Spin Selective Neutron Transportation and Shaping by using Multiplet Magnetic Lenses

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RIKEN : K. Hirota
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Contents:

1) Neutron Polarizing Guide based on the Quadrupole Magnet.

2) Pulsed Neutron Beam Focusing by using Multiplet-Magnetic Lens System for TOF SANS instruments.

Neutron Motion in a magnetic field

Potential Energy : H

$$H = -\boldsymbol{\mu}\cdot\mathbf{B} \quad \Rightarrow \quad \boxed{m\frac{d^2\boldsymbol{r}}{dt^2} = -\nabla\,\boldsymbol{\mu}\cdot\boldsymbol{B}}$$

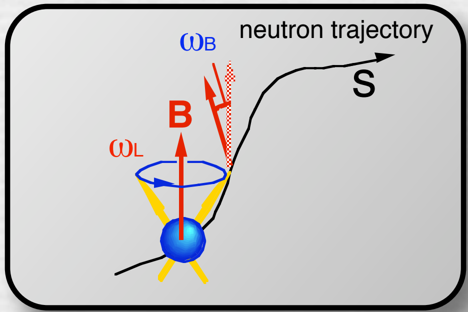
Magnetic field torque neutron spin

$$\frac{d\boldsymbol{\sigma}_n}{dt} = \gamma\,\boldsymbol{\sigma}_n \times \boldsymbol{B}, \qquad \boldsymbol{\sigma}_n = \boldsymbol{\mu}/|\boldsymbol{\mu}|$$

Larmore Precession

Larmore Angular Frequency : $\omega_L = \gamma|\boldsymbol{B}|$

Angular Frequency of magnetic field vector at neutron position : $\omega_B = \frac{ds}{dt}\left|\frac{\partial}{\partial s}\frac{\boldsymbol{B}}{|\boldsymbol{B}|}\right|$



If the magnetic field is strong enough,

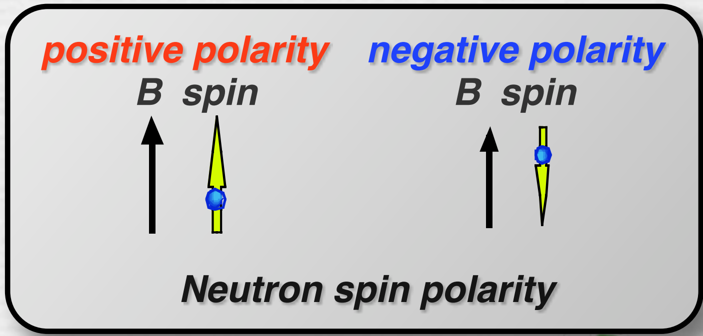
$$\frac{\omega_L}{\omega_B} >> 1$$

Spin component parallel to the magnetic field is almost conserved

Positive polarity

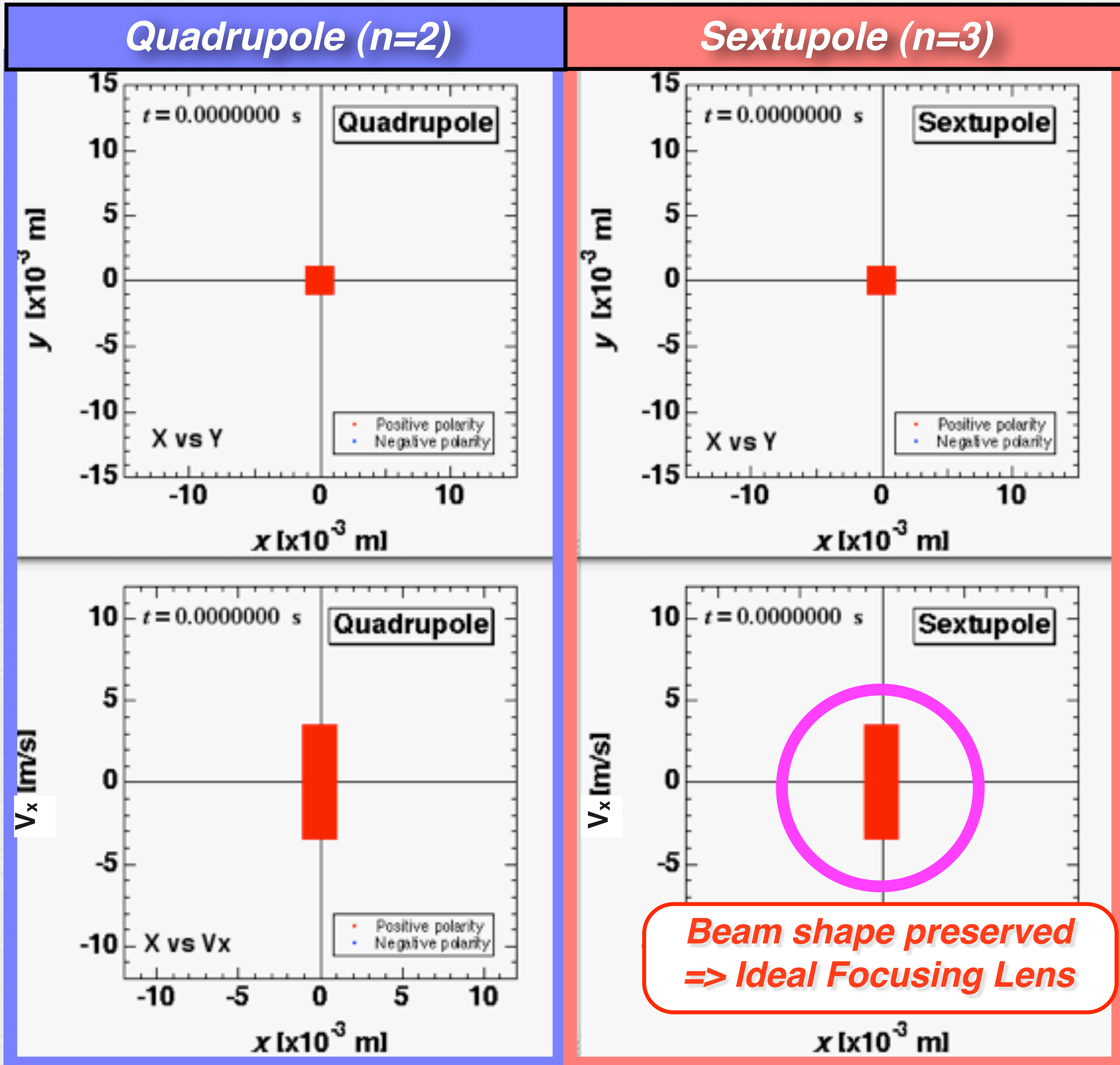
$$\frac{d^2\boldsymbol{r}}{dt^2} = \mp\left|\frac{\mu}{m}\right|\nabla|\boldsymbol{B}|$$

Negative polarity



Neutron motion in magnetic field

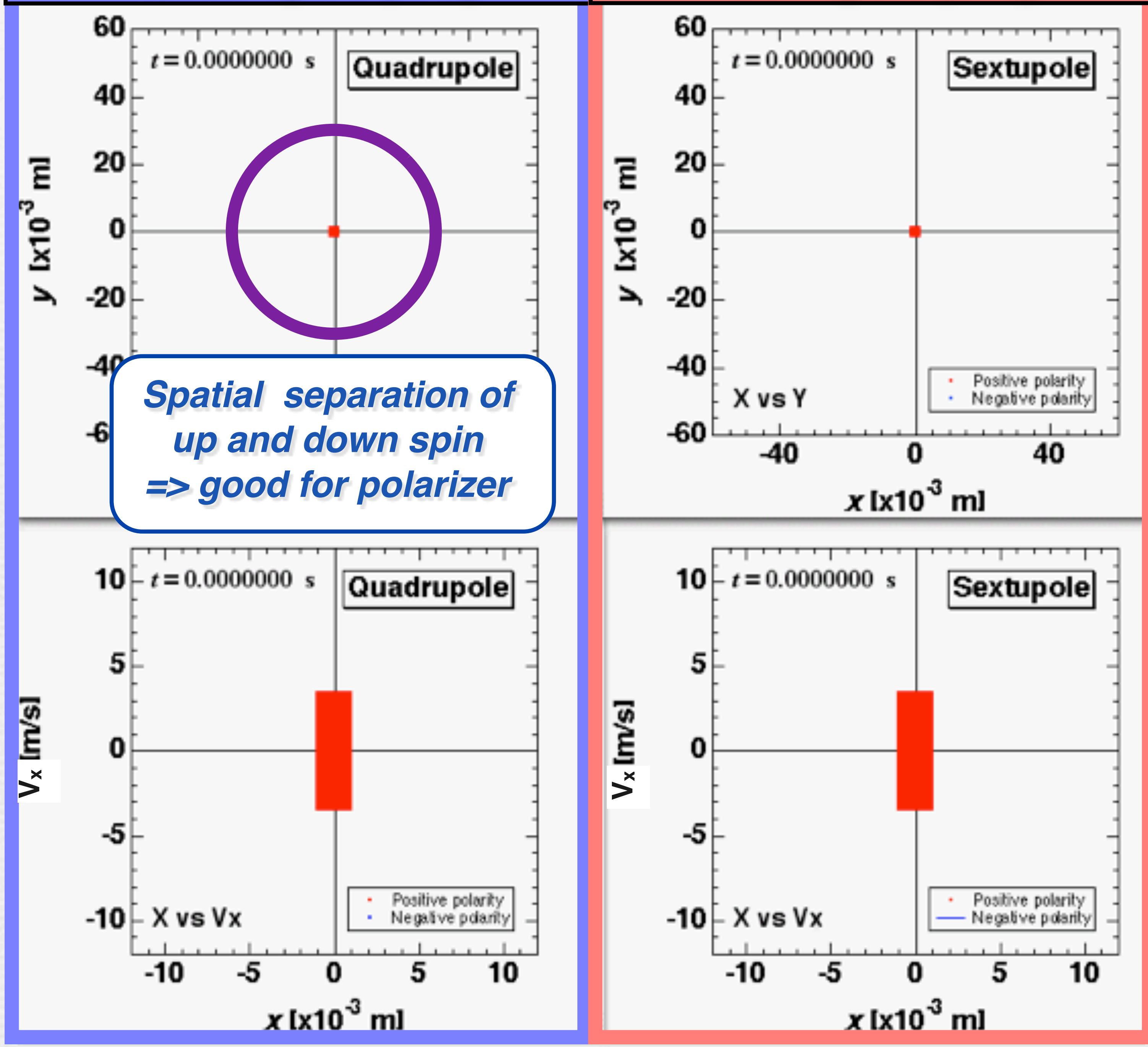
Condition :
|B|=2T
@r=2.5mm



Neutron motion in magnetic field

Condition :
|B|=2T
@r=2.5mm

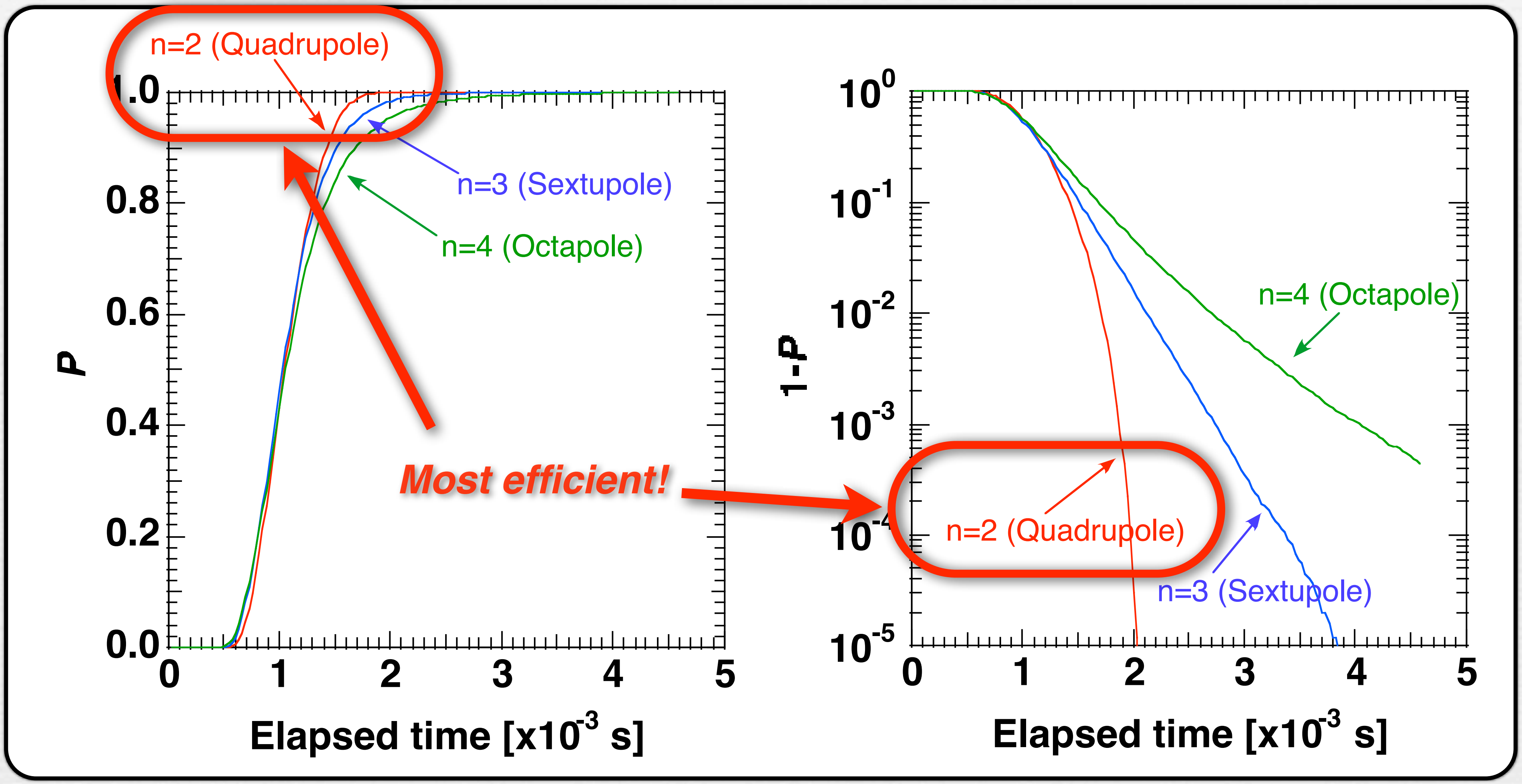
Quadrupole (n=2)	Sextupole (n=3)



Spatial separation of up and down spin => good for polarizer

Polarizing power

condition : IBI = 2T@r = 2.5mm

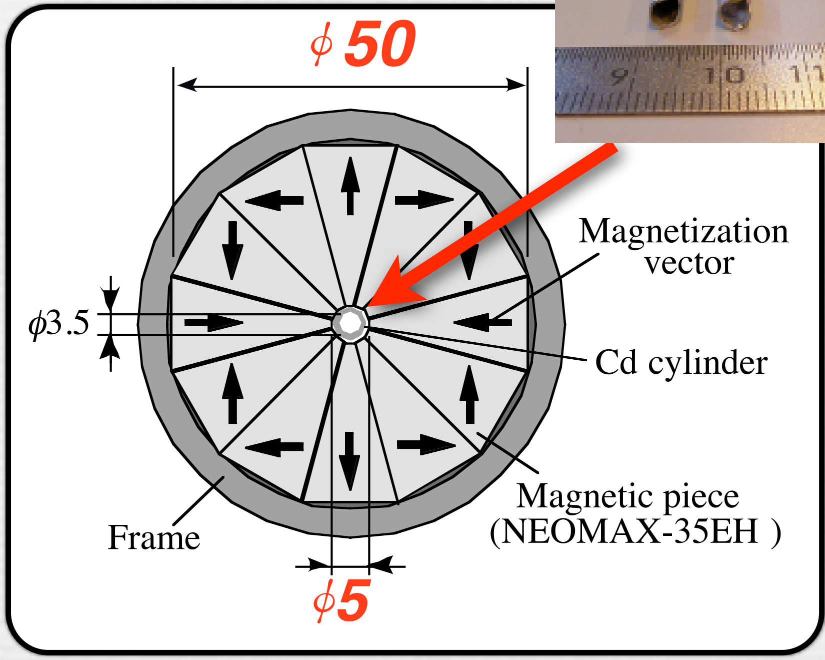


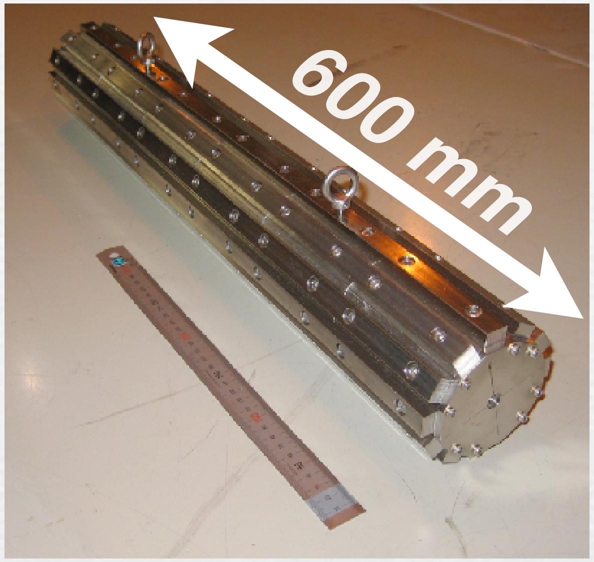
Polarization degree P as a function of the Elapsed time.

Here, P was calculated by counting the neutron numbers with up and down spins within r < 4mm after the elapsed time.

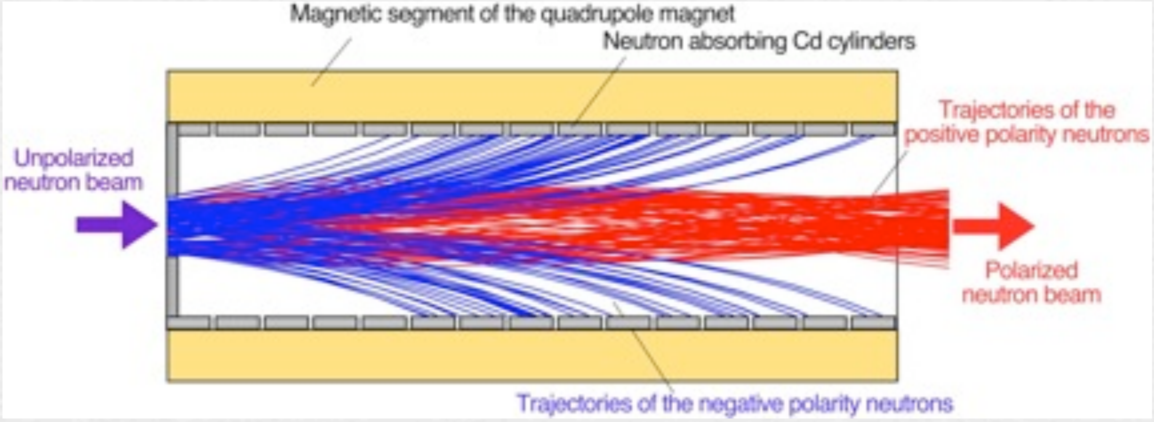
Halbach-type Quadrupole Magnet

Cd cylinder inserted into the magnet bore





Weight ~25kg



$|B| = G_q\, r$, $G = 800$ T/m

Acceleration of neutron

~ 4600 m/s^2 (~470G)

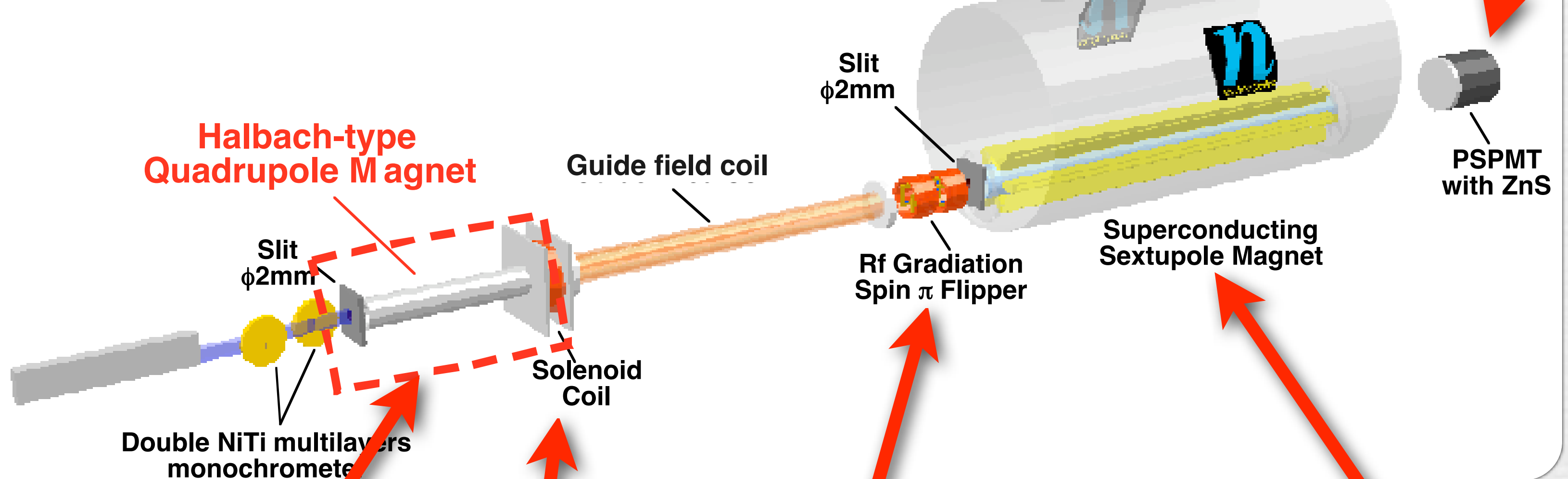
Cold Neutron Polarization Experiment

Experimental setup

λ=9.5Å

Beamline : NOP (C3-1-2-1) of JRR-3

2d-detector



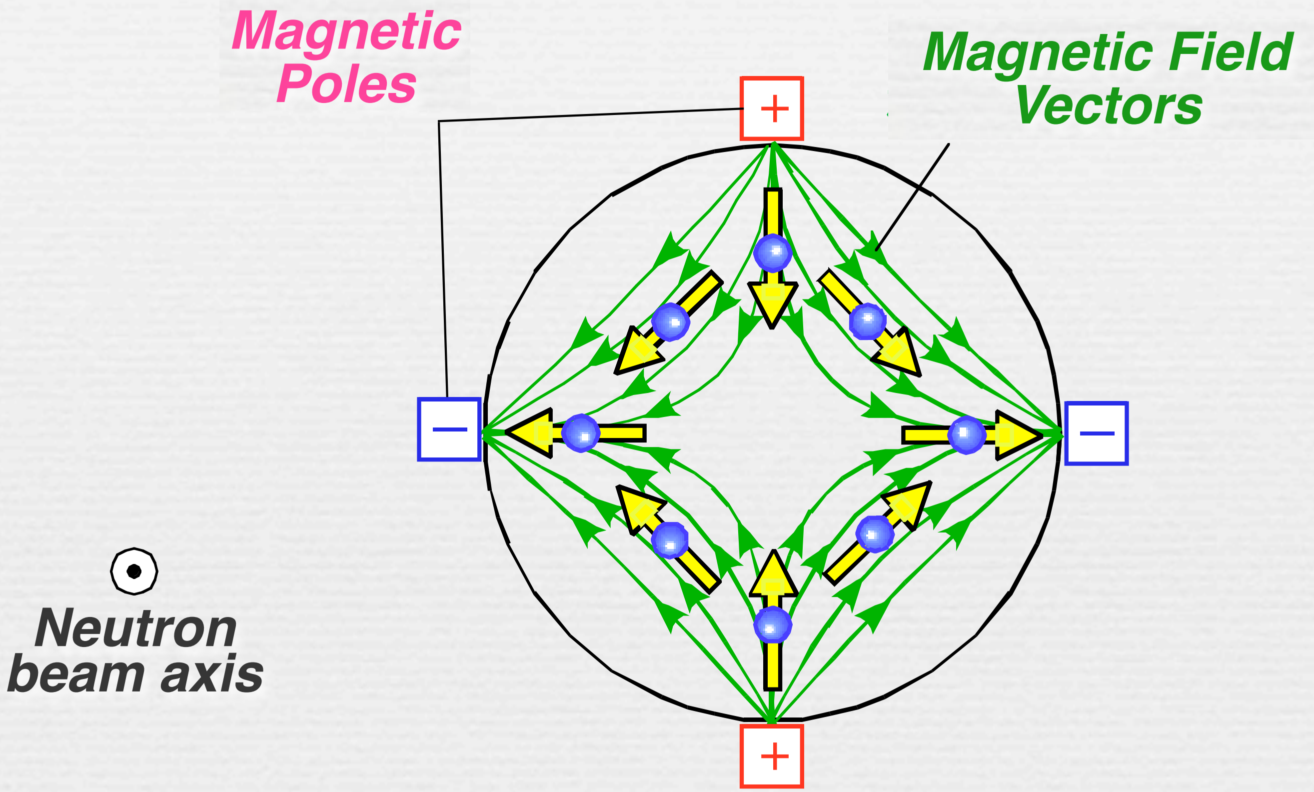
Quadrupole Magnet

Spin Flipper
(Rf gradient π-flipper)

Magnetic Lens
(Superconducting sextupole magnet)
for polarization analysis

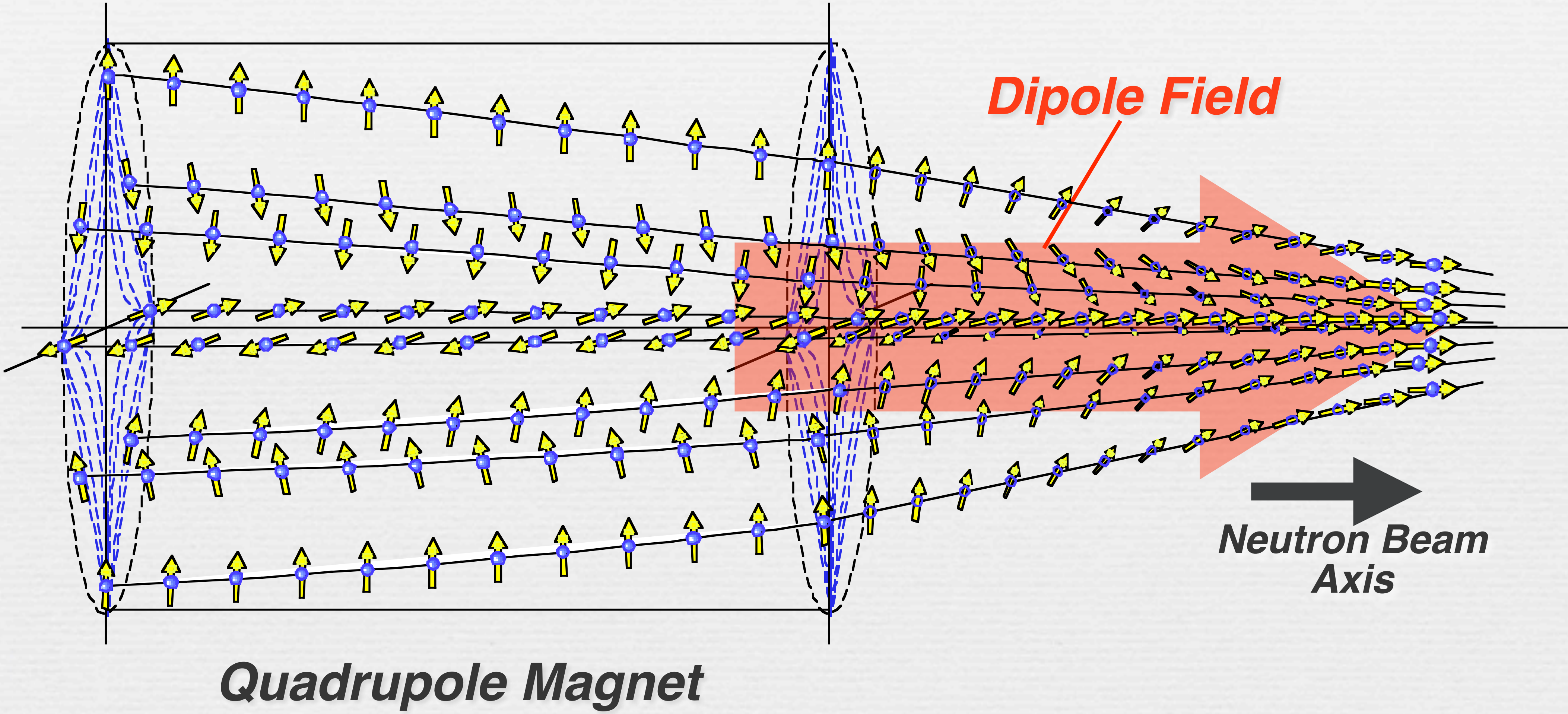
Solenoid Coil
for adiabatic spin transportation

Neutron Polarization inside the Quadrupole Magnet



Magnetic field distribution of quadrupole magnet

Neutron Polarization inside the Quadrupole Magnet

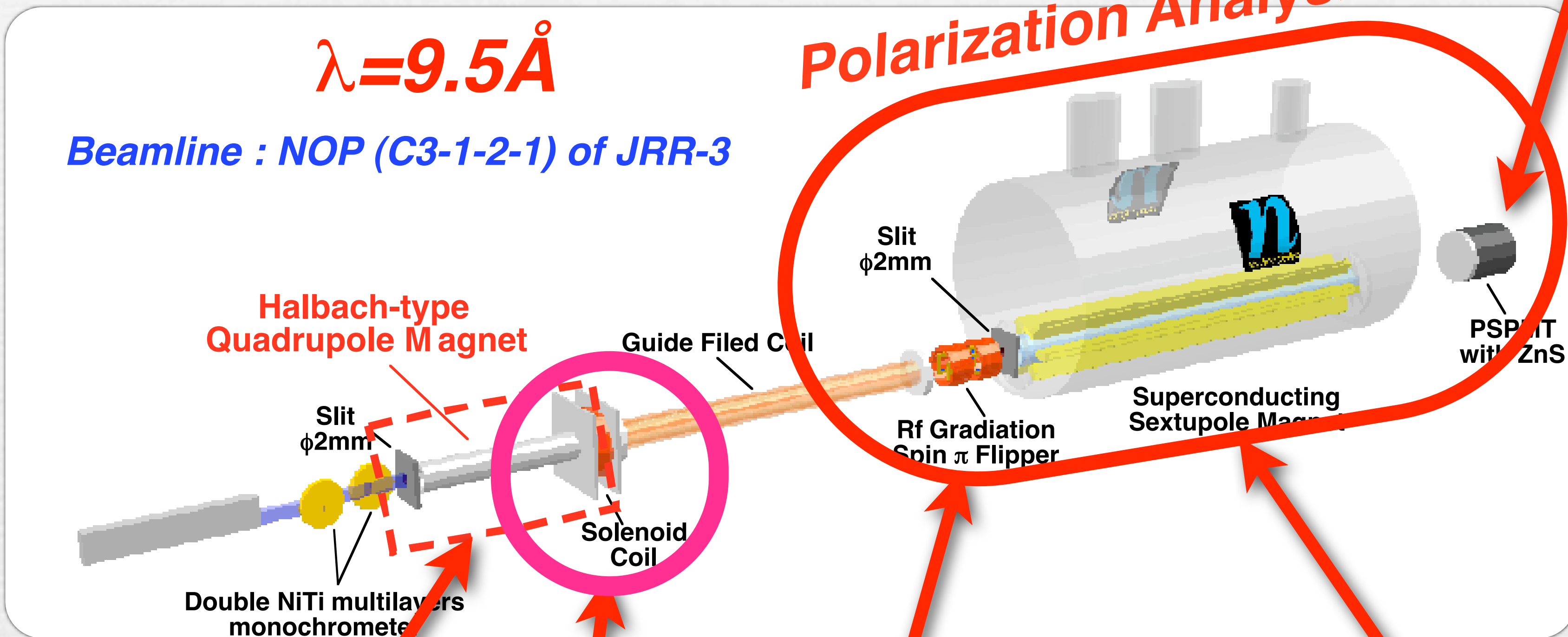


Cold Neutron Polarization Experiment

Experimental setup

Polarization Analysis

2d-detector



Quadrupole Magnet

Spin Flipper
(Rf gradient π-flipper)

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for polarization analysis

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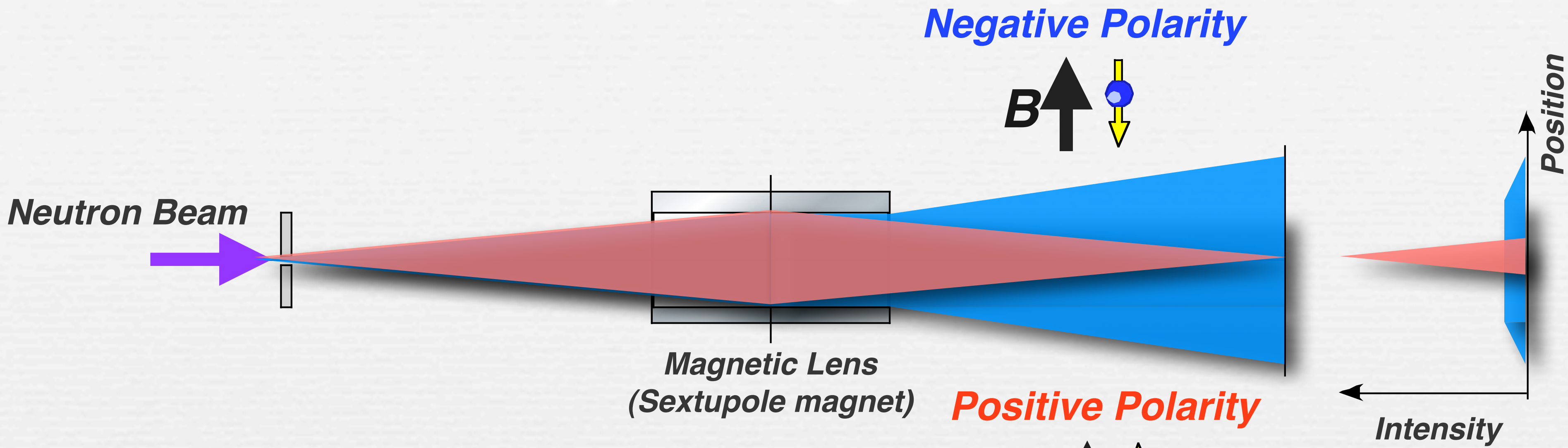
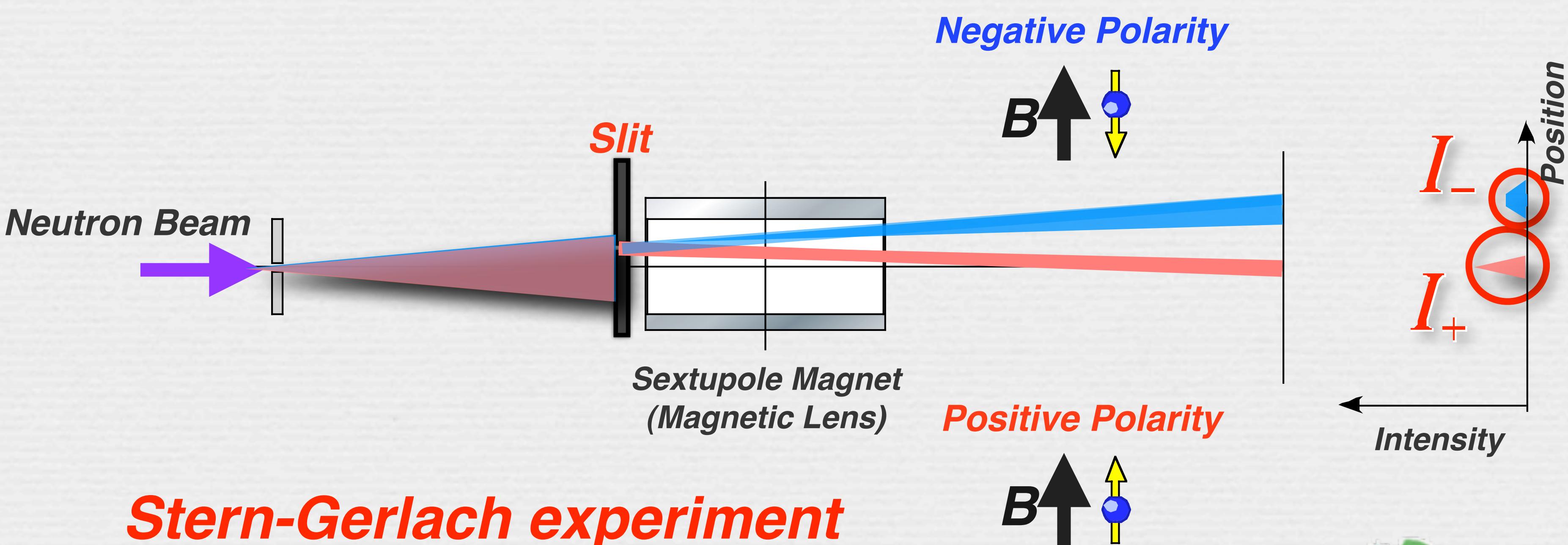
for adiabatic spin transportation

Polarization Analysis using the Magnetic Lens

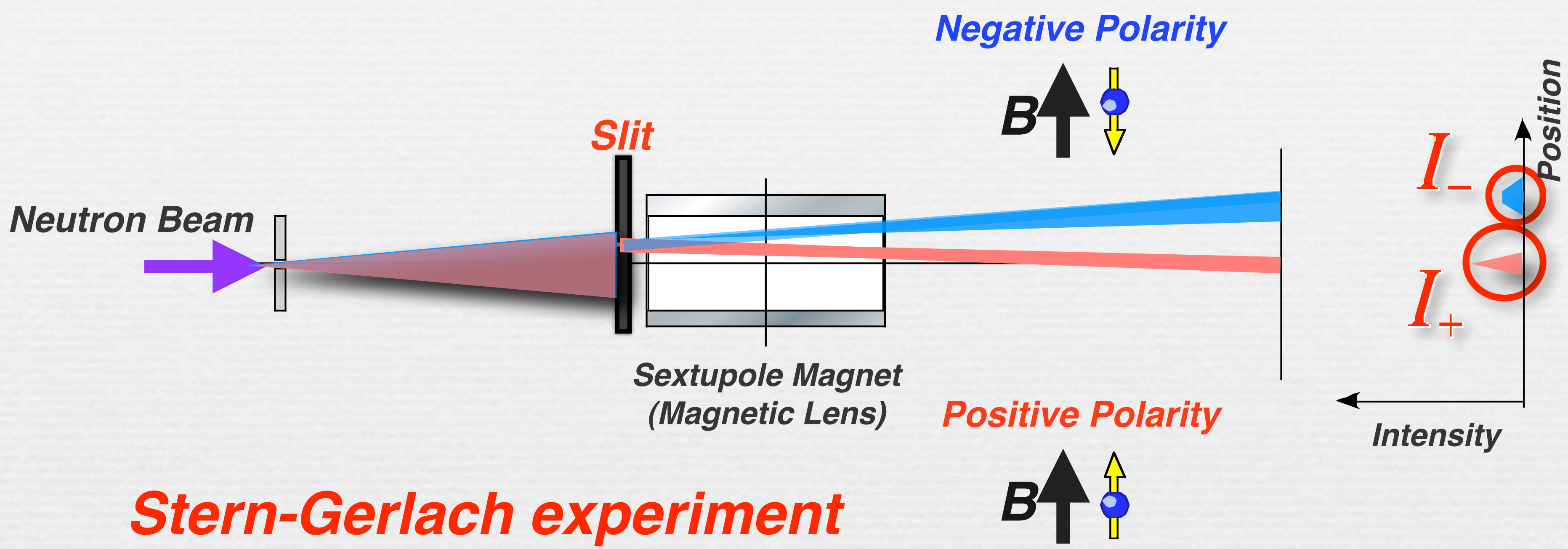




Stern-Gerlach experiment

Polarization degree : $P = \dfrac{I_+ - I_-}{I_+ + I_-}$

Polarization Analysis using the Magnetic Lens



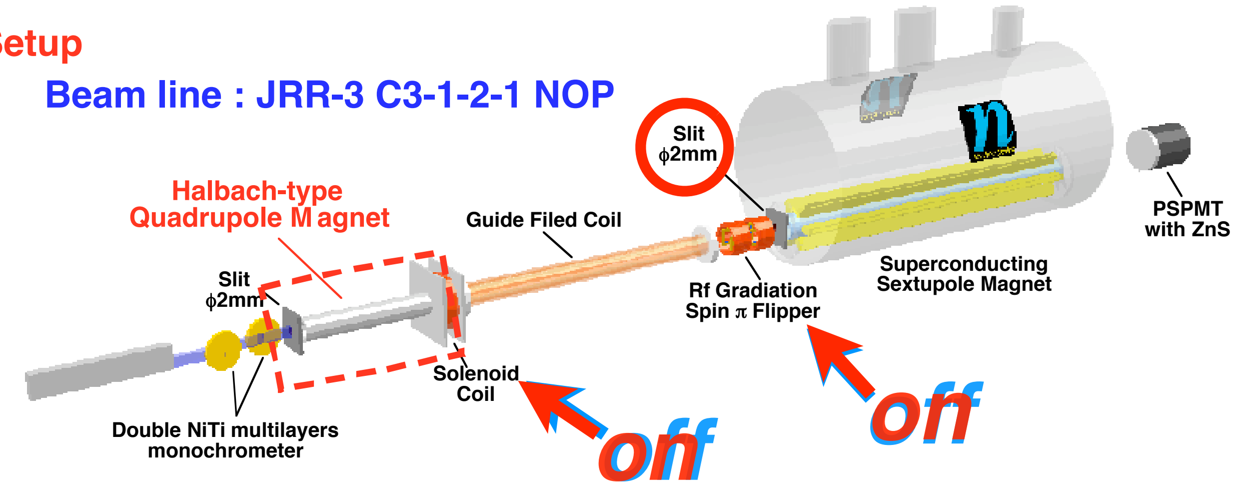
Stern-Gerlach experiment

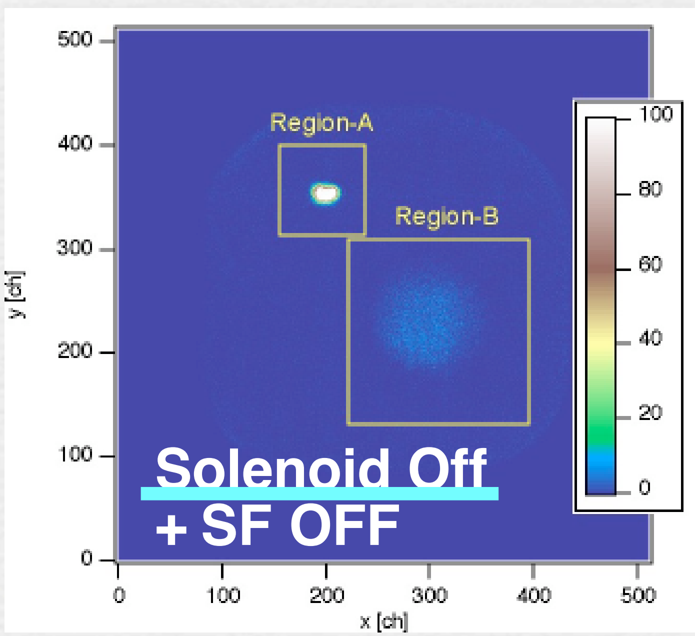
Polarization degree : $P = \dfrac{I_+ - I_-}{I_+ + I_-}$

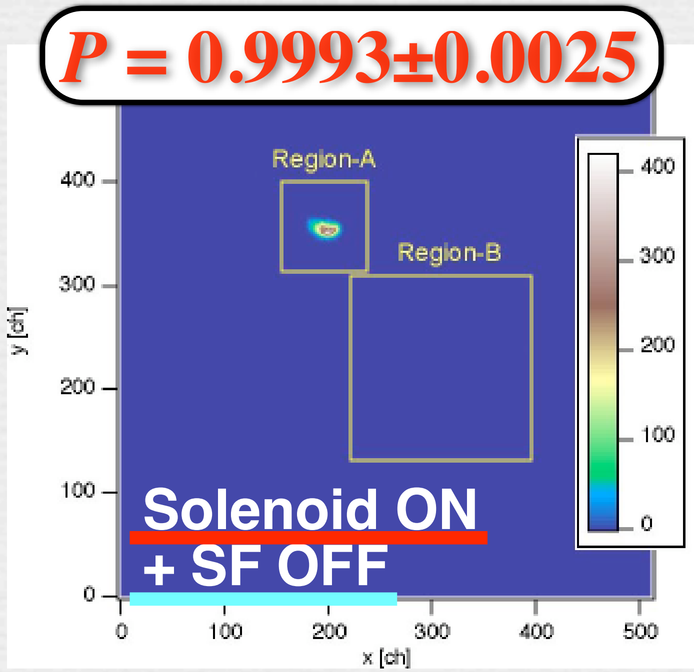
Experimental Result

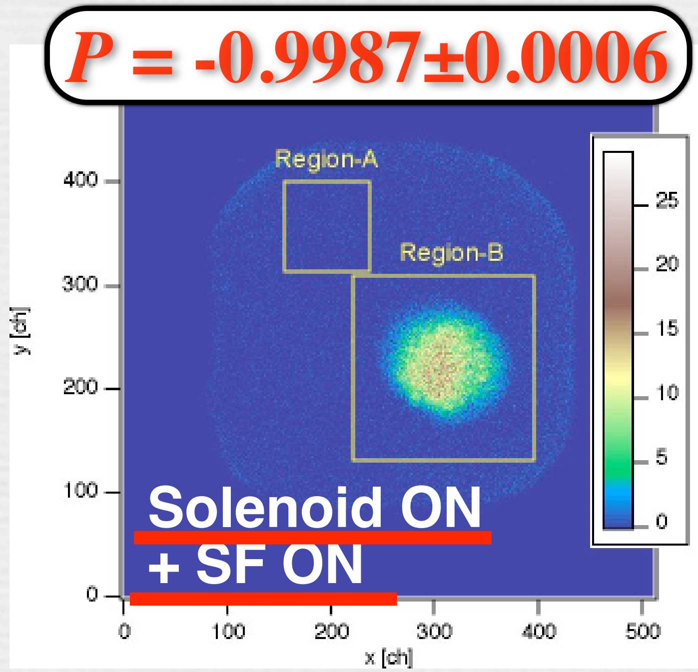
Setup

Beam line : JRR-3 C3-1-2-1 NOP



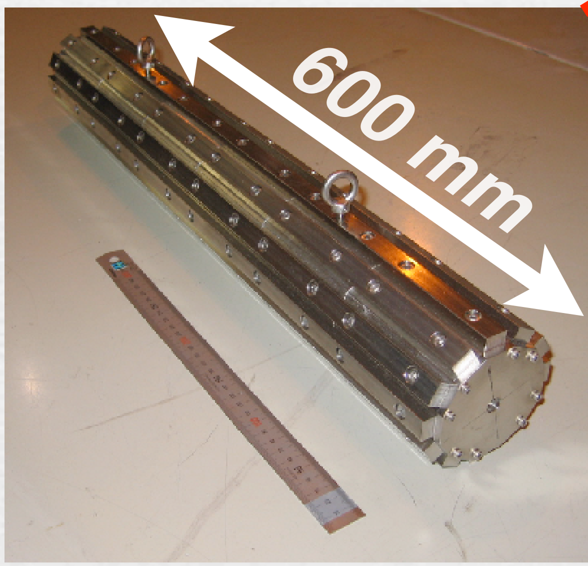




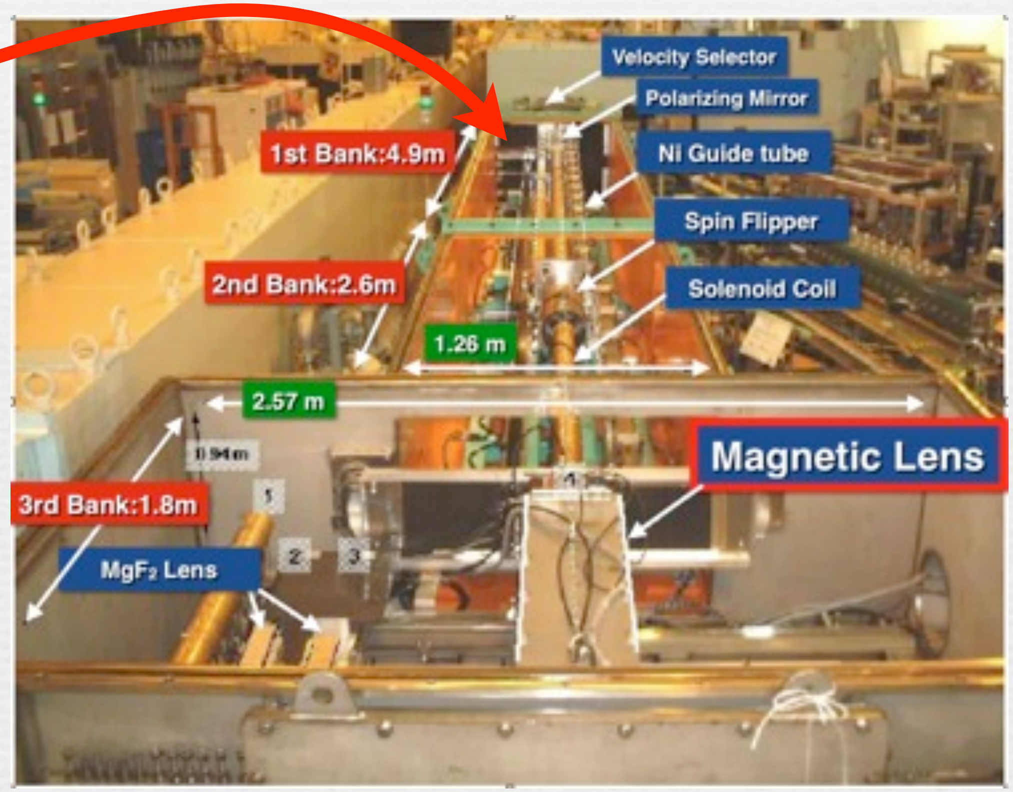


Plan of Practical Application

The Quadrupole Magnet are planed to be installed at the Focusing SANS Instrument SANS-J-II in March 2007 by JAEA Neutron Optics and Soft-matter Groups.

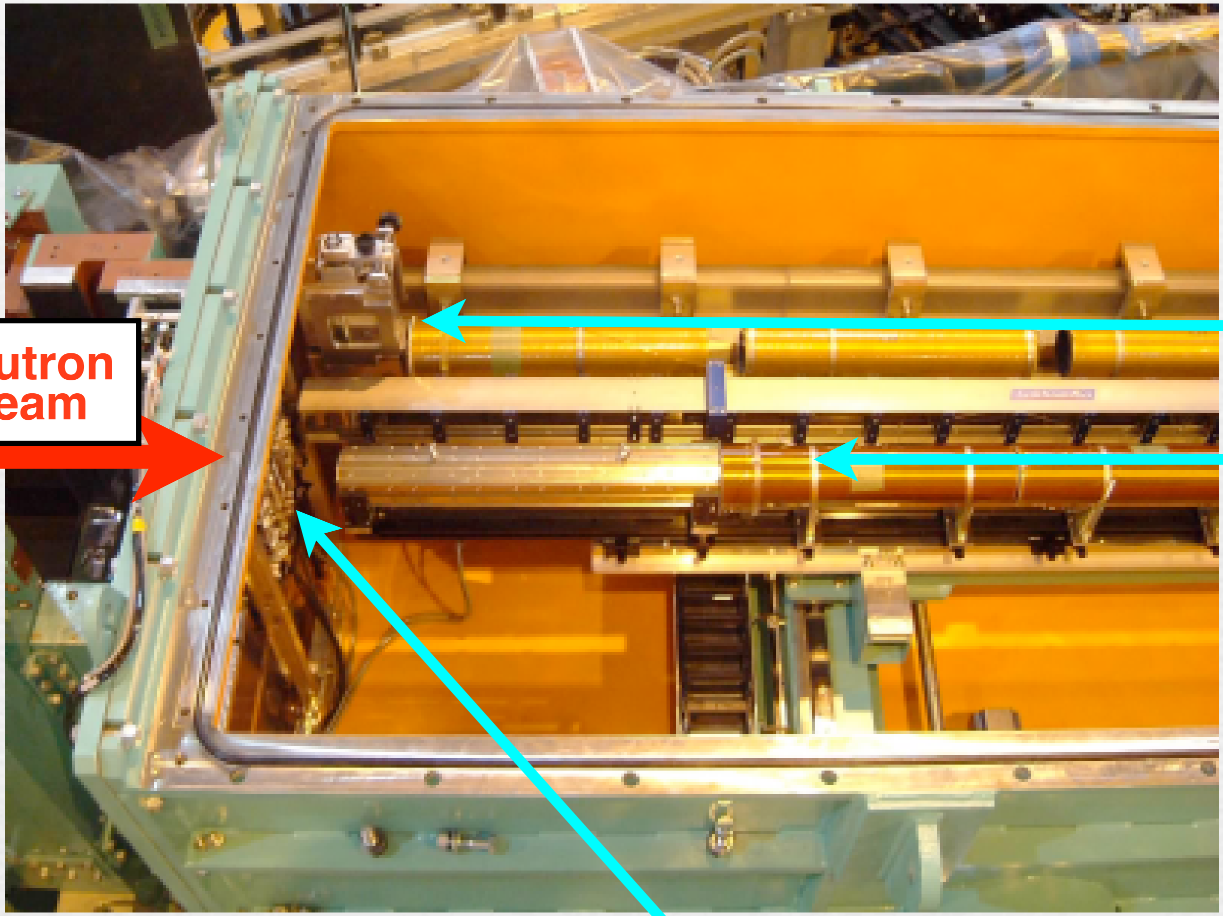


Halbach-type quadrupole magnet



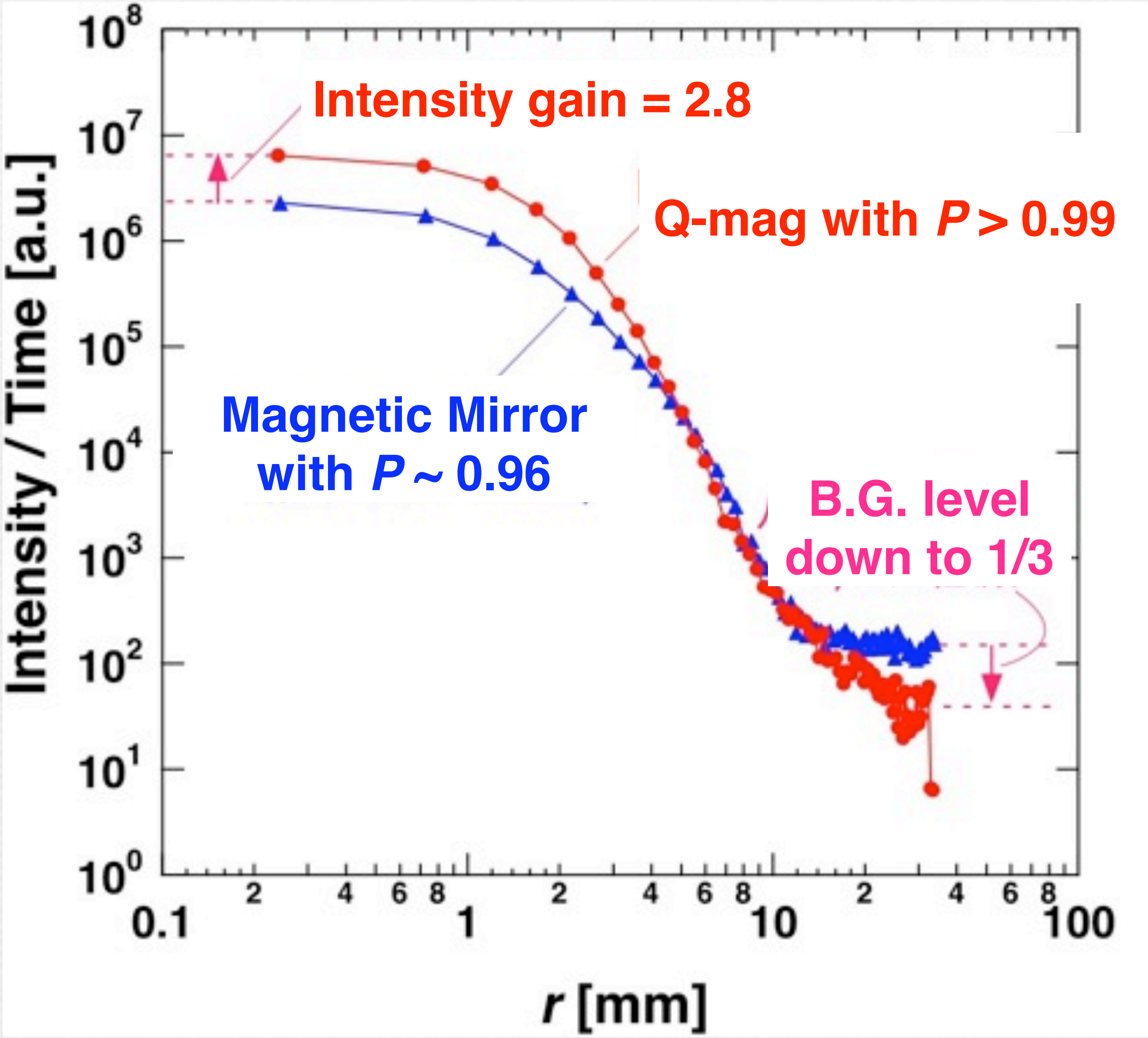
Focusing SANS Instrument with the Magnetic Lens (SANS-J-II of JRR3)

Neutron Polarizing and Transporting Devices of SANS-J-II



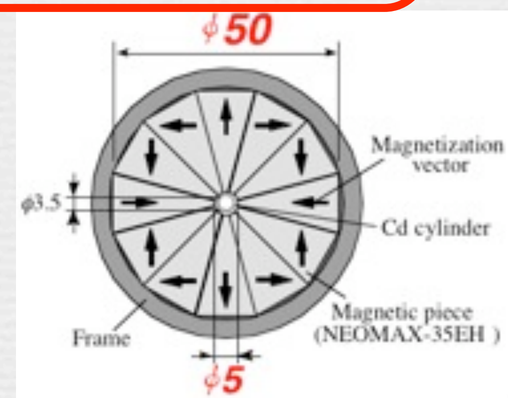
Inside of the Collimator chamber of SANS-J-II

Comparison
Magnetic mirror vs Quadrupole magnet



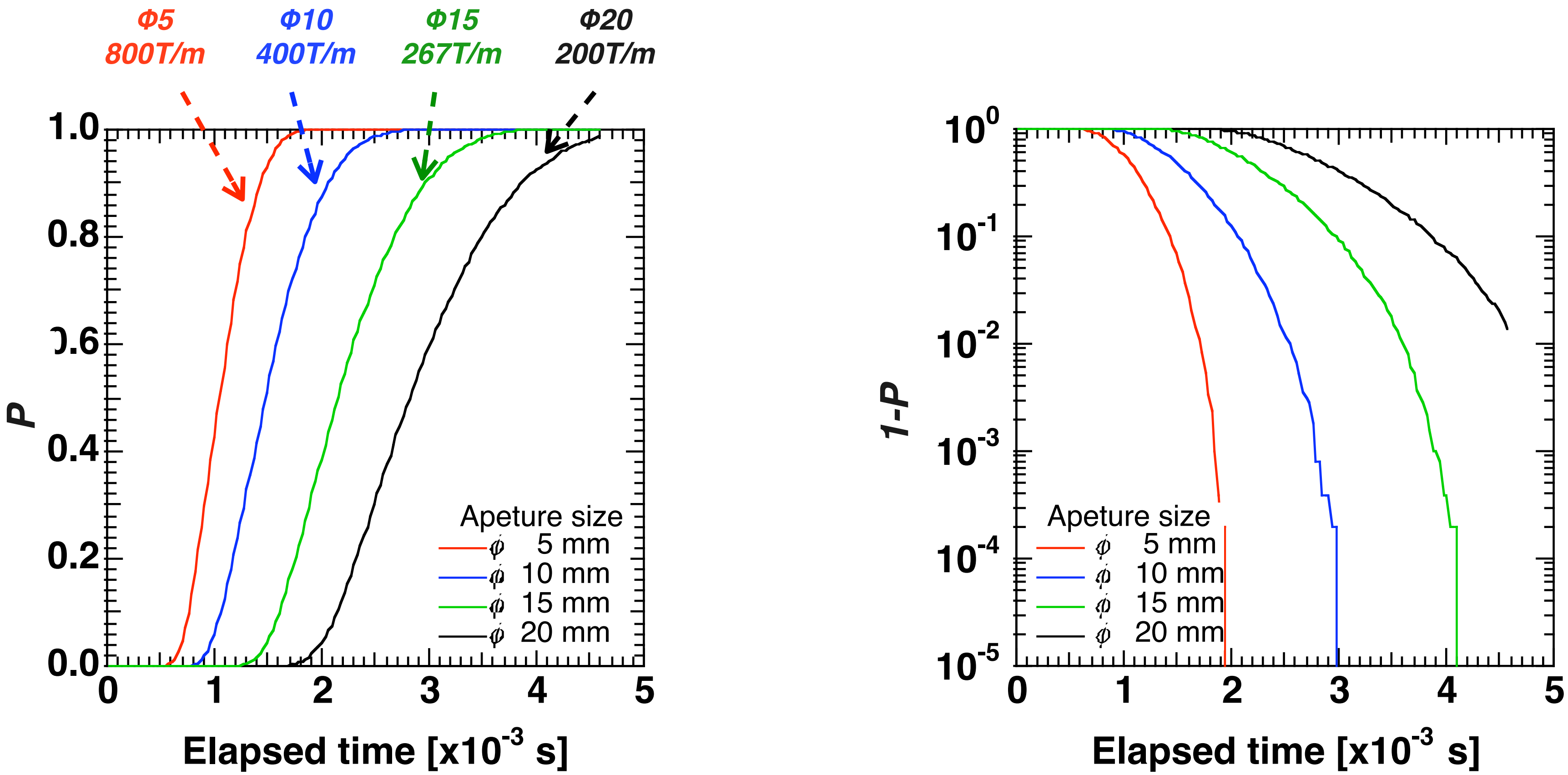
Characteristic of the Quadrupole Magnet Polarizer

- *High polarizing power* ＼(^o^)
  - *High Polarization degree of P=0.9993±0.0025 was achieved.*
- *High stability* o(^-^)o
  - *It is composed of the permanent magnets.*
- *High transmission* d(⌒o⌒)b
  - *No attenuation of polarized neutrons occurs, since they do not interact with any materials.*
- *Opening aperture is small.* (T.T)
  - *The magnet aperture can be enlarged to some extent.*
- *Magnet length must be made longer.* (^^;)
  - *With increasing magnet aperture ron*
  - *For higher energy neutron*
- *Acceptable beam divergence* o(^_^;)o
  - *Increases with maximum field strength. i.e. proportional to square root of |B|max*



Polarizing power of Quadrupole magnet with different aperture sizes

Condition : |B| = 2T *on the inner surface of the magnet*



The magnetic field strength at the inner surface of the magnet is set constant of |B|=2T, so that the magnetic field gradient linearly decreases with the aperture size.

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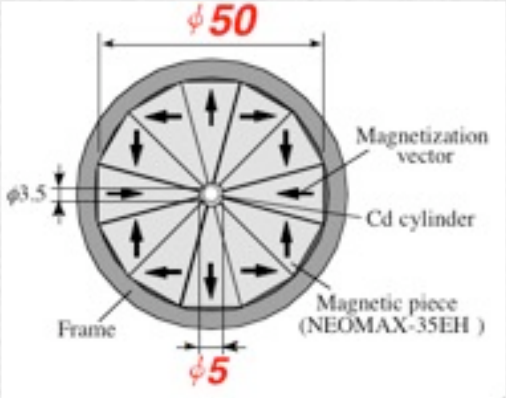
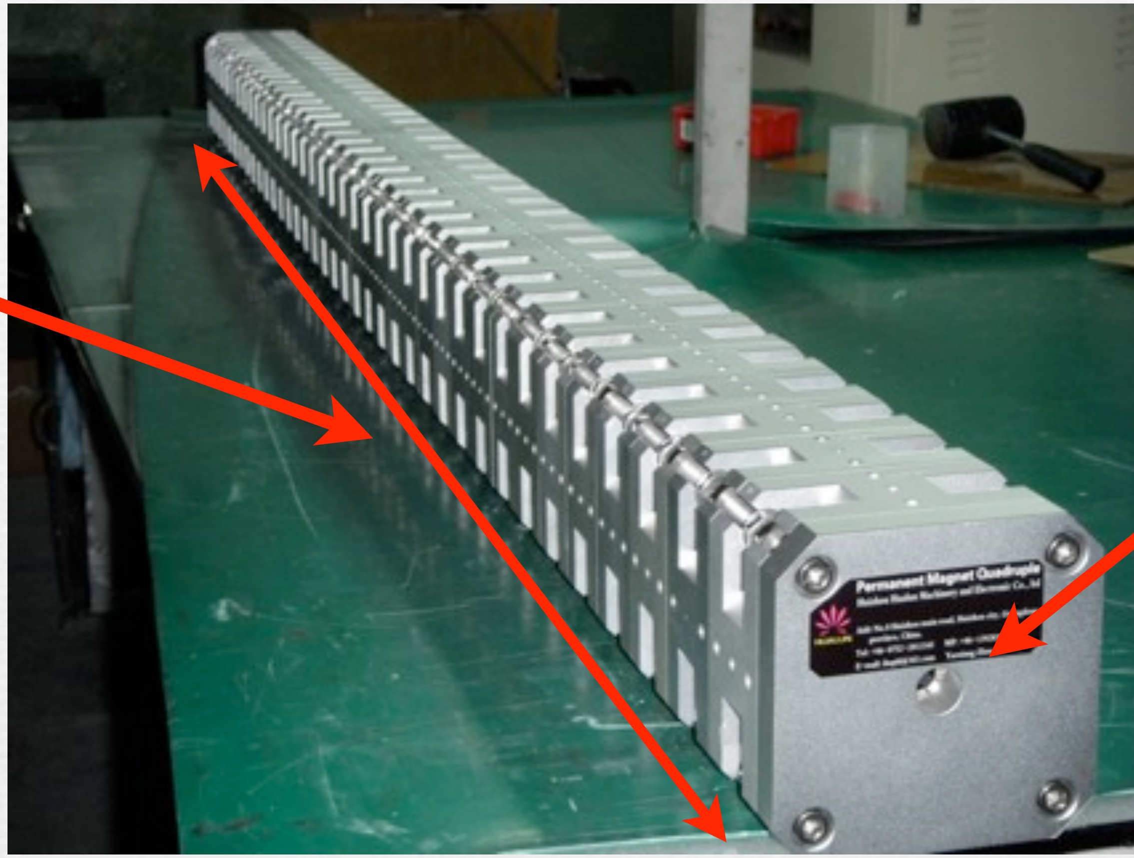


March 2009

Designed by Prof. Iwashita

Magnet length:
2200mm



Aperture size :
15mmϕ

Quadrupole Magnet with Extended-Halbach Magnetic Circuit

Target wavelength > 6 Å

This magnet is planed to be install into SANS-J-II of JRR-3

Characteristic of the Quadrupole Magnet Polarizer

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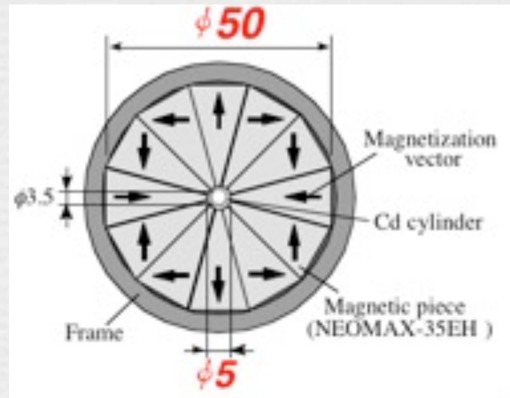


Acceptable Beam Divergence: θ_{max}

$$\theta_{\max} = \tan^{-1}\left(\mathrm{v}_{\perp} \big/ v_z \right) \approx \frac{\mathrm{v}_{\perp}}{v_z} = \frac{\sqrt{2\mu_n \left|B\right|_{\max} \big/ m_n}}{v_z}$$

Realized with permanent magnets

$$\left|B\right|_{\max} = 2\ \mathrm{T} \quad \Rightarrow \quad \mathrm{v}_{\perp} = 4.8\ \mathrm{m/s} \quad \Rightarrow \quad \theta_{\max} = 0.7\,\theta_{C,Ni}$$

$$\left|B\right|_{\max} = 4\ \mathrm{T} \quad \Rightarrow \quad \mathrm{v}_{\perp} = 6.8\ \mathrm{m/s} \quad \Rightarrow \quad \theta_{\max} \approx \theta_{C,Ni}$$

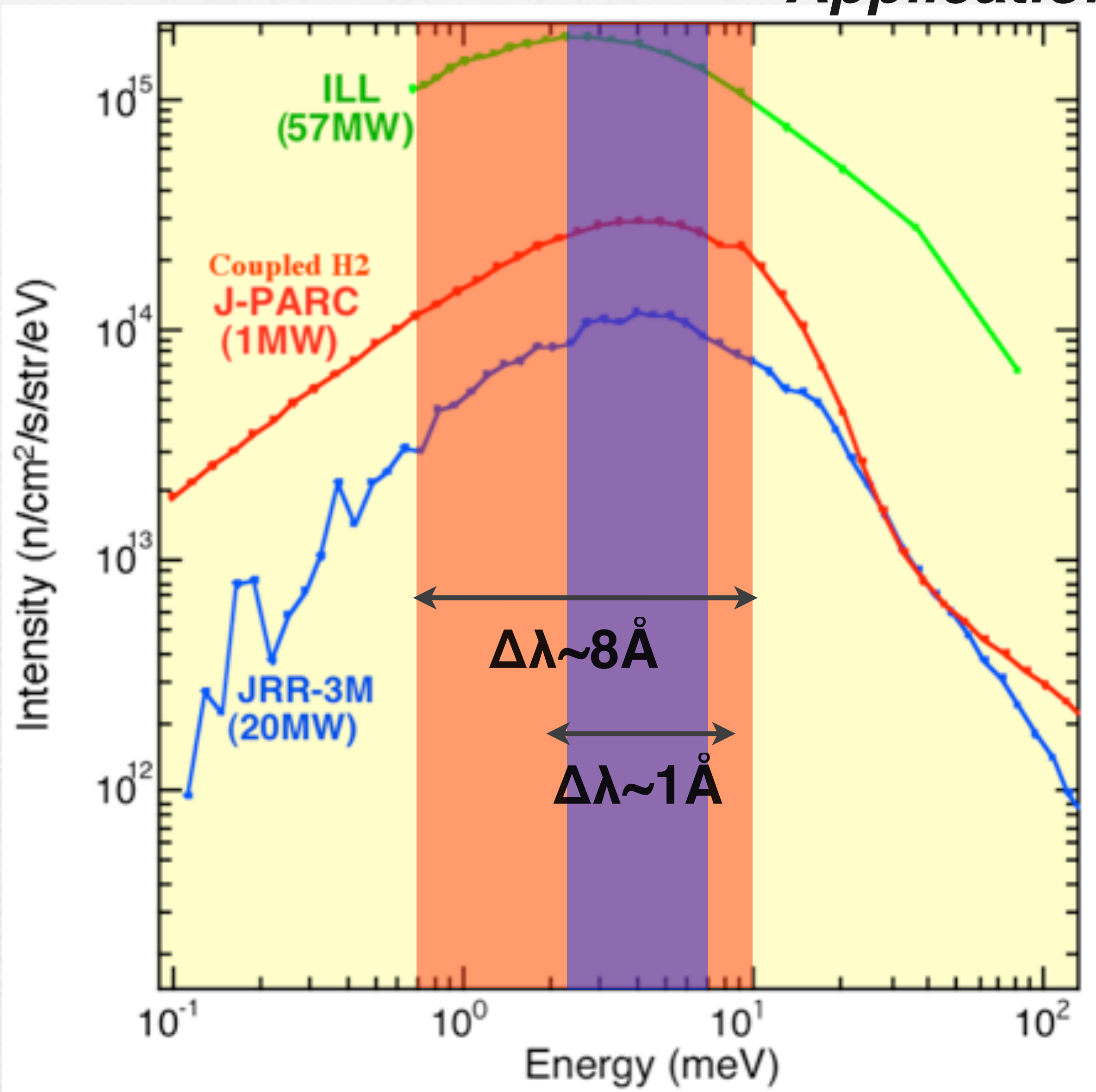
Realized with superconducting magnets

$\theta_{C,Ni}$: Critical angle of Ni mirror guide

2) Pulsed Neutron Focusing by using Multiplet-Magnetic Lens System for TOF SANS instruments.

Intensity of Neutron Source

Application to the SANS



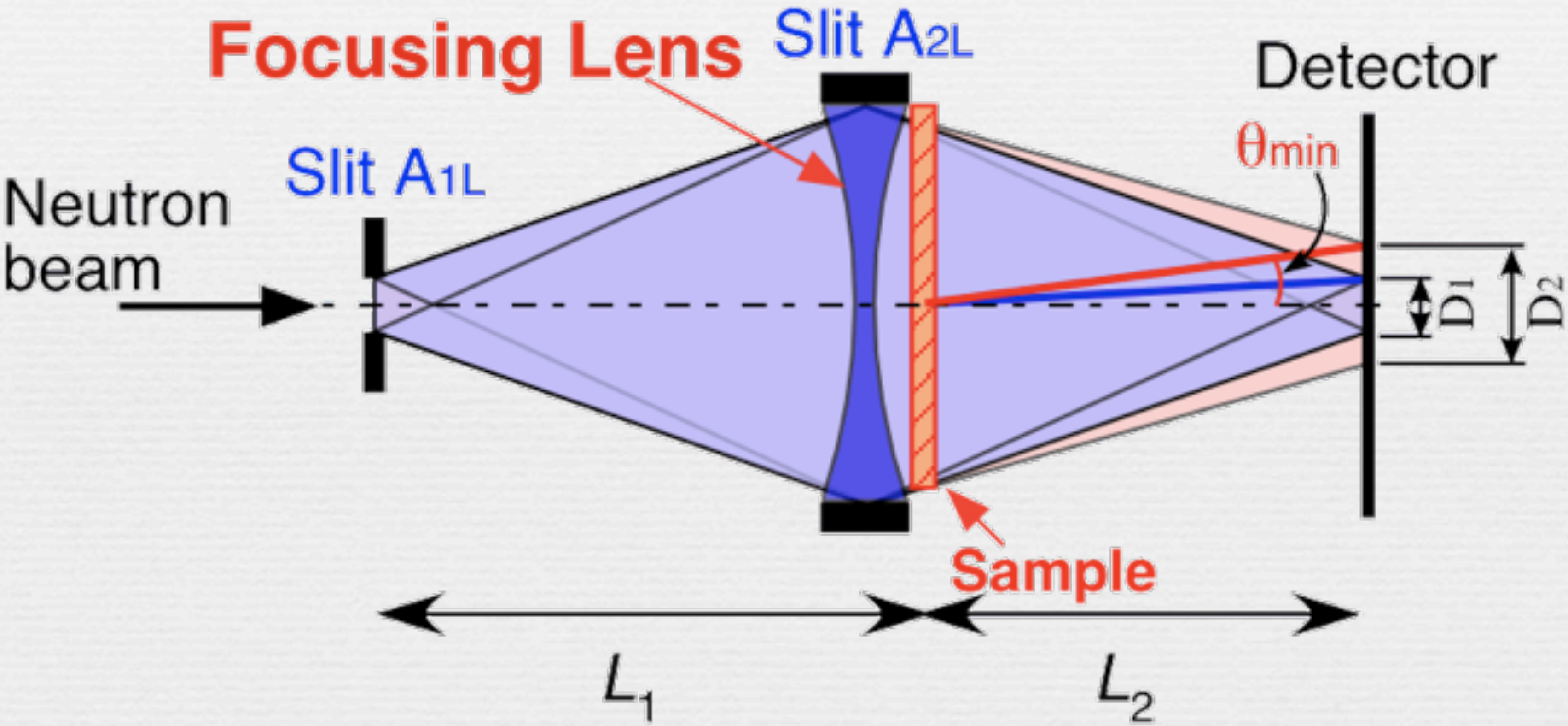
Conceptual design of TOF SANS Spectrometers

In order to get intensity gain by using neutron in wide wavelength range, the total flight-path should be shortened.

Type	Spectrometer	Total Flight-Path	Sample to Detector distance, L_2
TOF	J-PARC SANS	21 m	4.5 m
	Extended-Q SANS (SNS)	18 m	4 m
Steady	SANS-J-II (JRR-3)	-	10 m
	D11(ILL)	-	40 m
	NG3(NIST)	-	13 m

The short sample to detector distance L_2 tend to deteriorate the angular resolution in low-q region for SANS spectrometer. To compensate this effect, the neutron focusing technique becomes important for the TOF SANS spectrometers.

Focusing-geometry SANS (F-SANS) to extend low-Q limit



Setup of the F-SANS instrument

Developed Magnetic Lenses

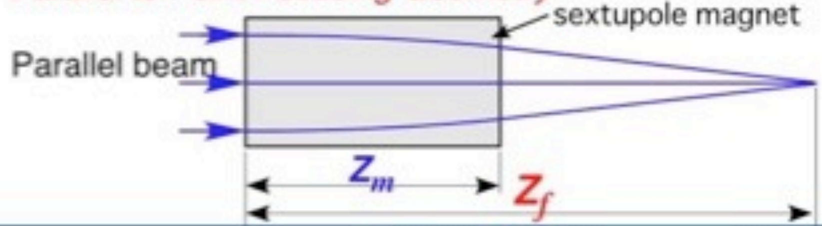
@Tokai Neutron Optics	 Superconducting Sextupole Magnet	 Extended Halbach Sextupole Magnet	 Sextupole Pulse Electro-Magnet
Manufacture year	2002	2002	2002
mode	Steady	Steady	Pulse
Magnet length Z_m	**2 m**	**2 m** (0.1m/unit)	**2 m**
Magnetic field gradient *)	12,800 Tm^{-2}@1.8K (9,480 Tm^{-2}@4.2K)	20,100 Tm^{-2}	7,500 Tm^{-2}
Effective aperture (diameter)	**ϕ 46.8 mm**	**ϕ 25 mm**	**ϕ 22 mm**
Focal length Z_f**) for 6 Å	**4.3 m**@1.8K (3.5 m@4.2K)	**3.2 m**	**6 m**

***) Definition of the Focal length*

$$Z_f = Z_m + \frac{h}{\sqrt{G\alpha m_n}\lambda}\cot\left(\frac{\sqrt{G\alpha m_n}\lambda}{h}Z_m\right)$$

Chromatic aberration!!

Parallel to Point Focusing Geometry



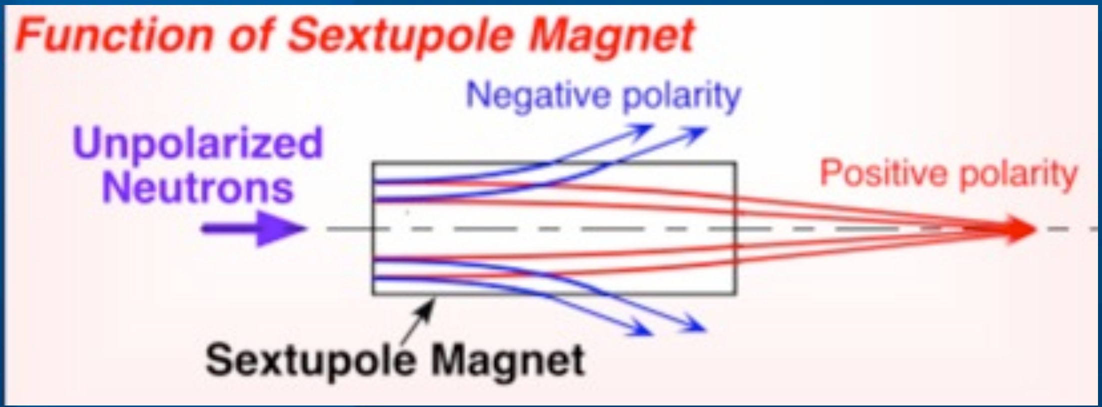
How to apply Magnetic Lens to Pulsed Neutrons?

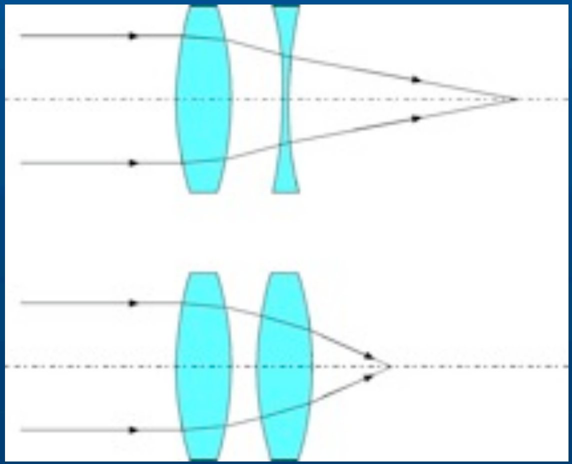
1. Changing the magnetic field strength with time

- Sextupole Pulse Electro-Magnet
- Sextupole Permanent Magnet with double layer structure
- Sextupole Permanent Magnet with variable bore size

2. Multiplet Magnetic Lens System

- Change the lens function (Focusing or Defocusing) with time





Multiplet Magnetic Lens with Spin Flippers

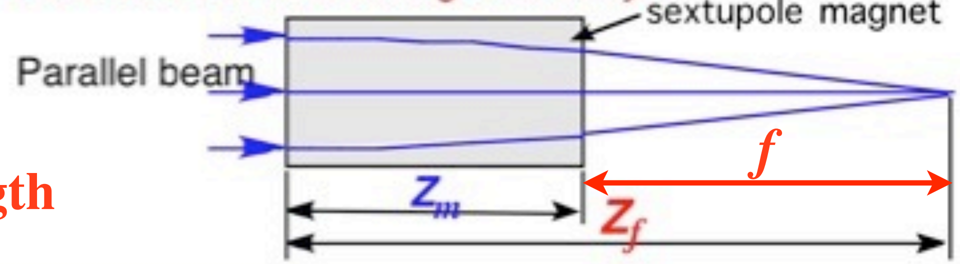
Definition of the Focal length

$$Z_f = Z_m + \frac{h}{\sqrt{G\alpha m_n \lambda}} \cot\left(\frac{\sqrt{G\alpha m_n \lambda}}{h} Z_m\right)$$

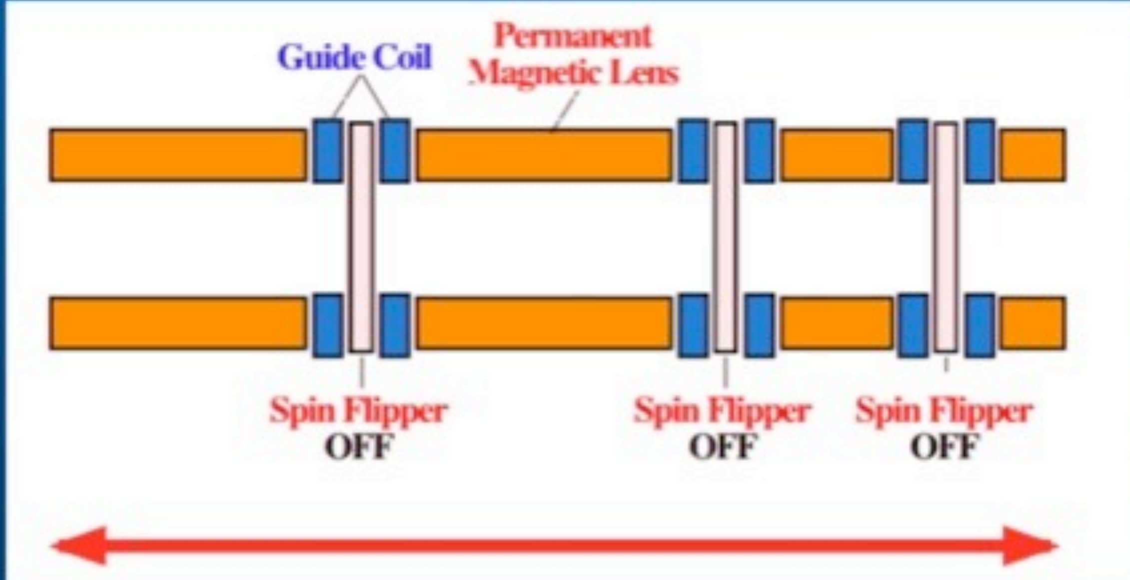
$$f = Z_f - Z_m \propto \sim \frac{1}{\lambda^2 Z_m}$$

magnet length

Parallel to Point Focusing Geometry



Changing effective magnet length by controlling the neutron spin state.



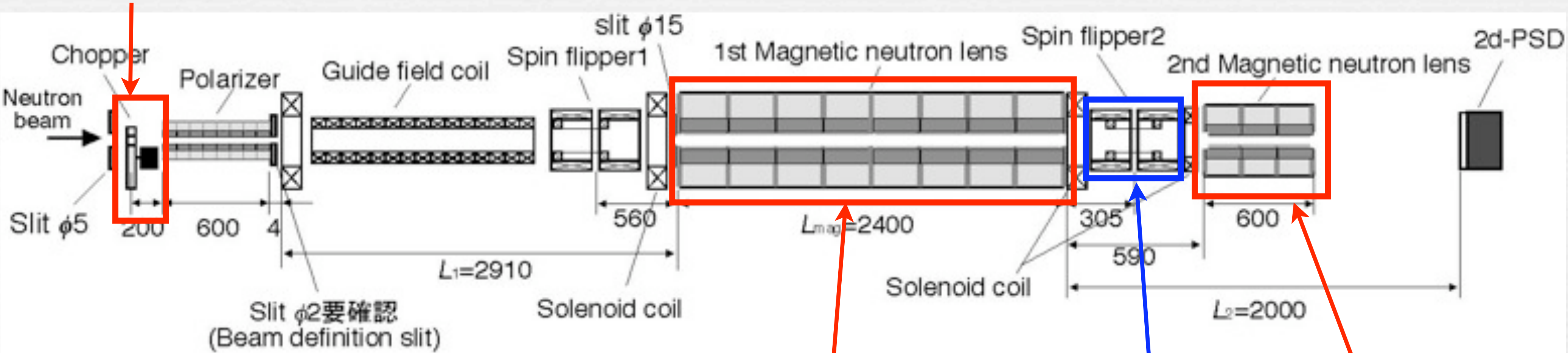
J. Suzuki
R. Pynn

Sextupole magnet focuses positively polarized neutron and defocus negatively polarize neutron!

Experimental test

Chopper to pulse a neutron beam

Beamline : JRR-3 C3-1-2-1 NOP



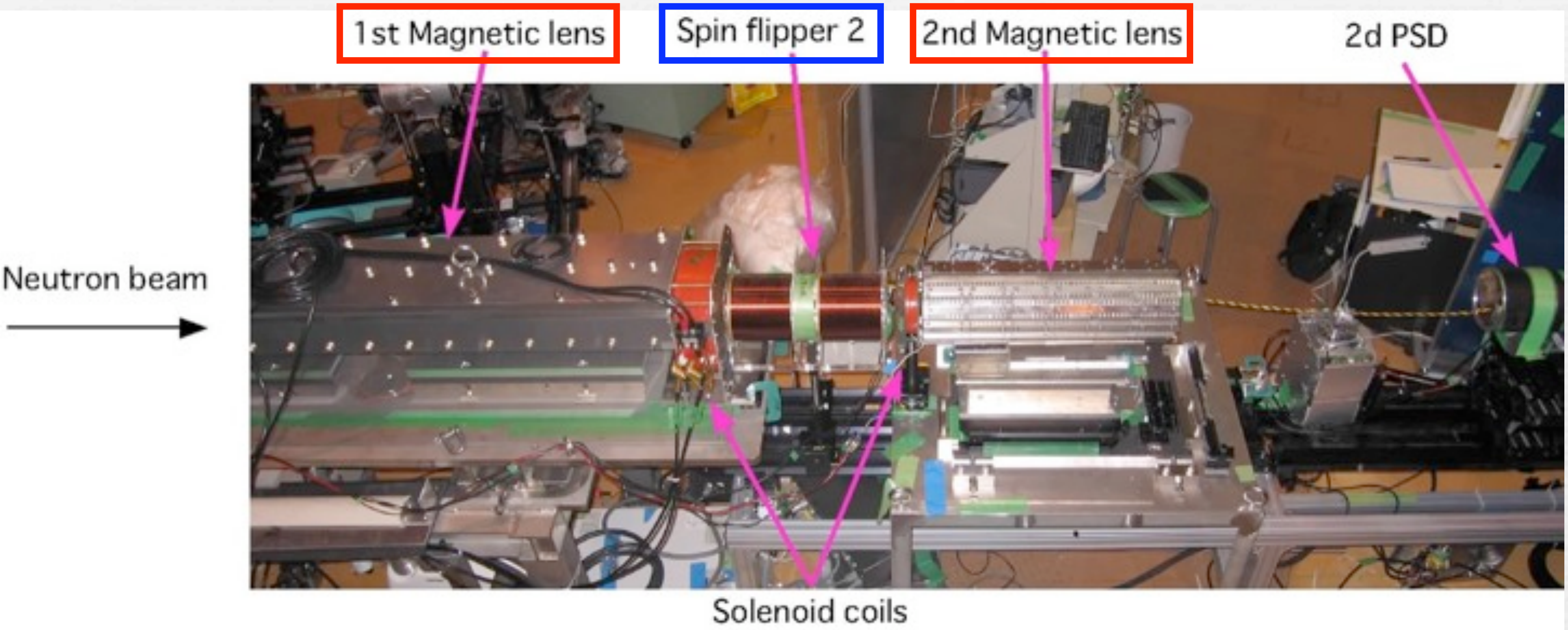
1st Lens

Spin flipper

2nd Lens

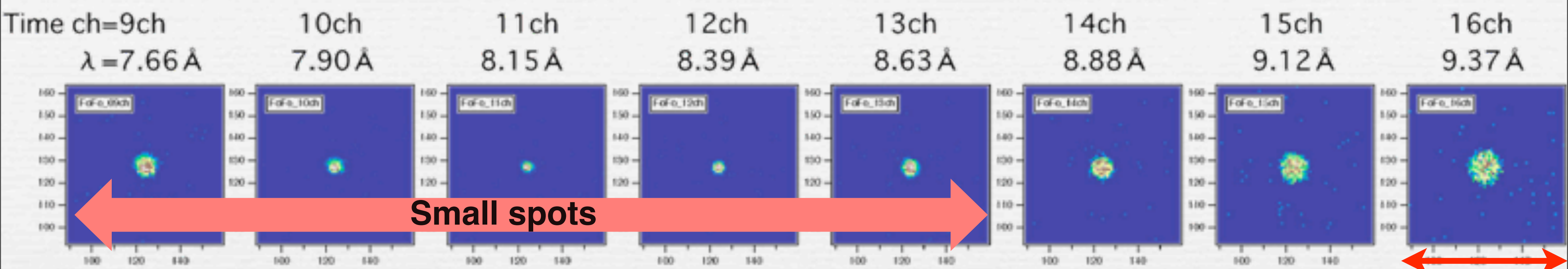
Experimental setup : Double magnet system

Beamline : JRR-3 C3-1-2-1 NOP



Experimental setup : Double magnet system

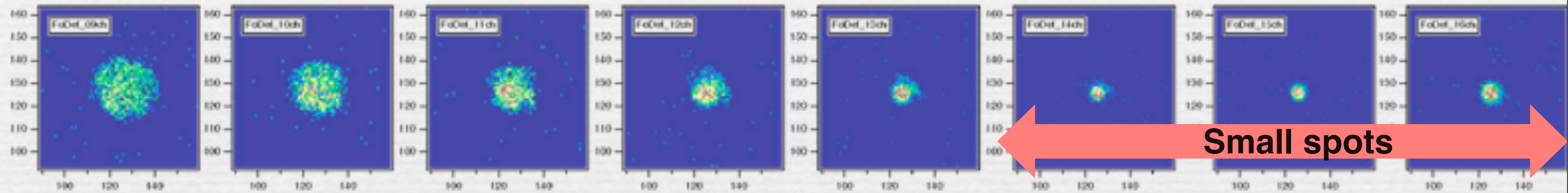
Experimental Result



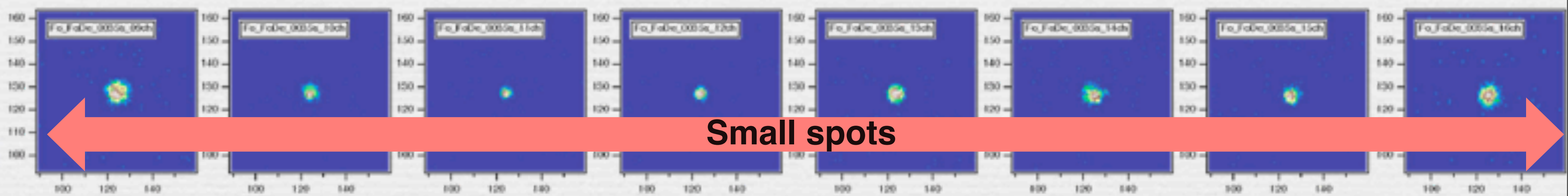
1st Lens : Focus,   2nd Lens : Focus (Spin Fliper is OFF)

Experimental Result

1st Lens : Focus, 2nd Lens : Focus (Spin Fliper is OFF)

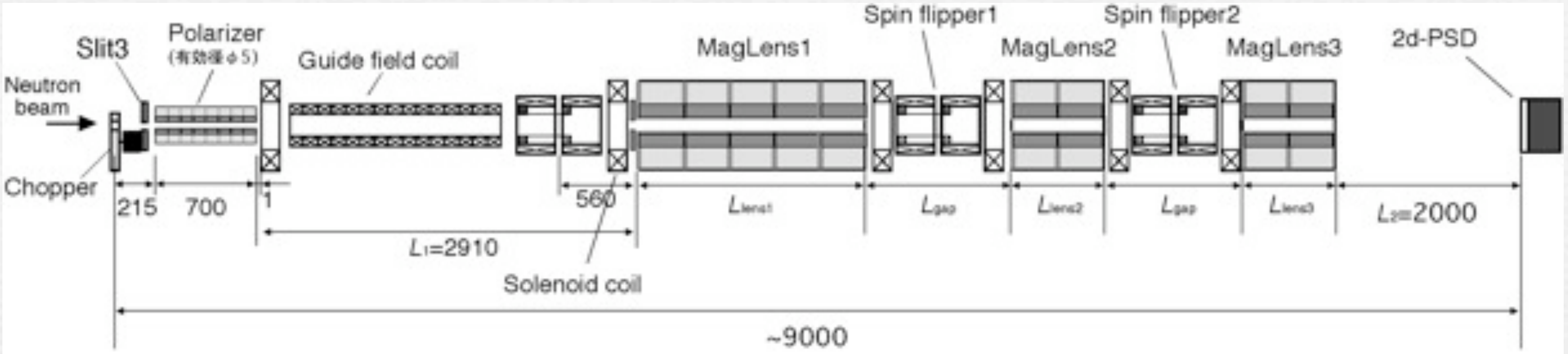


1st Lens : Focus, 2nd Lens : Defocus (Spin Fliper is ON)



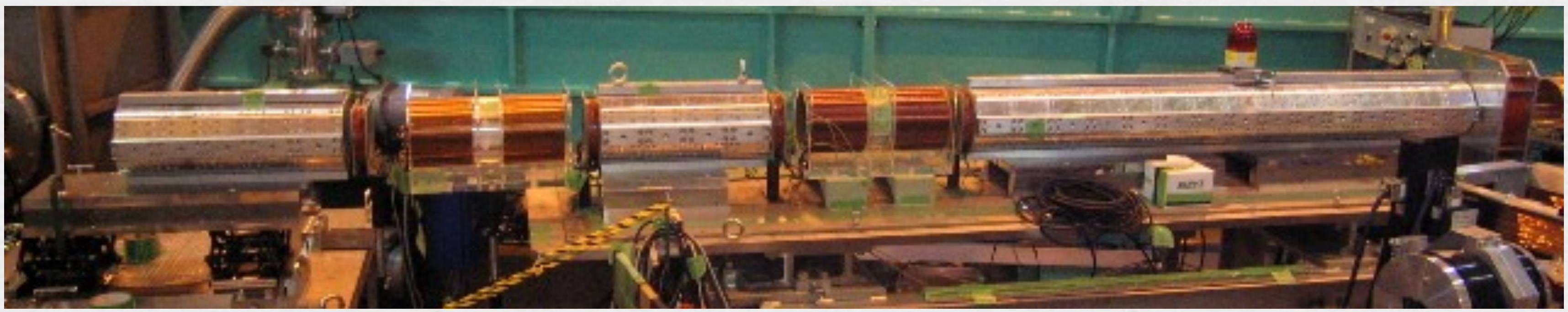
1st Lens : Focus, 2nd Lens : Focus -> Defocus
(Spin Fliper : OFF -> ON)

Triple Lens System



Schematic layout of the experimental setup of the triplet lens system.

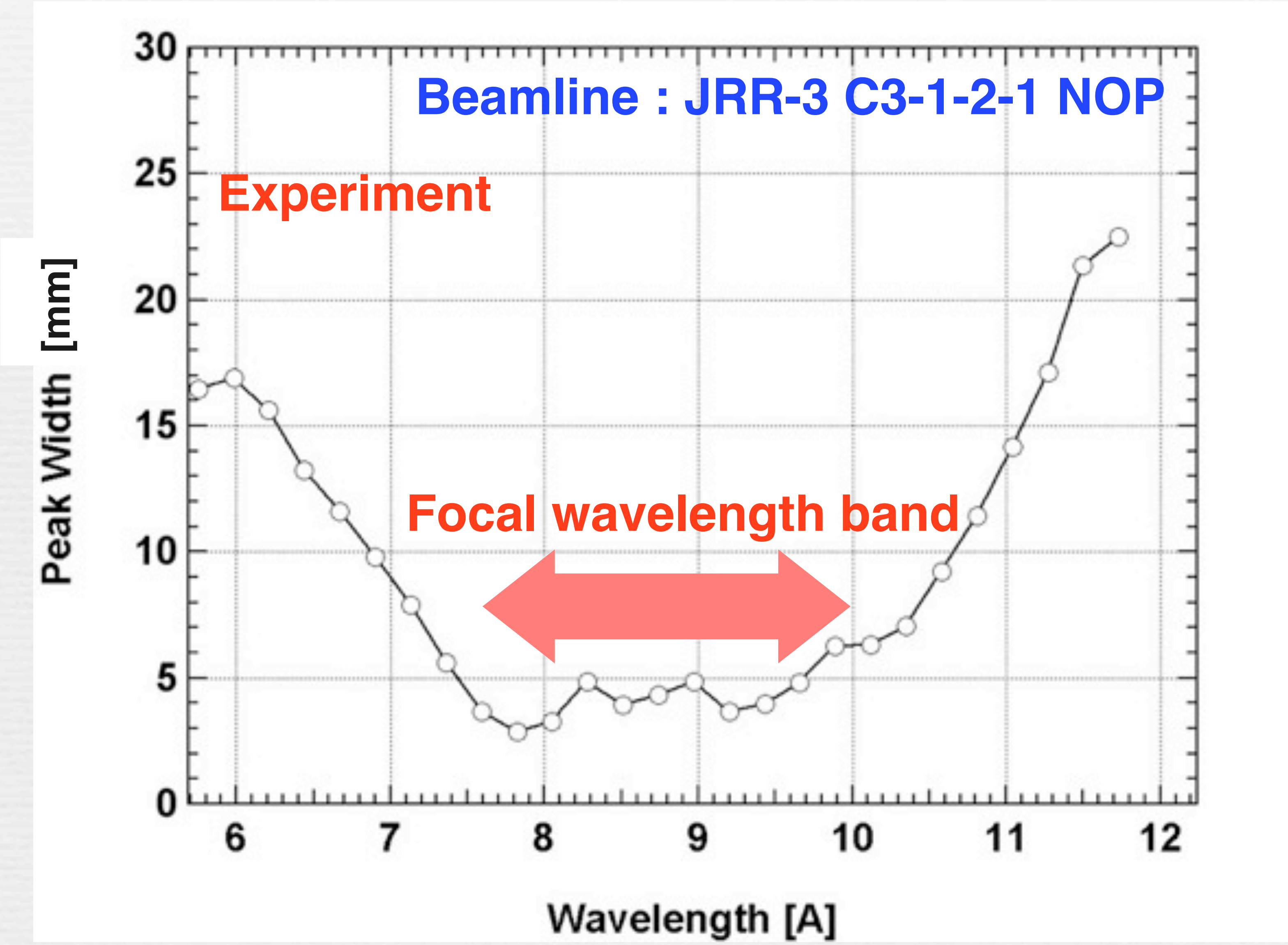
Beamline JRR-3 C3-1-2-1 NOP



Experimental setup

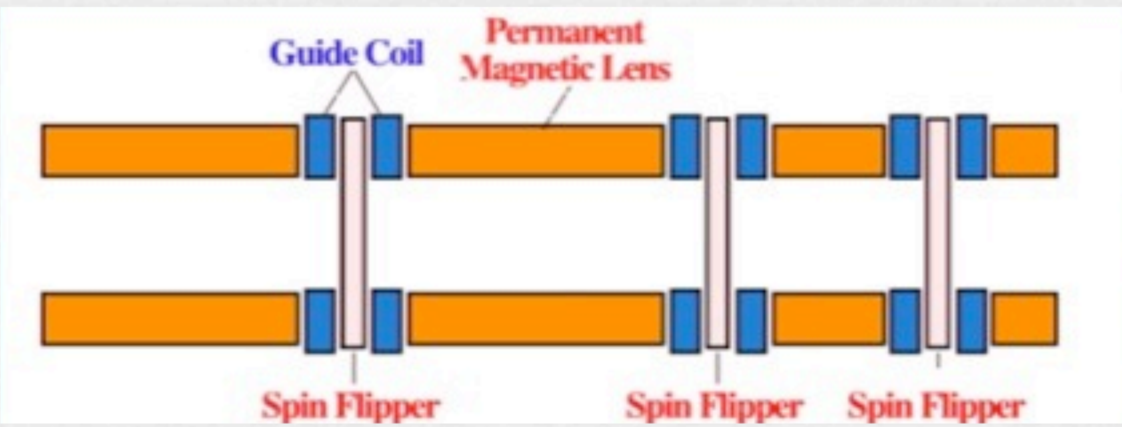
Neutrons with $\lambda > \sim 7$Å are available at NOP beamline

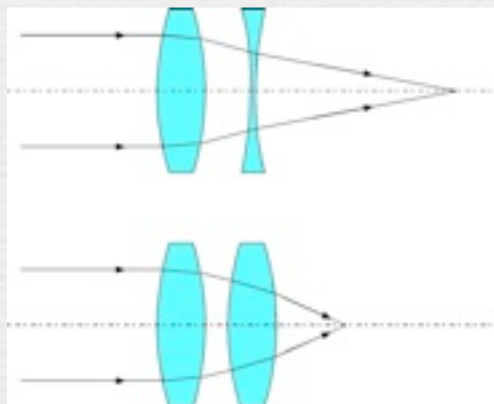
Tentative Experimental Result of the Triplet Lens System



Summary

The Multiple Lens System is considered very realistic, reasonable and feasible,
because
1) each component has been already developed,
2) the total system is relatively compact,
3) all components are linearly installed into the beam line, so that we can use pinhole and focusing geometry without making big change of experimental setup,
4) we can use polarized neutrons.

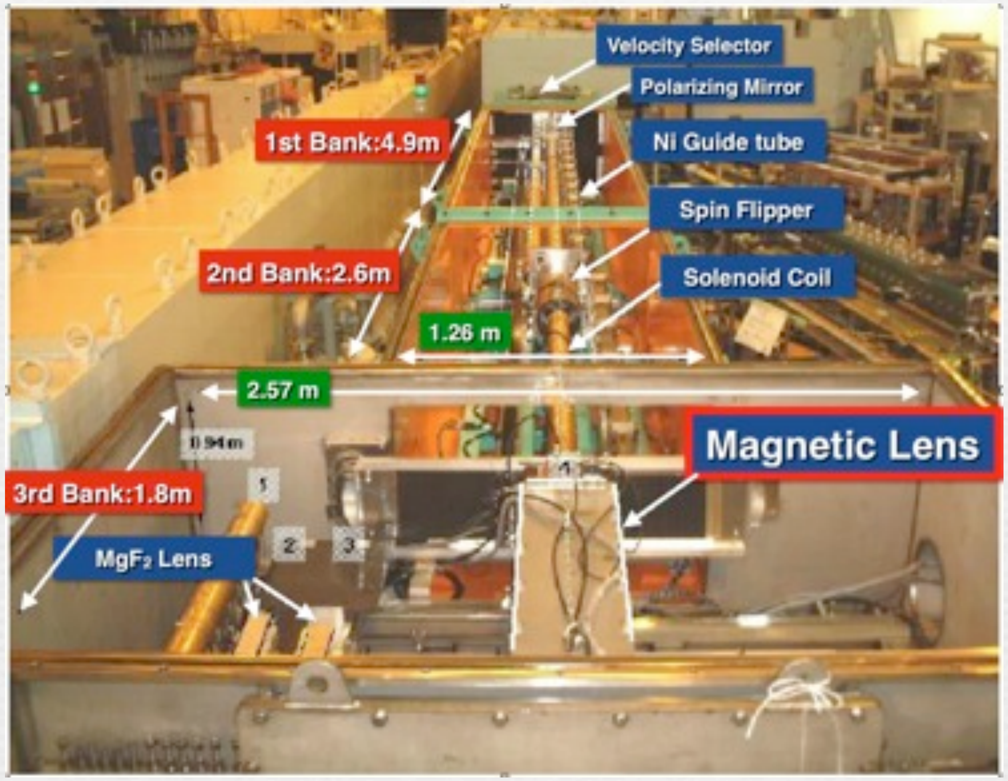




Multiple Lens System

Focusing geometry SANS Instrument with the Magnetic Lens

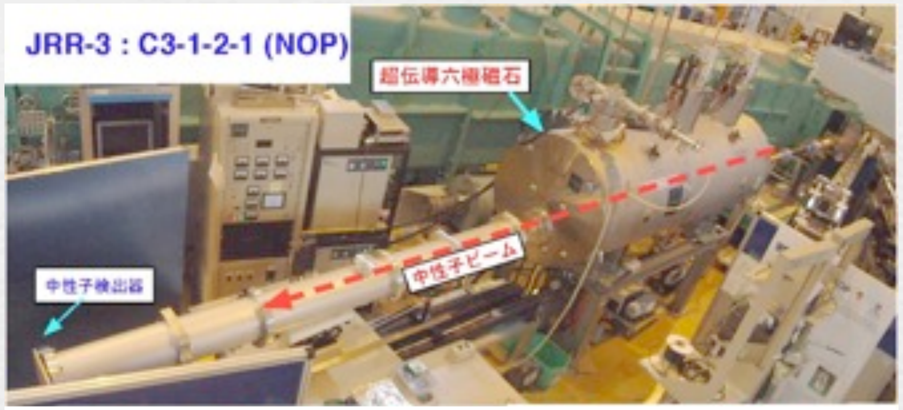
SANS-J-II of JRR-3



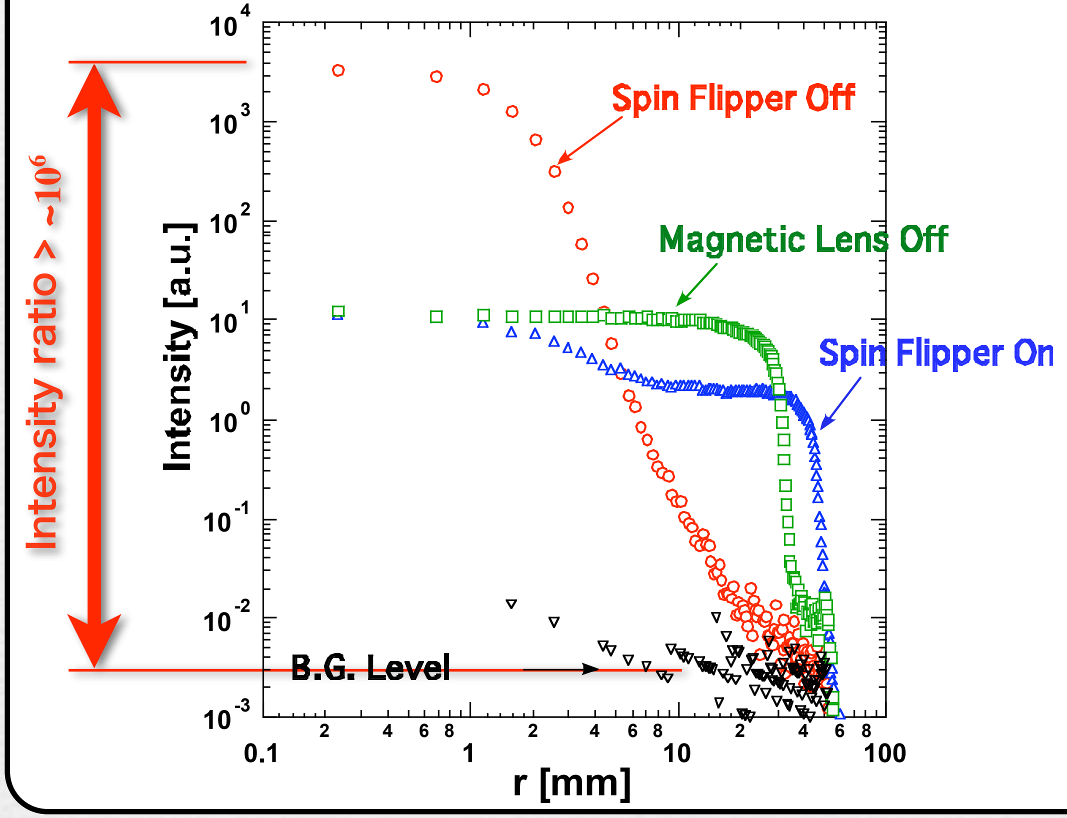
Constructed by JAEA Soft-matter & Neutron Optics Groups in 2005

Demonstration at a test beamline

Beamline : C3-1-2-1 NOP of JRR-3

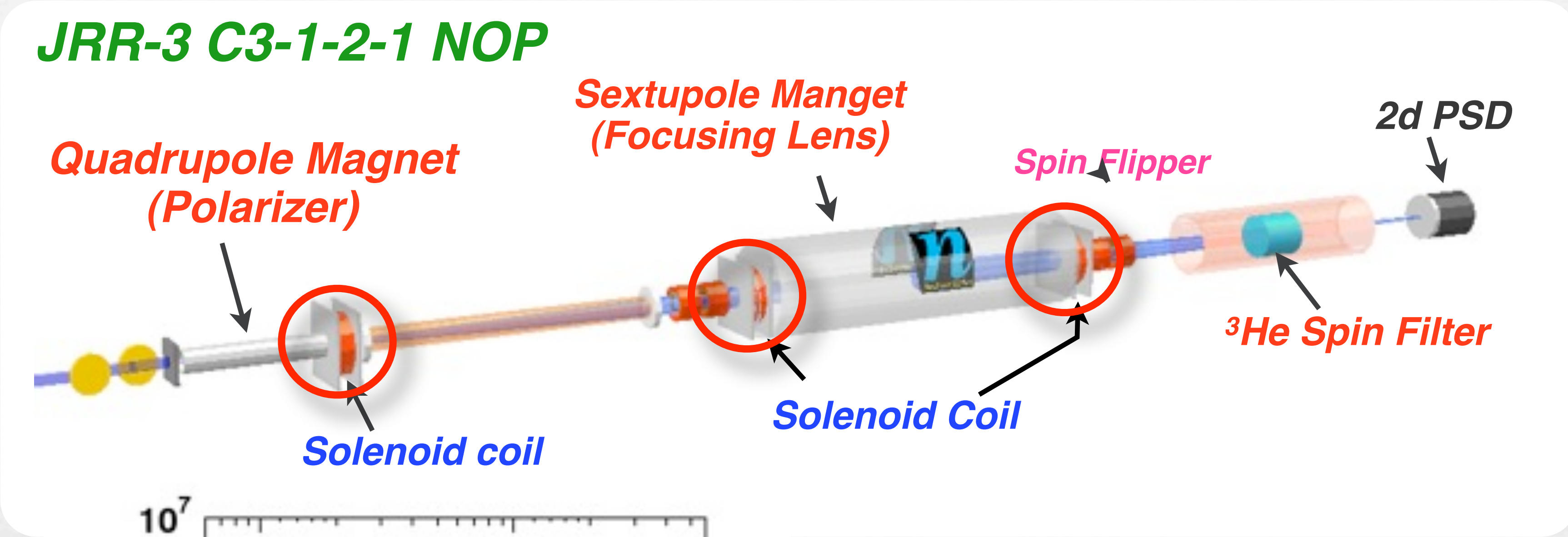


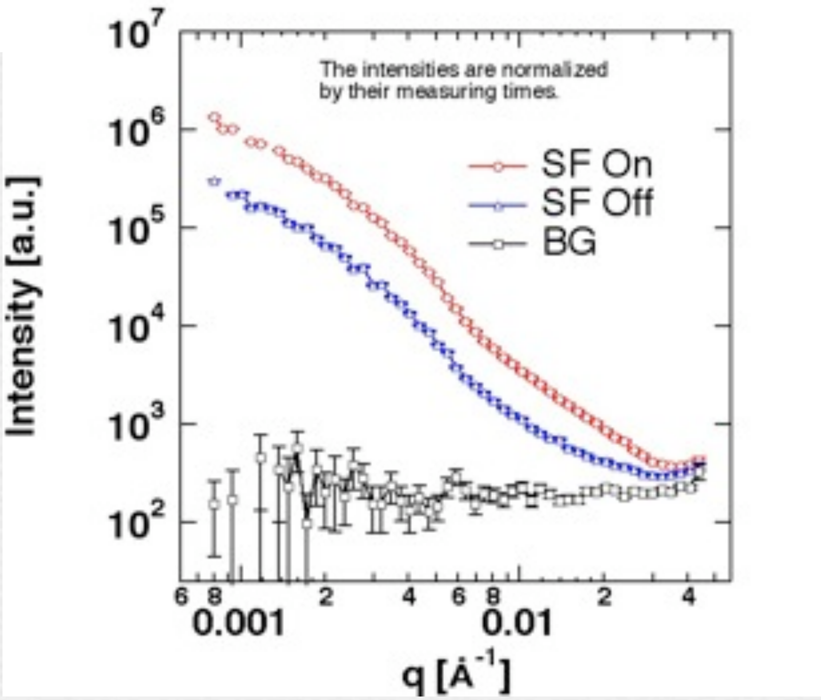
Focusing SANS setup using the magnetic lens



Test of ^{3}He Spin Filter @ NOP beamline

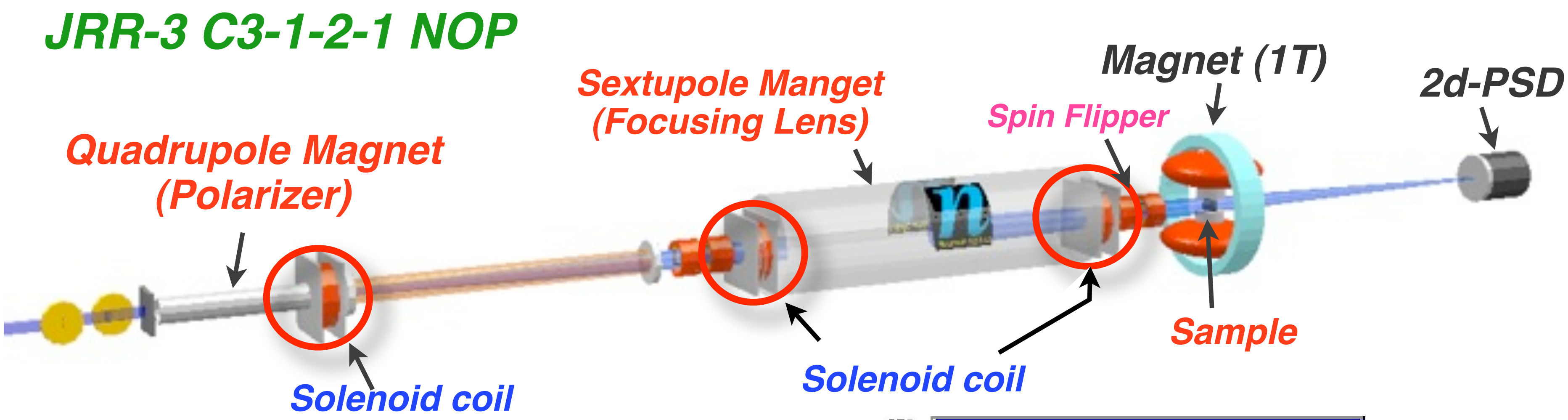
T. Ino (KEK) & JAEA Neutron Optics Group (2005)

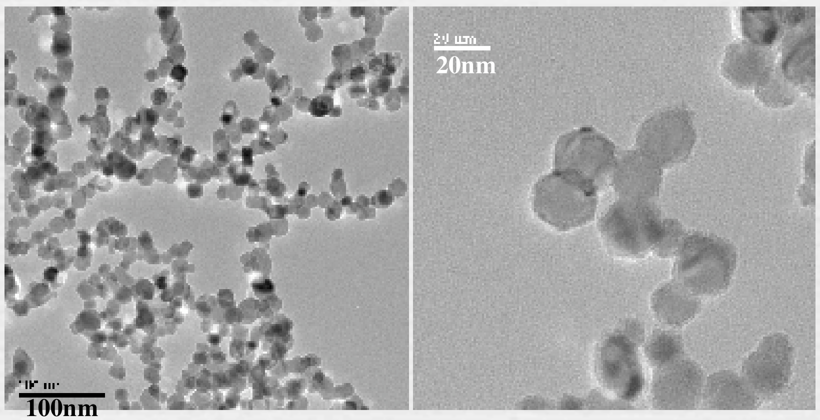




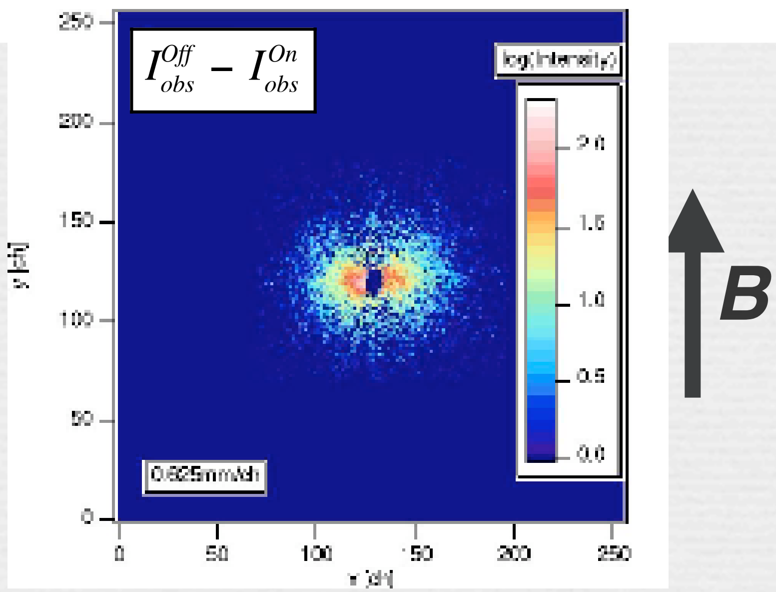
Focusing SANS experiment of Ni particles by using Polarized Neutrons

JEAE Neutron Optics Group





TEM picture of Ni particles



2d Netron Intenisty I^{+}-I^{-}

Anisotropic scattering typical for the magnetic scattering is observed.

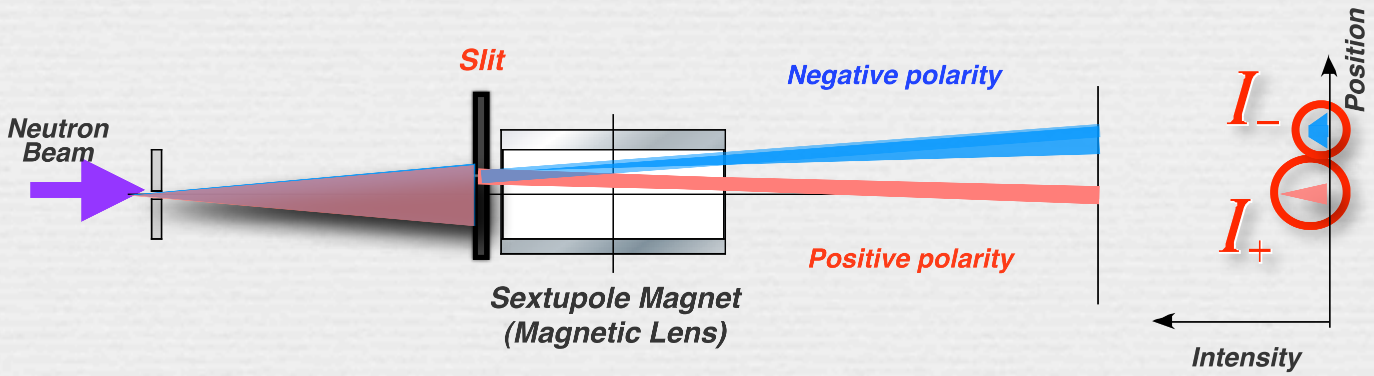
F A Q

Question :

How do we determine the polarization degree?

Answer:

We spatially separate positive and negative components by using the setup of Stern-Gerlach experiment. From the neutron count of each part after subtracting the BG count,We calculate the polarization degree.



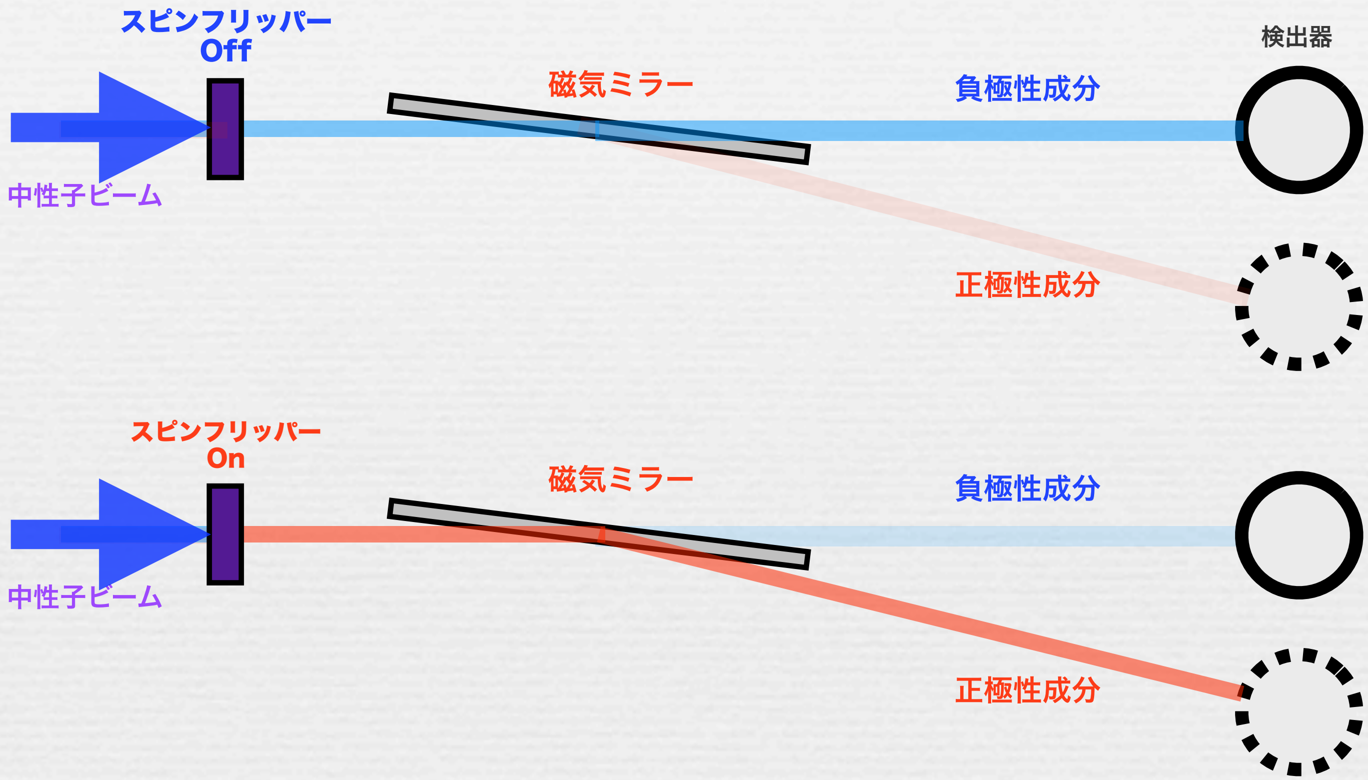
Stern-Gerlach experiment

Definition of the polarization degree

$$P = \frac{I_+ - I_-}{I_+ + I_-}$$

The obtained value is the product of polarization degree and analyzing power of the magnet.

質問2b:　なぜ、(普通の)スピンアナライザーを使わないのか？



$$\text{Flipping ratio } R = \frac{1 + P_i P_A (1 - D)}{1 + P_i P_A (1 - D)(1 - 2f)}$$

- P_i : Polarization efficiency of the polarizer
- P_A : Polarization efficiency of the analyzer
- f : Flipping efficiency of the spin flipper
- D : Depolarization factor

How to calculate the error of P ?

P is defiend as, $P = \dfrac{I_+ - I_-}{I_+ + I_-}$

Taking the derivatives of P, we thus find

$$\begin{cases} \dfrac{\partial P}{\partial I_+} = \dfrac{1}{I_+ + I_-} - \dfrac{I_+ - I_-}{(I_+ + I_-)^2} = \dfrac{2I_-}{{I_{tot}}^2} \\ \dfrac{\partial P}{\partial I_-} = -\dfrac{1}{I_+ + I_-} - \dfrac{I_+ - I_-}{(I_+ + I_-)^2} = -\dfrac{2I_+}{{I_{tot}}^2} \end{cases}$$

$$\because I_{tot} = I_+ + I_-$$

The covariance is obviously 0 here since the measurements are independent.

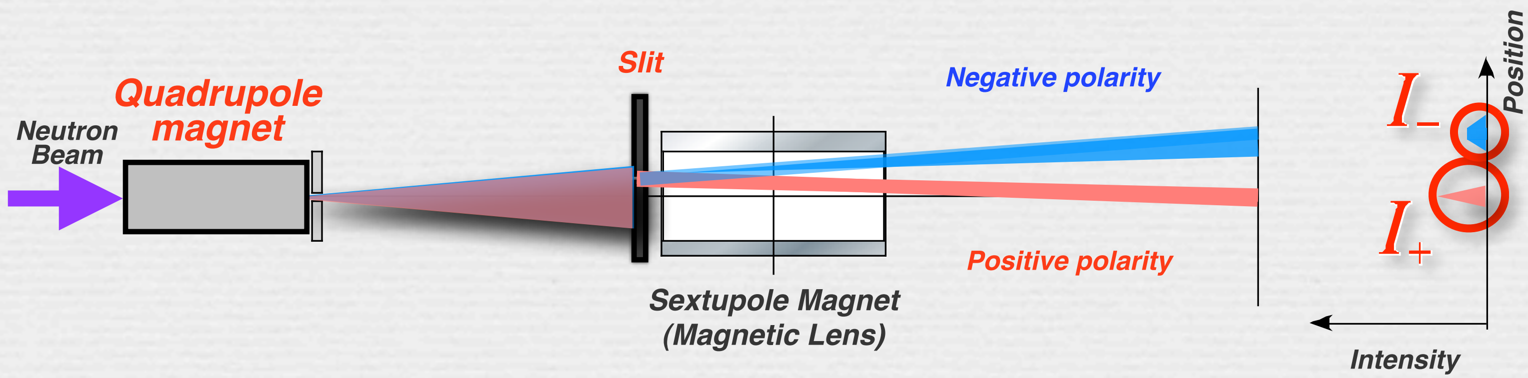
$${\sigma_P}^2 \cong \frac{4{I_-}^2}{{I_{tot}}^4}{\sigma_{I+}}^2 + \frac{4{I_+}^2}{{I_{tot}}^4}{\sigma_{I-}}^2$$

$$\sigma_P \cong \sqrt{\frac{4{I_-}^2}{{I_{tot}}^4}{\sigma_{I+}}^2 + \frac{4{I_+}^2}{{I_{tot}}^4}{\sigma_{I-}}^2}$$

F A Q

Question :

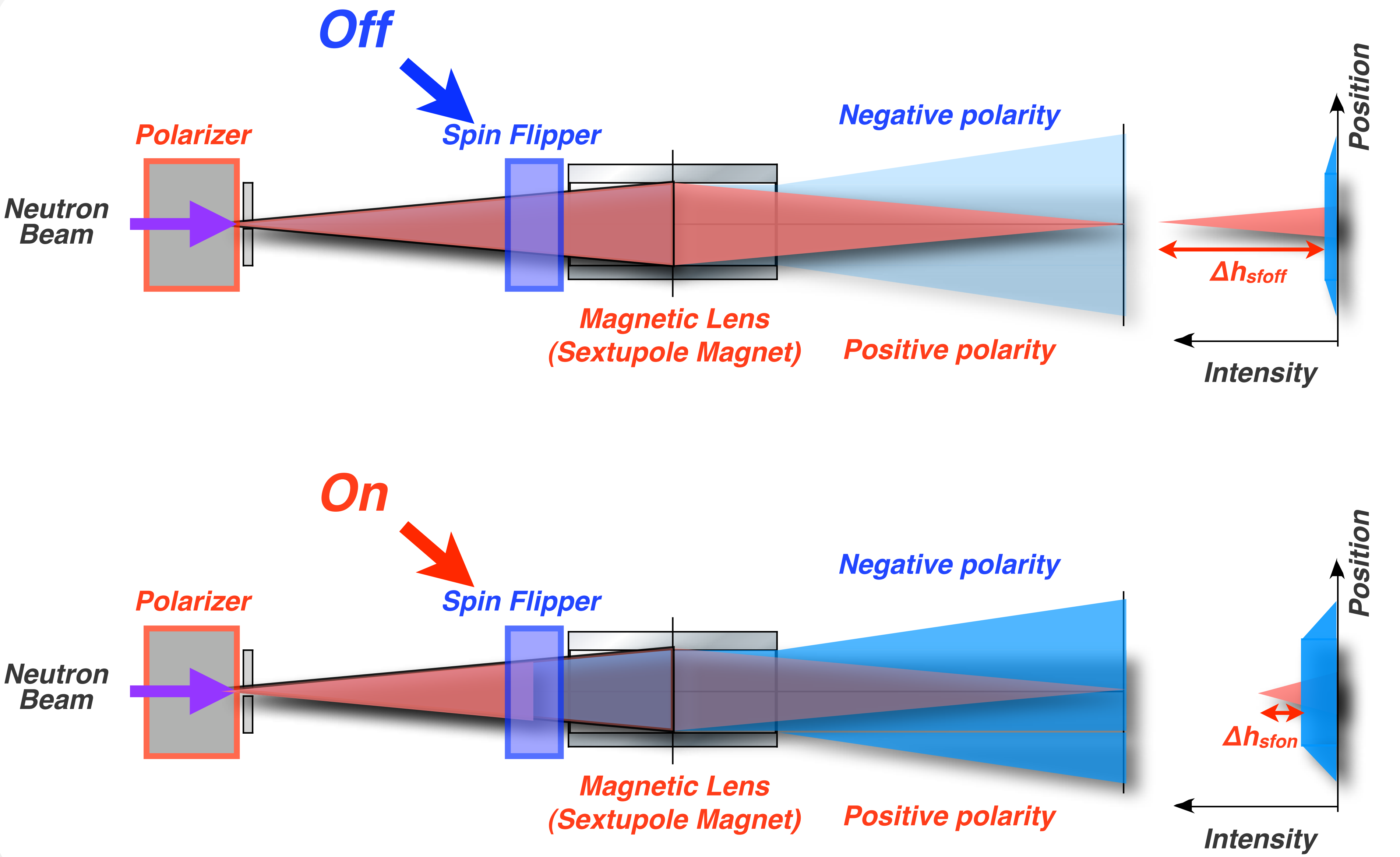
We are analyzing the small portion of the output beam.
What is the polarization of the whole amount of the output beam?
How can we measure the polarization of the whole amount of the output beam?



偏極度の定義

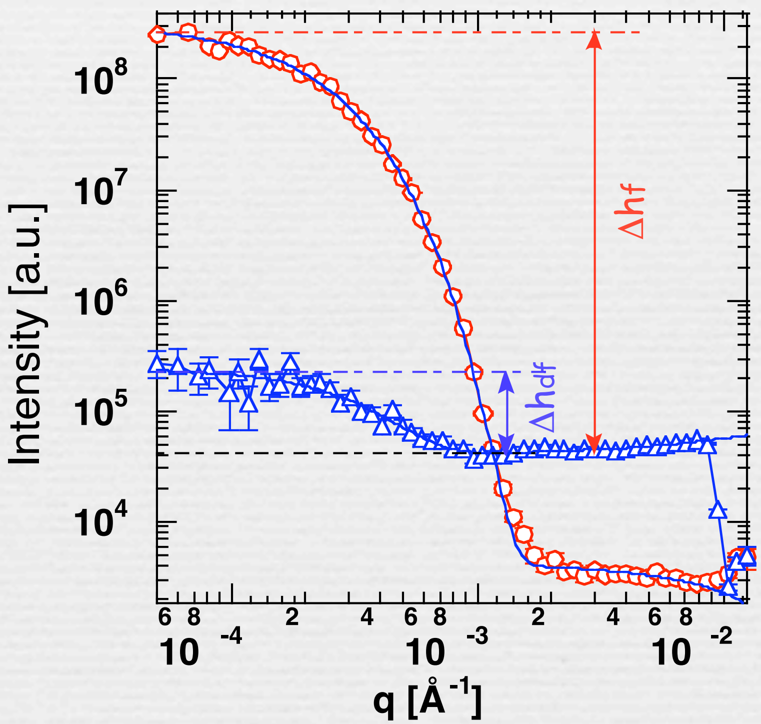
$$P = \frac{I_+ - I_-}{I_+ + I_-}$$

Polarization Analysis by using the magnetic lens



Result

$$\text{Flipping ratio} = \frac{\Delta h_f}{\Delta h_{df}} = \frac{1 + P_i P_A (1 - D)}{1 + P_i P_A (1 - D)(1 - 2f)}$$



Assumption : $P_A = f = 1, \quad D = 0$

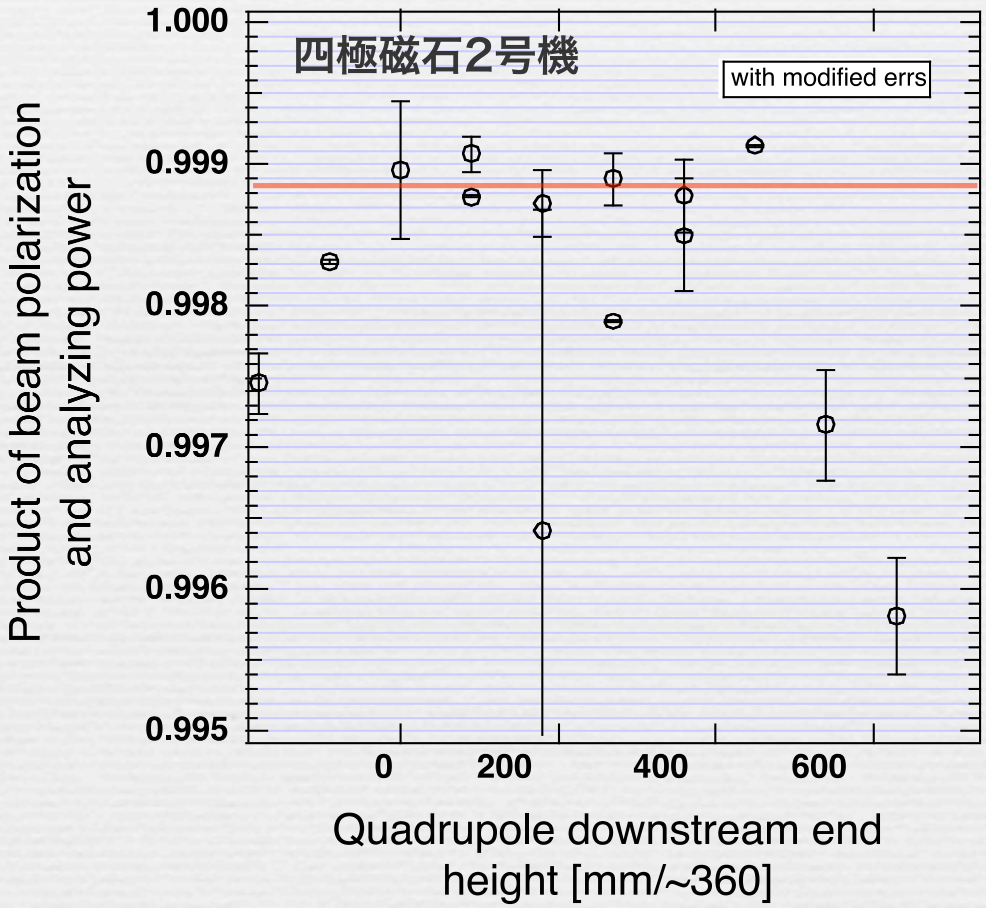
$$P_i = \frac{\Delta h_f / \Delta h_{df} - 1}{\Delta h_f / \Delta h_{df} + 1} \sim 0.999$$

Polarization Analysis by using the magnetic lens: Result 2

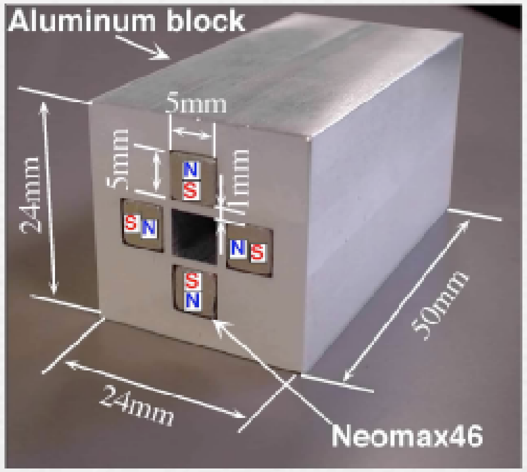
$$\text{Flipping ratio} = \frac{\Delta h_f}{\Delta h_{df}} = \frac{1 + P_i P_A (1 - D)}{1 + P_i P_A (1 - D)(1 - 2f)}$$

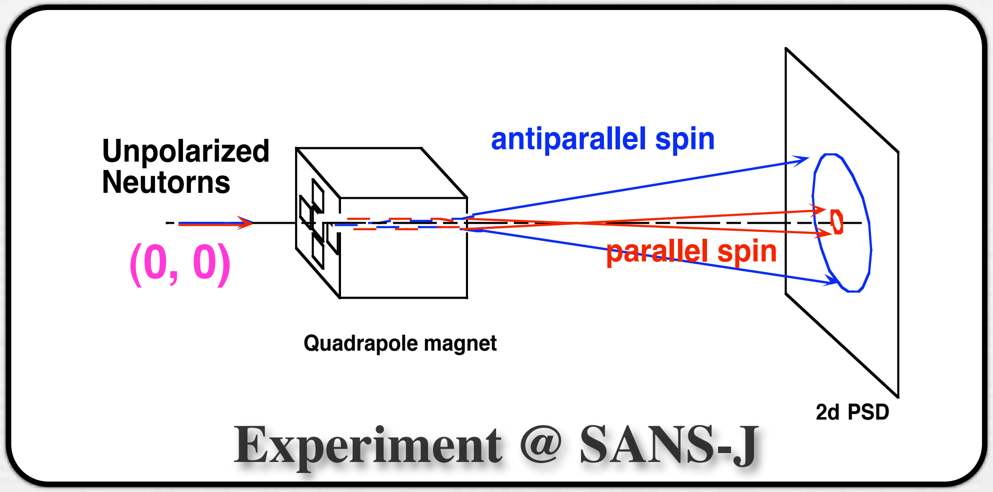
$$\text{Assumption}: P_A = f = 1, \quad D = 0$$

$$P_i = \frac{\Delta h_f / \Delta h_{df} - 1}{\Delta h_f / \Delta h_{df} + 1}$$



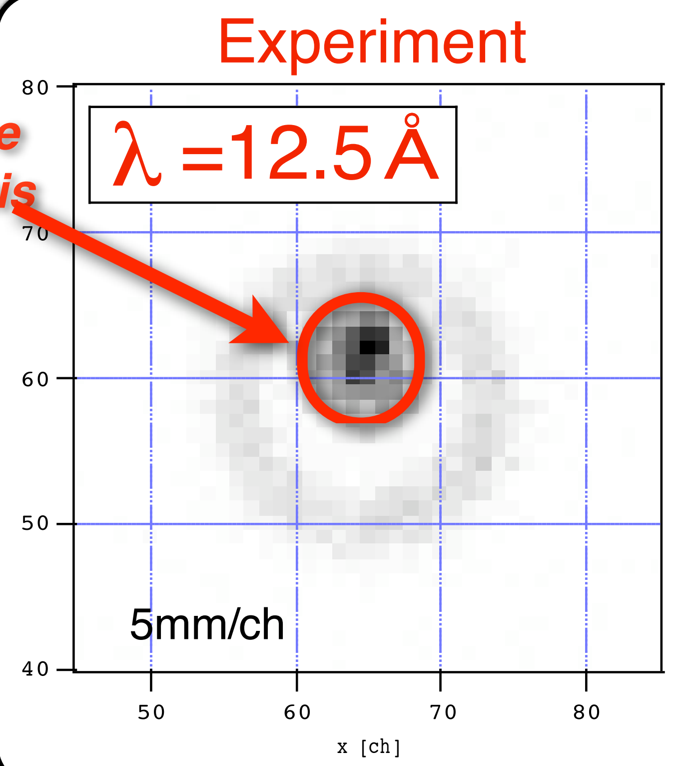
A previous study of the Quadrupole magnet

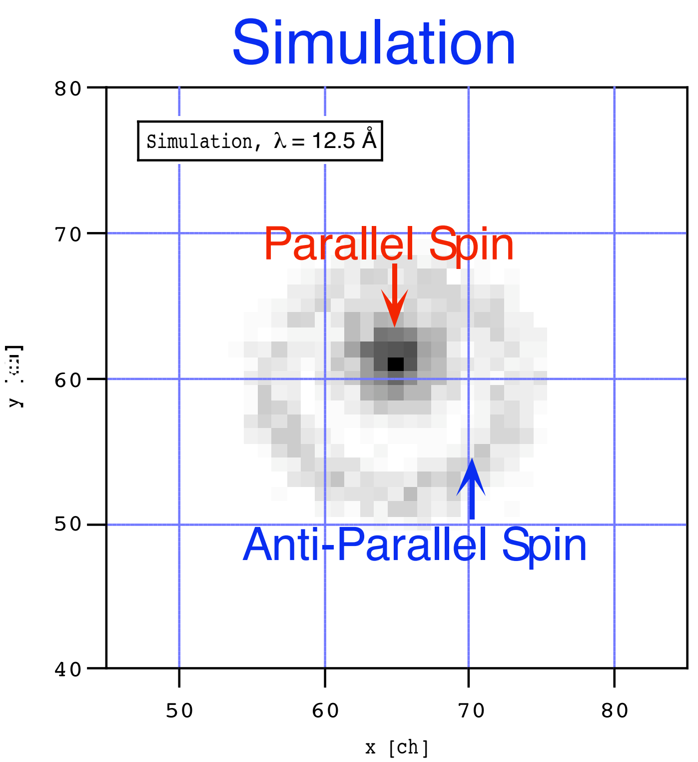




magnetic field strength : $|B| = G_q r$, $G = 140$ T/m

Extract the beam in this region





Function of the magnets