Supermirrors and Neutron Focusing

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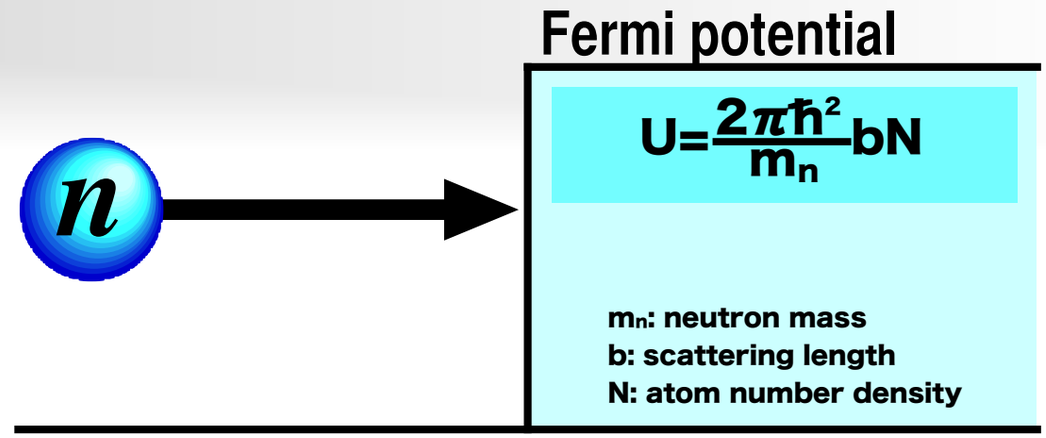
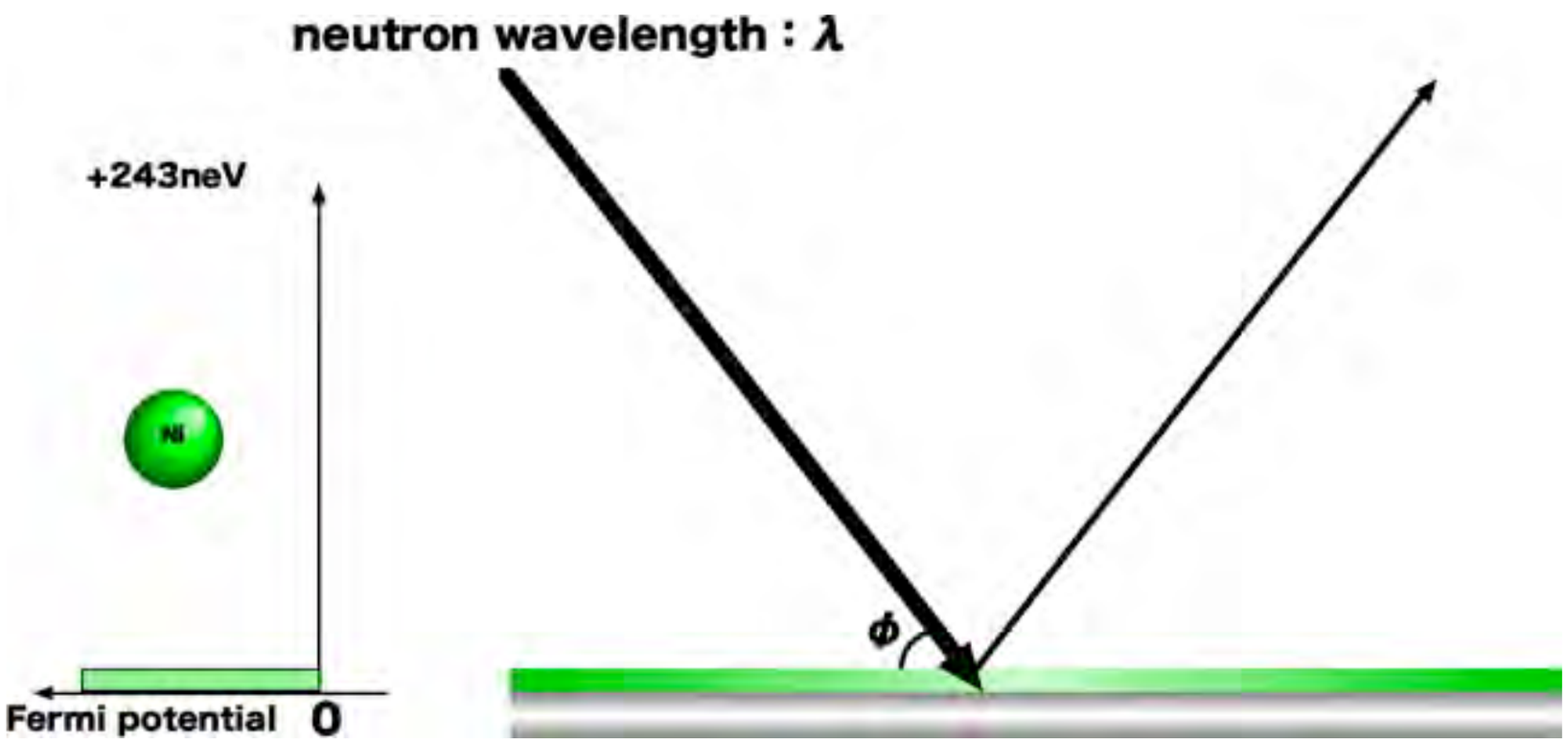
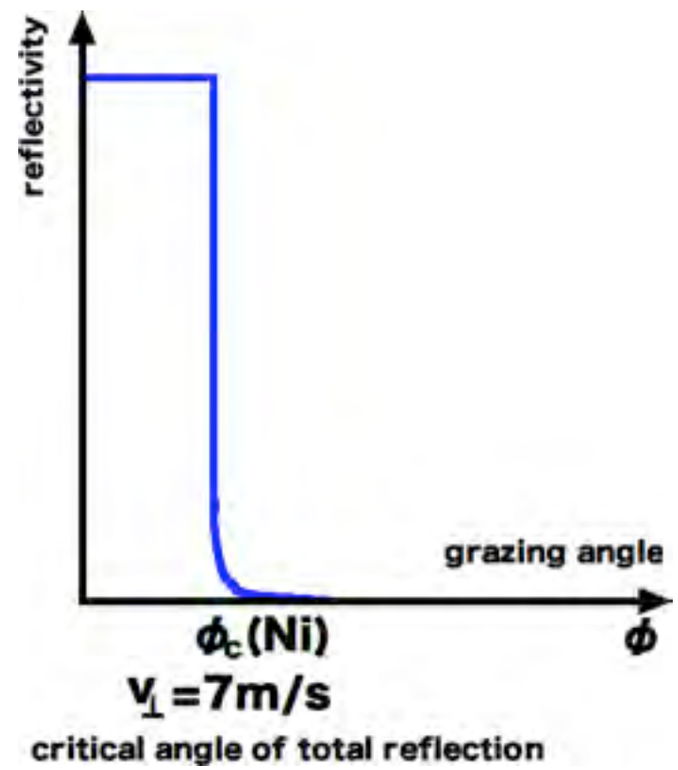
Neutron Reflection

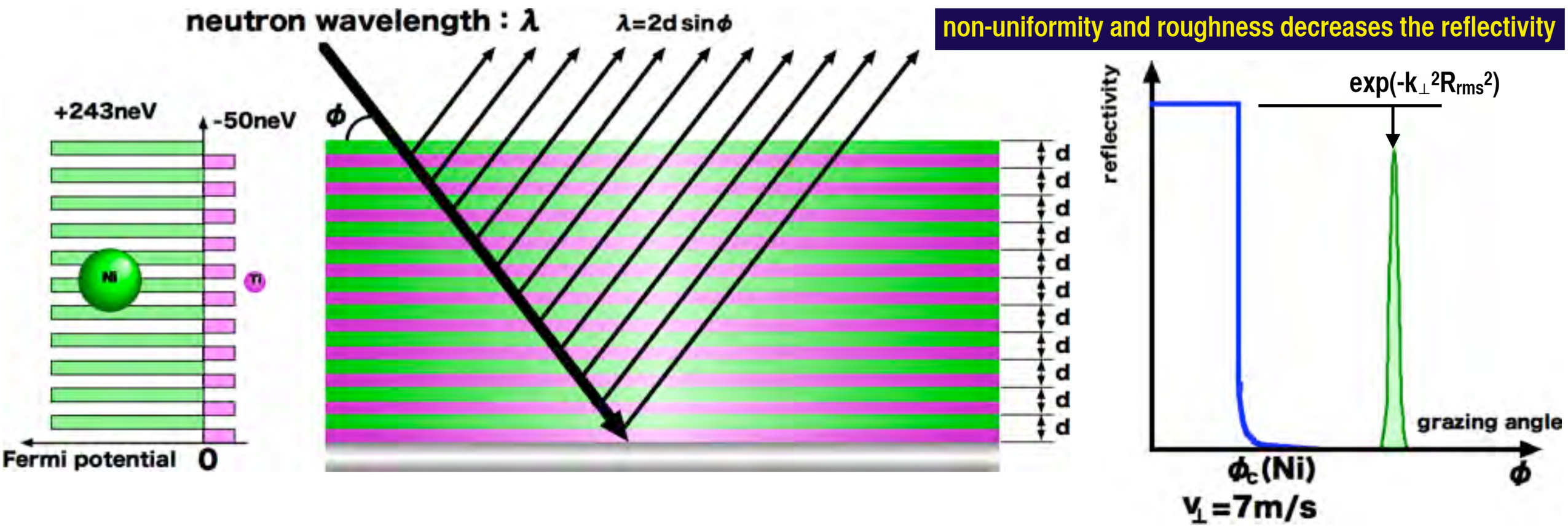






$\phi_c(Ni)/\lambda$=1.7 mrad/Å
$v_\perp(Ni)$=7 m/s

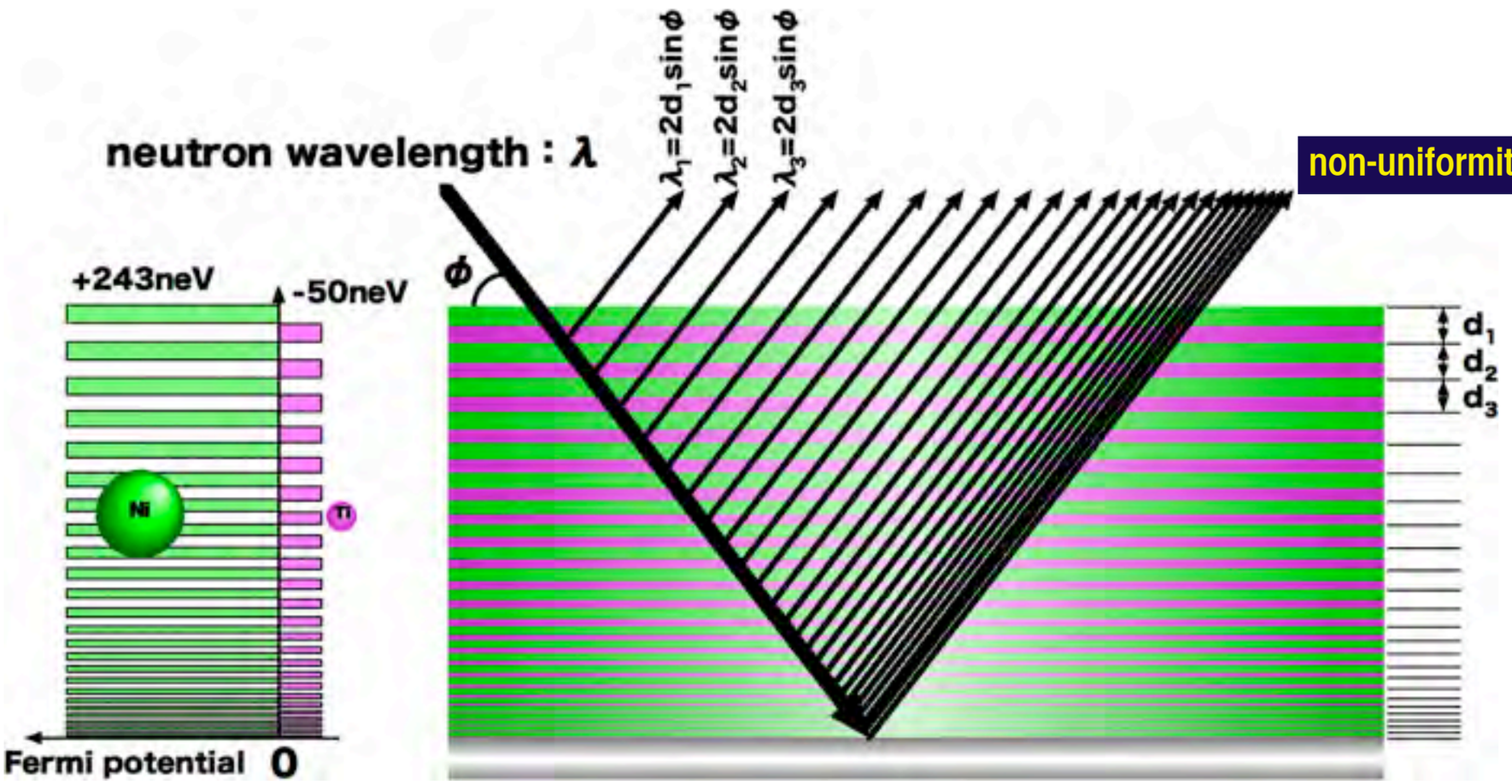
Multilayer Mirror (Monochromator)



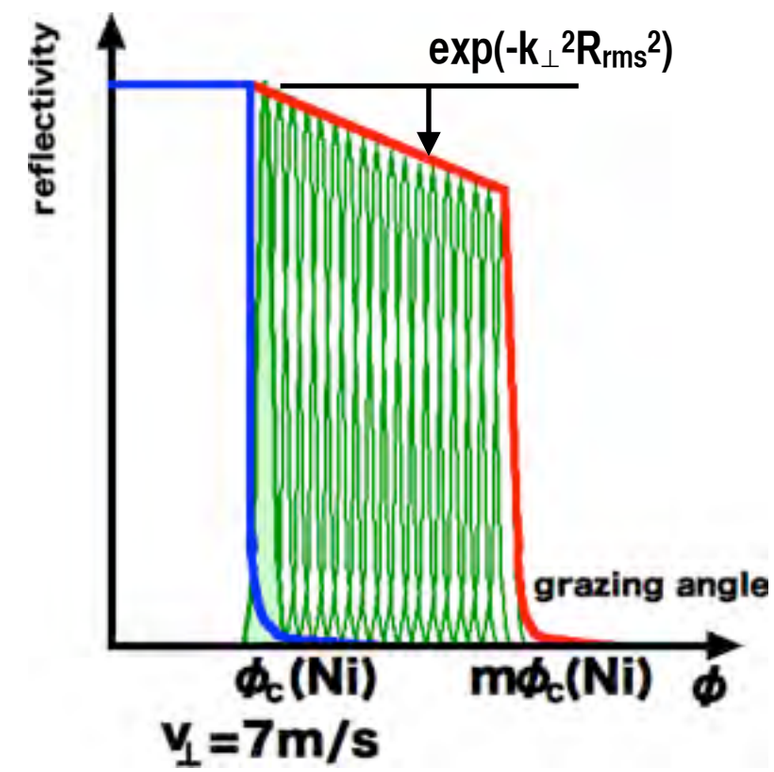
$\phi_c(Ni)/\lambda = 1.7$ mrad/Å

$v_\perp(Ni) = 7$ m/s

Supermirror



non-uniformity and roughness decreases the reflectivity

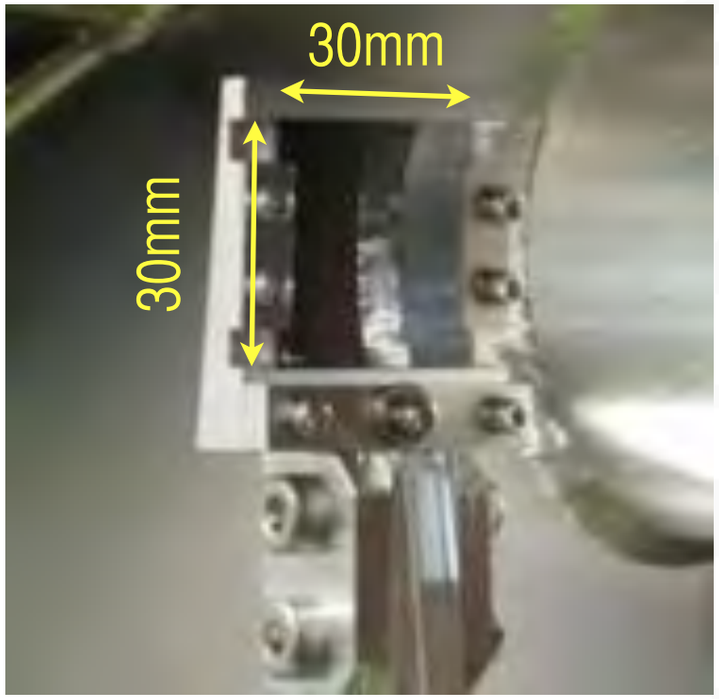


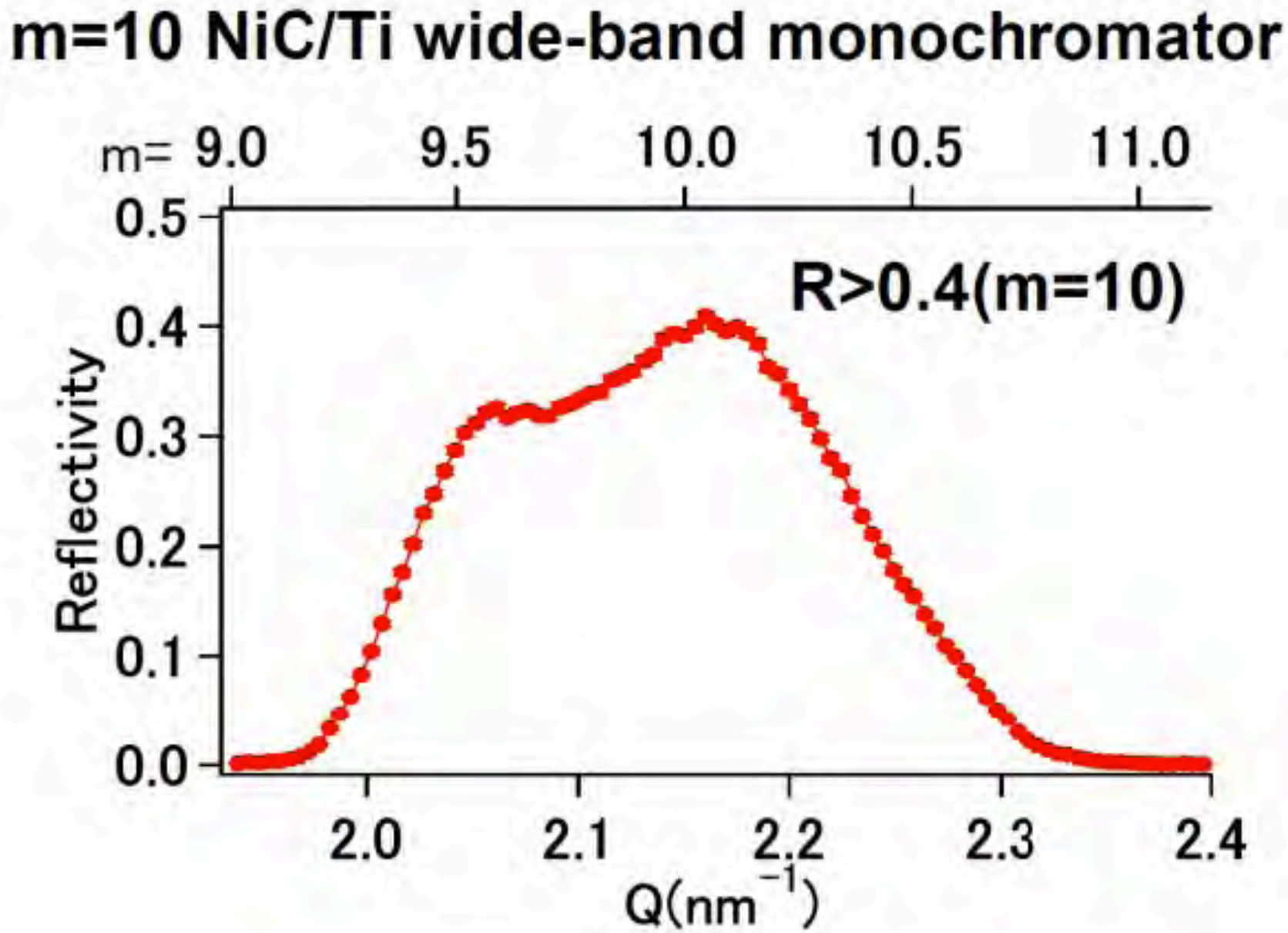
$m = \phi_c/\phi_c(Ni) = v_c(Ni)/v_c$

$\phi_c(Ni)/\lambda = 1.7$ mrad/Å
$v_\perp(Ni) = 7$ m/s

Monochromator

Quadruple-stack Multilayer

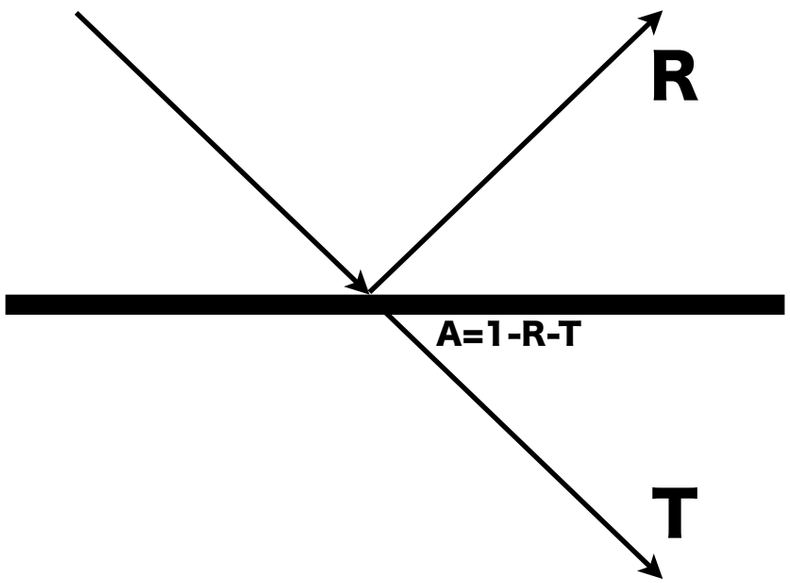




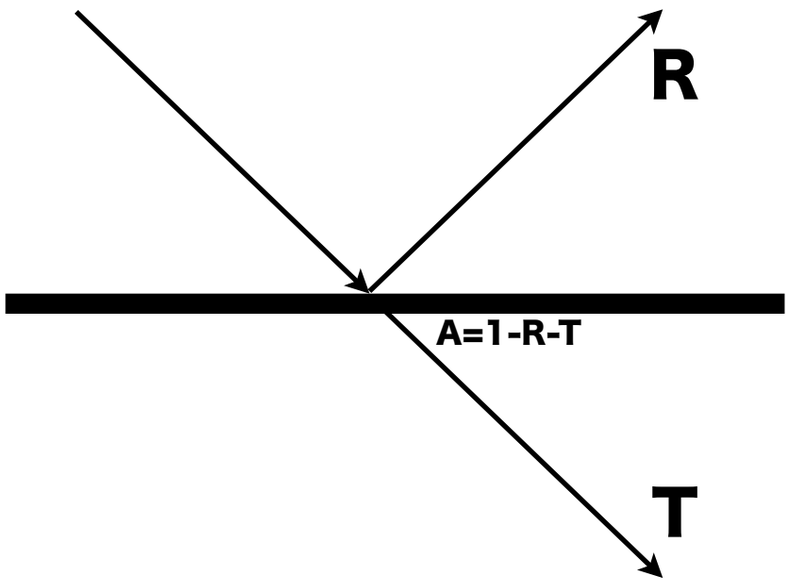
85060 bilayers in total = 4×(10336+10929 bilayers)

quadruple-stack of double-sided multilayer mirrors

Multiple-stack Multilayer

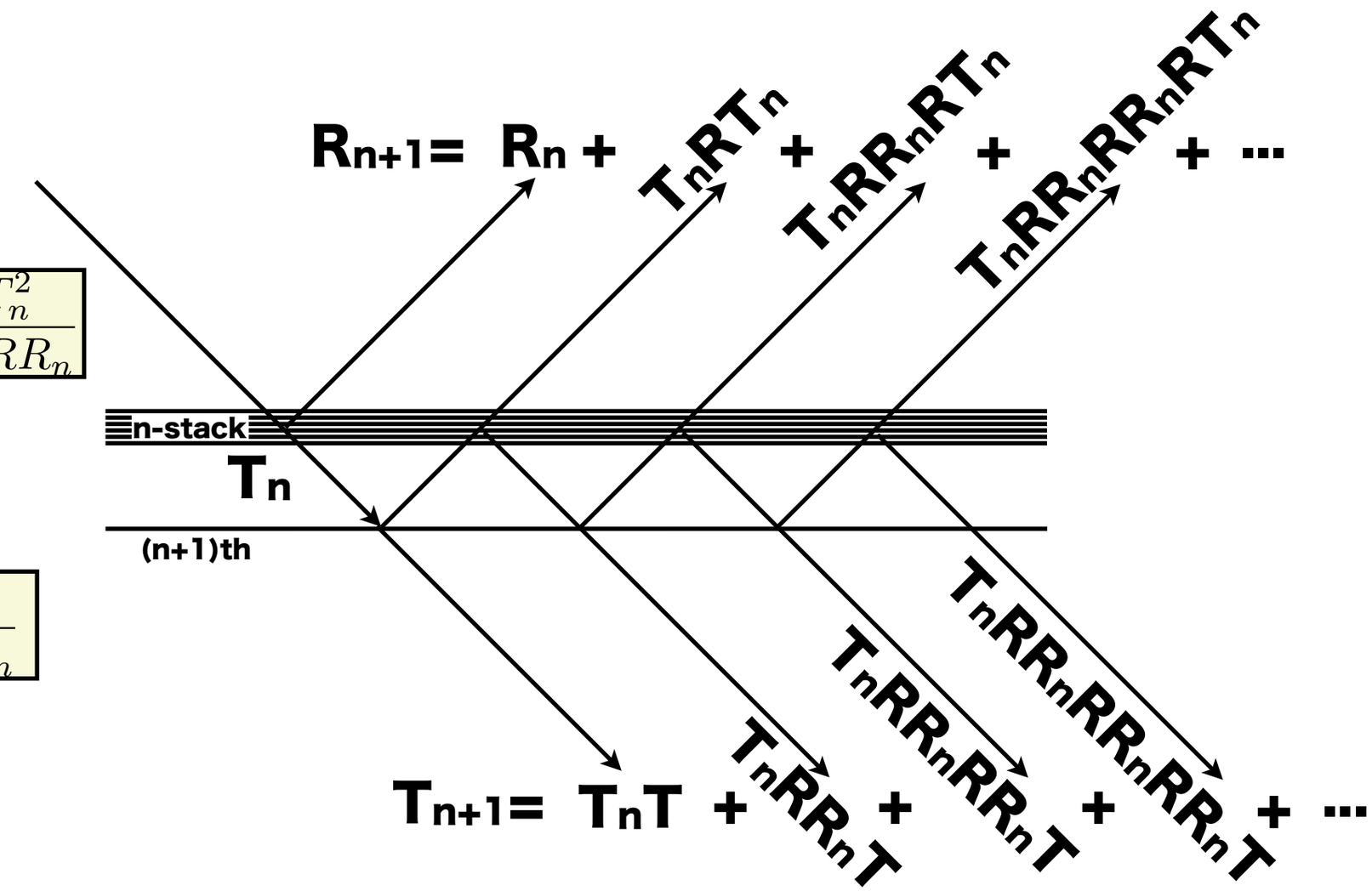


Multiple-stack Multilayer

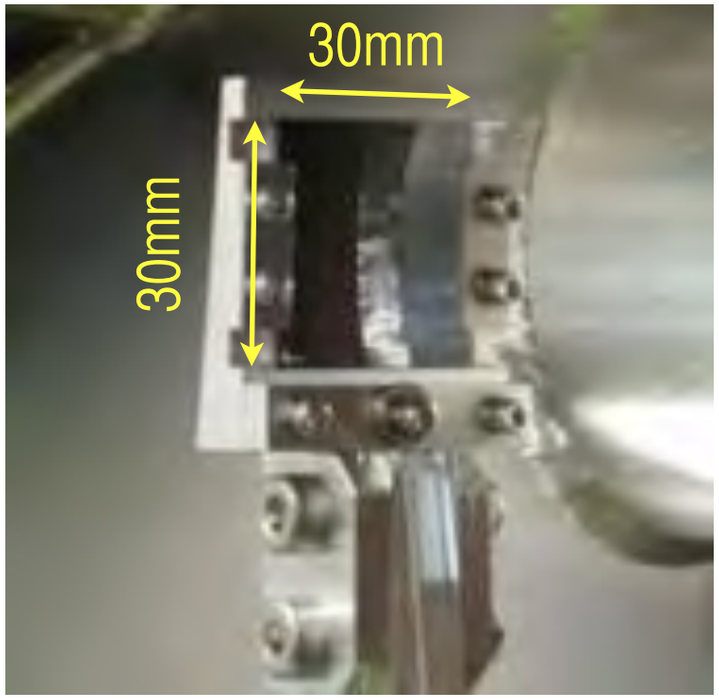


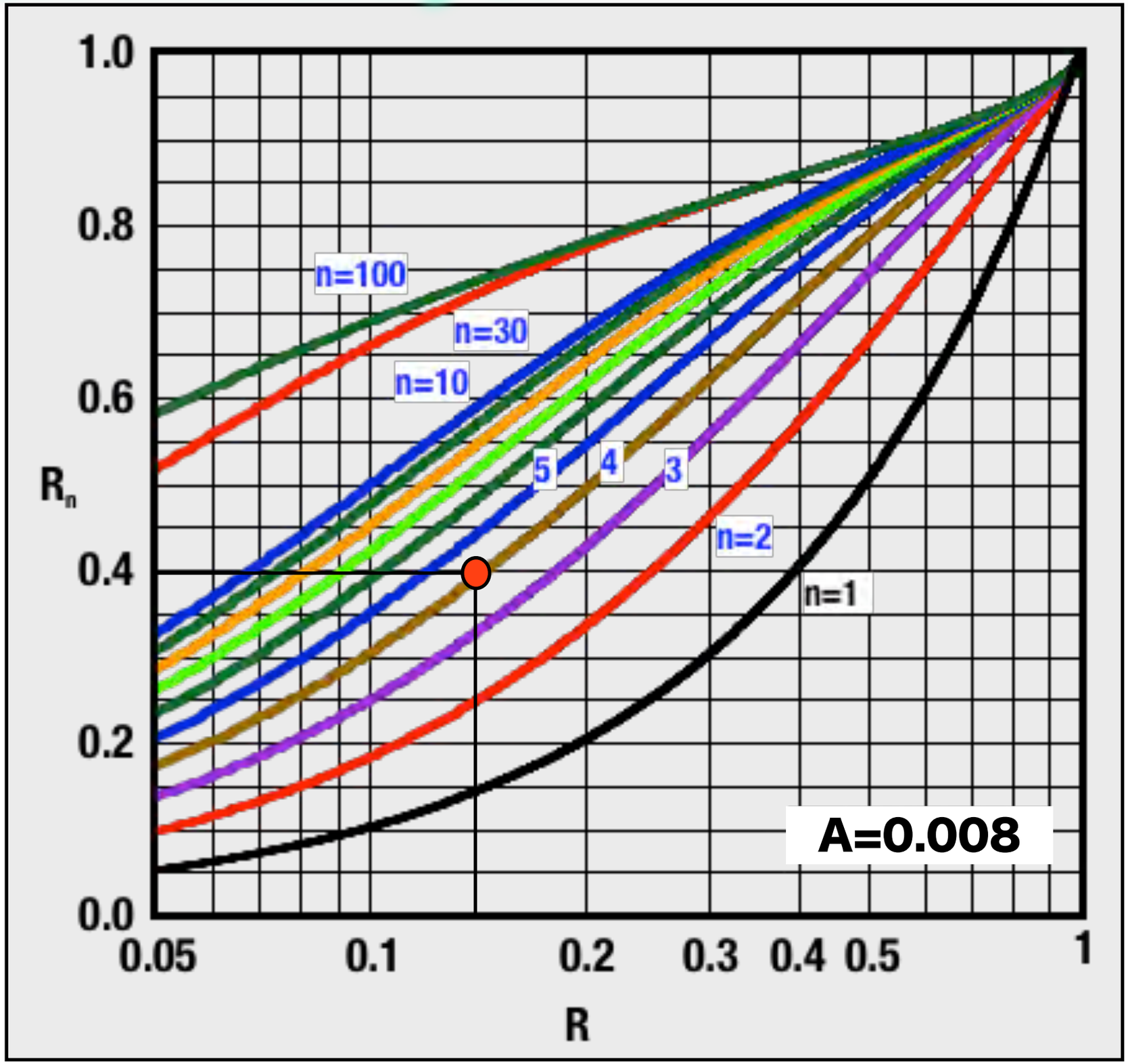
$$R_{n+1} = R_n + \frac{RT_n^2}{1 - RR_n}$$

$$T_{n+1} = \frac{TT_n}{1 - RR_n}$$

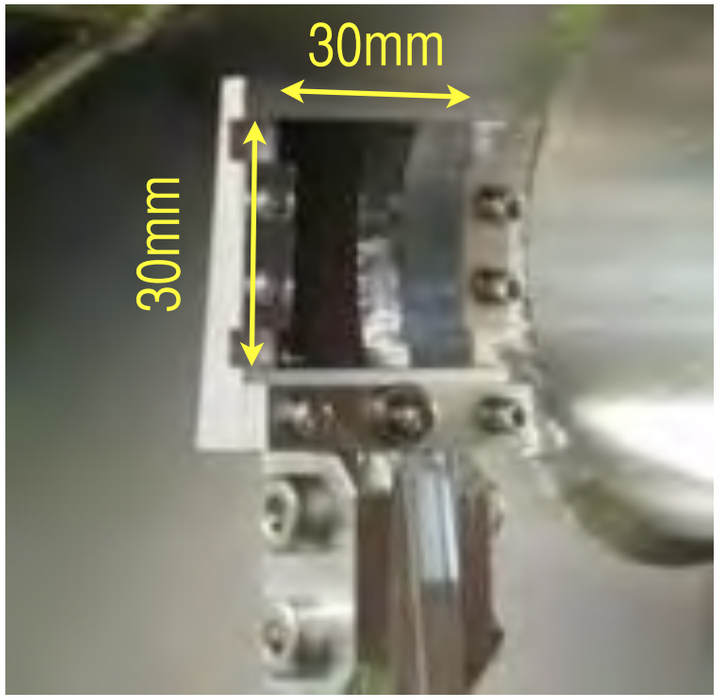


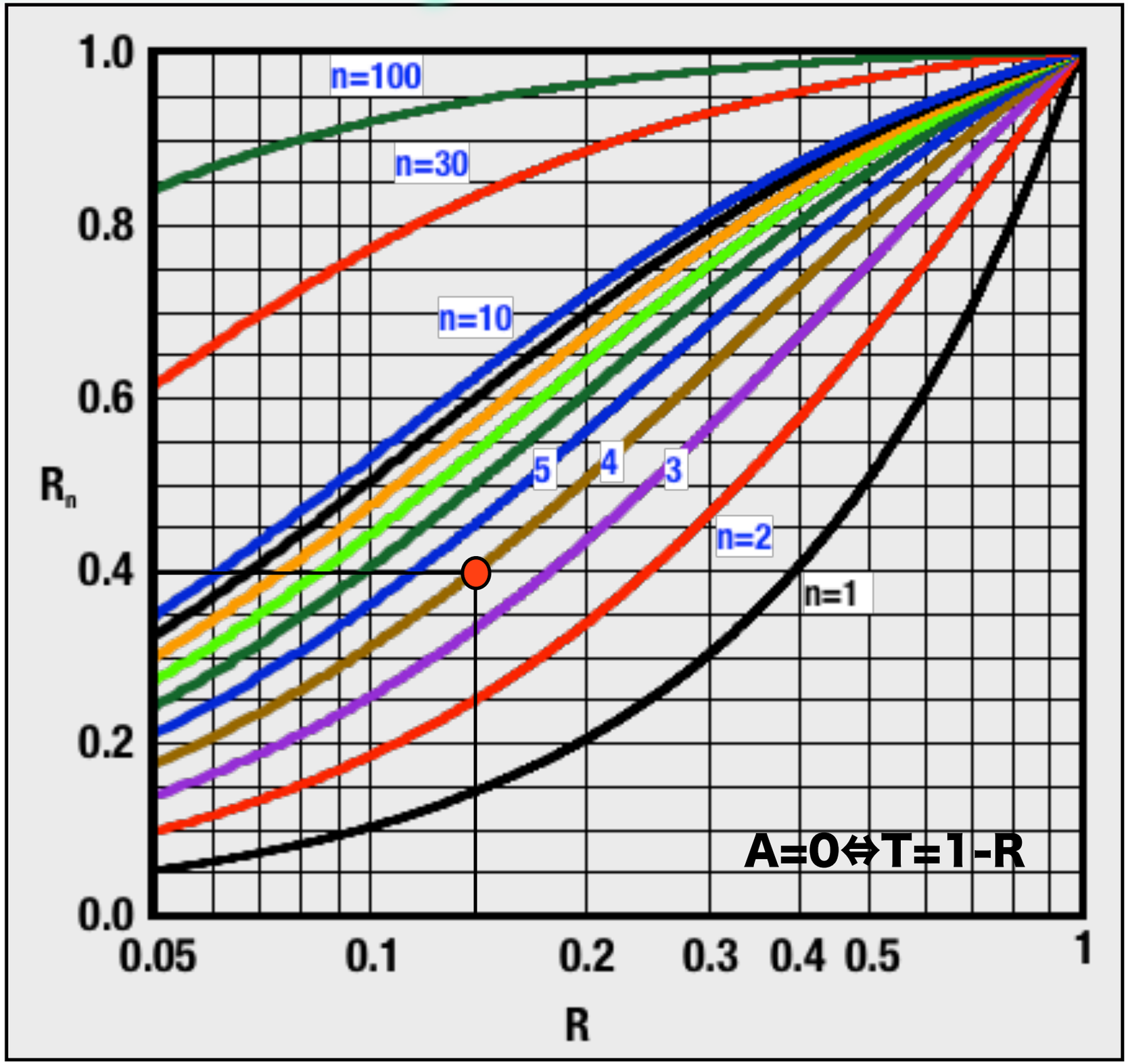
Multiple-stack Multilayer





Multiple-stack Multilayer

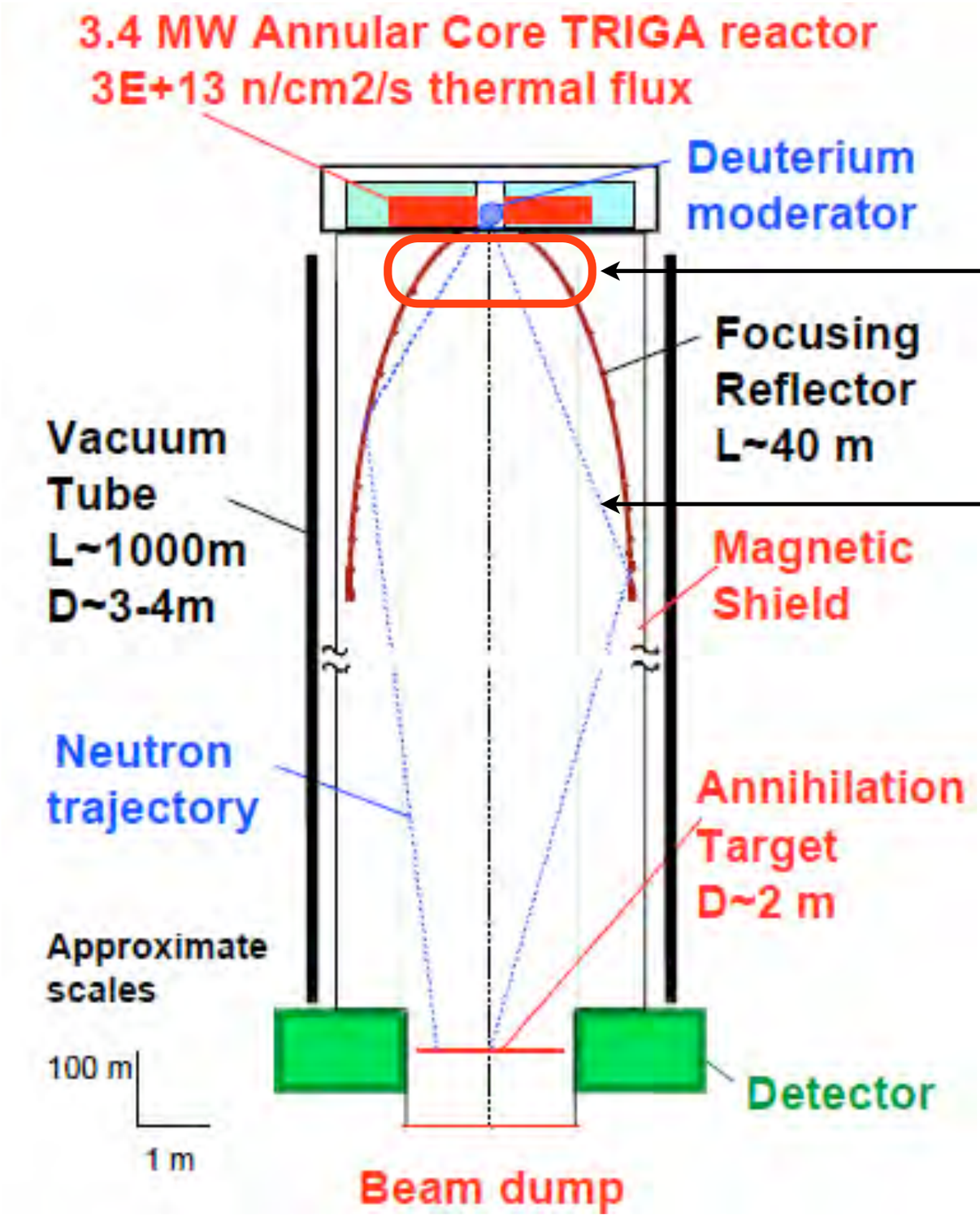




Option A

100-1000m Vertical Flight Path

Conceptual Scheme of Vertical Slow Neutron N-Nbar Experiment



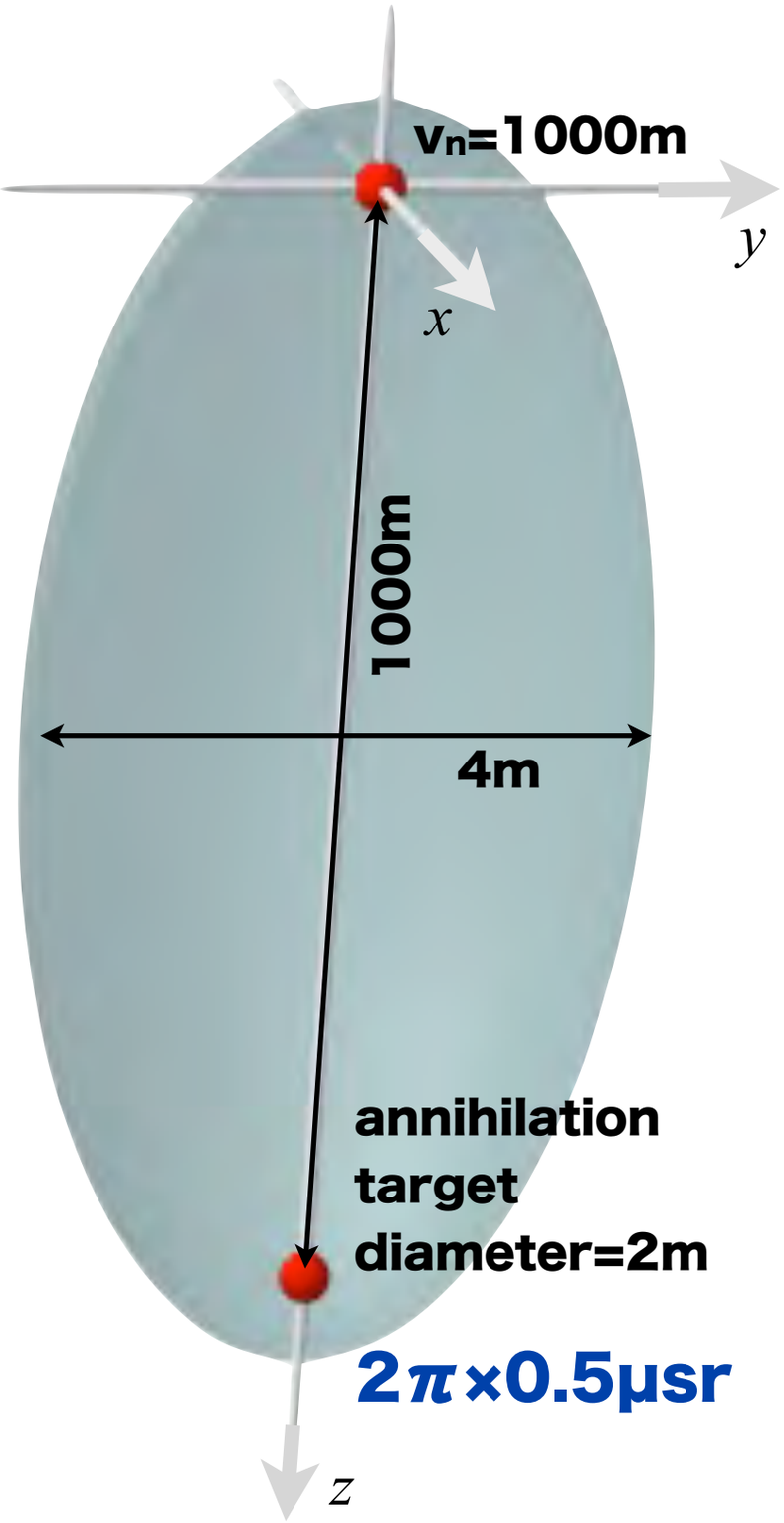
acceptance is dominated here

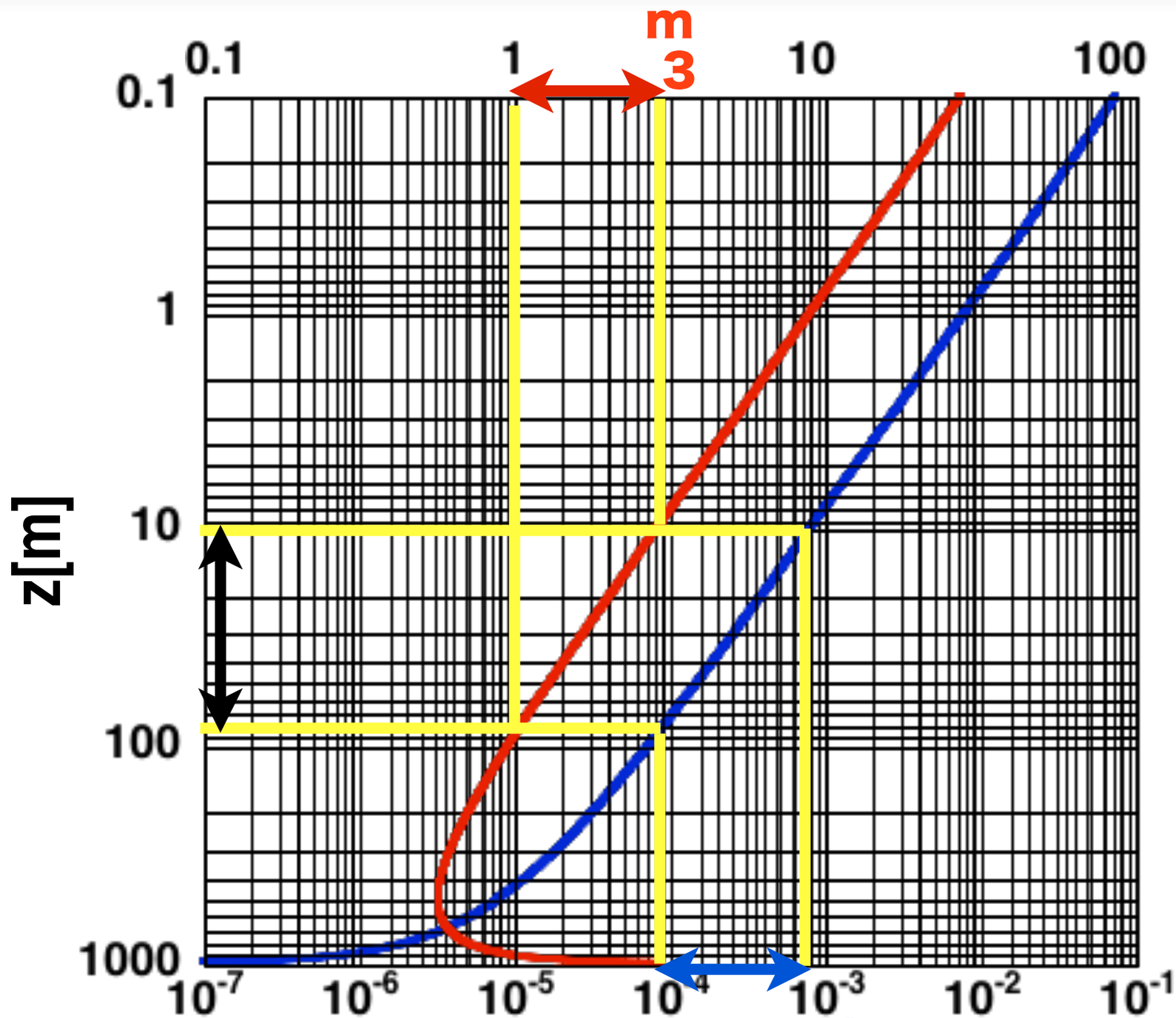
reflection angle is well-defined

band reflector is applicable

Focusing Mirror

m=3: 2πmsr

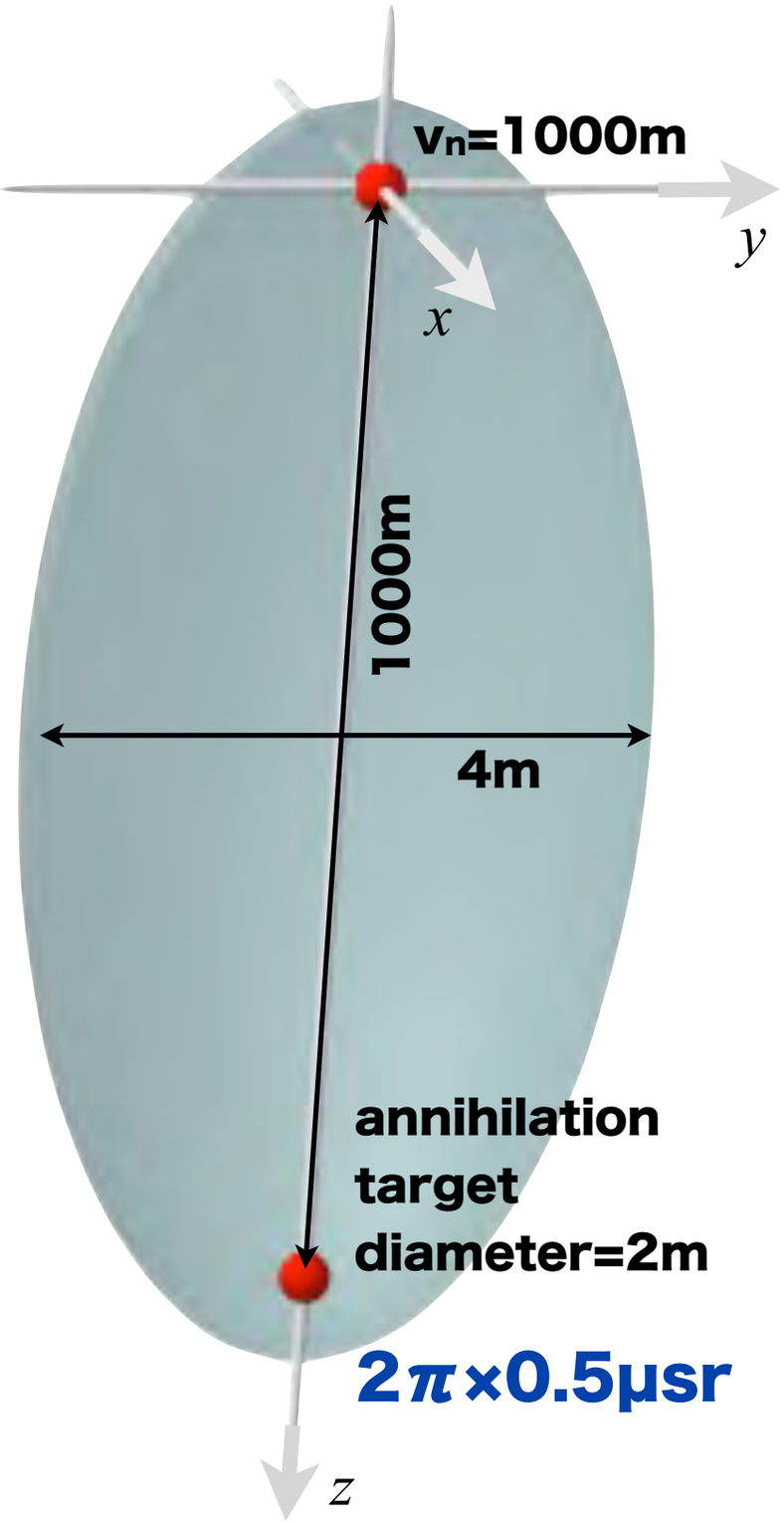


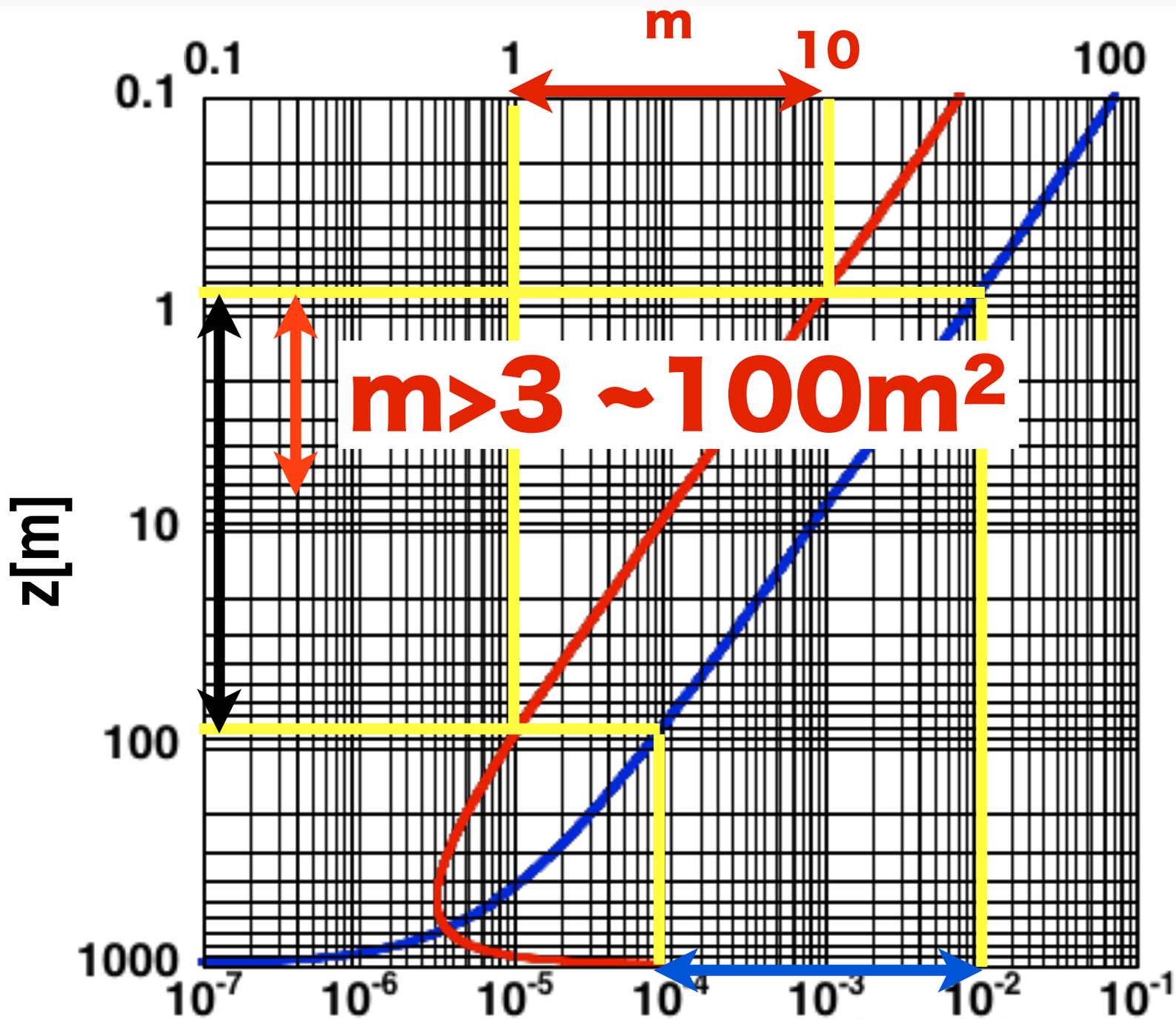


acceptance $\frac{1}{2\pi}\int_{1000m}^{z}\frac{d\Omega}{dz'}dz'$

Focusing Mirror

m=10: 2π×10msr



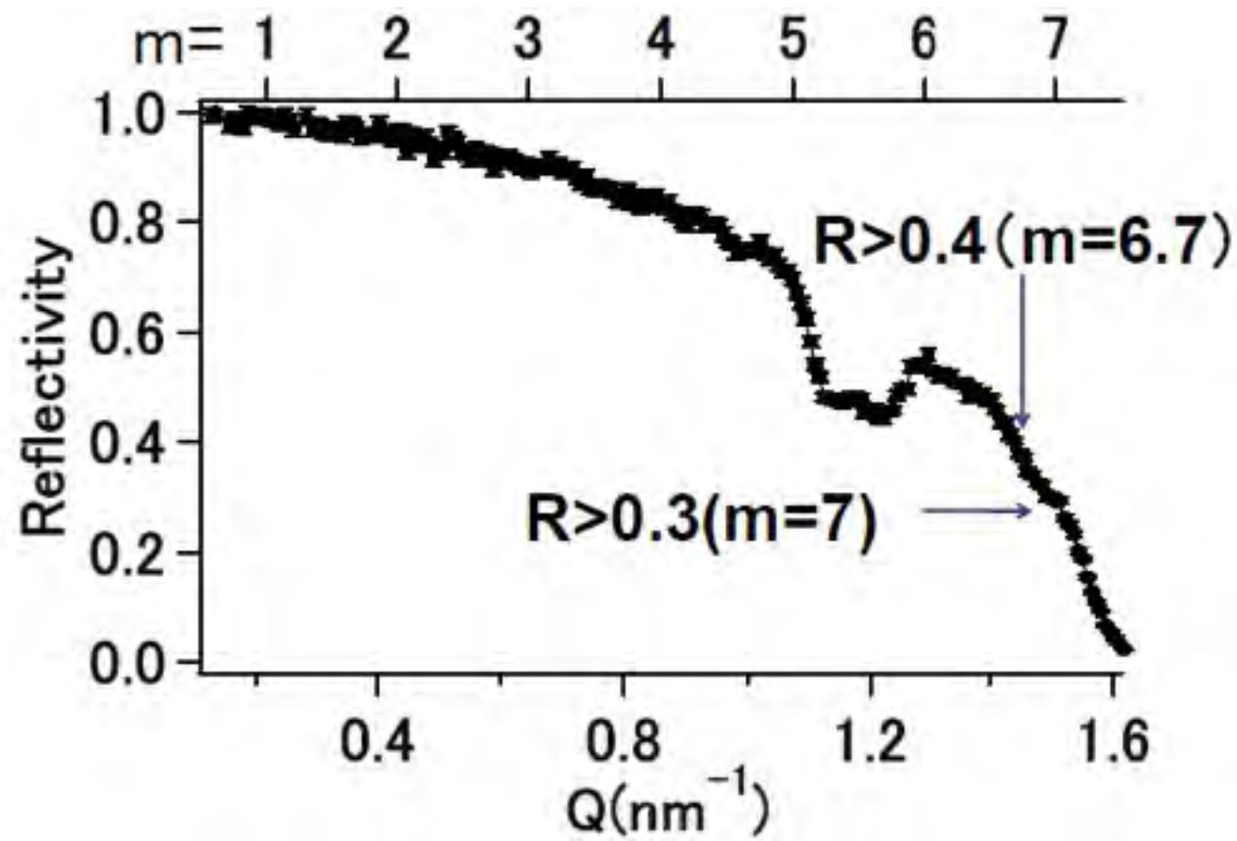


acceptance $\frac{1}{2\pi}\int_{1000m}^{z}\frac{d\Omega}{dz'}dz'$

Supermirror

First m=7 Supermirror

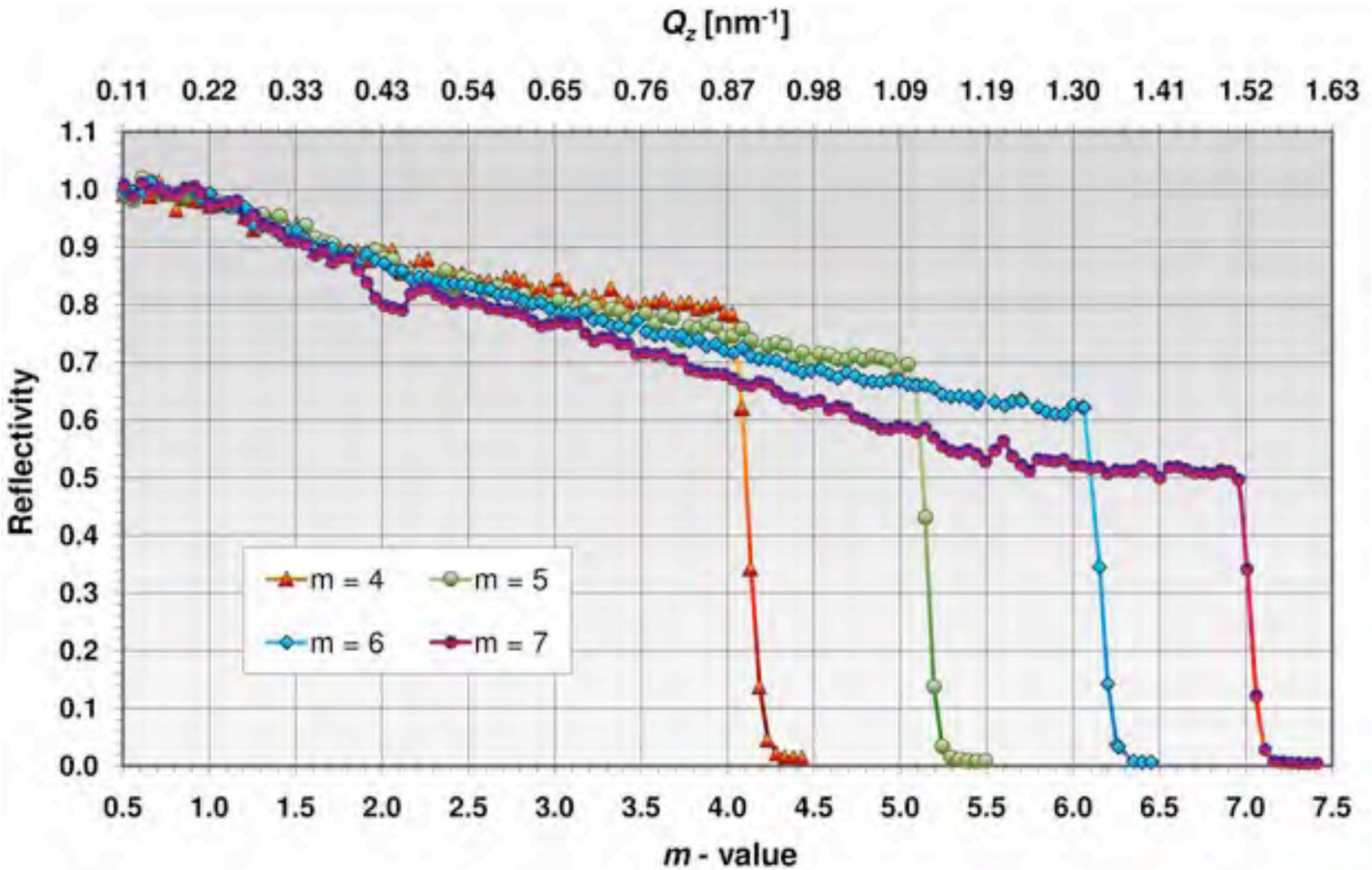
m=5 (4766 bilayers)
+ m=7 (7131 bilayers)



m=4-7 Supermirrors

http://www.swissneutronics.ch/

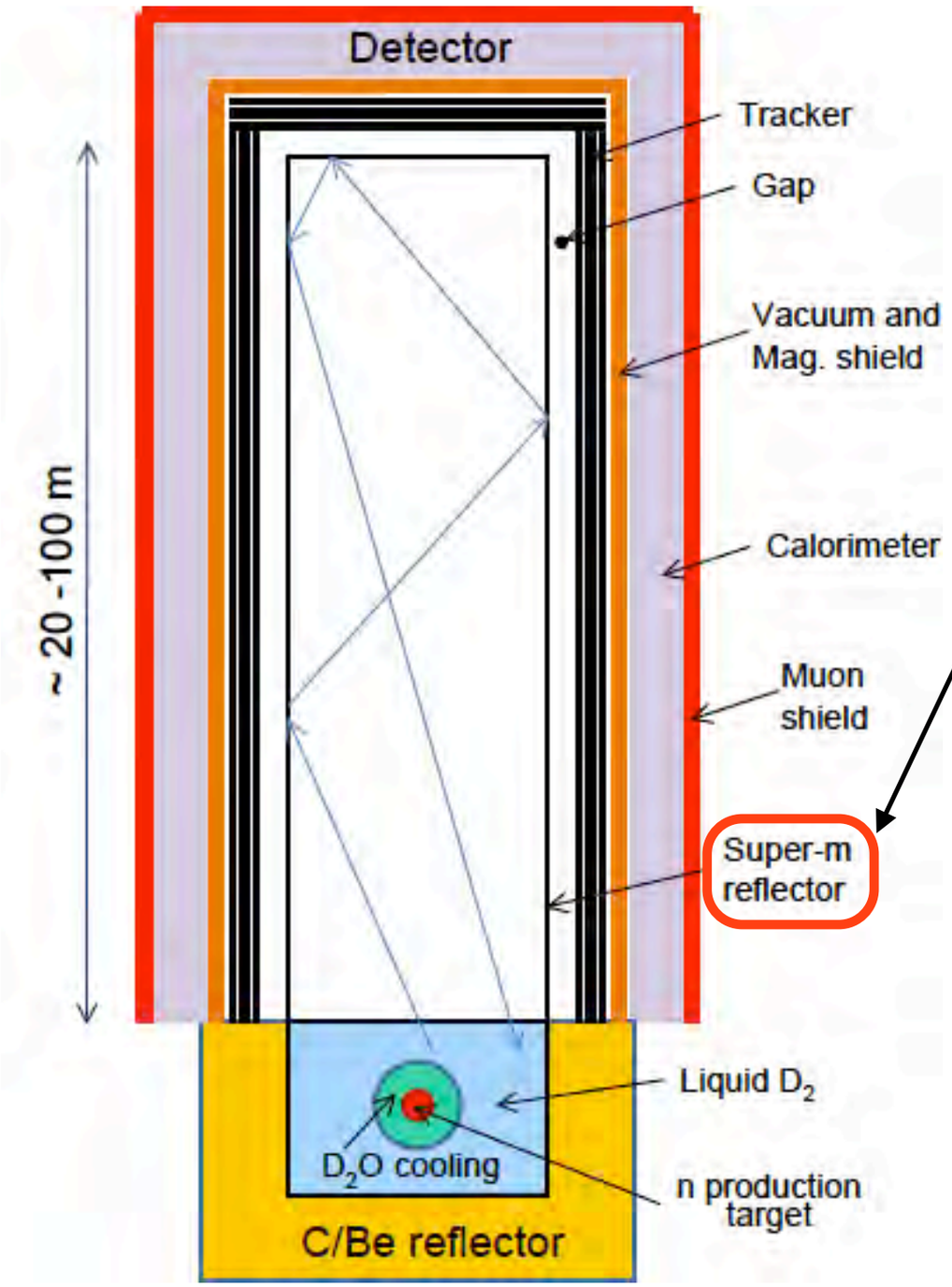
Supermirror: commercially available up to m=7 ($v_\perp$=50m/s)



Option B

10-100m Vertical Flight Path

n-nbar experiment using very cold neutrons



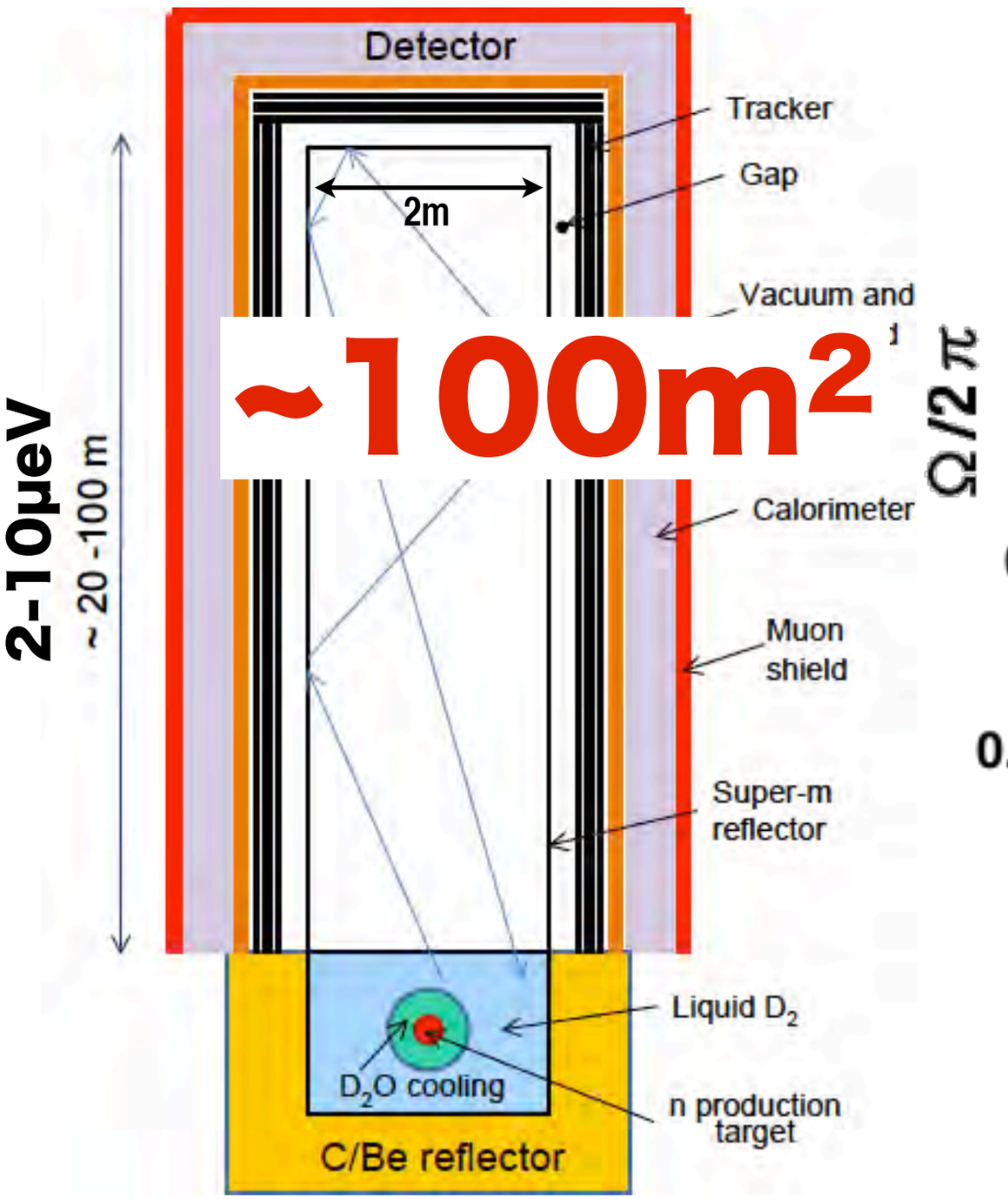
super-m reflector

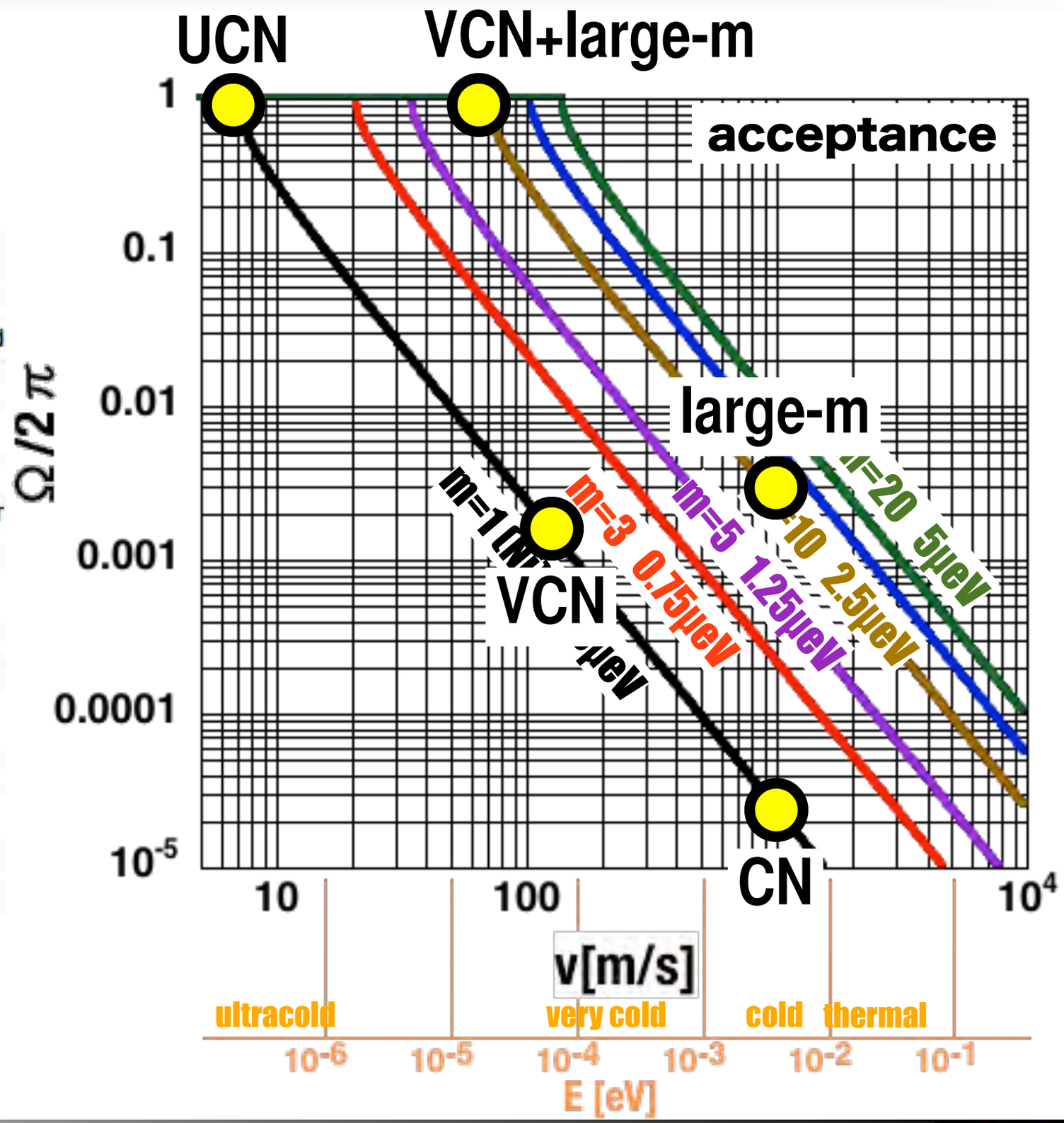
for enlarging acceptance

multilayer neutron mirror

(Super-m)

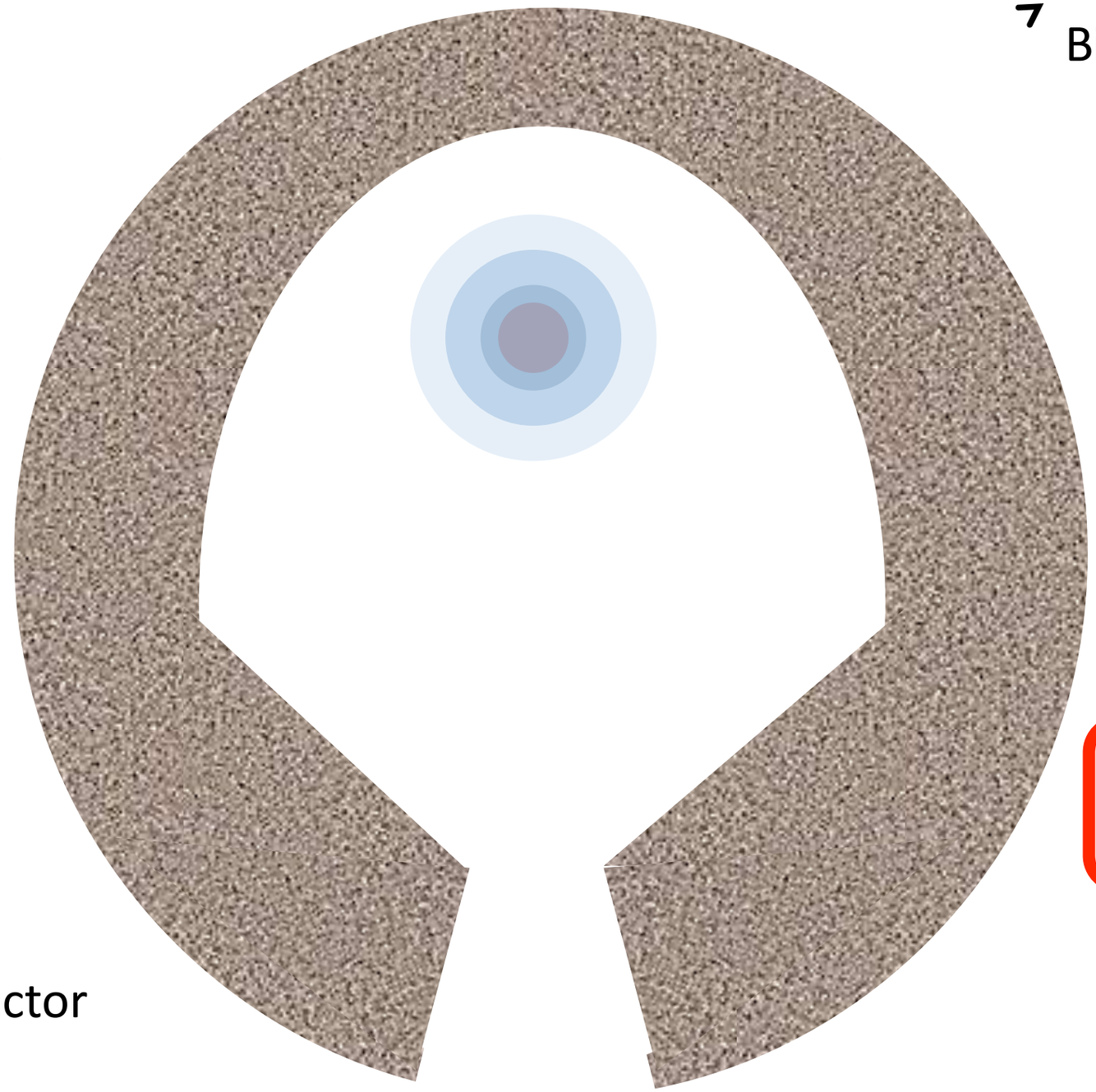
n-nbar experiment using very cold neutrons





Schematic of spallation target with UCN converter

(view along the beam)



Supermirror Demand

Option A: Focus to Vertically Remote Detector
monochromatic multilayer

~ 100m^2

Option B: Confinement of Very Cold Neutrons
supermirror

~ 100m^2

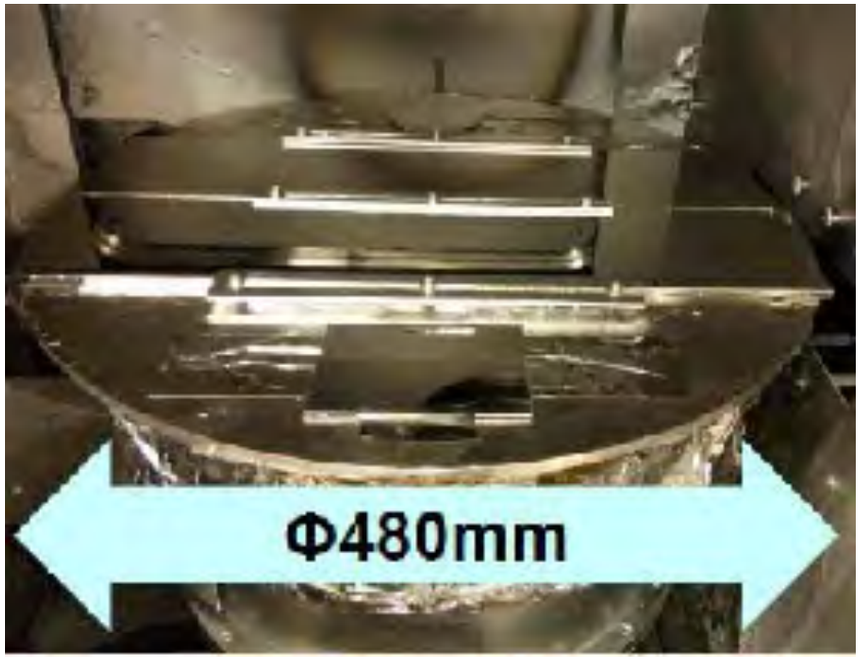
Enhancement of VCN Intensity
radiation-hard supermirror

~ 1m^2

Production Reality

Ion Beam Sputter @ KUR

2–3 MUSD/unit



0.1m²/batch

2 batch/day (m=3)

0.2 m²/day/unit

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5 units (10MUSD)

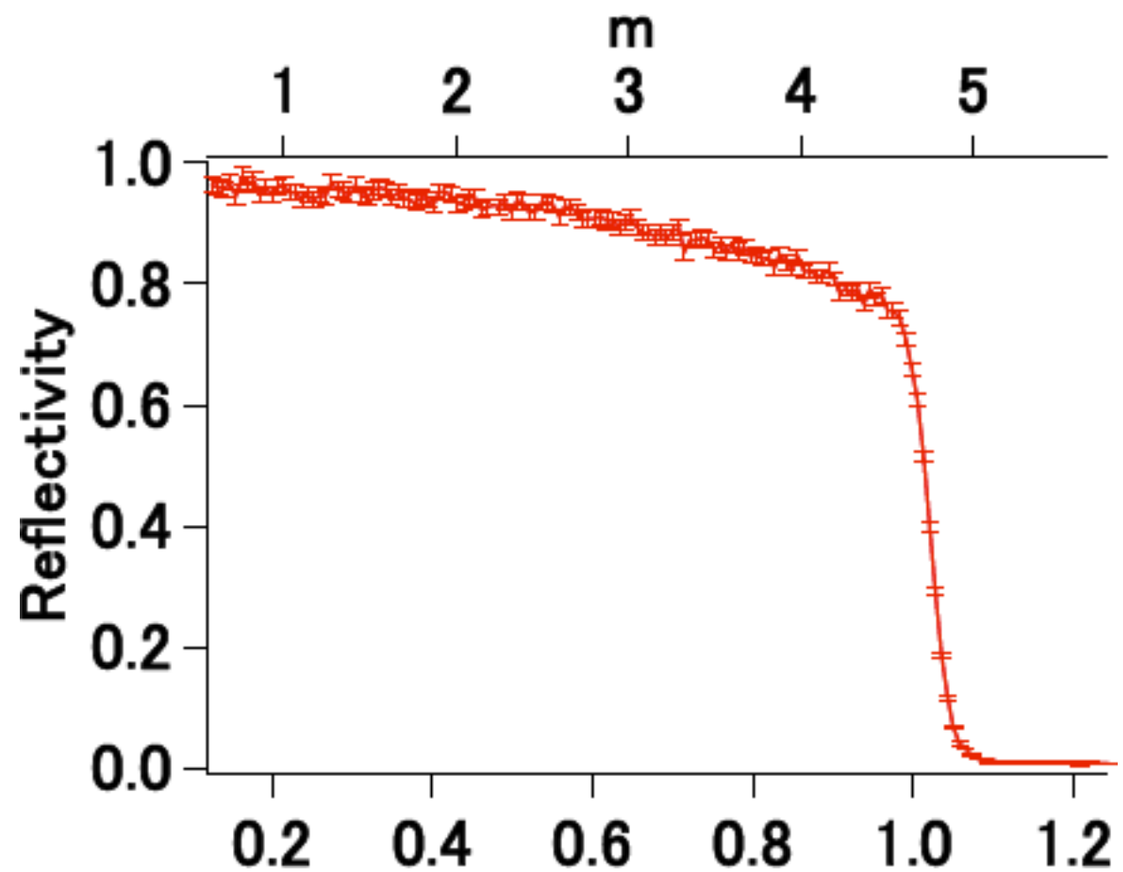
200 day/year (~0.3MUSD) → 100 m²/year 15MUSD

3 year R&D (~ 4MUSD)

A Quotation of m=3 Flat Mirror
100,000 JPY/0.01m² ~ 0.1 MUSD/m²

100 m² 10MUSD

Substrateless Supermirror



no substrate (radiation hardness expected)

DLC Supermirror?

DLC (Diamond-Like Carbon)

TNT Technical review No.77 (2009)

diamond

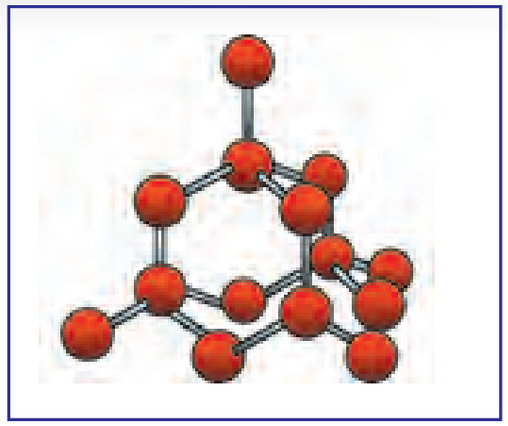
$$V_{\mathrm{diamond}} = \frac{2\pi\hbar^2}{m_n} bN = 303\mathrm{neV}$$

nuclear scattering length (b_c=6.65fm)

number density

d=3.515 g/cm³

b_C = 6.6535 fm

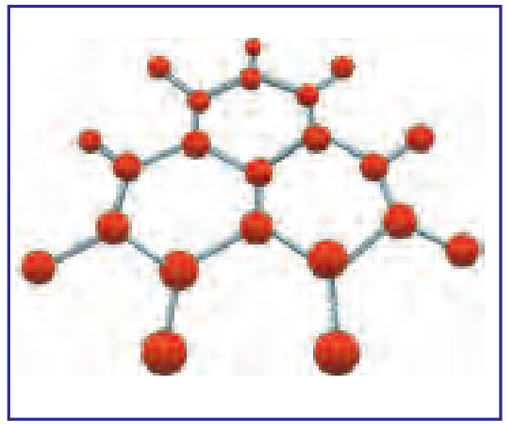


diamond (sp^3 hybrid)

graphite

$$V_{\mathrm{graphite}} = \frac{N_{\mathrm{graphite}}}{N_{\mathrm{diamond}}} \times 303\mathrm{neV} = 216\mathrm{neV}$$

d=2.267 g/cm³



graphite (sp^2 hybrid)

DLC **replace H with D**

$$V_{\mathrm{dDLC}} = \frac{N_{\mathrm{dDLC}}}{N_{\mathrm{diamond}}} \left(1 + 0.0031 \frac{N_{\mathrm{D}}}{N_{\mathrm{C}}}\right) \times 303\mathrm{neV}$$

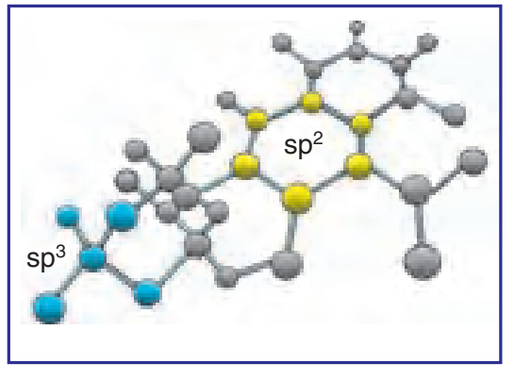
0.84

0.34

$$\simeq 255\mathrm{neV}$$

d=2 g/cm³

b_D = 6.674 fm



diamond-like carbon

(mixture of sp^2 and sp^3 hybrids)

DLC Multilayer?

DLC(CH)

$$V_{\mathrm{DLC}} = \frac{N_{\mathrm{DLC}}}{N_{\mathrm{diamond}}}\left(1 - 1.56\frac{N_{\mathrm{H}}}{N_{\mathrm{C}}}\right) \times 303\mathrm{neV}$$

1 1

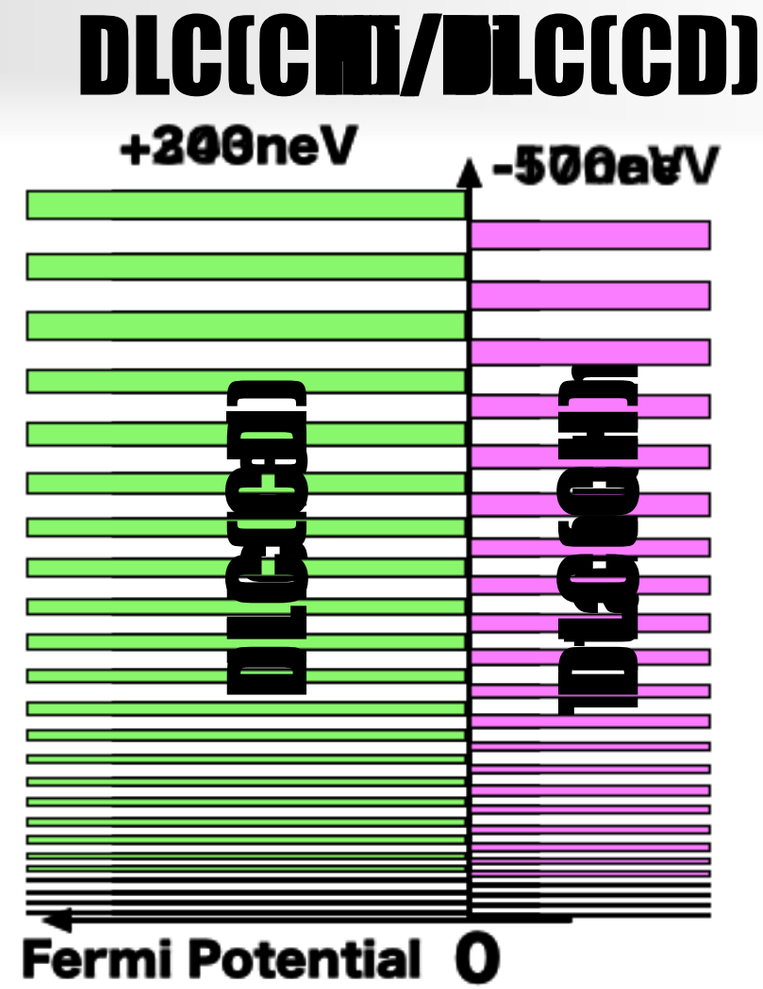
⇒ -170neV

DLC(CD)

$$V_{\mathrm{dDLC}} = \frac{N_{\mathrm{dDLC}}}{N_{\mathrm{diamond}}}\left(1 + 0.0031\frac{N_{\mathrm{D}}}{N_{\mathrm{C}}}\right) \times 303\mathrm{neV}$$

1 1

⇒ 300neV



JCANS

Japan Collaboration on Accelerator-driven Neutron Sources (since 2011/10/20)

for sharing R&D efforts on

- neutron production targets
- neutron moderators
- neutron reflectors
- radiation shields
- design methods
- management and maintenance

Hokkaido Univ., Faculty of Engineering — electron 45MeV

Y.Kiyanagi, M.Furusaka

for R&D, education

Kyoto Univ., Faculty of Science — proton 3.5MeV

T.Nagae, Y.Iwashita

for education

RIKEN, Innovation Center — proton 7MeV

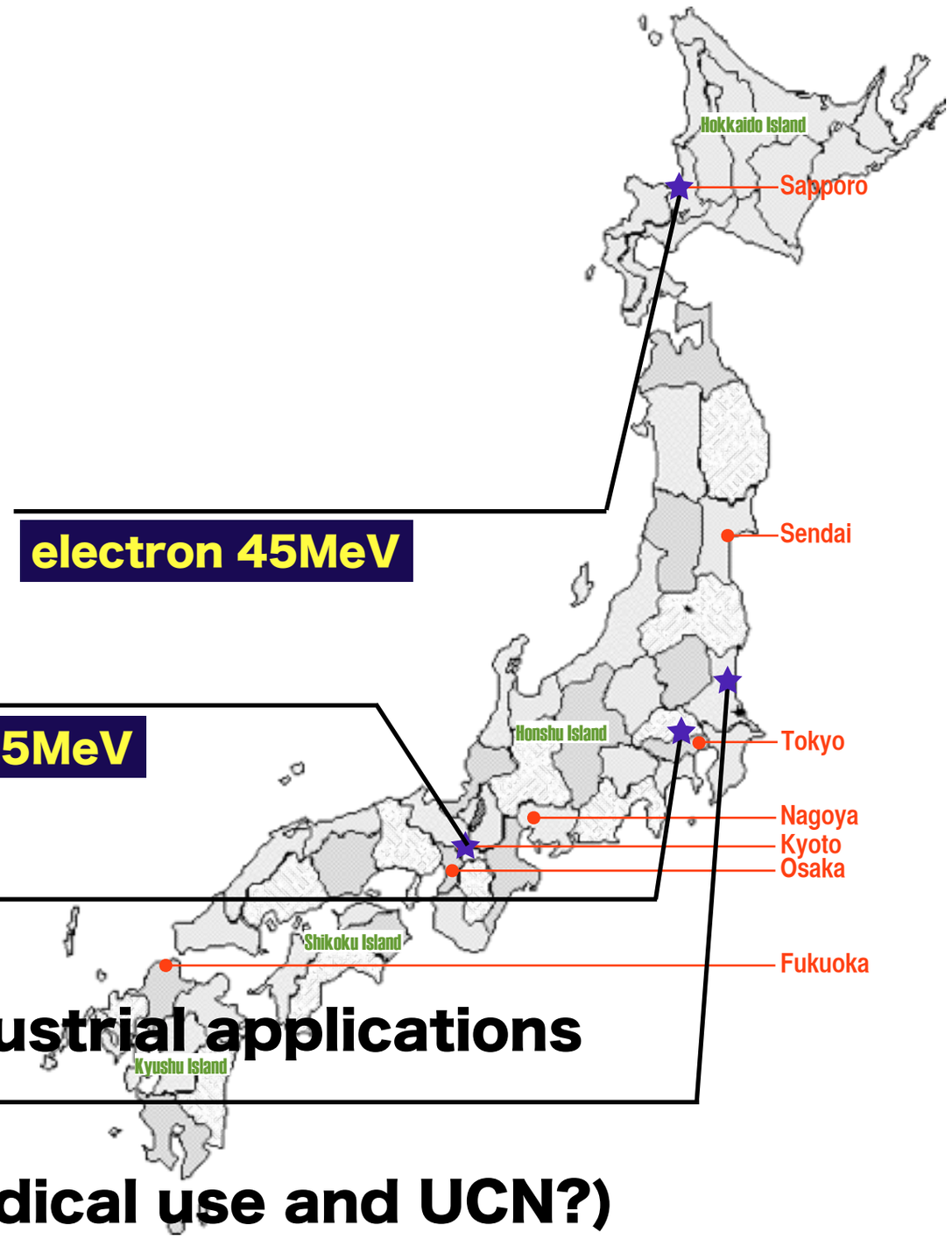
Y.Yamagata, Y.Otake, K.Hirota

for engineering and industrial applications

KEK, J-PARC — proton 3GeV

(H.M.Shimizu)

for special sources (medical use and UCN?)



Nagoya Univ., Faculty of Science

X-ray Mirror Production

Kobayashi-Maskawa Institute

Neutron Meeting at Nagoya (Nov, Dec 2012)

(proton 2.8MeV?)

Hokkaido Univ., Faculty of Engineering

Y.Kiyanagi, M.Furusaka

electron 45MeV

for R&D, education

Kyoto Univ., Faculty of Science

T.Nagae, Y.Iwashita

proton 3.5MeV

for education

RIKEN, Innovation Center

Y.Yamagata, Y.Otake, K.Hirota

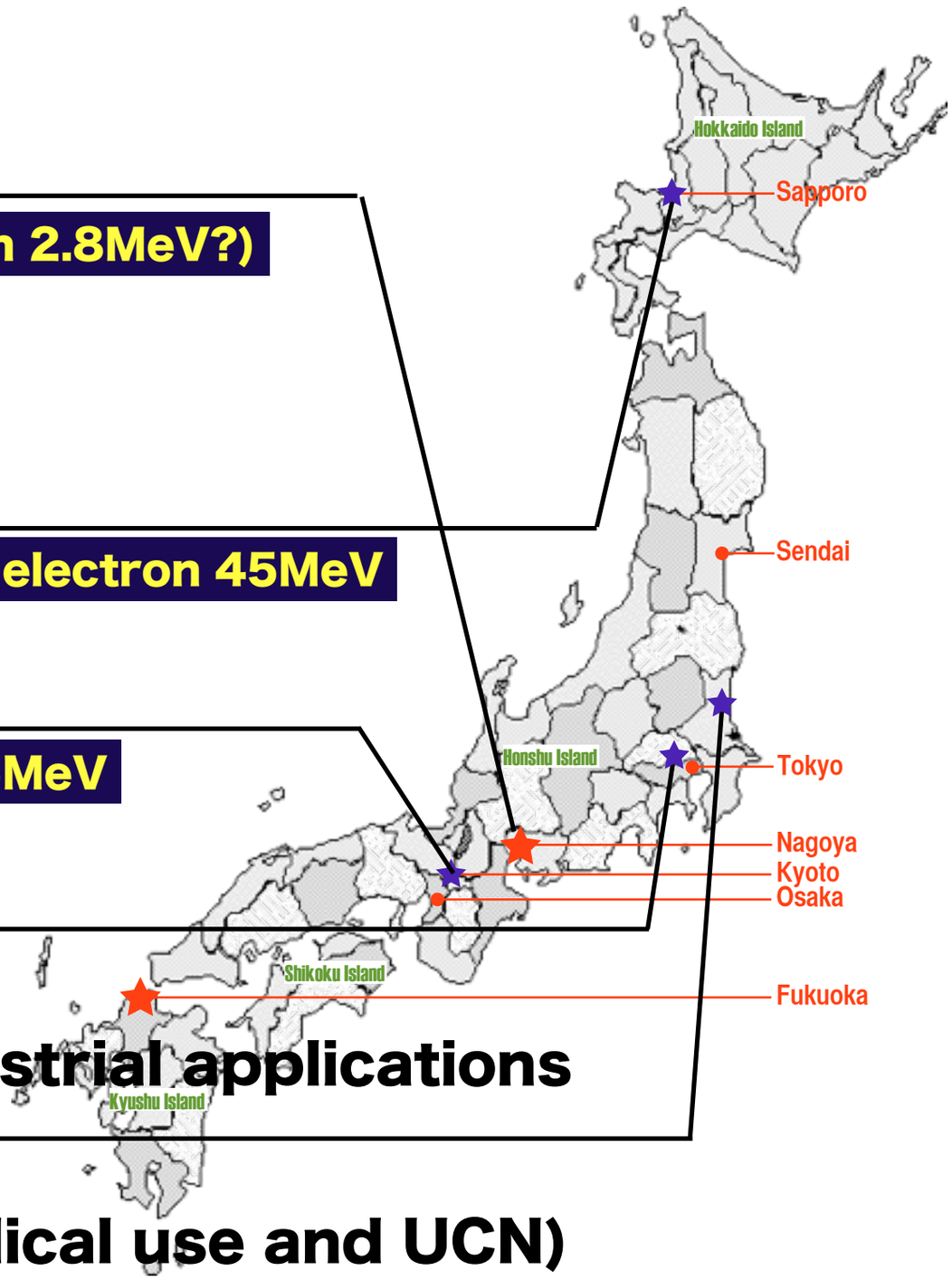
proton 7MeV

for engineering and industrial applications

KEK, J-PARC

proton 3GeV

for special sources (medical use and UCN)



Summary

Multilayer mirrors enhances the figure-of-merit of n-nbar experiments.

Multilayer fabrication technology was remarkably improved in the past decade.

monochromatic reflectors m≤10

Focusing of cold neutrons in vertical flight path

supermirrors m≤7

Confinement of VCN
Enhancement of VCN intensity

substrateless supermirrors m≤5

Enhancement of VCN intensity

THE END