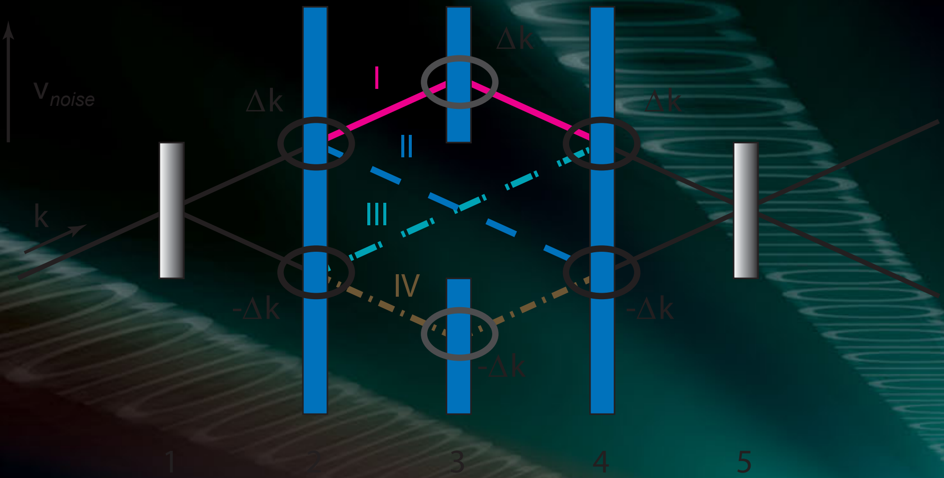


Neutron Interferometry at NIST

D. Pushin

UNIVERSITY OF WATERLOO | IQC Institute *for* Quantum Computing

NIST

Outline

- Introduction to Mach-Zehnder neutron interferometry

- Neutron Interferometer facility at NIST and ILL

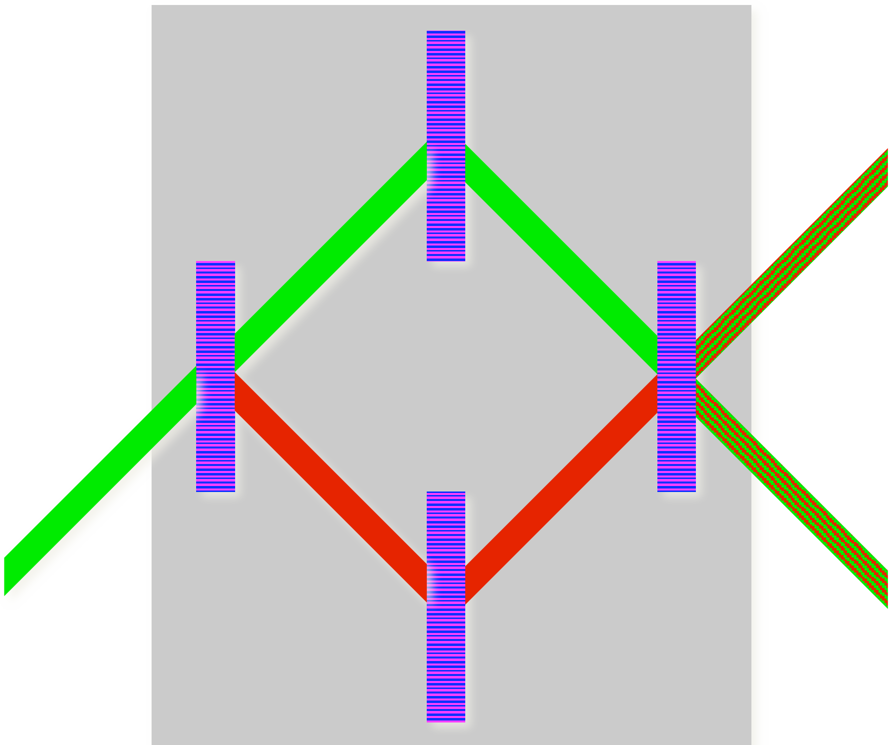
-Quantum error corrected MZ/NI for mechanical vibrations.

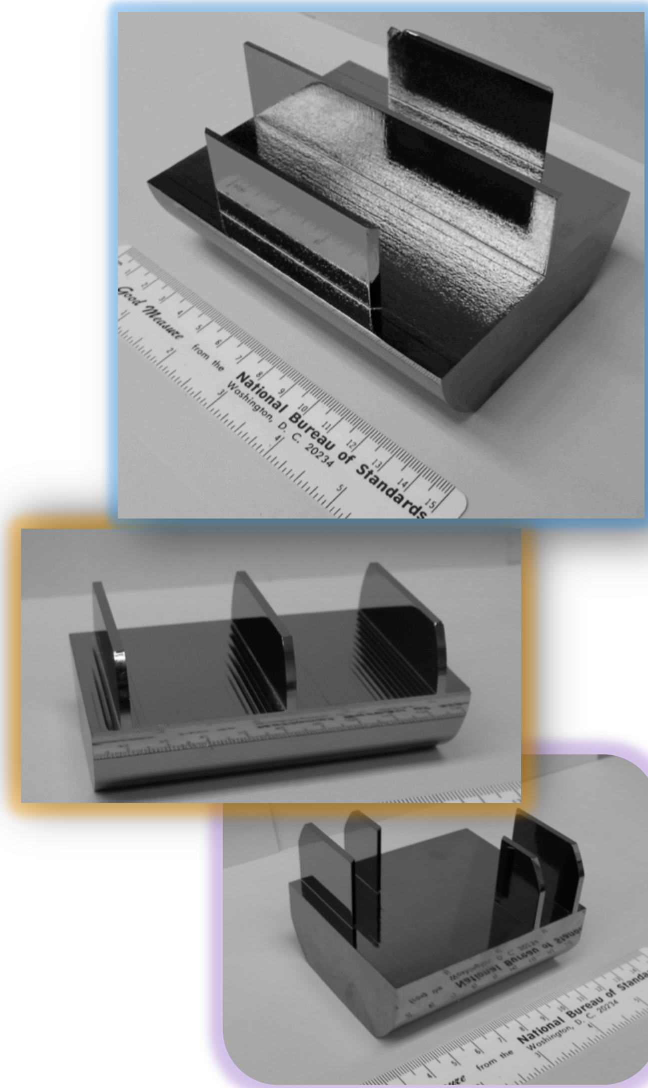
-Conclusion

-Quantum Discord

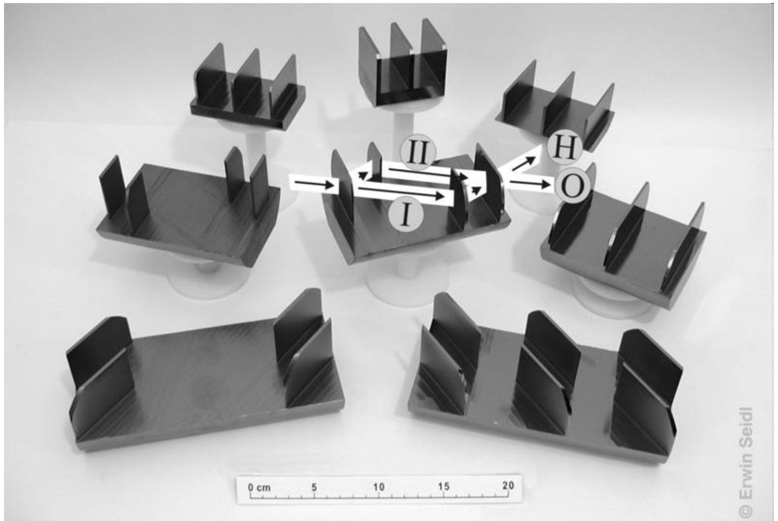
Neutron Interferometer

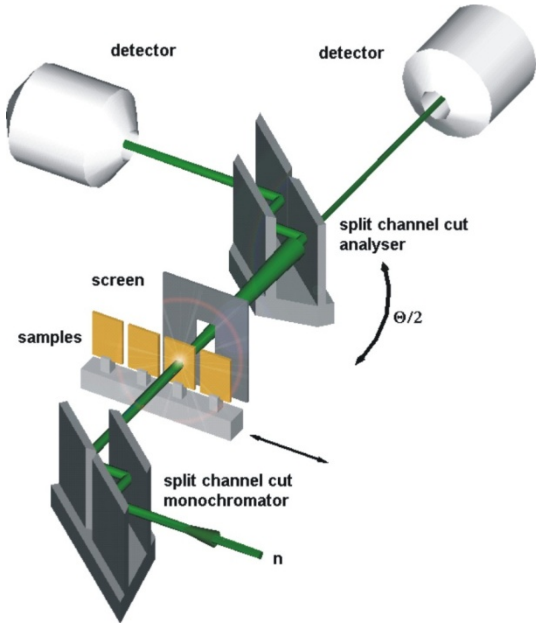
$$\psi = \frac{1}{\sqrt{2}}\left(|upper\rangle + |lower\rangle\right)$$





Main research topics: *interferometer & USANS*





Interferometer Option	*USANS Option*
• Measurement of basic quantum physics laws • Measurement of neutron-nuclei scattering lengths • Phase tomography imaging and measurements • Decoherence, dephasing and depolarisation experiments • Experiments with non-classical neutron states Recent results have been published in Nature, PRL, ILL-NEWS and other important journals.	• Pore structure of geological and composite materials • USANS from artificially structured materials • Polarized USANS experiments Studies of micro structures of light and heavy water hydrated calcium sulphates, fuel materials like bituminous coals and others have been published.

Interferometry

Size: Typically fits in one hand (100 x 100 mm^2)

Material: Silicon

First Demonstration: 1974

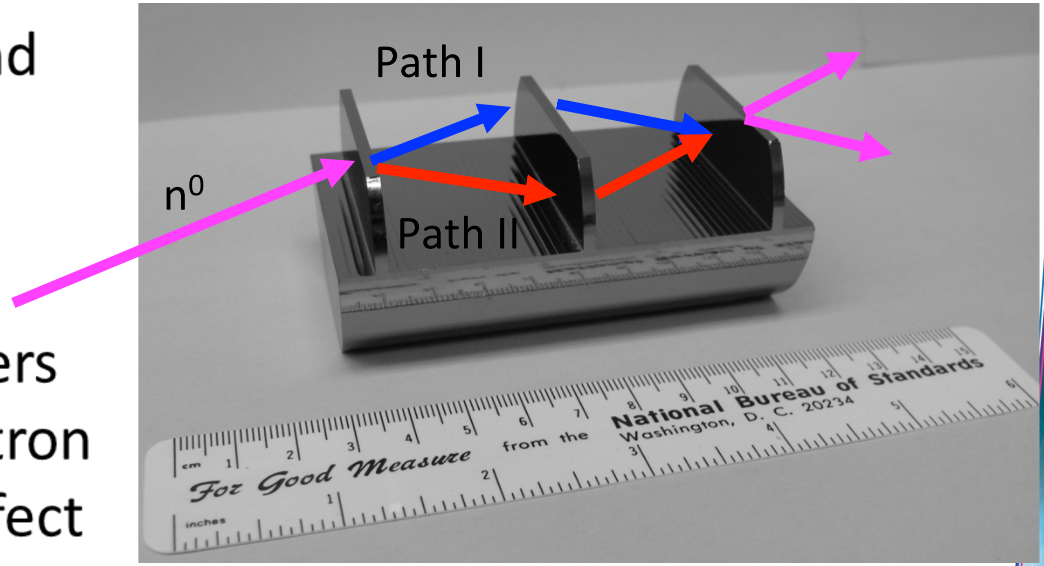
Path length: A few centimeters

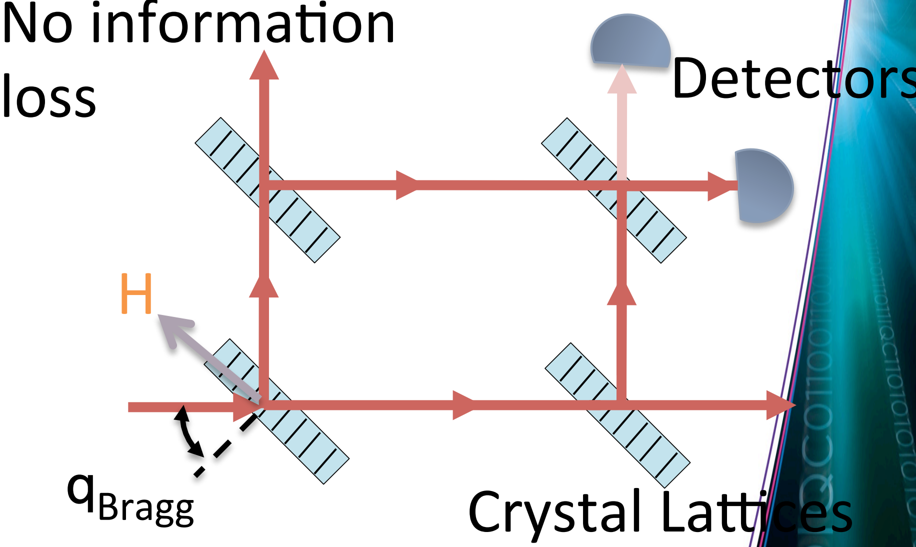
Method: Bragg diffracts neutron into two separate paths (Perfect example of self interference).

Contrast:

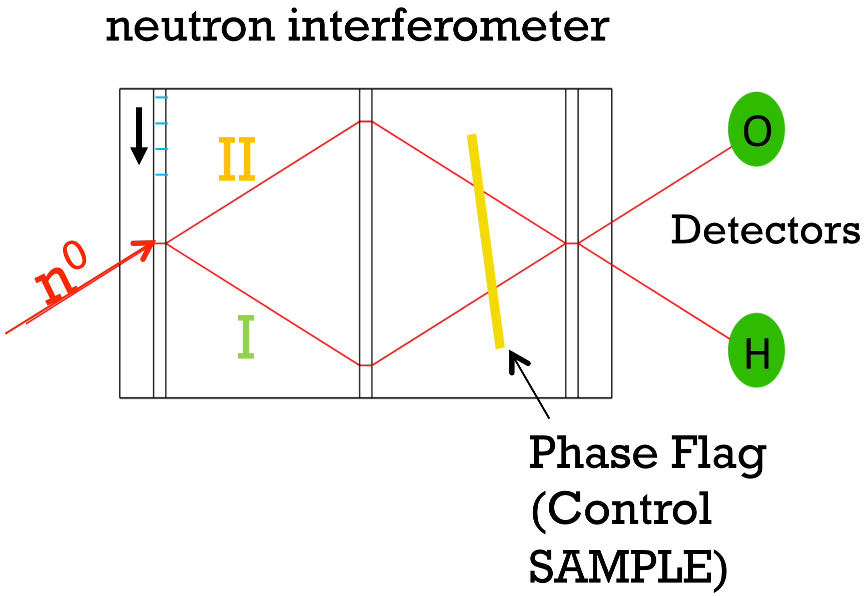
$$C = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min} - 2 * I_{bkgd})}$$

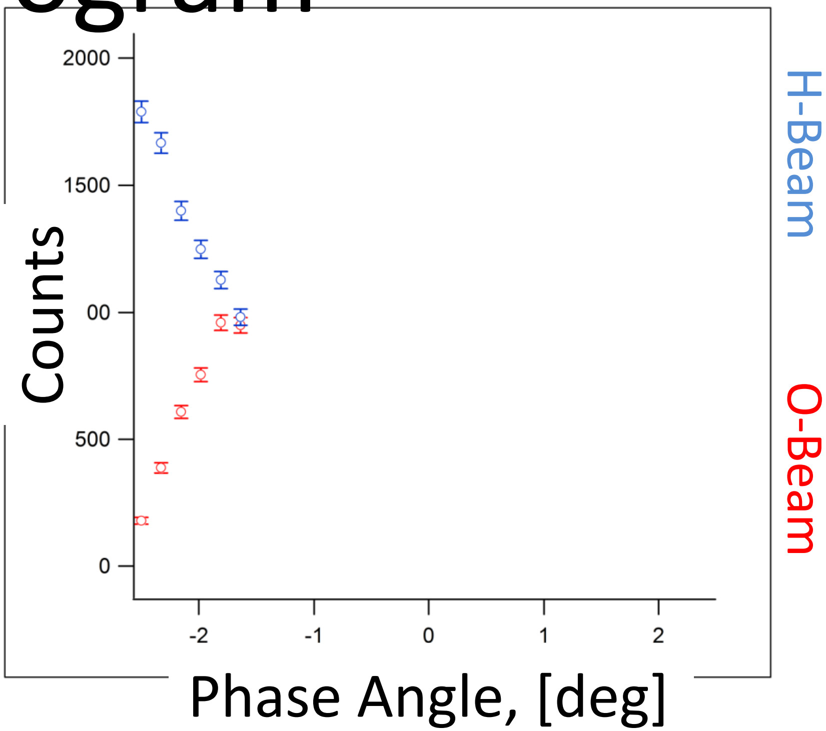
Varies with experiential conditions; maximum is <90%.

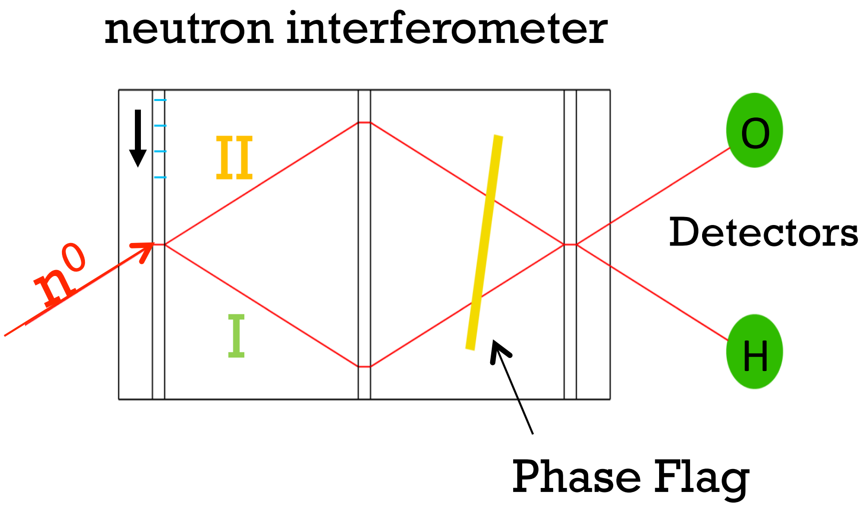


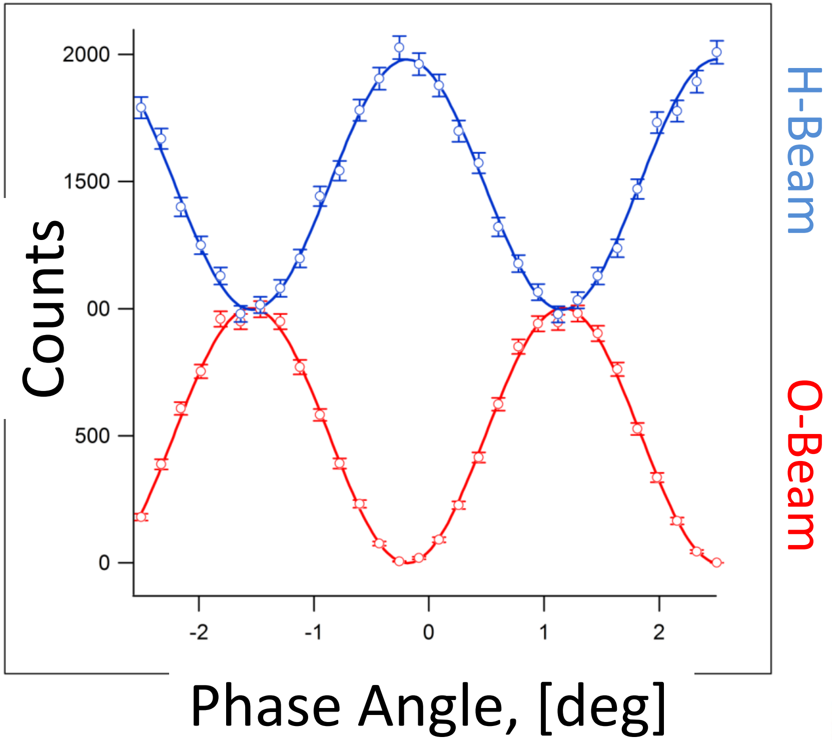


Interferogram







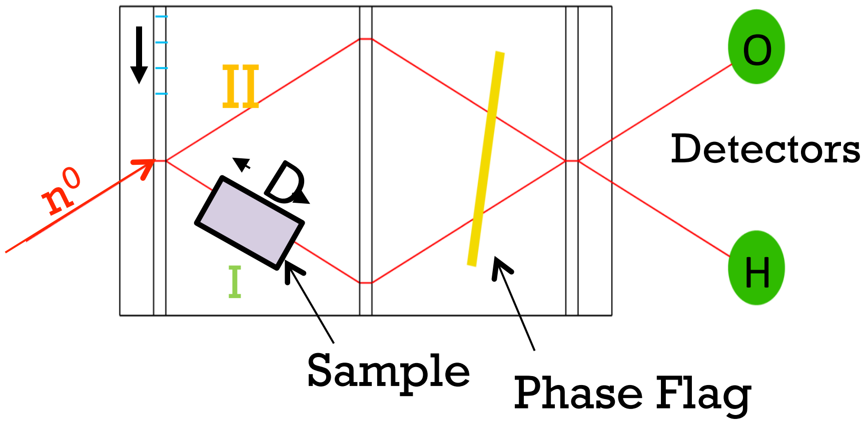


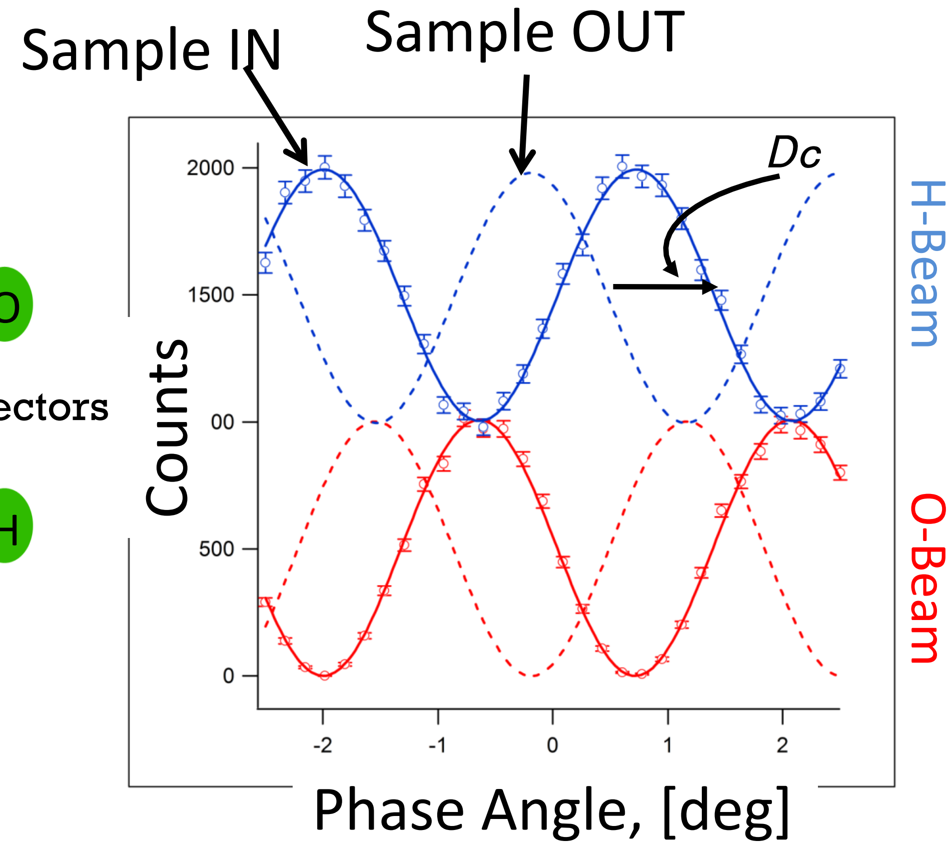
O BEAM: $I_O = A[1 + f\mathbf{cos}(\chi_2 - \chi_1)]$

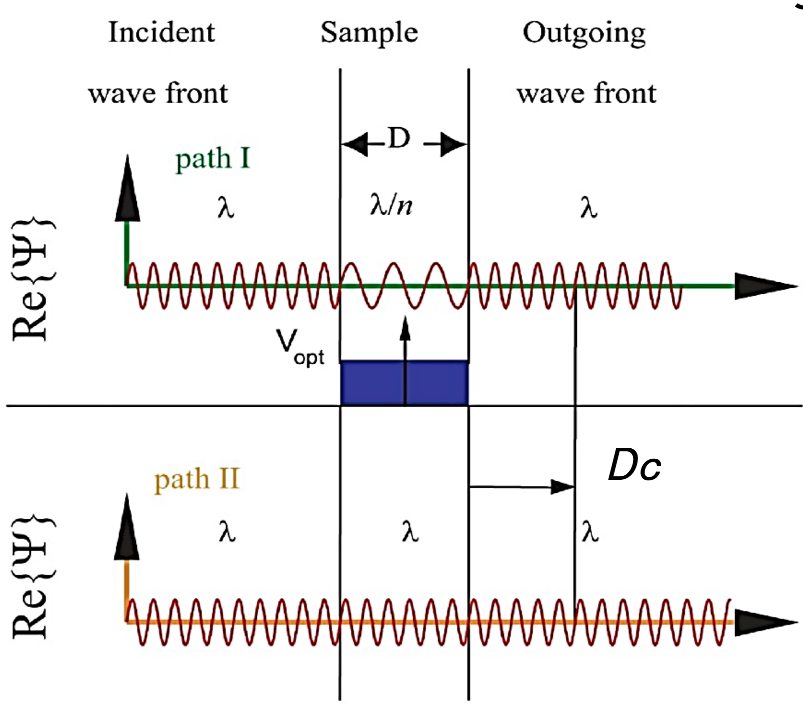
H BEAM: $I_H = B - Af\ \mathbf{cos}(\chi_2 - \chi_1)$

$I_O + I_H =$ A+B = constant

neutron interferometer







Index of refraction:

$$n \approx 1 - \frac{N\lambda^2}{2\pi} b$$

Relative phase shift:

$$\Delta\chi = k_0 D - n k_0 D = \frac{N\lambda D}{\cos\theta} b$$

A Sample of Phase Interactions

Nuclear
$\phi = -ND\lambda b_c$

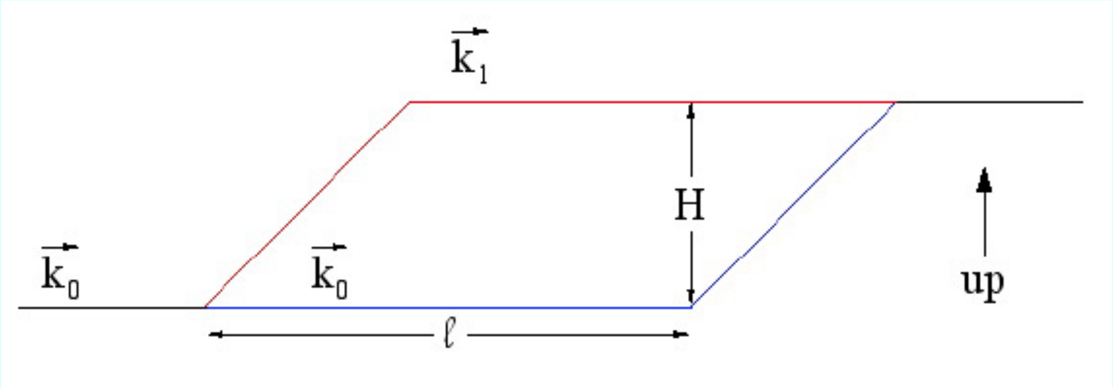
Magnetic
$\phi = \pm \frac{\mu B m_n \lambda D}{2\pi\hbar^2}$

Quantum Mechanical	
$\phi = \pm \frac{2\vec{\mu}}{\hbar c} \vec{E} \cdot \vec{D}$	Aharonov-Casher
$\phi = \pm \frac{\mu B t}{\hbar}$	Scalar Aharonov-Bohm
$\phi = \frac{\Omega}{2}$	Geometric Phase

Gravity or Reference Frame	
$\phi = \frac{m_n^2 g \lambda A \sin(\alpha)}{2\pi\hbar^2}$	Gravity
$\phi = \frac{2m_n}{\hbar} \vec{\omega} \cdot \vec{A}$	Coriolis

Historical gravity experiments with NI

Quantum Phase Shift Due To Gravity (COW Experiments)



$$\Delta\phi = \frac{2\pi\lambda g A}{h^2} m_{in} m_{grav}$$

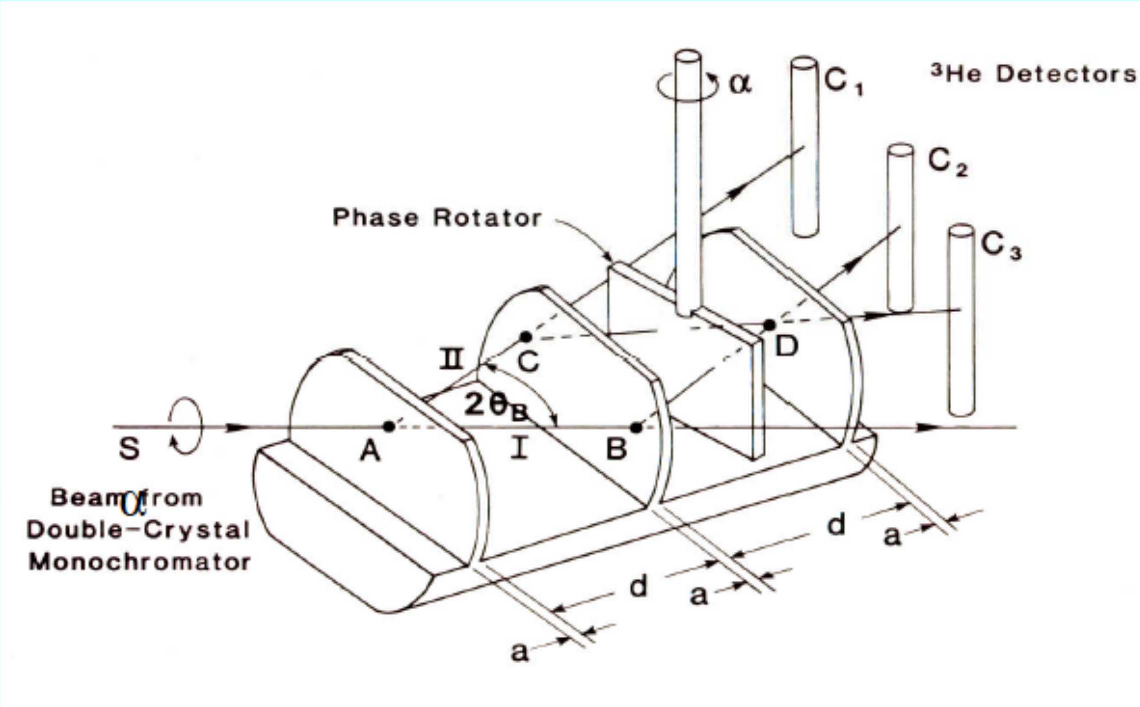
m_{in} = neutron inertial mass

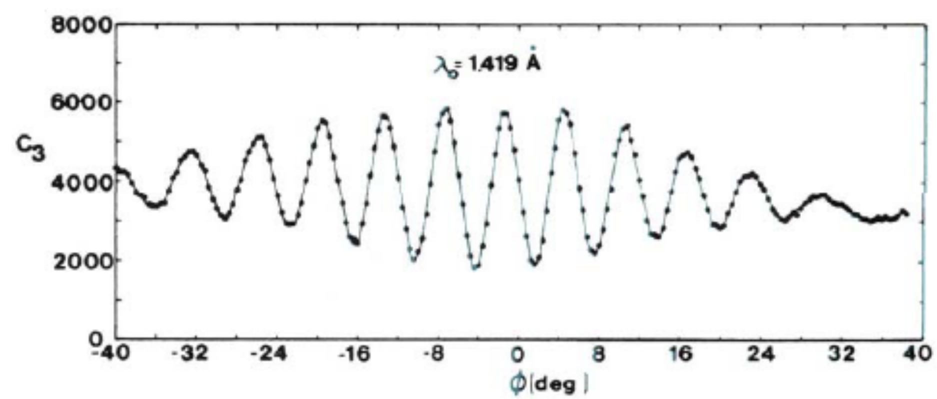
m_{grav} = neutron gravitational mass

$A = H\ell =$ area of parallelogram

test of weak equivalence principle at the quantum limit

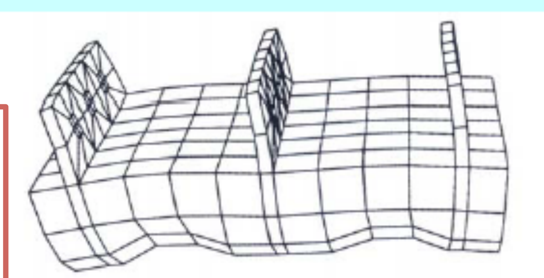
NI and gravity





$$\Delta\Phi(\alpha) = \Delta\Phi_{grav}(\alpha) + \Delta\Phi_{bend}(\alpha)$$

$$\Delta\Phi_{bend}(\alpha) = -(2\pi/\lambda)\Delta L_0 \sin\alpha$$

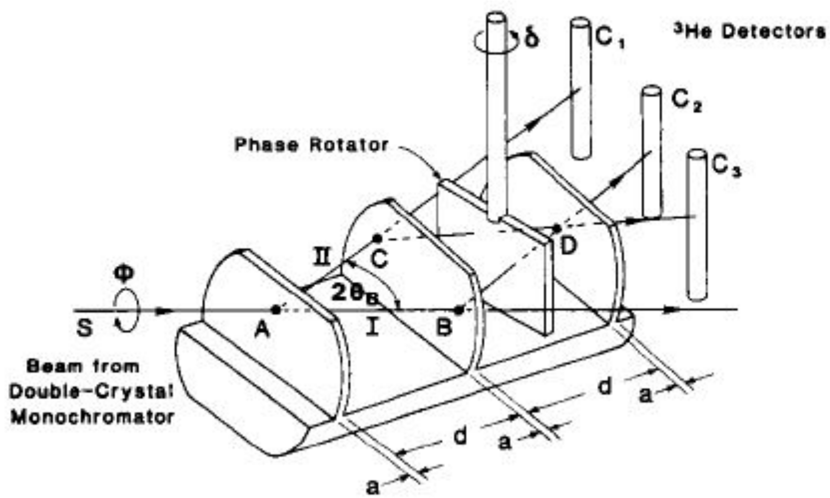


NI and gravity

Colella, Overhauser, Werner, PRL **34**, 1975
Staudenmann et al., PRA**21**, 1980

Werner et al (1988)

- First use of a rotating phase-shifter
- Interferogram measured as a function of the phase-shifter position for several tilt angles



Physica B+C, **151**, 22 (1988)

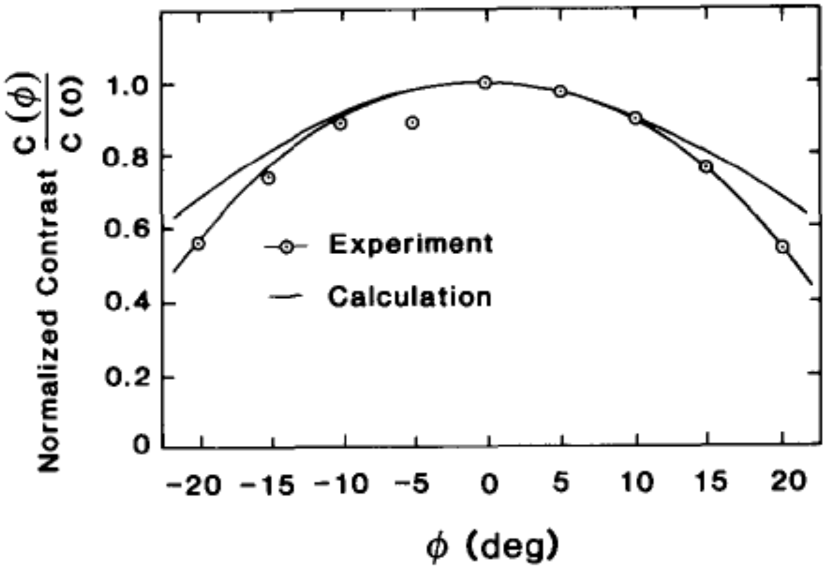


Fig. 8. The variation of the contrast of the data of fig. 6 as a function of the tipping angle ϕ. The data is normalized to 1.0 at $\phi = 0$.

Littrell et al (1997)

- Attempted to use neutrons instead of x-rays to quantify bending effects
- Neutrons of almost harmonic wavelengths diffracted off 220 and 440 lattice planes in symmetric and skew-symmetric interferometers
- Discrepancies of 1.6% (symmetric) and 0.9% (skew-symmetric) found between theory and experiment

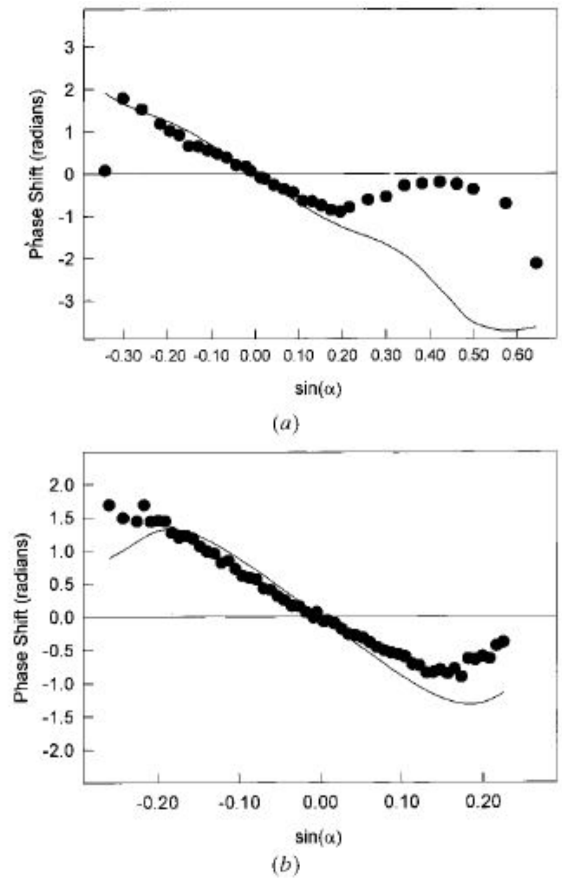
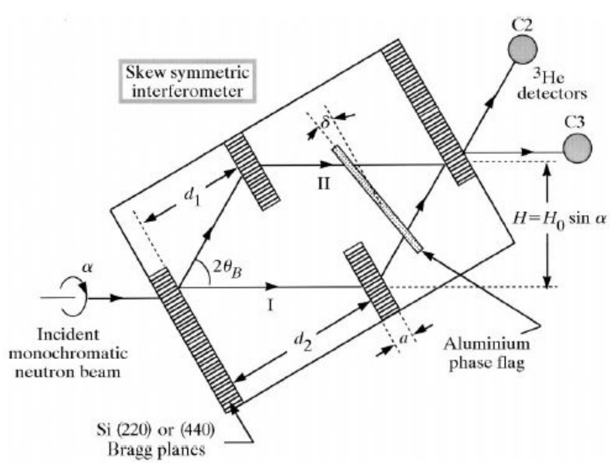


Fig. 16. Graphical representation of the difference between the phase shift measured using (a) the skew-symmetric interferometer and (b) the symmetric interferometer and $\Delta\Phi_{COW}$. The solid curves are the difference between the theoretical gravitational phase shift and $\Delta\Phi_{COW}$.



Acta Crystallographica, ***54***, *563 (1998)*

Historical COW experiments

Table 7.2 History of gravity-induced interference experiments—summary of results

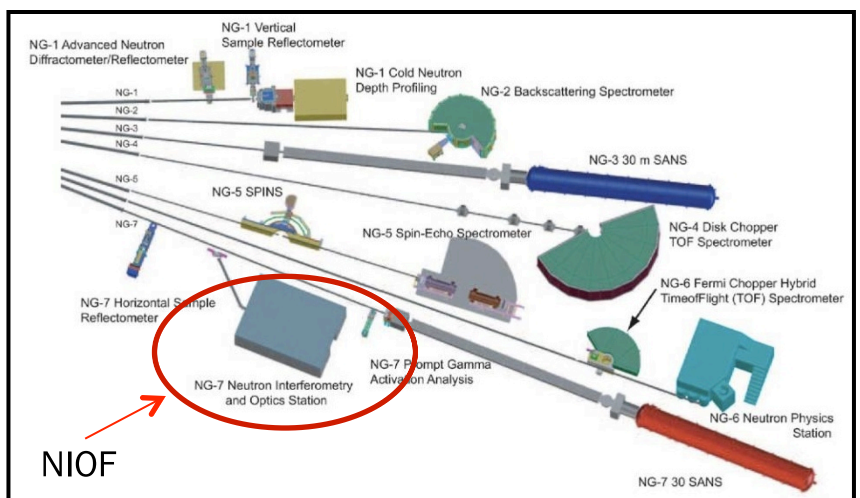
Authors	Interferometer	λ [Å]	A_0 [cm^2]	θ_B [deg]	q_{COW} (theory) [rad]	q_{COW} (exp) [rad]	q_{bend} [rad]	Agreement with theory
Colella *et al.* (1975)	Symmetric LLL #1	1.445(2)	10.52(2)	22.10(5)	59.8(1)	54.3(2.0)		12%
Staudenmann *et al.* (1980)	Symmetric LLL #2	1.419(2)	10.152(4)	21.68(1)	56.7(1)	54.2(1)	3.30(5)	4.4%
		1.060(2)	7.332(4)	16.02(1)	30.6(1)	28.4(1)	2.48(5)	7.3%
Werner *et al.* (1988)	Symmetric LLL #2	1.417(1)	10.132(4)	21.65(1)	56.50(5)	56.03(3)	1.41(1)	0.8%
Jacobson *et al.* (1993)	Symmetric LLL #2	1.422(1)	10.177(4)	21.73(1)	56.94(5)	54.7(2)	1.6(1)	3.9%
Littrell *et al.* (1997)	Skew-symmetric							
(440) reflection	full range data	1.078(6)	12.016(3)	34.15(1)	50.97(5)	49.45(5)	2.15(4)	3.0%
	restricted range data	1.078(6)	12.016(3)	34.15(1)	50.97(5)	50.18(5)	2.03(4)	1.5%
(220) reflection	full range data	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	97.58(10)	1.07(2)	3.0%
	restricted range data	2.1440(4)	11.921(3)	33.94(1)	100.57(10)	99.02(10)	1.01(2)	1.5%
Littrell *et al.* (1997)	Large symmetric LLL							
(440) reflection	full range data	0.9464(5)	30.50(1)	29.50(1)	113.60(10)	112.89(15)	8.09(6)	0.6%
	restricted range data	0.9464(5)	31.50(1)	29.50(1)	113.60(10)	112.62(15)	8.36(6)	0.9%
(220) reflection	full range data	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	222.38(30)	4.02(3)	0.6%
	restricted range data	1.8796(10)	30.26(1)	29.30(1)	223.80(10)	221.85(30)	4.15(3)	0.9%

Neutron Interferometry; Lessons in Experimental Quantum Mechanics by H.Rauch and S.Werner

Prospective Experiments

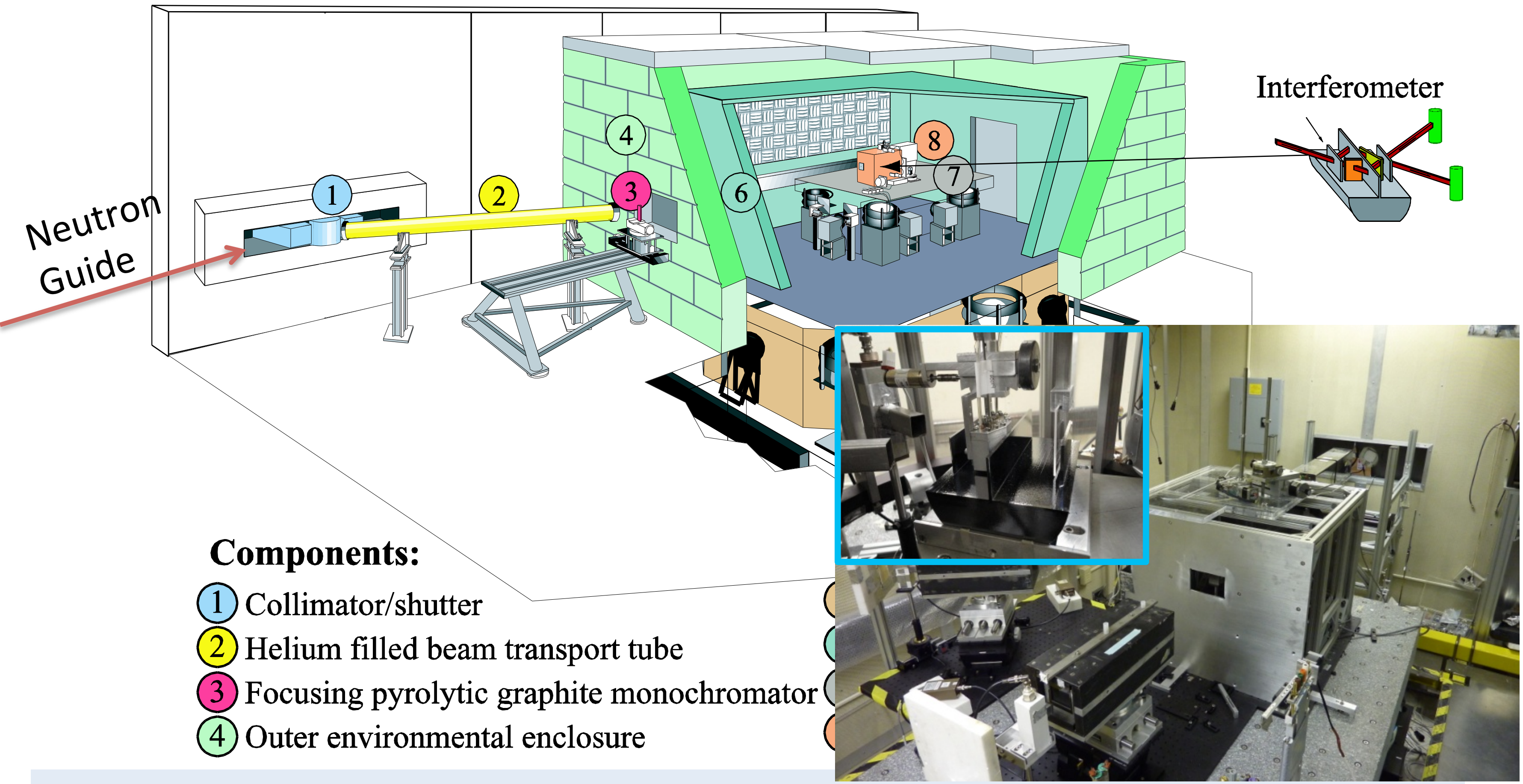
- Large interferometer (Zawisky *et all*)
  - Benefits: long path length would greatly increase the sensitivity of measurements
- Floating COW (Kaiser *et all*)
  - Concept is to submerge the interferometer in a fluid that has similar properties and then rotate the chamber about the incident axis
  - Benefits: would eliminate effects of interferometric bending and thus eliminate q_{bend}
  - Challenges include: finding a compatible fluid to eliminate all internal stresses

NIST



NG-1 Advanced Neutron Diffractometer/Reflectometer
NG-1 Vertical Sample Reflectometer
NG-1 Cold Neutron Depth Profiling
NG-2 Backscattering Spectrometer
NG-1
NG-2
NG-3
NG-4
NG-5
NG-7
NG-3 30 m SANS
NG-5 SPINS
NG-5 Spin-Echo Spectrometer
NG-4 Disk Chopper TOF Spectrometer
NG-6 Fermi Chopper Hybrid TimeofFlight (TOF) Spectrometer
NG-7 Horizontal S mple Reflectometer
NG-7 P ompt Gamma Activa on Analysis
NG-7 Neutron Interferometry and Optics Station
NG-6 Neutron Physics Station
NG-7 30 SANS
NIOF

NIOF at NIST

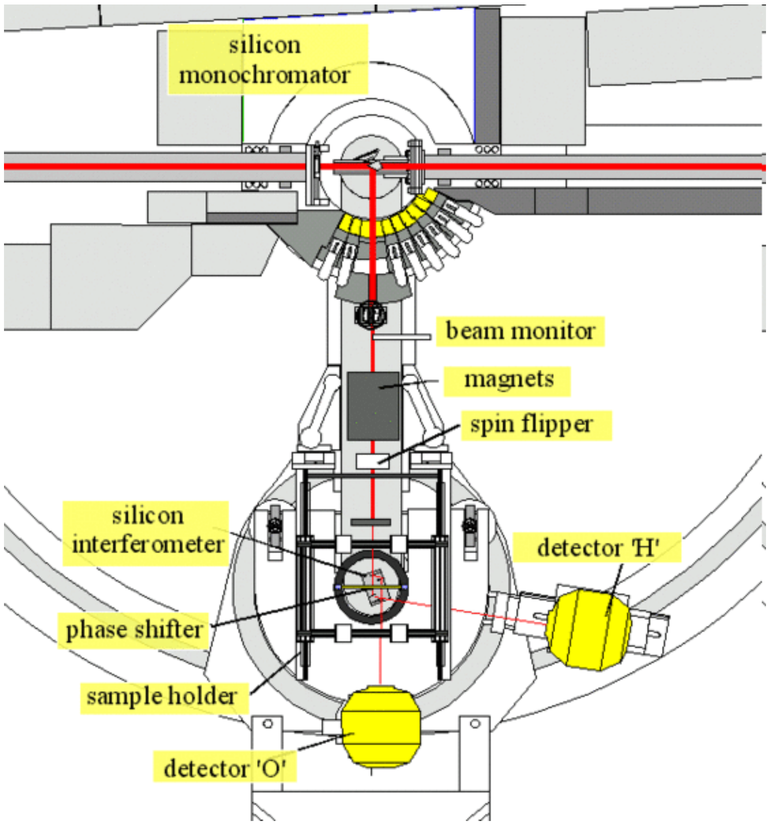


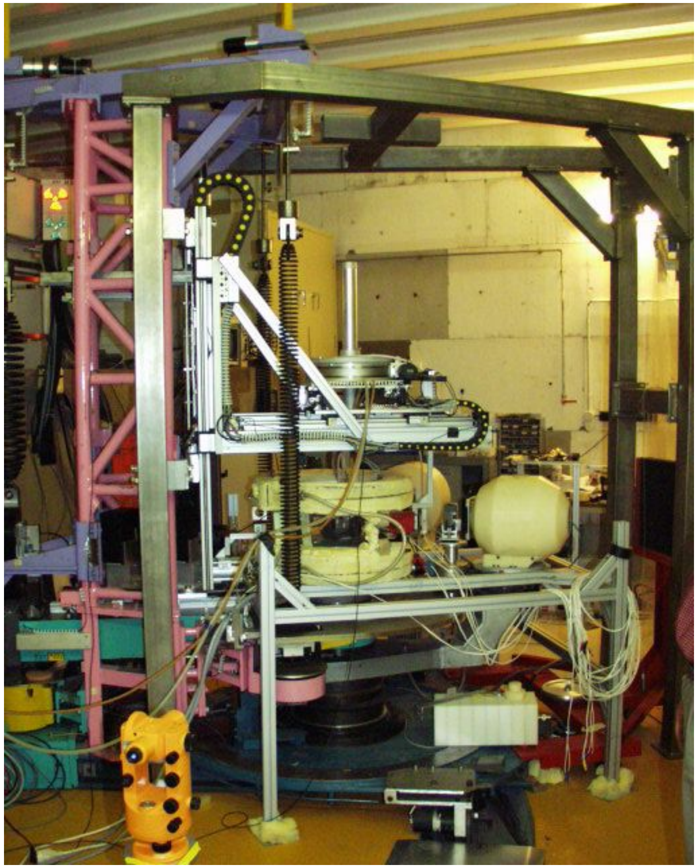
Isolated 40,000 Kg room is supported by six airsprings

Active Vibration Control eliminates vibrations above 0.5 Hz

Temperature Controlled to +/- 5 mK

Current setup of S18





Interferometer Option		USANS Option
Monochromator type:	perfect crystal silicon	channel-cut perfect crystal silicon
Reflecting planes:	[111], [220], [113], [331]	[220], [331]
Wavelength range:	0.6 Å < λ < 4 Å	1.6 Å < λ < 2.9 Å
Flux:	7000 n cm^{-2} s^{-1}	10000 n cm^{-2} s^{-1}
Visibility:	60% to 90%	10^5 (signal to background)
Resolution:	0.5° phase resolution	0.01 arcsec angular resolution $1.5 . 10^{-5}$ $Å^{-1}$ momentum resolution

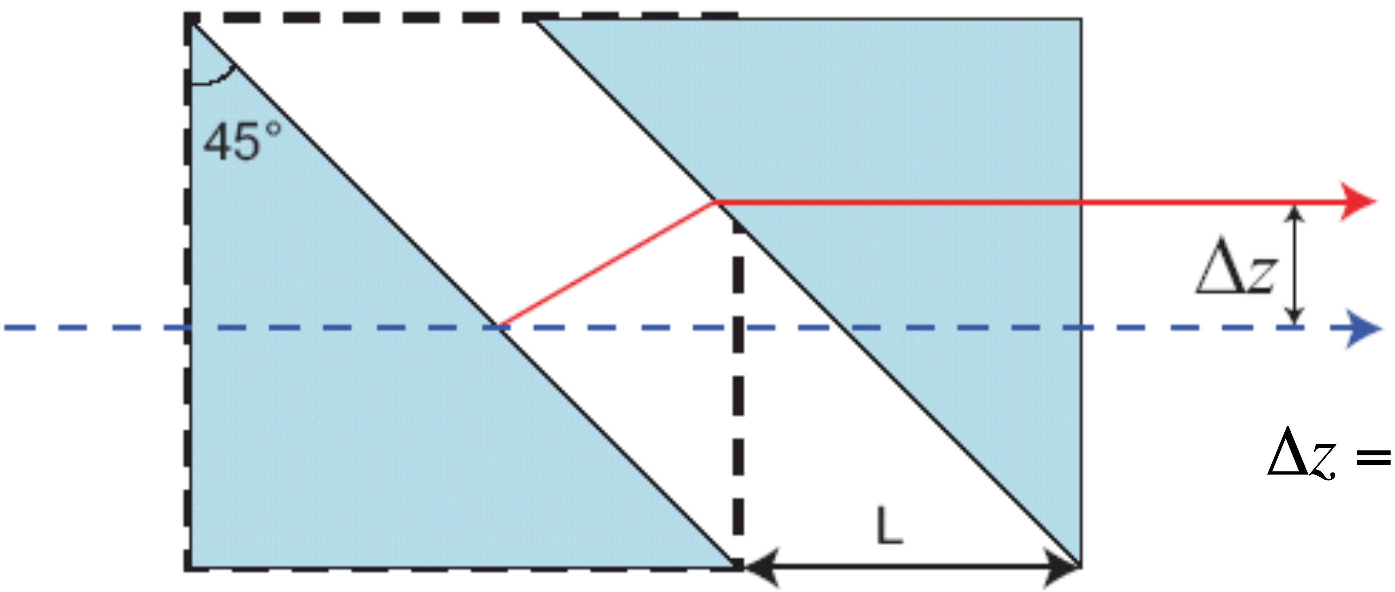
Vertical Coherence Length

How can we measure the coherence length

coherence function

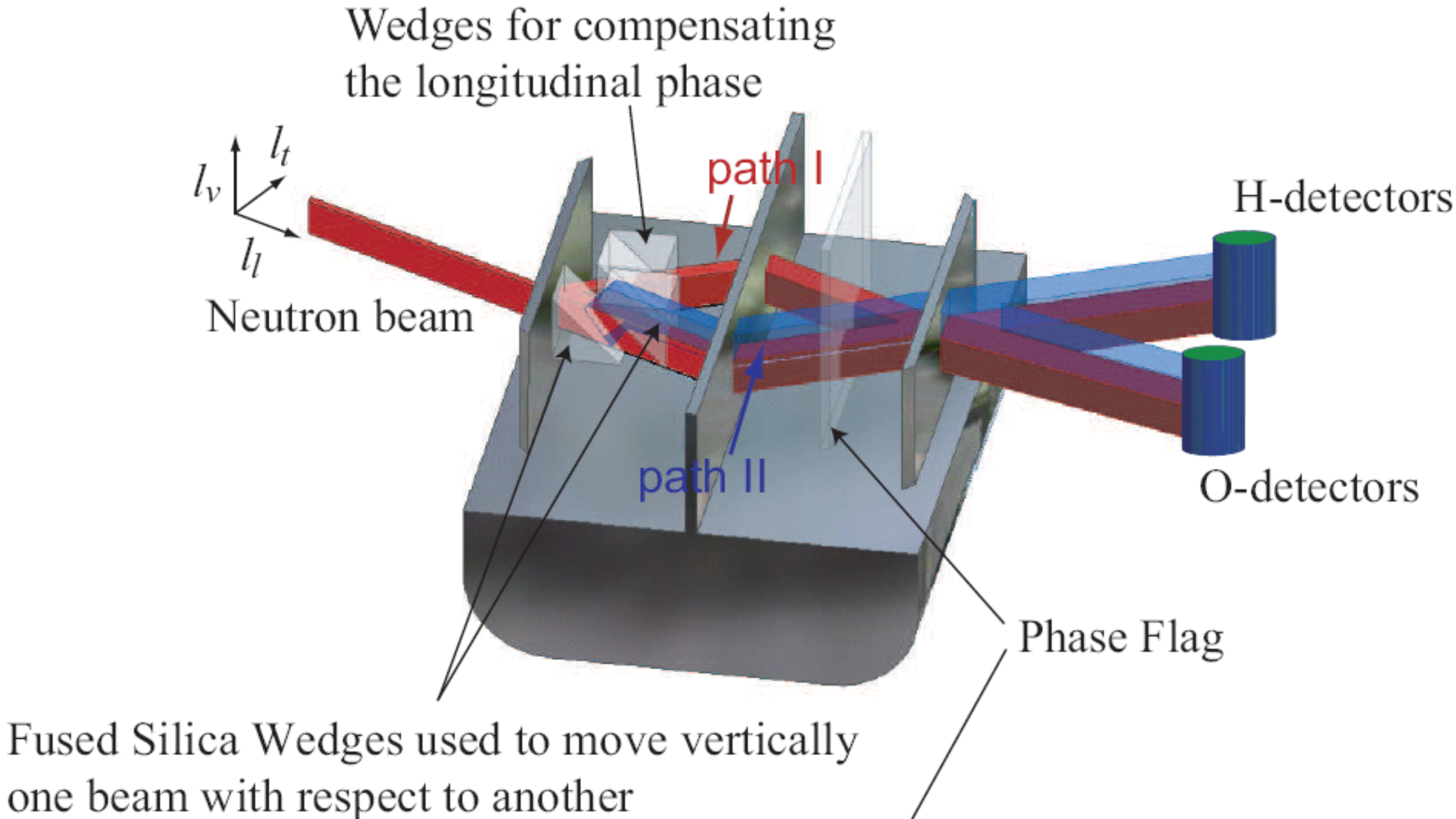
$$\Gamma(\Delta) = \langle \psi(0) | \psi(\Delta) \rangle$$

Contrast measurements directly yields the coherence function

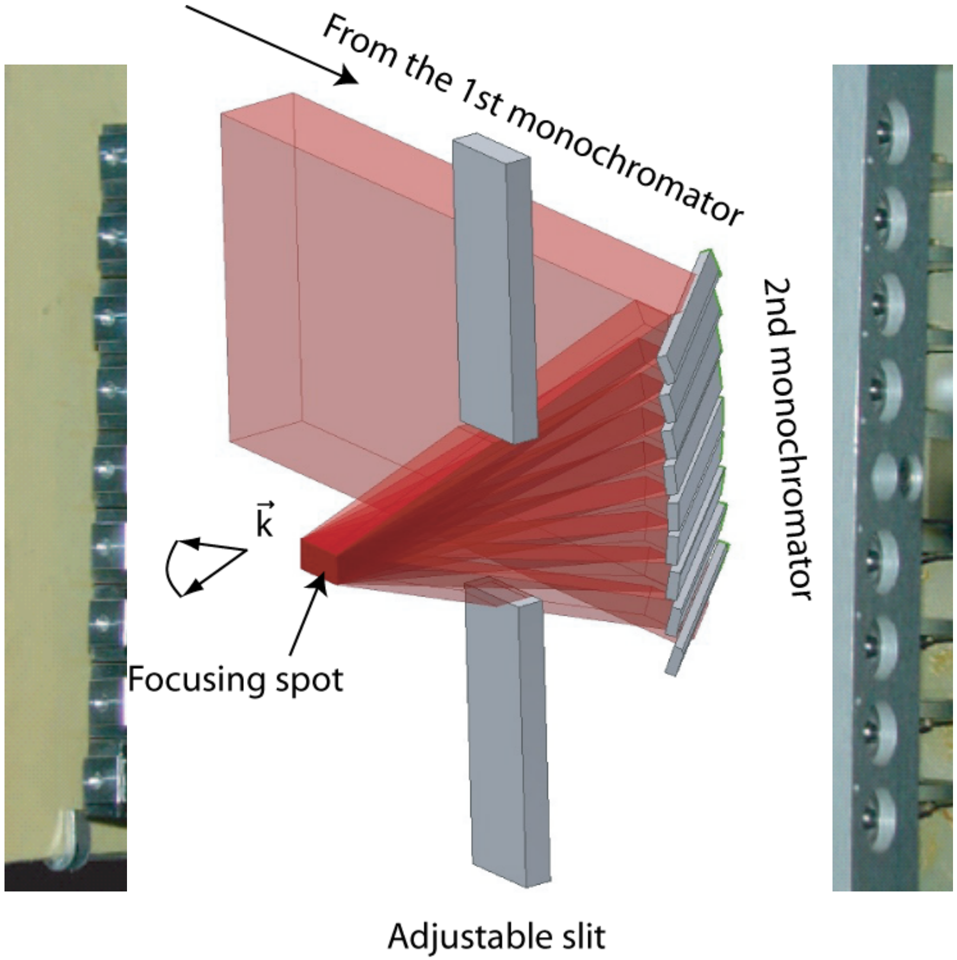


$$\Delta z = L(1 - n)$$

Coherence Measurements



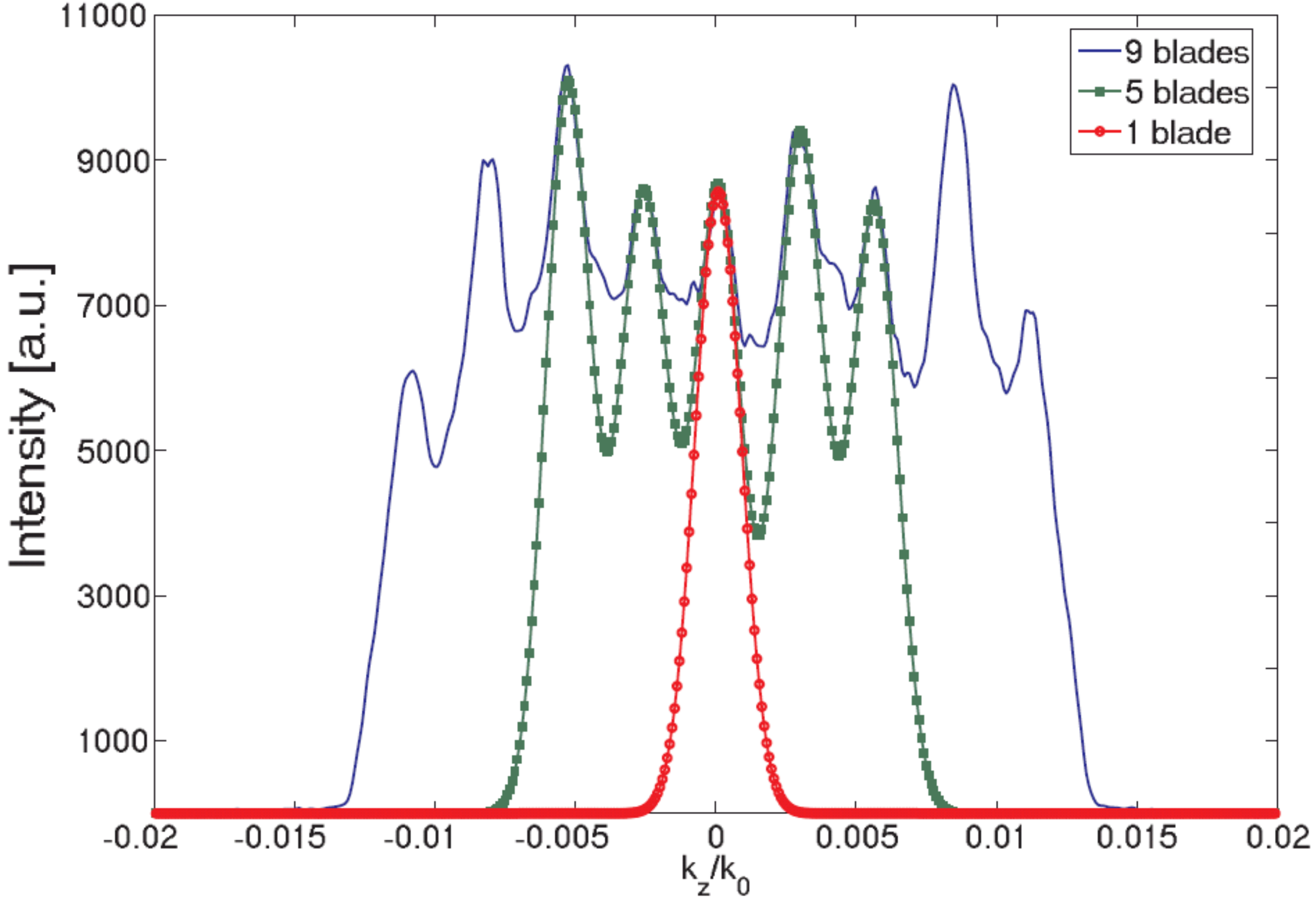
Vertical momentum distribution

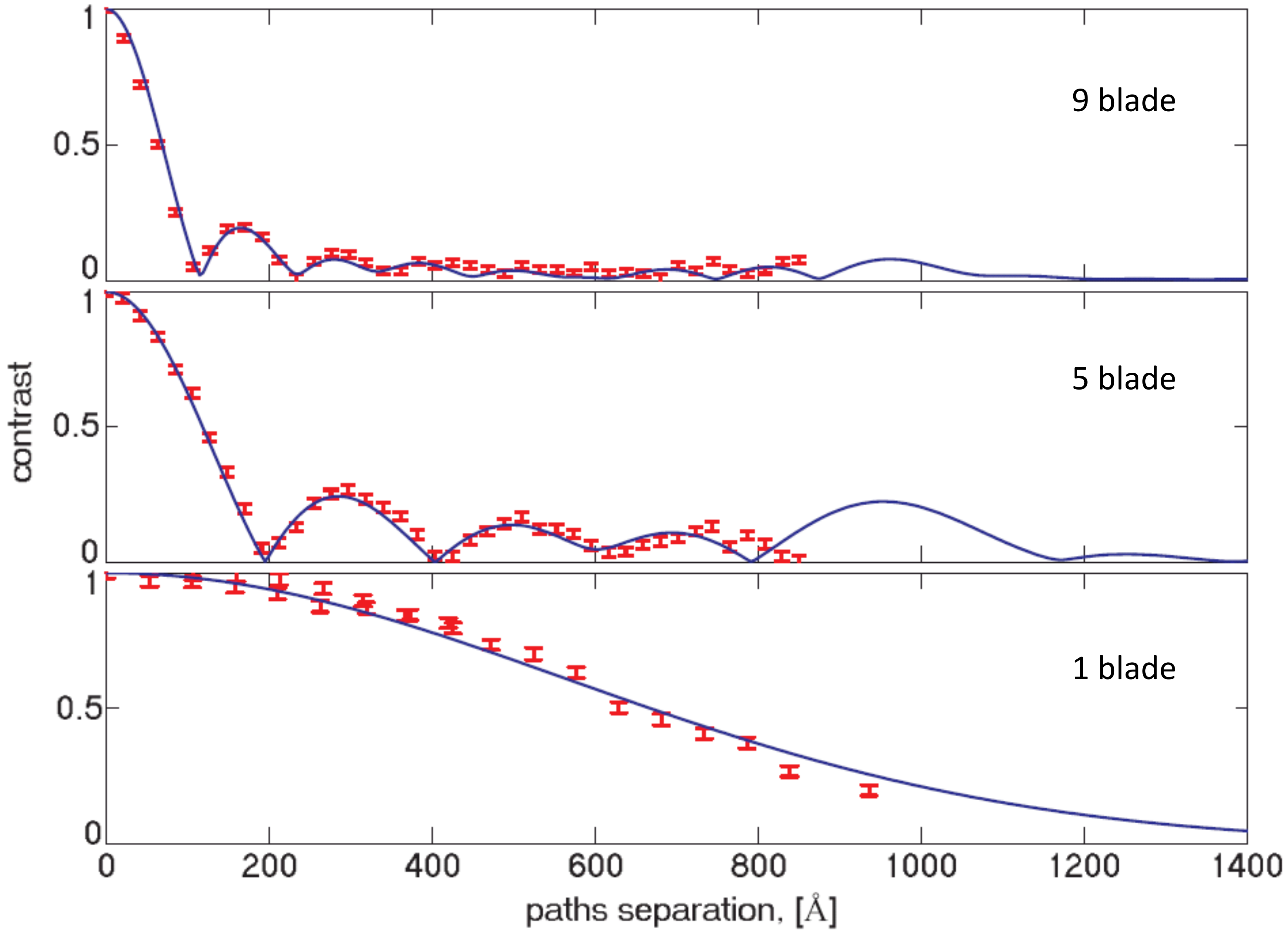


$$l_c = \frac{1}{2\delta k} \equiv \text{coherence length}$$

$$\delta \text{k} \equiv \text{spread in momentum}$$

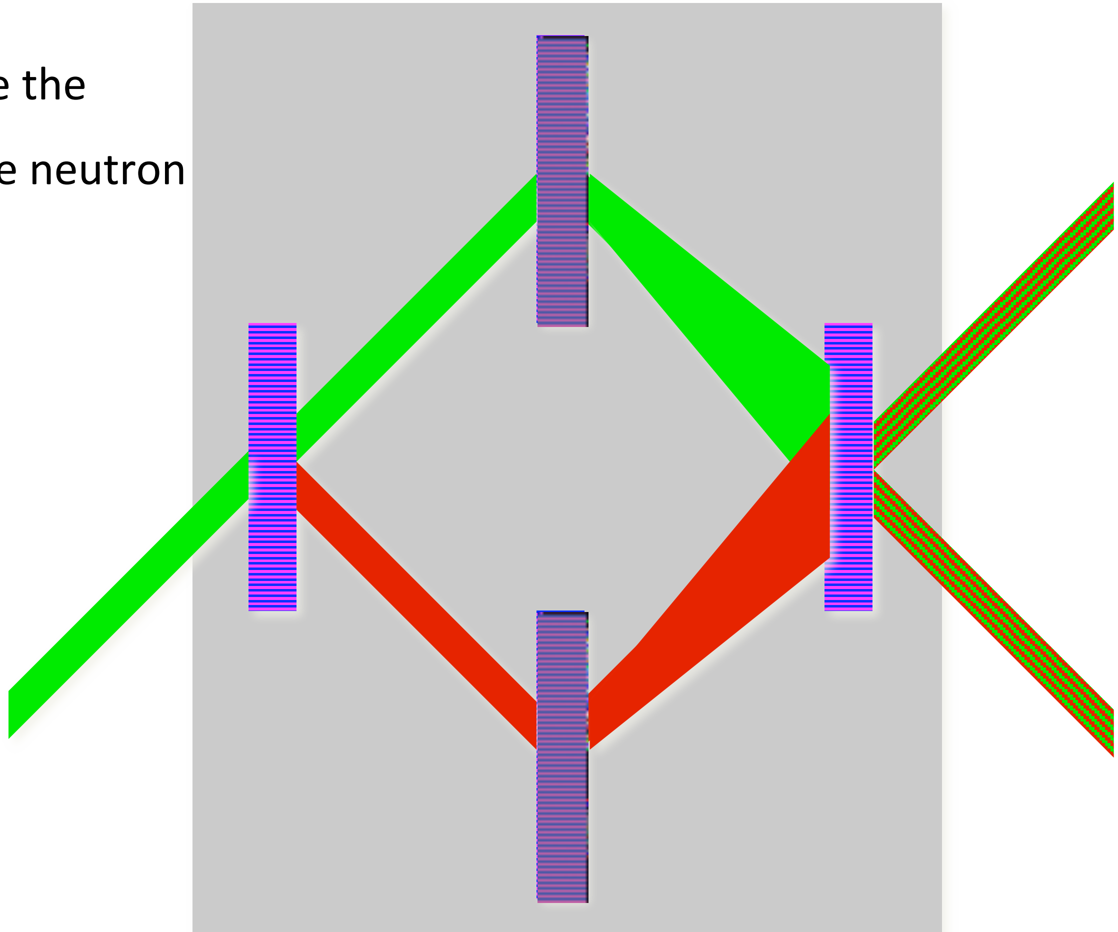
Vertical momentum distribution




9 blade
5 blade
1 blade
contrast
0
0.5
1
0
200
400
600
800
1000
1200
1400
paths separation, [Å]

Neutron interferometry with vibrations

Vibrations change the momentum of the neutron



Even low frequency vibrations are deadly.

DFS

- A two-level quantum system is considered to be coherent if precise knowledge of the relative phase between the two basis states is obtainable.

- In the case of a neutron interferometer, we are obtaining an expectation value measurement by averaging over many experiments consisting of interactions of individual neutrons with the device.

- The physical process leading to the development of the random relative phase for each neutron is mechanical vibrations.

DFS

Two-qubit Hilbert space:

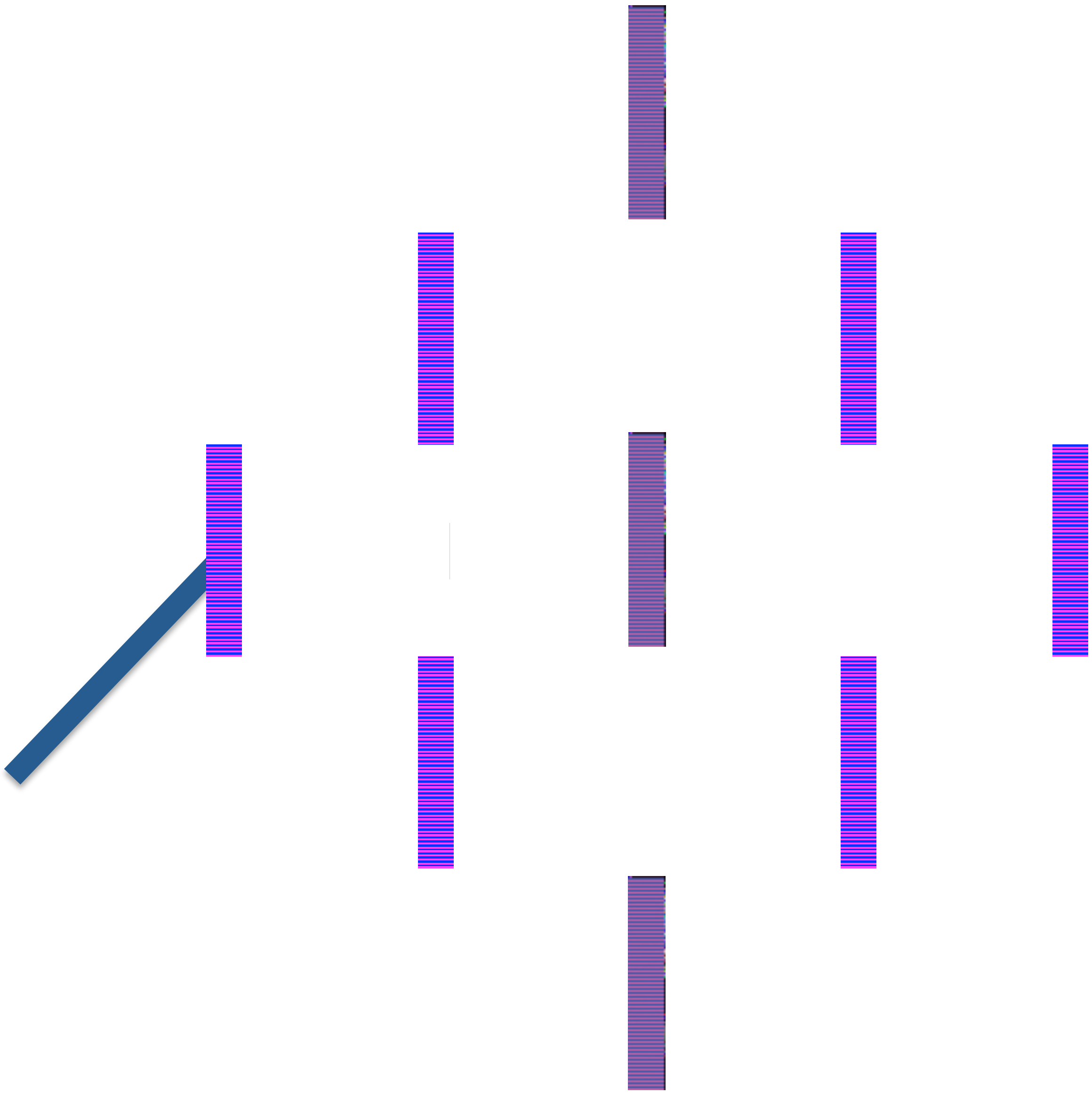
$$|0\rangle_1 \otimes |0\rangle_2 \rightarrow |0\rangle_1 \otimes |0\rangle_2$$
$$|0\rangle_1 \otimes |1\rangle_2 \rightarrow e^{i\phi} |0\rangle_1 \otimes |1\rangle_2$$
$$|1\rangle_1 \otimes |0\rangle_2 \rightarrow e^{i\phi} |1\rangle_1 \otimes |0\rangle_2$$
$$|1\rangle_1 \otimes |1\rangle_2 \rightarrow e^{2i\phi} |1\rangle_1 \otimes |1\rangle_2$$

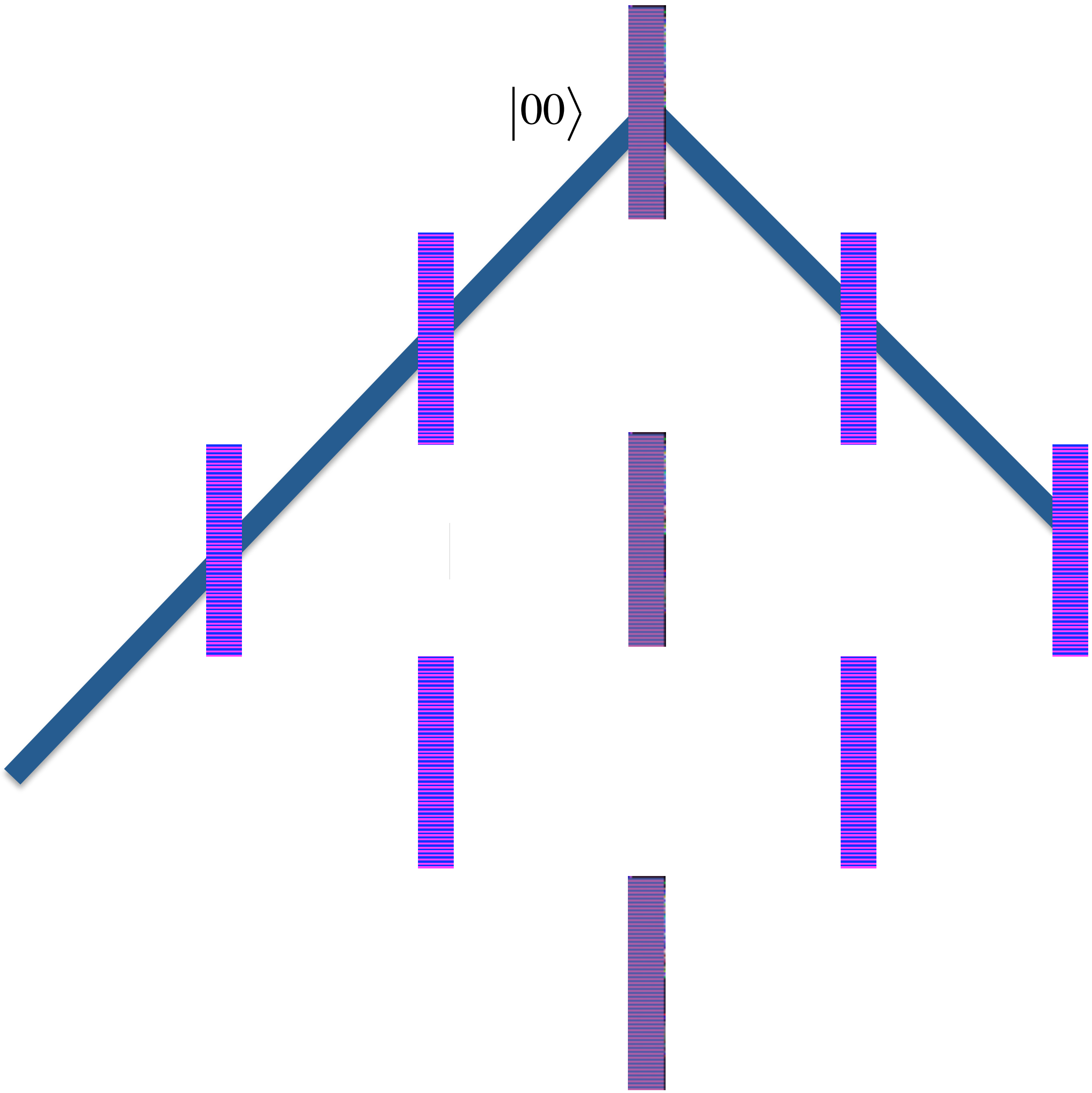
Defining:

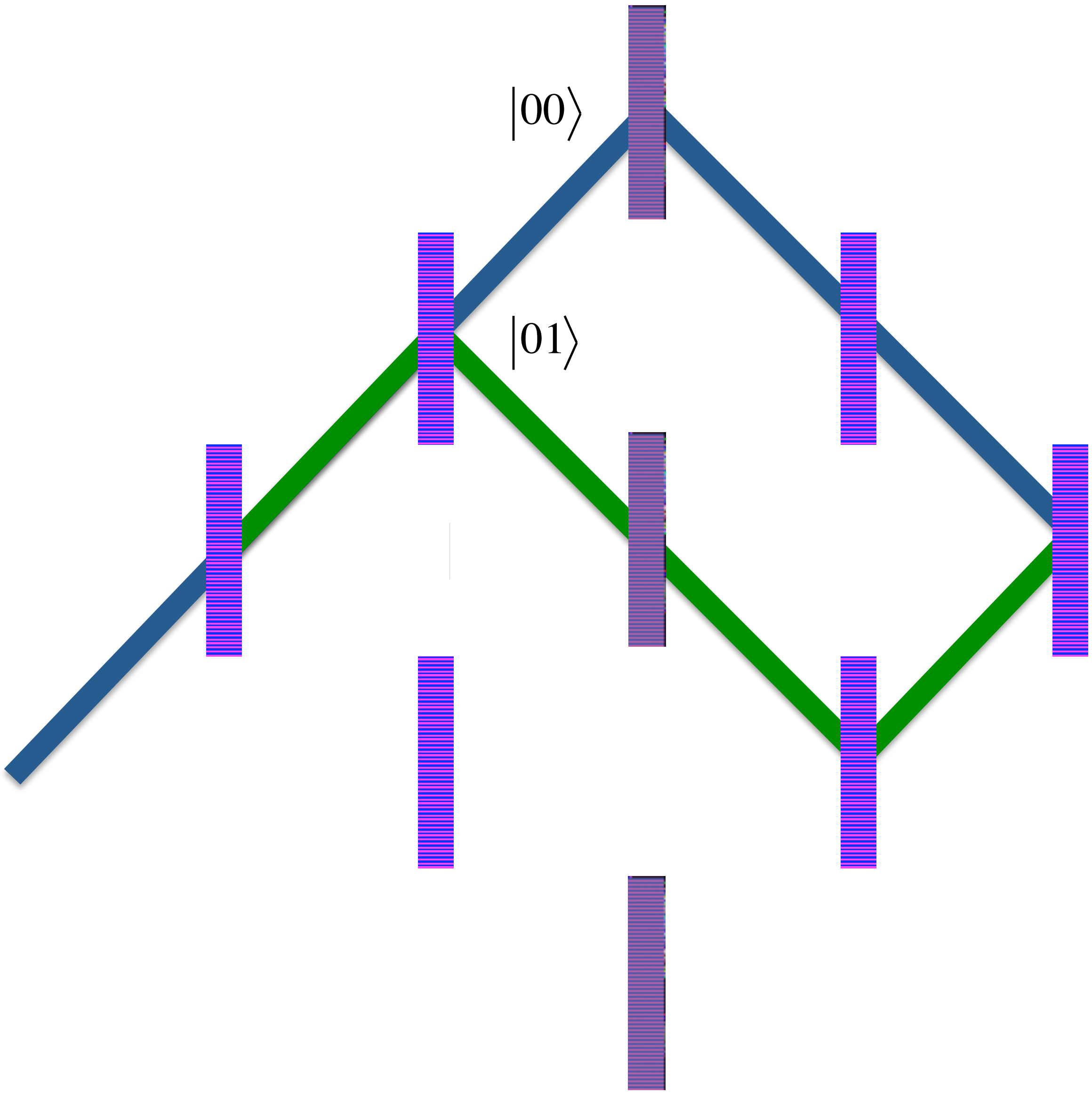
$$|0_L\rangle = |0\rangle_1 \otimes |1\rangle_2 \equiv |01\rangle, \quad |1_L\rangle = |10\rangle, \quad |\psi_L\rangle = a|0_L\rangle + b|1_L\rangle$$

Evolution:

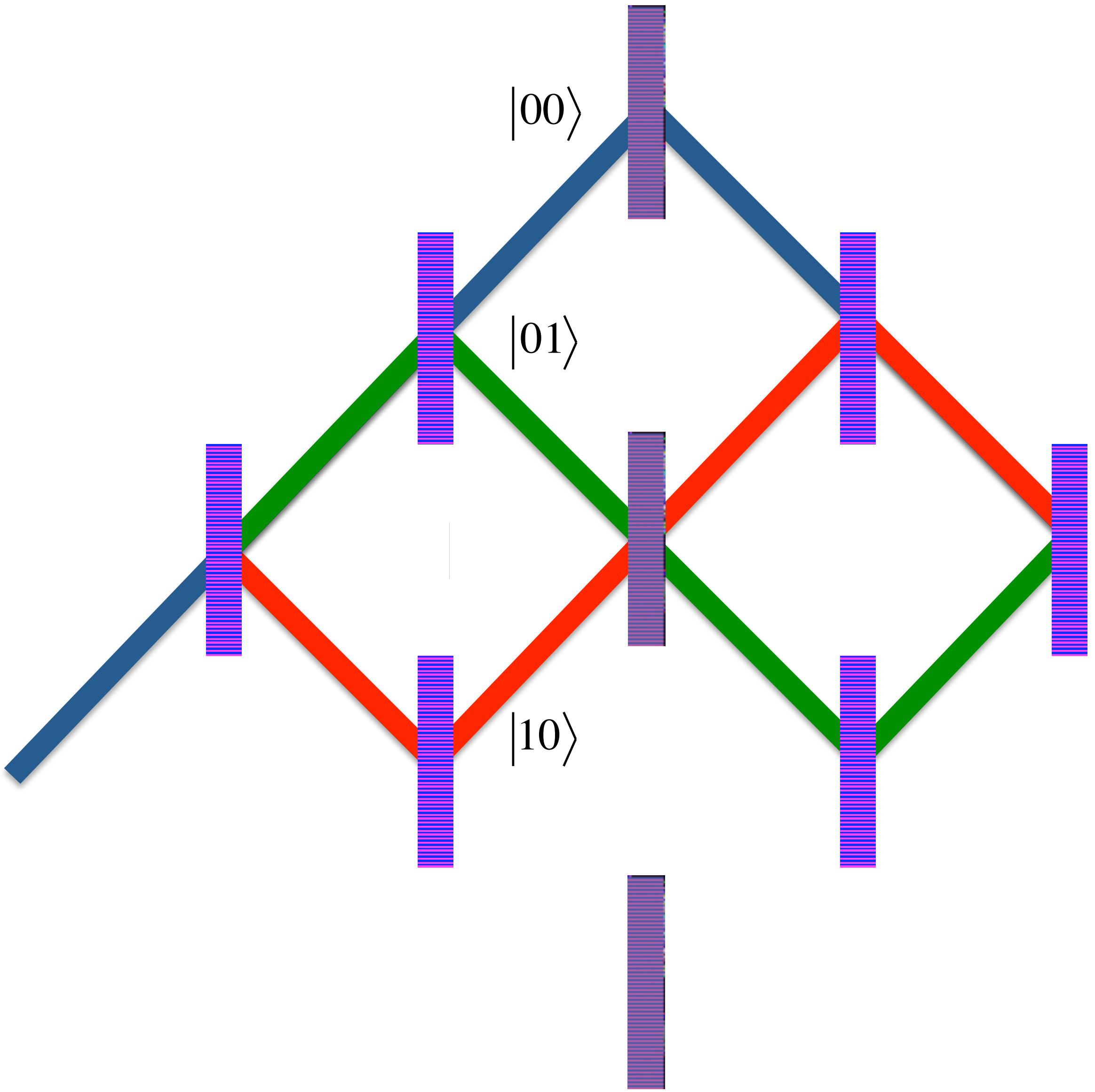
$$|\psi_L\rangle \rightarrow a|0\rangle_1 \otimes e^{i\phi}|1\rangle_2 + be^{i\phi}|1\rangle_1 \otimes |0\rangle_2 = e^{i\phi}|\psi_L\rangle$$

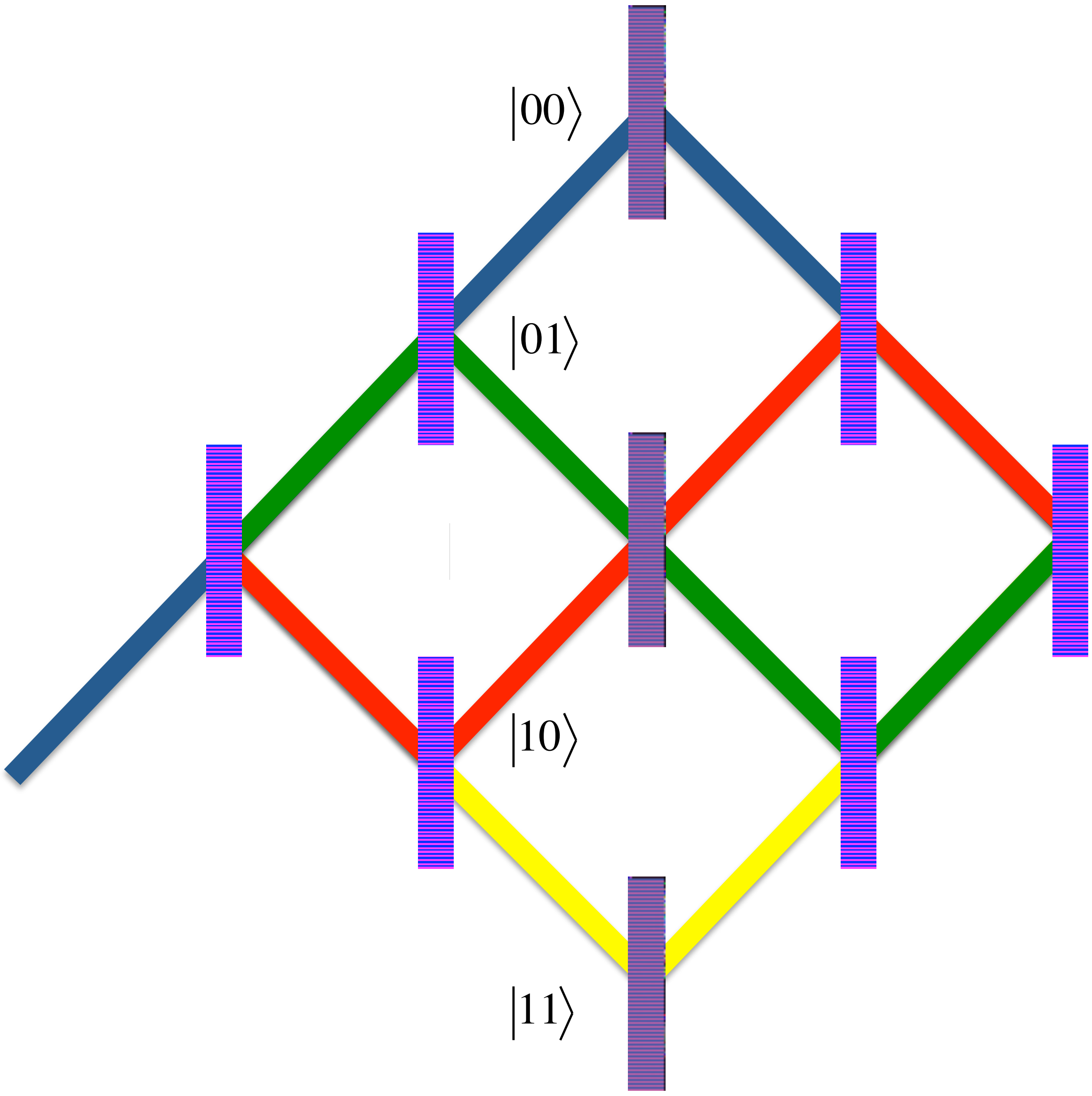



$|00\rangle$

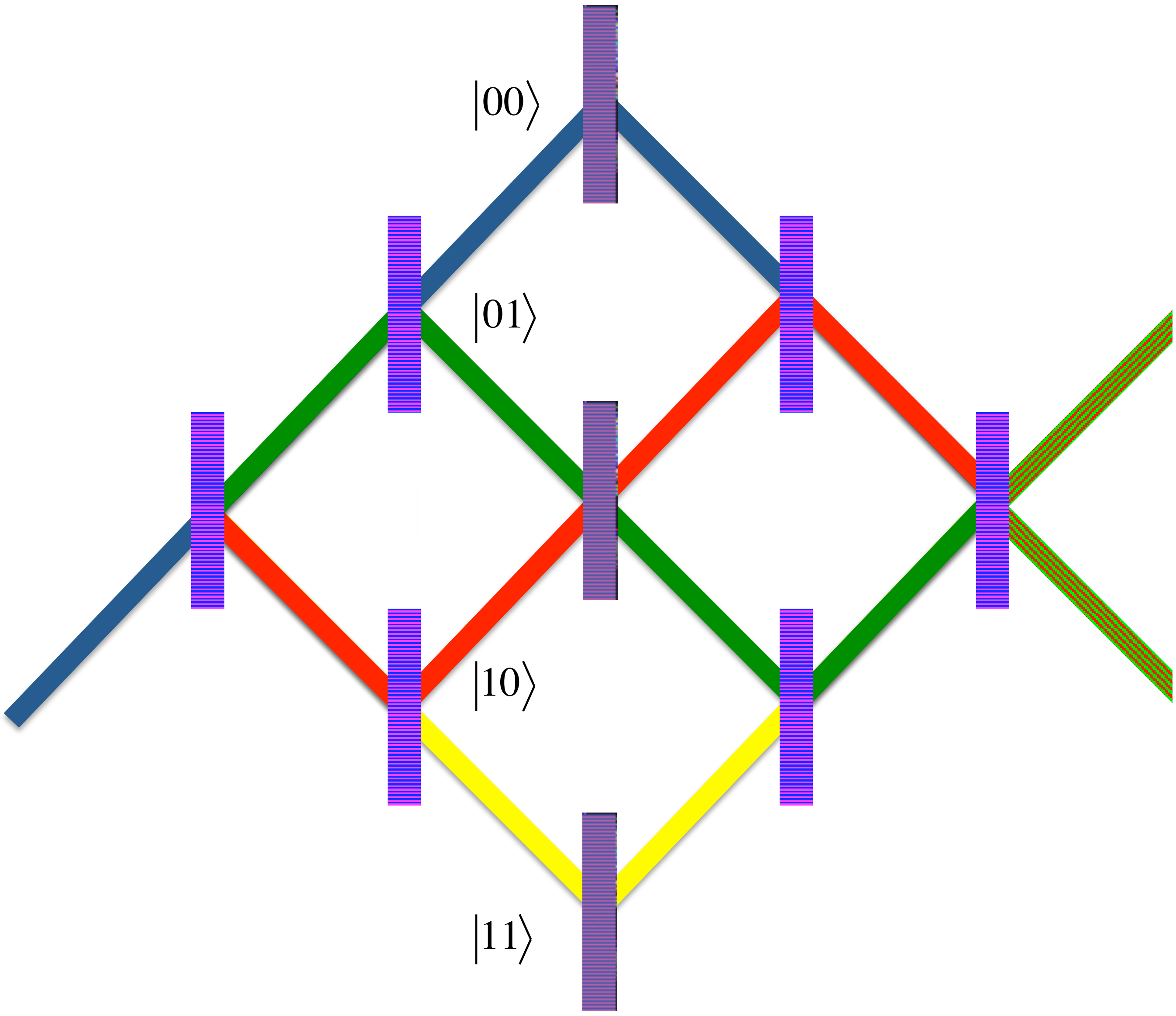


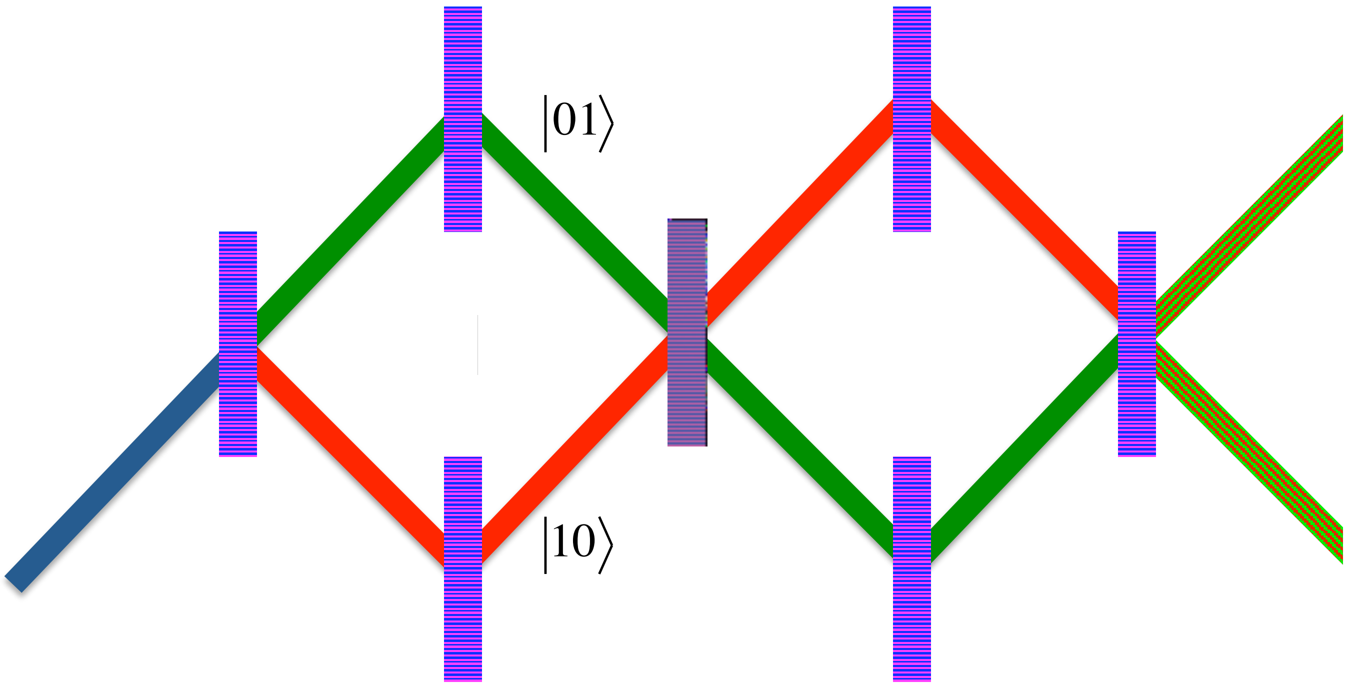
$|00\rangle$
$|01\rangle$


$|00\rangle$
$|01\rangle$
$|10\rangle$



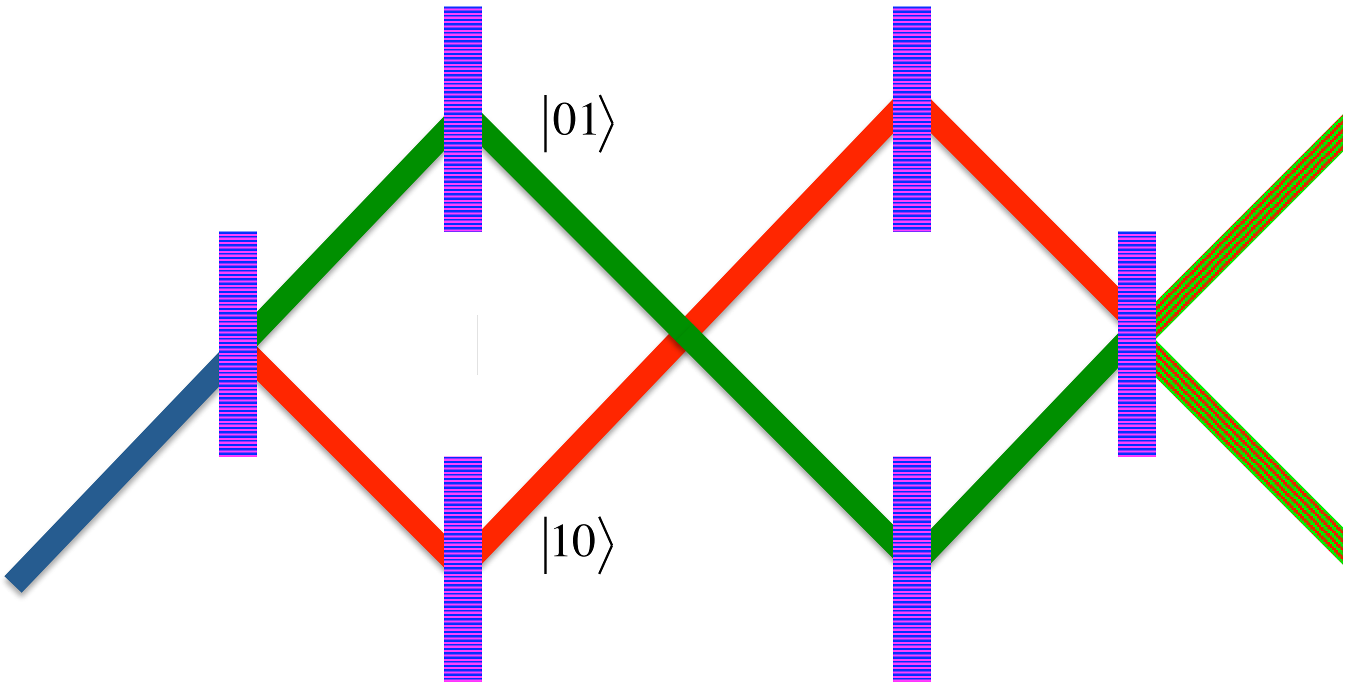
$|00\rangle$
$|01\rangle$
$|10\rangle$
$|11\rangle$


$|00\rangle$
$|01\rangle$
$|10\rangle$
$|11\rangle$

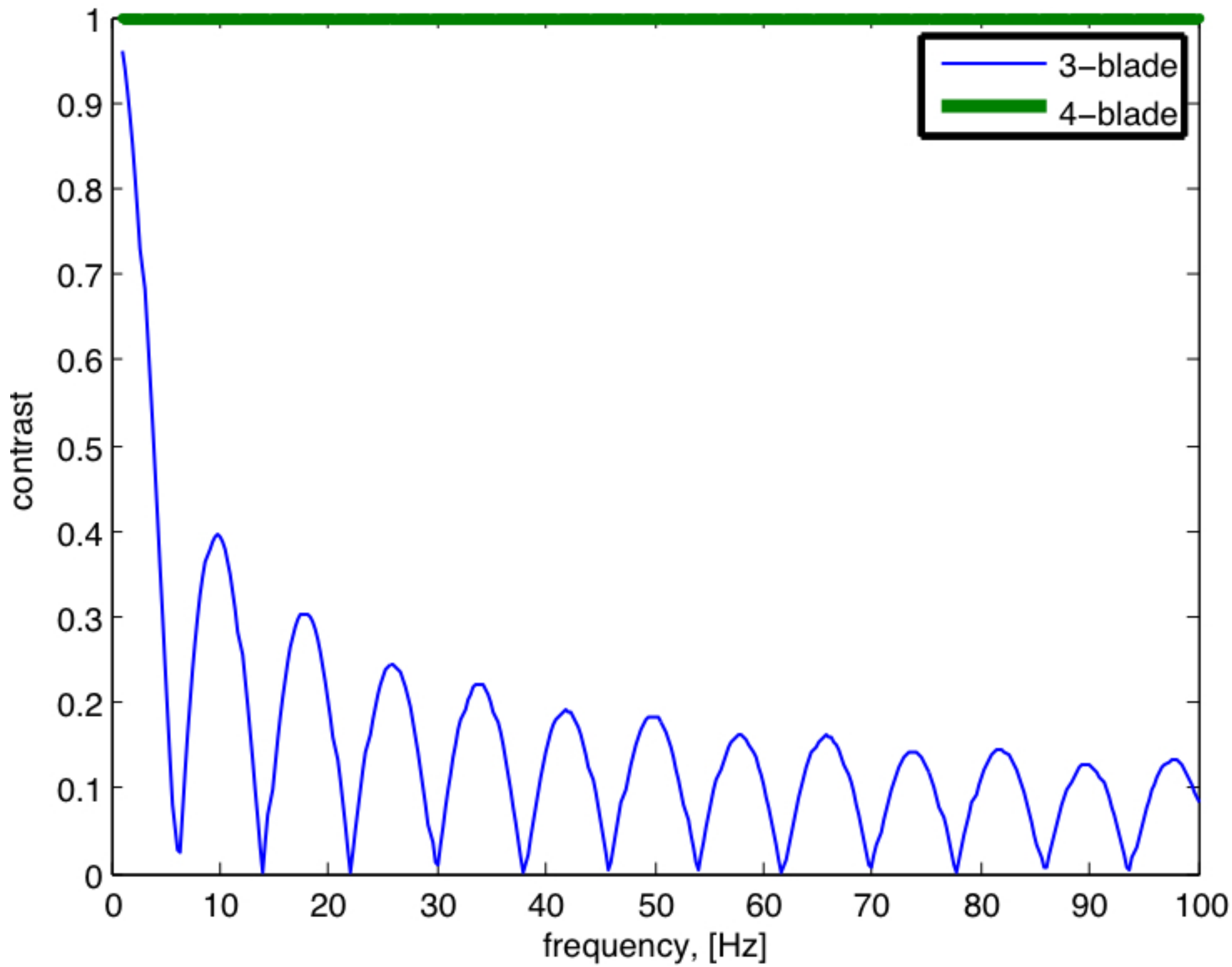


$|01\rangle$
$|10\rangle$

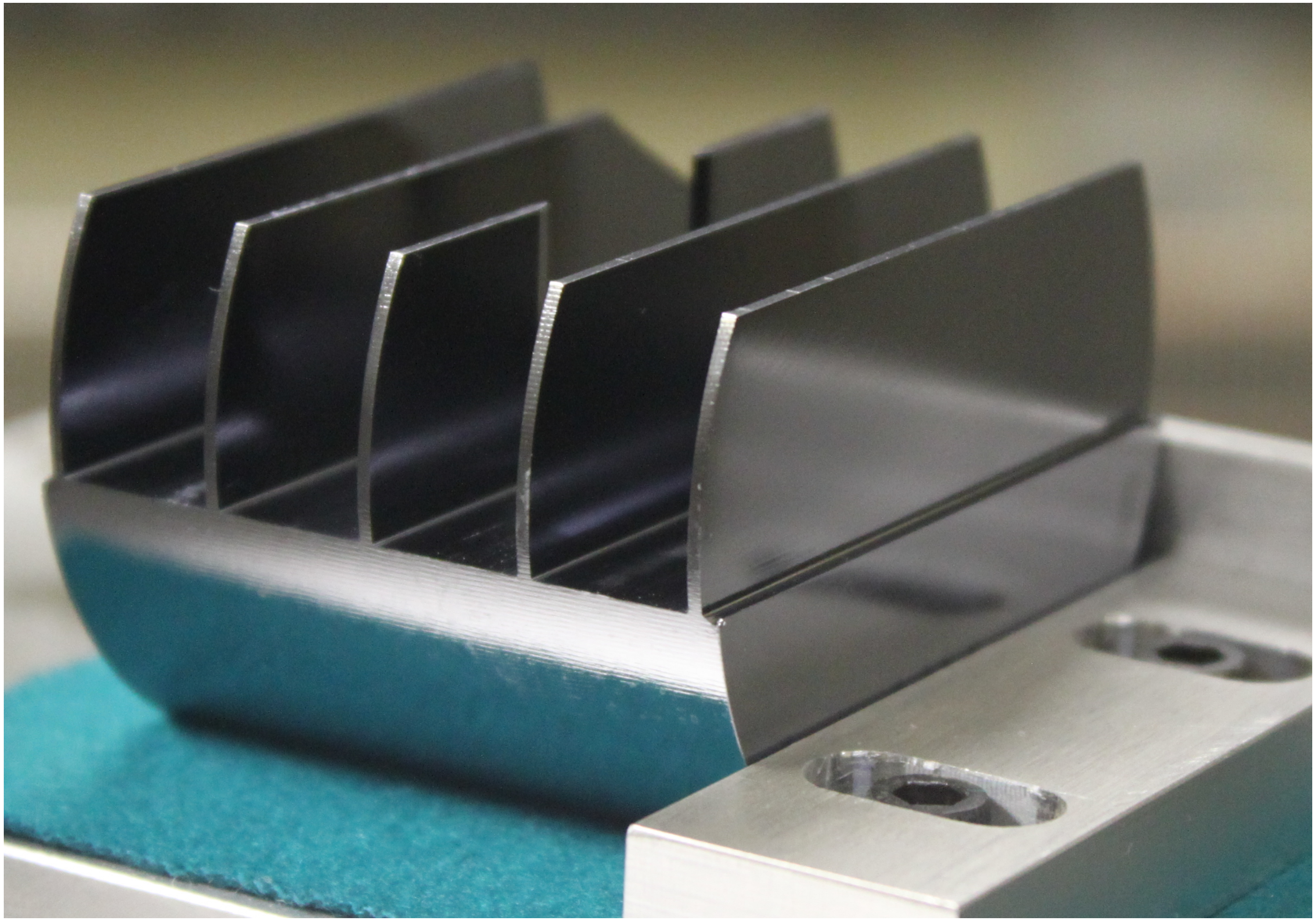
DFS

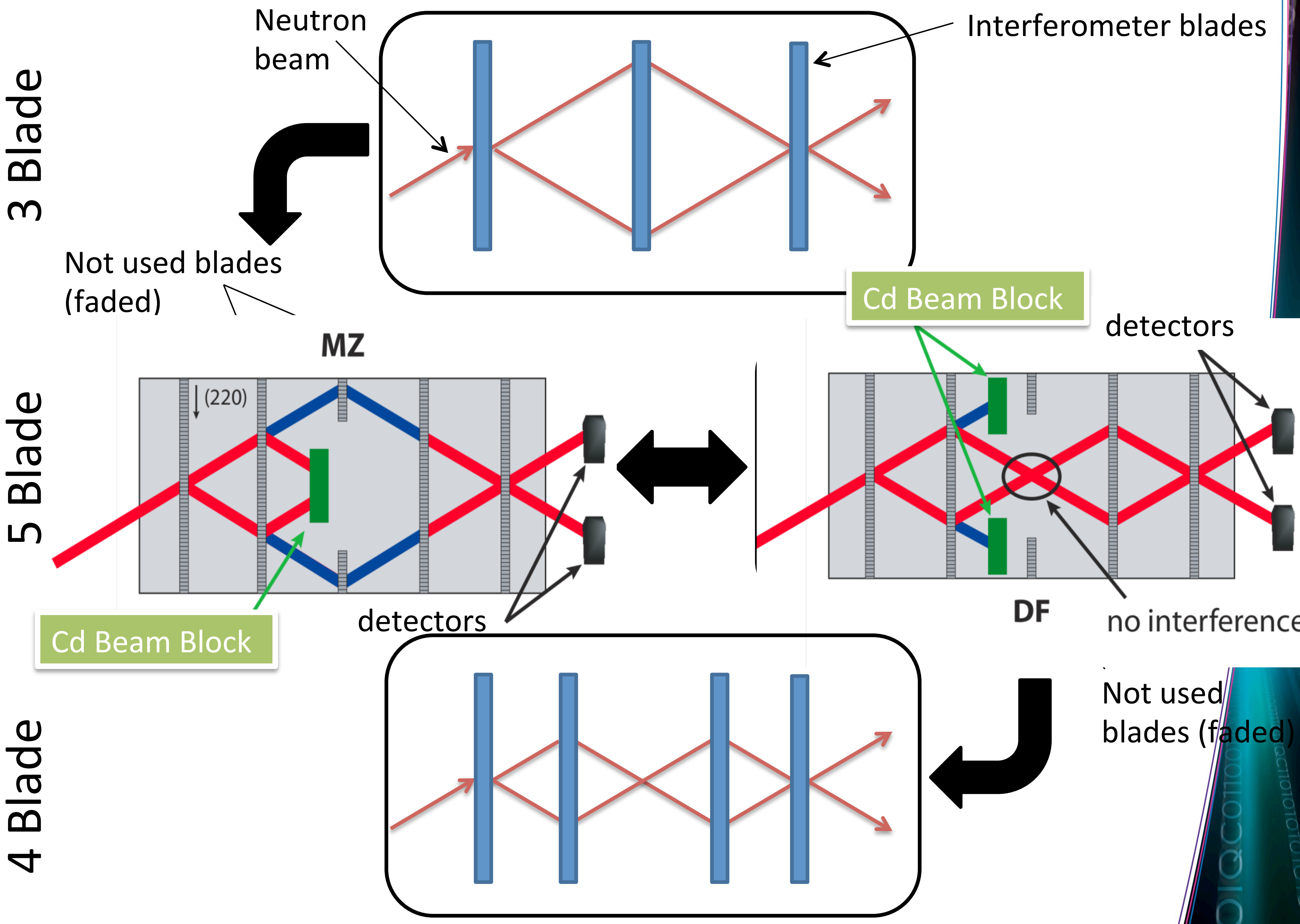


Numerical Simulations
Contrast due to rotational vibrations



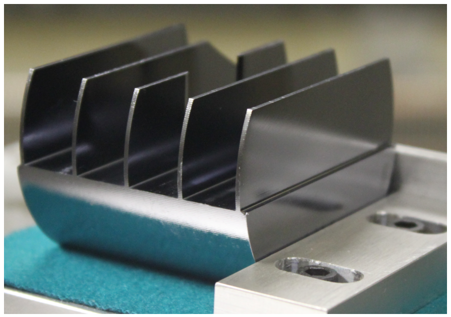
Experimental Setup
5-blade interferometer



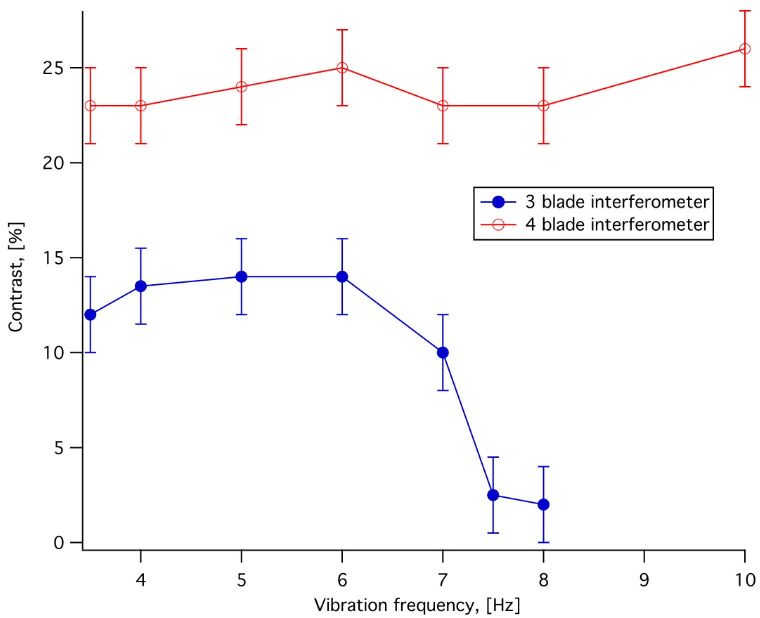

3 Blade
Neutron
beam
Interferometer blades
Not used blades
(faded)
Cd Beam Block
detectors
MZ
(220)
5 Blade
Cd Beam Block
detectors
DF
no interference
Not used
blades (faded)
4 Blade

Application of 8 Hz vibrations

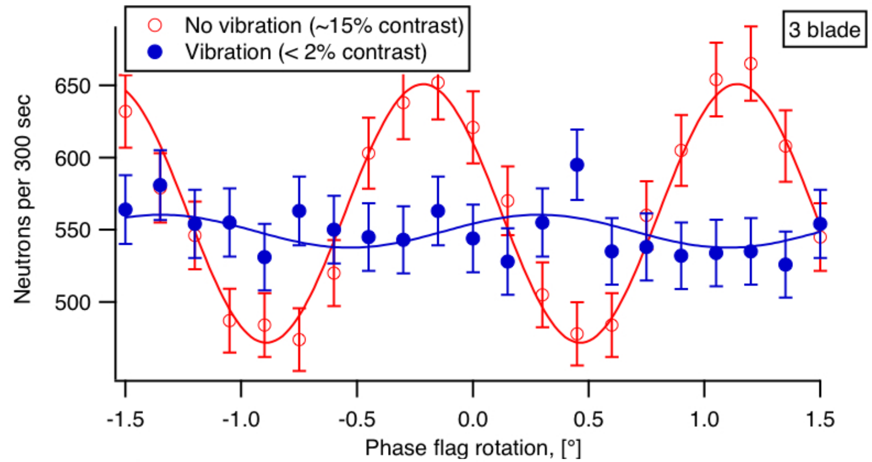
A demonstration of vibrational noise reduction was done using a smaller test five blade interferometer.

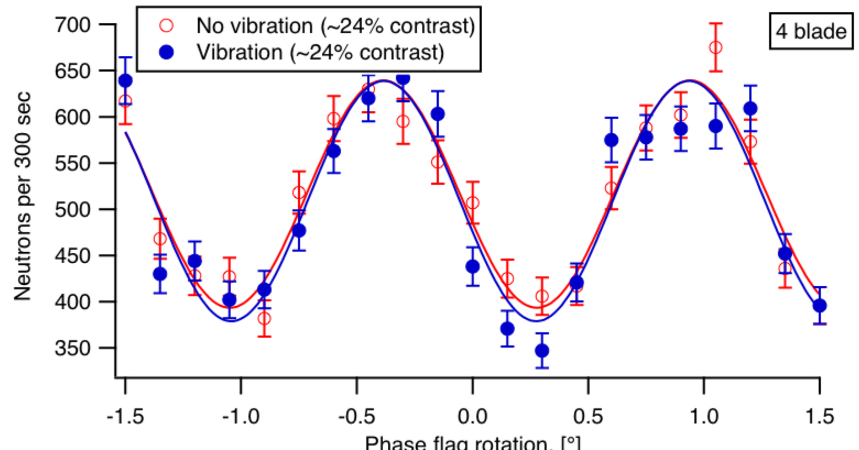


Vibrations were purposely introduced by rotating an off-centered weight and monitored via a seismograph.



For the 3 blade equivalent the contrast went from 15% to 0% with the addition of 8 Hz



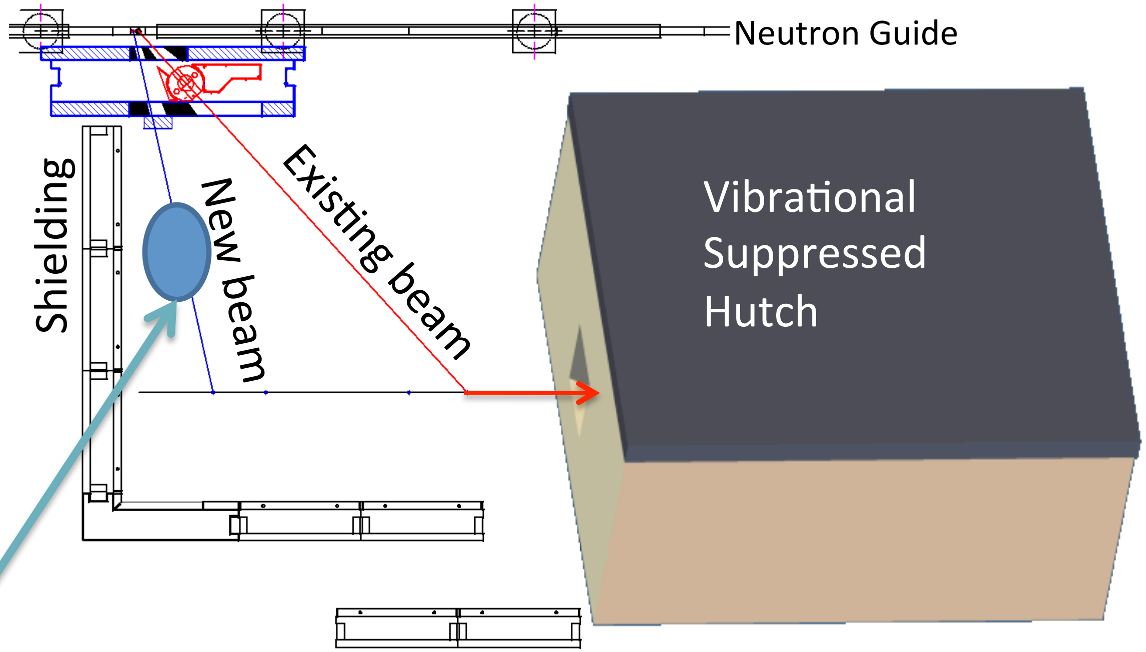


4 blade interferometer insensitive to low frequency vibrations!

New Beam Line

New Beamline

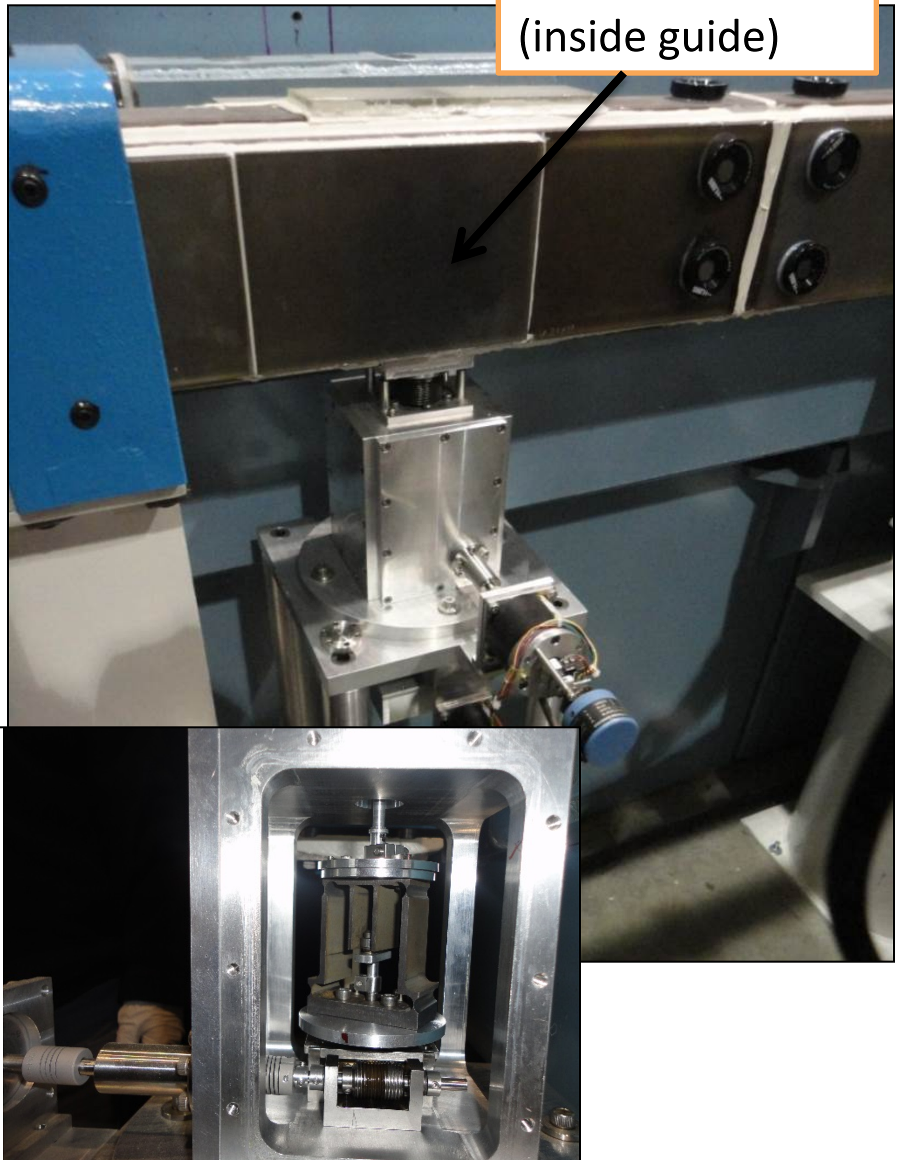
During the NCNR upgrade in 2011 a new beam line was installed next to the interferometer facility. The new beamline has a greater intensity than the existing NI.



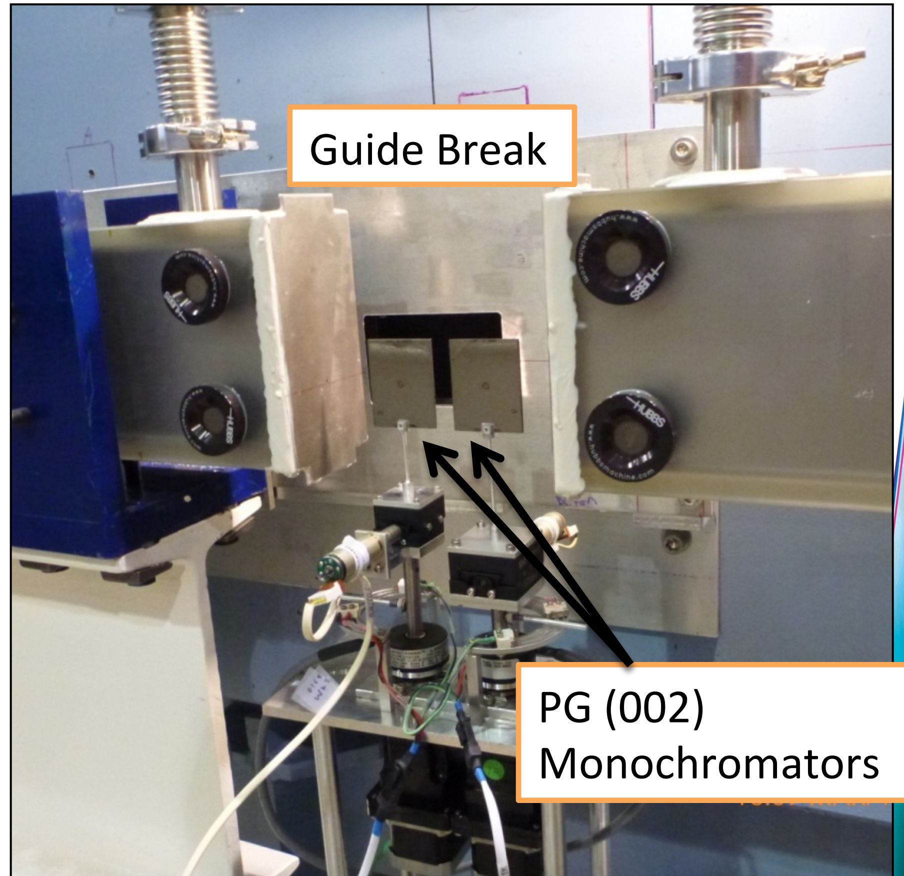
The new beamline will support first-principles tests, demonstration of QIP experiments, neutron spin related experiments, and other experiments where absolute phase stability is not crucial.

Guide Break

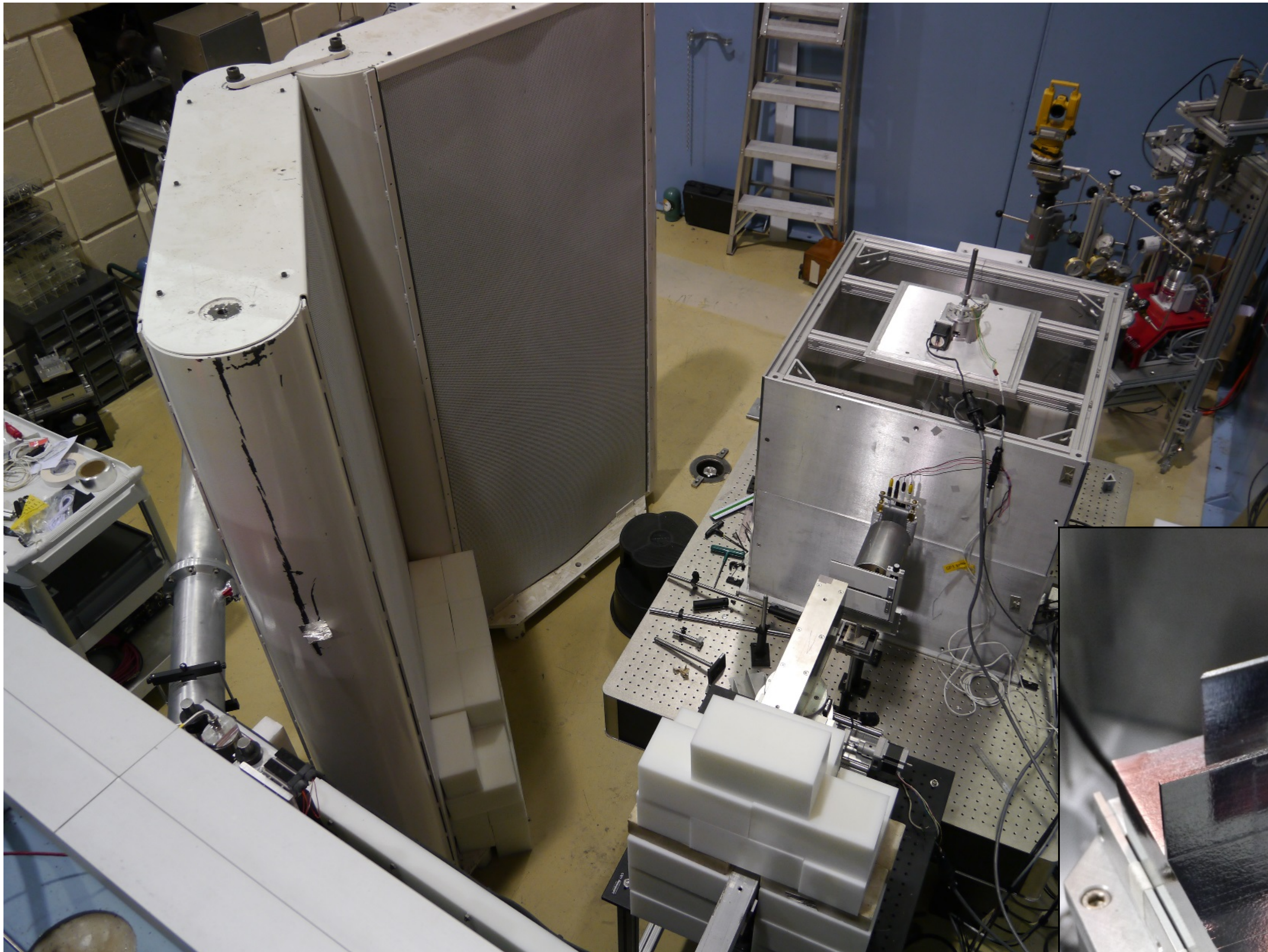
2011

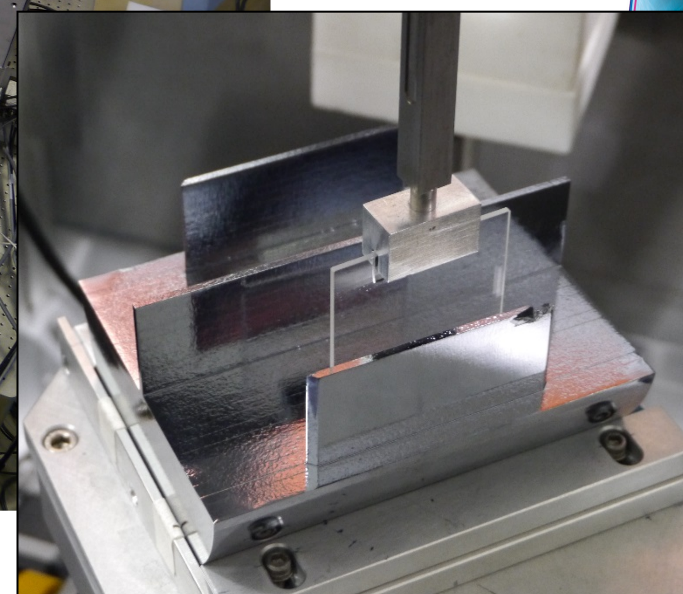


2012



What it looks like today

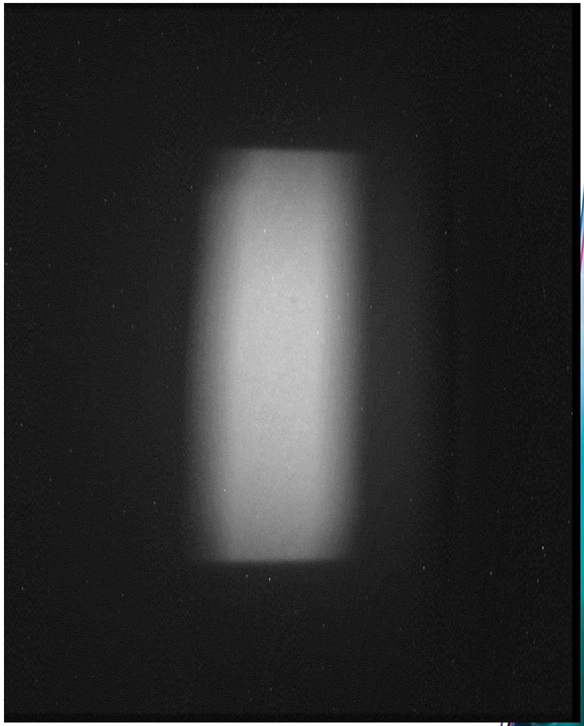




Beamline

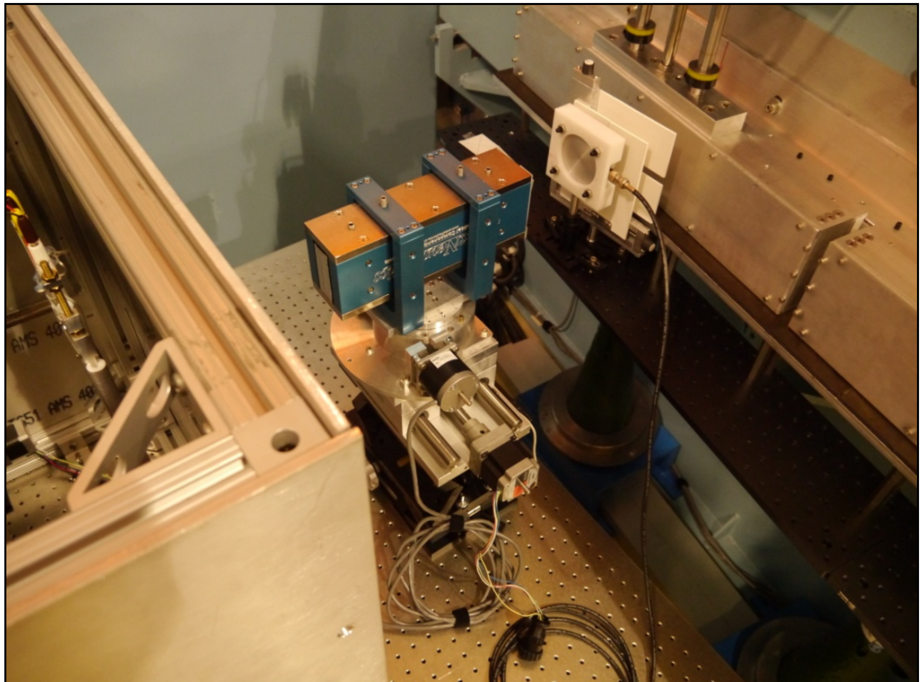
Flux = 3.2E6 neutrons /cm^2/s (measured)
Wavelength = 4.40 Angstroms (measured)
Adjustable slits
Nonmagnetic
Thermal isolation
3 dedicated polarizers

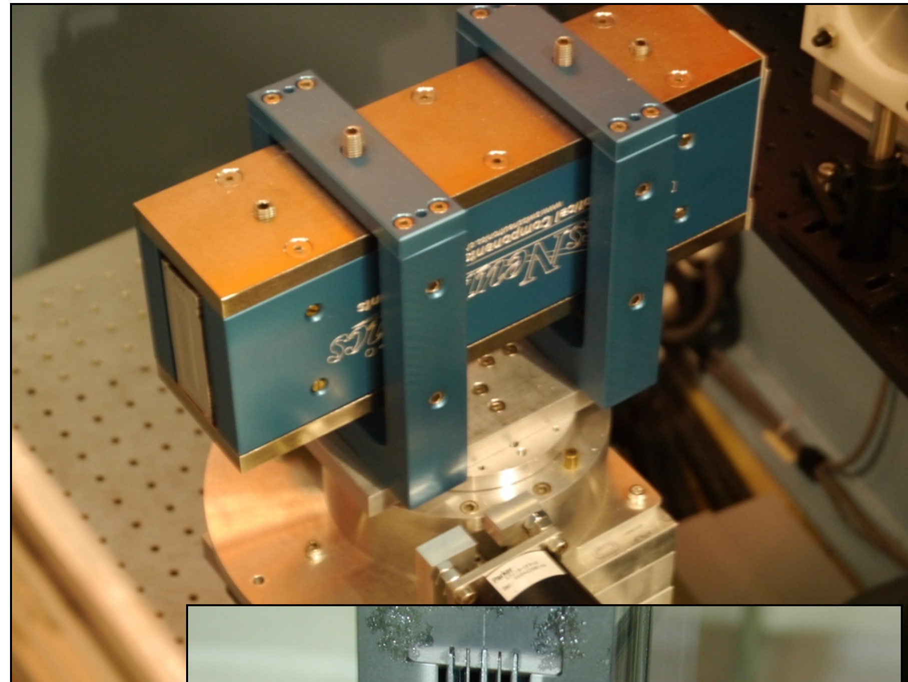
The Troubles….
Vibration stability issues
Lower measured polarization
Higher Backgrounds from fast neutrons
Higher lambda/2 flux

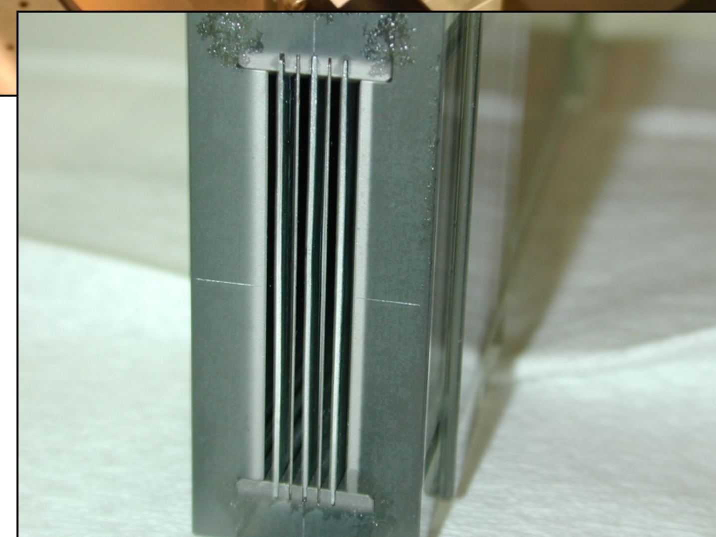


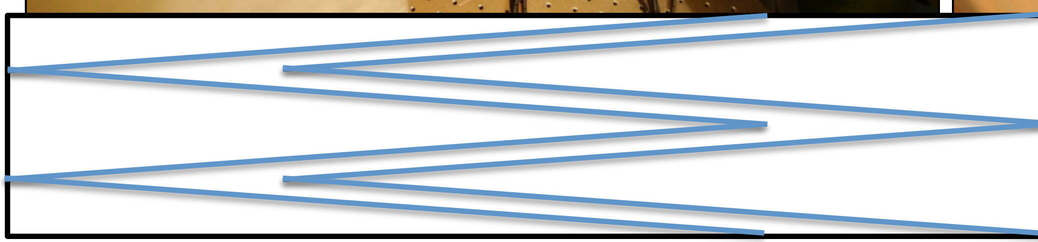
Beam image after shutter

New Double V Polarizers

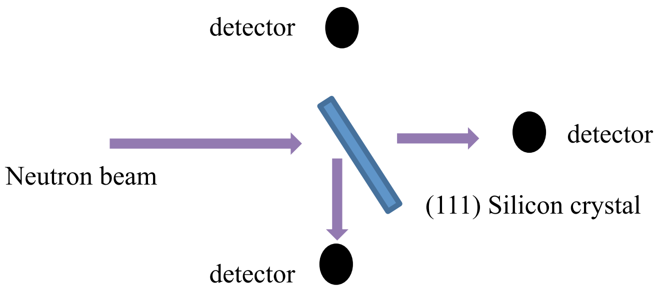


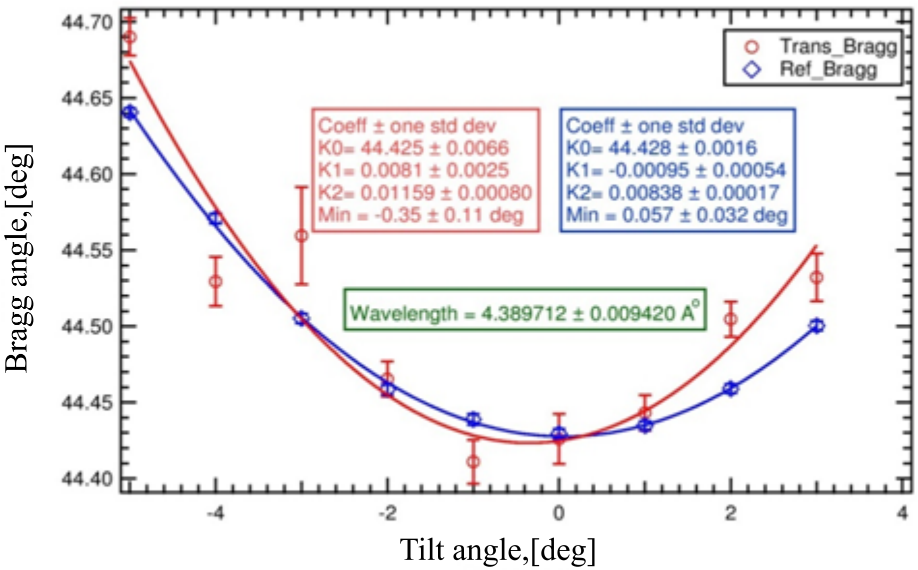


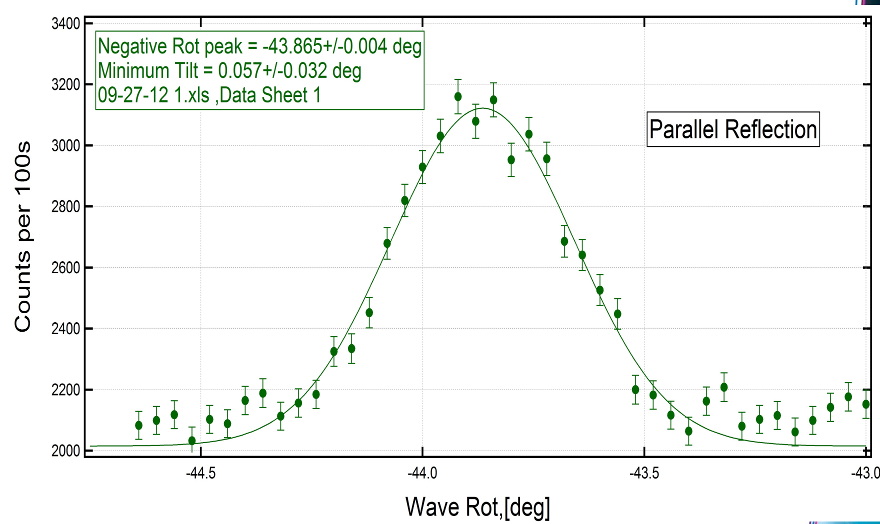


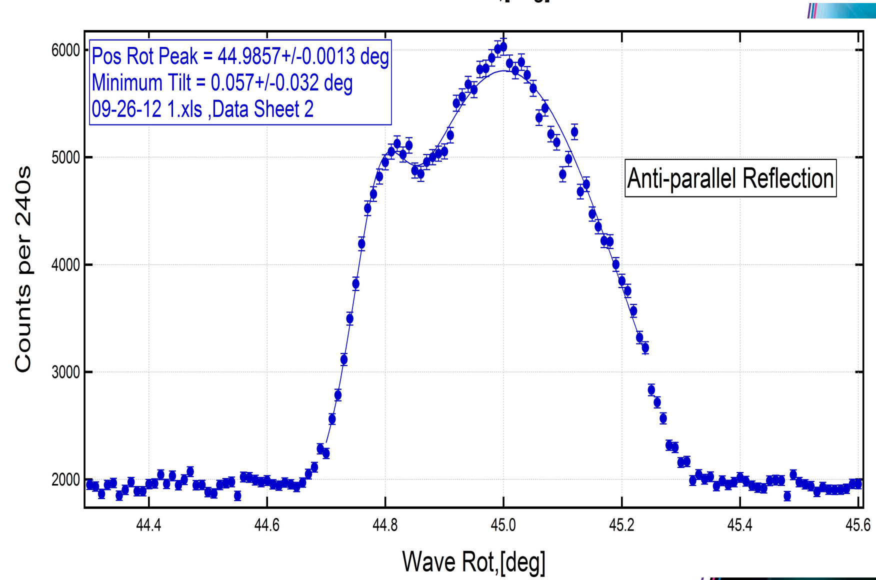


Wavelength Measurement of New Beamline









$\lambda = 2d\sin\theta$

Measuring θ ,we can measure wavelength.

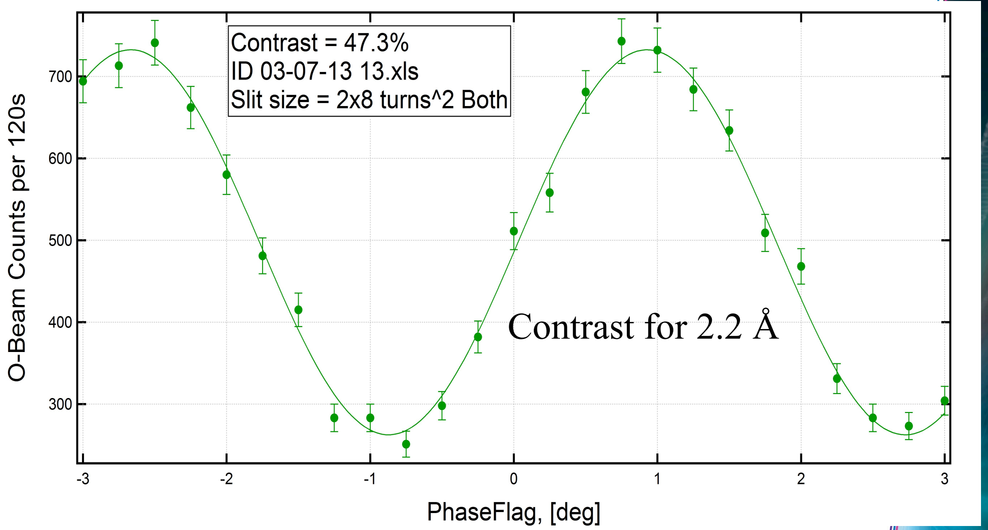
λ=4.390+/-0.009 Å (Measured)

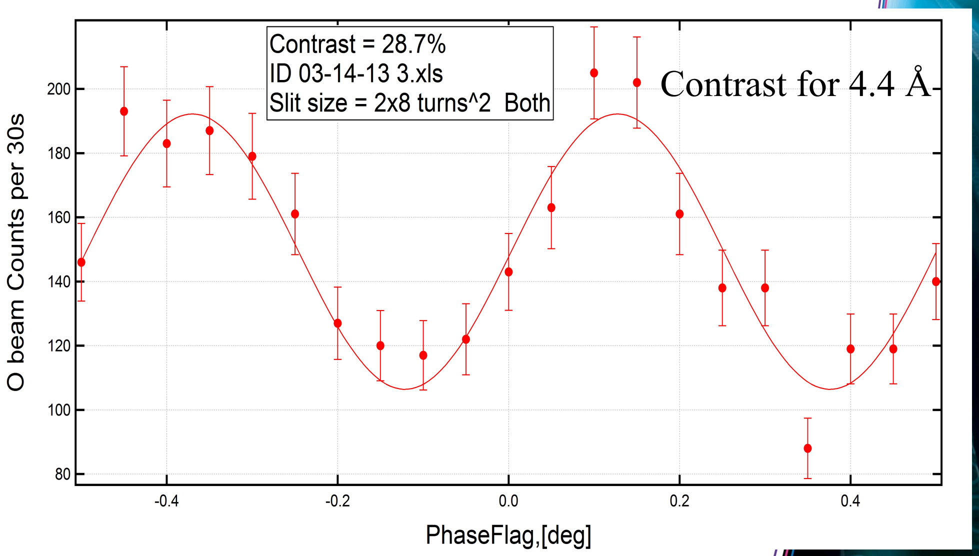
Contrast With TMC Table

Vibration isolation TMC Table

Each leg of TMC table has vibration isolation sensor (PZT sensor).

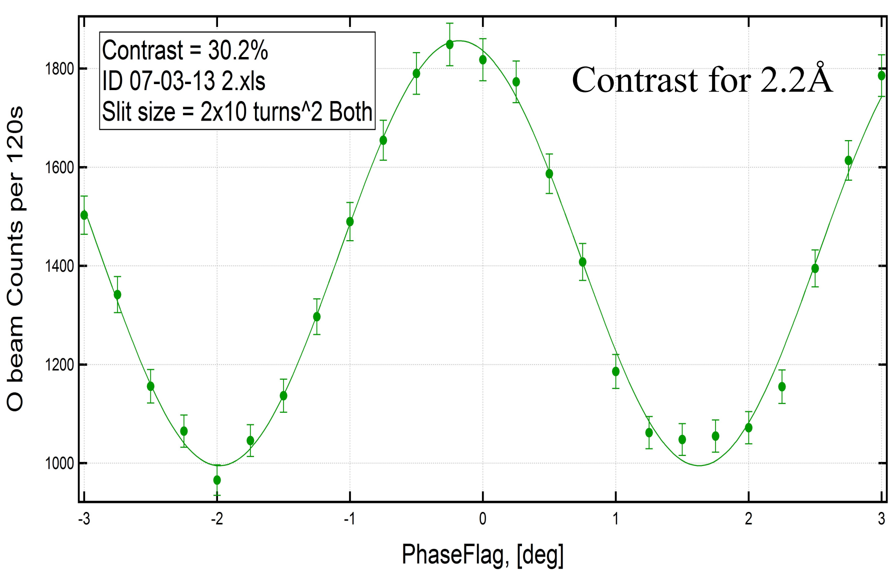
Contrast $f = (I_{max} - I_{min})/(I_{max} + I_{min})$ of O beam

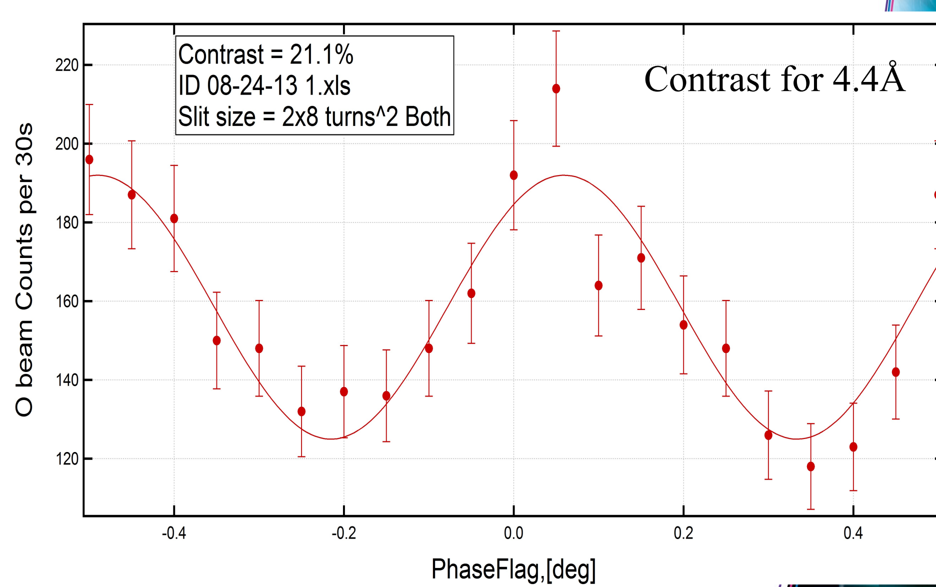




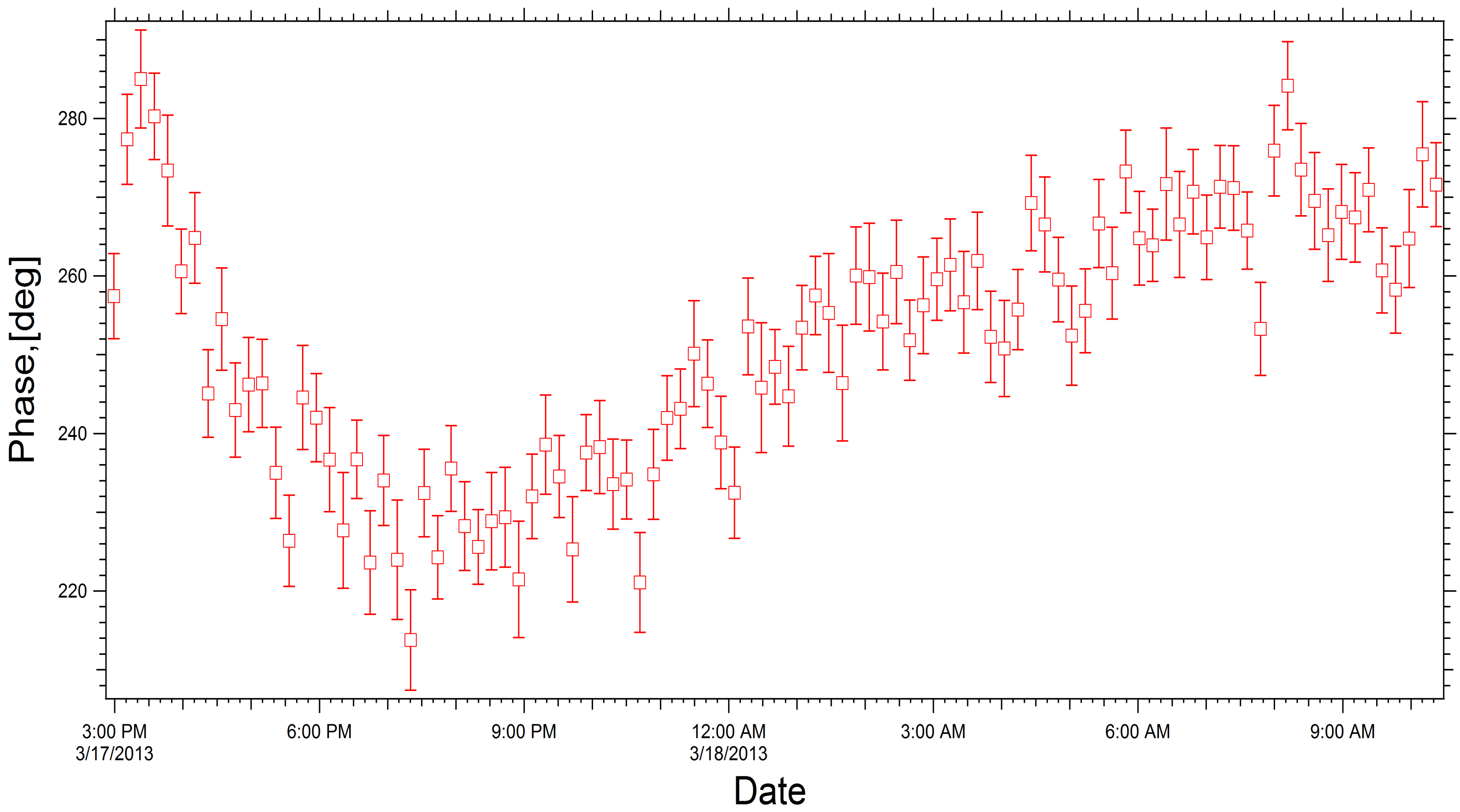
Contrast With Fixed Leg Table

TMC Table with fixed legs(No Vibration isolation)

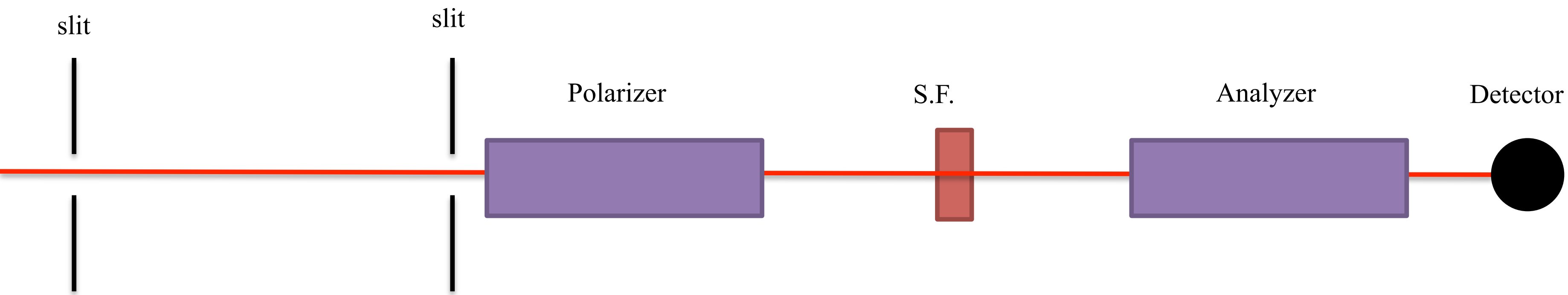




Phase Stability



Polarization Without Be Filter

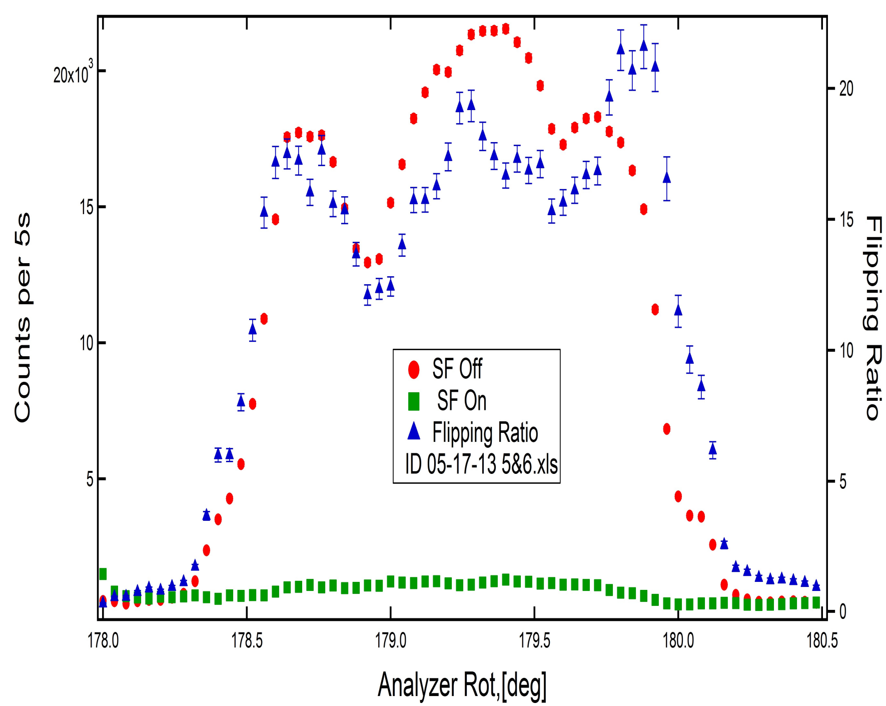


Flipping Ratio (f)
=SF Off Counts/SF On Counts

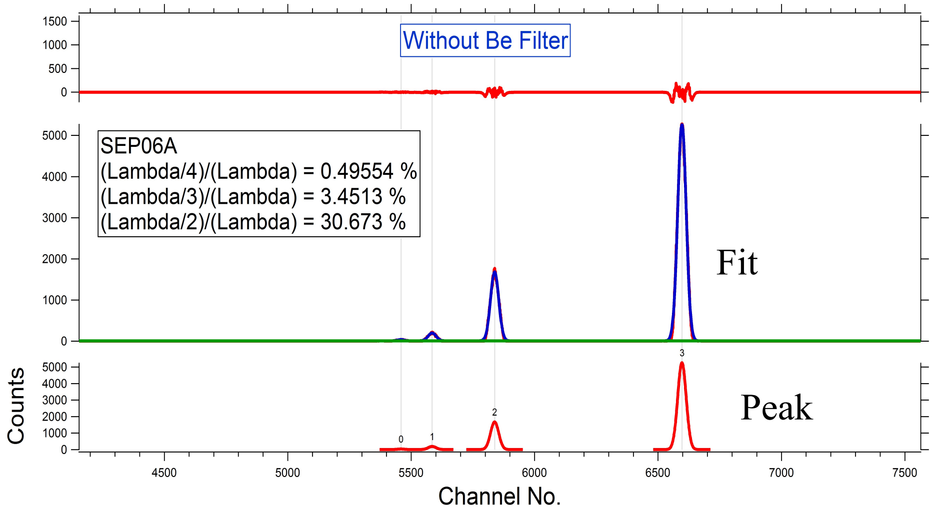
$P_n P_a = (f-1)/(f+1)$

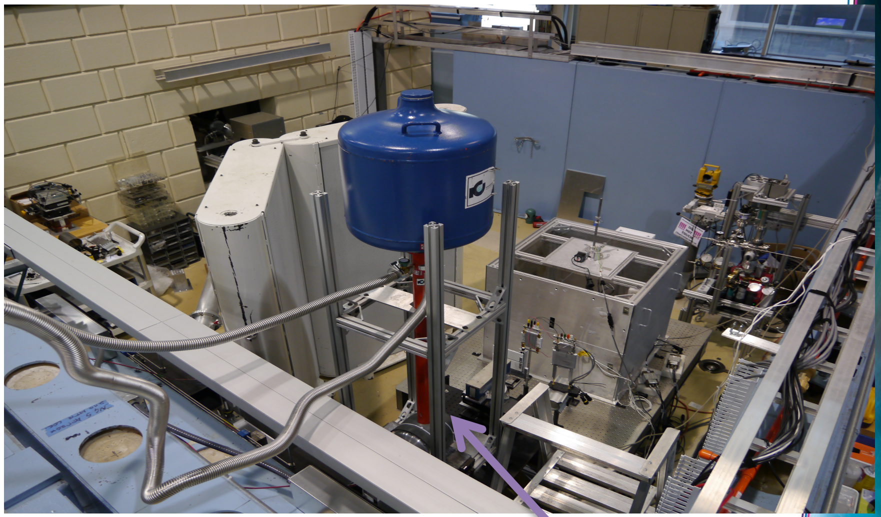
If $P_a = 100\%$ then

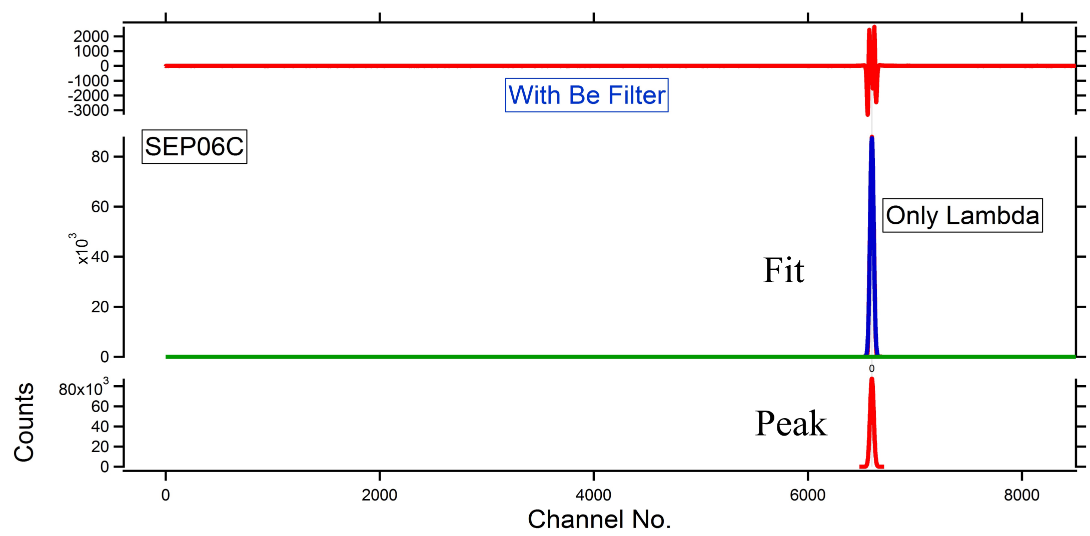
Polarization of neutron ~ 88%



Measurement of λ/n With Disc Chopper

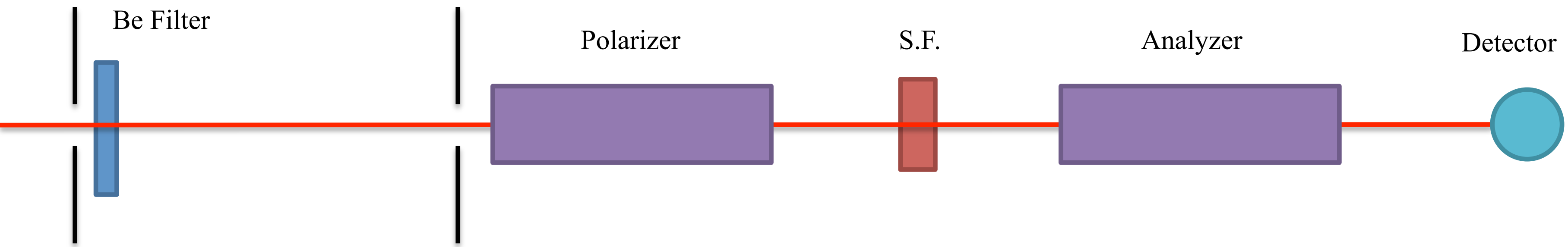






Be Filter

Polarization With Be Filter

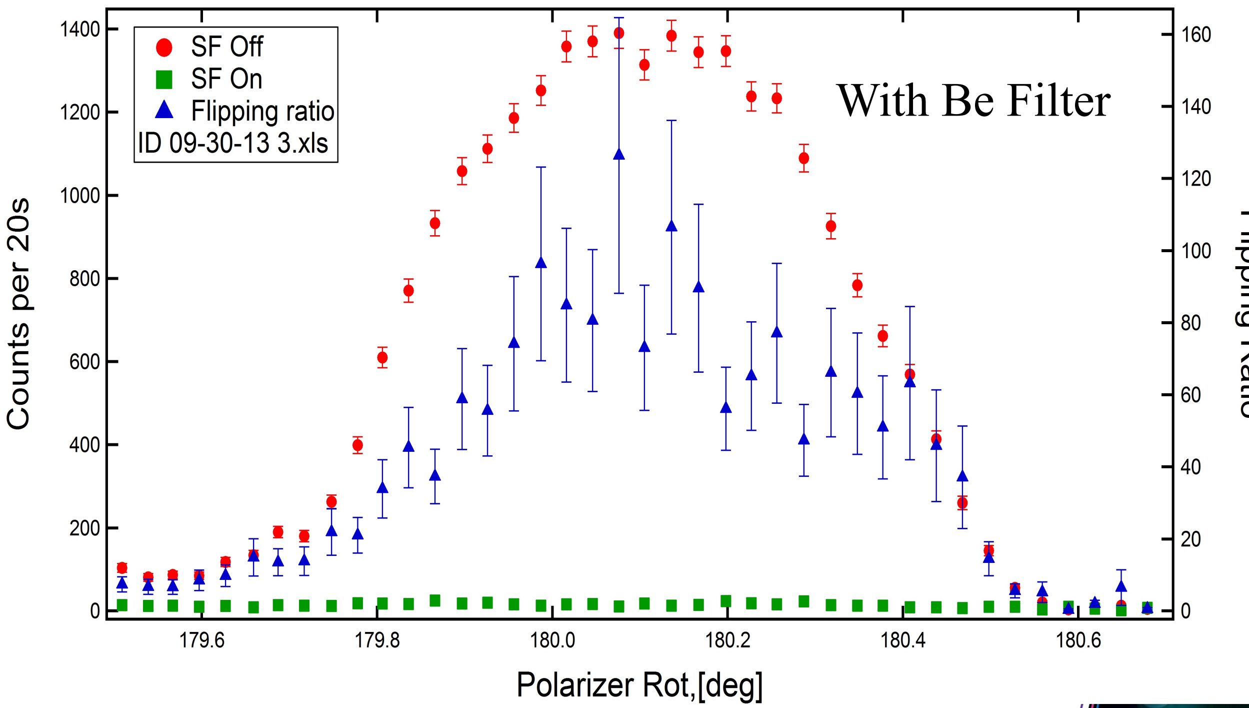


Flipping Ratio (f)
=SF Off Counts/SF On Counts

$P_n P_a = (f-1)/(f+1)$

If $P_a = 100\%$ then

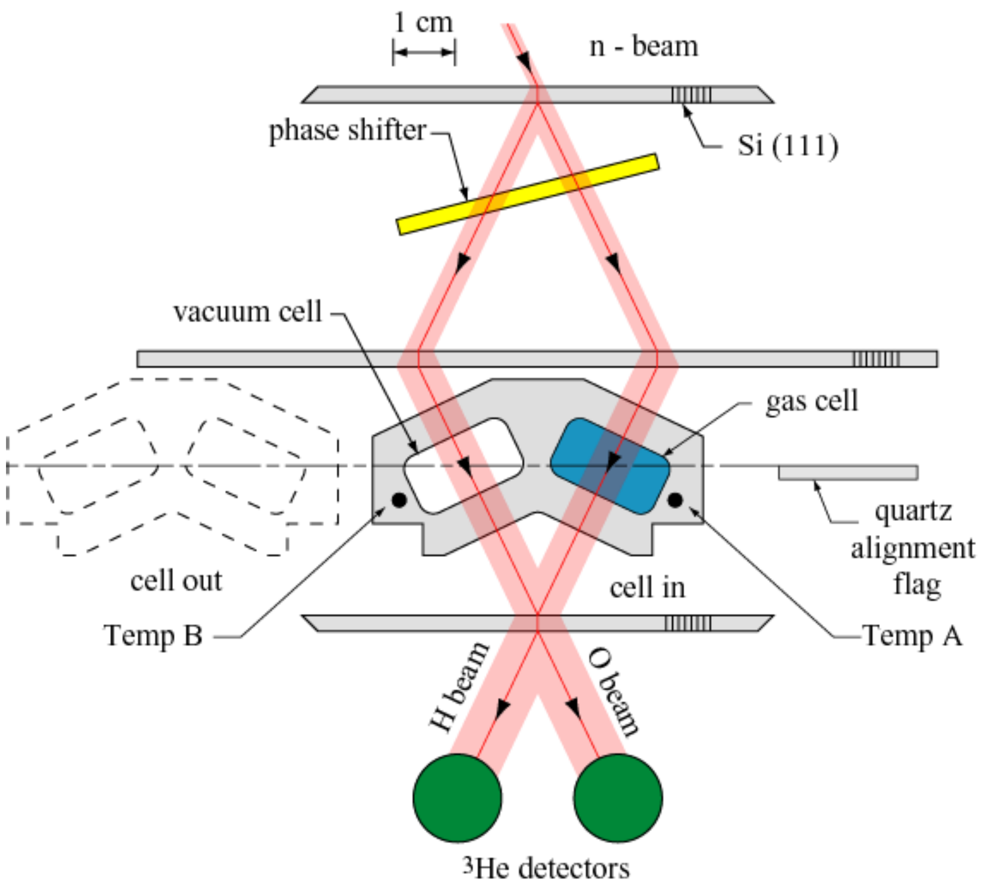
Polarization of neutron ~ 99%



Conclusions

- The neutron interferometer facility at NIST is functionally robust yet precise instrument capable of a wide array of both fundamental and applied neutron experiments.
- Now supports a 2nd beamline for neutron interferometry and fundamental physics applications.
- Have increased flux and other advantages over the existing facility.
- Some growing pains, but nothing unsolvable
- Working to maximize usability.

n-Few body scattering lengths



- The bound coherent scattering length is related to the free nuclear elastic coherent scattering lengths in the two S-wave spin channels.

- Precisely measured scattering lengths are becoming benchmarks for using few-body systems as the building blocks for modern many body nuclear potentials, neutron cross-section standards, and are also used in materials science research.

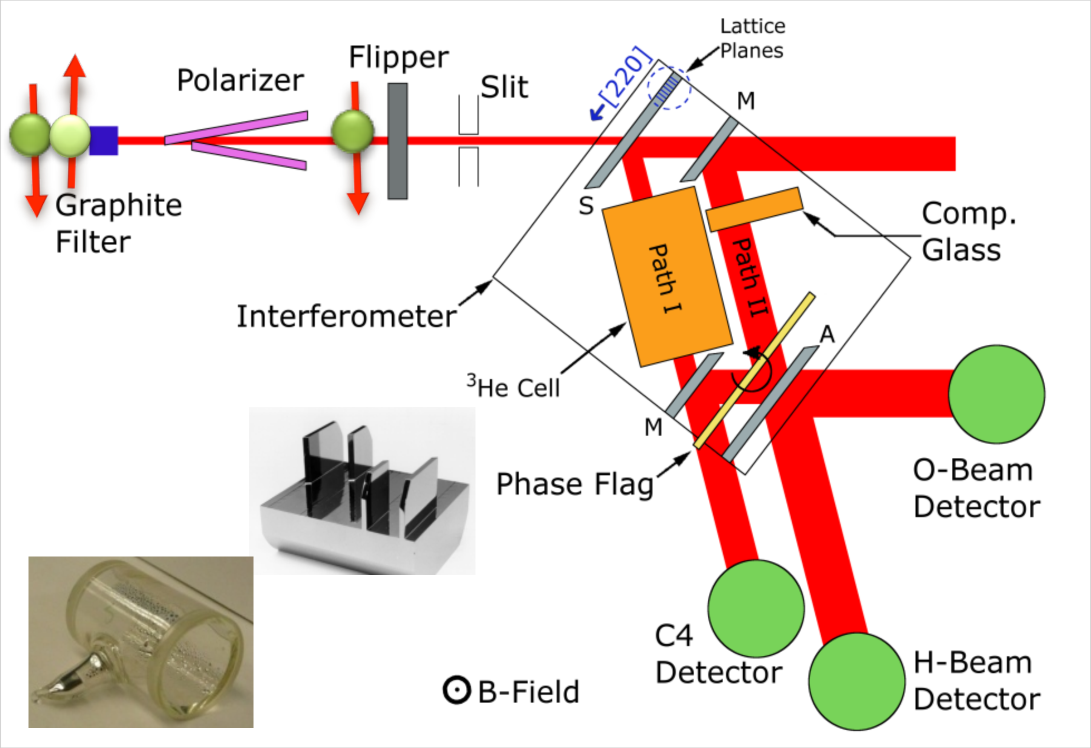
b_{np} = (-3.7384 ± 0.0020) fm - Two Body System

b_{nd} = (6.6649 ± 0.0040) fm - Three Body System

b_{n^3He} = (5.8572 ± 0.0072) fm - Four Body System

Precision Measurement of the Incoherent n-^{3}He Scattering Length

We measure the spin-incoherent (spin-dependent) scattering length using polarized ^{3}He gas trapped in a glass cell.

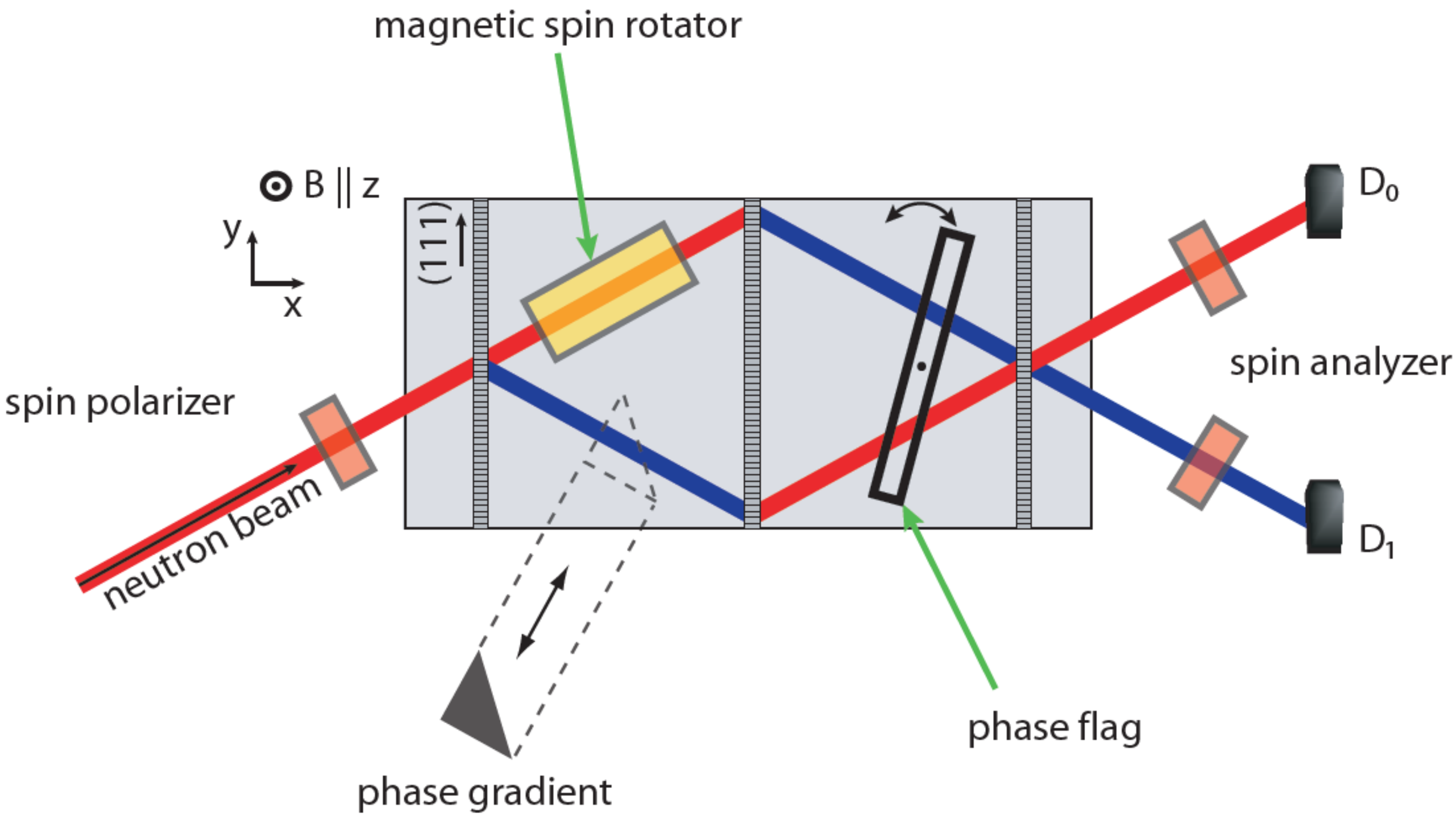


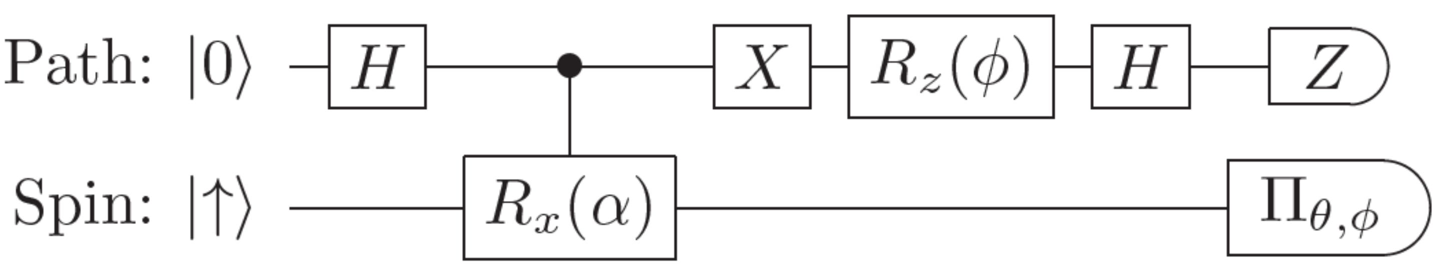
Our Result: $b_i = 2.429 \pm 0.012$ (stat) ± 0.014 (syst)

Quantum Discord

- Surface imperfections in interferometer blade introduce random phase noise to neutron beam travelling through interferometer.
- We investigate quantum coherences in the presence of this noise by entangling the spin and path d.o.f. in NI.

Setup

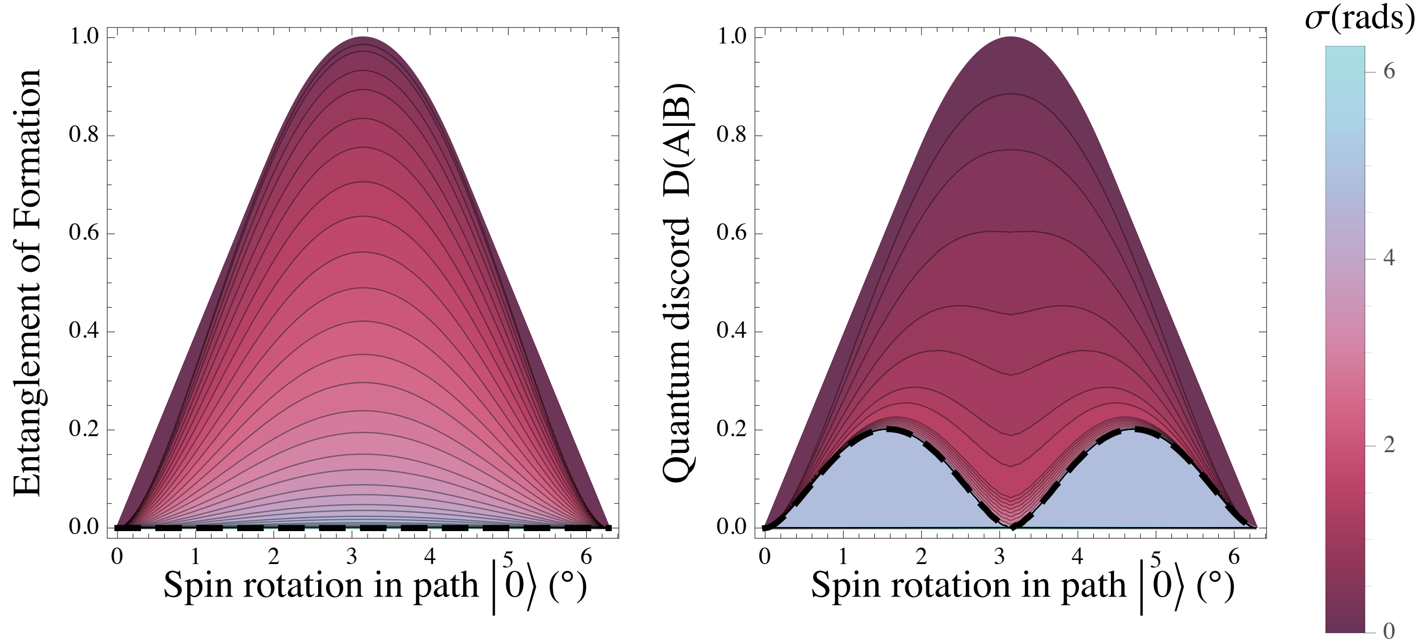

magnetic spin rotator
B || z
y
x
(111)
spin polarizer
neutron beam
spin analyzer
D_0
D_1
phase flag
phase gradient


Path: $|0\rangle$
H
X
$R_z(\phi)$
H
Z
Spin: $|\uparrow\rangle$
$R_x(\alpha)$
$\Pi_{\theta,\phi}$

Measures of correlations

- A convenient measure of entanglement for a two-qubit mixed-state is the entanglement of formation (EoF).
- However there are non-classical quantum states which have no entanglement.
- Quantum discord (QD) was proposed as a more general classication the quantum nature of correlations than entanglement.
- QD is a measure of how much disturbance measurement of one subsystem of a bipartite quantum system can induce on the other.
- We compare QD and EoF of output beam of noisy NI

Theoretical Results



As noise increases

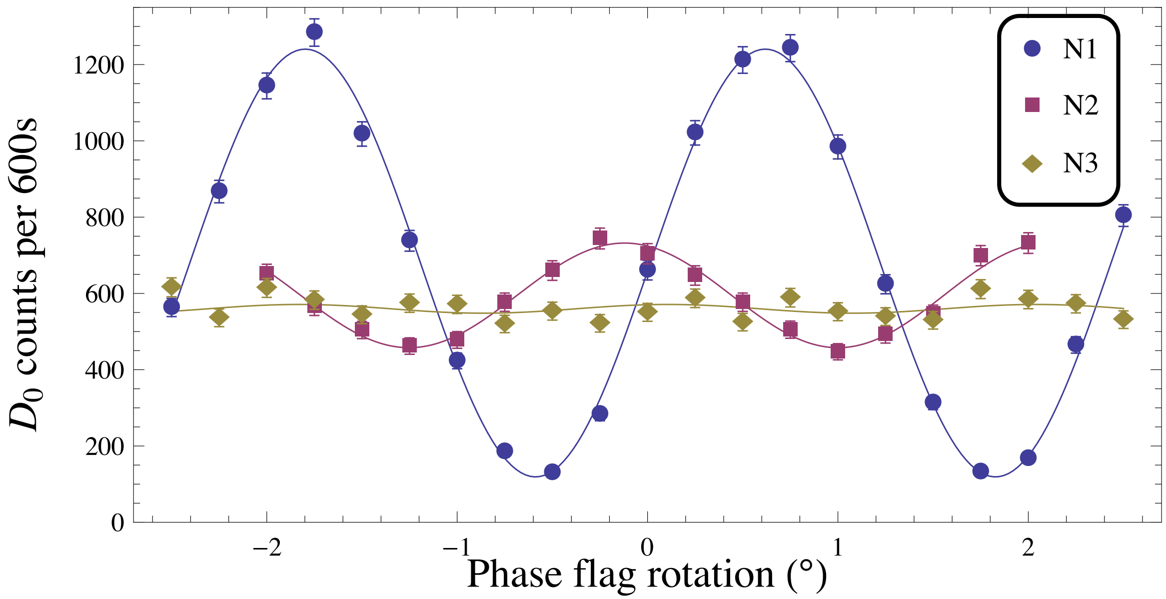
- Entanglement of the output state reduces to zero
- Quantum discord remains non-zero for all noise values

Conclusion

- Even in the presence of strong noise non-classical correlations persist between spin and path of the neutron beam.

Experiment: No spin filter

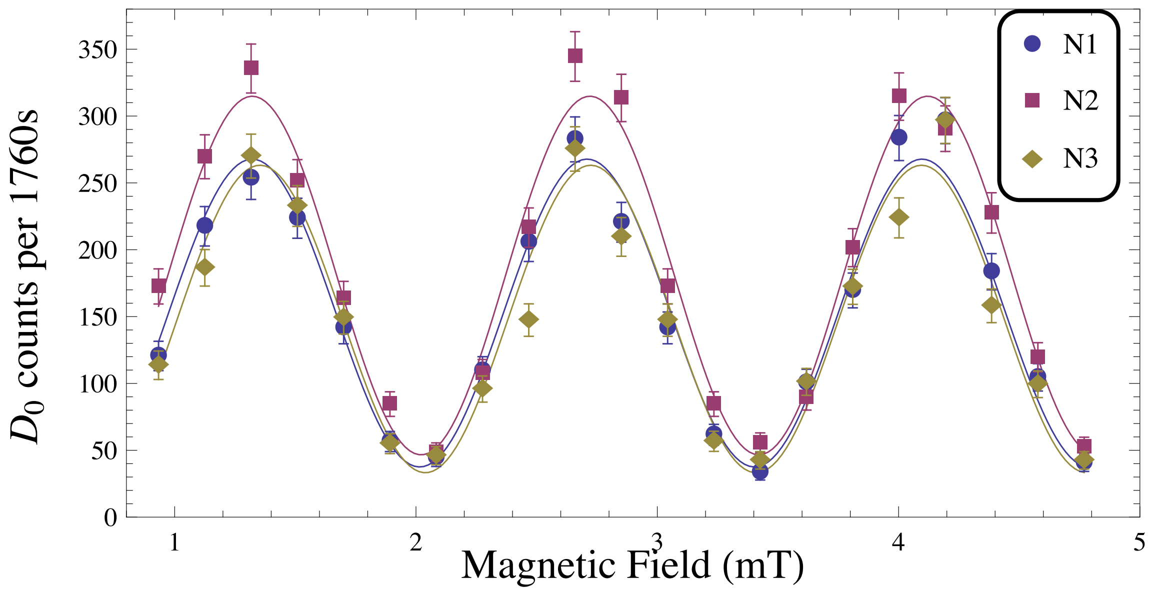
- Non-zero QD indicates that measurements performed on the spin of the neutron beam will induce a disturbance on the path state.
- We experimentally demonstrate this disturbance by comparing contrasts of three NI of deferent noise strengths with and without spin measurements.



Initial contrasts: C_1 = (82.5±1.3)%, C_2 = (23±1.5)%, C_3 = (2±1.7)%.

Experiment: With spin filter

- Spin filter on spin-down. Define spin-filtered contrast as max intensity variation of output intensity as function of spin-rotation angle instead of phase flag.
- Theory predicts spin-filtered contrast of 75.3% for initial spin polarization of 93%



Measured spin contrasts: S_1 = (78±3)%; S_2 = (74.2±2.2)%; S_3 = (84±4)%

Quantum Discord Summary:

- We used NI to investigated the role of quantum correlations in a simple bipartite quantum system in the presence of noise.
- As noise increases entanglement goes to zero, however QD remains non-zero. Non-zero QD indicates spin measurements will influence path state. This can be observed experimentally by comparing NI contrast with spin-filtered spin-contrast.
- Experimental results agree with our theoretical model predicting an increase in spin-filtered contrast over phase contrast for three NIs.
- The deviations between our measured spin-filtered contrast the value predicted by our theoretical model are consistent with phase variations over the acquisition time due to temperature and humidity fluctuations in the NI environment.

Even in the presence of strong phase noise, the NI still exhibits genuine quantum behaviour, and therefore must still be treated as a quantum system.

Instrument Personnel

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Youssef Helwa
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Thank you

UNIVERSITY OF WATERLOO

IQC Institute for Quantum Computing

NIST