PENeLOPE: testing of a one-of-a-kind neutron storage magnet

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

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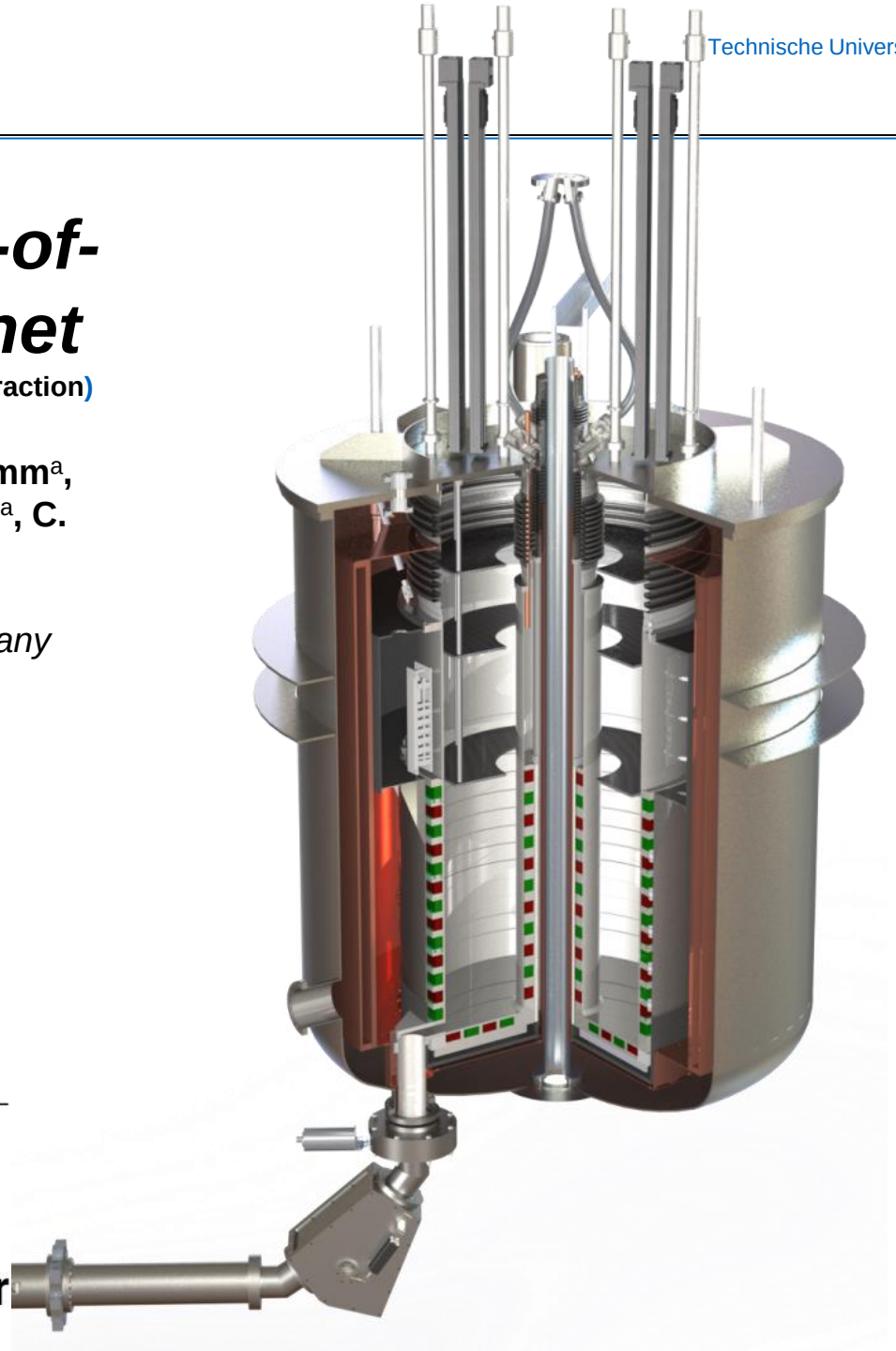

Outline

- Motivation to measure neutron lifetime
- Magnet design
- Magnet training

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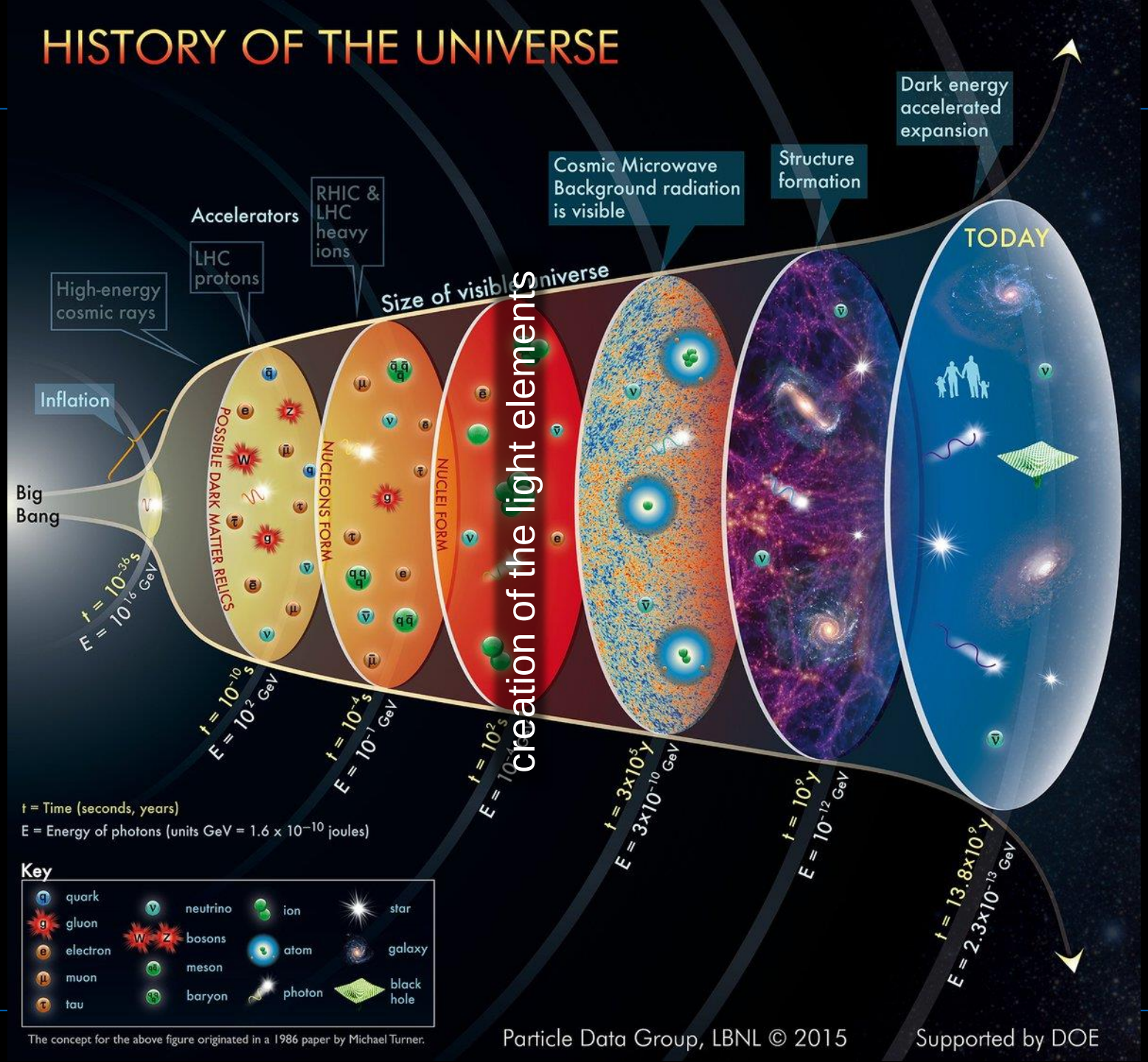
Excellence Cluster Universe



creation of the light elements

Neutrons and cosmology: nucleosynthesis

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

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

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

$$\frac{n_n}{n_p} := \frac{1}{6} \rightarrow \frac{1}{7}$$

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

deuterium fusion

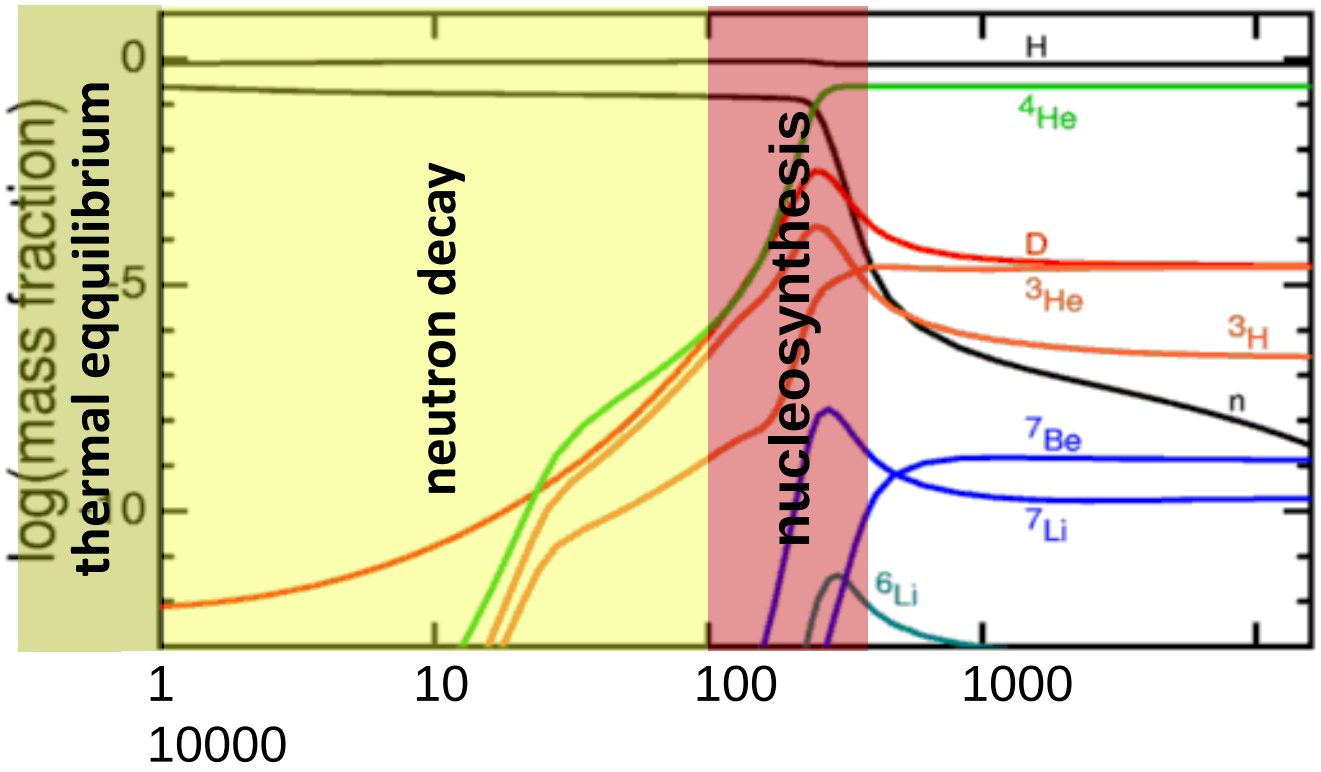
$$n + p \rightarrow d + \gamma$$

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

nucleosynthesis

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

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



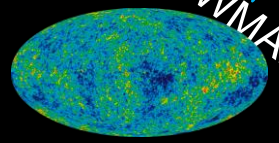
*T in sun 6000°C at surface to 15 Mio°C in the core

The long story of the neutron lifetime τ_n

Big Bang Nucleosynthesis: parametrization of helium abundance

$$Y_P = 0.228 + 0.023\, log\eta_{10} + 0.012 N_\nu + 0.018(\tau_n - 10.28)$$

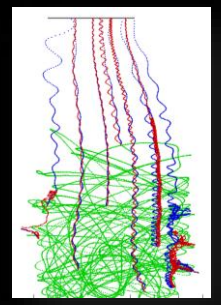
cosmic helium abundance He/p from old stars



cosmic baryon density $(n_\gamma/n_B)\cdot 10^{-10}$ WMAP, Planck

# of neutrino flavors 3

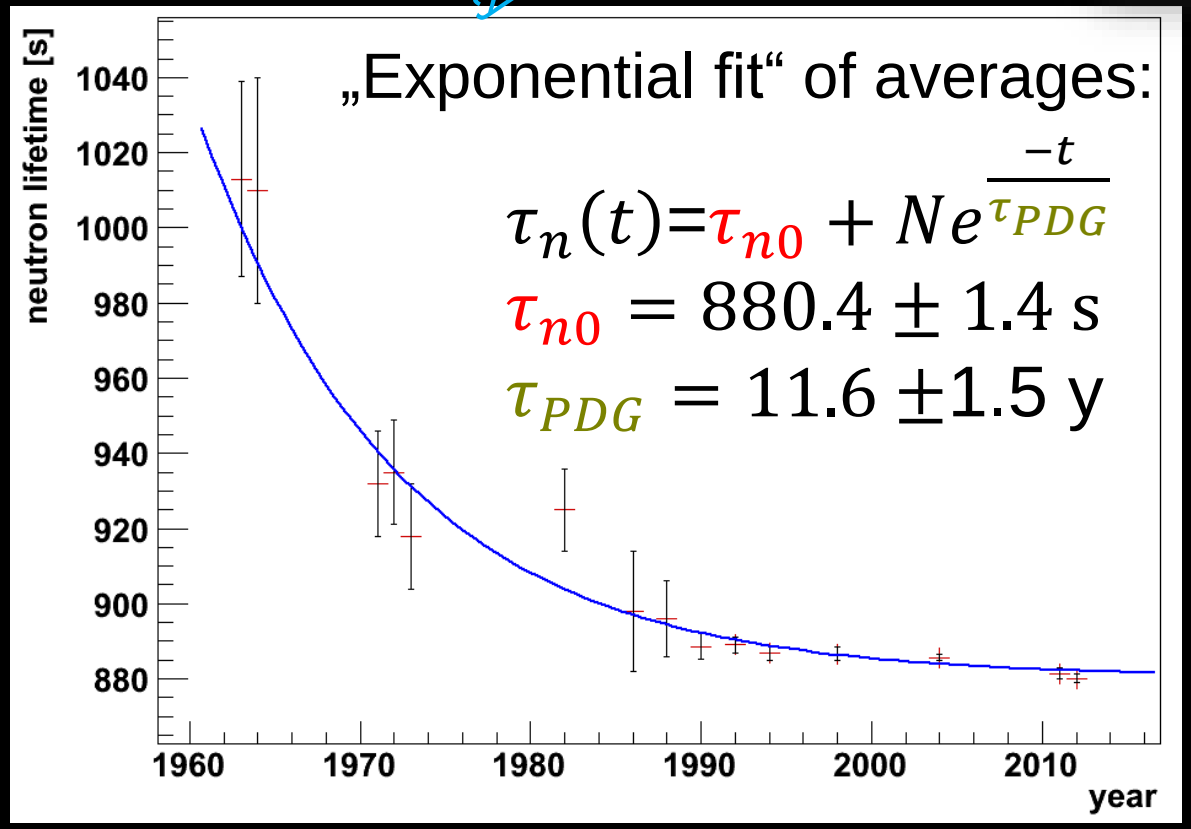
neutron lifetime PENeLOPE



- 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 50 years

⇒ **PENeLOPE**
(**P**recision **E**xperiment on the **N**eutron **L**ifetime **O**perating with **P**roton **E**xtraction)

- Combination of **magnetic storage of ultracold neutrons** and in-situ **proton detection**



Ultra-cold neutrons, why?

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)

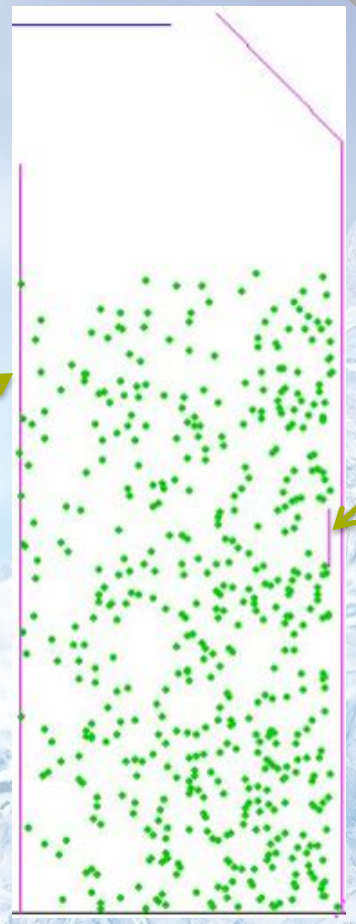
  UCN TRANSPORT, STORAGE

  NiP coated guide

- **Gravitation**
  (100 neV $\triangleq$ 1.02 m)

  UCN STORAGE, ENERGY MANIPULATION

- **Magnetic interaction**



August 29, 2017

Why are ultra-cold neutrons cool?

UCN are really cold:

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

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  UCN TRANSPORT, STORAGE

  NiP coated guide

- **Gravitation**
  (100 neV $\triangleq$ 1.02 m)

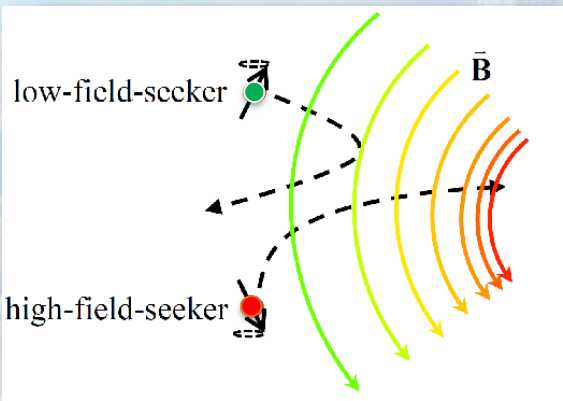
  UCN STORAGE, ENERGY MANIPULATION

- **Magnetic interaction**
  (force on magnetic moment)

  UCN STORAGE, POLARISATION

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

$$\vec{F} = \nabla(\vec{\mu}_{\mathrm{n}}\vec{B})$$



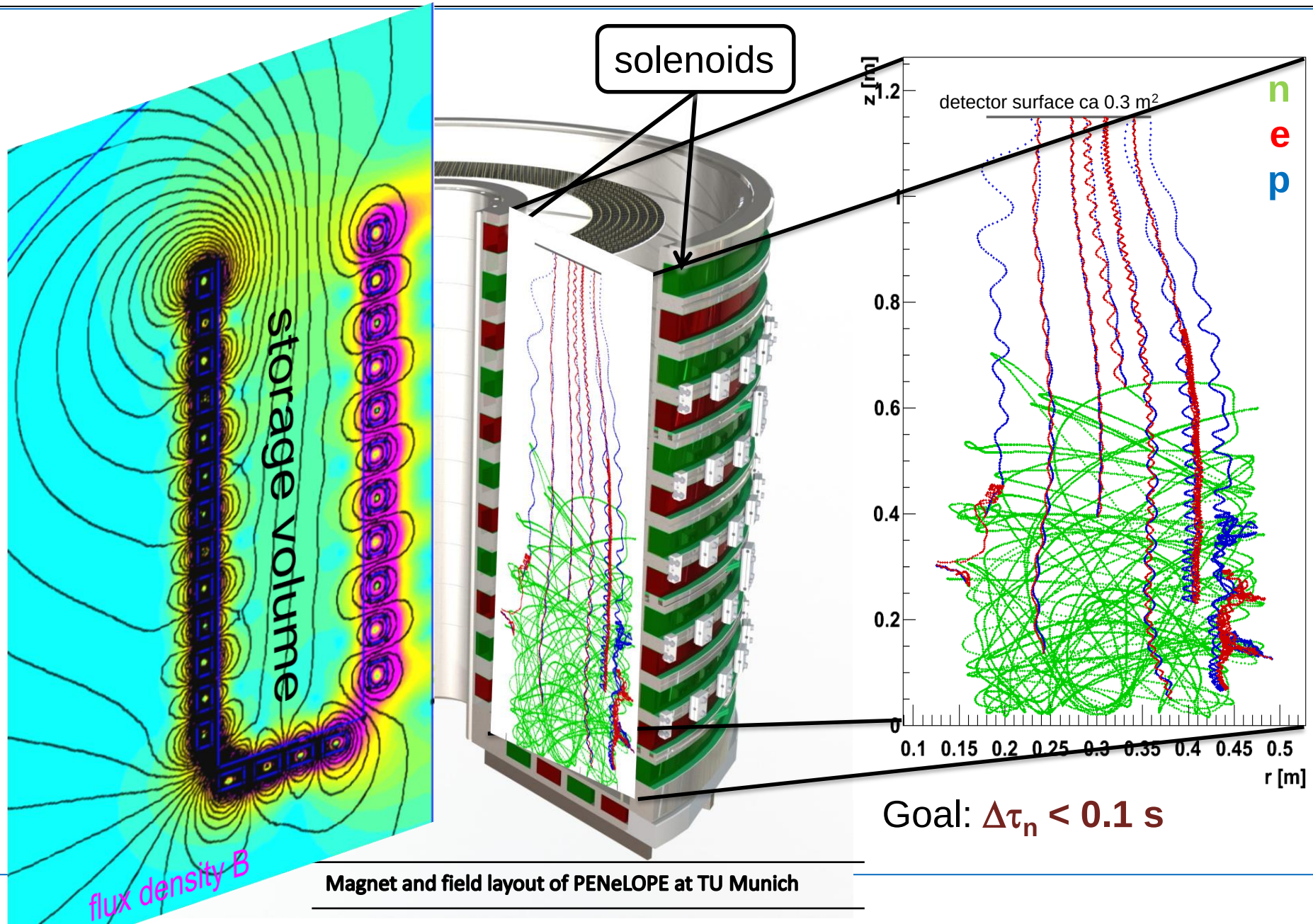
polarising magnet

← experiment

source

$$U = -\mu_{\mathrm{n}} \cdot \mathrm{B} \approx 240\ \mathrm{neV\ for\ 4\ T}$$

PENeLOPE principle



Goal: $\Delta\tau_n < 0.1$ s

Magnet and field layout of PENeLOPE at TU Munich

Particle dynamics simulation

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

protons

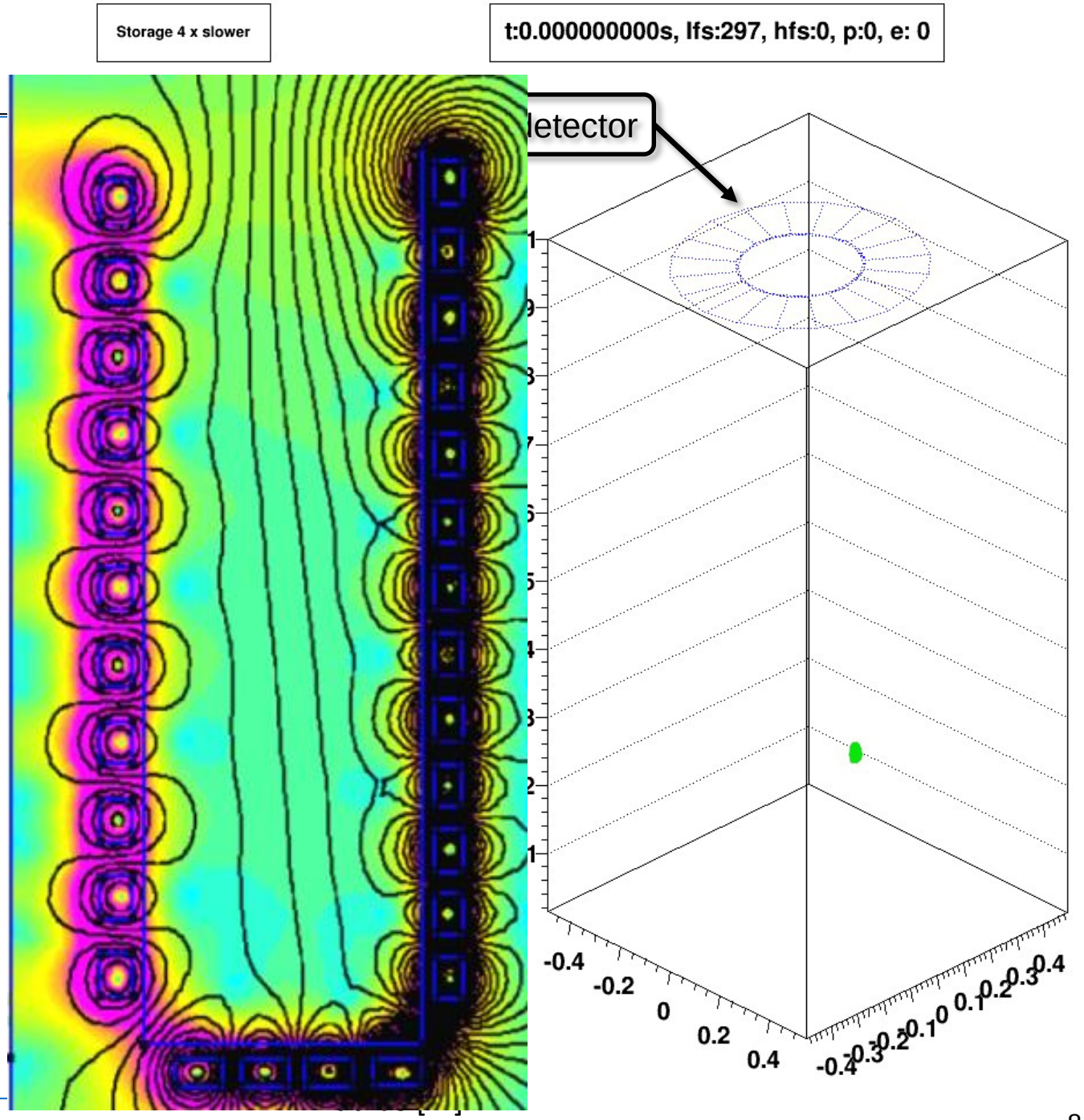
- **0-800 eV** initially
- accelerated to **30 keV**
- collection efficiency **70 %**

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

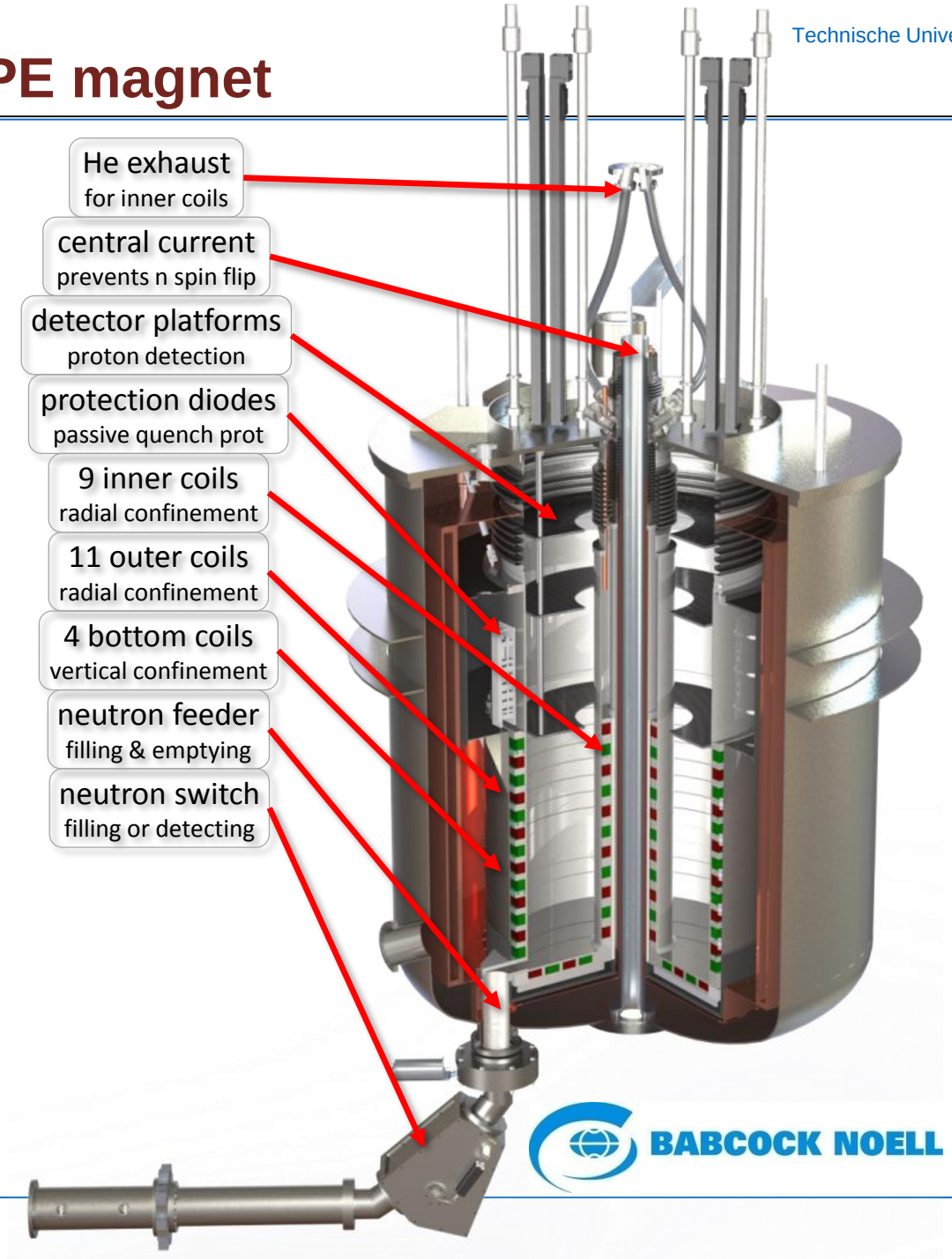


The PENeLOPE magnet

- 24 **thick, short solenoids** (up to 5 cm thick)
- **alternating** current directions createlarge **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)



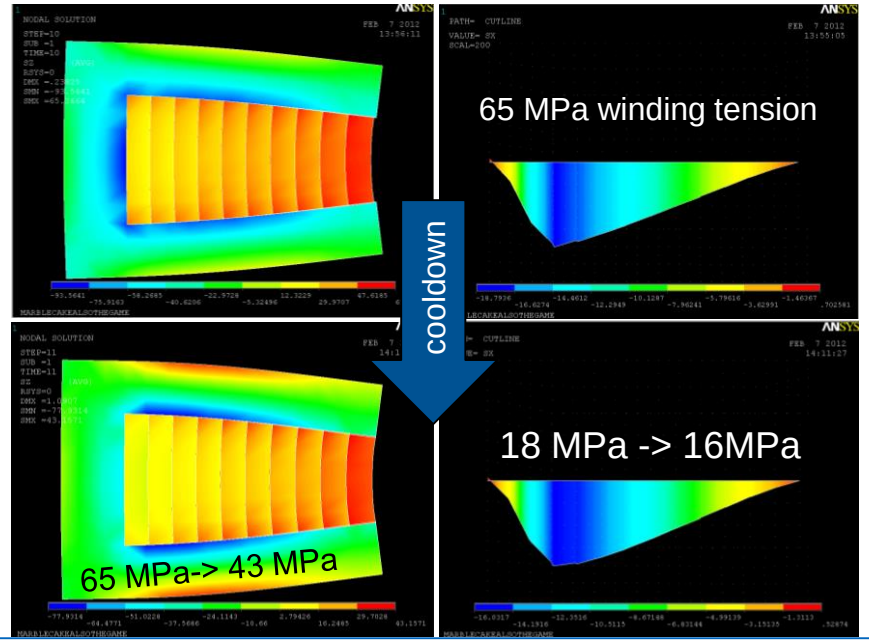
Stress control

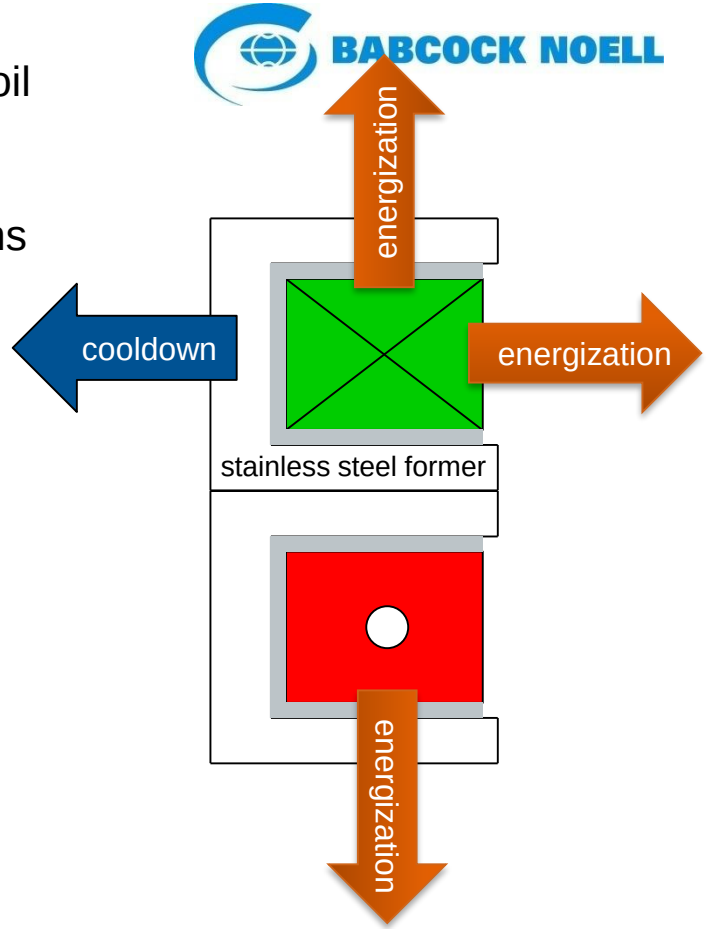
Different stresses act on the coil package:

- On **cooldown** stainless **steel former shrinks** more than coil
- On **energization, coils** want
  - to **expand** radially
  - to **separate axially** due to alternating current directions

⇒ **Winding tension** had to be chosen (**165 MPa**) so that
  - coil does not detach from former
  - winding layers do not separate
  - former doesn't buckle

⇒ **support structure** has to be rigid enough to withstand **> 1 MN** axially

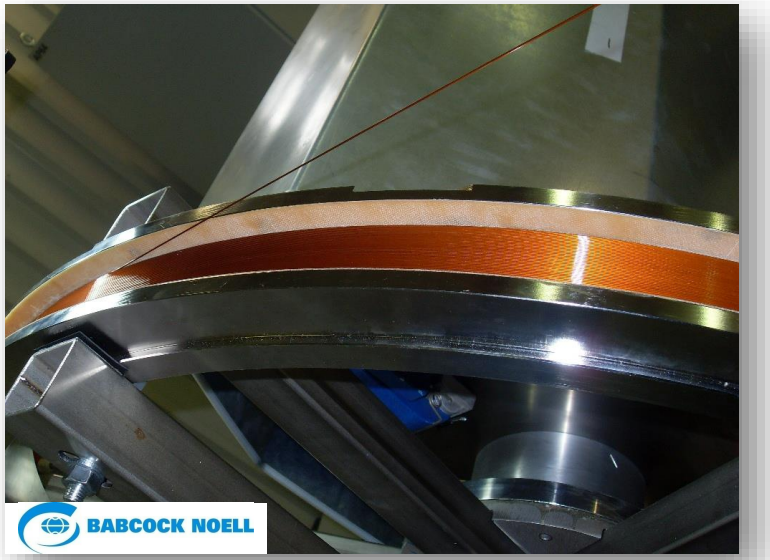




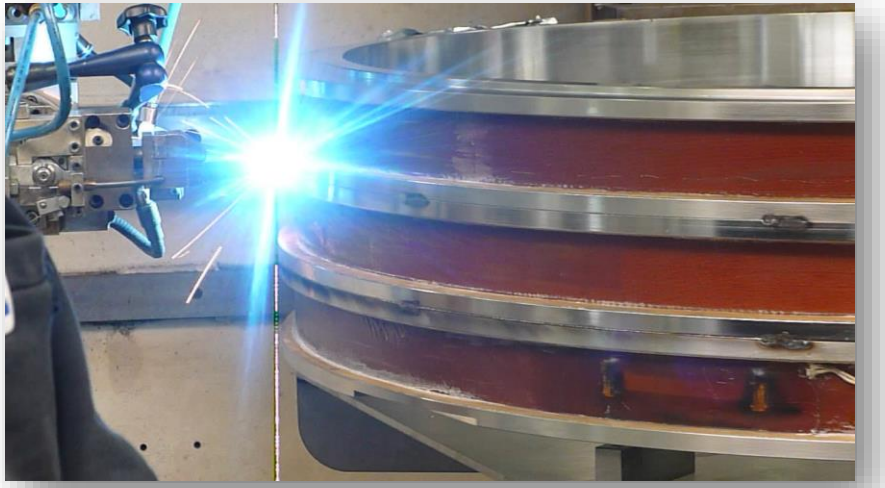
Tangential stress Radial stress

Magnet construction

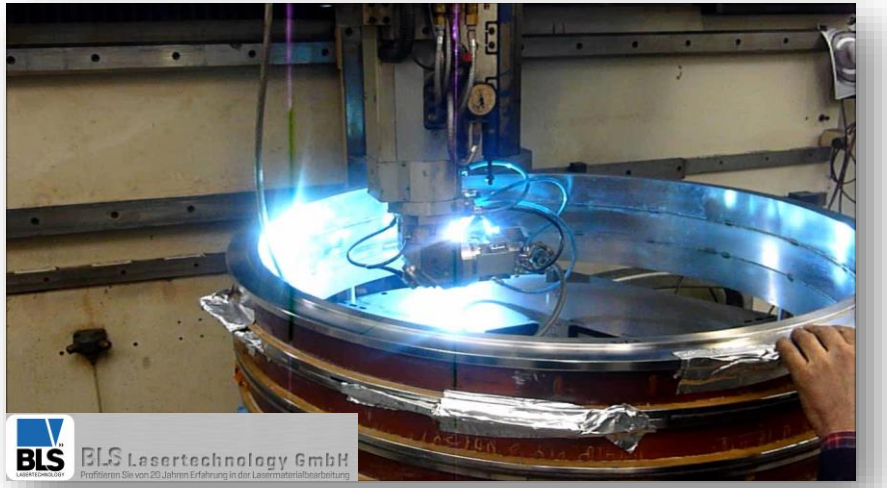
Winding outer coil at Babcock-Noell, Würzburg



Winding detail

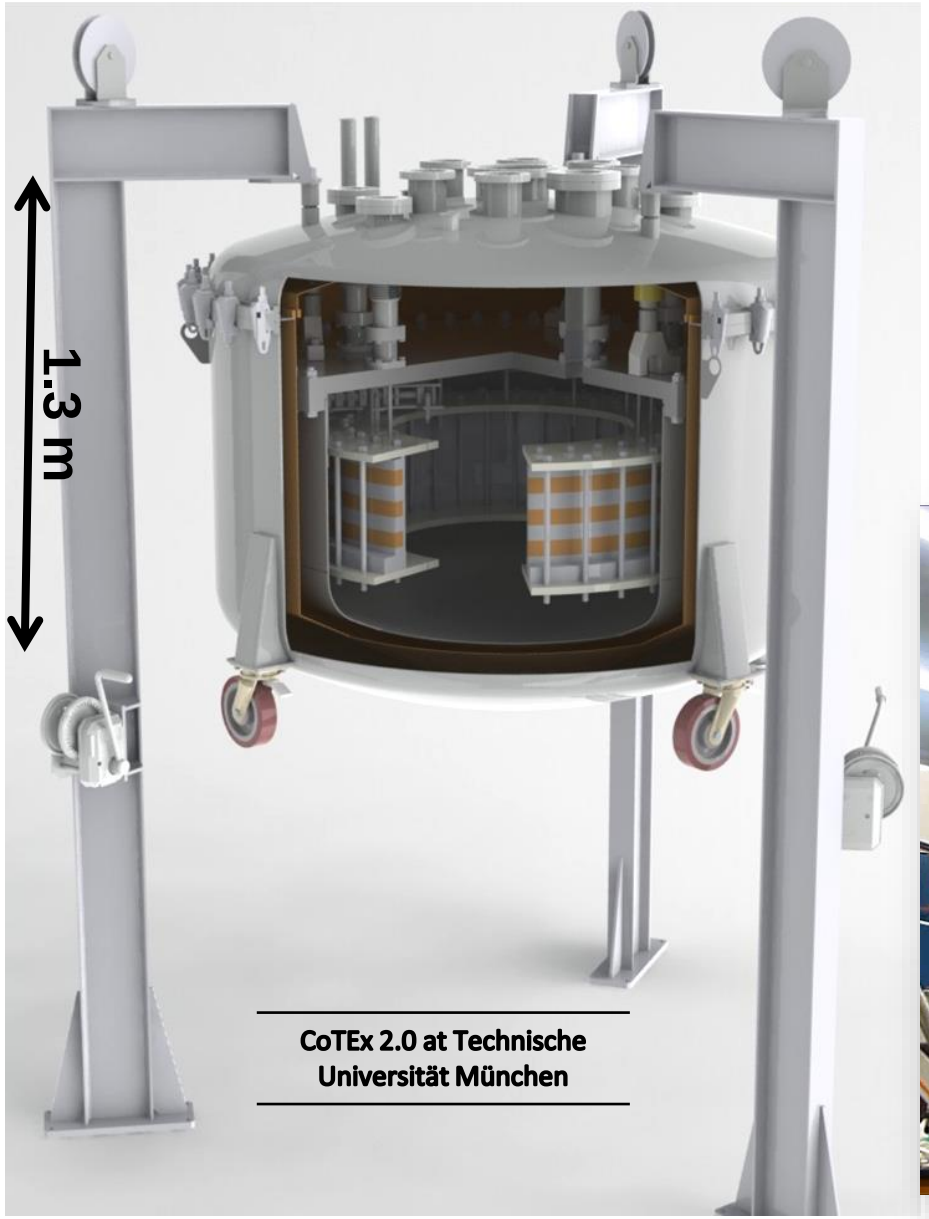


Laser welding outside of coil stack



Laser welding inside of coil stack

Magnet tests

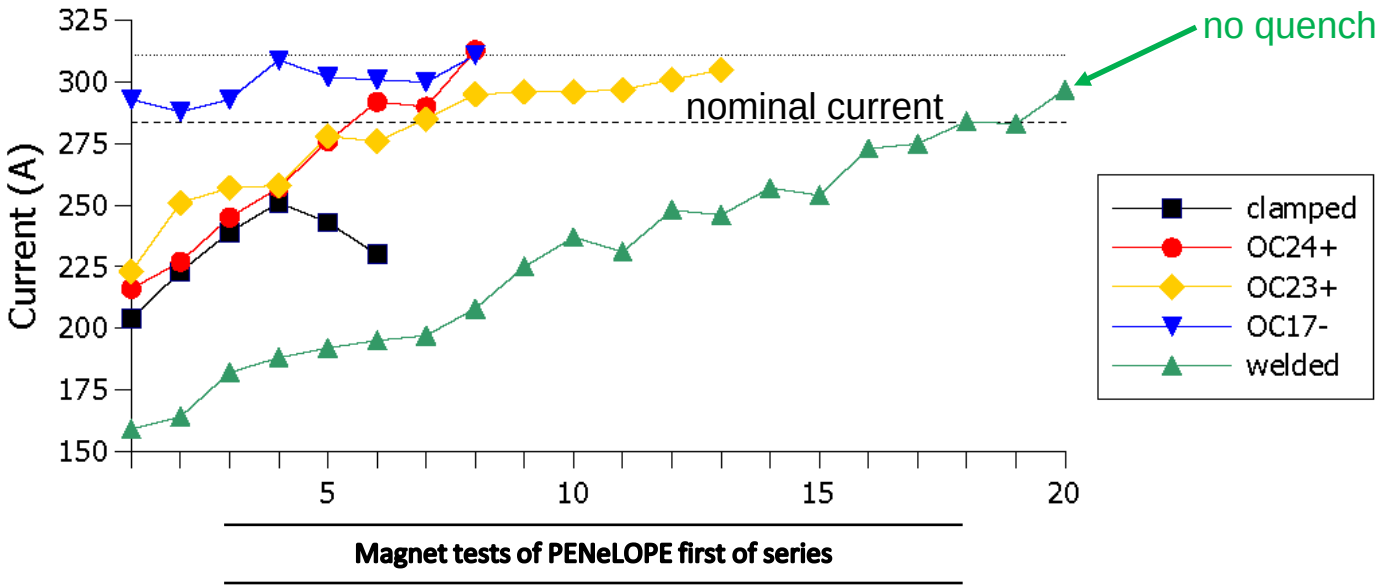


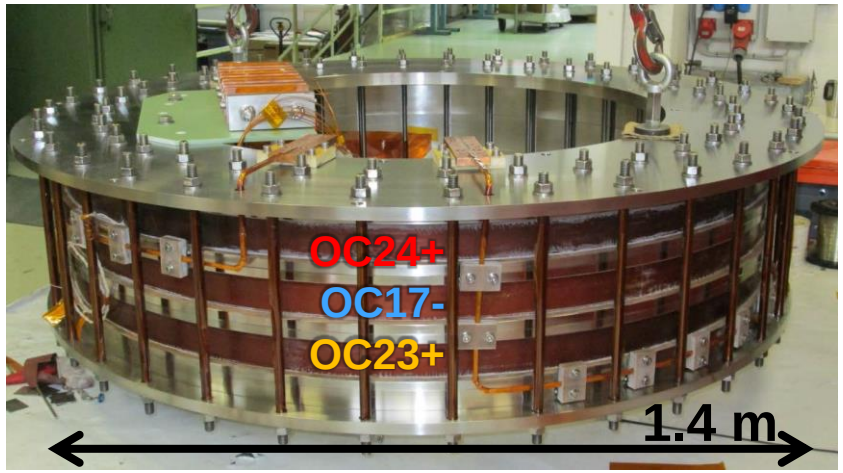
CoTEx 2.0 at Technische Universität München

First-of-series coils in CoTEx 2.0

Quench at 250 A (88% of nominal current)

Test campaign results 2014





Clamped coil stack

- to facilitate repairs if needed
- nominal current **not reached**
- **quench current dropped** after 4 quenches

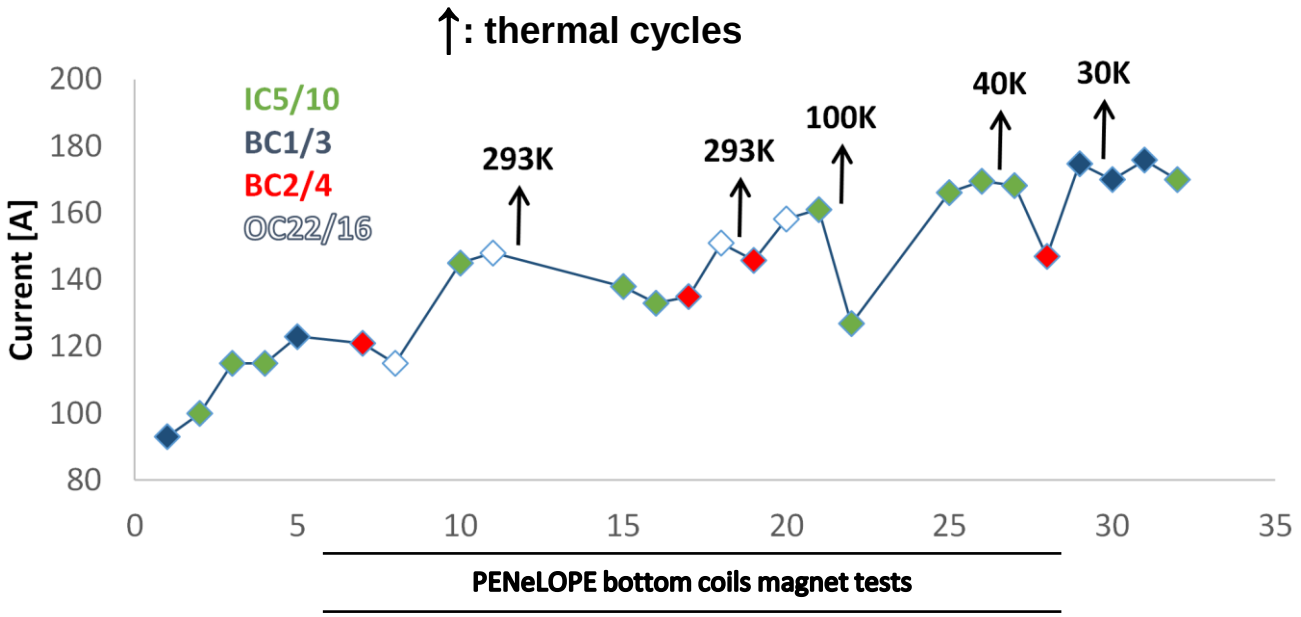
Single coils

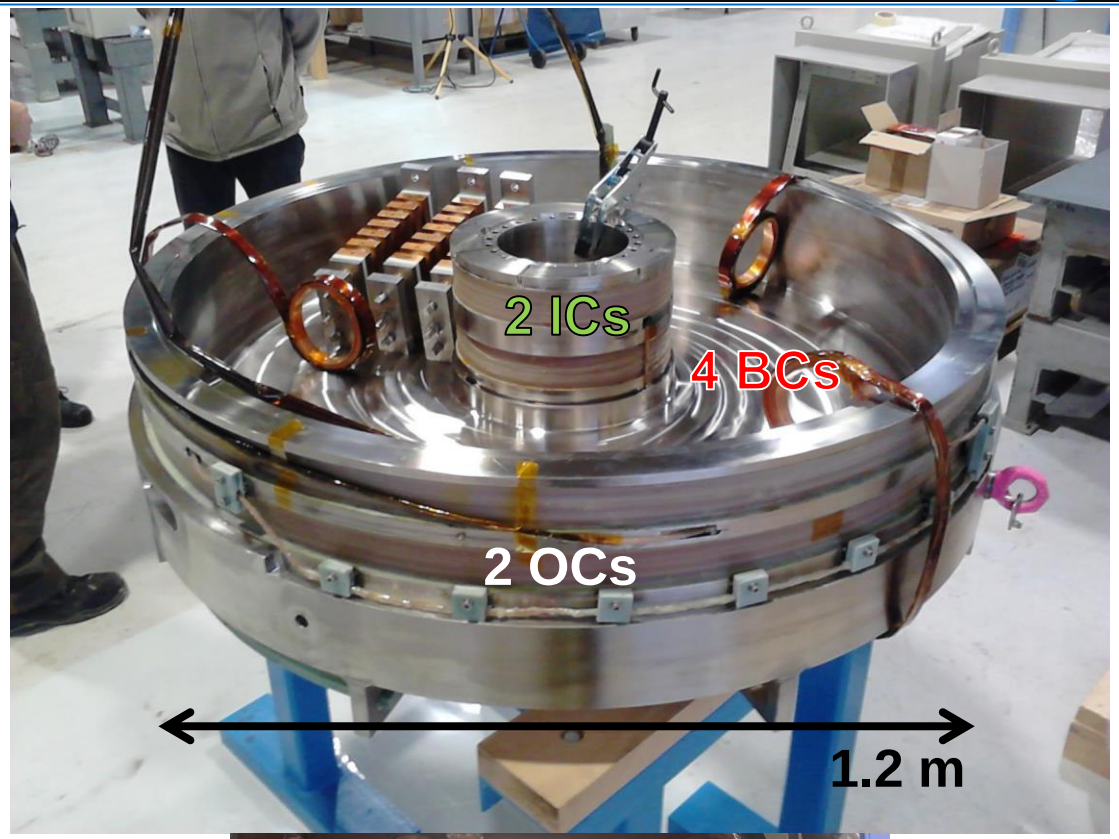
⇒ all reached nominal current

Laser-welded coil stack

⇒ long, but **successful training**

Test campaign results 2017





4 bottom coils (BC), 2 inner coils (IC), 2 outer coils (OC)

- quenches start at 35% of nominal current
- slope very flat
- no particular coil causes the quenches

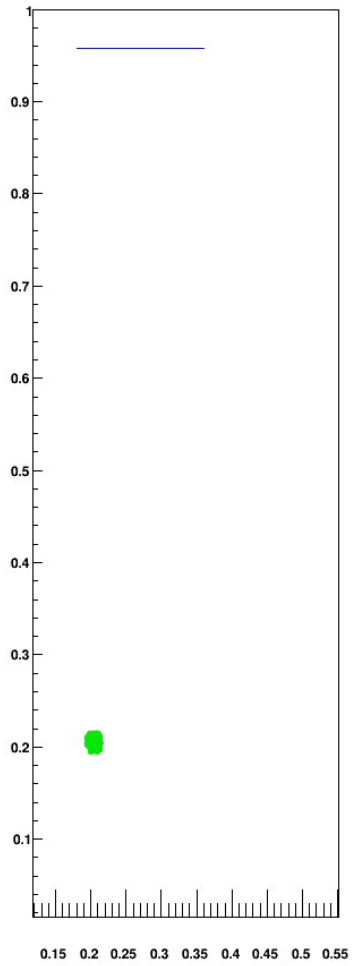
Any ideas?

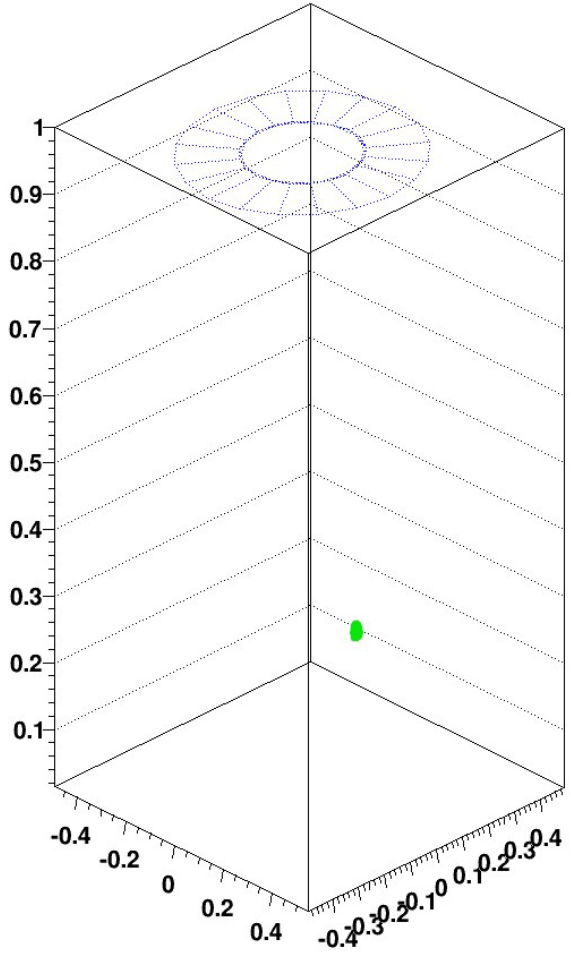
To be continued…

Conclusion

- PENeLOPE, a **one of a kind** superconducting magnet for fundamental physics
- **long development / design stage** necessary
- **tests of** manufactured **coils** are ongoing, but pose quite a few questions

- Experiments planned for 2019





Neutron spin flip suppression

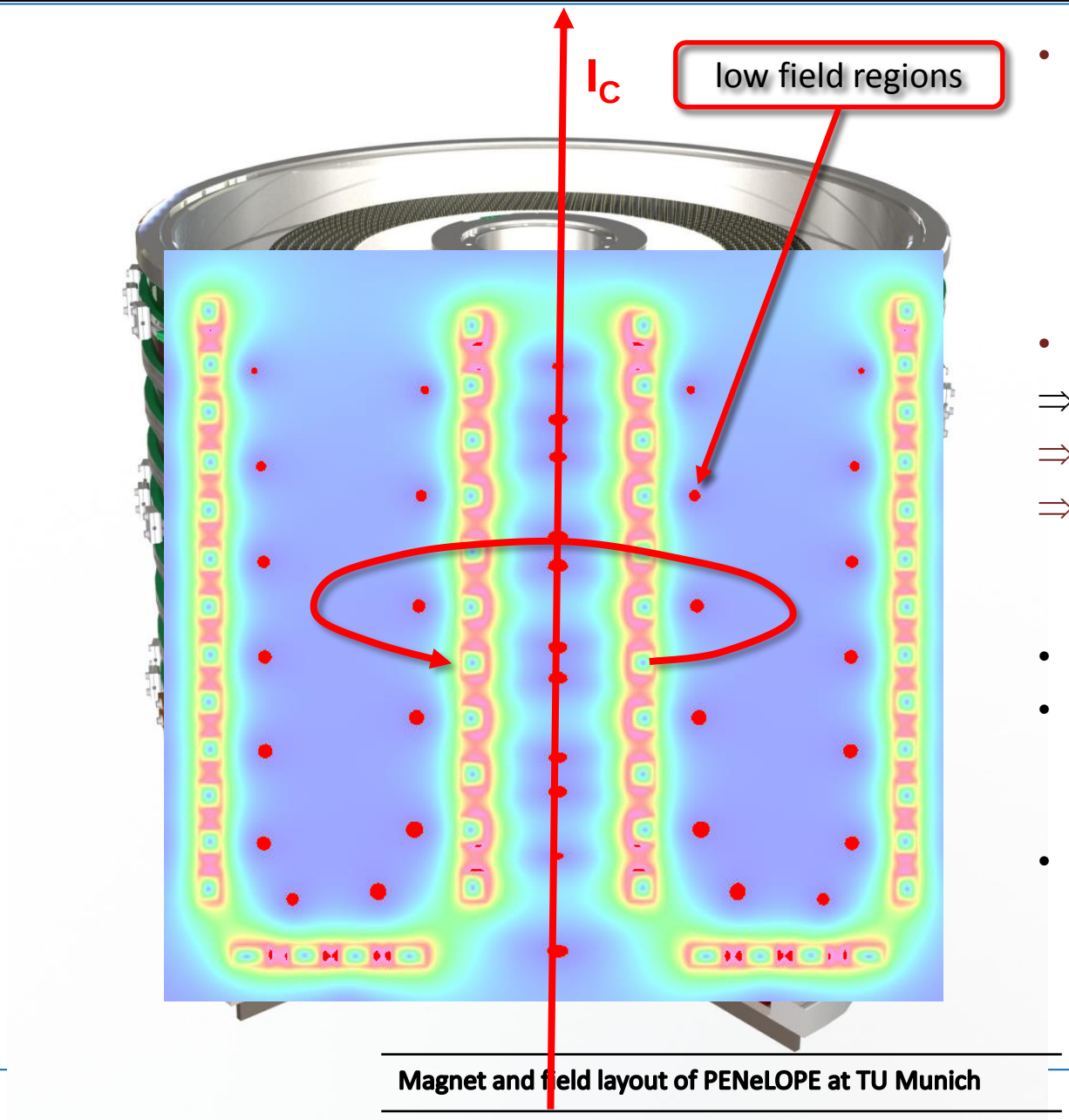
Why central solenoids???

Magnet and field layout of PENeLOPE at TU Munich

- **adiabatic condition for neutron spin transport**

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

Neutron spin flip suppression



Magnet and field layout of PENeLOPE at TU Munich

- **adiabatic condition for neutron spin transport**

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

- **violated in low field regions**

⇒ spin flip more likely

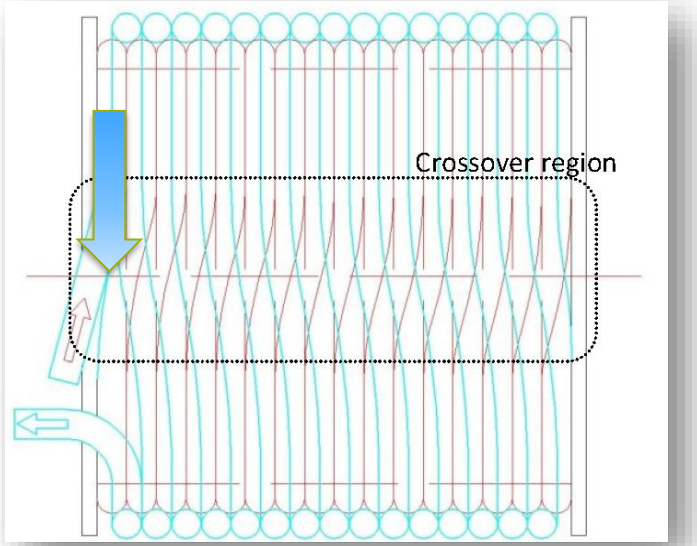
⇒ **UCN loss** from trap

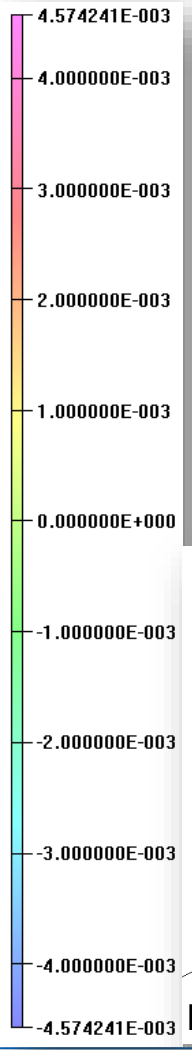
⇒ **systematic effect** on lifetime measurement ☹

- 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

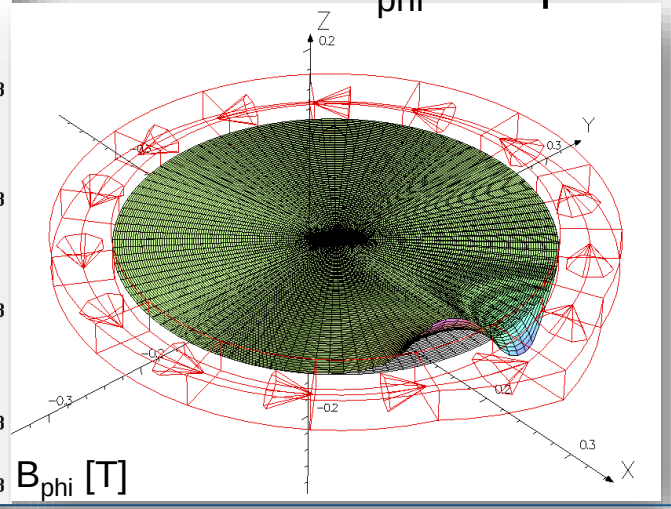
Coil bumpiness...?

Why do thick solenoids have bumps?

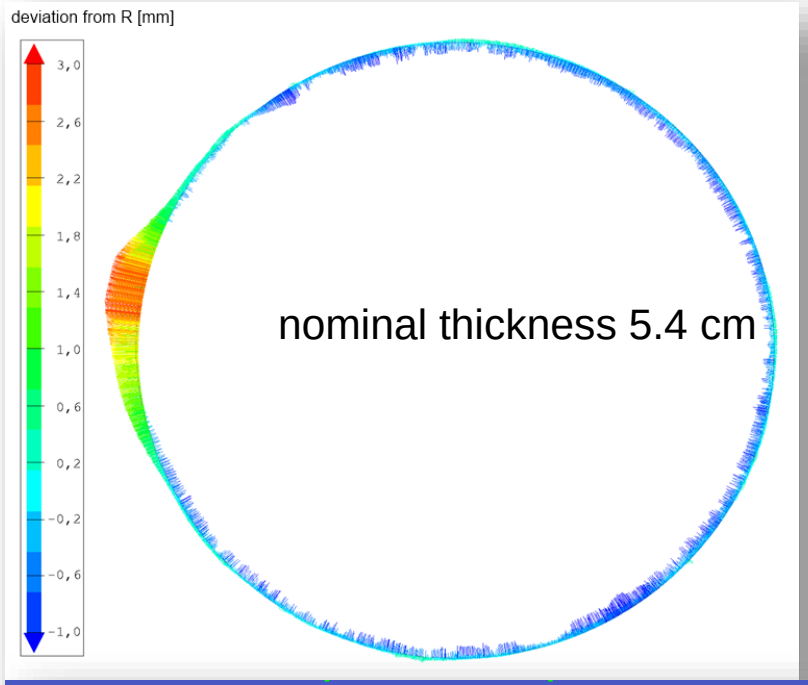


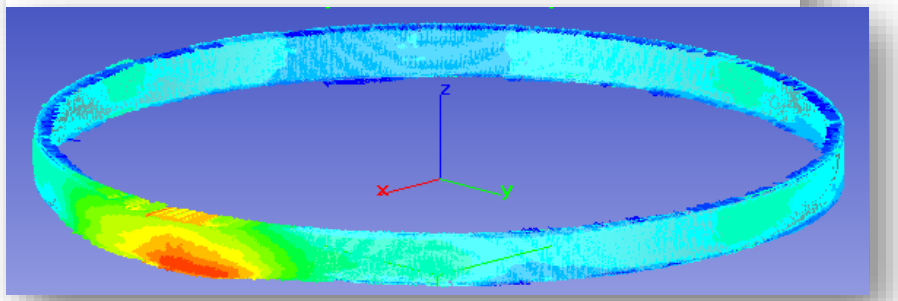


⇒ azimuthal B_{phi} component



3D laser scan of actual coil

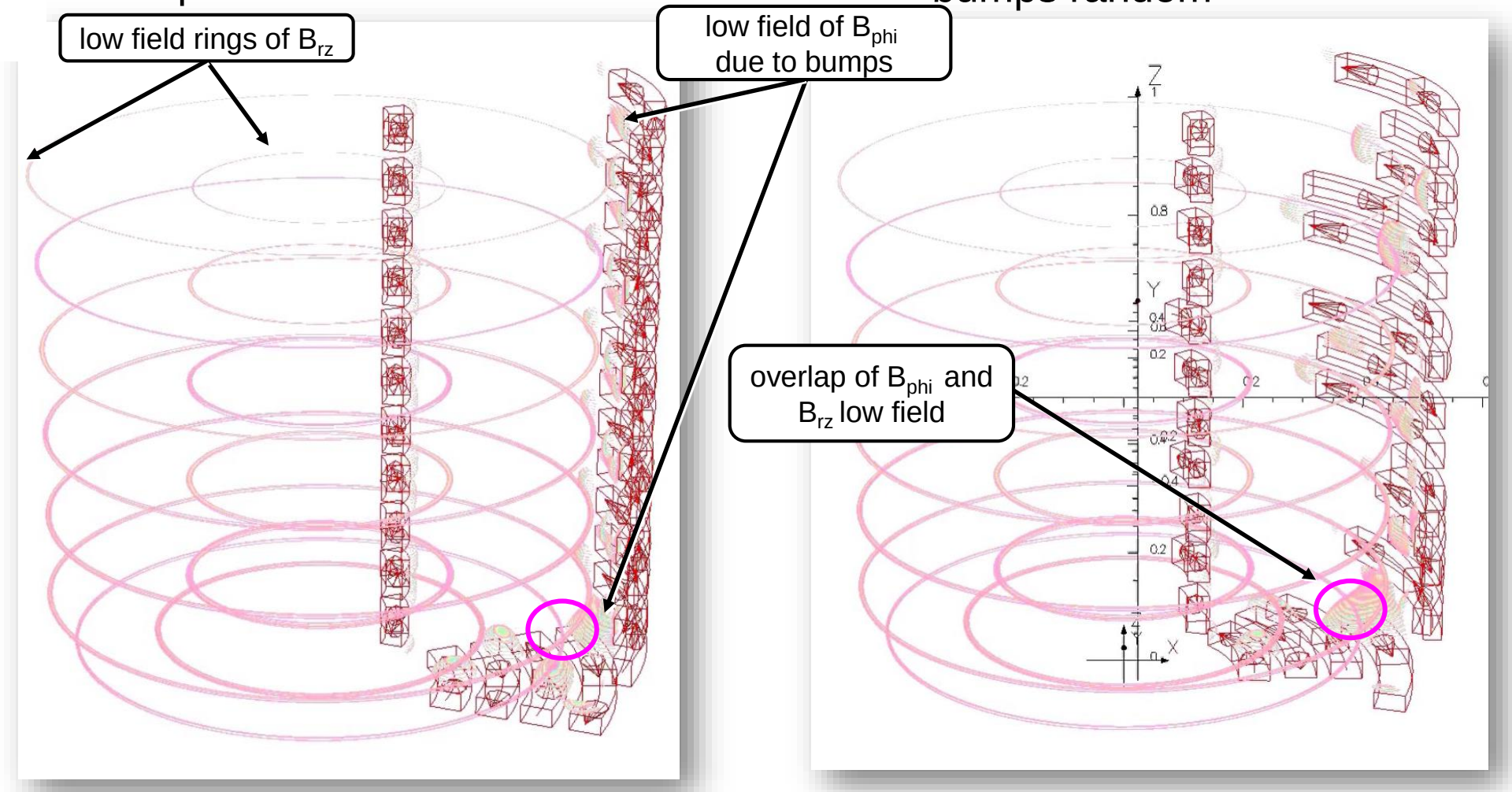




Coil bumpiness... consequences

all bumps above each other

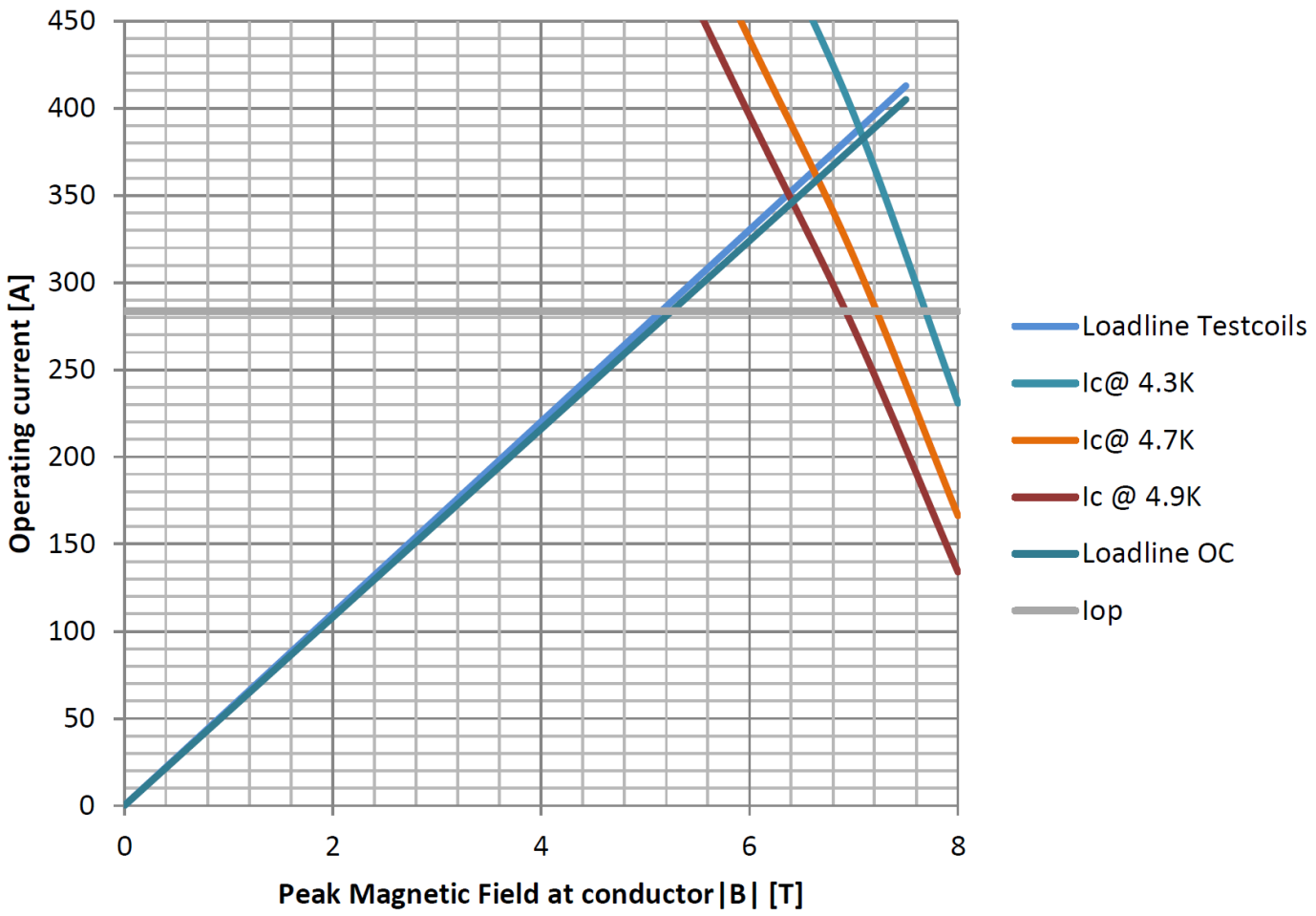
bumps random



⇒ possible global low field region ⇒ control individual coil rotations ☺

⇒ enhanced neutron spin flip!!! ☹

Magnet loadline



Quench prot. diodes

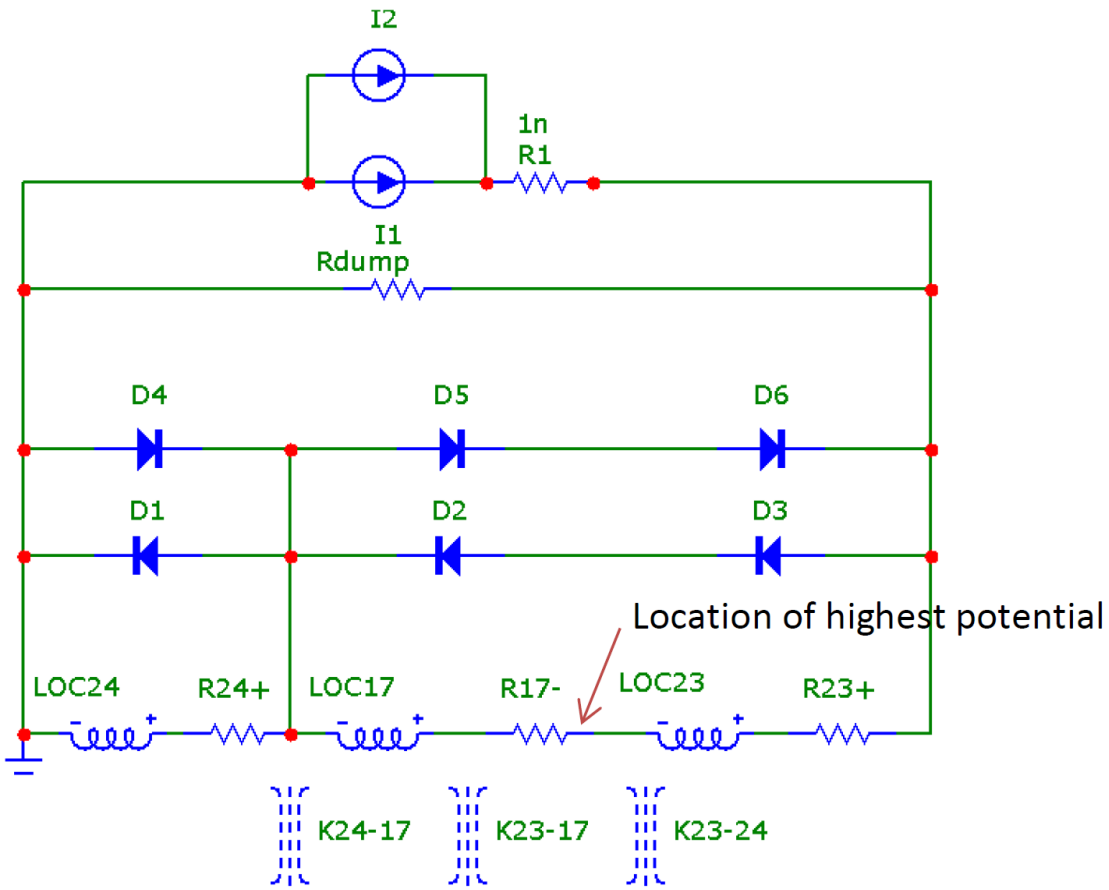
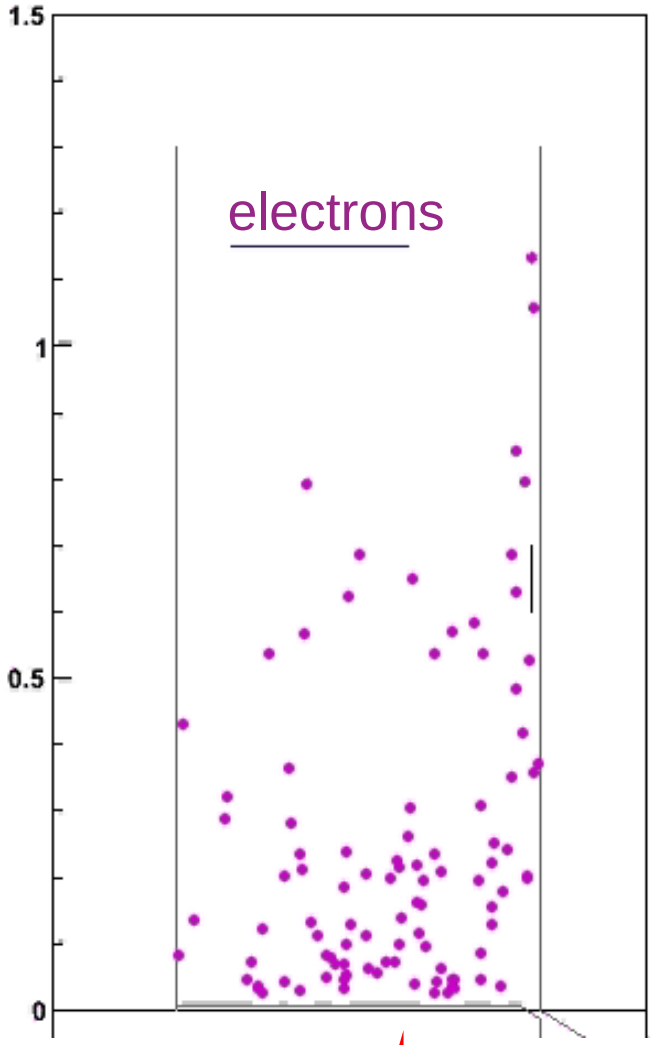
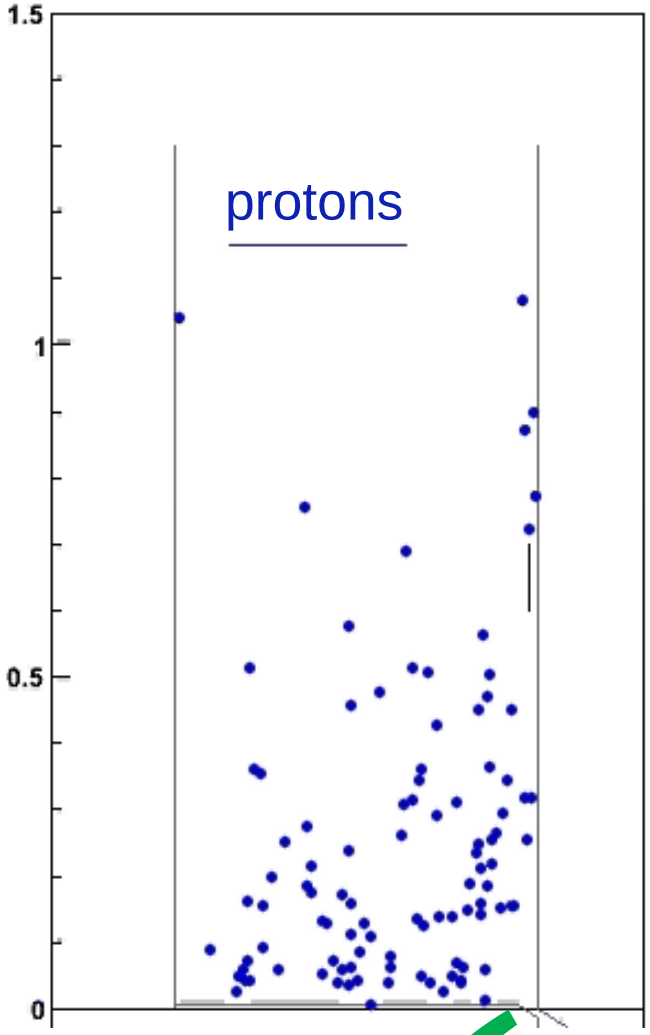


Figure 1.2: Simplified schematic of the planned test circuit. The resistors R## next to the inductors (coils) LOC## represent the ohmic resistance developing during a quench.

Electrons and protons

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





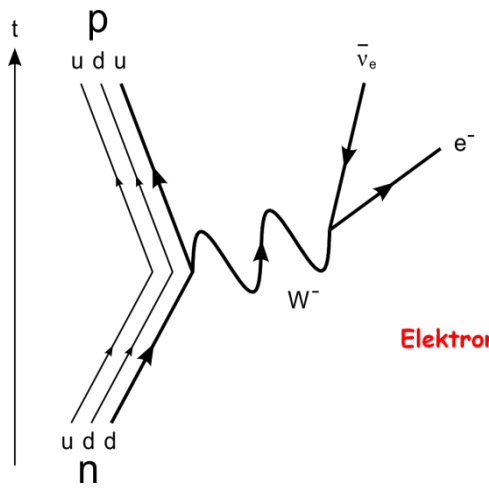
Physics Case 1: Quark mixing

- Cabibbo-Kobayashi-Maskawa Matrix

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

- Standard Model

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

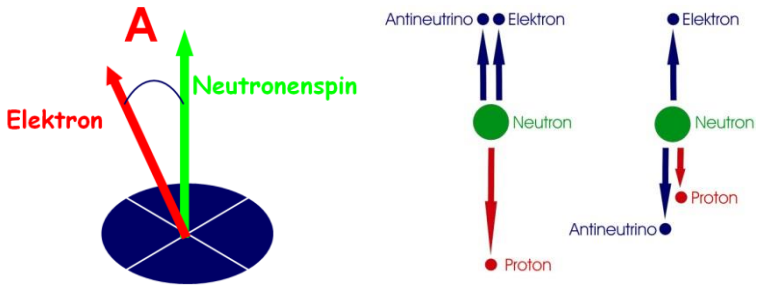


- Neutron decay

$$|V_{ud}|^2 = \frac{4908.7(1.9)\ \mathrm{s}}{\tau_n (1+3\lambda^2)}$$

- Coupling constants

$$\lambda = G_A / G_V = -1.2695 \pm 0.0029$$



$$A = -2\frac{|\lambda|^2 + \Re(\lambda)}{1+3|\lambda|^2} \qquad a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

PERKEO aSPECT

- Current PDG average

$$\tau_n = 885.7 \pm 0.8\ \mathrm{s}$$

Statistics

source flux (FRMII)	10^7 UCN/s
energy window	70 neV
polarized UCN in trap (results full MC including source, guides, slits etc)	10^7 UCN
proton collection/detection efficiency	60 % / 40 %
neutron collection/detection efficiency	70 % / 90 %
material storage lifetime	350 s
filling / cleaning / ramping / HFS cleaning time	200 s / 200 s / 100 s / 160 s
storage times	1000 s / 3000 s / 5000 s / 8000 s
# of cycles necessary to reach 0.1 s in both detection schemes	610
time necessary	37 days

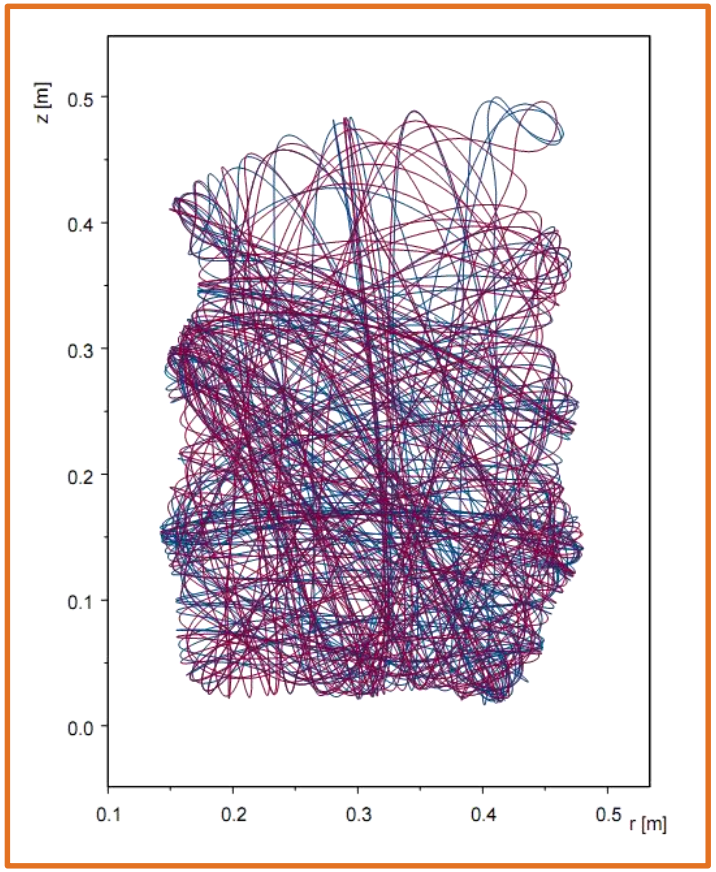
$$N(t) = N_{LFS}\left((1-f_M)e^{\frac{t}{\tau_n}} + f_M \cdot e^{\frac{t}{\tau_M}}\right) + N_{HFS}e^{\frac{t}{\tau_{HFS}}} + B$$

$\Rightarrow$

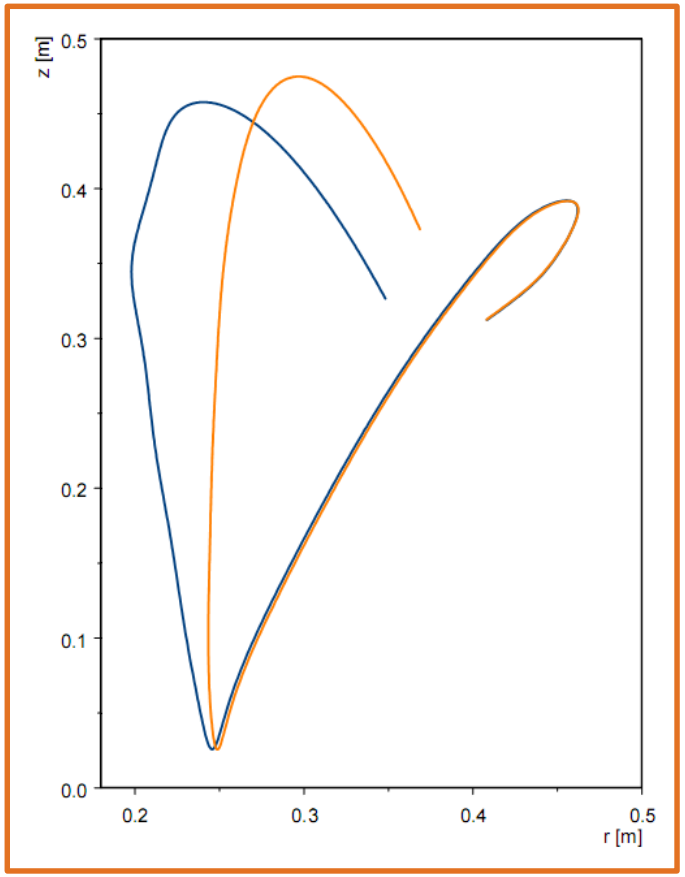
N_{LFS}: number of low field seekers - f_M: fraction of marginal UCN - τ_n: beta decay lifetime -τ_M: storage lifetime of marginal UCN
N_{HFS}: number of high-field seekers - τ_{HFS}: storage lifetime of HFS - B: const background

Chaos in the (magnetic) house?

Instability of UCN tracks – physics or numerics?



$\Delta z = 10^{-17}\mathrm{m}, t = 30\mathrm{s}$



$\Delta z = 10^{-17}\mathrm{m}, t = 0.7\mathrm{s}$

Spin flip suppression

- spin flip:
  - **systematic studies possible varying the central current**
  - around **2-3 % of dep. UCN reach** UCN **detector**

  MC simulations:
  - spin-flip loss time τ_{SF} ***> 10⁹ s***
  - systematic effect: $\Delta\tau_n < 0.01$ s

$$\frac{\mathrm{d}\boldsymbol{S}}{\mathrm{d}t} = \boldsymbol{\omega} \times \boldsymbol{B}$$

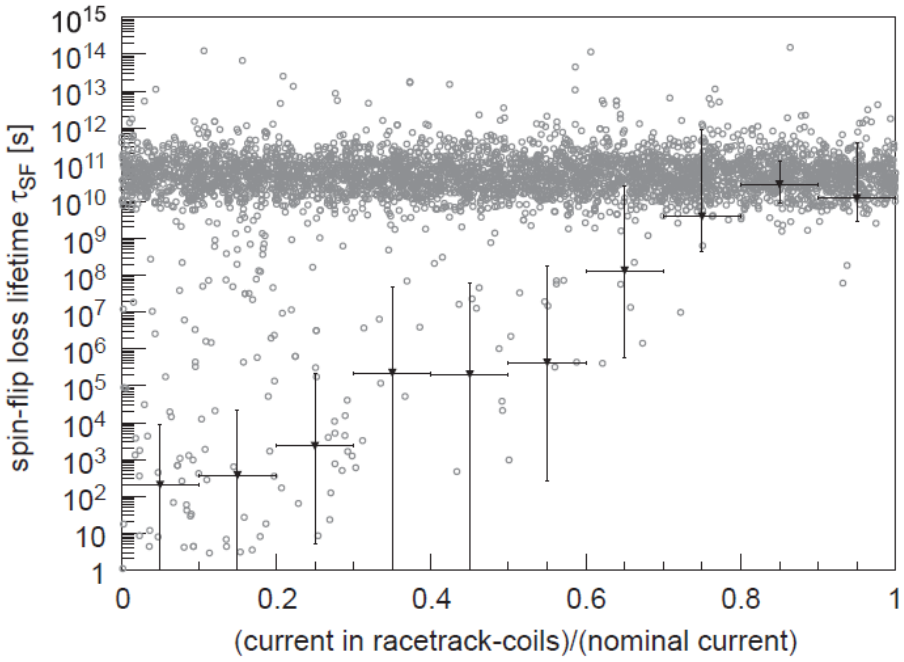


Fig. 2. Simulation on the storage lifetime of neutrons before spin-flip as a function of the current in the racetrack coils. Every single gray circle represents a single neutron. The mean spin-flip loss lifetime averaged over a current bin is shown as black triangles.

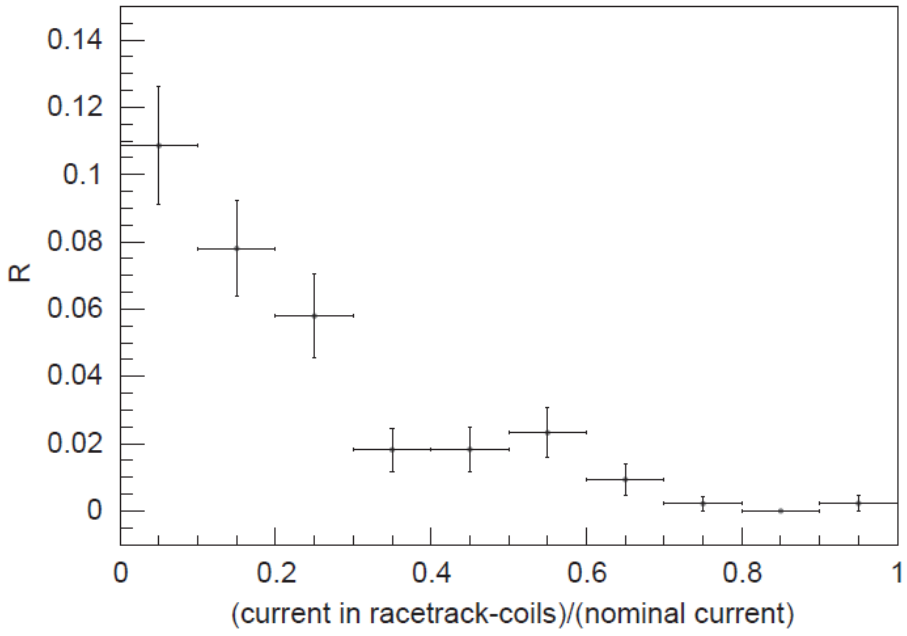
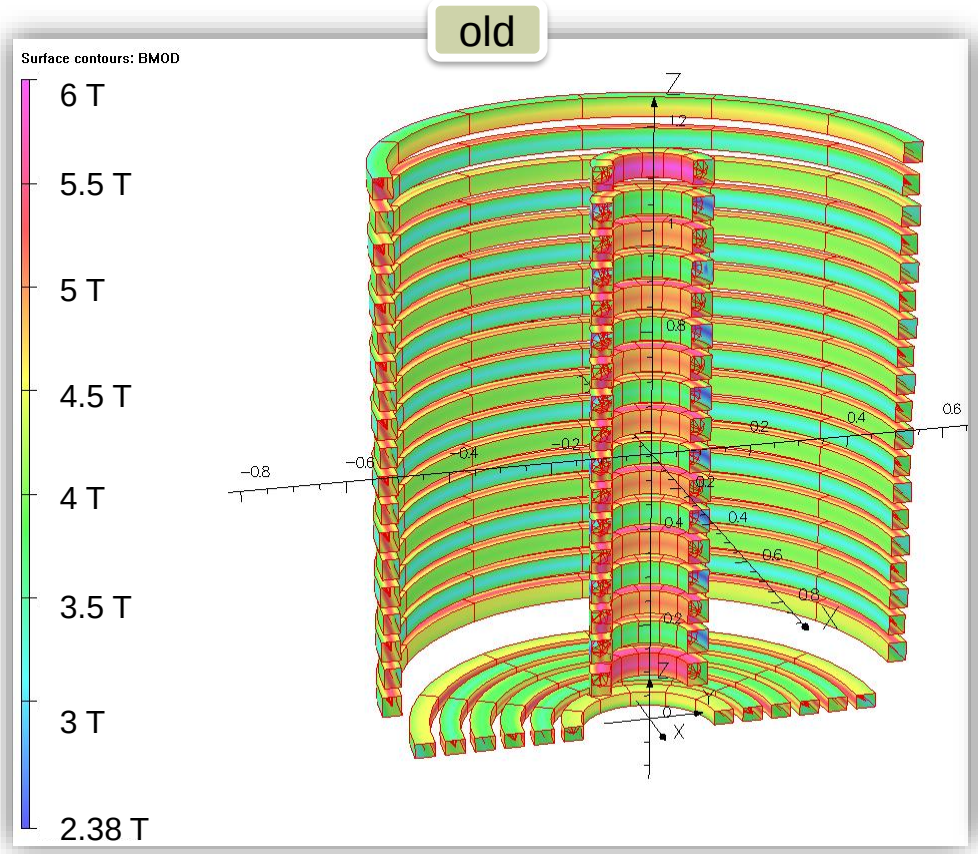


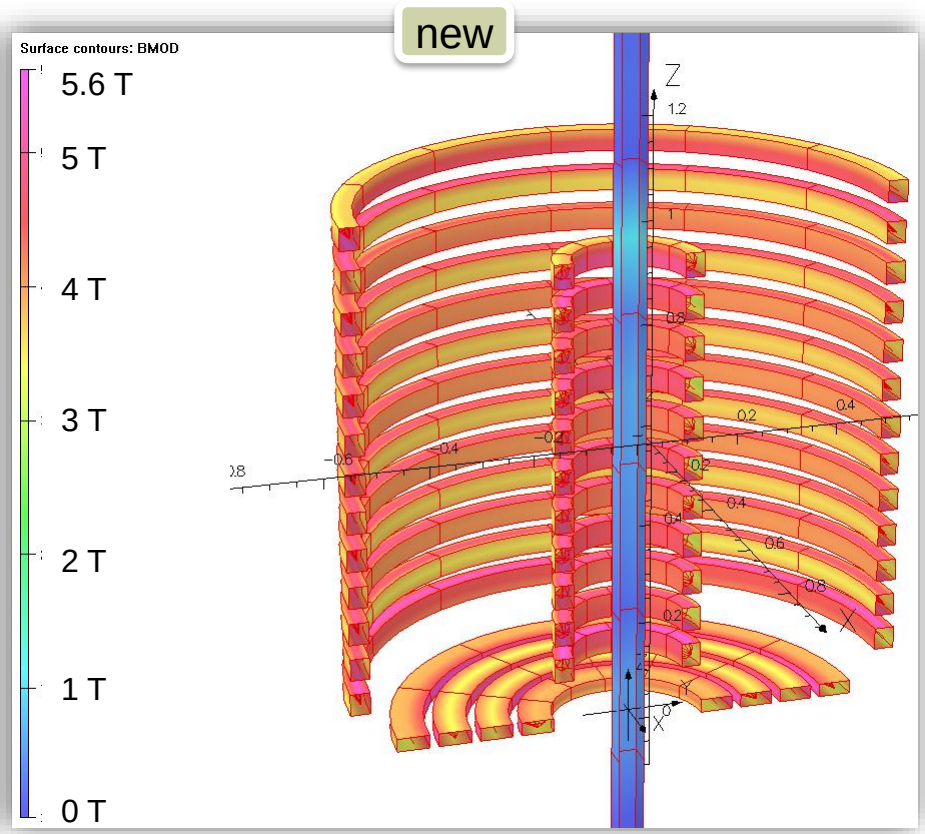
Fig. 3. Ratio R of the number of UCN with $\tau_{SF} < 10^8$ s to number of UCN with $\tau_{SF} > 10^8$ s within a racetrack coil current bin versus the current.

S. Materne, R.P. et al., NIM A **611**, (2009).

Coil revision 2010

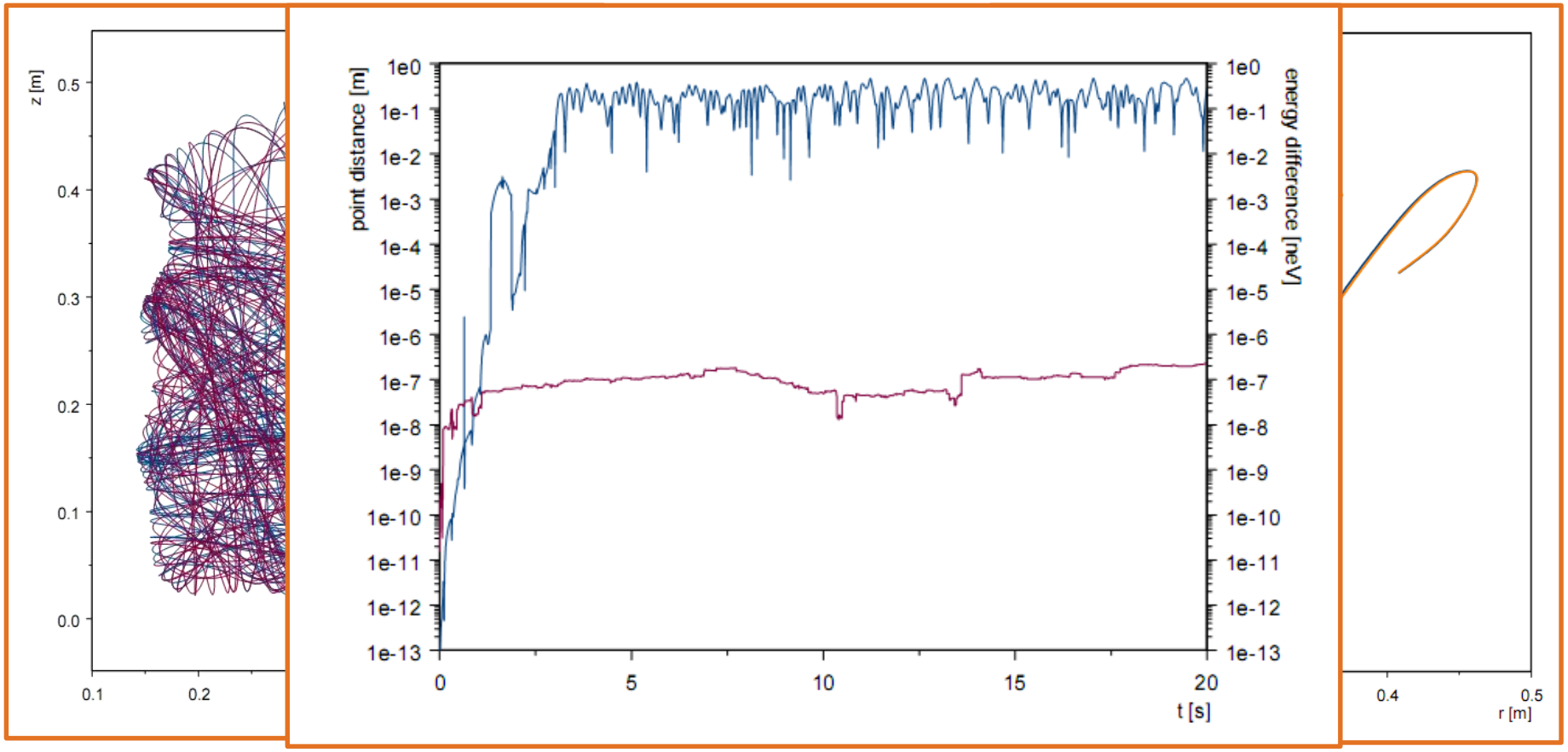
- topology unchanged
- bigger coil distances
- **less coils** 44 ⇒ 28
- **max. field** in conductor 6.1 ⇒ 5.5 T
- **storage potential** 74 ⇒ 115 neV
- **proton collection** 70 ⇒ 68 %
- **detector size** 0.3 ⇒ 0.23 m²
- central current in warm bore





Chaos in the (magnetic) house?

Instability of UCN tracks – physics or numerics?

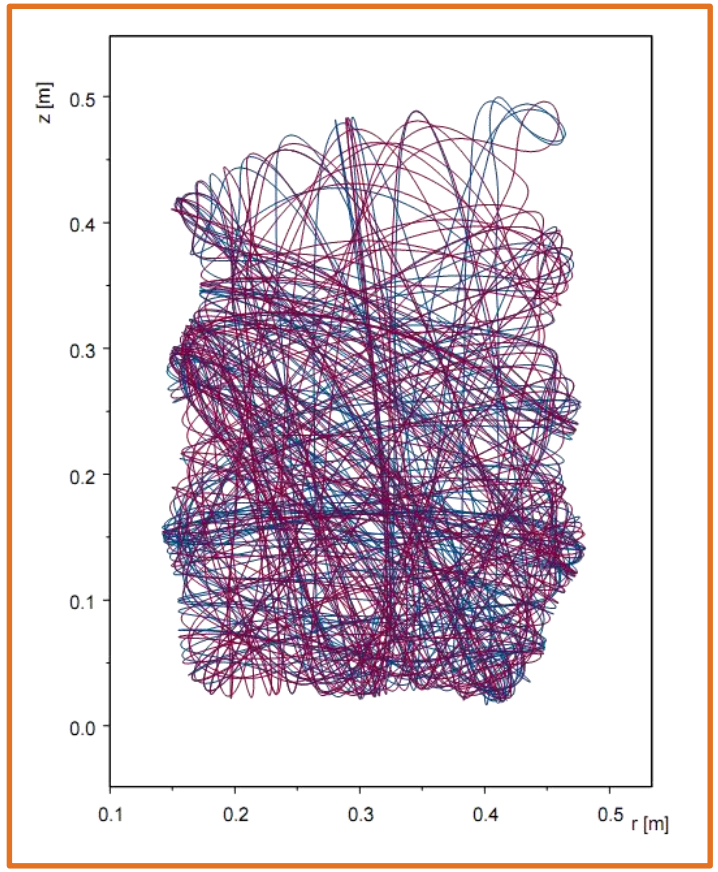


$\Delta z = 10^{-17}\mathrm{m}, t = 30\mathrm{s}$

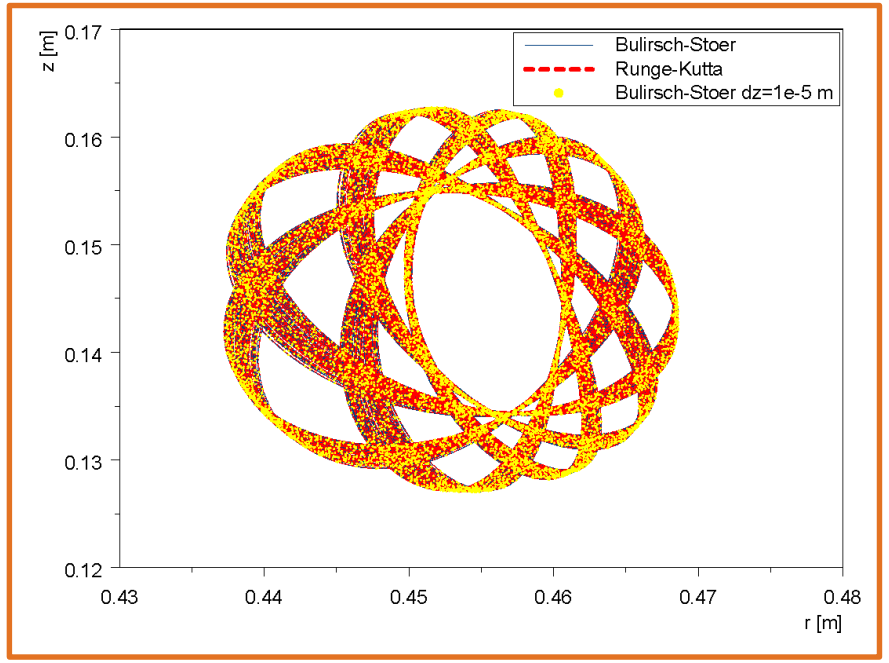
$\Delta z = 10^{-17}\mathrm{m}, t = 0.7\mathrm{s}$

Chaos in the (magnetic) house?

Instability of UCN tracks – physics or numerics?



$\Delta z = 10^{-17}\mathrm{m}, t = 30\mathrm{s}$



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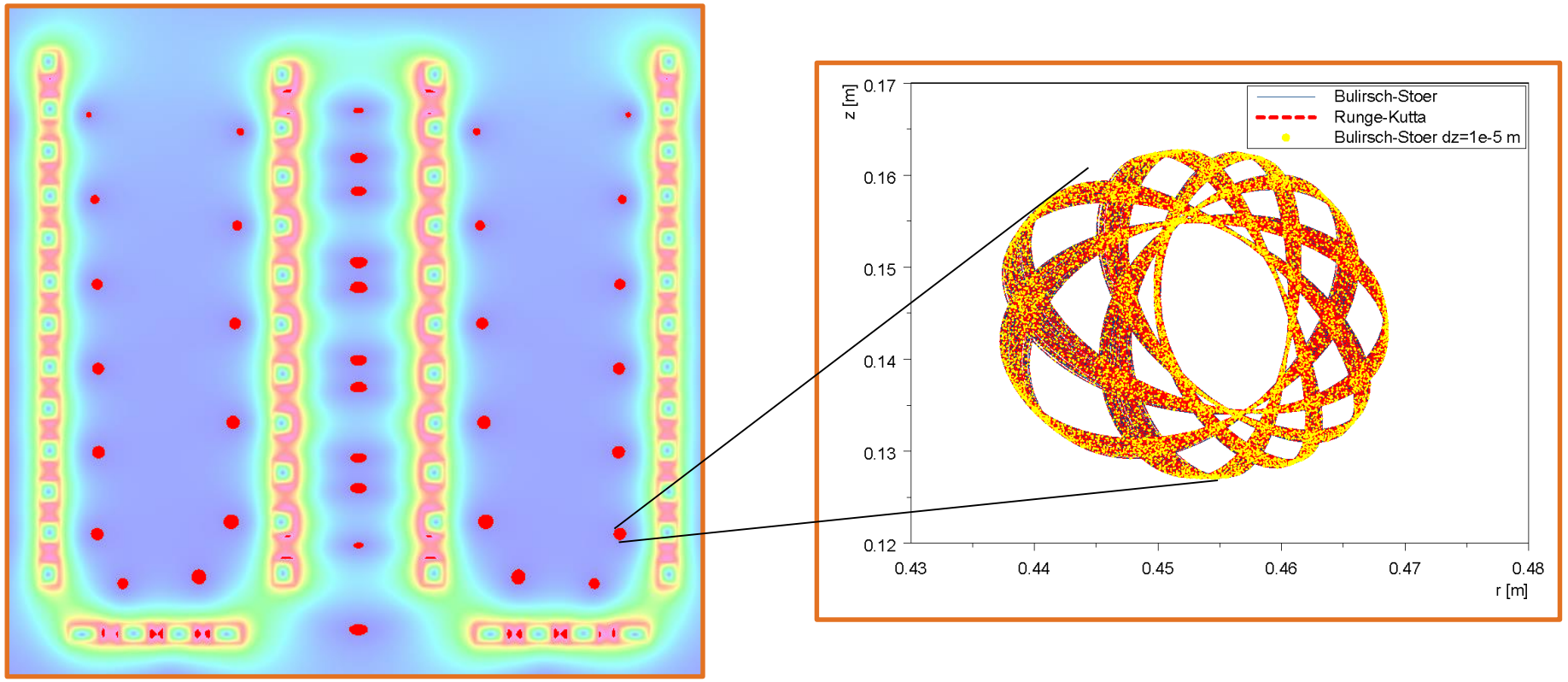


$$\Delta z = 10^{-17}\mathrm{m}, t = 30s$$

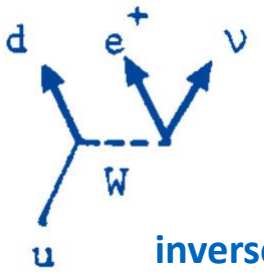
$\Rightarrow$

Reactions similar to neutron decay

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

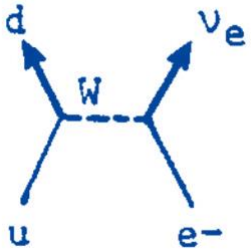
Solar astrophysics: p-p chain in the sun

$$p + p \rightarrow {}^2D + e^+ + \upsilon_e$$

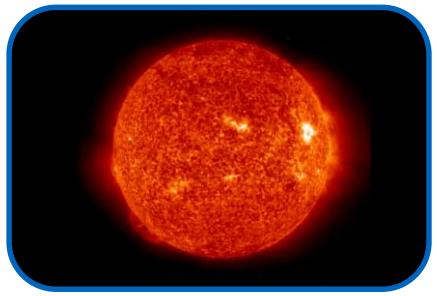


inverse n decay

$$p + e^- + p \rightarrow {}^2D + \upsilon_e$$



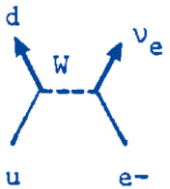
electron capture



$\Rightarrow$ long life of stars

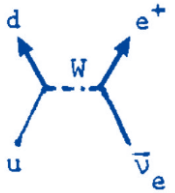
neutron star formation

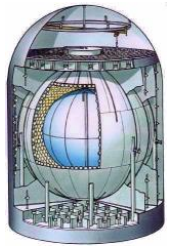
$$p + e^- \rightarrow n + \upsilon_e$$



neutrino detection

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

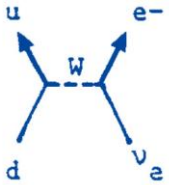


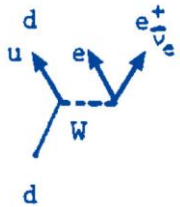


KamLAND detector

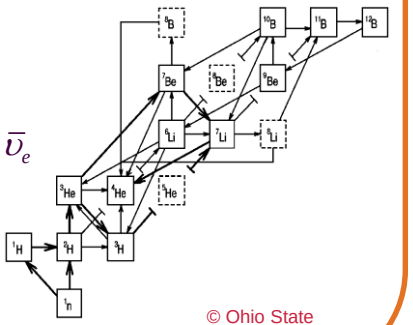
Big Bang nucleosynthesis

$$n + e^- \rightarrow p + \bar{\upsilon}_e \qquad n + \upsilon_e \rightarrow p + e^-$$





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



© Ohio State

$\Rightarrow$ ^{4}He abundance

W,Z production

$$p\bar{p} \rightarrow W + X \rightarrow e^- \bar{\upsilon}_e$$

$$p\bar{p} \rightarrow Z + X \rightarrow \upsilon\bar{\upsilon}, l^+ l^- \ldots$$

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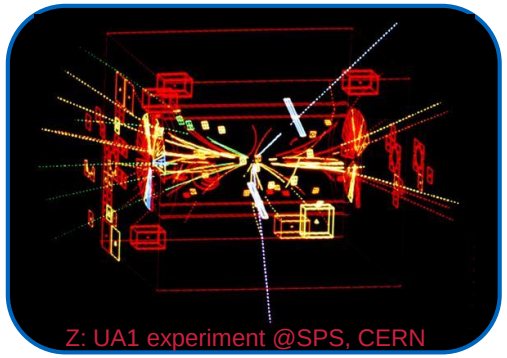


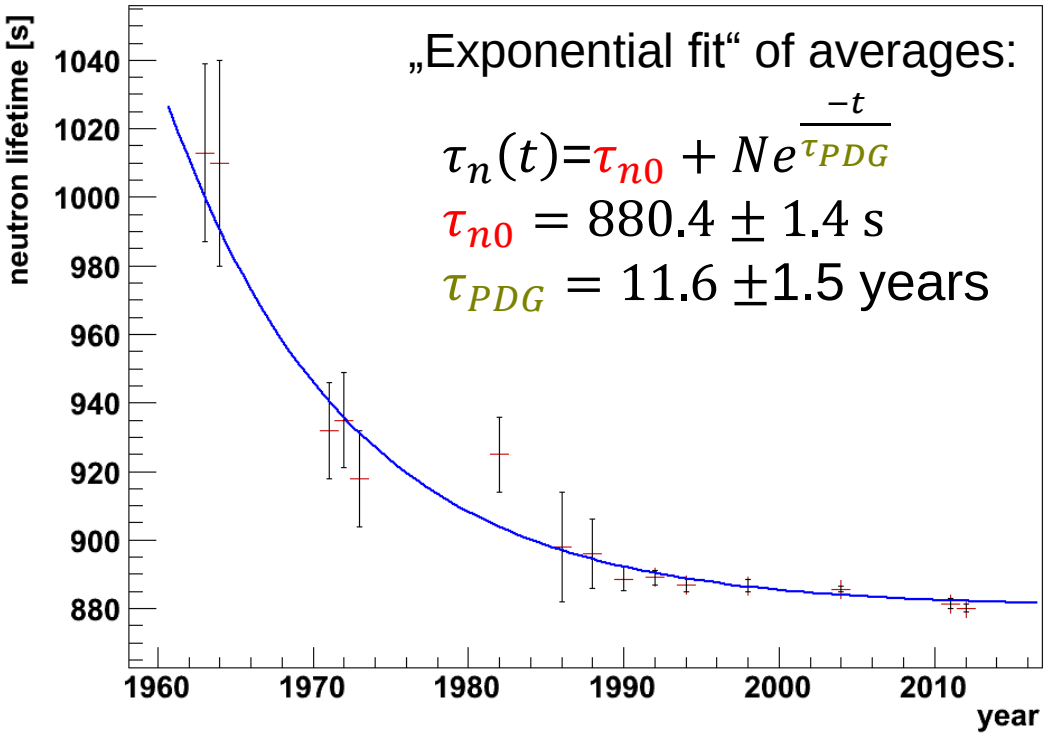
Z: UA1 experiment @SPS, CERN

Dubbers 1991
Byrne 2005

Neutron lifetime experiment

- 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 50 years

⇒ **PENeLOPE**
(**P**recision **E**xperiment on the **N**eutron **L**ifetime **O**perating with **P**roton **E**xtraction)
- Combination of **magnetic storage of ultra-cold neutrons** and in-situ **proton detection**



History of PDG averages of the neutron lifetime