Kyoto University Research Reactor Institute
neutron optics

Development of a very cold neutron spin interferometer (VCNSI)

and

related device developments(large-m (polarizing) supermirror and new cold neutron spin interferometer with BSEs）

Research Reactor Institute,
Kyoto University (KURRI)

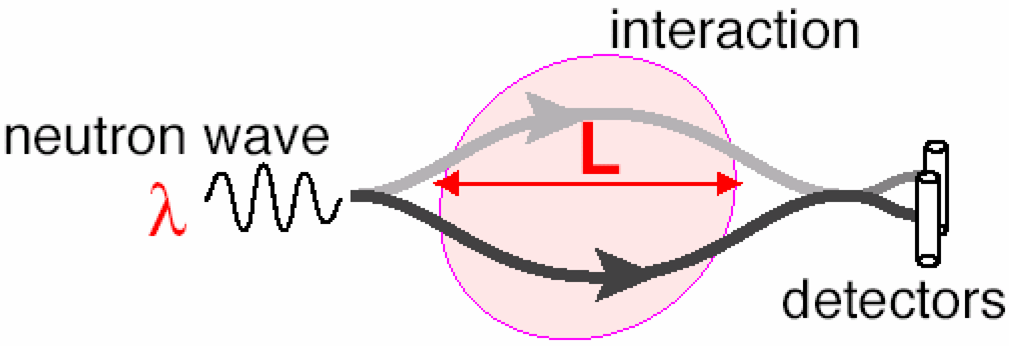
Masahiro Hino

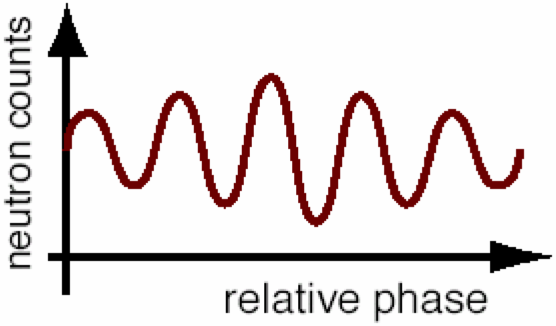
2006 Feb. 13 VCN workshop in PSI

Content

- **What is NSI? Example of NSI experiment (Larmor time is correct?)**
- **Development of VCNSI at ILL**
- **New NSI using Beam Splitting Etalon(BSE)**
- **Large-*m* (polarizing) supermirror developments at KURRI**

Neutron interferometry





$$\Delta\phi = 2\pi\frac{m\lambda L}{h^2}\Delta E$$

λ: neutron wavelength
L: interaction path length
ΔE: energy difference between two paths

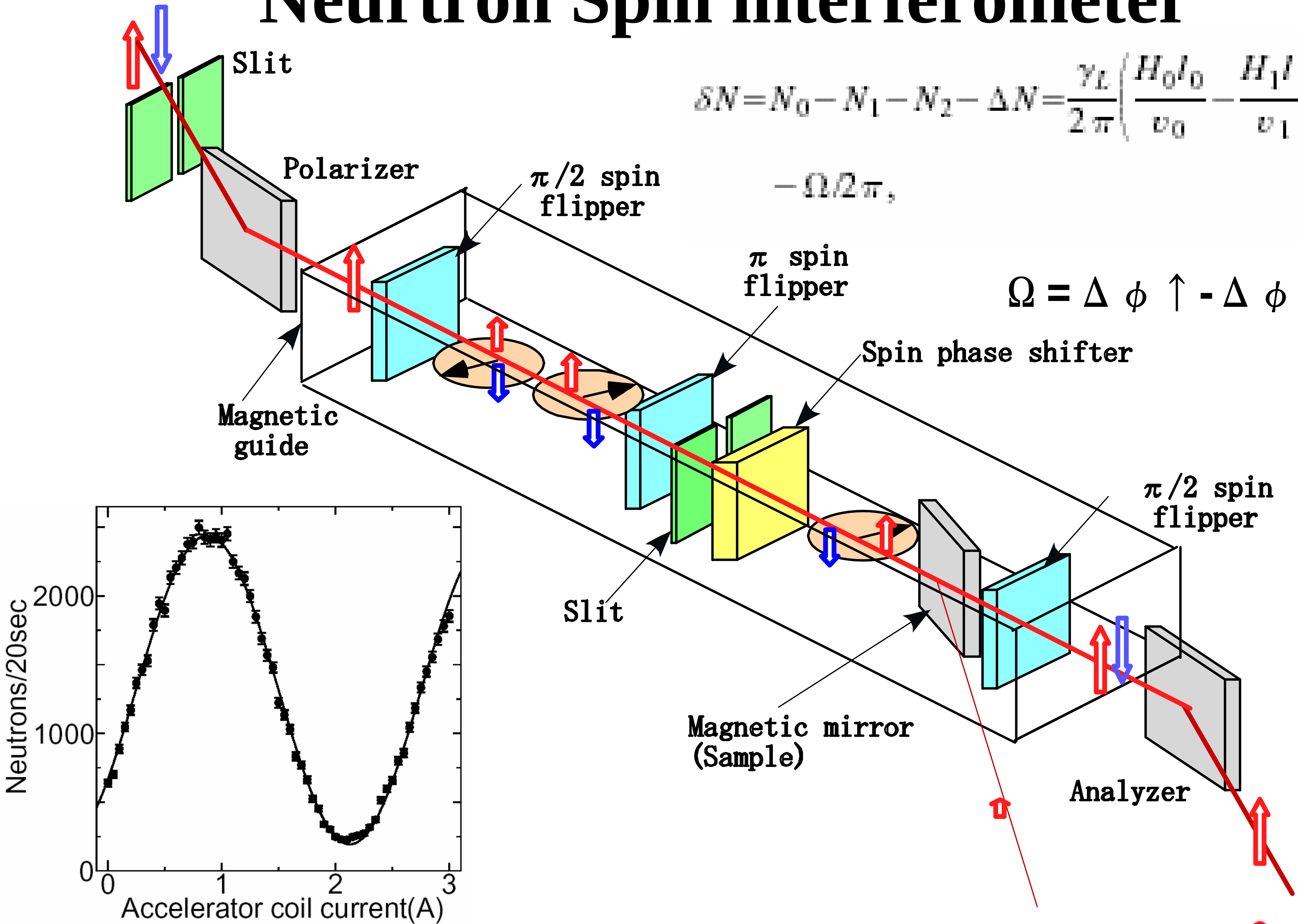
Large dimensional interferometer for long wavelength neutrons has the advantage to increase the sensitivity to small interaction.

Neurtron Spin interferometer

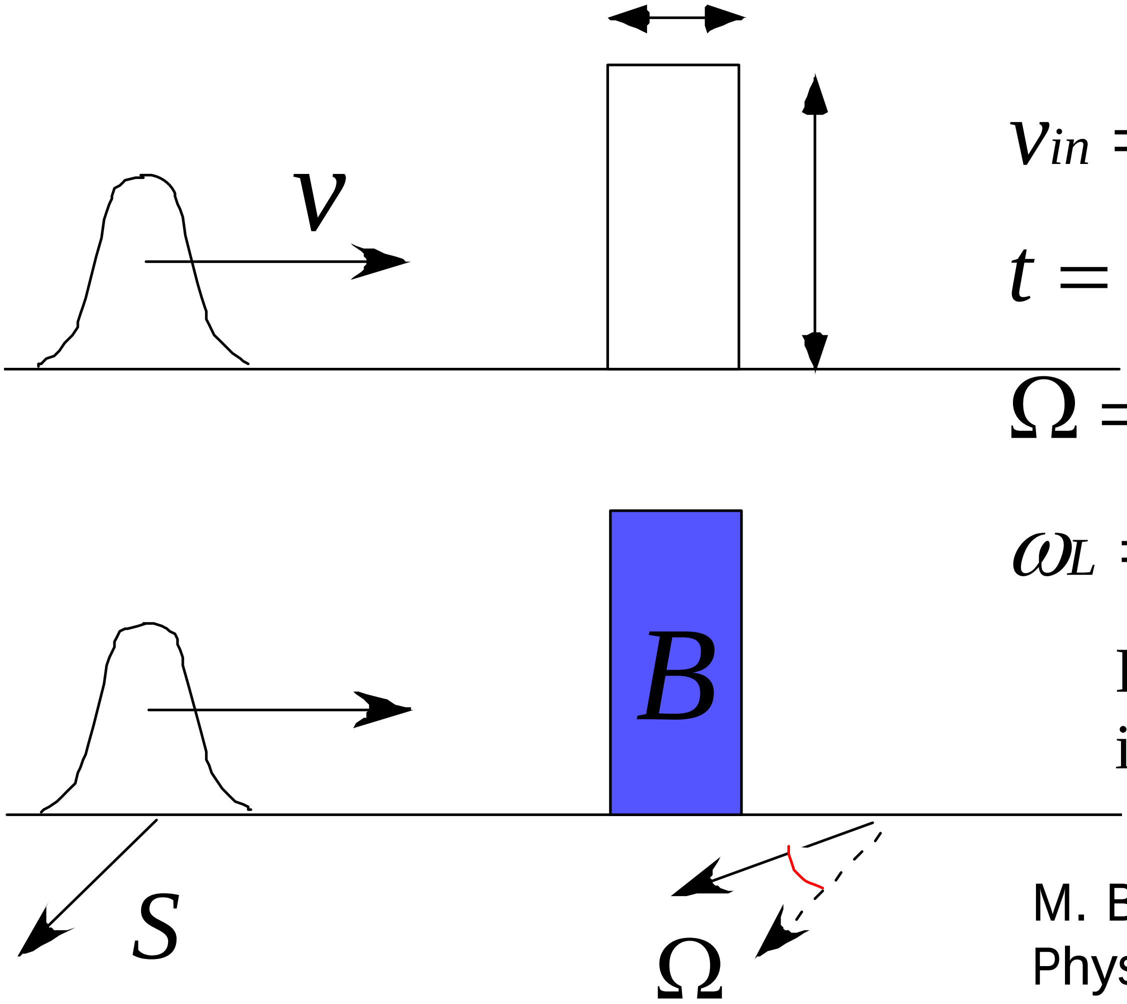
$$\delta N = N_0 - N_1 - N_2 - \Delta N = \frac{\gamma_L}{2\pi}\left(\frac{H_0 l_0}{v_0} - \frac{H_1 l_1}{v_1} - \frac{H_2 l_2}{v_1}\right.$$

$$-\Omega/2\pi,$$

$$\Omega = \Delta\phi\uparrow - \Delta\phi\downarrow$$



Dwell time of tunneling particle?



$$v_{in} = \sqrt{E - U / m}$$

$$t = d / v_{in} = d / i \, | v_{in} | \, ?$$

$$\Omega = \omega_L t$$

$$\omega_L = \mu B$$

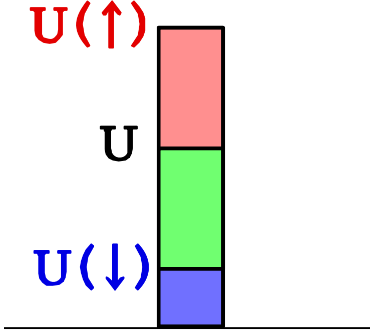
Is it possible to measure
it by using Larmor clock?

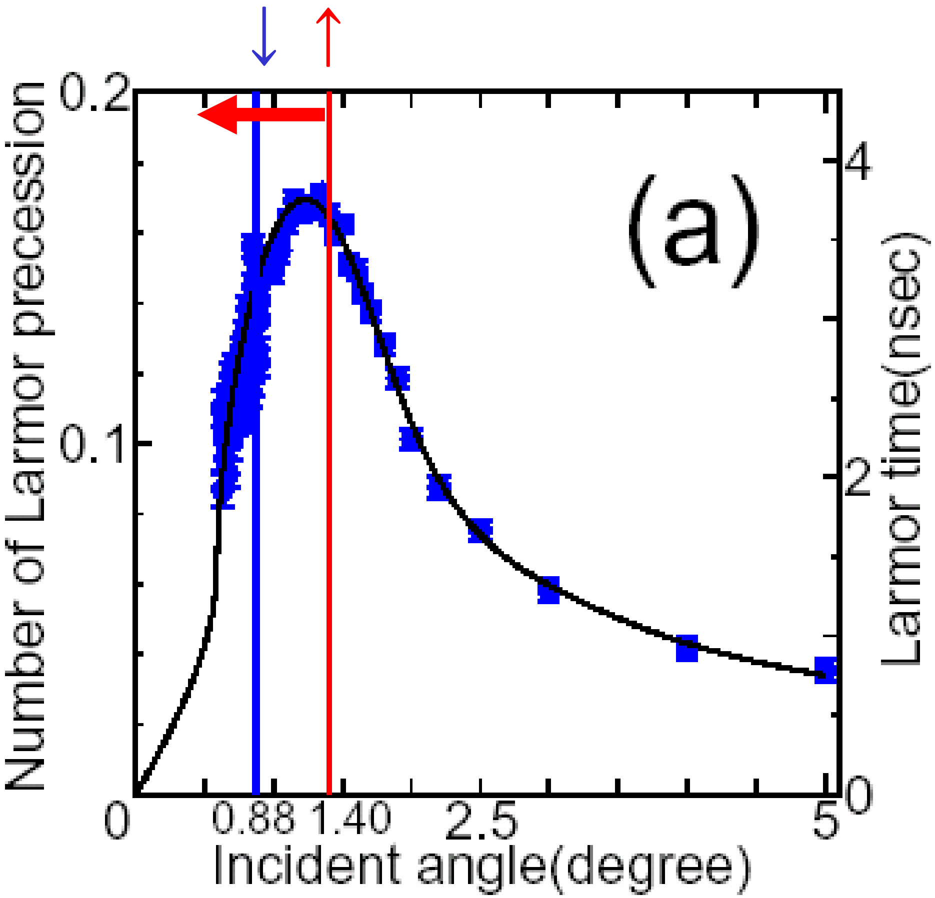
M. Buttiker,
Phys. Rev. B27, 6178(1983).

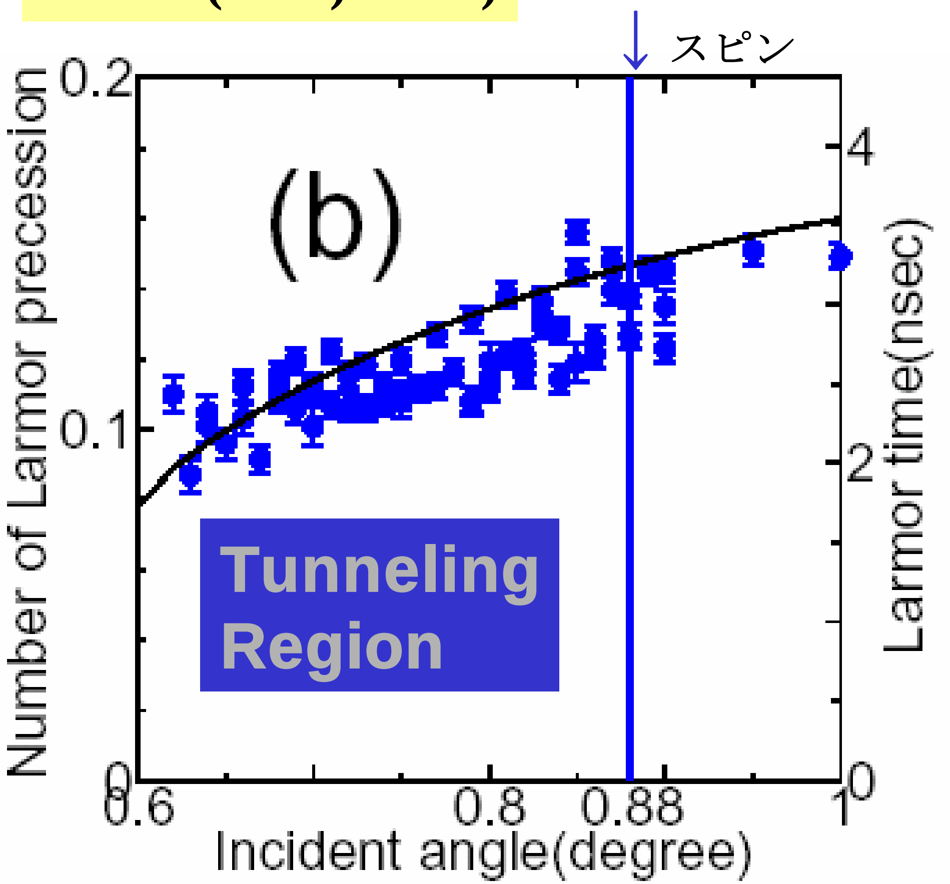
Measured spin precession of neutron transmitted through a magnetized thin layer

Permalloy45(PA):20nm

(M.Hino et al
PRA59(1999) 2261.)





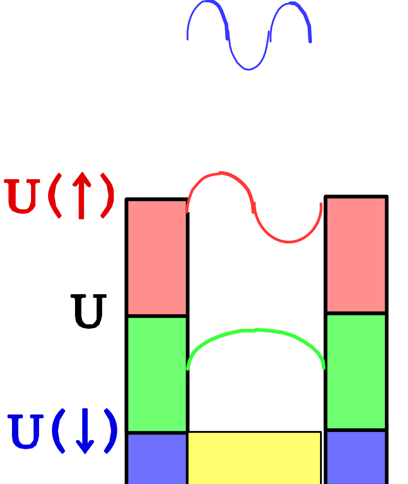


Incident wavelength 1.26nm(FWHM 3.5%)

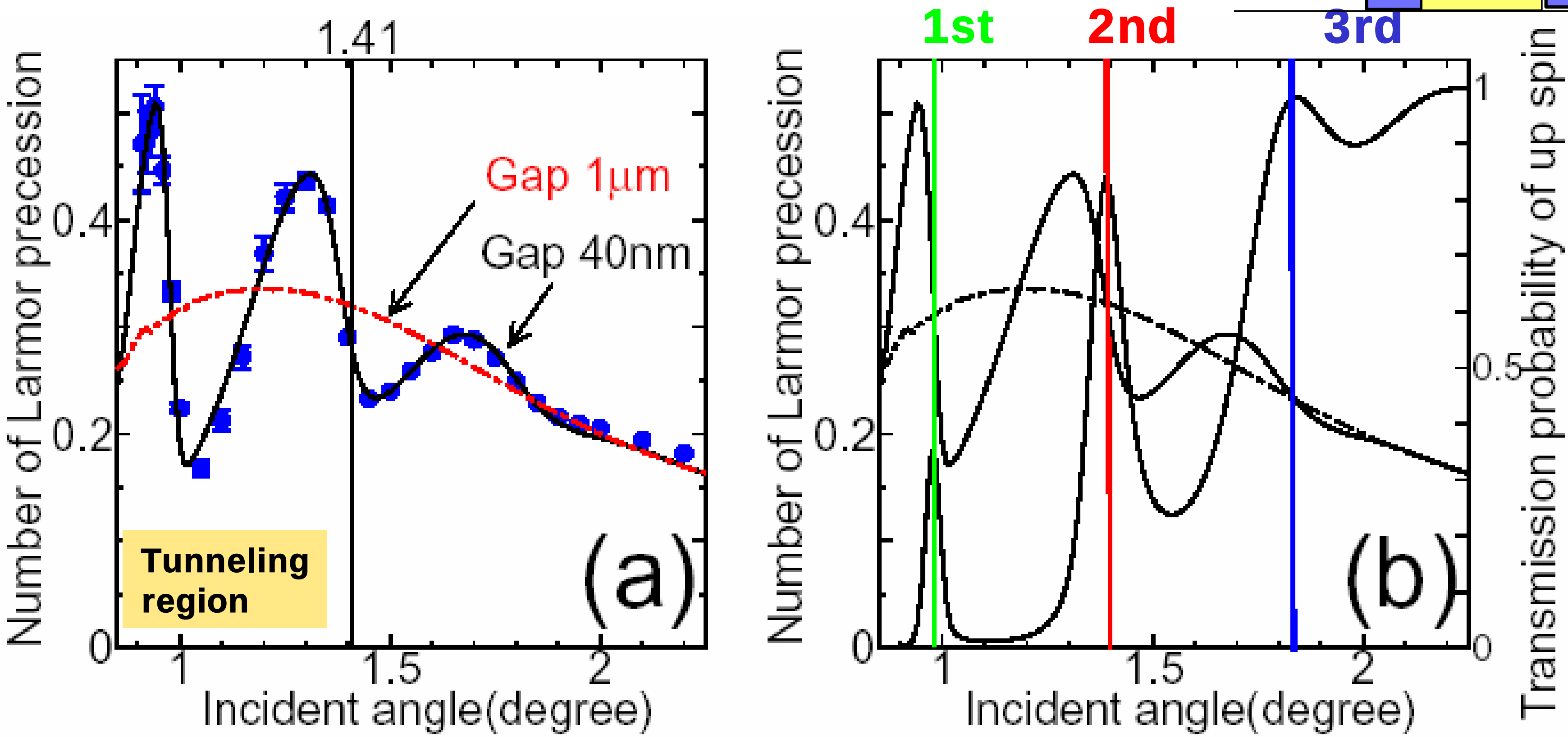
Measured spin precession of neutron transmitted through a magnetized thin layer

PA(20nm)-Ge(Gap)-PA(20nm)

(M.Hinoet al PRA61(2000) 013607.)

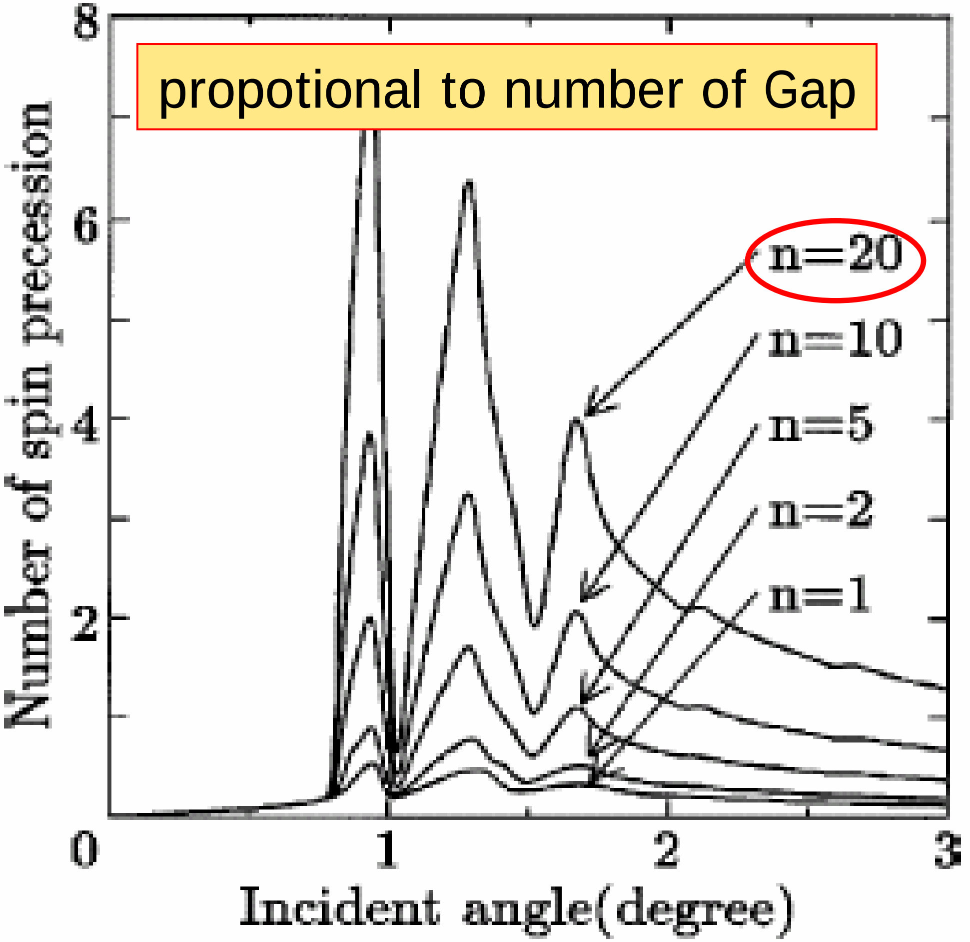


Incident wavelength 1.26nm(FWHM 3.5%)

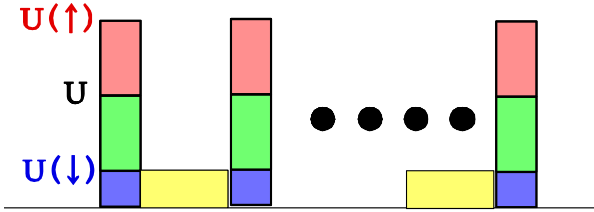


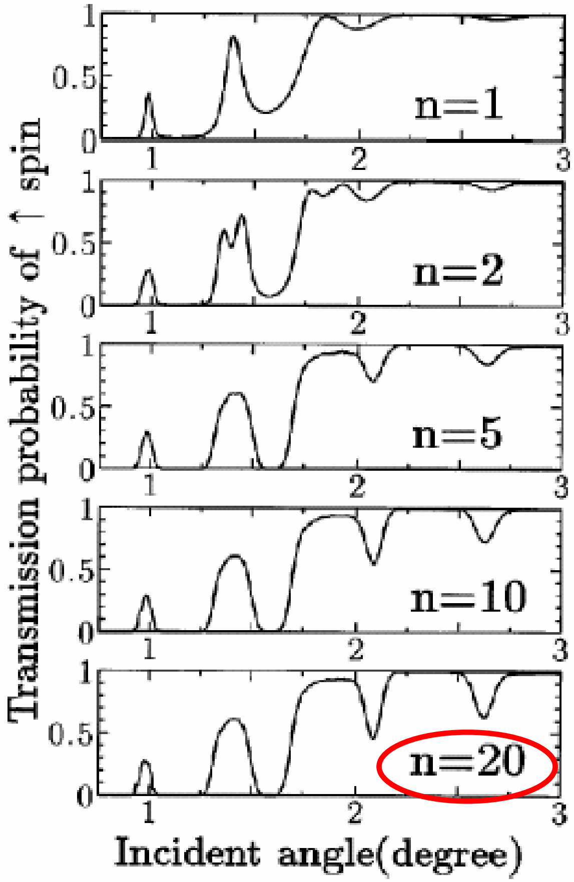
Calculation of spin precession and transmission probability of neutron transmitted through a Fabry-Perot mirror

$[\mathrm{PA}(20\mathrm{nm})\text{-}\mathrm{Ge}(40\mathrm{nm})]^{n}\text{-}\mathrm{PA}(20\mathrm{nm})$



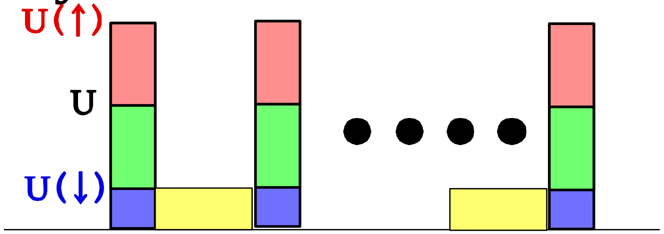
propotional to number of Gap





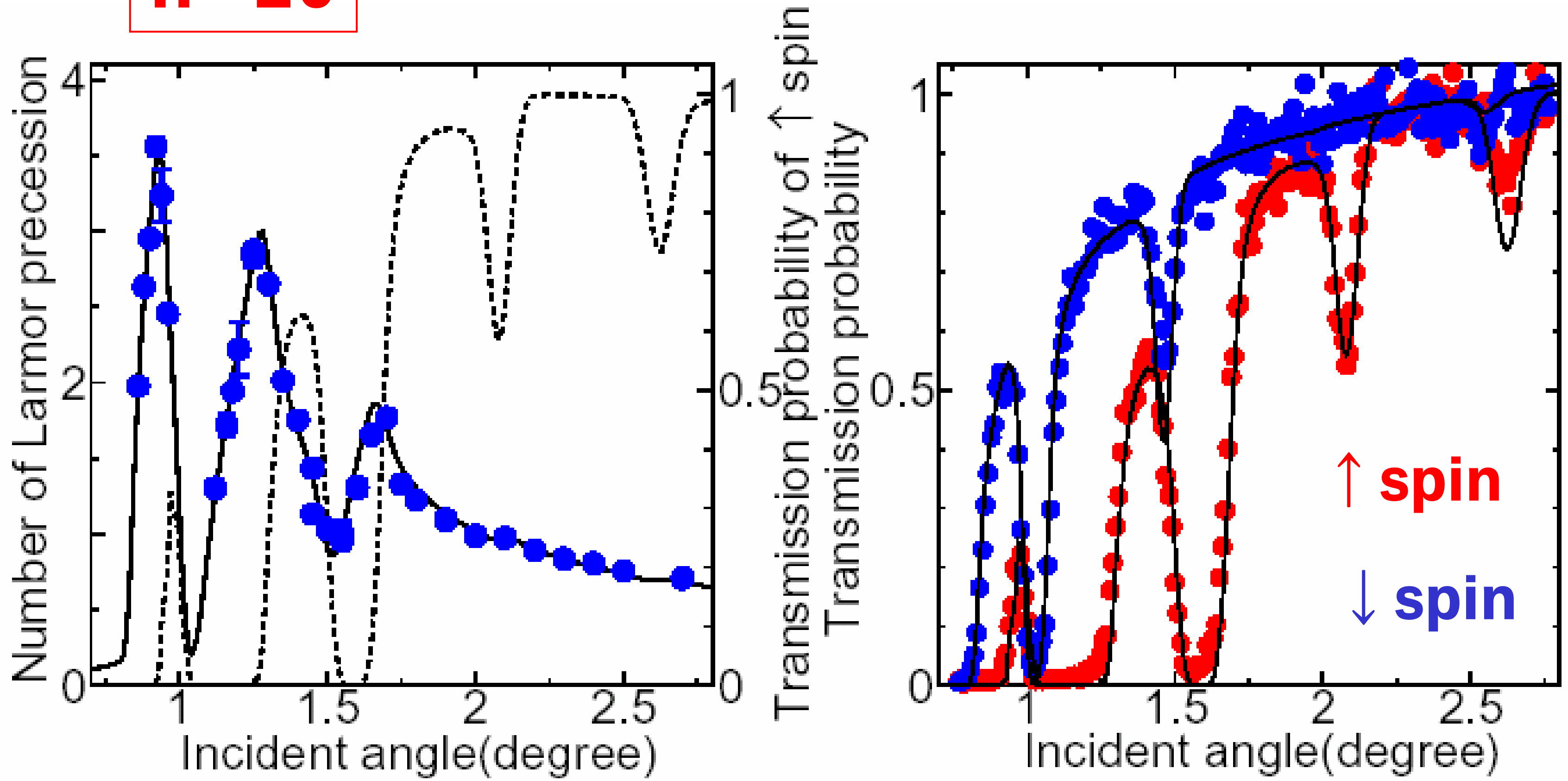
There is no decay in tunneling region

Calculation of spin precession and transmission probability of neutron transmitted through a Fabry-Perot mirror



[PA(20nm)-Ge(40nm)]^n-PA(20nm)

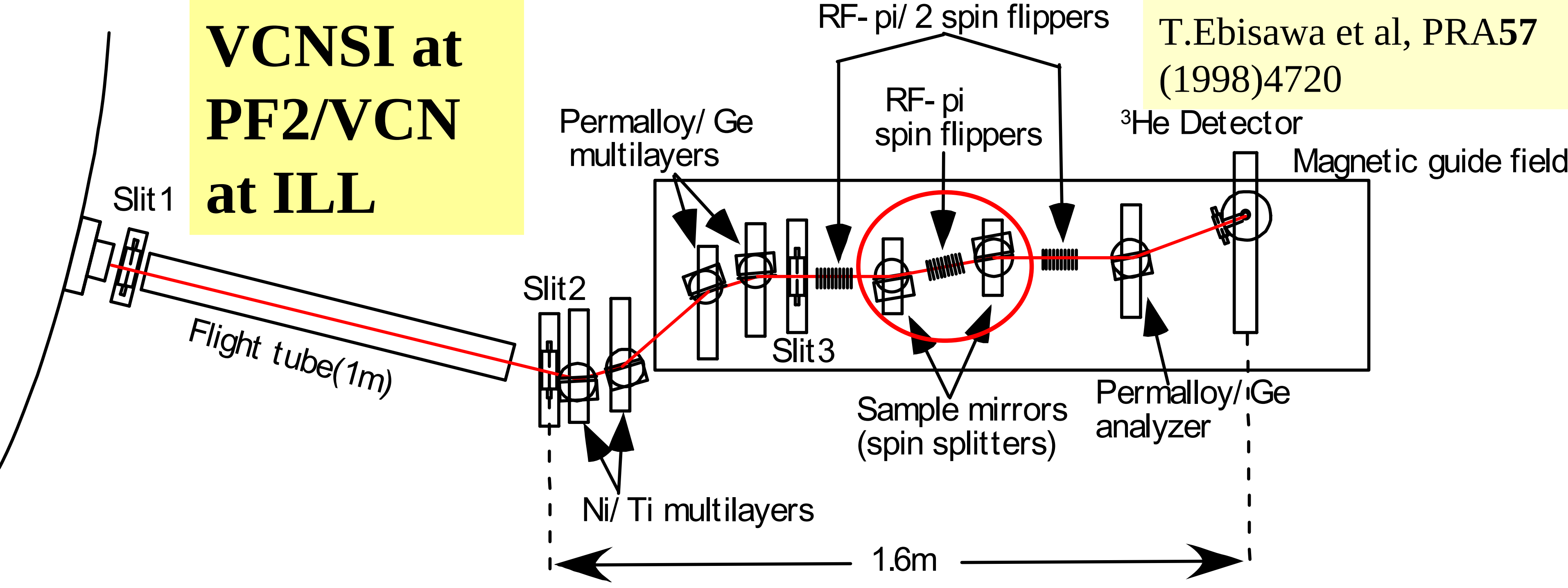
n=10



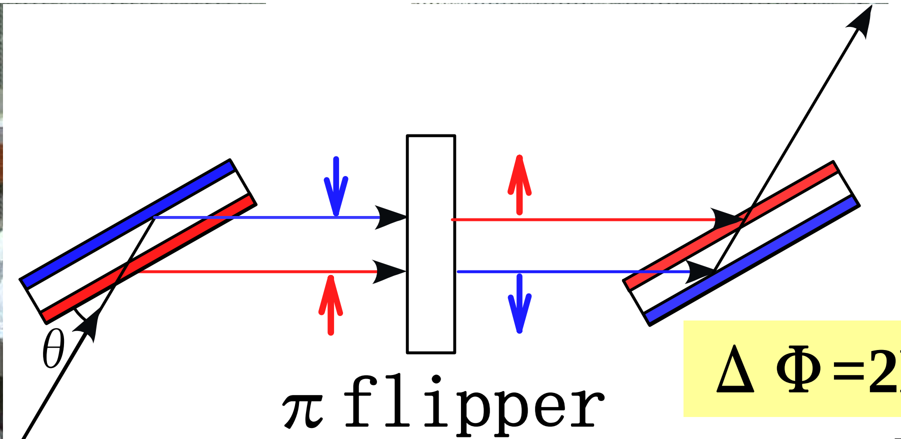
Incident wavelength 1.26nm(FWHM 3.5%)

VCNSI at PF2/VCN at ILL

T.Ebisawa et al, PRA**57** (1998)4720

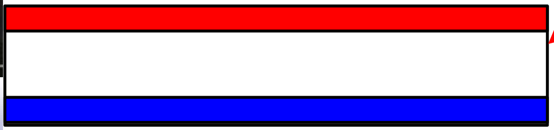


KURRI *neutron optics*



$$\Delta\Phi = 2D\sin\theta / \lambda$$

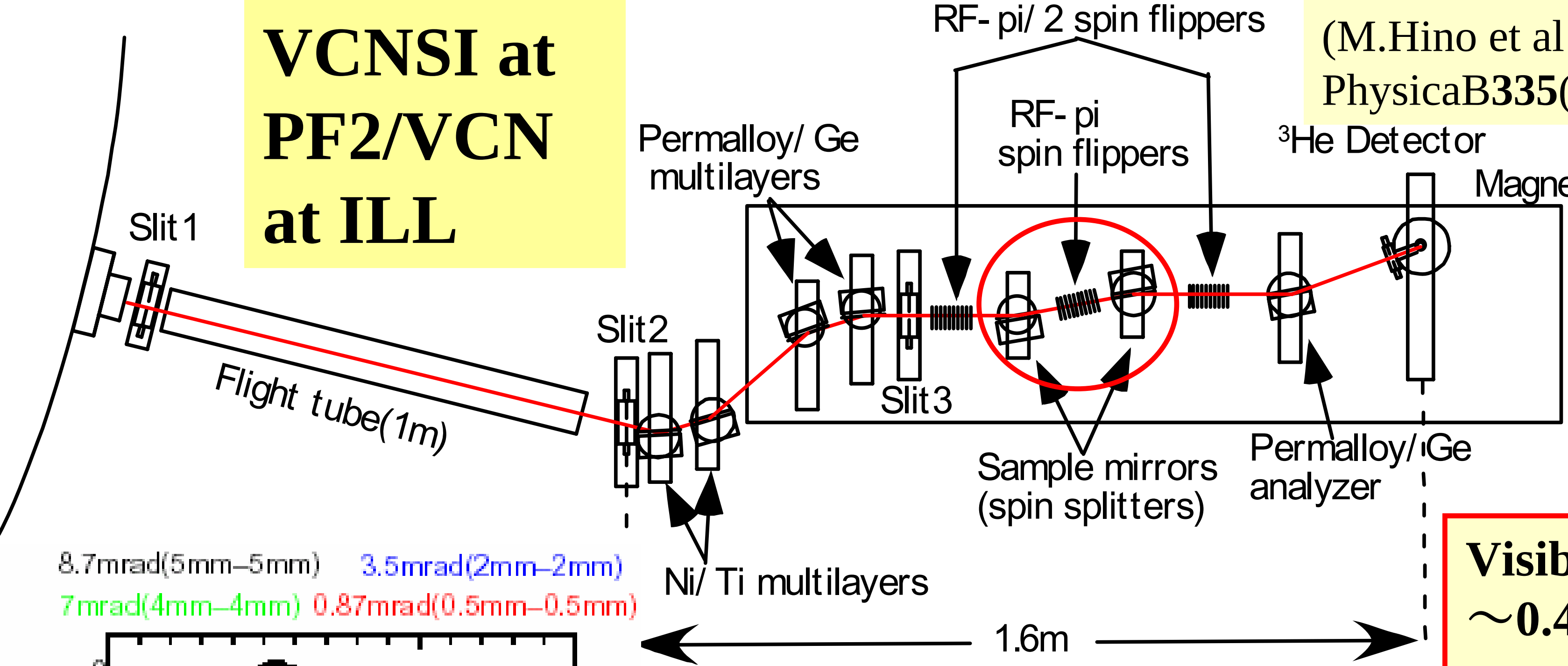
Gap thickness:D



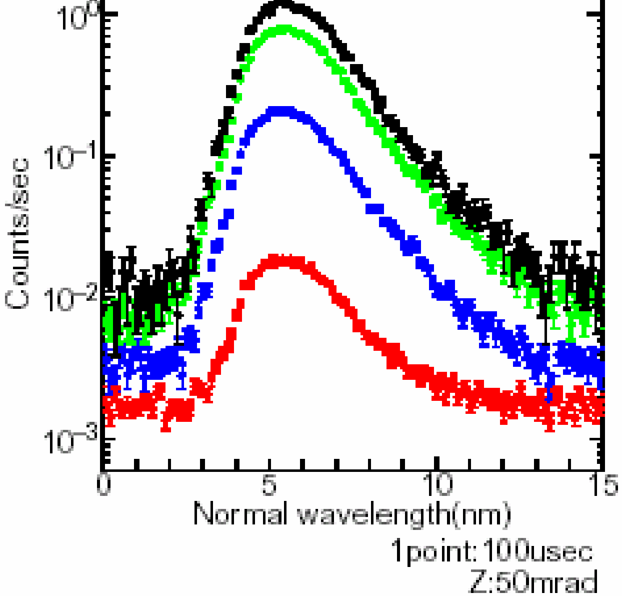
PA:magnetic layer
Ge:Gap layer
Ni:nonmagneitc layer
(for total reflection)

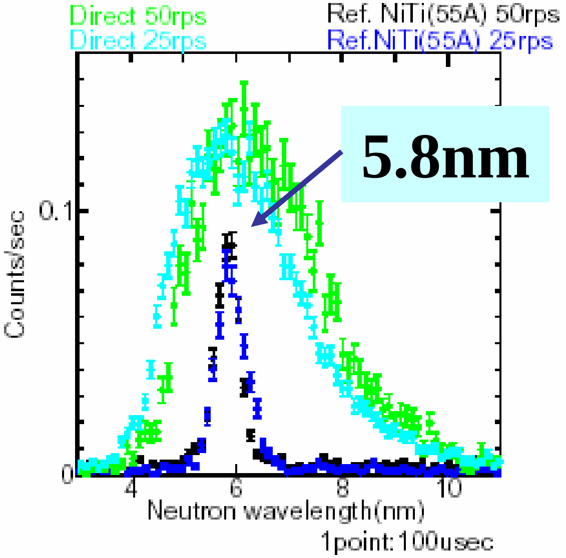
VCNSI at PF2/VCN at ILL

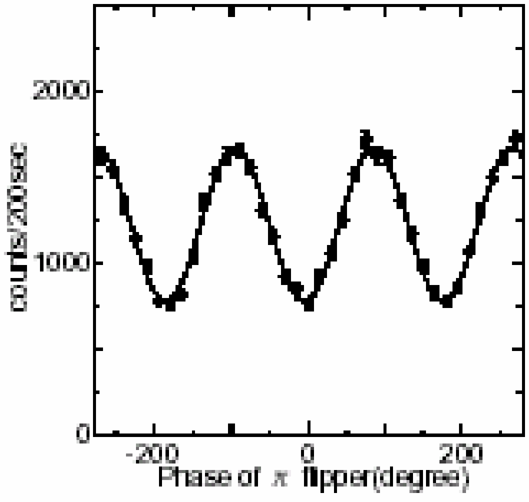
(M.Hino et al PhysicaB**335**(2003)230.



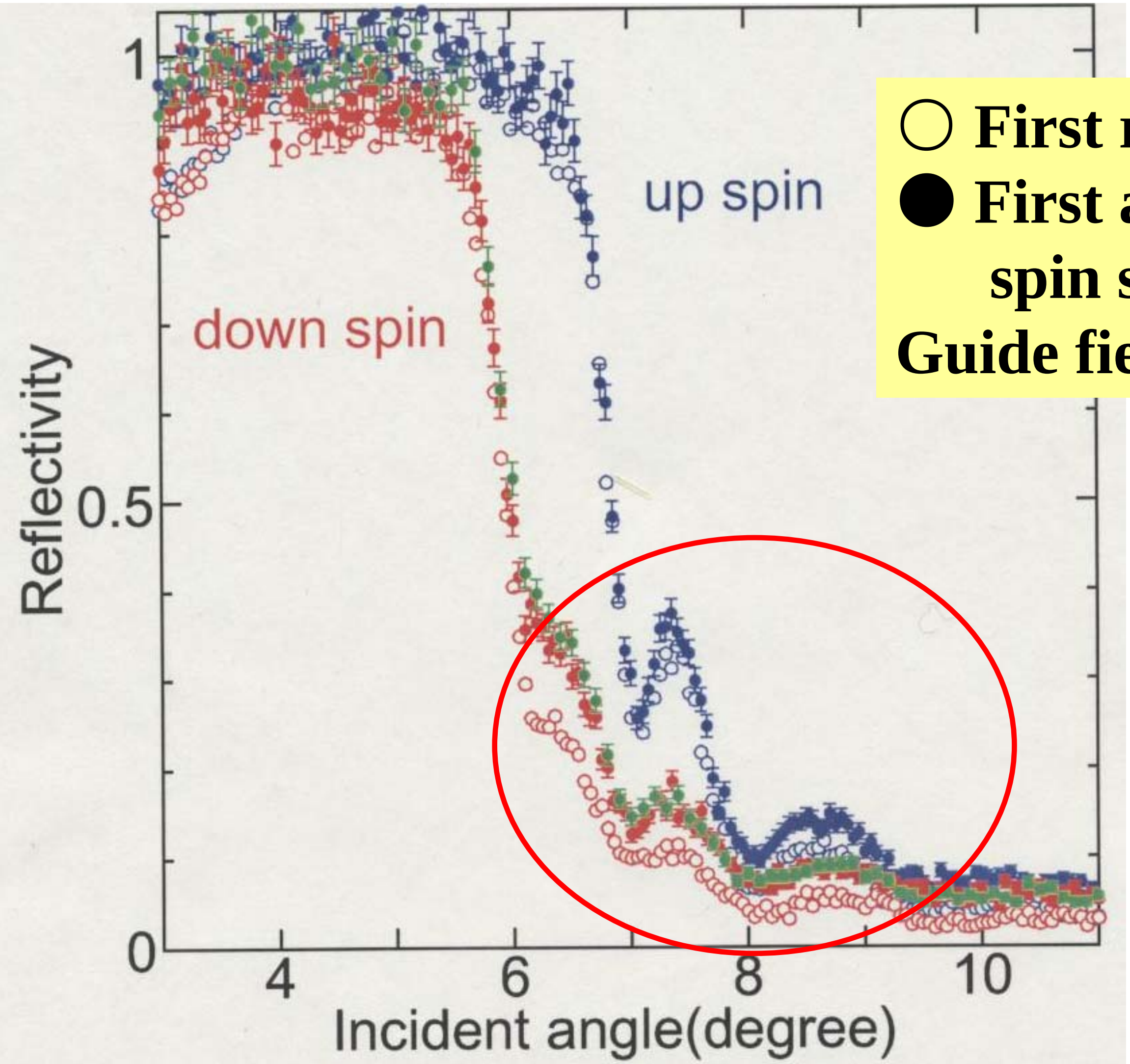
Visibility ～0.4 with sample mirrors







Why is so poor visibility with sample mirrors ?



○ First reflection by spin splitter
● First and second reflection by spin splitters
Guide field:3.6G   Guide field:18G

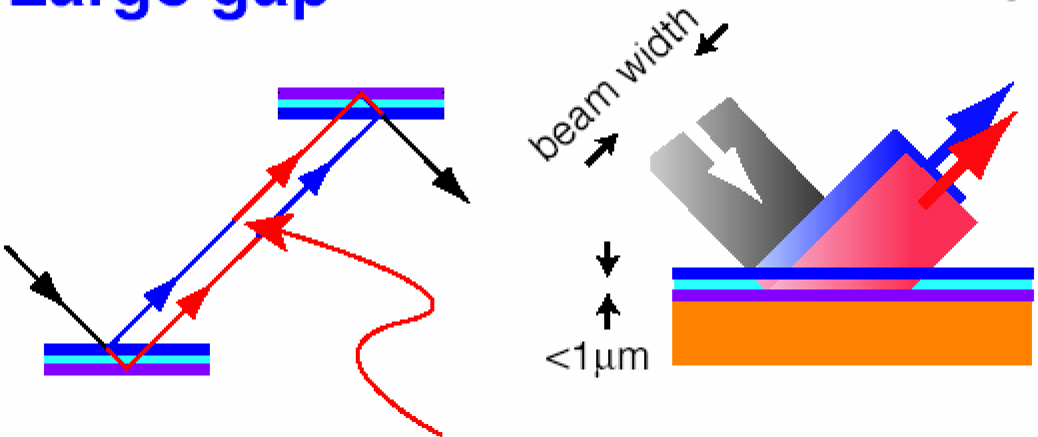
magnetic saturation of the Permalloy(PA) layer is not perfect

Sample mirror:
PA-Ge(1 μ m)-PA

New interferometer

Large gap

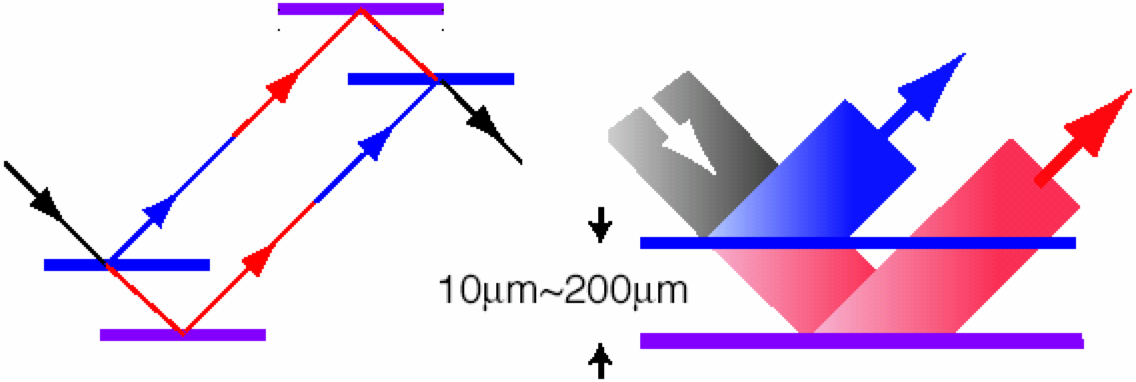
~ for wide applicability ~



Gap by vacuum evaporation $\lesssim$ 1μm

The two beams are overlapped each other.

- **We cannot insert any devices.**
- **Some interaction depends on not only L, λ but also the separation.**



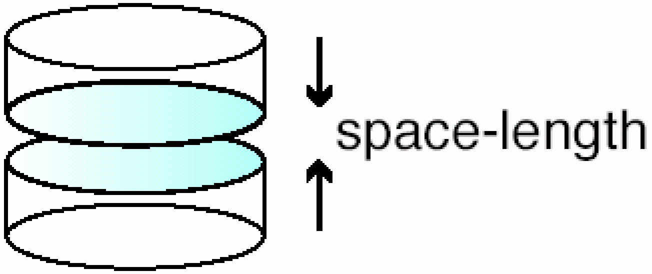
We want large gaps.

M.Kitaguchi et al**, A67(2003)033609**

New interferometer

Beam Splitting Etalon

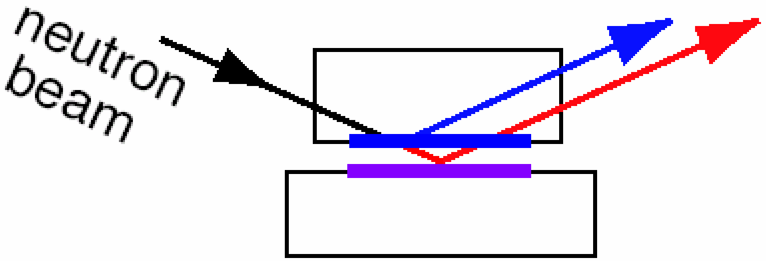
~ for wide applicability ~



air-spaced etalon

smooth, flat, and parallel

- fused silica
- roughness RMS < 3Å
- $\lambda_{\text{He-Ne}}$ /150
  matched front surfaces



The etalon functions as a 'pair mirror' with large gap.

Etalon with two mirrors splits glancing neutrons.

New interferometer

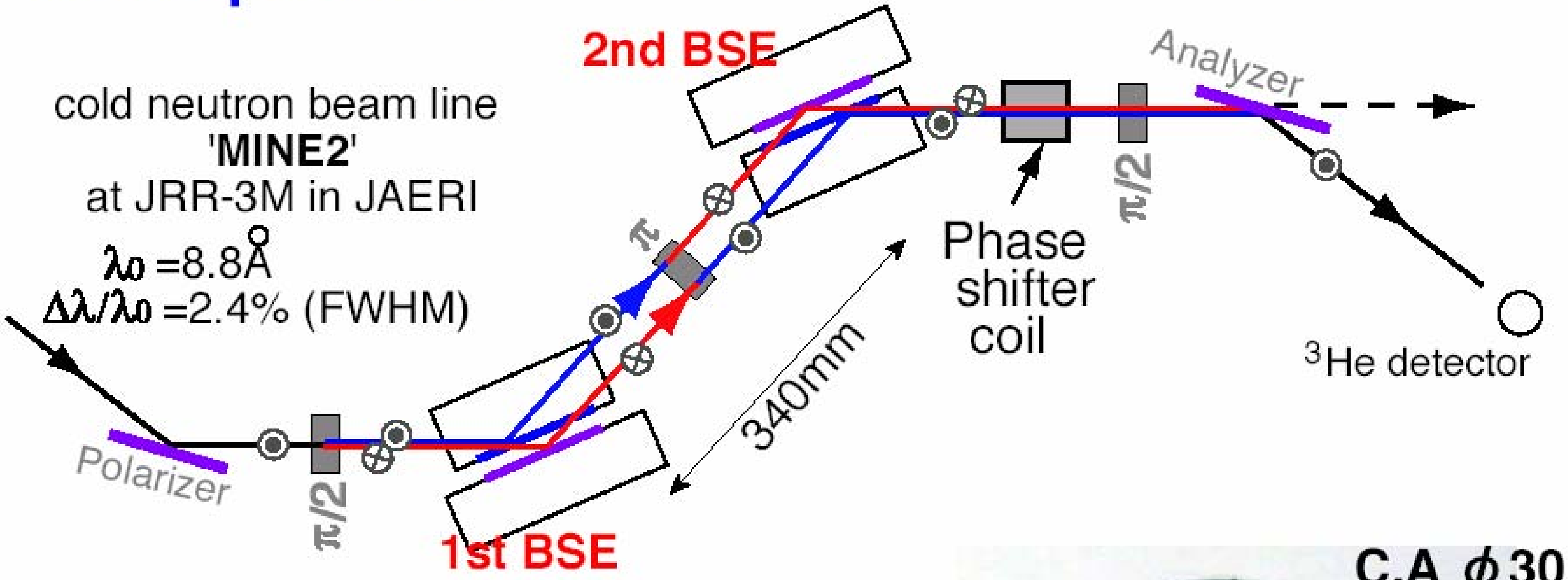
~ for wide applicability ~

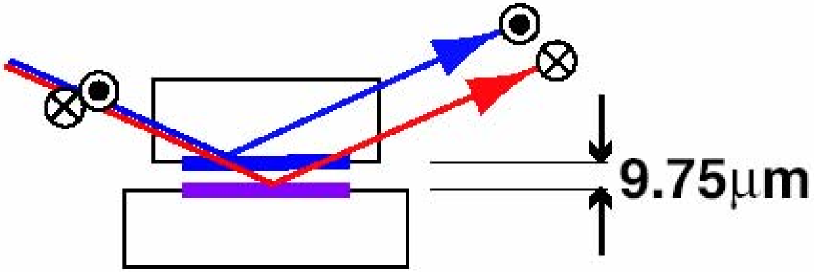
Test experiment

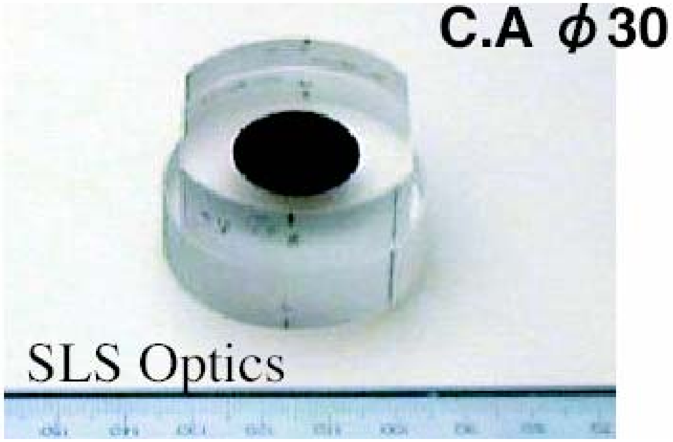
cold neutron beam line
'MINE2'
at JRR-3M in JAERI

$\lambda_0 = 8.8$ Å

$\Delta\lambda/\lambda_0 = 2.4\%$ (FWHM)





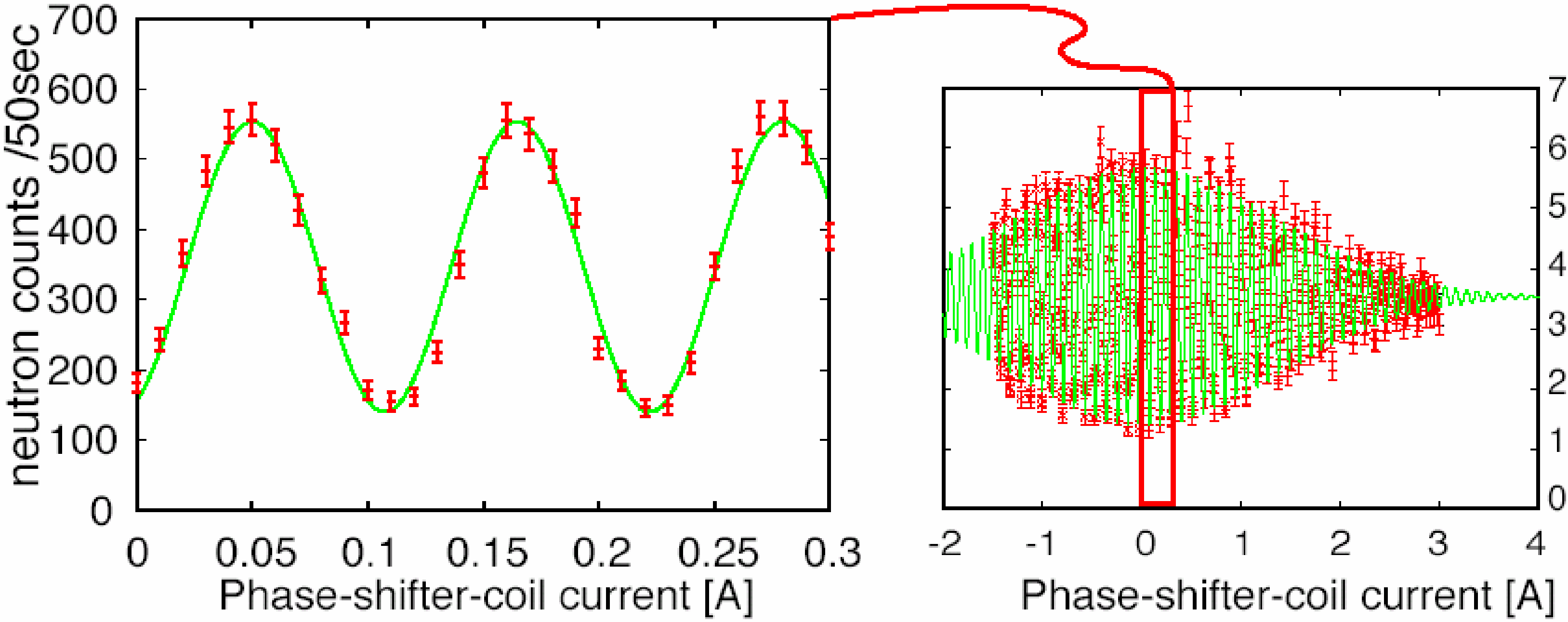


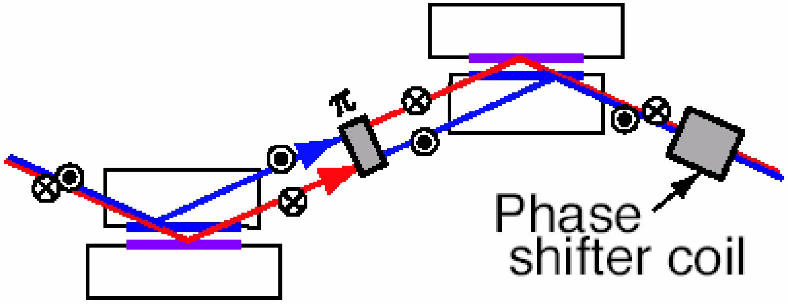
New interferometer

~ for wide applicability ~

Results

Interference fringes with the contrast of 60%



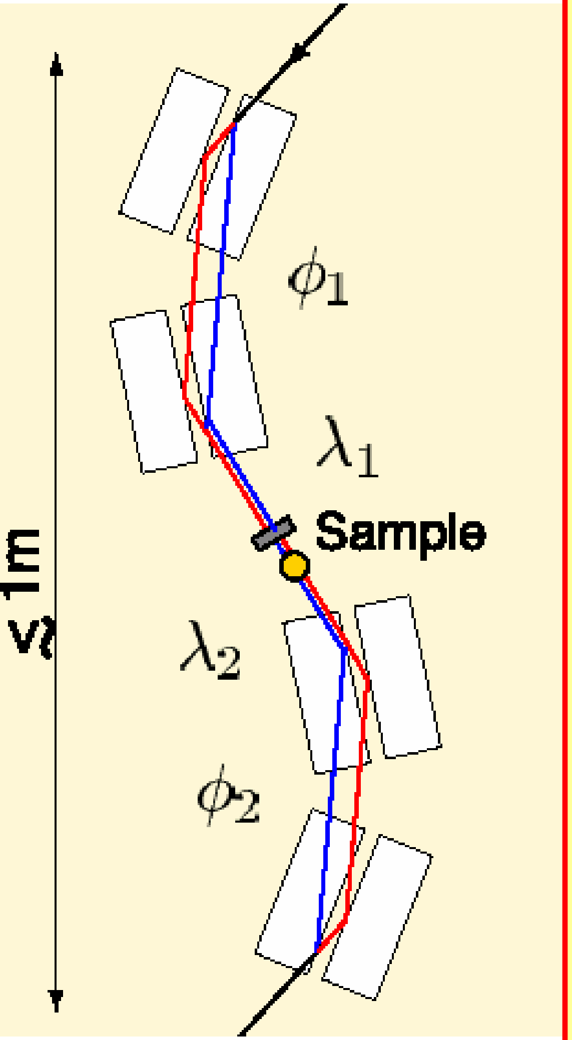


We are testing on experimens using BSEs with spacing of 200 μ m

It is possible to develop a very compact and high resolution NSE

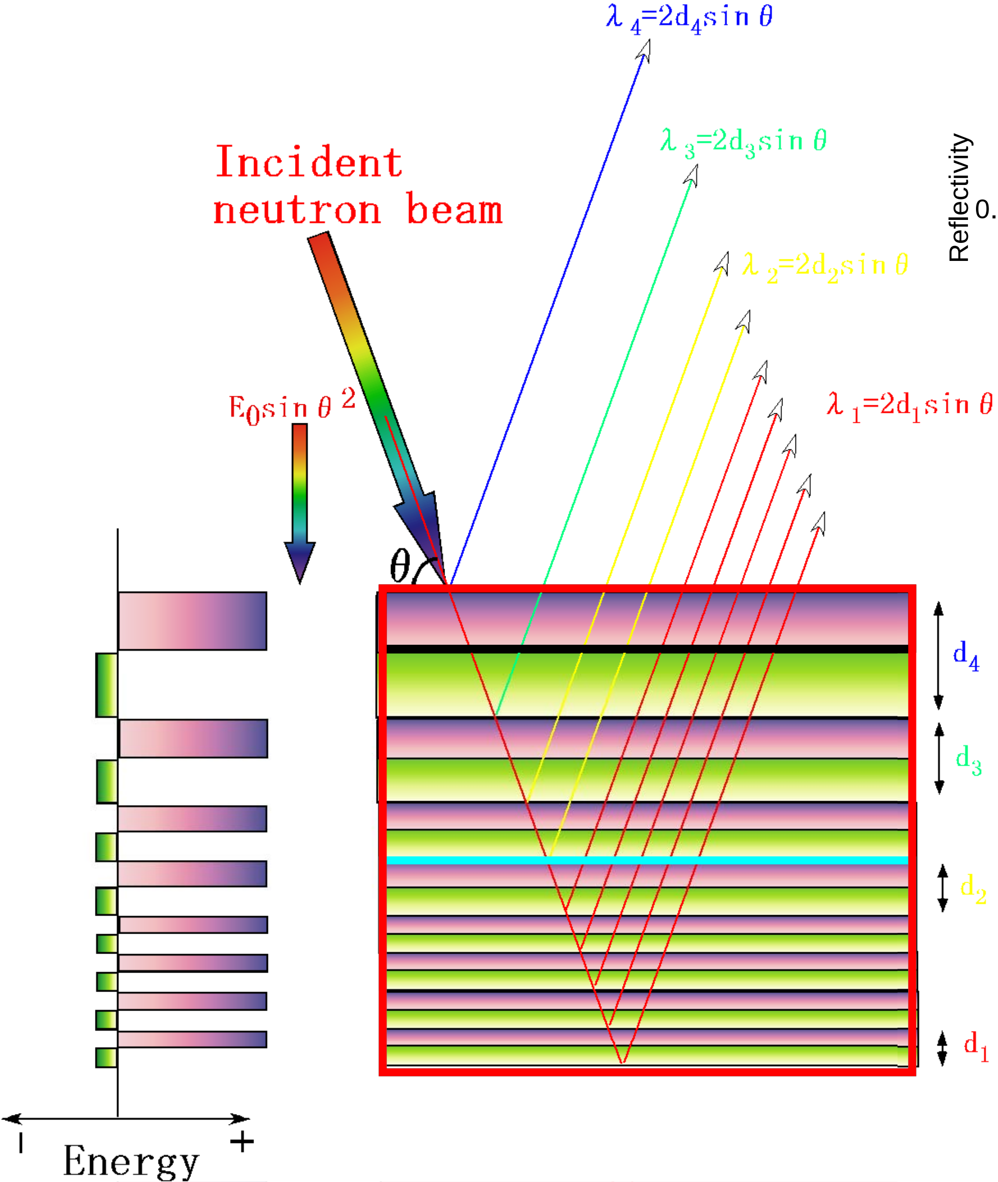
τ_{NSE}=4mD λ sin θ /h

T.Ebisawa et al. Phys. Lett.A259(1999)20.
M.Kitaguchi et al. SPIE 4785 104.

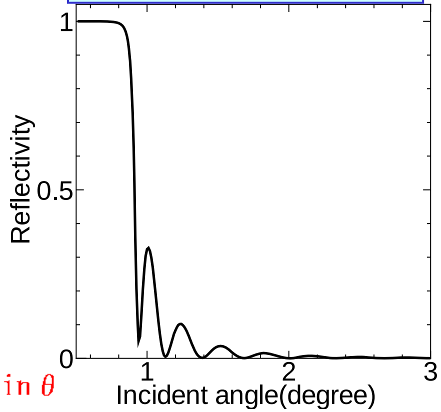


	Present	future possibility
Gap thickness	10 μm	200 μm
d-spacing (multilayer)	24nm	5.8nm~ (m~5 SM)
wavelength (6nm)	0.9nm	0.4～2nm
Number of spin precession	833	<66.6k (200k)
Fourier time(ns)	1.7	674 (2000)

Structure of neutron supermirror

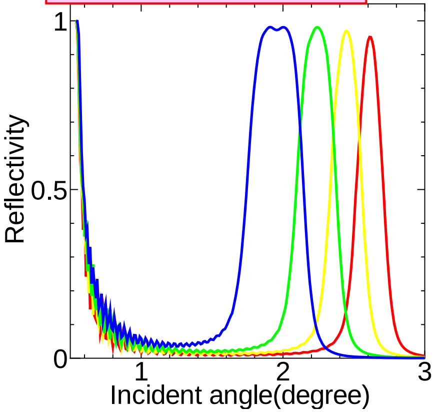


Thick layer

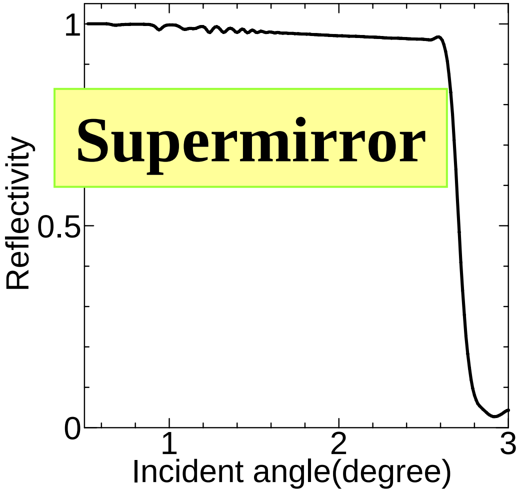


+

gradually d-spacing

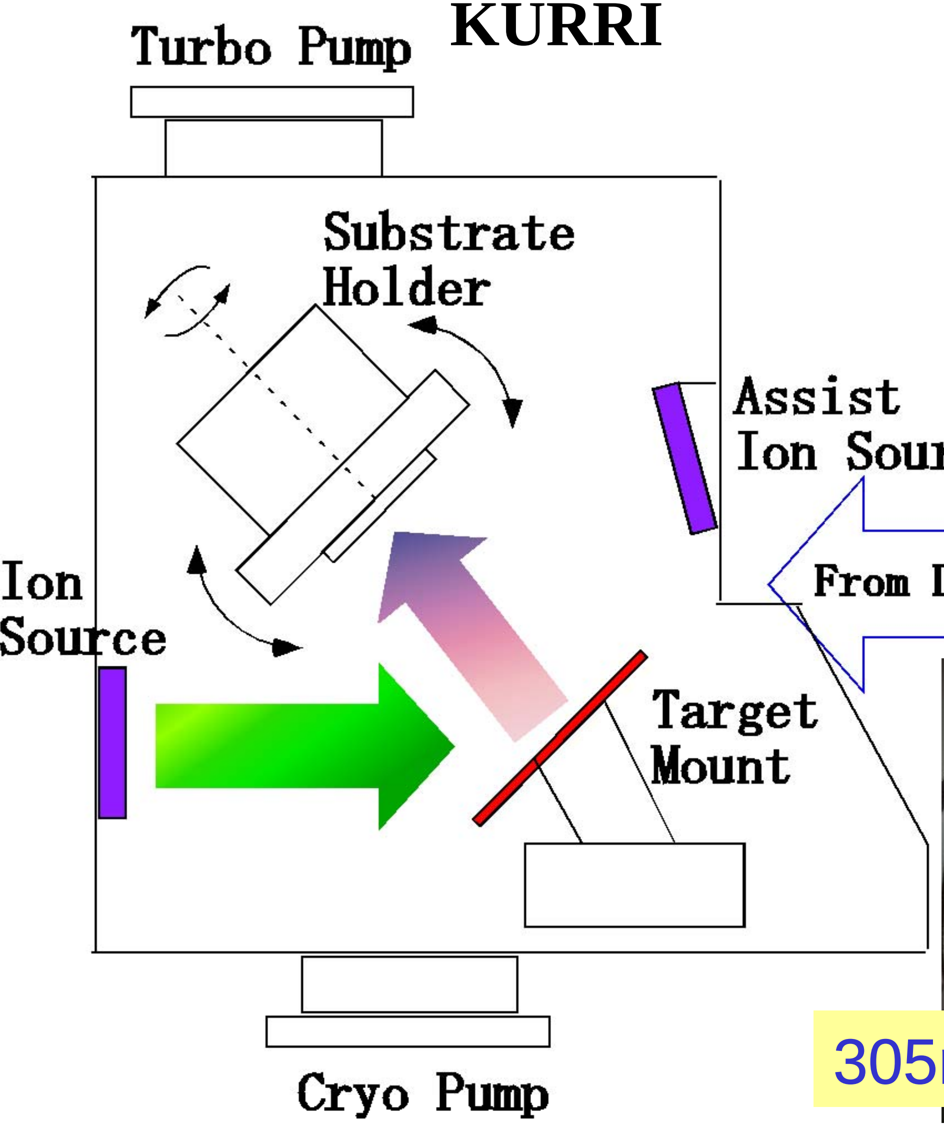


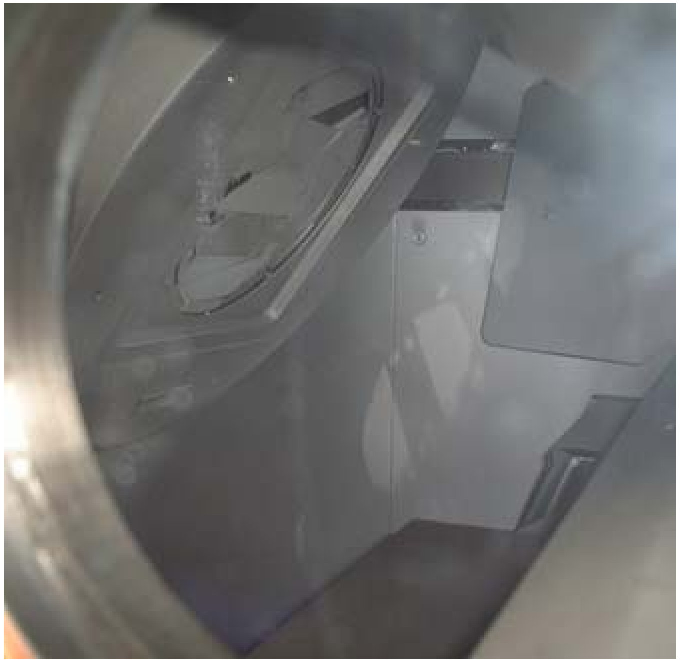
Supermirror

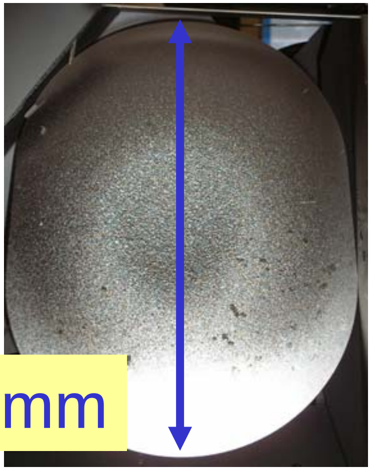


The performance is estimated by *m* and reflectivity at maximum angle of total reflection.

Schematic view of Ion Beam Sputtering instrument installed at KURRI







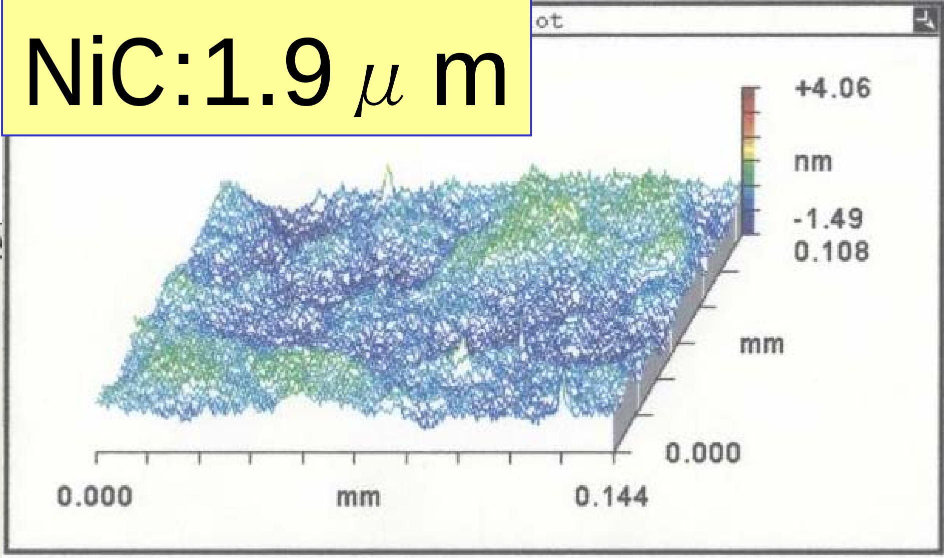
Process pressure
~8.0x10^{-5}Torr

Base pressure
~3.0x10^{-8}Torr

Maximum Sample size ϕ 8”(ϕ 200mm)

Surface roughness of Ni,NiC monolayer by using Zygo

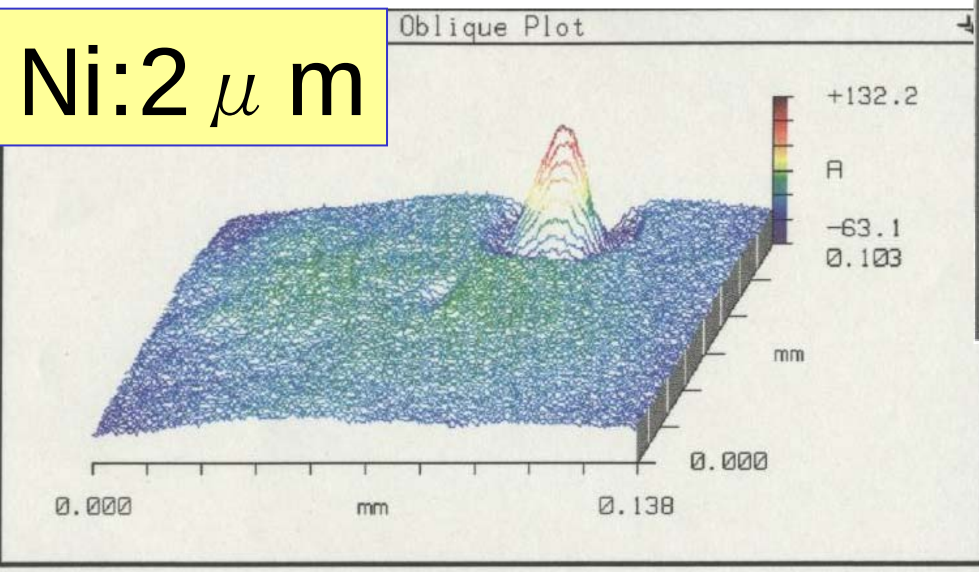
NiC:1.9 μm



PV: 7 nm

RMS:0.5nm

Ni:2 μm

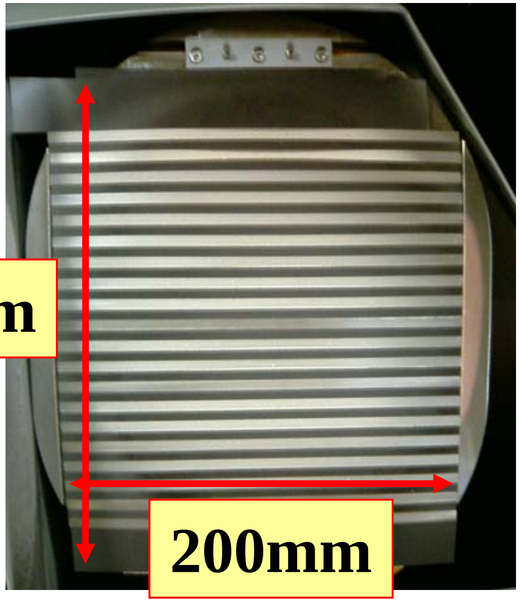


PV:19.5nm

RMS:1.4nm

Adding carbon decrease surface roughness of Ni thick layer.

J. Wood, SPIE 1738(1992) 22.
B.Vidal et al ibid, 141.
K.Soyama, Dr. thesis.



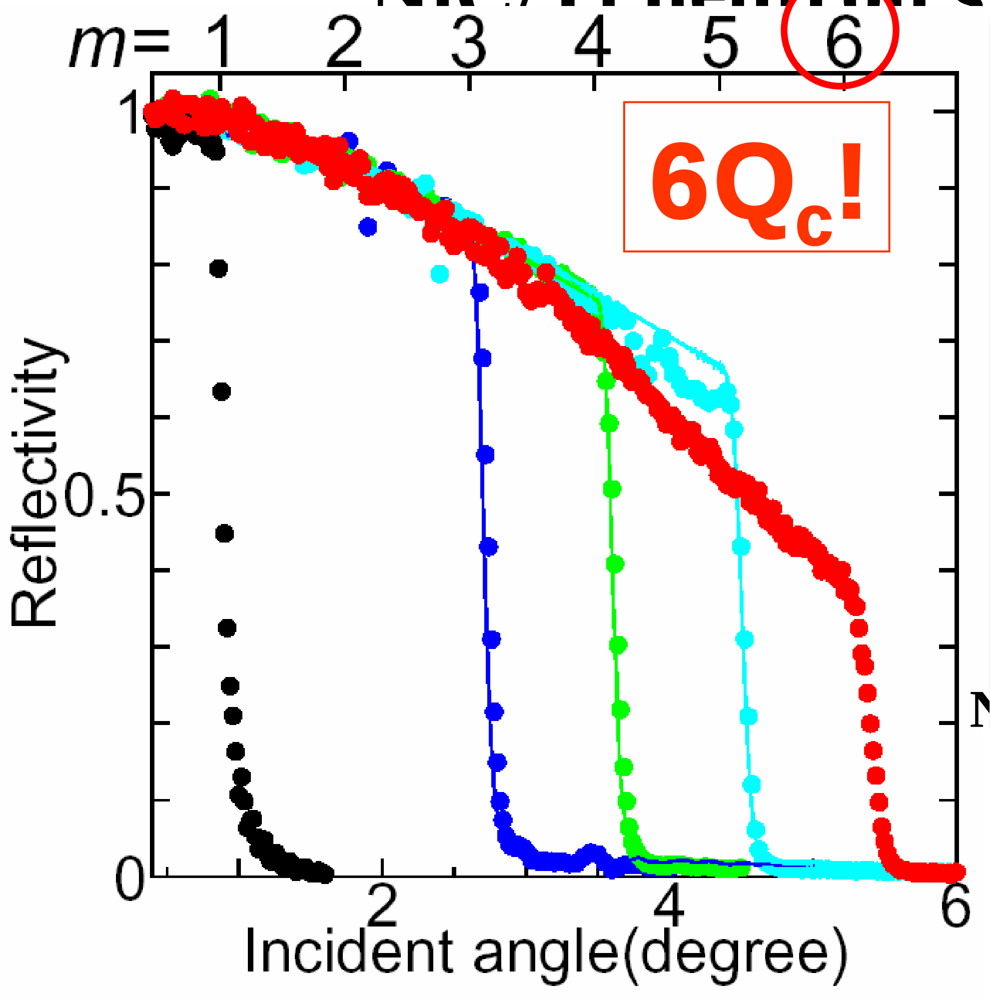
250mm

200mm

NiC target of IBS

3Q (400), 4Q(1200), 5Q(3000), 6 Q (5000 layers)

NiC/Ti neutron supermirror



See m=3,4,5.....

The roughness σ =0.55nm

Independence from number of layers !

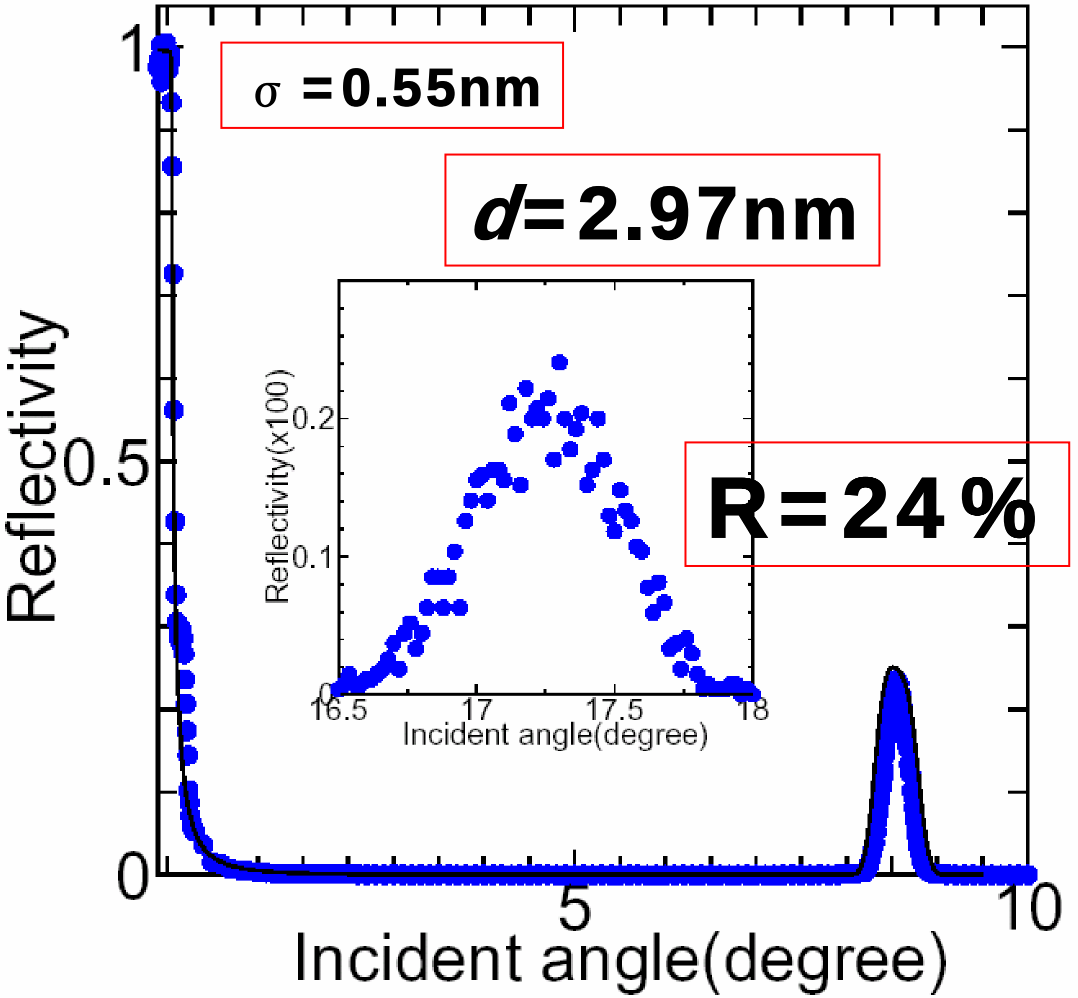
There is no growth of Ni crystal with increment of number of layers. The increment of interface roughness is estimated to be less than 0.2nm

The performance is estimated by *m* and reflectivity at maximum angle of total reflection.

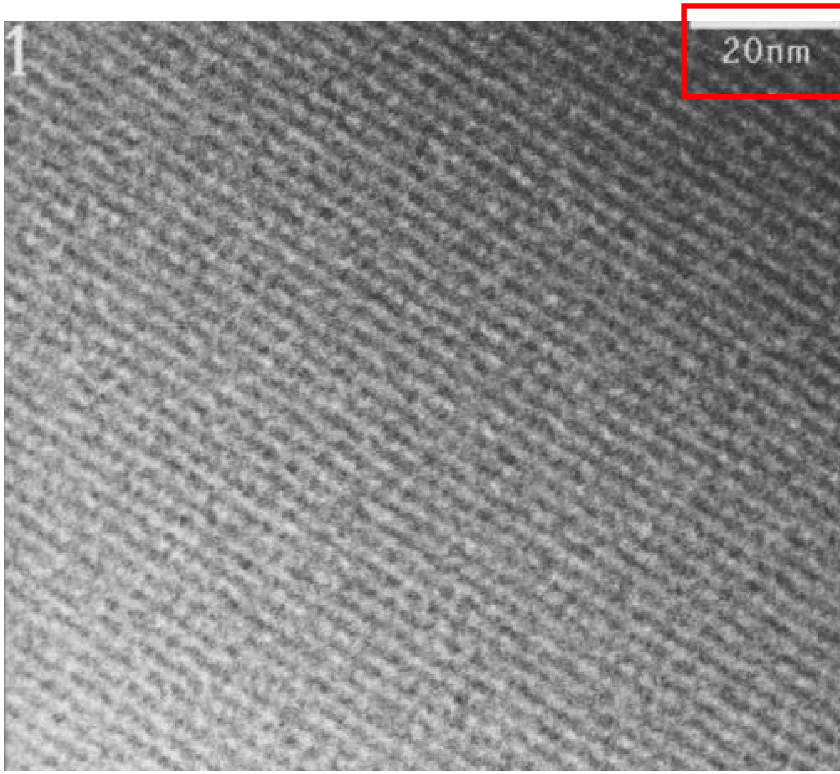
Incident wavelength 0.88nm （FWHM 2.7%)

M.Hino et al. Nucl.Inst.Meth. A **529** (2004) 54 .

NiC/Ti multilayer（10000layers）

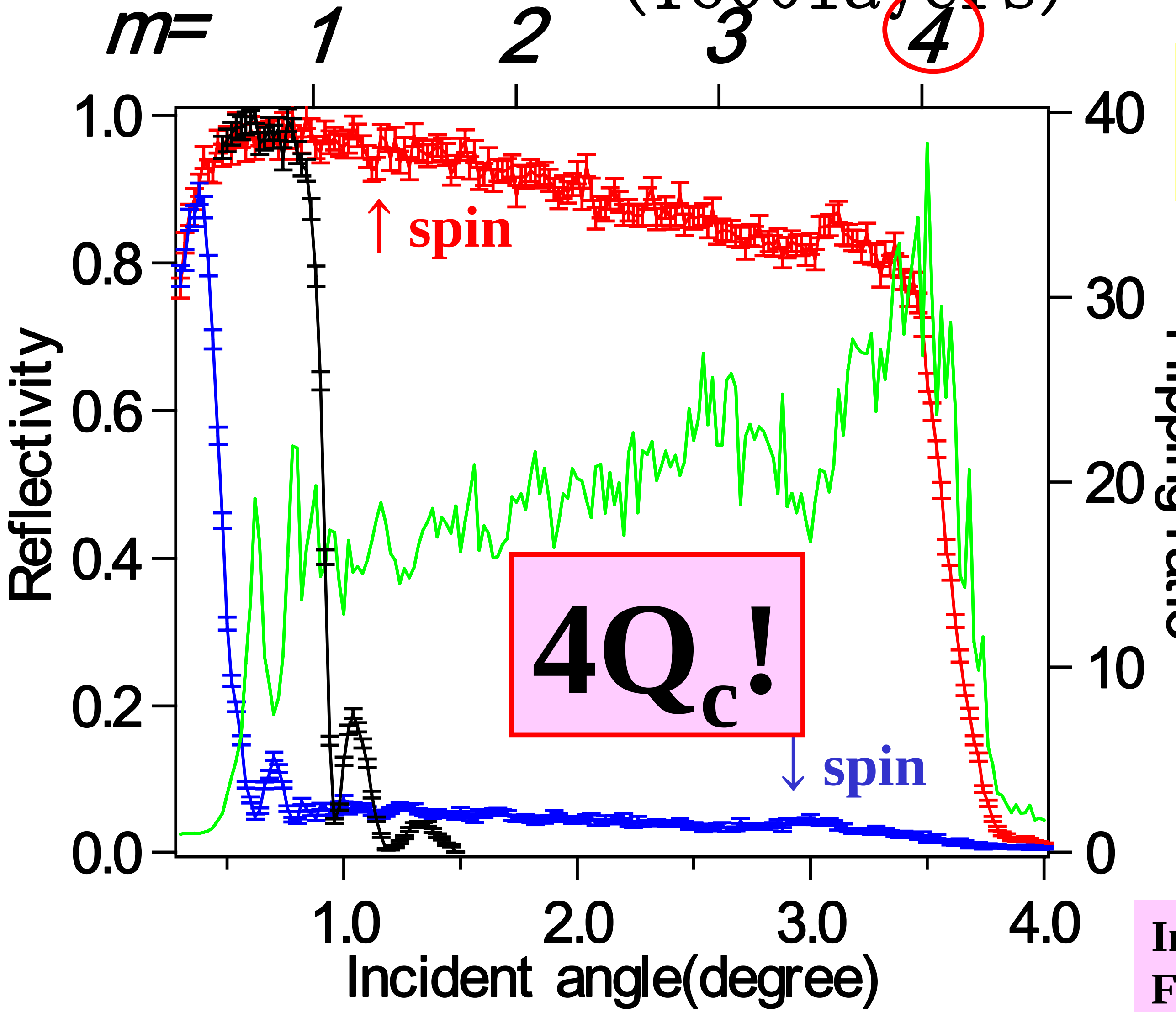


Incident wavelength 0.88nm(FWHM:2.7%)



The TEM picture measured by HMI (T.Krist)

m=3.9 Fe/Si polarizing supermirror (1600layers)



$4Q_c$!

Applied magnetic field 45mT

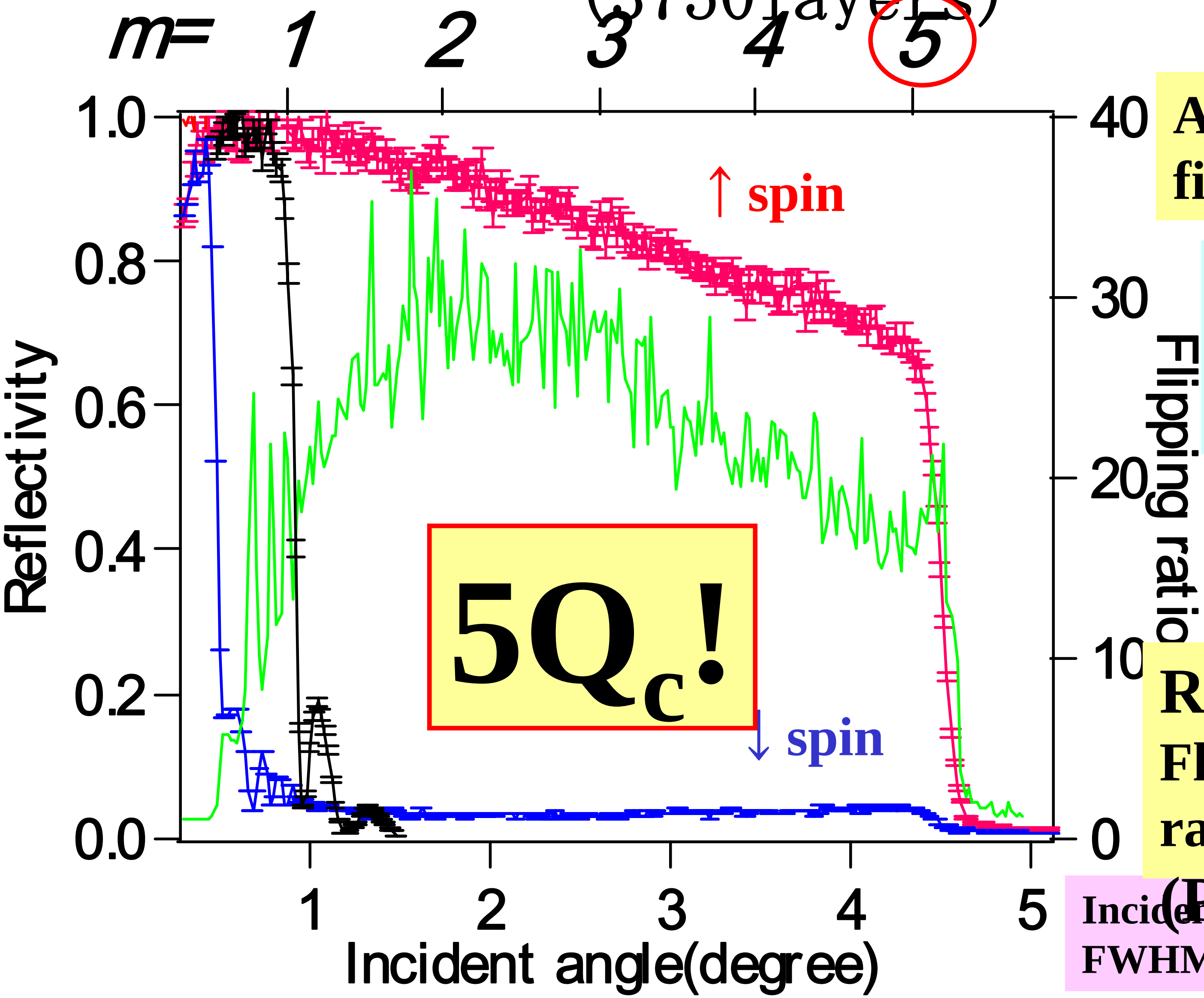
Black line: Reflectivity of NiC(60nm)

ratio=$R_{\uparrow}$ / $R_{\downarrow}$

R>0.80(*m*=3.9)
Flipping ratio~20
(P>0.9)

Incident wavelength 0.88nm
FWHM(2.7%)

m=5 Fe/Ge polarizing supermirror (3750layers)



$5Q_c$!

Applied magnetic field 45mT

Black line: Reflectivity of NiC(60nm)

ratio=$R_\uparrow$ / $R_\downarrow$

R>0.67
Flipping ratio~20
(P>0.9)

Incident wavelength 0.88nm
FWHM(2.7%)

Summary

- **It is shown that neutron spin interferometer is powerful tool for investigation in neutron optics and fundamental quantum mechanical tests.**

- **Development of VCN spin interferometer was shown. Though the visibility id not so high, a compact neutron spin echo spectrometer using VCNSI method seems within reach.**

- **We have observed interference fringes with the contrast of 60% by using BSEs of 10 μm.**

- **m=6 NiC/Ti supermirror, Fe/Si and Fe/Ge polarizing supermirrors of m=3.9 and 5 were successfully fabricated using IBS instrument installed at KURRI. The Reflectivity and Polarizing efficiency is following: $R(m=3.9)>0.8$, $R(m=5)>0.67$: $P(m=3.9,5)>0.90$**

Collaborators

Kyoto University

KURRI : Yuji Kawabata, Masaaki Kitaguchi

Fac. Nucl. Eng.: Hirotoshi Hayashida, Seiji Tasaki

Dept. Physics : Haruhiko Funahashi

KEK(RIKEN)

Hirohiko Shimizu

JAEA (Former JAERI)

Toru Ebisawa, Ryuji Maruyama, Dai Yamazaki

ILL

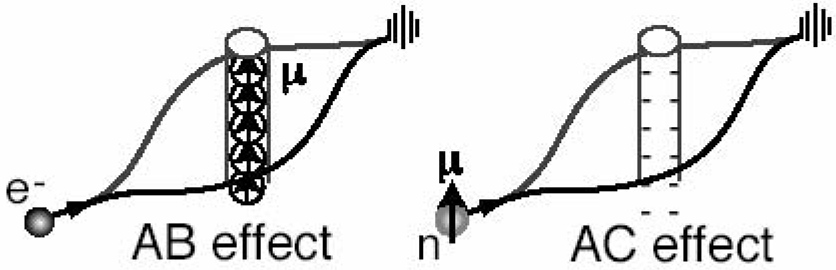
P.Geltenbort, R.Gaehler, T.Brenner, J.Butterworth

Osaka University

Norio Achiwa, Masahiko Utsuro

Aharonov-Casher effect

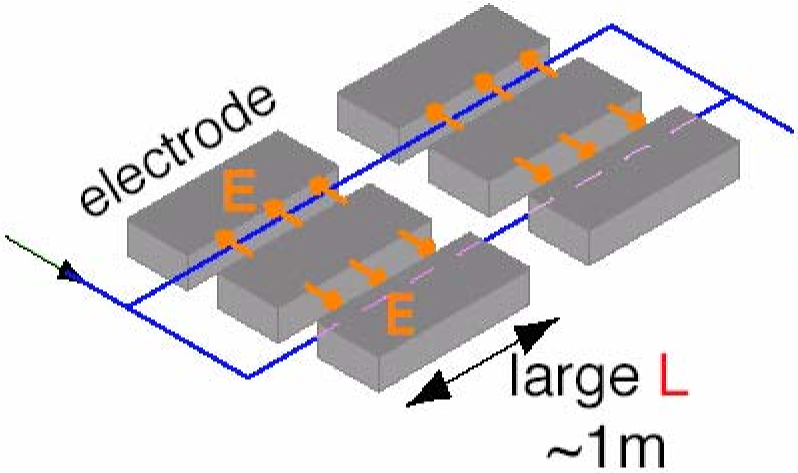
A. Cimmino et al, Phys. Rev. Lett. 63(1989) 380



$$\Delta\phi_{AC} = \pm \frac{4\pi\mu\Lambda}{\hbar c}$$

$$\Lambda = 2LE/4\pi$$

Λ:effective lineal charge density
L:the path length
E:electric field



- **Large L provides high precision measurement**

  10 times as sensitive as Si case

- **We can study the topological nature of AC effect by inserting the electrodes into the area enclosed by the paths.**