Polarised Neutrons

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Content

- Beam polarisation vector
- Spin flippers and Spin filters
- Cross-section & scattered polarisation vector
- PND - Polarised neutron diffraction (powder, crystal)
- UPA - Uniaxial polarisation analysis
- SNP - Spherical neutron polarimetry
- Polarimetric Neutron Spin Echo

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Beam polarisation vector

neutron spin & neutron magnetic moment

- The neutron carries a spin $\vec{s}$ which is an internal angular momentum with a quantum number $s = 1/2$. The general spin wave of an itinerant neutron is:

$$|\chi\rangle = a|+\rangle + b|-\rangle \text{ where } |a|^2 + |b|^2 = 1$$

- The 3 components of this angular momentum are given by the Pauli matrices representing $\vec{\sigma} = 2\vec{s}/\hbar$:

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -\imath \\ \imath & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

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Beam polarisation vector

neutron spin & neutron magnetic moment

- The neutron carries a magnetic moment:

$$\mu_n = \gamma_n \mu_B \vec{\sigma} \text{ where } \gamma_n = -1.913$$

- The gyromagnetic ratio of the neutron is the ratio between the magnetic moment and the spin moment:

$$\vec{\mu_n} = \gamma_L \vec{s}$$

$$\text{where } \gamma_L = \frac{2\gamma_n \mu_B}{\hbar} = -1.832 \cdot 10^8 \text{ rad.s}^{-1}.\text{T}^{-1}$$

NB: the magnetic moment and spin are opposed.

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Beam polarisation vector

polarisation of a neutron beam

- The neutron beam is a statistical ensemble of several quantum states and the beam polarisation $\vec{P} = \langle \vec{\sigma} \rangle$.
- We use the density matrix to describe this statistical quantum system:

$$\hat{\rho} = \frac{1}{2}\left(\mathbb{1} + \vec{\sigma} \cdot \vec{P}\right) = \frac{1}{2}\begin{bmatrix} 1 + P_z & P_x - \imath P_y \\ P_x + \imath P_y & 1 - P_z \end{bmatrix}$$

Only 3 real numbers are required to describe this 2x2 matrix, i.e. the statistical quantum situation.

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Beam polarisation vector

polarisation of a neutron beam

- The beam polarisation can therefore be seen as a vector in space:

$$\vec{P} = \langle \vec{\sigma} \rangle = trace\,(\hat{\rho}\ \vec{\sigma})$$

- We can measure each of the 3 orthogonal components in any arbitrary direction *u* in space:

$$P_u = trace\,[\hat{\rho}\ \ (u_x \sigma_x + u_y \sigma_y + u_z \sigma_z)]$$

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Beam polarisation vector

polarisation of a neutron beam

- Experimentally, we always measure the component parallel to the field direction (quantization axis):

$$P = \frac{(r_{p,+} - r_{b,+}) - (r_{p,-} - r_{b,-})}{(r_{p,+} - r_{b,+}) + (r_{p,-} - r_{b,-})}$$

$$\sigma_P^2 = 4\frac{(r_{p,+} - r_{b,+})^2 \left(\sigma_{r_{p,-}}^2 + \sigma_{r_{b,-}}^2\right) + (r_{p,-} - r_{b,-})^2 \left(\sigma_{r_{p,+}}^2 + \sigma_{r_{b,+}}^2\right)}{(r_{p,+} - r_{b,+} + r_{p,-} - r_{b,-})^4}$$

where *r* is a neutron count rate, *p/b* stand for peak/background, +/- for the spin states.

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Beam polarisation vector

polarisation of a neutron beam

- For historical reasons, some people prefer to measure the *flipping ratio*:

$$R = \frac{r_{p,+} - r_{b,+}}{r_{p,-} - r_{b,-}} \quad \left(P = \frac{R-1}{R+1} \right)$$

$$\sigma_R^2 = \frac{(r_{p,+} - r_{b,+})^2 \left(\sigma_{r_{p,-}}^2 + \sigma_{r_{b,-}}^2 \right) + (r_{p,-} - r_{b,-})^2 \left(\sigma_{r_{p,+}}^2 + \sigma_{r_{b,+}}^2 \right)}{(r_{p,-} - r_{b,-})^4}$$

but it has no physical meaning and *P* is recommanded.

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Beam polarisation vector

polarisation of a neutron beam

- You can optimise the distribution of the times spent on the peak, the background and the [+] and [-] spin states to reduce the error bar.

  Hopelessly, only [+]/[-] counting times can be optimsed with a 2D detector.

  See http://www.ill.eu/sane/software/xop-plugins-for-igor-pro/neutron-scattering-xop/ for an Igor Pro XOP providing all routines.

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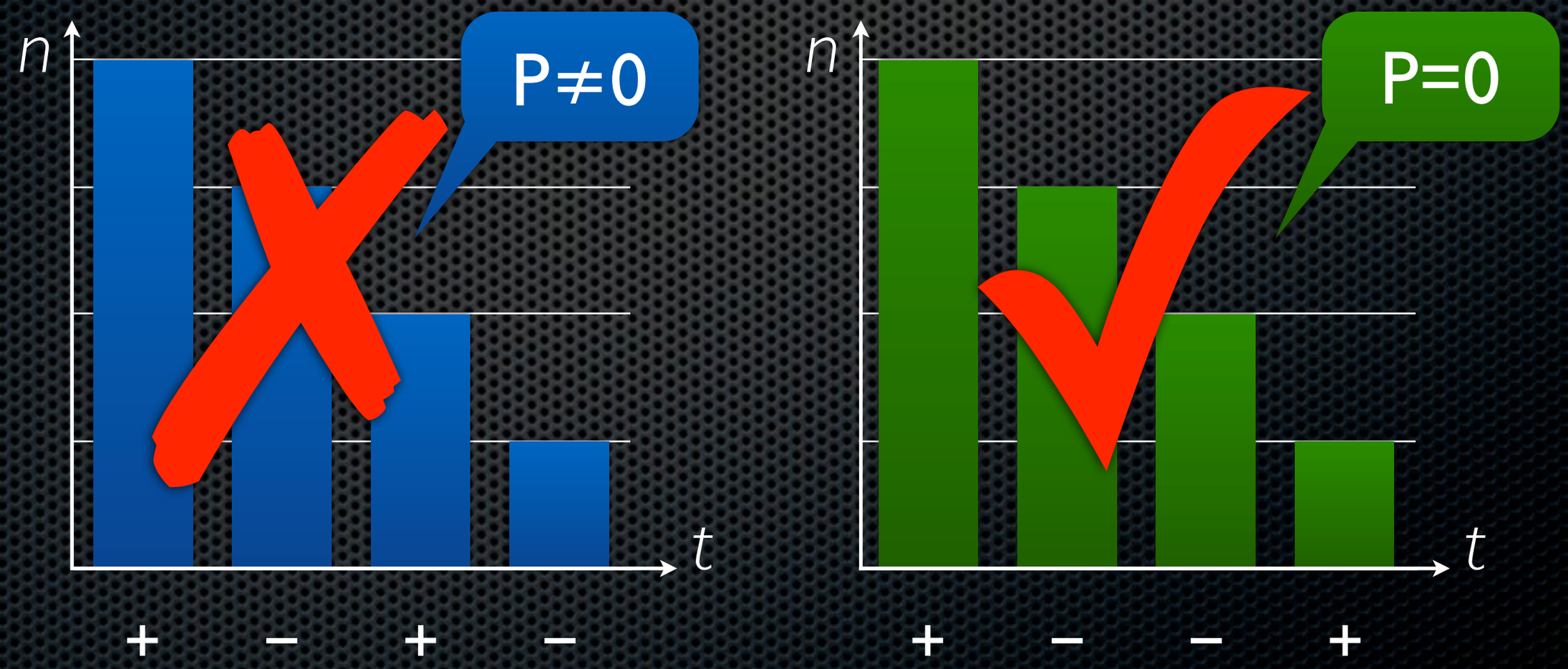
Beam polarisation vector

polarisation of a neutron beam

- You must compensate for the variations of the incident flux: choose the right sequence and a stable detector.



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Beam polarisation vector

polarisation of a neutron beam

- Using a *flipping control unit*, you can also minimize the error bar by taking advantage of the high-precision clock of your counter:

$$P_{opt} = \frac{M_b\, t_p\, t_{b,+}\, t_{b,-}\, (N_{p,+} t_{p,-} - N_{p,-} t_{p,+}) - M_p\, t_b\, t_{p,+}\, t_{p,-}\, (N_{b,+}\, t_{b,-} - N_{b,-}\, t_{b,+})}{M_b\, t_p\, t_{b,+}\, t_{b,-}\, (N_{p,+} t_{p,-} + N_{p,-} t_{p,+}) - M_p\, t_b\, t_{p,+}\, t_{p,-}\, (N_{b,+}\, t_{b,-} + N_{b,-}\, t_{b,+})}$$

$$\sigma^2_{P_{opt}} = \frac{M_b\, t_p^2\, t_{b,+}^2\, t_{b,-}^2}{P_d^2} \left[\begin{array}{c} ((1+P_{opt})\; t_{p,+}\, N_{p,-} - (1-P_{opt})\; t_{p,-}\, N_{p,+})^2 + \\ M_b \left((1+P_{opt})^2\; t_{p,+}^2\, N_{p,-}^2 + (1-P_{opt})^2\; t_{p,-}^2\, N_{p,+}^2 \right) \end{array} \right]$$

$$+ \frac{M_p\, t_b^2\, t_{p,+}^2\, t_{p,-}^2}{P_d^2} \left[\begin{array}{c} ((1+P_{opt})\; t_{b,+}\, N_{b,-} - (1-P_{opt})\; t_{b,-}\, N_{b,+})^2 + \\ M_p \left((1+P_{opt})^2\; t_{b,+}^2\, N_{b,-}^2 + (1-P_{opt})^2\; t_{b,-}^2\, N_{b,+}^2 \right) \end{array} \right]$$

with P_d = denominator of P_{opt}

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Beam polarisation vector

polarisation of a neutron beam

- Heusler Cu_2MnAl crystals: monochromatised beam, large $\lambda/2$ contamination, ≈15 cm height max. (mag. saturation), 95% polarisation with some variation on the beam section.
- Polarising supermirrors: efficient above 2.5Å, 85-95% polarisation but angular dependent unless in crossed geometry (reduced transmission).
- ^{3}He spin filters: polarisation decoupled from optical functions, compromise polarisation/transmission.

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Beam polarisation vector

the action of a magnetic field

- In a magnetic field, the polarisation rotates around the field in a Larmor precession with the frequency:

$$\omega_L(\mathrm{rad/s}) = 18\,325\ B(G)$$

- With *B* aligned along the *z*-axis, we find:

$$\begin{cases} P_x(t) = \cos(\omega_L.t)P_x(0) - \sin(\omega_L.t)P_y(0) \\ P_y(t) = \sin(\omega_L.t)P_x(0) + \cos(\omega_L.t)P_y(0) \\ P_z(t) = P_z(0) \end{cases}$$

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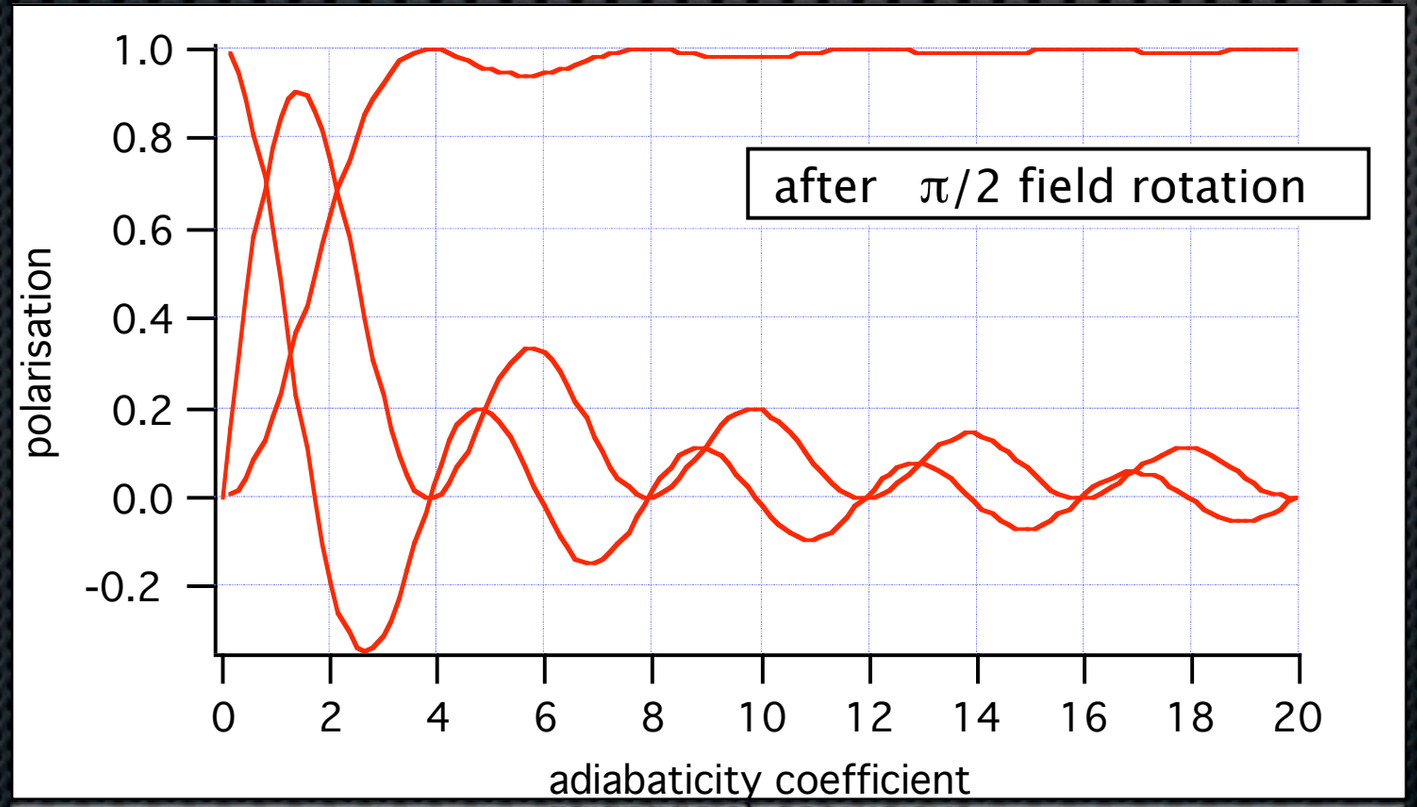
Beam polarisation vector

the action of a magnetic field

- If the guiding field rotates slowly compared to the Larmor precession frequency, the polarisation is transported adiabatically.



$$E = \frac{\omega_L}{\omega_B} \gg 30$$

Zeeman energy conserved

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Beam polarisation vector

the action of a magnetic field

- If the guiding field rotates slowly compared to the Larmor precession frequency, the polarisation is transported adiabatically.

Typically, for a 90° rotation over 10 cm

λ [Å]	0.4	1	4	10
B [G]	255	102	25	10

$$E = \frac{\omega_L}{\omega_B} \gg 30$$

Zeeman energy conserved

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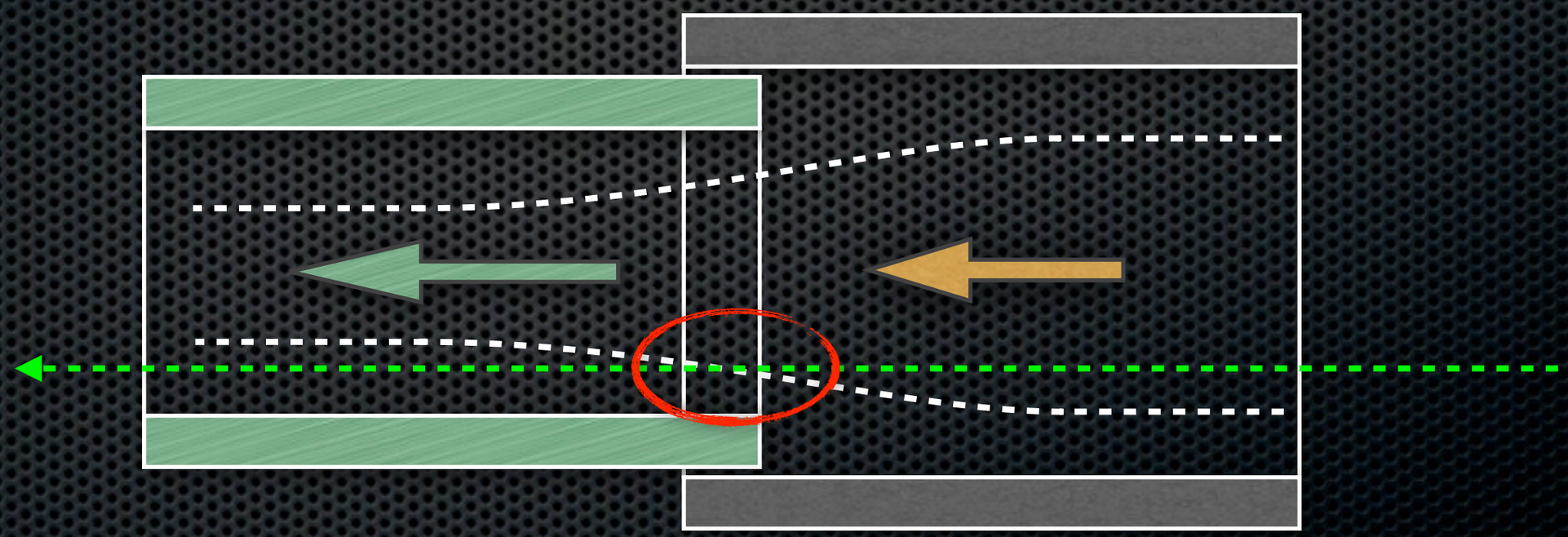
Beam polarisation vector

the action of a magnetic field

- When setting up guiding fields, always be careful with the reduction of the field amplitude at the location where neutrons see a field rotation.



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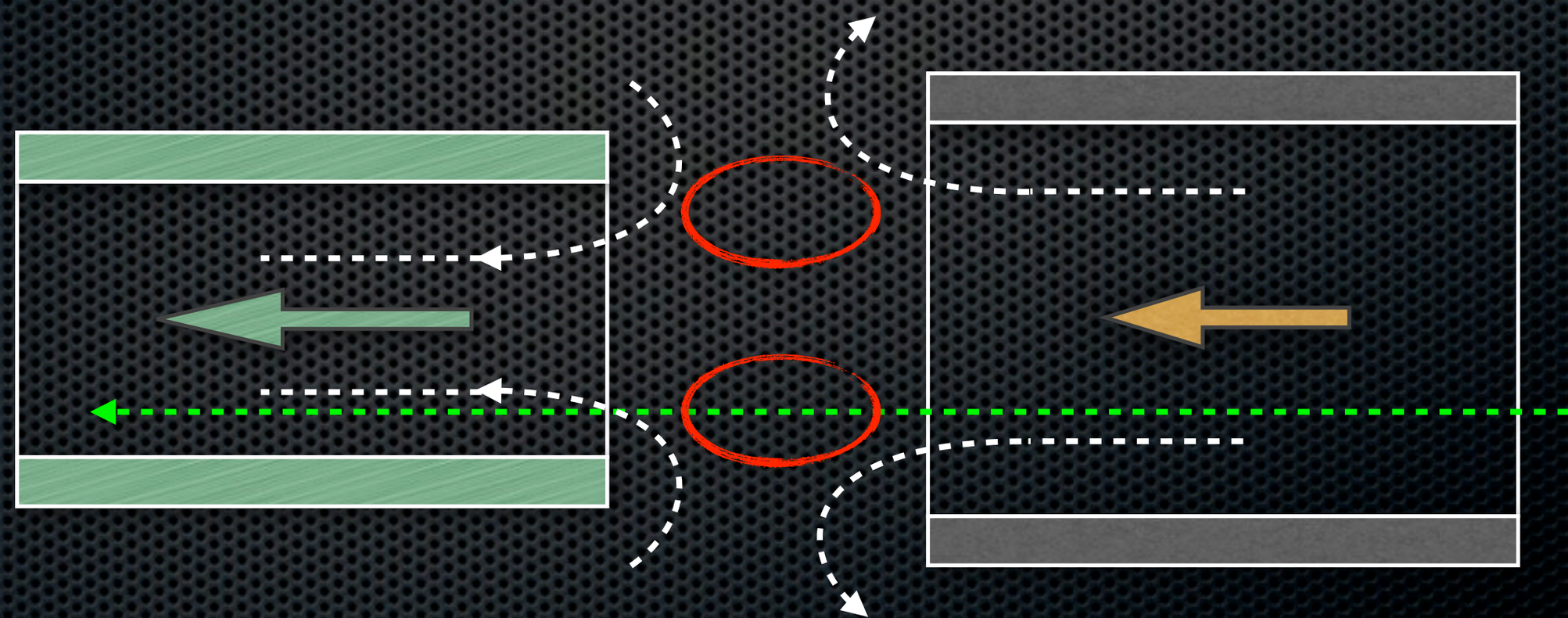
Beam polarisation vector

the action of a magnetic field

- The gaps between guiding field coils can lead to depolarisation, even when the fields are parallel. Also true for permanent magnets.



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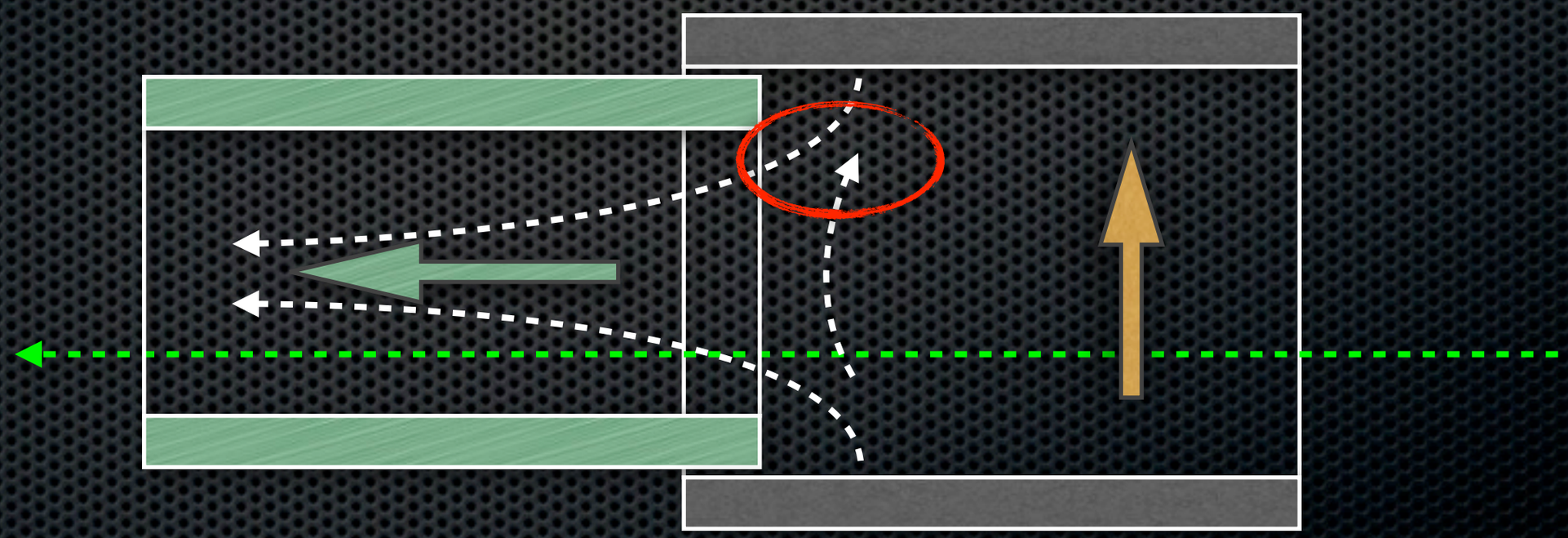
Beam polarisation vector

the action of a magnetic field

- In spin rotators, the loss of polarisation generally comes from the region where the fields cancel, which is also where the field (polarisation) rotates.



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Beam polarisation vector

the action of a magnetic field

- The Magnaprobe is a very useful tool. It illustrates very well the true shape of the magnetic field…

  but <u>NOT its magnitude</u> !

λ [Å]	0.4	1	4	10
B [G]	255	102	25	10

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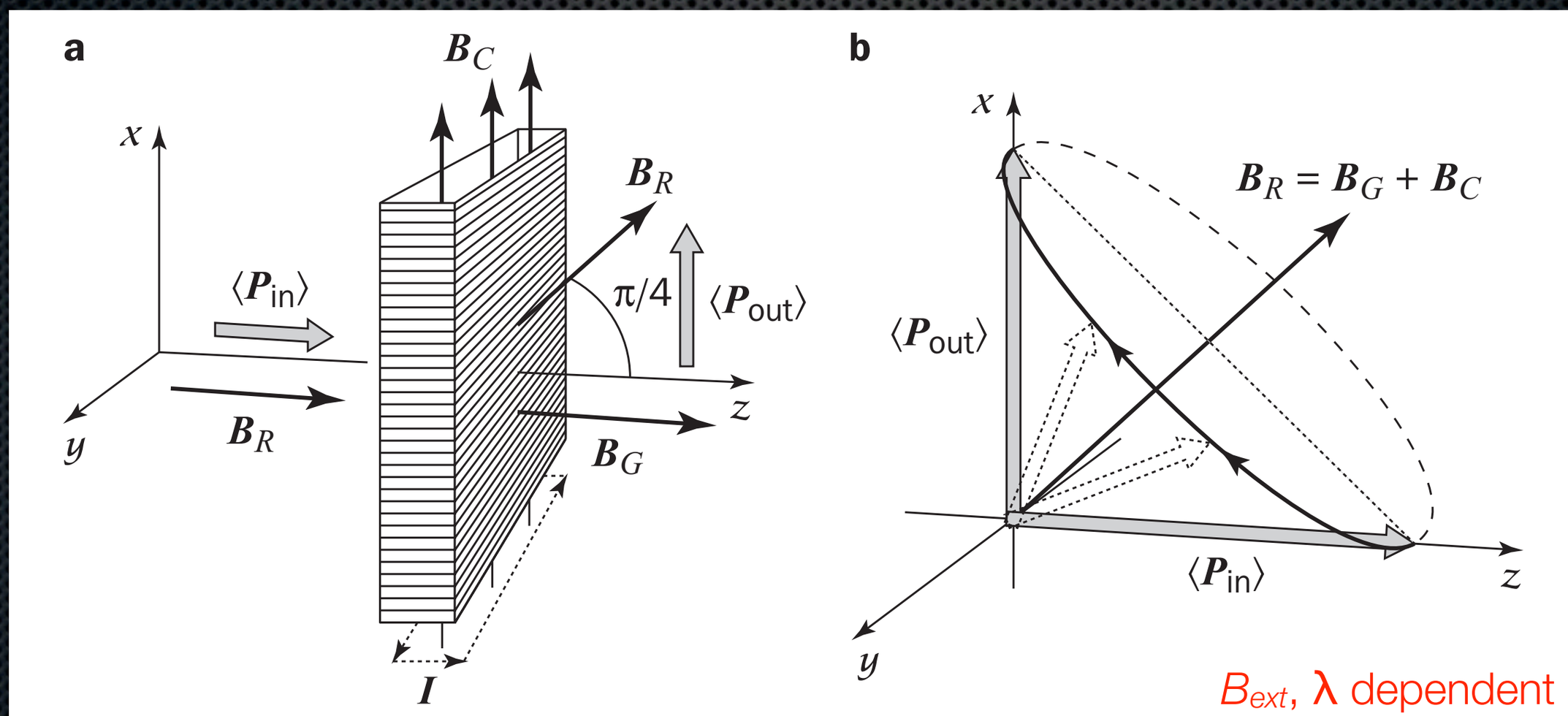
Spin Flippers & Spin Filters

Mezei's flipper

- Example of a π/2 flipper: the neutrons enter and exit the coil non-adiabatically.



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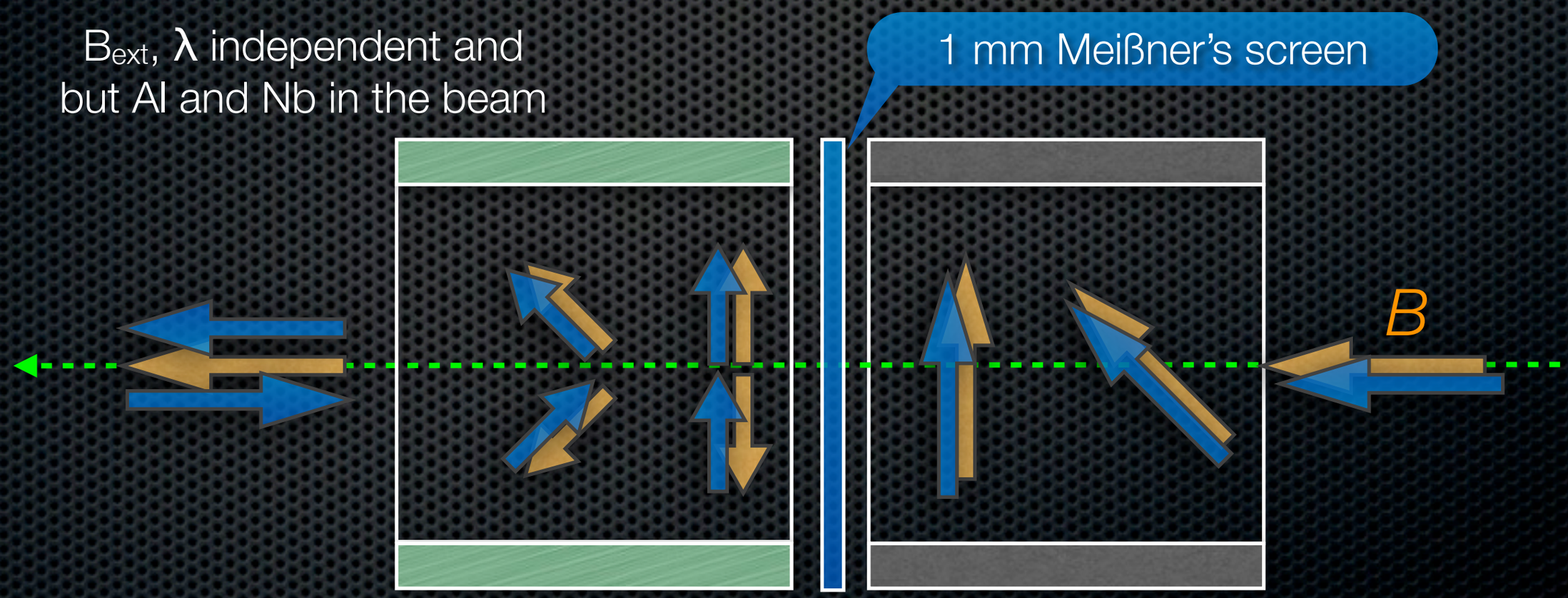
Spin Flippers & Spin Filters

Tasset's cryoflipper

- The neutrons enter the second coil non-adiabatically. Perfect flipper even in 400G stray field.

B_{ext}, λ independent and but Al and Nb in the beam



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Spin Flippers ...

Tasset's cryoflipper

- 99.9% efficient
- $\lambda > 0.4$ Å
- 10L liquid He
- 3 weeks autonomy
- Al & Nb in beam
- To be cooled down in zero field !

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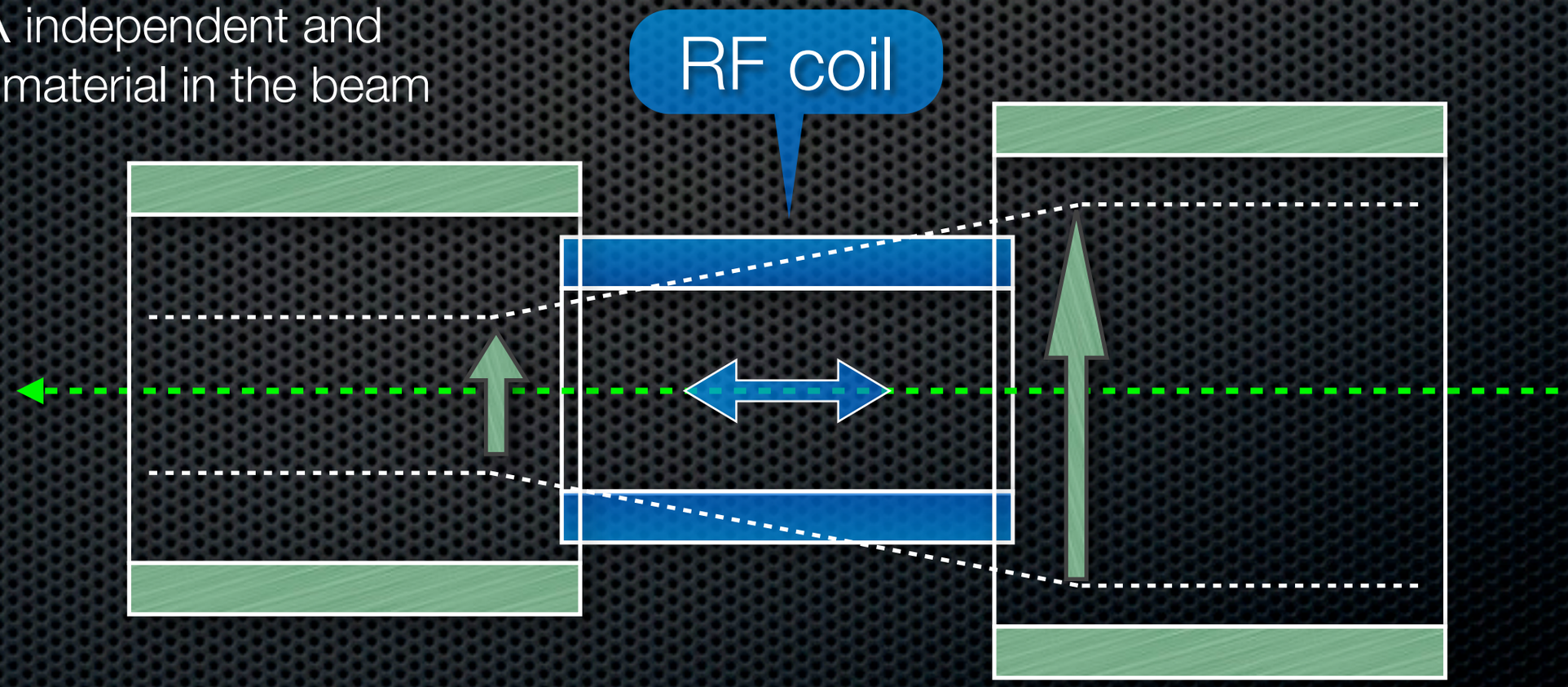
Spin Flippers & Spin Filters

RF adiabatic flipper

- In the rotating frame of the neutron, the polarisation follows the effective field and rotates adiabatically.

λ independent and
no material in the beam



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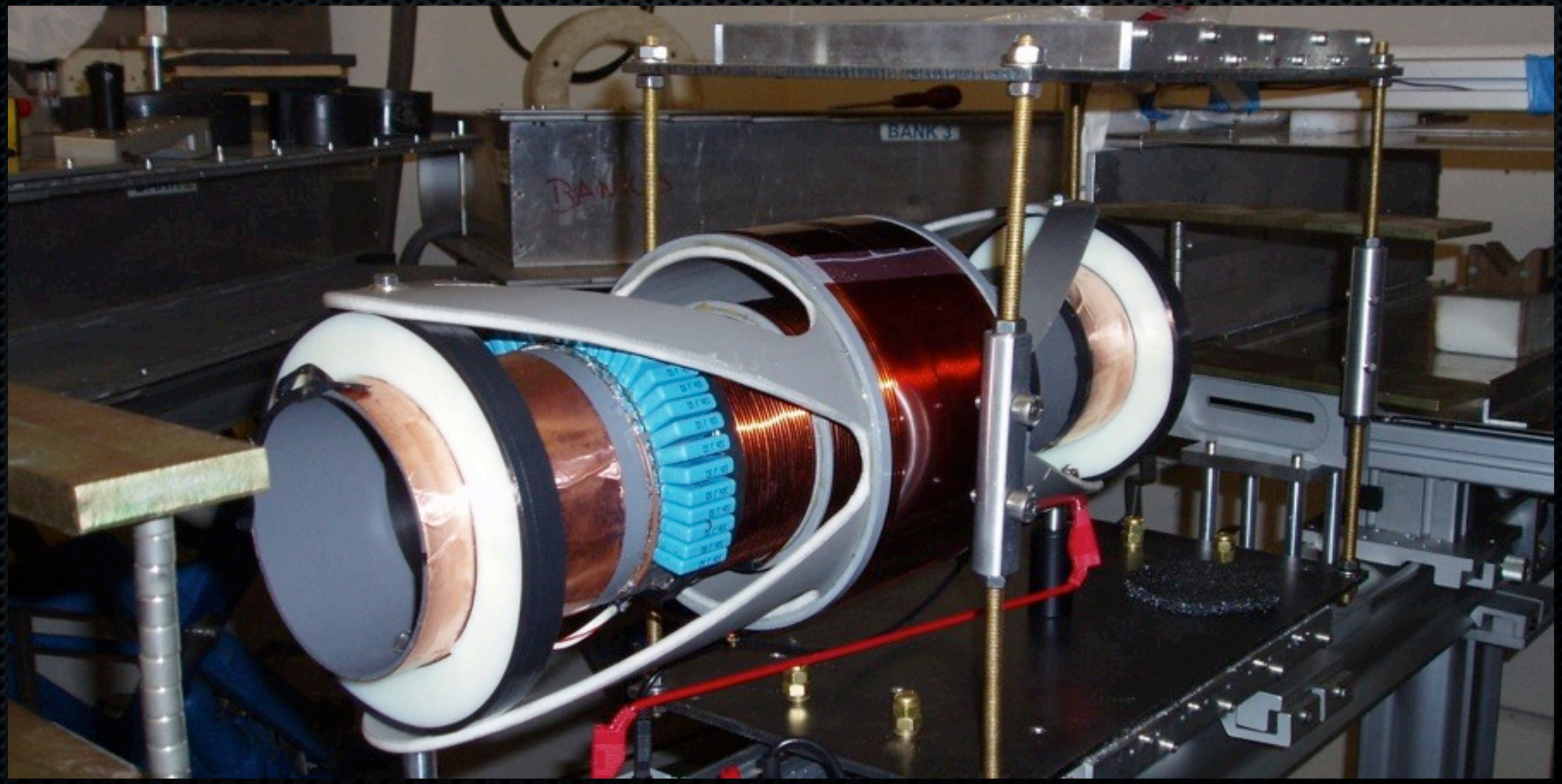
Spin Flippers & Spin Filters

RF adiabatic flipper

153 kHz/10 A adiabatic flipper for λ>0.4Å



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Spin Flippers & Spin Filters

^{3}He spin filters: optimised opacity

- Spin filters are characterised by their opacity:

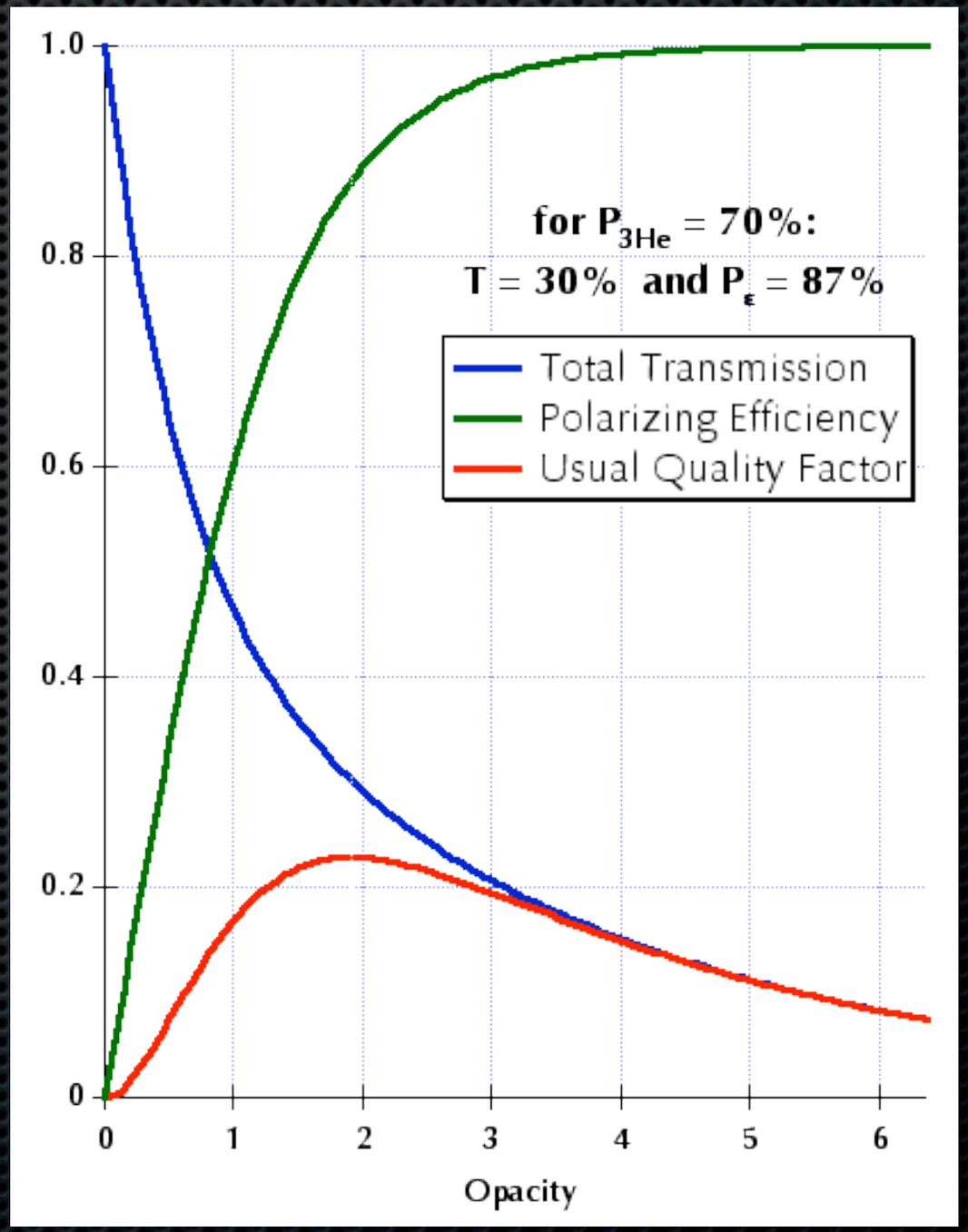
$$\mathcal{O} = N\,\ell\,\sigma_{\nparallel}$$

$$\simeq 0.0797\ p[\mathrm{bar}]\ \ell[\mathrm{cm}]\ \lambda[\mathrm{\AA}]$$

- The total transmission and polarising efficiency are:

$$T_n \propto \cosh\left(\mathcal{O} P_{^3He}\right)$$

$$P_\epsilon = \tanh\left(\mathcal{O} P_{^3He}\right)$$



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Spin Flippers & Spin Filters

^{3}He polarising techniques: MEOP & SEOP

MEOP

- low pressure (≈0.6 mbar) followed by compression
- cell ready in 1-2 hours
- 75 - 80% ^{3}He polarisation on instrument
- large system delivering gas remotely

SEOP

- directly at nominal pressure (1-4 bar)
- cell ready after 1-2 days
- 75 - 82% ^{3}He polarisation on instrument
- compact system which can be installed on beam

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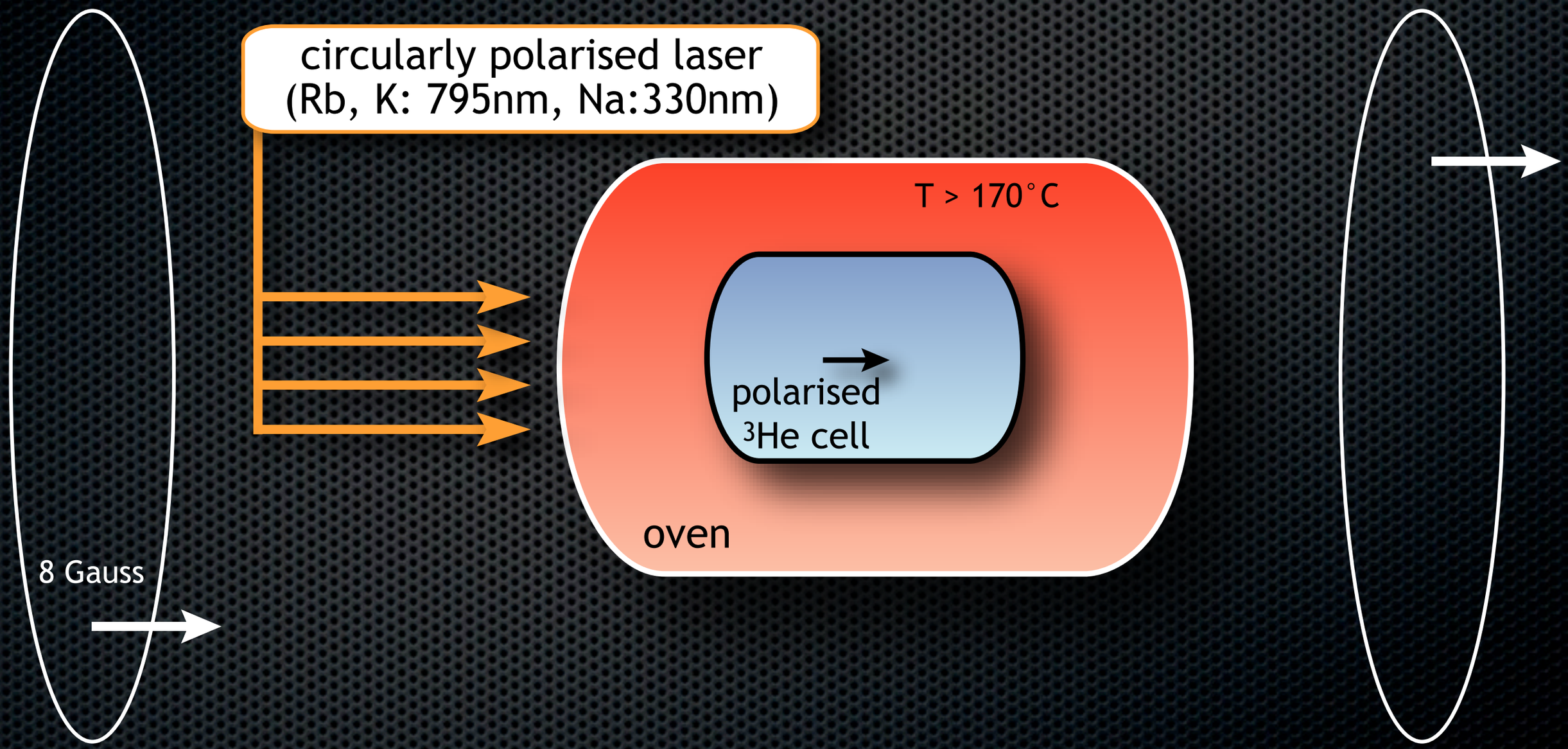
Spin Flippers & Spin Filters

^{3}He polarising techniques: SEOP station



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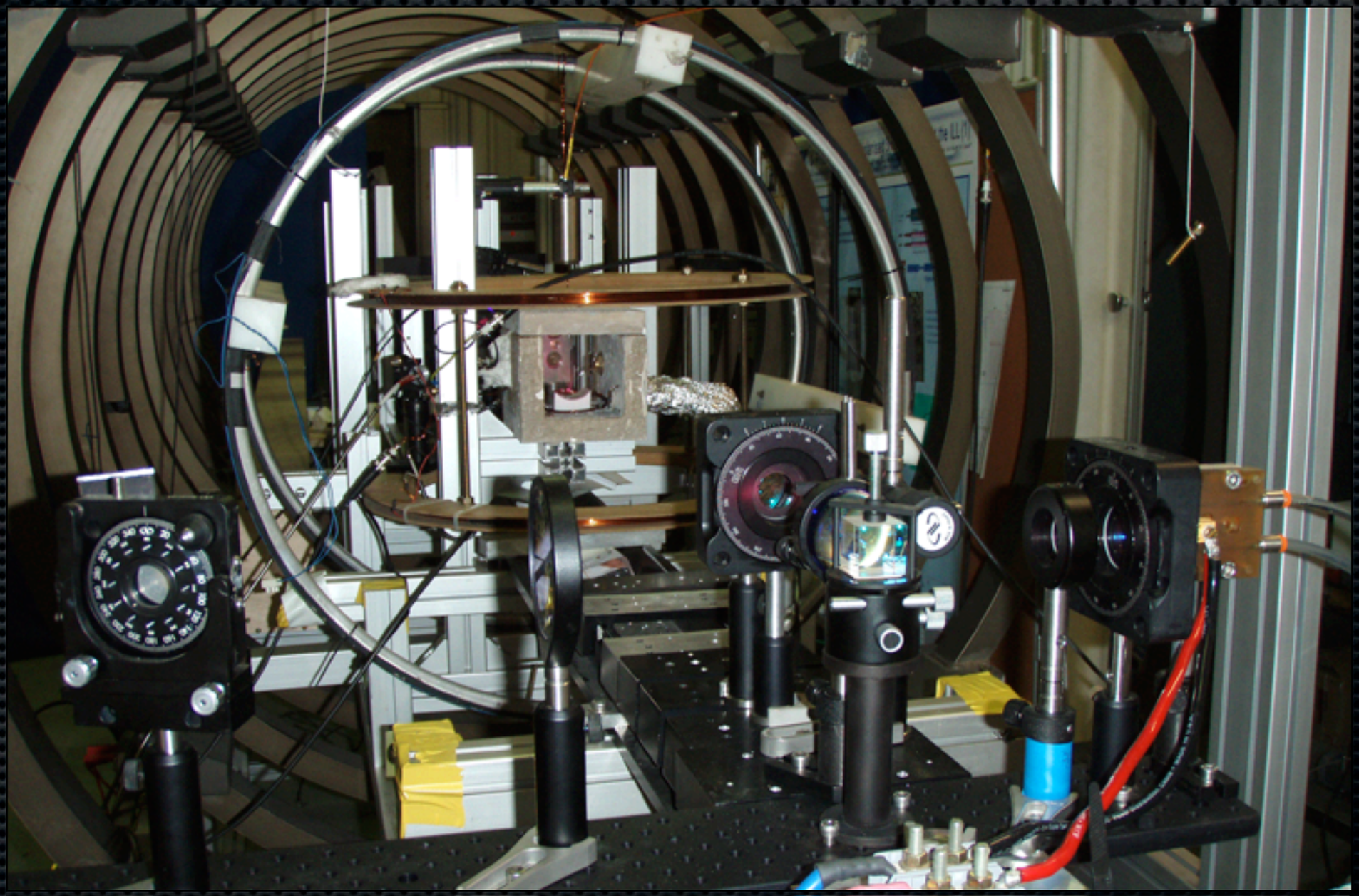

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Spin Flippers & Spin Filters

^{3}He polarising techniques: SEOP station

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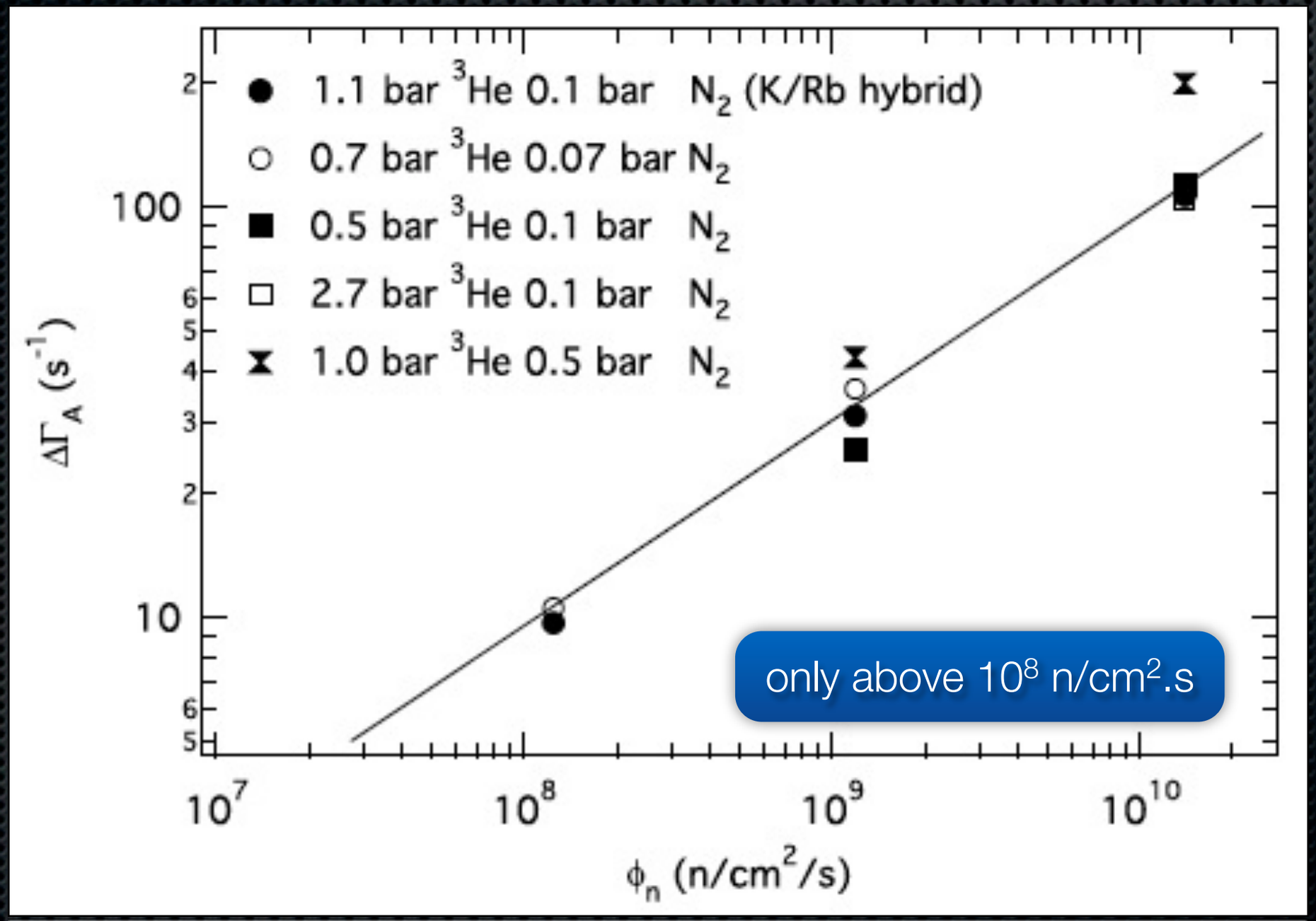
Spin Flippers & Spin Filters

^{3}He polarising techniques: SEOP station



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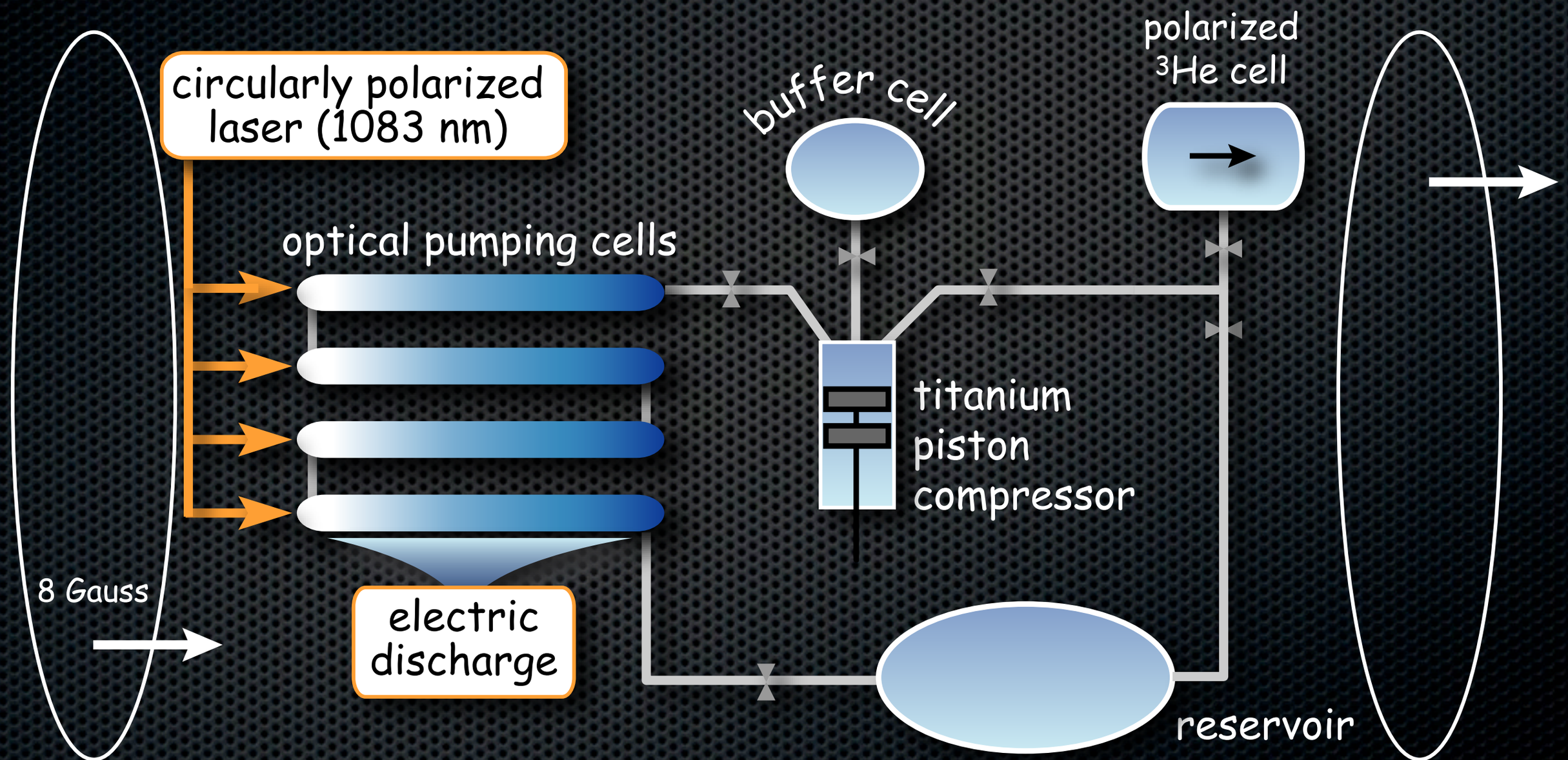
^{3}He polarising techniques: MEOP station



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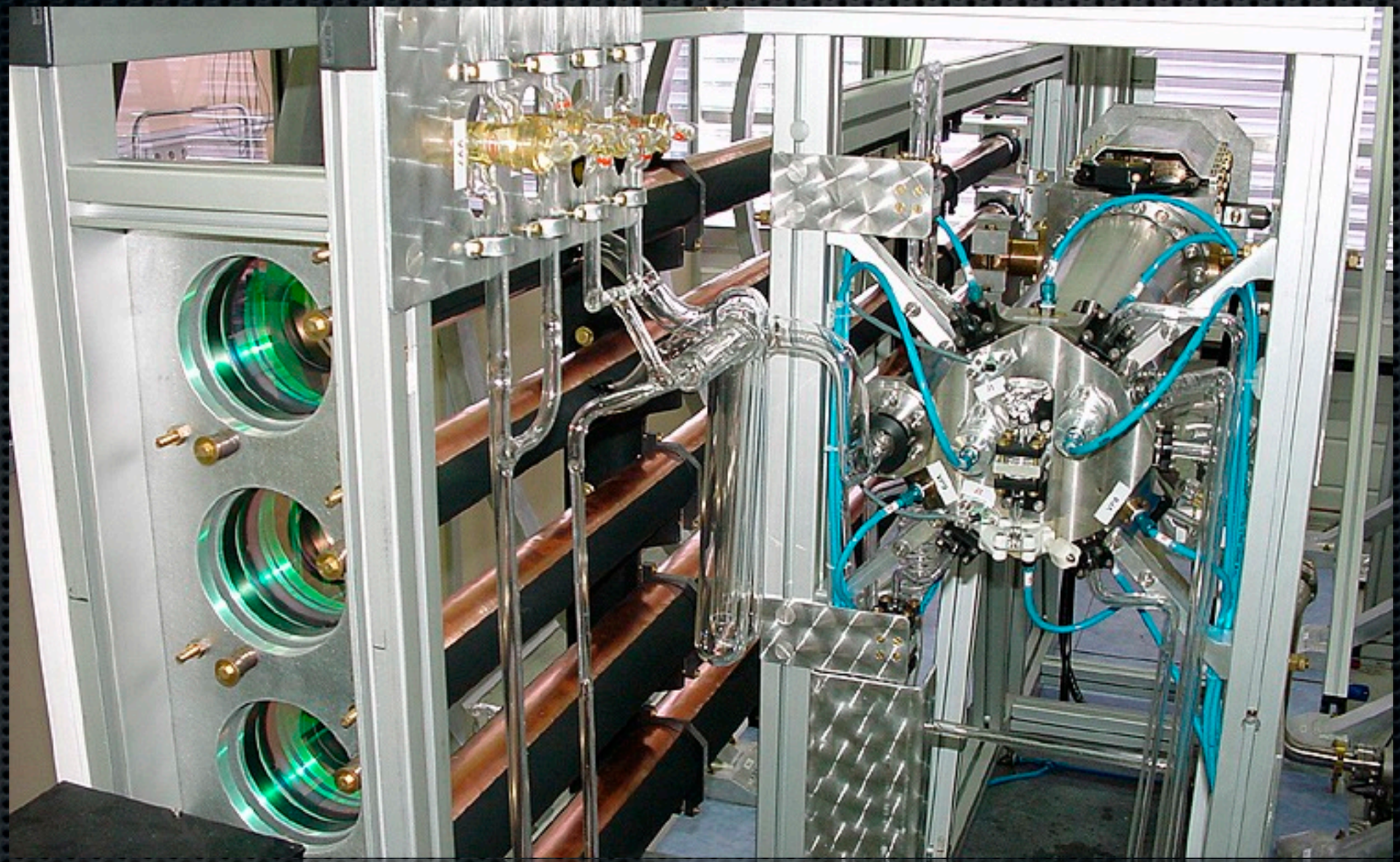

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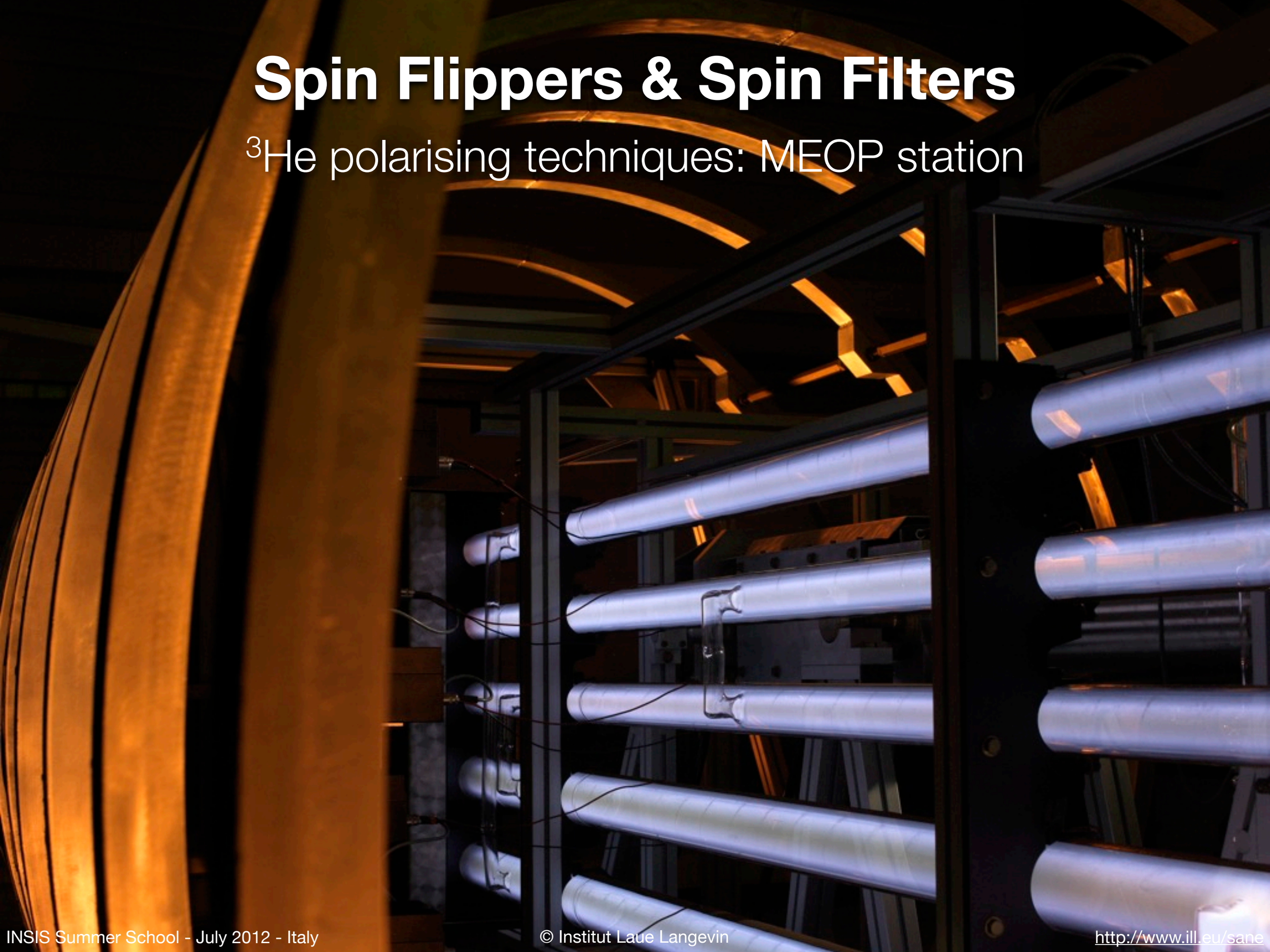

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Spin Flippers & Spin Filters

^{3}He spin filters: cells & magnetostatic cavities

- The main difficulty resides in the ability to build good cells and preserve the ^{3}He polarisation on the instrument:

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Spin Flippers & Spin Filters

^{3}He spin filters: cells & magnetostatic cavities

- The main difficulty resides in the ability to build good cells and preserve the ^{3}He polarisation on the instrument:

$$\frac{1}{T_1} = \frac{1}{T_{wall}} + \frac{1}{T_{field}} + \frac{1}{T_{dipolar}}$$

$$= \gamma \frac{S}{V} + \frac{1.7 \cdot 10^4}{p\,[\mathrm{bar}]} \left(\frac{1}{B_r} \frac{\partial B_r}{\partial r\,[\mathrm{cm}]} \right)^2 + \frac{p\,[\mathrm{bar}]}{830}$$

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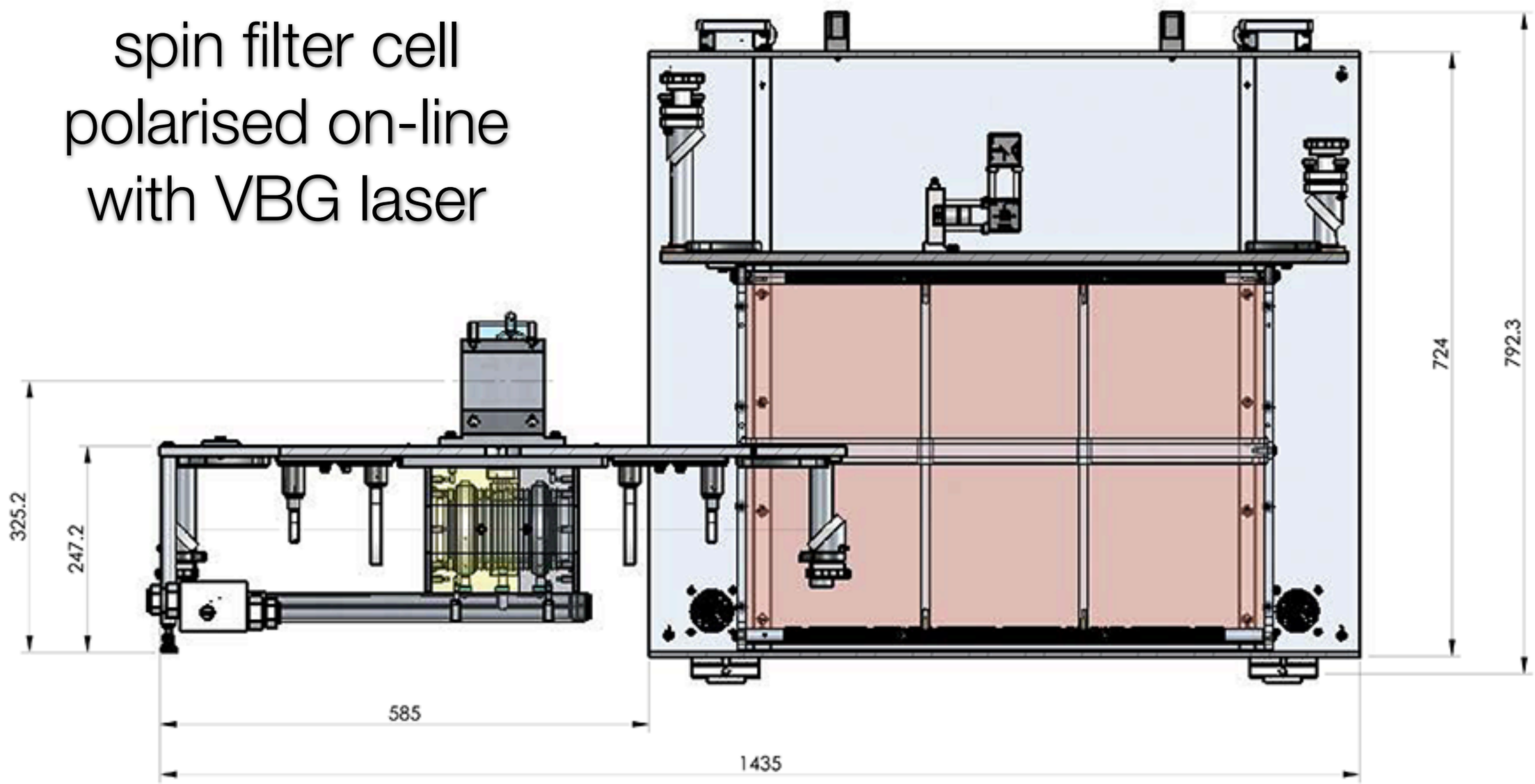
Spin Flippers & Spin Filters

^{3}He spin filters: cells & magnetostatic cavities

spin filter cell
polarised on-line
with VBG laser



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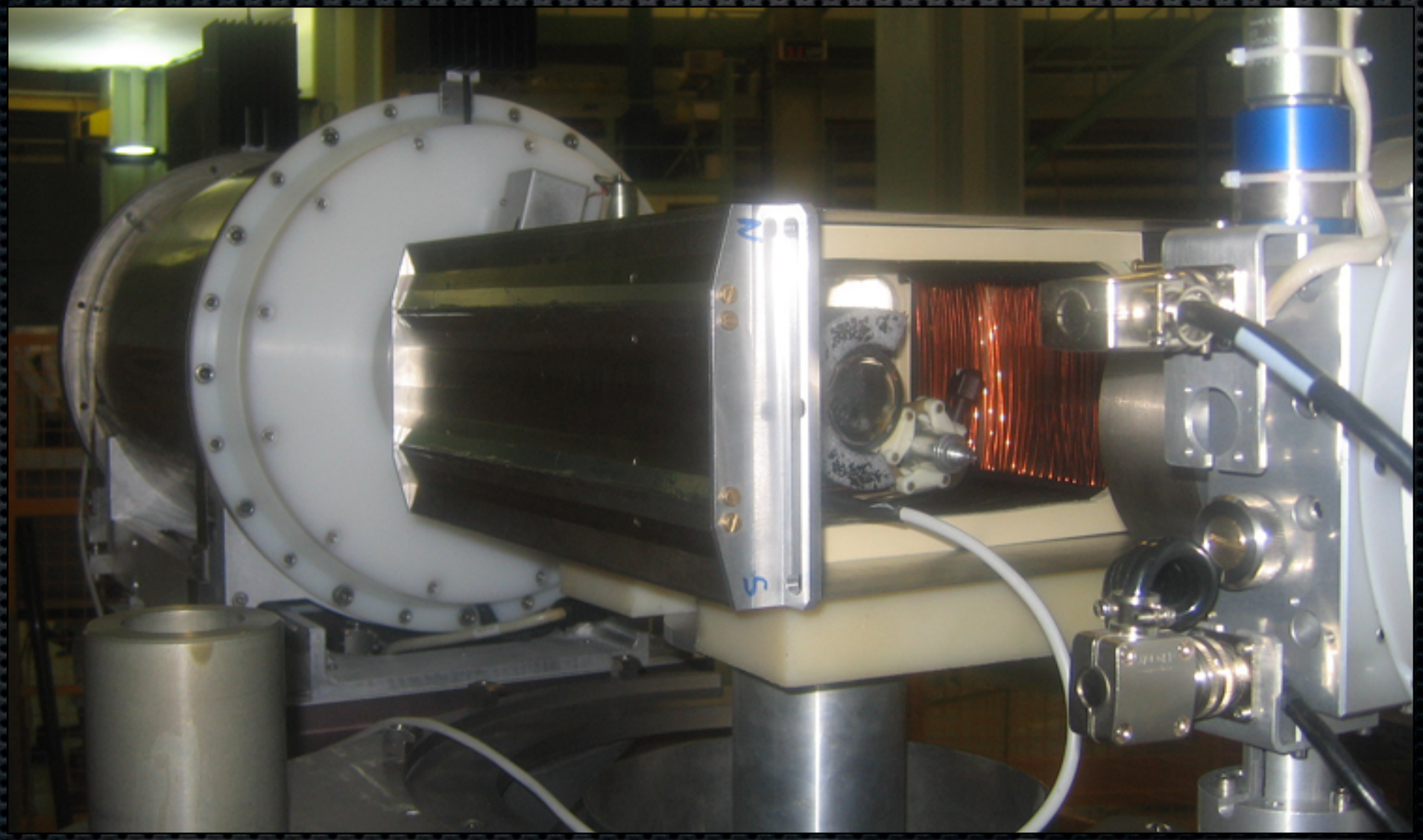
Spin Flippers & Spin Filters

^{3}He spin filters: cells & magnetostatic cavities

long T_1 + RF coil flipping ^{3}He polarisation



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Cross-section & scattered polarisation vector

theory: Maleyev, Blume,... $(\vec{Q} = \vec{k}_i - \vec{k}_f)$

Contribution	Elastic scattering	Inelastic scattering
(n) Nuclear	$\sigma_n = NN^*$ $\{\vec{P}_f\sigma\}_n = \vec{P}_i\,\sigma_n$	$\sigma_n = \frac{k_f}{k_i}\mathcal{H}\left(N_{-\vec{Q}}, N_{\vec{Q}}\right)$ $\{\vec{P}_f\sigma\}_n = \vec{P}_i\,\sigma_n$
(m) Magnetic (I)	$\sigma_m = \vec{M}_\perp \cdot \vec{M}_\perp^*$ $\{\vec{P}_f\sigma\}_m = -\,\vec{P}_i\,\sigma_m\ + \ldots$ $.. \ 2\Re\left(\vec{M}_\perp\left(\vec{P}_i \cdot \vec{M}_\perp^*\right)\right)$	$\sigma_m = \frac{k_f}{k_i}\,S_{\alpha\beta}\,\delta_{\alpha\beta}$ $\{\vec{P_{f,\alpha}}\sigma\}_m = \frac{k_f}{k_i}P_{i\beta} \cdot \ldots$ $.. \ [(S_{\alpha\beta} + S_{\beta\alpha}) - \delta_{\alpha\beta}\delta_{\beta\alpha}]$ $S_{\alpha\beta} = \mathcal{H}\left(M^\alpha_{\perp,-\vec{Q}}, M^\beta_{\perp,\vec{Q}}\right)$
(c) Magnetic (II)	$\sigma_c = \imath\vec{P}_i \cdot \left(\vec{M}_\perp^* \wedge \vec{M}_\perp\right)$ $\{\vec{P}_f\sigma\}_c = -\,\imath\left(\vec{M}_\perp^* \wedge \vec{M}_\perp\right)$	$\sigma_c = \frac{k_f}{k_i}\,\imath\,S_{\alpha\beta}\,\epsilon_{\alpha\beta\gamma}\,P_{i\gamma}$ $\{\vec{P}_{f,\alpha}\sigma\}_c = -\frac{k_f}{k_i}\imath\epsilon_{\alpha\beta\gamma}S_{\beta\gamma}$ $S_{\alpha\beta} = \mathcal{H}\left(M^\alpha_{\perp,-\vec{Q}}, M^\beta_{\perp,\vec{Q}}\right)$
(i) Nuclear–magnetic	$\sigma_i = 2\vec{P}_i \cdot \Re\left(N^*\vec{M}_\perp\right)$ $\{\vec{P}_f\sigma\}_i = 2\Re\left(N^*\vec{M}_\perp\right)\ +$ $2\vec{P}_i \wedge \Im\left(N^*\vec{M}_\perp\right)$	$\sigma_i = \frac{k_f}{k_i}\,\imath\,\vec{S}_+ \cdot \vec{P}_i$ $\{\vec{P}_f\sigma\}_i = \frac{k_f}{k_i}\left(\vec{S}_+ + \imath\vec{S}_- \wedge \vec{P}_i\right)$ $\vec{S}_\pm = \mathcal{H}_\pm\left(N_{-\vec{Q}}, \vec{M}_{\perp,\vec{Q}}\right)$

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Cross-section & scattered polarisation vector

theory: Maleyev, Blume,... ($\vec{Q} = \vec{k}_f - \vec{k}_i$)

Contribution	Elastic scattering	Inelastic scattering
(n) Nuclear	$\sigma_n = NN^*$ $\{\vec{P}_f\sigma\}_n = \vec{P}_i\,\sigma_n$	$\sigma_n = \frac{k_f}{k_i}\mathcal{H}\left(N_{-\vec{Q}}, N_{\vec{Q}}\right)$ $\{\vec{P}_f\sigma\}_n = \vec{P}_i\,\sigma_n$
(m) Magnetic (I)	$\sigma_m = \vec{M}_\perp \cdot \vec{M}_\perp^*$ $\{\vec{P}_f\sigma\}_m = -\,\vec{P}_i\,\sigma_m\ + \ldots$ $.. \ 2\Re\left(\vec{M}_\perp\left(\vec{P}_i \cdot \vec{M}_\perp^*\right)\right)$	$\sigma_m = \frac{k_f}{k_i}\,S_{\alpha\beta}\,\delta_{\alpha\beta}$ $\{\vec{P_{f,\alpha}}\sigma\}_m = \frac{k_f}{k_i}P_{i\beta} \cdot \ldots$ $.. \ [(S_{\alpha\beta} + S_{\beta\alpha}) - \delta_{\alpha\beta}\delta_{\beta\alpha}]$ $S_{\alpha\beta} = \mathcal{H}\left(M^\alpha_{\perp,-\vec{Q}}, M^\beta_{\perp,\vec{Q}}\right)$
(c) Magnetic (II)	$\sigma_c = -\,\imath\vec{P}_i \cdot \left(\vec{M}_\perp^* \wedge \vec{M}_\perp\right)$ $\{\vec{P}_f\sigma\}_c = \imath\left(\vec{M}_\perp^* \wedge \vec{M}_\perp\right)$	$\sigma_c = -\,\frac{k_f}{k_i}\,\imath\,S_{\alpha\beta}\,\epsilon_{\alpha\beta\gamma}\,P_{i\gamma}$ $\{\vec{P}_{f,\alpha}\sigma\}_c = \frac{k_f}{k_i}\imath\epsilon_{\alpha\beta\gamma}S_{\beta\gamma}$ $S_{\alpha\beta} = \mathcal{H}\left(M^\alpha_{\perp,-\vec{Q}}, M^\beta_{\perp,\vec{Q}}\right)$
(i) Nuclear–magnetic	$\sigma_i = 2\vec{P}_i \cdot \Re\left(N^*\vec{M}_\perp\right)$ $\{\vec{P}_f\sigma\}_i = 2\Re\left(N^*\vec{M}_\perp\right) -$ $2\vec{P}_i \wedge \Im\left(N^*\vec{M}_\perp\right)$	$\sigma_i = \frac{k_f}{k_i}\,\imath\,\vec{S}_+ \cdot \vec{P}_i$ $\{\vec{P}_f\sigma\}_i = \frac{k_f}{k_i}\left(\vec{S}_+ - \imath\vec{S}_- \wedge \vec{P}_i\right)$ $\vec{S}_\pm = \mathcal{H}_\pm\left(N_{-\vec{Q}}, \vec{M}_{\perp,\vec{Q}}\right)$

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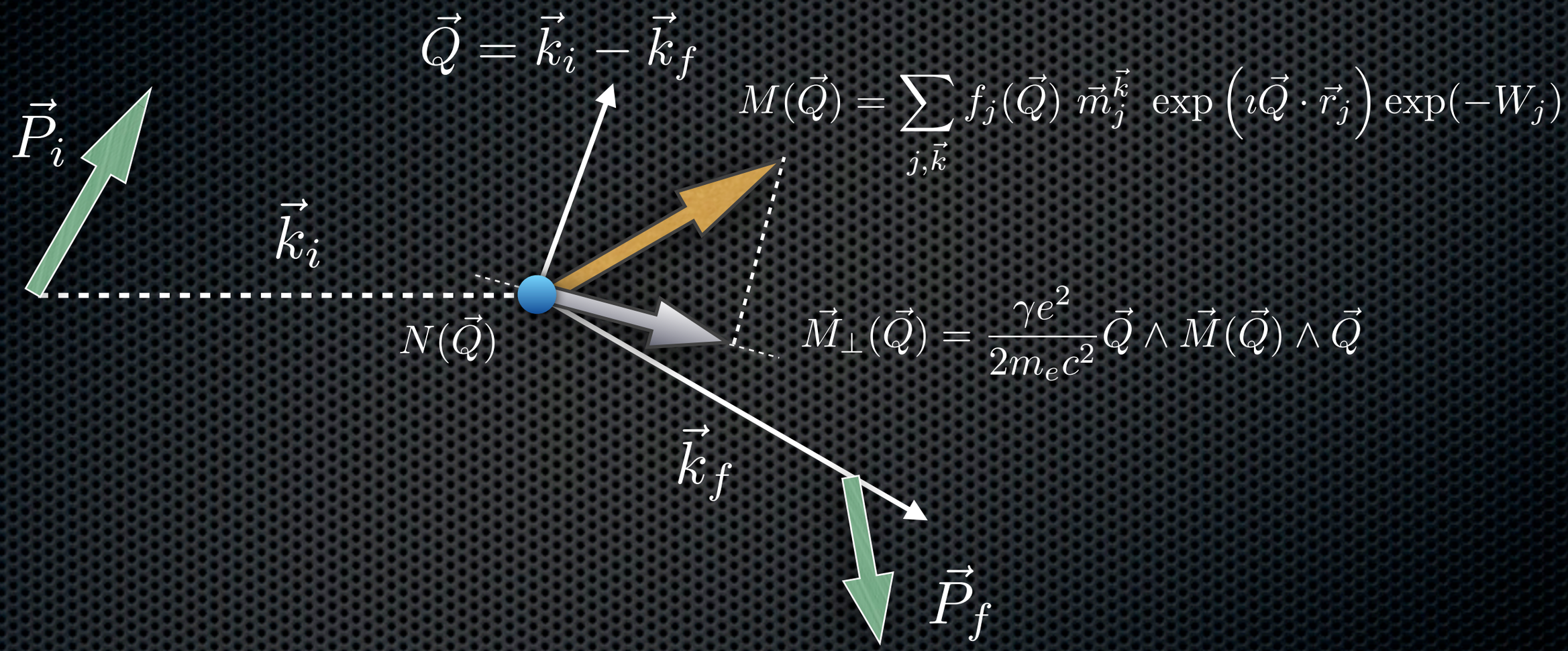
Cross-section & scattered polarisation vector

theory: Maleyev, Blume,...



In general, the polarisation of a neutron beam will change both in magnitude and direction upon scattering from a magnetic material.

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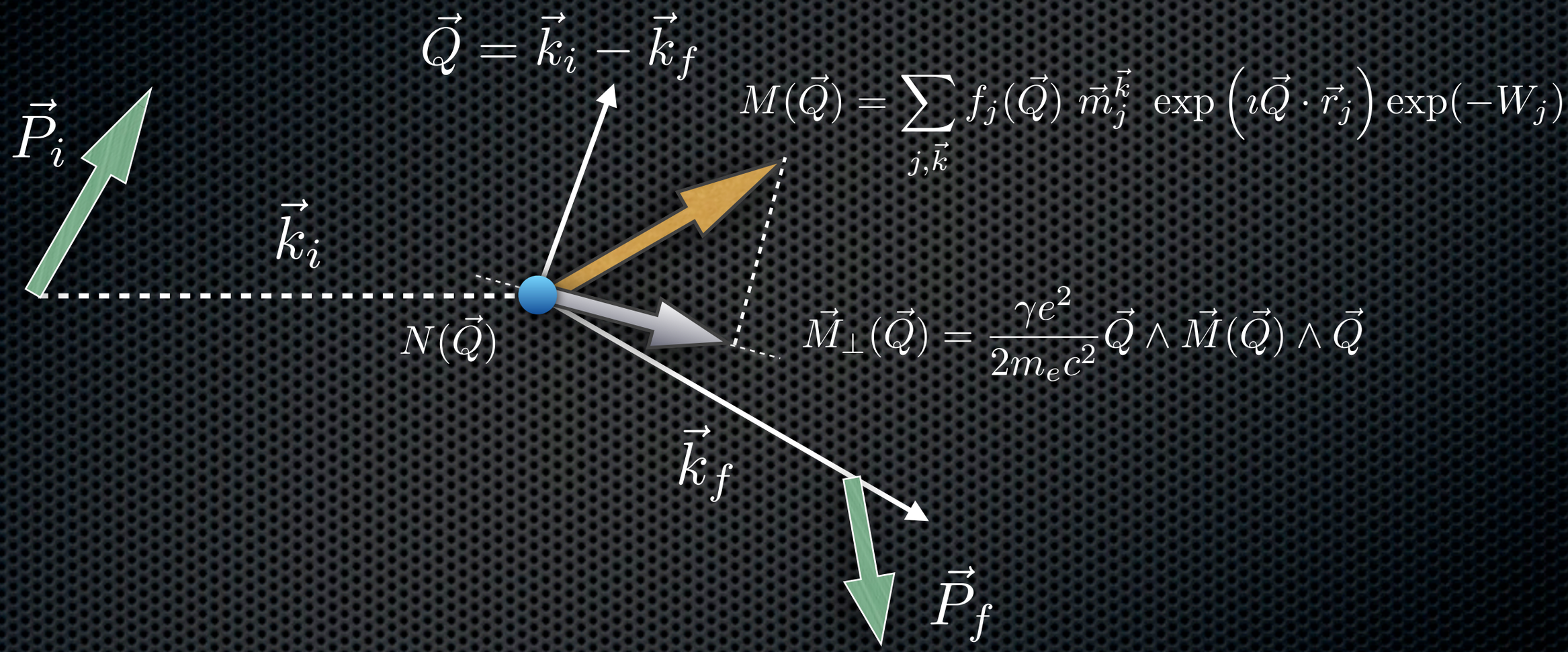
Cross-section & scattered polarisation vector

theory: Maleyev, Blume,...



The changes in direction that take place on scattering by a magnetic interaction vector are highly dependent on their relative orientations.

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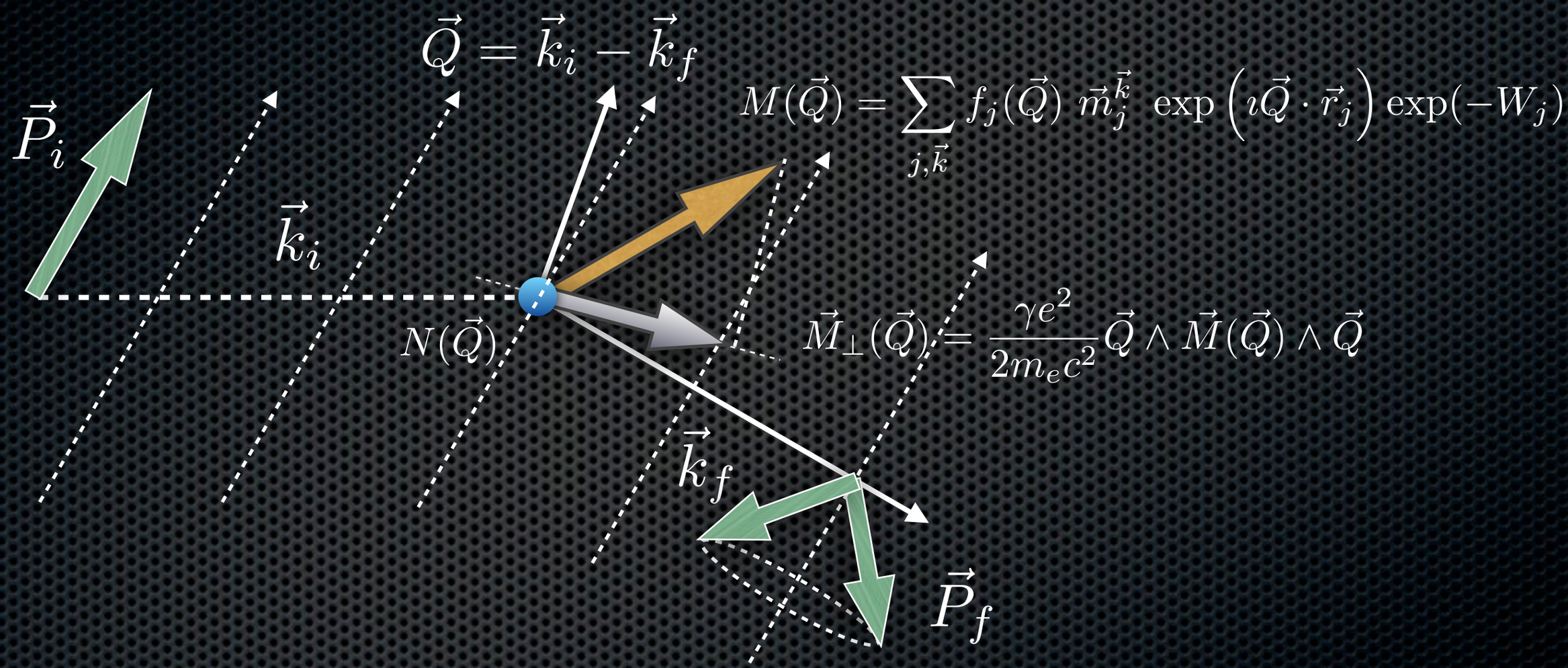
Cross-section & scattered polarisation vector

theory: Maleyev, Blume,...



When a magnetic field is applied at the sample, the Larmor precessions lead to the loss of the components perpendicular to the field.

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Polarised neutron diffraction

applied to the measurement
of magnetisation distributions

- The nuclear-magnetic interference term is exploited to measure ferro- and para-magnetic distributions.

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + 2\vec{P}_i \cdot \Re(N^* \vec{M}_\perp) + i\vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp)$$

- The chiral term allows to measure the anti-ferromagnetic distributions of chiral systems.

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Polarised neutron diffraction (powder)

magnetisation of disordered systems
with no anisotropy and low magnetisation

- Method: flipping difference

$$\left(\frac{\partial\sigma}{\partial\Omega}\right)_+ = NN^* + M_\perp M_\perp^* + 2P_i N\, M_\perp + \imath P_i \cdot 0$$

$$\left(\frac{\partial\sigma}{\partial\Omega}\right)_- = NN^* + M_\perp M_\perp^* - 2P_i N\, M_\perp - \imath P_i \cdot 0$$

$$\Delta = 4P_i\, N\, M_\perp$$

➥ Background suppressed, higher sensitivity, easy to scale and to correct for polarisation

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Polarised neutron diffraction (powder)

magnetisation of disordered systems
with no anisotropy and low magnetisation

- The instrument is a powder diffractometer featuring:
  - a polariser and a flipper
  - a cryomagnet (typically 40 mK to 300 K, 0 to 10 T)
  - a radial oscillating collimator to get rid of the background when measuring without polarised neutrons
  - a method for determining the incident polarisation and the sample depolarisation

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Polarised neutron diffraction (powder)

magnetisation of
disordered systems
with no anisotropy and
low magnetisation
e.g.
molecular magnets
nano-scale samples
biological samples
...

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Polarised neutron diffraction (powder)

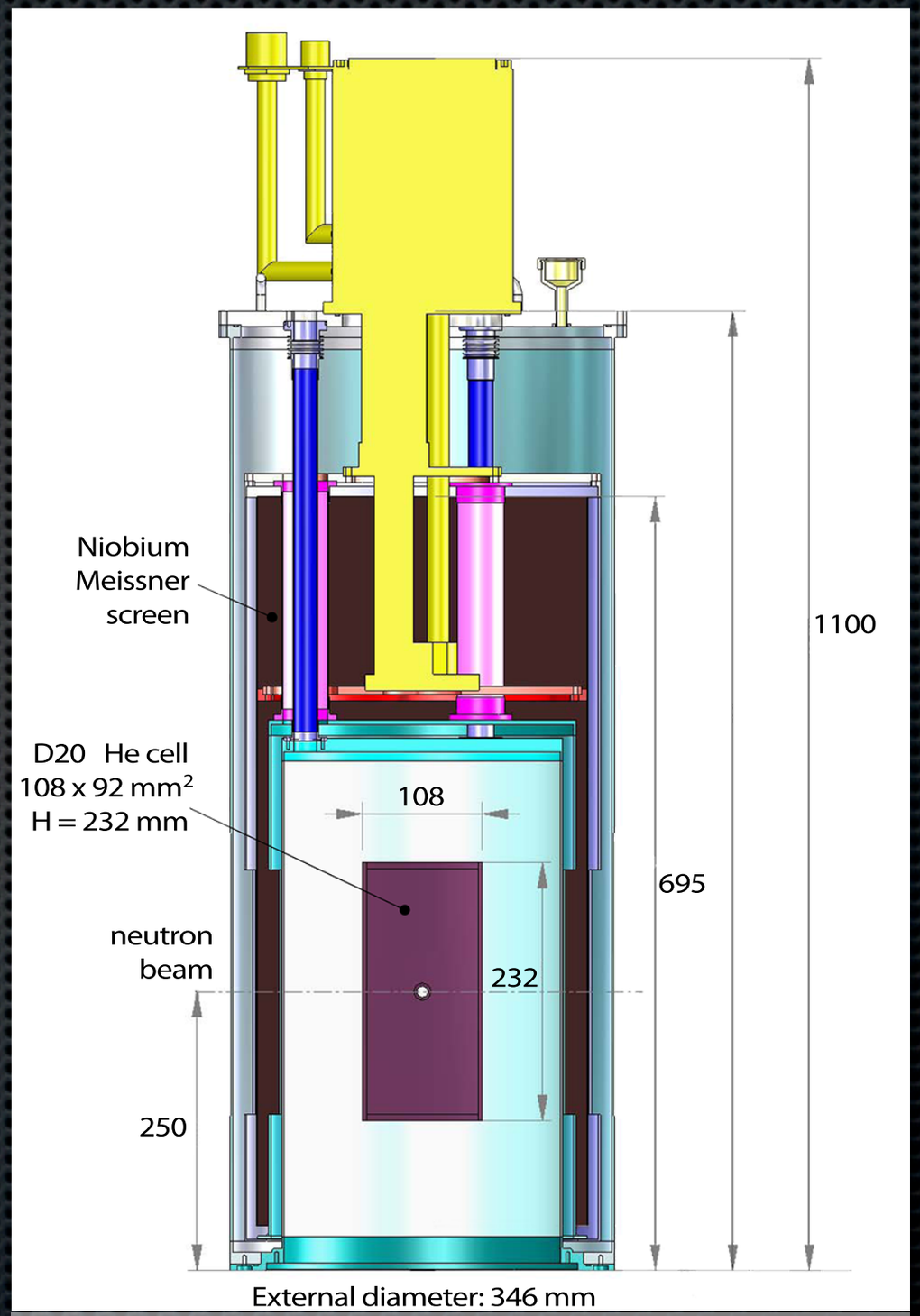
polariser/flipper used on D20

Cryopol

neutron beam polarised
with a ^{3}He spin filter

^{3}He polarisation maintained
with homogeneous field
trapped in Meißner cylinder

polarisation flipped
using non-adiabatic transition



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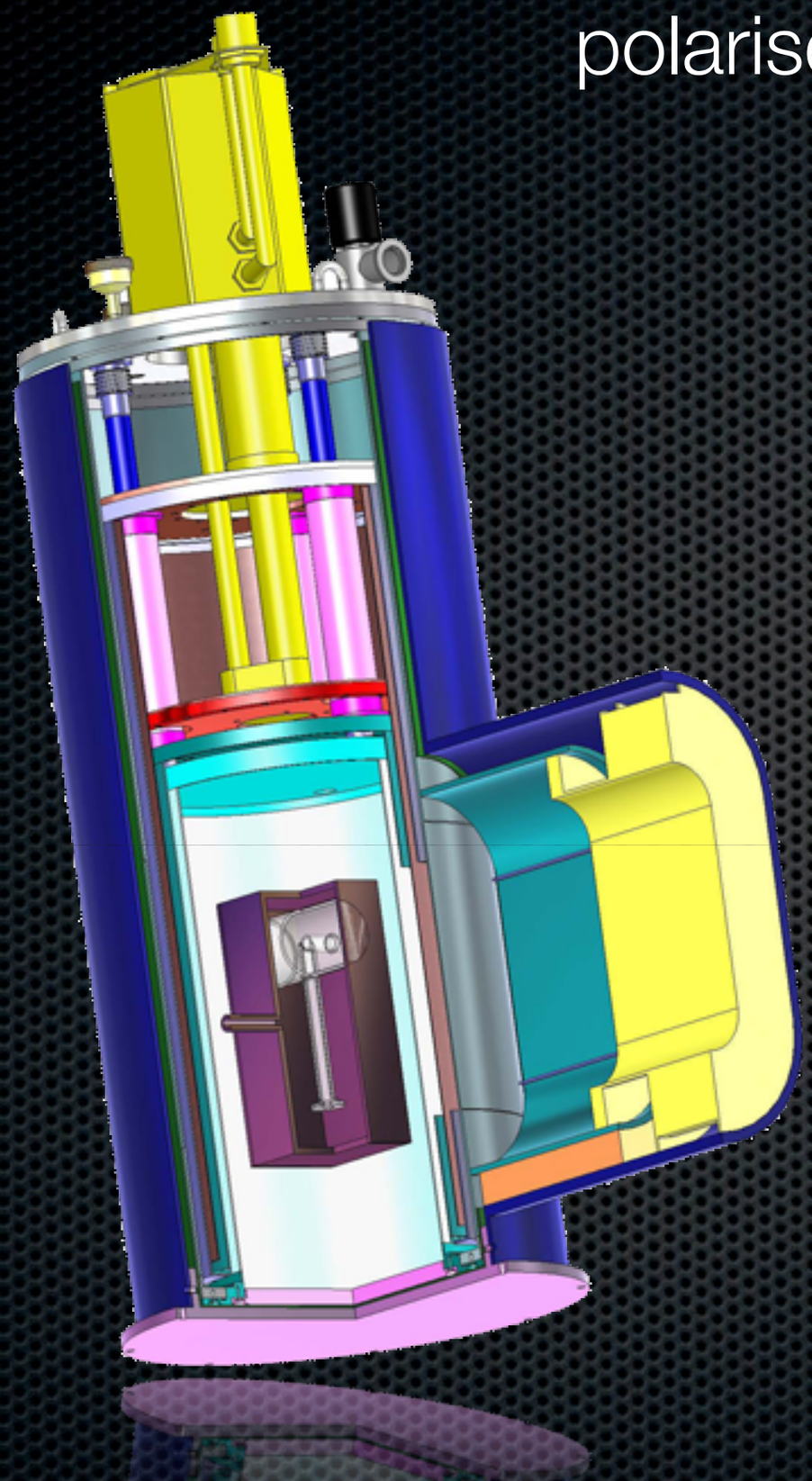
Polarised neutron diffraction (powder)

polariser/flipper used on D20



Cryopol

99.9 % flipping efficiency above 0.3 Å in 400 G

$T_1 \approx 120$ hours at 1 bar

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Polarised neutron diffraction (powder)

polariser/flipper used on D20

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Polarised neutron diffraction (powder)

magnetisation of disordered systems
with no anisotropy, low magnetisation

- The incident beam polarisation is determined continuously using two monitors placed before and after the spin filter:

$$\epsilon = \sqrt{1 - \frac{(M_{20}/M_{10})^2}{(M_2/M_1)^2}}$$

$$\sigma_\epsilon^2 = \frac{M_1^3 M_{20}^3 \left[M_1 M_2 (M_{10} + M_{20}) + M_{10} M_{20} (M_1 + M_2)\right]}{M_{10}^3 M_2^3 (M_{10}^2 M_2^2 - M_1^2 M_{20}^2)}$$

M_{10} and M_{20} are measured for $P_{3He} = 0$

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Polarised neutron diffraction (powder)

magnetisation of disordered systems
with no anisotropy, low magnetisation

- The [+] and [-] spectra are corrected for the time-dependent transmission and efficiency of the filter:

$$P_{^3He} = \frac{V_0}{p\,N_a\,\ell\,\sigma_a\,\lambda} \ln\left(\sqrt{\frac{1+\epsilon}{1-\epsilon}}\right)^2$$

$$\tau = \exp\left(-\frac{p\,N_a\,\ell\,\sigma_a\,\lambda}{V_0}\right) \cosh\left(\frac{p\,N_a\,\ell\,\sigma_a\,\lambda\,P_{^3He}}{V_0}\right)$$

- The spectra are then averaged at each temperature and magnetic applied field.

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Polarised neutron diffraction (powder)

magnetisation of disordered systems
with no anisotropy, low magnetisation

- The scale factor is determined from the refinement of the non-polarised measurements (spin filter removed - flux x3).
- The scale factor is then corrected for the transmission of the glass of the cell T_G and the depolarisation in the sample D_S:

$$4P_i\,N\,M_\perp \propto \frac{1}{T_G\,D_S}\,\frac{1}{N}\sum_{j=1}^{N}\left(\frac{1}{\epsilon(t_j)\,\tau(t_j)}\,I_\Delta(t_j)\right)$$

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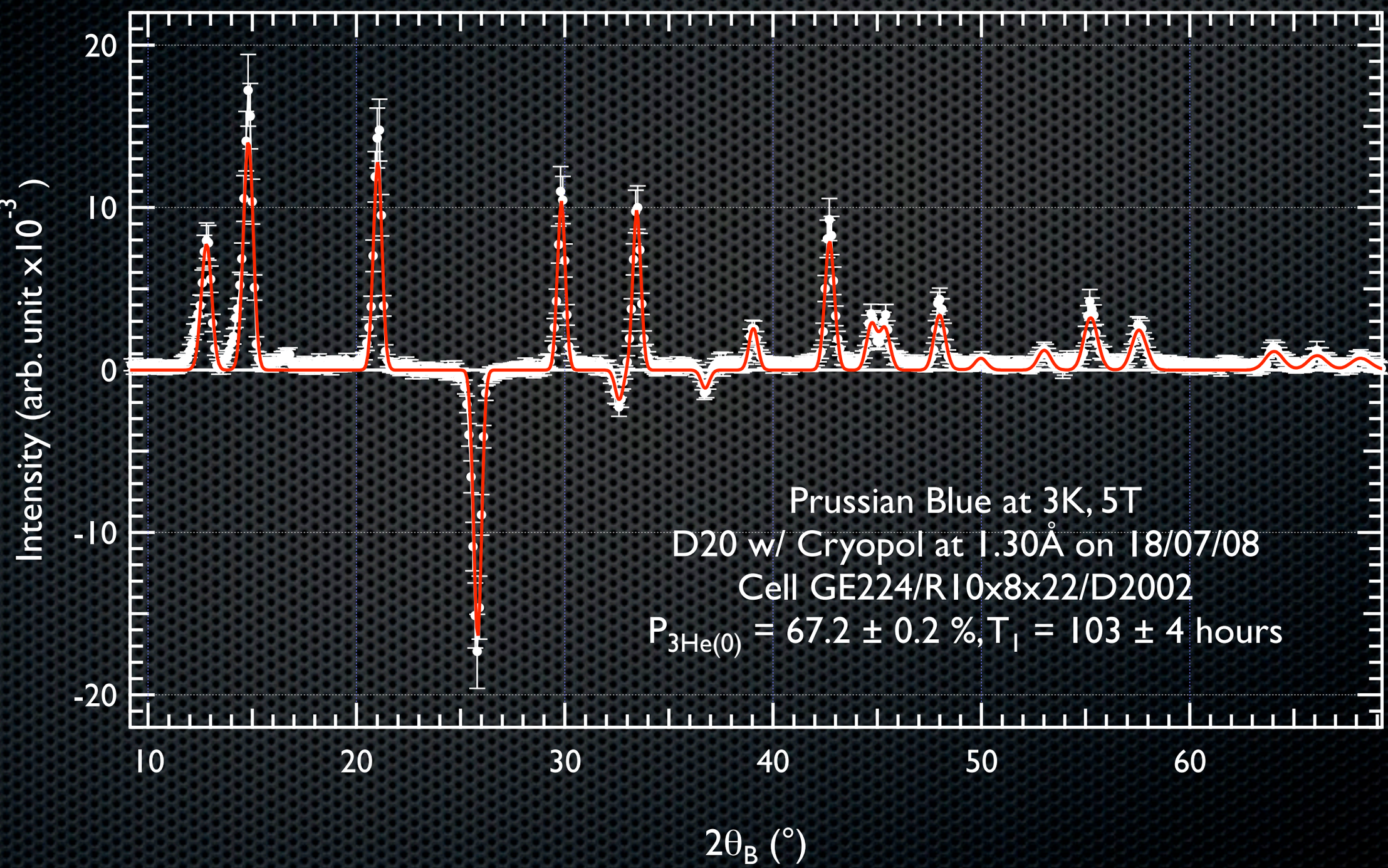
Polarised neutron diffraction (powder)

Example: deuterated Prussian Blue



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Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field

- Method: flipping ratio

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + \imath\vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp) + 2\vec{P}_i \cdot \Re(N^*\vec{M}_\perp)$$

➥ We exploit the interference term to enhance the sensitivity

$$\|\vec{M}_\perp\| \propto \frac{1}{10}N \text{ and } \vec{P}_i = 0 \Rightarrow \quad I \propto N^2 + \underline{0.01N^2}$$

$$\|\vec{M}_\perp\| \propto \frac{1}{10}N \text{ and } \vec{P}_i = \pm\begin{pmatrix}0\\0\\1\end{pmatrix} \Rightarrow \frac{I_+ - I_-}{I_+ + I_-} \propto \frac{0.2\cancel{N^2}}{\cancel{N^2} + 0.01\cancel{N^2}}$$

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Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field

- Method: flipping ratio

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + \cancel{\imath \vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp)} + \boxed{2\vec{P}_i \cdot \Re(N^* \vec{M}_\perp)}$$

For a ferromagnetically aligned sample, we measure:

$$R = \frac{I_+}{I_-} = \frac{N^2 + \sin^2(\alpha)\ M_\perp^2 + 2p_+\ \sin^2(\alpha)\ N.M_\perp}{N^2 + \sin^2(\alpha)\ M^2 + 2p_-\ \sin^2(\alpha)\ N.M_\perp}$$

where p_+ and p_- are the incident polarisations, **α** is the angle between $\vec{Q}$ and $\vec{B}$.

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Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field

- Method: flipping ratio

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + \cancel{\imath \vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp)} + 2\vec{P}_i \cdot \Re(N^* \vec{M}_\perp)$$

We deduce *M* from the equation:

$$\gamma = \frac{R+1}{R-1} \pm \sqrt{\left(\frac{R+1}{R-1}\right) - \sin^2(\alpha)}$$

where **γ** is the ratio *M/N*. The distribution in real space is obtained by Fourier transformation (max. Entropy).

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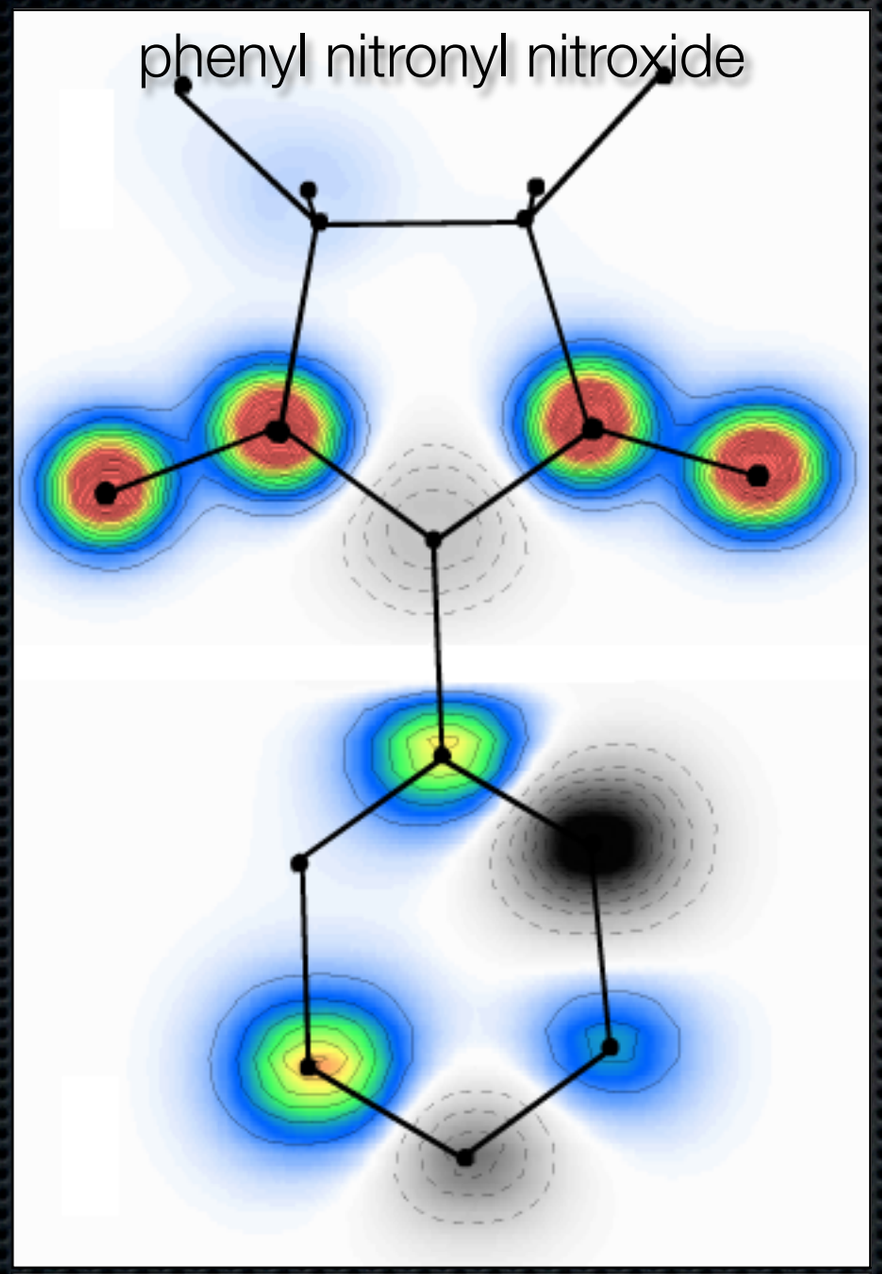
Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field



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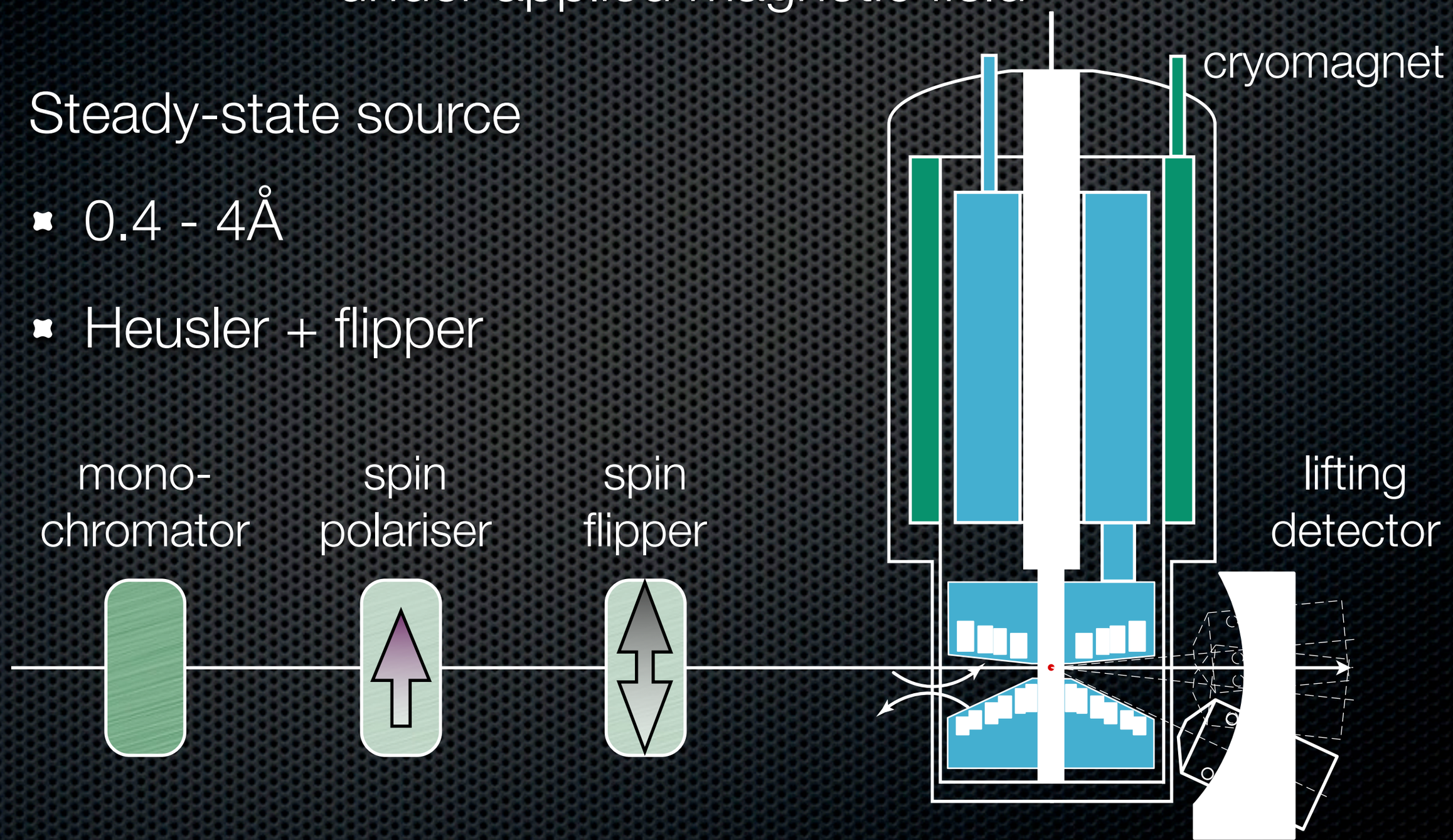
Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field

- Steady-state source
  - 0.4 - 4Å
  - Heusler + flipper



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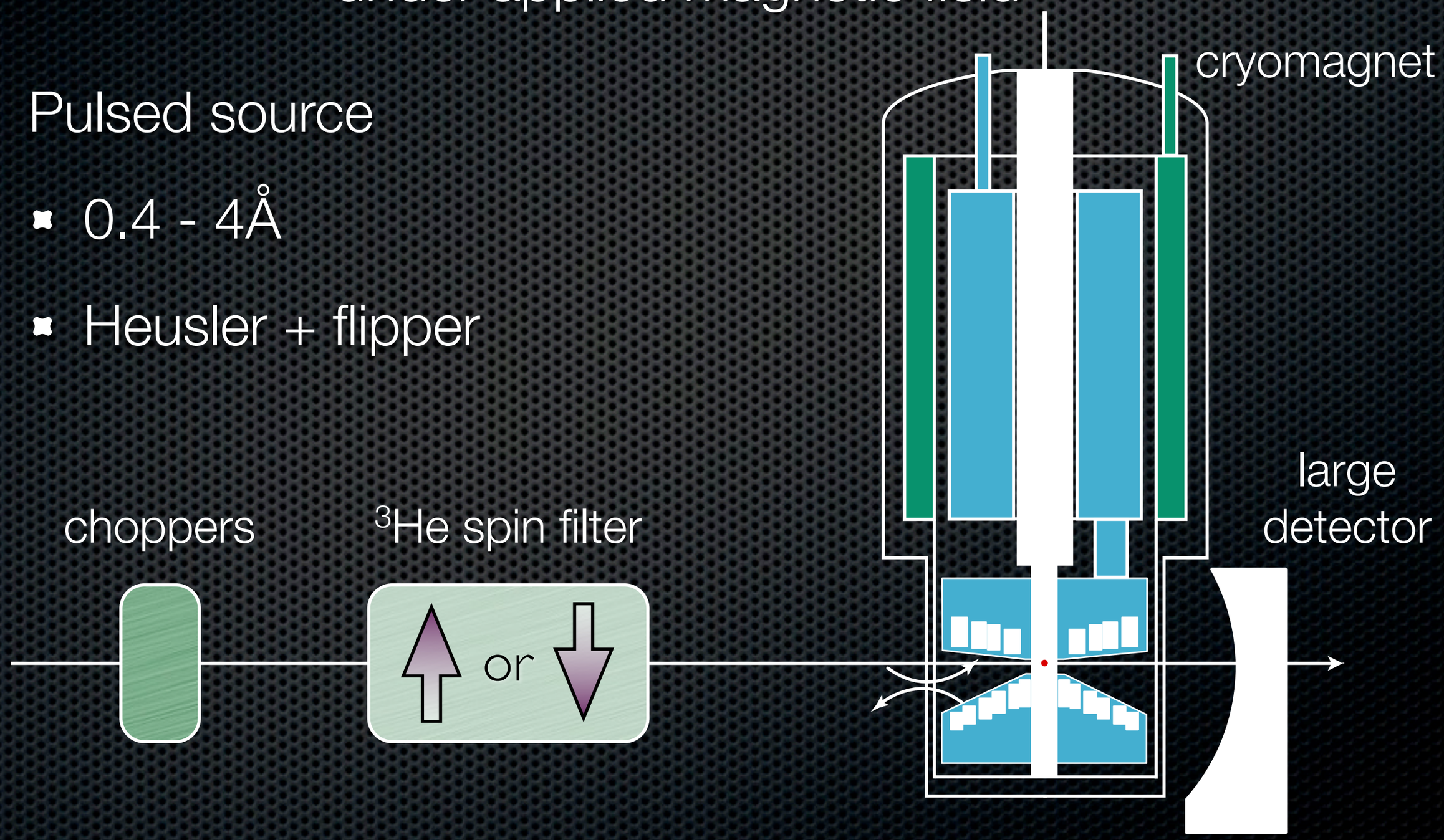
Polarised neutron diffraction (Xtal)

magnetisation of single crystals
under applied magnetic field

- Pulsed source
  - 0.4 - 4Å
  - Heusler + flipper



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Uniaxial polarisation analysis

for separating the nuclear and magnetic contributions

- The incident polarisation is set adiabatically in any direction $\vec{z}$ or $\vec{Q}$:

$$\sigma_{+,+} = N_0 \frac{(2\pi)^3}{v_0} |N + M_{\perp,z}|^2$$
$$\sigma_{-,-} = N_0 \frac{(2\pi)^3}{v_0} |N - M_{\perp,z}|^2$$
$$\sigma_{+,-} = N_0 \frac{(2\pi)^3}{v_0} |M_{\perp,x} + \imath M_{\perp,y}|^2$$
$$\sigma_{-,+} = N_0 \frac{(2\pi)^3}{v_0} |M_{\perp,x} - \imath M_{\perp,y}|^2$$

- If the polarisation is parallel to the scattering vector $\vec{Q}$, only the nuclear contribution participates to the non-spin-flip cross-section.

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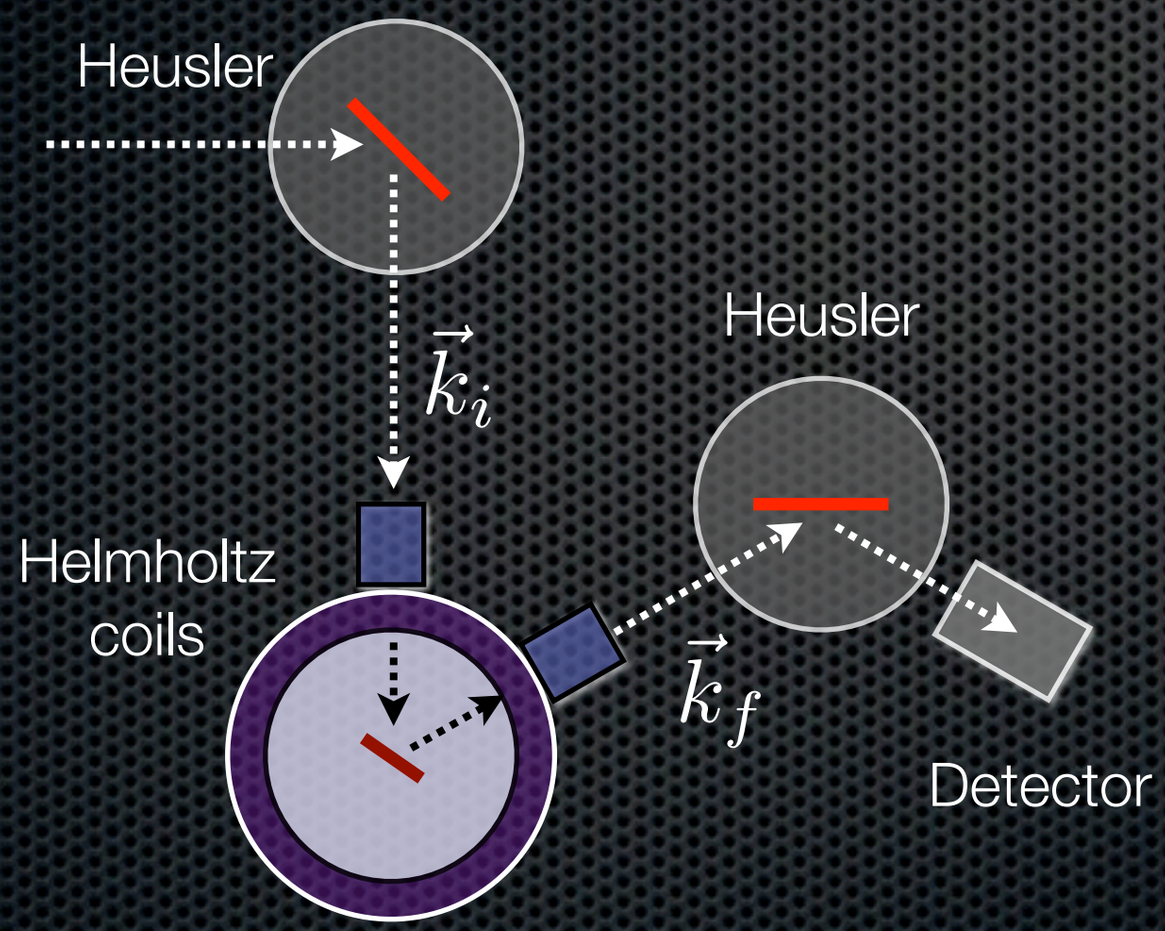
Uniaxial polarisation analysis

for separating the nuclear and magnetic contributions

- On three-axis spectrometers



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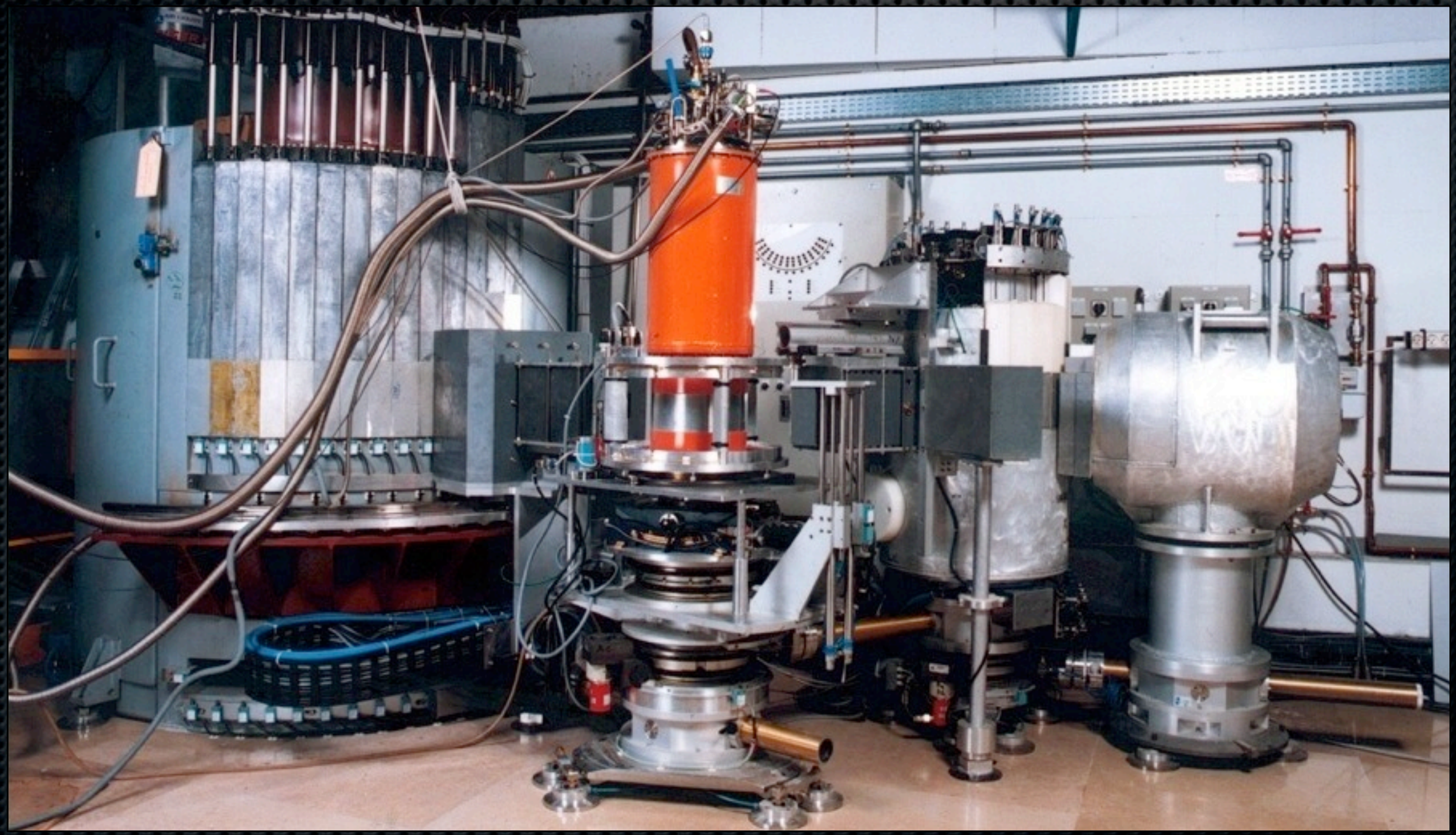
Uniaxial polarisation analysis

for separating the nuclear and magnetic contributions



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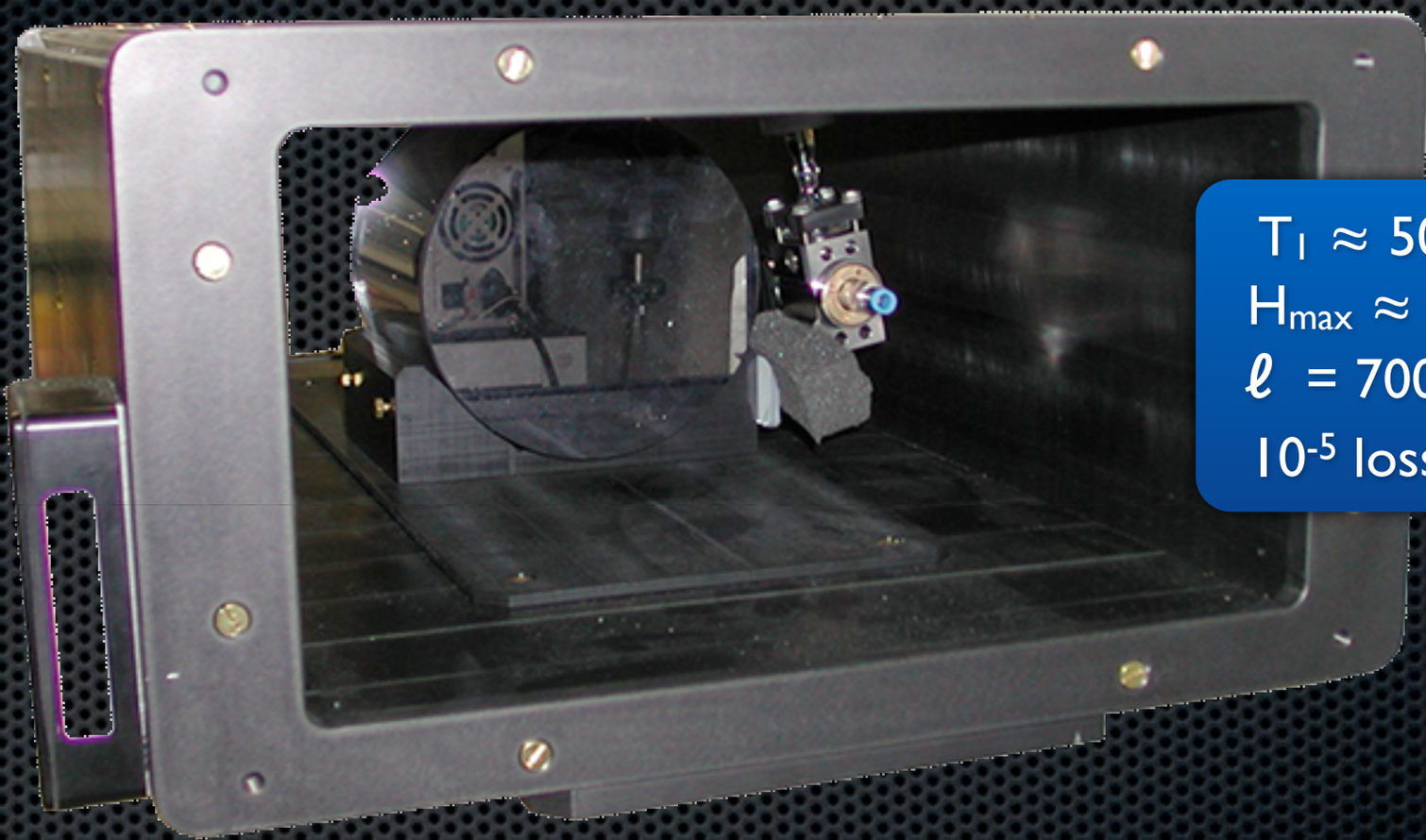
Uniaxial polarisation analysis

for separating the nuclear and
magnetic contributions on SANS, Reflectometers



$T_1 \approx 500$ h
$H_{max} \approx 10$G
$\ell = 700$ mm
10^{-5} loss/flip

Ø140 Si-windowed cell, pneumatic valve,
permanent static field, flipper included.

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Uniaxial polarisation analysis

XYZ Method
generalisation to PSD detector

- Separation of the nuclear coherent, magnetic, spin incoherent and isotope incoherent contributions

$$\sigma_x^{sf} = \frac{1}{2}\left(\cos^2\,\alpha + 1\right)\sigma_{mag} + \frac{2}{3}\,\sigma_{si}$$
$$\sigma_x^{nsf} = \frac{1}{2}\left(\sin^2\,\alpha + 1\right)\sigma_{mag} + \frac{1}{3}\,\sigma_{si} + \sigma_{nc} + \sigma_{ii}$$
$$\sigma_y^{sf} = \frac{1}{2}\left(\sin^2\,\alpha + 1\right)\sigma_{mag} + \frac{2}{3}\,\sigma_{si}$$
$$\sigma_y^{nsf} = \frac{1}{2}\left(\cos^2\,\alpha + 1\right)\sigma_{mag} + \frac{1}{3}\,\sigma_{si} + \sigma_{nc} + \sigma_{ii}$$
$$\sigma_z^{sf} = \frac{1}{2}\,\sigma_{mag} + \frac{2}{3}\,\sigma_{si}$$
$$\sigma_z^{nsf} = \frac{1}{2}\,\sigma_{mag} + \frac{1}{3}\,\sigma_{si} + \sigma_{nc} + \sigma_{ii} \qquad \left(\alpha = \widehat{\vec{Q}, \vec{x}}\right)$$

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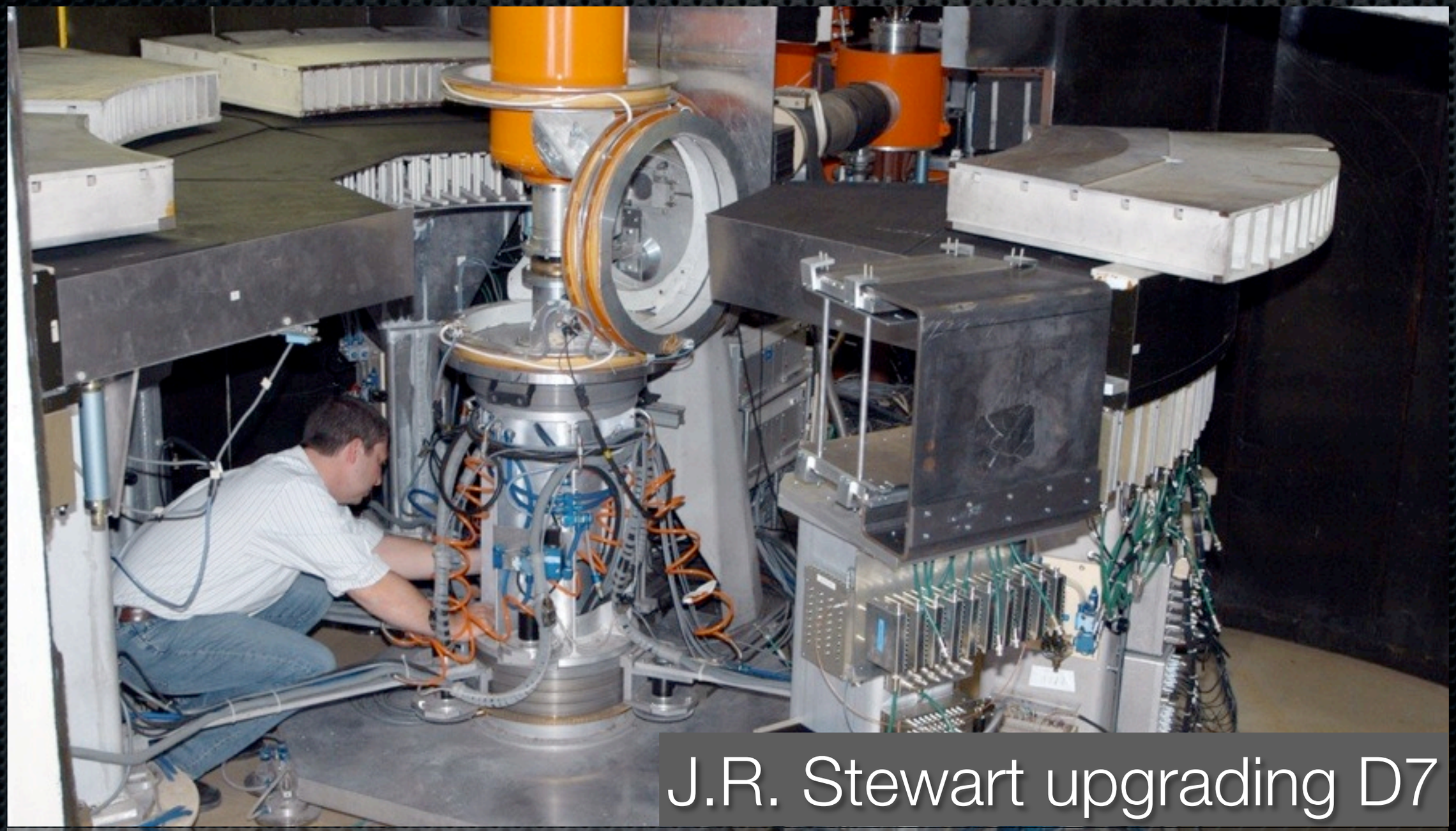
Uniaxial polarisation analysis

XYZ Method: generalisation to PSD detector



J.R. Stewart upgrading D7

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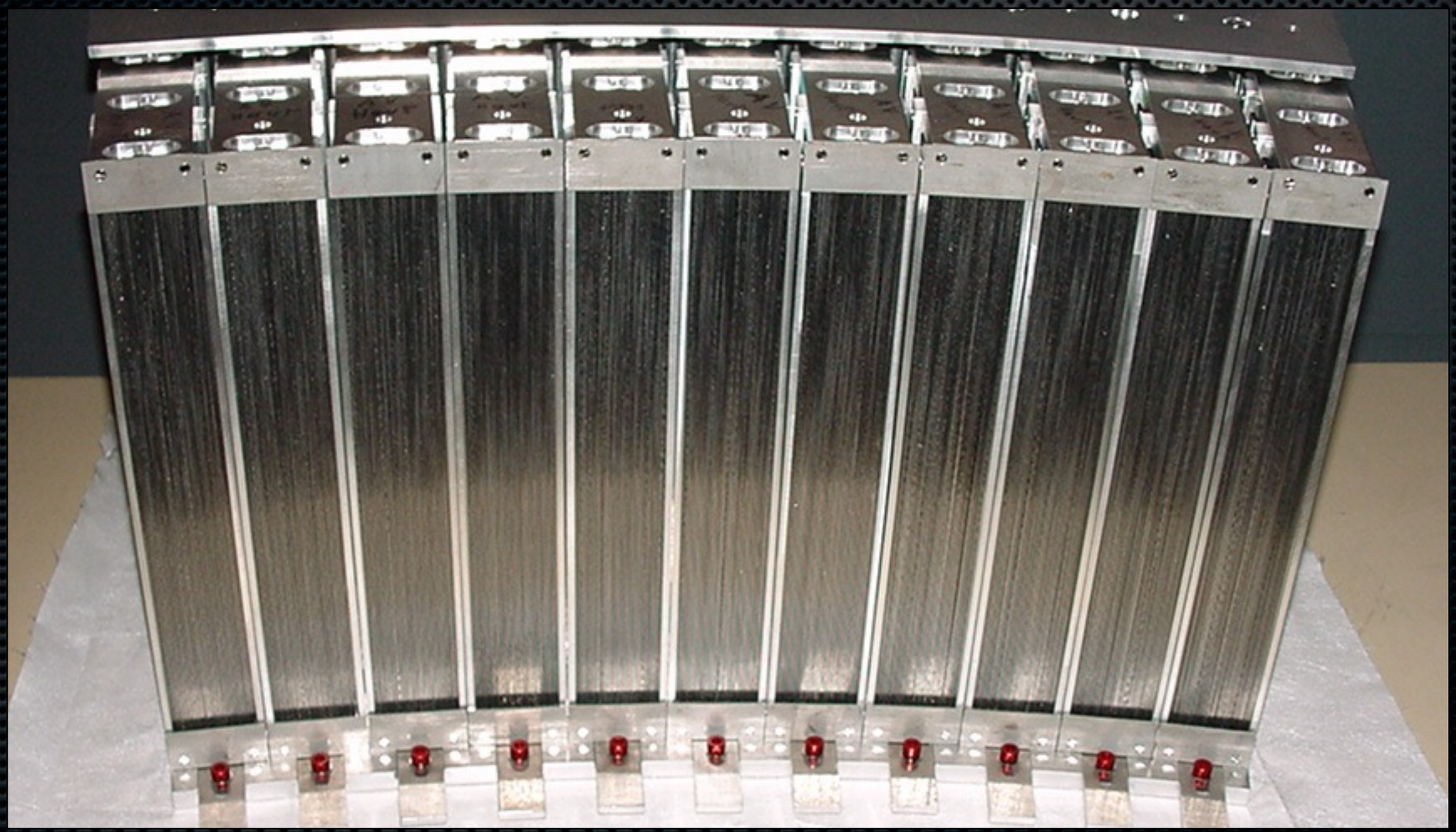
Uniaxial polarisation analysis

XYZ Method: generalisation to PSD detector



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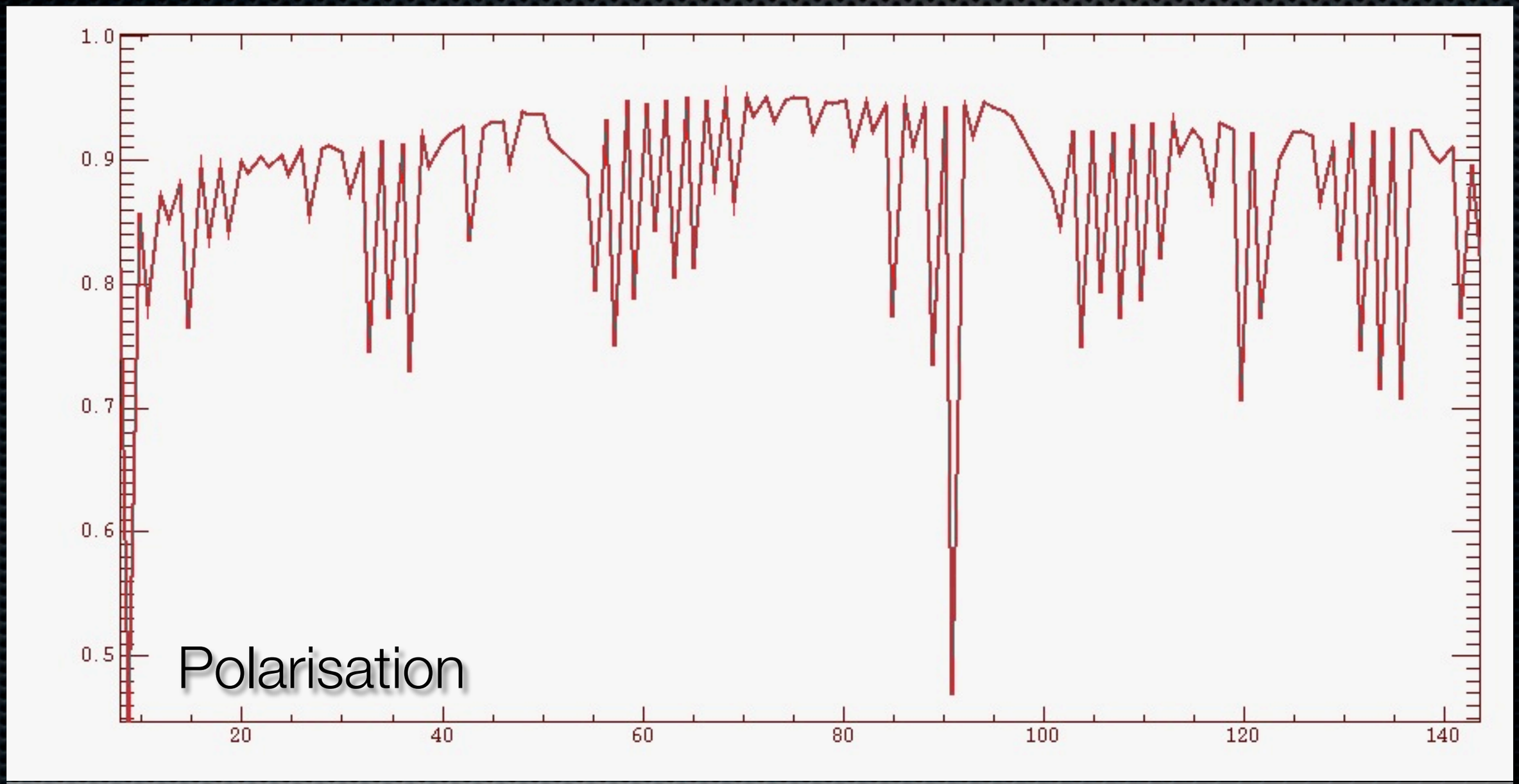
Uniaxial polarisation analysis

XYZ Method: generalisation to PSD detector



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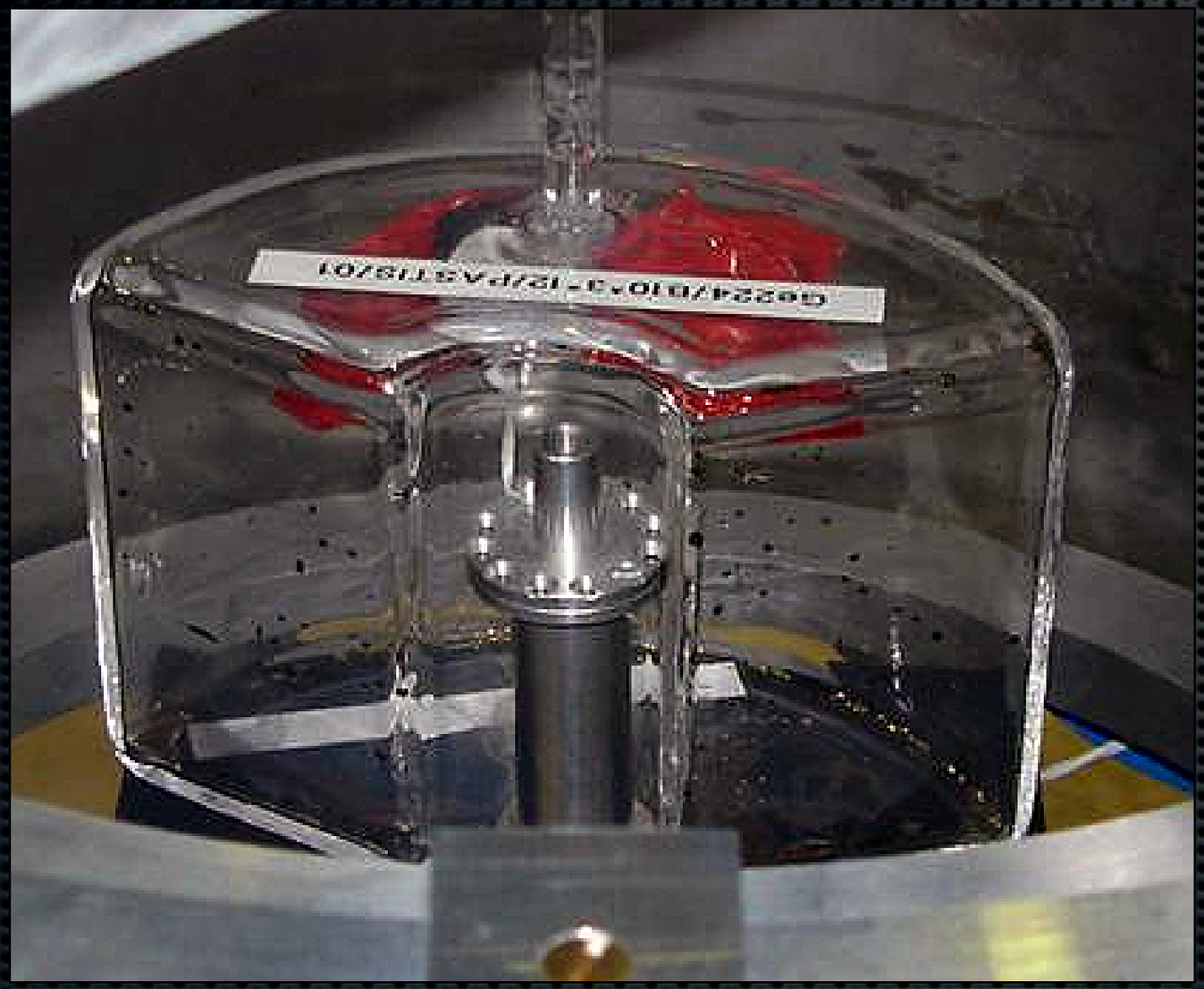
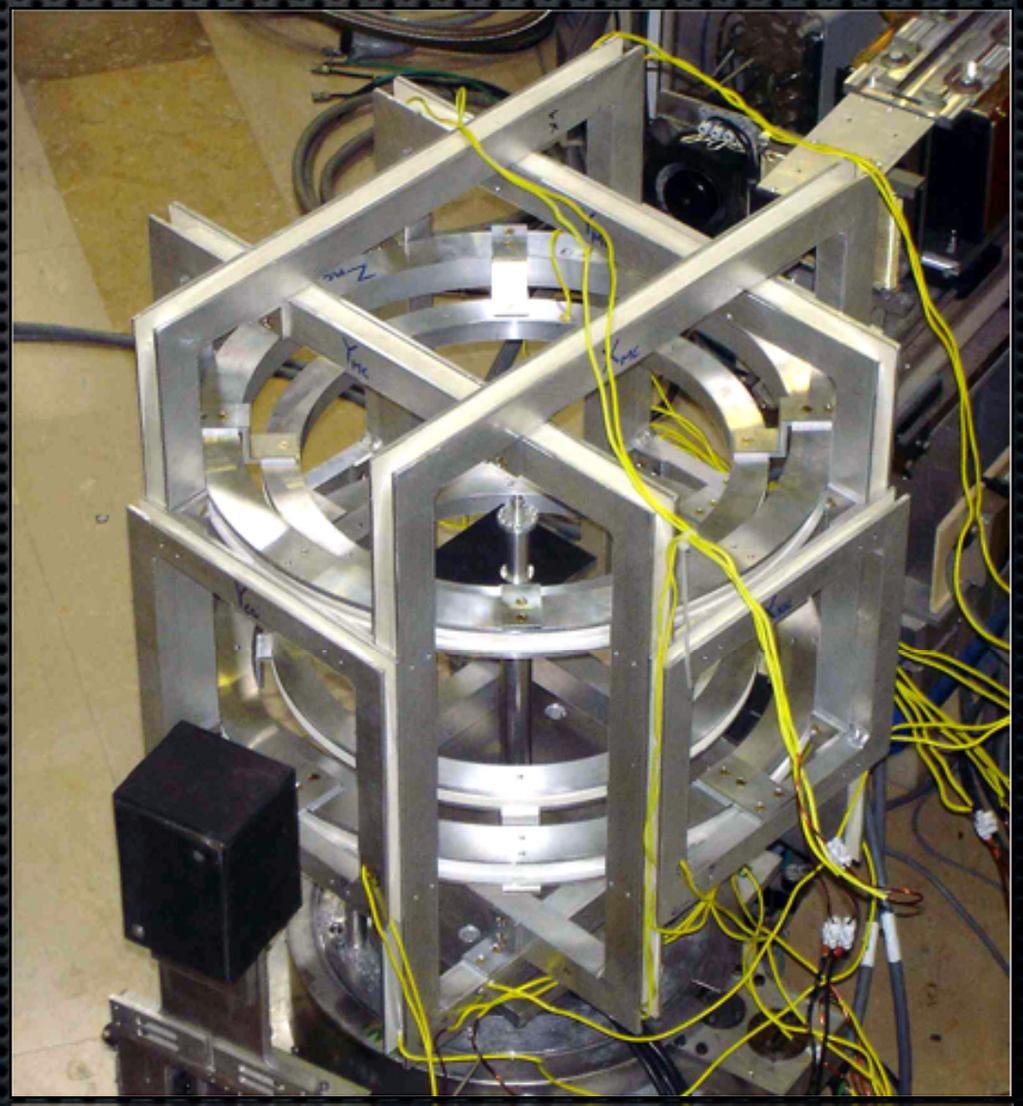
Uniaxial polarisation analysis

XYZ Polarisation Analysis





PASTIS v1 - $T_1 \approx 100$ hours

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Uniaxial polarisation analysis

XYZ Polarisation Analysis

- PASTIS v2.0:
- Ø 700 mm
- $T_1 \approx 70$ hours
- Ø 40 sample at 1.5 K
- No dark angle
- Could greatly be improved in Ø 800 mm !

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Spherical neutron polarimetry

$$\mathrm{P}_{i,j} = \frac{P_i\,\mathbb{P}_{i,j} + P_j^{\dagger}}{\|\vec{P}_f\|} \text{ with } (i,j) \in \{x,y,z\}$$

A useful strategy is to measure the scattered polarisation with incident polarisation parallel to each of the polarisation axes in turn.

$$\mathbb{P} = \begin{bmatrix} N.N^* - \vec{M}_\perp.\vec{M}_\perp^* & 2\Im(NM_{\perp,z}^*) & -2\Im(NM_{\perp,y}^*) \\ -2\Im(NM_{\perp,z}^*) & N.N^* - \vec{M}_\perp.\vec{M}_\perp^* + 2\Re(M_{\perp,y}M_{\perp,y}^*) & 2\Re(M_{\perp,y}M_{\perp,z}^*) \\ 2\Im(NM_{\perp,y}^*) & 2\Re(M_{\perp,y}M_{\perp,z}^*) & N.N^* - \vec{M}_\perp.\vec{M}_\perp^* + 2\Re(M_{\perp,z}M_{\perp,z}^*) \end{bmatrix}$$

$$\vec{P}^{\dagger}\,\sigma = \begin{bmatrix} 2\Im(M_{\perp,y}M_{\perp,z}^*) \\ 2\Re(NM_{\perp,y}^*) \\ 2\Re(NM_{\perp,z}^*) \end{bmatrix} \text{ with } \sigma = N.N^* + \vec{M}_\perp.\vec{M}_\perp^* + \vec{P}_i.\begin{bmatrix} 2\Im(M_{\perp,y}M_{\perp,z}^*) \\ 2\Re(NM_{\perp,y}^*) \\ 2\Re(NM_{\perp,z}^*) \end{bmatrix}$$

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Spherical neutron polarimetry

A lot of directional information is lost when only intensities are measured.

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + \imath\vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp) + 2\vec{P}_i \cdot \Re(N^*\vec{M}_\perp)$$

The vector properties of the neutron polarisation provide a way of recovering some of this information.

$$\vec{P}_f \frac{\partial\sigma}{\partial\Omega} = \vec{P}_i NN^* - \vec{P}_i(\vec{M}_\perp \cdot \vec{M}_\perp^*) + 2\Re(\vec{M}_\perp(\vec{P}_i \cdot \vec{M}_\perp^*) + \imath(\vec{M}_\perp \wedge \vec{M}_\perp^*) + 2\Re(N^*\vec{M}_\perp) + 2\vec{P}_i \wedge \Im(N^*\vec{M}_\perp)$$

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Spherical neutron polarimetry

Antiferromagnetic single crystals
with <u>non-zero</u> propagation vector

$$\frac{\partial\sigma}{\partial\Omega} = \cancel{NN^*} + \vec{M}_\perp \cdot \vec{M}_\perp^* + \imath\vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp) + \cancel{2\vec{P}_i \cdot \Re(N^* \vec{M}_\perp)}$$

The polarisation rotates around the magnetic interaction vector by 180° - not a spin flip !

$$\vec{P}_f \frac{\partial\sigma}{\partial\Omega} = \cancel{\vec{P}_i NN^*} - \vec{P}_i(\vec{M}_\perp \cdot \vec{M}_\perp^*) + 2\Re(\vec{M}_\perp(\vec{P}_i \cdot \vec{M}_\perp^*) +$$

$$\imath(\vec{M}_\perp \wedge \vec{M}_\perp^*) + \cancel{2\Re(N^* \vec{M}_\perp)} + \cancel{2\vec{P}_i \wedge \Im(N^* \vec{M}_\perp)}$$

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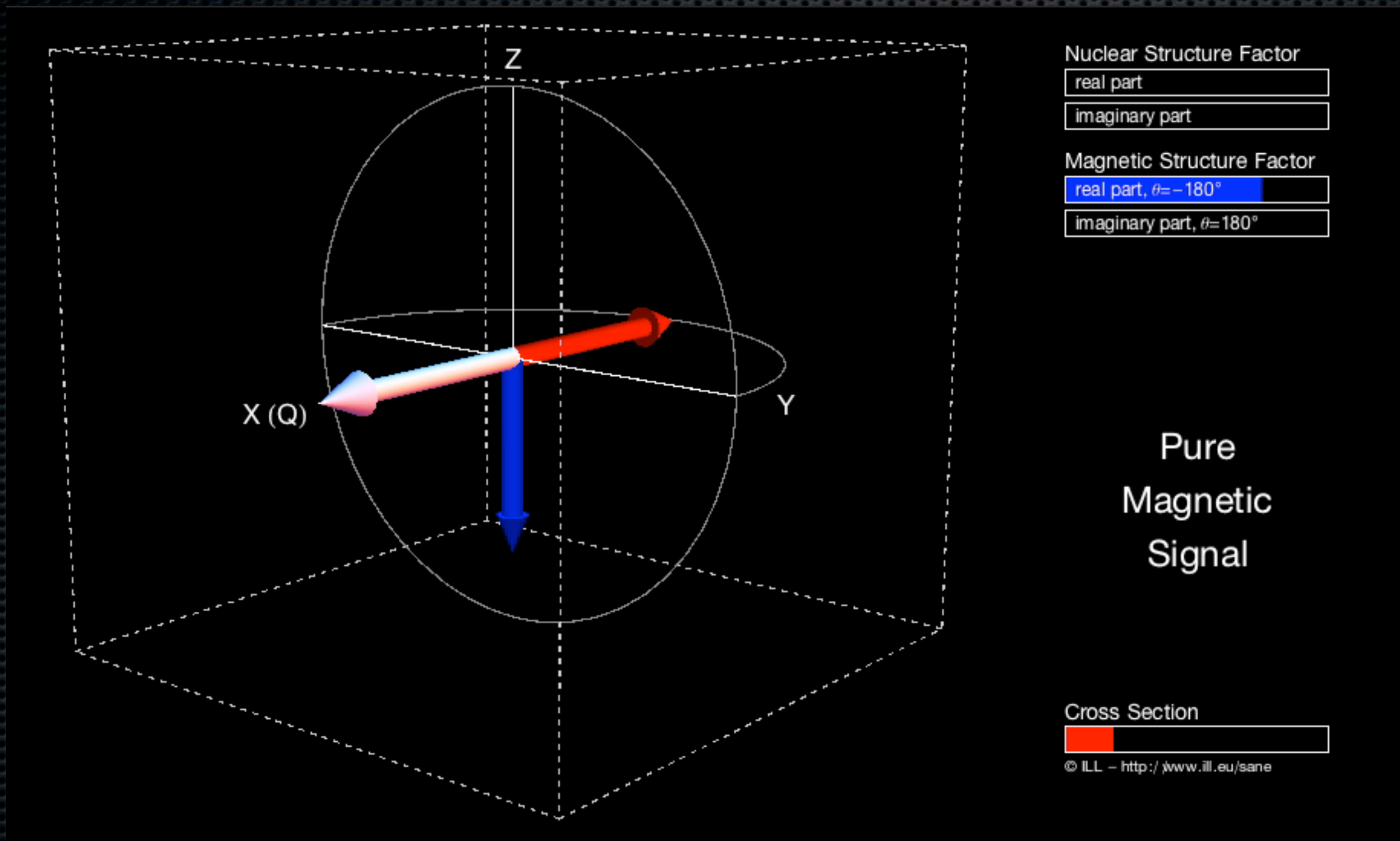
Spherical neutron polarimetry

Antiferromagnetic single crystals: $\tau \neq 0$



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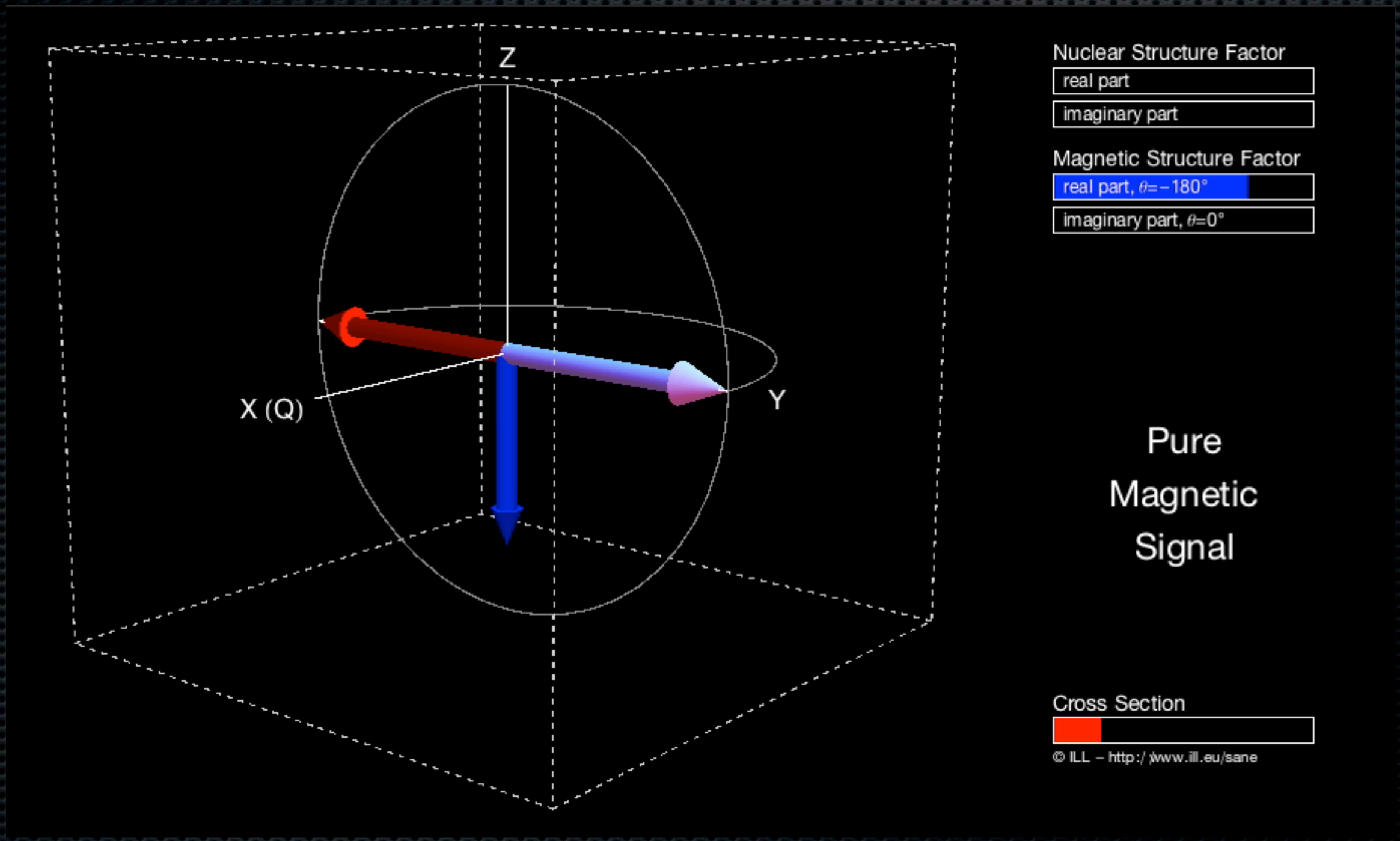
Spherical neutron polarimetry

Antiferromagnetic single crystals: $\tau \neq 0$



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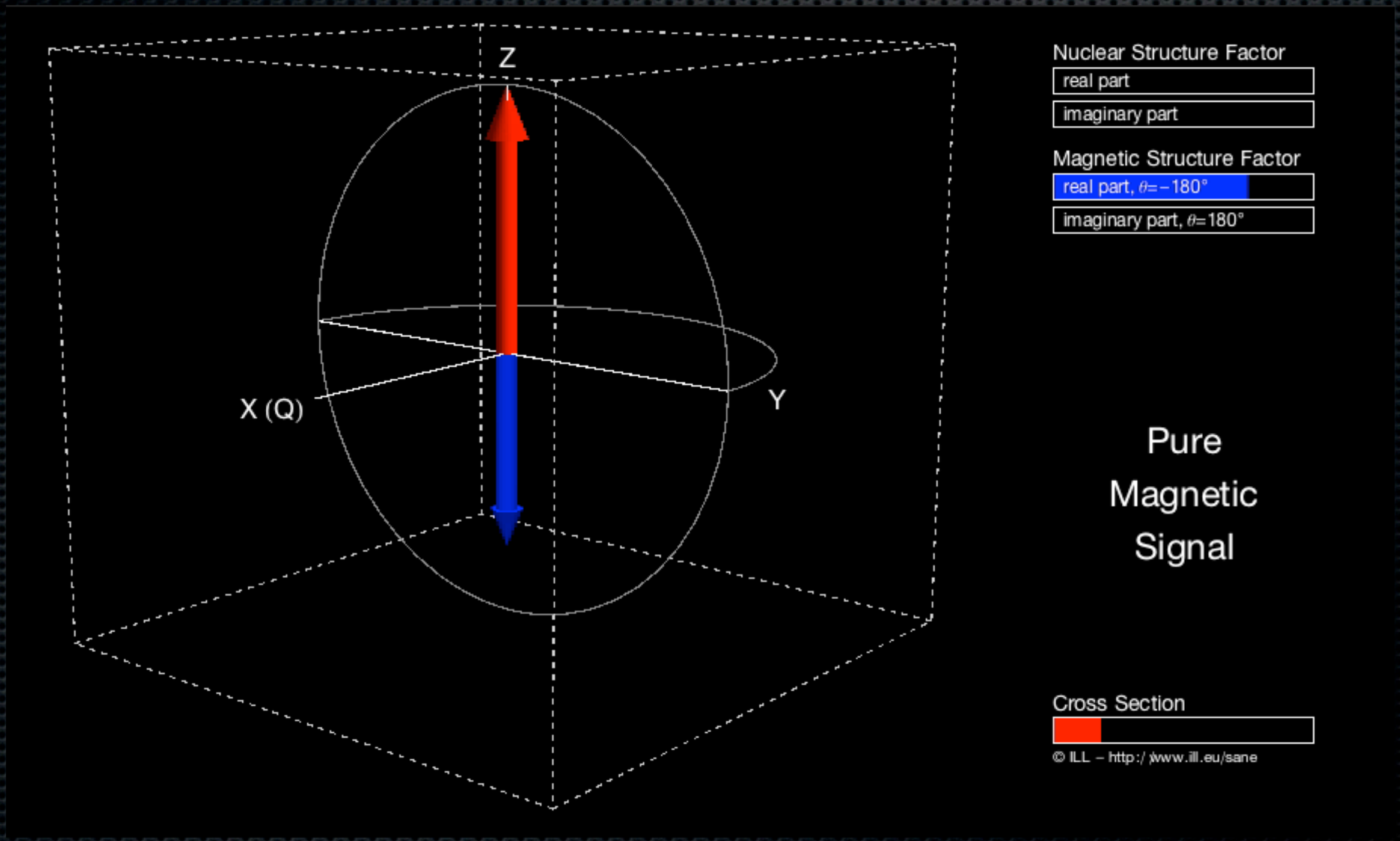
Spherical neutron polarimetry

Antiferromagnetic single crystals: $\tau \neq 0$



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Spherical neutron polarimetry

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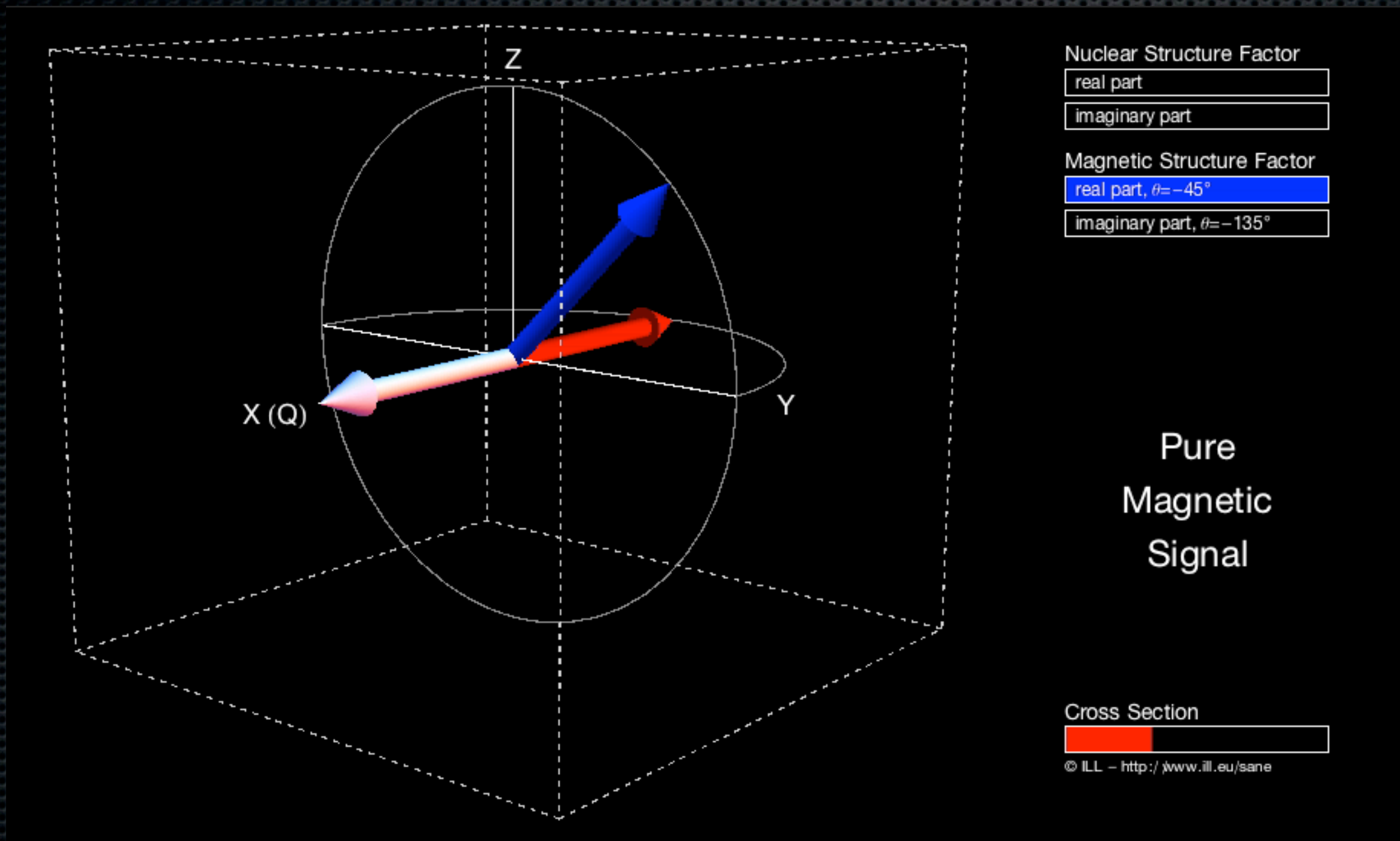

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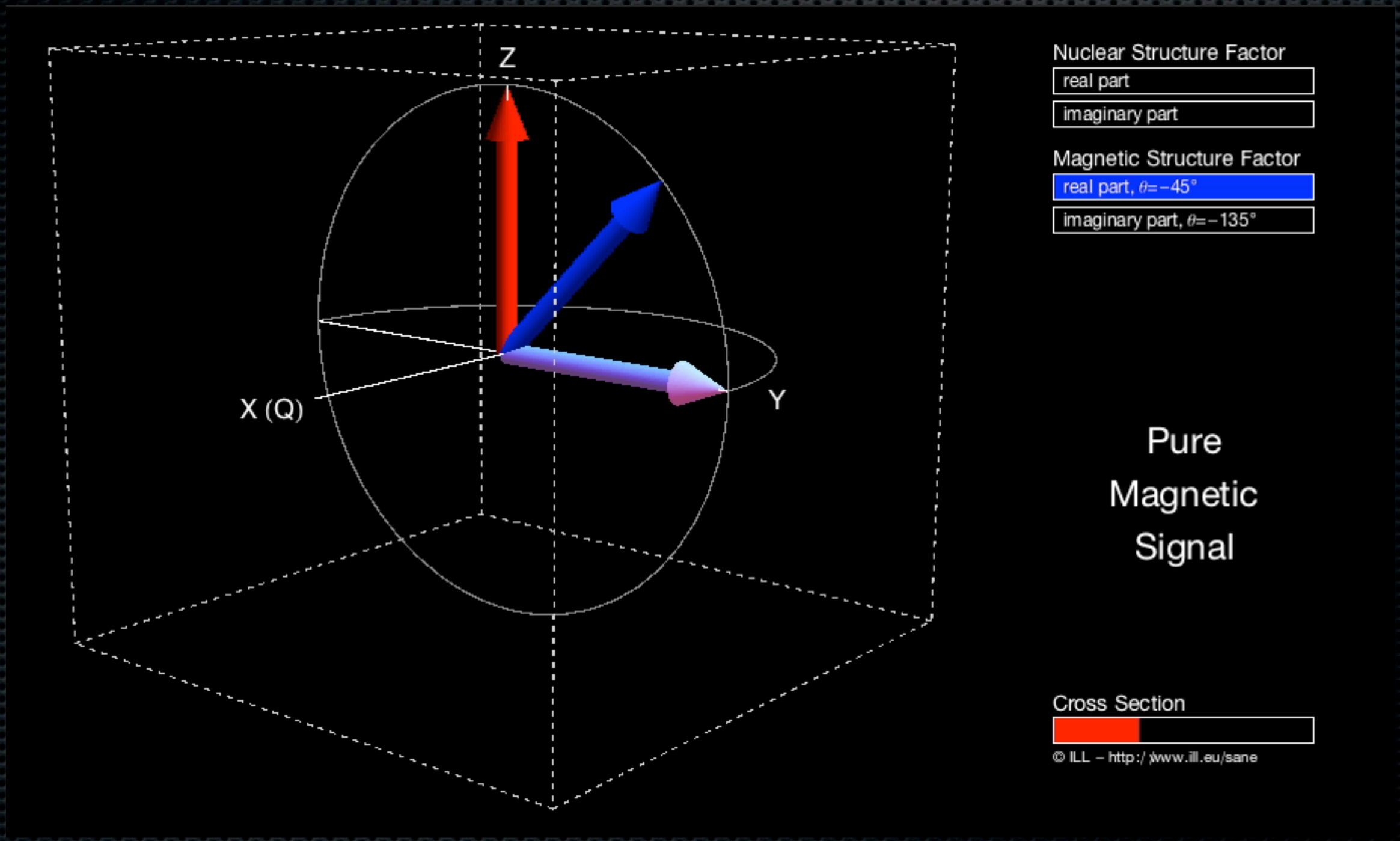

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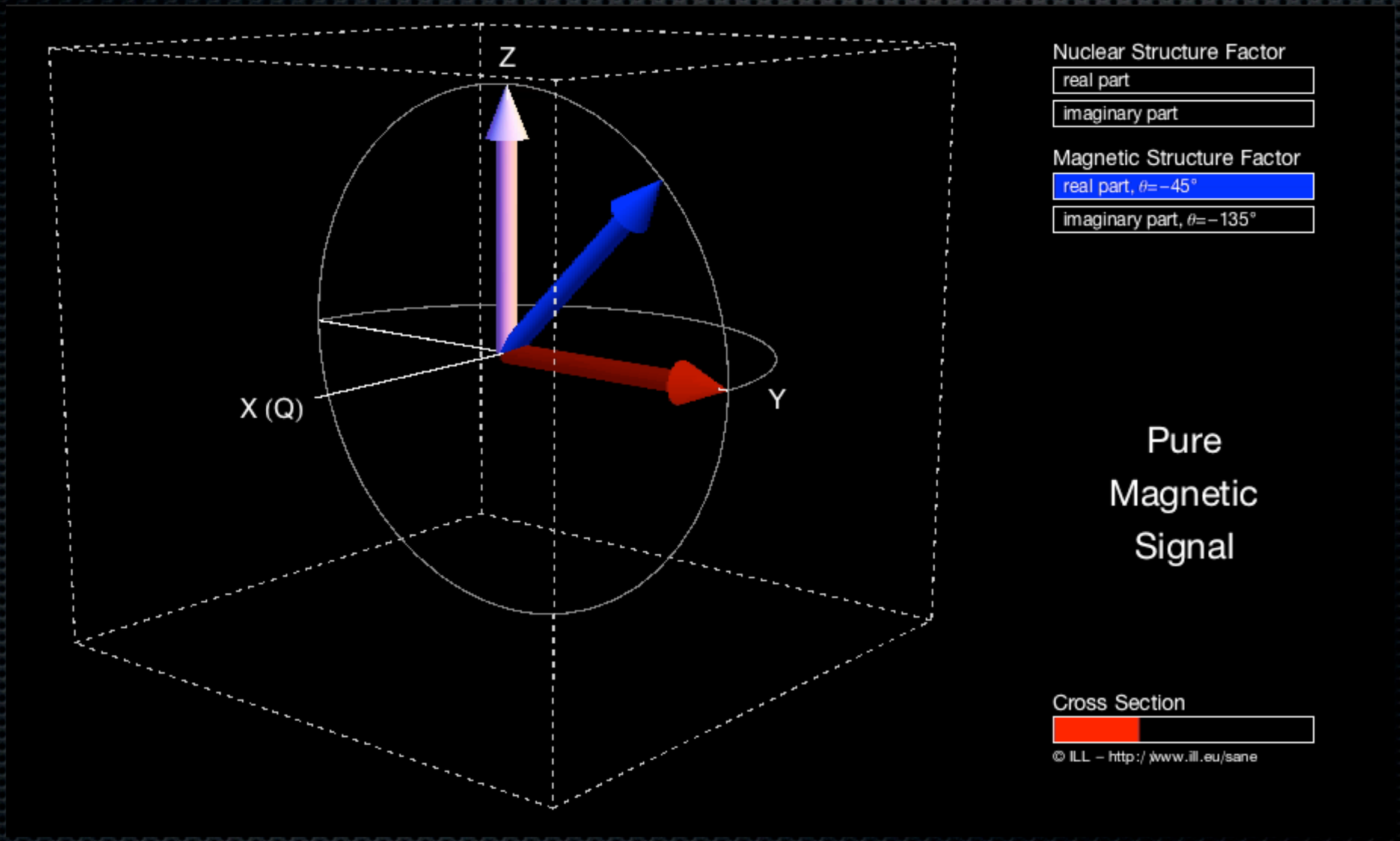

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Spherical neutron polarimetry

Antiferromagnetic single crystals
with <u>zero</u> propagation vector

$$\frac{\partial\sigma}{\partial\Omega} = NN^* + \vec{M}_\perp \cdot \vec{M}_\perp^* + \imath\vec{P}_i \cdot (\vec{M}_\perp^* \wedge \vec{M}_\perp) + 2\vec{P}_i \cdot \Re(N^*\vec{M}_\perp)$$

The polarisation rotates toward or around the
magnetic interaction vector.

$$\vec{P}_f \frac{\partial\sigma}{\partial\Omega} = \vec{P}_i NN^* - \vec{P}_i(\vec{M}_\perp \cdot \vec{M}_\perp^*) + 2\Re(\vec{M}_\perp(\vec{P}_i \cdot \vec{M}_\perp^*) +$$

$$\imath(\vec{M}_\perp \wedge \vec{M}_\perp^*) + 2\Re(N^*\vec{M}_\perp) + 2\vec{P}_i \wedge \Im(N^*\vec{M}_\perp)$$

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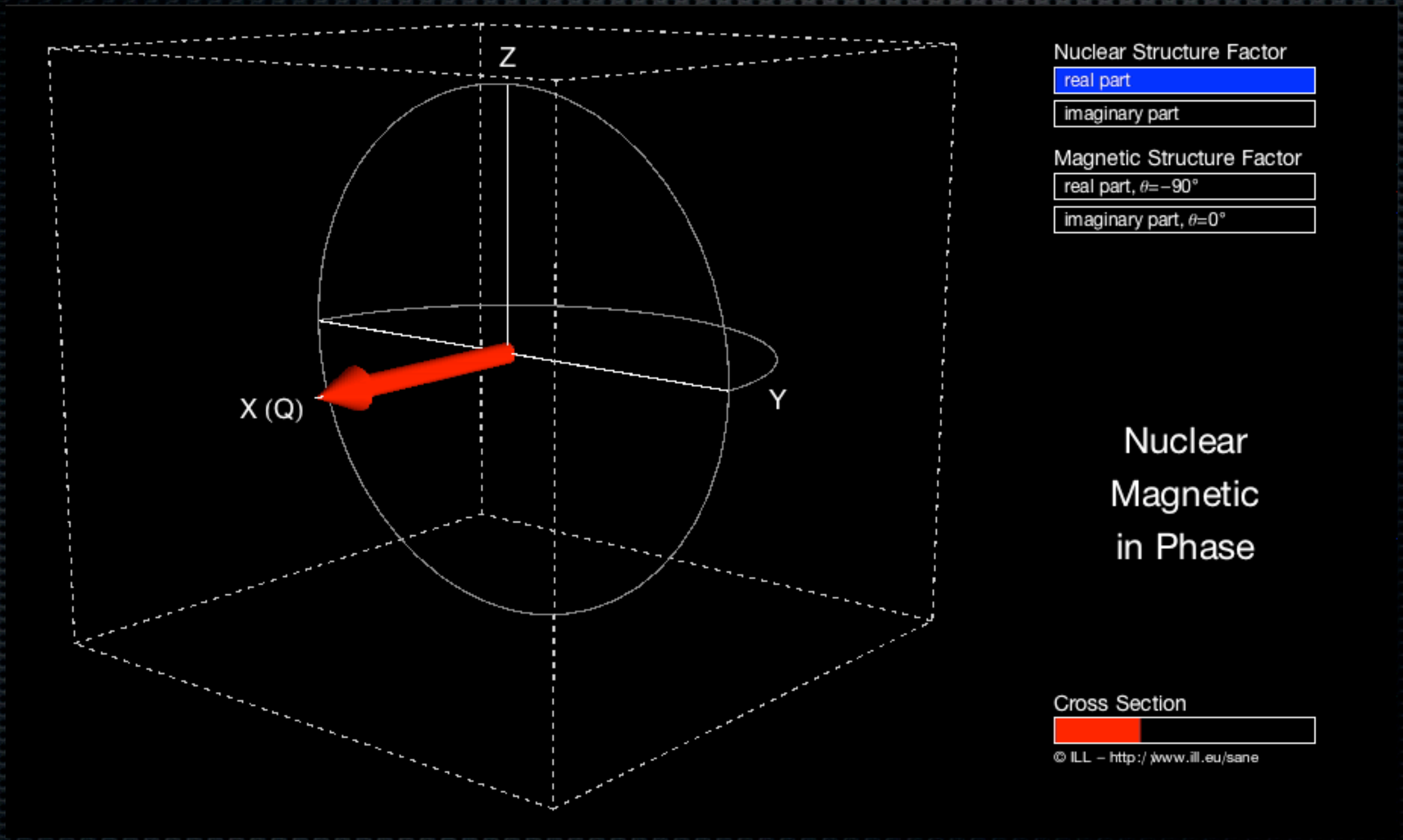
Spherical neutron polarimetry

Antiferromagnetic single crystals: $\tau=0$



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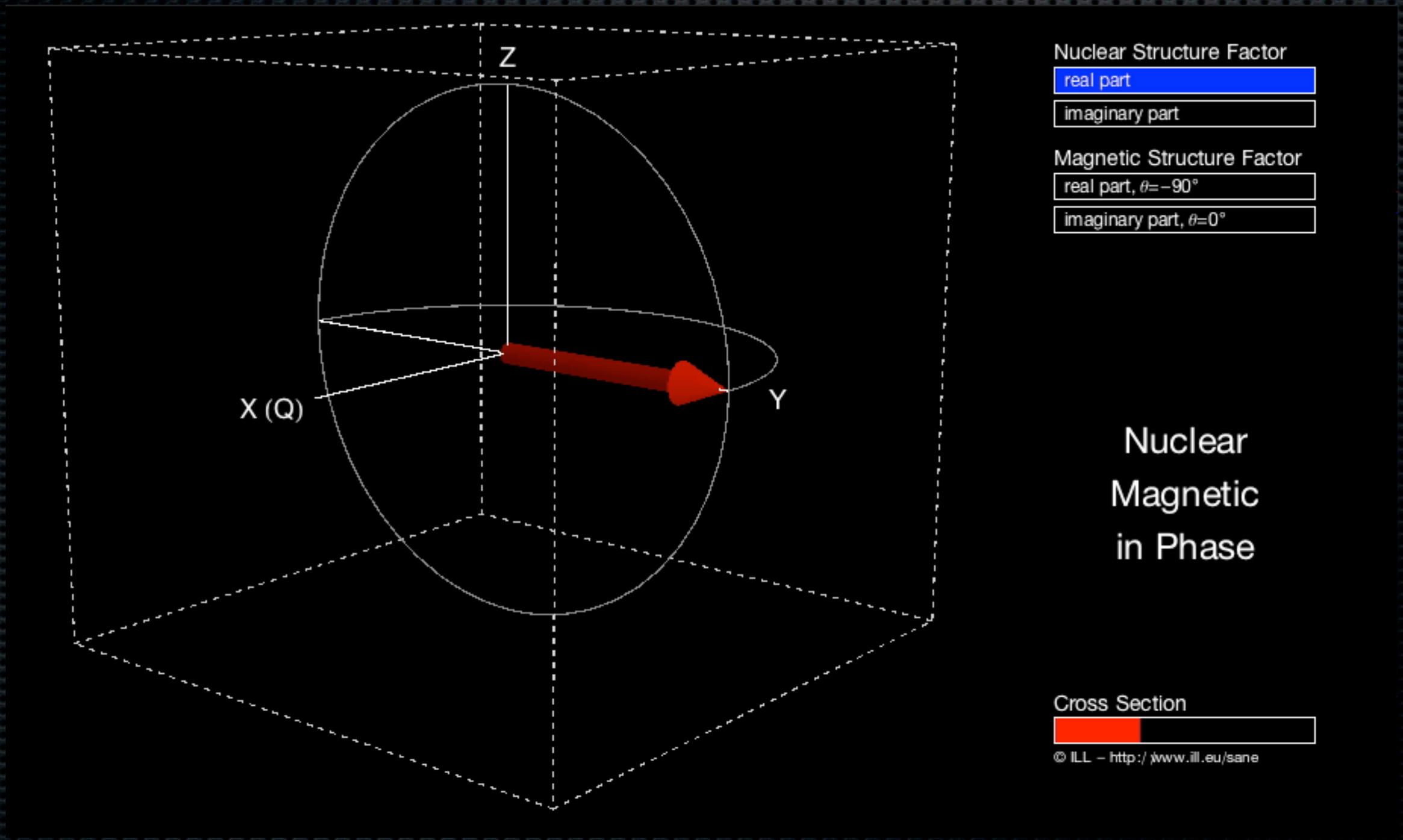
Spherical neutron polarimetry

Antiferromagnetic single crystals: $\tau=0$



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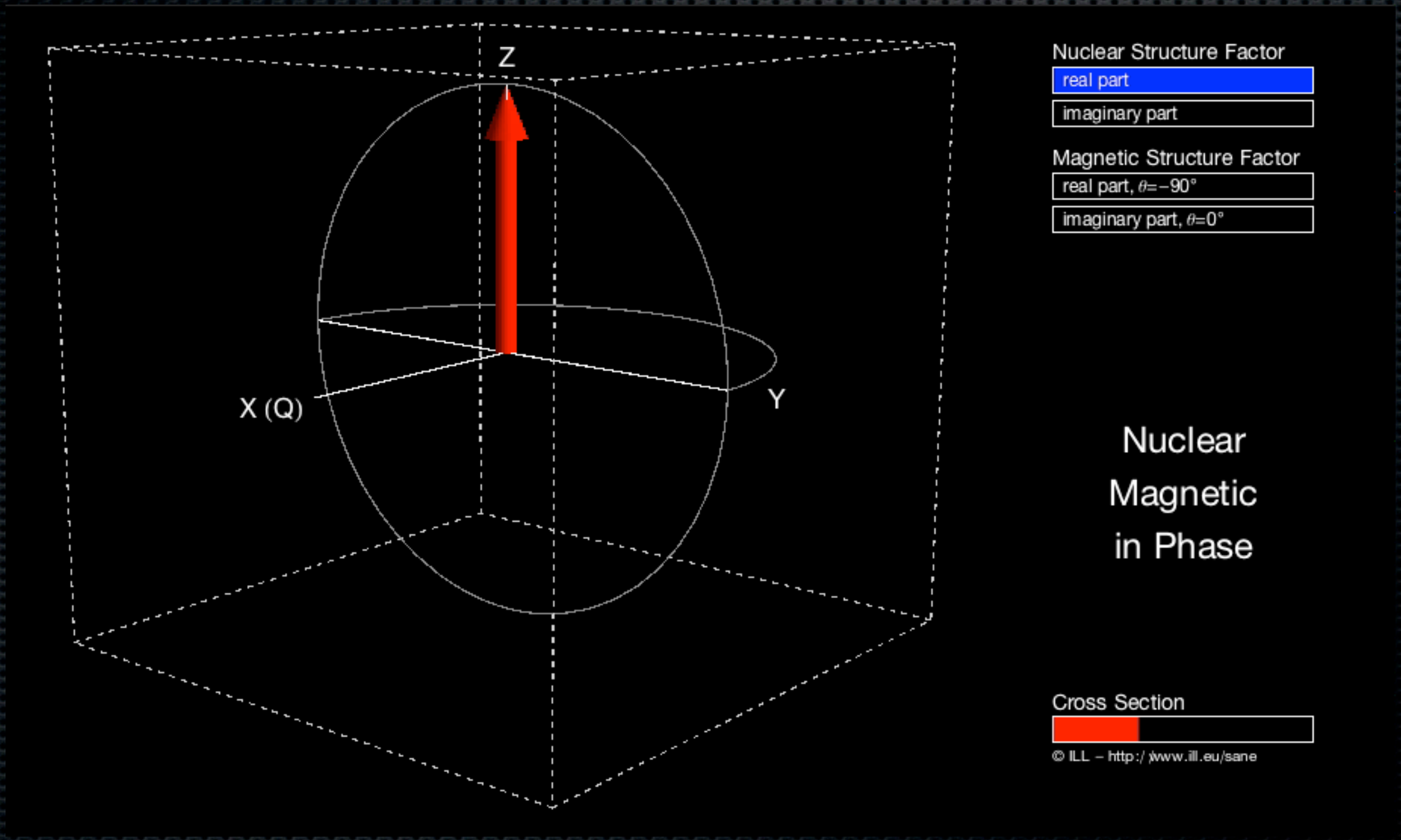
Spherical neutron polarimetry

Antiferromagnetic single crystals: τ=0



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Spherical neutron polarimetry

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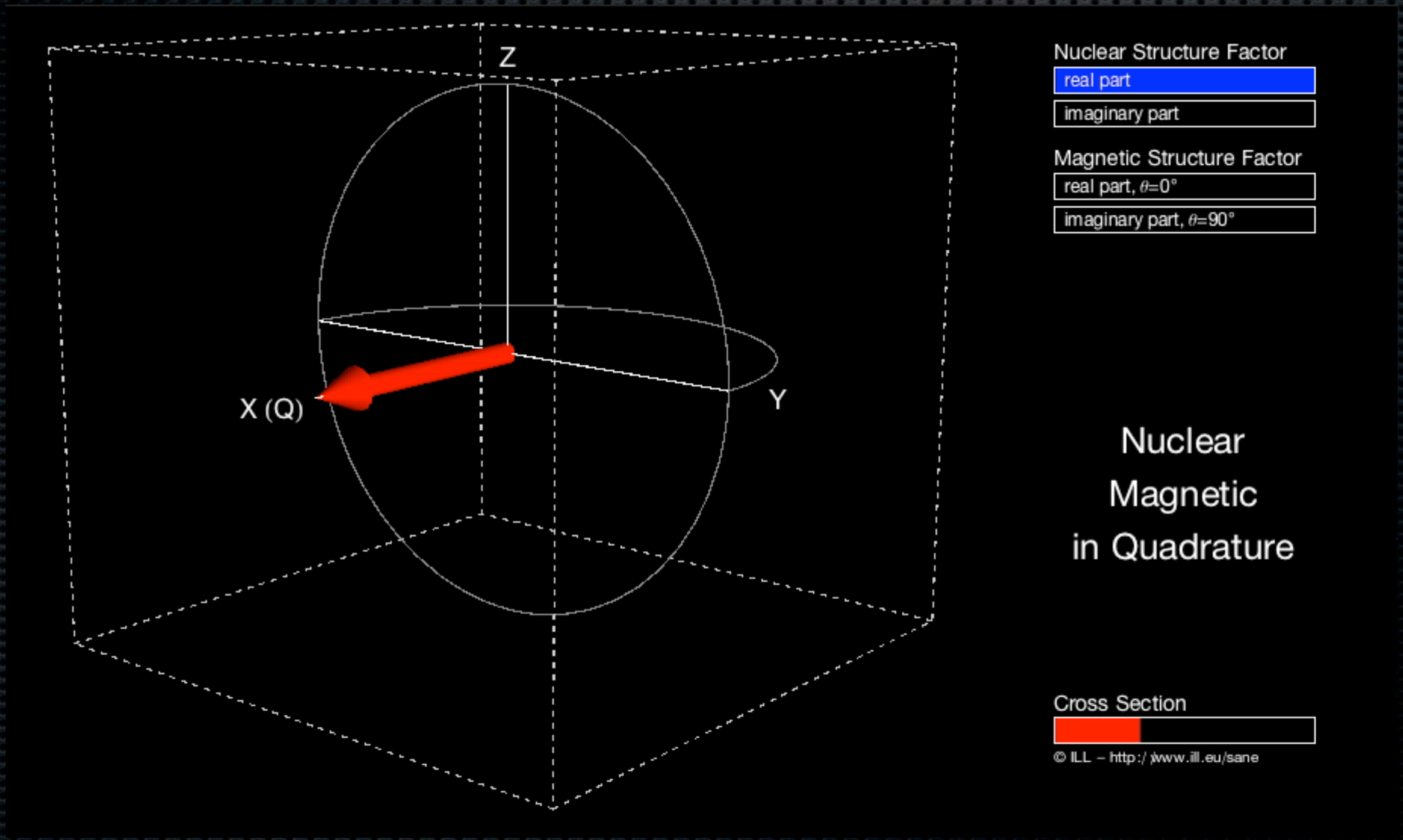

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Spherical neutron polarimetry

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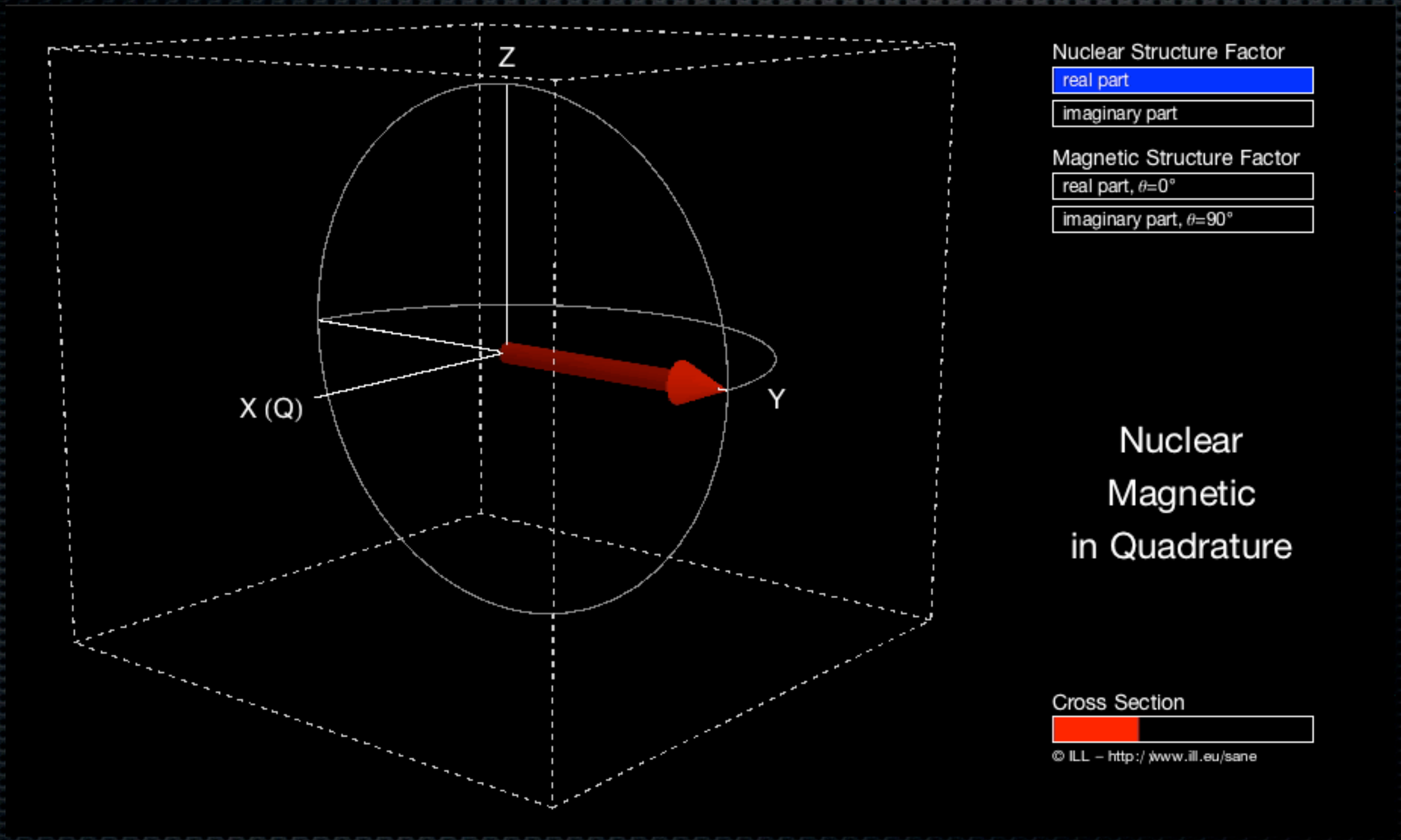

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Spherical neutron polarimetry

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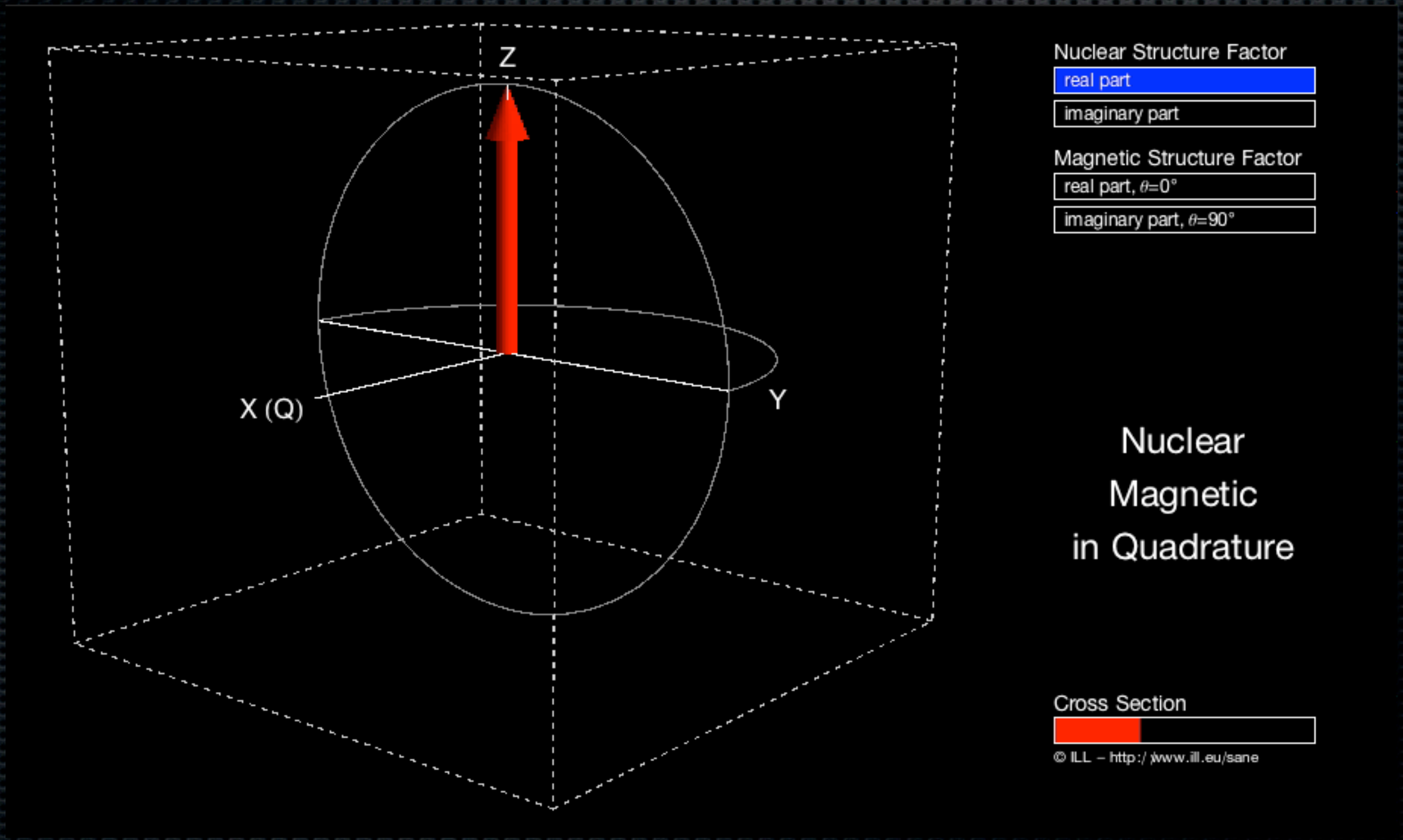

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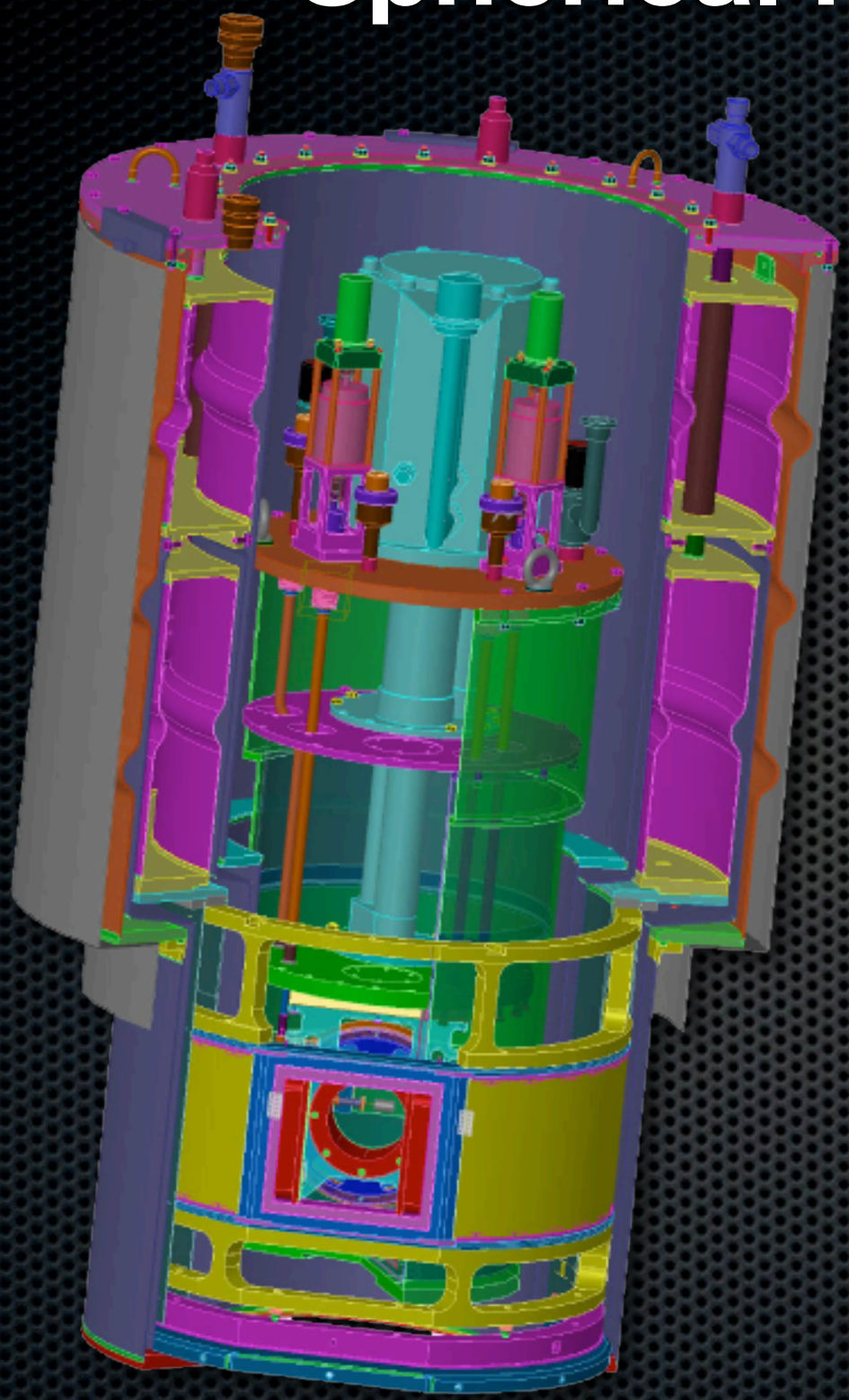

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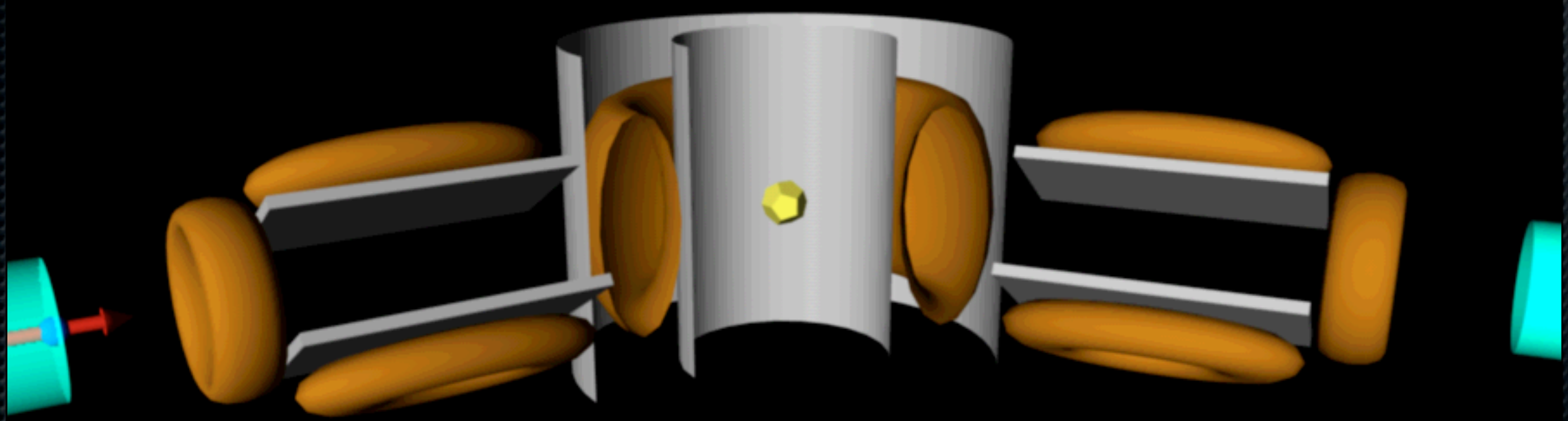
Spherical neutron polarimetry



Cryopad - <2mG in zero-field chamber

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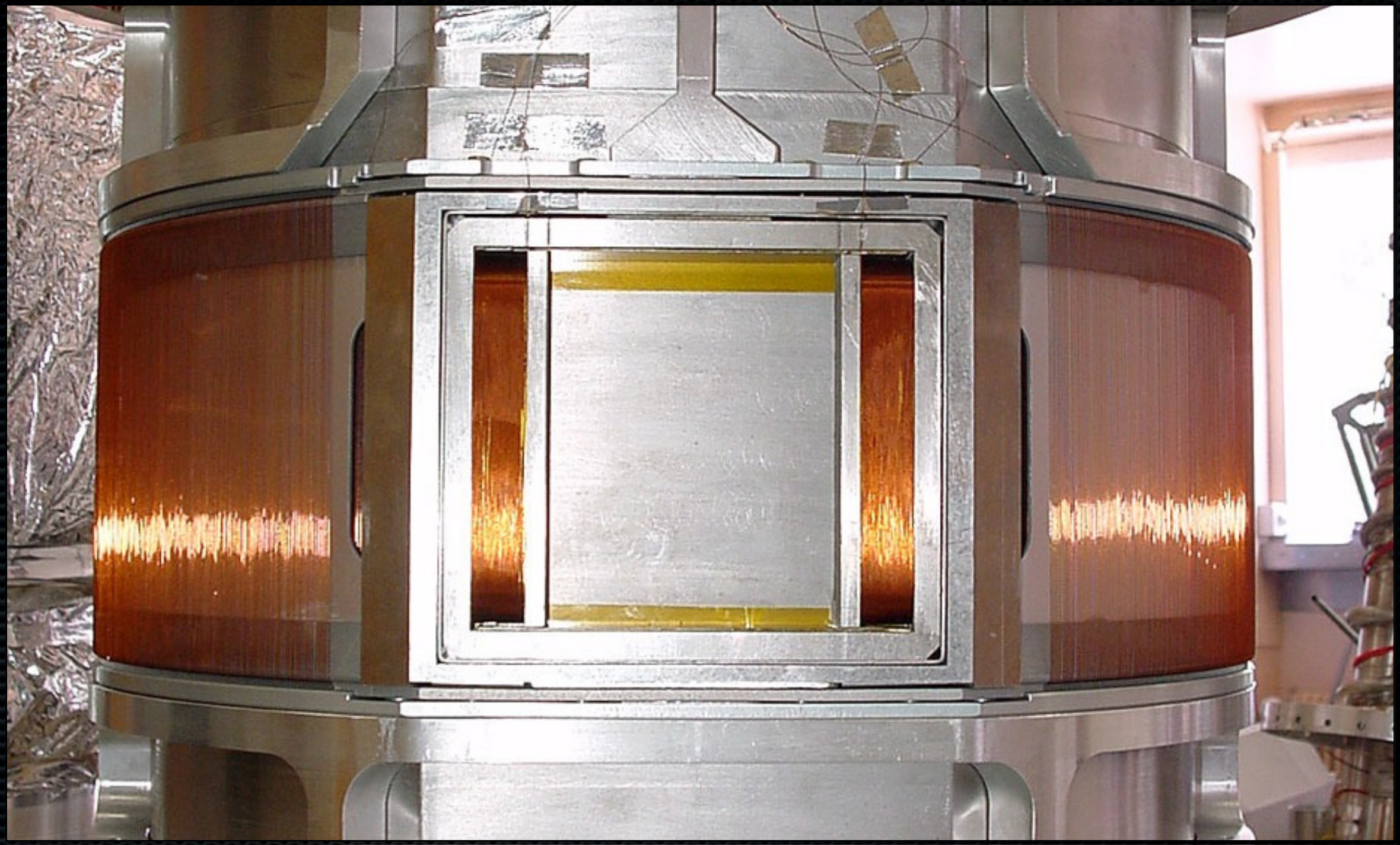
Spherical neutron polarimetry



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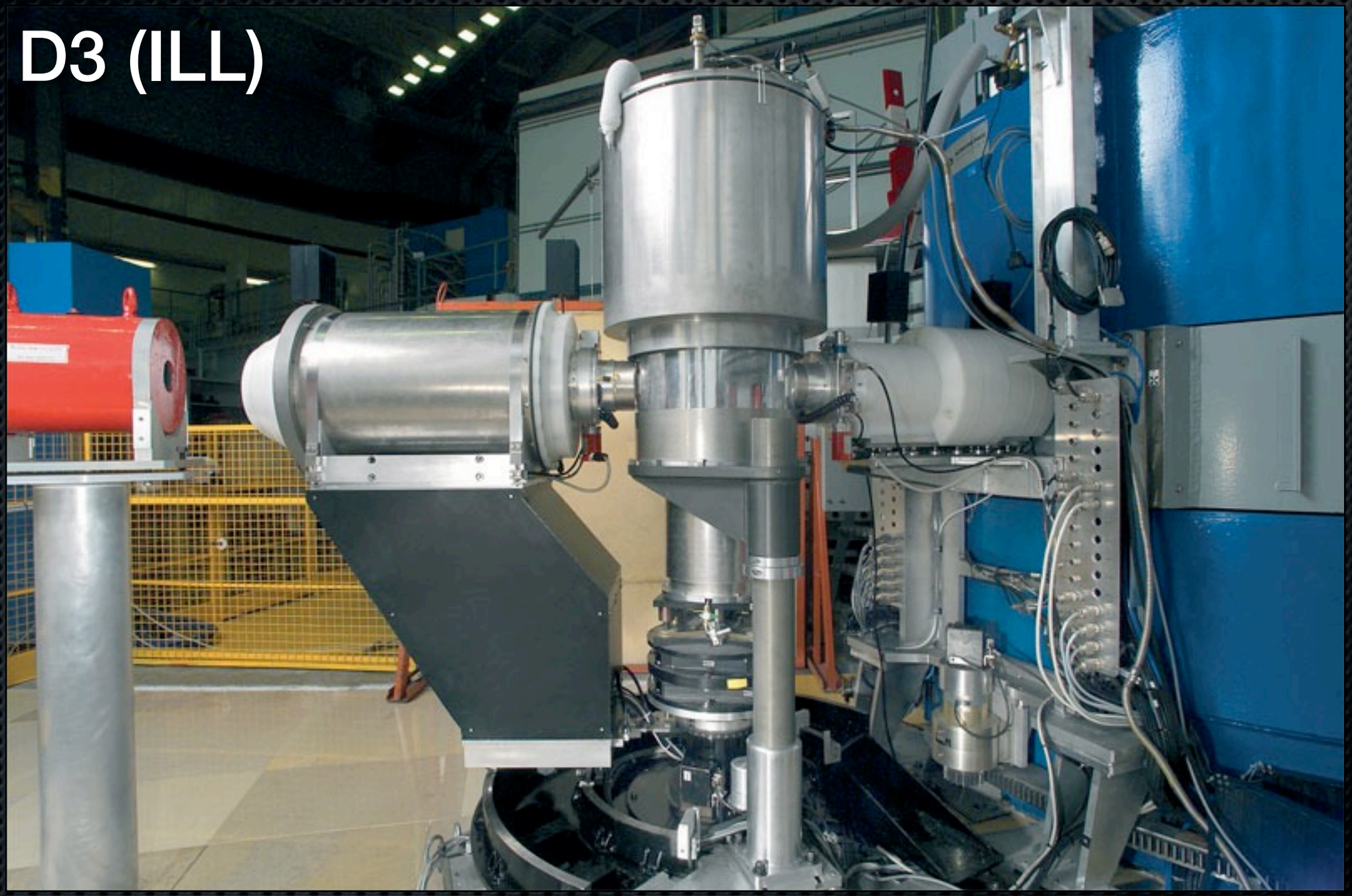
Spherical neutron polarimetry



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Spherical neutron polarimetry

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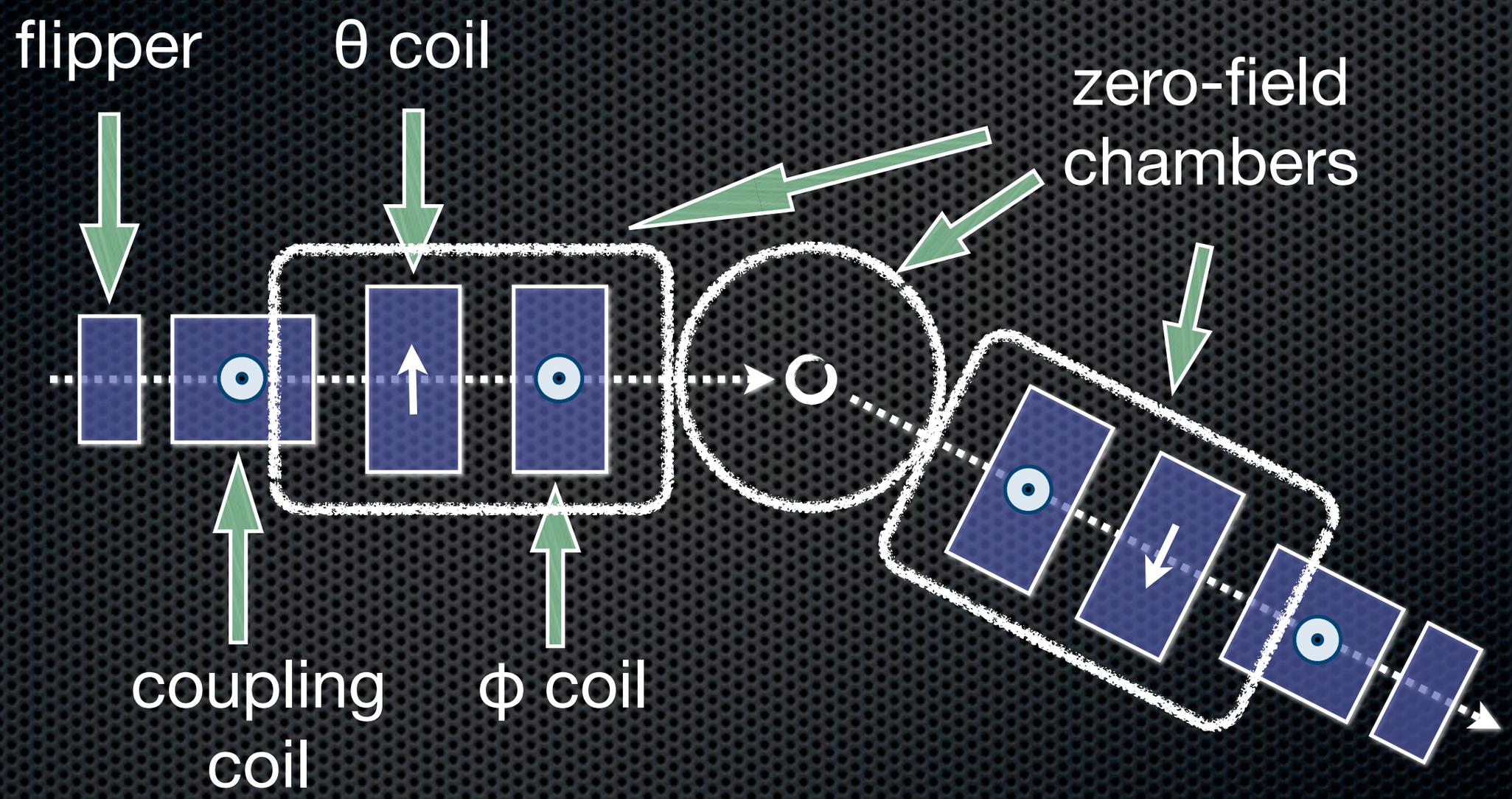
Spherical neutron polarimetry



μPAD - PSI & FRM II

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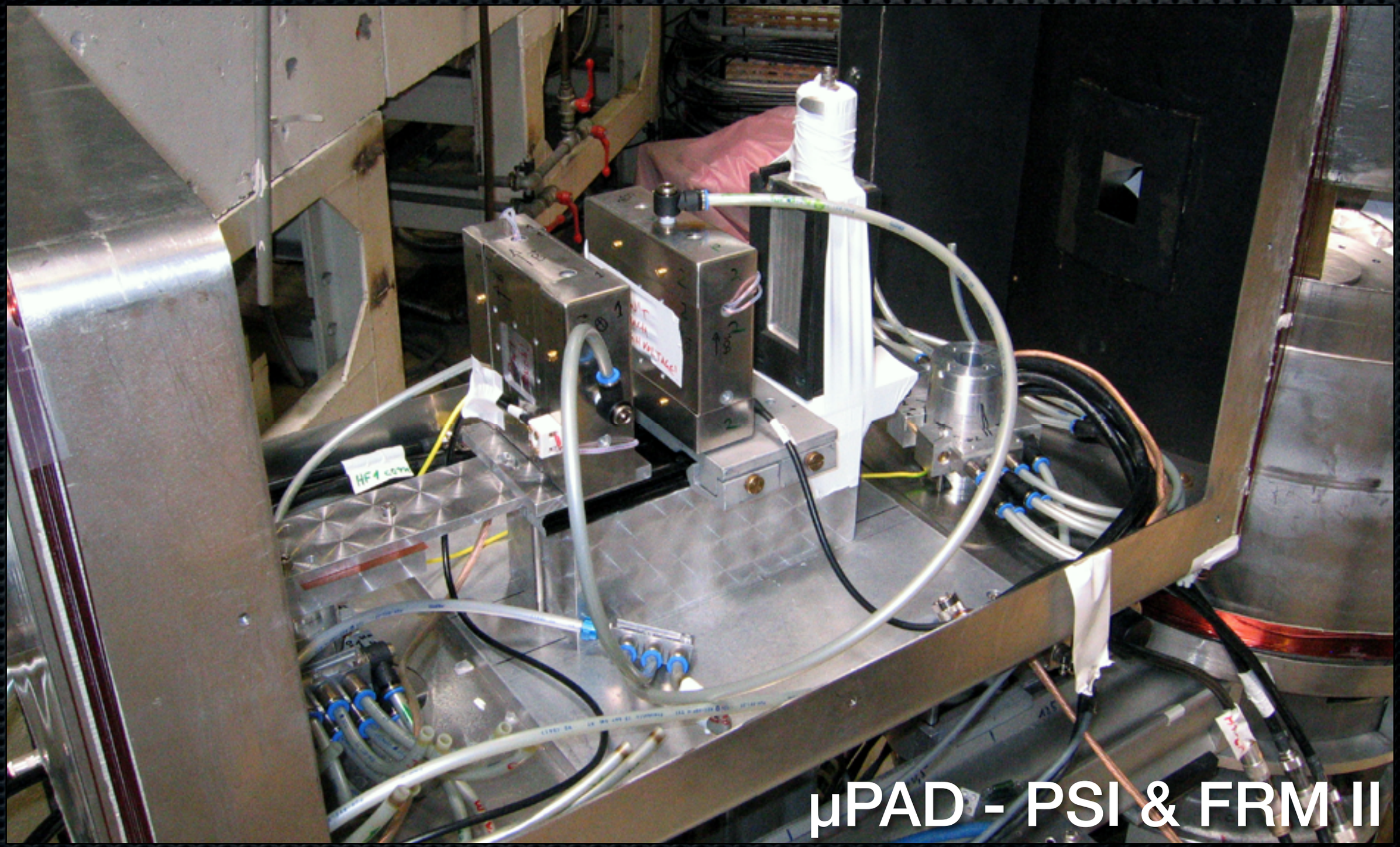
Spherical neutron polarimetry



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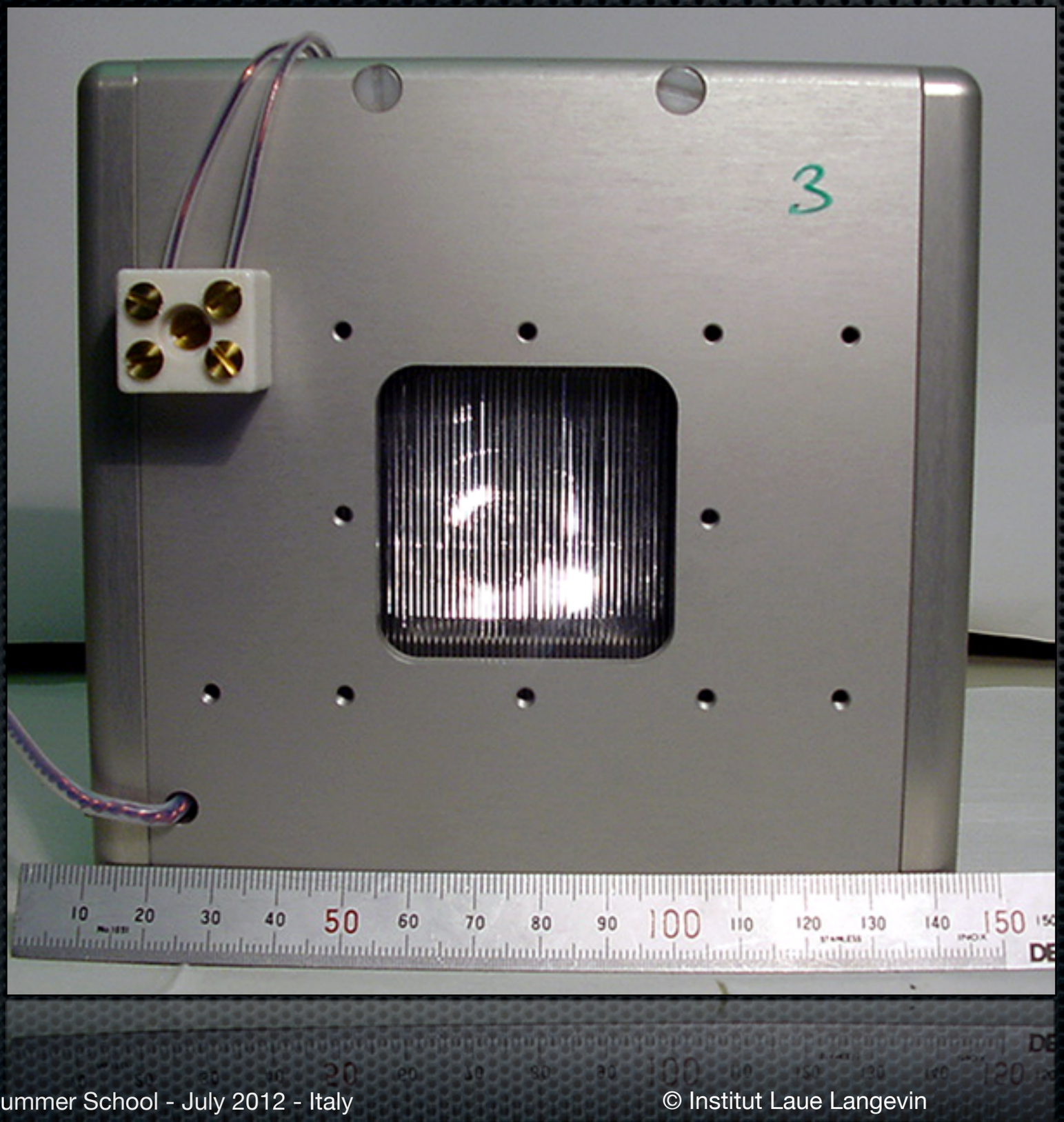
Spherical neutron polarimetry



μPAD, yes but…

problem of leakage at high field i.e. for short wavelengths

problem with zero-field chamber at long wavelength because of field environment

μ-metal “pumps” external fields

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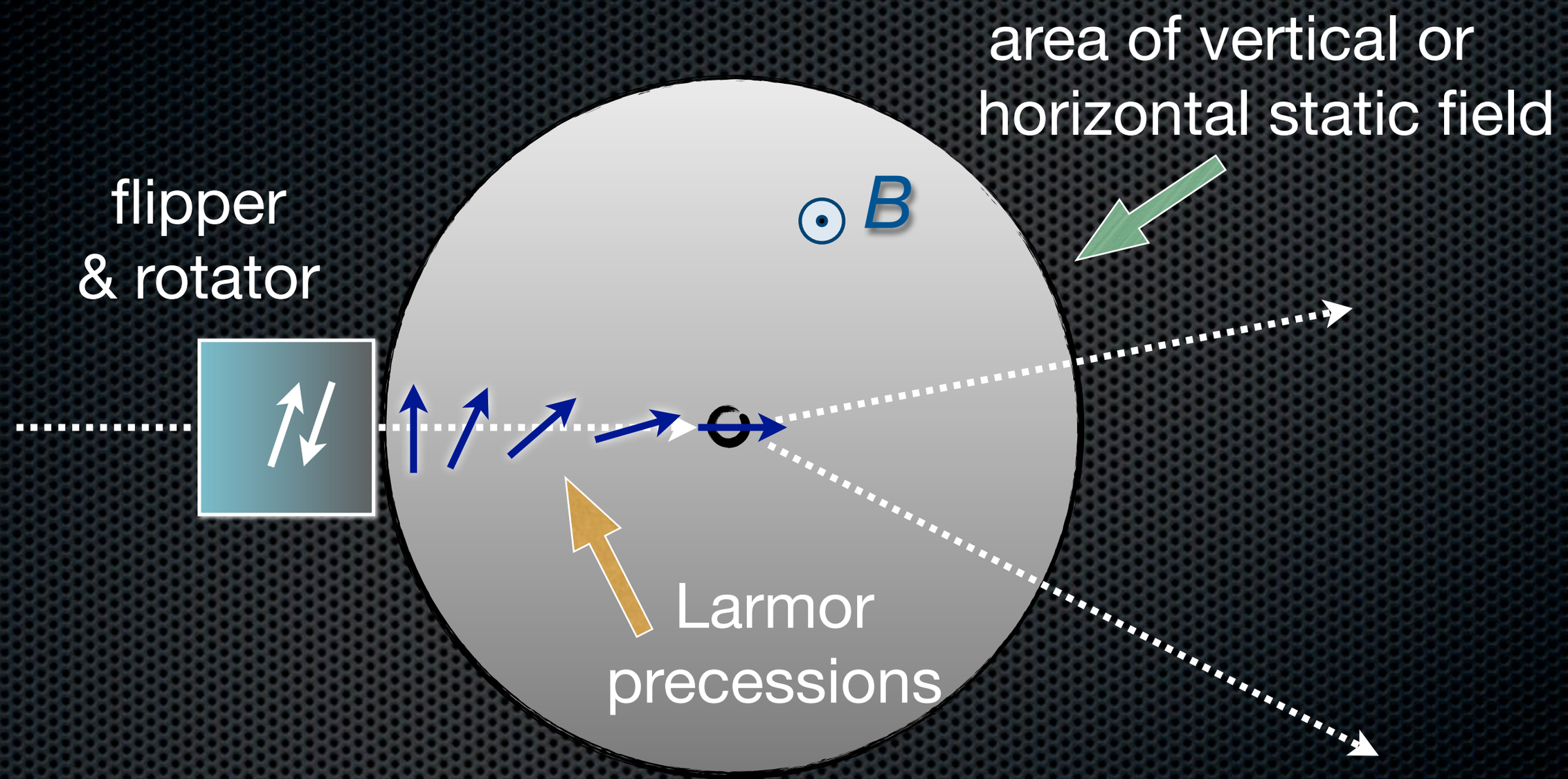
Spherical neutron polarimetry



dnsPAD: the incident direction of polarisation is controlled with the field applied around the sample area.

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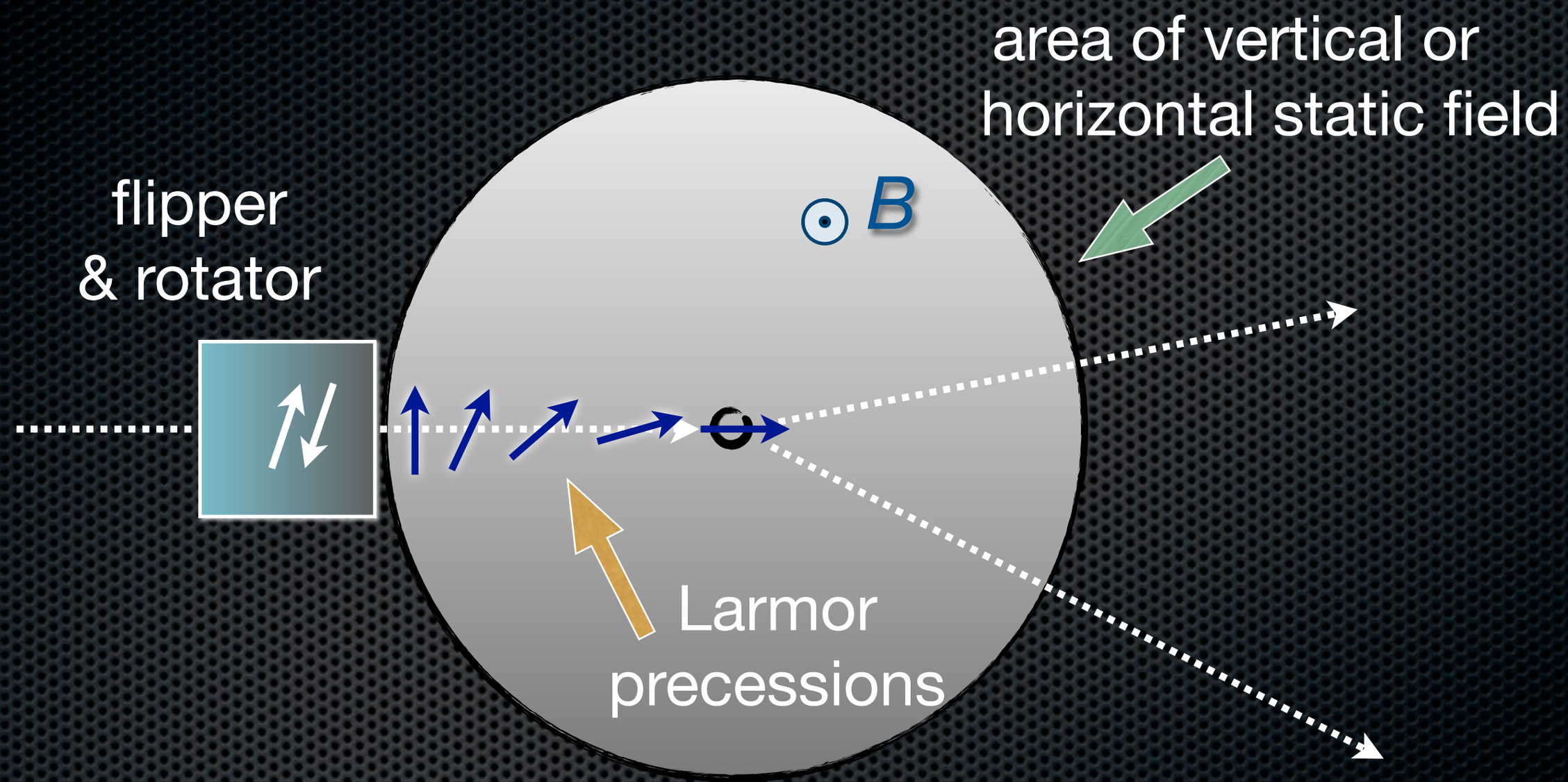
Spherical neutron polarimetry



dnsPAD: the applied field decreases the resolution with which the orientation of the polarisation is set.

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Spherical neutron polarimetry

Cr_2O_3 test experiment carried out on DNS confirmed

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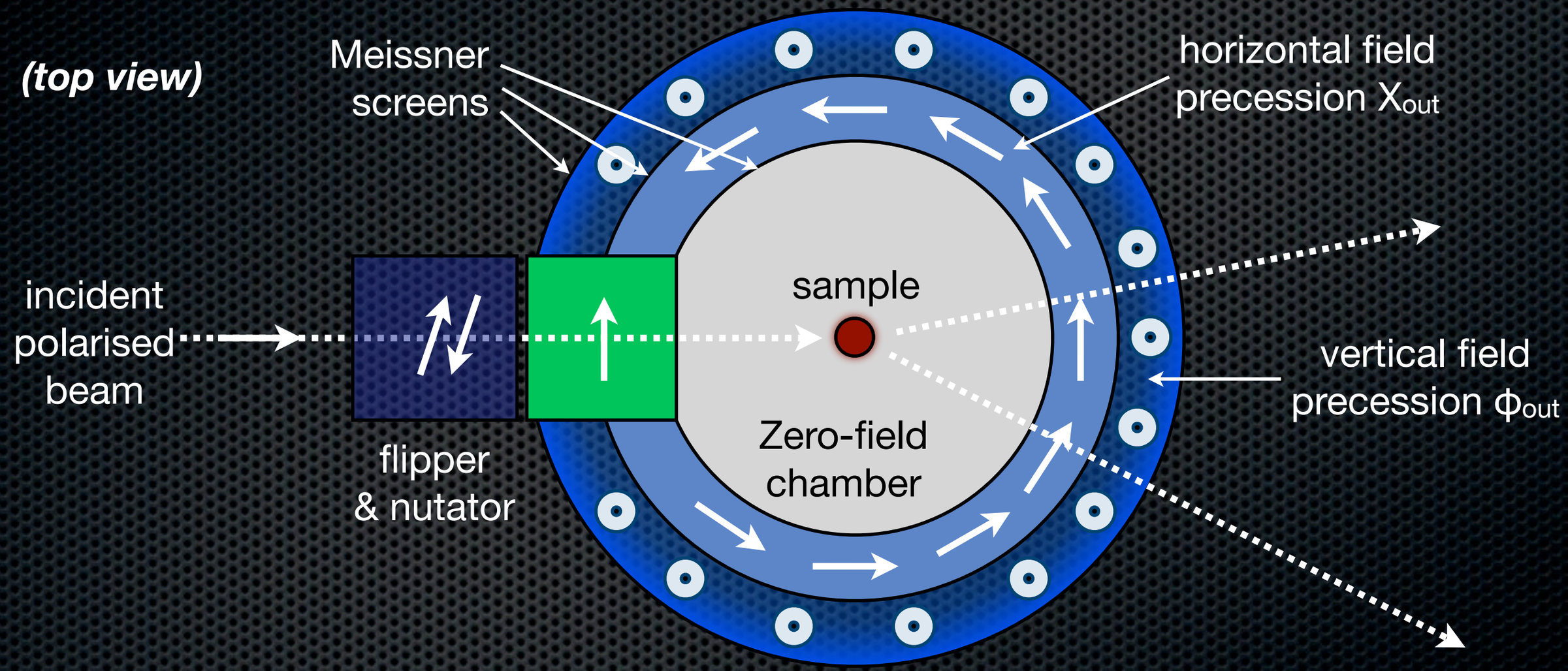
Spherical neutron polarimetry

Time of Flight Polarimetry?



Solution proposed with a ^{3}He spin filter as analyser…

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Content

- Beam polarisation vector
- Spin flippers and Spin filters
- Cross-section & scattered polarisation vector
- PND - Polarised neutron diffraction (powder, crystal)
- UPA - Uniaxial polarisation analysis
- **SNP - Spherical neutron polarimetry**
- Polarimetric Neutron Spin Echo

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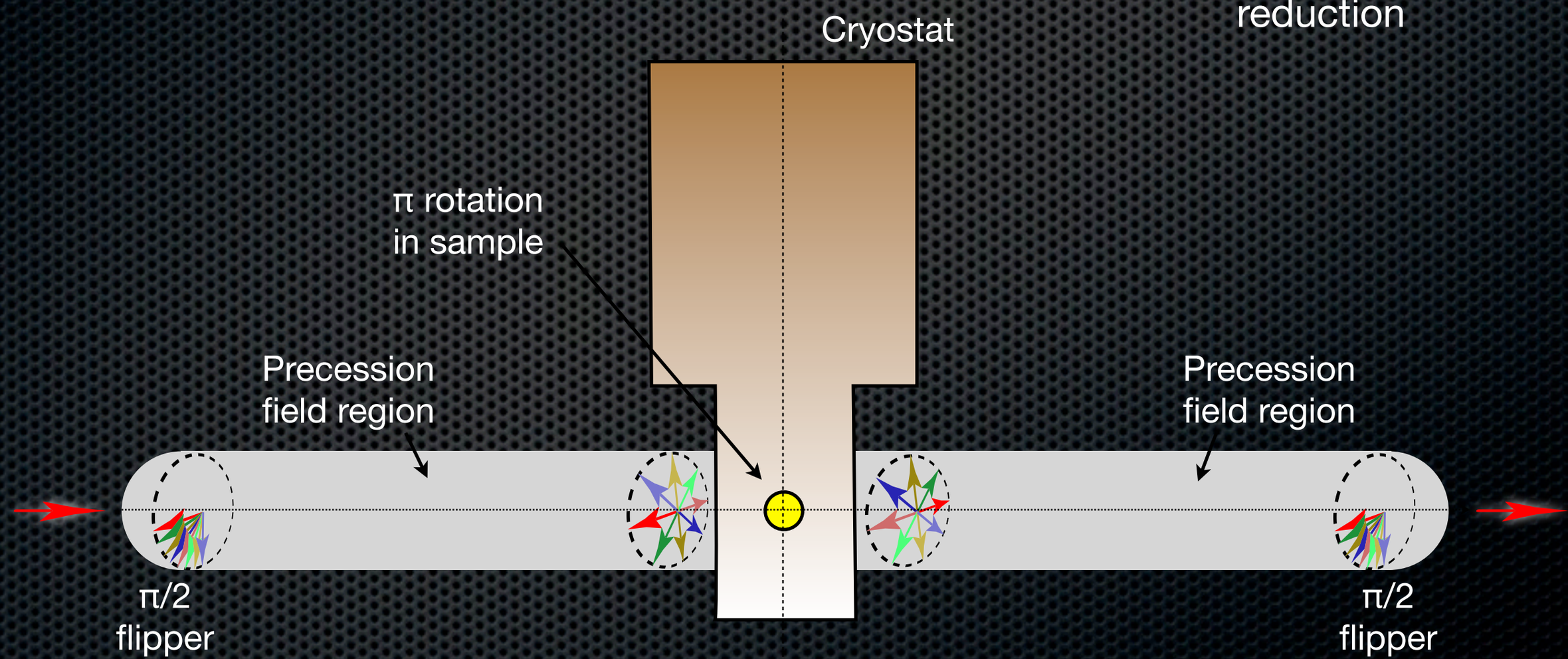
Polarimetric Neutron Spin Echo

Spin-Echo Spectrometer

paramagnetic

high-resolution spectroscopy with relatively low flux reduction



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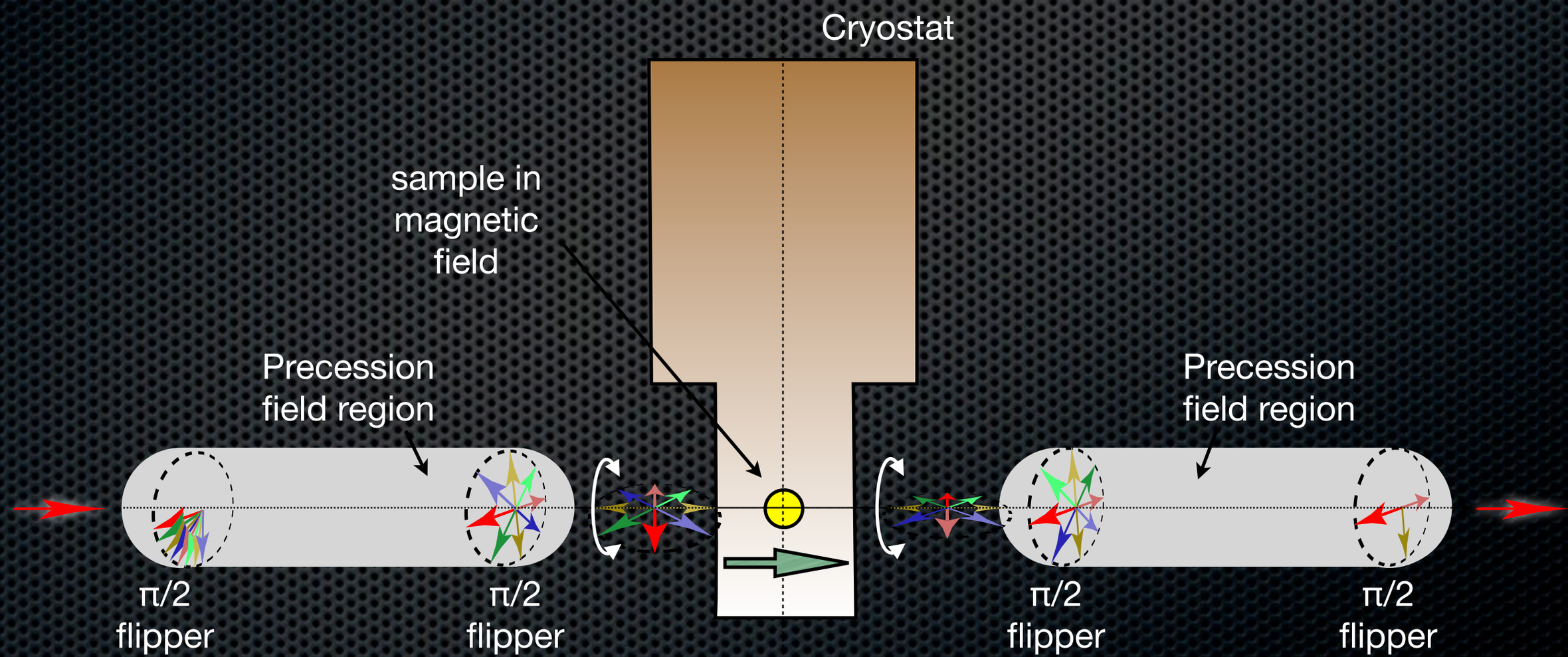
Polarimetric Neutron Spin Echo

Spin-Echo Spectrometer

ferromagnetic

one component is lost,
intensity divided by 2



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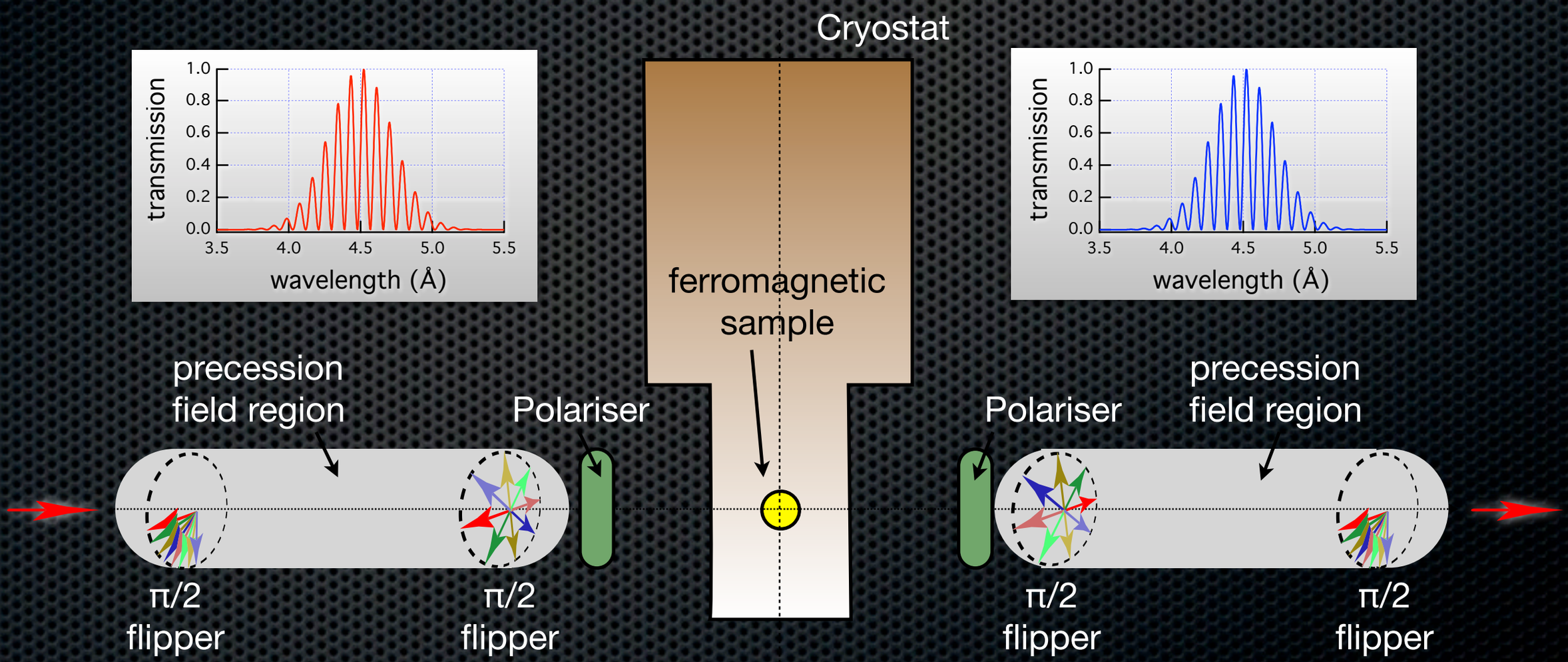
Polarimetric Neutron Spin Echo

Spin-Echo Spectrometer

intensity modulated

ferromagnets in low field,
intensity divided by 4



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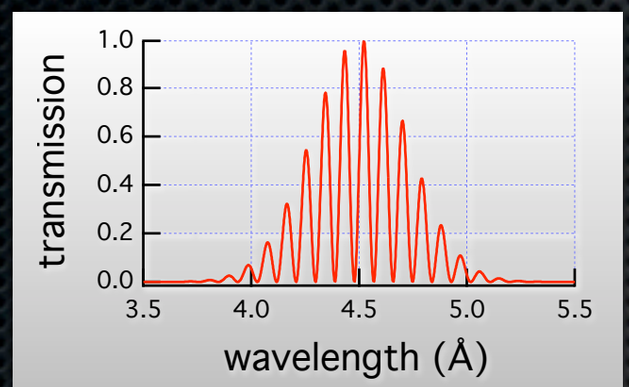
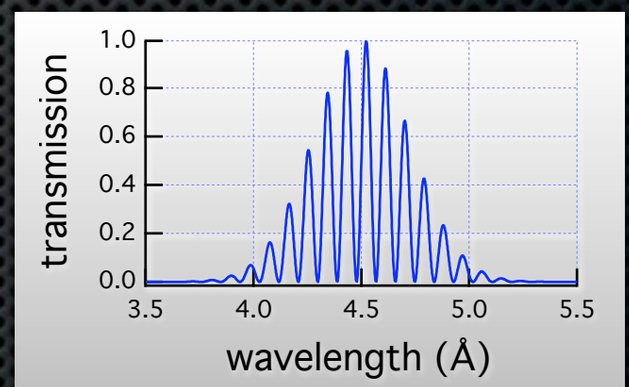
Polarimetric Neutron Spin Echo

Spin-Echo Spectrometer

polarimetric mode

antiferromagnets in zero-field, intensity divided by 4





Cryopad

Cryostat

sample in zero-field chamber

precession field region

Polariser

300G

π/2 flipper

π/2 flipper

θ_{in}

X_{in}

X_{out}

θ_{out}

1mG!

incident nutator

outgoing nutator

precession field region

300G

π/2 flipper

π/2 flipper

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