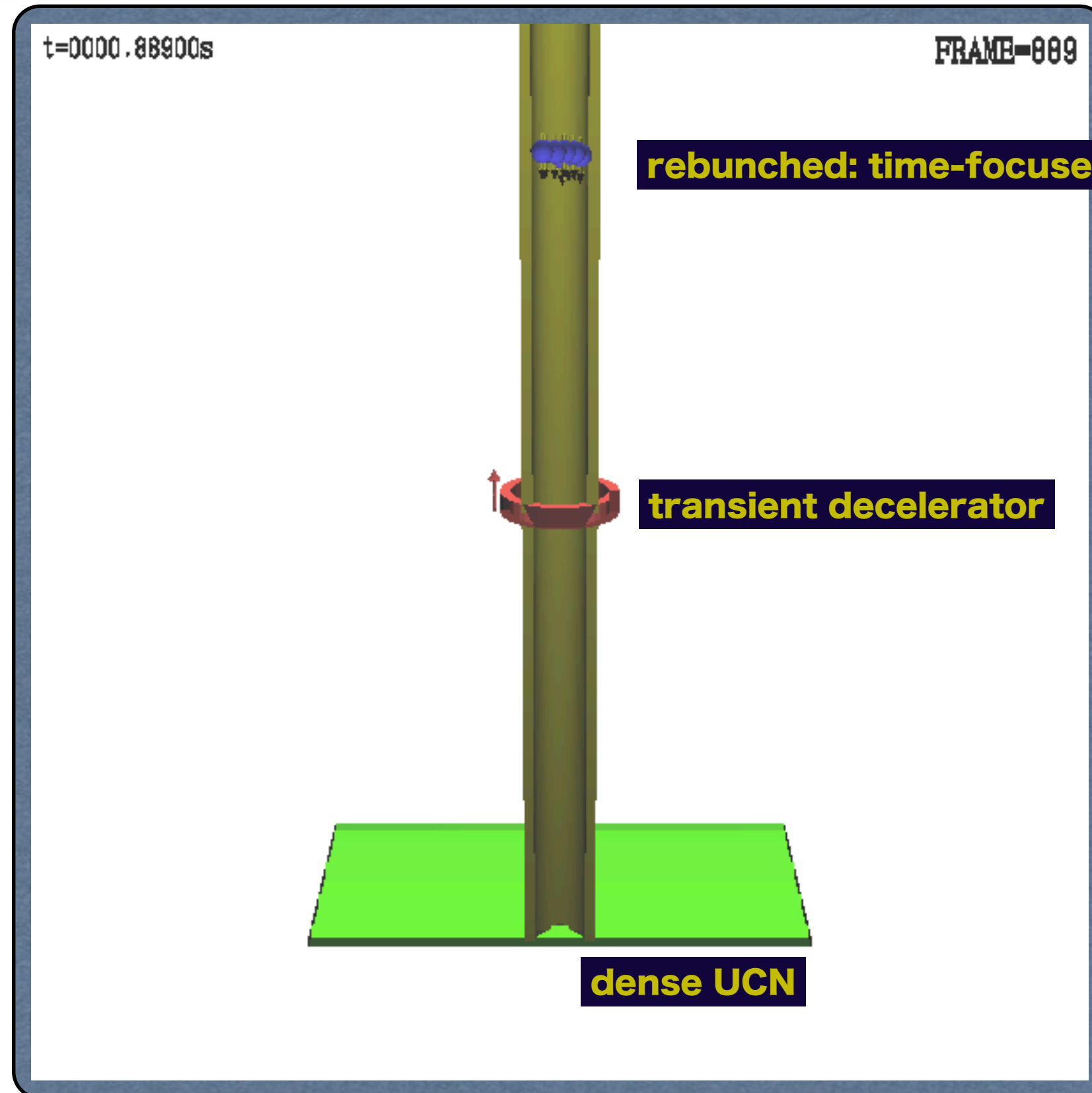
Density Decreases

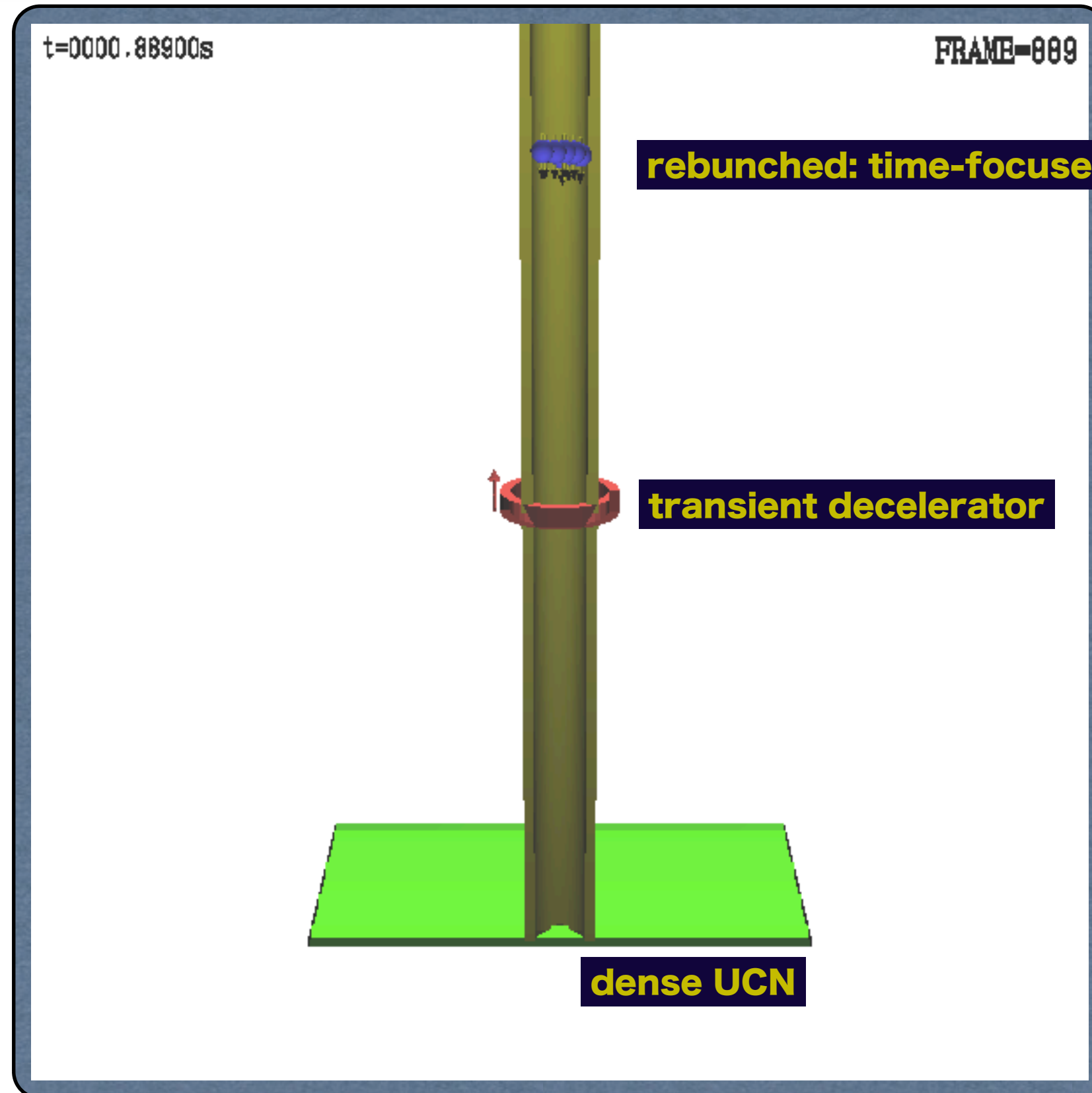


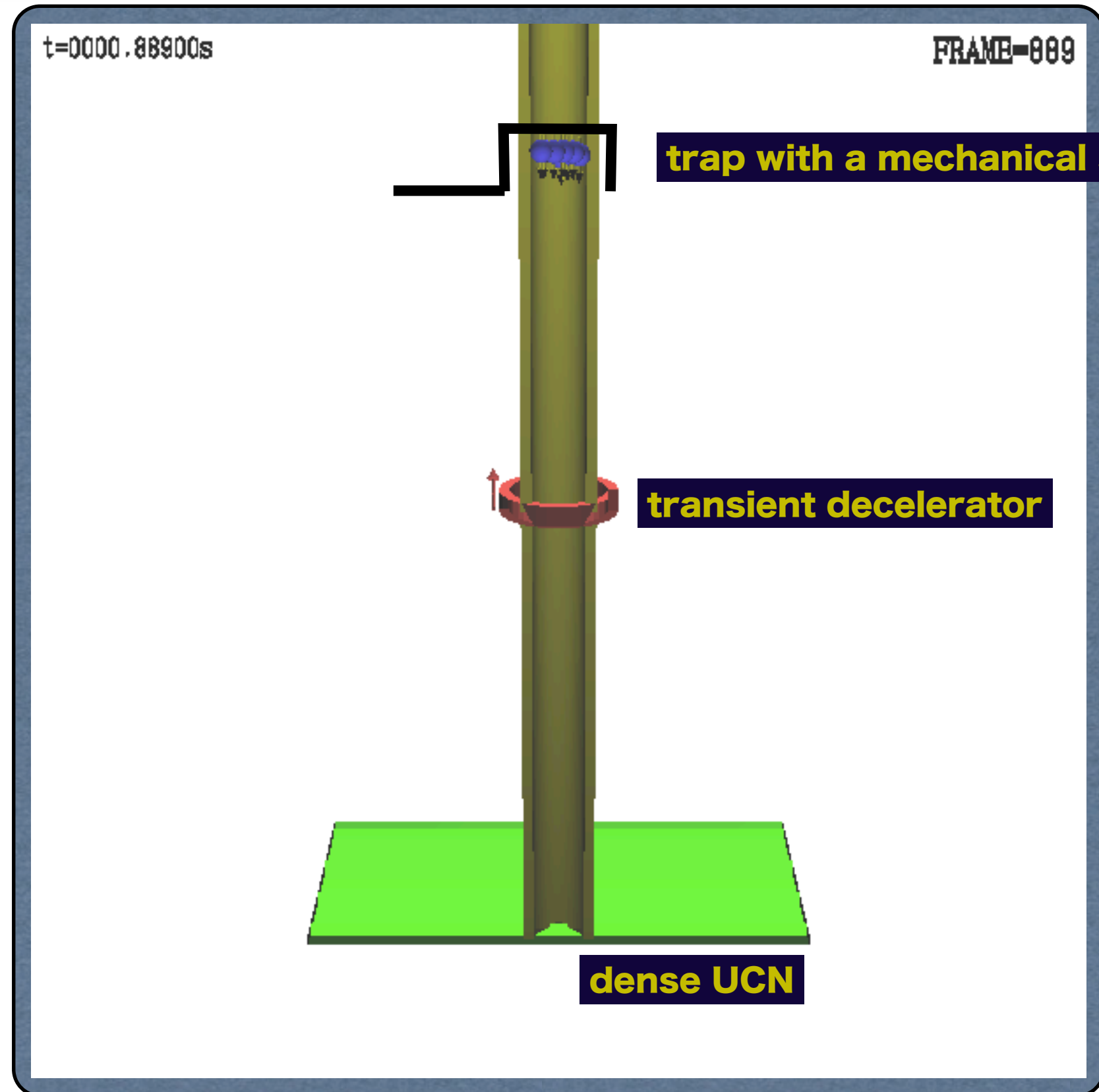


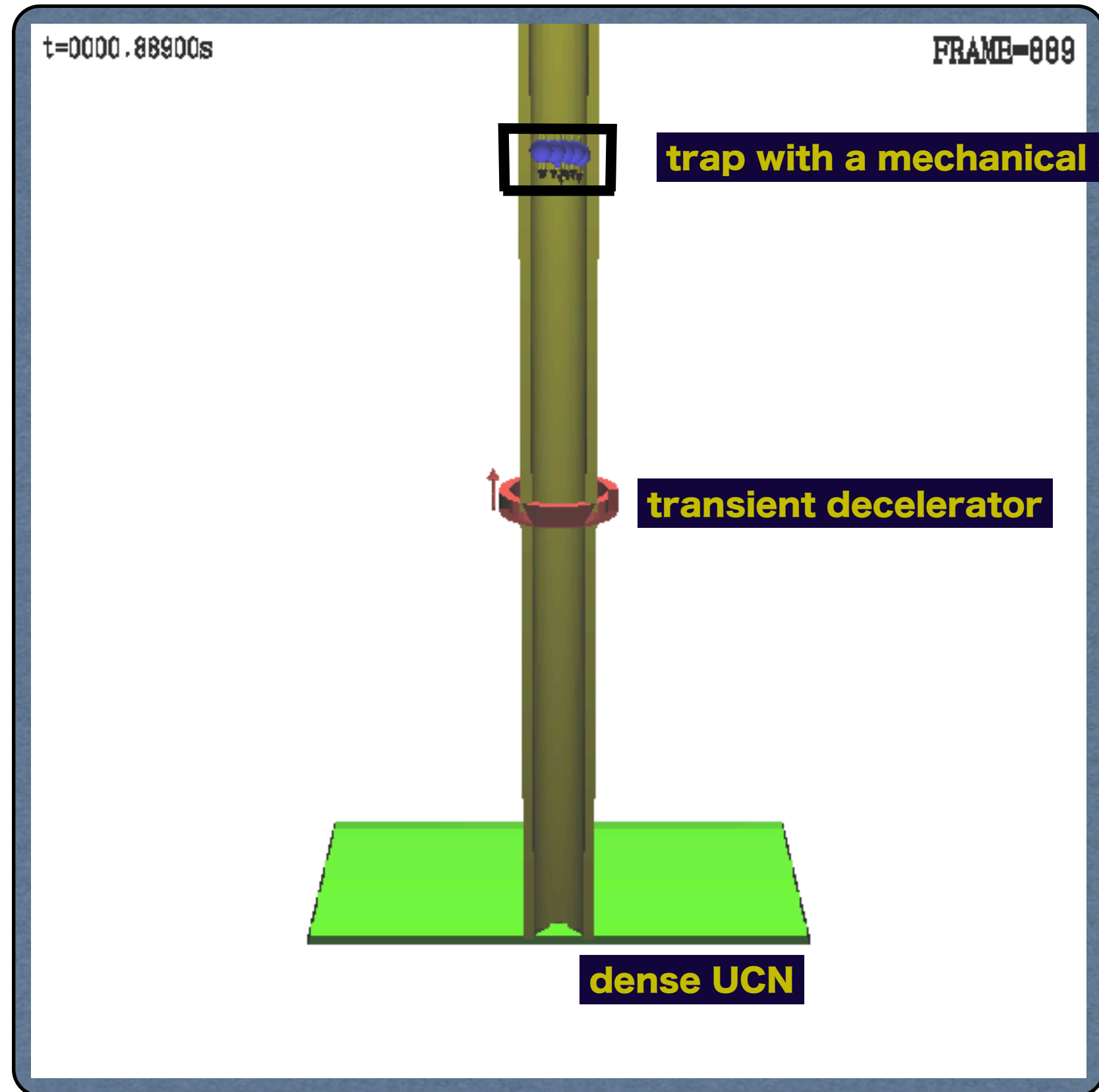












Geant4 Simulation

EDM Cell(Quartz)
Radius : 23cm
Height : 20cm
Loss prob : 3.0×10^{-4}
Diffuse : 0.1

UCN guide (DLC)
Length : 10m
Fermi pot : 241neV
Loss prob : 3.0×10^{-4}
Diffuse : 0.05

Shutter2
Open @ 8sec
Close @ 800sec

UCN Tank (DLC)
Height : 2.5m
Radius : 70cm
Fermi pot : 241neV
Loss prob : 3.0×10^{-4}
Diffuse : 0.1

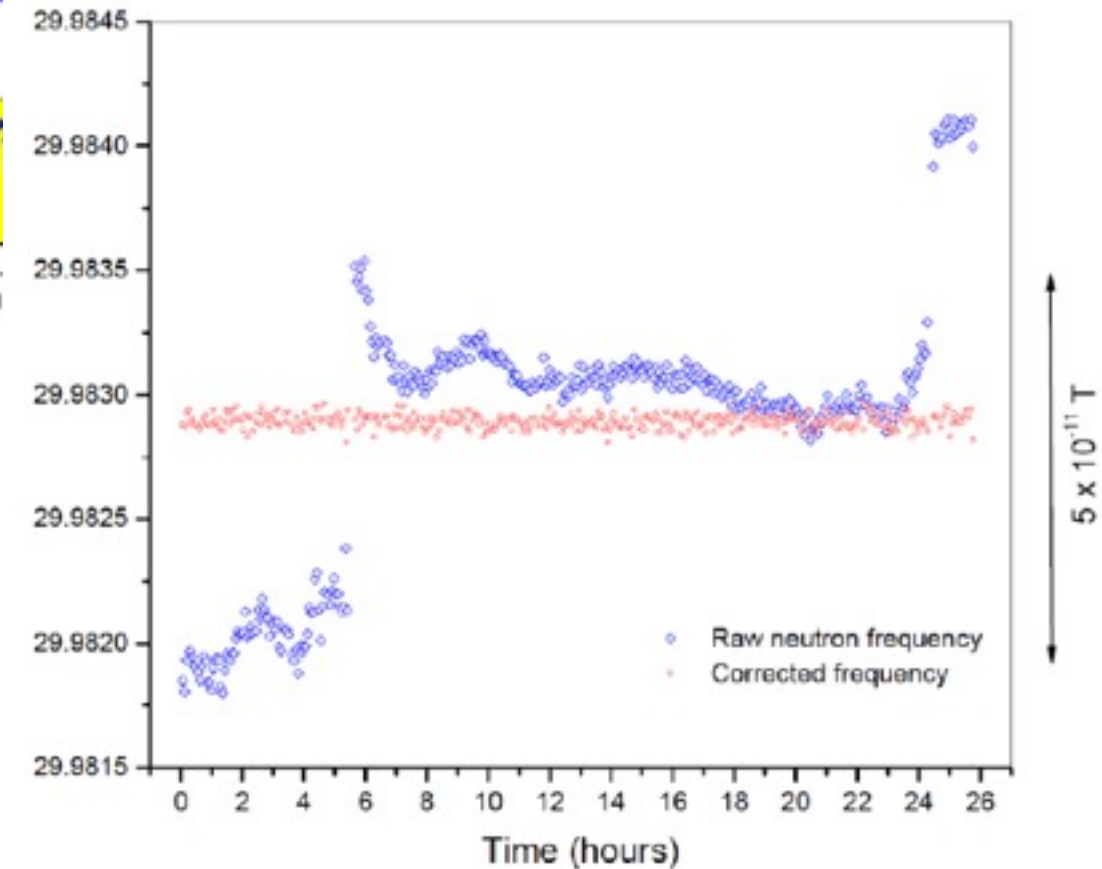
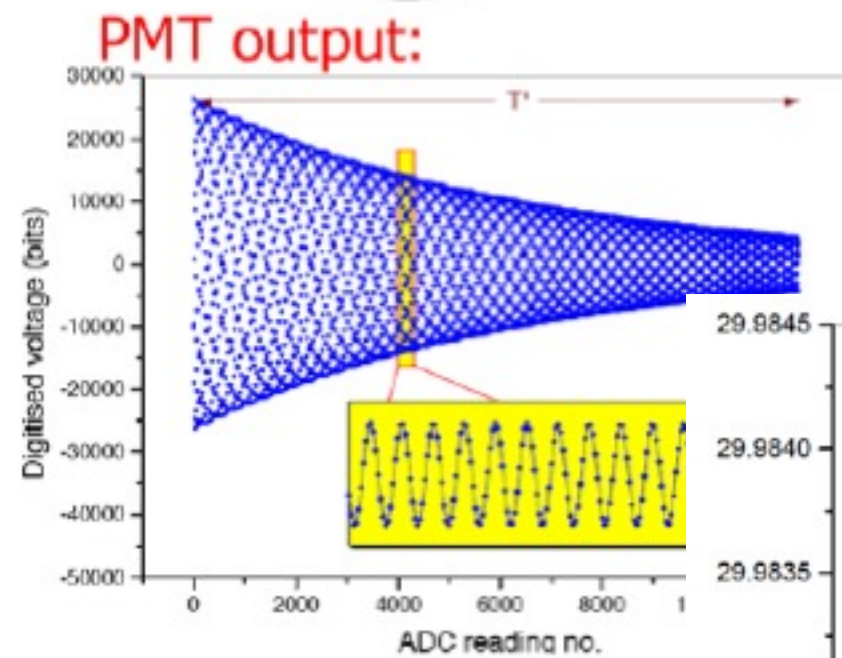
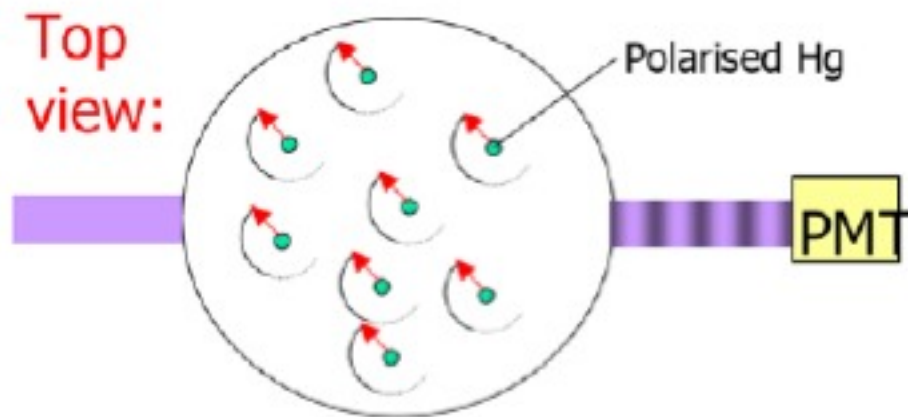
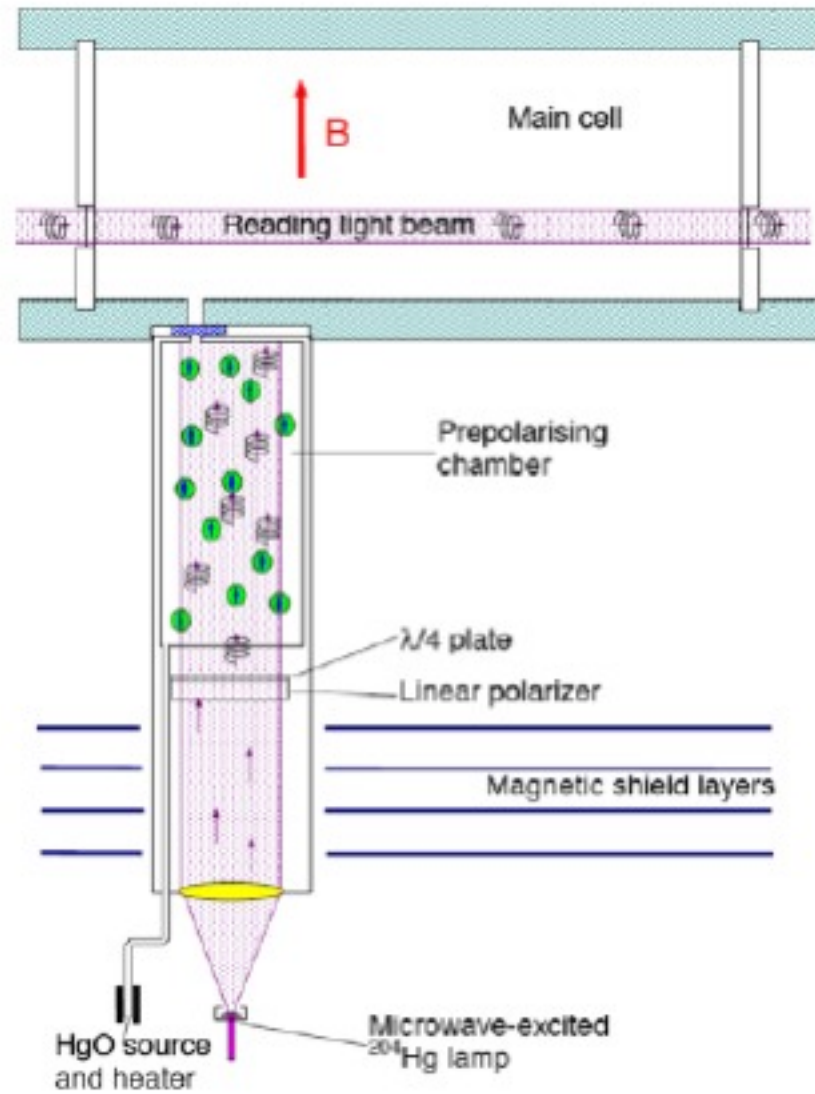
Shutter1
Open @ 0sec
Close @ 8sec

sD2 converter
Radius : 25cm
 V_x : -7m/sec ~ 7m/sec, uniform
 V_y : -7m/sec ~ 7m/sec, uniform
 V_z : 4.2~8.3m/sec, uniform
Beam on : 8sec

Lines : 10767
Quads : 1196
Triangles : 500



Magnetometry

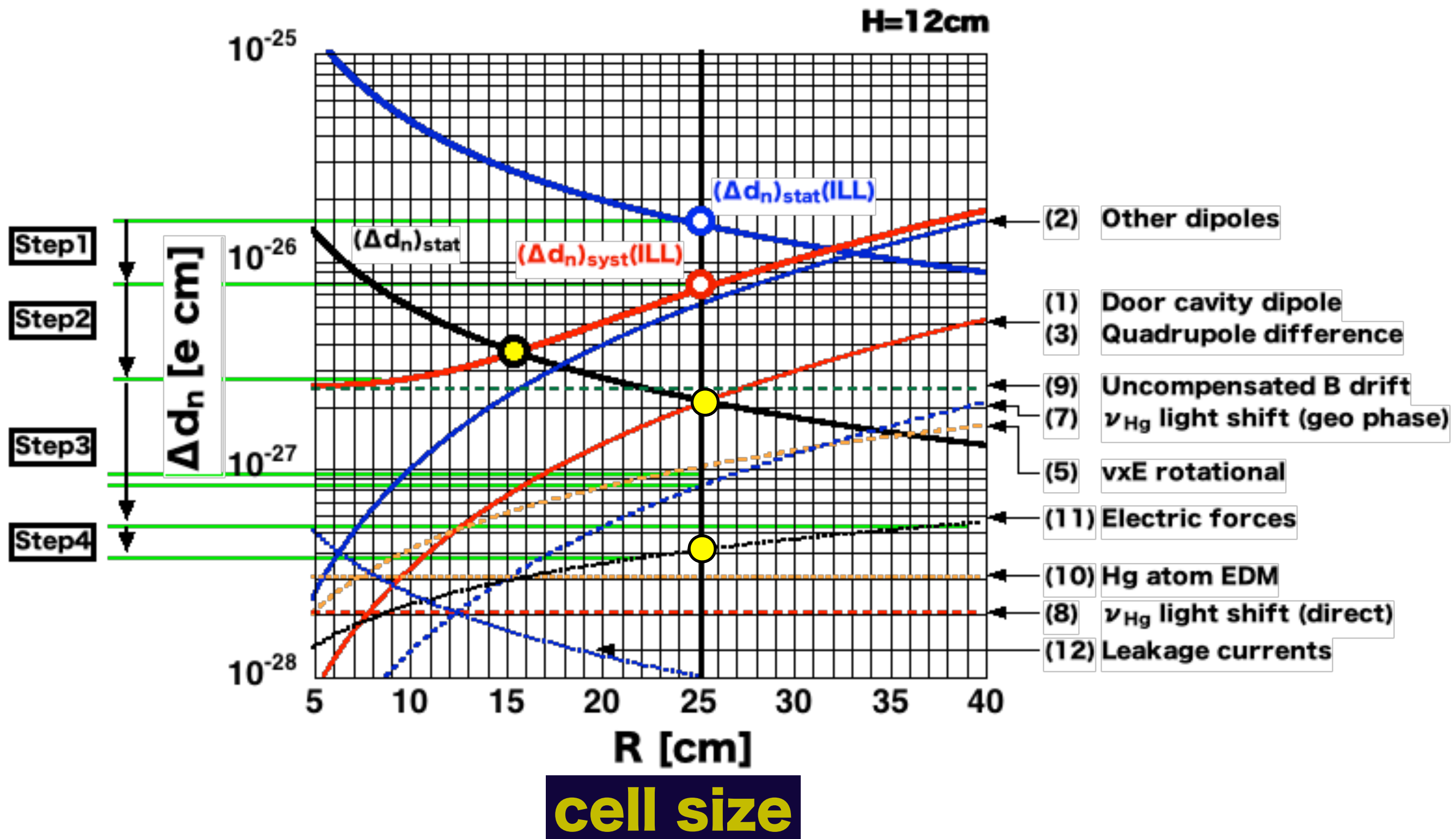


Measure the average magnetic field in the UCN storage chamber.

Experimental Errors

$$\rho_0 = 6200 \text{ cm}^{-3}$$

5000h



R&D Plans

- UCN Storage

Reflectivity, Diffuse reflection @ J-PARC/MLF w/ CN
storage time, depolarizing effect @ J-PARC/MLF w/ UCN

- UCN Transport

Reflectivity, Diffuse reflection @ J-PARC/MLF w/ CN
demonstration of rebuncher @ J-PARC/MLF w/ UCN

- Magnetometry

Hg co-magnetometer @ KEK

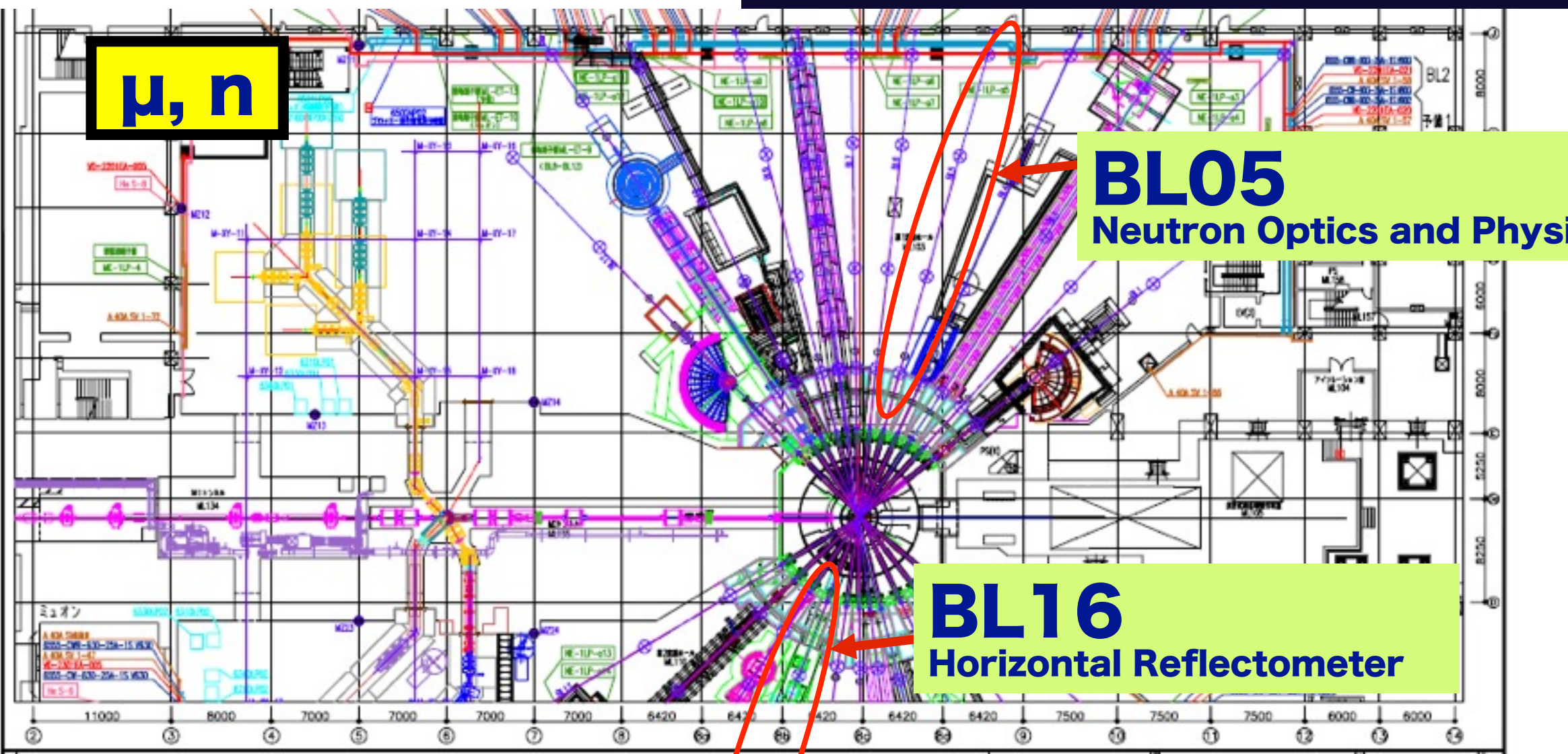
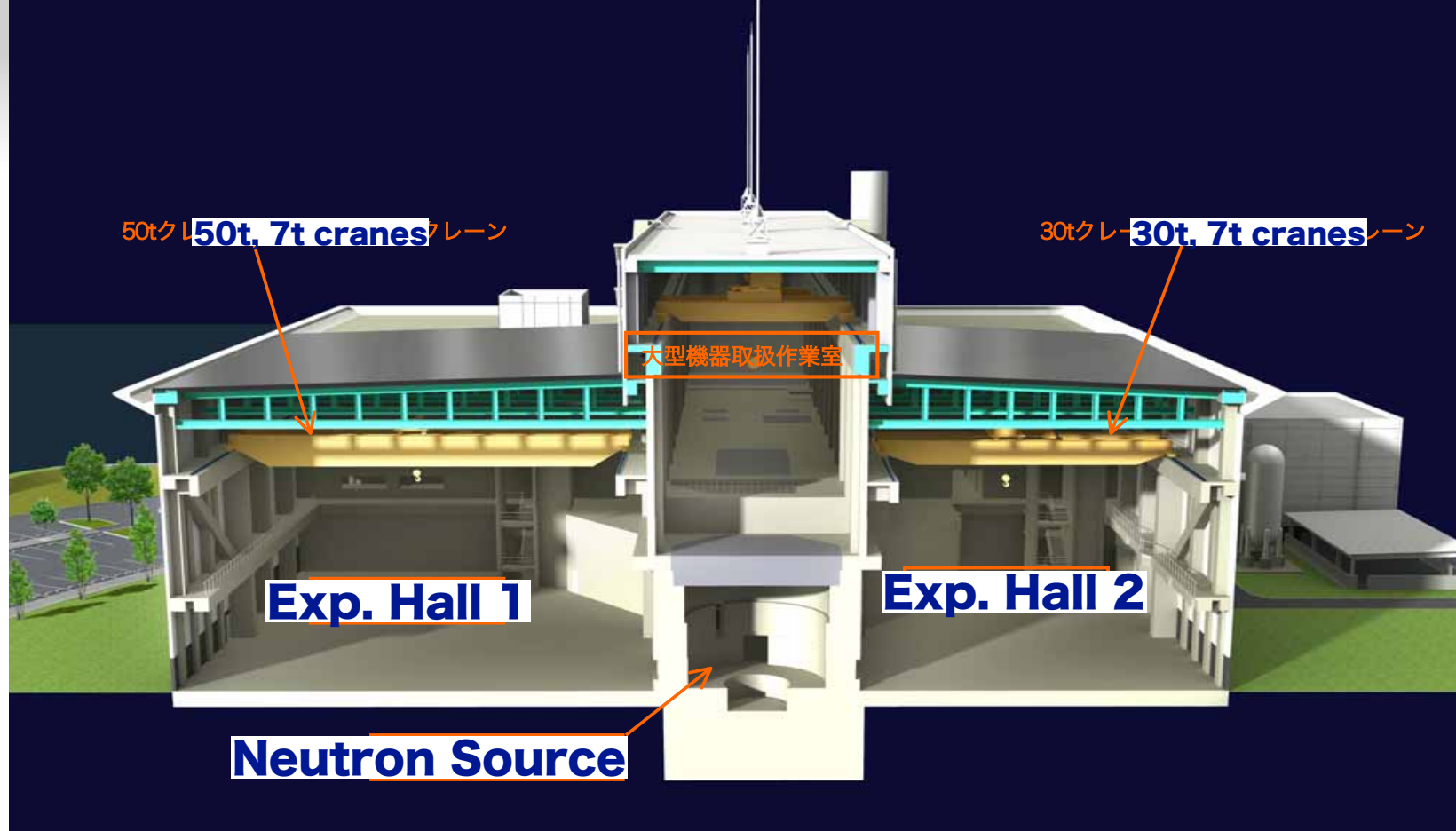
Rb NOMR magnetometer @ T.I.T/RIKEN

1 ~ 2 year



J-PARC MLF

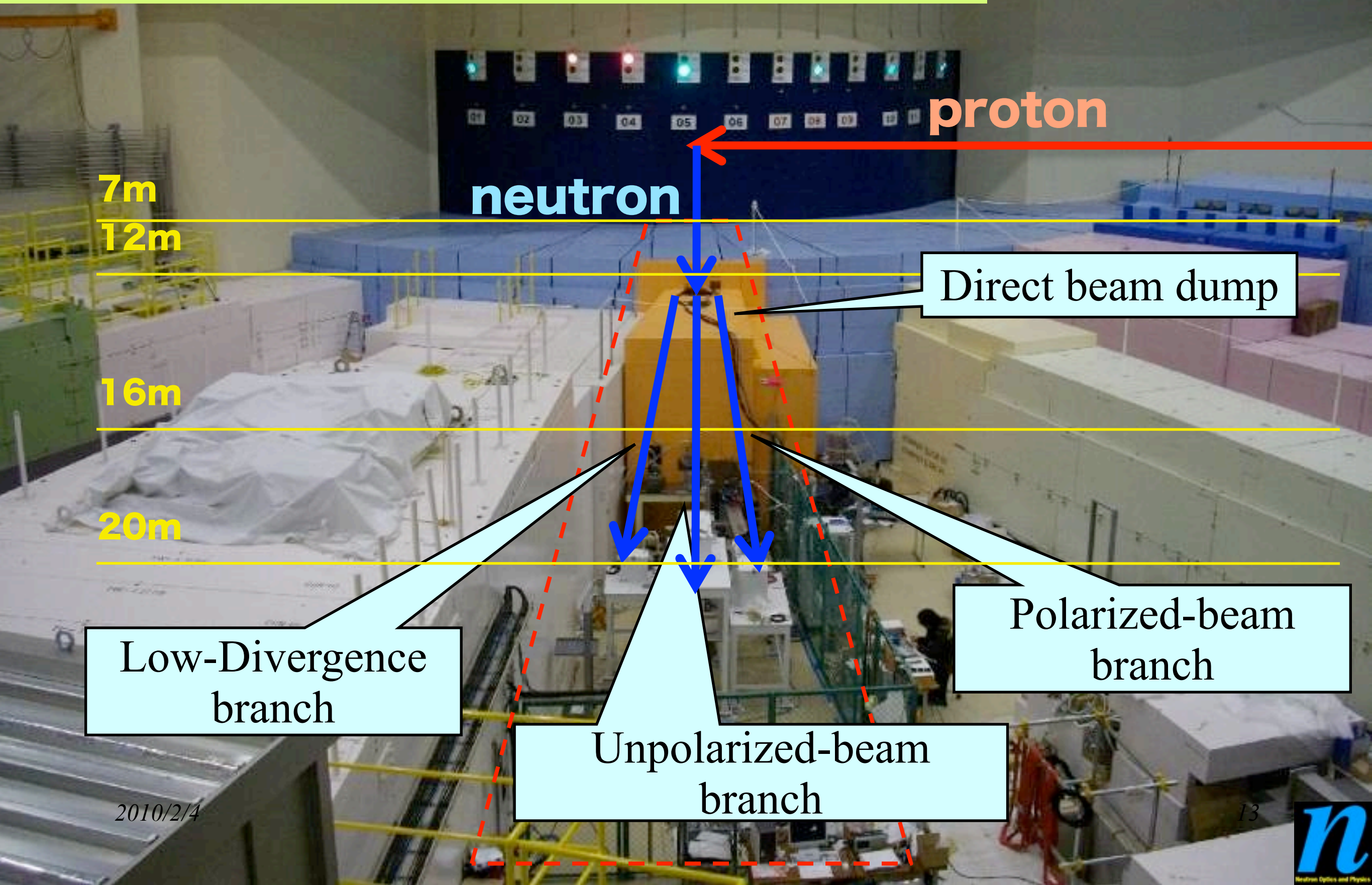
Material and Life-science Facility



提供 原研大強度陽子加速器施設建設室

J-PARC BL05

Neutron Optics and Physics (NOP)



proton

neutron

Direct beam dump

Polarized-beam
branch

Low-Divergence
branch

Unpolarized-beam
branch

Polarized-beam Branch

$4.0 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$

$10 \text{ cm} \times 4 \text{ cm}$ $P=0.998$

instantaneous decay rate $\sim 10^5 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

Unpolarized-beam Branch

$1.2 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$

$5 \text{ cm} \times 4 \text{ cm}$

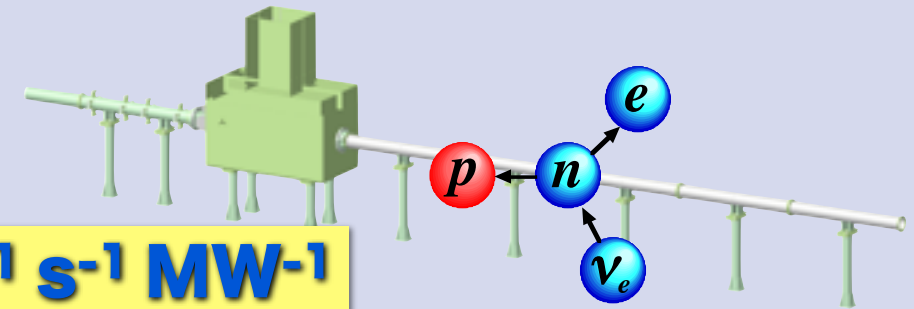
Low-divergence-beam Branch

$9.2 \times 10^5 \text{ cm}^{-2} \mu\text{sr}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

“Decay”

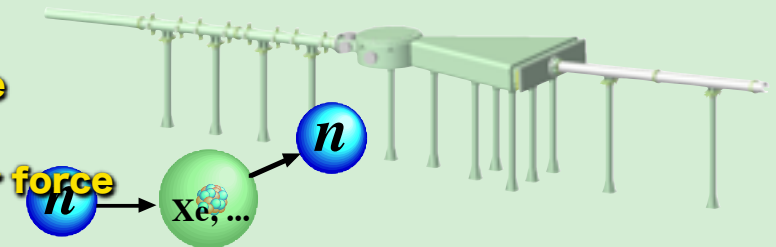
- decay parameters
- unitarity of CKM matrix
- T-violation

$10^4 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$



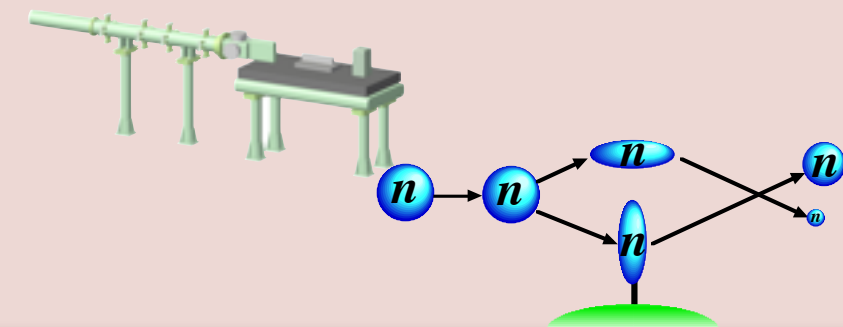
“Scattering”

- unknown medium range force
- large extra-dimension
- charge symmetry of nuclear force etc.



“Interference”

- gravitational phase shift
- Aharonov-Casher effect etc.



K.Mishima et al., NIM A600 (2009) 423.



Instantaneously Luminous

background separated in time
 wide wavelength range

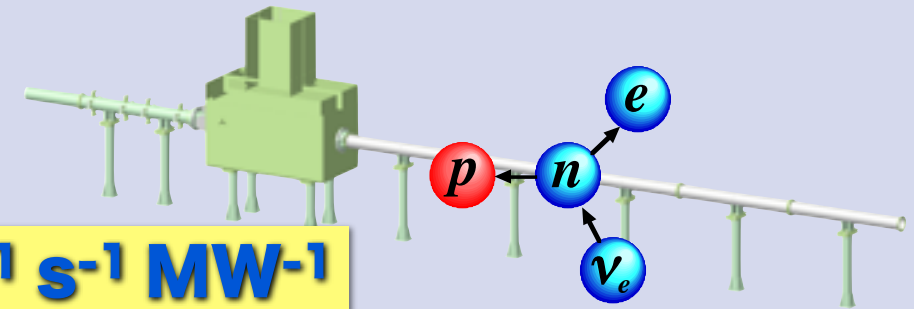
Polarized-beam Branch

$4.0 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $10 \text{ cm} \times 4 \text{ cm}$ $P=0.998$

“Decay”

- decay parameters
- unitarity of CKM matrix
- T-violation

$10^4 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$



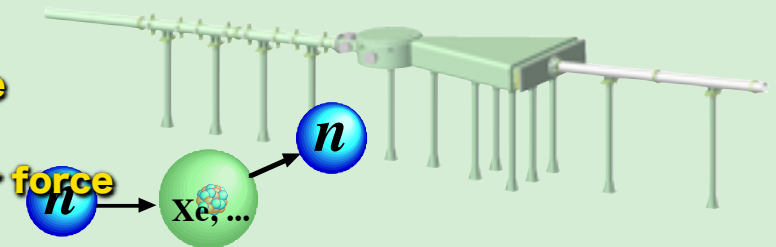
instantaneous decay rate $\sim 10^5 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

Unpolarized-beam Branch

$1.2 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $5 \text{ cm} \times 4 \text{ cm}$

“Scattering”

- unknown medium range force
- large extra-dimension
- charge symmetry of nuclear force etc.

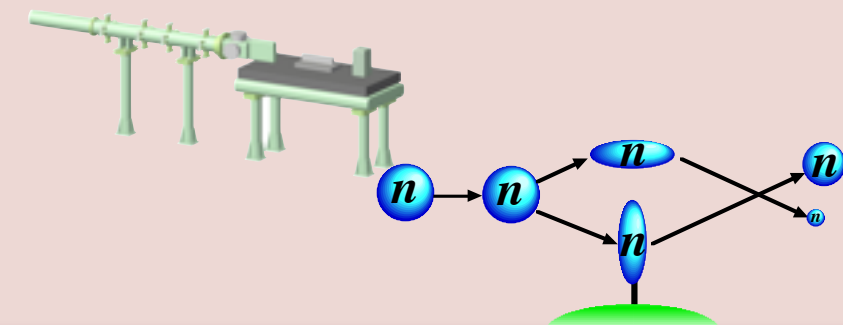


Low-divergence-beam Branch

$9.2 \times 10^5 \text{ cm}^{-2} \mu\text{sr}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

“Interference”

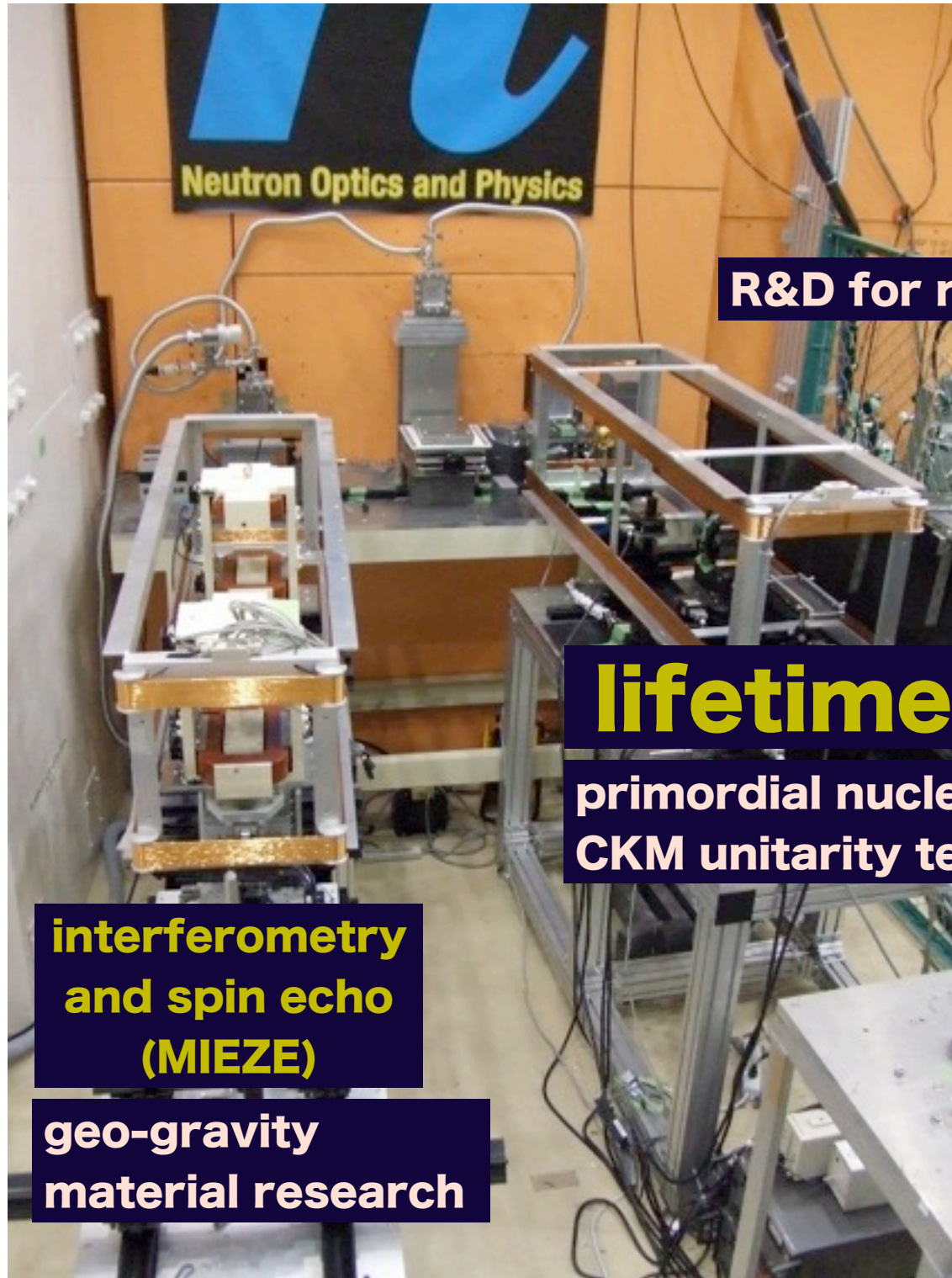
- gravitational phase shift
- Aharonov-Casher effect etc.



K.Mishima et al., NIM A600 (2009) 423.



On-going Researches at BL05



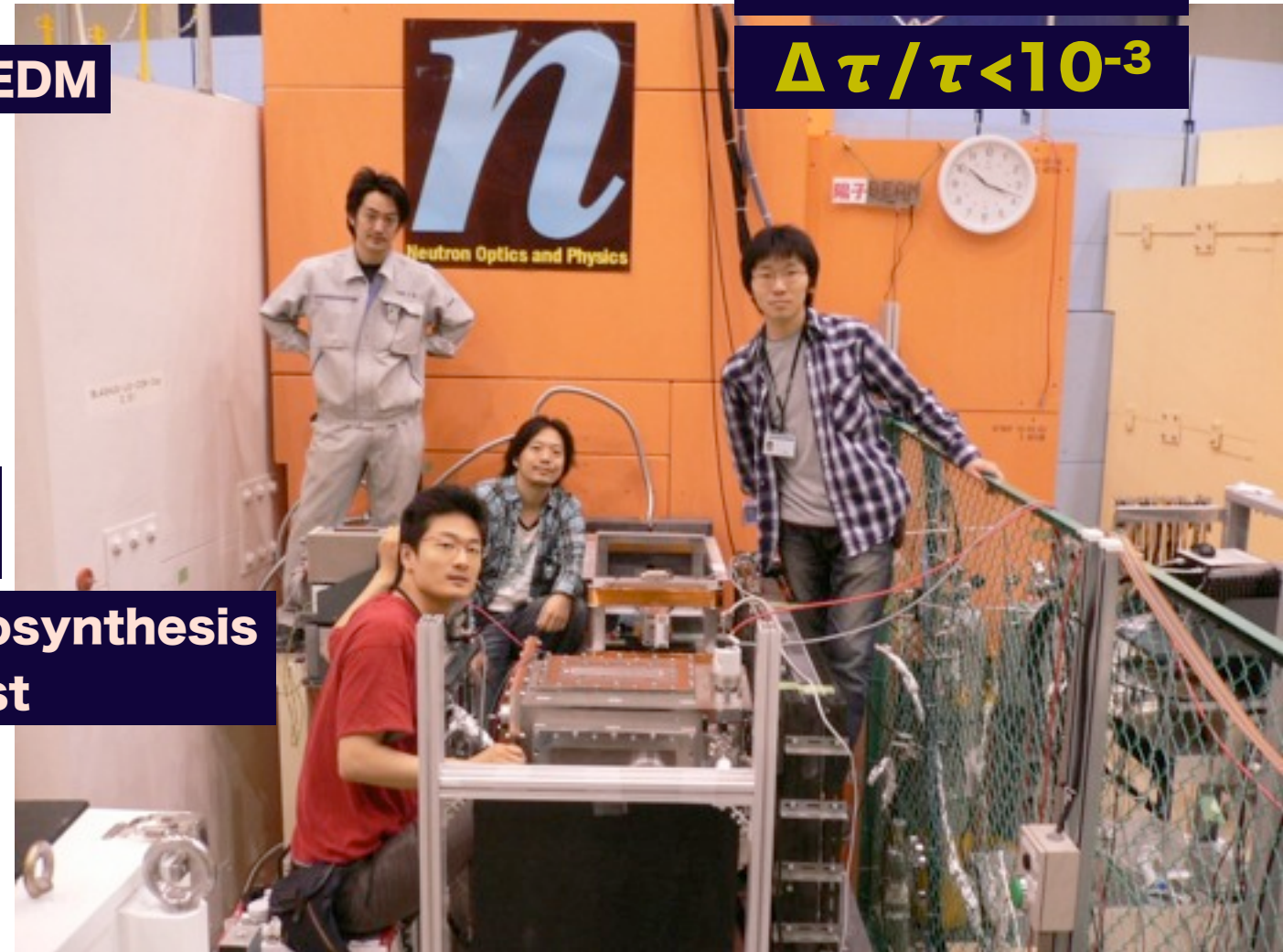
R&D for nEDM

lifetime

primordial nucleosynthesis
CKM unitarity test

interferometry
and spin echo
(MIEZE)

geo-gravity
material research

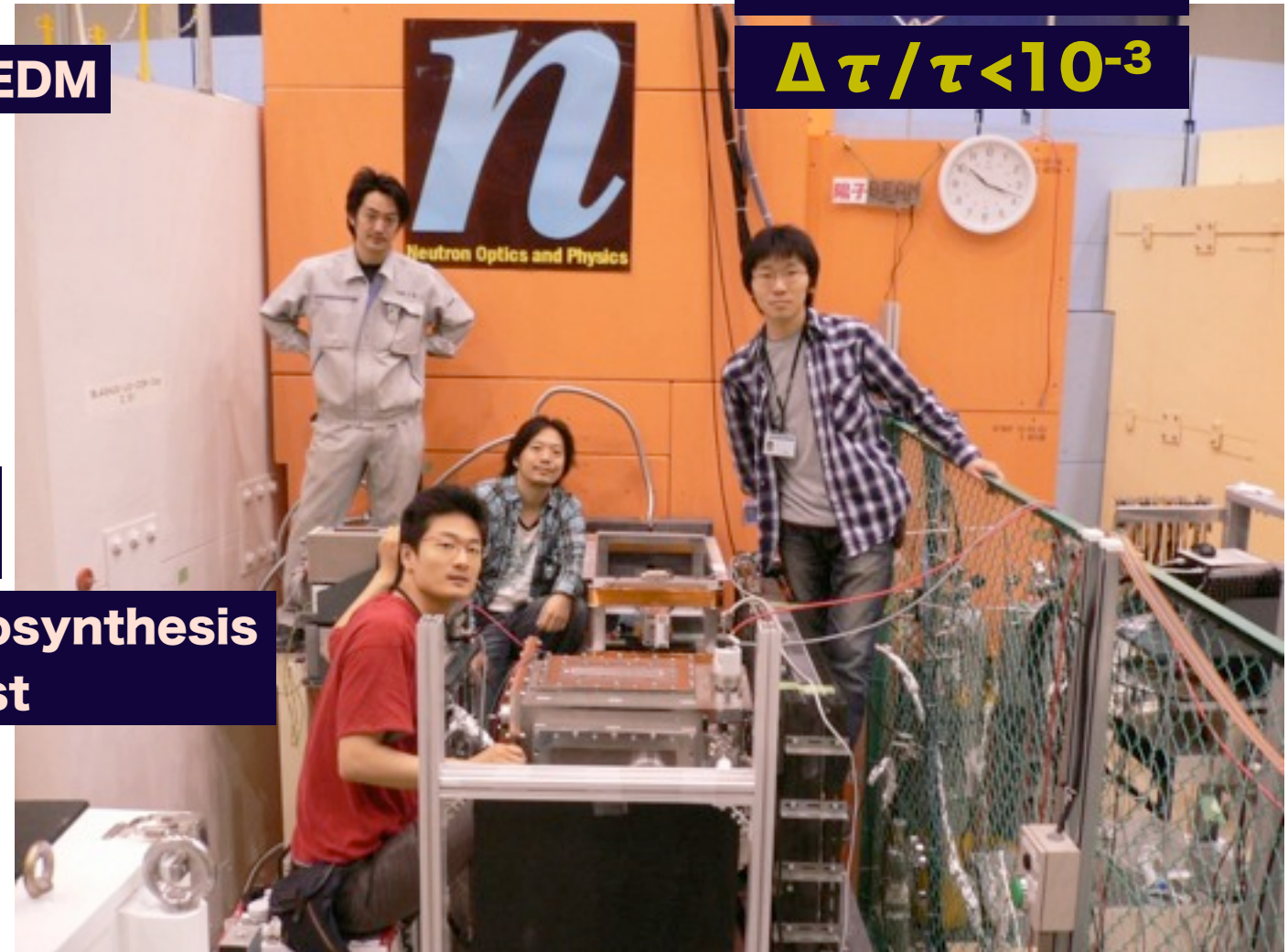
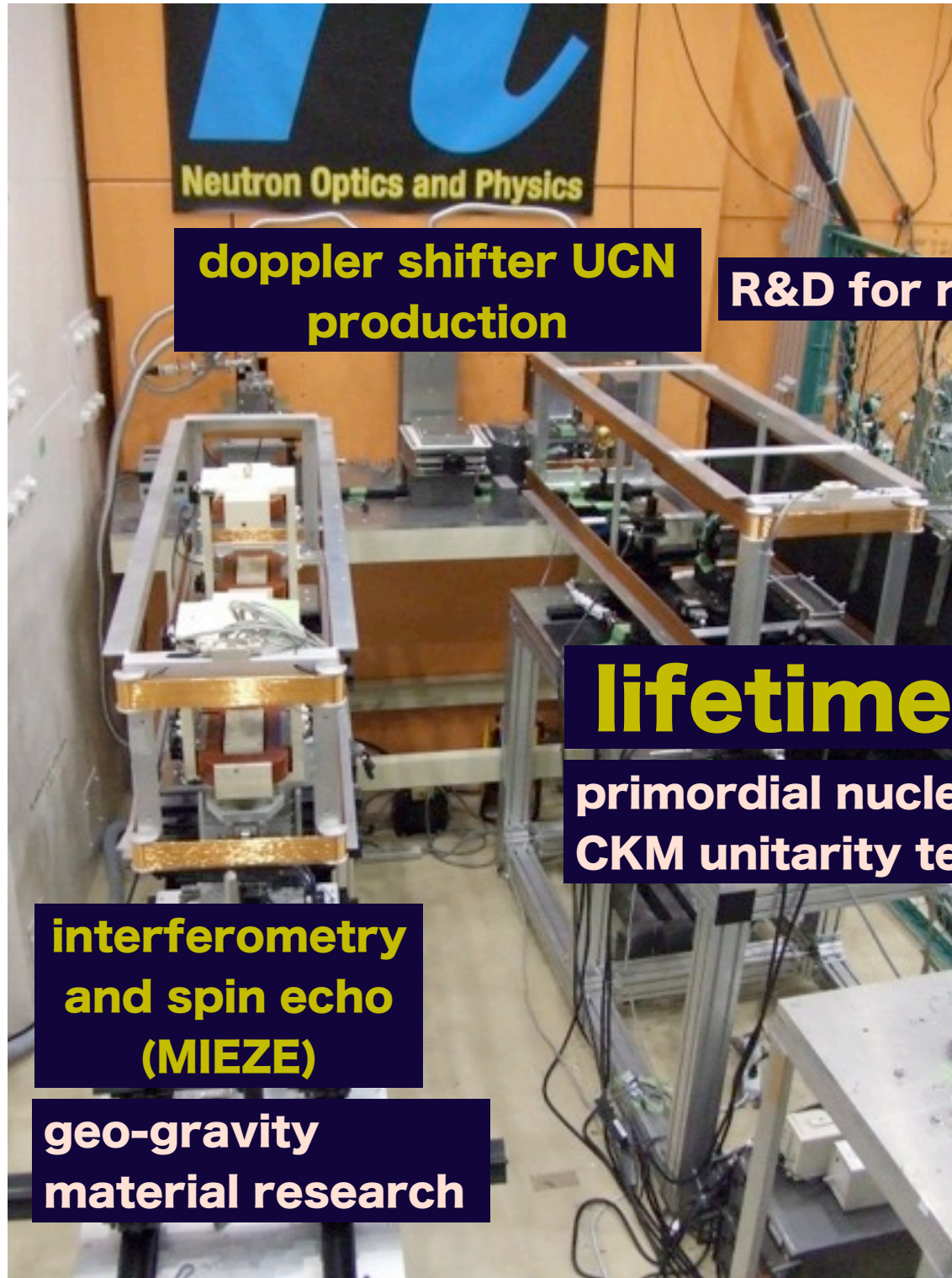


lifetime

$\Delta\tau/\tau < 10^{-3}$



On-going Researches at BL05



Neutron Lifetime



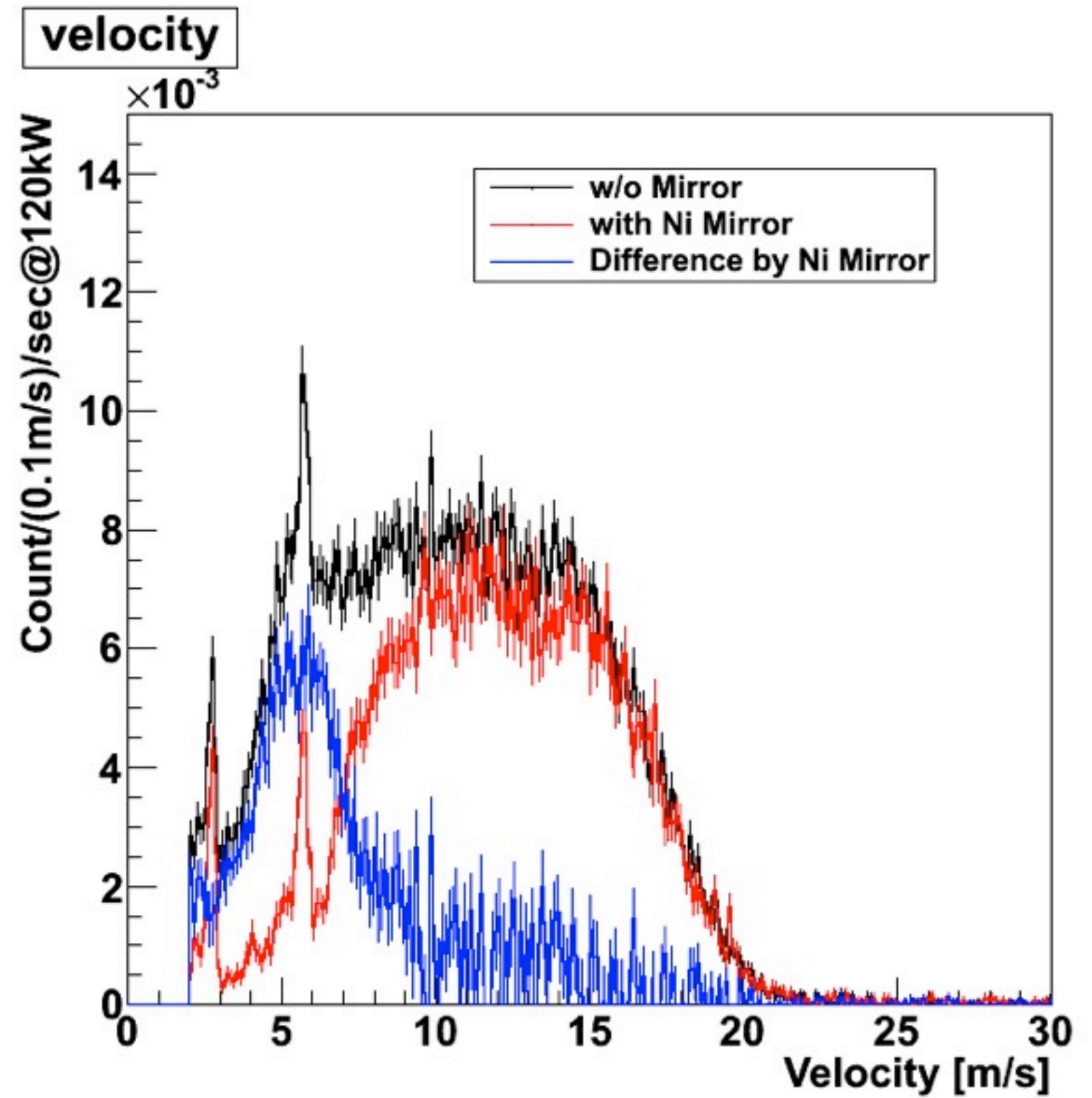
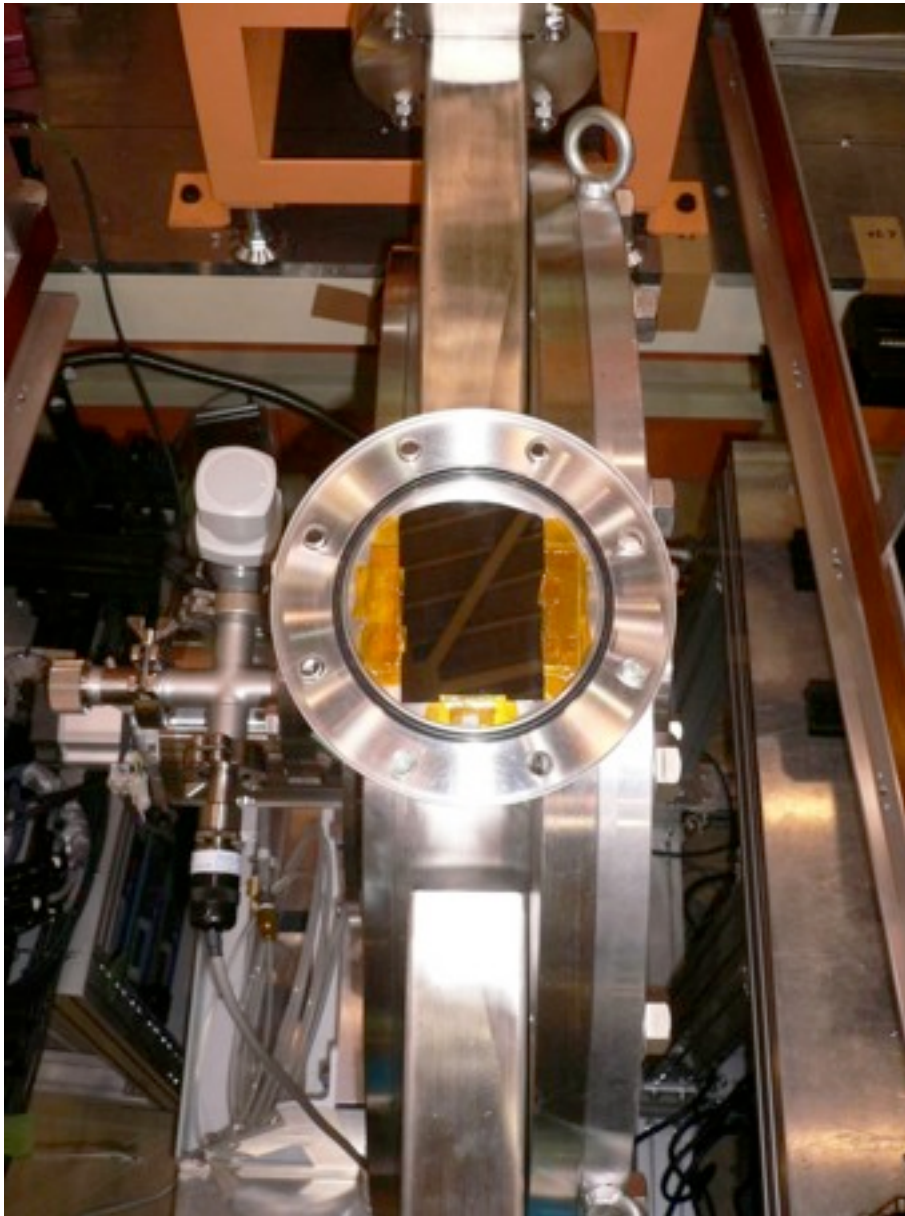
Doppler Shifter



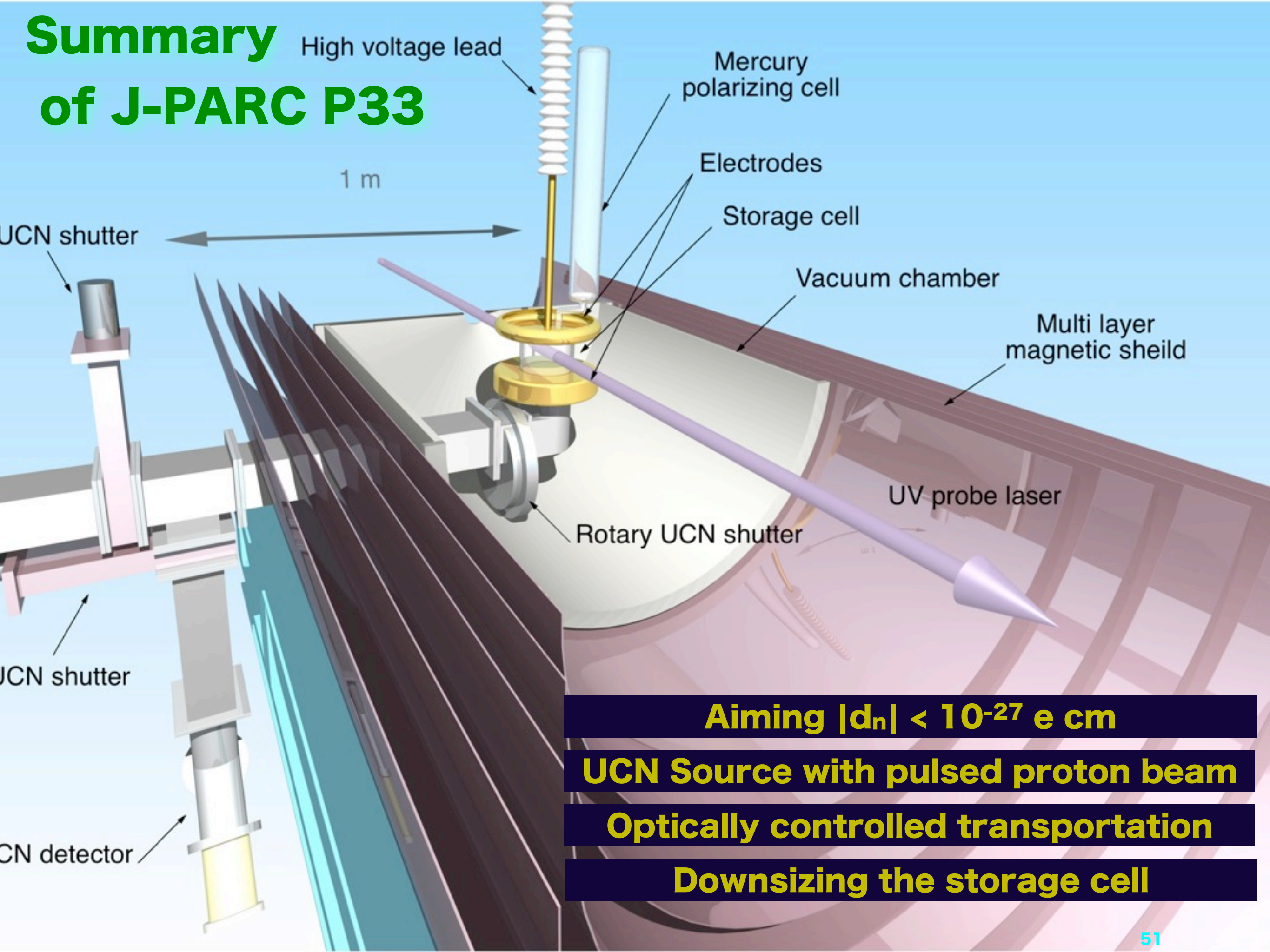
Date(2010/06/12) by(T.Yoshioka)
Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))
Conf(将来計画検討小委員会) At(Tokyo)



Doppler Shifter



Summary of J-PARC P33



Aiming $|d_n| < 10^{-27} \text{ e cm}$

UCN Source with pulsed proton beam

Optically controlled transportation

Downsizing the storage cell

THE END



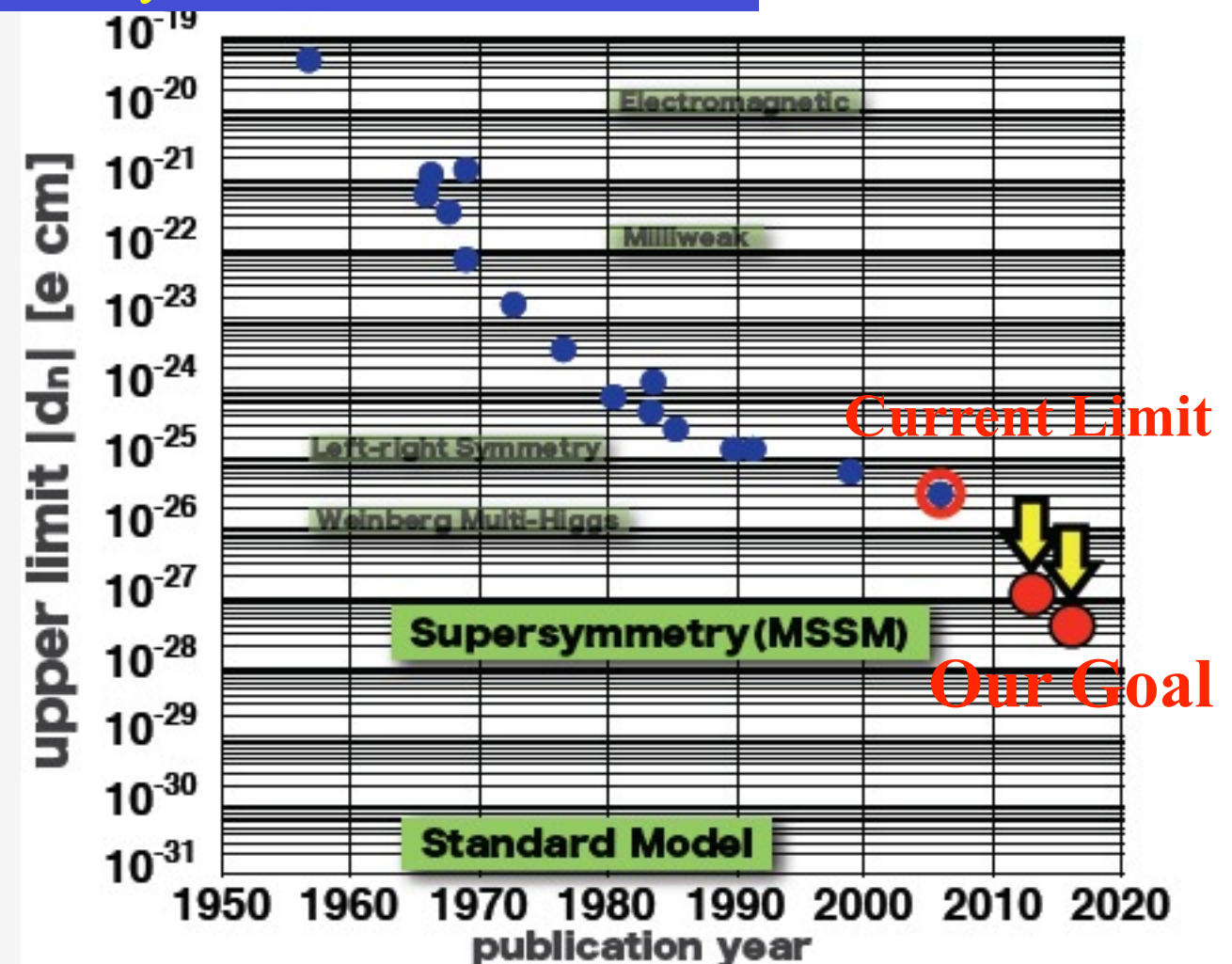
BACKUP



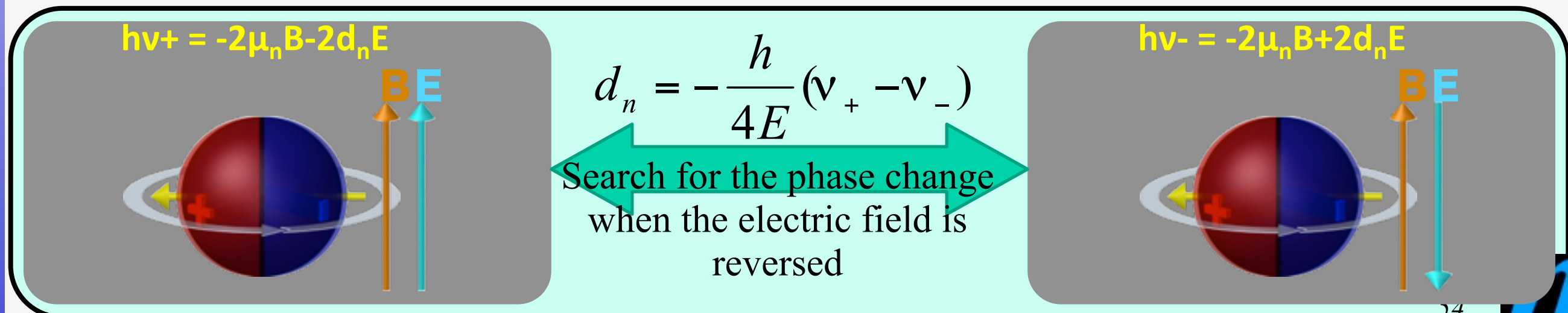
Neutron Electric Dipole Moment (nEDM)

- nEDM is T and P violation process, and also violates CP assuming CPT invariance.
 - Present experimental sensitivities are very close to those theoretical predictions.
 - Some BSM predict $d_n \sim 10^{-27 \sim 28}$ (SM predicts $d_n \sim 10^{-32}$).
 - Current upper limit : 2.8×10^{-26} (90% C.L.)
- nEDM measurement provides strong constraints on these theories.

History of nEDM measurement



Measurement principle



標準理論における時間反転対称性の破れ

strong CP problem

$$|d_n| < 10^{-16} \text{ e cm}$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta' \gamma_5})\psi$$

CKM phase

$$|d_n| < 10^{-32} \text{ e cm}$$

$$\mathcal{L}_Y = -Y_{ij}^d \overline{Q_{Li}^I} \phi d_{Rj}^I - Y_{ij}^u \overline{Q_{Li}^I} \epsilon \phi^* u_{Rj}^I + \text{h.c.}$$

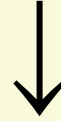
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\theta_{12} = 13.04 \pm 0.05^\circ, \theta_{13} = 0.201 \pm 0.011^\circ, \theta_{23} = 2.38 \pm 0.06^\circ, \text{ and } \delta_{13} = 1.20 \pm 0.08$$

及び 標準理論を超える新しい物理

SUSY etc.

精密測定



量子論的ループを通じた新しい物理の探索

$$\delta_{\text{NEW}} = \frac{\Delta O_{\text{NEW}}}{O_{\text{SM}}} \sim \frac{\alpha}{\pi} \left(\frac{M}{M'} \right)^2$$

新しい物理を発見できる場合

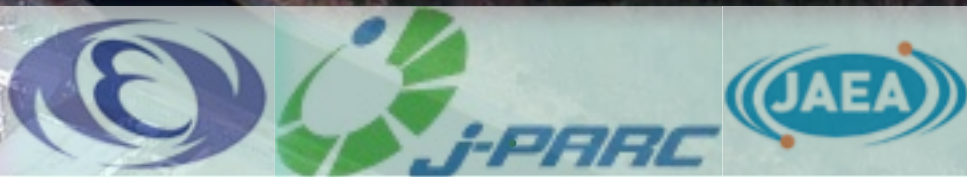
標準理論が正確に予言できる場合

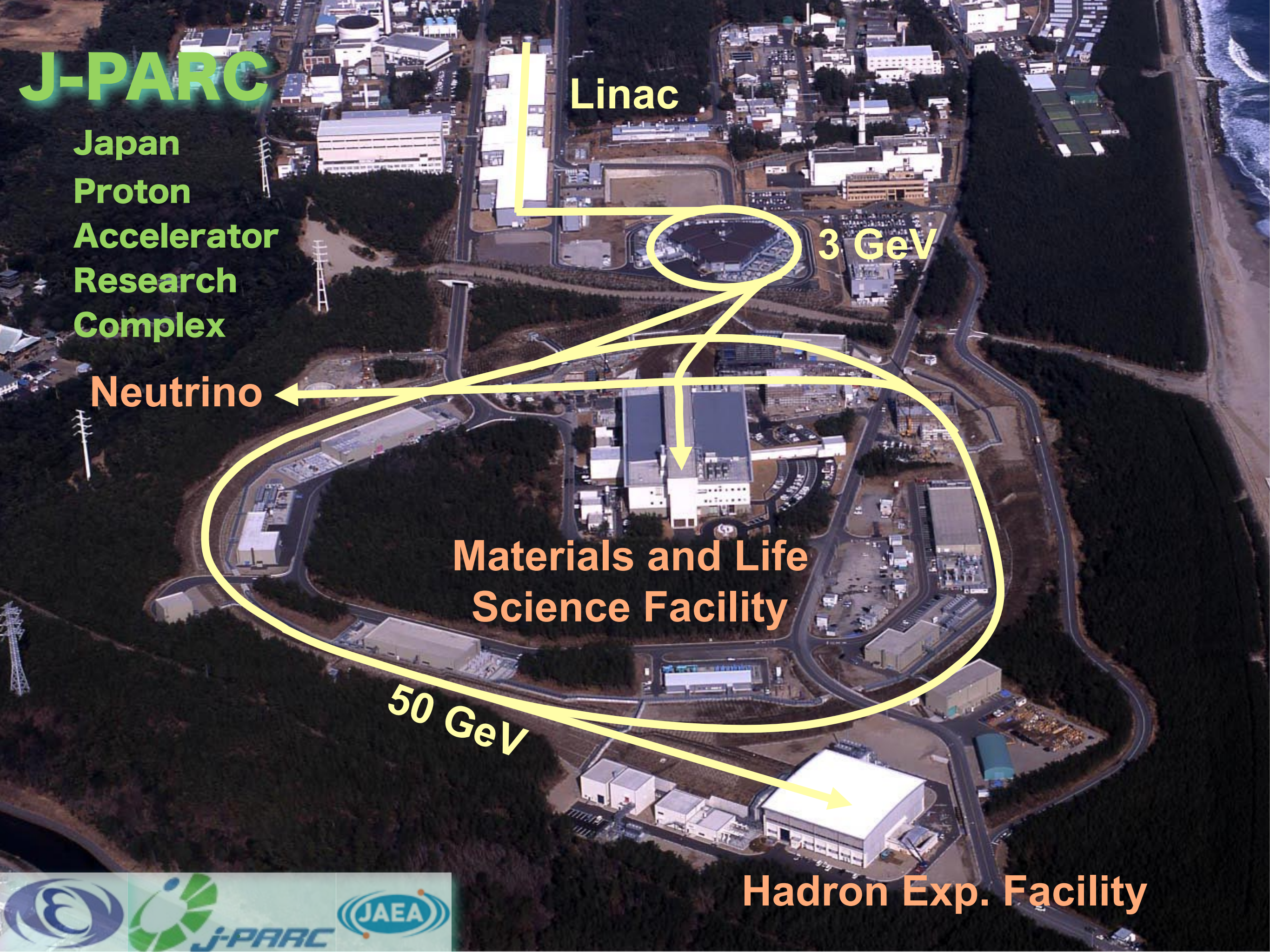
各種精密測定 of 標準理論からのズレを比較検討する場合

標準理論において禁止或は抑制されている場合

J-PARC

Japan
Proton
Accelerator
Research
Complex





J-PARC

Japan
Proton
Accelerator
Research
Complex

Linac

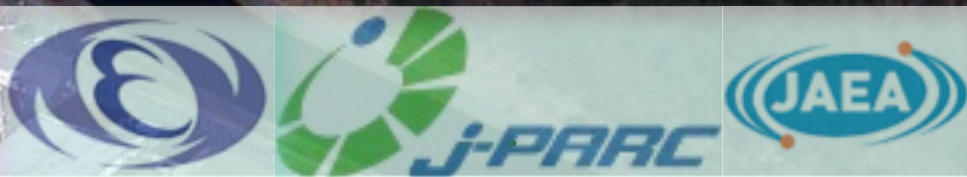
3 GeV

Neutrino

Materials and Life
Science Facility

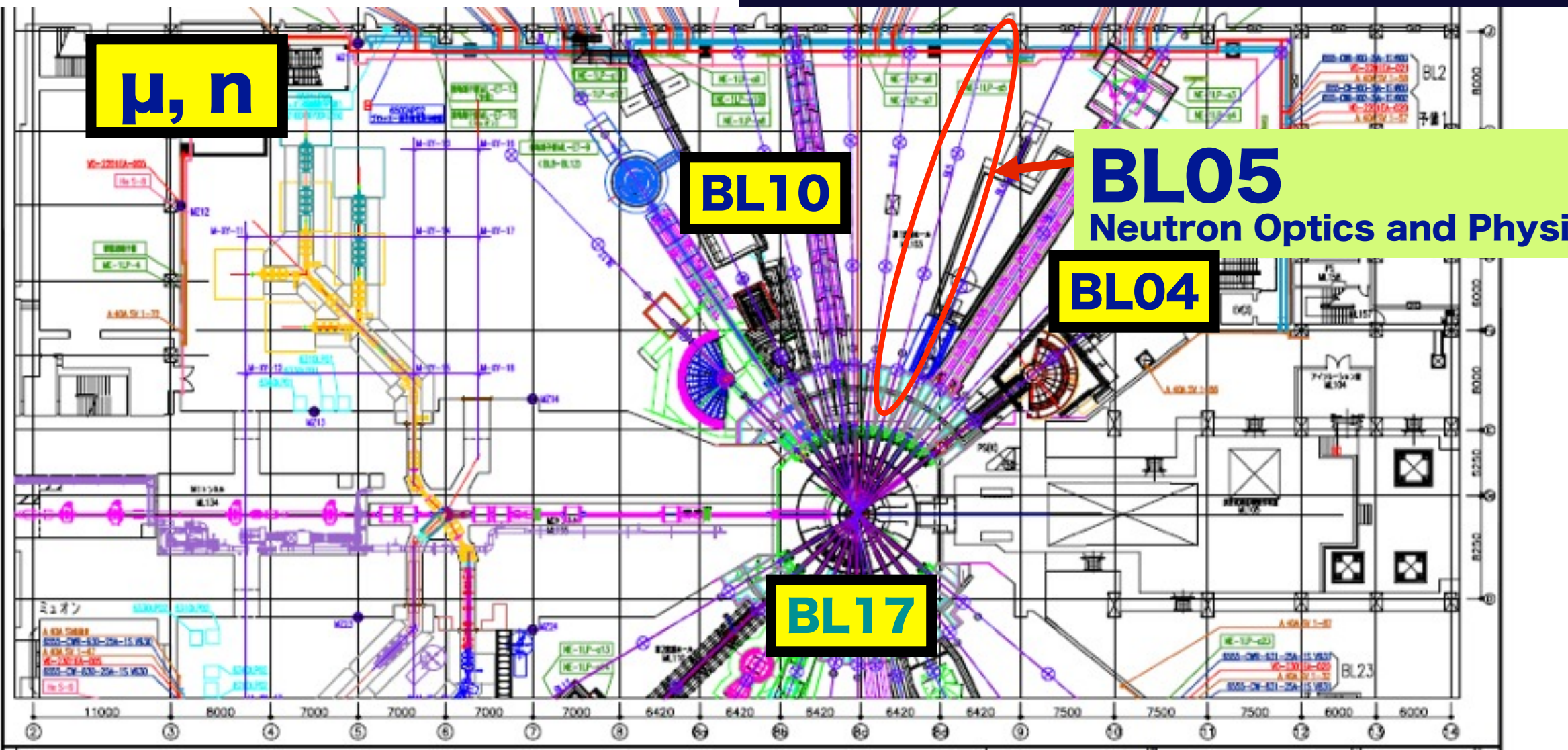
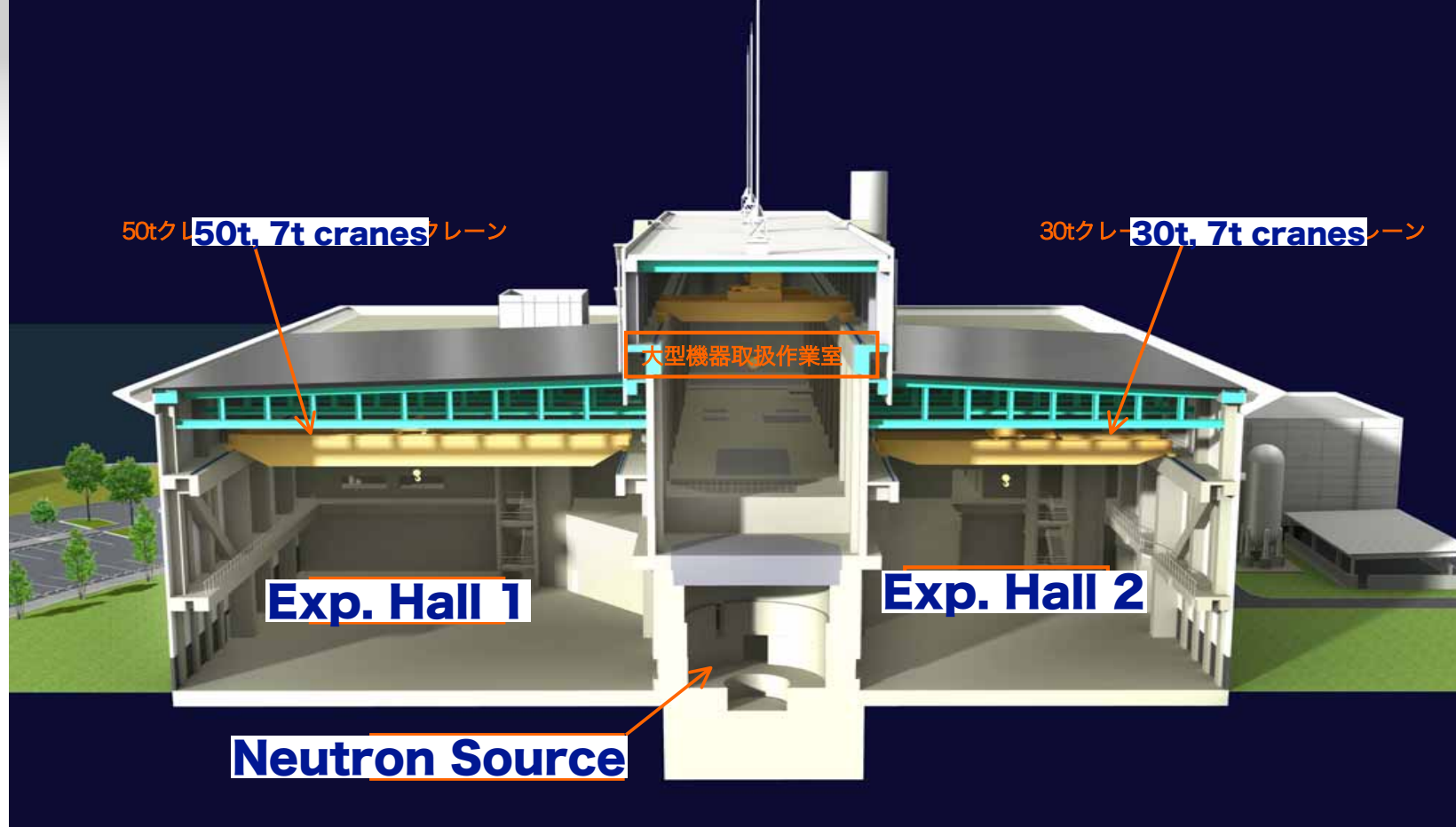
50 GeV

Hadron Exp. Facility

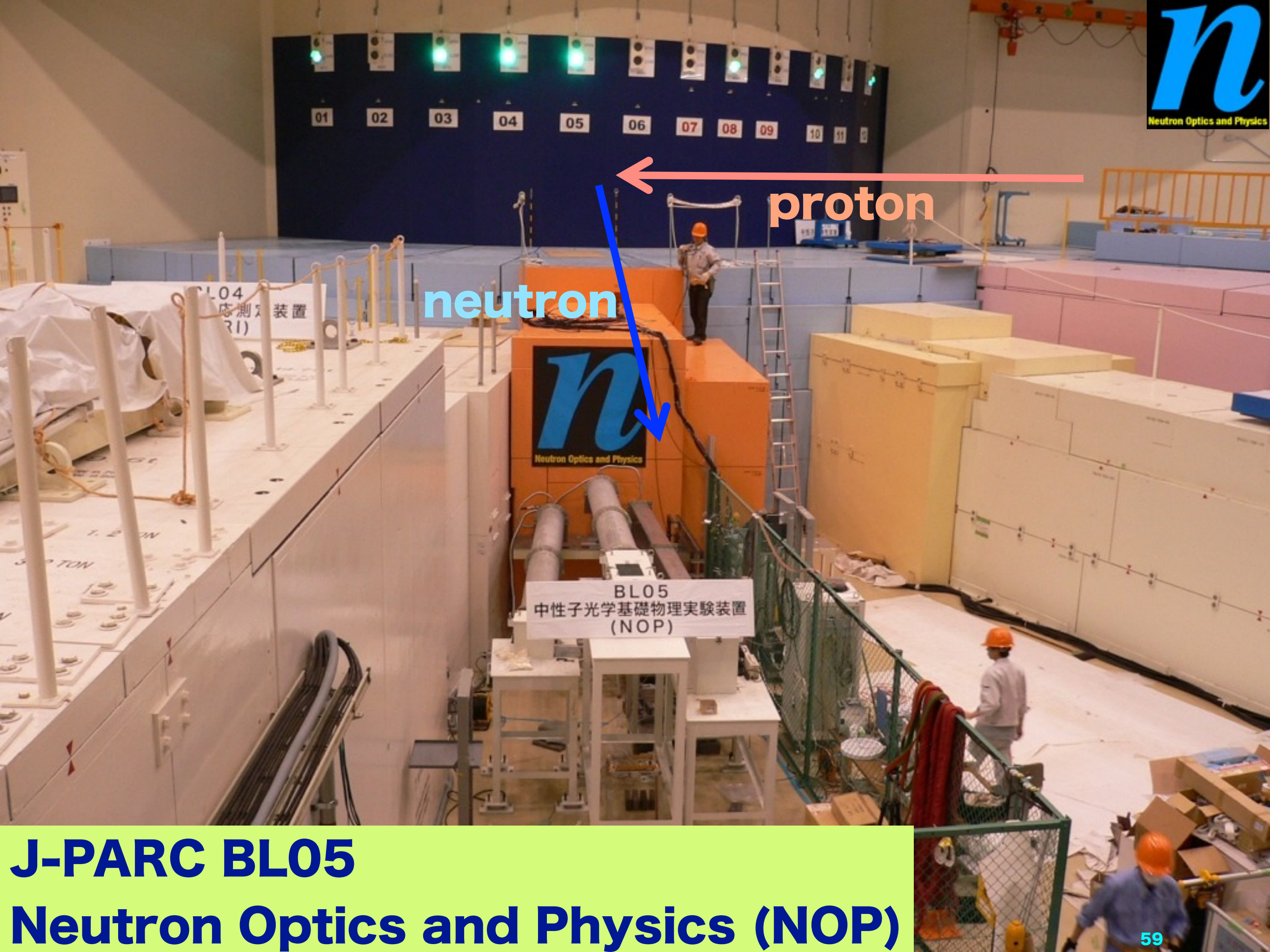


J-PARC MLF

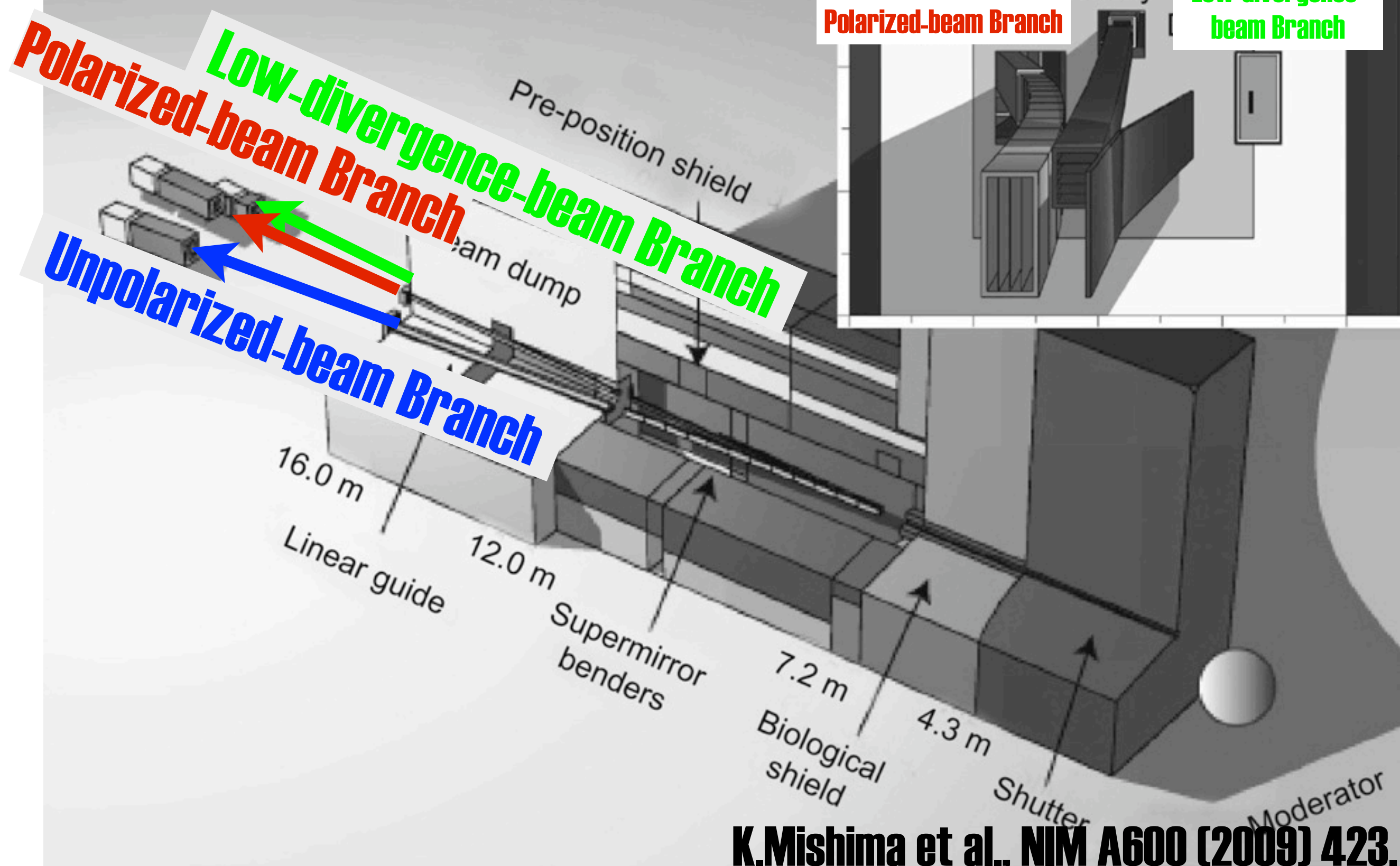
Material and Life-science Facility



提供 原研大強度陽子加速器施設建設室

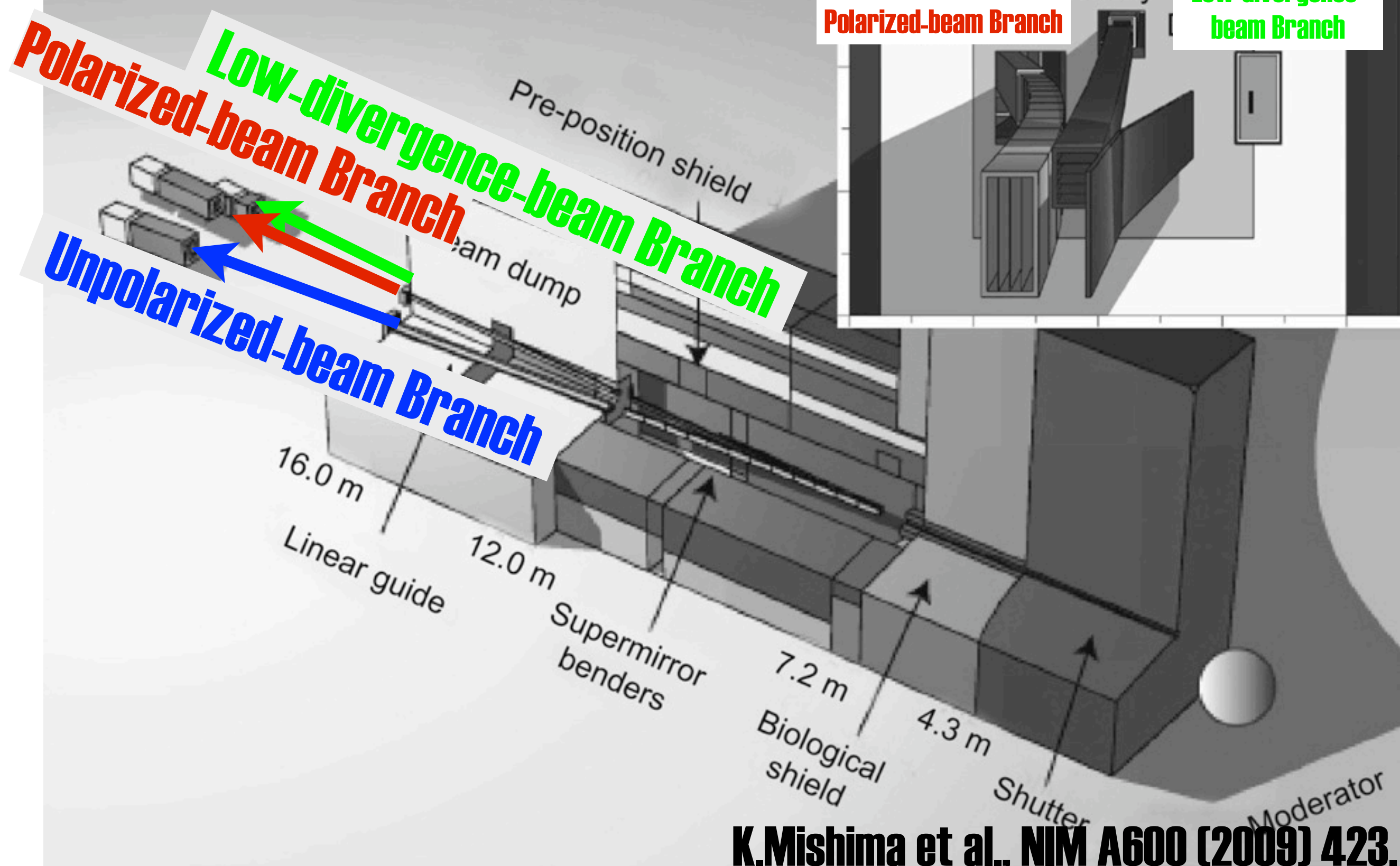


J-PARC BL05
Neutron Optics and Physics (NOP)



K.Mishima et al., NIM A600 (2009) 423.





K.Mishima et al., NIM A600 (2009) 423.



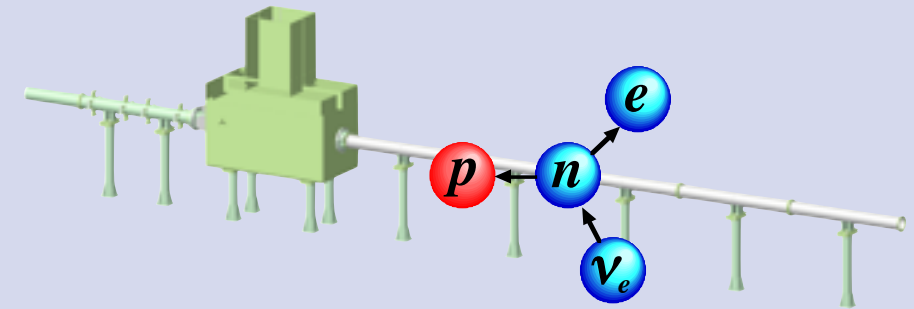
Polarized-beam Branch

Unpolarized-beam Branch

Low-divergence-beam Branch

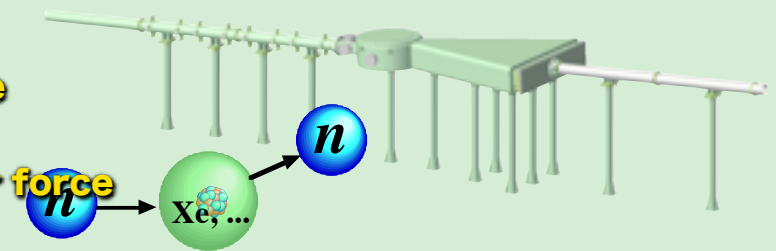
“Decay”

- decay parameters
- unitarity of CKM matrix
- T-violation
- nucleosynthesis



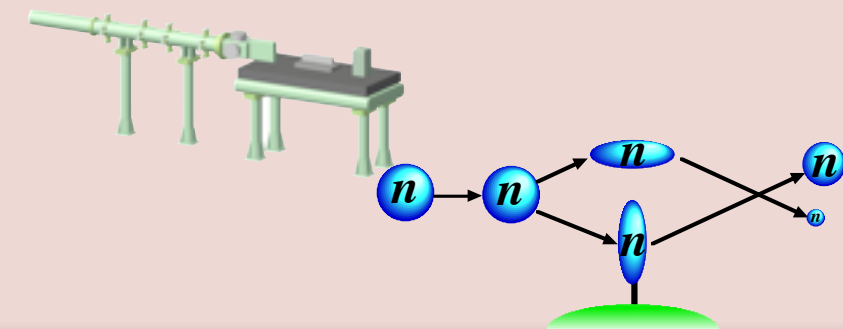
“Scattering”

- unknown medium range force
- large extra-dimension
- charge symmetry of nuclear force etc.



“Interference”

- gravitational phase shift
- Aharonov-Casher effect etc.



K.Mishima et al., NIM A600 (2009) 423.



Polarized-beam Branch

$4.0 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $10 \text{ cm} \times 4 \text{ cm}$ $P=0.998$

instantaneous decay rate $\sim 10^5 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

Unpolarized-beam Branch

$1.2 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $5 \text{ cm} \times 4 \text{ cm}$

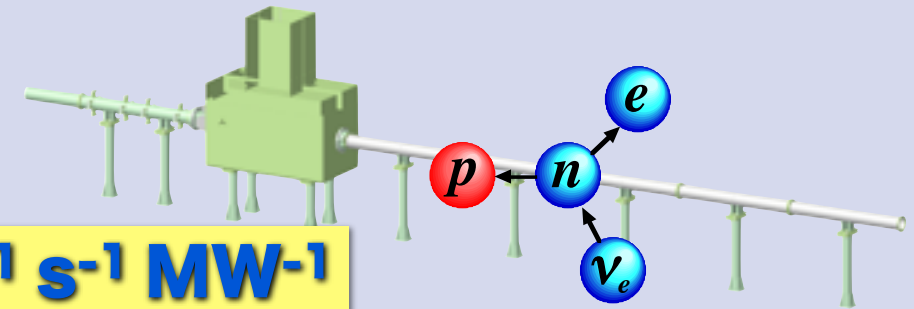
Low-divergence-beam Branch

$9.2 \times 10^5 \text{ cm}^{-2} \mu\text{sr}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

“Decay”

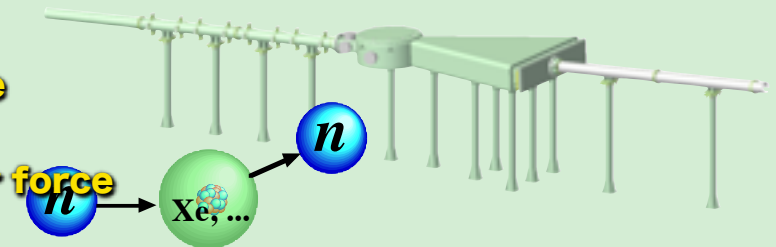
- decay parameters
- unitarity of CKM matrix
- T-violation

$10^4 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$



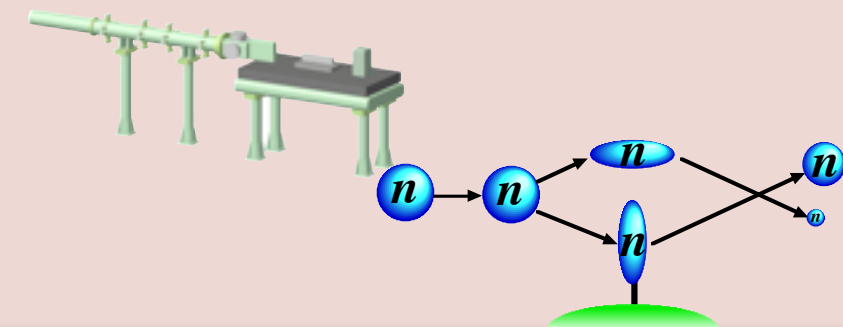
“Scattering”

- unknown medium range force
- large extra-dimension
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“Interference”

- gravitational phase shift
- Aharonov-Casher effect etc.



K.Mishima et al., NIM A600 (2009) 423.



Instantaneously Luminous

background separated in time
wide wavelength range

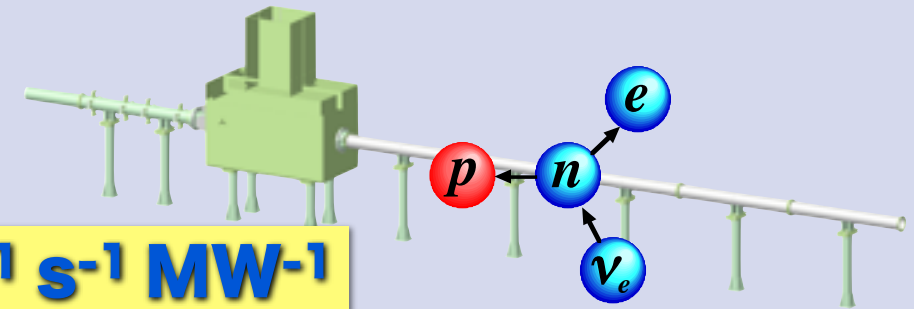
Polarized-beam Branch

$4.0 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $10 \text{ cm} \times 4 \text{ cm}$ $P=0.998$

“Decay”

- decay parameters
- unitarity of CKM matrix
- T-violation

$10^4 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$



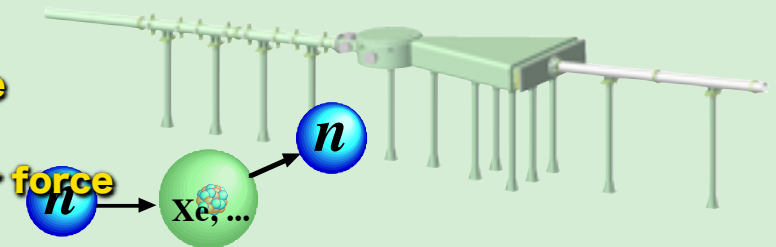
instantaneous decay rate $\sim 10^5 \text{ decay m}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

Unpolarized-beam Branch

$1.2 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \text{ MW}^{-1}$
 $5 \text{ cm} \times 4 \text{ cm}$

“Scattering”

- unknown medium range force
- large extra-dimension
- charge symmetry of nuclear force etc.

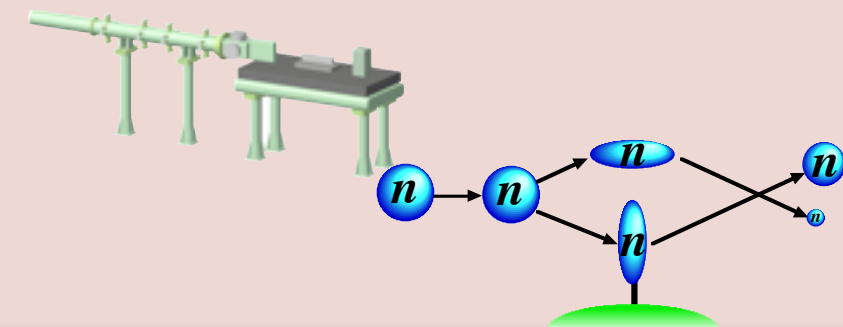


Low-divergence-beam Branch

$9.2 \times 10^5 \text{ cm}^{-2} \mu\text{sr}^{-1} \text{ s}^{-1} \text{ MW}^{-1}$

“Interference”

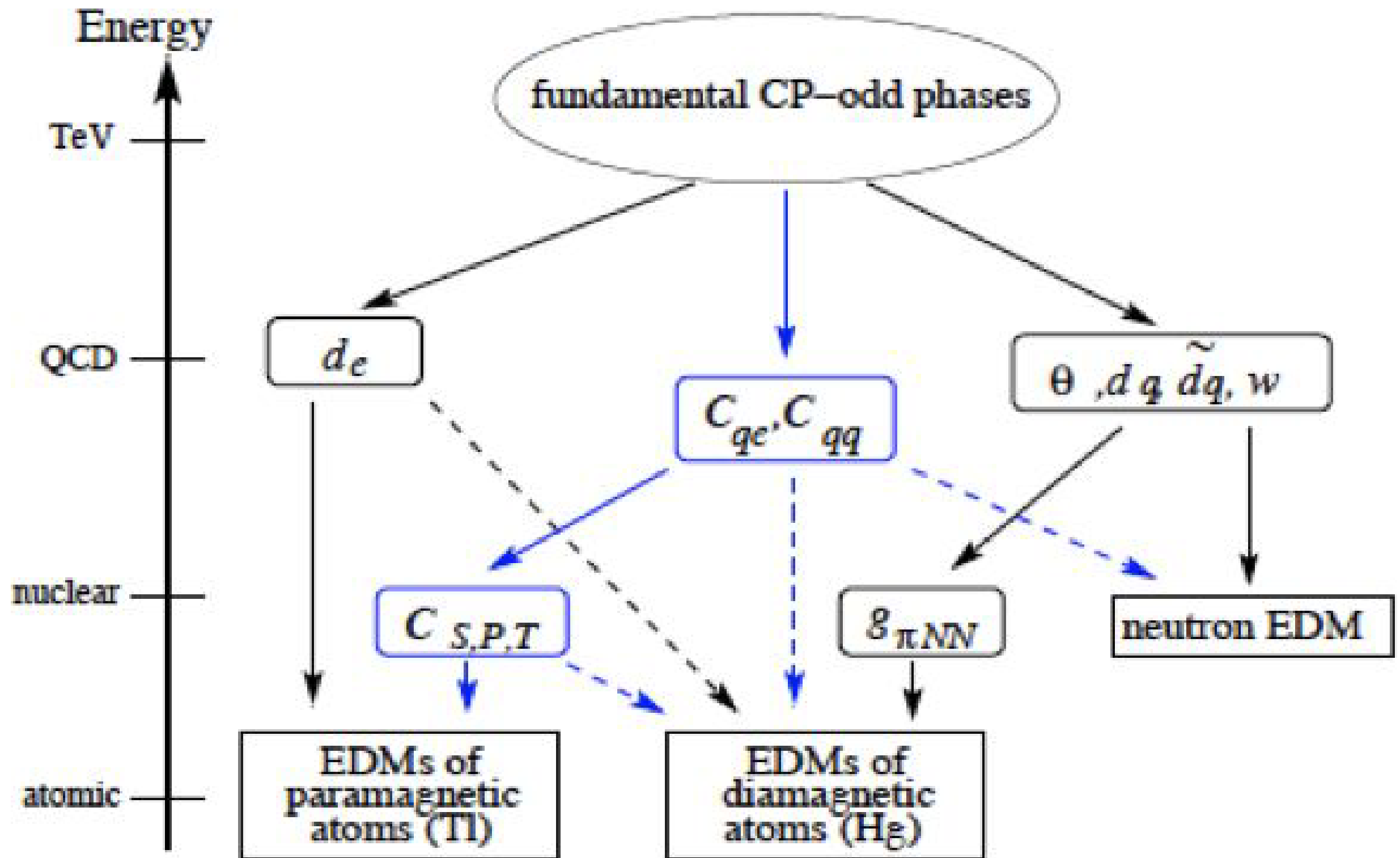
- gravitational phase shift
- Aharonov-Casher effect etc.



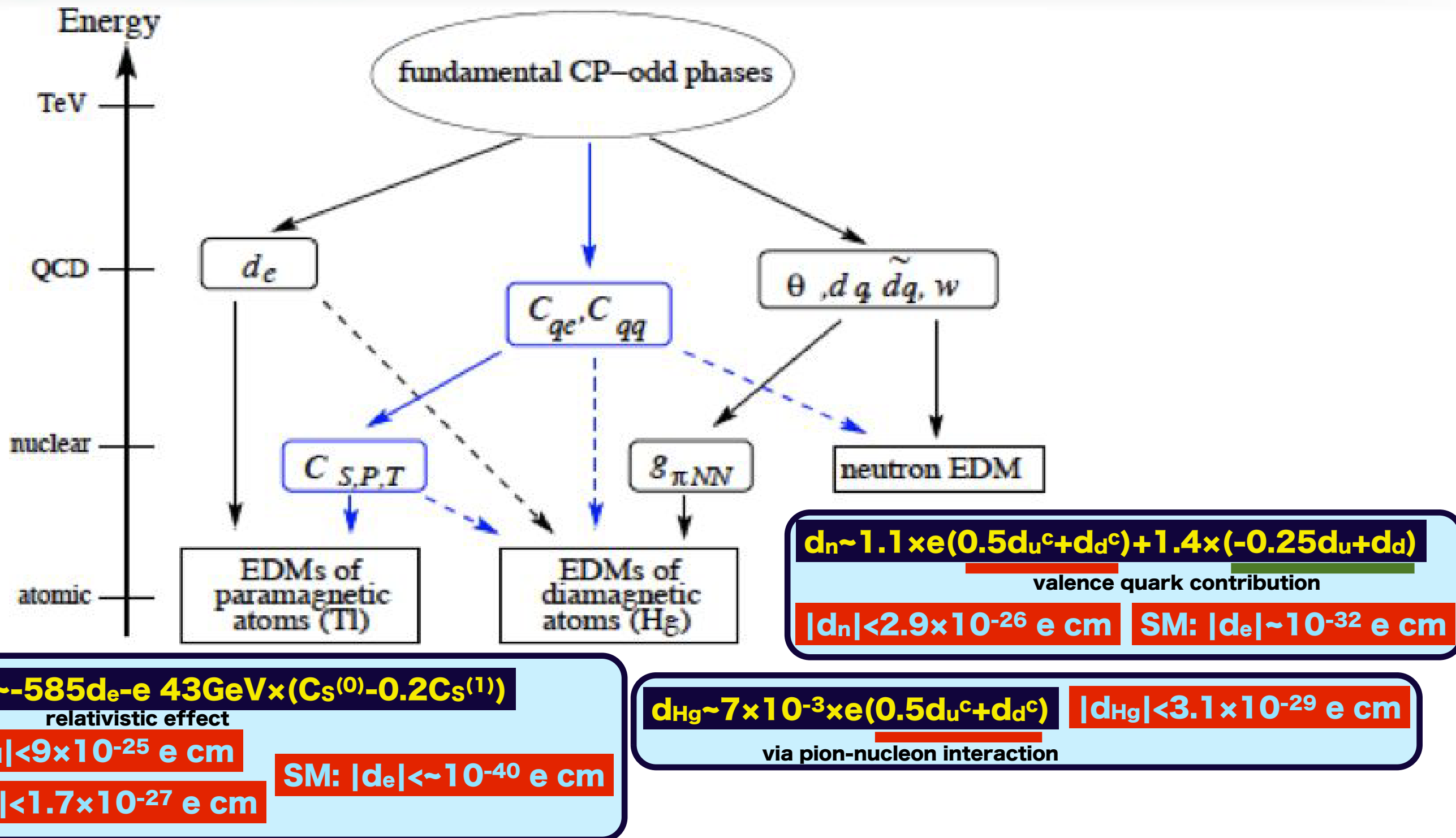
K.Mishima et al., NIM A600 (2009) 423.



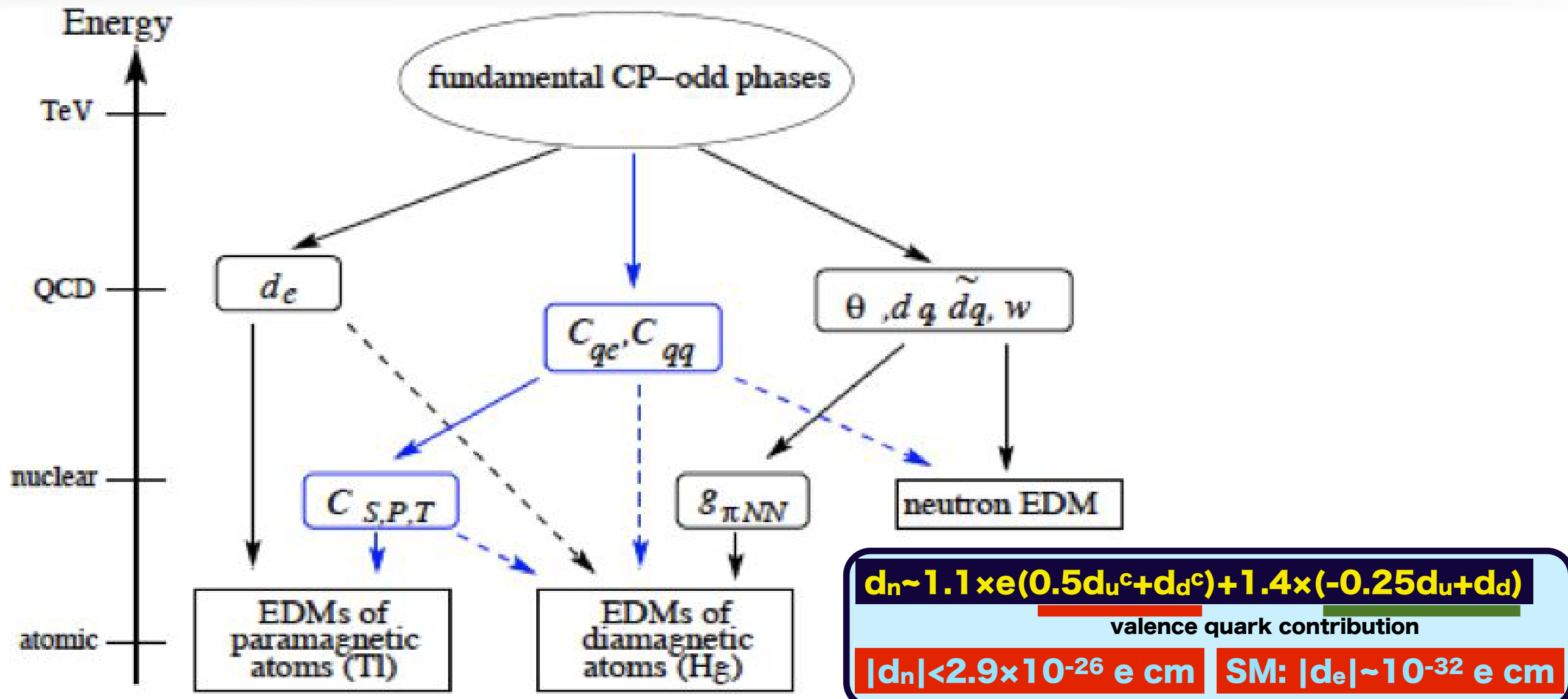
TeV → EDM



TeV → EDM



TeV → EDM



$$d_{\text{Tl}} \sim -585 d_e - e \cdot 43 \text{ GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)})$$

relativistic effect

$$|d_{\text{Tl}}| < 9 \times 10^{-25} \text{ e cm}$$

$$|d_e| < 1.7 \times 10^{-27} \text{ e cm}$$

$$\text{SM: } |d_e| < \sim 10^{-40} \text{ e cm}$$

$$d_{\text{Hg}} \sim 7 \times 10^{-3} e (0.5 d_u^c + d_d^c)$$

$$|d_{\text{Hg}}| < 3.1 \times 10^{-29} \text{ e cm}$$

via pion-nucleon interaction

$$d_D \sim (d_u + d_d) - 0.2 e (d_u^c + d_d^c) + 6 e (d_d^c - d_u^c)$$

constituent particle EDMs

pion exchange

$$|d_D| \Rightarrow 10^{-29} \text{ e cm}$$

$$d_n \sim 1.1 e (0.5 d_u^c + d_d^c) + 1.4 e (-0.25 d_u + d_d)$$

valence quark contribution

$$|d_n| < 2.9 \times 10^{-26} \text{ e cm}$$

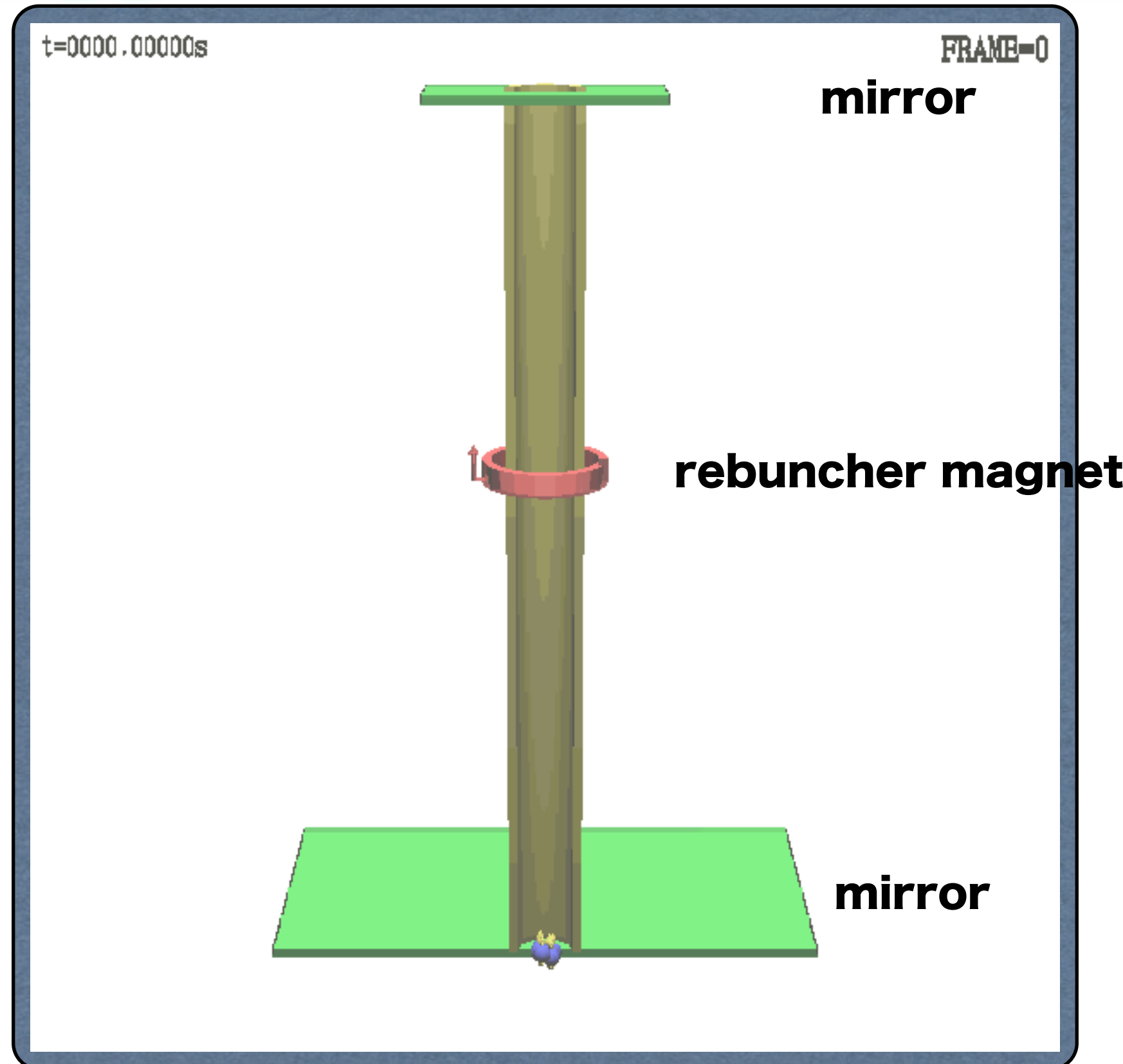
$$\text{SM: } |d_e| \sim 10^{-32} \text{ e cm}$$

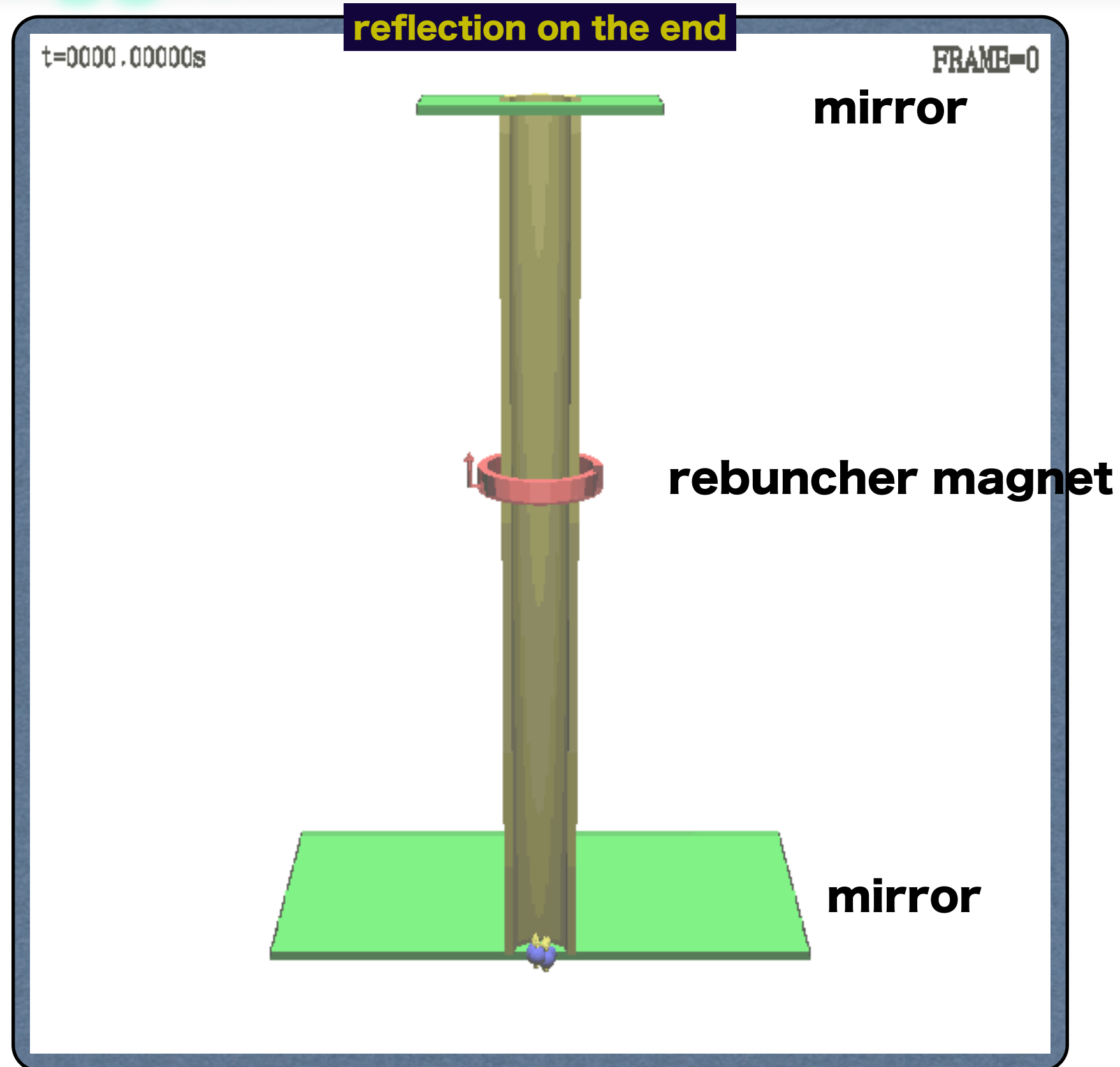


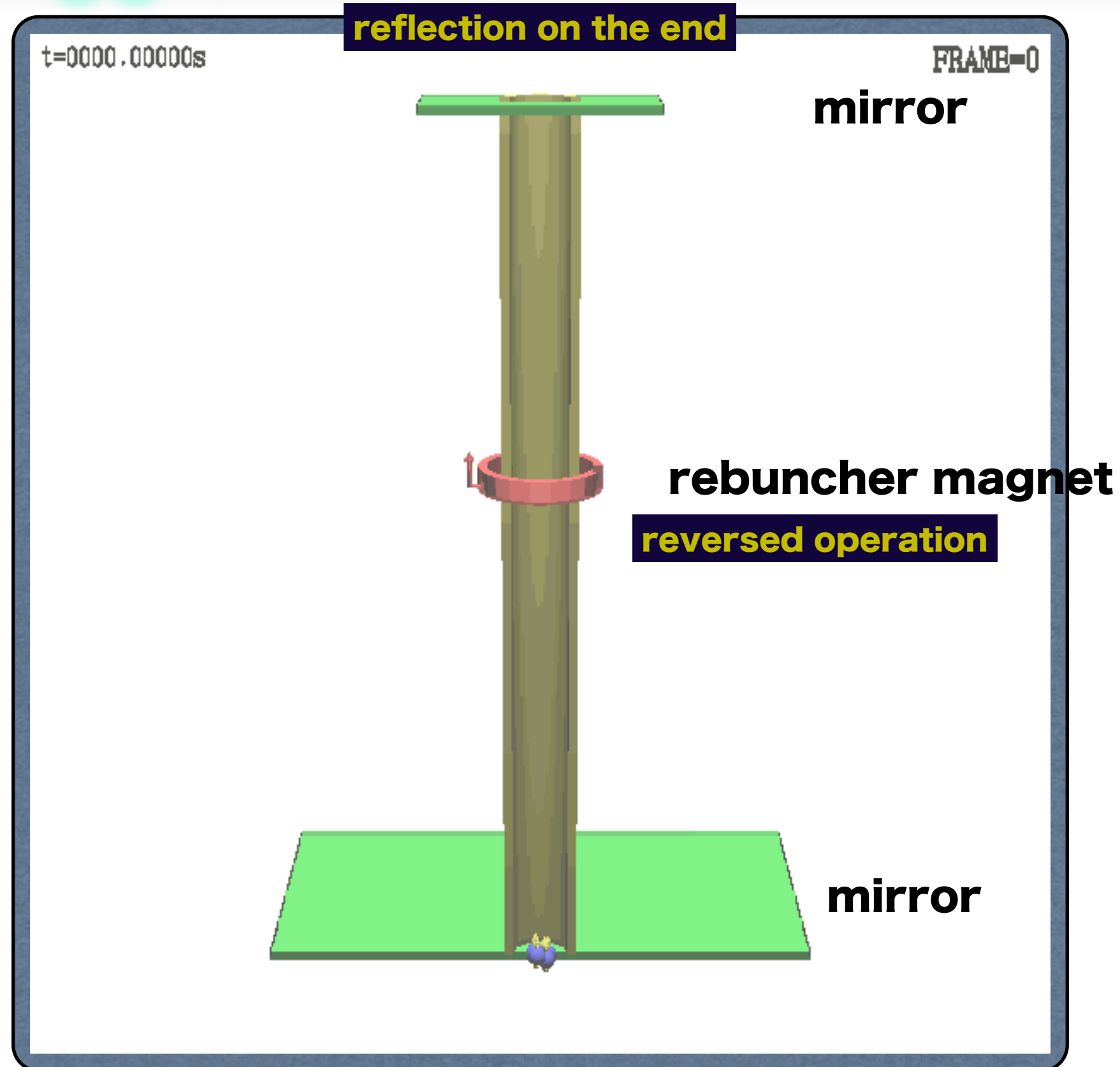
Date(2010/06/12) by(T.Yoshioka)

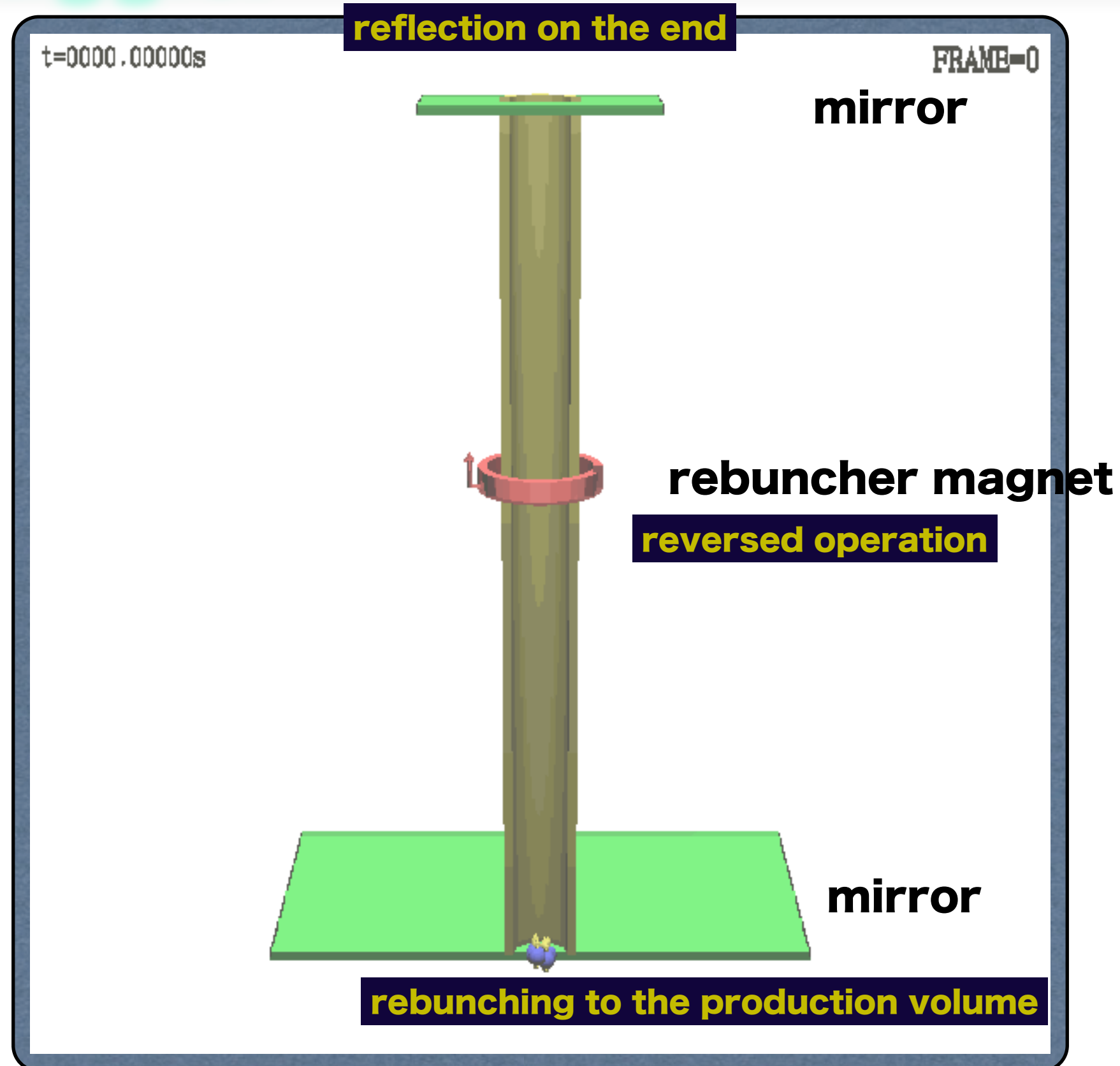
Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))

Conf(将来計画検討小委員会) At(Tokyo)



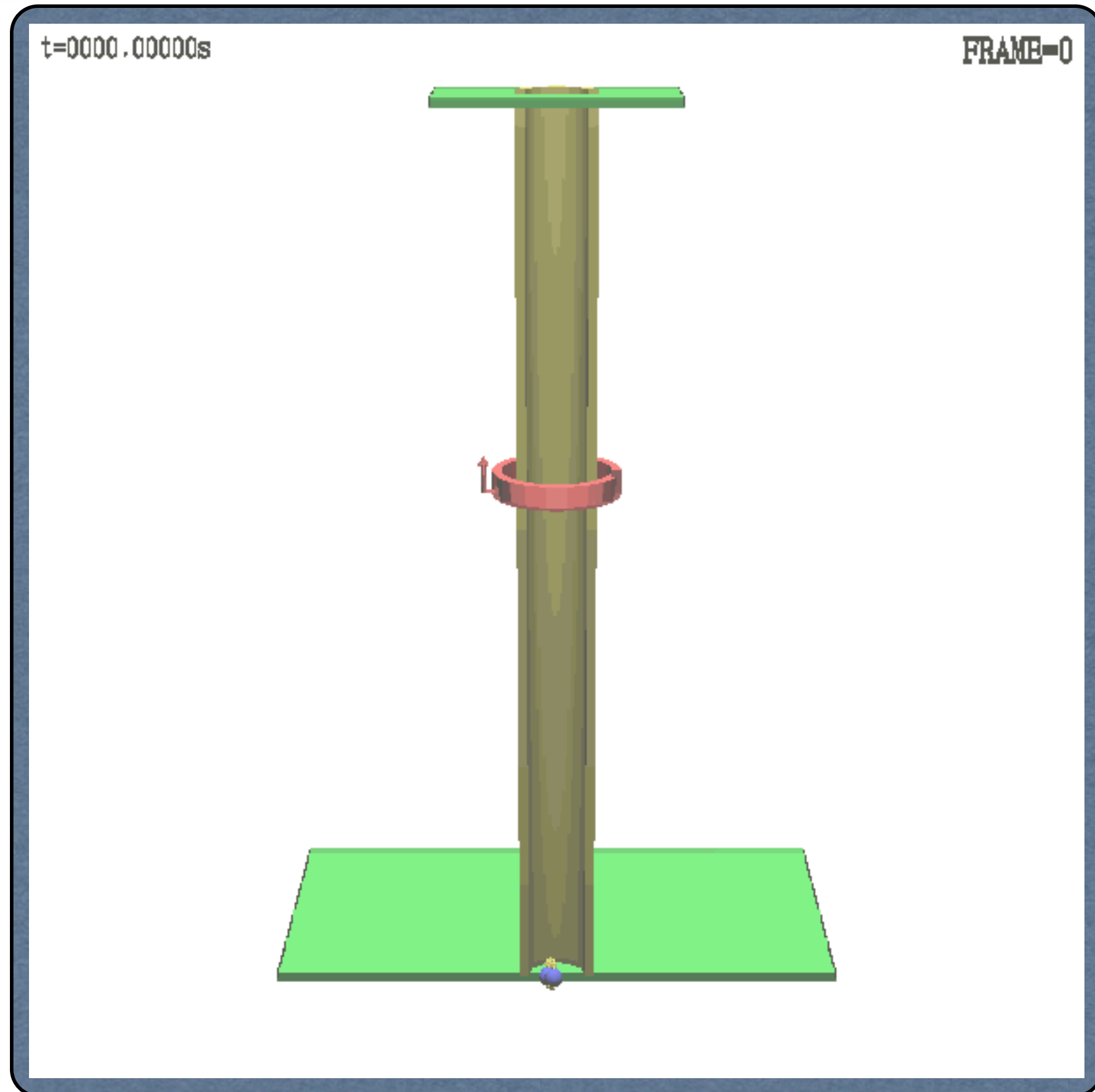






UCN Condenser

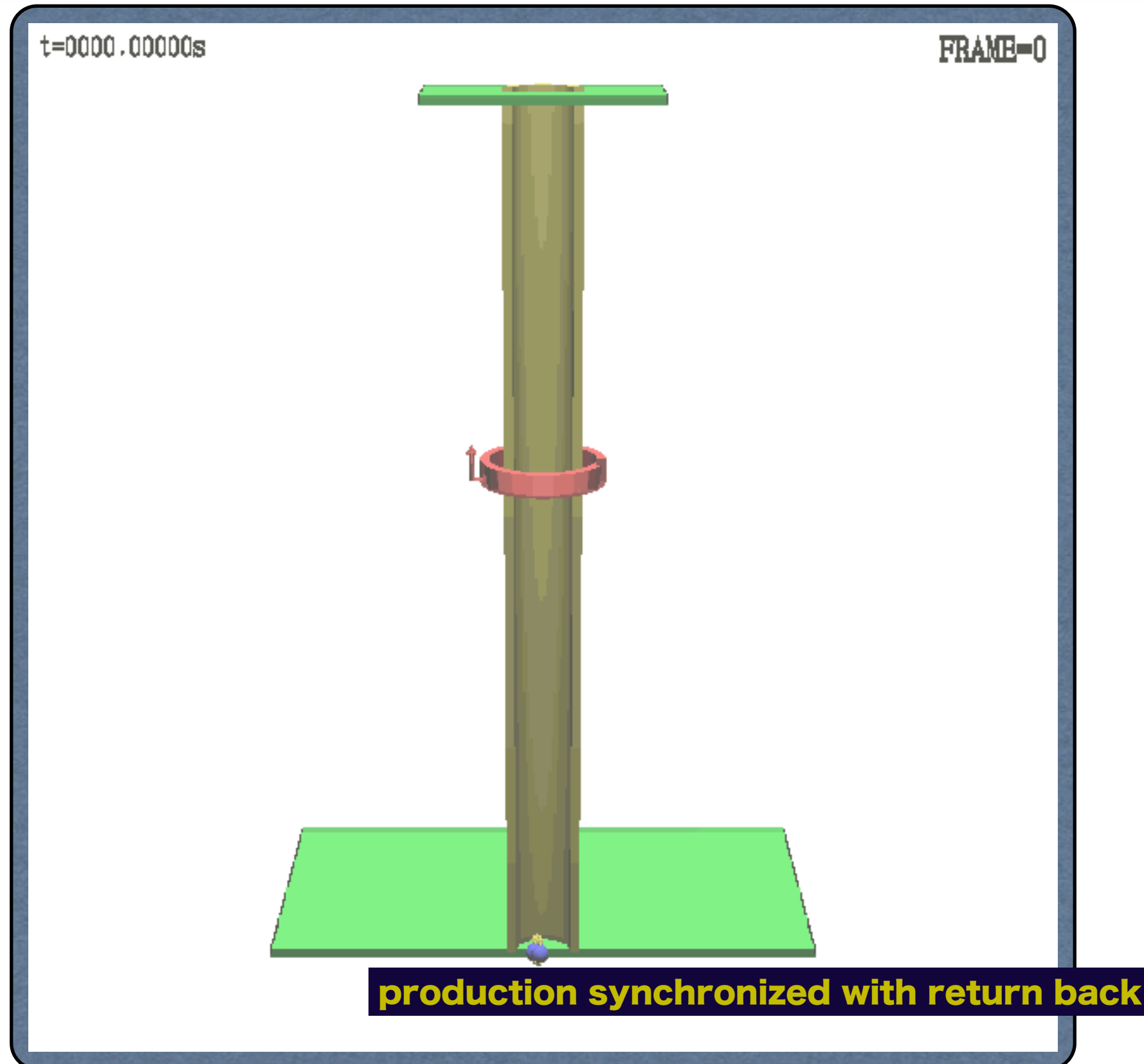
Pulsed Source+Rebuncher+Juggler

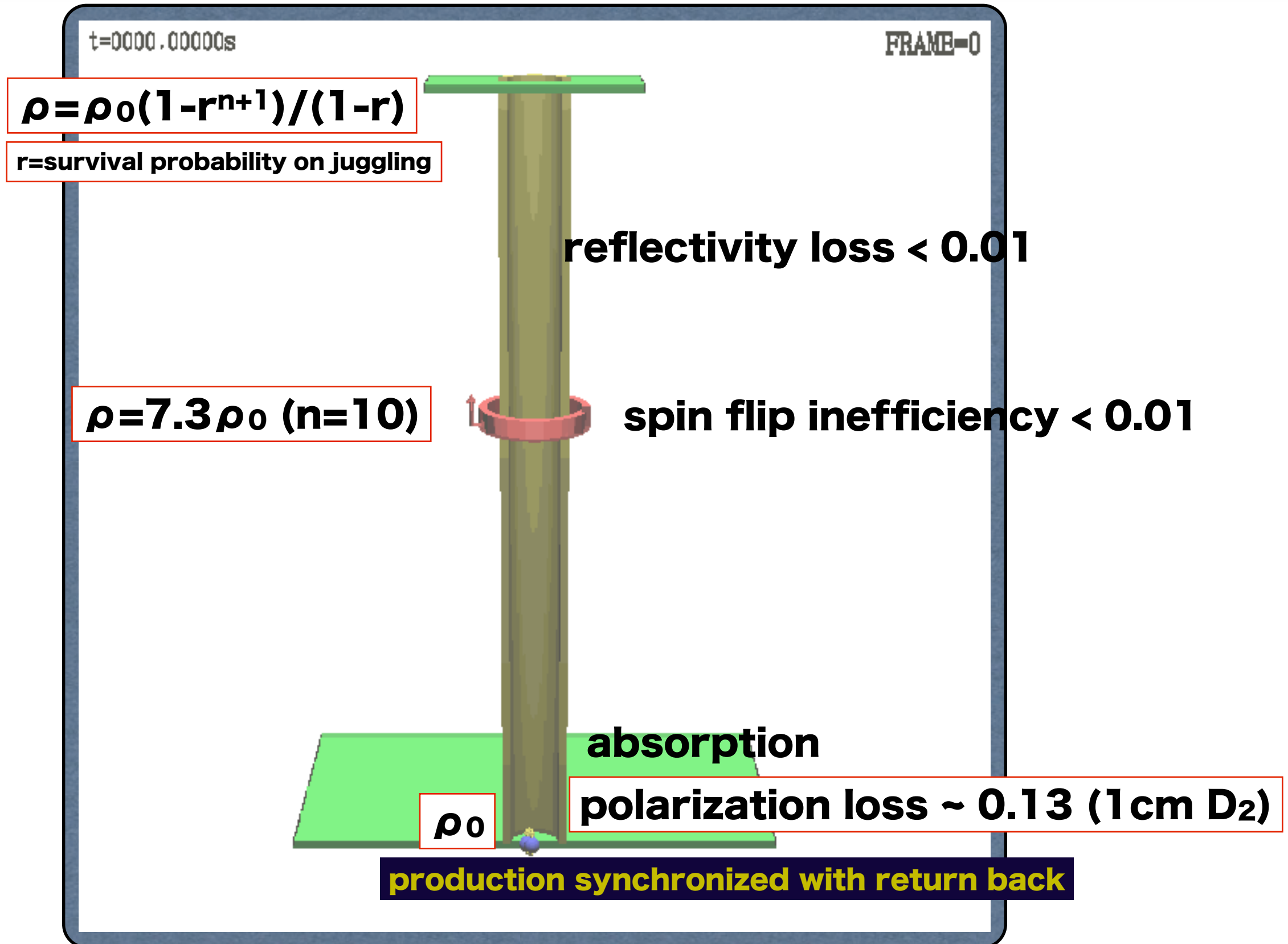


Date(2010/06/12) by(T.Yoshioka)
Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))
Conf(将来計画検討小委員会) At(Tokyo)

UCN Condenser

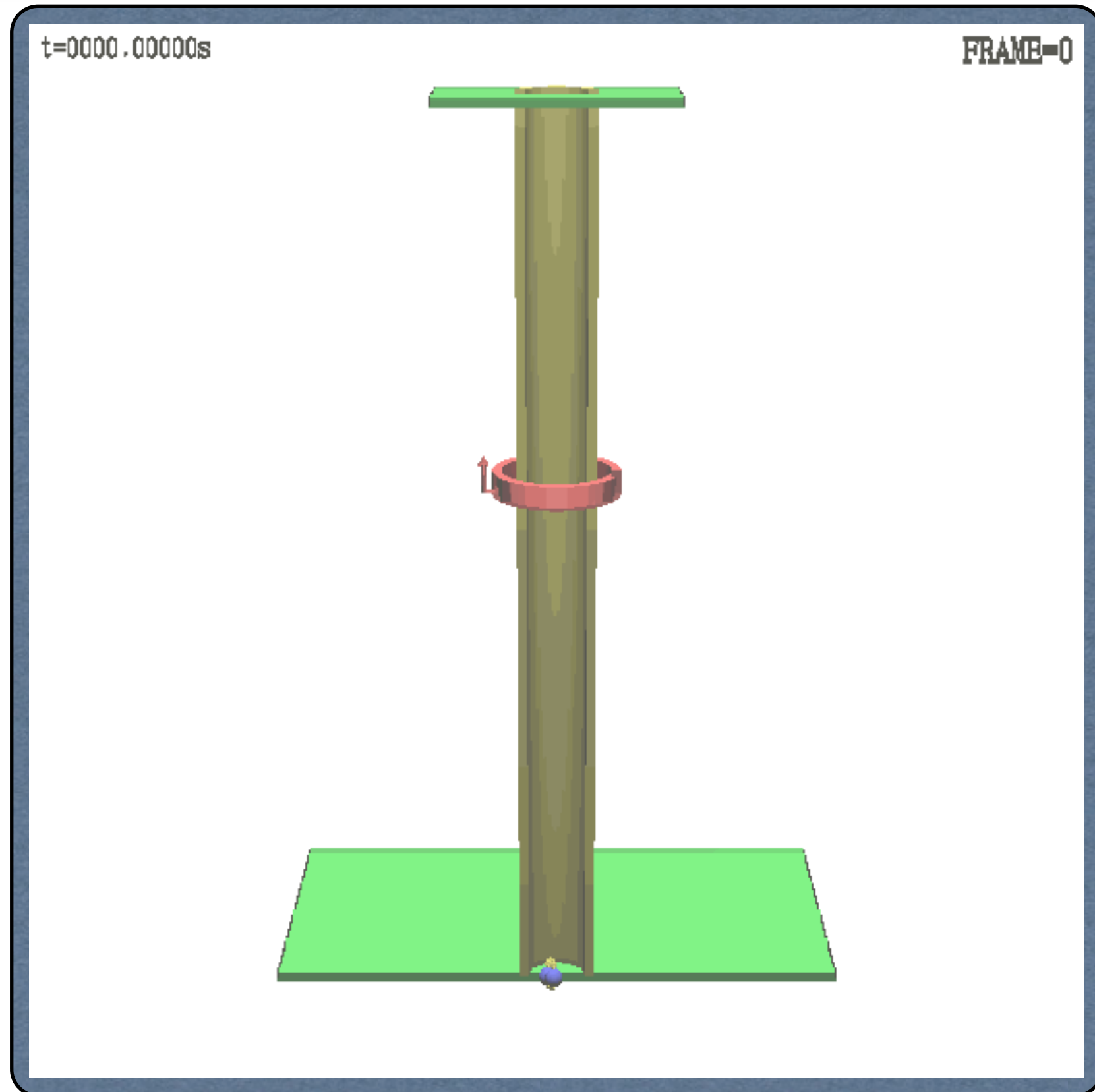
Pulsed Source+Rebuncher+Juggler





UCN Condenser

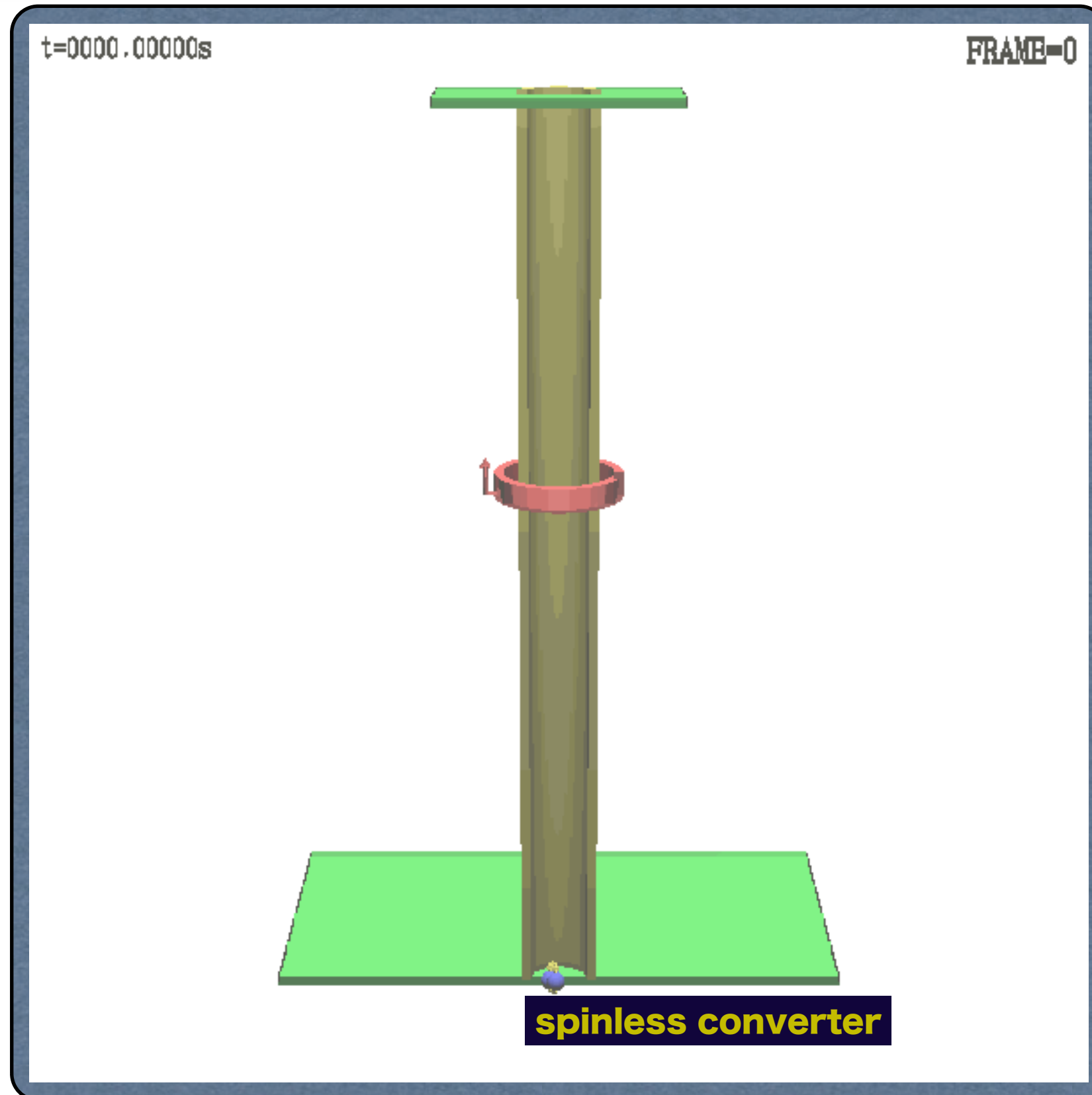
Pulsed Source+Rebuncher+Juggler

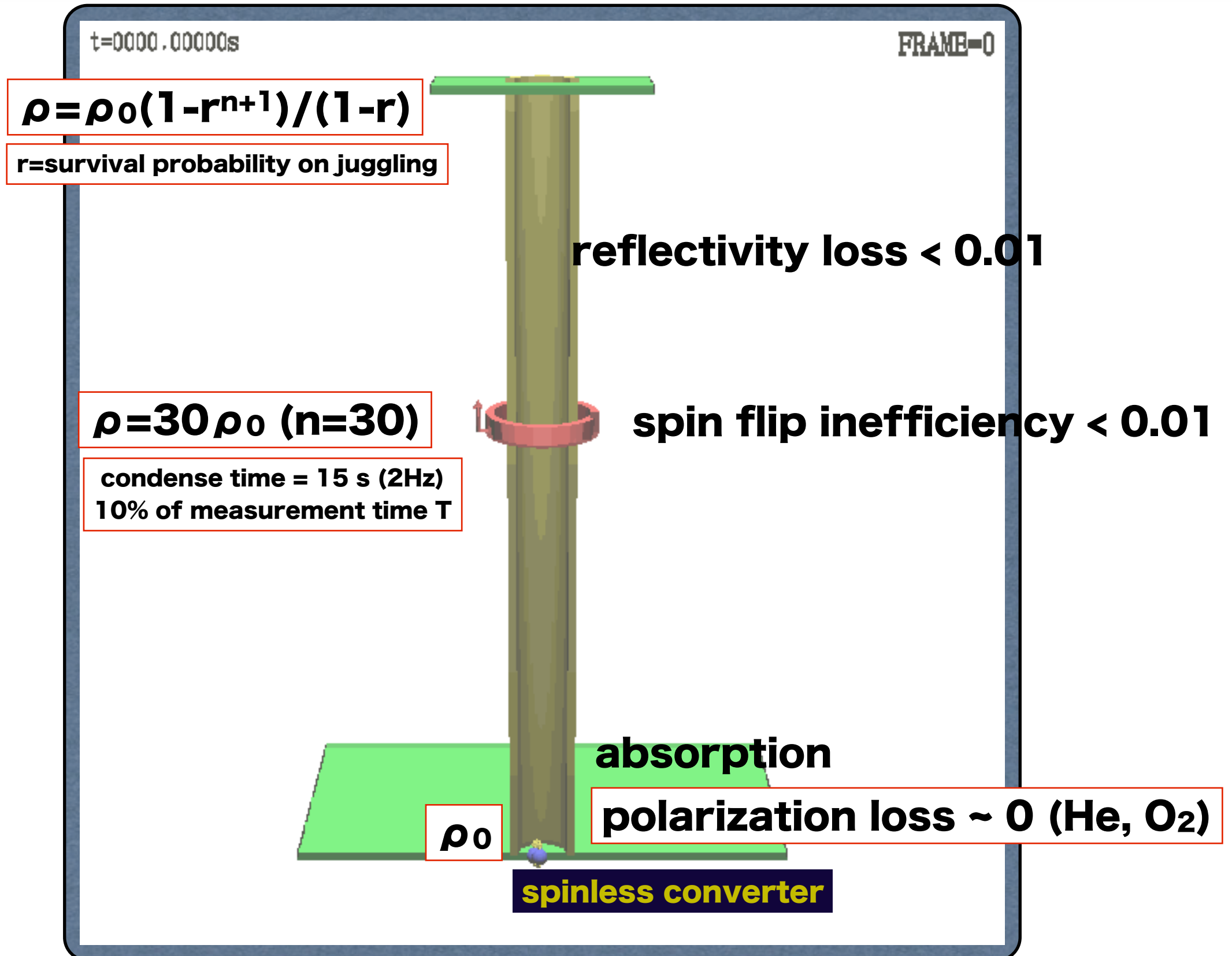


Date(2010/06/12) by(T.Yoshioka)
Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))
Conf(将来計画検討小委員会) At(Tokyo)

UCN Condenser

Pulsed Source+Rebuncher+Juggler



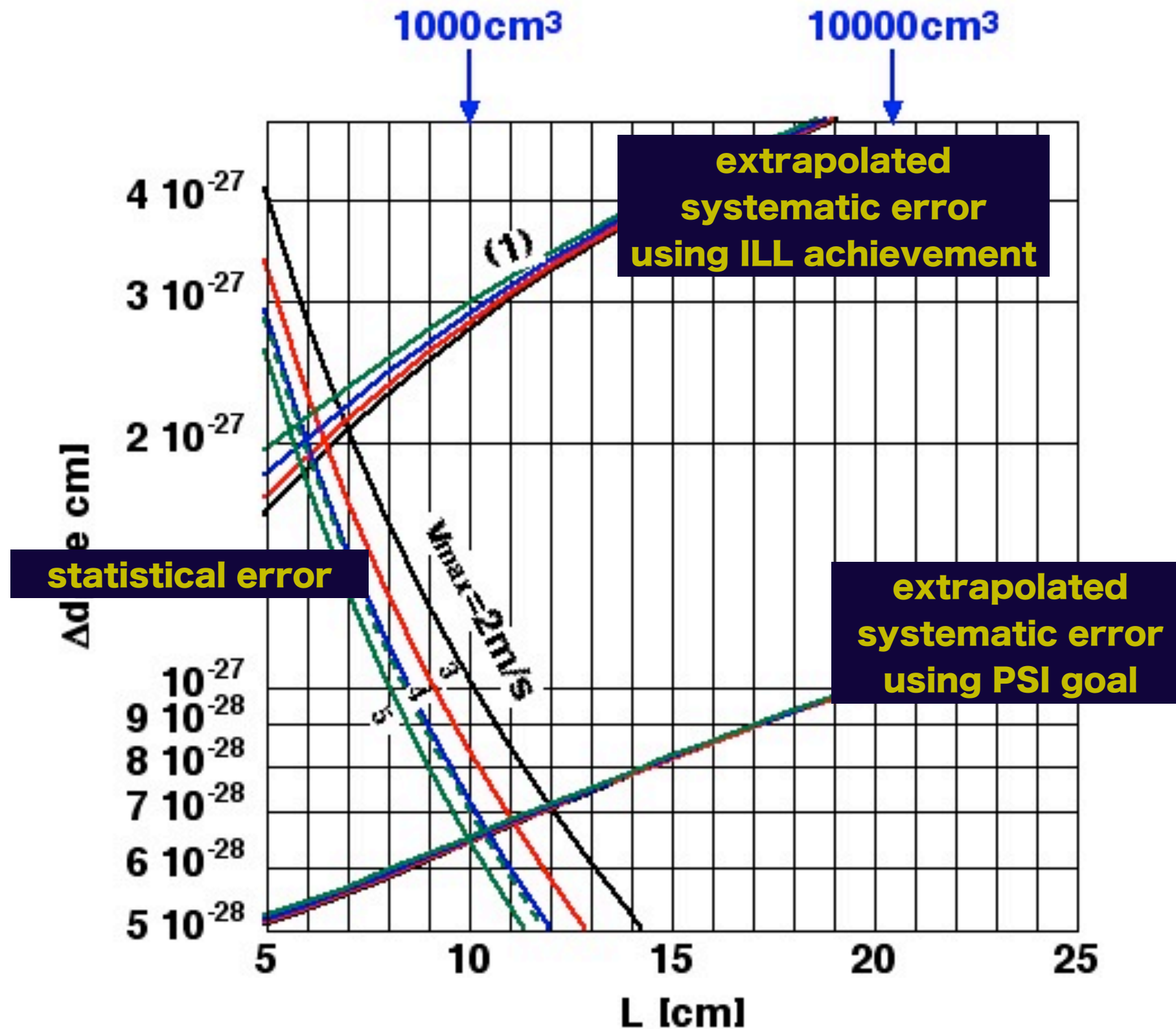


Experimental Errors

$$\rho_0 = 93000 \text{ cm}^{-3}$$

$$5000h$$

$$T=150s$$

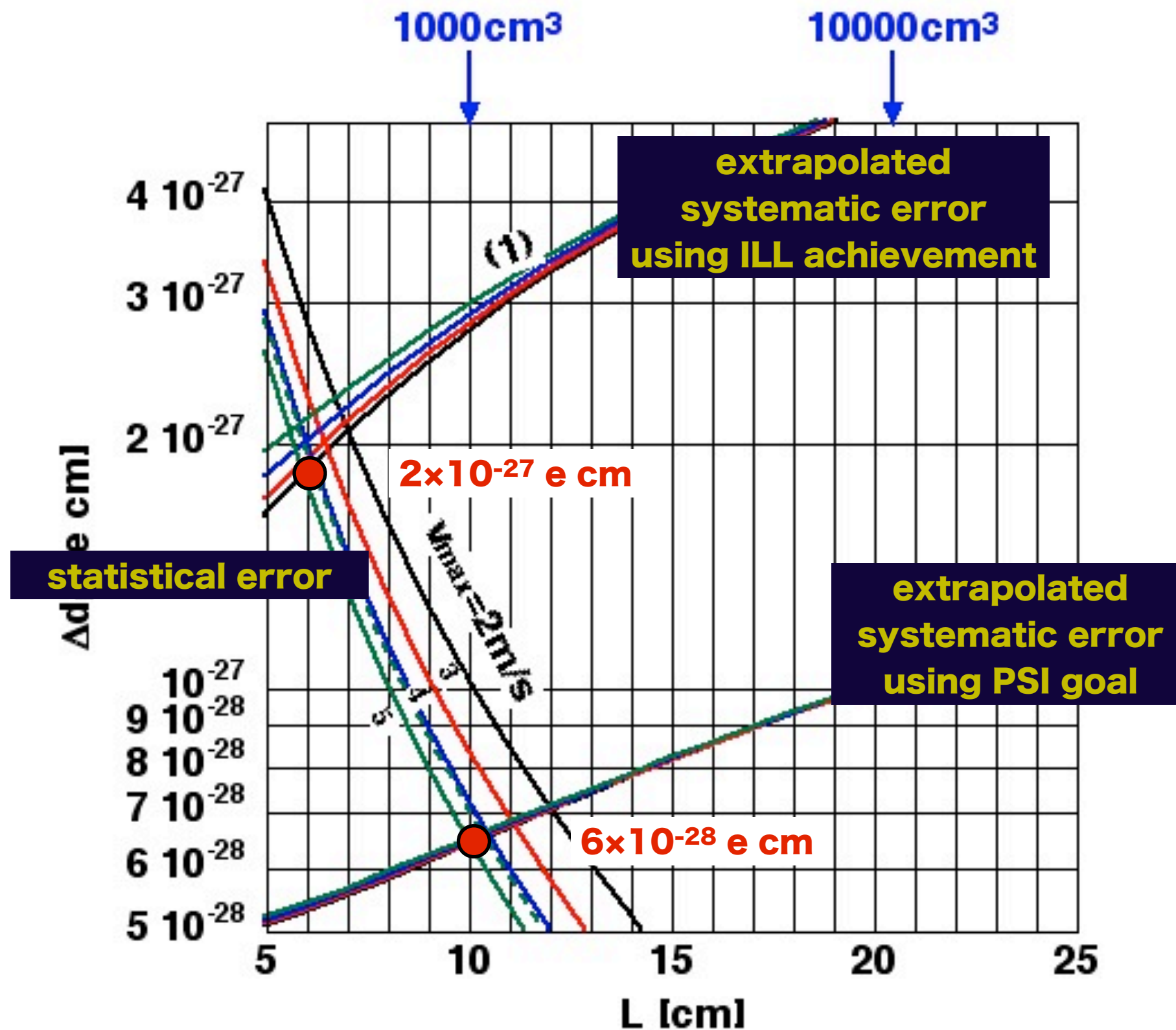


Experimental Errors

$$\rho_0 = 93000 \text{ cm}^{-3}$$

$$5000h$$

$$T=150s$$



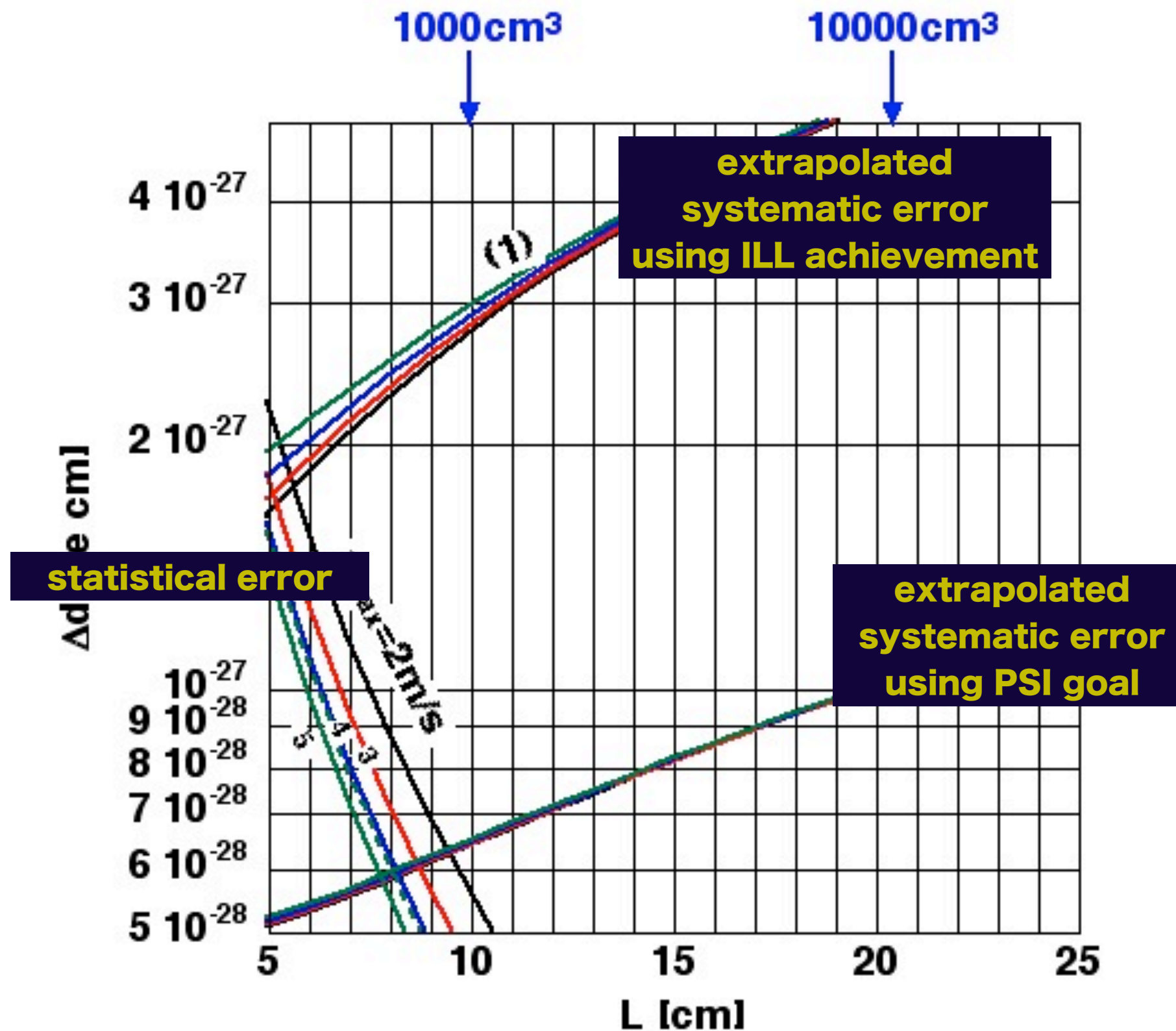
cell size

Experimental Errors

$$\rho_0 = 620000 \text{ cm}^{-3}$$

5000h

T=150s

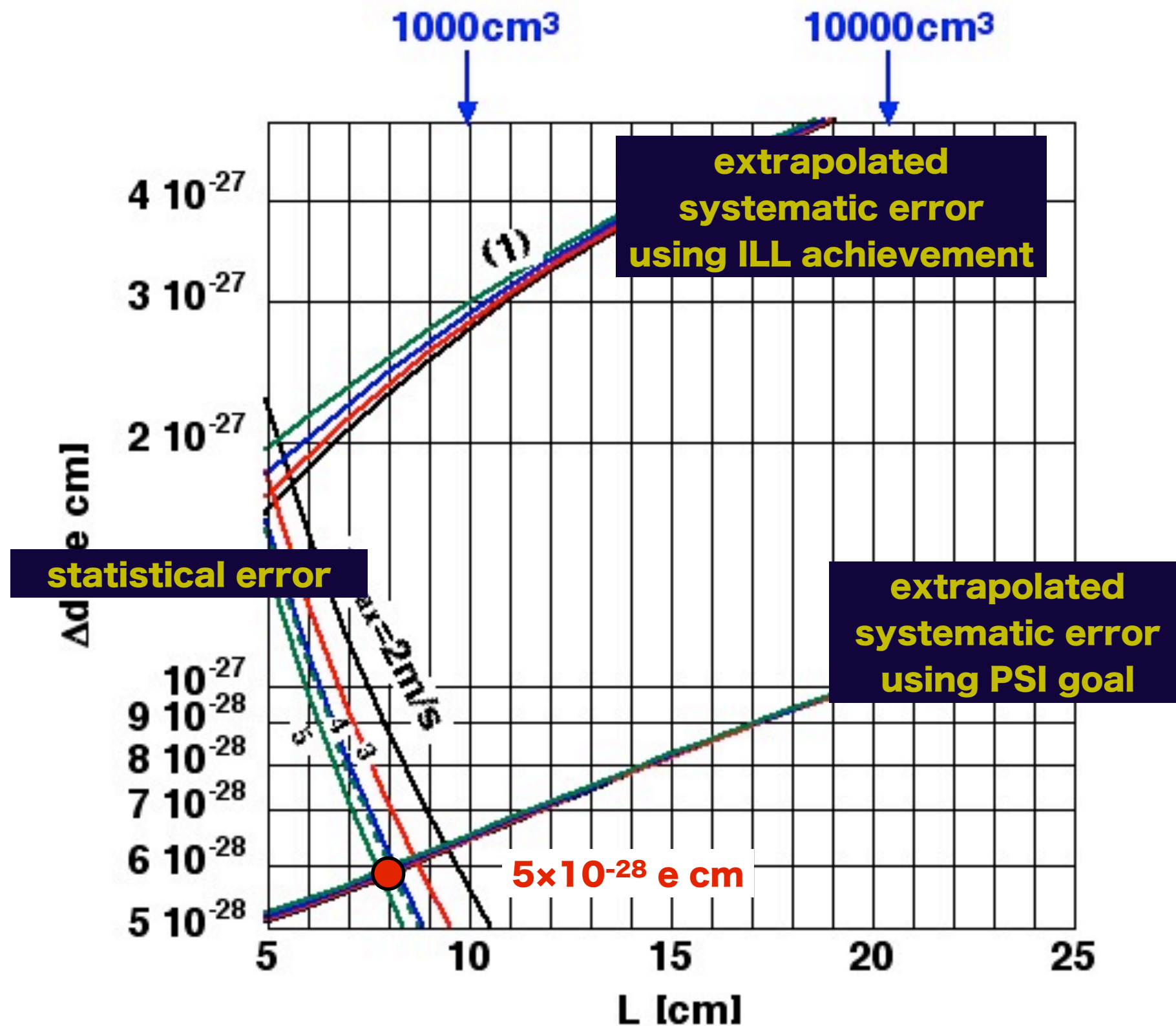


Experimental Errors

$$\rho_0 = 620000 \text{ cm}^{-3}$$

5000h

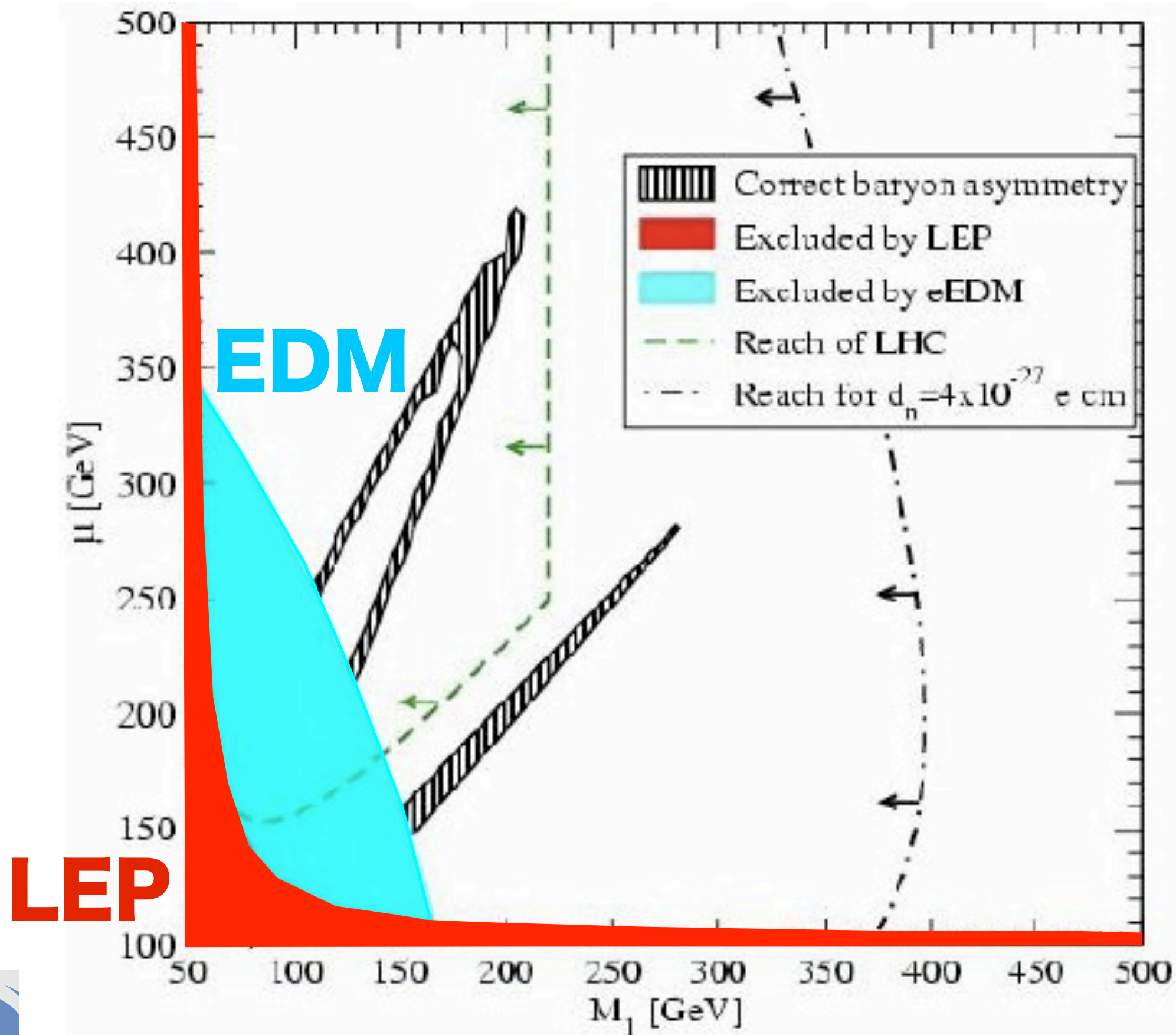
T=150s



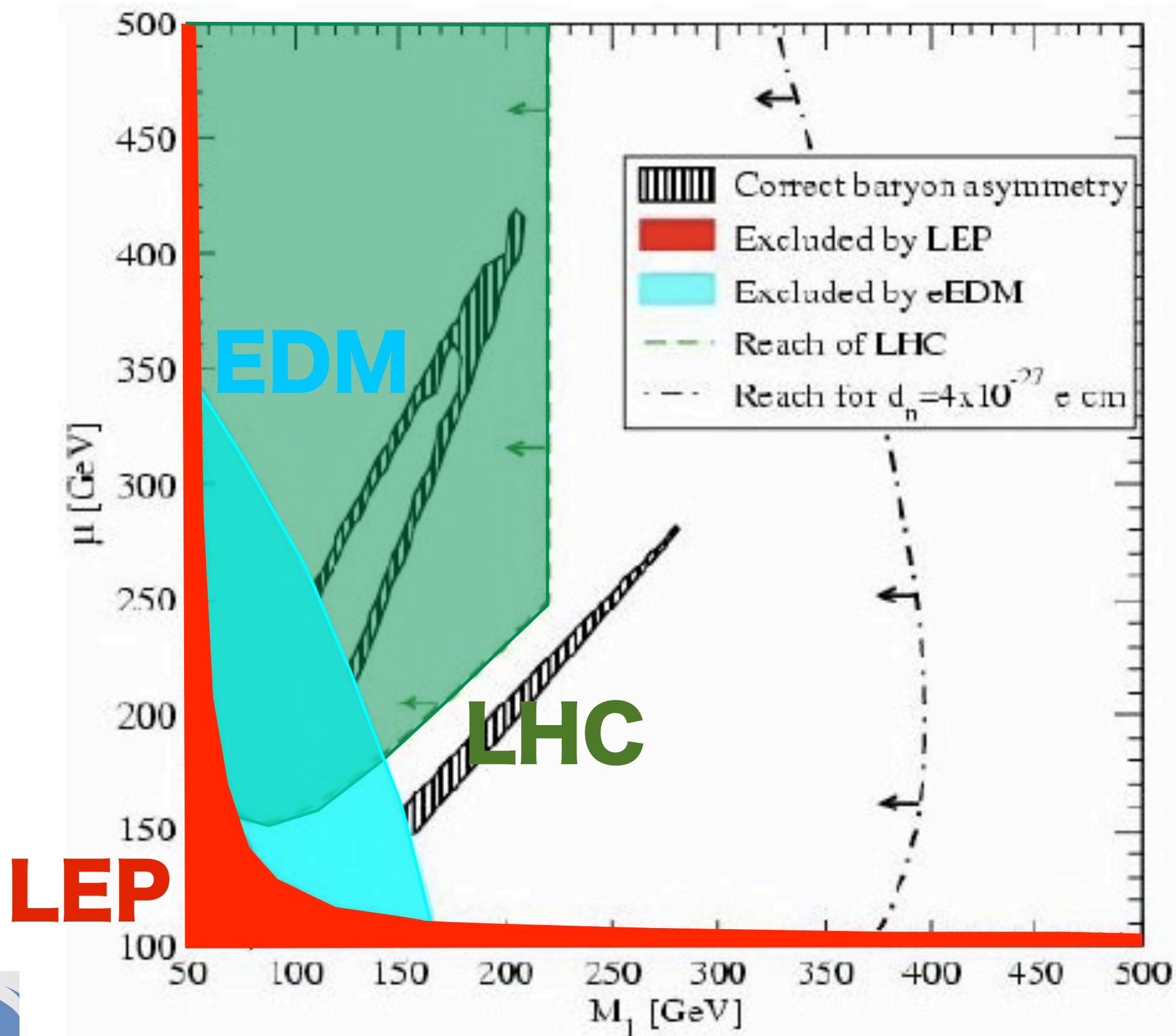
cell size



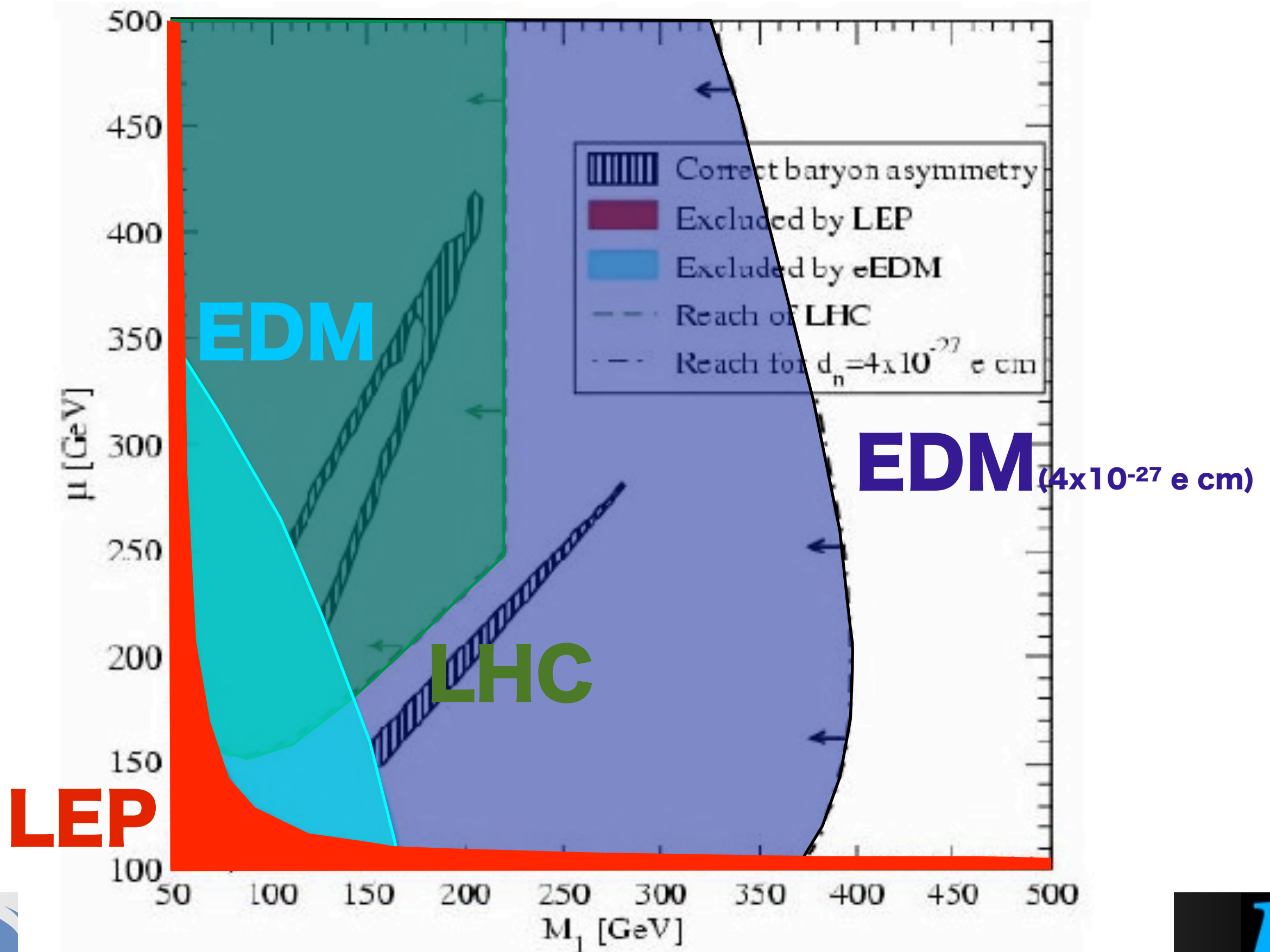
nEDM probing beyond-SM



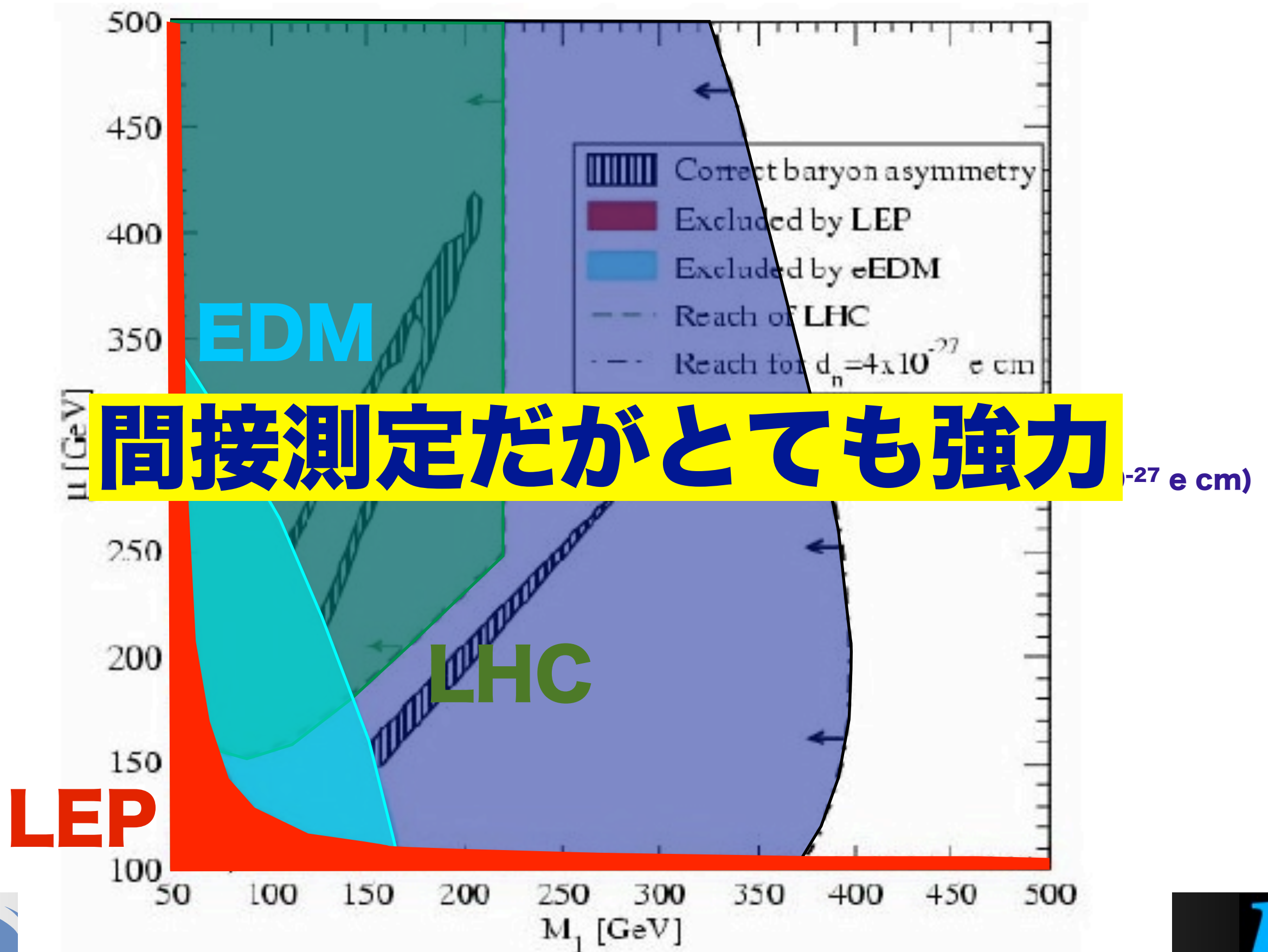
nEDM probing beyond-SM



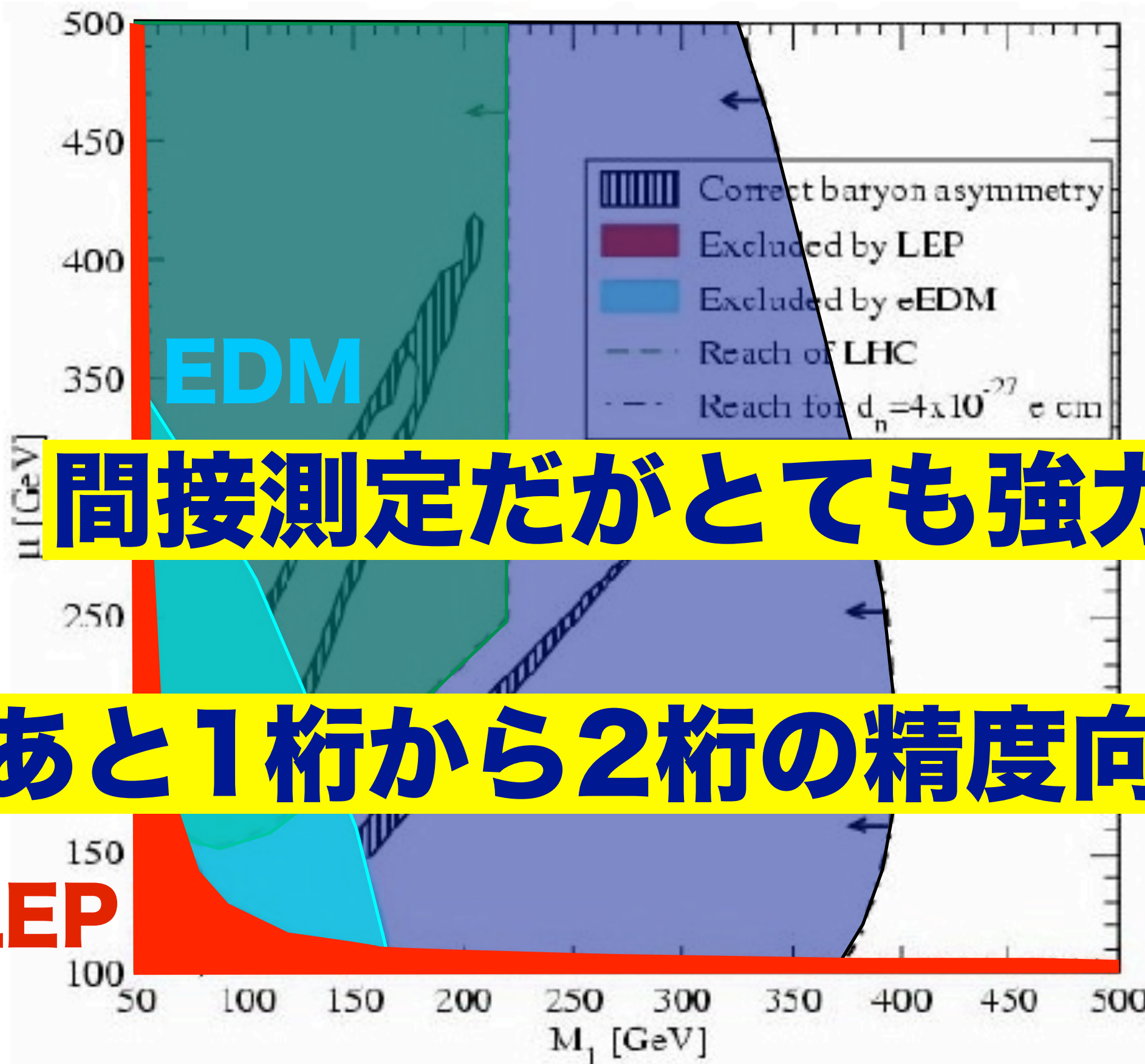
nEDM probing beyond-SM



nEDM probing beyond-SM



nEDM probing beyond-SM



間接測定だがとても強力

あと1桁から2桁の精度向上

10^{-27} e cm)



Magnetometry

Hg magnetometer

100fT

Cs magnetometer

3fT

^3He magnetometer

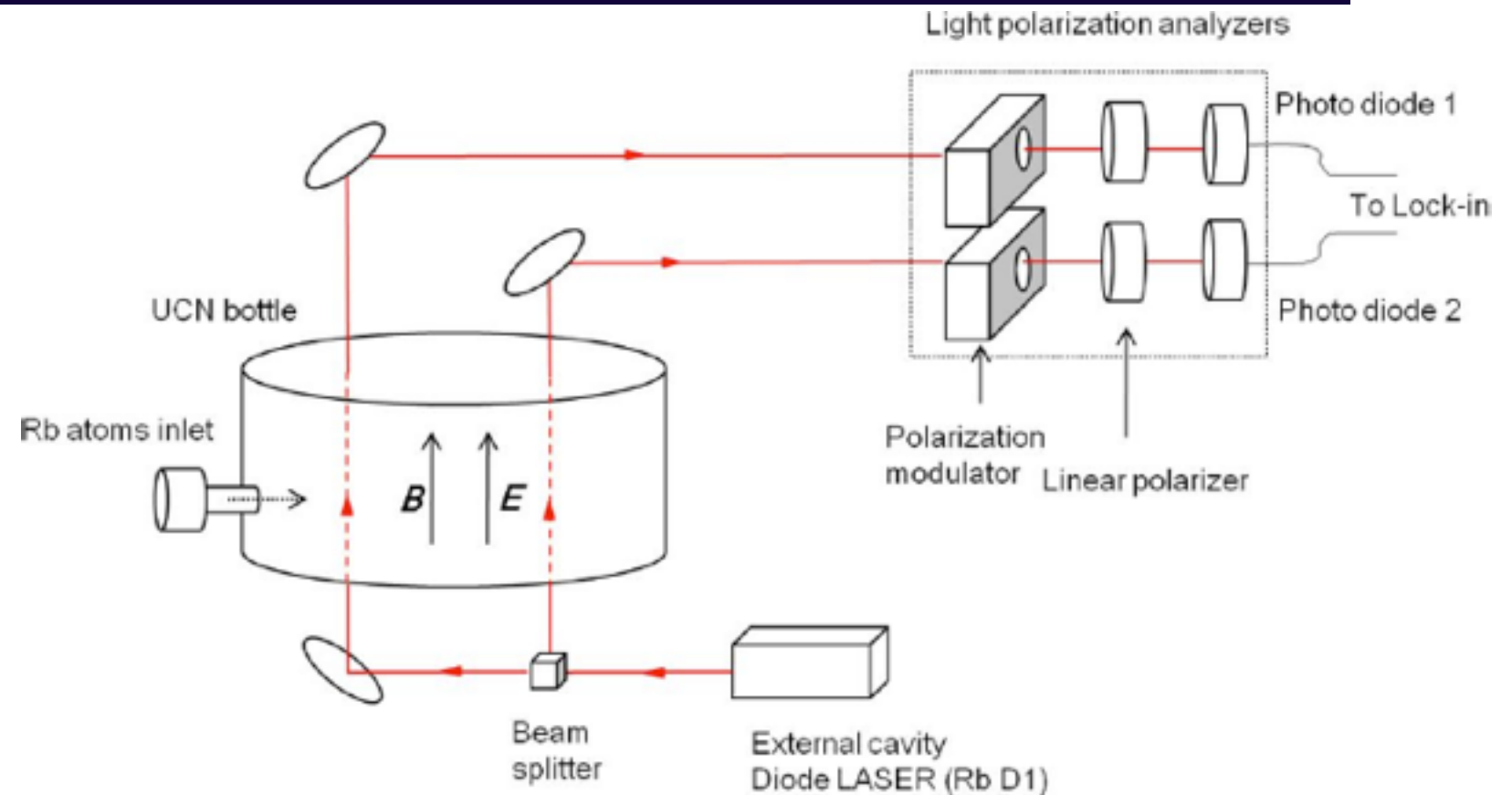
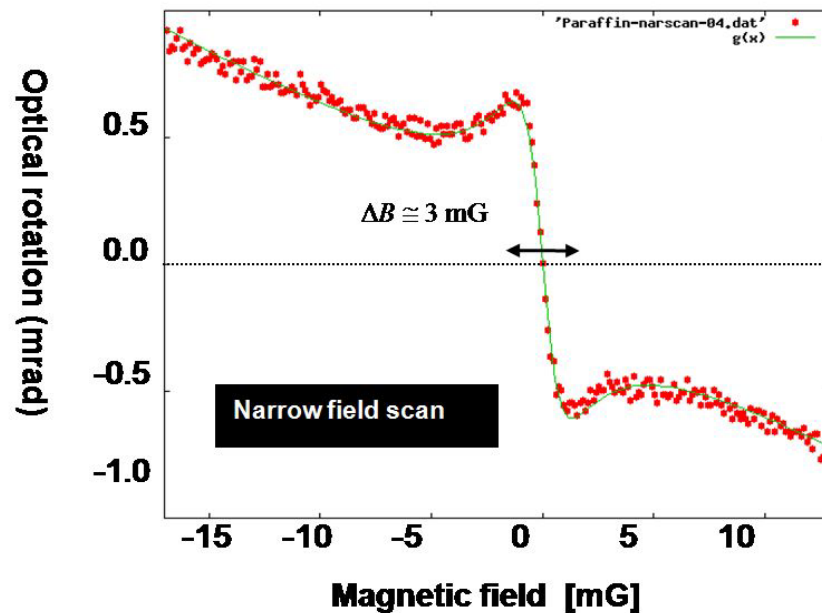
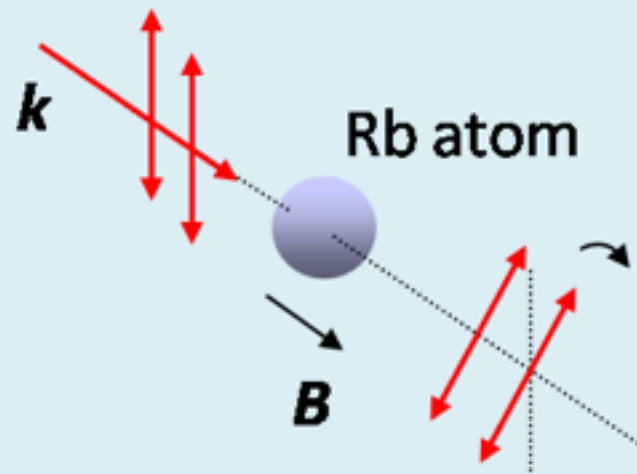
1fT

SQUID magnetometer

**80aT/Hz $^{1/2}$
requires low temperature**

Rb NMOR magnetometer (Nonlinear Magneto-Optical Rotation)

Linear polarized light



300aT/Hz $^{1/2}$

100aT @ 0.1-0.01Hz

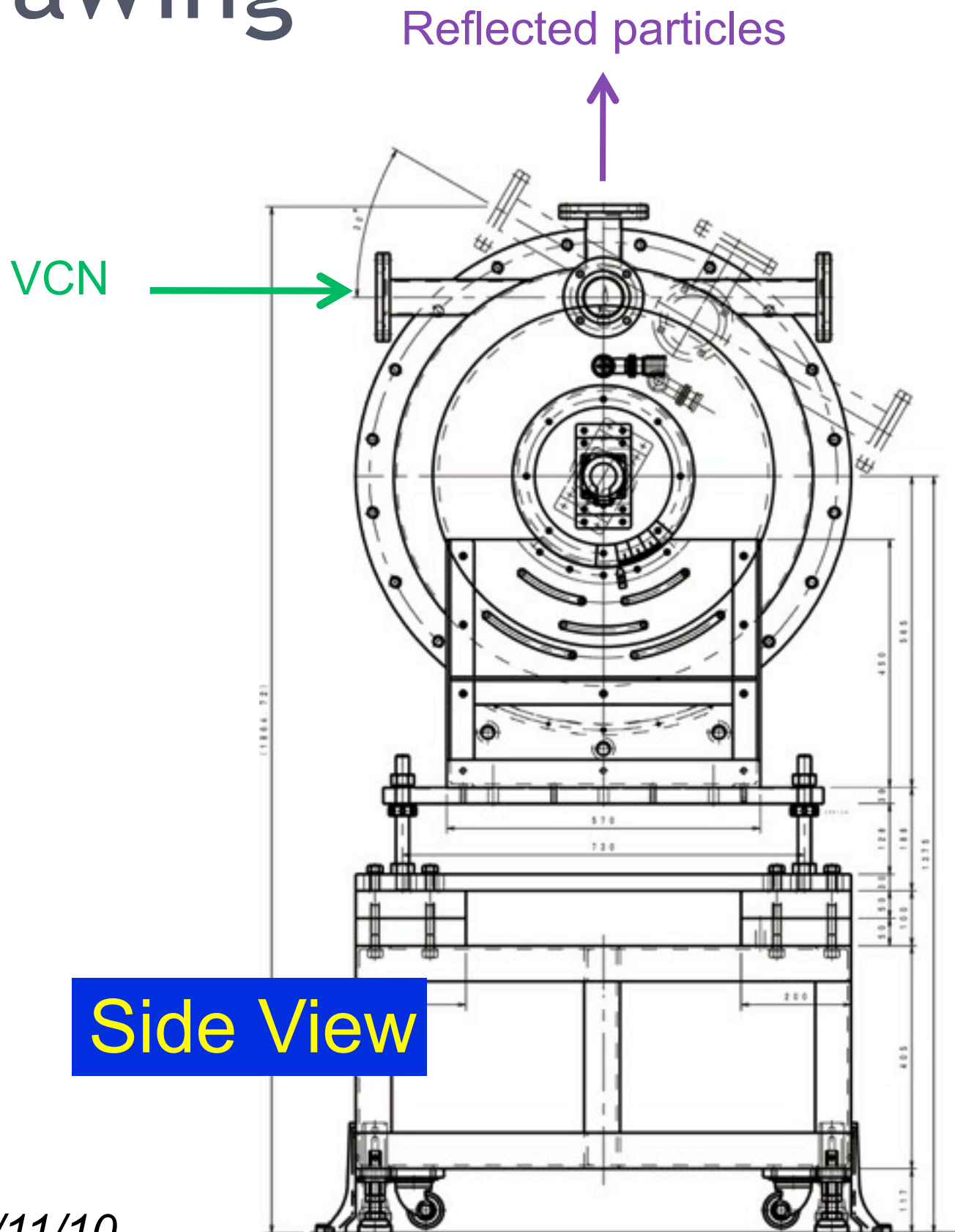
K.Asahi, A.Yoshimi, Tokyo Inst. Tech

UCN production by a Doppler

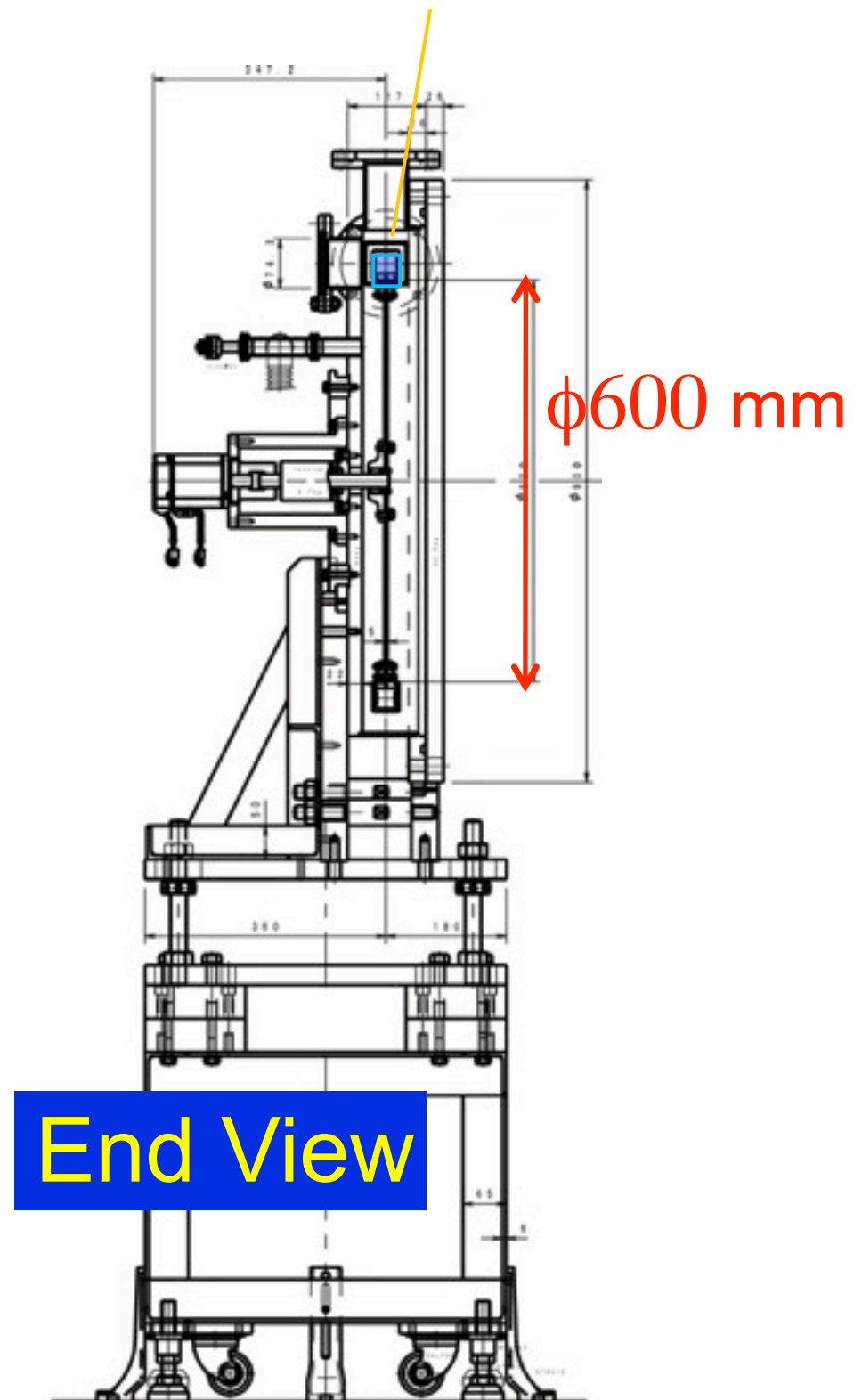
K. Mishima (KEK), S.Imajo(Kyoto Univ.)
and the NOP Collaboration



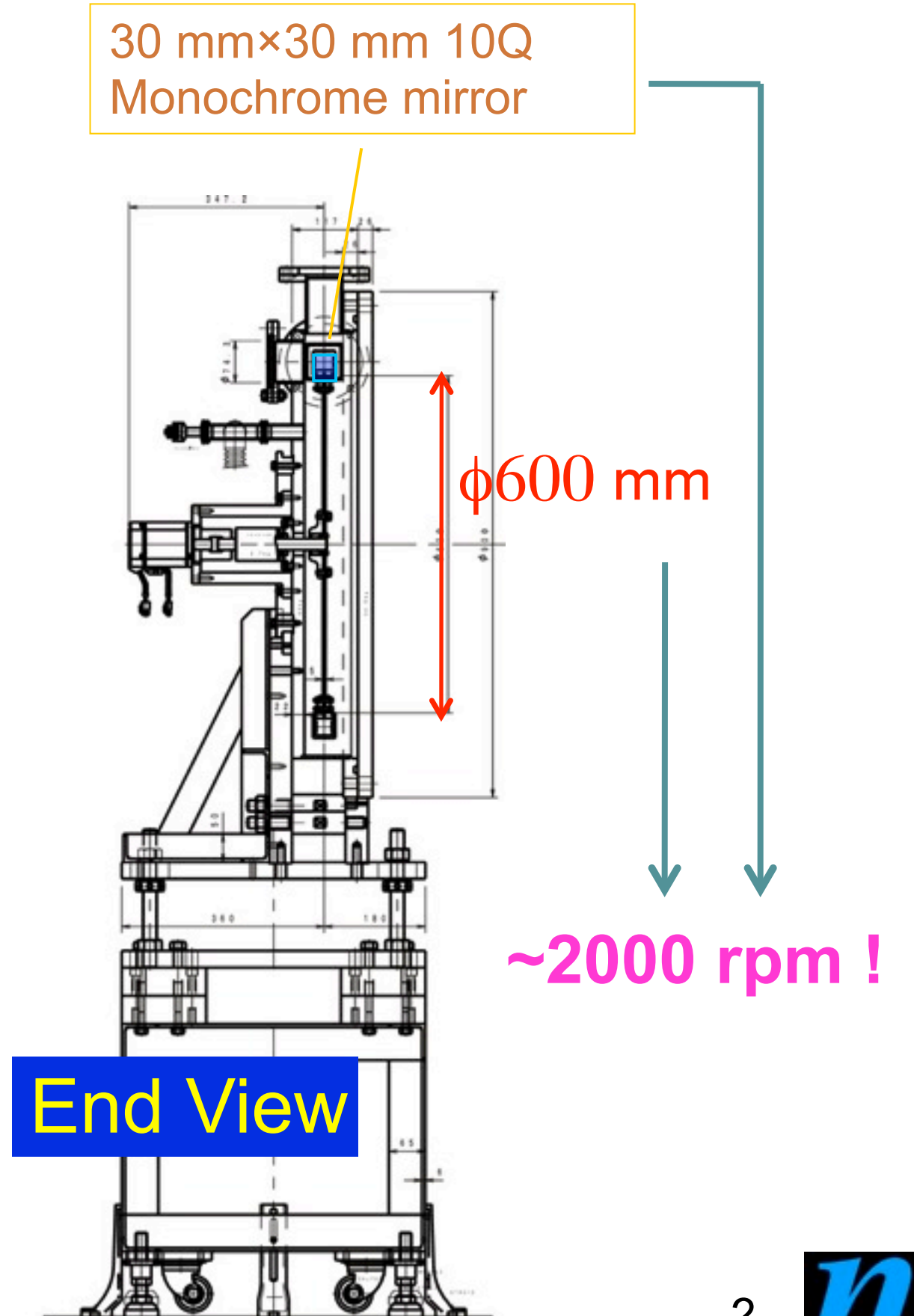
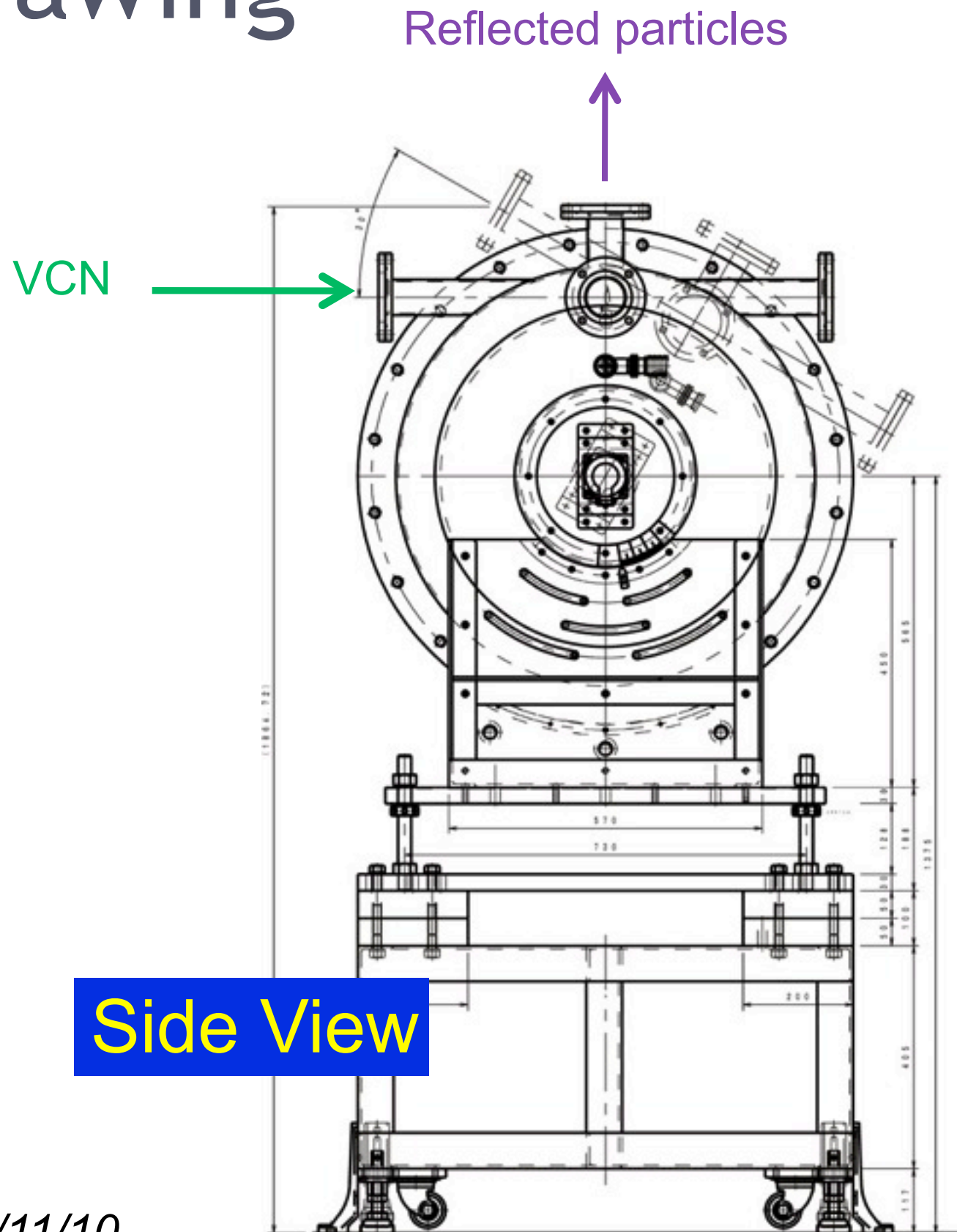
Drawing



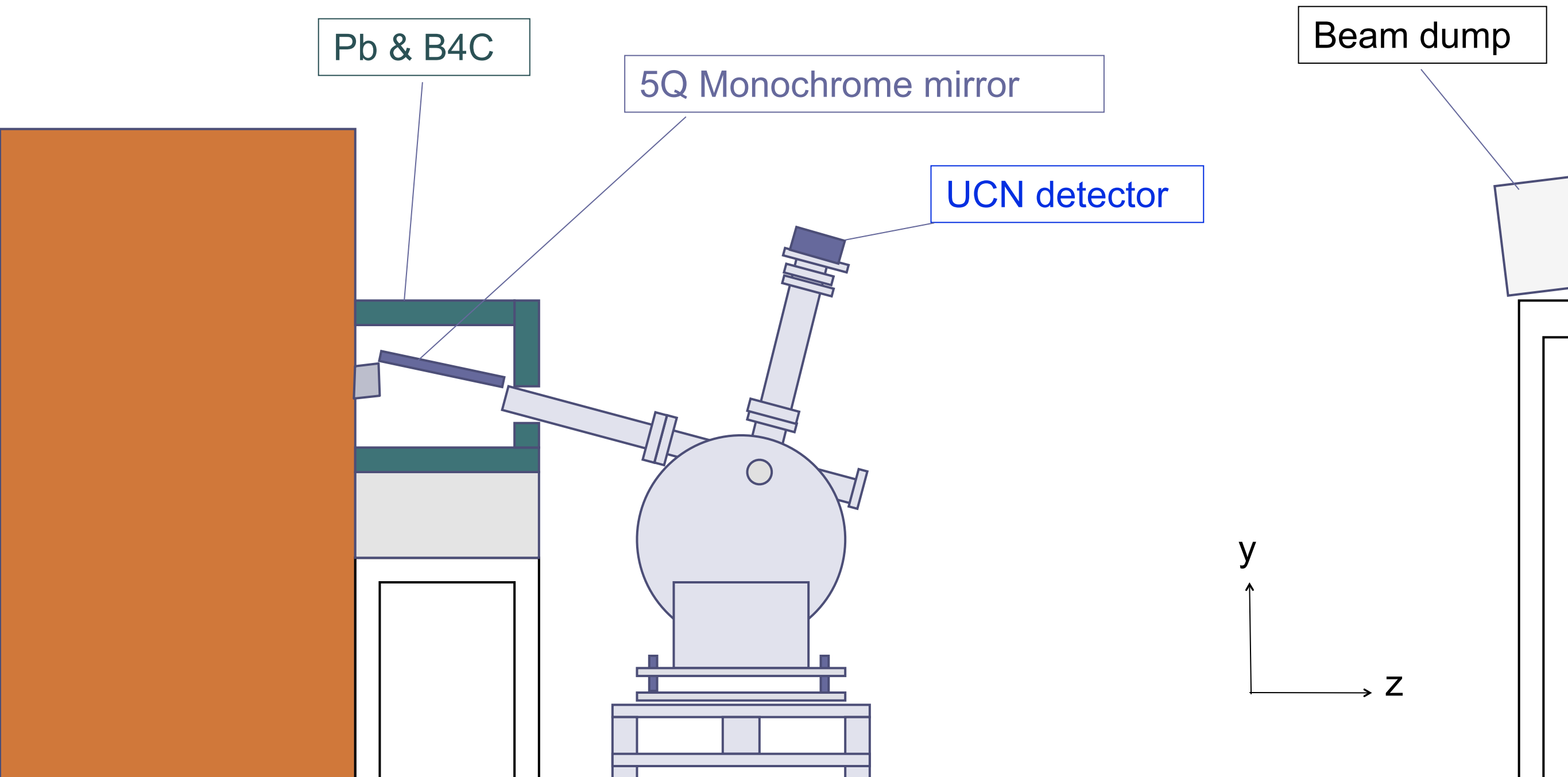
30 mm×30 mm 10Q
Monochrome mirror



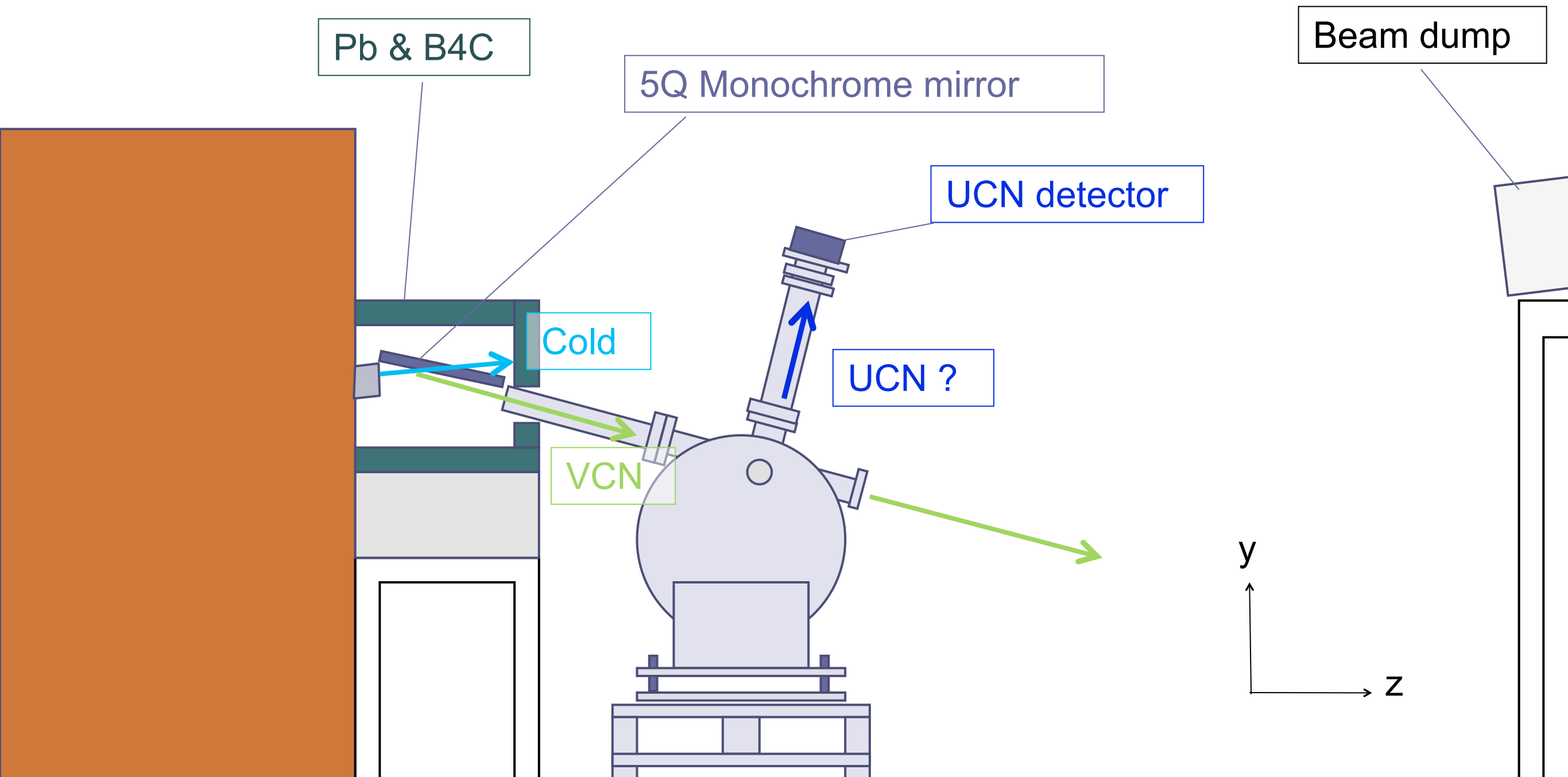
Drawing



Beamline Configuration



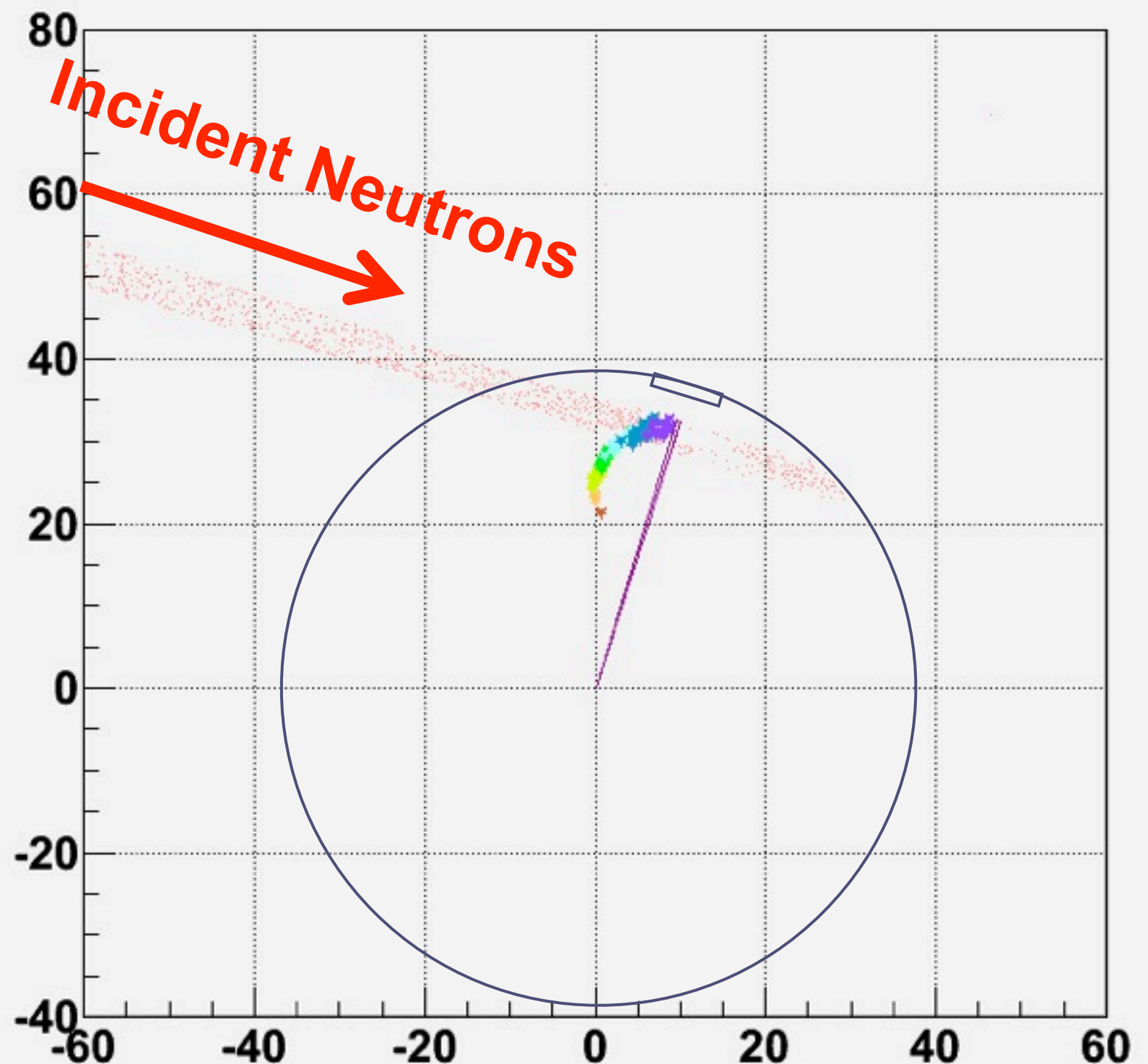
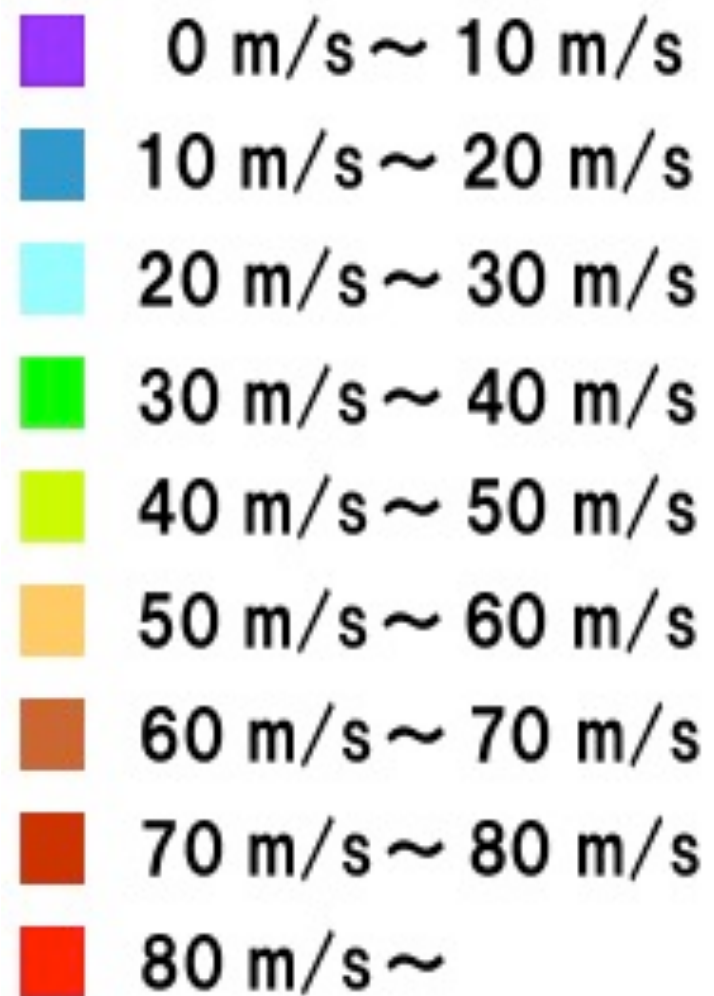
Beamline Configuration



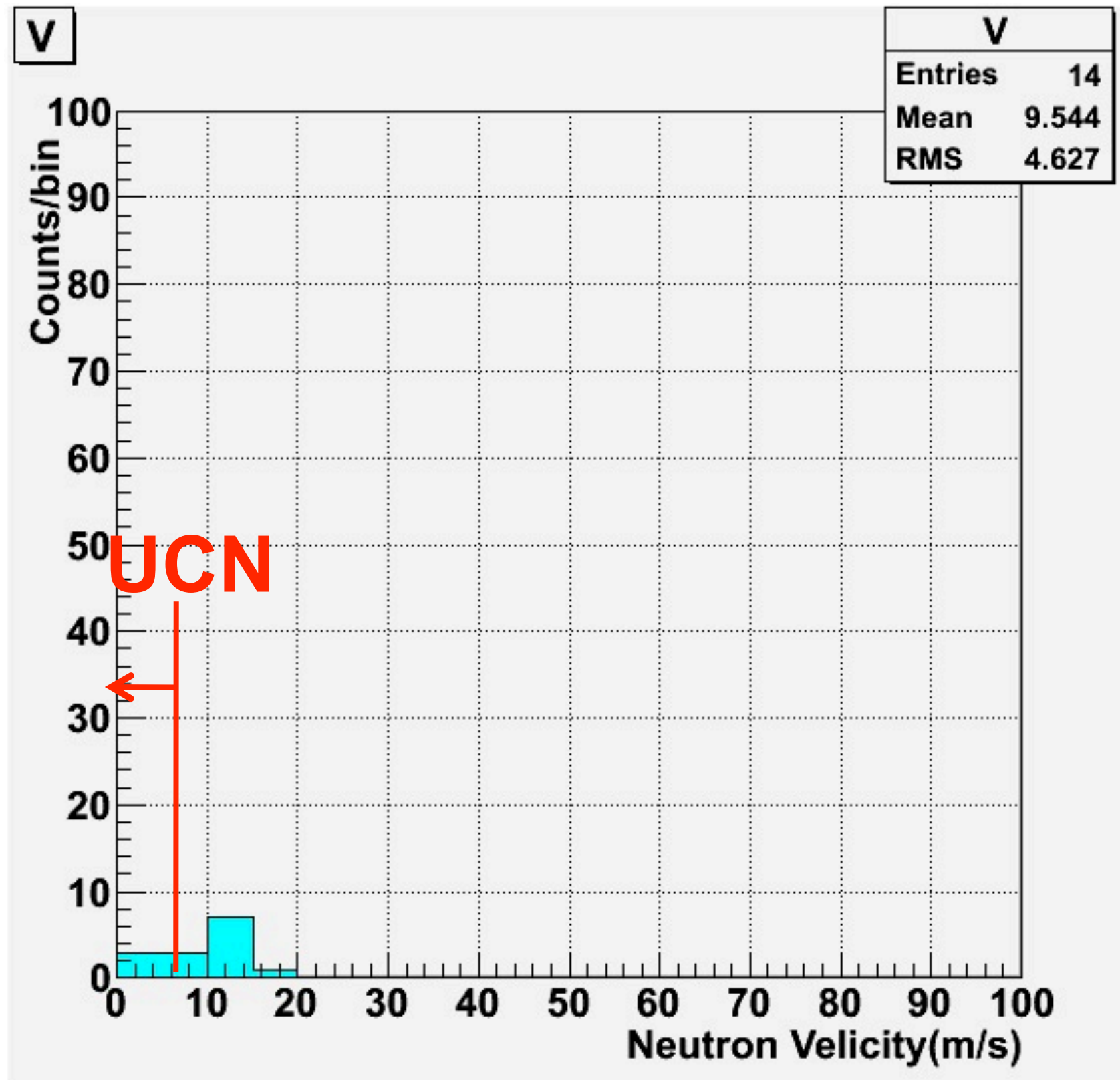
Simulation Setup

- Incident neutrons
 - Energy Spectrum : measured spectrum (previous page)
 - Velocity : 100 m/s ~ 200 m/s
 - Divergence : ± 10 mrad
- Supper Mirror
 - 10Qc (will/can be made using IBS in KUR)
 - Mirror size : 30 mm x 30 mm
 - Assuming 100% reflectivity for <137 m/s neutrons

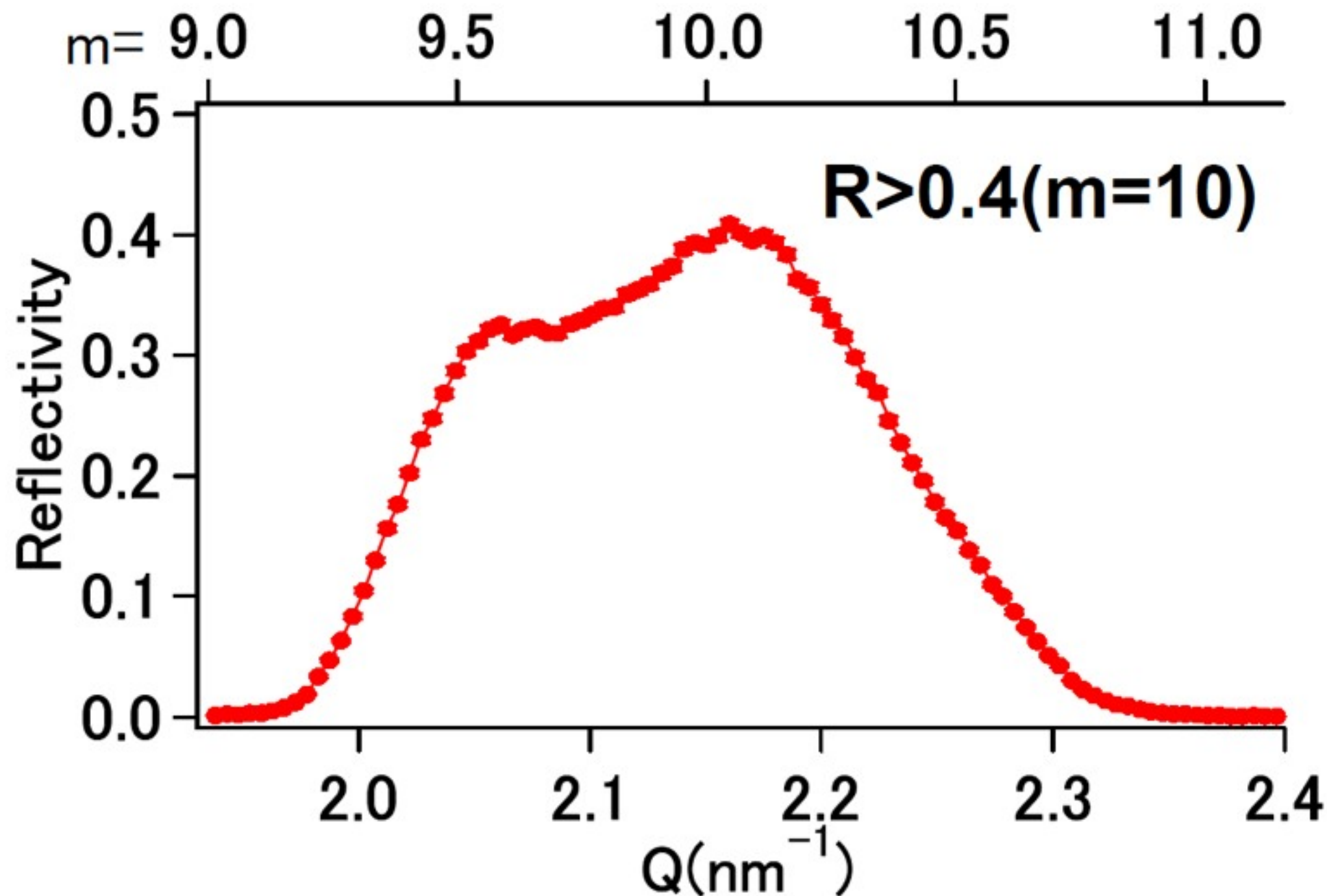
Simulation w/ extraction hole



Extraction Efficiency



$m=10$ NiC/Ti wide-band monochromator



The Doppler Shifter



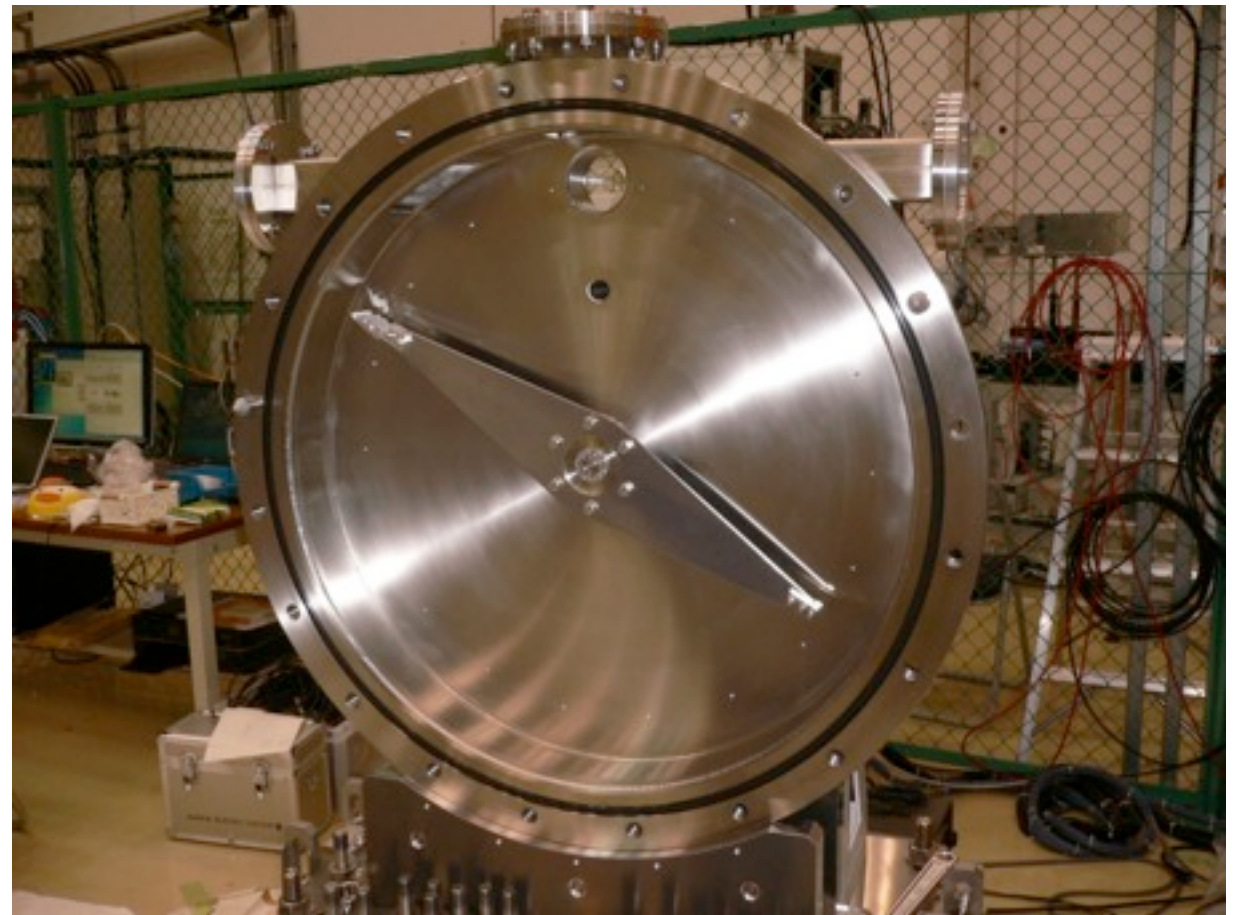
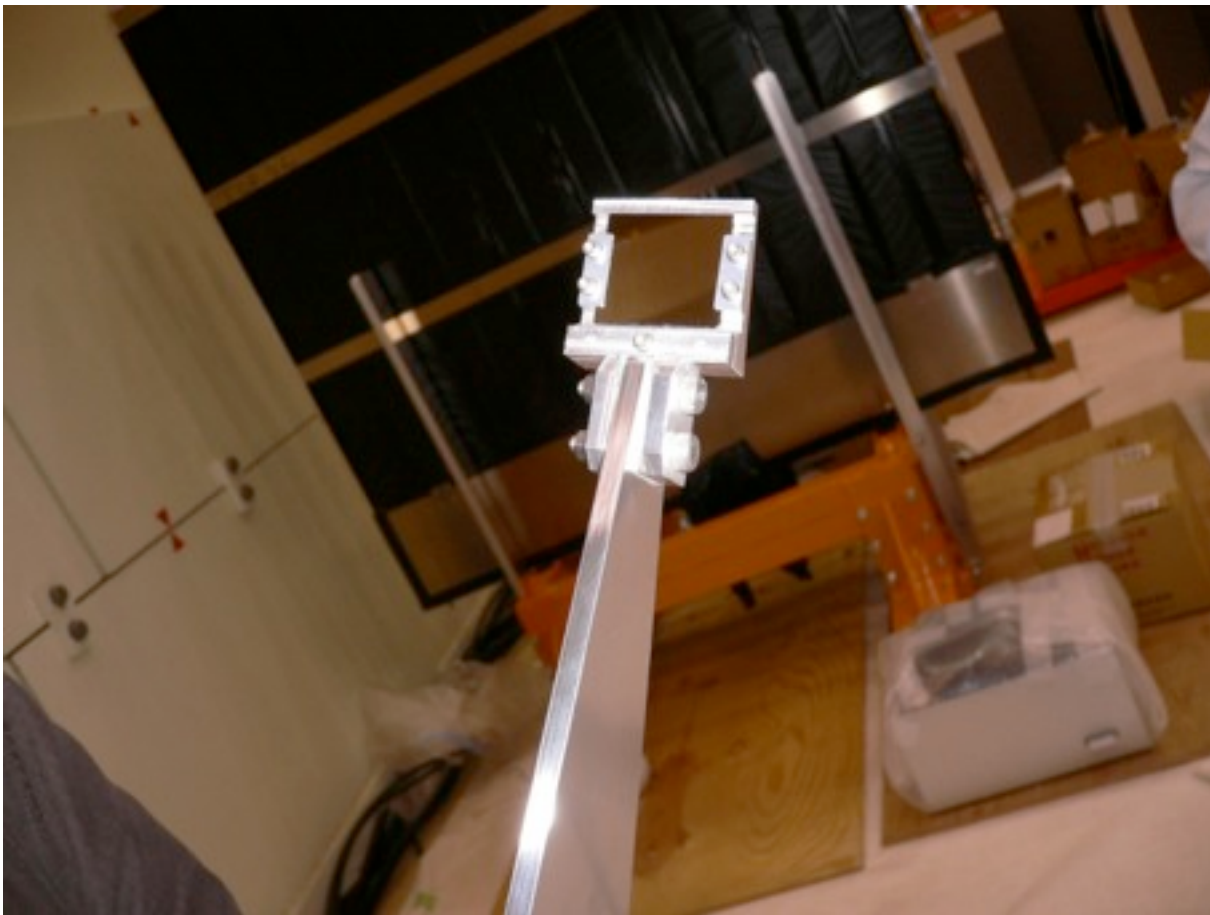
06/11/10



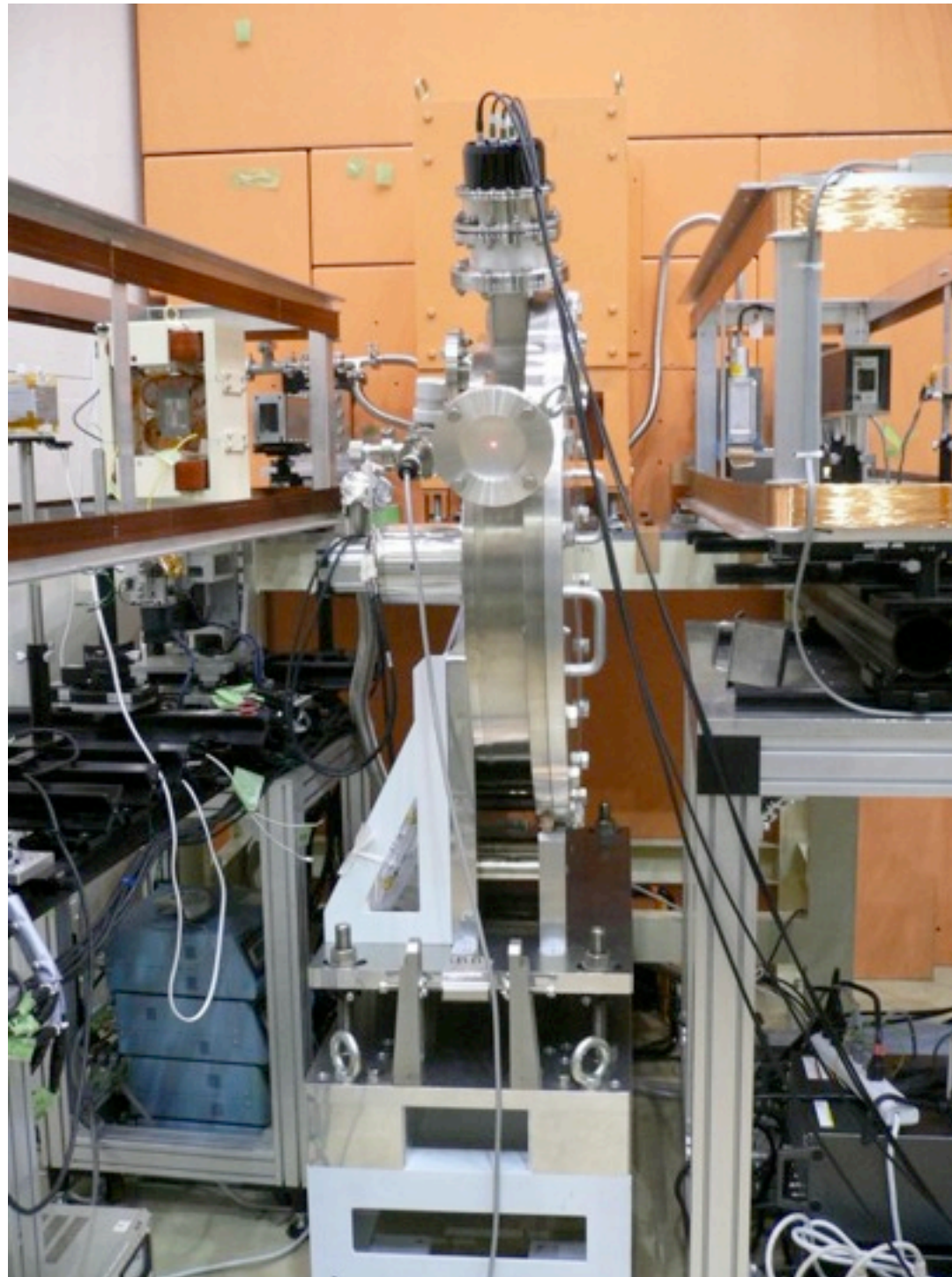
nEDM検討会 @ KEK

8

A stack of 10Qc Monochromatic mirrors



Installation in Beamline



コントロール

位相制御
0.15deg p-p

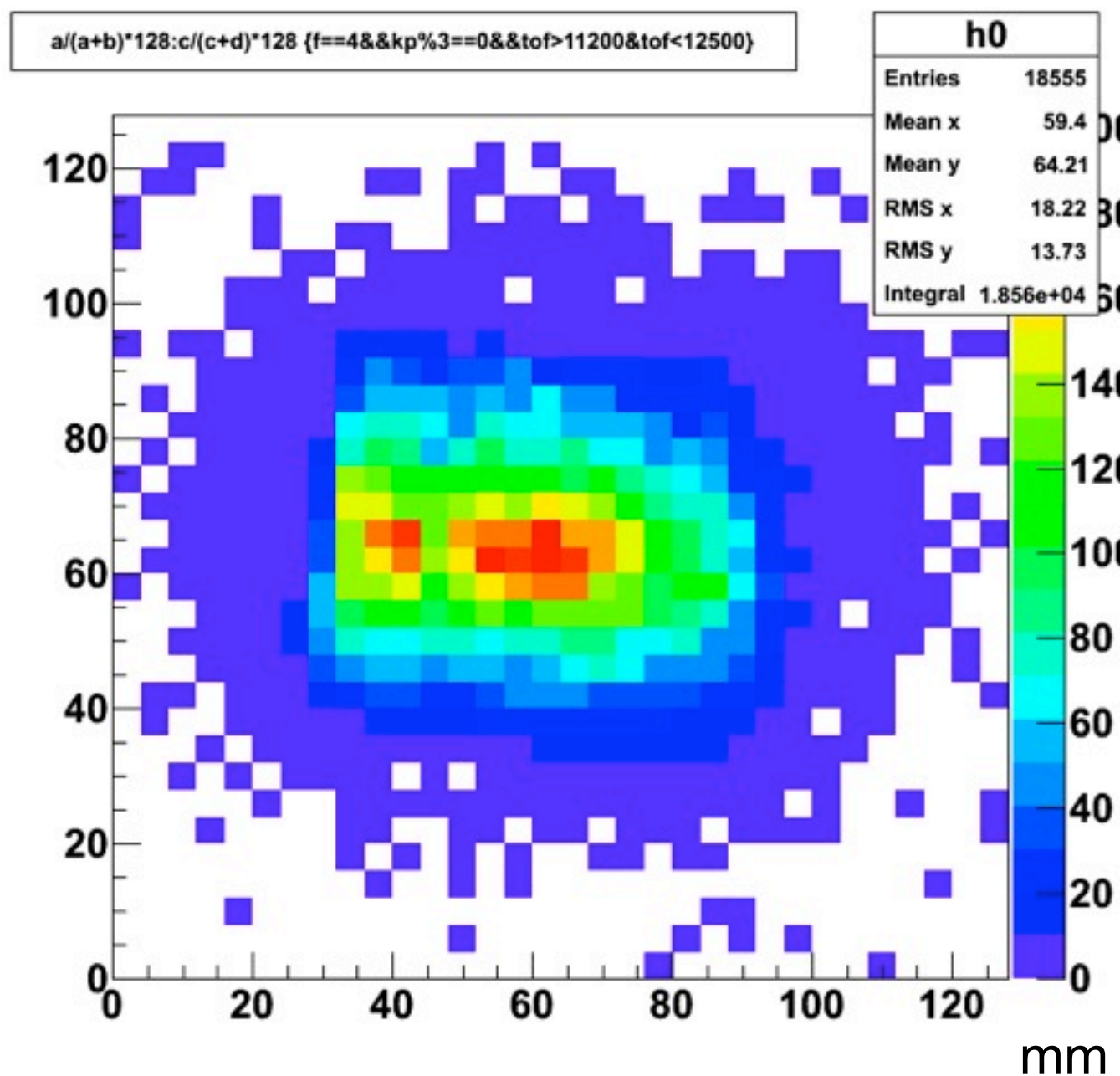


Experimental setup



透過ビームと
UCNを同時に測定。

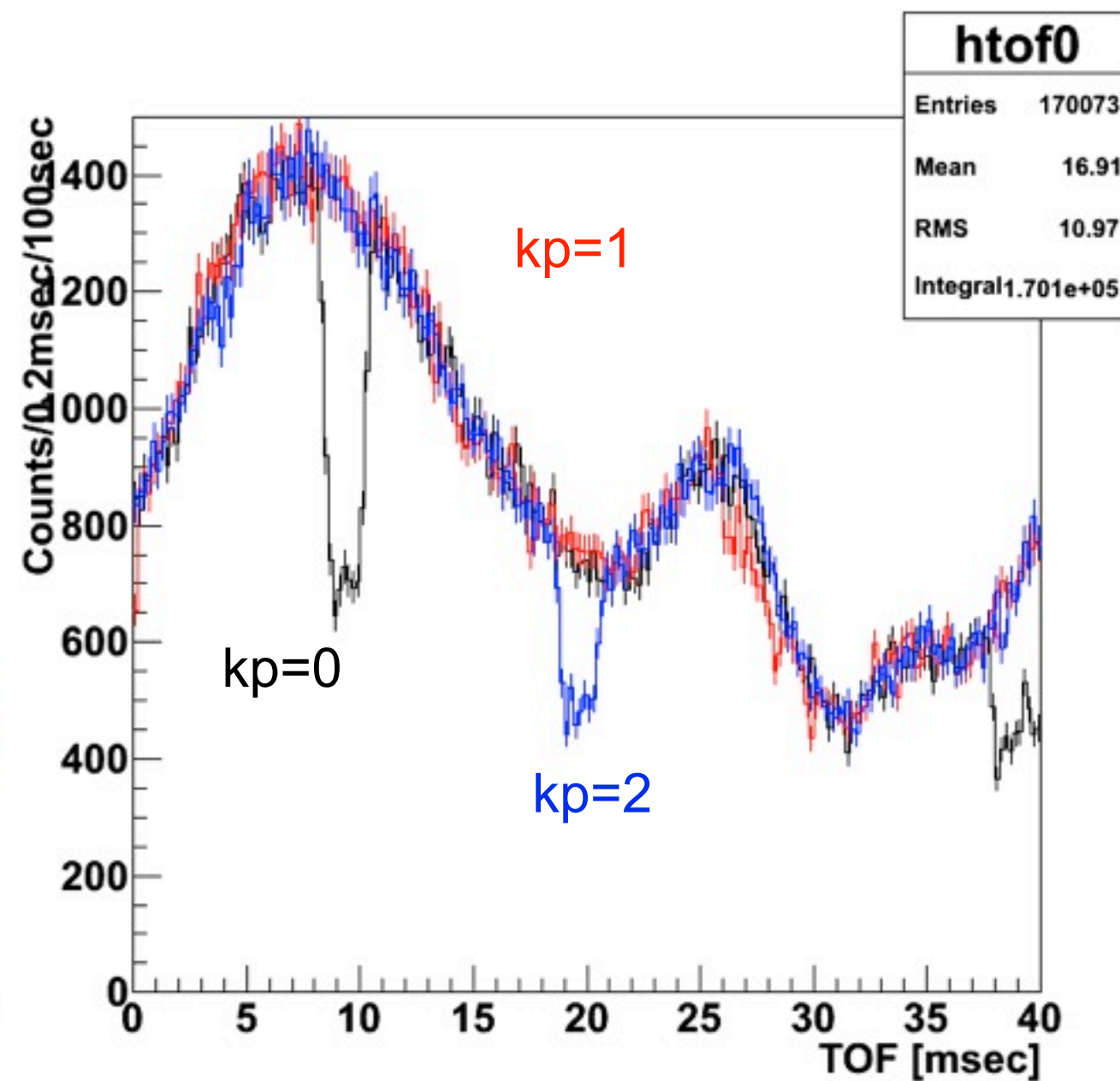
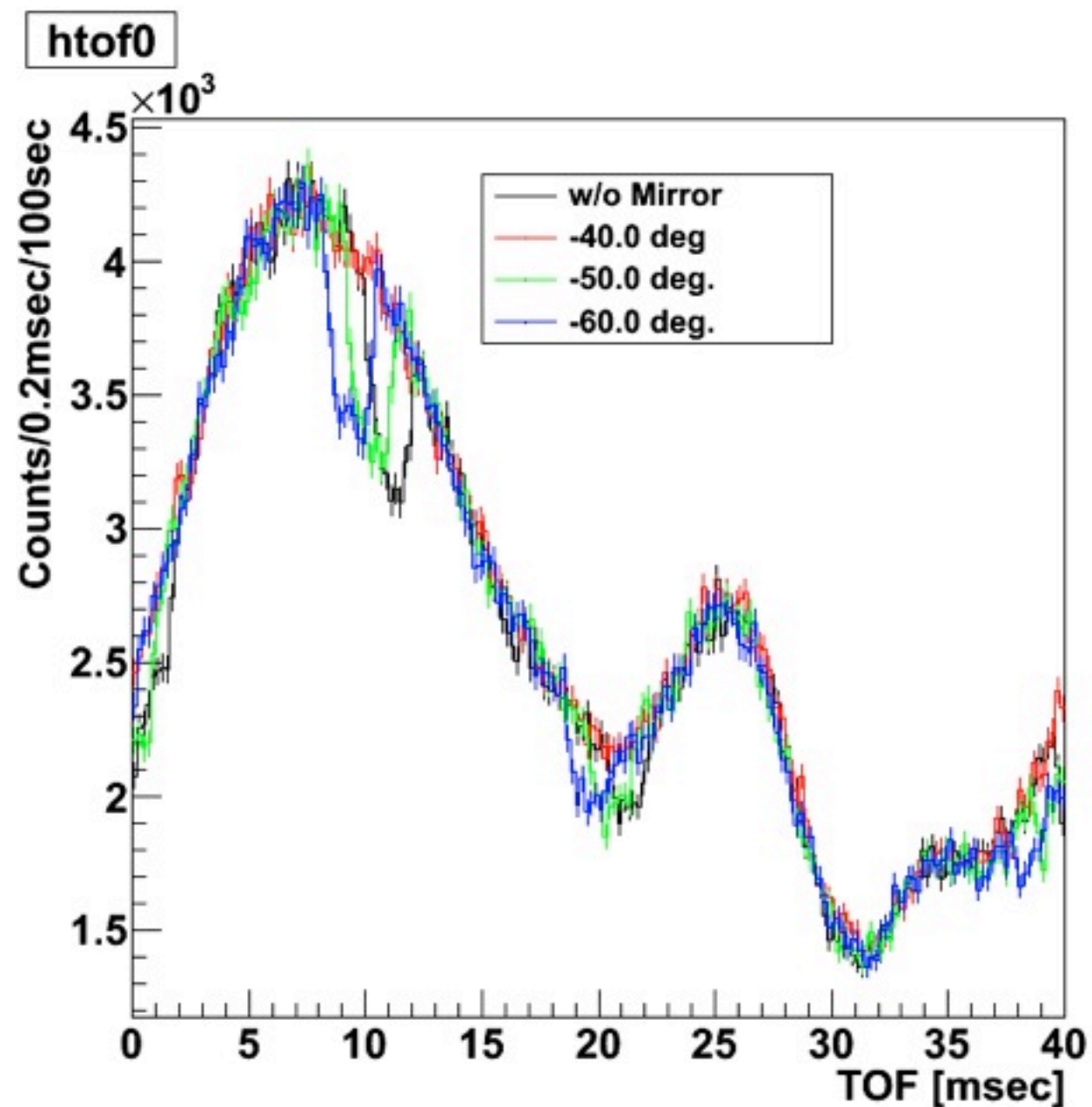
ビーム広がり



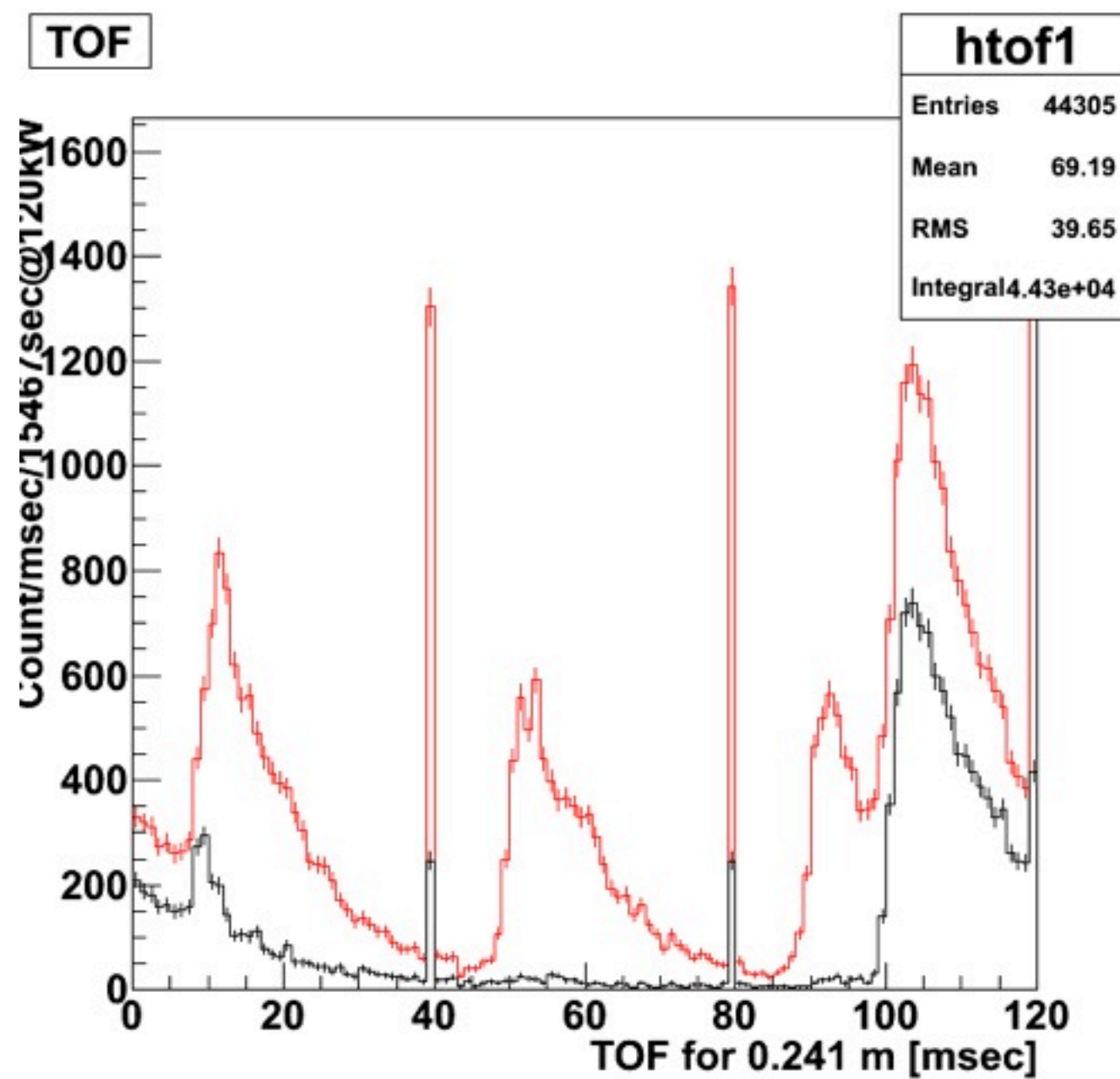
Count rate~14kcps
検出効率 ~ 70~100%

モノクロミラーで120~150m/sを
切りだす。ターゲットは136 m/s

透過VCNビーム

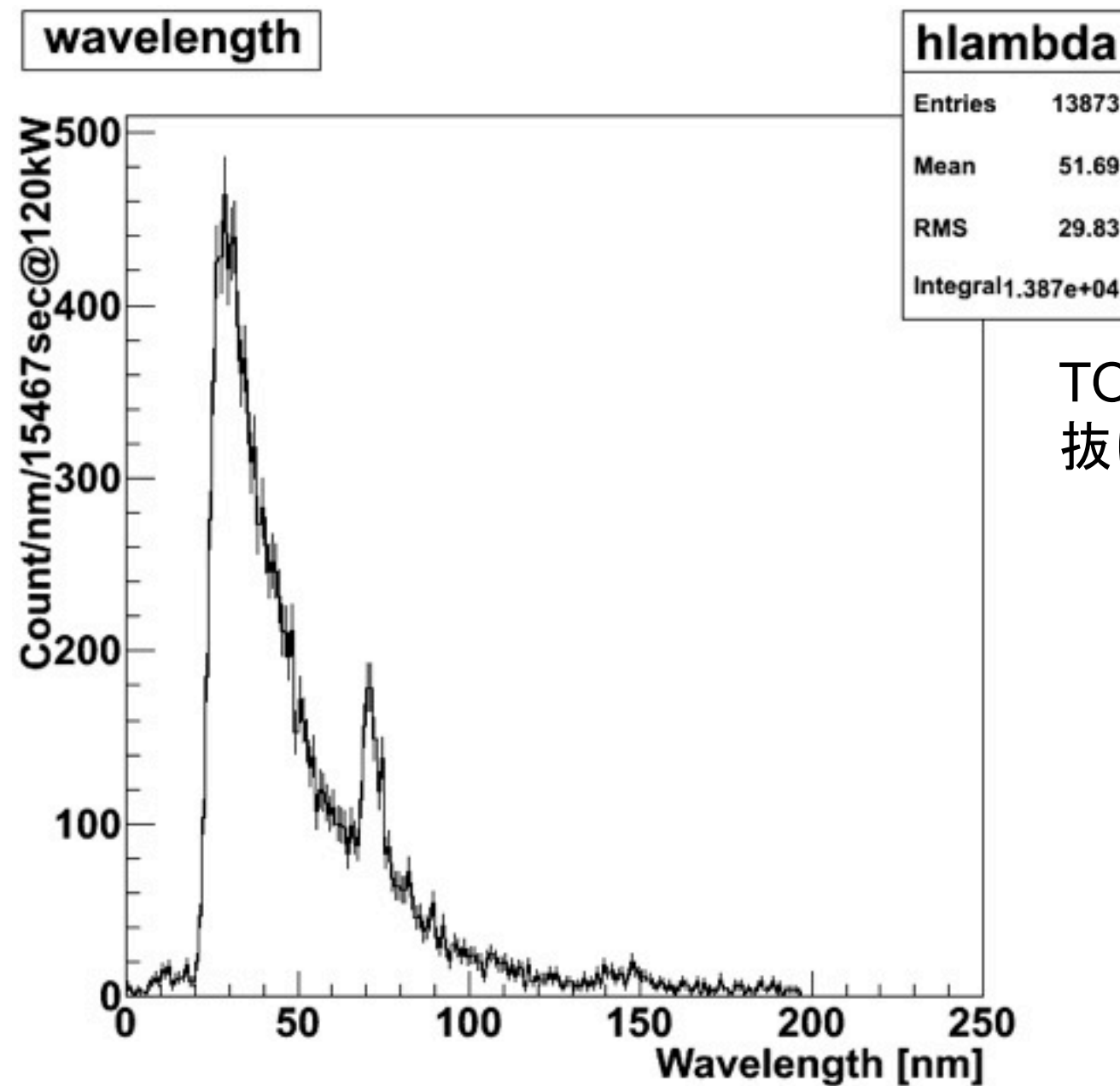


UCN Results



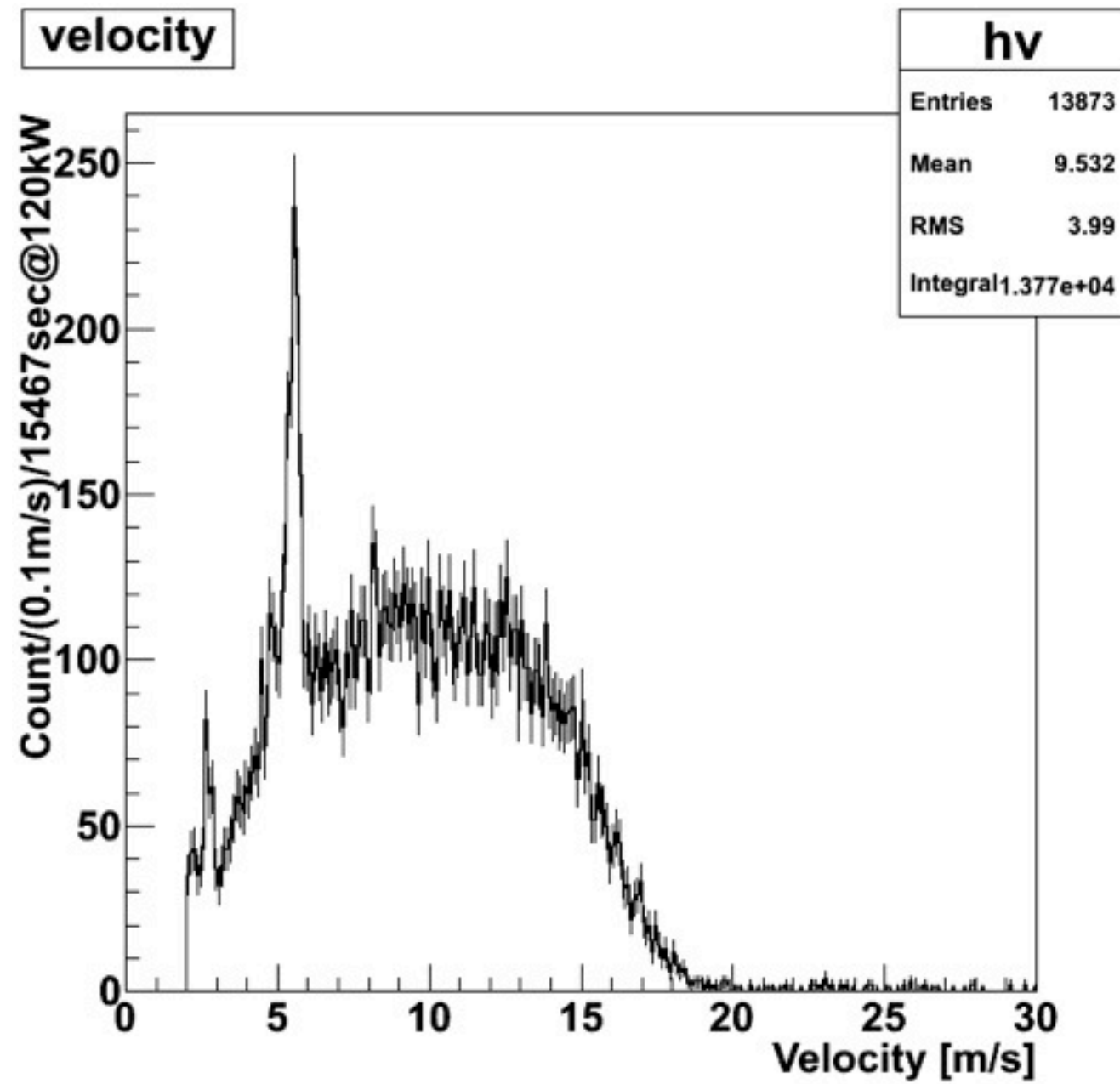
赤: $ph > 0ch$ ($n+\gamma$)
黒: $ph > 400ch$

Results

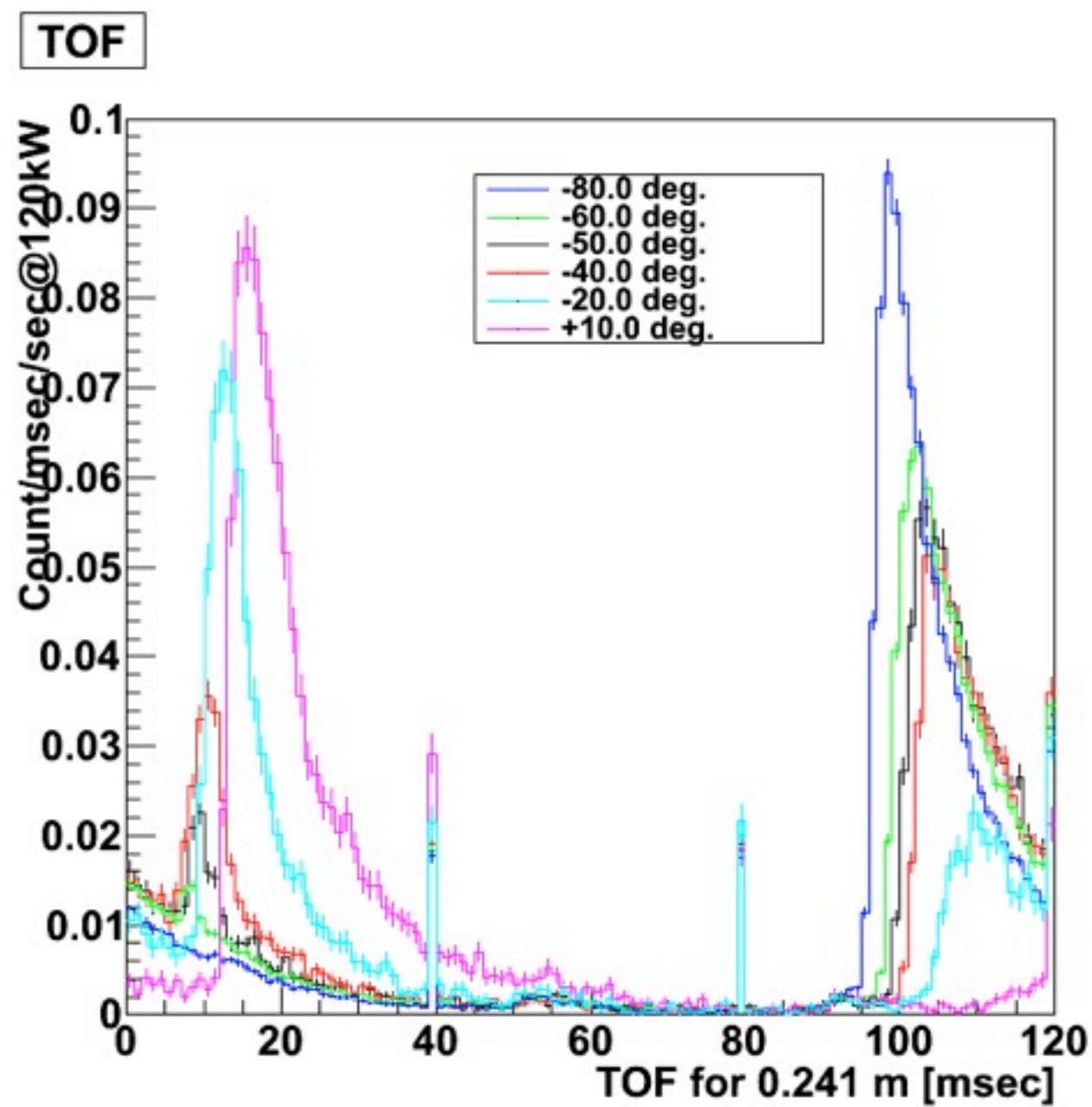


TOF原点は透過ビームの
抜けから84msに決定。

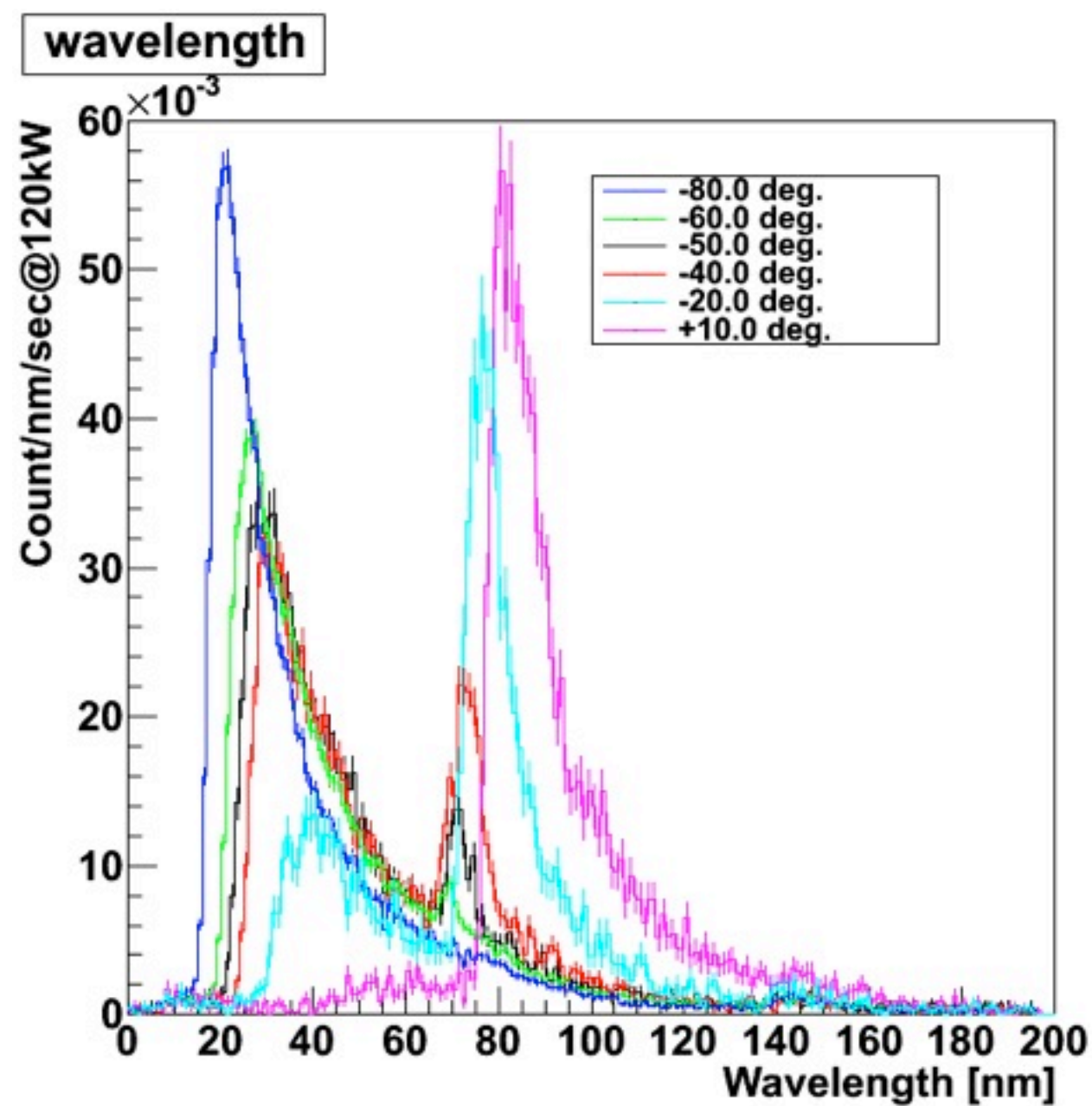
Results



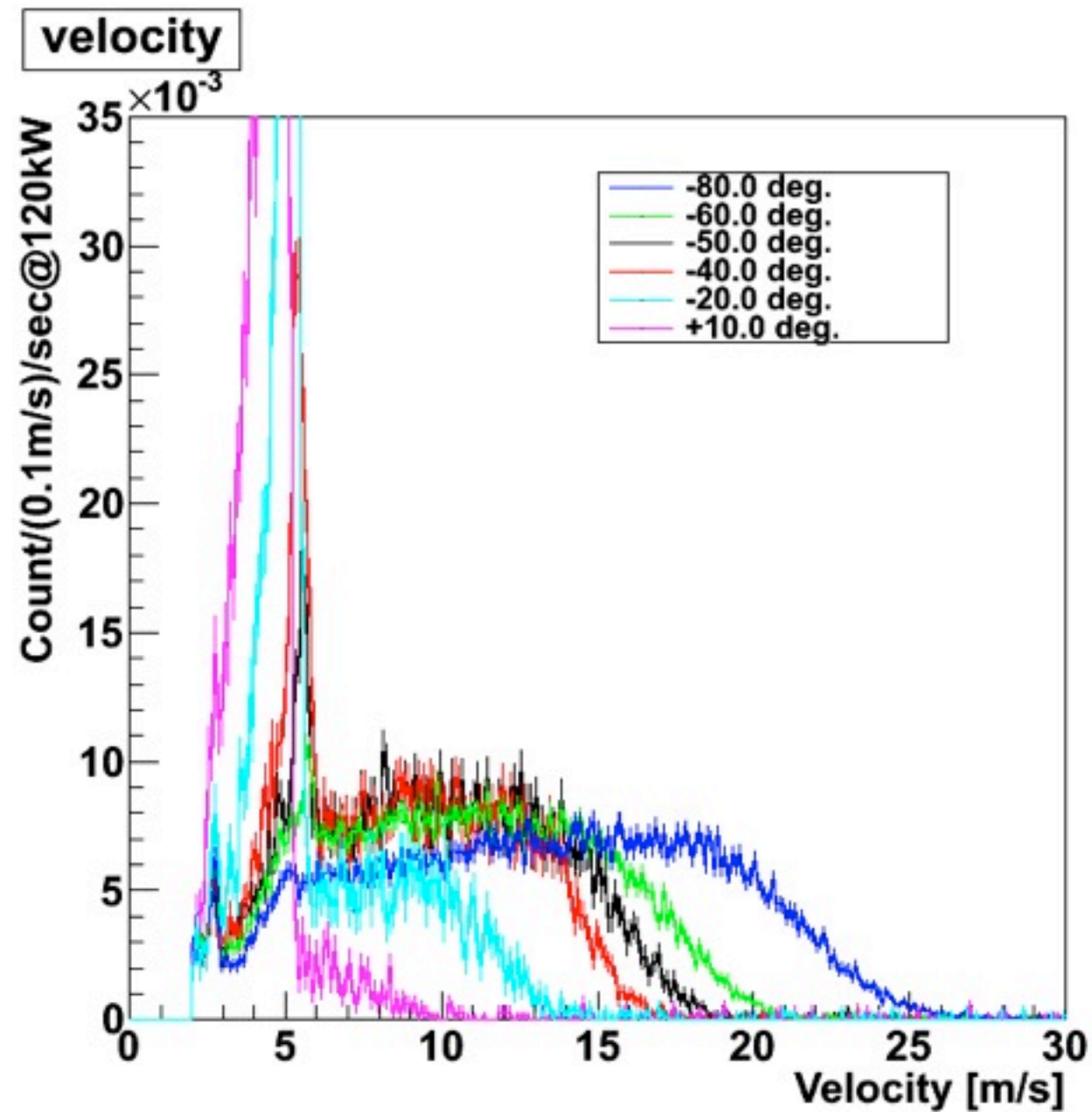
位相を変えてみる。



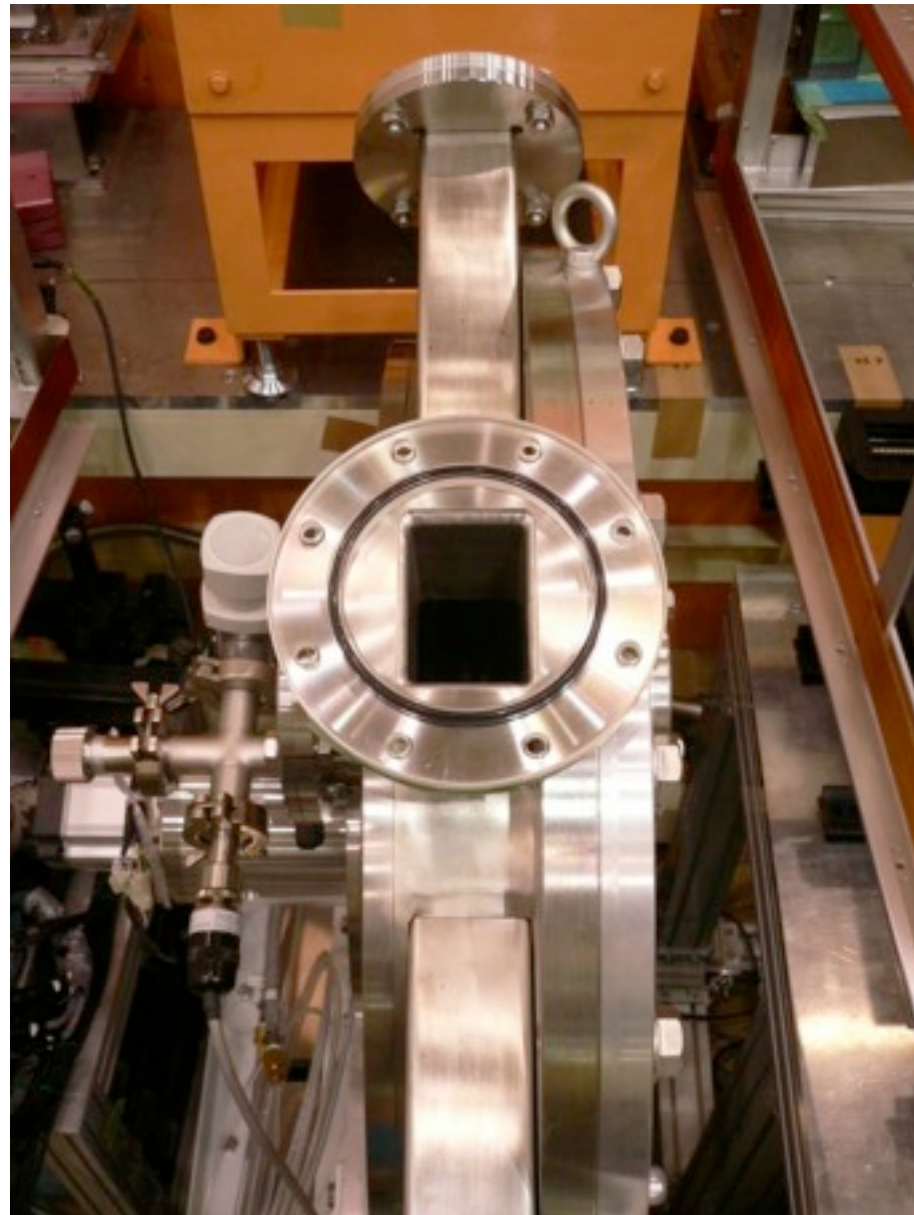
位相を変えてみる。



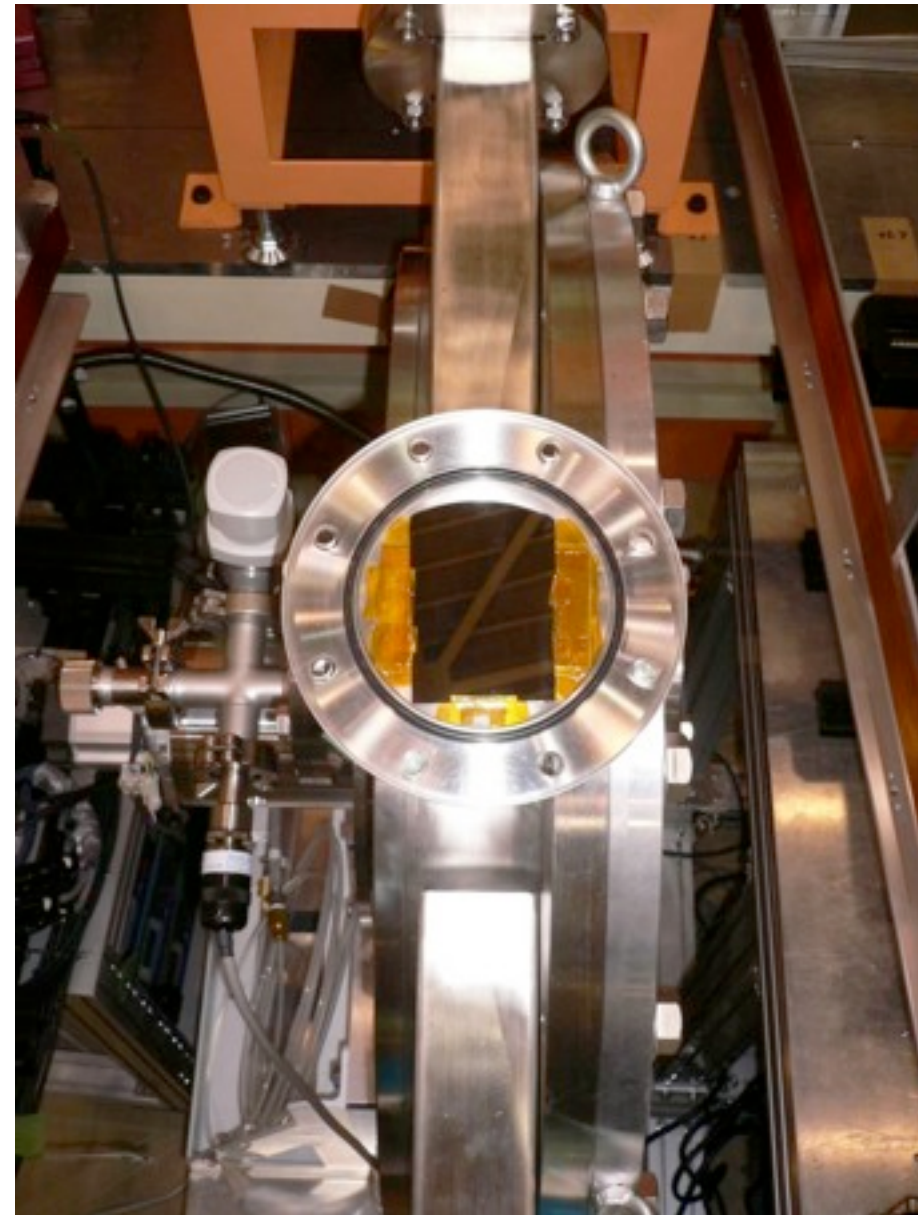
位相を変えてみる。



Ni Mirrorを置いてみる。



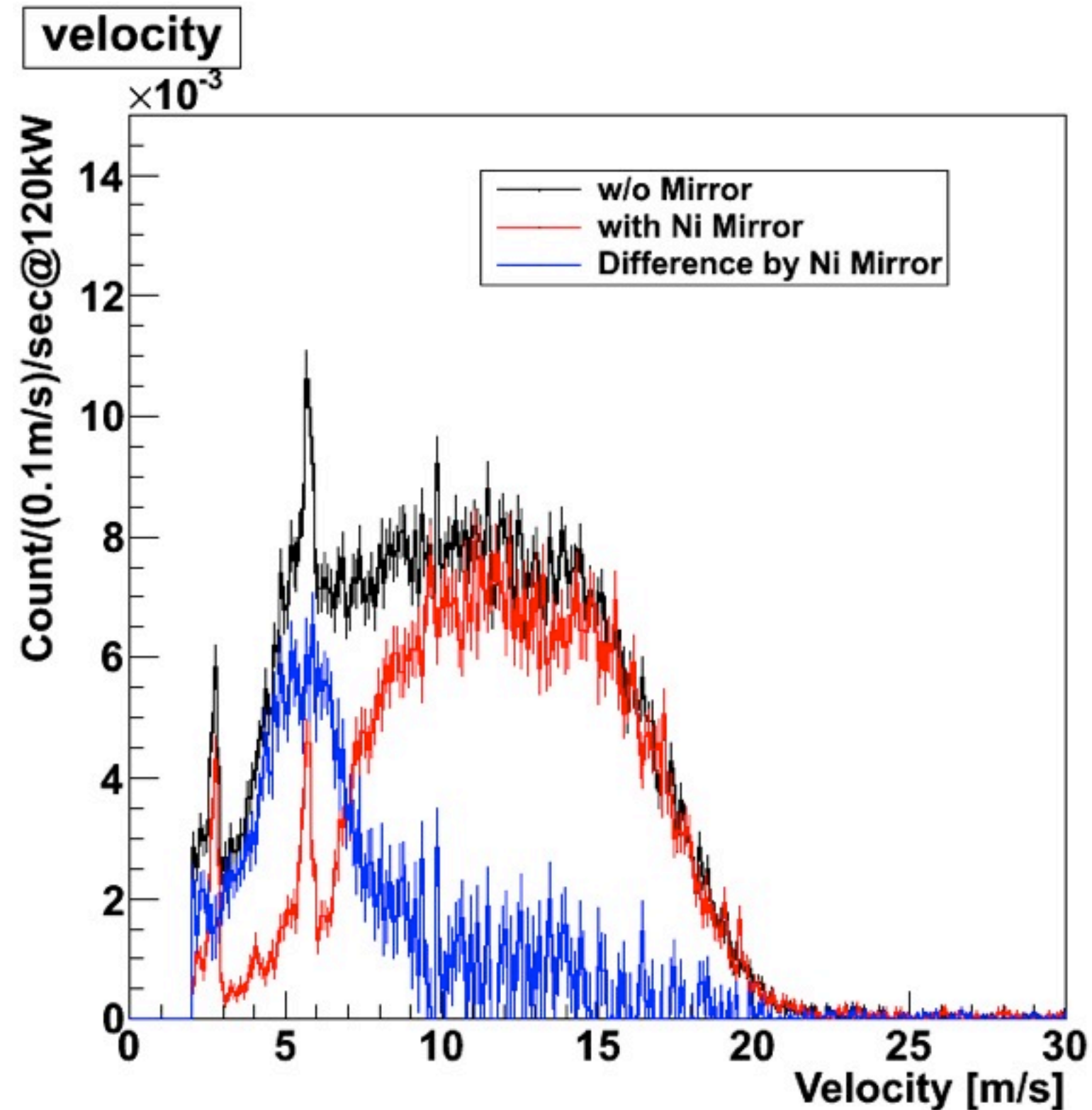
Mirror



Ni mirror on Si(0.3mm)

Ni Mirrorを置いてみる。

nEDM検討会 @ KEK 06/11/10



UCN yieldと蓄積

- VCN count は14 kcps (予想は50kcps)
- UCN? ($v < 20\text{m/s}$) count rateは 1.0 cps
- UCN ($v < 7\text{m/s}$) は0.3 cps
- Vcnのz方向が 136m/s , x-y方向のdivergenceが 10mrad より $v_x = v_y < 1.4\text{m/s}$ のはず。

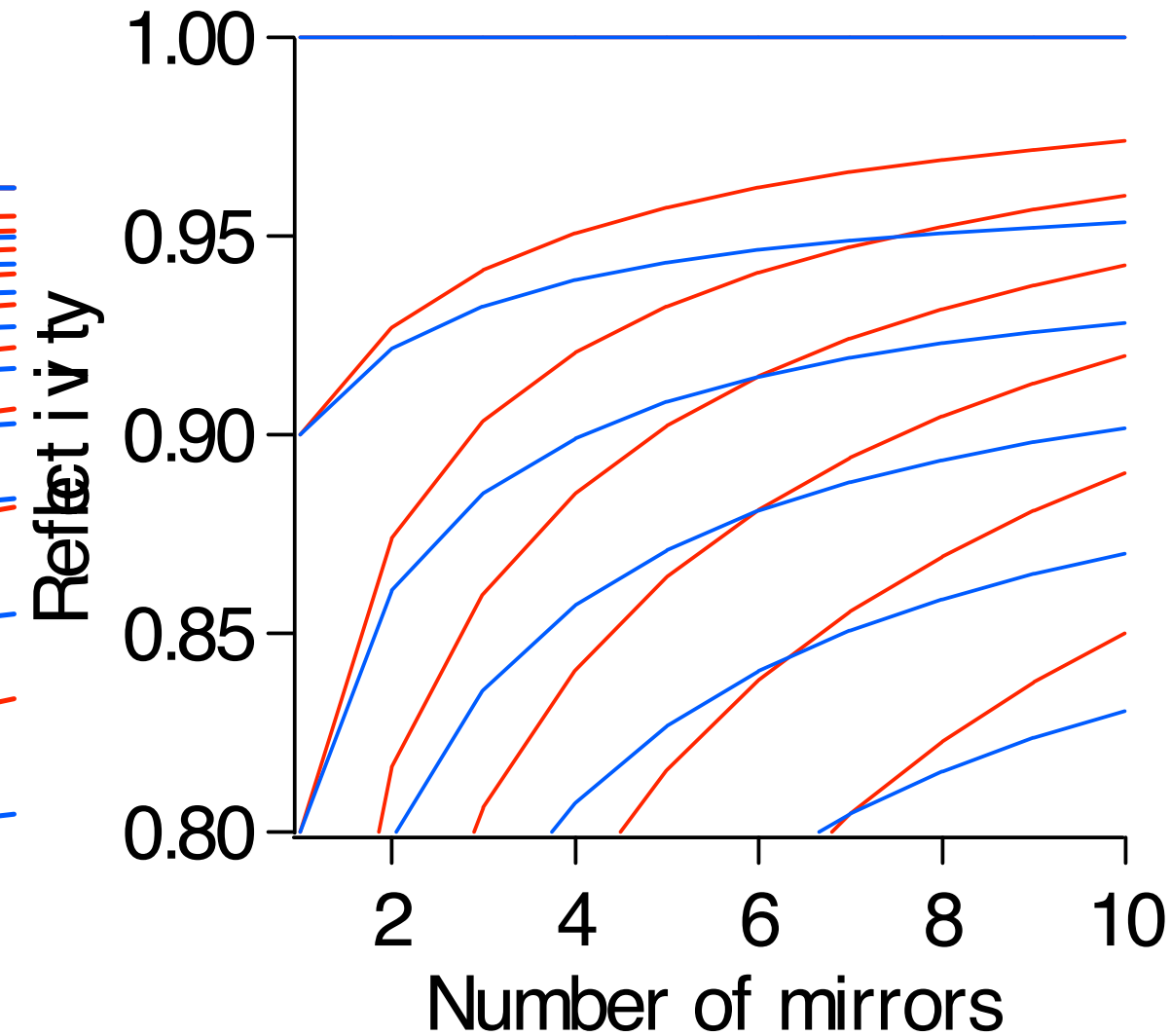
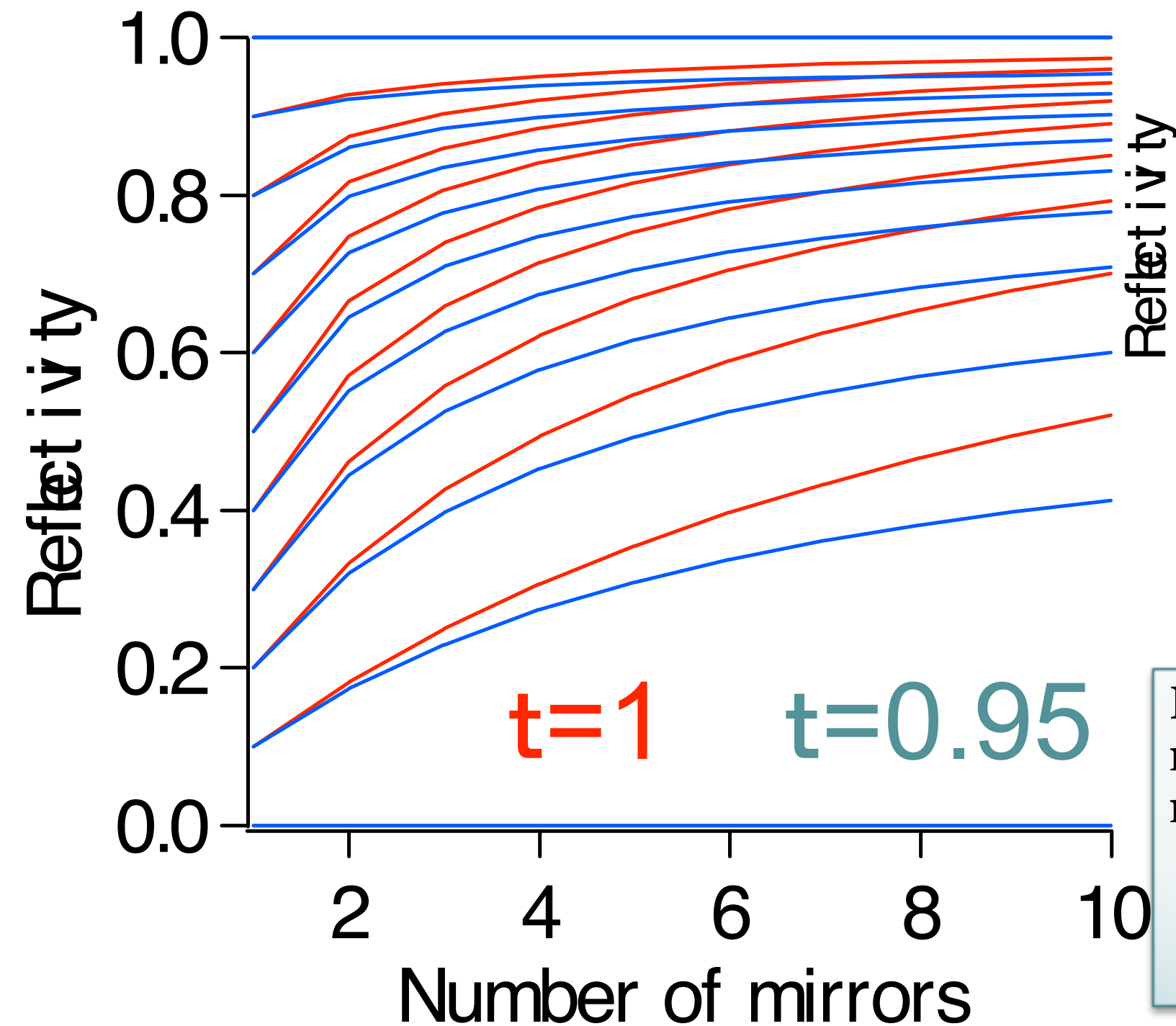
Summary

- UCNらしきTOFを確認。
- Ni on 0.3mmSi基板を置いたところ、6~9m/sの成分がなくなった。以上からUCNと結論できるだろう。
- V_{cn} のz方向が136m/s, x-y方向のdivergenceが10mradより $v_x = v_y < 1.4\text{m/s}$ のはず。

Backup

Effective reflectivity as a function of number of stacking mirrors

nEDM検討会 @ KEK 06/11/10



By stacking mirrors, it is possible to realize small-d wide-band monochromater with high reflectivity

コントロール

位相制御
0.15deg p-p



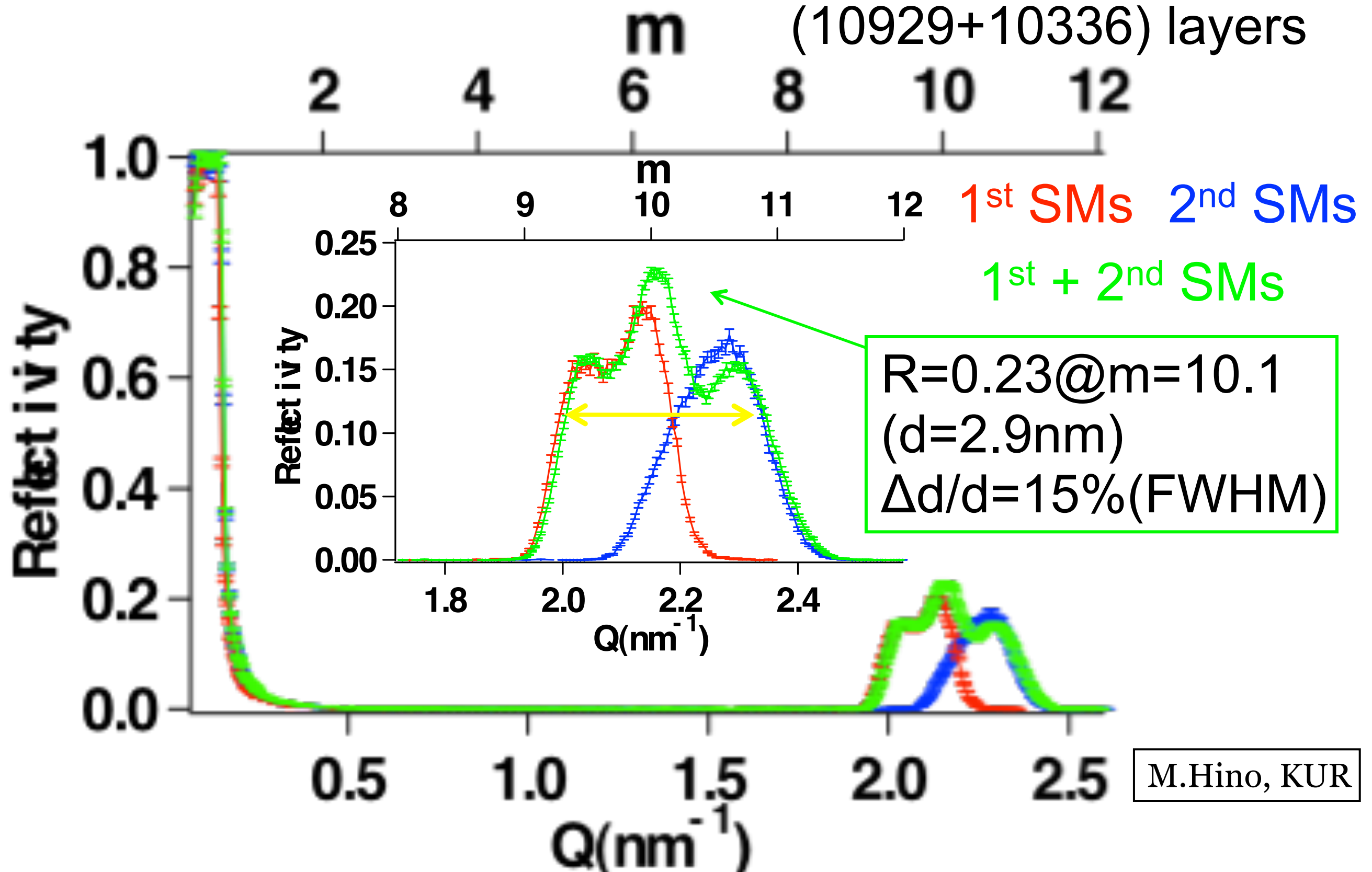
UCN Flux and Density

- Total flux : 2×10^8 n/cm²/sec/MW with 10 mrad divergence
- Velocity 100 m/sec ~ 200 m/sec : 1.2% of total flux.
- 3GeV synchrotron repetition : 25Hz
- UCN Conversion efficiency = 3×10^{-4}
- UCN production = 720 UCN/cm²/s with 100% reflection
- UCN production length ~ 5cm (0.8ms)

UCN density : 5.7 UCN/cm³

UCN density with focusing option
30~140 UCN/cm³

m=10 stacknig NiC/Ti wide band multilayers (10929+10336) layers



Outline

○ In-Flightによる中性子寿命測定

○ 実験のconfigurationの検討

○ 信号検出の方法について

○ バックグラウンドの評価

関連講演

J-PARC BL05：吉岡瑞樹, 12aSA-4

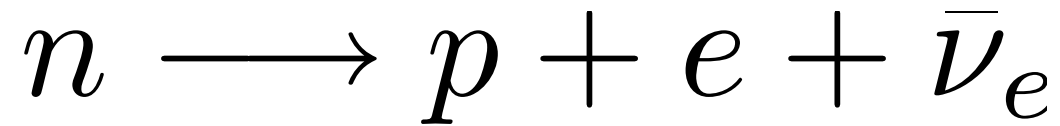
中性子ベータ崩壊の物理：音野瑛俊, 12aSA-7

スピNFLリップチョッパー：竹谷薫, 10aSF-5

ほか本学会シンポジウム「中性子基礎物理」の各講演



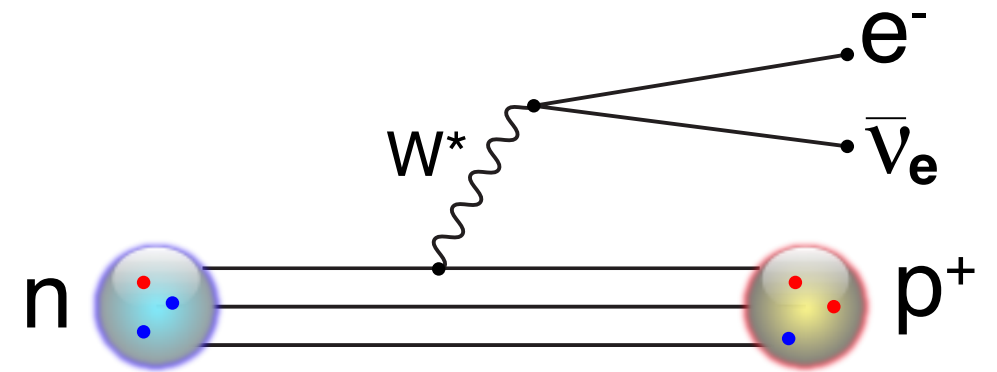
中性子寿命



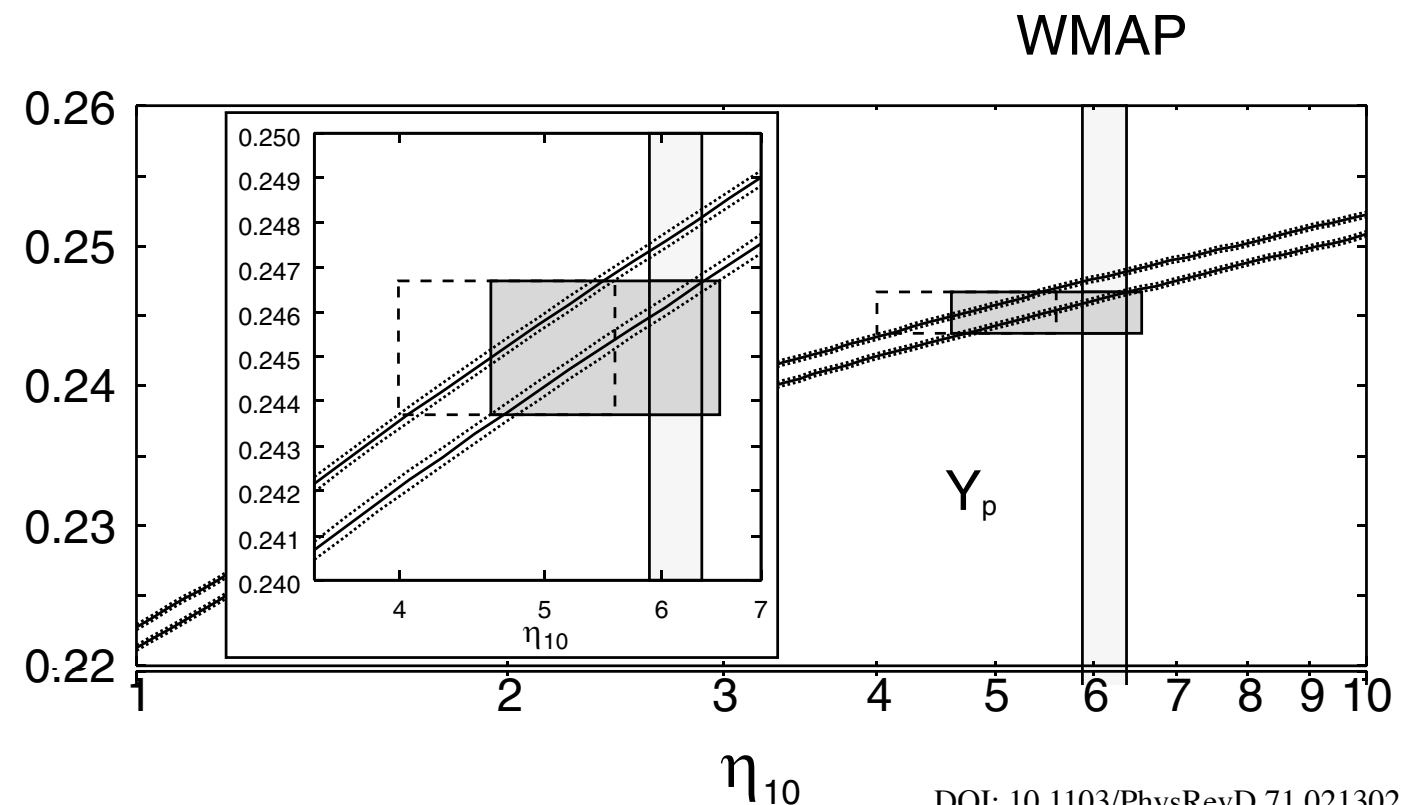
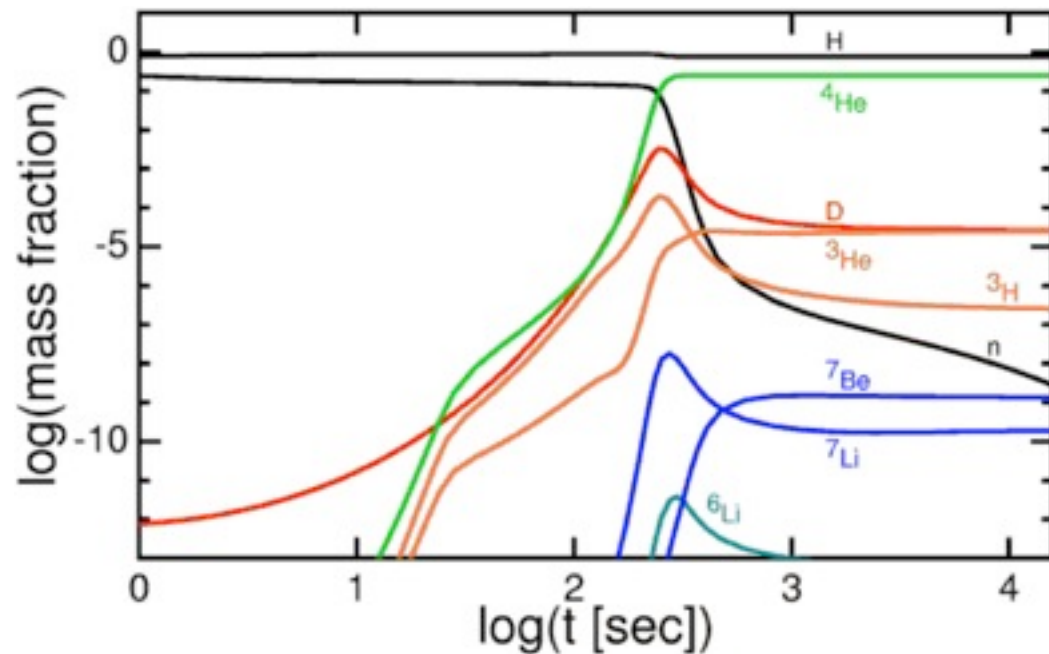
$$\tau_n = 885.7 \pm 0.8 \text{ s (PDG2008)}$$

$$\tau_n = 878.5 \pm 0.7 \pm 0.3 \text{ s (PNPI-ILL)}$$

- 寿命が異なる実験間で1%程度のずれを生じている
- 宇宙の ^4He 量の観測値, WMAP+理論との整合性に影響
- 最も精度が高いとされる従来のUCNボトルを用いた測定とは異なる測定原理を用いた検証が必要



ベータ崩壊の物理の詳細は
音野瑛俊, 12aSA-7



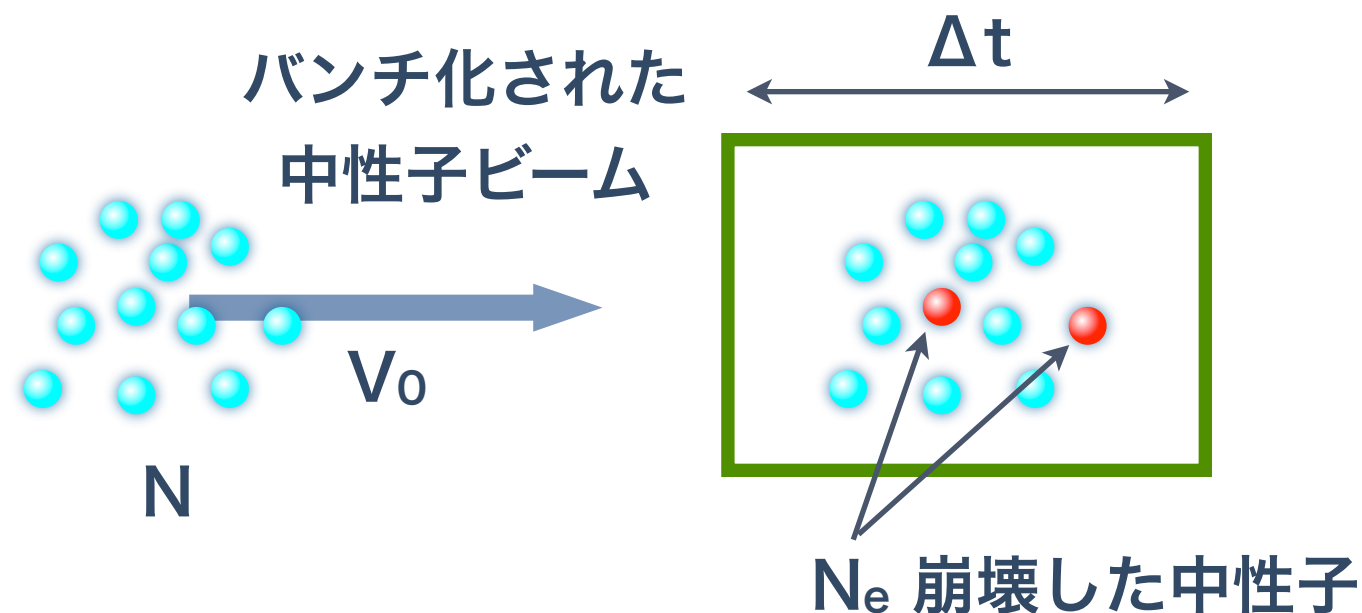
DOI: 10.1103/PhysRevD.71.021302

In-Flightでの中性子寿命測定の実理

TPCによる崩壊電子測定

$$\tau^{-1} = \frac{1}{N} \frac{N_e}{\Delta t}$$

$^3\text{He}(n,p)$ 反応による
フラックス測定



ベータ崩壊反応個数

$$\tau^{-1} = \frac{N_e}{N_p} \times \rho_0 \times \sigma(n,p) \times v_0$$

^3He 反応個数

^3He ガス濃度

(n,p) 断面積@ v_0

中性子速度

ベータ崩壊とフラックス測定を
同時に行うことで系統誤差を抑える

系統誤差を下げるために主に努力すべき項目

- ①ベータ崩壊検出効率
- ②バックグラウンドの除去
- ③ ^3He ガス濃度の精密測定

0.1%精度で寿命を決めたい

先行実験

R.Kossakowski et al. (1989)

$\tau = 878 \pm 27(\text{stat}) \pm 14(\text{sys})$

実験全体の戦略

ベータ崩壊と $^3\text{He}(n,p)$ の同時測定

信号の検出

- 信号の検出効率
- Fiducial Volumeの確定
- 統計

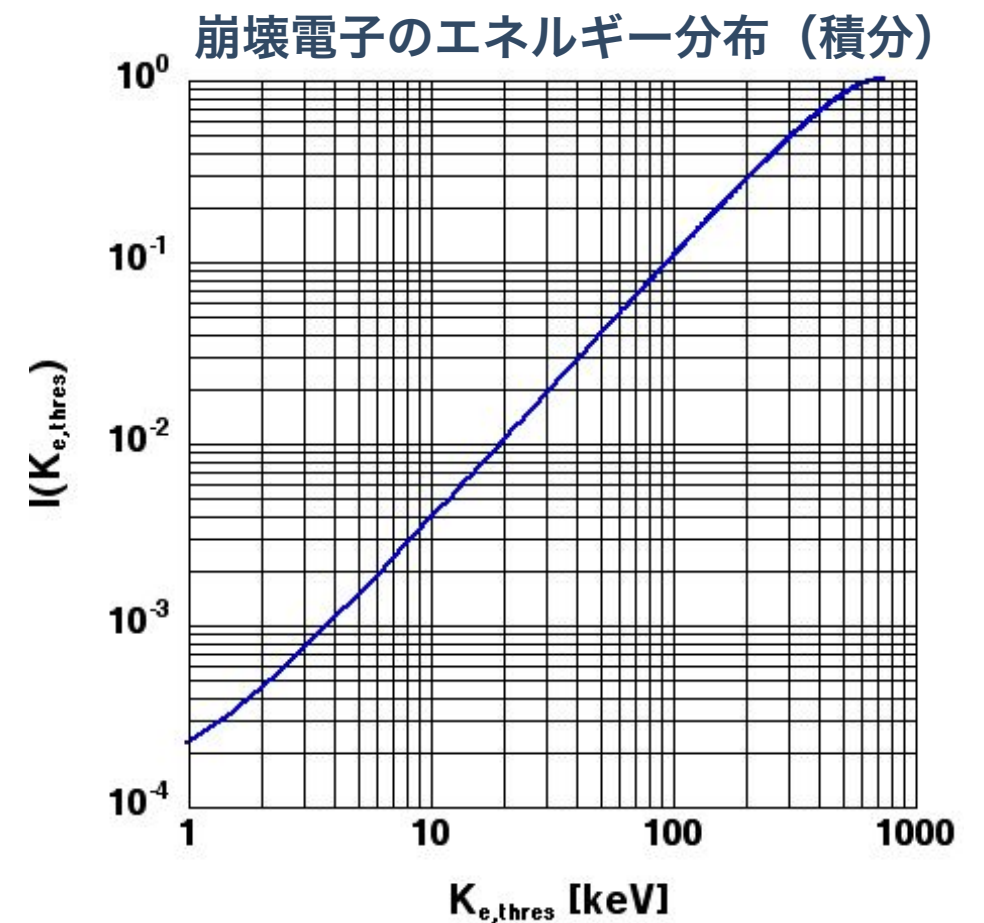
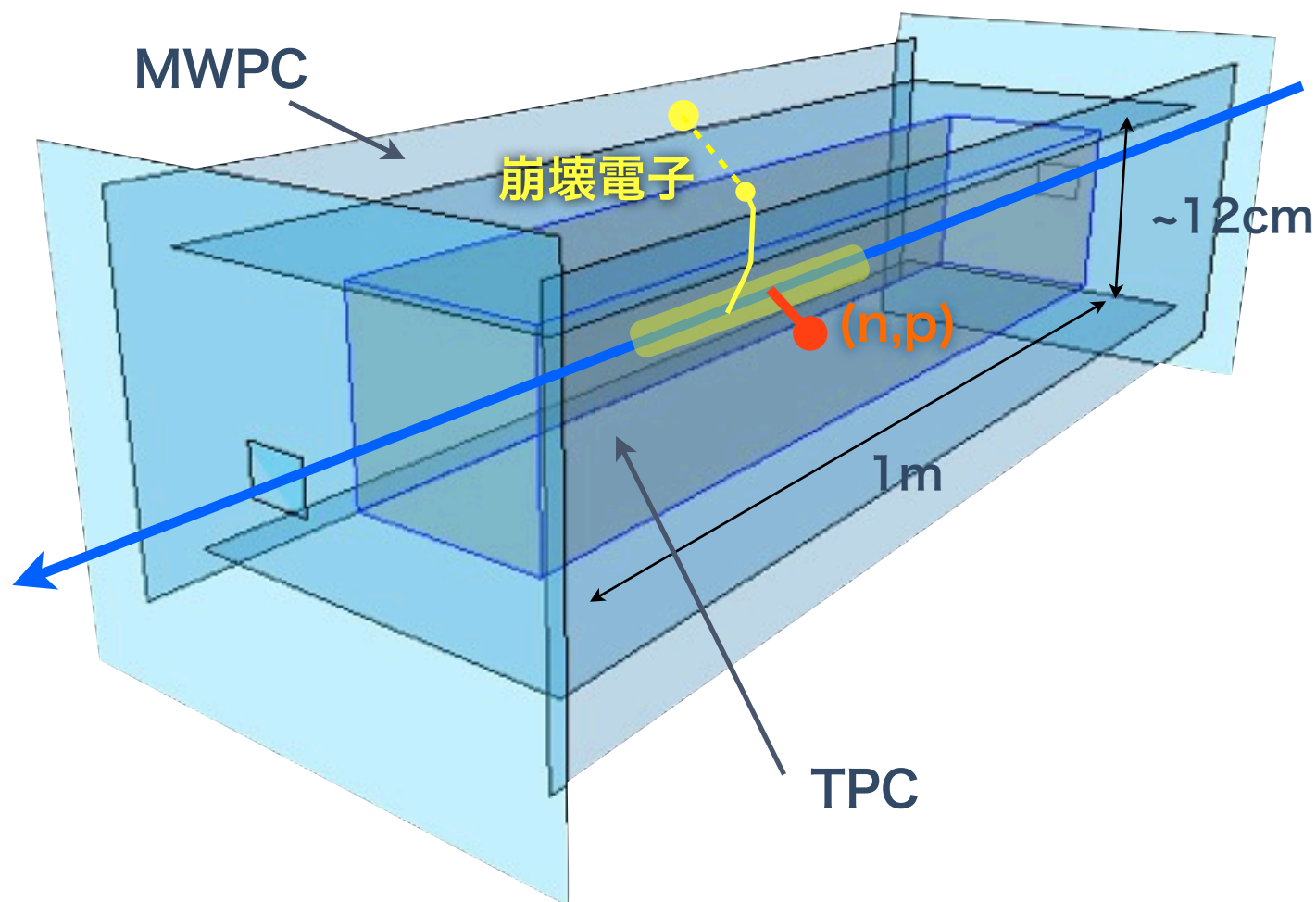
バックグラウンドの抑制

- バックグラウンドの把握
- 抑制方法の確立

↑
検出器と解析の両面

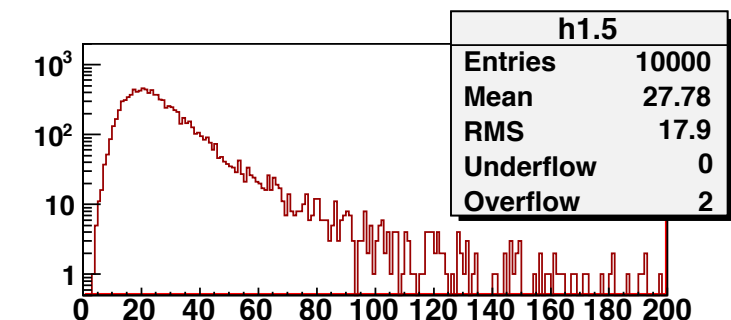
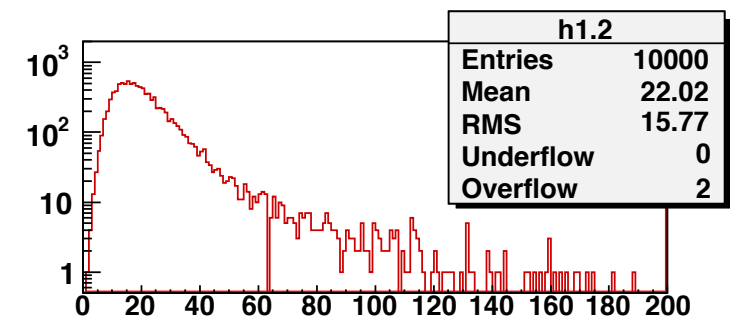
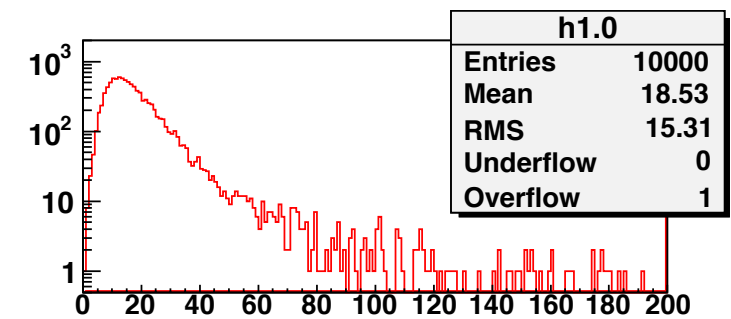
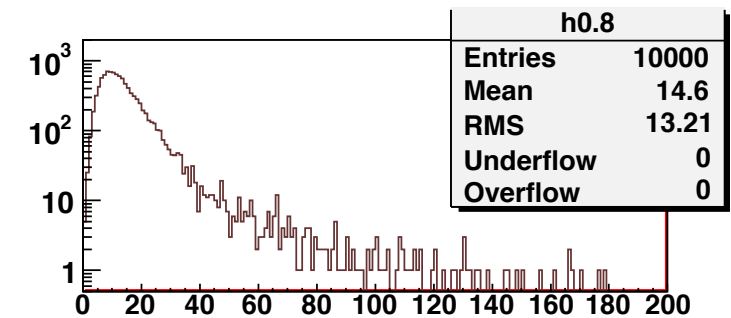
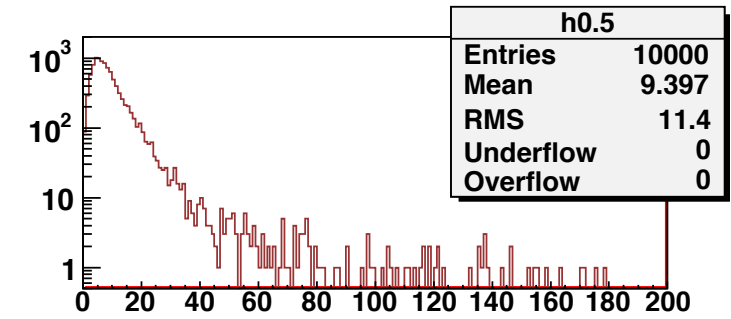
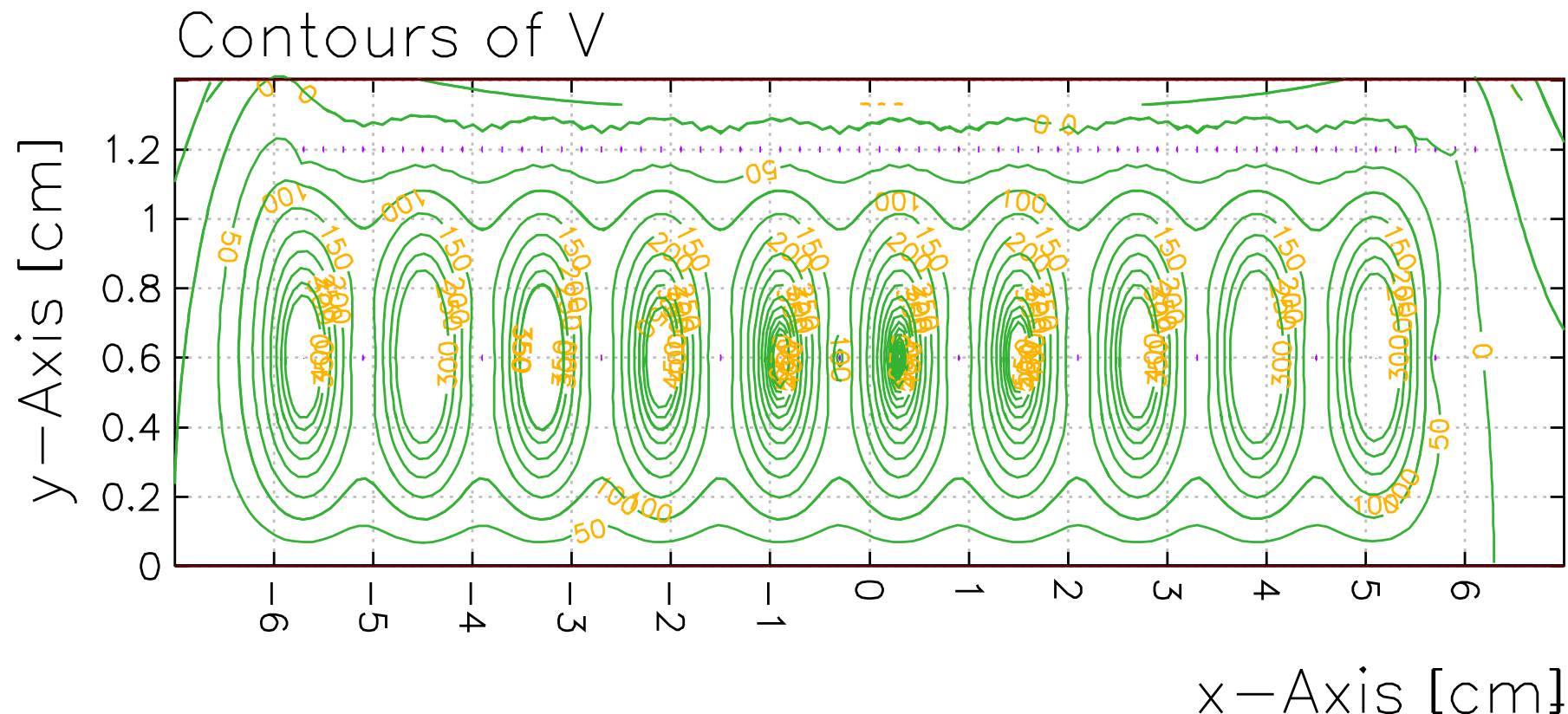
Detector Concept

- ビーム軸方向に1mのTPC
- 外周にMWPC等のタイミング・カウンタを配置
- TPCガスの選択 $\text{He}/\text{CO}_2 = 85/15$ (中性子散乱の少ないガス) + 希少 ^3He
- $^3\text{He}/^4\text{He}$ ガスの分圧比が重要→真空引きの上で封じ切り
- 崩壊電子のうち3keV以上を100%検出できる
- $^3\text{He}(n,p)(750\text{keV})$ の検出も同時に行えるダイナミック・レンジ→Hi/Loの2種類の読み出し

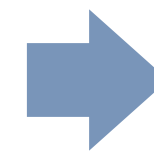


Multiplication / FrontEnd Electronics

- He/CO₂=85/15(1atm)のガス中で, m.i.pがTPC中でワイヤあたりいくつペアを生成するかシミュレーションする
- ワイヤ・ピッチが12mmあれば1pair以下になる確率を 10^{-3} 以下に抑えられる
- 下図のワイヤデザインで増幅率 4.4×10^4 @ $V_{\text{anode}}=1650\text{V}$ (実測)
- 1pairまで信号を検出するためにはENC < 2000のプリアンプが必要
→KEKオンラインエレクトロニクスグループと共同で開発の予定



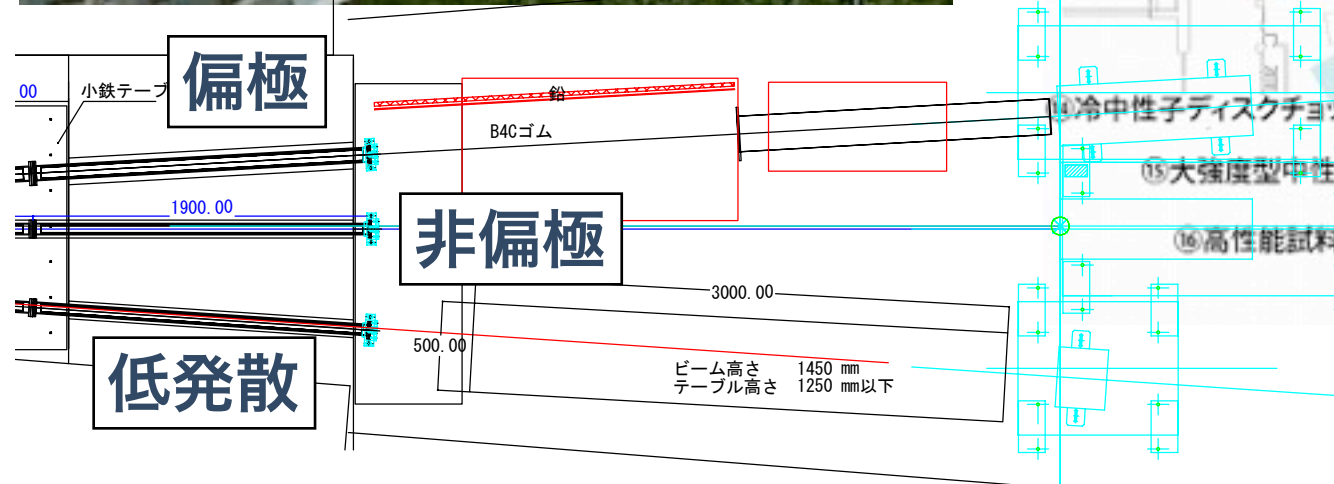
中性子ビームライン



ビームラインの詳細は
吉岡瑞樹, 12aSA-4



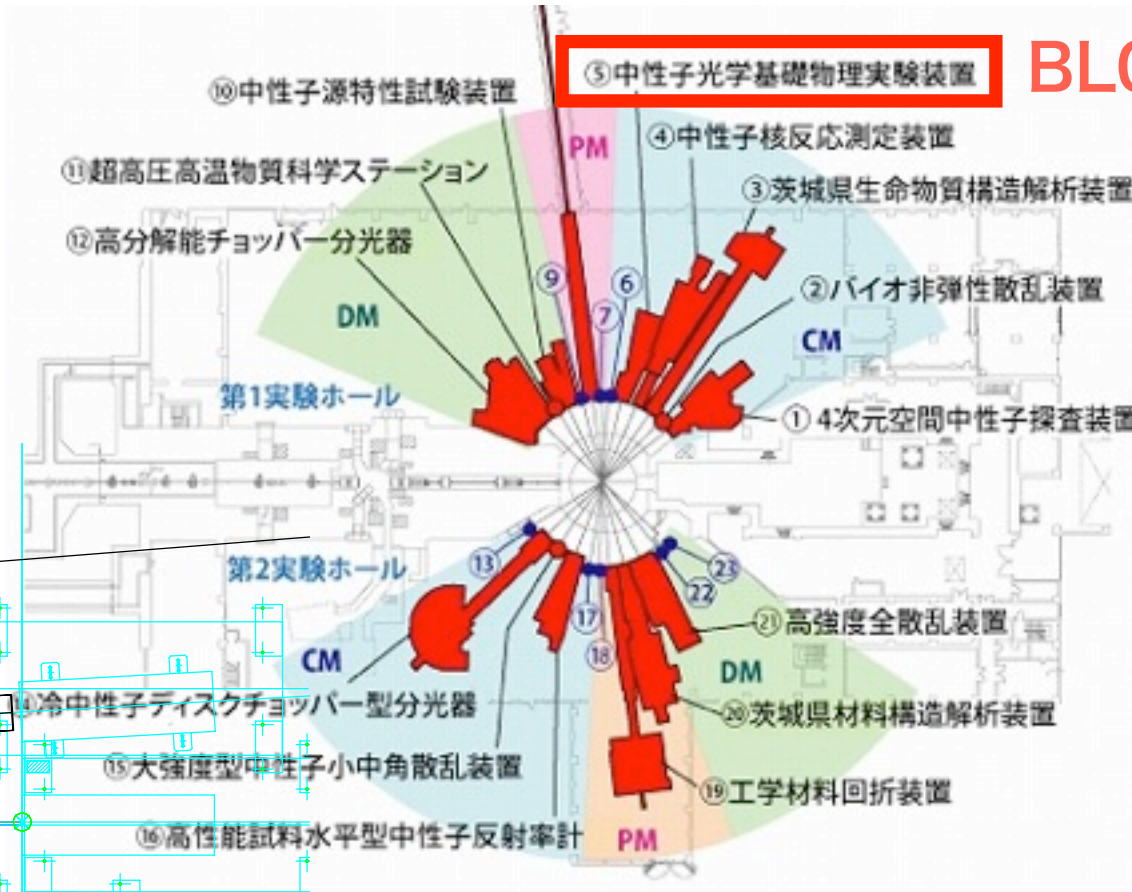
J-PARC



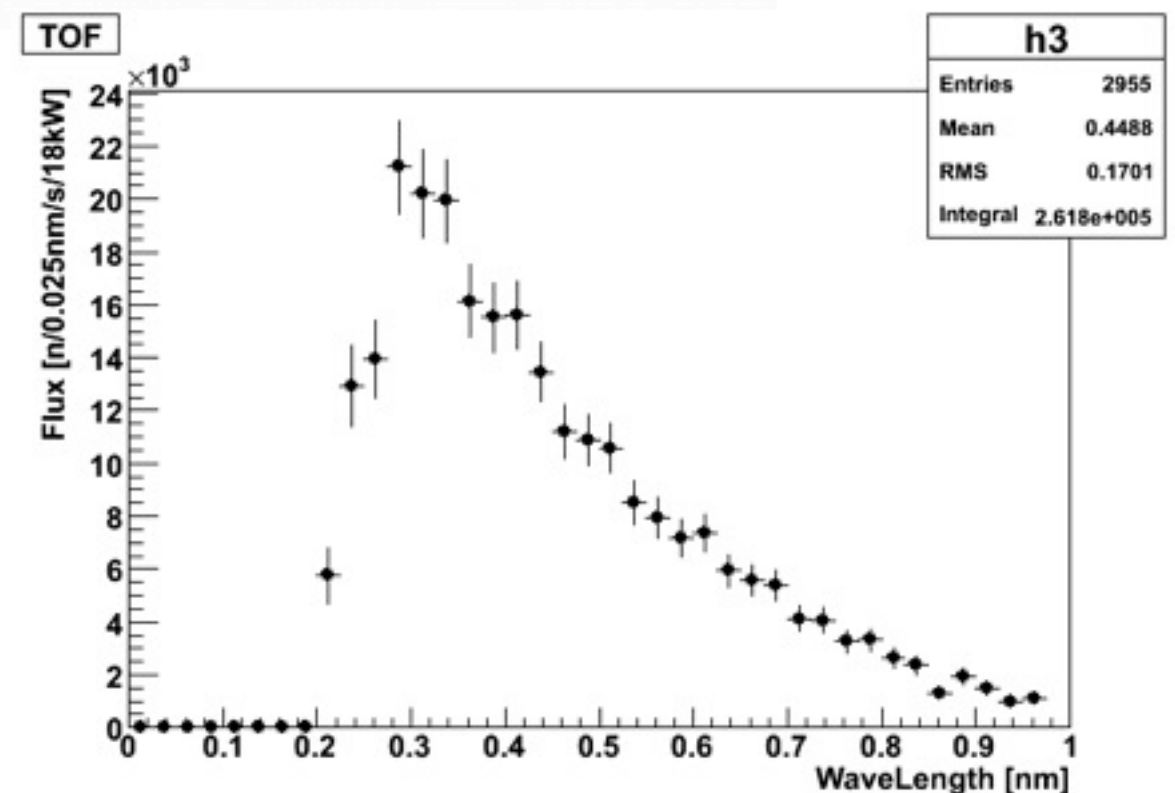
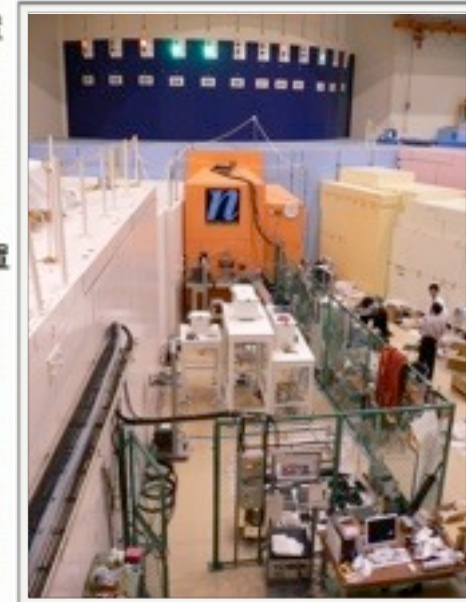
中性子基礎物理実験用途のビームライン
パルス中性子・偏極率98%

冷中性子偏極ビーム 1000m/s,
偏極ラインはビーム断面積 $2 \times 2 \text{ cm}^2$ で $4 \times 10^5 \text{ n/s}$

2009年6月時点ビーム強度20kW運転を実現
2009年後期の運転では100kW運転の予定

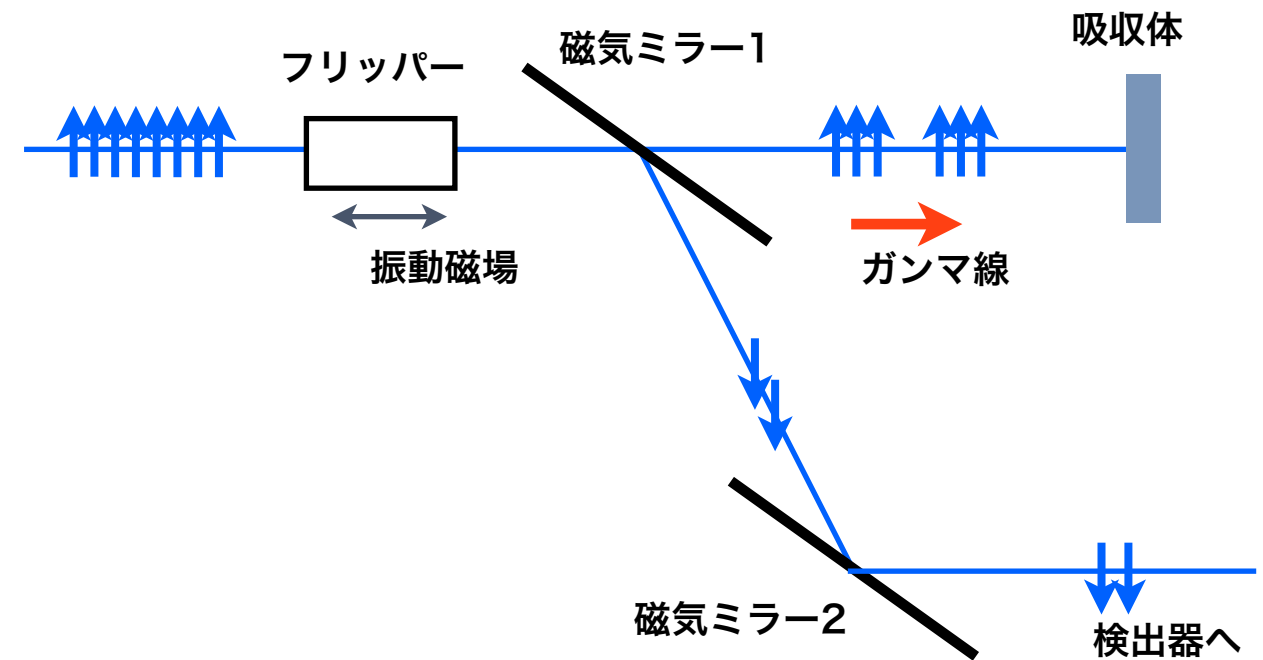


BL05

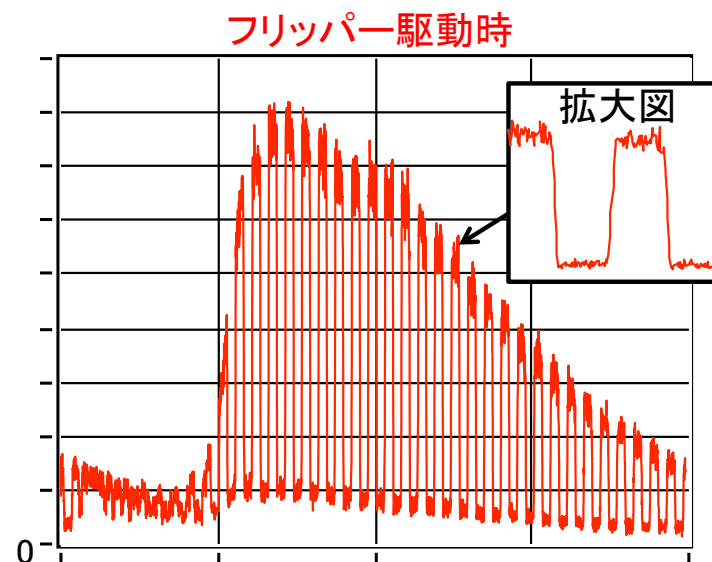


Spin Flip ChopperとFiducial Volume

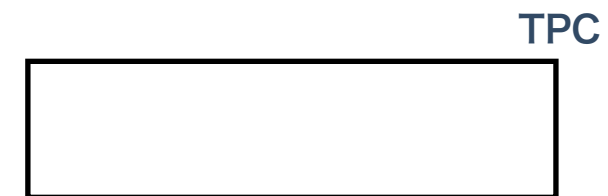
- ・ラムゼー型スピNFLリッパーを局所時間だけ動作させる
→中性子ストリームの局所的なスピン反転
- ・磁気ミラーを用いてスピンを分離する
→中性子ビームの切り出し・バンチ化が可能
- ・多段のSpin Flip Chopperを用いることで
160000:1のコントラストを実現可能
- ・現在の立ち上がり時間 $\sim 5\mu\text{s} \Leftrightarrow 5\text{cm}$ の切り出しが可能
- ・1mのTPCでFiducial Volumeを最大化するとバンチ長は50cm
→30cm以上のFiducial Volumeを確保できる



➡ Spin Flip Chopperの詳細は
竹谷薫, 10aSF-5



event rate

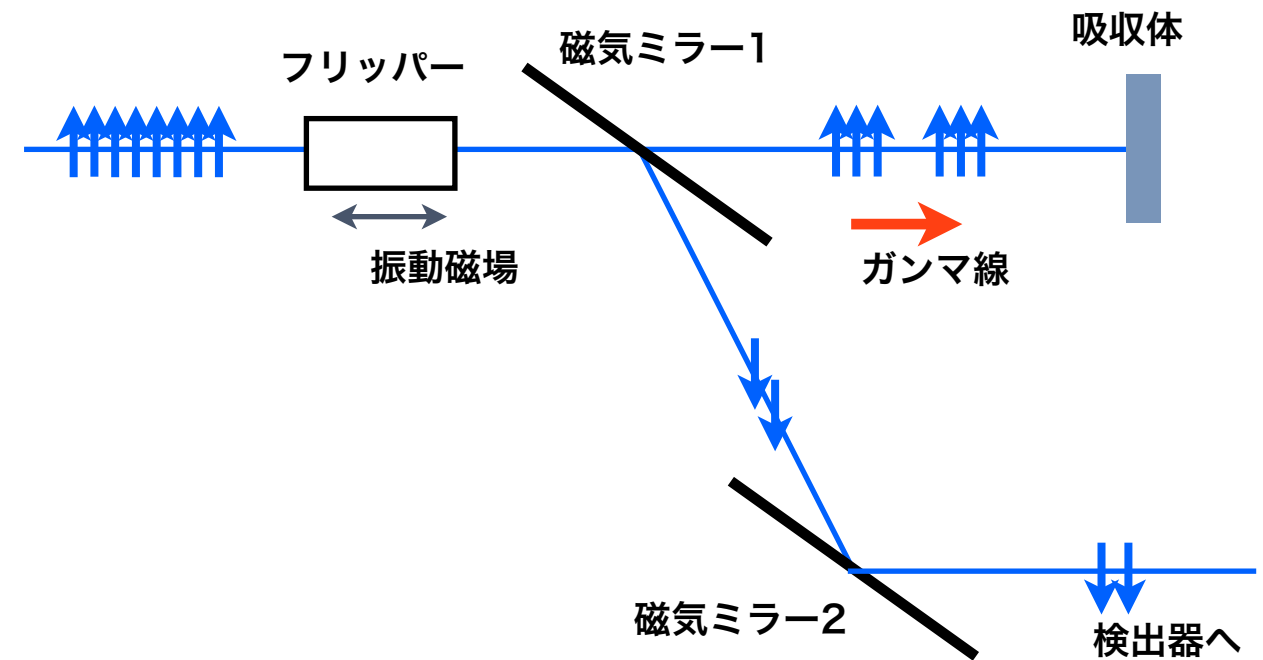


TPC

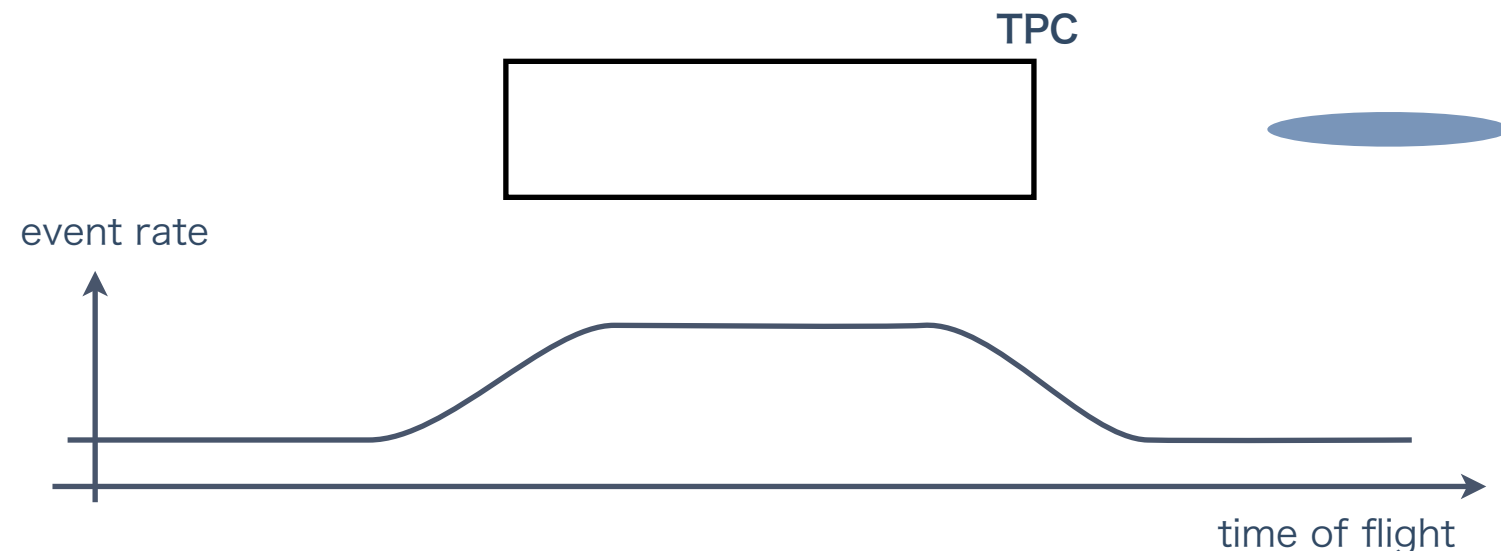
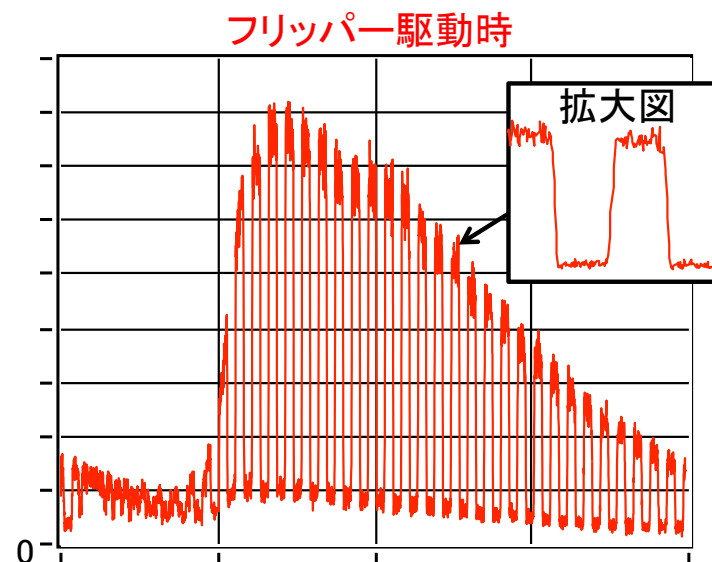
time of flight

Spin Flip ChopperとFiducial Volume

- ・ラムゼー型スピNFLリッパーを局所時間だけ動作させる
→中性子ストリームの局所的なスピン反転
- ・磁気ミラーを用いてスピンを分離する
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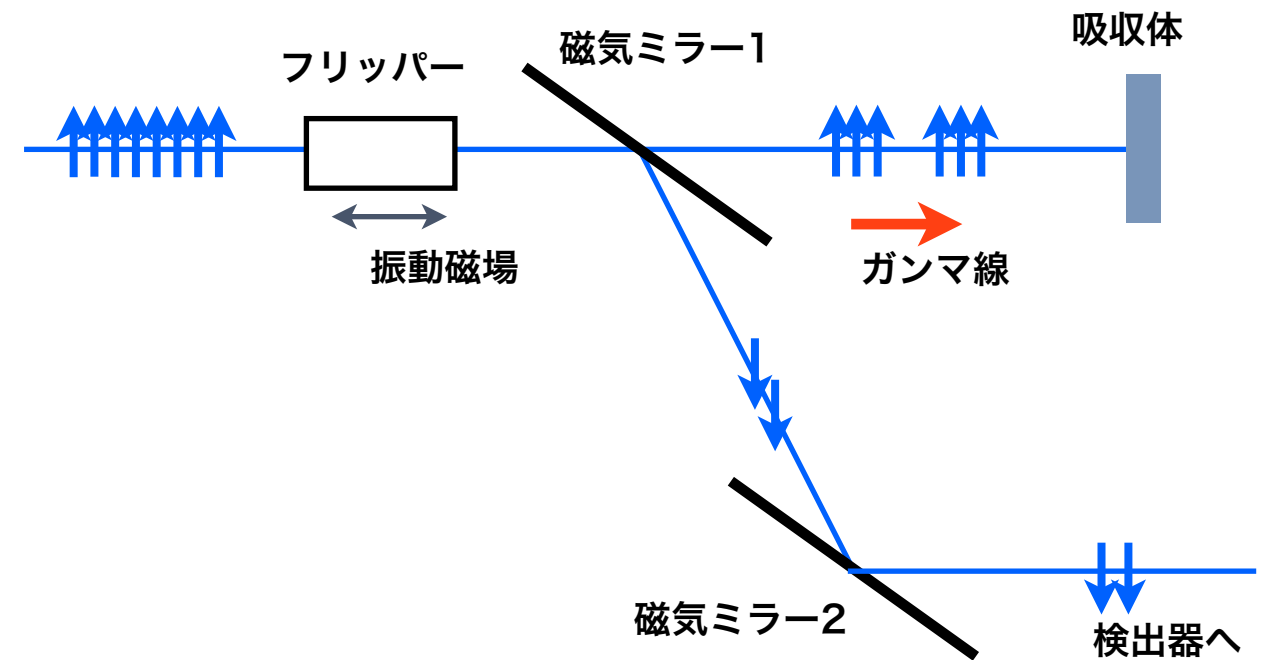


➡ Spin Flip Chopperの詳細は
竹谷薫, 10aSF-5

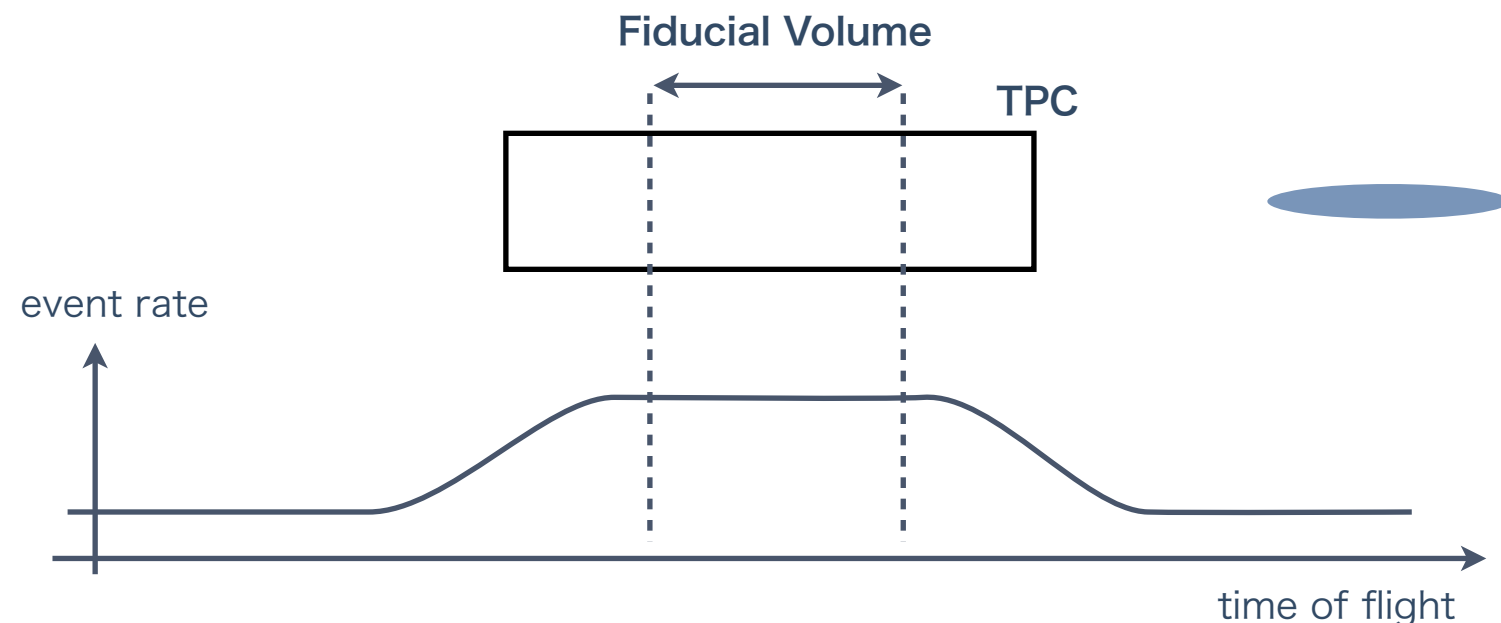
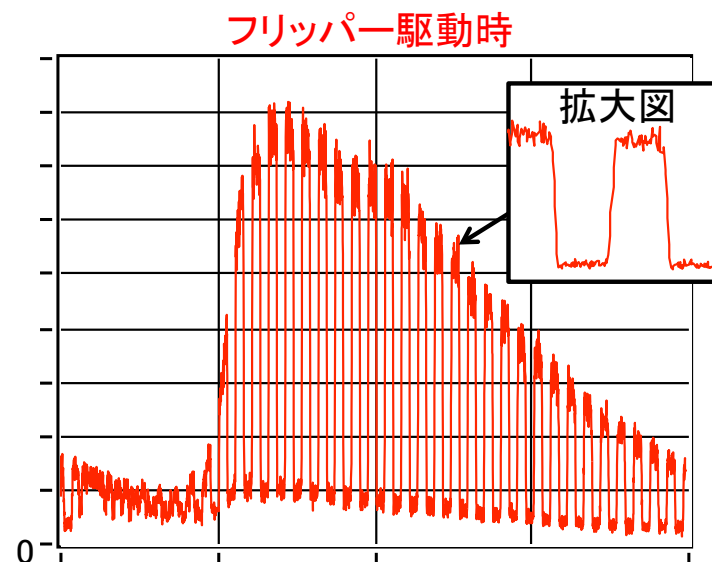


Spin Flip ChopperとFiducial Volume

- ・ラムゼー型スピNFLリッパーを局所時間だけ動作させる
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➡ Spin Flip Chopperの詳細は
竹谷薫, 10aSF-5



Event Rateと統計

○現状：20kW運転で $4 \times 10^5/\text{s} \rightarrow$ 約0.4 decay/m/s相当

○100kWで運転するとき

Fiducial Volumeを30cm, 1 bunchを20個のsub-bunchに切る場合,
1 stripあたり 1.5×10^{-3} decay $\rightarrow$ 信号のmultiplicityは $O(10^{-6})$

○100kWでは 10^6 decayを貯めるのに15日

○ $^3\text{He}(n,p)$ 反応

○ $\sigma_{(n,p)} = 5333$ barn

○Multiplicityを避けるため10/m/s以下を要請すると
 ^3He の分圧1Pa以下.

$\rightarrow$ $^3\text{He}/^4\text{He}$ の分圧比は 10^{-5} 以下に設定

○現状では東大地殻化学実験施設のスペクトロメータで
 $^3\text{He}/^4\text{He} = 10^{-4}$ の分圧比に対して0.5%の精度で
測定可能

$\rightarrow$ 精度向上のための研究協力を行っていく



Data Acquisition

Mother board (Copper) にDaughter card (Finesse) を4枚載せて使用。
Copperから直接TCP/IP 100BASE (100Mbit /sec)で読み出し

FINESSE 65MHz 12bitFADC (8ch)

Clock : 10MHz

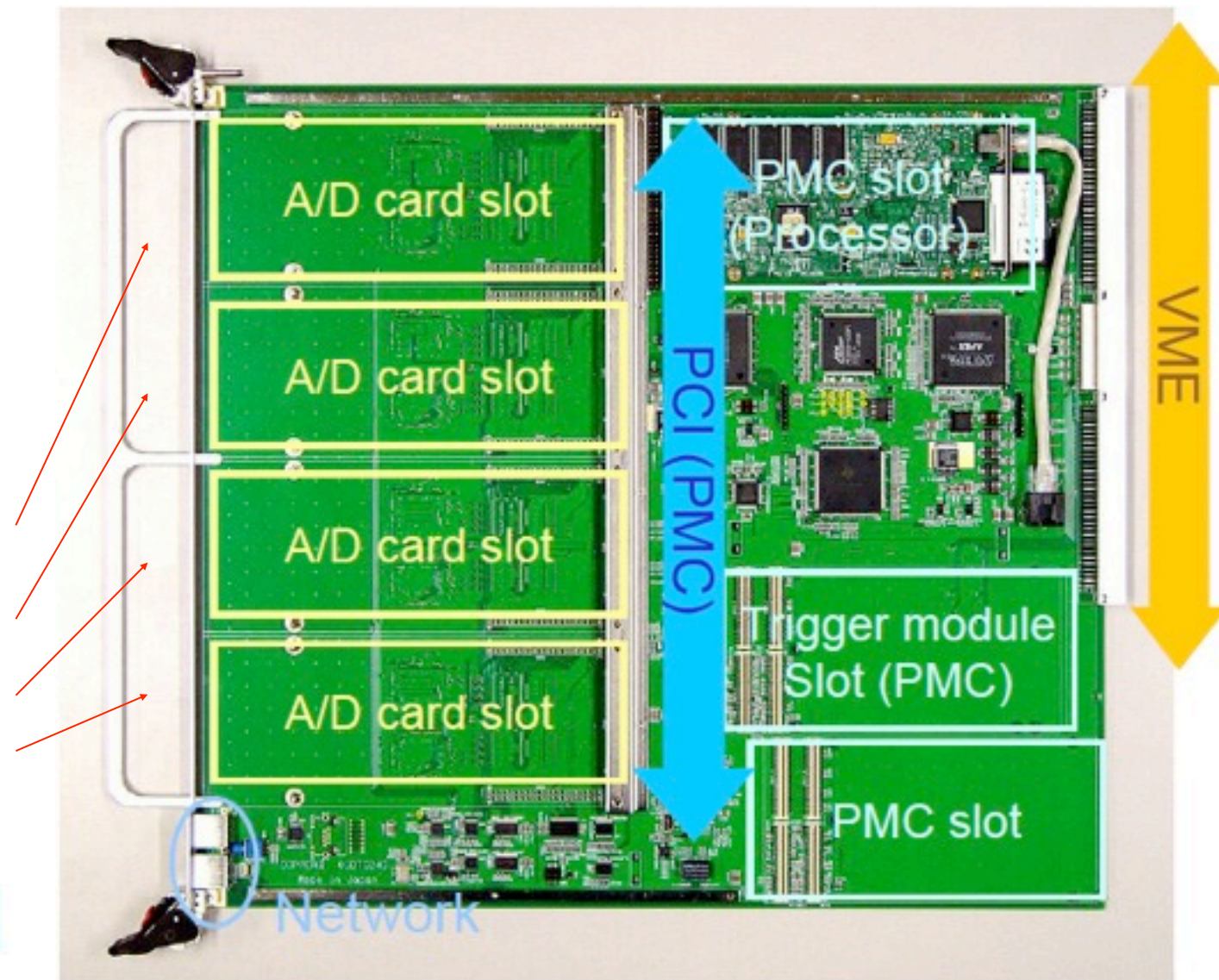
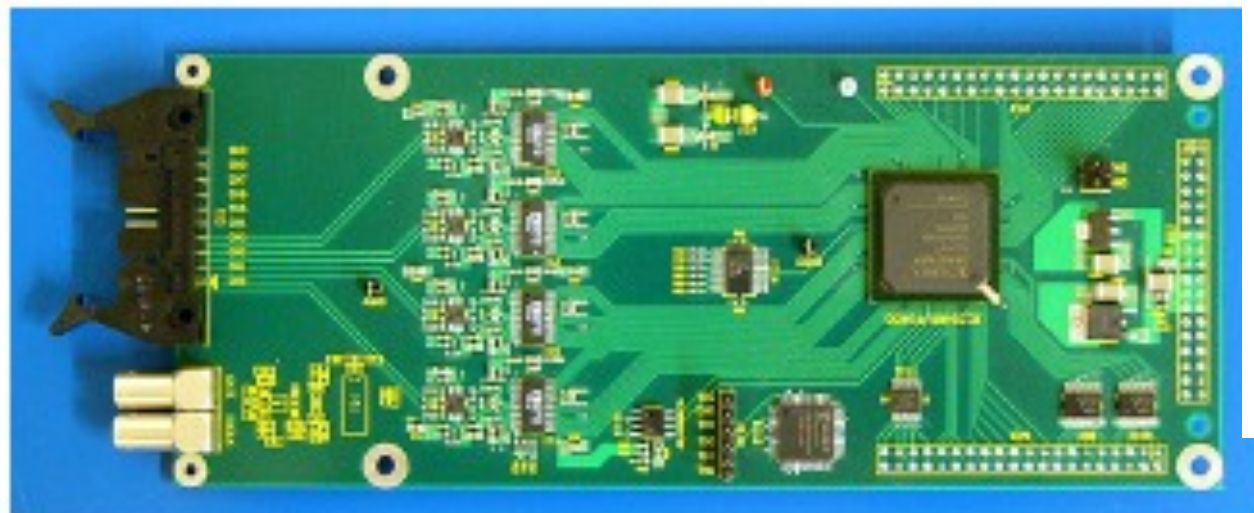
Dynamic range : 100 μ sec

Data size : 2kbyte /ch /event

Channel数 : 16 ch

~100count /sec までDAQ可能

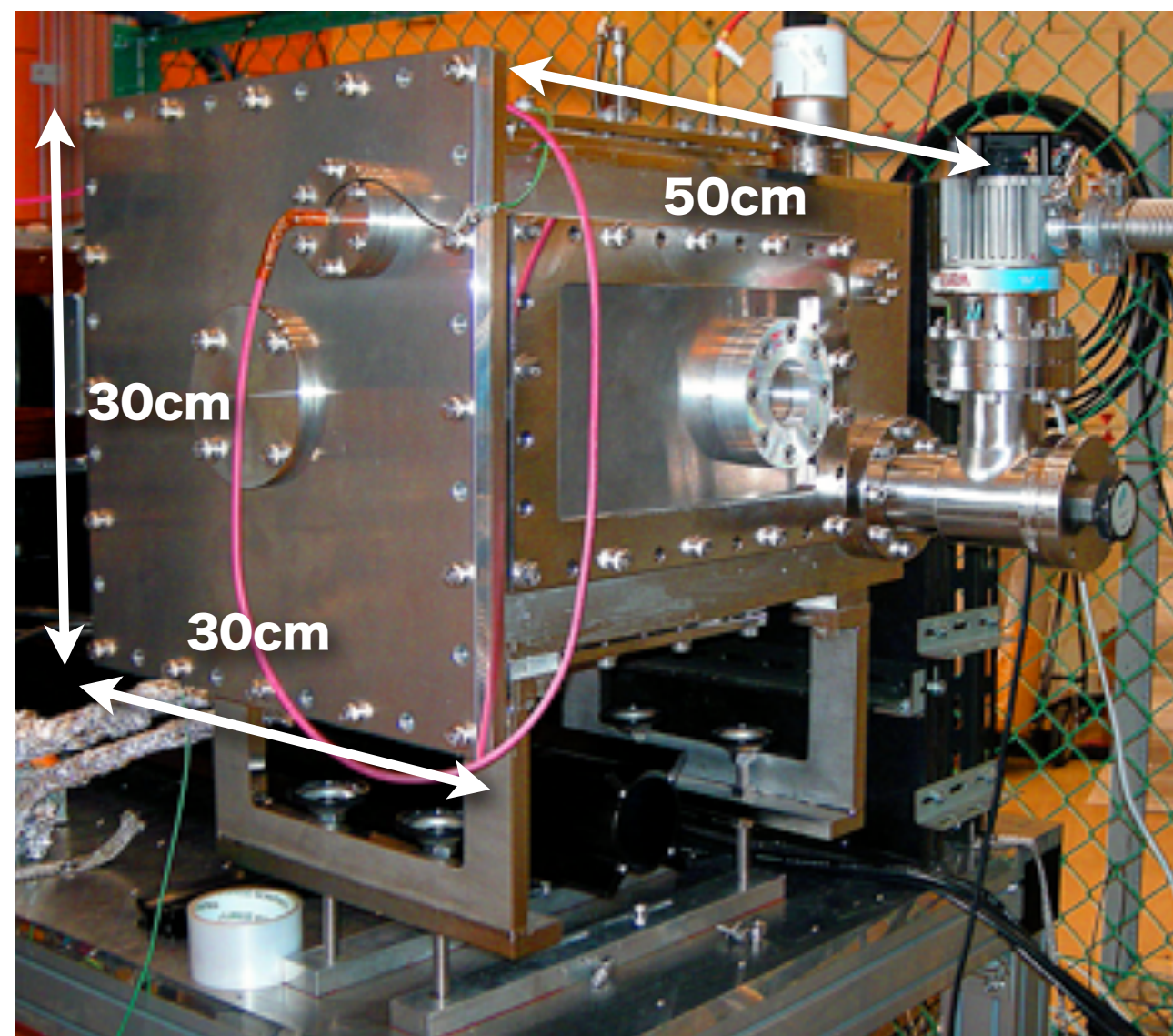
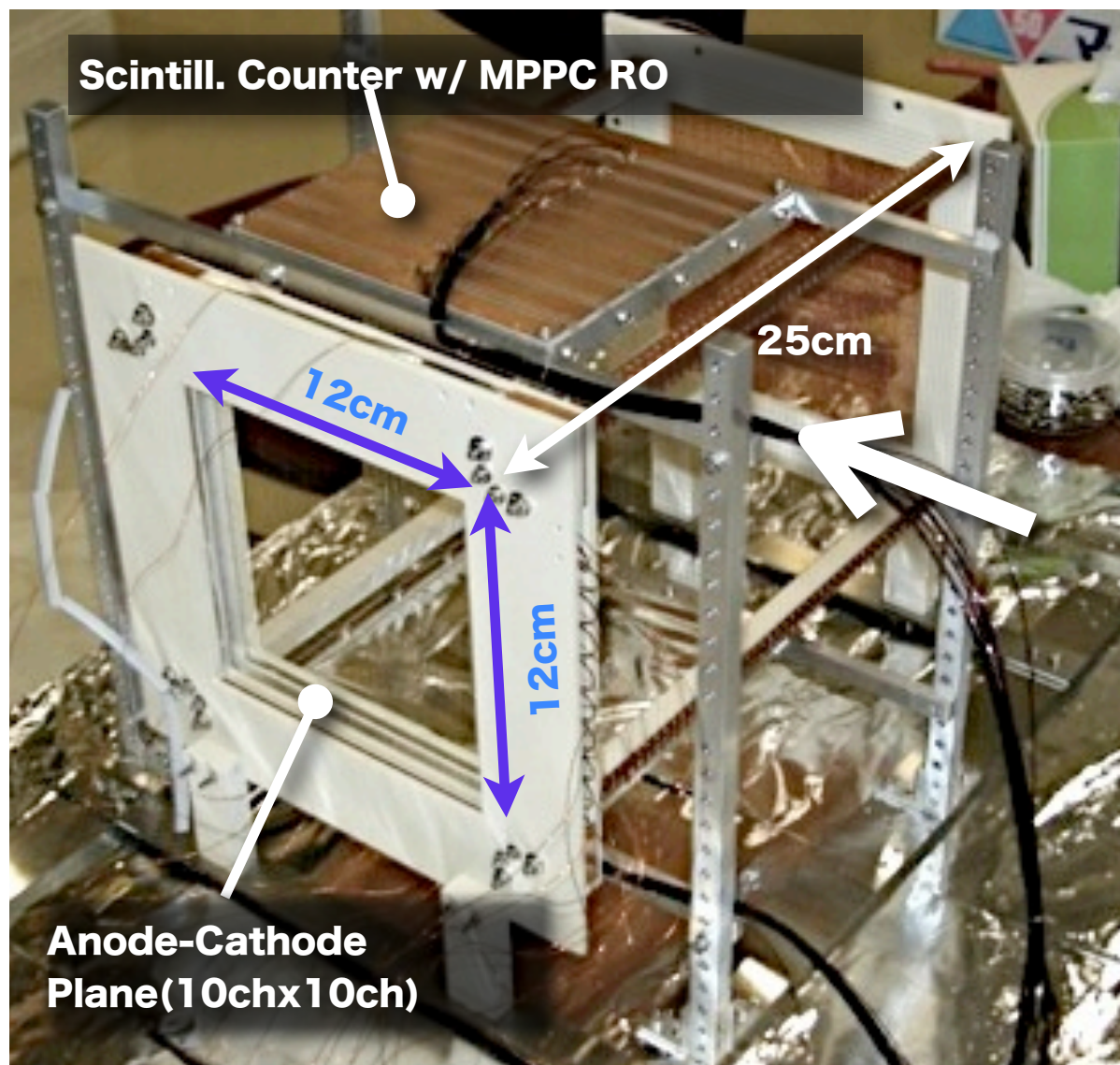
(ビームテストでは~100count/secでDAQ)



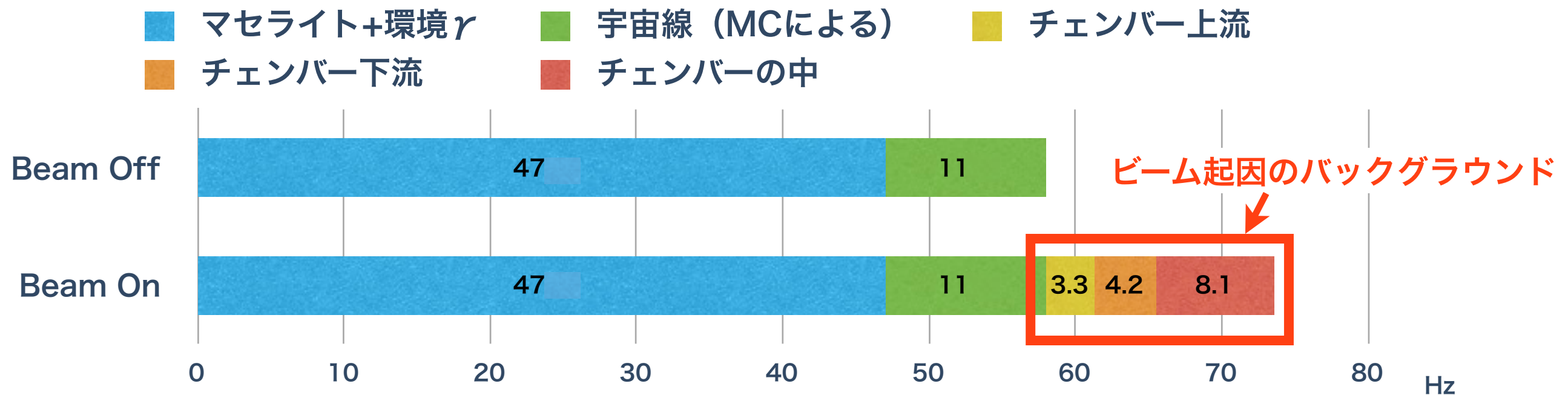
バックグラウンドの測定

2009/6/1～2009/6/21 ビームテスト

プロトタイプTPCを用いてバックグラウンド環境の計測を行った

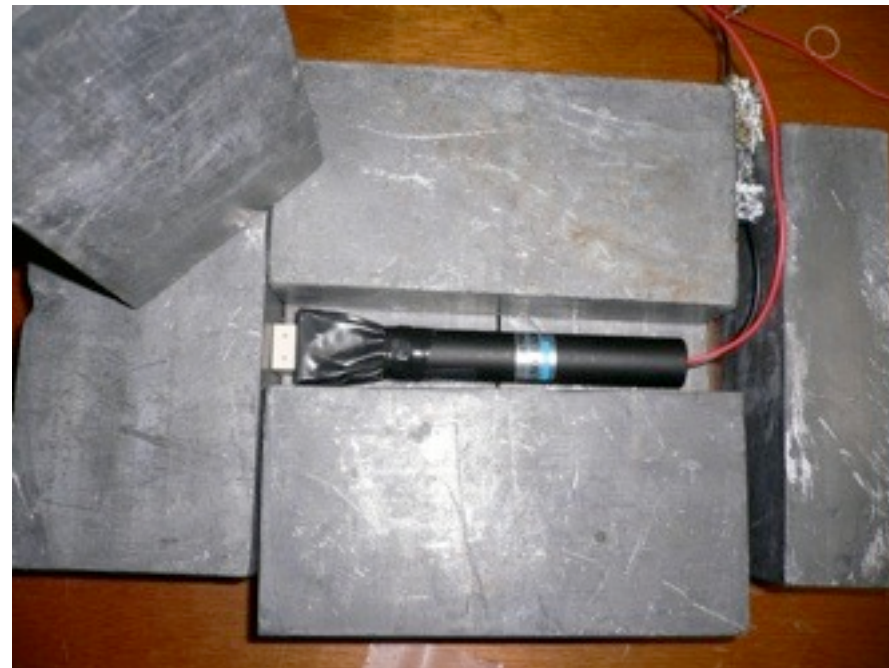
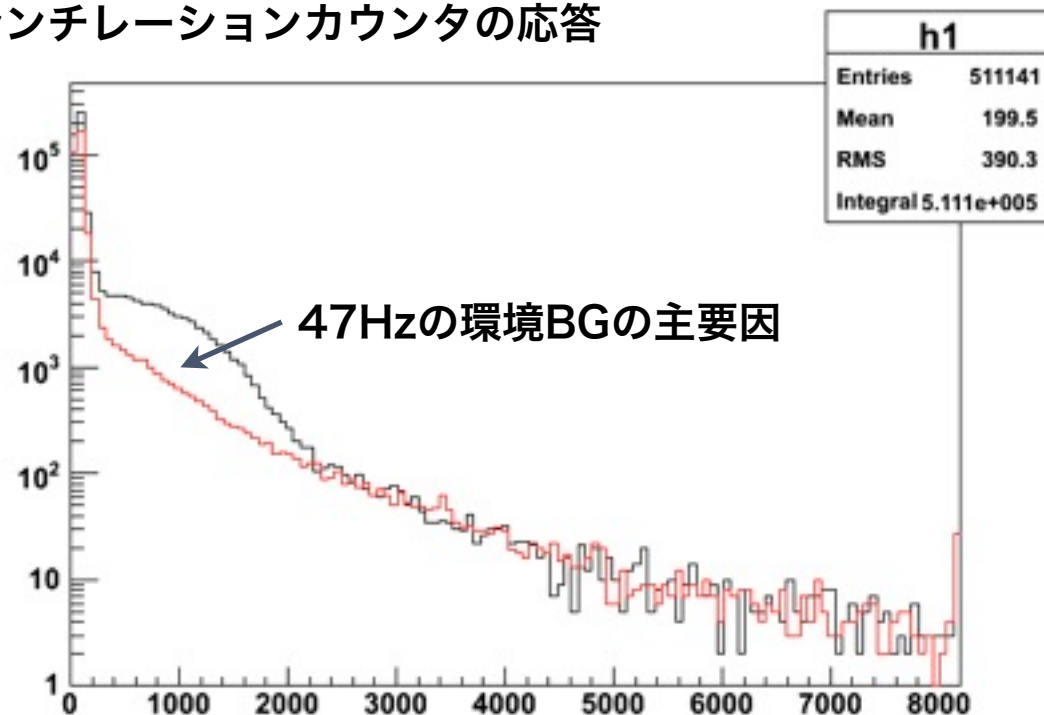


TPCカウントレートに占めるBG



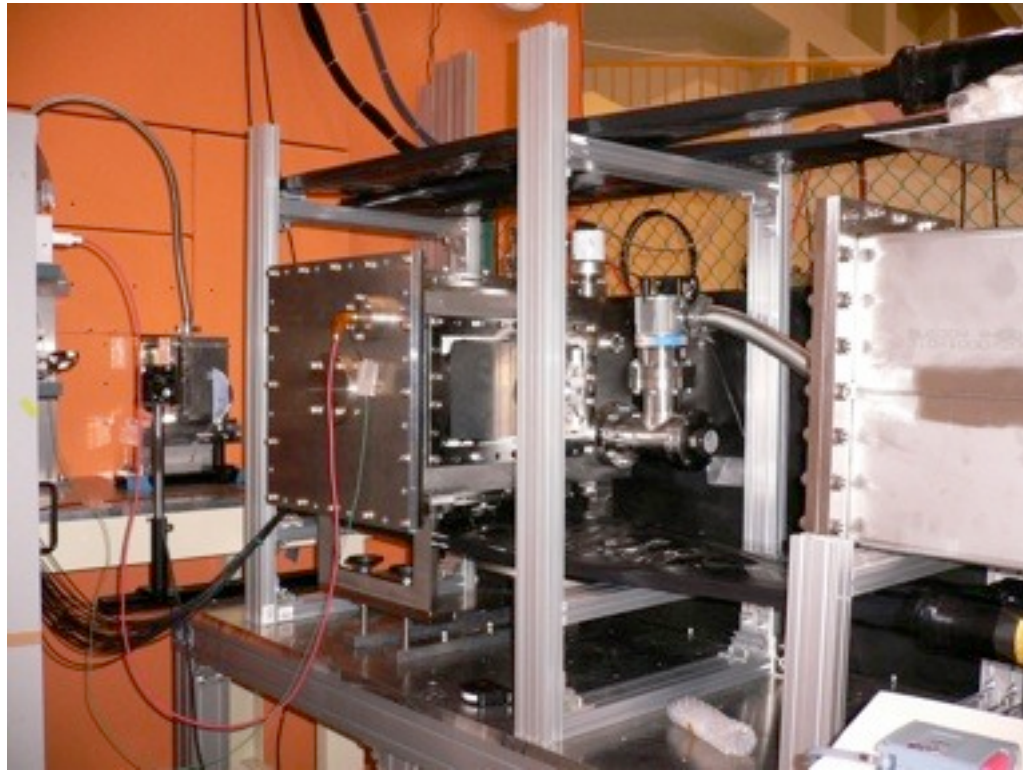
(cf. 中性子崩壊イベント=0.05Hz)

マセライトの有無による
シンチレーションカウンタの応答

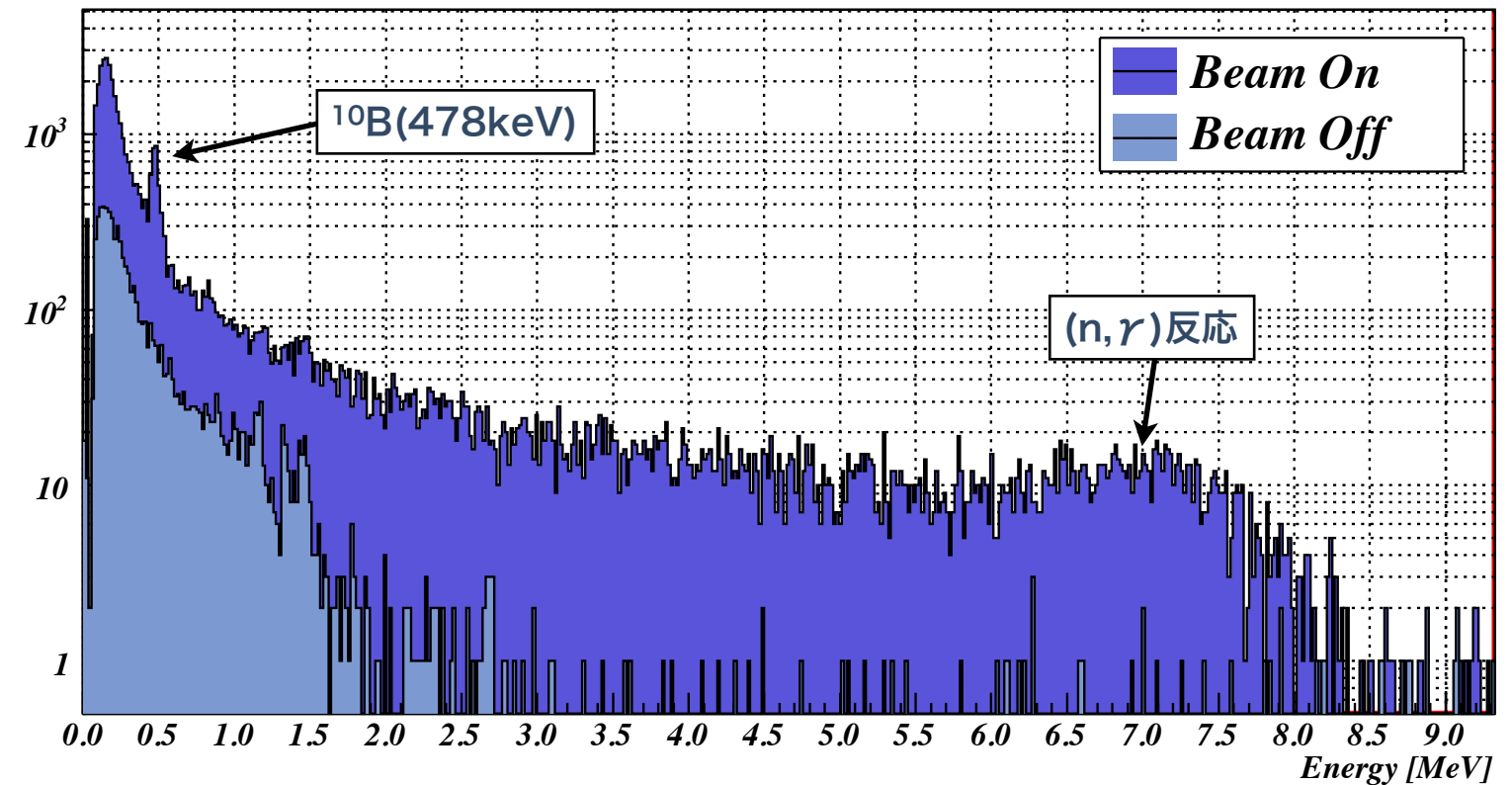


バックグラウンドガンマ線

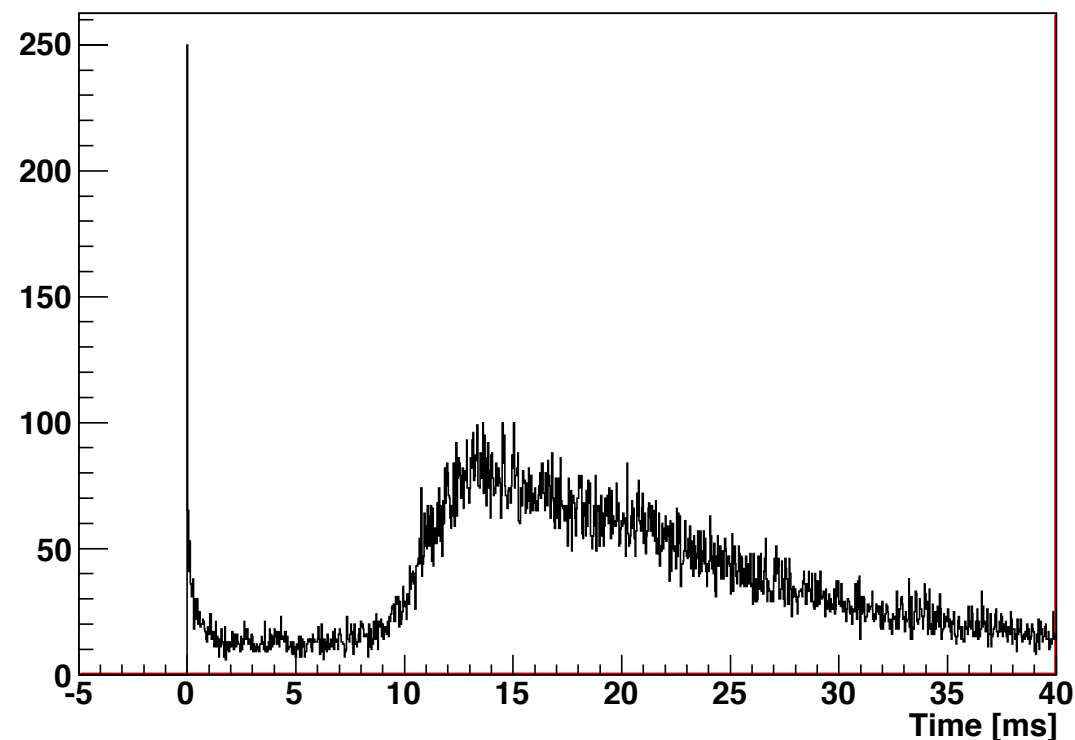
測定環境



NaIスペクトル



NaI/TOF(Beam On)



2inch NaI

- BeamOn: 400Hz
- BeamOff: 62Hz
- Difference: 338Hz

コンプトン散乱などを通じて崩壊電子に対するバックグラウンドになる

ガス散乱によるBG γ のシミュレーション

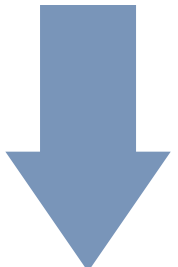
PHITS+Geant4によるシミュレーション

中性子散乱フラックス

(n, γ)によるガンマ線フラックス

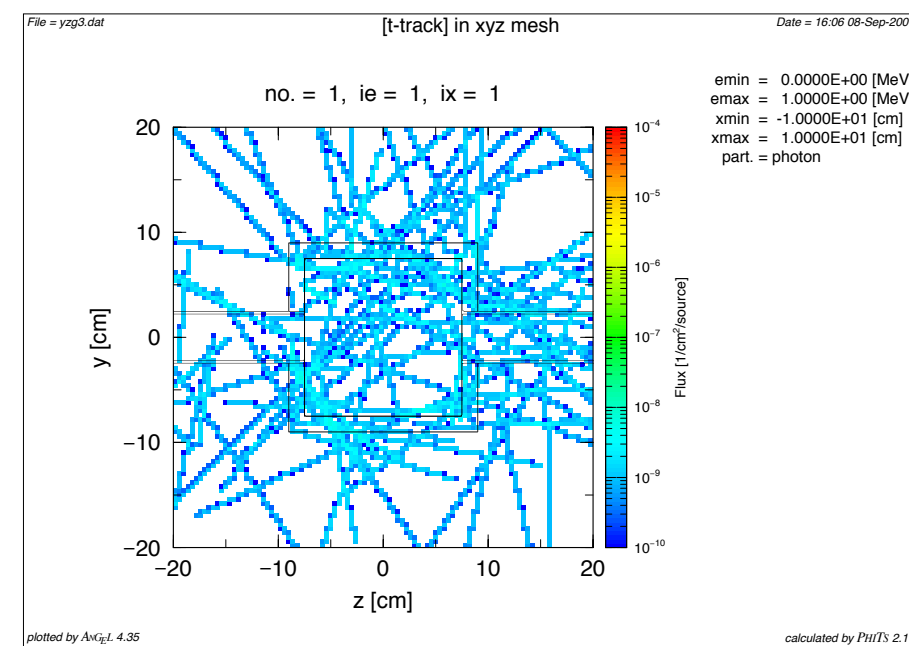
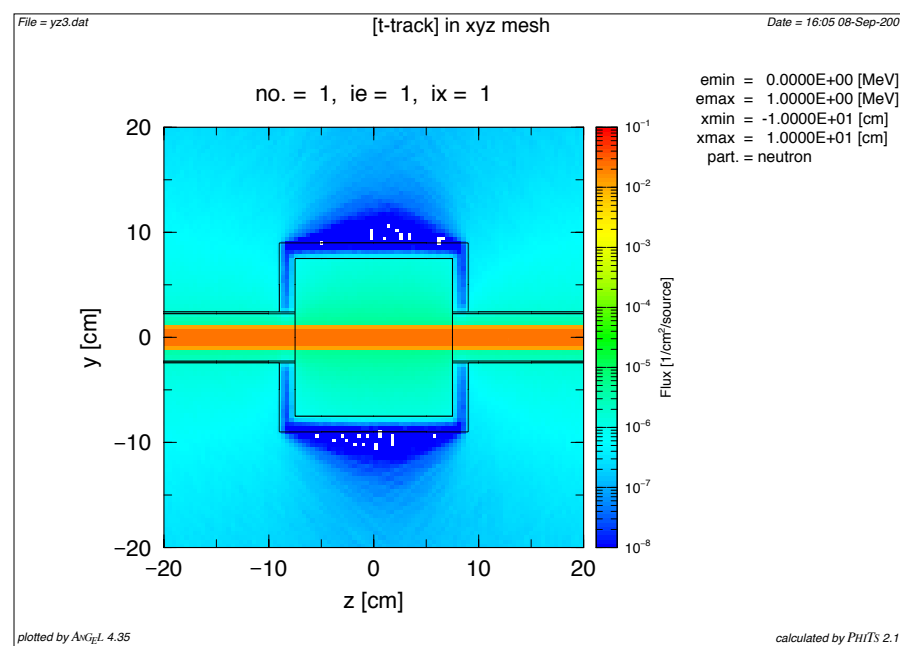
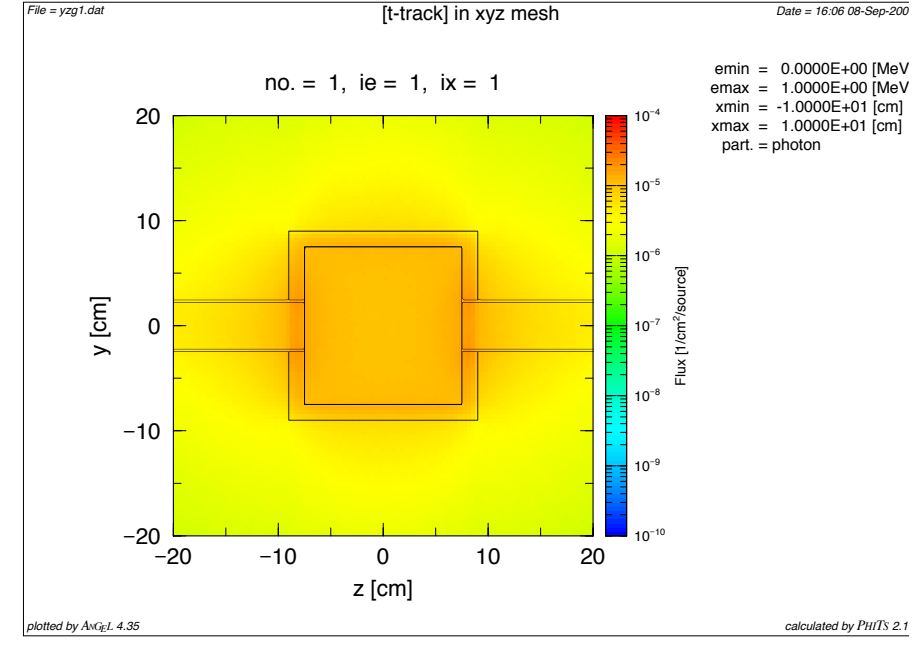
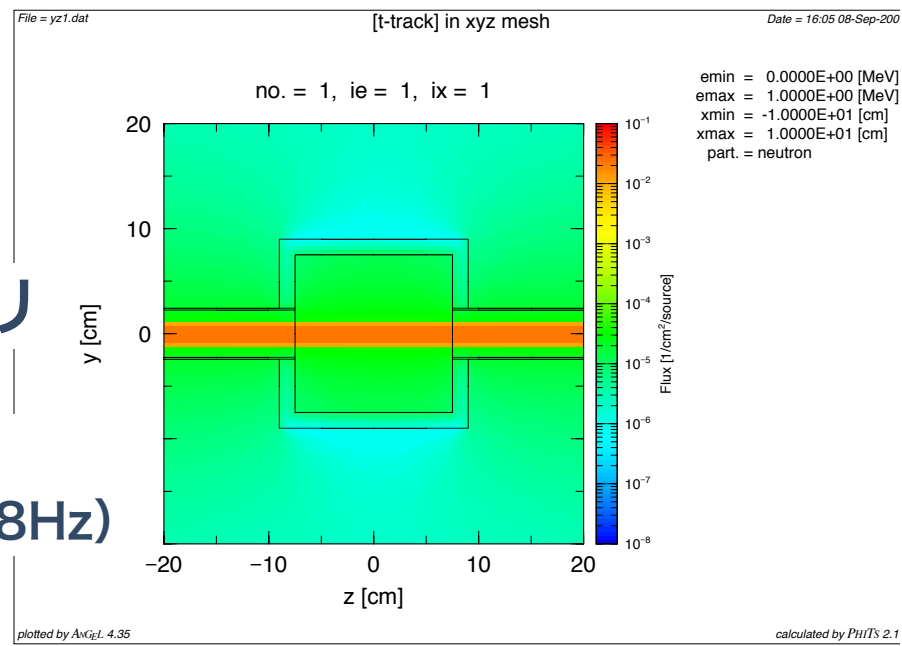
SUS304容器ジオメトリ

ビームの発散を考慮しない場合,
1Hz程度の β を生む (測定では8Hz)



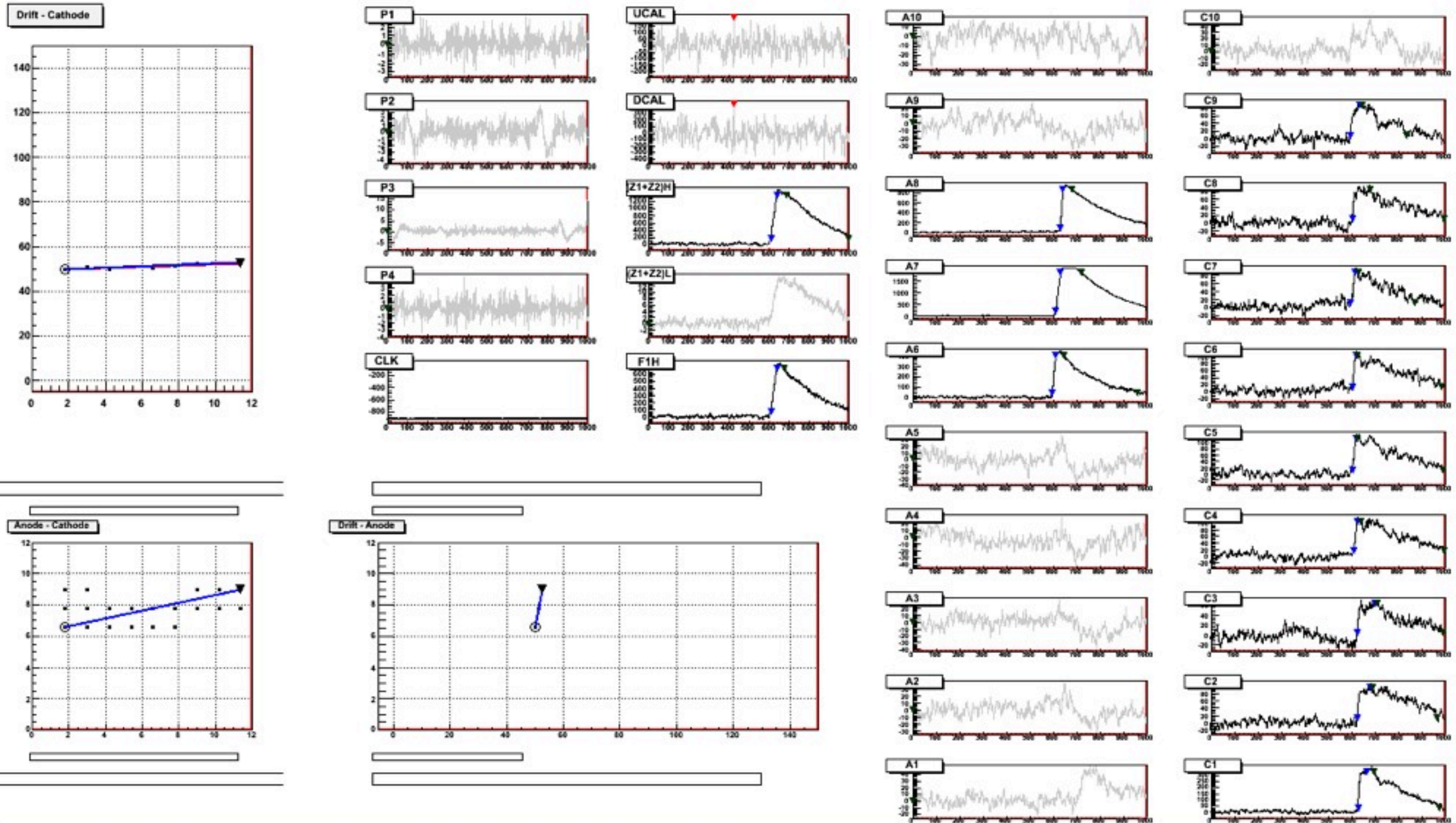
10⁻³-10⁻⁴

内壁をLiFにしたもの



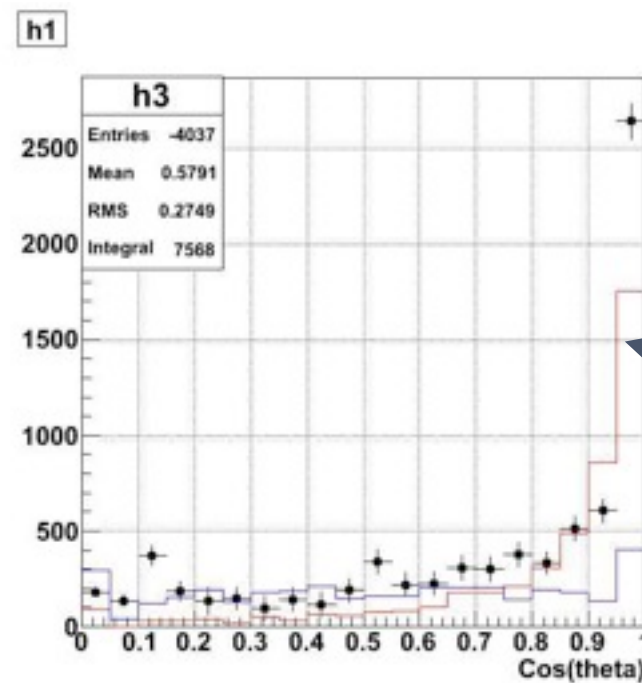
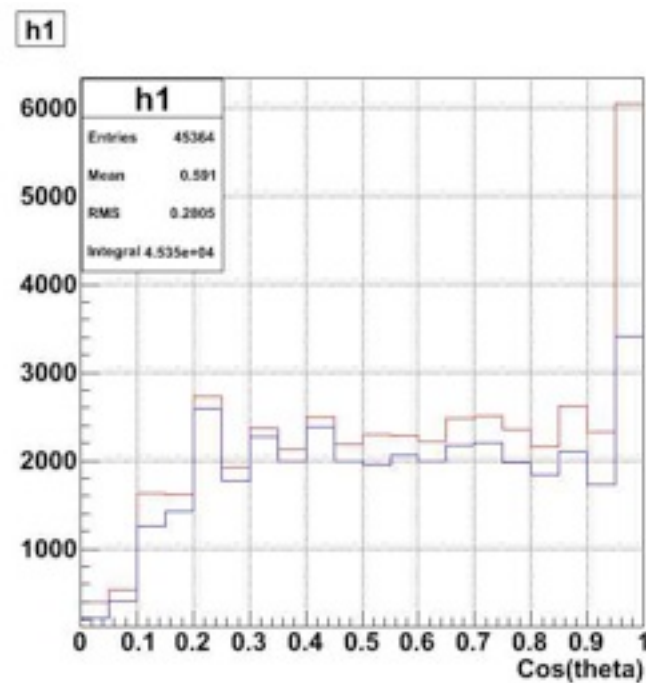
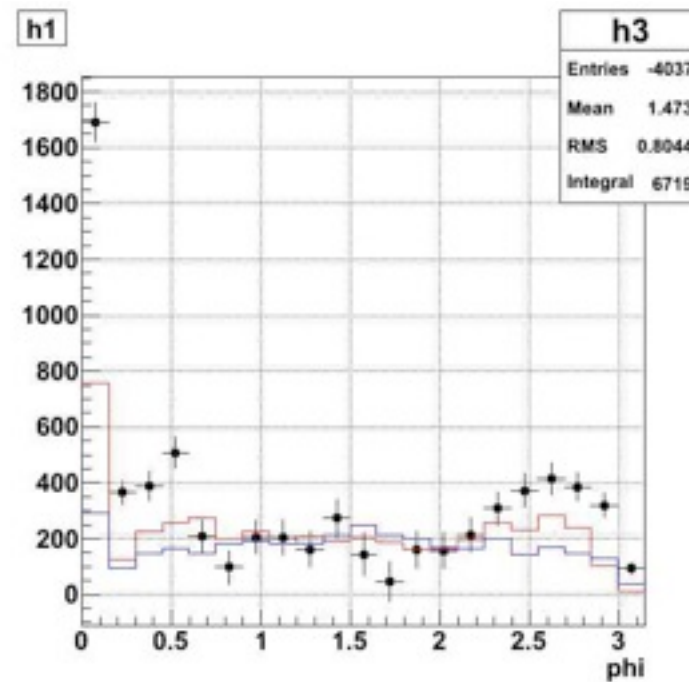
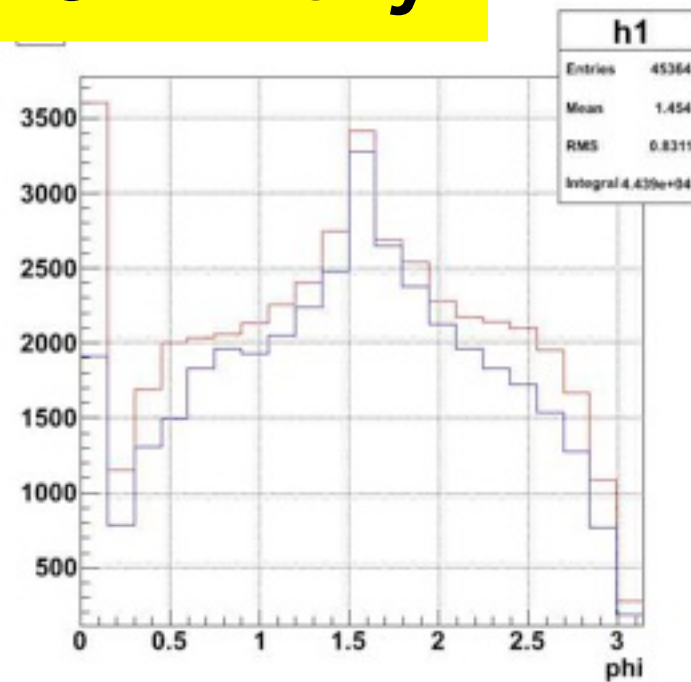
BGイベントのデータ解析

Kudos Event Display v0.4.5 run00400, Event 628



バックグラウンドの角度分布

Preliminary



BeamOn - BeamOff

シミュレーション

赤：ビーム軸上から γ が来る

青：等方的に γ が来る

バックグラウンドのまとめ

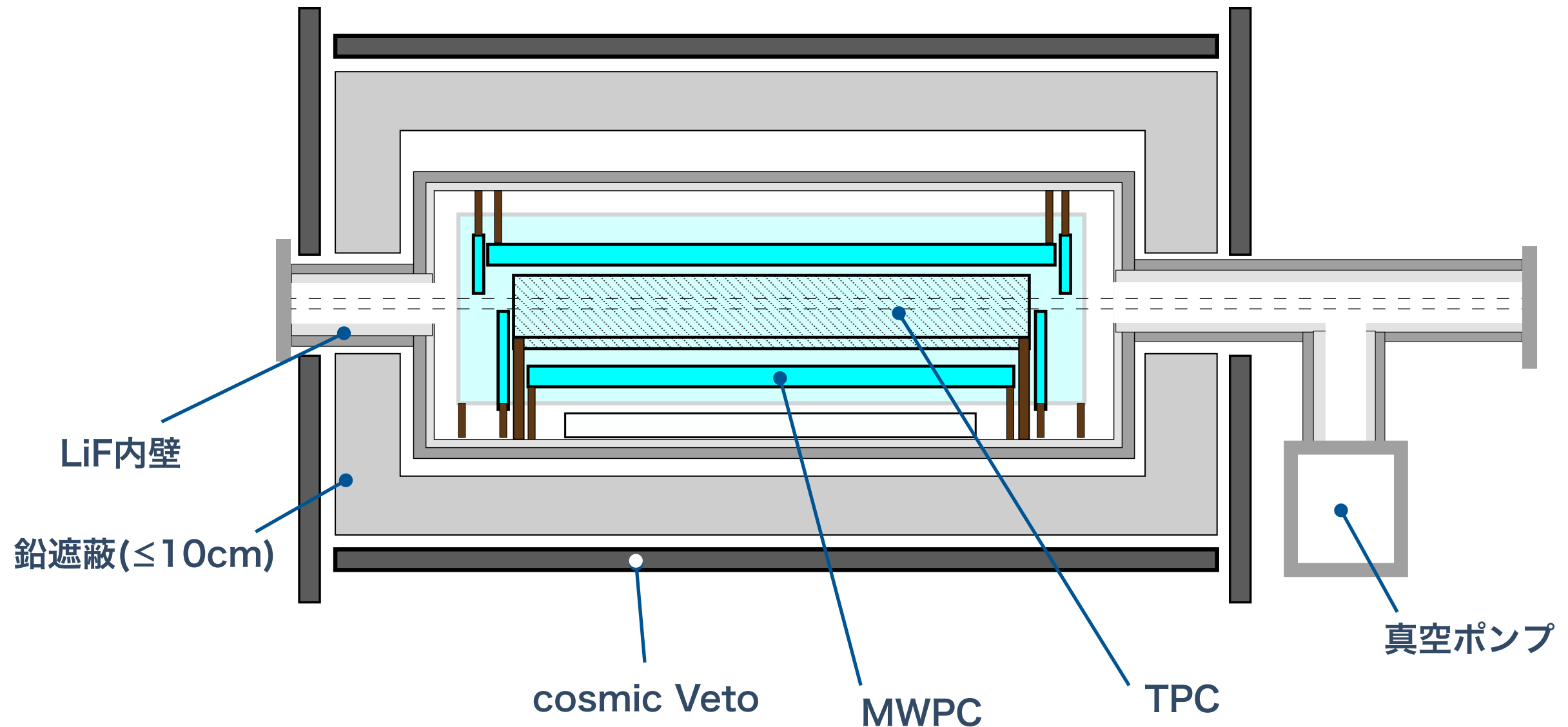
○TPC構造体のマセライトに含まれる ^{40}K からの β 線

- 材質に注意して検出器を構成する

○ビーム起因のバックグラウンド

- ビームラインの ^{10}B からの γ (478keV)
 - ビーム上下流の空気散乱による γ
- 鉛遮蔽を十分に積むことで抑制可能
- チェンバー内のガスによる散乱で即発 γ
 - 中性子がチェンバー内壁に直接当たる即発 γ
- LiFで内壁を覆うことで対応
チェンバー内の物質質量にも注意

バックグラウンド抑制の戦略

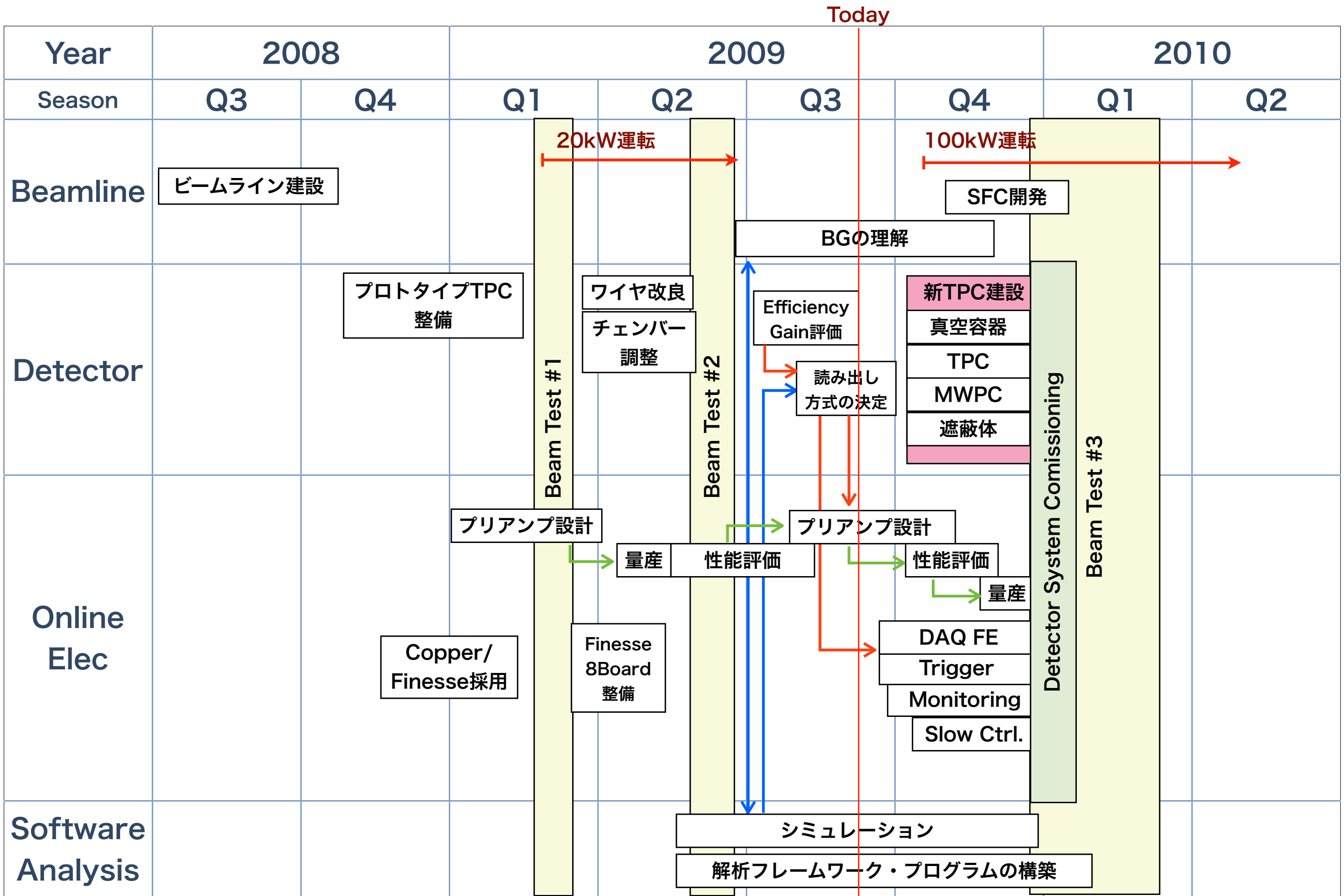


今後、検出器の構造体を考慮した

- ・バックグラウンド環境
- ・アクセプタンス
- ・ベータ崩壊信号の多重クーロン散乱や後方散乱の効果

のシミュレーションを詳細に行っていく→本格的な検出器設計の段階へ

Experiment Planning



まとめ

○In-Flightでの中性子寿命測定

- 信号の検出：検出効率・Fiducial Volume・統計量に一定のメド
- 技術開発：プリアンプ, $^3\text{He}/^4\text{He}$ 分圧測定精度

○バックグラウンド

- ビームテストでバックグラウンドの起源・量について計測した
- 定量的に詰めの段階
- 外側の遮蔽と内側のLiFでBG削減

○検出器の設計・シミュレーションを今後進めていく

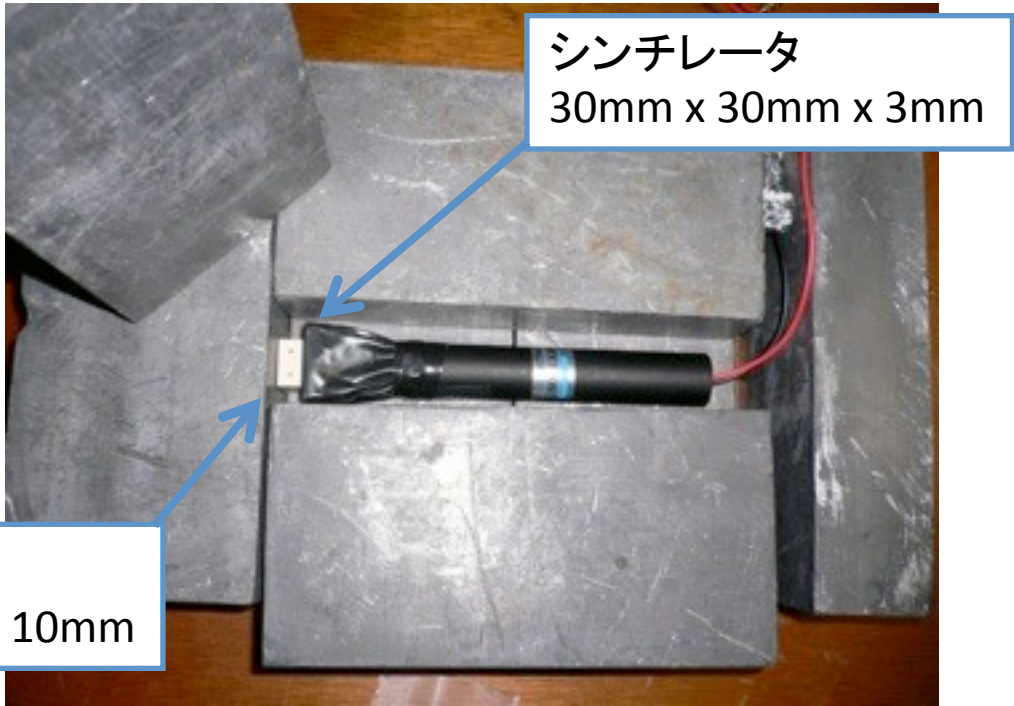
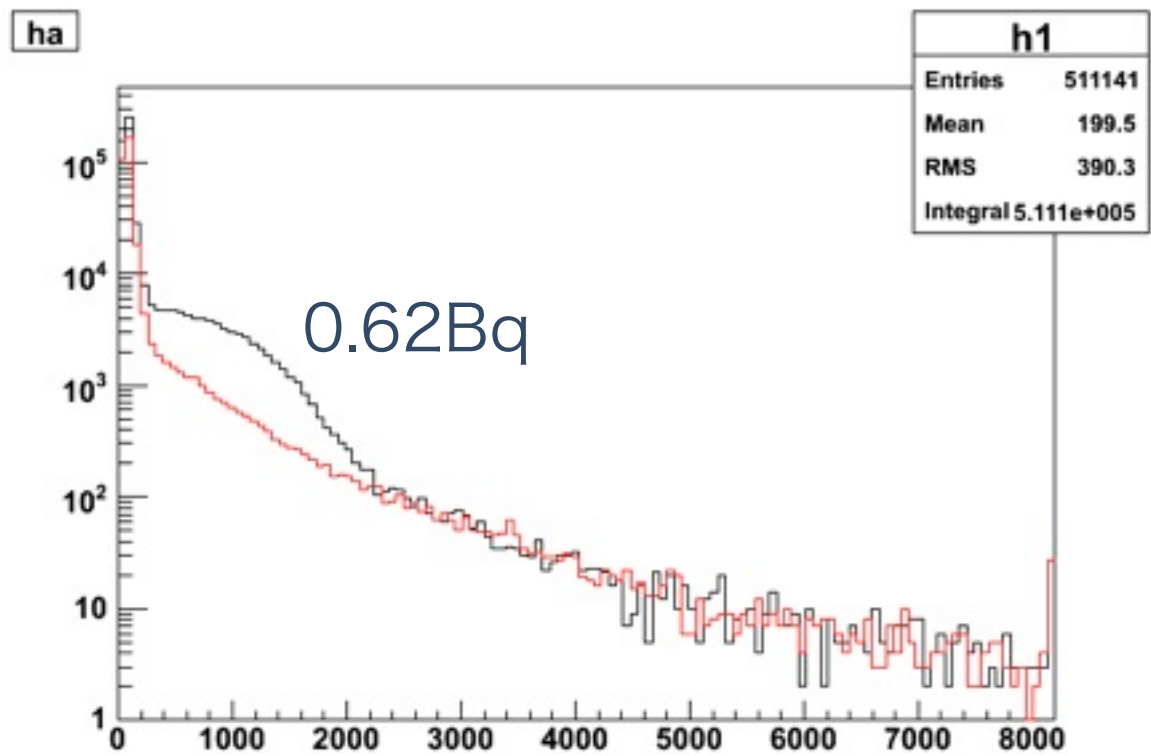
Backup

Preamp. Spec Proposal

Dynamic Range	Range1: -75fC ~ +25fC Range2: -500fC ~ -5fC
Conversion Gain	Range1: 2V/pC (0.5pF) Range2: 10V/pC (0.05pF)
Gain Tolerance	~1%
ENC	<2000e @ 1pF
Crosstalk	0.5us, 1us, 10us, Variable
Peaking Time	<20mW/ch
Power Dissipation	32ch

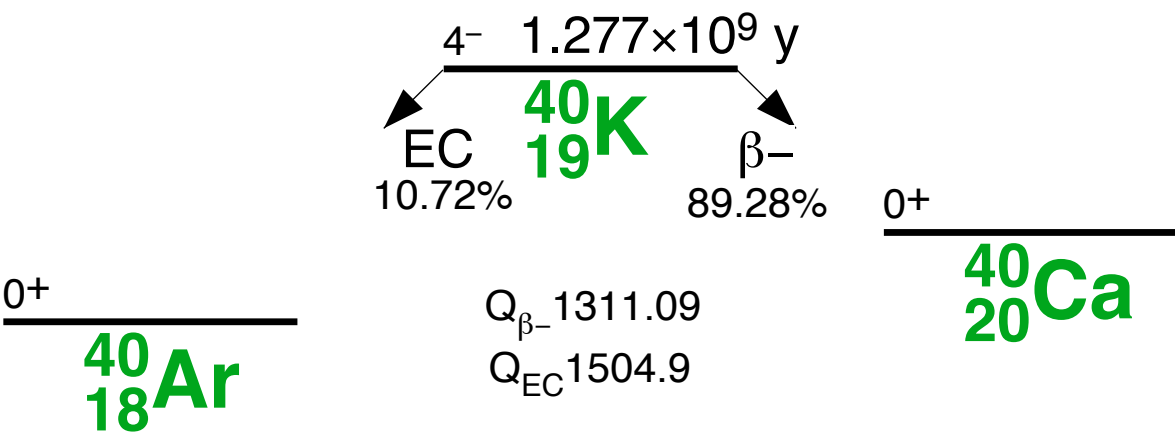
房安氏の提案による（2009/9/6現在）

マセライト由来のβバックグラウンド



マセライトの組成

Compound	wt%
SiO ₂	47
MgO	17
Al ₂ O ₃	16
K ₂ O	11
F	9

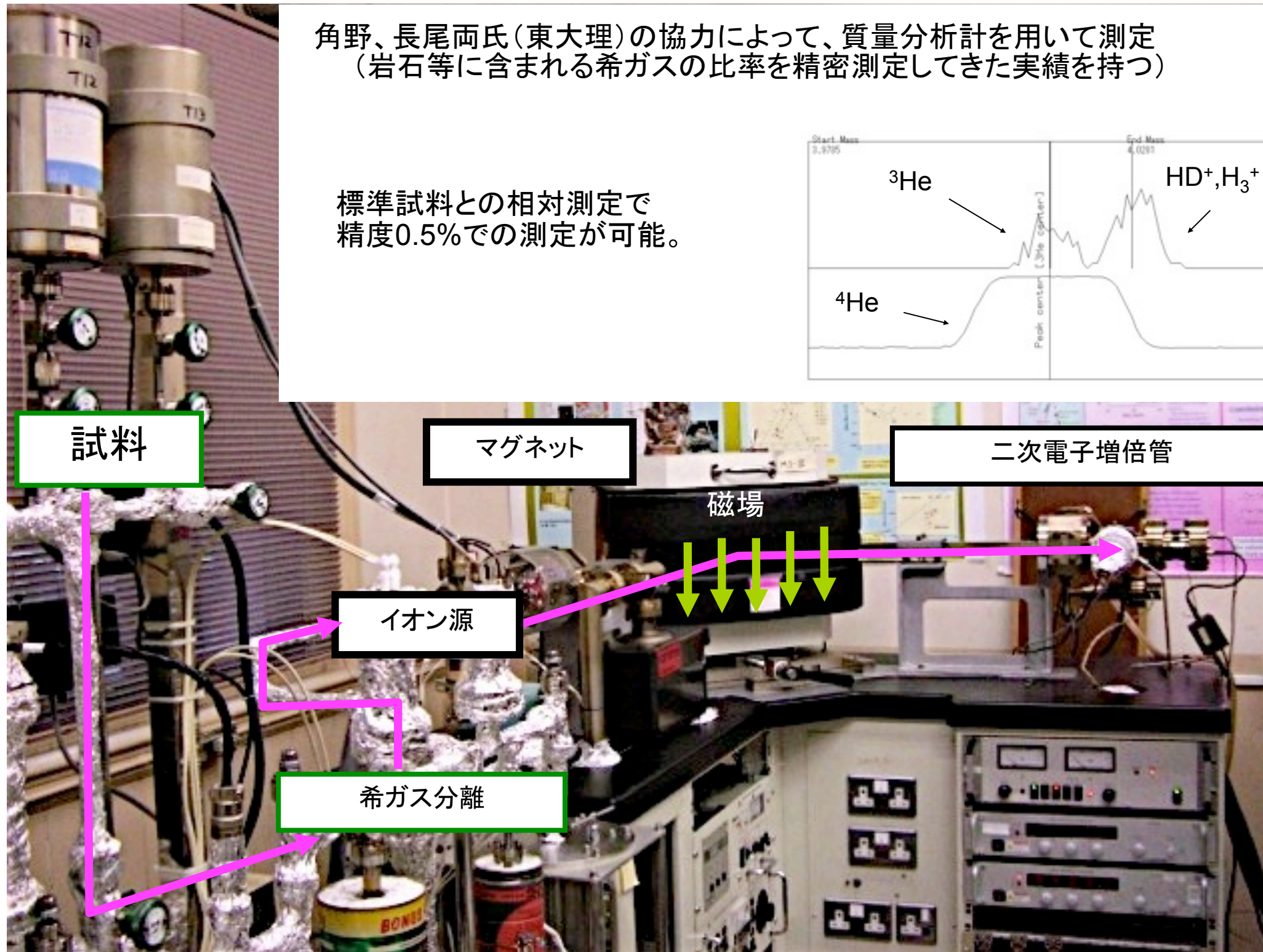
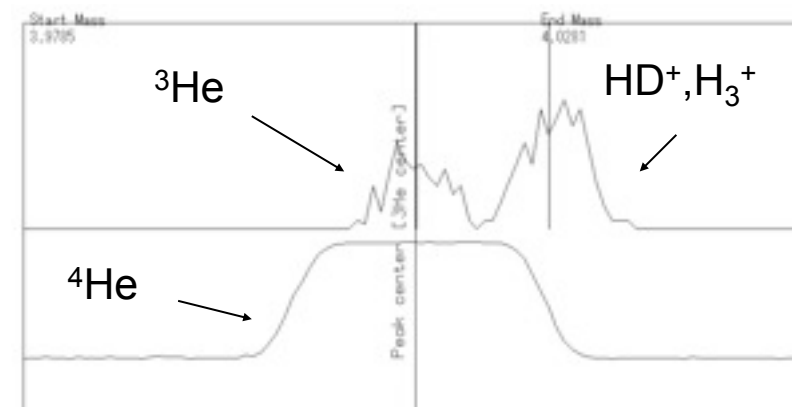


$^3\text{He}(n,p)$ の検出と分圧測定

$^3\text{He}(n,p)^3\text{H}$ の断面積 = 5333 barn 750keV full energy deposit

角野、長尾両氏(東大理)の協力によって、質量分析計を用いて測定
(岩石等に含まれる希ガスの比率を精密測定してきた実績を持つ)

標準試料との相対測定で
精度0.5%での測定が可能。



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Polarization Branch

Experiment	Beta decay
Mirror	Magnetic Supermirror(2.8Qc)
Configuration	Polygonal approximation 12unit $\times$ 0.262 deg. (R=82m)
Cross-section	40mm $\times$ 100mm
Channel	4ch
Bender Length	4.5 m (375mm $\times$ 6 $\times$ 2)
Bending Angle	3.14 deg.

Unpolarized-beam Branch

Experiment	Scattering
Mirrors	Supermirror (3Qc)
Configuration	Real Curve
Curvature	100m
Cross-section	50mm $\times$ 40mm
Channel	5ch
Bender Length	4.0 m (2.0m $\times$ 2)
Bending Angle	2.58 deg.

Low Divergence Branch

Experiment	Interferometer
Mirrors	Supermirror (3Qc)
Configuration	2 mirrors
Critical Angle	0.95 deg.
Bending Angle	3.85 deg.