PENeLOPE

(Precision Experiment on the Neutron Lifetime Operating on Proton Extraction)

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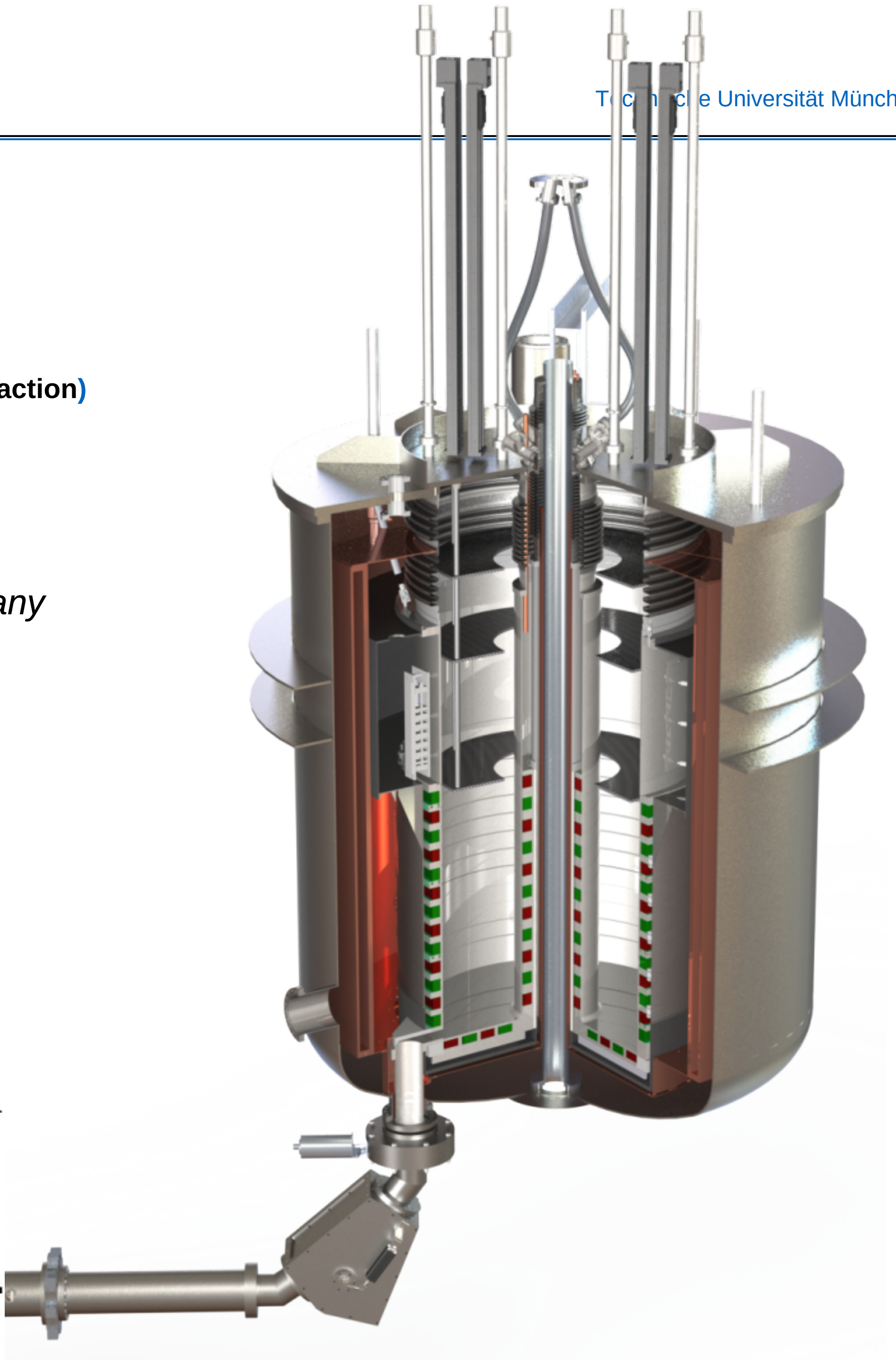
Outline:

- τ_n motivation
- PENeLOPE design
- Status



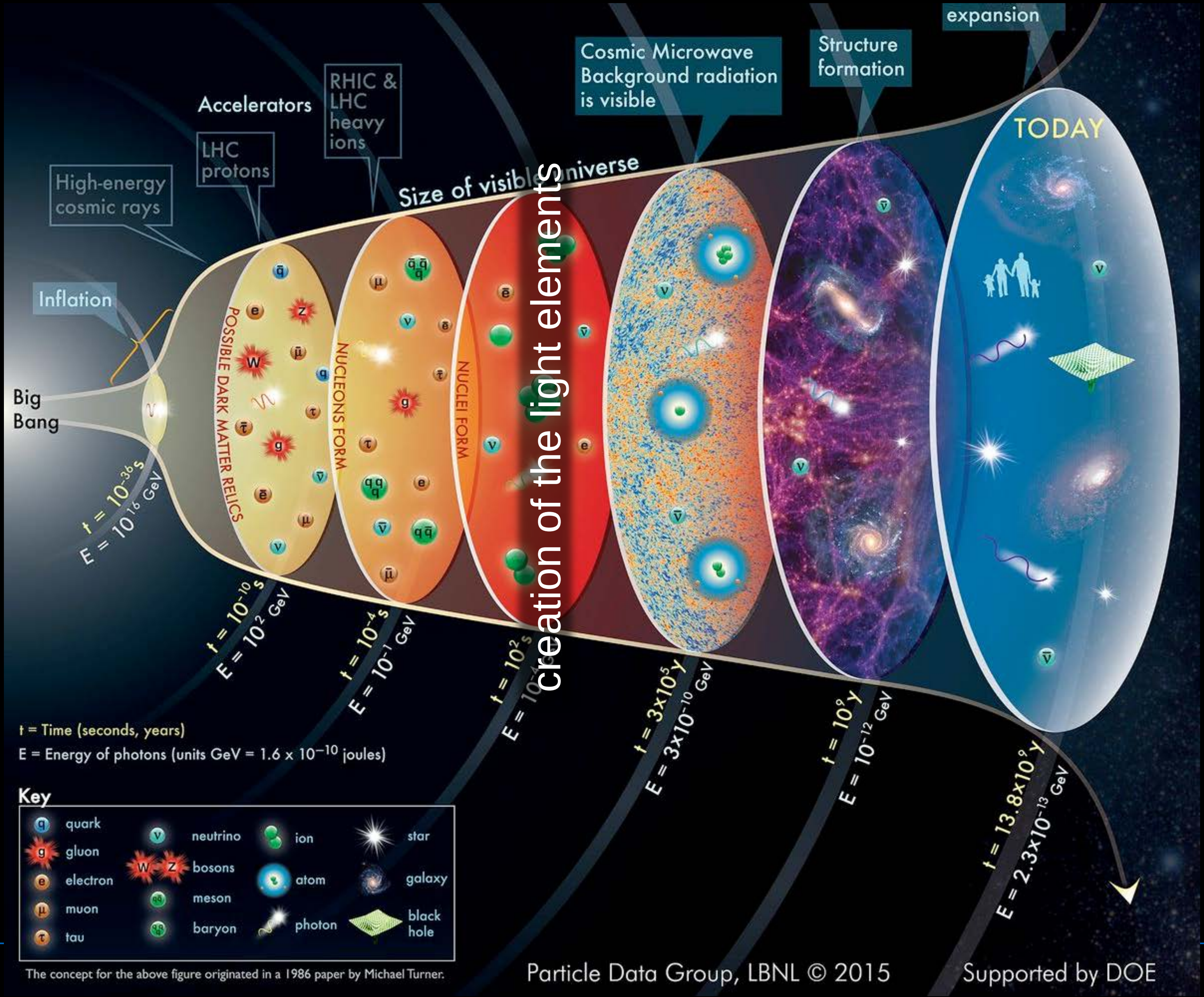
TUM
LMU
Excellence Cluster Universe

Deutsche Forschungsgemeinschaft
DFG

MLL

Bundesministerium für Bildung und Forschung

Neutrons and the universe



creation of the light elements

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

Neutrons and cosmology: nucleosynthesis

t < *1* s, *kT* > *1.3* MeV (15 billion ºC)*

thermal equilibrium

$$p + e^- \rightleftharpoons n + \nu$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

1 s < *t* < *100* s, *0.1* MeV < *kT* < *1.3* MeV

neutron decay

$$n \longrightarrow p + e^- + \bar{\nu}$$
$$\frac{n_\mathrm{n}}{n_\mathrm{p}} := \frac{1}{6} \to \frac{1}{7}$$

t > *100* s, *kT* < *0.1* MeV, bec. of γ/B

deuterium fusion

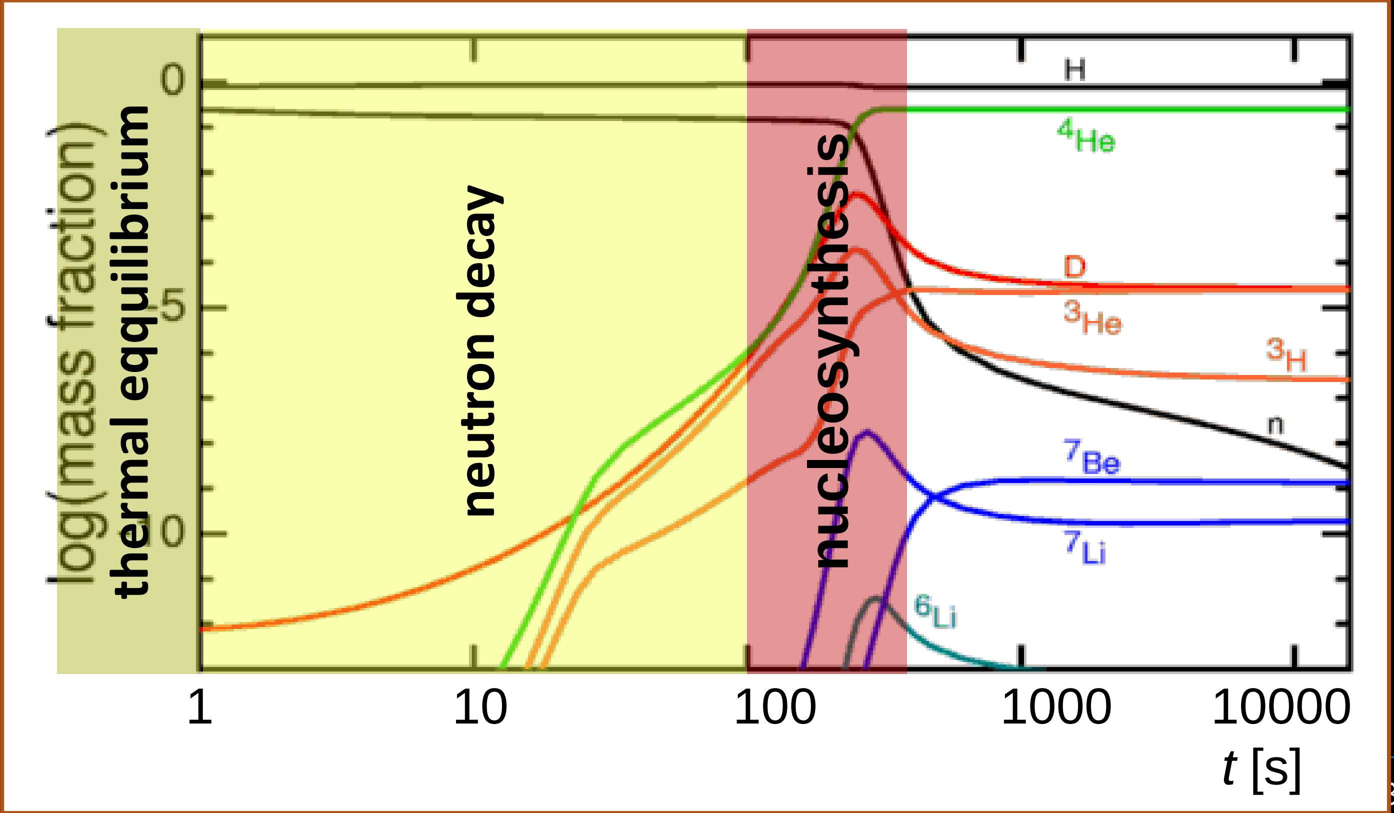
$$n + p \longrightarrow d + \gamma$$

t > *100* s, *kT* < *0.1* MeV (1.2 billion ºC)

nucleosynthesis

$$\begin{aligned} d + p &\rightarrow {}^3\mathrm{He} + \gamma \\ d + d &\rightarrow {}^3\mathrm{H} + p \\ d + d &\rightarrow {}^3\mathrm{He} + n \\ {}^3\mathrm{He} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Be} + \gamma \\ {}^3\mathrm{He} + d &\rightarrow {}^4\mathrm{He} + p \end{aligned}$$

$$\begin{aligned} {}^3\mathrm{He} + n &\rightarrow {}^3\mathrm{H} + p \\ {}^7\mathrm{Li} + p &\rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \\ {}^7\mathrm{Be} + n &\rightarrow {}^7\mathrm{Li} + p \\ {}^3\mathrm{He} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Be} + \gamma \end{aligned}$$



*T in sun 6000ºC at surface to 15 MioºC in the core

Neutrons and cosmology: nucleosynthesis

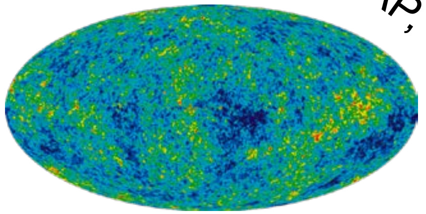
Parameters of Big Bang Nucleosynthesis

$$Y_P = 0.228 + 0.023\, log\eta_{10} + 0.012N_\nu + 0.018\tau_n$$


© Anglo-Australian Observatory, photograph by David Malin

cosmic helium abundance He/p

from old stars



cosmic baryon density

$(n_\gamma/n_B)\cdot 10^{-10}$

WMAP, Planck

# of neutrino flavors

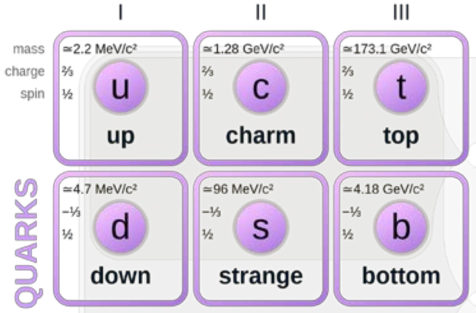
3

neutron lifetime

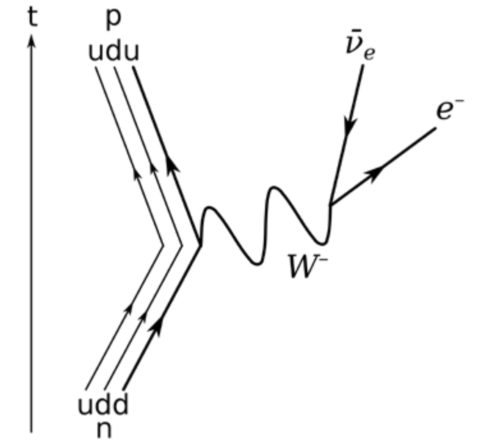
PENeLOPE

Quark-mixing

- Quark Mixing



β - Decay



$$n \rightarrow p + e^- + \bar{\nu}_e + 0.783MeV$$

- Cabbibo-Kobayashi-Maskawa (CKM) Matrix:
  - Mixing between 3 generations of quarks

weak eigenstates

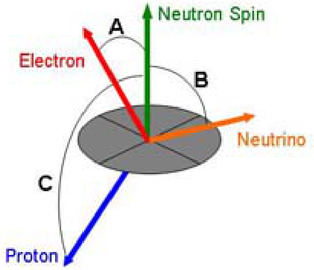
mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- From Fermi's Golden Rule:

$$|V_{ud}|^2 = \frac{10^3}{0.1897(1+3(\frac{g_A}{g_V})^2)(1+0.0739(8))} \cdot \frac{1}{\tau_n}s$$

- Unitarity in CKM (1st row):
  - Check to see if **only** 3 generations of mixing occurs
  - 2.2σ deviation from unitarity



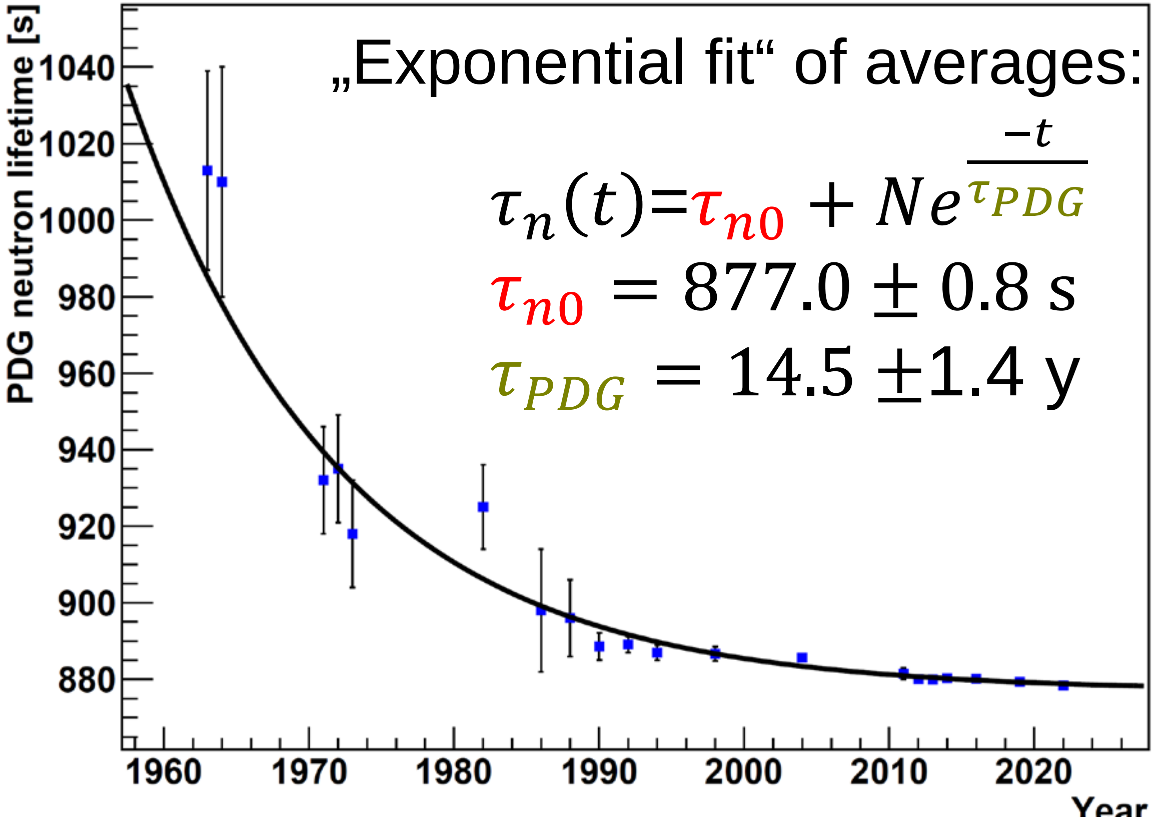
$$|V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = |0.97373 \pm 0.00031|^2 + |0.2243 \pm 0.0008|^2 + |(3.82 \pm 0.20) \times 10^{-3}|^2 = 0.9985 \underline{\pm 0.007}$$

Fermi's Golden Rule: Gershon, (2011) https://doi.org/10.1007/s12043-012-0418-y
CKM : https://pdg.lbl.gov/2020/reviews/rpp2022-rev-ckm-matrix.pdf

Neutron lifetime „constant“

- the particle data group (PDG) reviews all major particle properties annually *http://pdg.lbl.gov/*
- PDG „world“ averages of the neutron lifetime for the last 60 years

⇒ **We’re honing in, but slowly…**



„Exponential fit“ of averages:

$$\tau_n(t) = \tau_{n0} + N e^{\frac{-t}{\tau_{PDG}}}$$

$$\tau_{n0} = 877.0 \pm 0.8\ \mathrm{s}$$

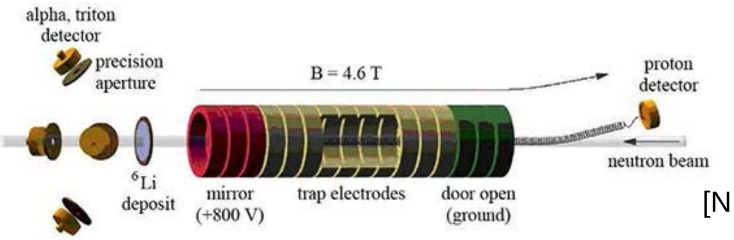
$$\tau_{PDG} = 14.5 \pm 1.4\ \mathrm{y}$$

Beam vs Trap Experiments

Neutron Beam Measurements

- Direct a beam of cold neutrons down a long guide
- Capture decay protons using magnetic fields and count t
- Best measurement: Yue 2013

$$\tau_n = 887.7 \pm 2.2 \text{ s}$$



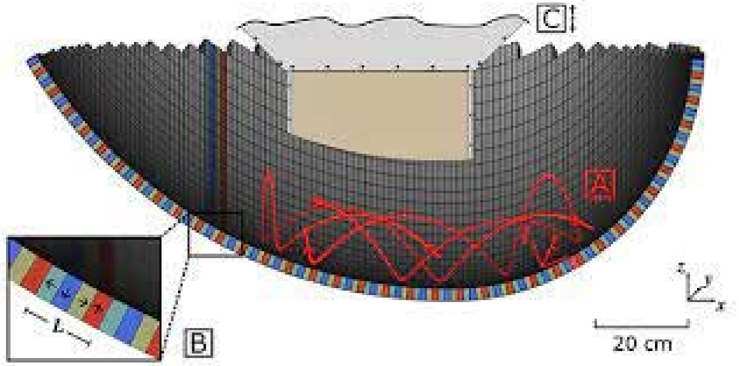
[NIST]

https://doi.org/10.1103/PhysRevLett.111.222501

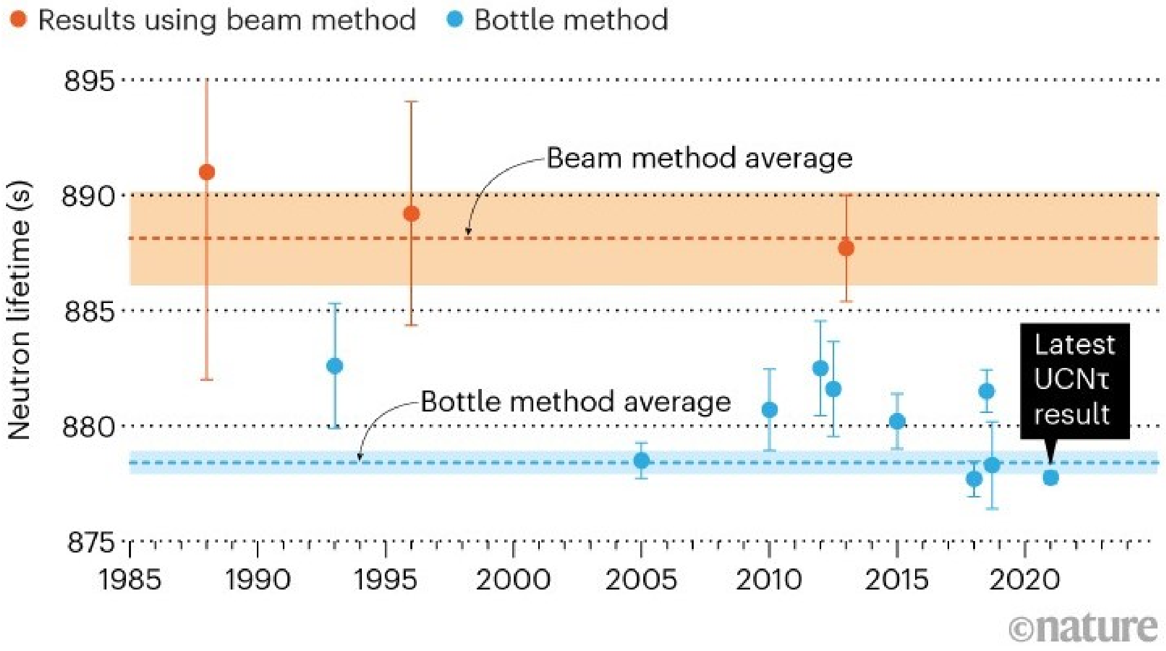
UCN Trap Measurements

- Store UCN in a container
- Count how many UCN are left over after waiting for some time
- Best measurement so far: Gonzales 2021

$$\tau_{\mathrm{n,UCN}\tau} = 877.75 \pm 0.28_{\mathrm{stat}}{}^{+0.22}_{-0.16,\mathrm{syst}} \text{ s}$$



https://doi.org/10.1103/PhysRevLett.127.162501 [UCNτ]



NIST Beam DOI: 10.1103/PhysRevLett.65.289
Davide Castelvecchi, ‘Physicists make most precise measurement ever of neutron’s lifetime’, Nature Magazine (2018)

How to store neutrons magnetically?

UCN are really cold:

$$E_{\mathrm{kin}} < 300\ \mathrm{neV} \triangleq T < 3\ \mathrm{mK}$$

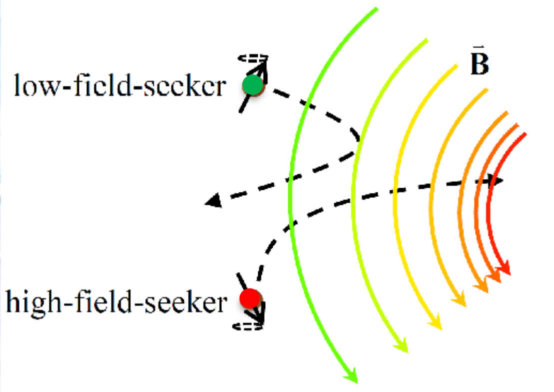
They can be manipulated using:

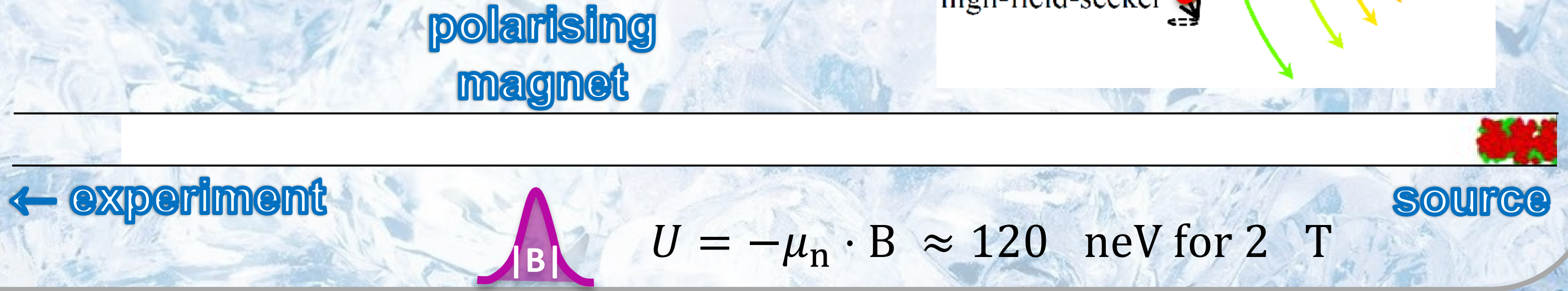
- **Strong interaction**
  (Fermi potential up to 350 neV, total reflection from walls)
  UCN TRANSPORT, STORAGE
- **Gravitation**
  $(100\ \mathrm{neV} \triangleq 1.02\ \mathrm{m})$
  UCN STORAGE, ENERGY MANIPULATION

- **Magnetic interaction**
  (force on magnetic moment)
  UCN STORAGE, POLARISATION

$$\mu_n = -60.3\,\frac{\mathrm{neV}}{\mathrm{T}}$$

$$\vec{F} = \nabla(\vec{\mu}_n \vec{B})$$

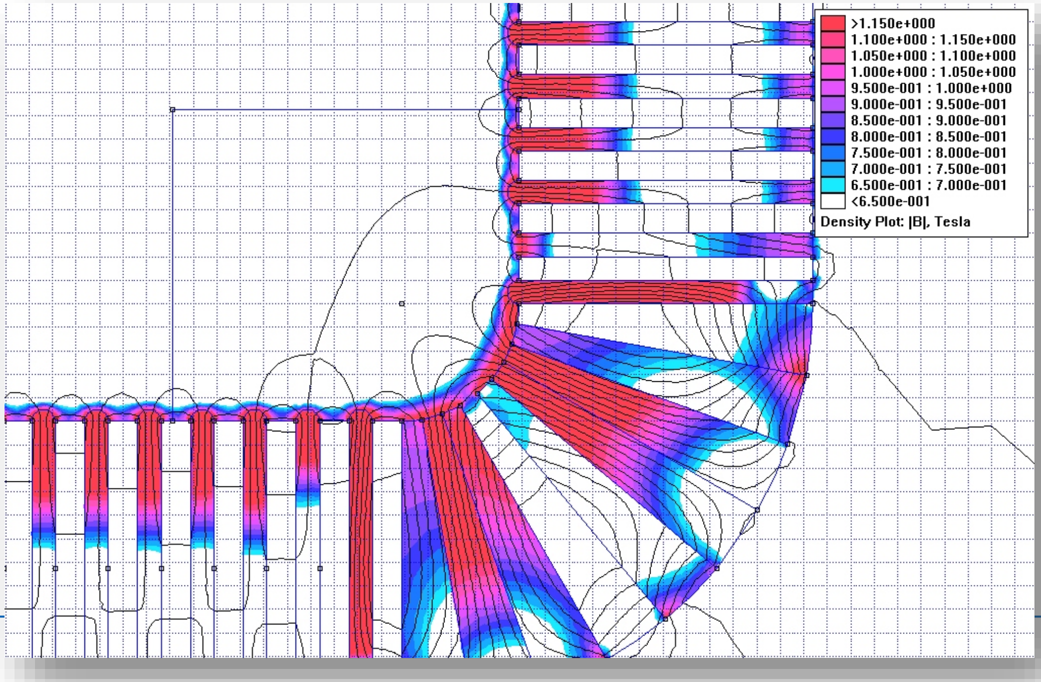


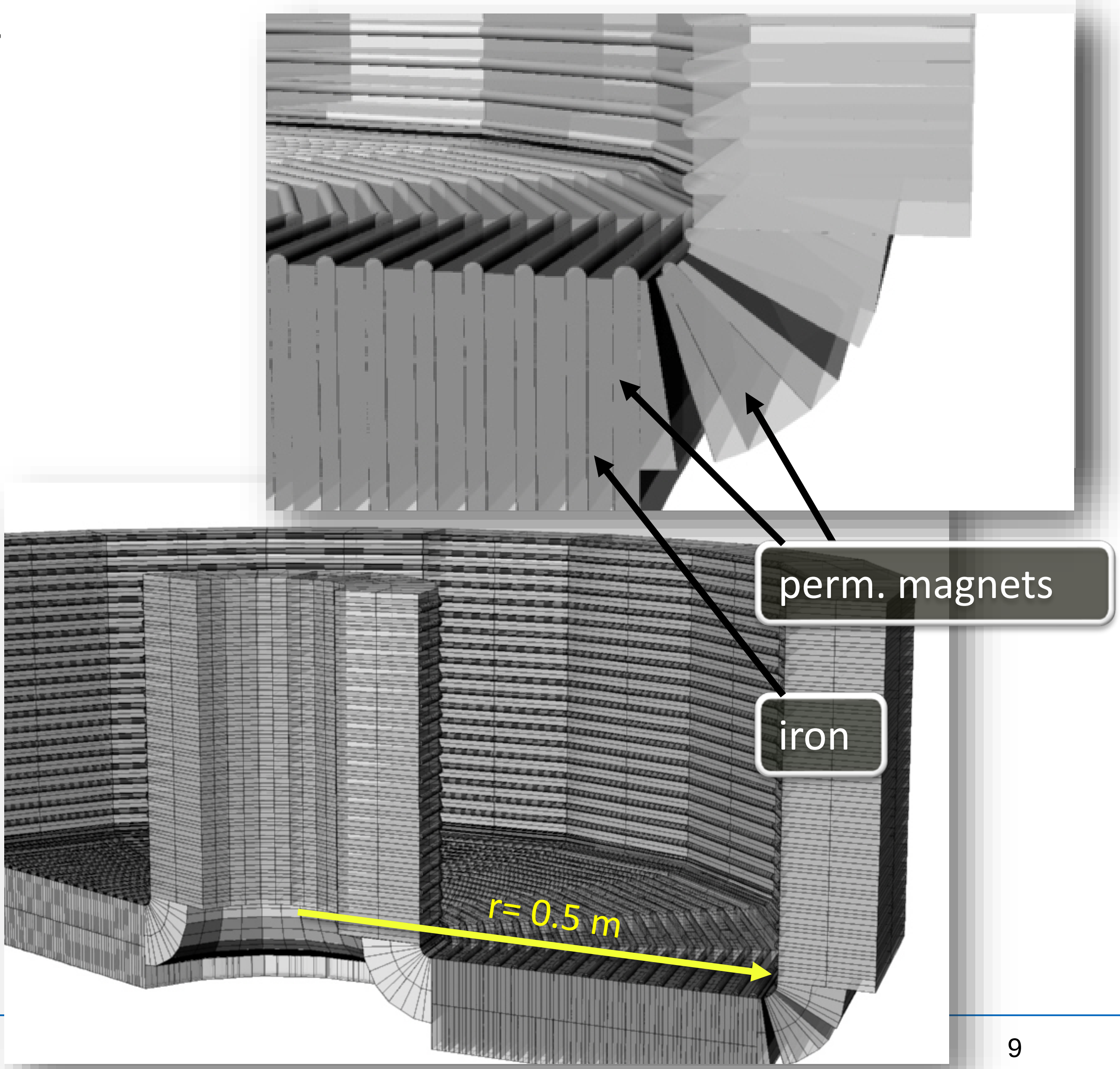


$$U = -\mu_n \cdot \mathrm{B} \approx 120\ \mathrm{neV\ for}\ 2\ \mathrm{T}$$

History of the experiment

- idea came to TU Munich with S. Paul in 1997
- magnetic storage: create large field surrounding low field region
- different topologies were studied:
  - **Ioffe type trap**: current bars dodekapol + 2 solenoids
  - **U shaped multipole**
  - ca 2001: **large permanent magnet trap**, multipole in z-direction





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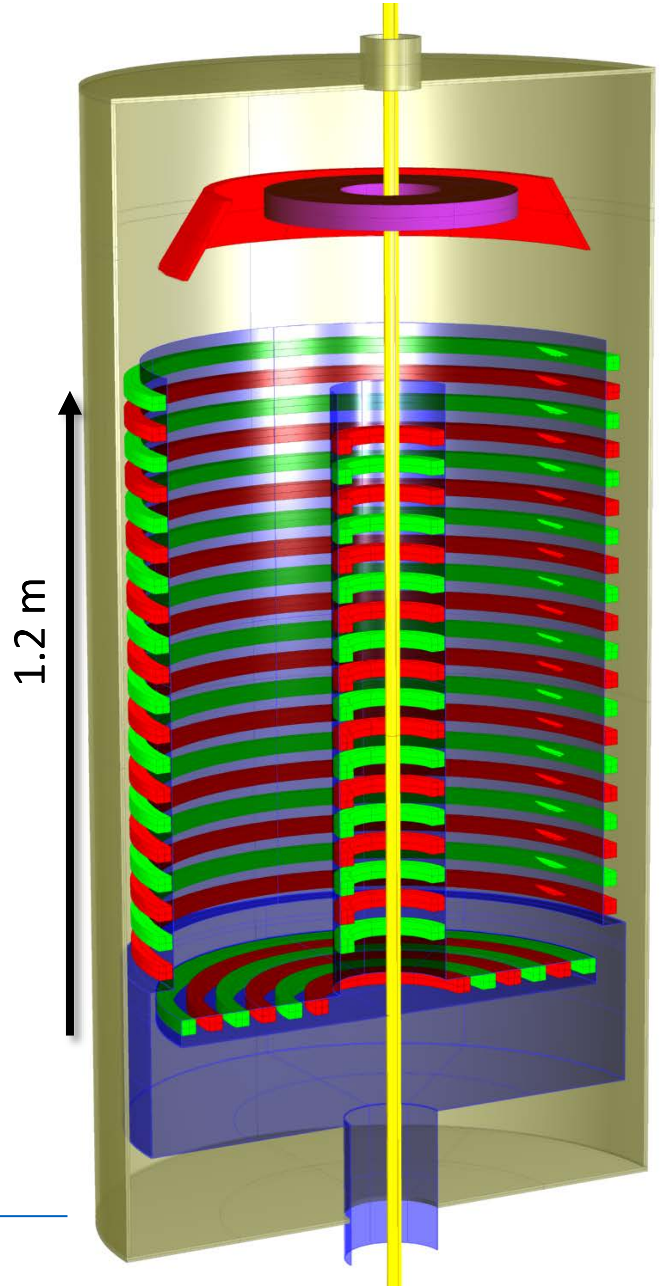
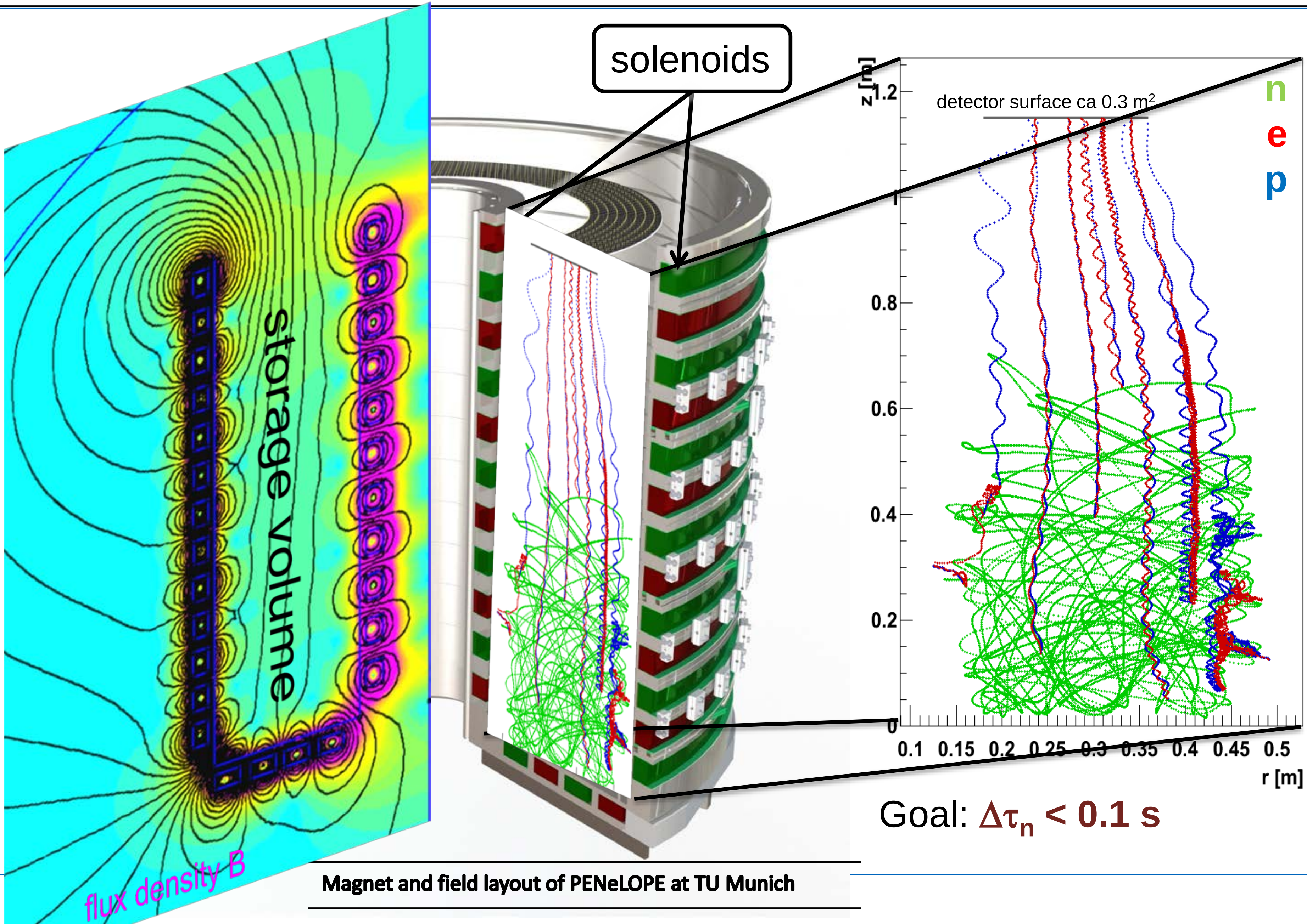


PENeLOPE principle

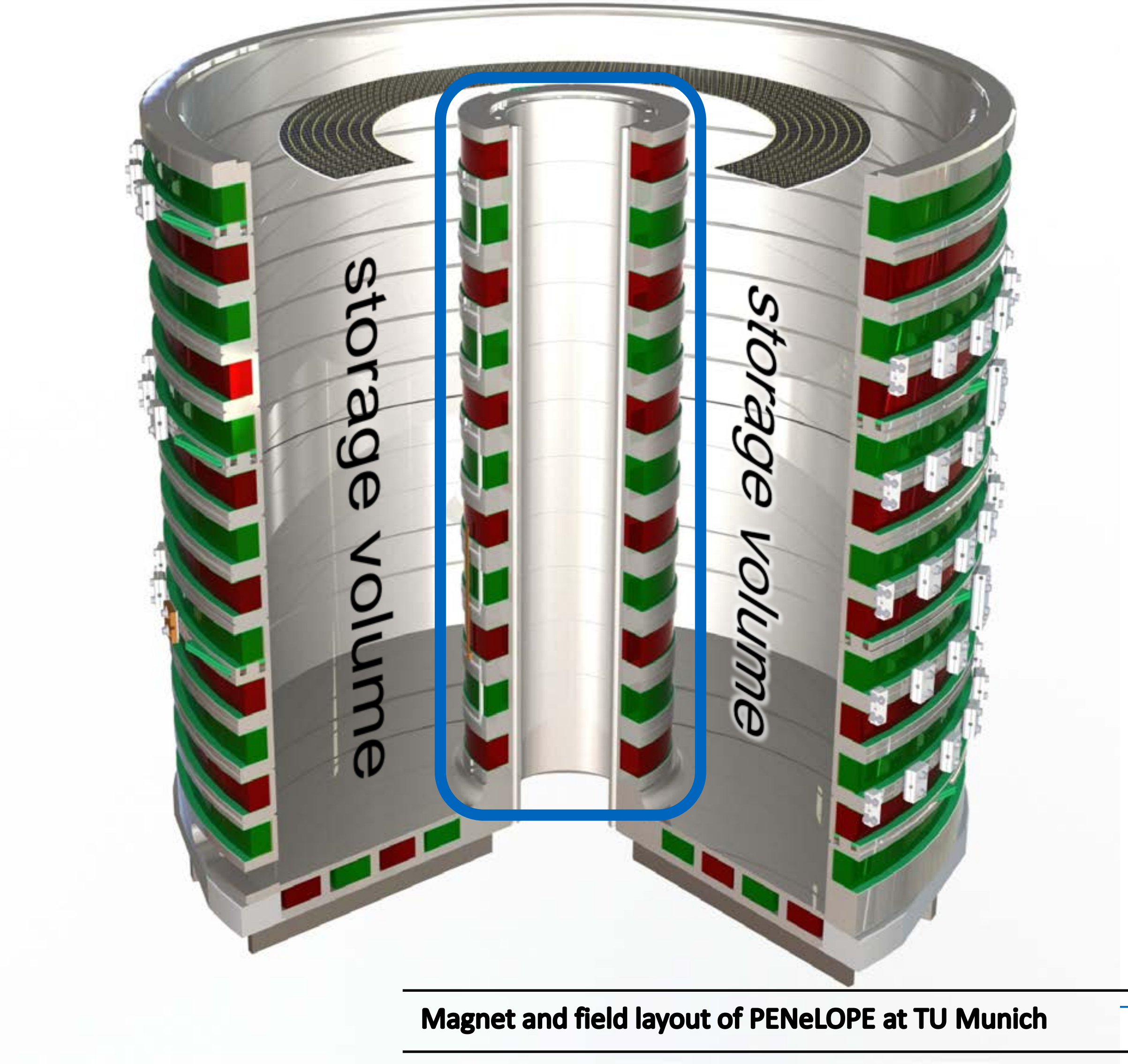


Magnet and field layout of PENeLOPE at TU Munich

Goal: $\Delta\tau_n < 0.1$ s

Neutron spin flip suppression

Why central solenoids???

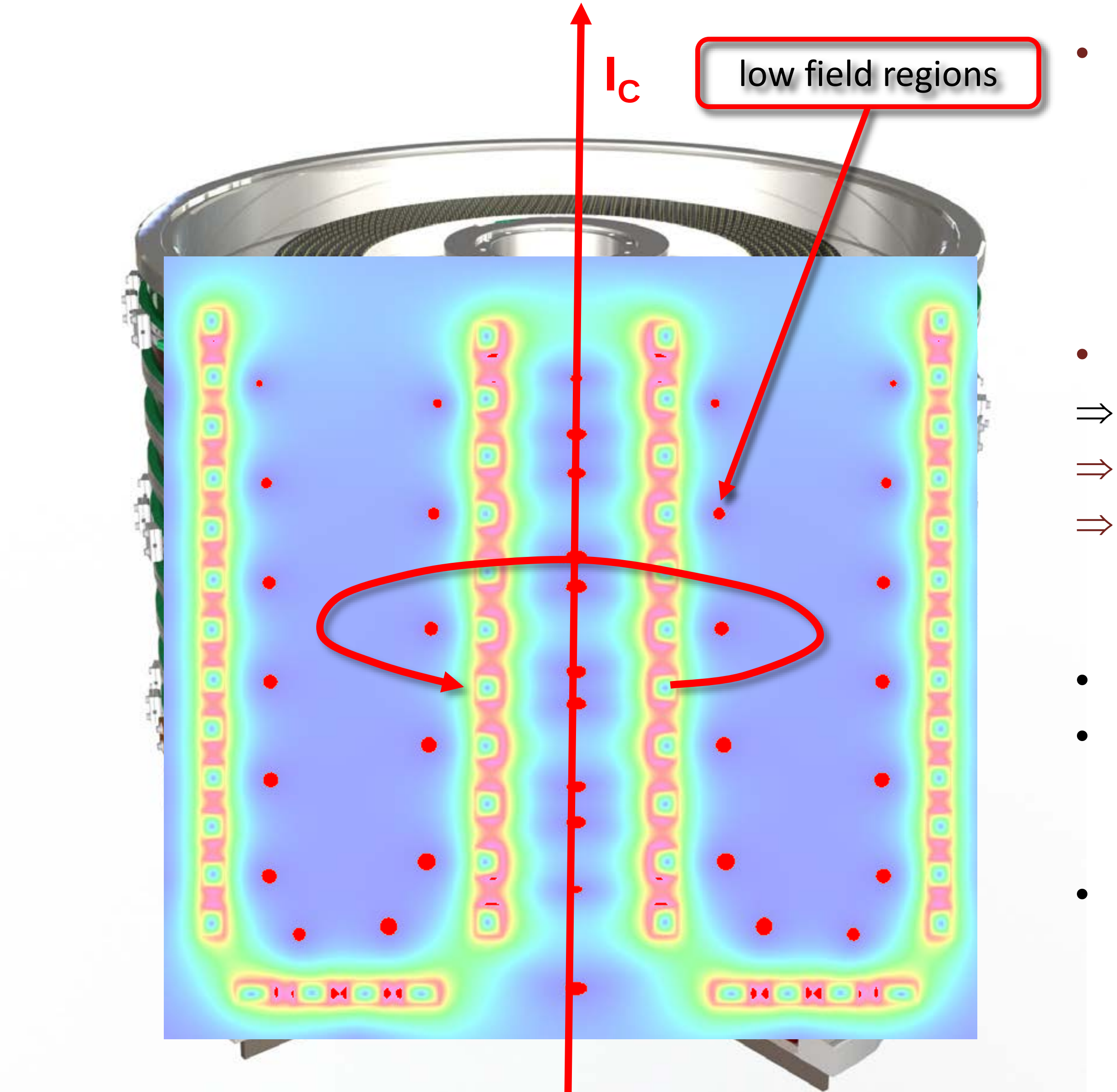


Magnet and field layout of PENeLOPE at TU Munich

- **adiabatic condition for neutron spin transport**

$$\omega_{\text{Larmor}} \gg \frac{\dot{\boldsymbol{B}}}{|\boldsymbol{B}|}$$

Neutron spin flip suppression



Magnet and field layout of PENeLOPE at TU Munich

- **adiabatic condition for neutron spin transport**

$$\boldsymbol{\omega}_{\text{Larmor}} \gg \frac{\dot{\boldsymbol{B}}}{|\boldsymbol{B}|}$$

- **violated in low field regions**

⇒ spin flip more likely

⇒ **UCN loss** from trap

⇒ **systematic effect** on lifetime measurement ☹

- all **storage coil fields** are in **r-z plane**
- fill low field regions with **central current** creating **azimuthal field** ☺

- Central solenoids necessary to prevent neutrons from hitting central current bars

TRIUMF Particle dynamics simulation

$$n \rightarrow p + e^- + \bar{\nu}_e$$

protons

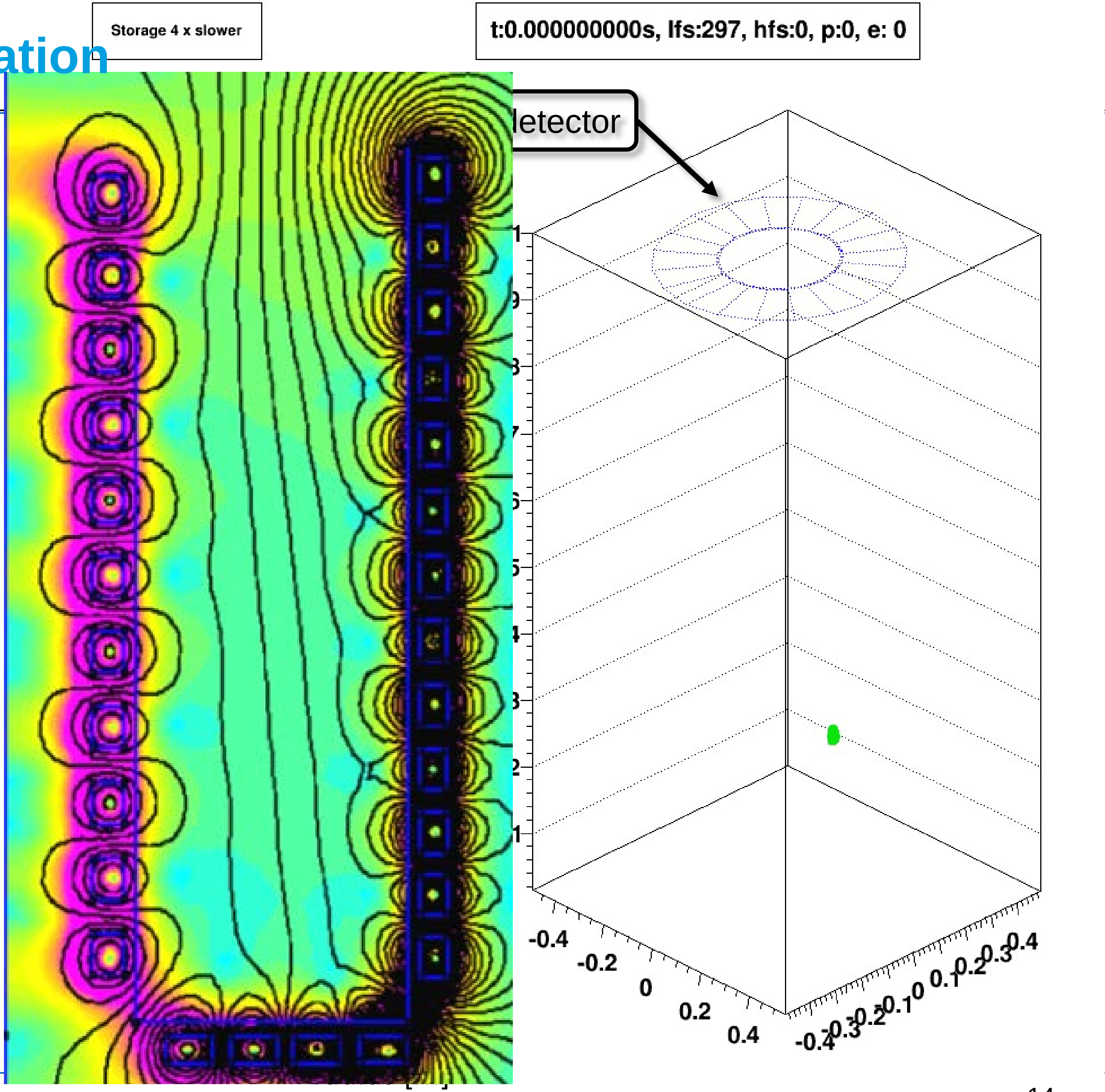
- **0-800 eV** initially
- accelerated to **30 keV**
- collection efficiency **70 %**

electrons

- **0-760 keV**
- follow field lines
- not influenced by „lab“ high voltage
- collection efficiency **35 %**

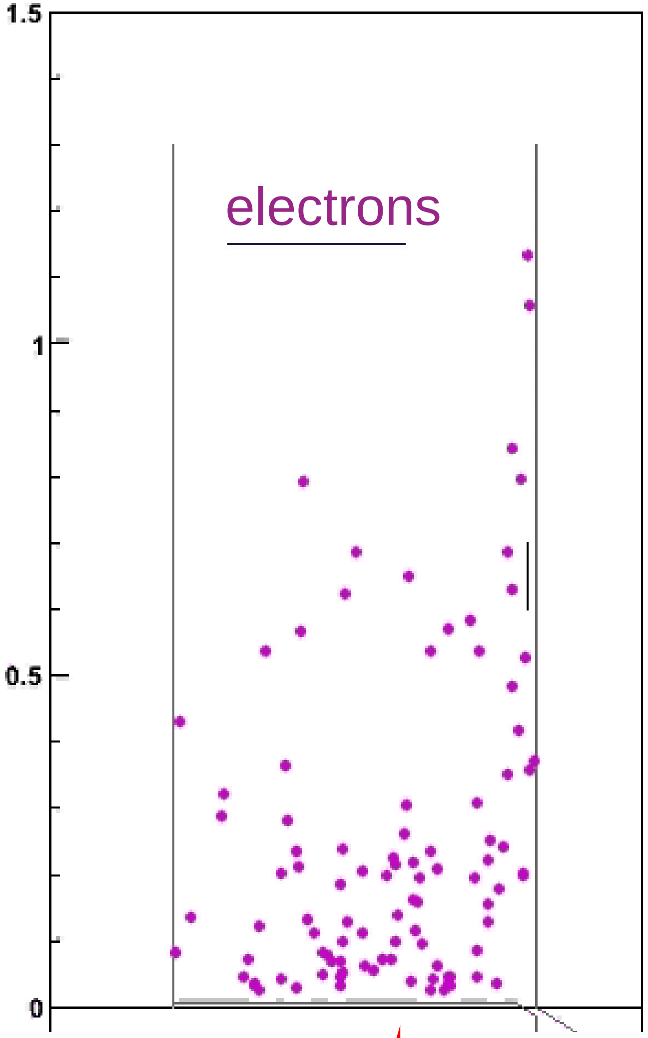
neutrons

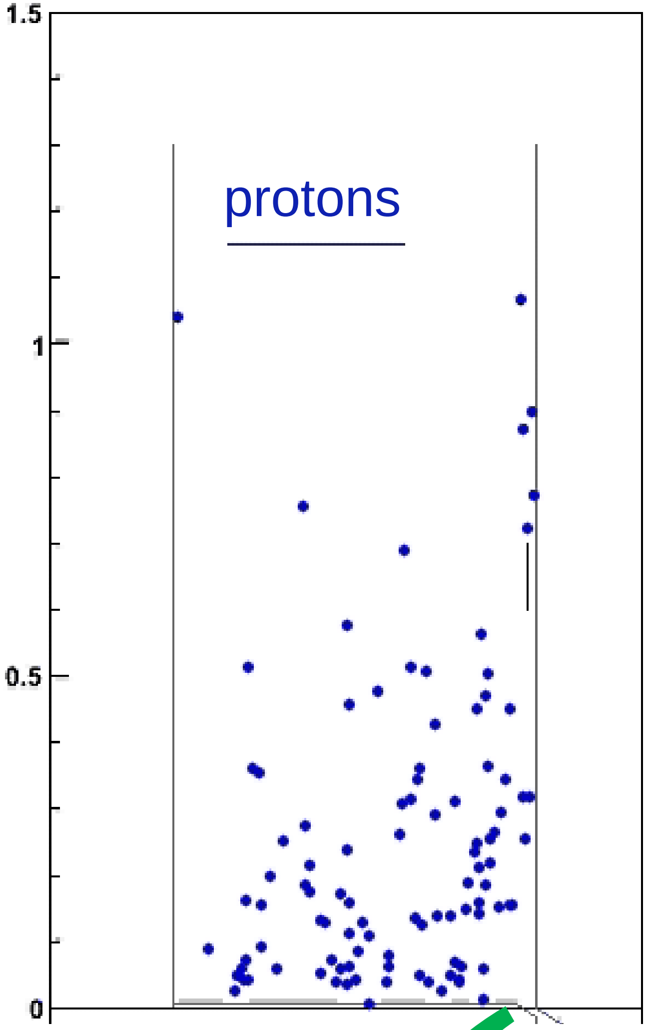
- **30-120 neV**
- low-field seekers
- chaotic trajectories



Electrons and protons

kinetic energy of protons
much less than electrons
⇒ electrostatic manipulation
possible
⇒ detector on HV



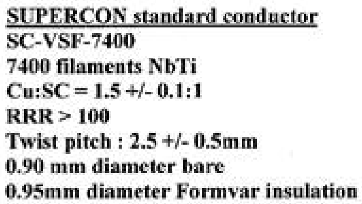


✗ 35%

✓ 70%

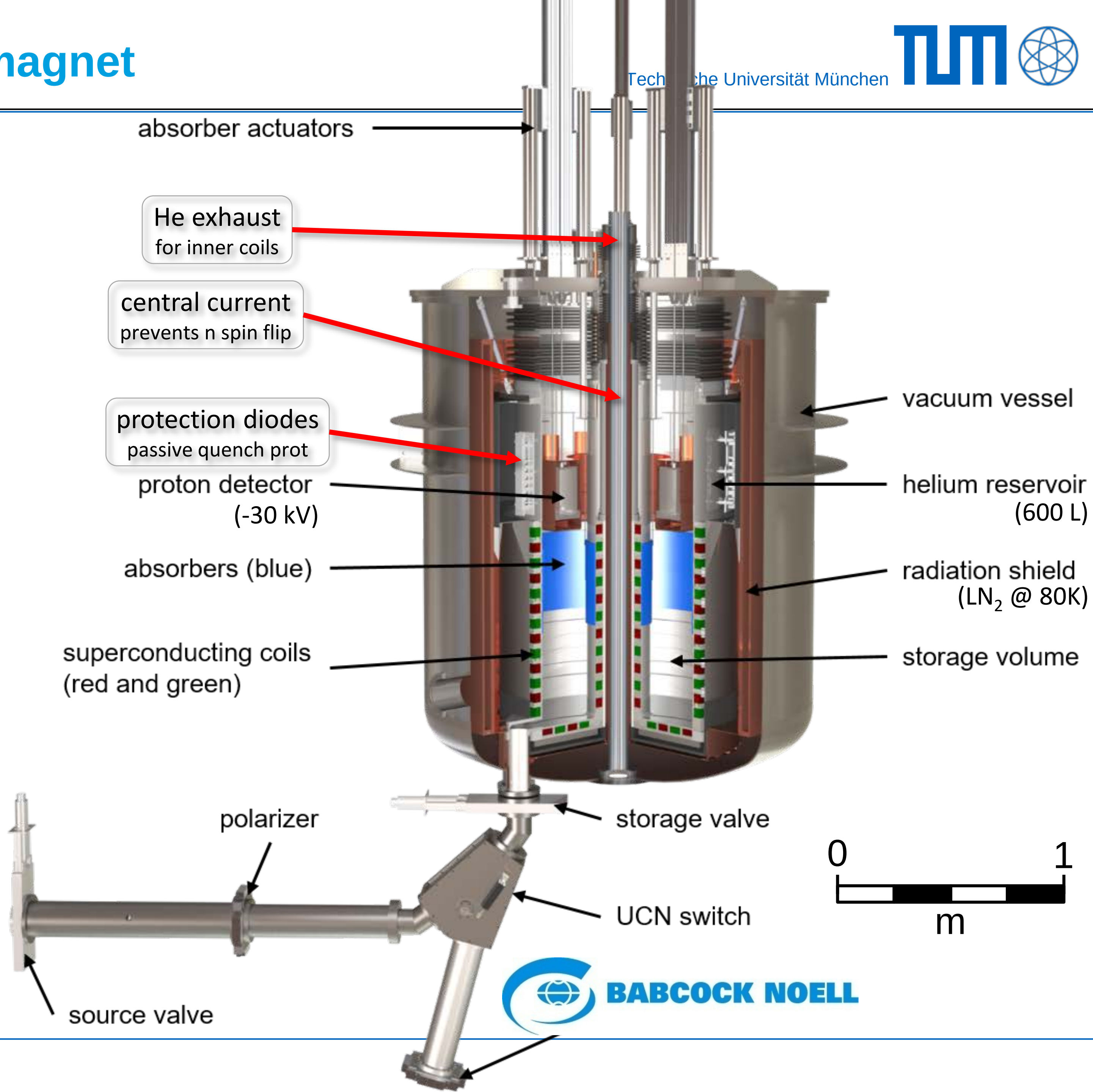
The PENeLOPE magnet

- 24 **thick, short solenoids** (up to 5 cm thick)
- **alternating** current directions create large **axial** repelling **forces** (up to 1.2 MN)
- NbTi wire



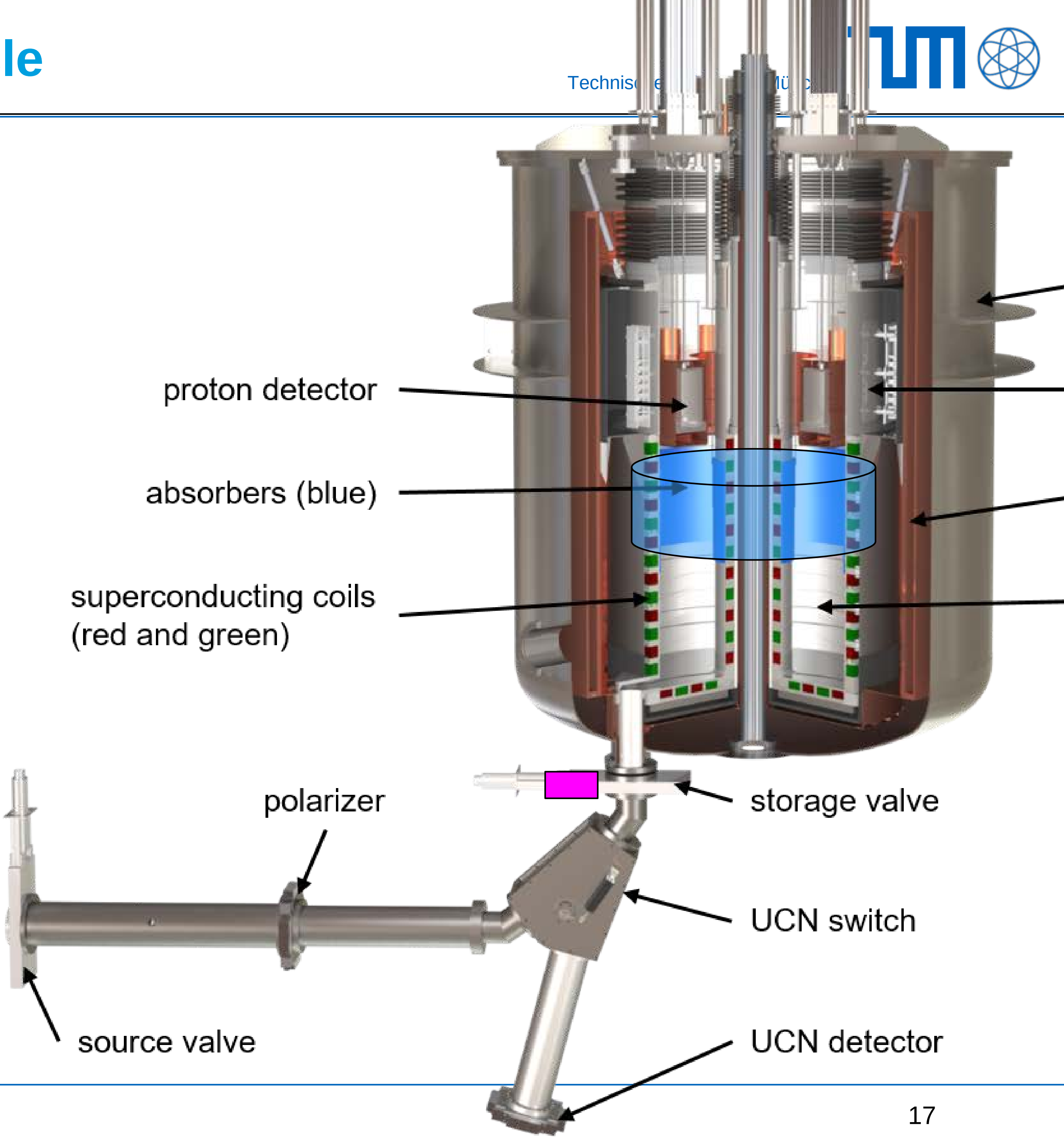
SUPERCON standard conductor
SC-VSF-7400
7400 filaments NbTi
Cu:SC = 1.5 +/- 0.1:1
RRR > 100
Twist pitch : 2.5 +/- 0.5mm
0.90 mm diameter bare
0.95mm diameter Formvar insulation

- between 32 and 58 wire layers
- high current density (315 A/mm²)
- **maximum field 5.5 T**
- usable field 1.8 T
- **very little space** for support structure
- high inductive voltages (4 kV)



Experiment cycle

Experiment phase	Storage valve	Absorber height [cm]	Duration [s]
Fill ultracold neutrons in experiment	open	70	200
Spectrum cleaning	Closed	70	150
Magnet ramp up	Closed	70	100
High-field seeker cleaning	Open	0	100
Detect decay protons and spin-flipped UCN?	Open	70	up to several 1000
Ramp down magnet	Open	70	100
Count remaining neutrons	Open	70	200

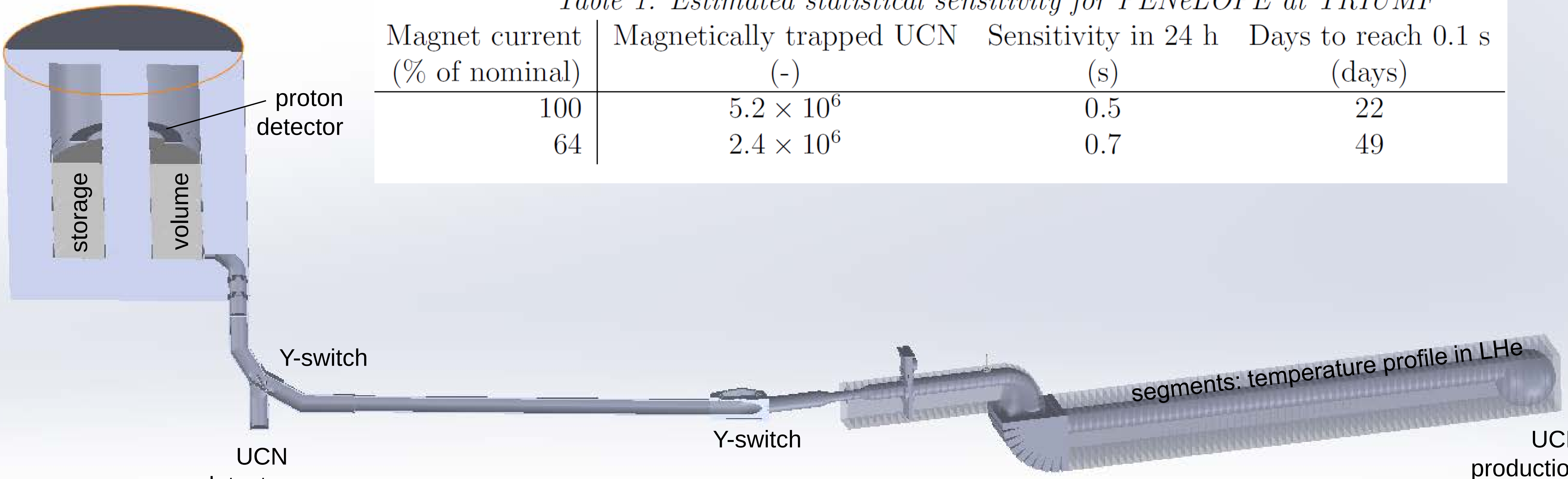


Statistical prospect for PENeLOPE at TRIUMF

- Assuming 14M UCN/s produced in the TUCAN source between 0 and 233 neV
- Connecting PENeLOPE to the full TUCAN source in PENTrack MC simulation
- Filling time: 250 s

Table 1: Estimated statistical sensitivity for PENeLOPE at TRIUMF

Magnet current (% of nominal)	Magnetically trapped UCN (-)	Sensitivity in 24 h (s)	Days to reach 0.1 s (days)
100	5.2×10^6	0.5	22
64	2.4×10^6	0.7	49



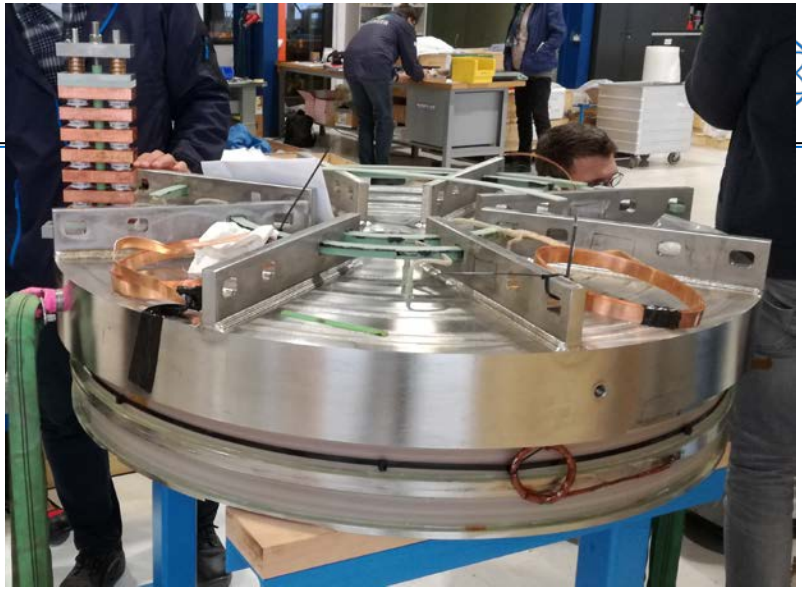
Systematic effects/checks

All to be below 10^{-4}

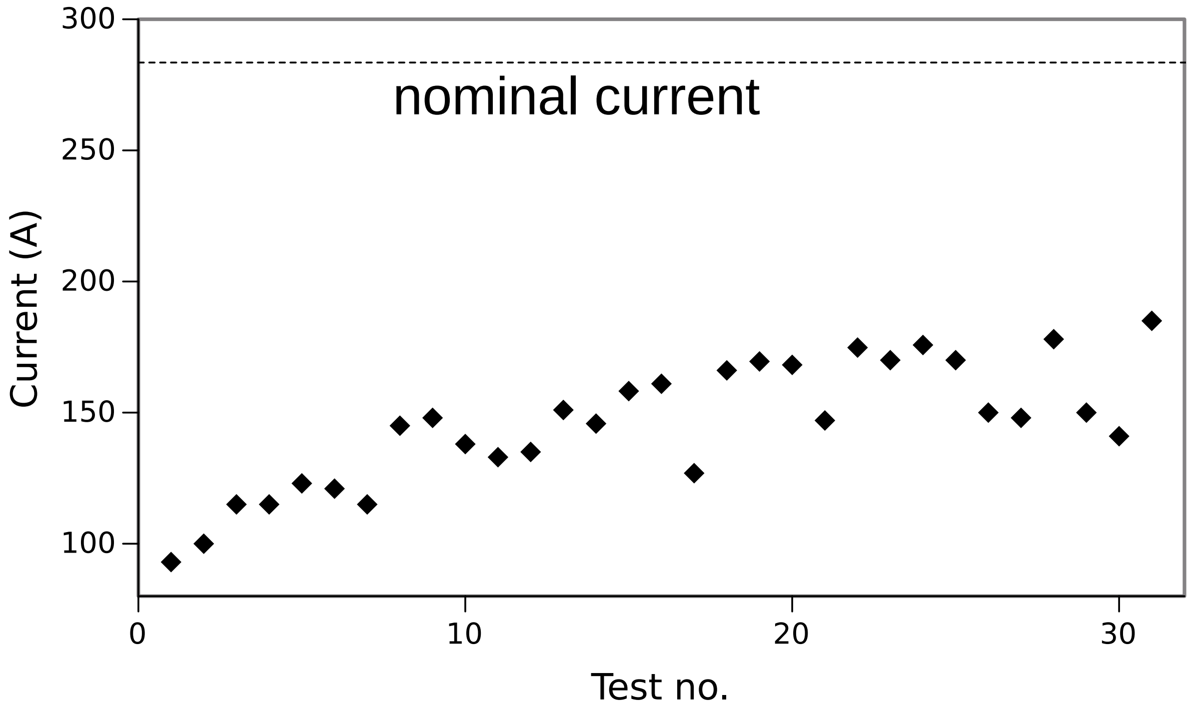
- Marginally trapped UCN (less than 10^{-4})
- Energy gain of low-field-seekers (no mechanism known)
- High-field-seekers (less than 10^{-4})
- Depolarized UCN ($\tau > 10^{8}$ s)
- Rest gas absorption ($p < 5 \times 10^{-8}$ mbar, $\Delta\tau < 0.03$ s)
- Time-dependent detector background (not critical for UCN detector)
- Detector drift (normalization and background measurements will help)
- Space charge effects (does not affect UCN measurement)

S. Materne et al. / Nuclear Instruments and Methods in Physics Research A 611 (2009) 176–180

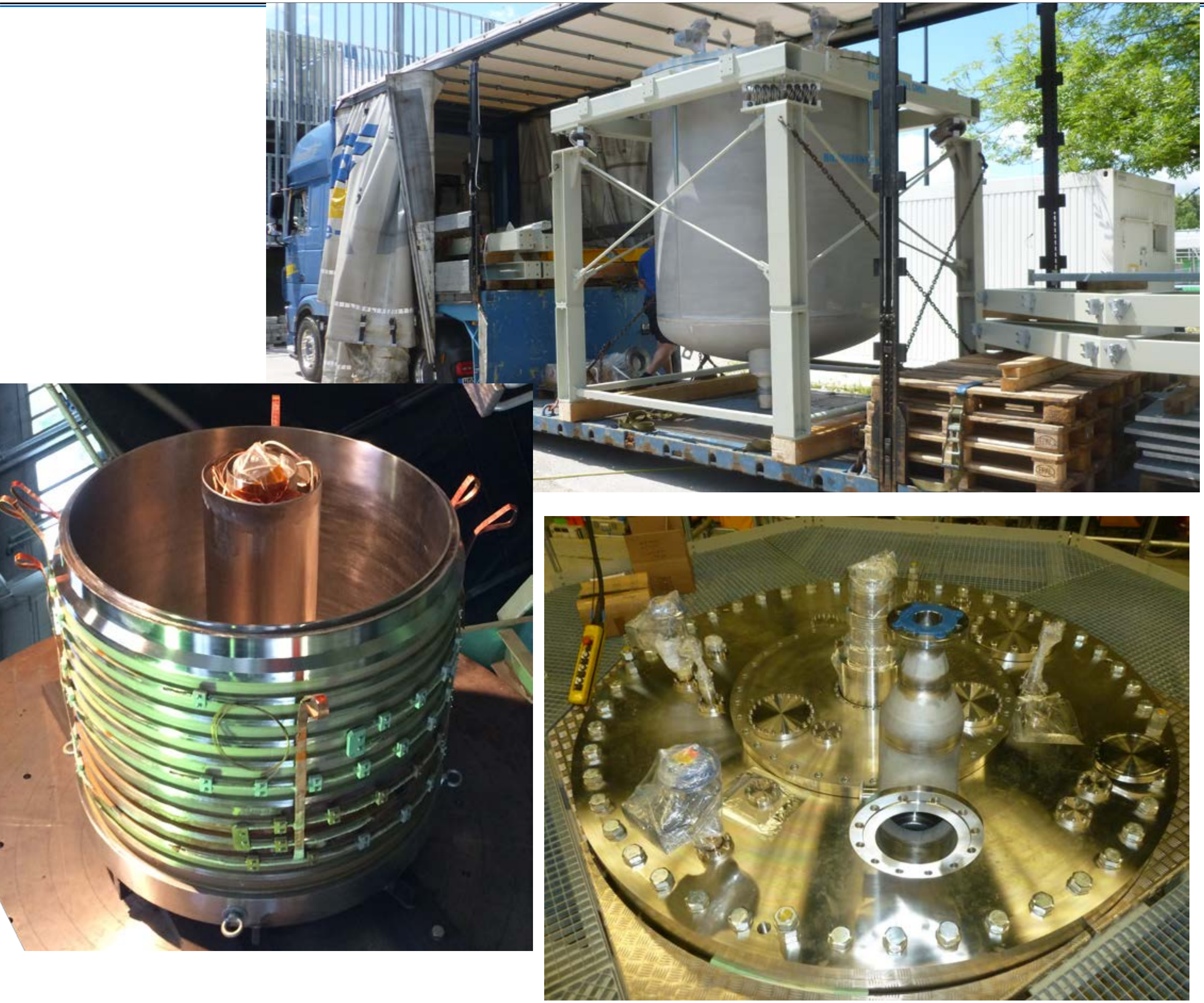
Coil tests with partially completed magnet



- Bottom coils + 2 inner coils + 2 outer coils:
- Reached only 65% of nominal current



Status



- Cryostat and magnet **completed**
- Delivered to TUM in 2020 (pandemic…)
- 2021 to 2022: cooldown attempts with marginal liquefier
- Summer 2022: liquefier at TUM died and no replacement planned

⇒ **Cryo testing and quench training planned at TRIUMF**

⇒ PRIS submitted to PMOG (meeting tomorrow)

⇒ Meson hall liquefier and adjacent space available during shutdown 2024

⇒ Very important milestone for

  ⇒ Funding applications

  ⇒ Attracting new collaborators

Summary

- The neutron lifetime is a very important fundamental parameter that still has not been nailed down well enough.
- PENeLOPE is taking the next step using magneto-gravitational storage in a superconducting magnet
- After long, difficult and expensive development and construction the main component (magnet and cryostat) has been completed and is ready for testing ⇒ **quench training at TRIUMF and results are most important milestone**
- Prospects for a competitive measurement at TRIUMF are very good.