Polarizing neutron optics using high-*m* polarizing supermirror

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OUTLINE

Principle and state-of-the-art of supermirrors

- non-polarizing supermirror
- polarizing supermirror

Neutron beam polarization

- Polarization devices
- experiment & simulation of V-cavity for cold neutrons
- simulation of V-cavity for hot neutrons

Polarization analysis

- wide angle polarization analysis with supermirror devices

Conclusions

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Principle of Neutron Supermirror

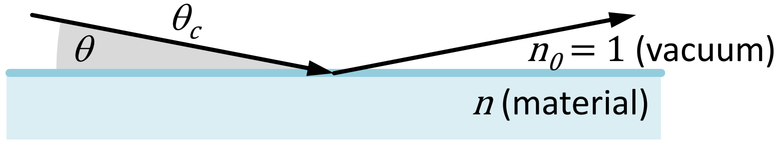
Total reflection from smooth surfaces

- refractive index of most material slightly smaller than 1

↳ total reflection for $\theta \leq \theta_c$

- $\theta_c = \sqrt{\frac{\rho b}{\pi}} \cdot \lambda$ e.g. $\theta_{c,nat.Ni} = 0.1 \frac{\circ}{\text{Å}} \cdot \lambda$

  ρ : nuclear density
  b : coherent scattering length



Bragg reflection from a multilayer

- depth graded multilayer of two materials

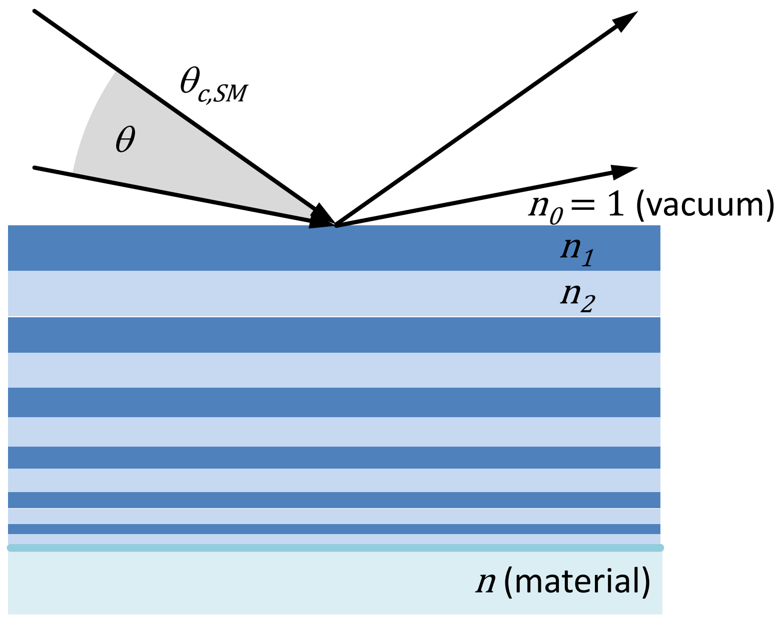
↳ bragg reflection for $\theta_c \leq \theta \leq \theta_{c, SM}$

- $\theta_{c,SM} = m \cdot 0.1 \frac{\circ}{\text{Å}} \cdot \lambda$

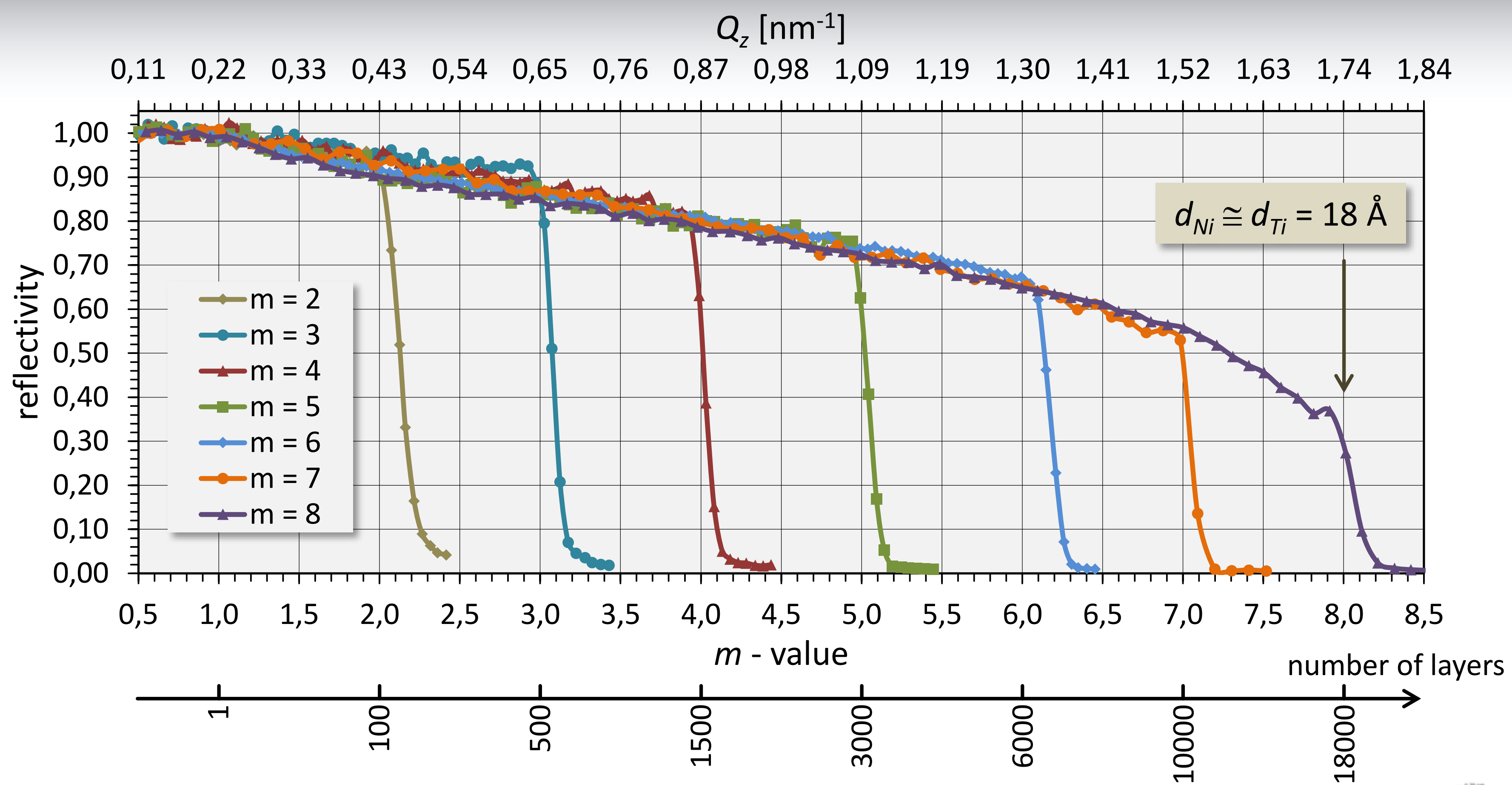
  m : multiple of $\theta_{c,nat.Ni}$

- reflectivity $\propto (\rho_1 \cdot b_1 - \rho_2 \cdot b_2)^2$

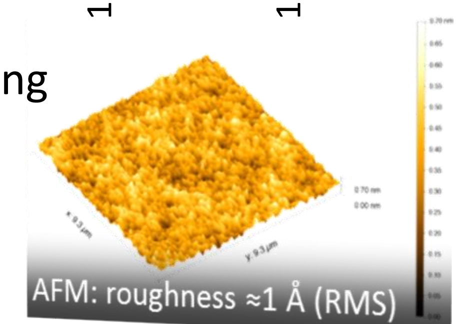
↳ b_{Ni} = 10.3 fm, b_{Ti} = -3.4 fm



Non-Polarizing Supermirror Reflectivity – State of the Art



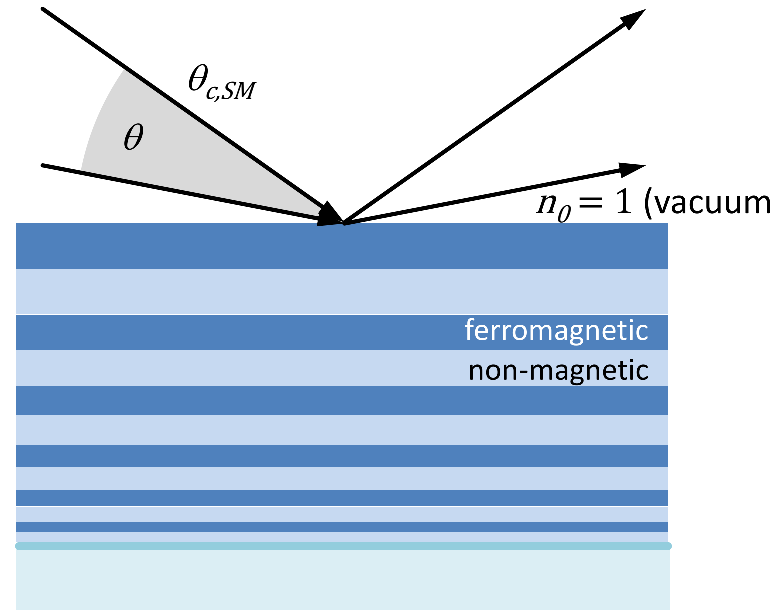
- sophisticated processes for large area super-polishing and coating
- stabilization of interface roughness
  ⇔ slope of *R* independent of *m*-value
- large *m*-values and high reflectivity ⇔ no compromises



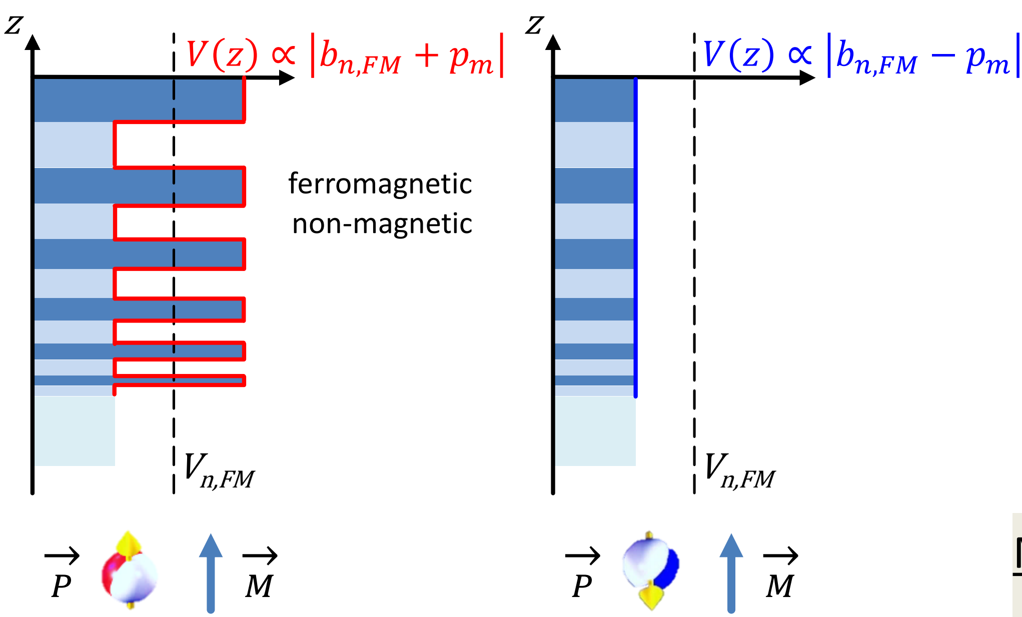
AFM: roughness ≈1 Å (RMS)

Principle of Polarizing Neutron Supermirror

- Ferromagnetic (FM) / non-magnetic (NM) layers
- Spin dependent interaction of neutron with FM: $\left(b_{n,FM} \pm p_m\right)$
- Contrast matching: $\left(b_{n,FM} - p_m\right) = b_{n,NM}$



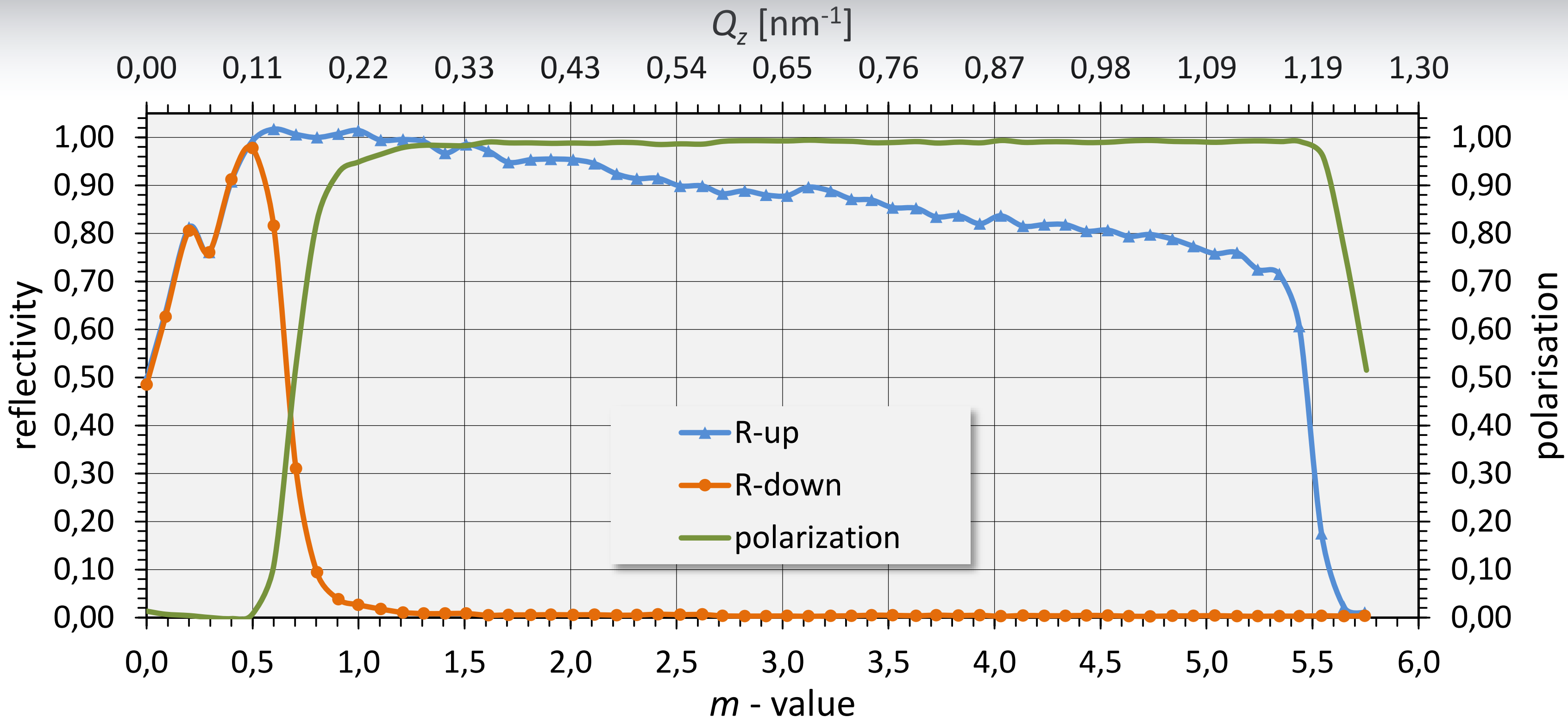
Quantum mechanical representation



Materials for polarizing supermirror

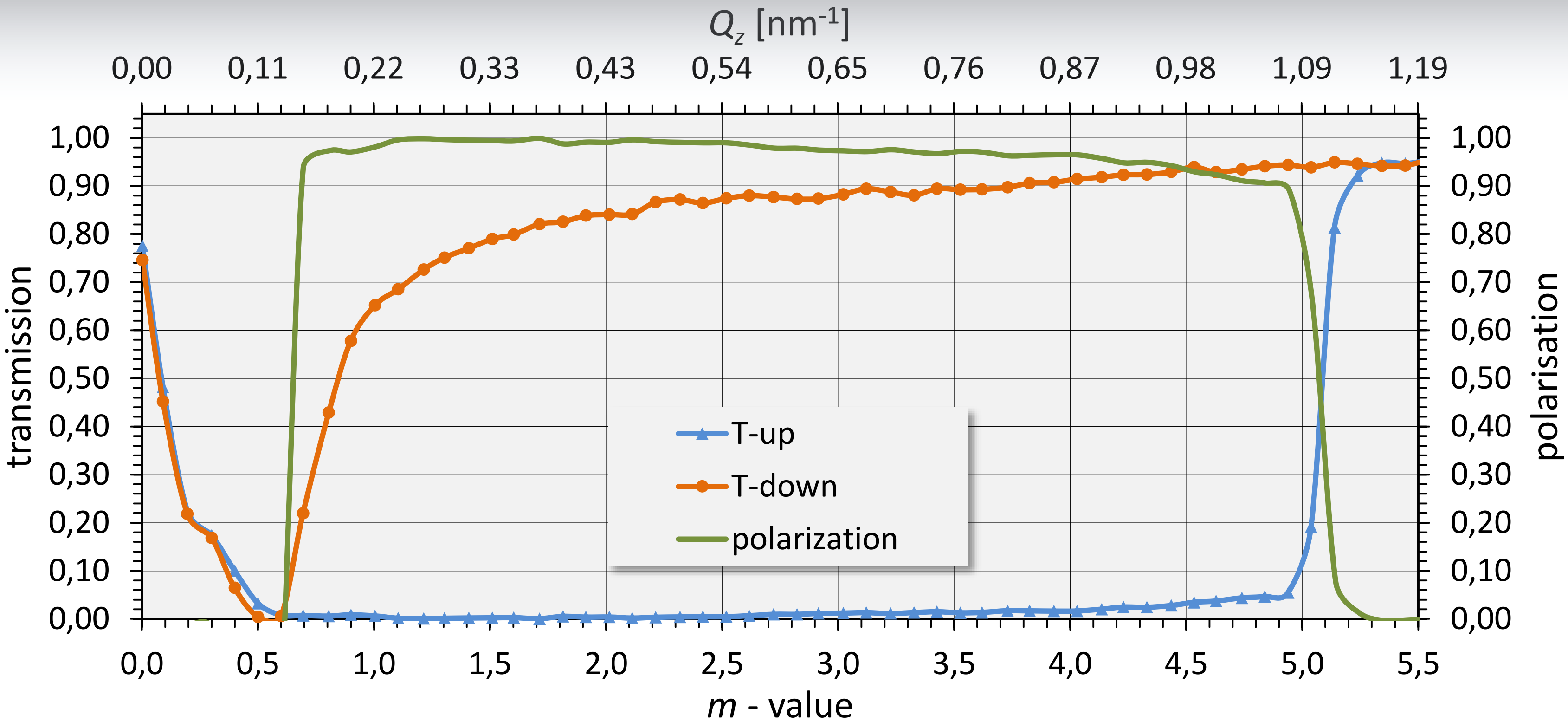
- Fe / Si
- FeCoV / TiZr
- FeCoV / TiN_x
- Co / Ti

PERFORMANCE OF POLARIZING FE/SI SUPERMIRROR - REFLECTION



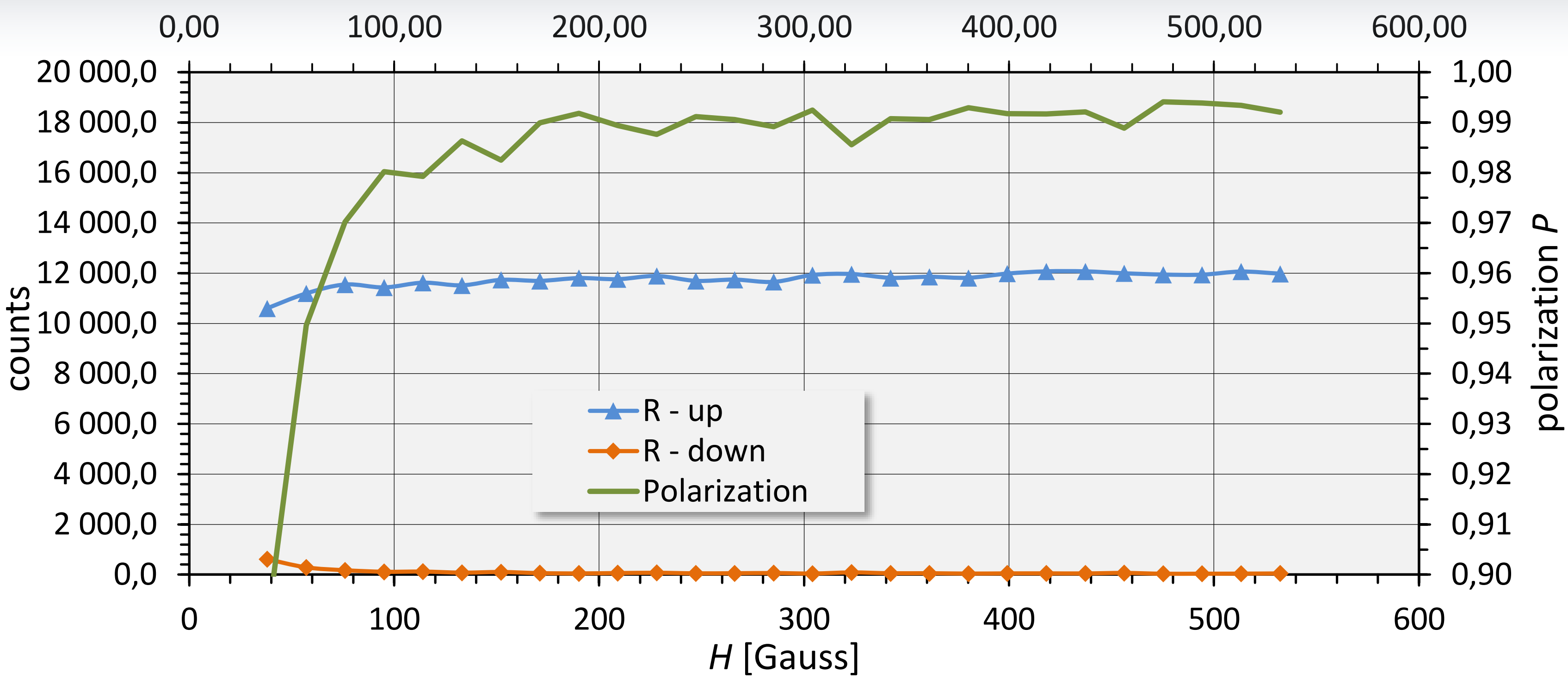
- large *m*-values and high reflectivity ⇔ no compromises
- average polarization in reflection: $P_{ave,\ refl} \geq 99\%$

Performance of Polarizing Fe/Si Supermirror - Transmission



- large *m*-values and high reflectivity ⇔ no compromises
- average polarisation in reflection: $P_{ave, refl} \geq 99\%$
- average polarisation in transmission: $P_{ave, trans} \geq 96\%$ (double-sided coating on Si-wafer)

Magnetic Field Dependence of Polarizing Fe/Si Supermirror



- sample: Fe/Si, m = 5.5
- measurement: scan of applied magnetic field (550 G -> 40 G) at angle of incidence m = 4

↳ **minimum required magnetic field *H* > 200 G**

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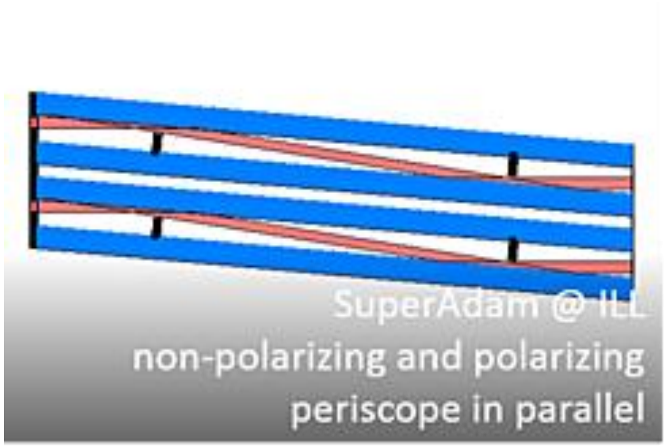
Polarizing Devices in Reflection Mode

Polarizing reflector for OFFSPEC @ ISIS

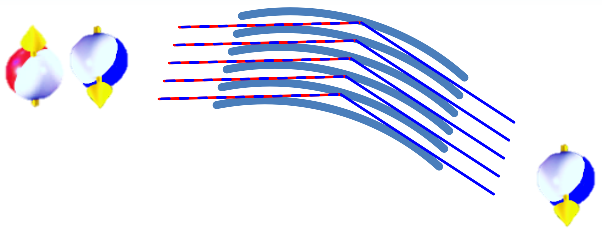
- dimensions: 500 mm × 60 mm
- coating: $FeCoV/TiN_x$, $m = 3$
- polarization (flipping ratio): >99% (100)



Polarizing periscope for SuperAdam @ ILL

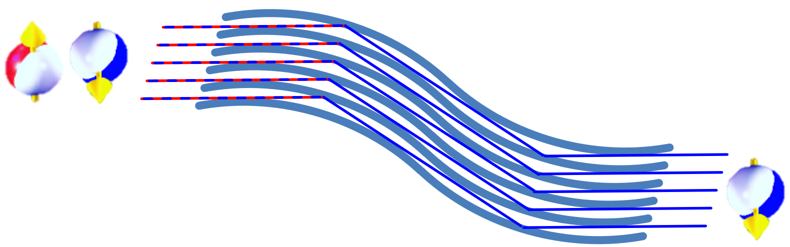
- non-polarizing & polarizing mode
- double reflection (periscope)
- coating: Fe/Si bandpass, $3.7 \leq m \leq 4.3$
- polarization (flipping ratio): >99.5% (400)

Polarizing Bender (Reflection & Transmission)



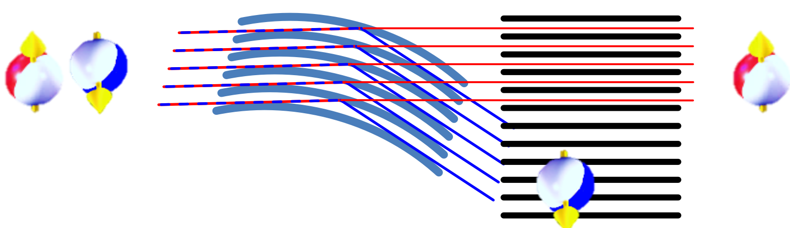
<u>Reflection bender</u>

- neutrons of one spin state absorbed in substrate or dedicated absorbing coating
- increased divergence -> dilution of phase space
- deflection of beam



<u>S-shaped bender</u>

- neutrons of one spin state absorbed in substrate or dedicated absorbing coating
- increased divergence -> dilution of phase space
- no deflection of beam
- clear cut-off of wavelength



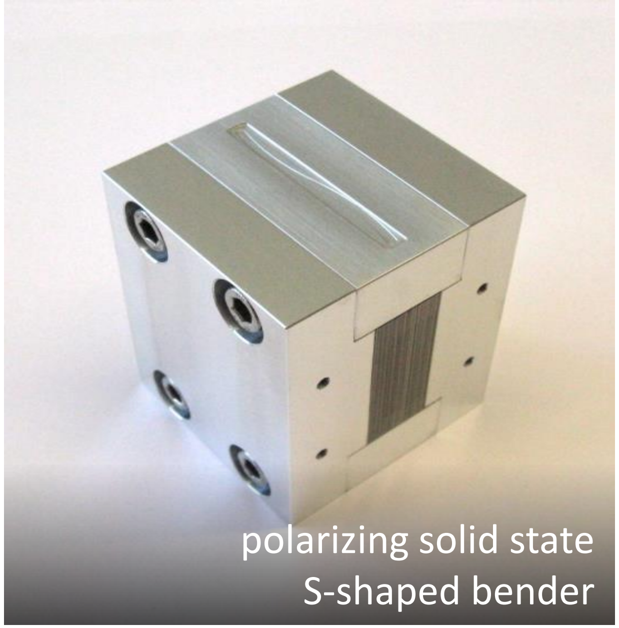
<u>Transmission bender + collimator</u>

- neutrons of one spin state absorbed in collimator
- uniform phase space
- no deflection of beam

Polarizing Bender (Reflection & Transmission)

Standard bender

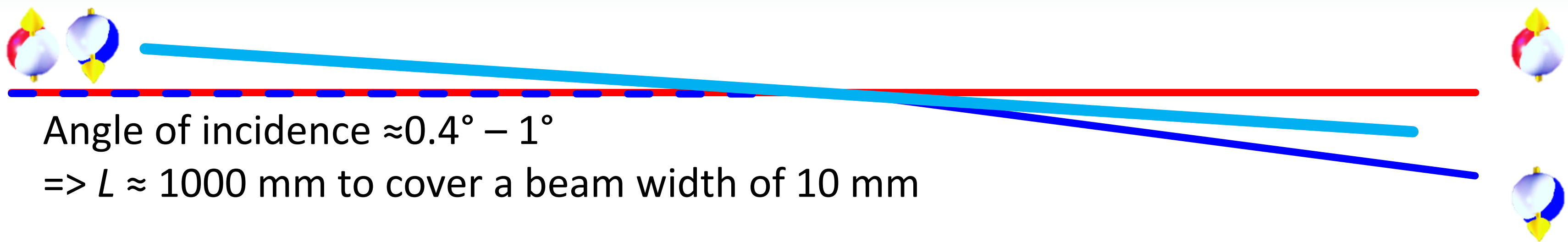
- neutrons propagate in vacuum (air)
- channel walls made of glass (t = 0.2-0.3 mm)
- channel width $\gtrsim$2 mm
- length of bender ≈400 mm to a few meter
- «geometrical loss» of neutrons

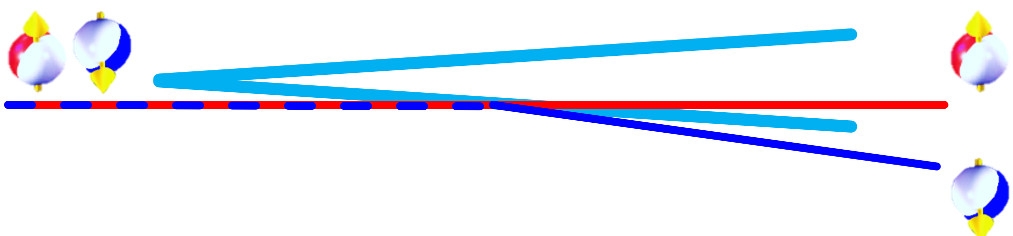


Solid state bender

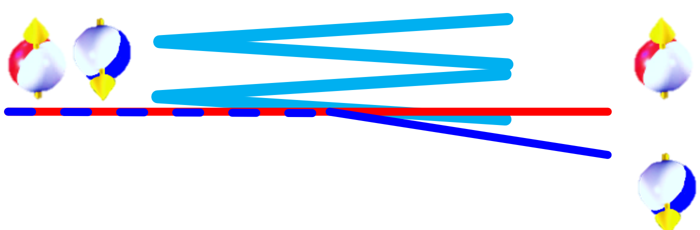
- neutrons propagate in silicon
- virtually no channel walls
- channel width ≈0.1-0.6 mm
- length of bender ≈30-60 mm
- loss of neutrons due to absorption in Si

Polarizing Devices in Transmission Mode

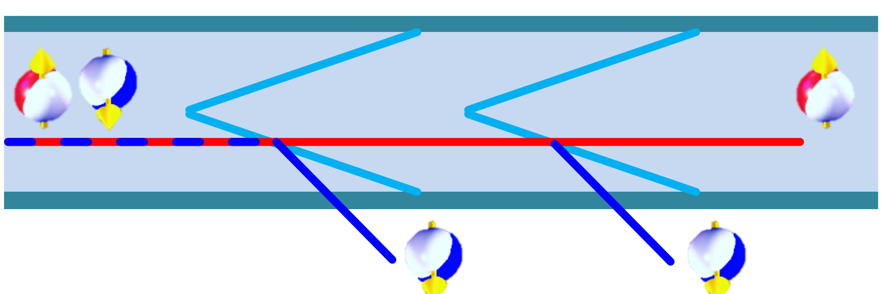




V-cavity

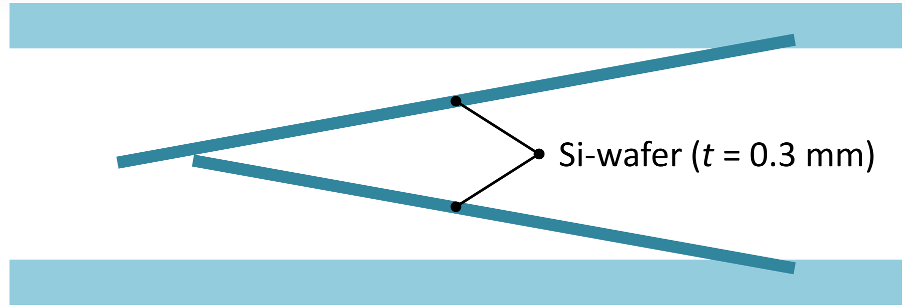


multichannel V-cavity



concept double V-cavity

Design of Polarizing V-Cavities



<u>Features</u>

- serial (double V)
- parallel (multi-channel) arrangements
- serial and parallel
- avoid streaming of “up” neutrons:
  - overlaps at tip
  - intrusion at sides

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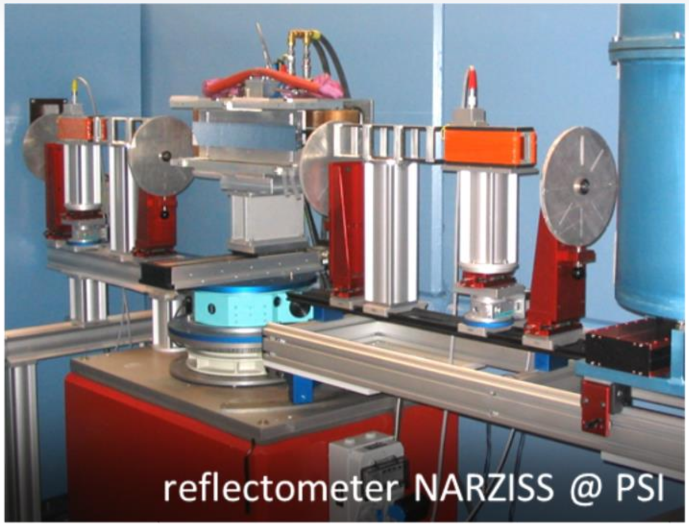
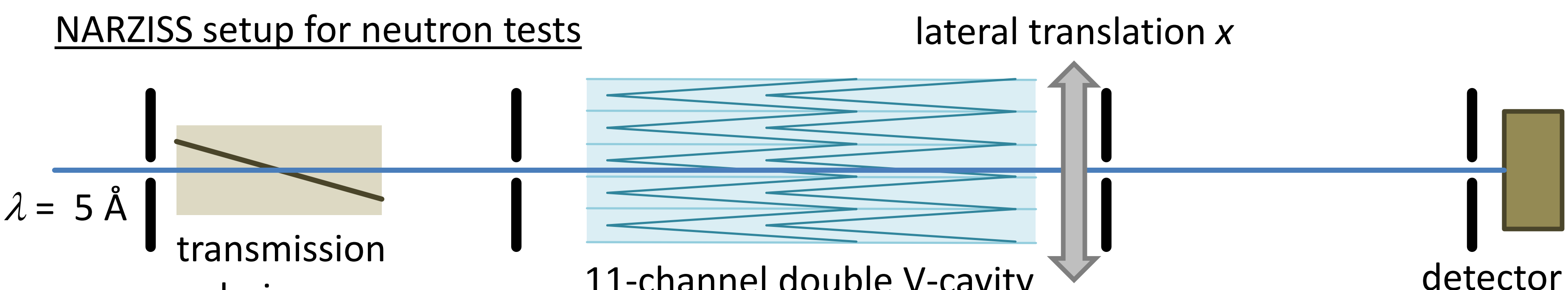
Multi-Channel V-Cavities – Experimental Setup

Features of multi-channel cavity (PONTA @ JRR-3m)

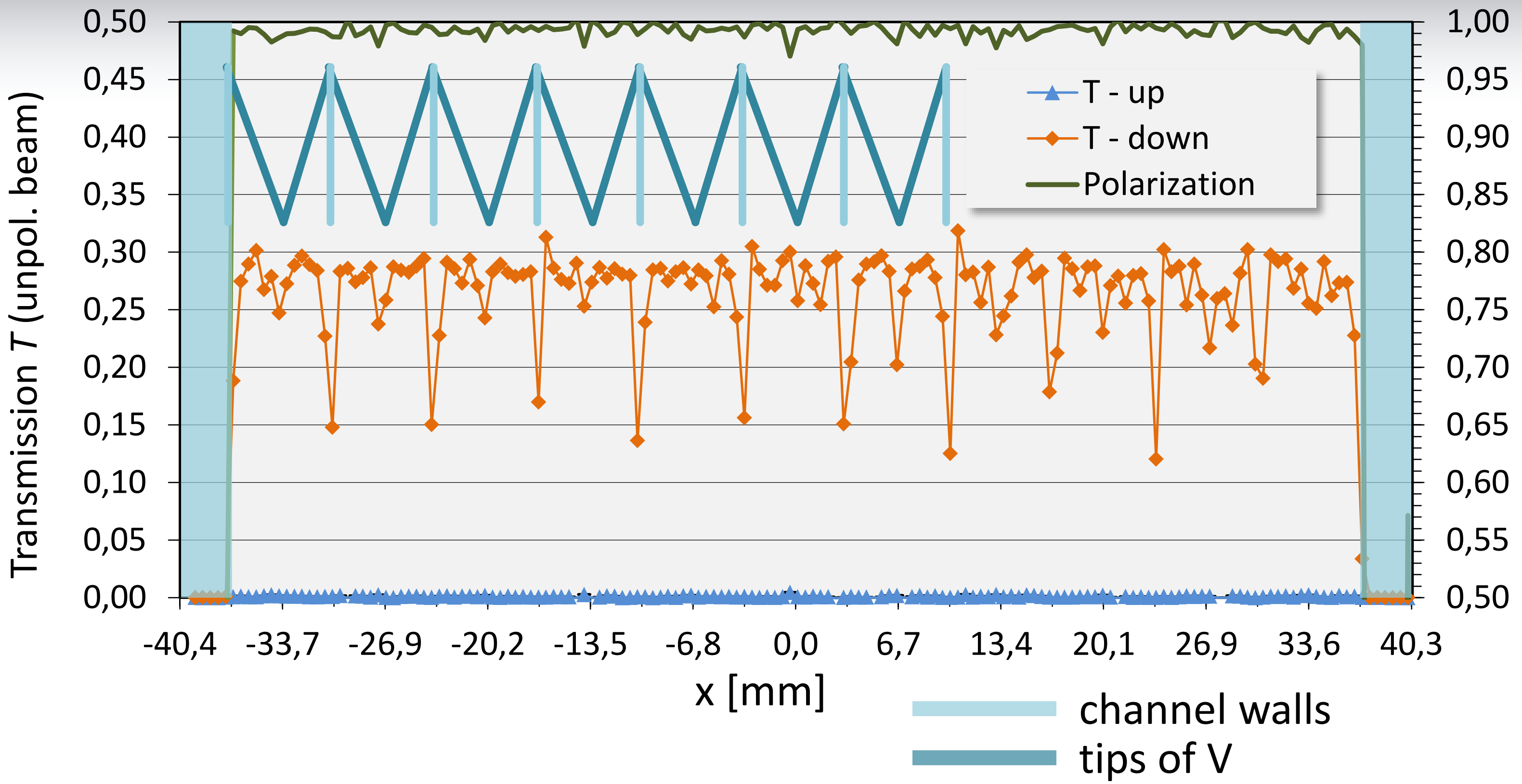
- 11-channel double V-cavity
- width of channels: w_{ch} = 6.45 mm
- thickness of separators: t_{blade} = 0.3 mm
- thickness of Si-wafer: t_{Si} = 0.3 mm
- polarizing Fe/Si supermirror: m = 5.0
- taper angle of Vs: θ_V = ±0.6°
- length: L = 500 mm



NARZISS setup for neutron tests



Multi-Channel V-Cavities – Experimental Results

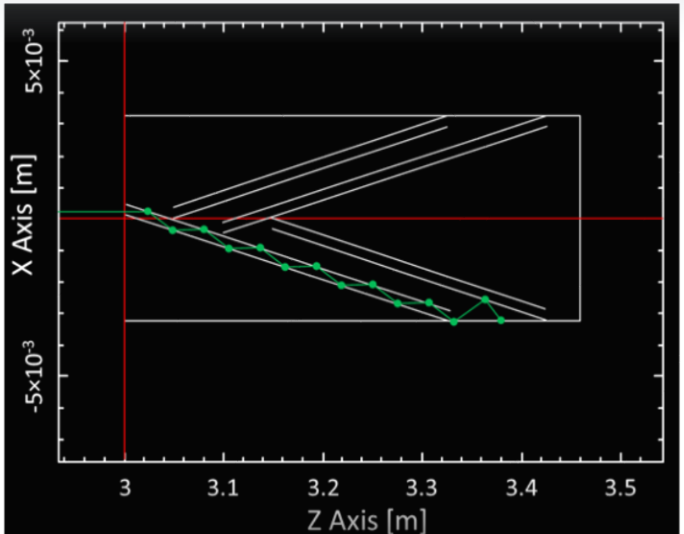


⇘ average polarization: P_{ave} = 99%

⇘ average transmission: T_{ave} = 26%

(100 unpolarized neutrons in ⇔ 26 polarized neutrons out)

Multi-Channel V-Cavities– Simulation Setup

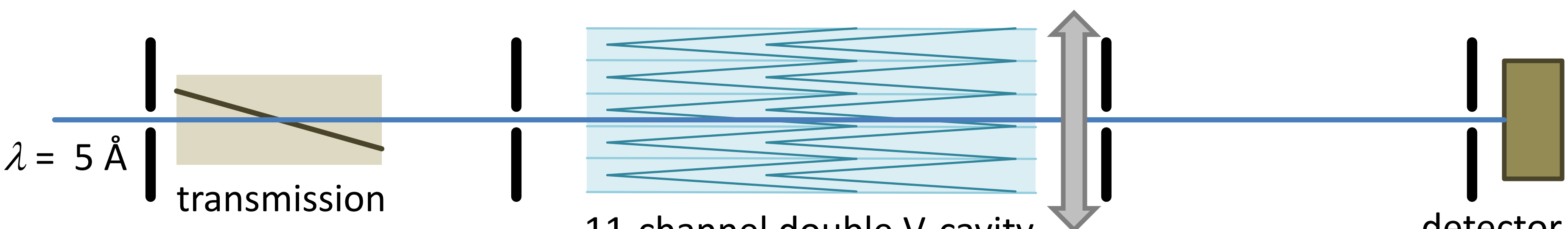


McStas ray-tracing in V-cavities

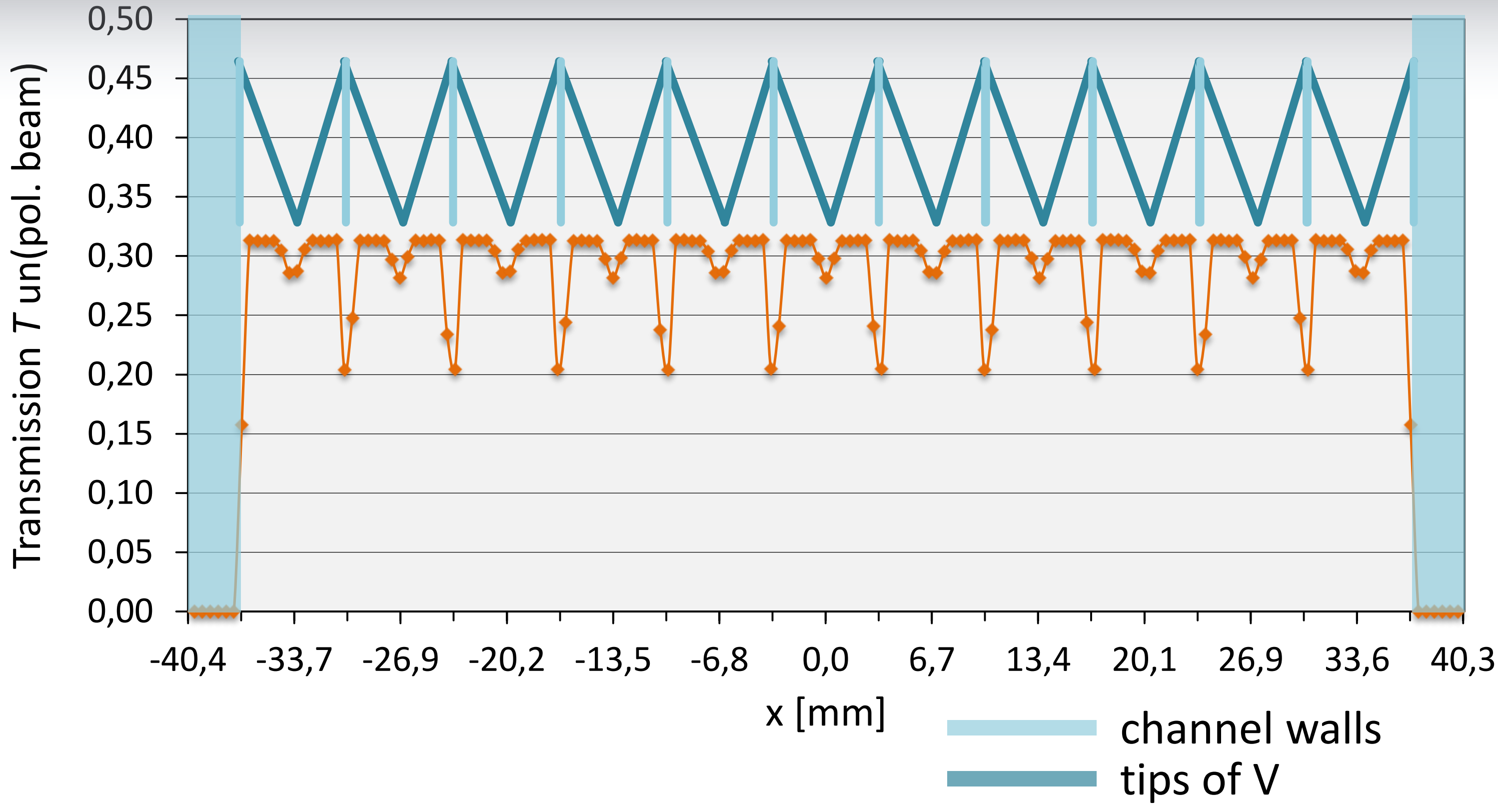
<u>Features of McStas component</u>

- input: measured spin-dependent reflectivity of Fe/Si polarizing supermirror
- absorption in Si-wafer and Fe/Si supermirror
- multiple reflections within Si-wafers
- overlap of Si-wafers at tip of Vs

<u>McStas setup for simulation</u>



Multi-Channel V-Cavities– Simulation Results



↳ average polarization: P_{ave} = 99.9% ⇔ measured 99%

↳ average transmission: T_{ave} = 29% ⇔ measured 26%
(100 unpolarized neutrons in ⇔ 29 polarized neutrons out)

↳ **excellent matching experiment ⇔ simulation**

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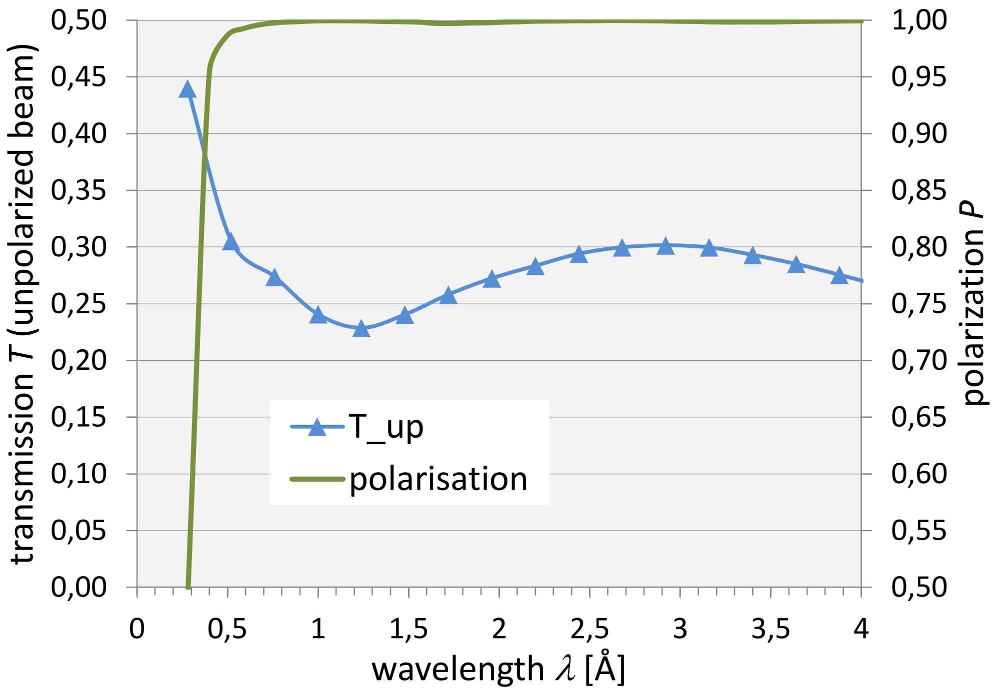
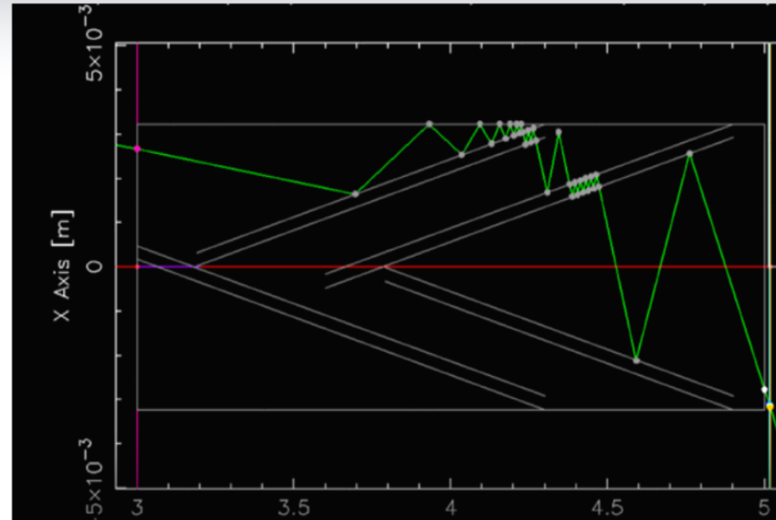
Polarization of Neutrons with Short Wavelength

Features of cavity

- double V-cavity
- thickness of Si-wafer: t_{Si} = 0.3 mm
- polarizing Fe/Si supermirror: m = 6.0
- taper angle of Vs: θ_V = ±0.15°
- length: L = 2000 mm





McStas ray-tracing in V-cavities

Performance

- $\lambda_c \cong 0.3$ Å
- $P \cong 1$
- $T \cong 25\% - 30\%$ (100 unpol → 30 pol)

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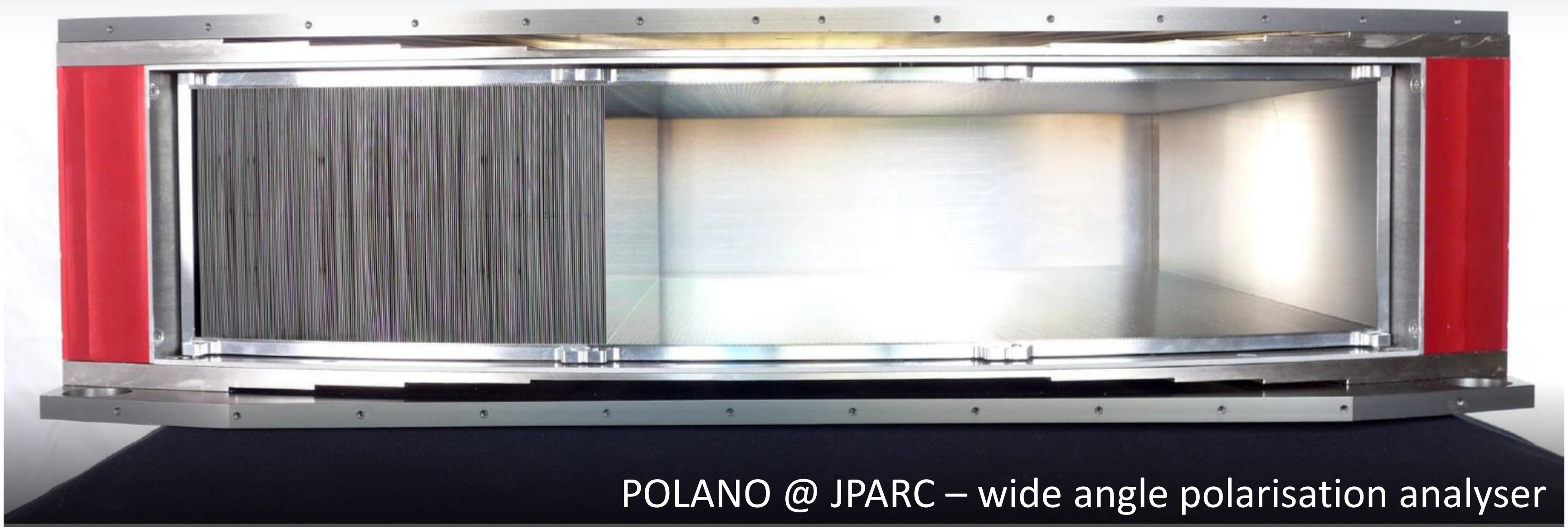
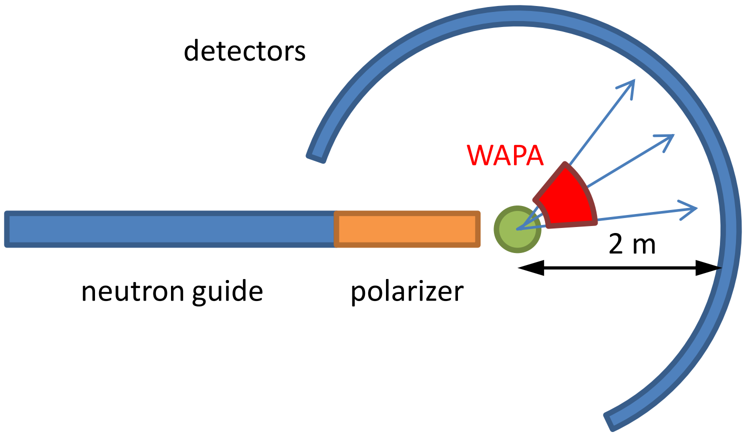
Wide Angle Polarization Analyzer (WAPA)



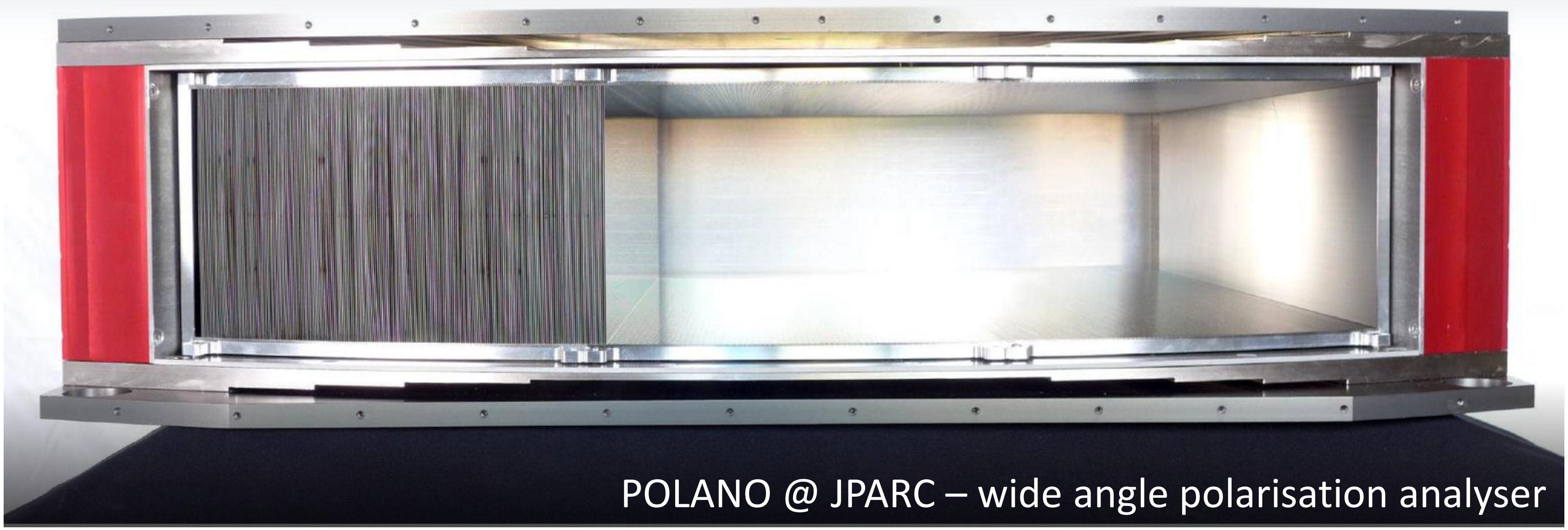
Radial bender – working principle



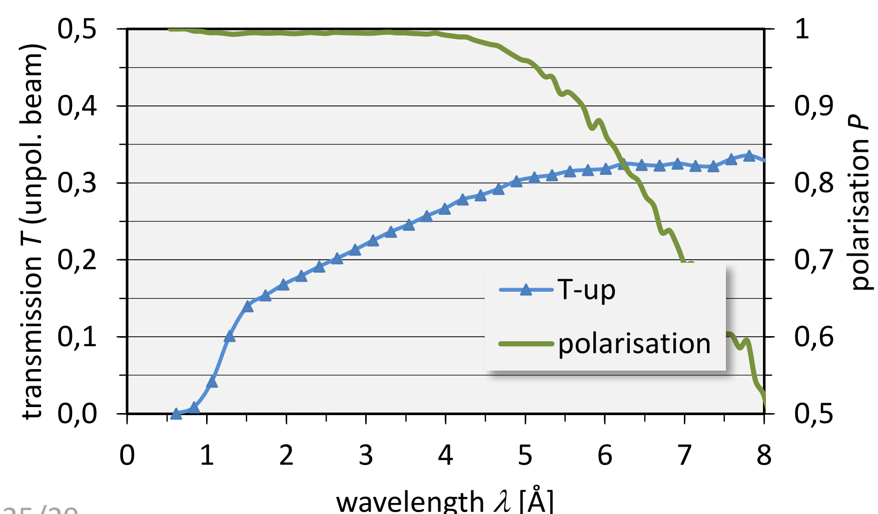
Characteristics of radial bender

- critical wavelength: λ = 1.7 Å
- angular coverage: Ω = 40°
- Fe/Si (concave/convex): m = 5.5/1.5
- WAPA assembled with 250/660 channels

WIDE ANGLE POLARIZATION ANALYZER (WAPA)

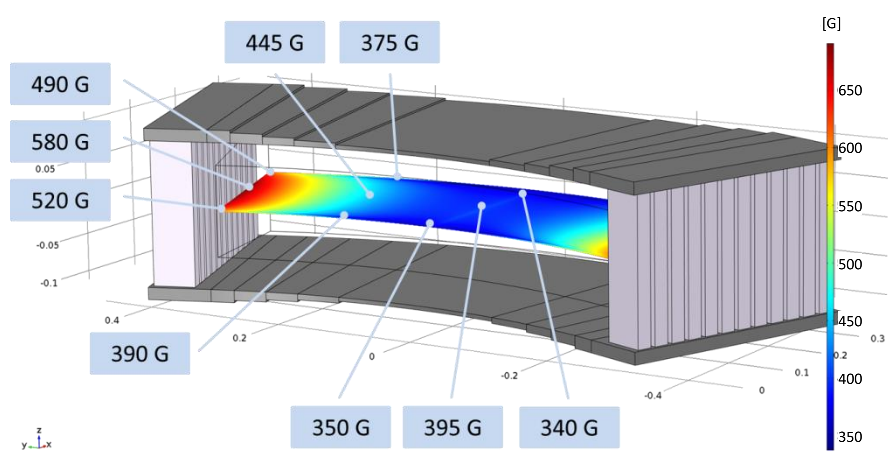


McStas simulations



Magnetic field calculation:

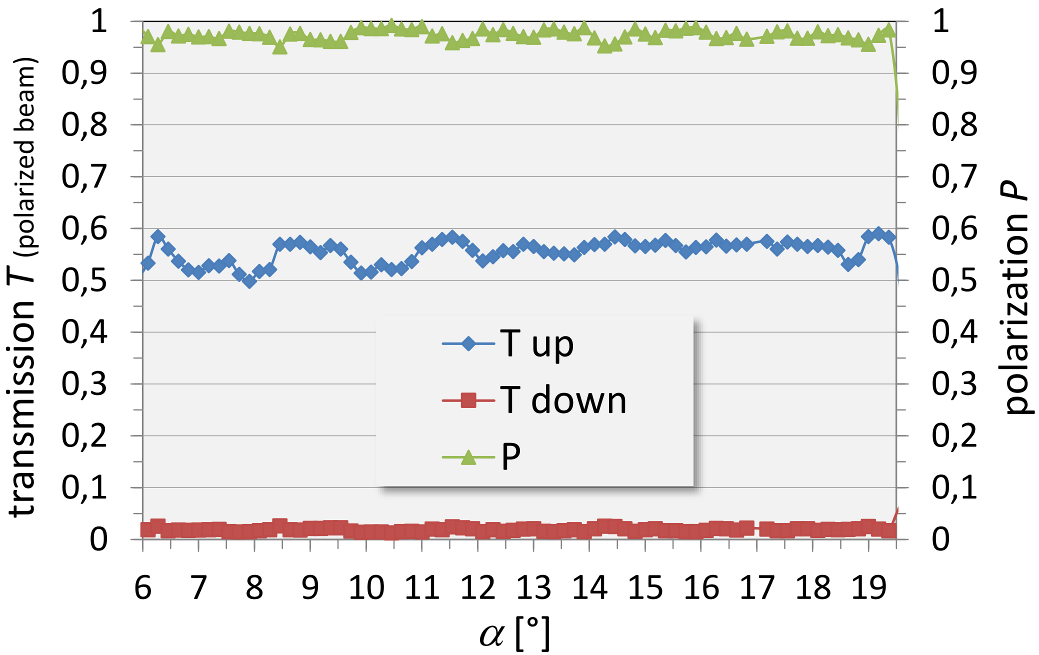
- optimization of magnetic casing



Wide Angle Polarization Analyzer (WAPA)

<u>Neutron tests</u>

- instrument BOA @ PSI
- @ wavelength λ = 3 Å



<u>Performance</u>

- Average transmission (polarized beam): $\langle T_{up} \rangle = 0.55$
- Average polarization: $\langle P \rangle = 97.5\%$

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CONCLUSIONS

- polarizing supermirrors with excellent reflectivity at large *m*-values are available, which enable applications for cold to hot
- computation tools for precise simulation of devices
- sophisticated manufacturing and assembly technologies enable complex neutron optical devices

Benefits of polarization optics with supermirror
- high polarization and efficiency (reflectivity, transmission)
- no maintenance
- push button solutions (efficient use)

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THE END

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