Superfluid-helium UCN sources: “in-beam“ versus “in-pile“

Oliver Zimmer

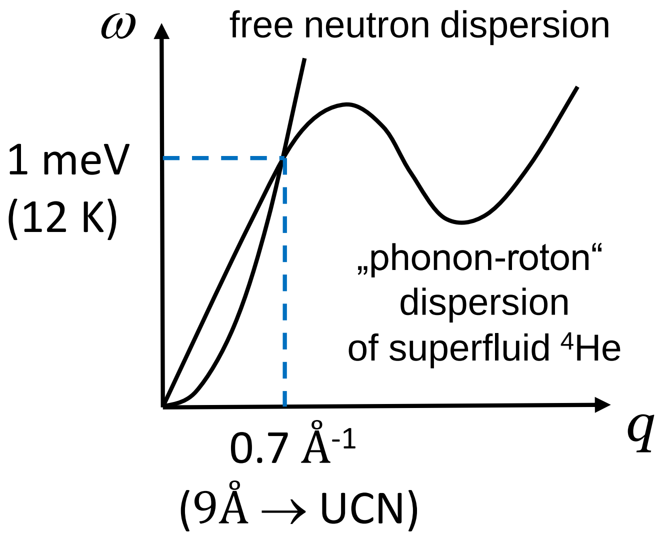
Workshop on Very Cold and Ultra Cold Neutron Sources for ESS, zoom@ESS, 2-4 February

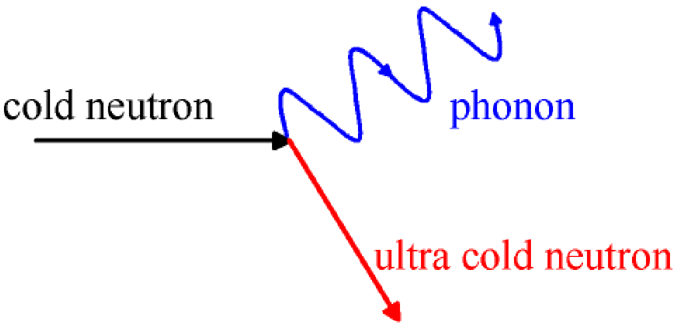
Contents

1. Basic facts
2. Comparison of “in-pile” / “in-beam”
3. Examples for both types of sources
4. What might be achievable “in-beam” at ESS?

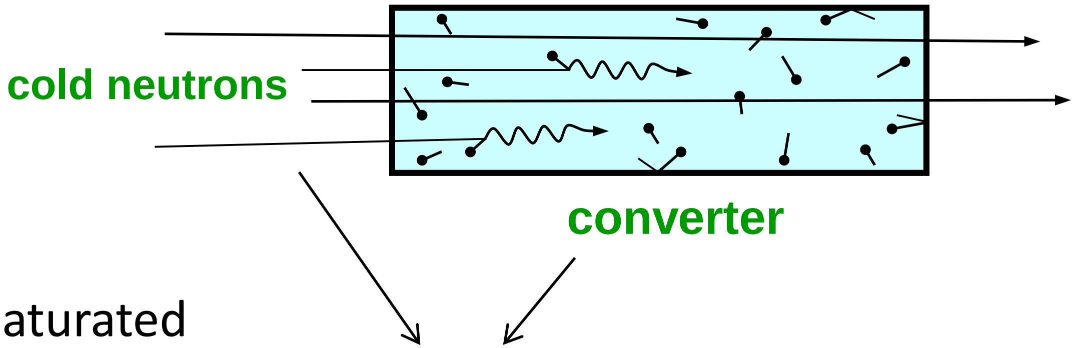
UCN production in superfluid He

Golub & Pendlebury, PL **53A** (1975) 133





$\sigma_{capture}$ (^{4}He) = 0



saturated
UCN density: $\boldsymbol{\rho = \dot{\rho}\,\tau}$

$$\tau^{-1} = \tau^{-1}_{ß} + \tau^{-1}_{up} + \tau^{-1}_{abs} + \tau^{-1}_{wall}$$

with only $\tau_{ß}$ and τ_{up}:

T [K]	τ_{max} [s]
1.2	30
1	100
0.8	310
0.7	510
0.6	710
0	880

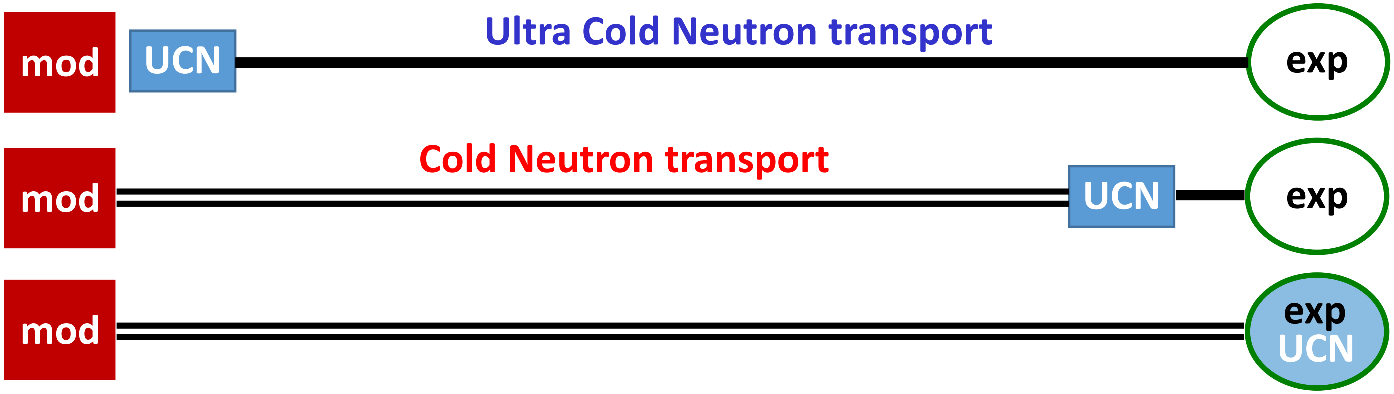
→ τ close to $\tau_{ß}$
for $T < 0.6$ K + low wall loss

“in-pile”

“in-beam”

“in-situ”

→ Skyler’s talk



- **Cold-Neutron solid angle**: small / large (*defines type of UCN source*)
  - → lower / higher UCN production rate and flux
  - → high-density, “accumulation” / high-flux, “current” -type source
- **Radiation levels:** low / high → heat load on converter
  - → lower / higher cooling power required
  - → **< 0.6 K** / **> 1 K** attainable
  - → maximum / reduced saturated UCN density
  - → free / limited choice of UCN reflectors
- **Distance of experiment from source**: identical / close / far away
  - → **no** / lower / higher UCN transport losses
  - → **no** / smaller / larger dilution of UCN density from source to experiment
- **Access for troubleshooting**: easy / difficult
  - → better / worse duty cycle
  - → straightforward / difficult source optimization

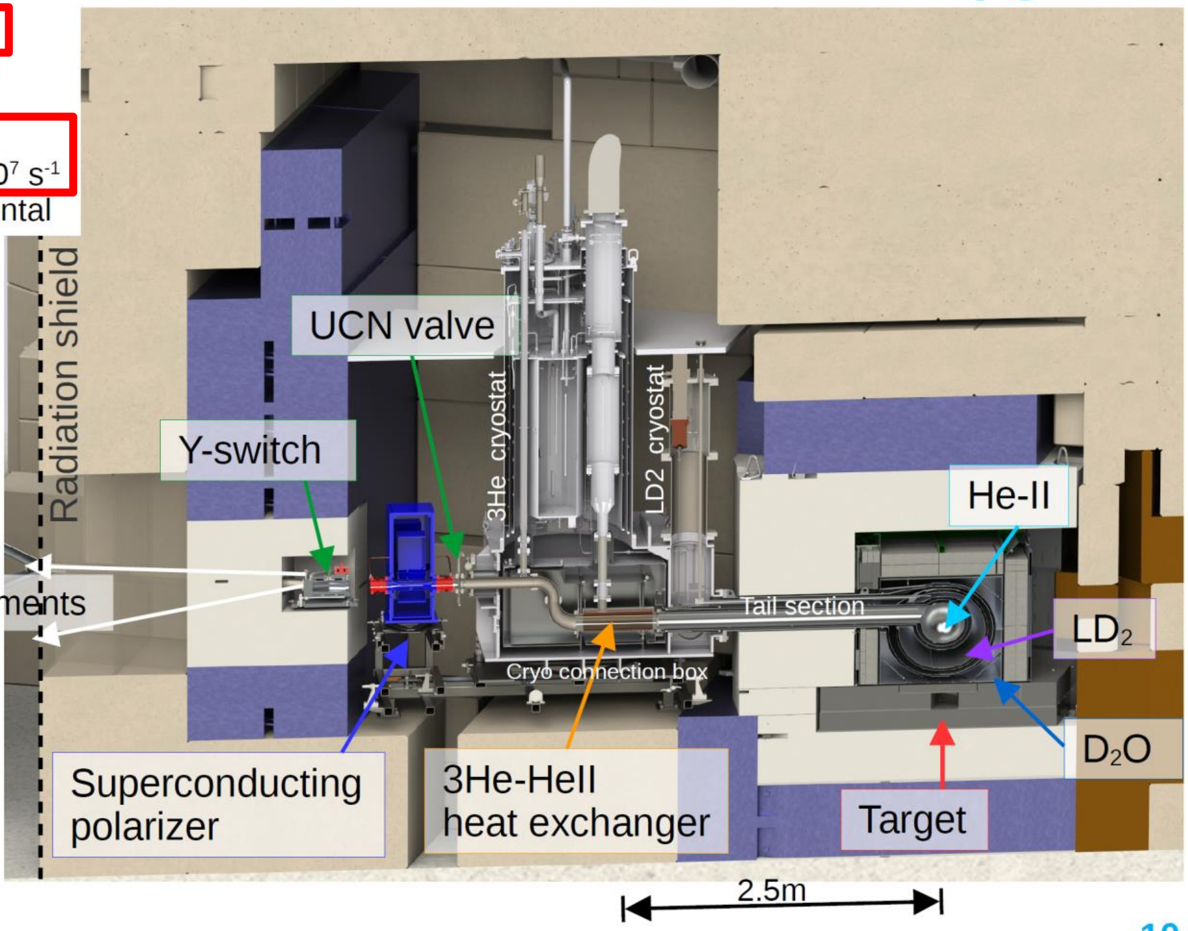
TUCAN spallation source based He-II UCN source

(building on work by Masuda et al.)

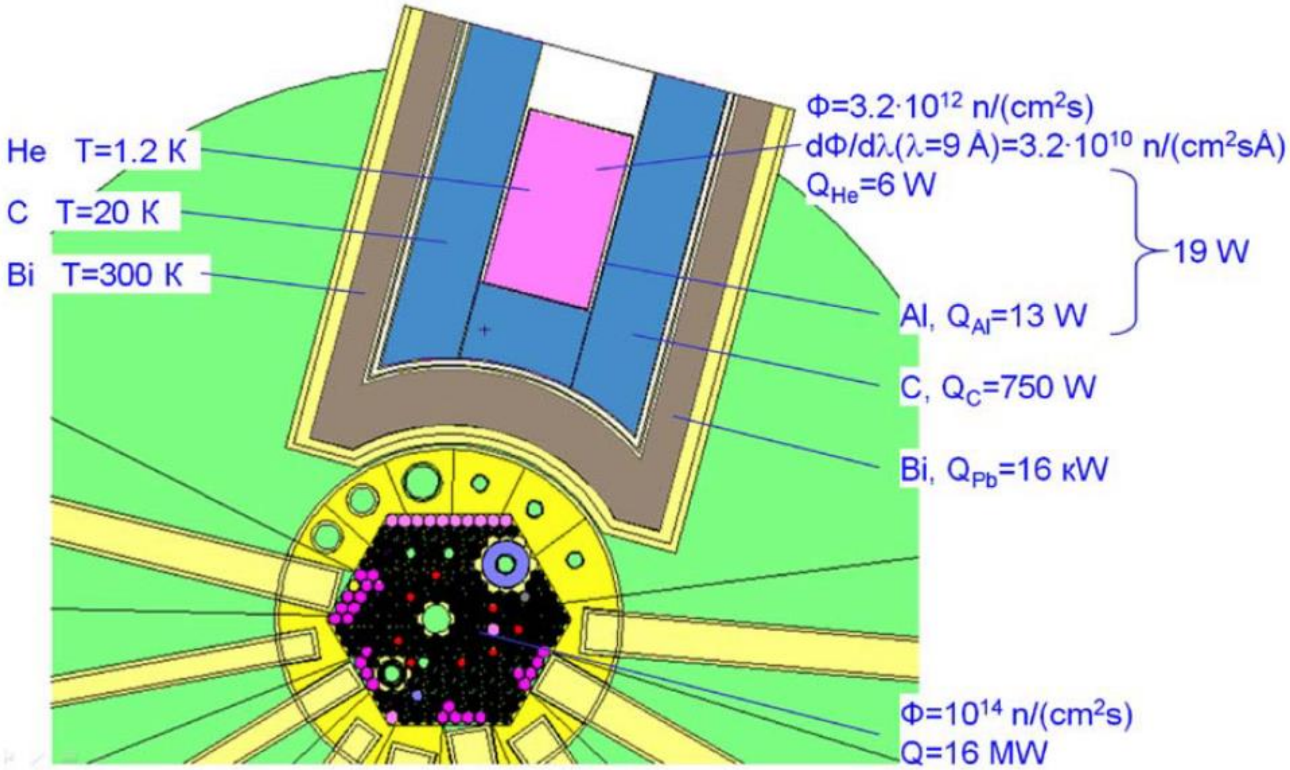
@ TRIUMF

	demonstrated	projected
Cooling power (~1K)	0.3 W	→ 10 W
Beam current on target	1 μA	→ 40 μA
Cold moderator @20 K	sD2O	→ LD2
UCN prod. vol.	8 L	→ 28 L
UCN production rate	2×10^{4} s^{-1}	→ 1.4×10^{7} s^{-1}
UCN extraction	vertical	→ horizontal

TUCAN source upgrade



In-pile source project for WWR-M reactor in Gatchina



Simulated performances: → **Anatoly's talk**

$\dot{\rho} = 2.9 \times 10^3\ \mathrm{s^{-1}cm^{-3}}$

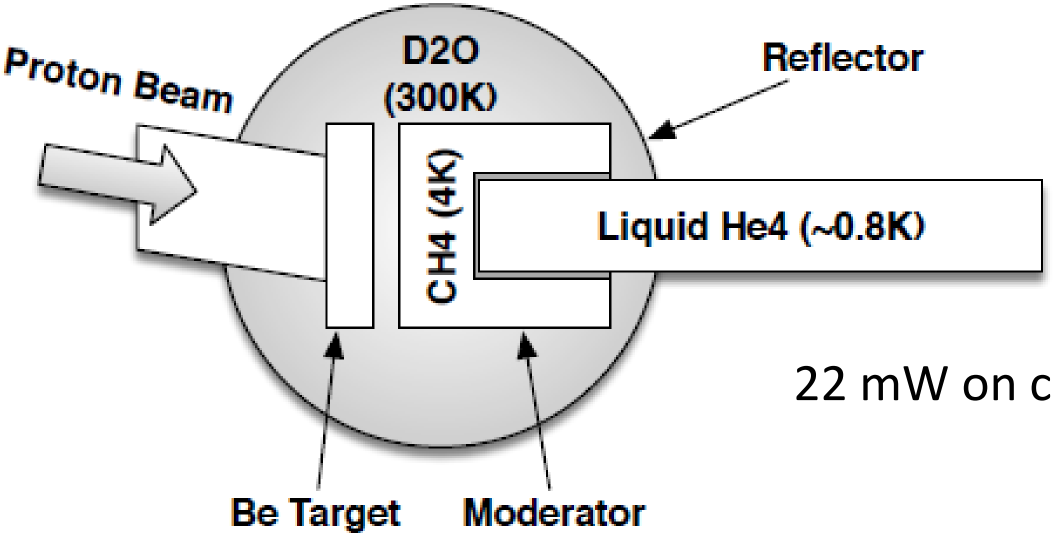
$\dot{\rho}V = 10^8\ \mathrm{s^{-1}}$ [SuperSUN: $1.6 \times 10^5\ \mathrm{s^{-1}}$]

$\rho = 5.8 \times 10^4\ \mathrm{cm^{-3}}$ [$1.7 \times 10^3\ \mathrm{cm^{-3}}$ polarised]

Ultracold Neutron Production at Compact Neutron Sources

Yun Chang Shin,[1,*] W. Michael Snow,[2,3] David V. Baxter,[2,3] Chen-Yu Liu,[2,3] Dongok Kim,[1,4] Younggeun Kim,[1,4] and Yannis K. Semertzidis[1,4]

arXiv:1810.08722v3 (October 2018)



22 mW on converter

<u>Simulated performances:</u>

$\dot{\rho} = 56\ \mathrm{s}^{-1}\mathrm{cm}^{-3}$ in 1.35 litres He, with methane pre-moderator,

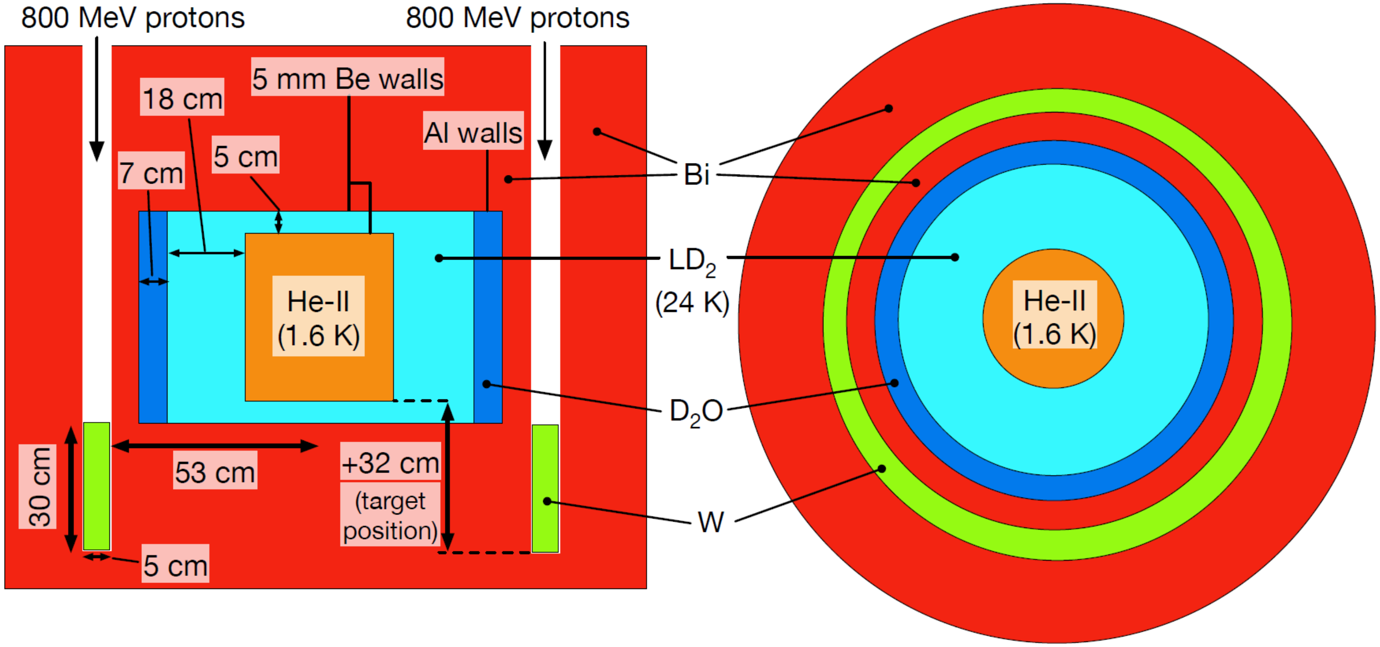
$80\ \mathrm{s}^{-1}\mathrm{cm}^{-3}$ with methane hydrate clathrate

$\tau = 50\ \mathrm{s}\ \rightarrow \rho = 4000\ \mathrm{cm}^{-3},\ \ \rho V = 5 \times 10^{6}$

A next-generation inverse-geometry spallation-driven ultracold neutron source

K.K.H. Leung,[1,2,a)] G. Muhrer,[3,4,b)] T. Hügle,[4,5] T.M. Ito,[4] E.M. Lutz,[1,2] M. Makela,[4] C.L. Morris,[4]
R.W. Pattie, Jr.,[4,6] A. Saunders,[4] and A.R. Young[1,2,c)]

arXiv:1905.09459 (October 2019)



100 W on converter

Simulated performances: → **Kent's talk**

$\dot{\rho} = 5 \times 10^4\ \mathrm{s}^{-1}\mathrm{cm}^{-3}$ in 40 litres He-II

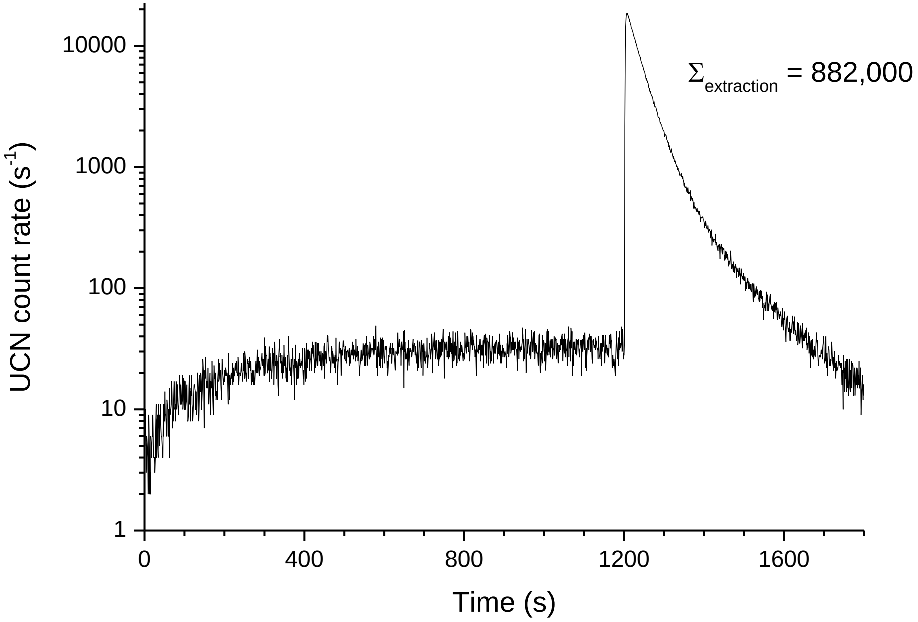
UCN flux extracted through 5-m long Ø18 cm guide: $5 \times 10^8\ \mathrm{s}^{-1}$

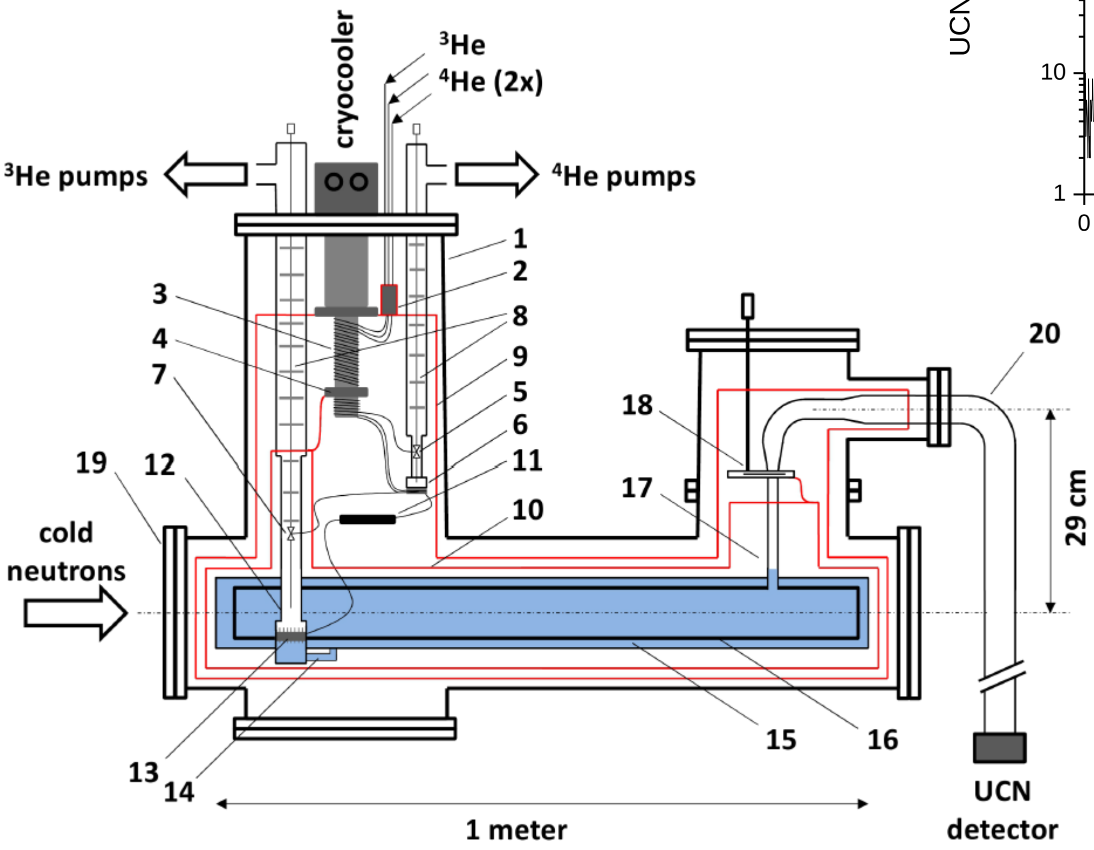
$\rho \rightarrow 10^4\ \mathrm{cm}^{-3}$ in large external trap

He-II UCN source development (TUM & ILL, 2004+)

window- and gap-less vertical UCN extraction
+ light cryogenics adapted to needs

$$\dot{\rho} = 4.5\ \mathrm{s}^{-1}\mathrm{cm}^{-3} \text{ in 4 litres}$$
$$\rho \rightarrow 220\ \mathrm{cm}^{-3}\ (E < 100\ \mathrm{neV})$$





Cryogenics **46** (2006) 799

Phys. Rev. Lett. **99** (2007) 104801

Eur. Phys. J. C **67** (2010) 589

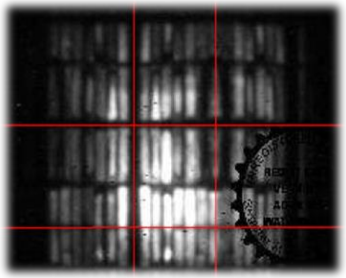
Phys. Rev. Lett. **107** (2011) 134801

Phys. Rev. C **90** (2014) 015501

Phys. Rev. C **92** (2015) 024004

Phys. Rev. C **93** (2016) 025501

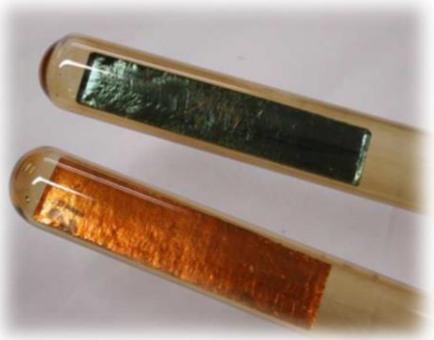
He-II UCN source prototypes SUN-1&2 @ ILL

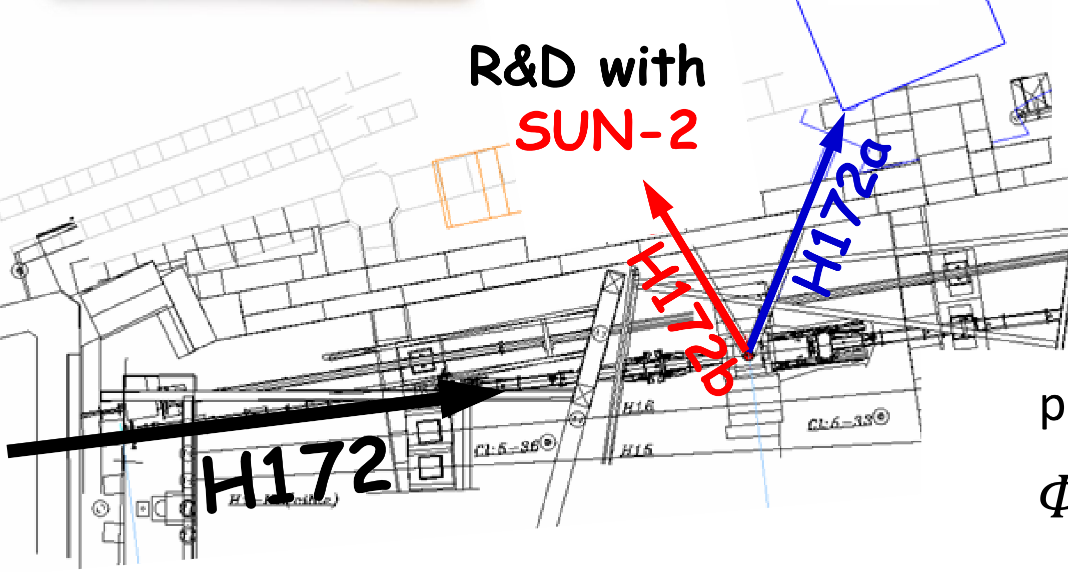


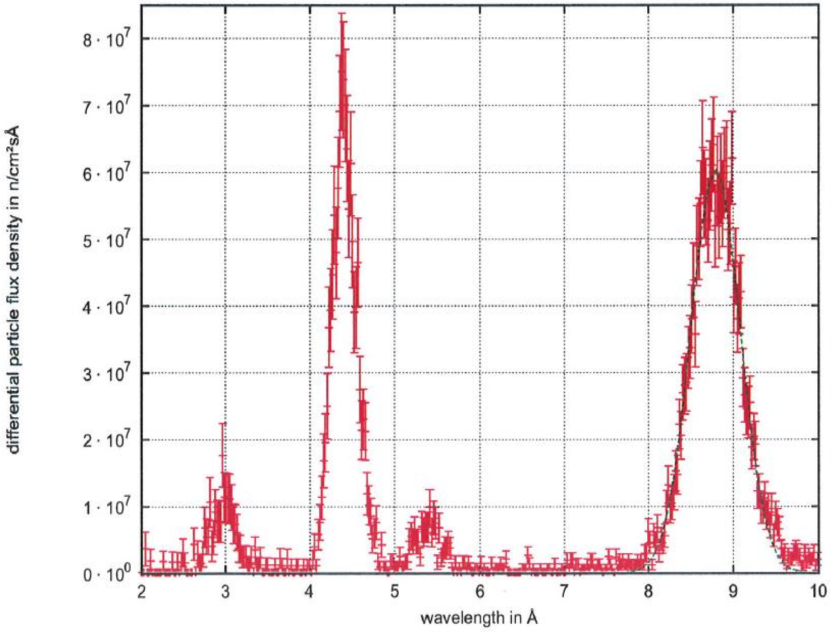
H172a and H172b secondary 9Å beams:

Bragg reflection off stage-I /-II intercalated graphite

$$\Phi^* = 9 \times 10^7 \text{ s}^{-1}\text{cm}^{-2}\text{Å}^{-1}$$



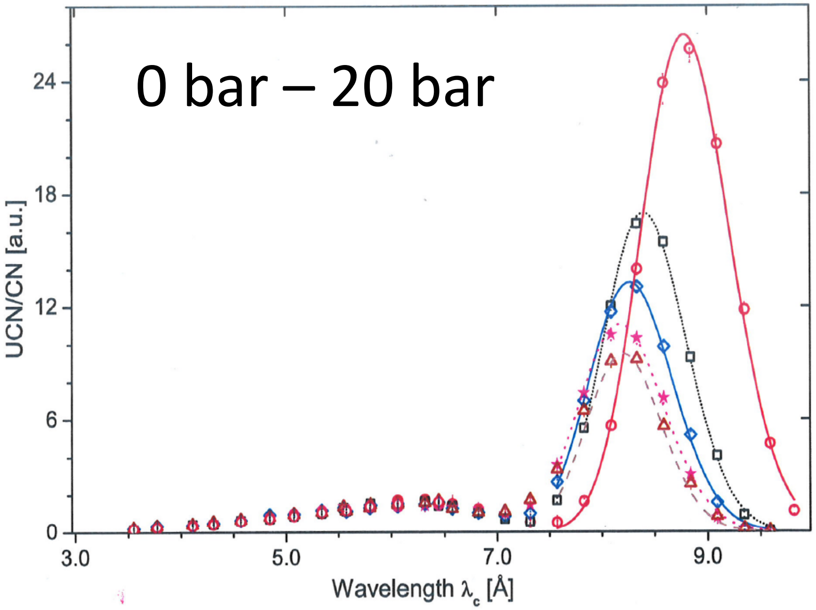


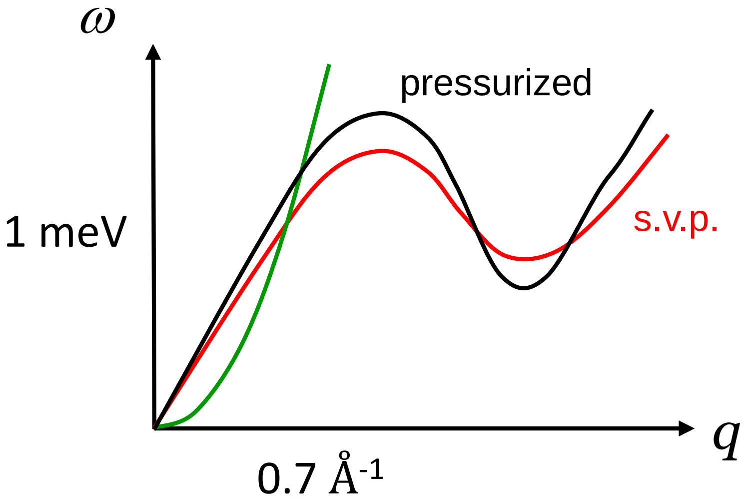


primary beam: $8 \times 8\ \text{cm}^2$, $m = 2$

$$\Phi^* = 5.4 \times 10^8 \text{ s}^{-1}\text{cm}^{-2}\text{Å}^{-1}$$

UCN production in pressurized He-II, using SUN-1 @ PF1B





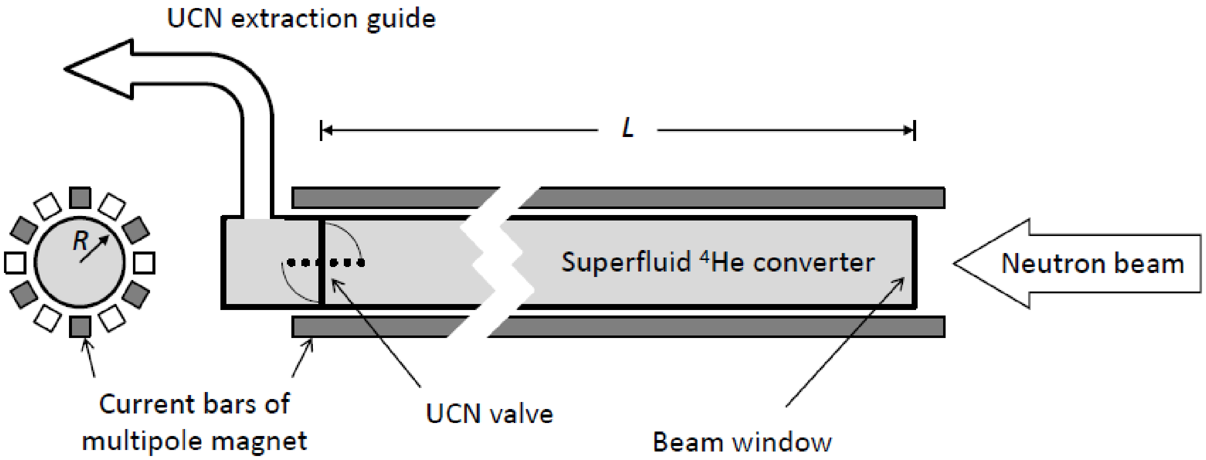
Schmidt-Wellenburg et al.,
PRC **92** (2015) 024004

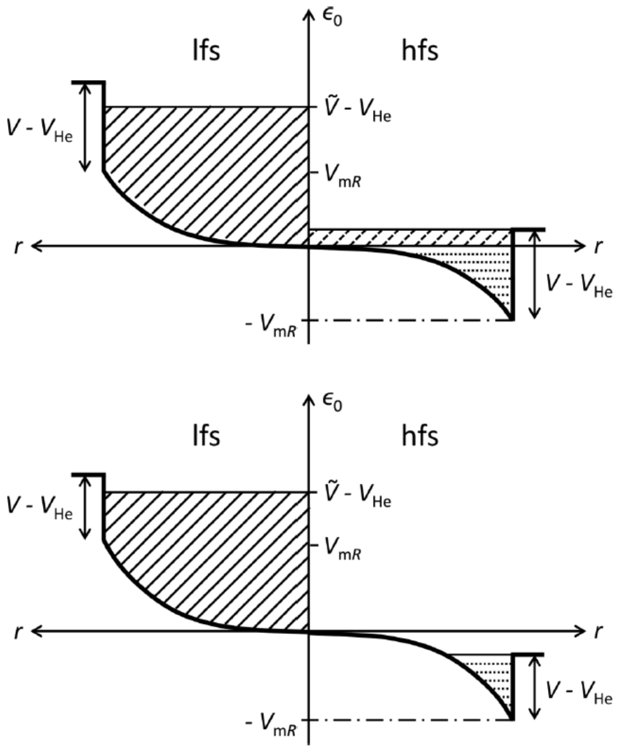
from left to right:
Philipp Schmidt-Wellenburg
Amel Rahli, Torsten Soldner,
Kent Leung

ILL project SuperSUN → Estelle's talk

- Single-user facility (PanEDM)
- magnetic multipole reflector:
  → strongly reduced wall losses
  → fully polarised UCN

Phys. Rev. C **92** (2015) 015501





Projected performances:

$\dot{\rho} = 13.5\ \mathrm{s}^{-1}\mathrm{cm}^{-3}$ in 12 litres He-II, $\dot{\rho}V = 1.6 \times 10^5\ \mathrm{s}^{-1}$

$\rho = 330\ \mathrm{cm}^{-3}$ (phase I, without magnet, fomblin spectrum)

$1700\ \mathrm{cm}^{-3}$ (phase II, with magnet, polarised, E < 230 neV)

Test of 4 m, Ø-50 NiMo coated glass guide for PanEDM at SUN-2

Transmission: 85 % for spectrum with *E* < 100 neV

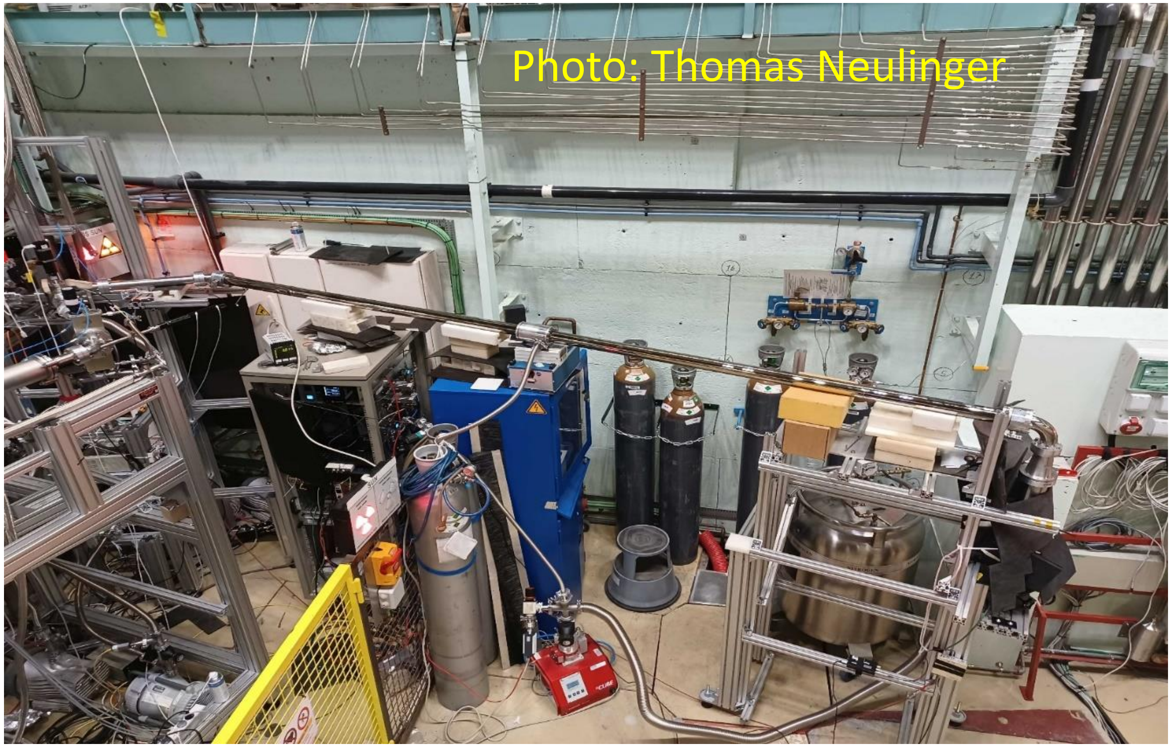


Photo: Thomas Neulinger

Hanno Filter
et al.

Long-guide (> 10 m) transmission previously validated by

TUM group → **Andreas' talk**

PSI group → **Bernhard's talk**

→ No show stopper for in-pile type sources

but don't forget guide volume in accumulation-type UCN sources

Properties of planned ESS liquid-D2 moderator (Luca Zanini):

Moderator brilliance $\frac{d\Phi}{d\lambda d\Omega}$ at 9Å:

$$3.4 \times 10^{11}\ \mathrm{s^{-1}cm^{-2}sr^{-1}\text{Å}^{-1}}$$ (time average at 5 MW)

Usable moderator surface: $24_{\mathrm{vertical}} \times 40_{\mathrm{horizontal}}\ \mathrm{cm}^2$

Beam extraction with mirrors:

Critical angle for natural nickel ($m = 1$):

$$1.73\ \mathrm{mrad/\text{Å}} \ \leftrightarrow\ 15.6\ \mathrm{mrad/(9\text{Å})}$$

$$\leftrightarrow\ \Omega = \pi\theta_c^2 = 7.65 \times 10^{-4}\ \mathrm{sr}$$

UCN production rate density (Be-coated converter, *E* ≤ 233 neV), due to moderator brilliance at 9Å within Ω:

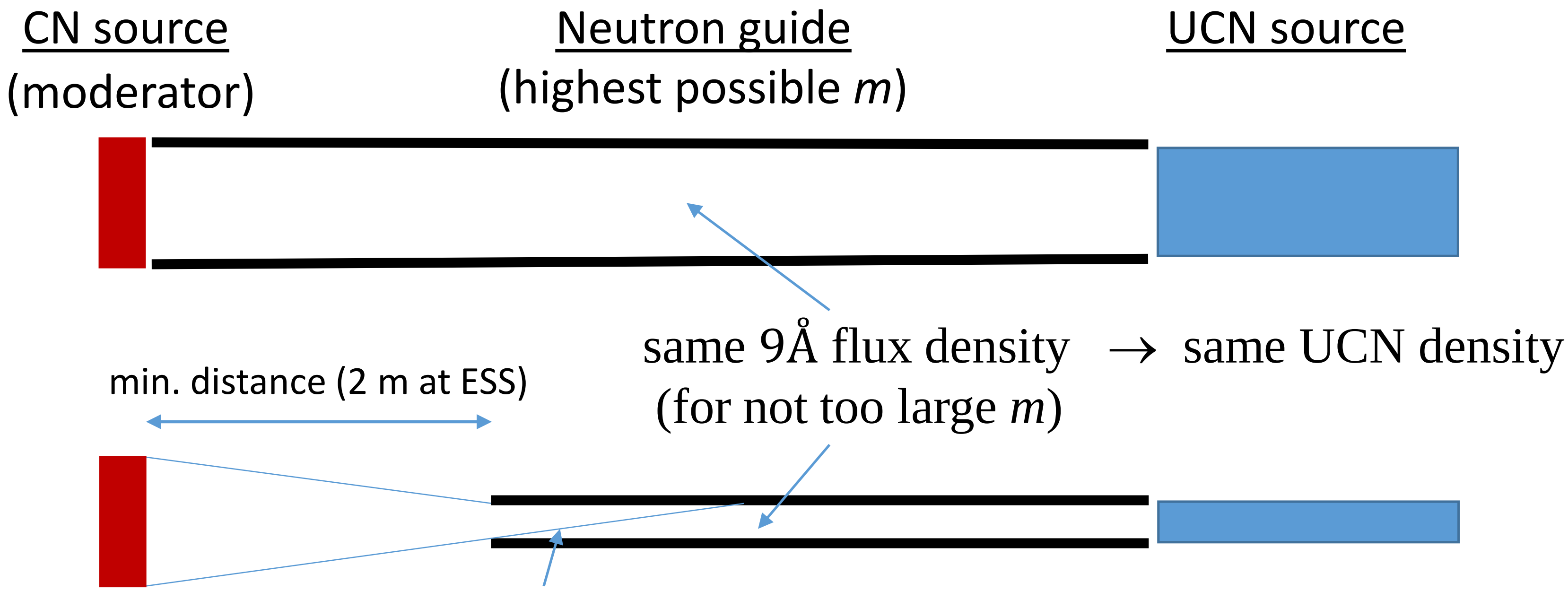
$$\boxed{\dot{\rho} \approx 12.9\ \mathrm{s^{-1}cm^{-3}} \times m^2}$$

$$\dot{\rho} \approx 4.97(38) \times 10^{-8}\ \text{Å}\mathrm{cm}^{-1} \left.\frac{d\Phi}{d\lambda}\right|_{9\text{Å}}$$

Schmidt-Wellenburg et al.,
NIM A 611, 259 (2009)

Neutron guide for CN delivery to the UCN source?

For highest UCN density, we need to fill the beam phase space of a guide:



CN source
(moderator)

Neutron guide
(highest possible *m*)

UCN source

same 9Å flux density → same UCN density
(for not too large *m*)

min. distance (2 m at ESS)

$\theta_{\text{crit}} = 15.6 \text{ mrad} \times m$
$= 19 \text{ cm} / (2 \text{ m}) \text{ for } m = 6$ → much too large

Problems:

- large *m*-values (as needed) → guide illumination losses
- narrower guide and UCN source → lower total UCN production
- increased CN transport losses → lower UCN density

Challenge for an in-beam UCN source at ESS:

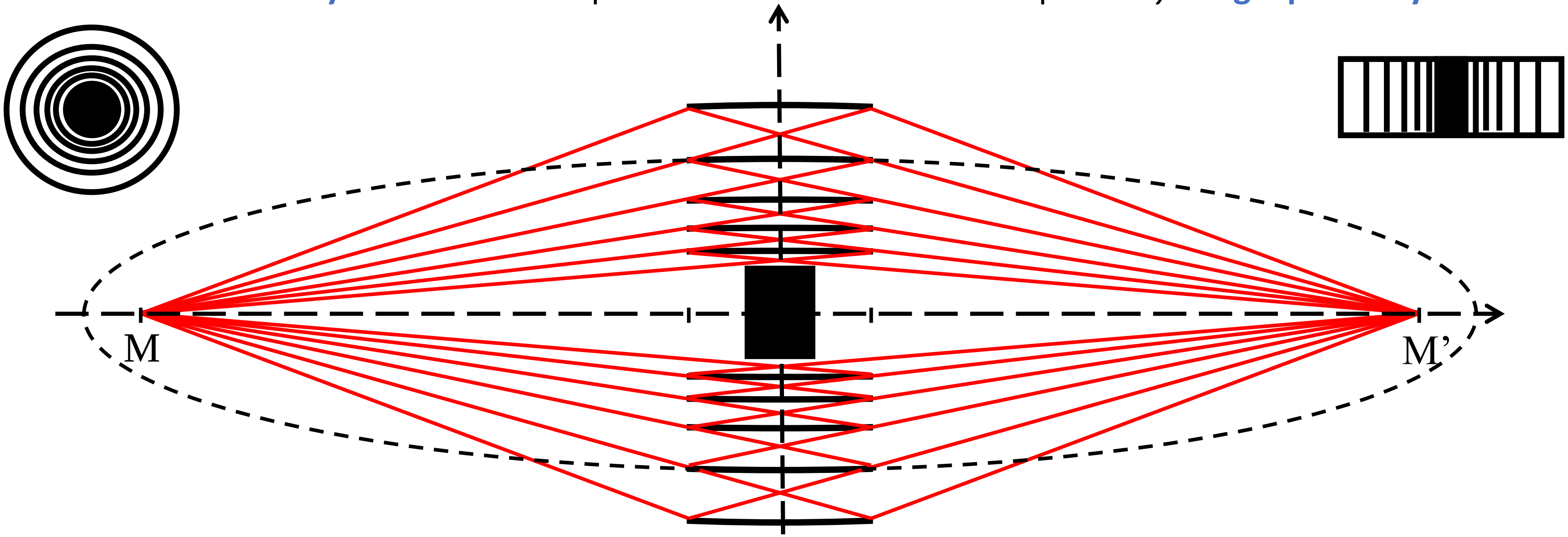
- Need a neutron delivery system with high brilliance transfer from moderator to UCN source, with largest technically possible solid angle (m^2)
- A neutron guide (even a fancy one) is sub-optimal due to the problem of illumination losses, unless it can be approached sufficiently close to the moderator (much closer than 2 m)
- Neutron imaging from the moderator to the UCN source seems a viable solution

Multi-mirror imaging optics for low-loss transport of divergent neutron beams and tailored wavelength spectra

arXiv:1611.07353

Toroidal system: radial component *r*

cartesian component *y*: **single planar system**



Device based on single reflections with well-defined kinematics

→ able to fill large solid angle even from a small source

→ opportunities for neutron scattering instruments, see:

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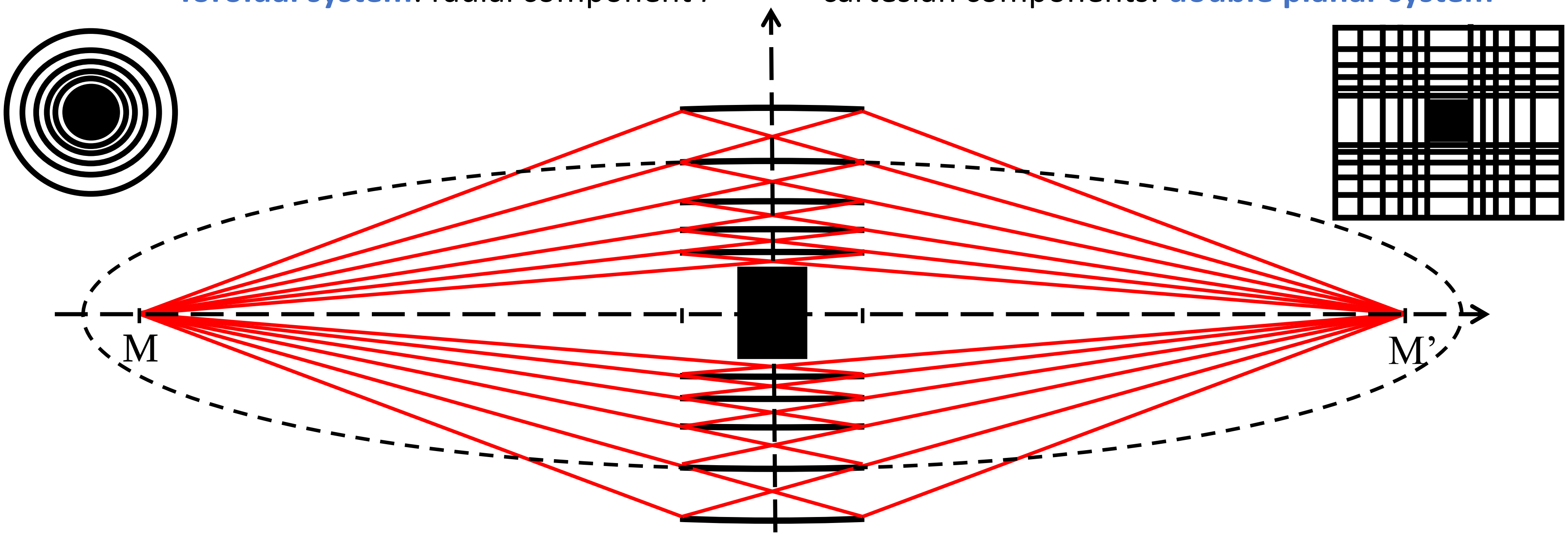
Multi-mirror imaging optics for low-loss transport of divergent neutron beams and tailored wavelength spectra

arXiv:1611.07353



Toroidal system: radial component *r*

cartesian components: **double planar system**

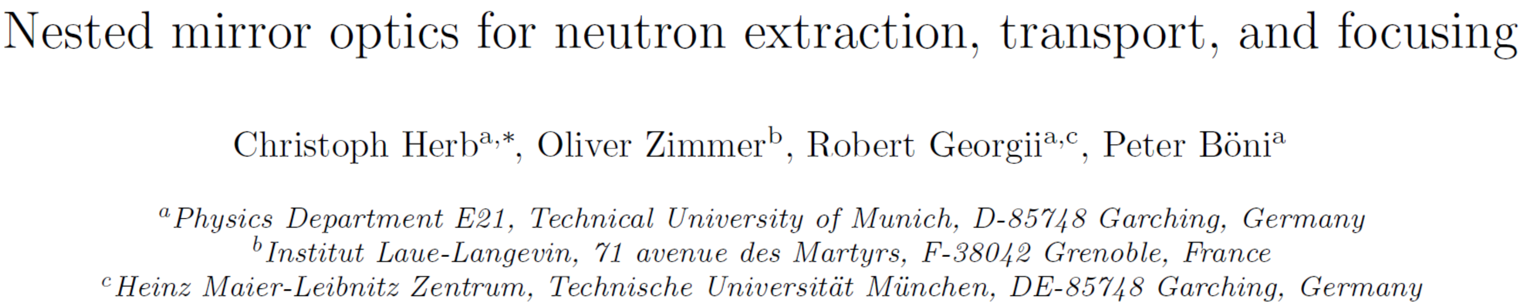
Device based on single reflections with well-defined kinematics

→ able to fill large solid angle even from small source

→ opportunities for neutron scattering instruments, see:

J. Neutron Research 20 (2018) 91

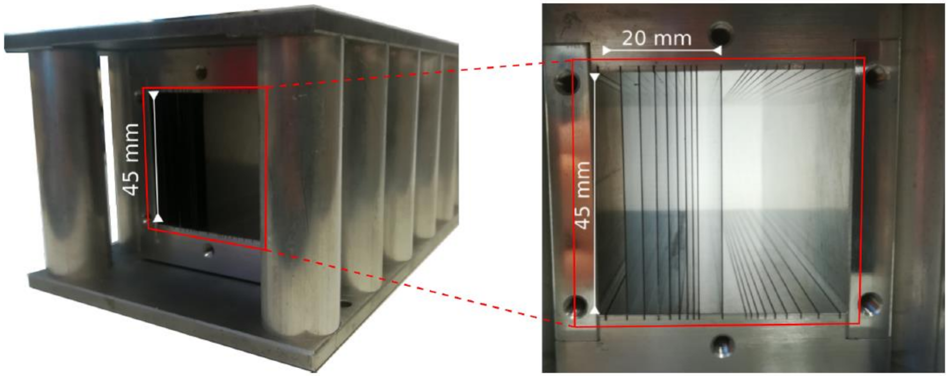
Experimental demonstration (look at arXiv in a few days from now)

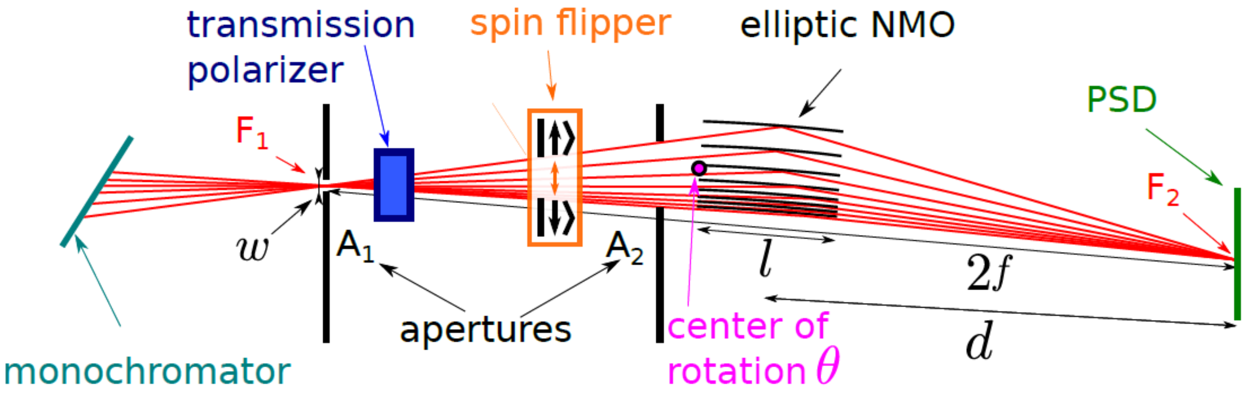


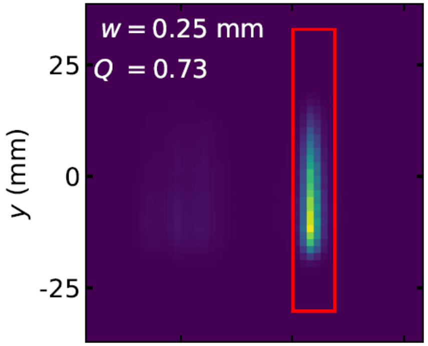
Nested mirror optics for neutron extraction, transport, and focusing

Christoph Herb[a,*], Oliver Zimmer[b], Robert Georgii[a,c], Peter Böni[a]

[a] *Physics Department E21, Technical University of Munich, D-85748 Garching, Germany*
[b] *Institut Laue-Langevin, 71 avenue des Martyrs, F-38042 Grenoble, France*
[c] *Heinz Maier-Leibnitz Zentrum, Technische Universität München, DE-85748 Garching, Germany*

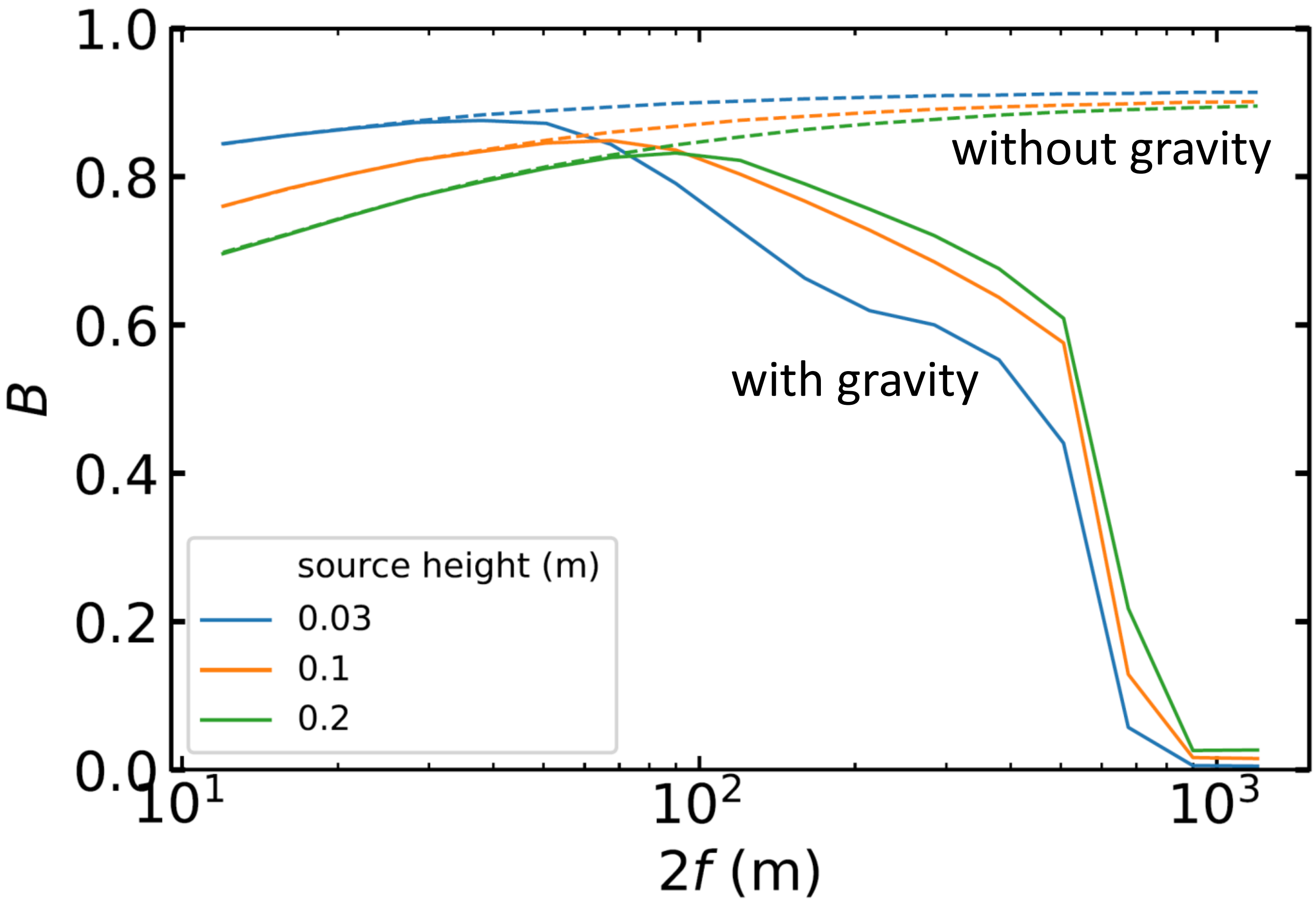






Integrated brilliance transfer by single planar elliptic NMO

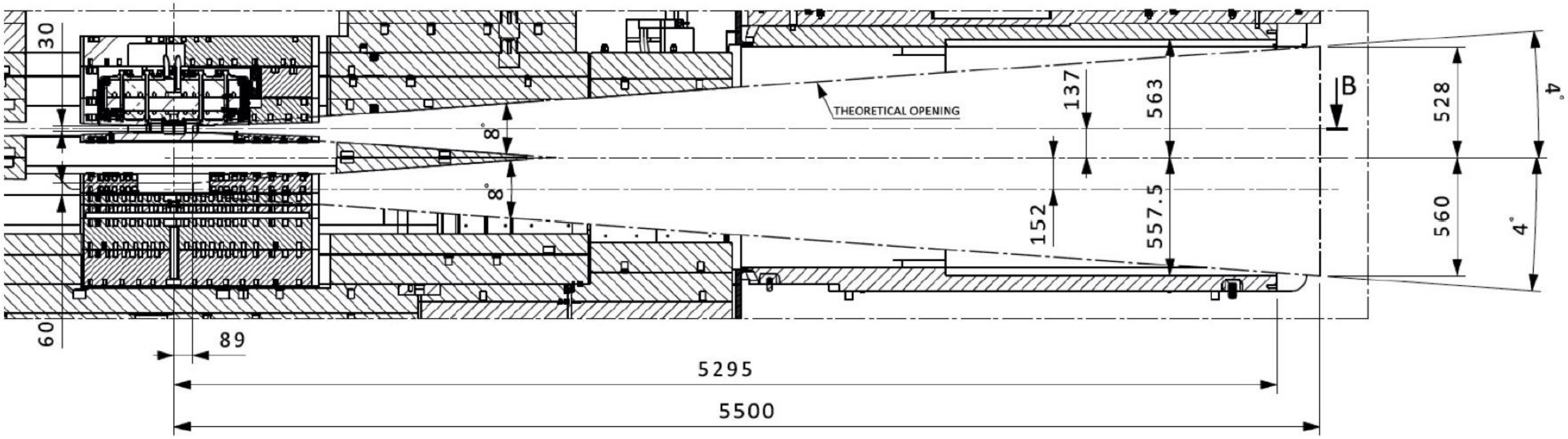
- $m = 6$ supermirrors with 72 % edge reflectivity
- NMO scaled to full $m = 6$ acceptance for each distance $2f$



McStas simulation by **Christoph Herb**

Implementation at ESS?

Solid angle for NMO with $m = 6$ supermirrors seems available in large beam port for nnbar project:



$$\dot{\rho} \approx 12.9\,\mathrm{s}^{-1}\mathrm{cm}^{-3} \times m^2 \times B^2$$

Assumptions for conclusions:

- imaging neutron transport from a moderator area of $20 \times 20\ \mathrm{cm}^2$
- double planar NMO with $m = 6$ supermirrors, $B^2 = 50\ \%$

Conclusions:

Typical source volume: $V = 120$ litres

(for 3 m long source, remember 17 m mean free path for 9Å neutrons)

$$\boxed{\begin{array}{ll} \dot{\rho} = 209\ \mathrm{s^{-1}cm^{-3}}, & \dot{\rho}V = 2.5 \times 10^{7}\ \mathrm{s^{-1}} \\ \rho = 6.3 \times 10^{4}\ \mathrm{cm^{-3}}, & \rho V = 7.5 \times 10^{9} \end{array}}\ (\text{for }\ \tau = 300\ \mathrm{s}, E < 233\ \mathrm{neV})$$

Further opportunities

- Large source → more (or stronger) poles for magnetic reflector possible
- Viewing a VCN moderator might further increase available 9Å flux
- NMOs enable beam phase space transformations:
  - ➢ less divergent beam, e.g., for multi-chamber EDM project
  - ➢ more divergent beam for UCN density increase in smaller volume