R&D for cold and ultra-cold neutrons

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for NOP collaboration

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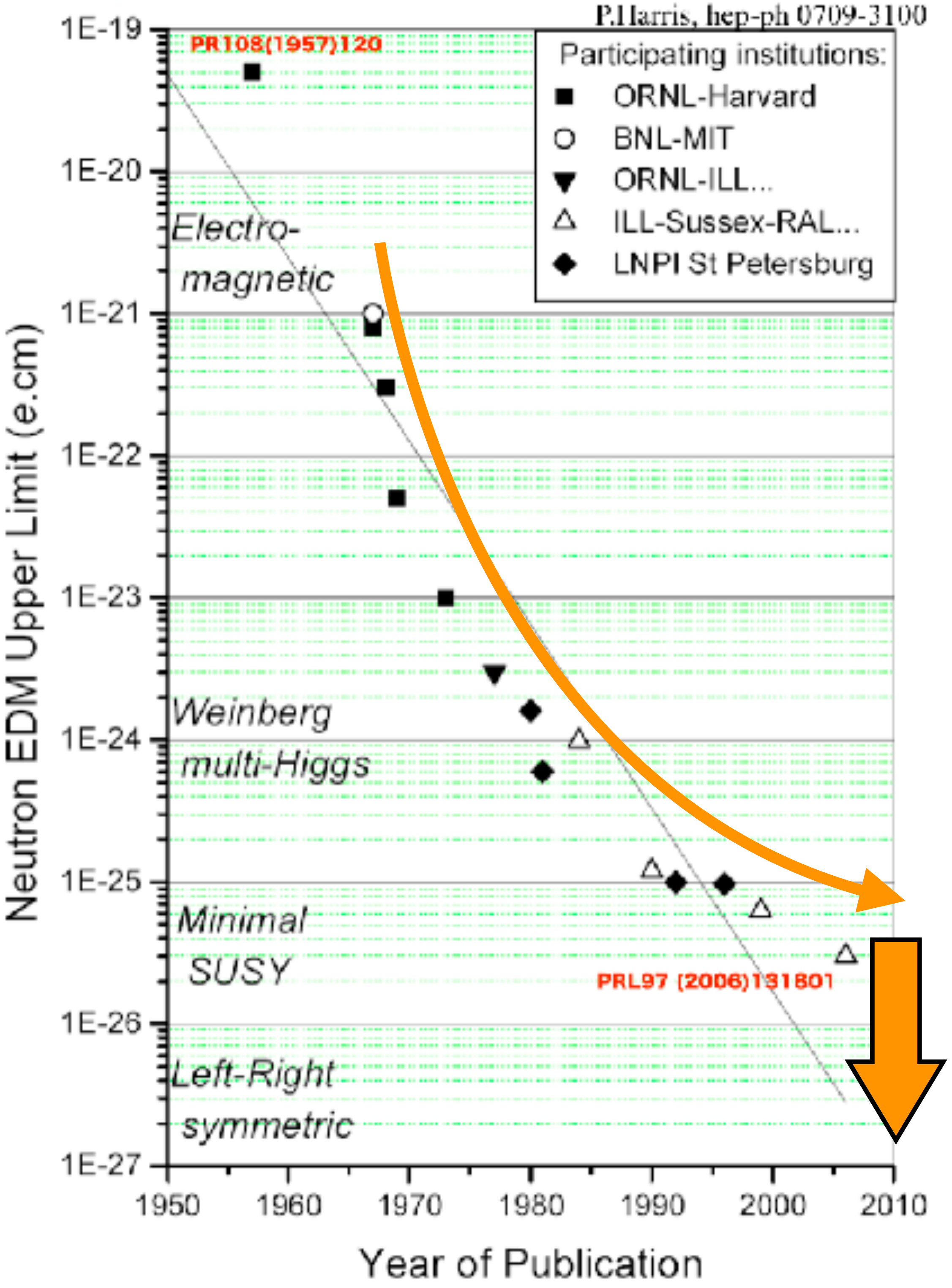
New approach for neutron EDM

- New approach to neutron EDM
- UCN precision optics
    - Efficient transport optics for dense UCN
    - Efficient UCN production with concentration of neutron velocity
- Cold and very-cold neutron interferometer
- Summary

New approach for neutron EDM



Present upper limit $|d_n| < 3.0 \times 10^{-26}\ e\ \mathrm{cm}$

is approaching to the predictions of some physics beyond the standard model of particle physics.

Standard Model : $|d_\mathrm{n}| \sim 10^{-32}\ e\ \mathrm{cm}$

New Physics (SUSY ...) :

$|d_\mathrm{n}| \sim 10^{-27 \sim -28}\ e\ \mathrm{cm}$

New approach required

High power proton beam (by accelerator)

Converted by Superthermal process

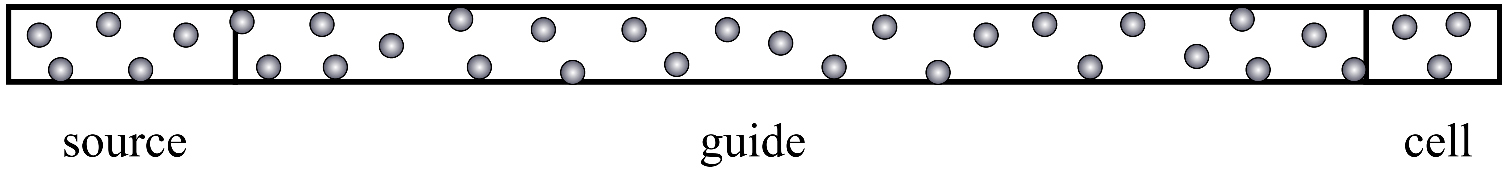
High precision optics

How to increase UCN density

Use intense source

High power proton beam (by accelerator)
and large volume neutron target can make intense UCNs.

High power proton beam also makes heavy heat load at the source.
It is difficult to increase the UCNs anymore.



UCNs are spread spatially while transport, however,
intense source makes enough UCNs at the cell.

Most of UCNs are not used for measurement.

More efficient way ? ➔ **UCN precision optics**

Efficient transport optics for dense UCN

How to increase UCN density

Use efficient transport

If UCN pulse can be delivered, we can get dense UCNs at the cell.

How can we realize such kind of transport ?

?

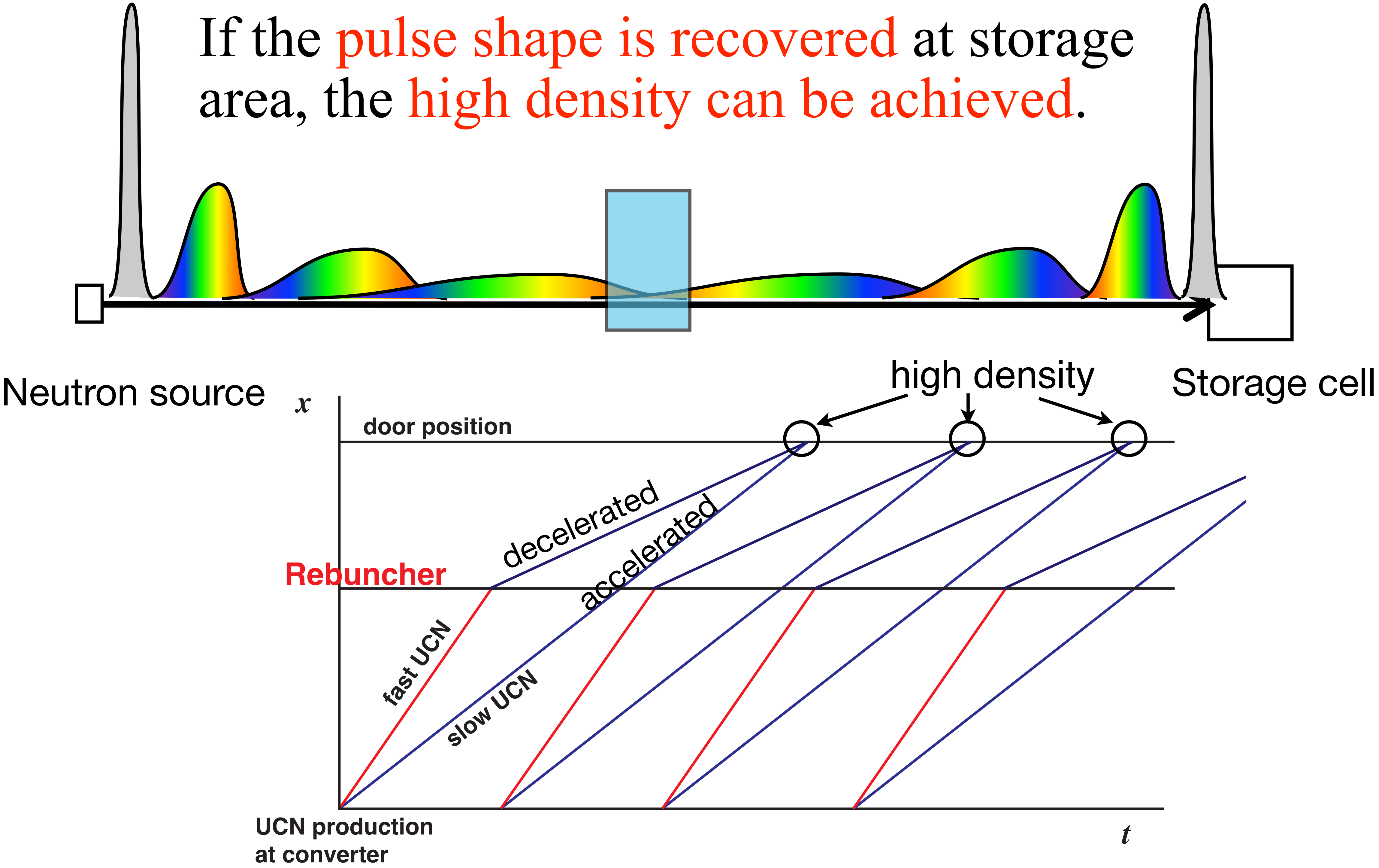
UCN Rebuncher, **a UCN optical device**

requires controlling the UCN velocity properly
and keeping velocity before and after the device.

Pulsed UCN transport

UCN Rebuncher = Neutron Accelerator

If the pulse shape is recovered at storage area, the high density can be achieved.



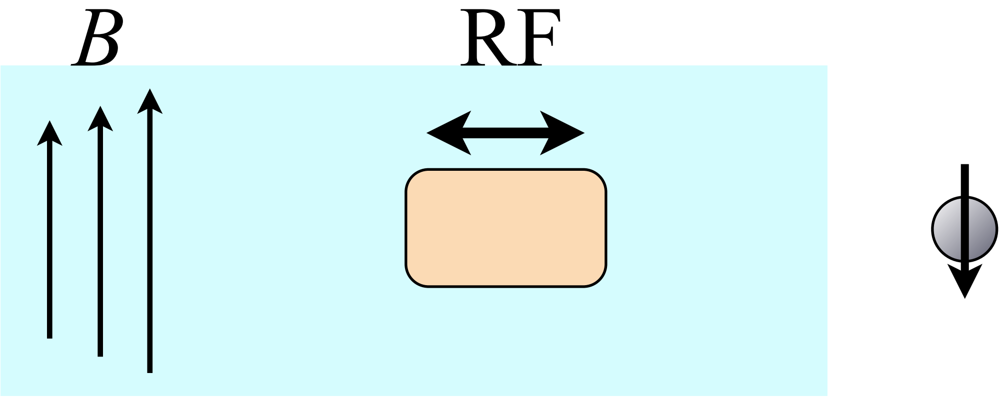
Rebuncher

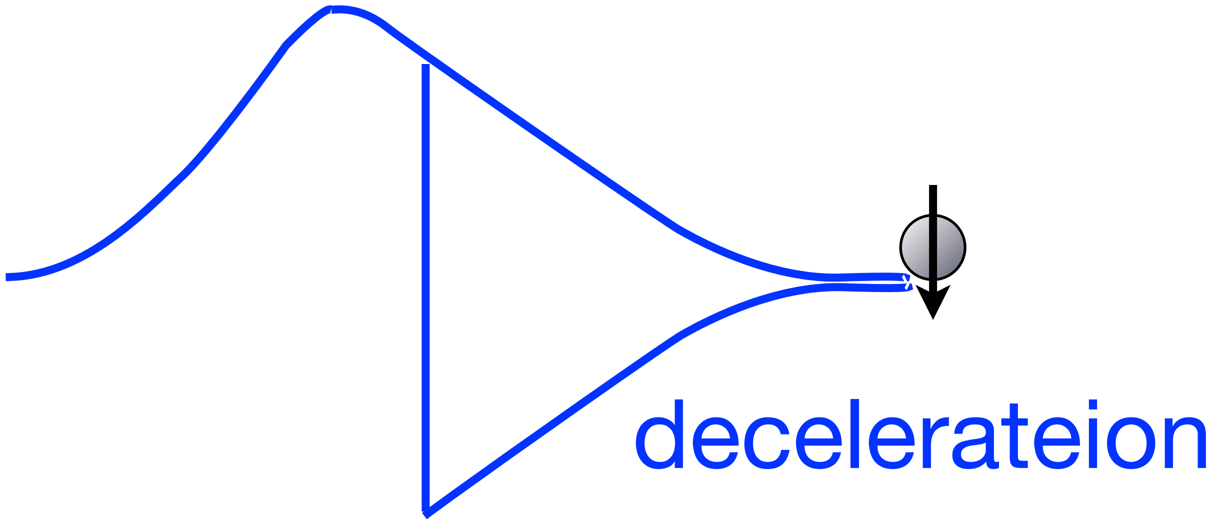
Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.

RF magnetic field in gradient field gives/removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

30 MHz = 1T = 120 neV

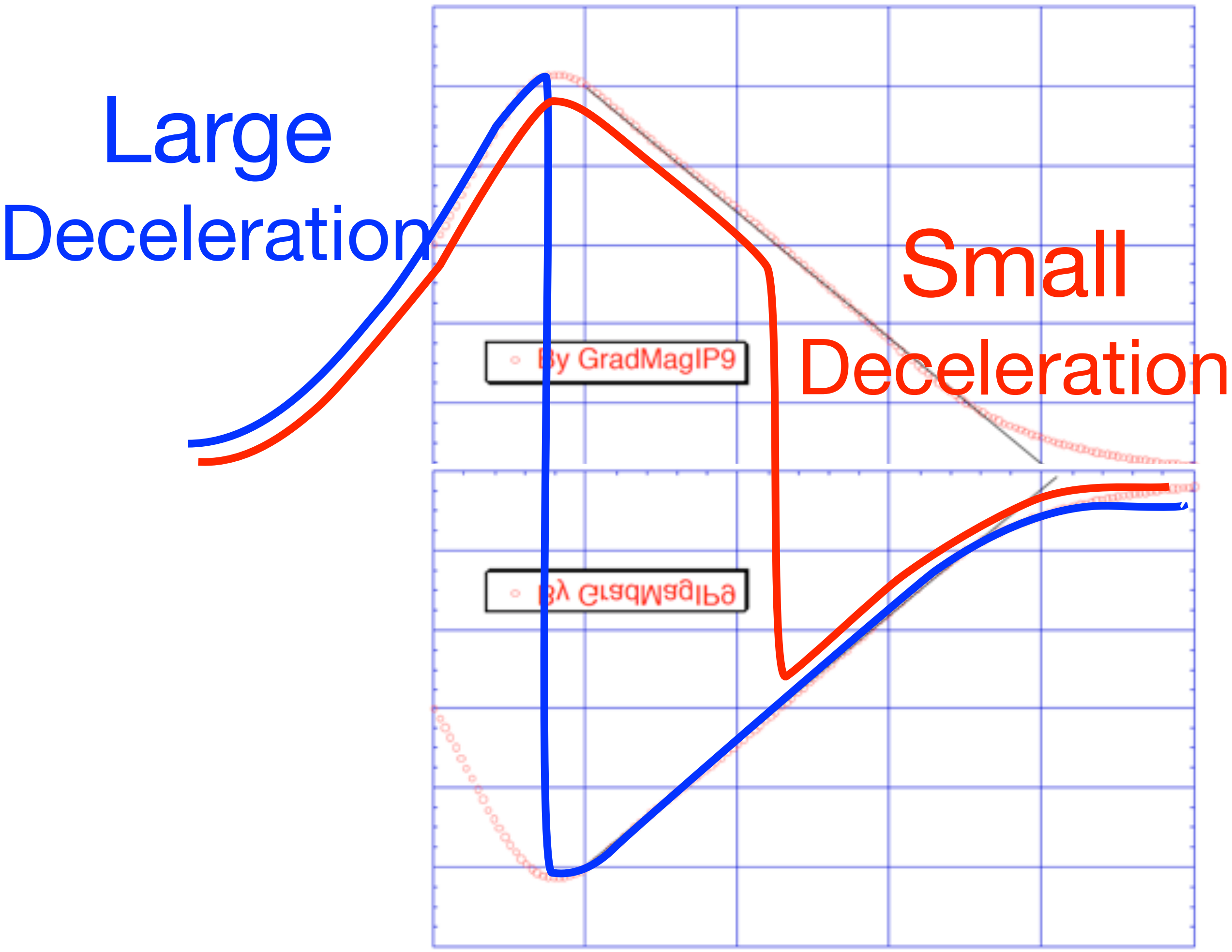




Opposite-spin neutrons are accelerated.

Rebuncher

Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.



RF magnetic field in gradient field gives/removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

30 MHz = 1T = 120 neV

Faster neutrons arrive early.

Large deceleration = High Freq. RF

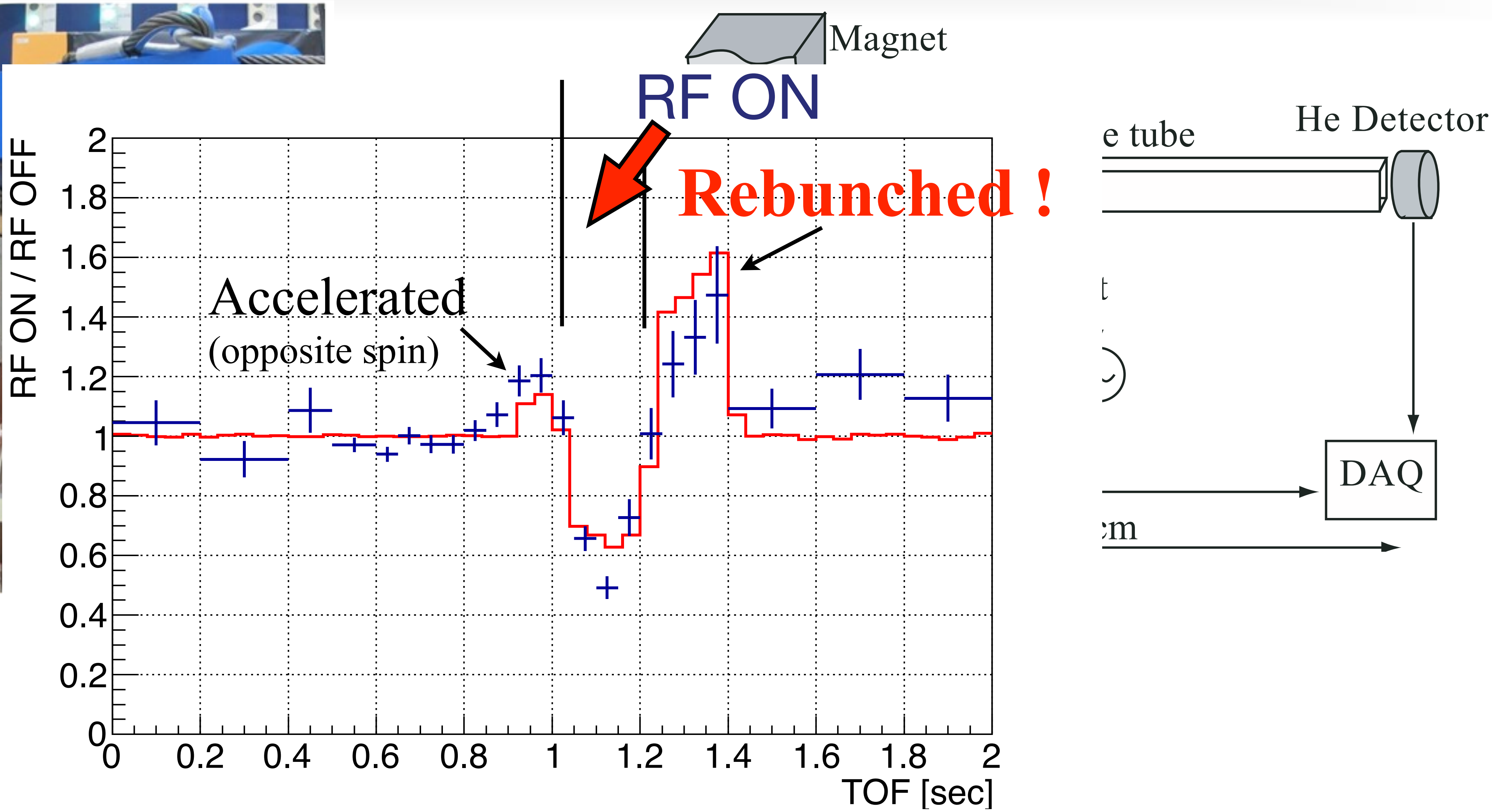
Slower neutrons arrive late.

Small deceleration = Low Freq. RF

Energy exchange is proportional to the RF frequency.

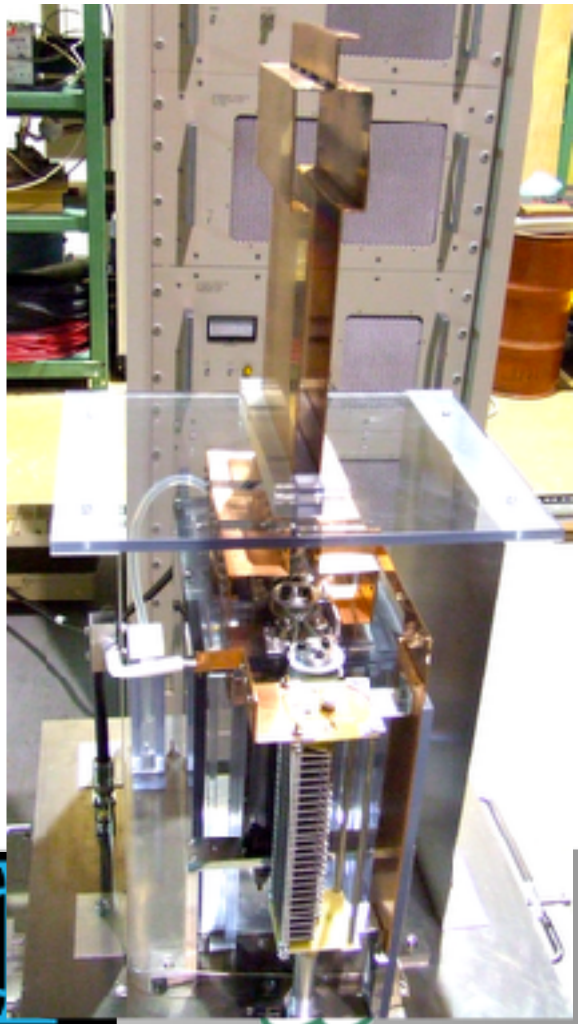
Sweeping frequency according to time

Demonstration of Rebuncher



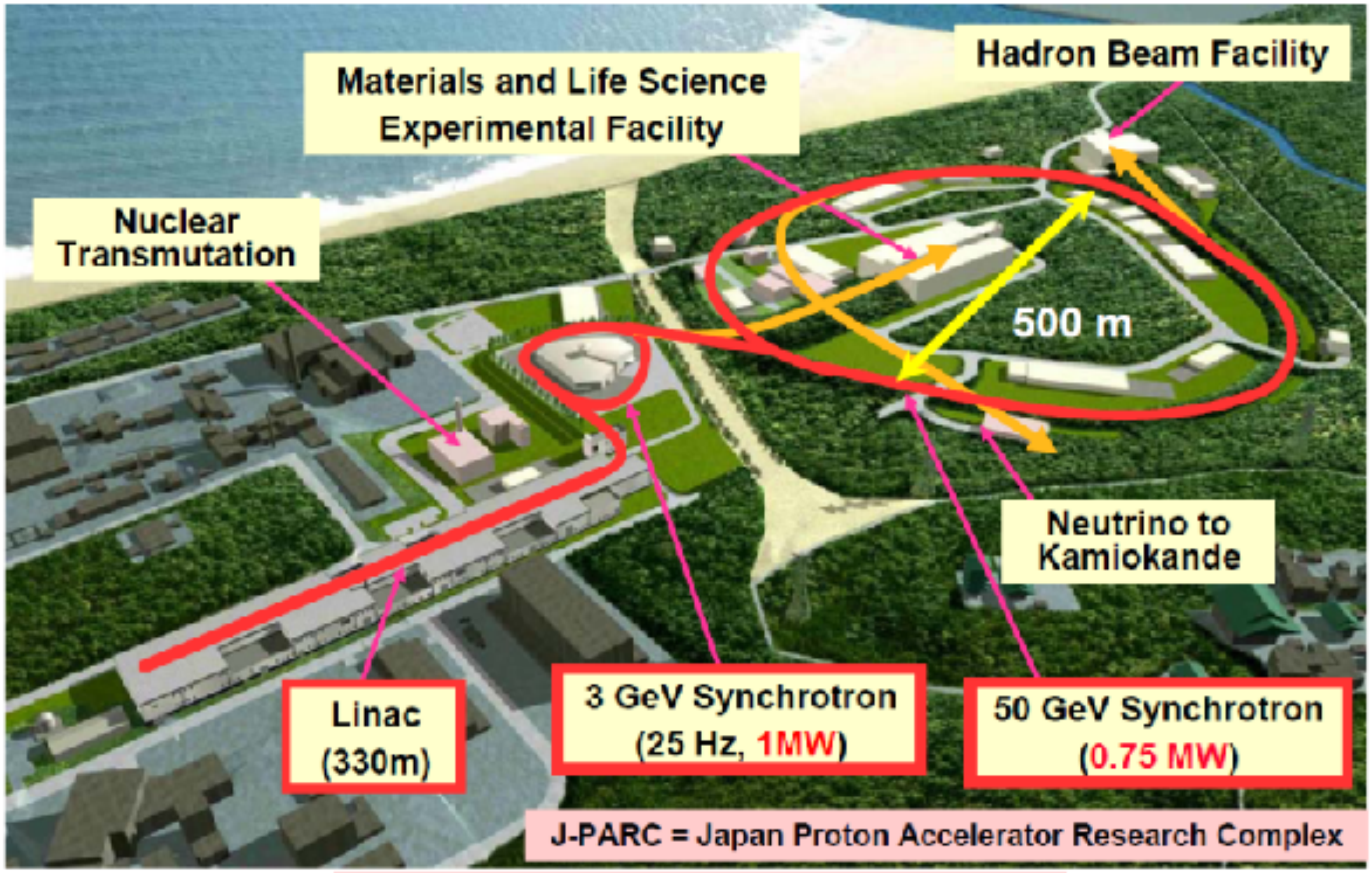
Blue : Exp. Data
Red : Simulation

Y. Arimoto, et., al.,
Phys. Rev. A 86, 023843 (2012).



Rebunching of UCNs was demonstrated !

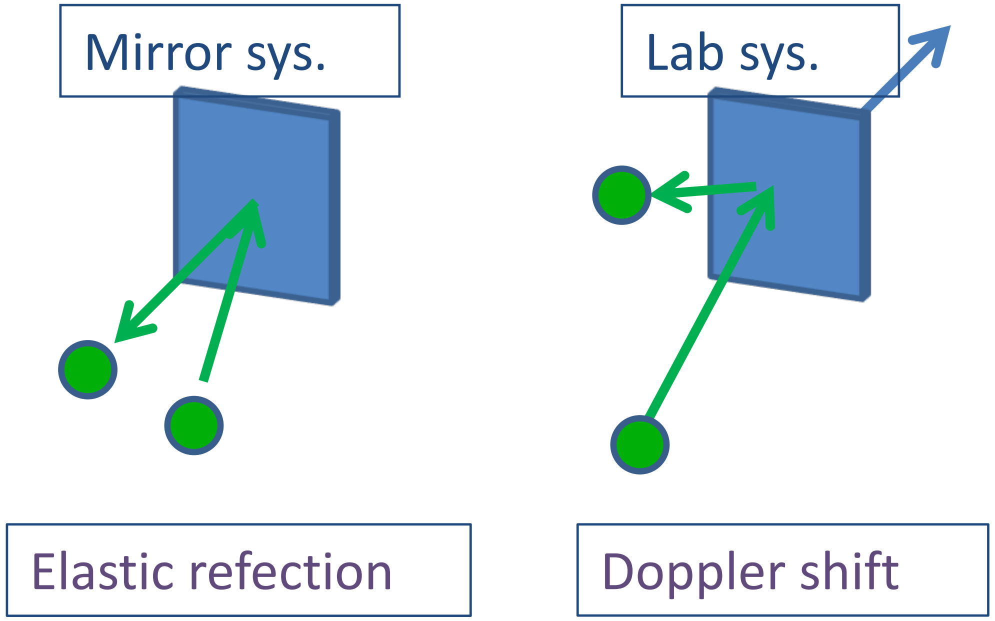
Neutron Optics and Physics beamline (NOP) at J-PARC



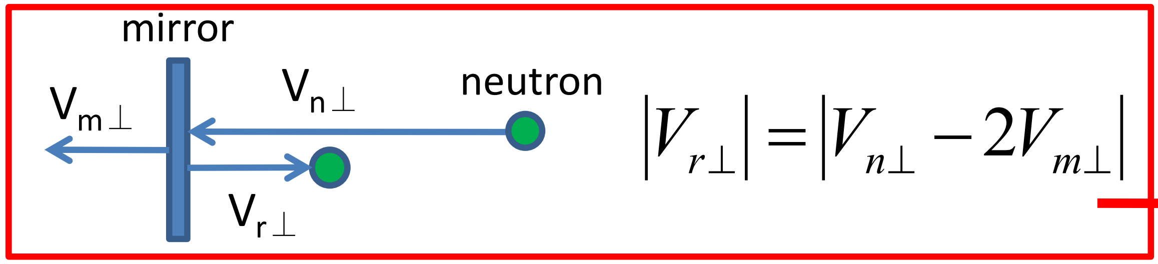
Joint Project between KEK and JAEA

UCN generator at NOP beamline

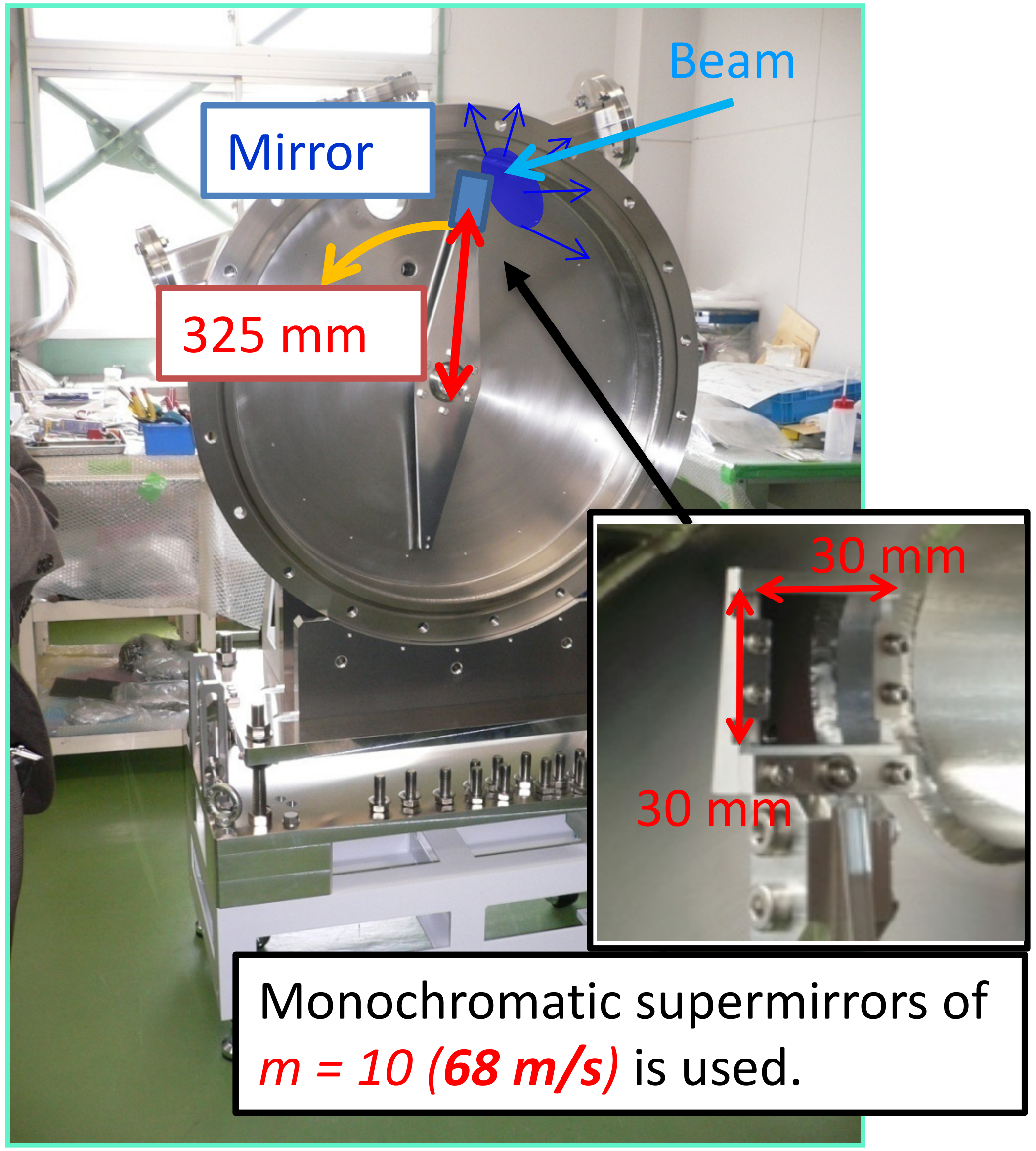
Doppler shifter



Moving mirror reduce velocity of neutrons.



$$\left|V_{r\perp}\right| = \left|V_{n\perp} - 2V_{m\perp}\right|$$

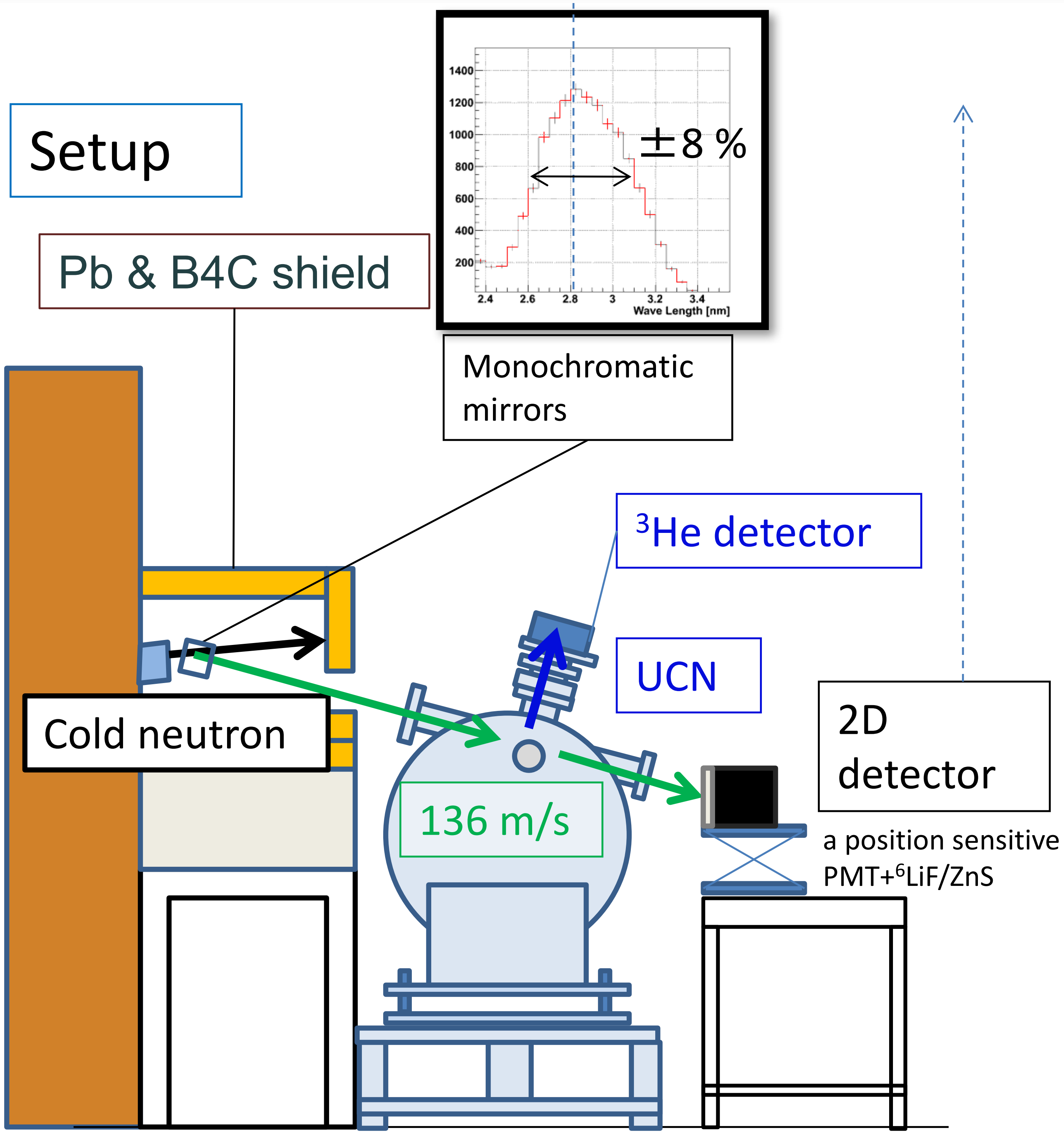


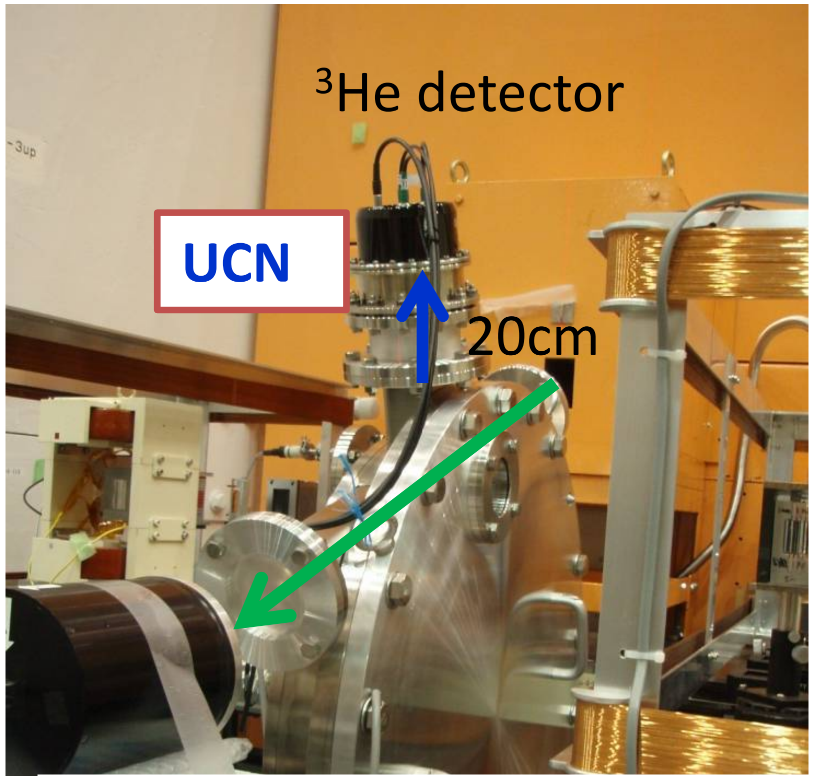
Monochromatic supermirrors of *m = 10* (***68 m/s***) is used.

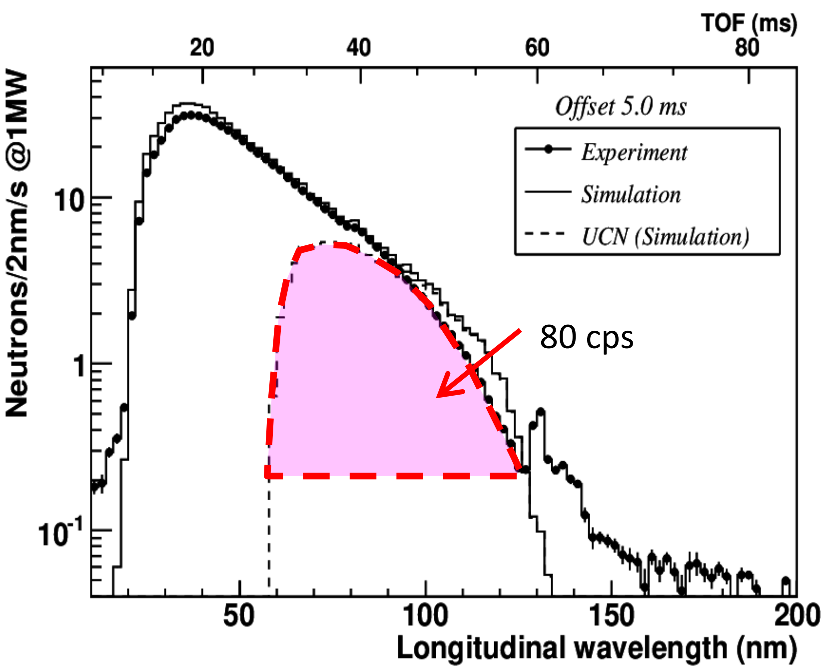
Mirror velocity should be half of the neutron velocity to produce UCN.

Doppler shifter is on the Beamline.
Pulsed UCNs are provided.

UCN generator at NOP beamline



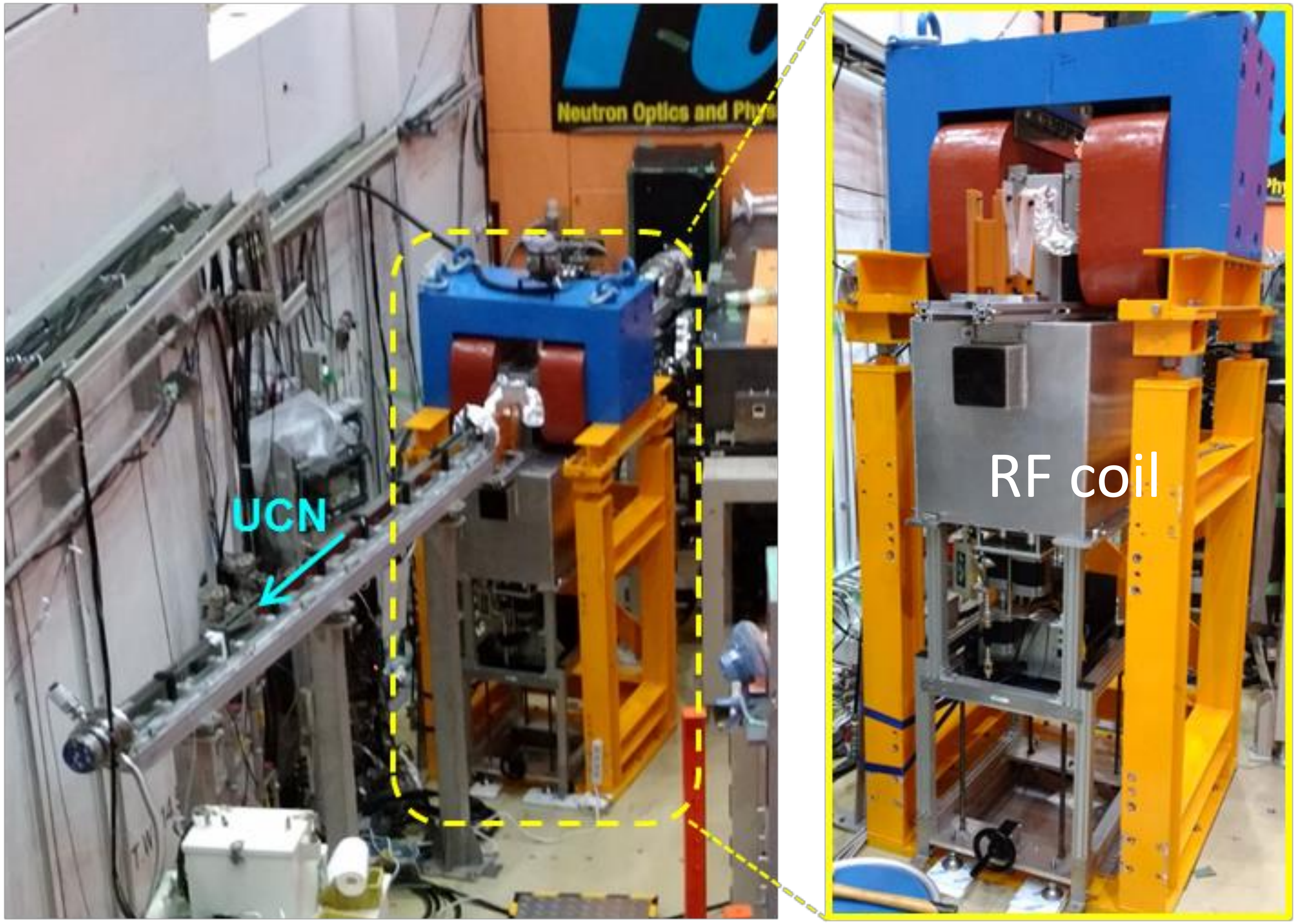




S. Imajo et al., *Progress of Theoretical and Experimental Physics* 2016.1 (2016) 013C02.

Rebuncher at J-PARC

Test with upgraded Rebuncher

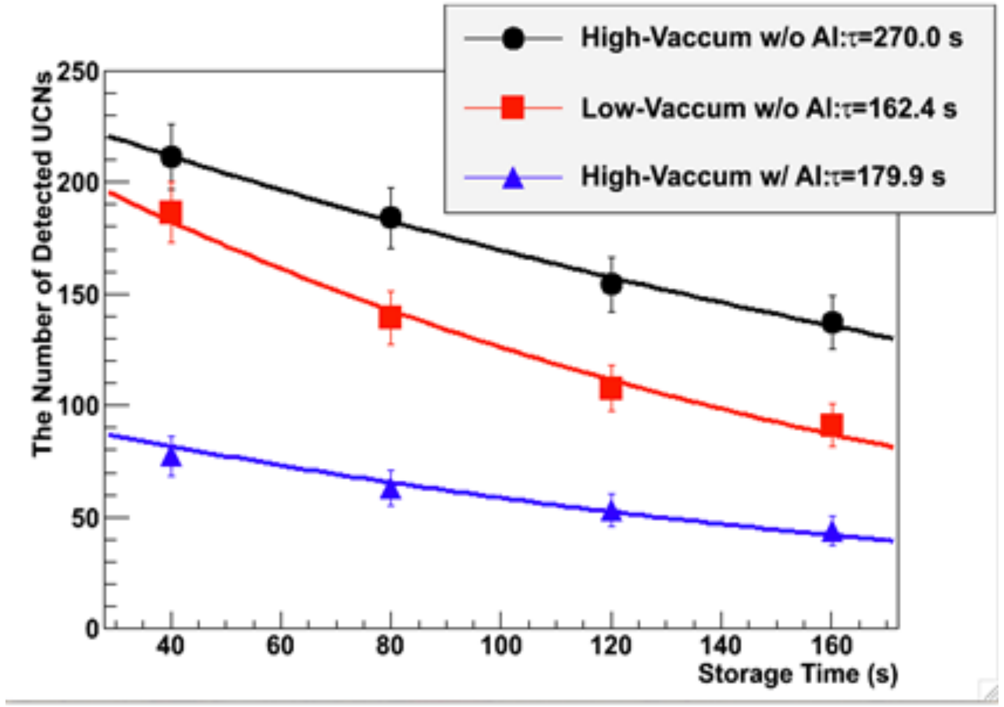


Large RF power injection to increase spin flip probability

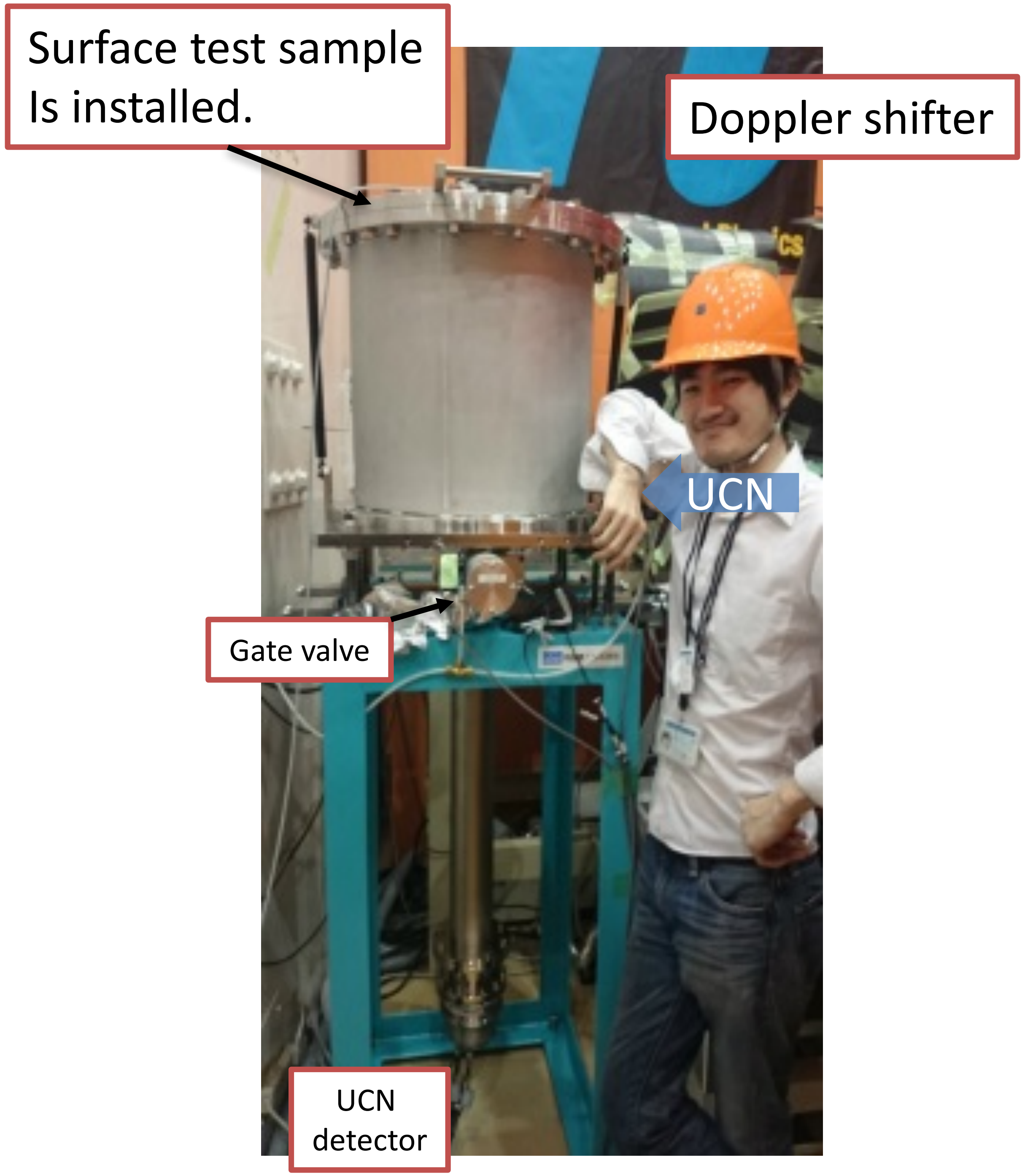
Large variable capacitor for wide range RF matching

Storage of UCNs

UCN storage chamber has made to measure reflectivity of test surfaces.
Storage time of 270 sec have demonstrated.



R. Katayama et al., JPS meeting (Sep.2015)



Neutron mirror can be tested by inserting into the chamber.

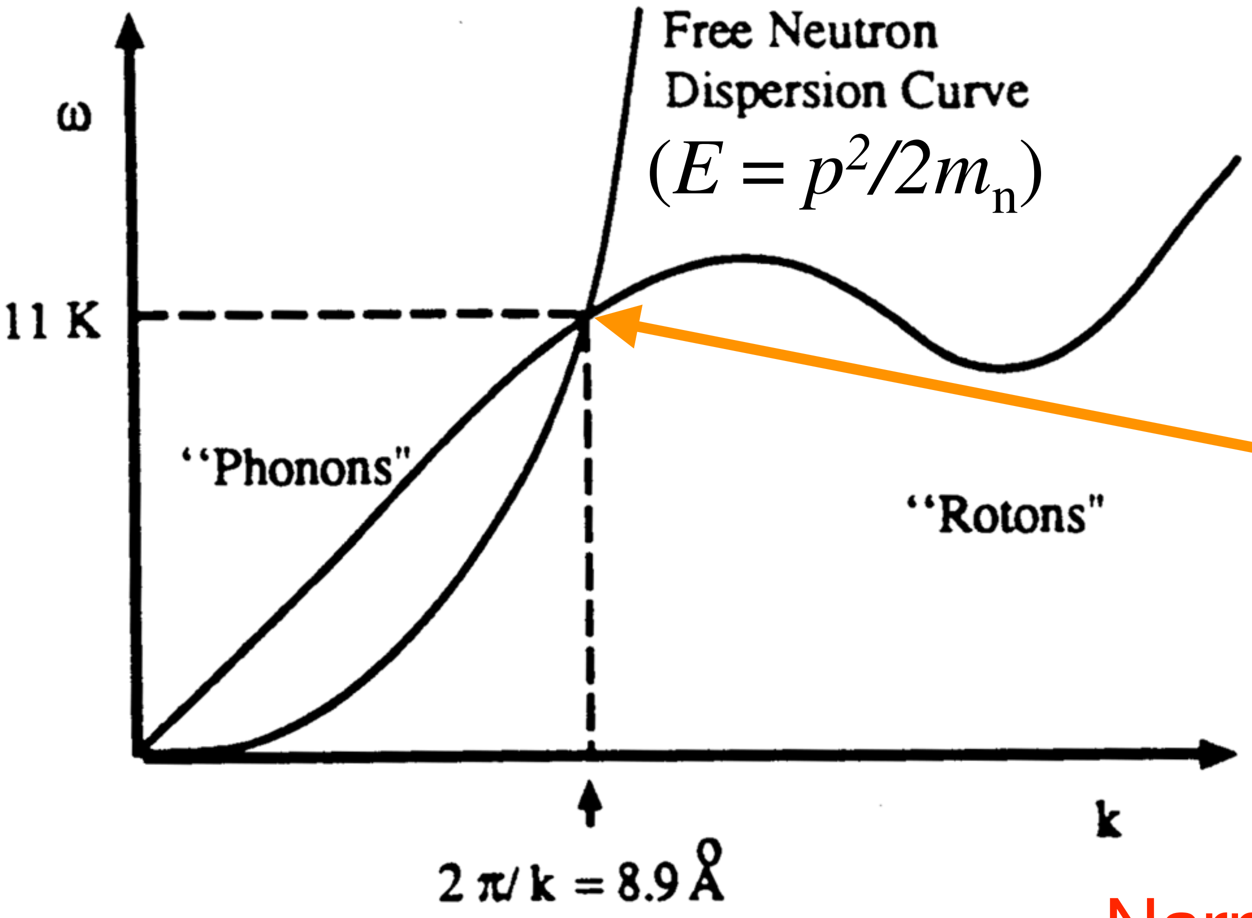
Efficient UCN production with concentration of neutron velocity

UCN production by superfluid He converter

Superthermal source

Neutron with 1 meV transfers all energy and momentum to phonon and down-scatters to UCNs in superfluid He.

Dispersion curve



UCN production

$$P_{\mathrm{UCN}}(V_{\mathrm{c}}) = N\,\sigma V_{\mathrm{c}}\frac{k_{\mathrm{c}}}{3\pi}\int_0^\infty \frac{\mathrm{d}\phi}{\mathrm{d}\lambda}\,s(\lambda)\,\lambda\,\mathrm{d}\lambda$$

$$s(\lambda) = \hbar\int S(q,\hbar\omega)\delta(\hbar\omega - \hbar^2k^2/2m_{\mathrm{n}})\mathrm{d}\omega$$

Single phonon excitation

$$s_{\mathrm{I}}(\lambda) \;=\; \underline{S^*\delta(\lambda^* - \lambda)}$$

where $\lambda^* = 2\pi/q^*$

Narrow-bandwidth neutrons are required.

UCN production by superfluid He converter

Superthermal source

Neutron with 1 meV transfers all energy and momentum to phonon and down-scatters to UCNs in superfluid He.

468 E. Ko

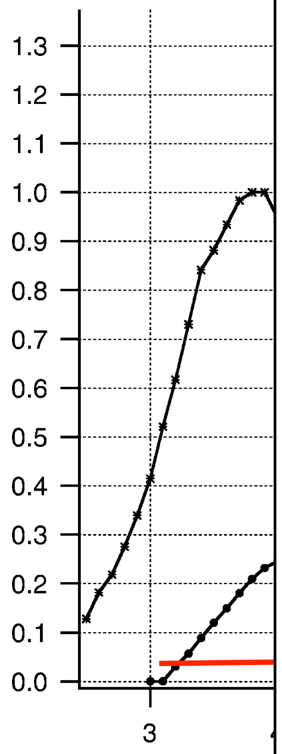
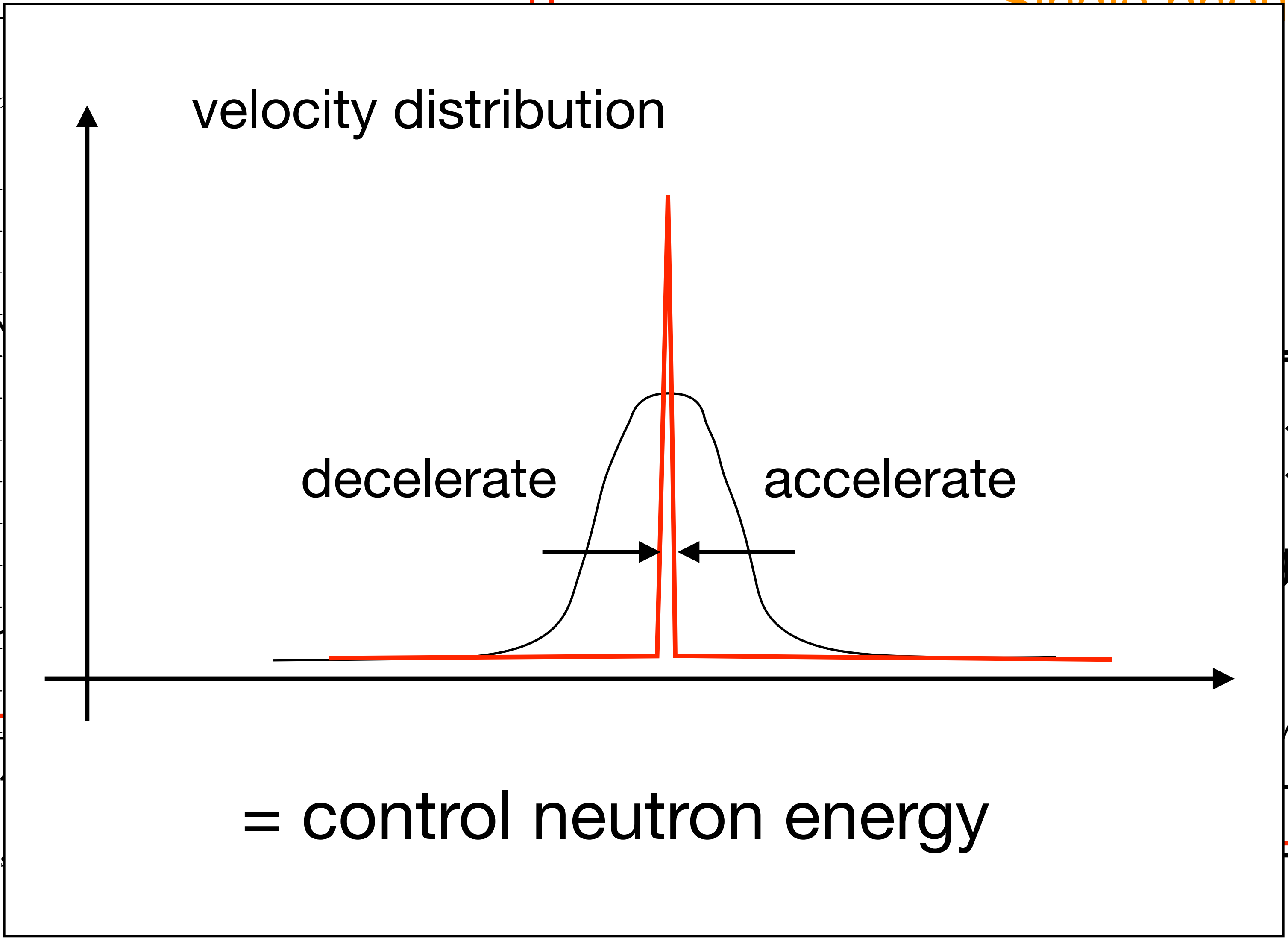


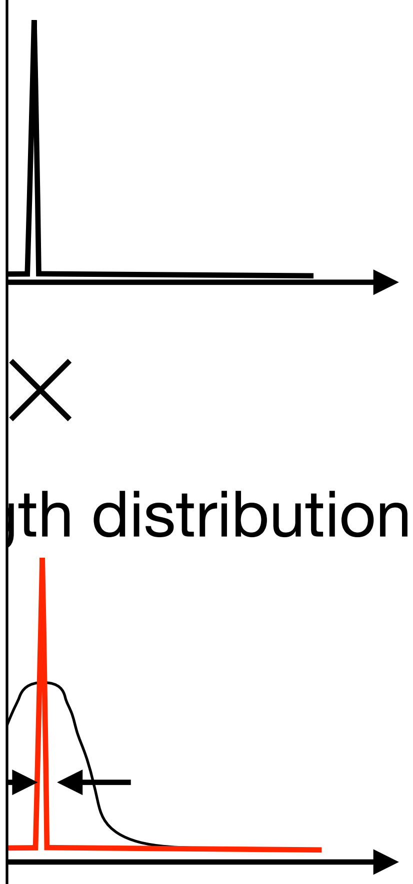
Fig. 3. The energy spectrum of the flux meas



= control neutron energy

Single phonon excitation

$S^* \delta(\lambda^* - \lambda)$



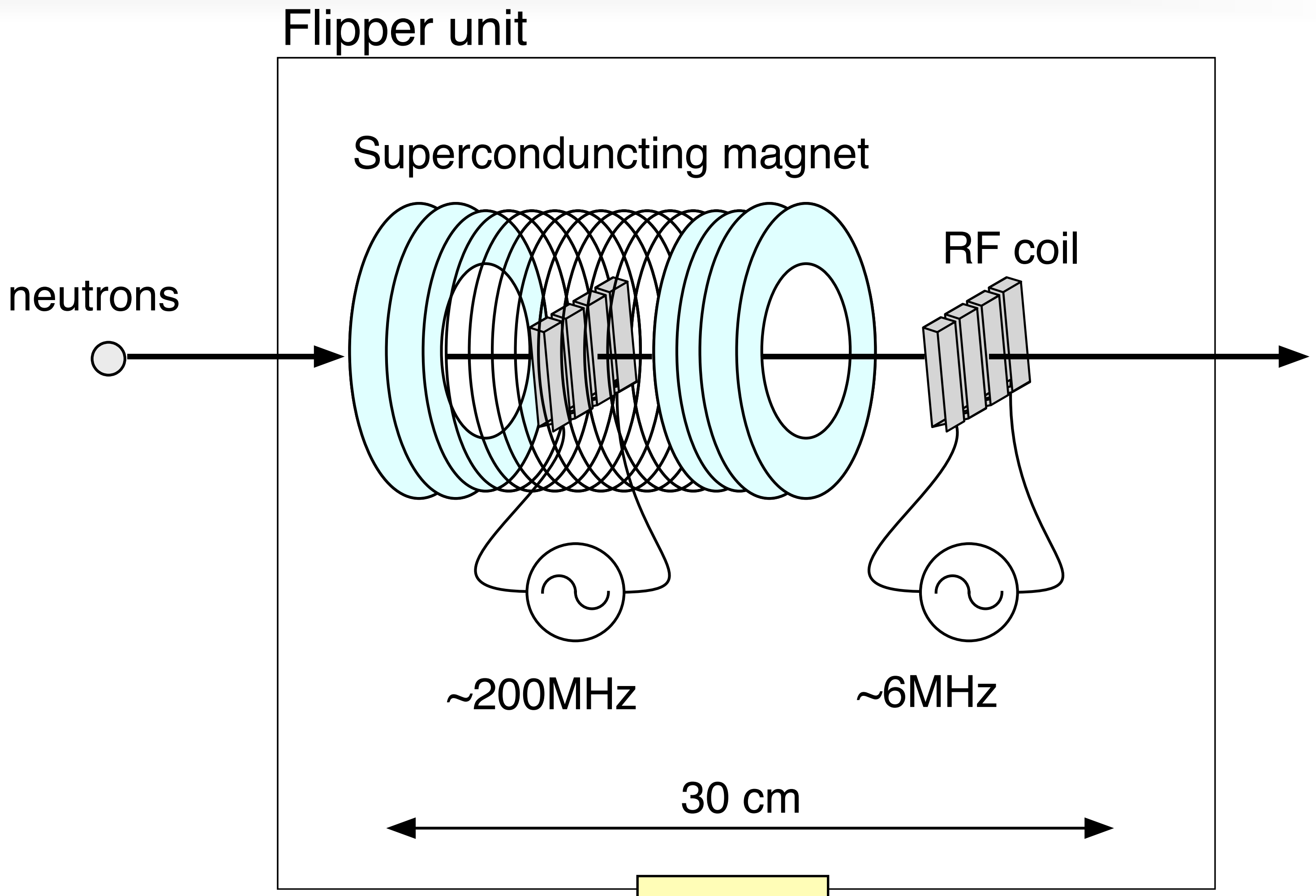
Narrow-bandwidth neutrons are required.

Deceleration and acceleration by spin flip

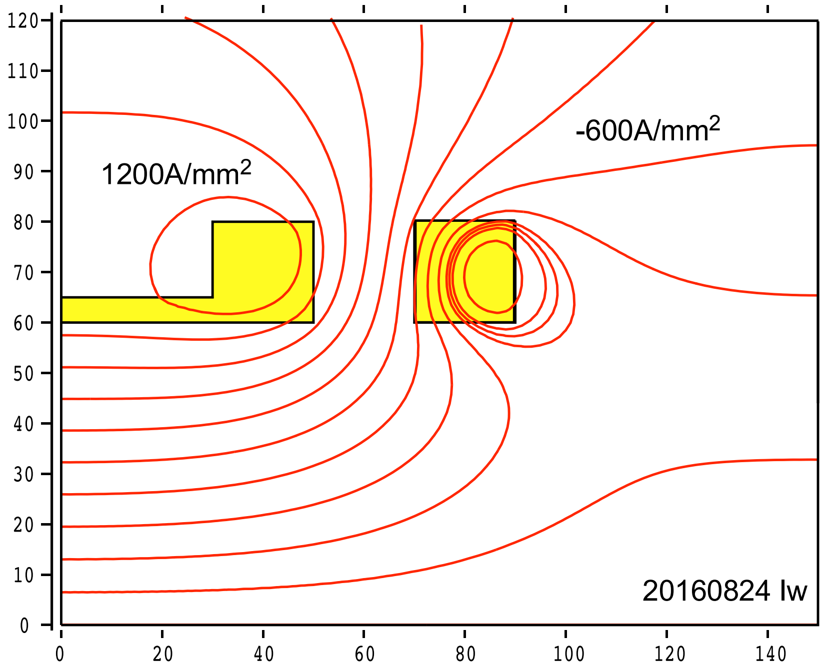
RF spin flipper

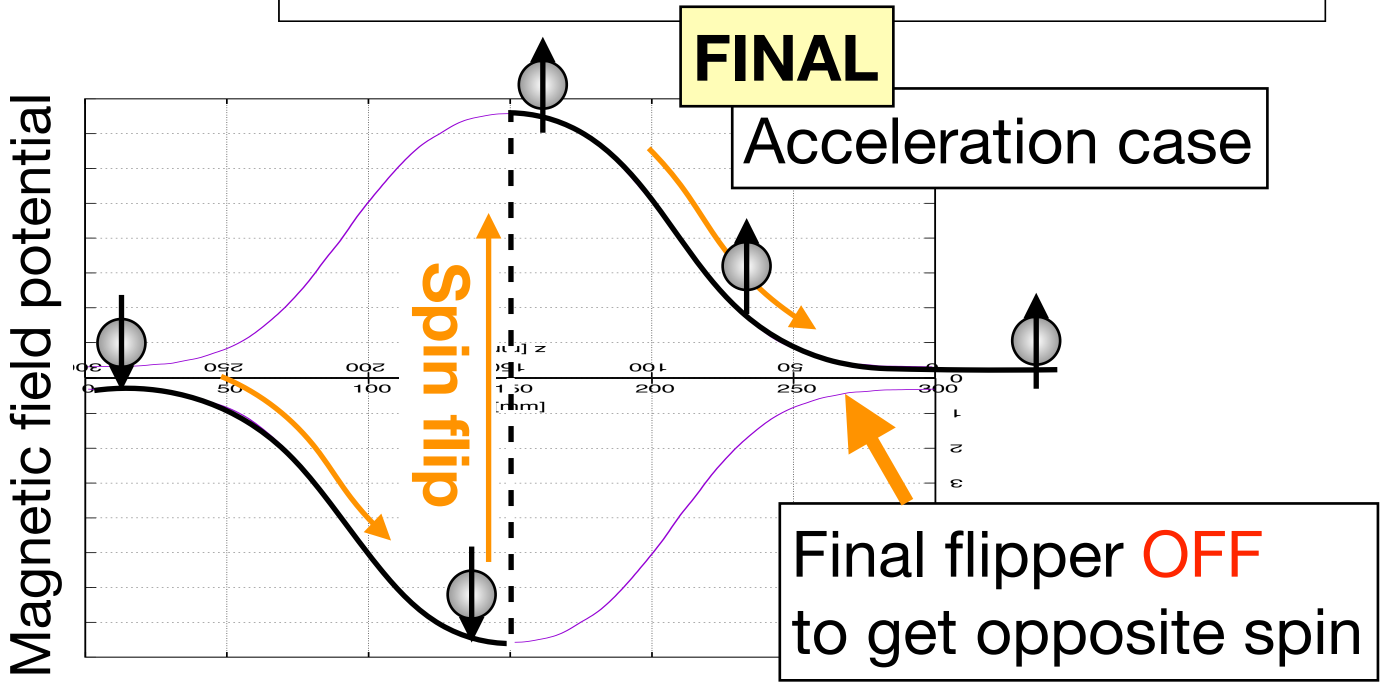
RF spin flipper (RSF) can decelerate and / or accelerate the neutrons.

RSF in 7.5 T magnetic field changes the energy of 0.9 μeV.



Calculation of magnetic field

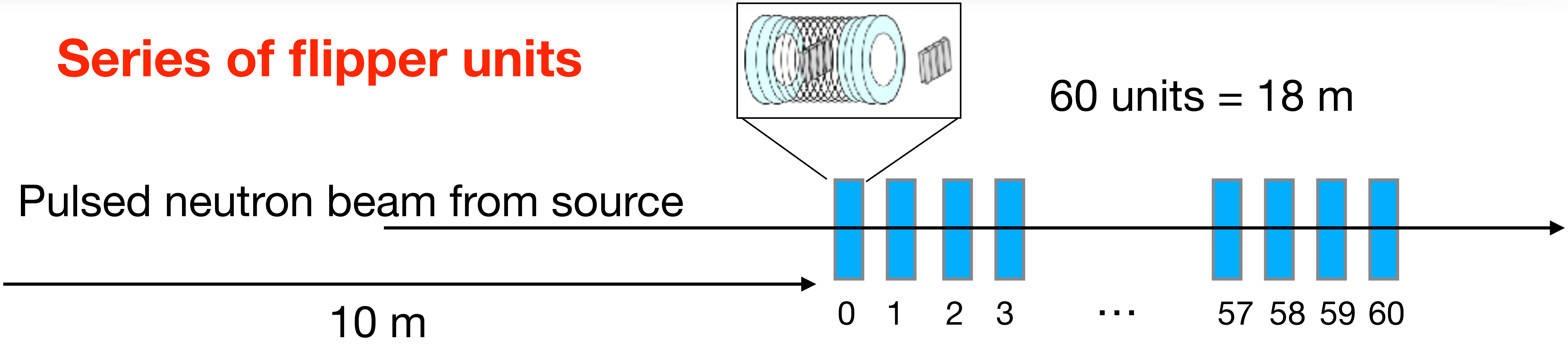




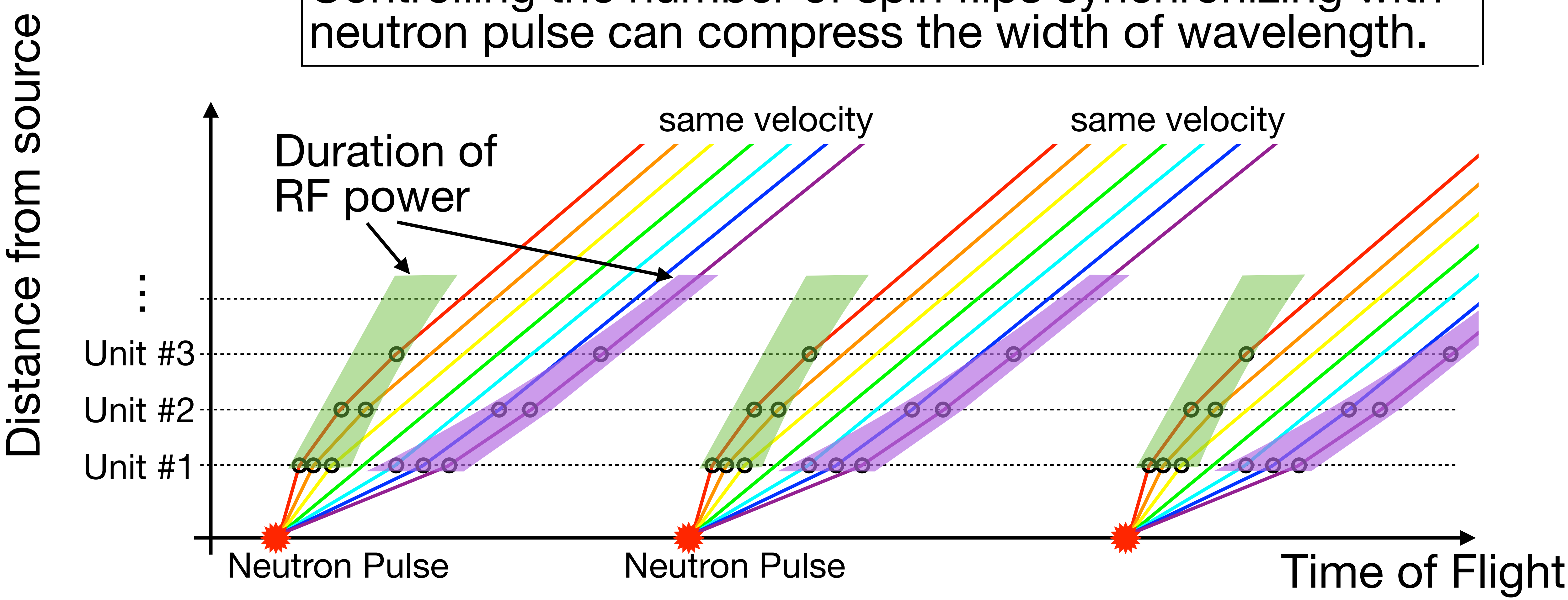
Final flipper OFF to get opposite spin

Neutron Velocity Concentrator

Series of flipper units

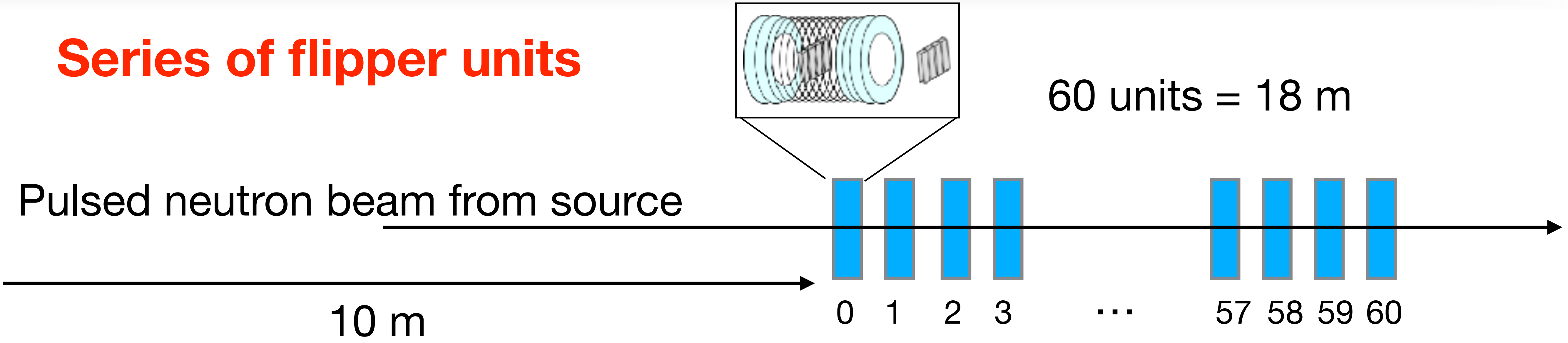


Controlling the number of spin flips synchronizing with neutron pulse can compress the width of wavelength.



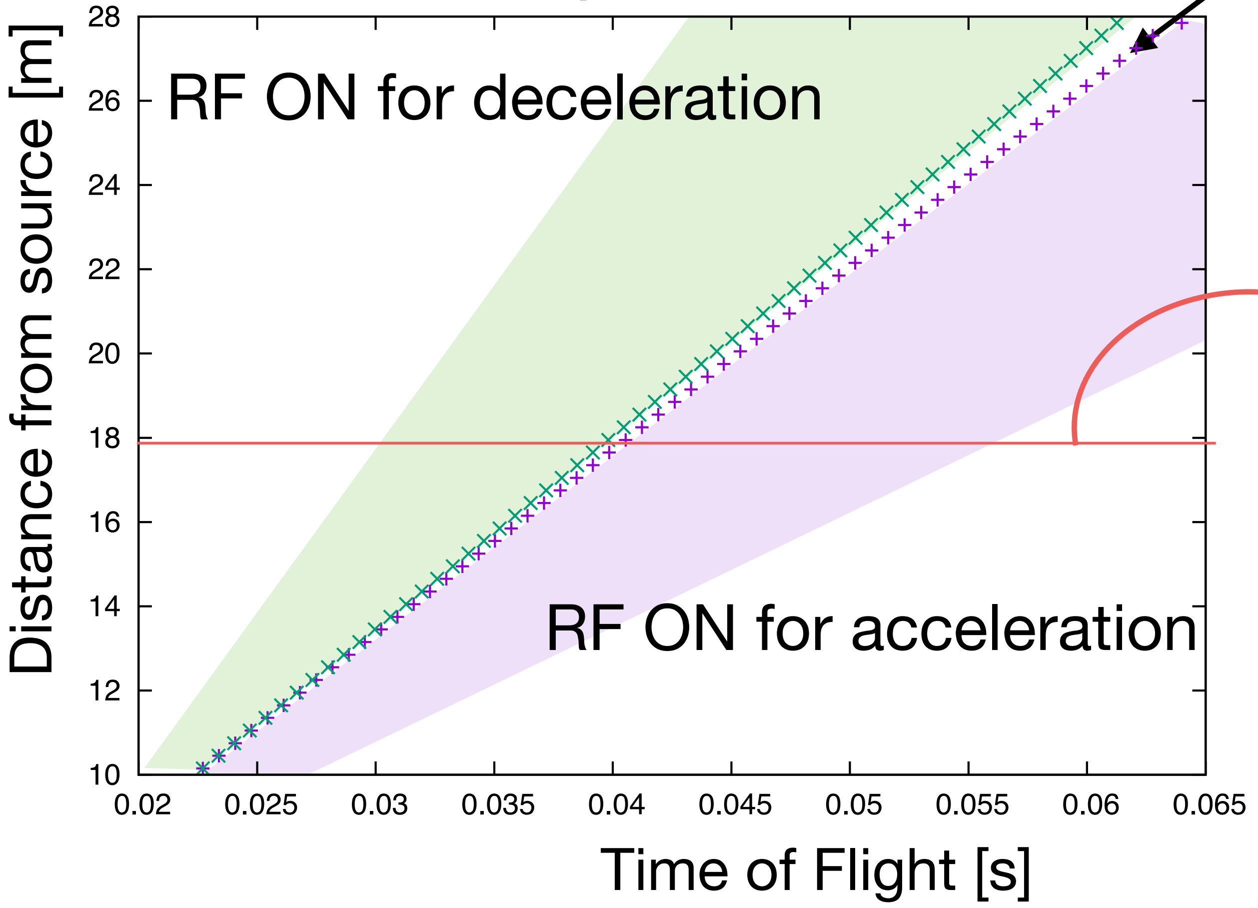
Neutron Velocity Concentrator

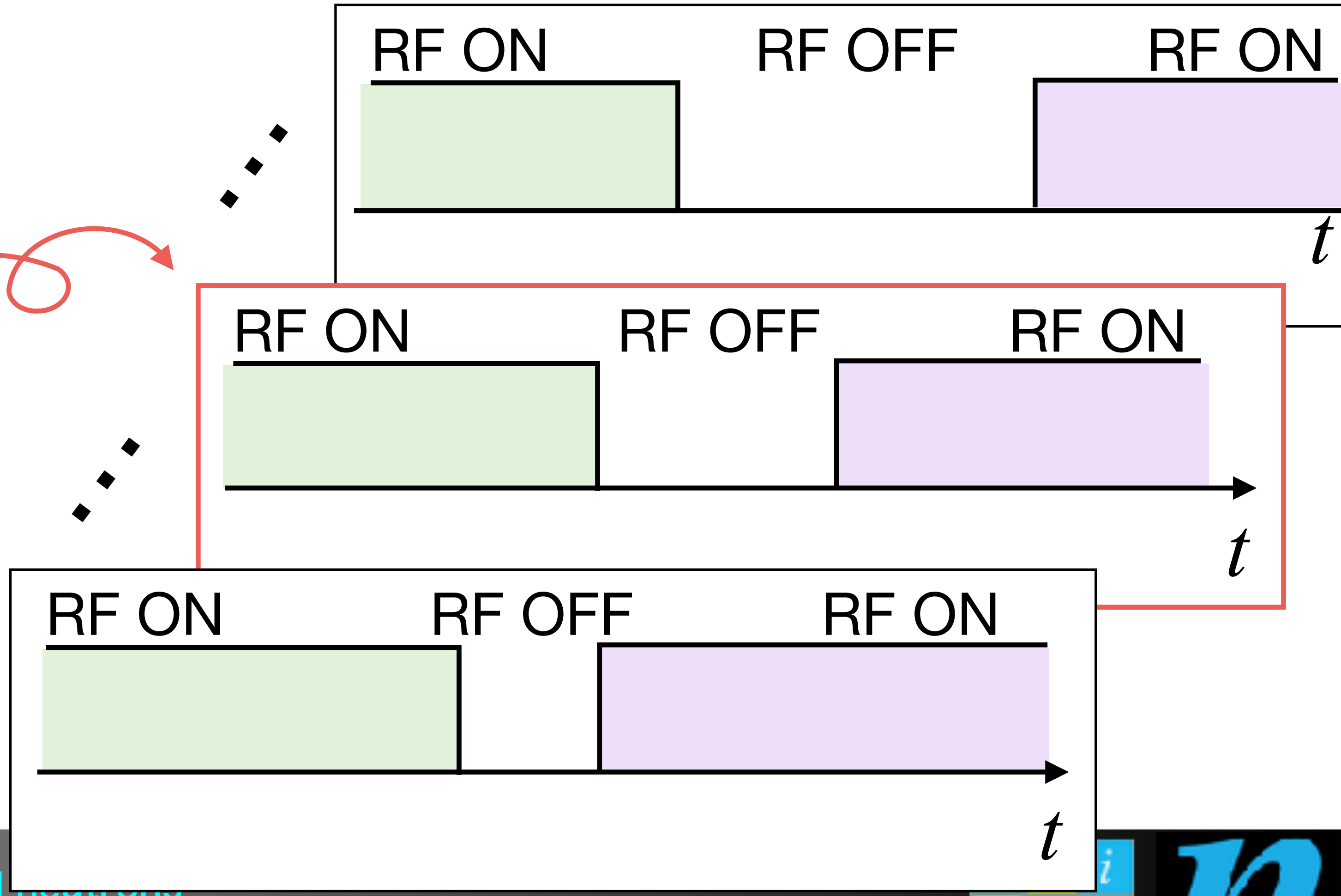
Series of flipper units



RF OFF for velocity concentration

Duration of RF power

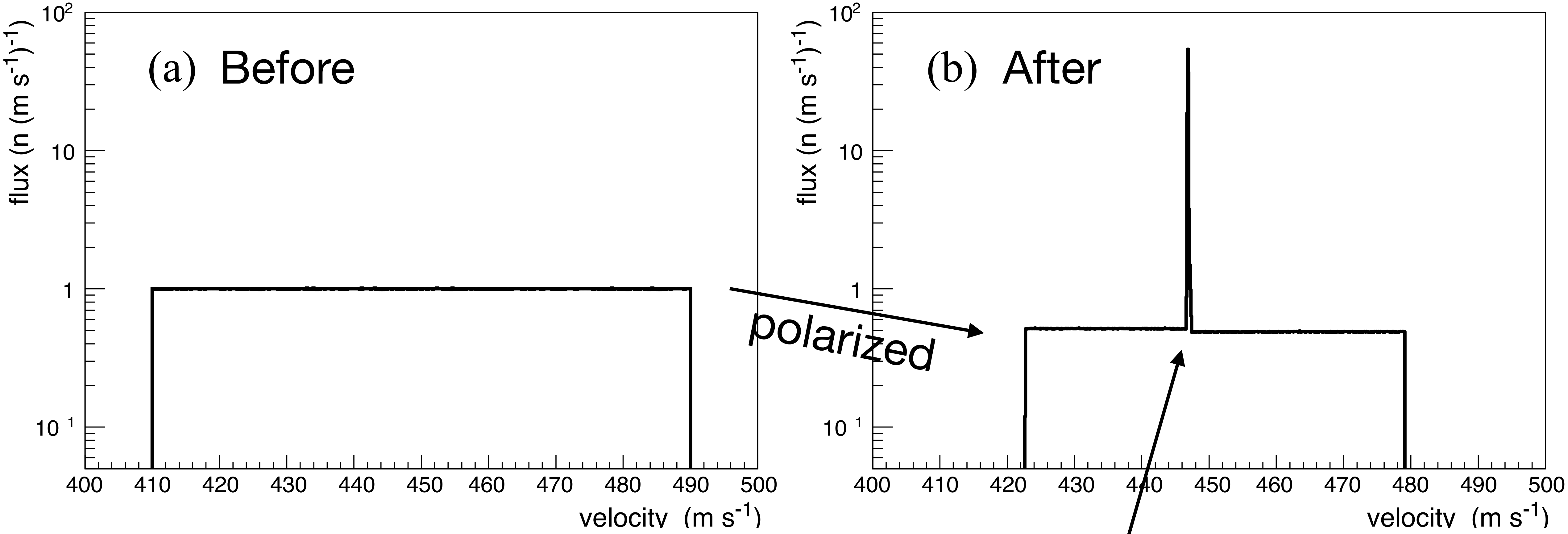




Neutron Velocity Concentrator

Monte-Carlo simulation

Velocity distribution after the **Velocity Concentration**



Flat velocity distribution

Flipping probability = 1

Neutron pulse width = 0

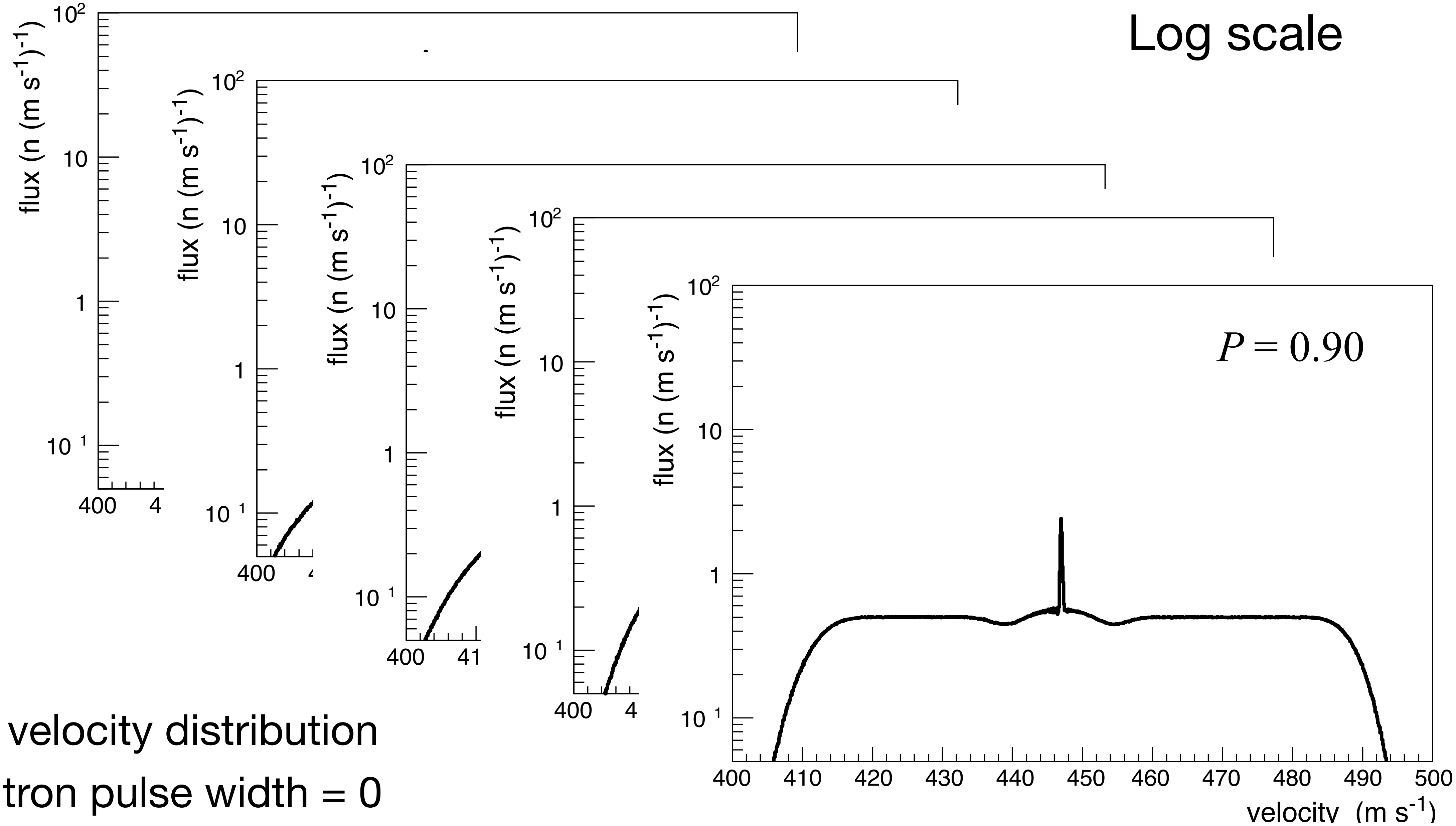
100 times larger at the target velocity

Neutron Velocity Concentrator

Monte-Carlo simulation

Velocity distribution after the **Velocity Concentration**

Log scale



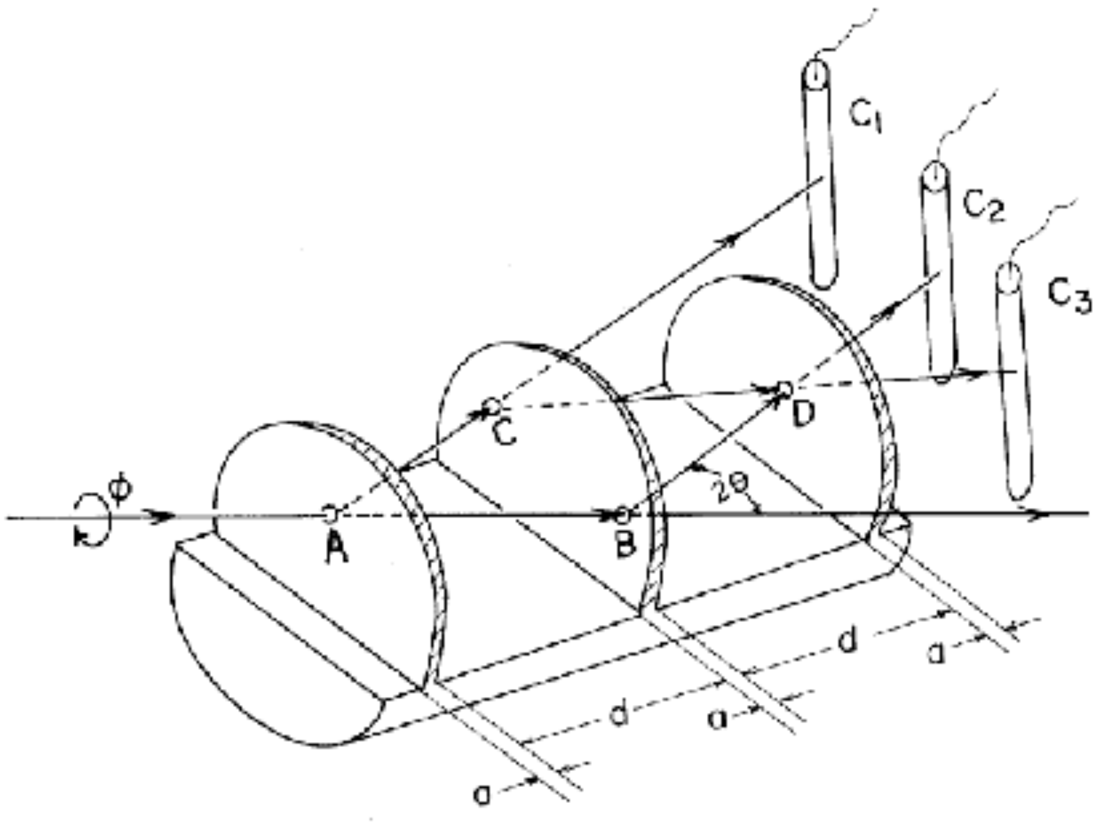
Flat velocity distribution

Neutron pulse width = 0

Cold and very-cold neutron interferometer

Neutron Interferometer

Demonstration with Silicon single crystal



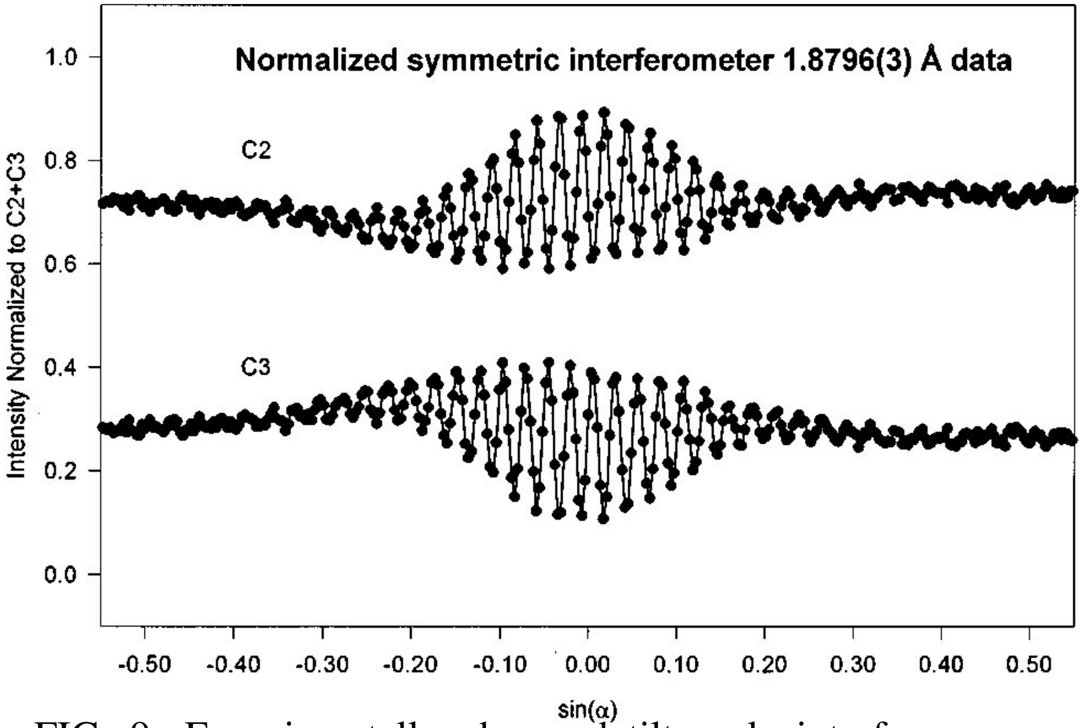


FIG. 9. Experimentally observed tilt-angle interferogram normalized to *C*21 *C*3 to compensate for the dependence on tilt of the intensity of neutrons accepted by the interferometer for 1.8796-Ö neutrons in the symmetric interferometer.

K. C. Littrell, B. E. Allman, and S. A. Werner,
Phys.Rev.A56 (1997) 1767.

Neutron feels gravitational potential of the earth.

Discrepancy of 0.8% was observed by large interferometer.

Neutron Interferometer for General Relativity

Hamiltonian for a spin-1/2 particle with post-Newtonian correction

$$\mathrm{H}_{\mathrm{pN}} = \frac{\mathbf{p}^2}{2m} + \underbrace{m\phi}_{1} - \underbrace{\boldsymbol{\omega}\cdot(\mathbf{L}+\mathbf{S})}_{2}$$

$$+ \frac{1}{c^2}\left(\underbrace{\frac{4GMR^2}{5r^3}\boldsymbol{\omega}\cdot(\mathbf{L}+\mathbf{S})}_{3} - \frac{\mathbf{p}^4}{8m^3} + \underbrace{\frac{m}{2}\phi^2}_{4} + \underbrace{\frac{3}{2m}\mathbf{p}\cdot\phi\mathbf{p}}_{5} + \underbrace{\frac{3GM}{2mr^3}\mathbf{L}\cdot\mathbf{S}}_{6} + \underbrace{\frac{6GMR^2}{5r^5}\mathbf{S}\cdot[\mathbf{r}\times(\mathbf{r}\times\boldsymbol{\omega})]}_{7} \right)$$

M: mass of Earth
R: Earth radius

ω: angular velocity of Earth
ϕ: Newtonian gravitational potential

m: neutron mass
$\mathbf{L}=\mathbf{x}\times\mathbf{p}$
$\mathbf{S}=\hbar\boldsymbol{\sigma}/2$

Example : $\lambda = 0.88$ nm, $A = 3.3 \times 10^{-4}$ m², $\Delta\theta = 1.6$ deg

S. Wajima, M. Kasai, T. Futamase,
PRD 55, 1964 (1997)

COW

$\Delta\phi_1 = 3 \quad (\propto \lambda \cdot A)$

Sagnac

$\Delta\phi_2 = 0.5 \quad (\propto A)$

Lense-Thirring

$\Delta\phi_3 = 2 \times 10^{-10} \quad (\propto A)$

redshift correction (potential)

$\Delta\phi_4 = 2 \times 10^{-9} \quad (\propto \lambda \cdot A)$

redshift correction (kinetic)

$\Delta\phi_5 = 3 \times 10^{-5} \quad (\propto \lambda \cdot A)$

$\Delta\phi_6 = 5 \times 10^{-24}$

$\Delta\phi_7 = 5 \times 10^{-24}$

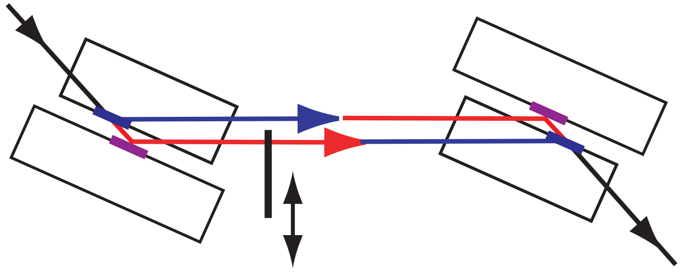
$A = 1$ m² → $\Delta\phi_5 = 0.1$

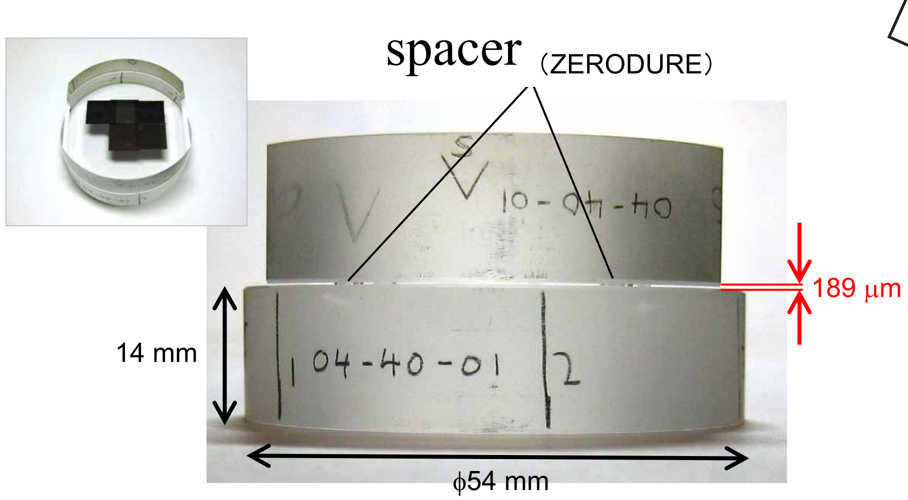
→Large-scale interferometer with long-wavelength neutrons

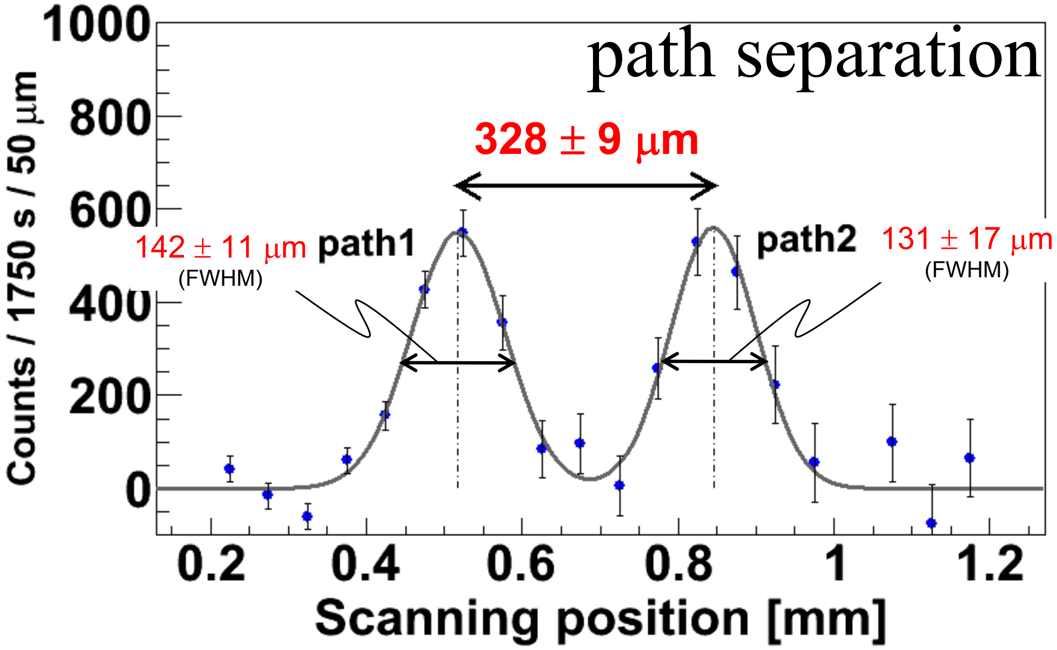
Cold-Neutron Interferometer

Demonstrated by precision arrangement of multilayer mirrors

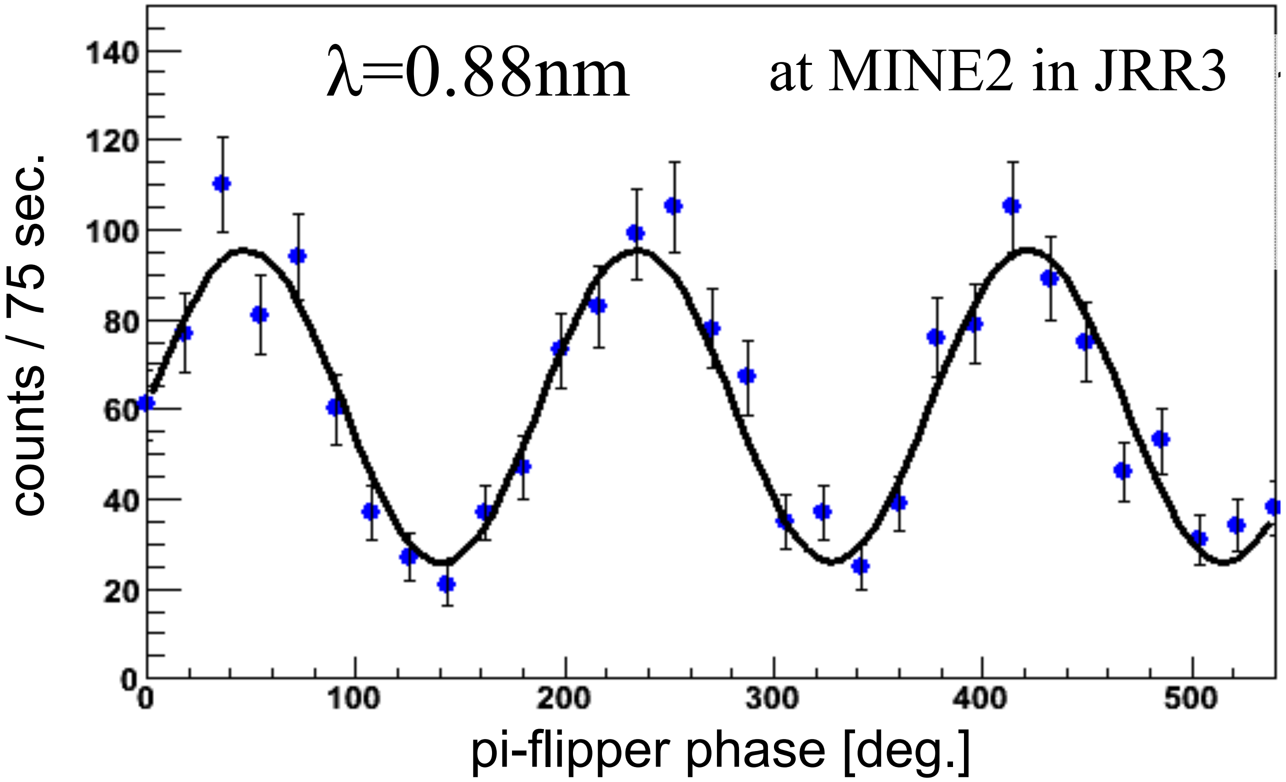
with complete path-separation by using Etalons







Y. Seki et al., J. Phys. Soc. Jpn. **79** (2010) 124201.



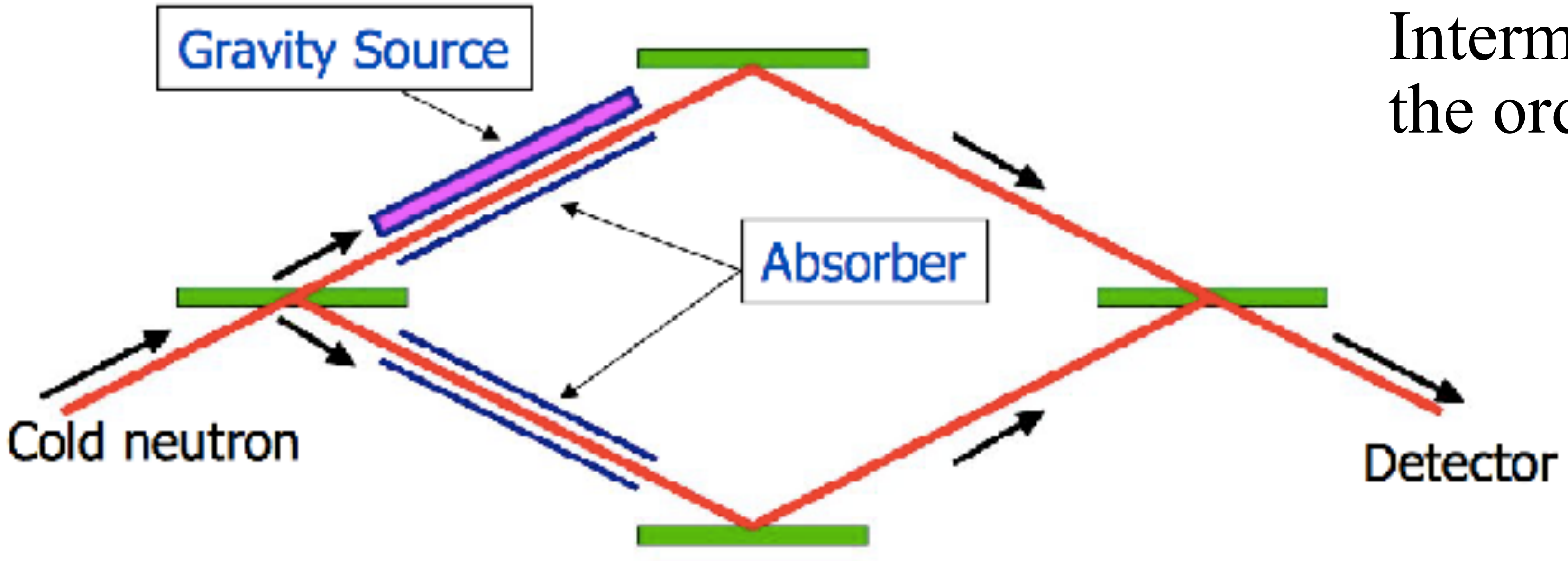
Sensitivity ~ feV

Cold-neutron interferometer can be realized with J-PARC pulsed neutrons by using multilayer mirrors.

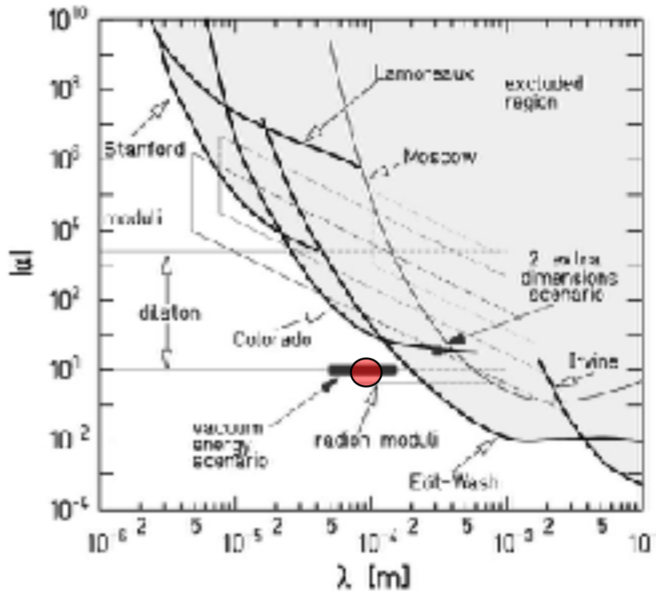
Stability is one of biggest problems.
(similar to 2 crystal interferometer)

Cold-Neutron Interferometer for unknown forces

Large-scale interferometer with long-wavelength neutrons has the advantage to study gravity precisely.



Intermediate-range force of the order of 100μm can be studied ?



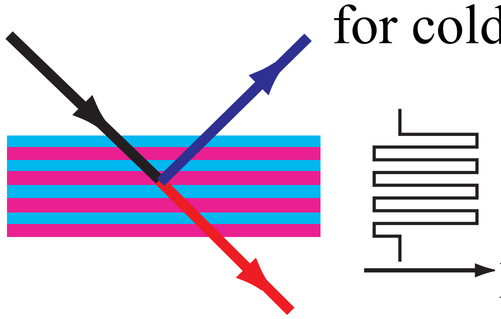
Neutron multilayer mirrors must be used for cold neutrons.

Neutron supermirror can be applied for pulsed neutrons.

Precision alignment of mirrors is required.

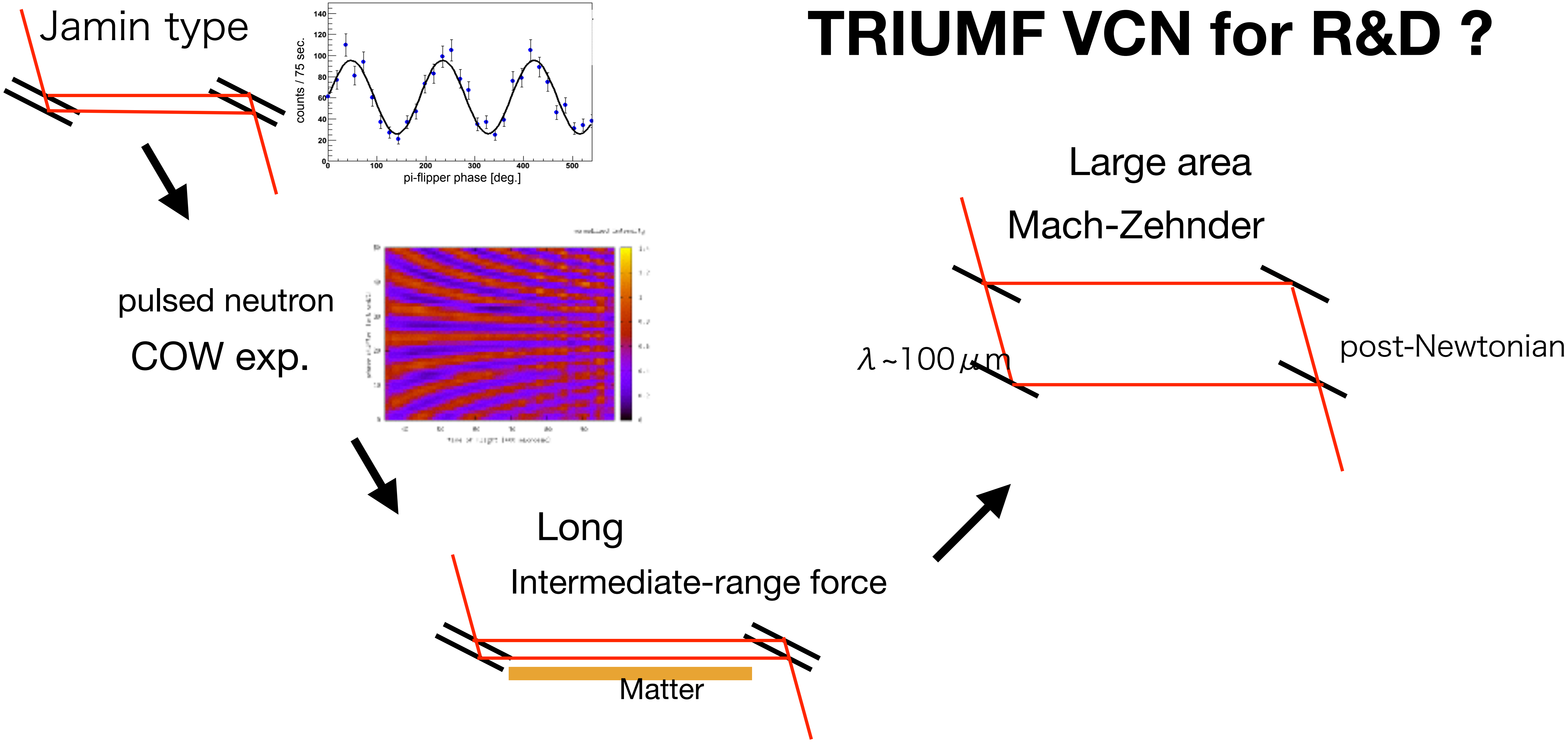
~ nm = wavelength of neutrons

Bragg reflection for cold neutrons



R&D for cold, very-cold neutron interferometer

1m^2, long-wavelength interferometer
can search the effect of General Relativity.



TRIUMF VCN for R&D ?

Summary

For detail study of neutron EDM, new approaches are required.
(even if nEDM is discovered.)

UCN precision optics is a powerful tool.

Various R&D for cold and ultra-cold neutrons are in progress.

Neutron Rebuncher transports UCNs with keeping density.

Neutron Velocity Concentrator increases cold neutrons suitable for generating UCNs with He-II converter.

Neutron interferometer with slow neutrons has the advantage to measure small interaction, induced by gravity.