The next phase of the search for a neutron electric dipole moment at the Paul Scherrer Institute

-

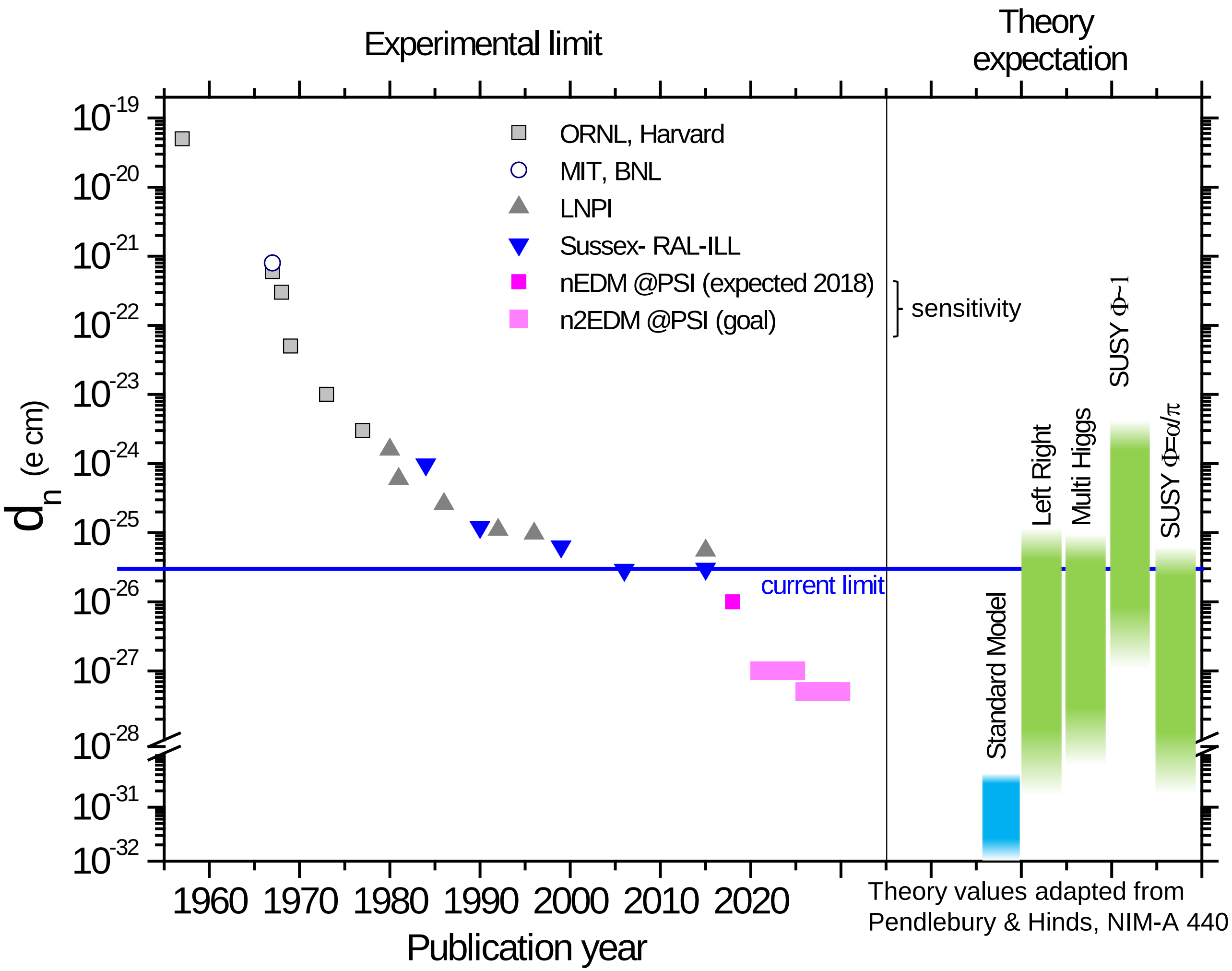
Status of n2EDM

Bernhard Lauss
Paul Scherrer Institute

on behalf of the nEDM collaboration

Oct. 16, 2017

Sensitivity goals for the neutron electric dipole search at PSI



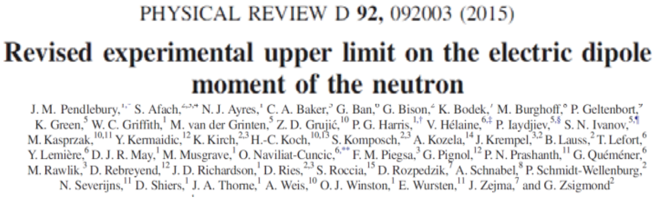
Theory values adapted from
Pendlebury & Hinds, NIM-A 440 (2000) 471

1 - data collected - present analysis (talk by Philipp Schmidt-Wellenburg)

2 - n2EDM apparatus - baseline design - sensitivity goal

3 - n2EDM apparatus - final sensitivity goal

current limit: Baker et al., PRL 2006 revised in


PHYSICAL REVIEW D **92,** 092003 (2015)

Revised experimental upper limit on the electric dipole moment of the neutron

J. M. Pendlebury,[1,*] S. Afach,[2,3,4] N. J. Ayres,[1] C. A. Baker,[5] G. Ban,[6] G. Bison,[2] K. Bodek,[7] M. Burghoff,[8] P. Geltenbort,[9] K. Green,[5] W. C. Griffith,[1] M. van der Grinten,[5] Z. D. Grujić,[10] P. G. Harris,[1,†] V. Hélaine,[6,‡] P. Iaydjiev,[5,§] S. N. Ivanov,[5,¶] M. Kasprzak,[10,11] Y. Kermaidic,[12] K. Kirch,[2,3] H.-C. Koch,[10,13] S. Komposch,[2,3] A. Kozela,[14] J. Krempel,[3,2] B. Lauss,[2] T. Lefort,[6] Y. Lemière,[6] D. J. R. May,[1] M. Musgrave,[1] O. Naviliat-Cuncic,[6,**] F. M. Piegsa,[3] G. Pignol,[12] P. N. Prashanth,[11] G. Quéméner,[6] M. Rawlik,[3] D. Rebreyend,[12] J. D. Richardson,[1] D. Ries,[2,3] S. Roccia,[15] D. Rozpedzik,[7] A. Schnabel,[8] P. Schmidt-Wellenburg,[2] N. Severijns,[11] D. Shiers,[1] J. A. Thorne,[1] A. Weis,[10] O. J. Winston,[1] E. Wursten,[11] J. Zejma,[7] and G. Zsigmond[2]

recent review


lanl.arXiv.org > hep-ex > arXiv:1607.06609

High Energy Physics - Experiment

The quest to find an electric dipole moment of the neutron

P. Schmidt-Wellenburg

What's necessary for conducting a successful nEDM experiment

- reliably working accelerator (or reactor)

&

What's necessary for conducting a successful nEDM experiment

- reliably working accelerator (or reactor)

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- reliably working UCN source

&

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What's necessary for conducting a successful nEDM experiment

- reliably working accelerator (or reactor)

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- reliably working UCN source

&

- reliably working experiment apparatus

&

- dedicated collaboration

outline of this talk


2017 meeting - Bern

The nedm collaboration at PSI

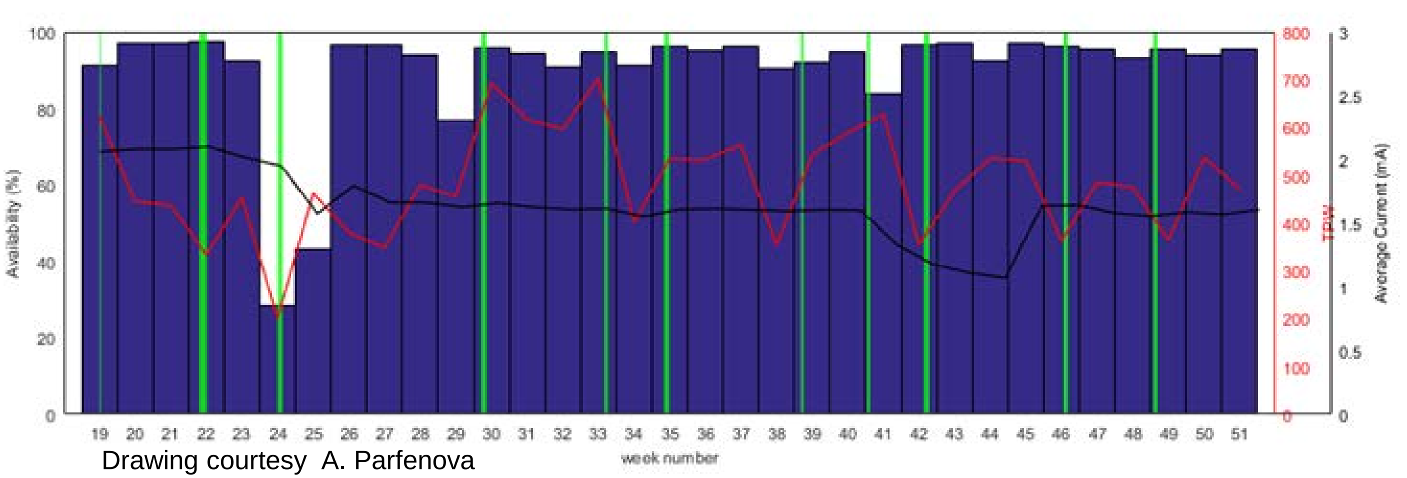
M. Burghoff, A. Schnabel	*Physikalisch Technische Bundesanstalt, **Berlin***
E. Chanel, F. Piegsa	*Universität Bern, **Bern***
C. Abel, N. Ayres, C.W. Griffith, P. Harris, J. Thorne	*University of Sussex, **Brighton***
G. Ban , P. Flaux, T. Lefort, Y. Lemiere, O. Naviliat-Cuncic	*Laboratoire de Physique Corpusculaire, **Caen***
K. Bodek, D. Rozpedzik, J. Zejma	*Institute of Physics, Jagiellonian University, **Cracow***
A. Kozela	*Henryk Niedwodniczanski Inst. Of Nucl. Physics, **Cracow***
Z. Grujic, A. Weis	*Département de physique, Université de Fribourg, **Fribourg***
L. Ferraris, G. Pignol, A. Leredde, D. Rebreyend	*Laboratoire de Physique Subatomique et de Cosmologie, **Grenoble***
V. Bondar, P. Koss, N. Severijns, E. Wursten	*Katholieke Universiteit, **Leuven***
C. Crawford	*University of Kentucky, **Lexington***
W. Heil	*Inst. für Physik, Johannes-Gutenberg-Universität, **Mainz***
D. Ries	*Inst. für Kernchemie, Johannes-Gutenberg-Universität, **Mainz***
S. Roccia	*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, **Orsay***
G. Bison, P.-J. Chiu[2], M. Daum, N. Hild[2], B. Lauss, P. Mohan Murthy[2], D. Pais[2], P. Schmidt-Wellenburg, G. Zsigmond	*Paul Scherrer Institut, **Villigen***
S. Emmenegger, K. Kirch[1], H.C. Koch, S. Komposch, J. Krempel, M. Rawlik	*Eidgenössische Technische Hochschule, **Zürich***

also at: [1] *Paul Scherrer Institut,* [2] *Eidgenössische Technische Hochschule*

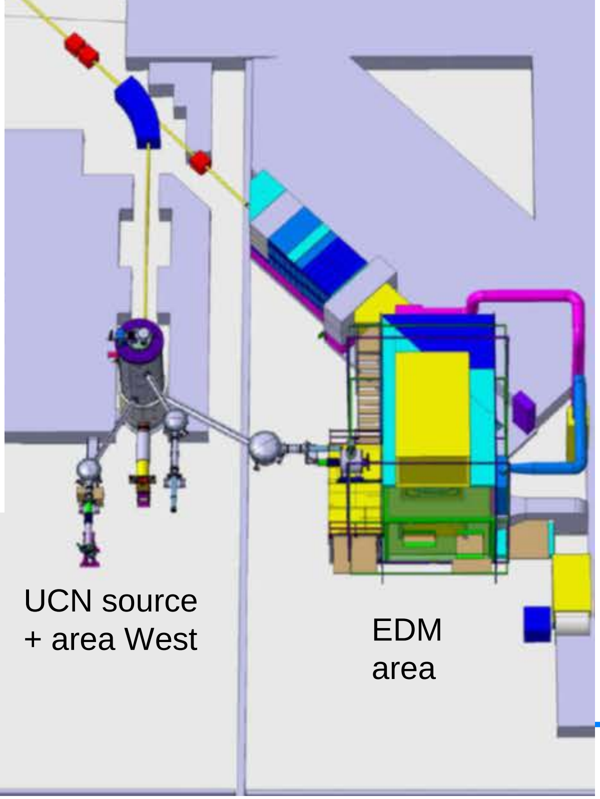
What's necessary for conducting a successful nEDM experiment

- reliably working accelerator (or reactor)

PSI's proton accelerator



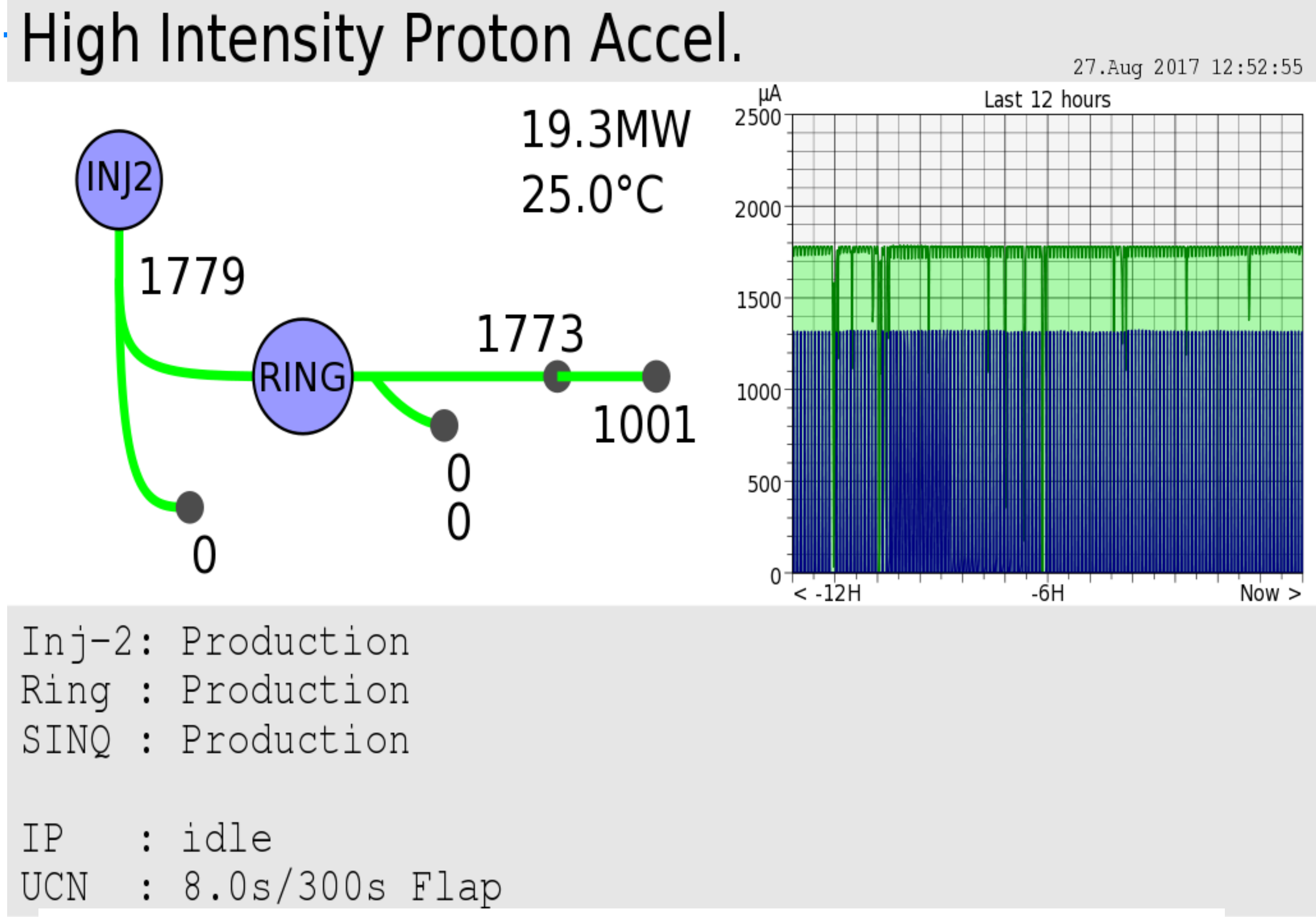
Drawing courtesy A. Parfenova



beam availability in 2016
(2015 and 2017 better)

Total user beam time	4812 h
Outages (downtime) unscheduled outages (current < 1 mA, time > 5 min.)	462 h
availability	90 %

PSI's proton accelerator



High Intensity Proton Accel.

27.Aug 2017 12:52:55

```
Inj-2: Production
Ring : Production
SINQ : Production

IP   : idle
UCN  : 8.0s/300s Flap
```

- cavity upgrades planned for 2018 and 2019

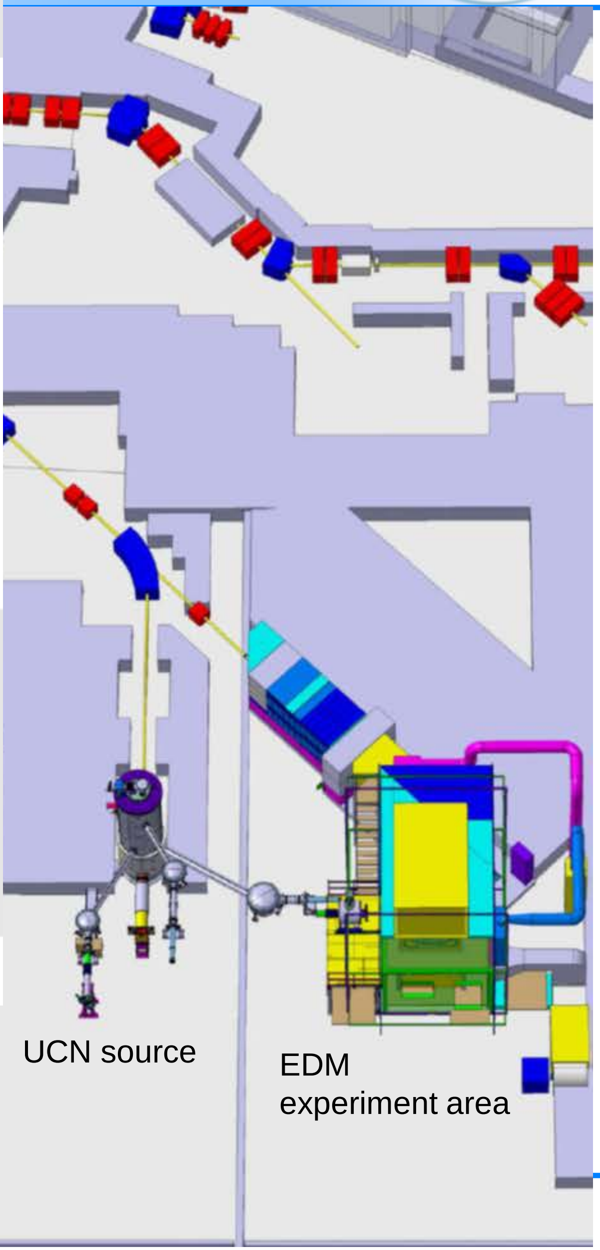
(new resonators in injector 2 / new flat tops)

- 2.4 mA operation was approved in 2016

→ 2020 continuous operation with up to 2.4 mA

+ High power upgrade to 3.0mA ?

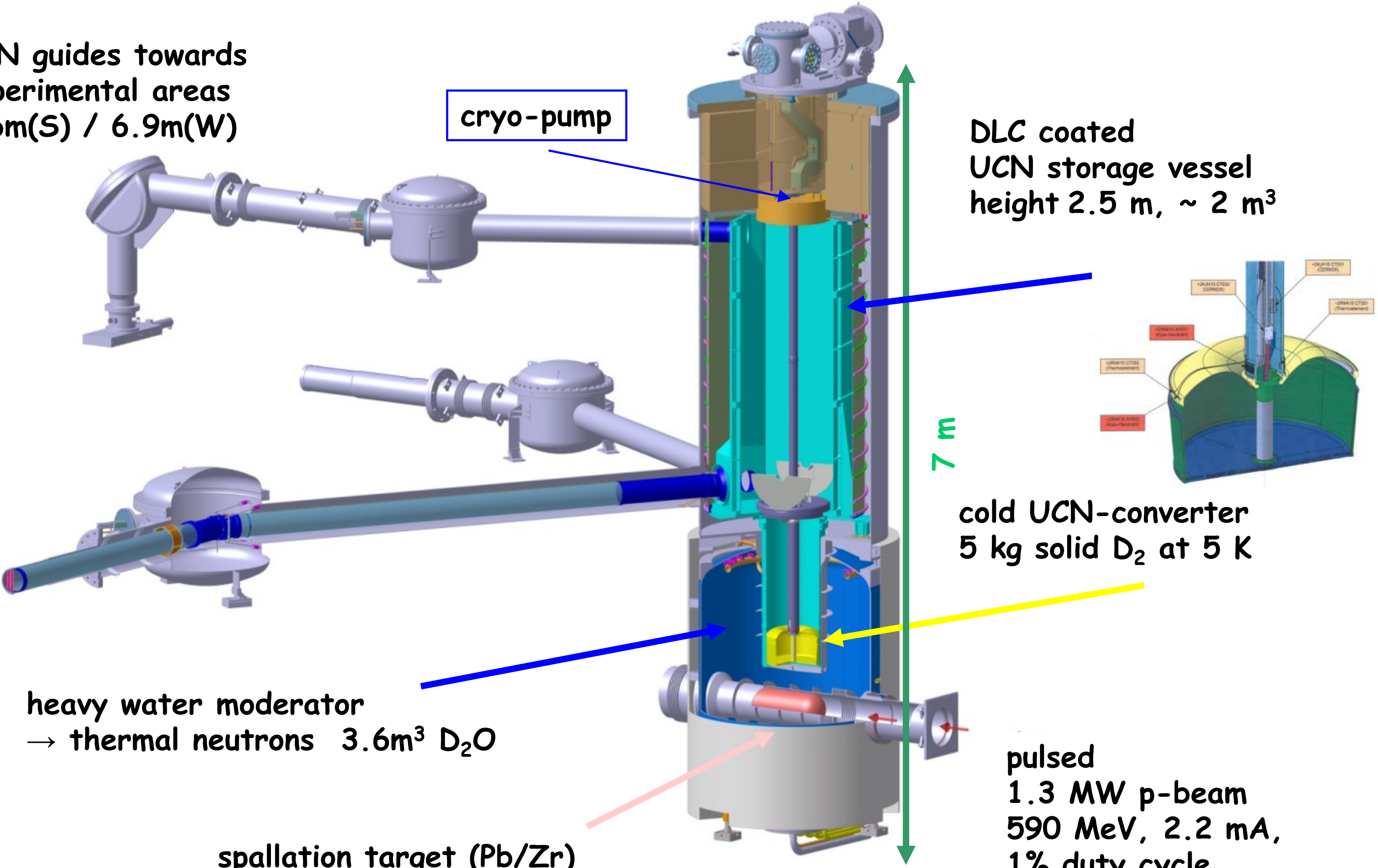
UCN rate increases linear with beam current



What's necessary for conducting a successful nEDM experiment

- reliably working UCN source

UCN Source at PSI



UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

cryo-pump

DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

cold UCN-converter
5 kg solid D_2 at 5 K

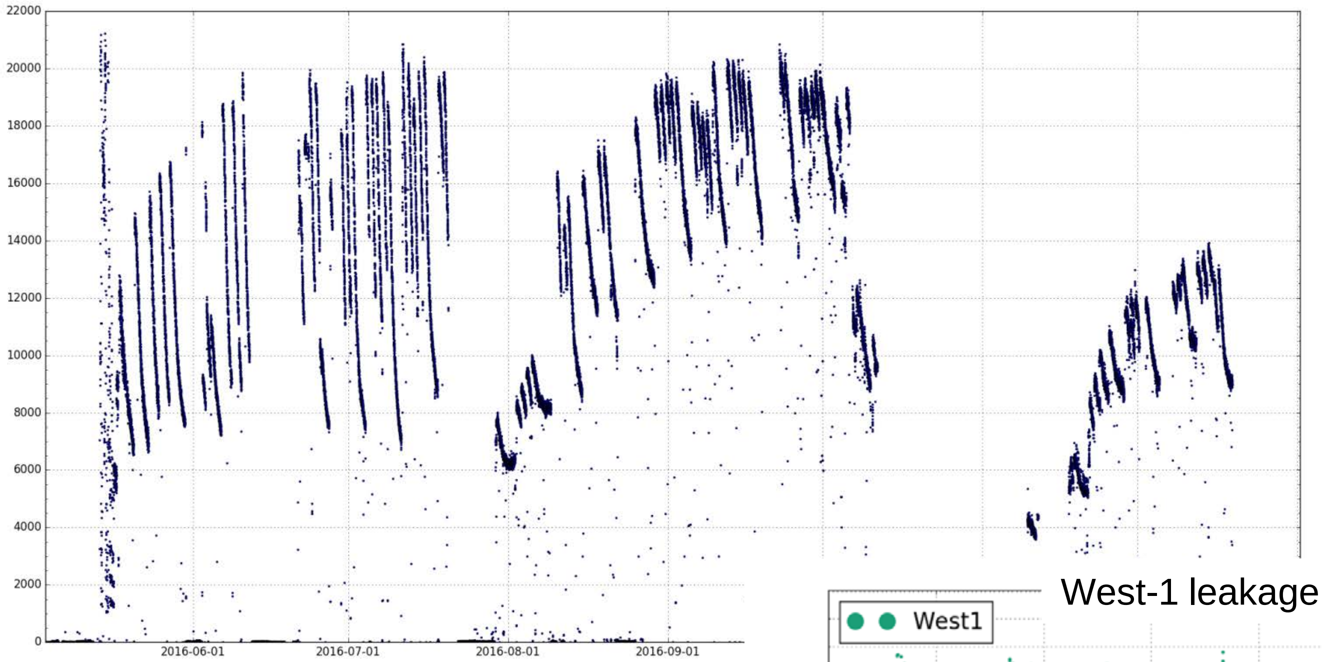
heavy water moderator
→ thermal neutrons 3.6m^3 D_2O

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

pulsed
1.3 MW p-beam
590 MeV, 2.2 mA,
1% duty cycle

UCN Source at PSI

2016: UCN source monitoring with nEDM detector



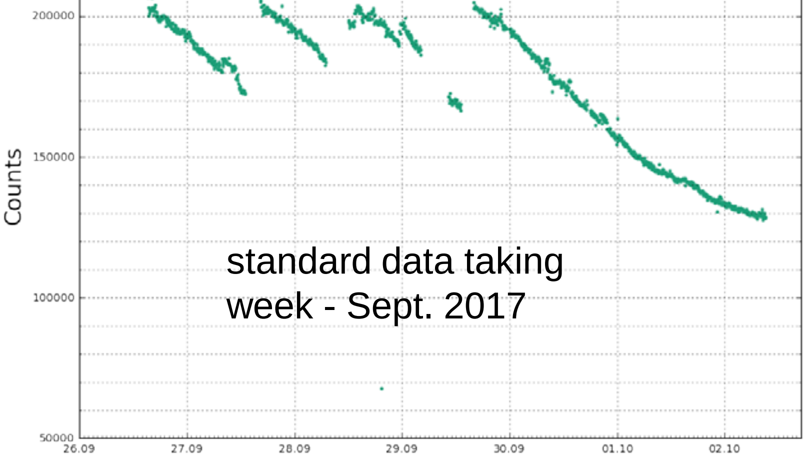
139 nEDM data taking days in 2016

2016: 2 failures of
He cooling plant

continuous source operation May-Dec (proton beam operation)

- daily "conditioning" of the solid D2 leads to
full regain of UCN output loss
+ same gain over long time

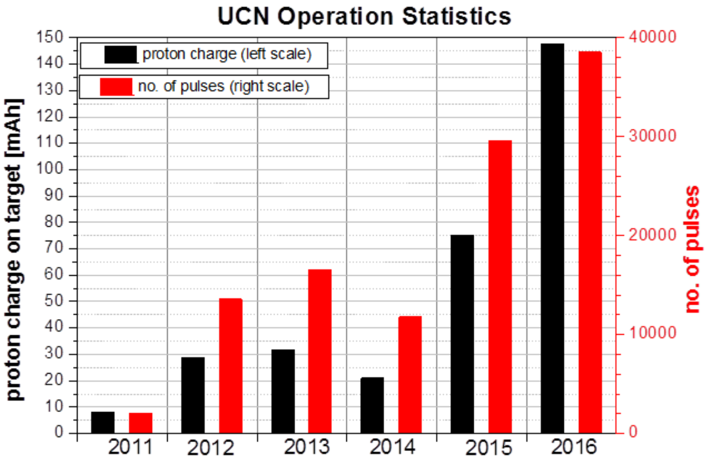
West-1 leakage measurement



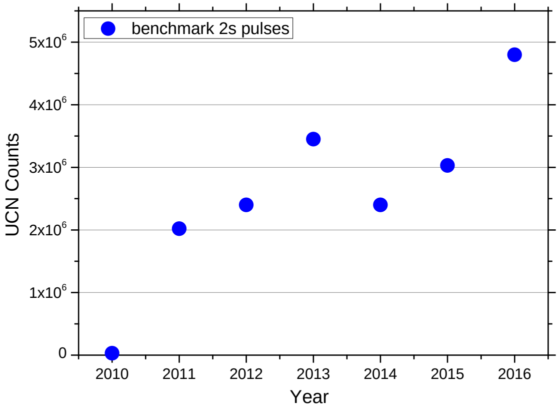
standard data taking
week - Sept. 2017

2016 operation - UCN Source at PSI

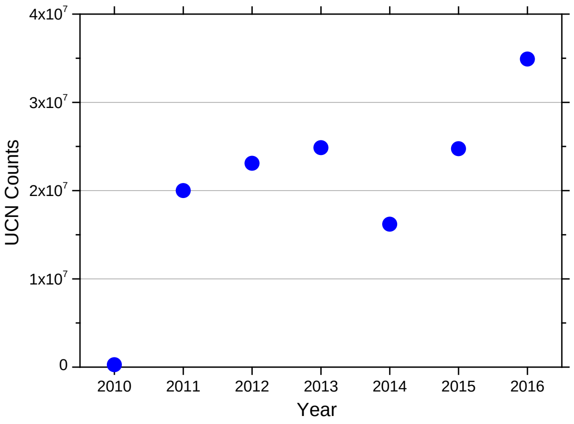
UCN



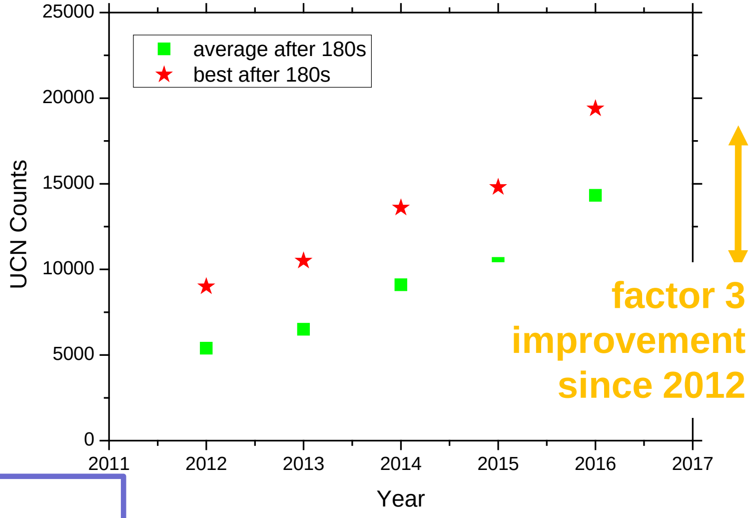
UCN
per
benchmark
pulse



beamport
max UCN
per pulse



nEDM



factor 3
improvement
since 2012

1. largest number of beam pulses and produced UCN
2. highest UCN production in a benchmark pulse
3. highest number of UCN delivered to beamport & nEDM

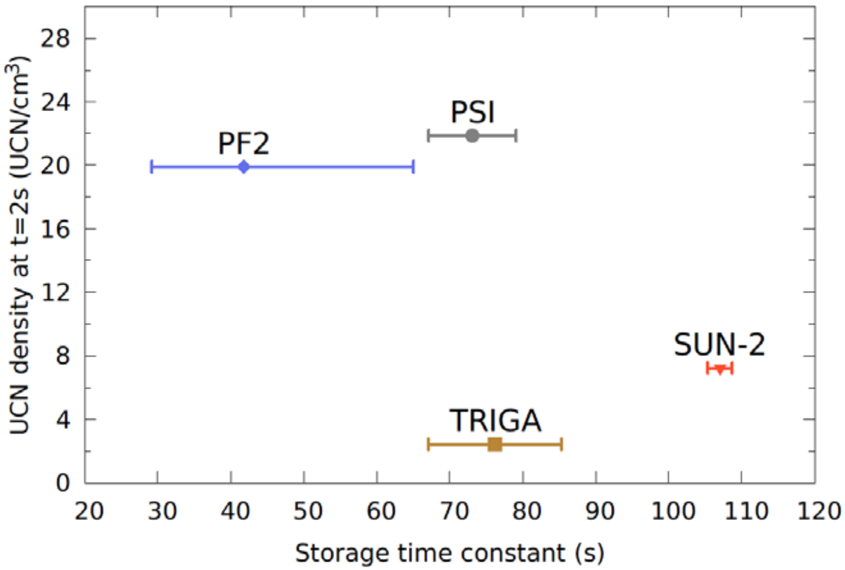
- upgrade possibilities under study

Effort to establish a standard for comparison of UCN density

PHYSICAL REVIEW C **95**, 045503 (2017)

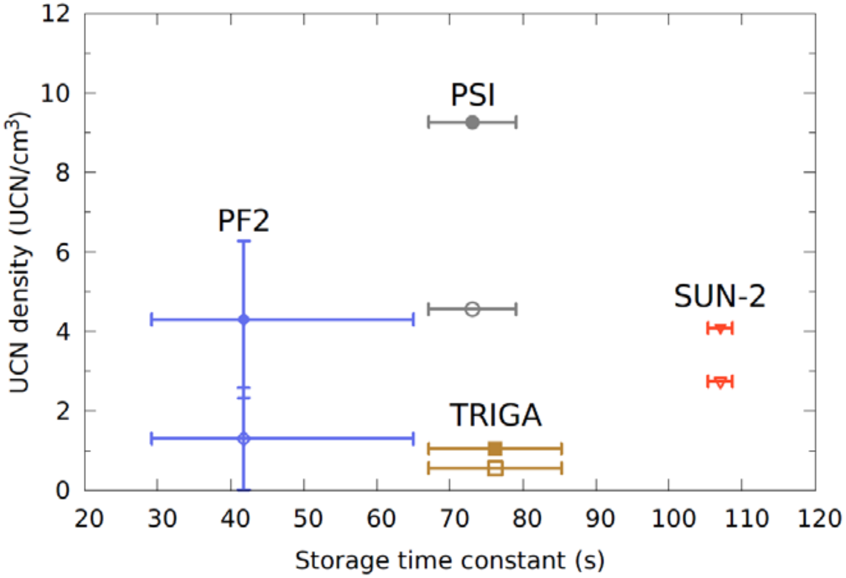
Comparison of ultracold neutron sources for fundamental physics measurements

storage times = 2s



UCN density after storage in 20l external stainless-steel bottle

storage times = 50s, 100s



published joint work of TRIGA Mainz- ILL Grenoble - PSI comparing the source preformances

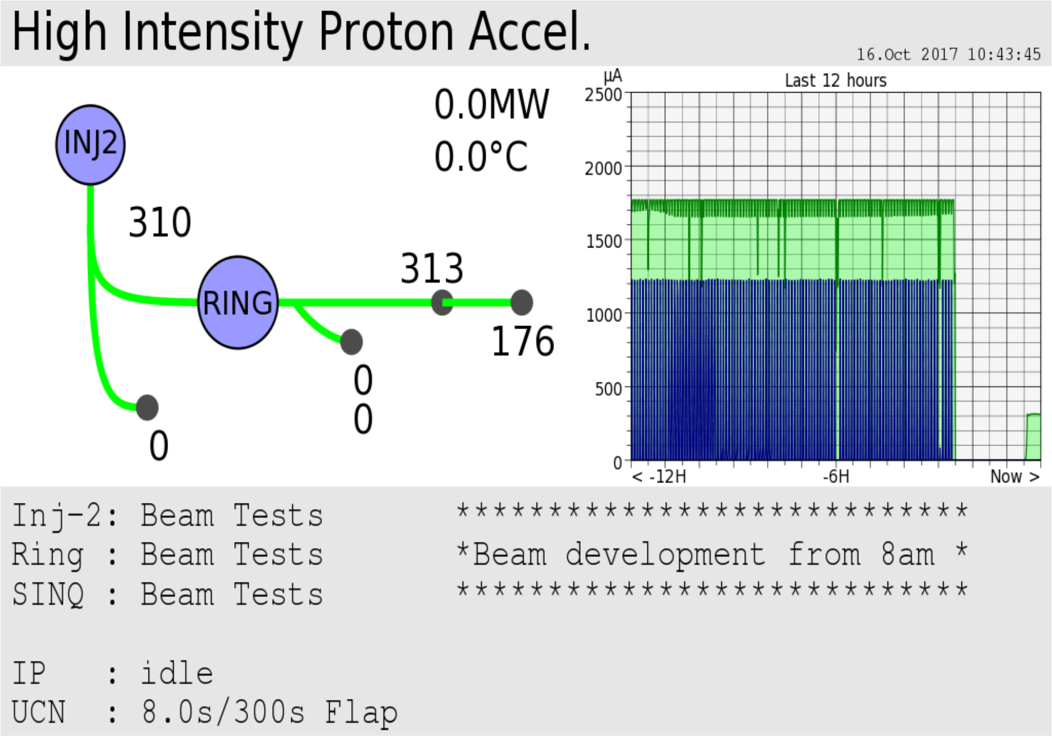
G.Bison et al., Phys.Rev.C95 (2017) 045503

Definition of "standard" method and device for UCN density measurement:
G.Bison et al., Nucl.Instrum.Meth. A 830 (2016) 449

What's necessary for conducting a successful nEDM experiment

- a new experimental apparatus

News: this morning saw the last UCN in the present nEDM apparatus



```
Inj-2: Beam Tests        ***************************
Ring : Beam Tests        *Beam development from 8am *
SINQ : Beam Tests        ***************************

IP   : idle
UCN  : 8.0s/300s Flap
```

the n2EDM construction phase starts today !

Reminder:the EDM measurement principle

Measurement of the difference of neutron precession frequencies in parallel/anti-parallel E and B fields:

$$\mu_n = 60\ \mathrm{neV/T}$$

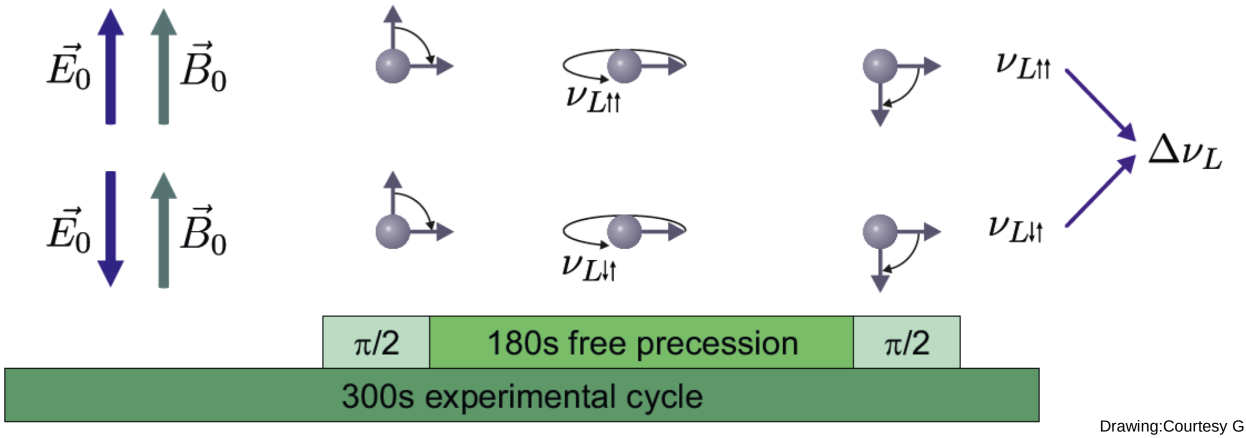
$$\vec{B} = 1\ \mu\mathrm{T}$$

$$\nu_B \approx 29\,\mathrm{Hz}$$

$$\vec{E} = 11\ \mathrm{kV/cm}$$

$$d_n < 3\times 10^{-26}\, e\ cm$$

$$\nu_E < 160\,\mathrm{nHz}$$



Drawing:Courtesy G.Bison

$$\nu_n = \frac{2\mu_n}{h}\left|\vec{B}\right| \pm \frac{2d_n}{h}\left|\vec{E}\right|$$

$$d_n = \frac{1}{2E}\left(h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) + \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

High-precision control and measurement of frequency and magnetic field necessary (fT level)

new apparatus - n2EDM

→ Room temperature experiment using the Ramsey method of oscillatory fields
new apparatus will be better adapted to the PSI UCN source and have several improved subsystems

$$\sigma(d_n) = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

α Visibility of resonance
T Time of free precession
N Number of neutrons
E Electric field strength

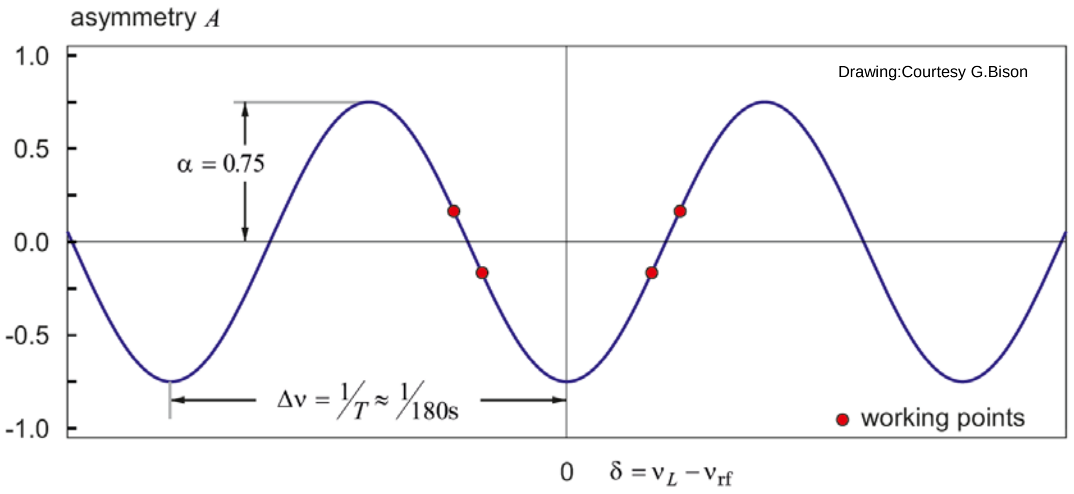
$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$A(f_{\mathrm{RF}}) = \alpha \cos\left[2\pi(T + 4t/\pi)(f_{\mathrm{RF}} - f_n)\right]$$

nEDM results are still statistically limited

→

design the apparatus to maximize the number of stored UCN with adequate systematics improvement !



Drawing:Courtesy G.Bison

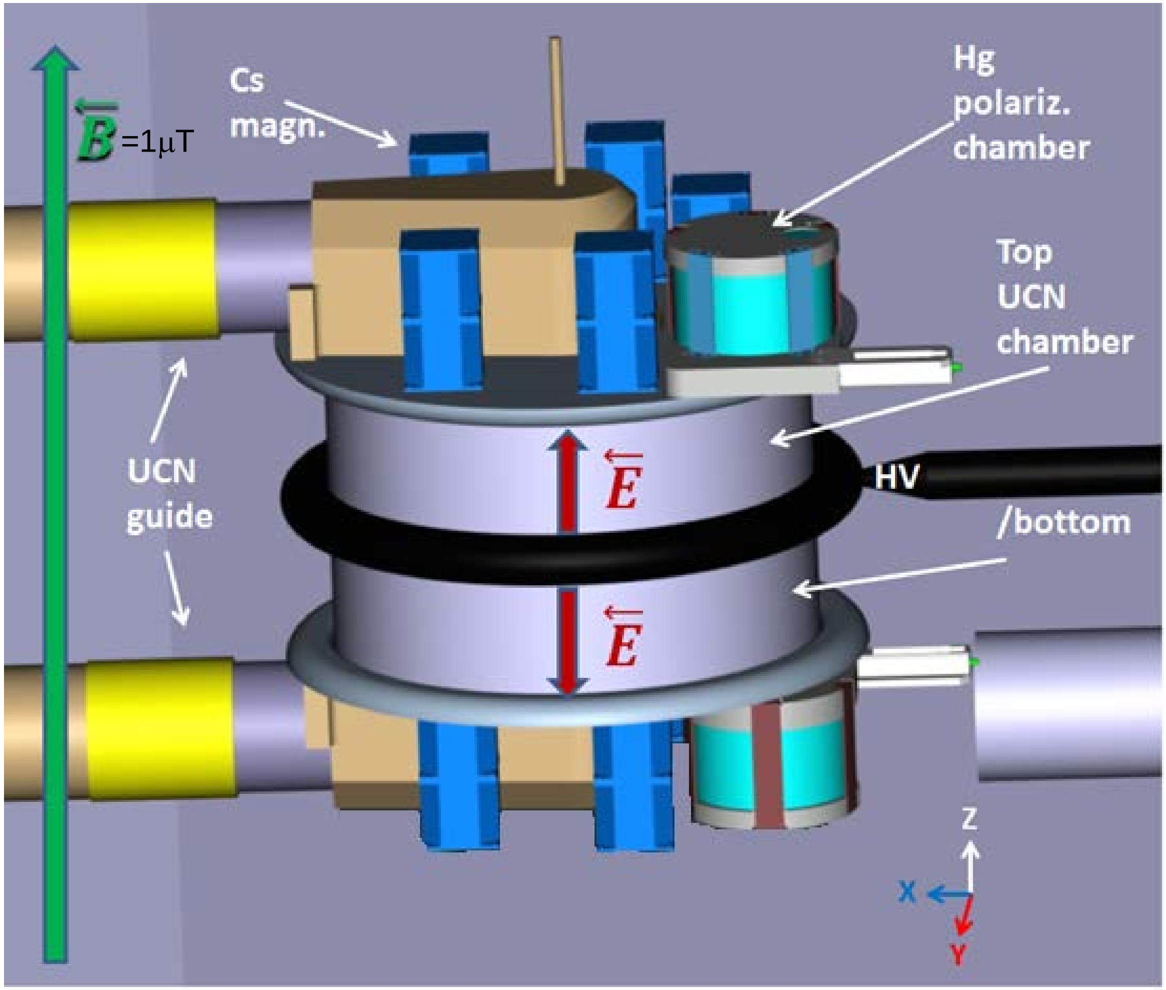
New apparatus - n2EDM Design-Strategy

Maximize UCN statistics with adequate adaption of systematics.
Goal: Construct a baseline apparatus ready in 2020 and upgrade from there.

Main features of the new apparatus:

- **A large volume horizontally-positioned double precession chamber for UCN**
- **Laser-based Hg co-magnetometer**
- **Arrays of high performance Cs magnetometers**
- **^{3}He magnetometer for B-field calibration**
- **Large magnetically shielded room to provide a large shielded volume for the experiment**
- **Large field coils to improve field homogeneity and allow for a sizeable vacuum vessel**
- **High efficiency spin-sensitive UCN detection system**

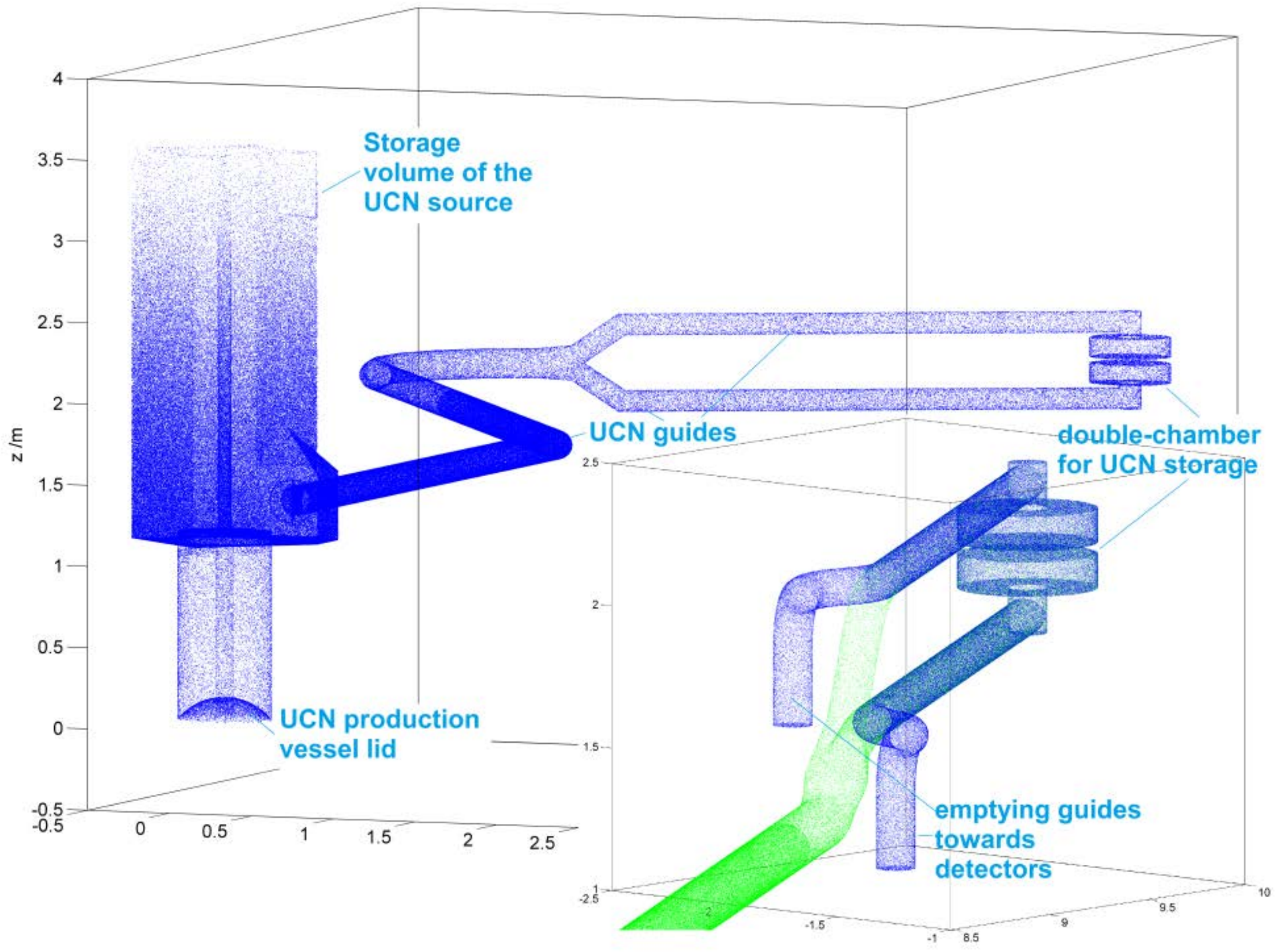
Main features of the new apparatus - core setup



Inspired by the pioneering Gatchina double-chamber setup **I.Altarev et al. JETP Lett.44(1986)460** and several years of our **own upgrade and operating experience** with the present nEDM setup

- 2 neutron precession chambers
- Hg co-magnetometer in both chambers with laser read out
- Baseline scenario: UCN chamber with materials and coatings as present chamber, but larger diameter of storage volume - upgrades in development
- Surrounded by calibrated Cs arrays on ground potential (>50 sensors)
- large NiMo (^{58}NiMo) coated UCN guides

Important design aid: Full simulation of the PSI UCN source and n2EDM setup



Full detailed model benchmarked with previous measurements at the UCN source and with the present nEDM setup. MC used to optimize UCN geometry:

- guides
- chamber
- position
- height

talk by Geza Zsigmond on MCUCN packag

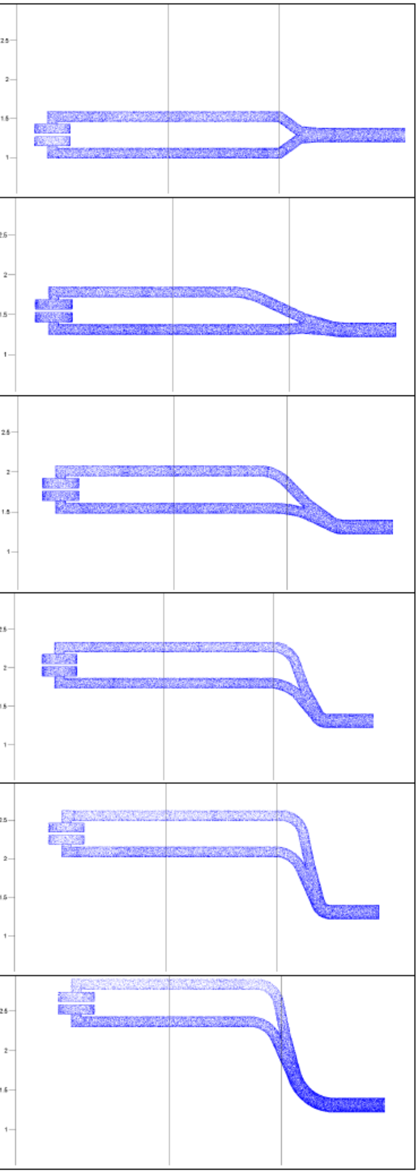
lanl.arXiv.org > physics > arXiv:1709.05974

Physics > Instrumentation and Detectors

The MCUCN simulation code for ultracold neutron physics

G. Zsigmond

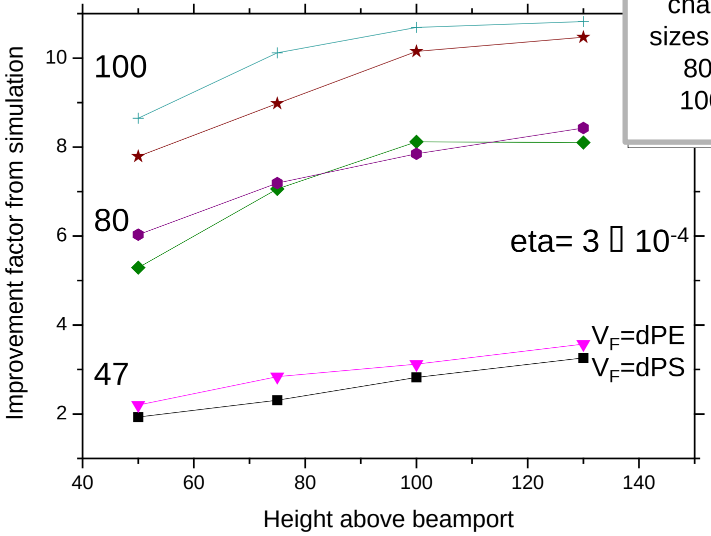
Example: height positioning of UCN chamber



- minimize necessary bends in UCN guides
- optimize chamber position (severe implications for hardware)
- optimize height, chamber size and coating for storable UCN statistics and mechanical feasibility

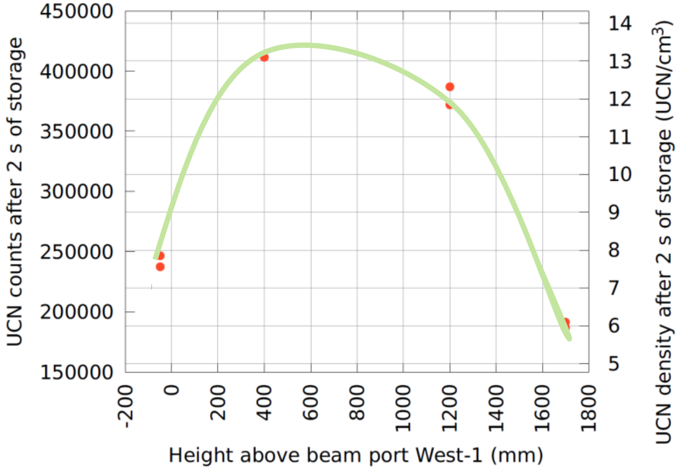
Neutron statistics improvement

Simulation (n2EDM)



chamber sizes 47cm, 80cm, 100cm

Measurement (standard bottle)



Simulation results:

present nEDM chamber as benchmark, selected n2EDM chambers and positions, calculated using the average UCN source performance in 2016

(e.g. 139 nEDM data taking days in 2016)

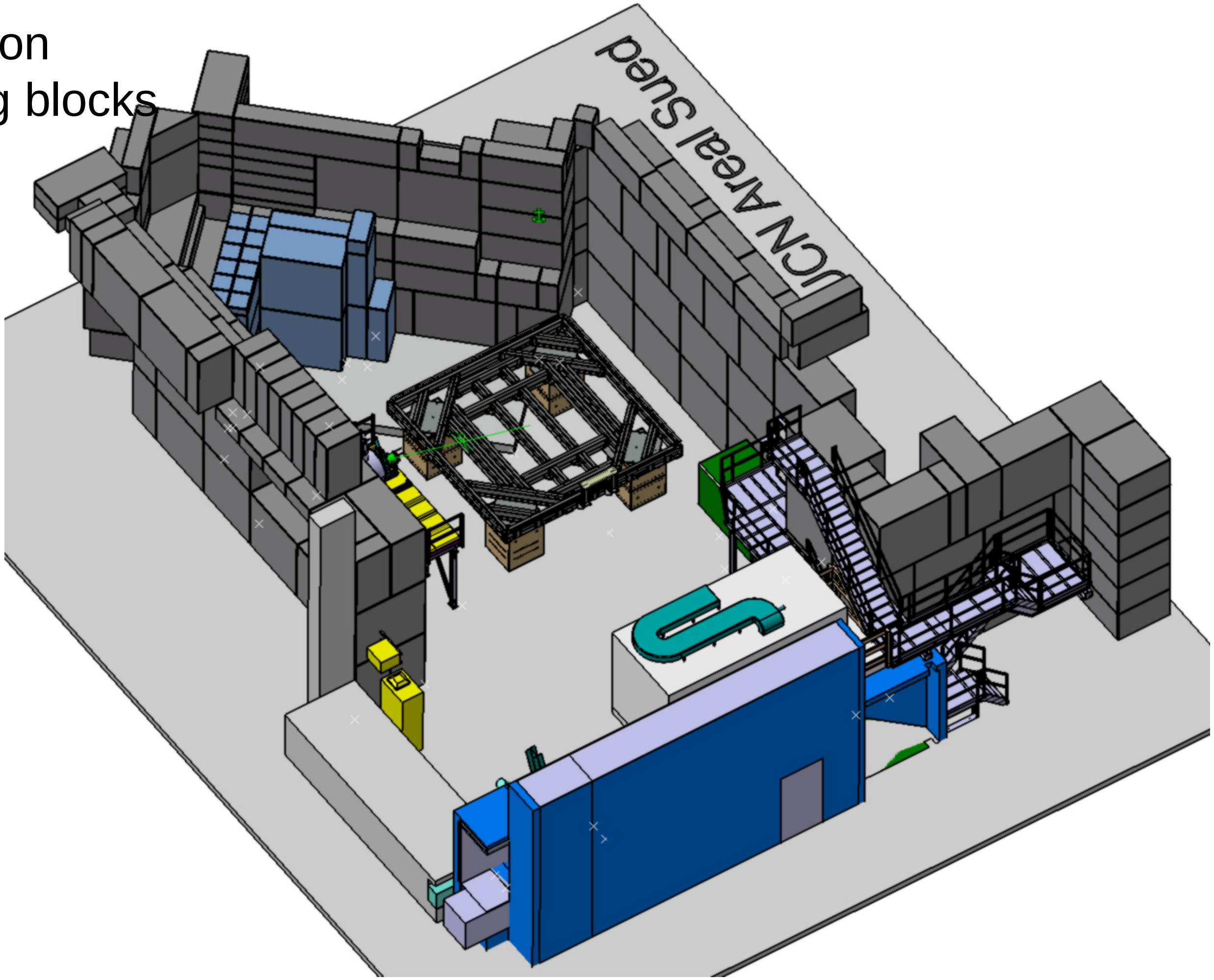
	Current	n2EDM	n2EDM	n2EDM	n2EDM	n2EDM	n2EDM
phase	2016 average	comm.	comm.	meas.	meas.	meas.	meas.
ID (cm)	47	47	47	80	80	100	100
coating	dPS	dPS	iC	dPS	iC	dPS	iC
α	0.75	0.8	0.8	0.8	0.8	0.8	0.8
E (kV/cm)	11	15	15	15	15	15	15
T (s)	180	180	180	180	180	180	180
N	15′000	50′000	100′300	121′000	292′000	160′000	400′000
$\sigma(d_n)$ (e·cm) per day	11×10^{-26}	4.1×10^{-26}	2.8×10^{-26}	2.6×10^{-26}	1.7×10^{-26}	2.3×10^{-26}	1.4×10^{-26}
$\sigma(d_n)$ (e·cm) 500 data days	5.0×10^{-27}	1.8×10^{-27}	1.3×10^{-27}	1.2×10^{-27}	7.5×10^{-28}	1.0×10^{-27}	6.4×10^{-28}

different chamber sizes , improved coatings (presently investigating different options)
E = 180 kV (no HV magnetometer)
α ~ 0.85 (depolarization by bouncins and B gradient)

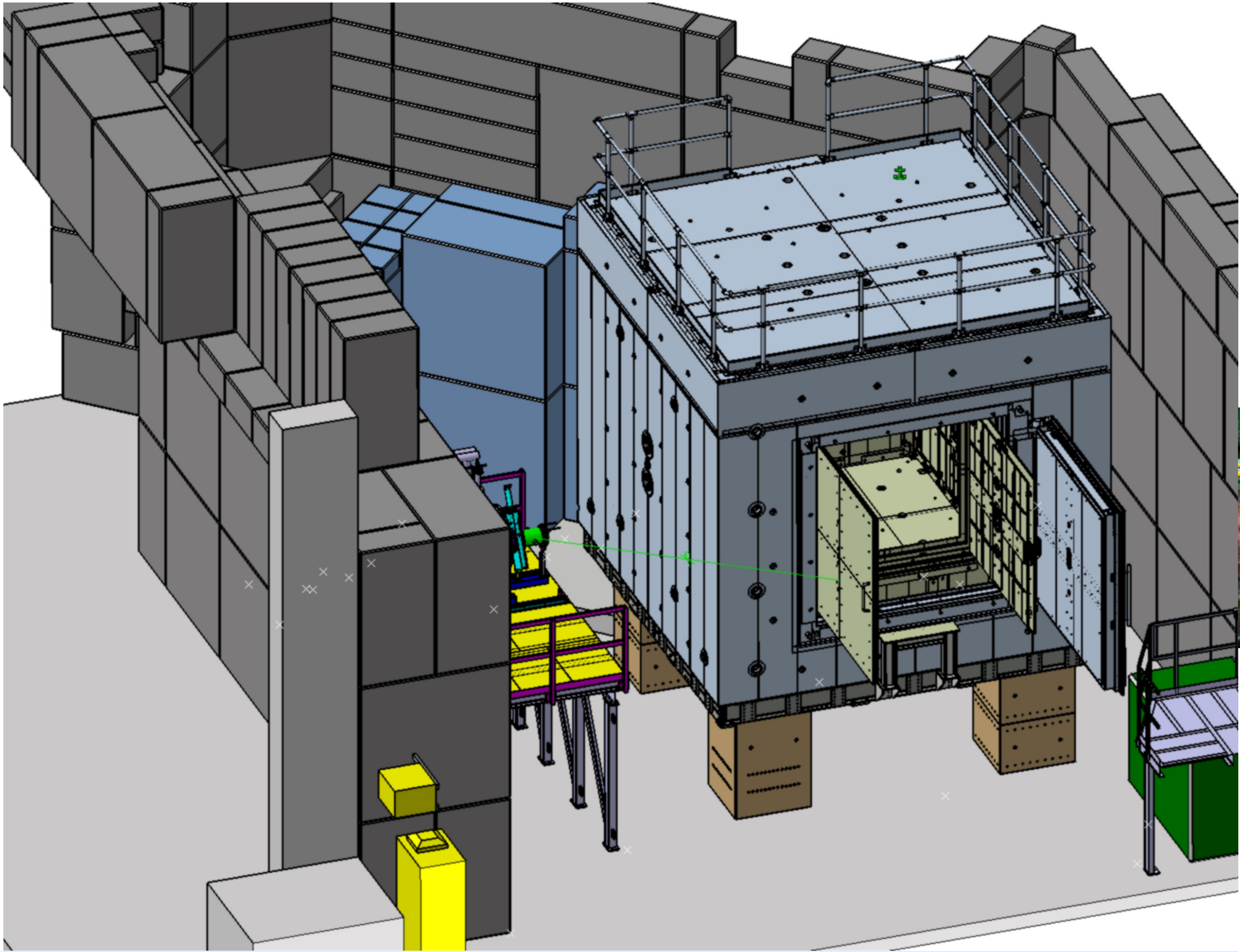
Prepare experiment area

- remove present installation
- change parts of shielding blocks
- new base foundation

- setup platform
under construction

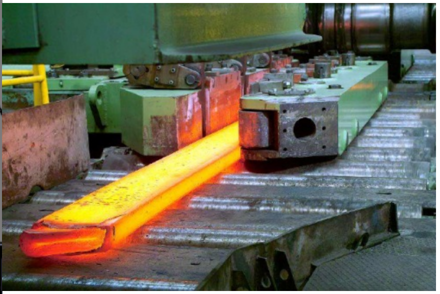


New magnetically shielded room - MSR



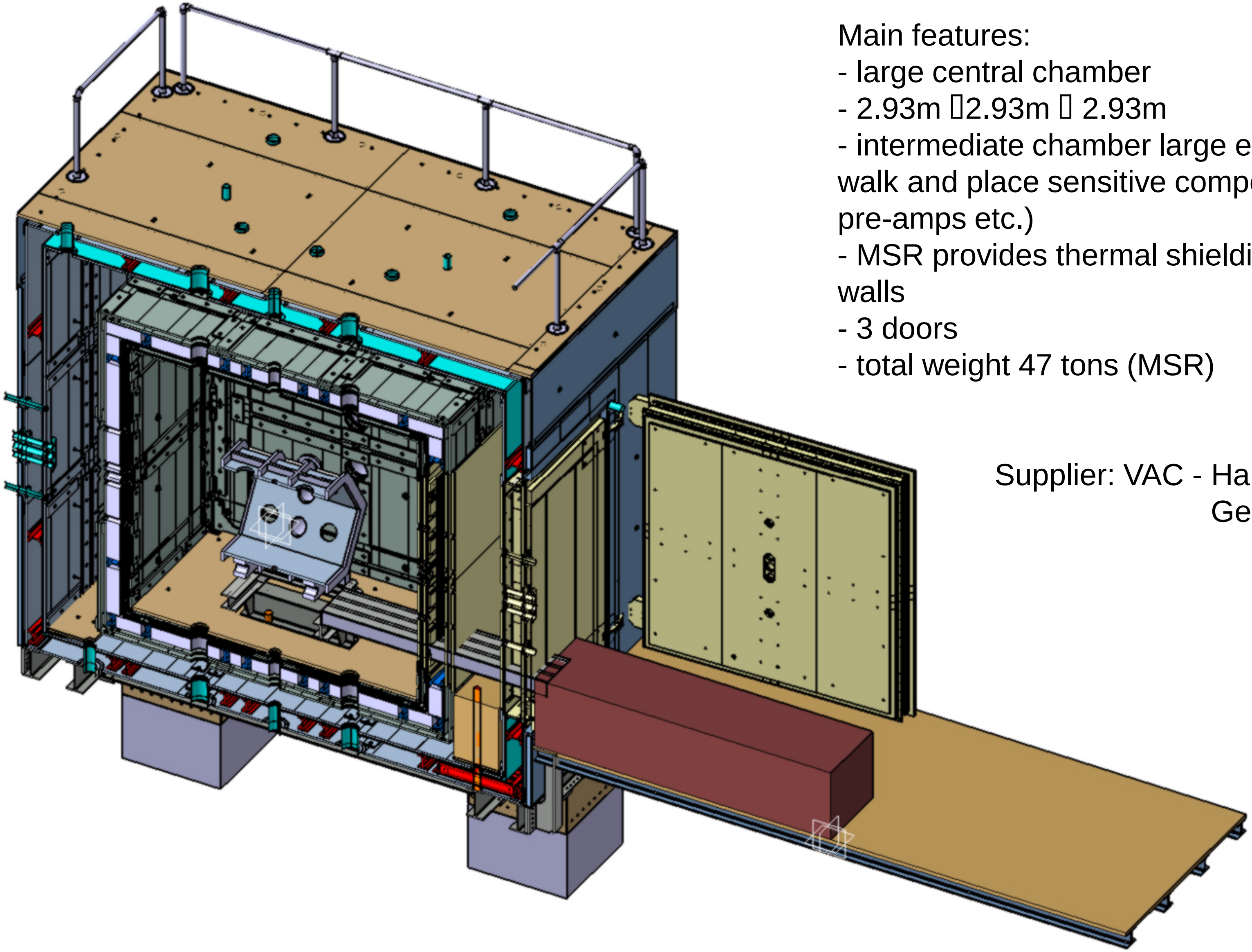
~17 tons of selected mu-metal sheets

- ore melted and material selected at VAC production facility



- several sheets of mu-metal glued together into installation panels

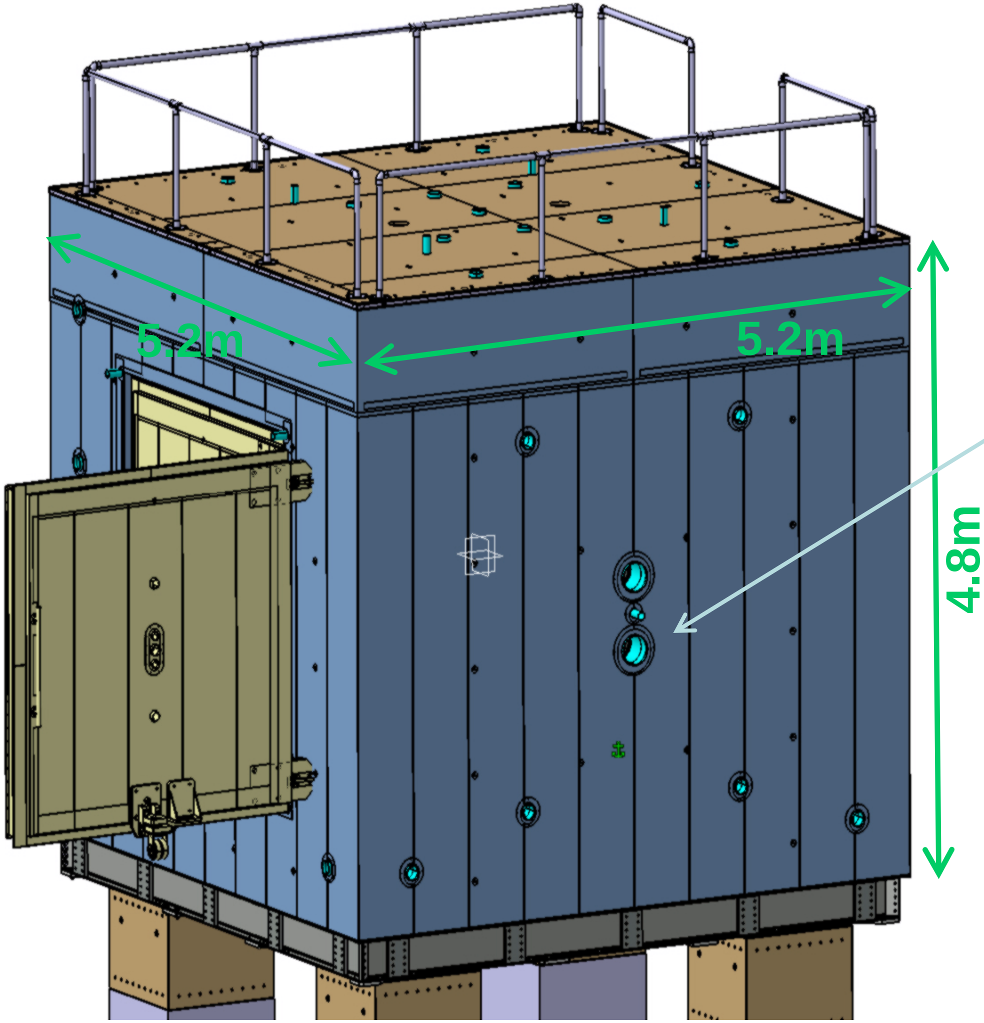
MSR



Main features:
- large central chamber
- 2.93m 2.93m 2.93m
- intermediate chamber large enough to walk and place sensitive components (e.g. pre-amps etc.)
- MSR provides thermal shielding in both walls
- 3 doors
- total weight 47 tons (MSR)

Supplier: VAC - Hanau,
Germany

MSR



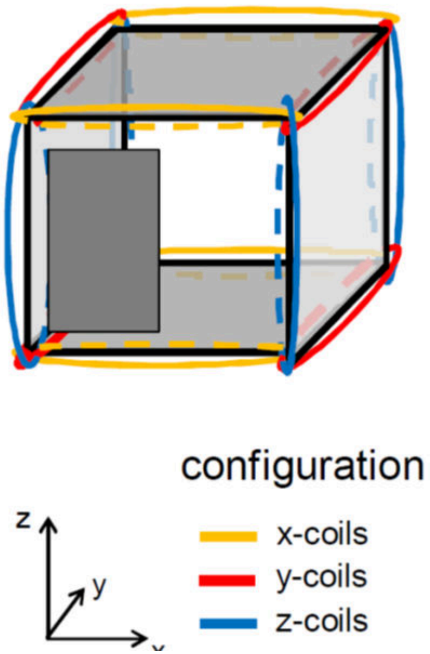
setup features:
- (2 + 4) layers mu-metal
- Al eddy current shield
- 78 openings for experiment use
- largest openings Φ=220mm
for 2 UCN guides
for 2 main pumping ports

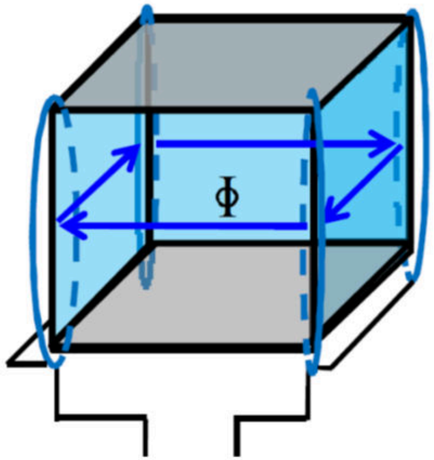
expected performance:
- quasistatic shielding factor guaranteed >70'000 (expected >100'000)
- central B-field < 0.5nT
- central gradient < 0.3 nT/m

Installation scheduled to start in Feb.2018

Important: minimizing the magnetic field

Degaussing scheme and coils layout based on PTB-Berlin experience (A. Schnabel) published in J.Voigt et al. Metrol.Meas.Sys. 20,2 (2013) 239

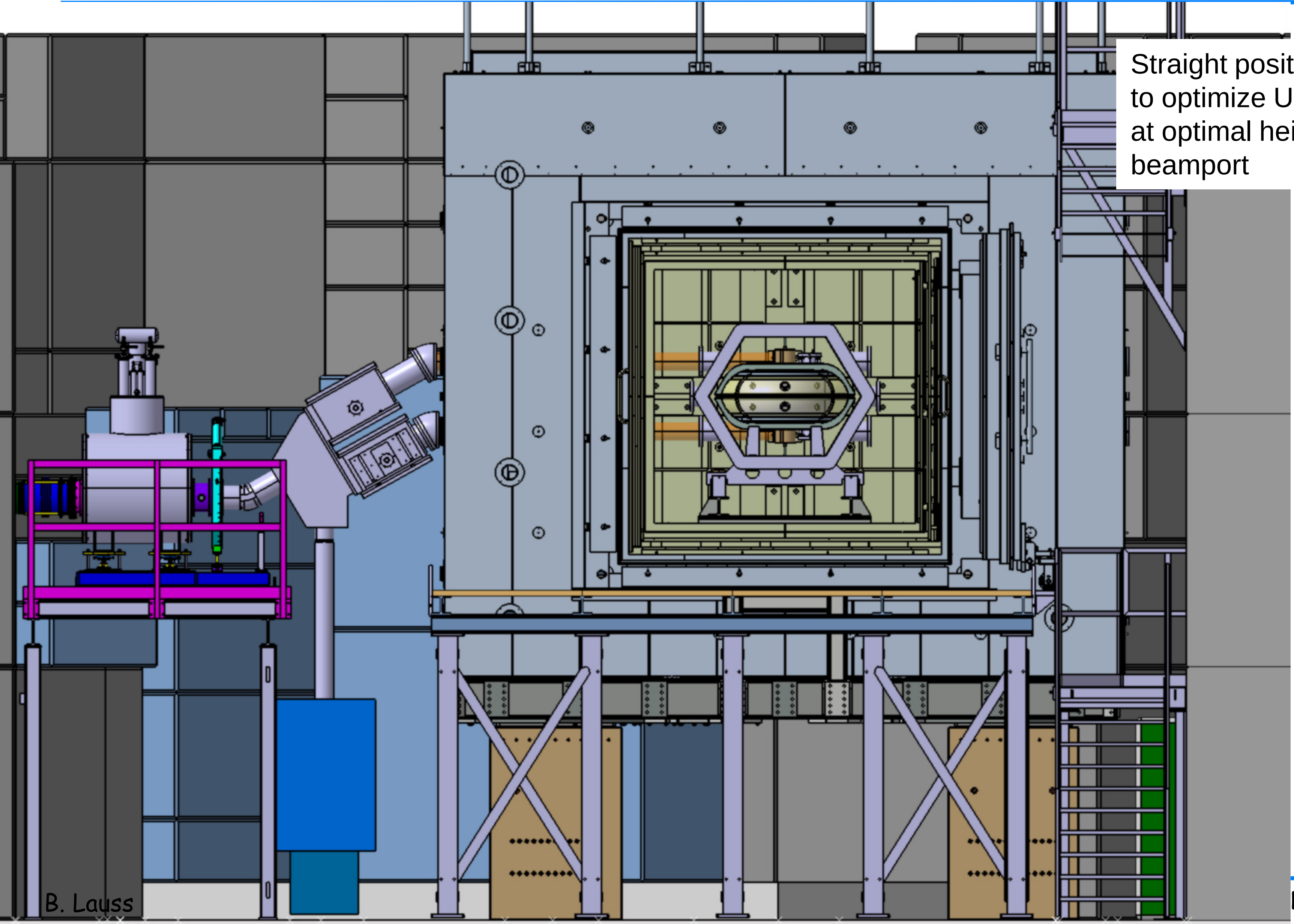




planned minimization from outside to inside for each layer and direction possible

- innermost room has additional 2 coils on all sides and in all 3 directions to drive magnetic flux in all walls and wall centers

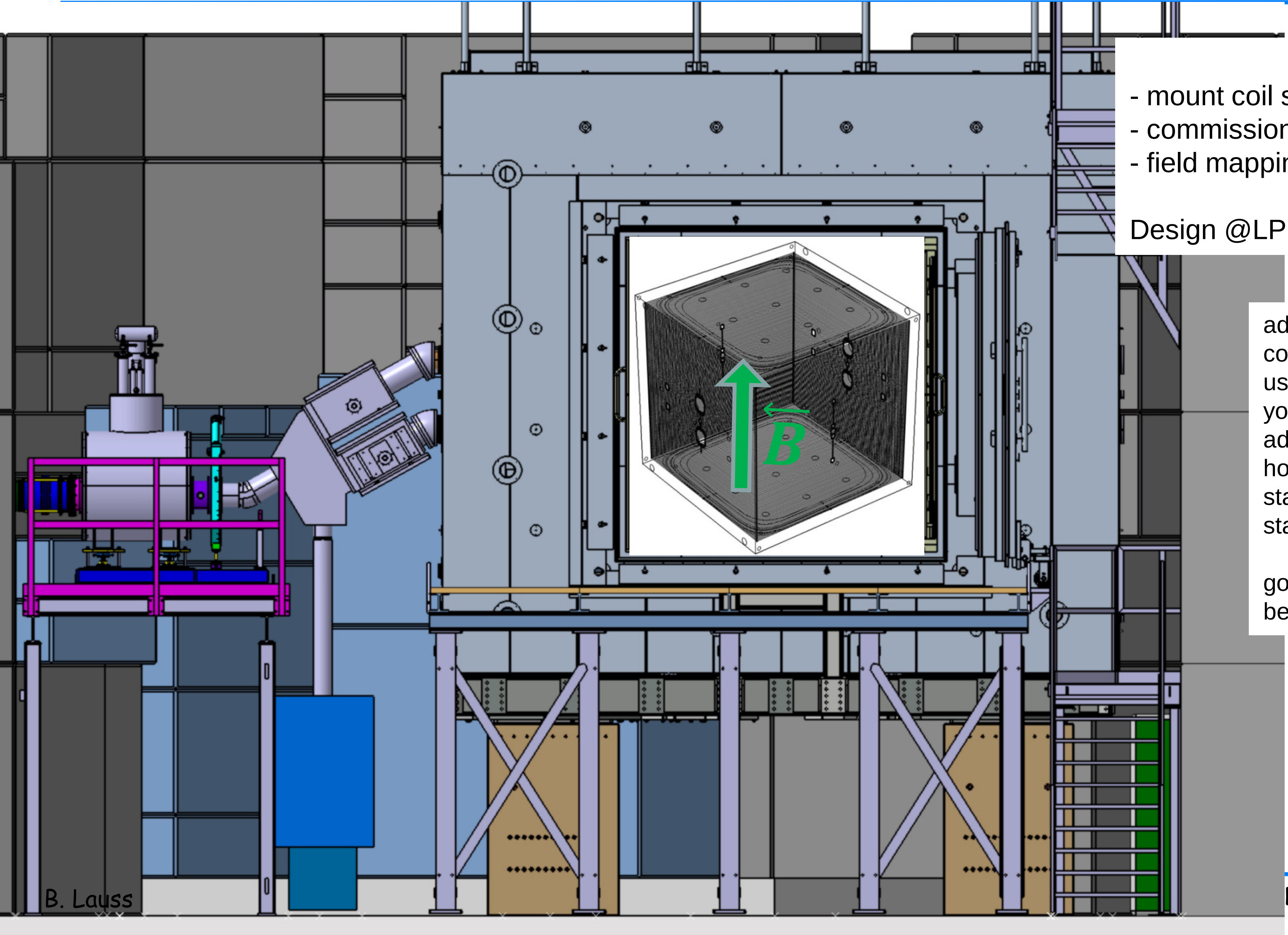
New apparatus - overall setup



Straight position in area South to optimize UCN statistics at optimal height above beamport

B. Lauss

Field coil system - 1μT



B. Lauss

- mount coil system
- commission individual coils
- field mapping

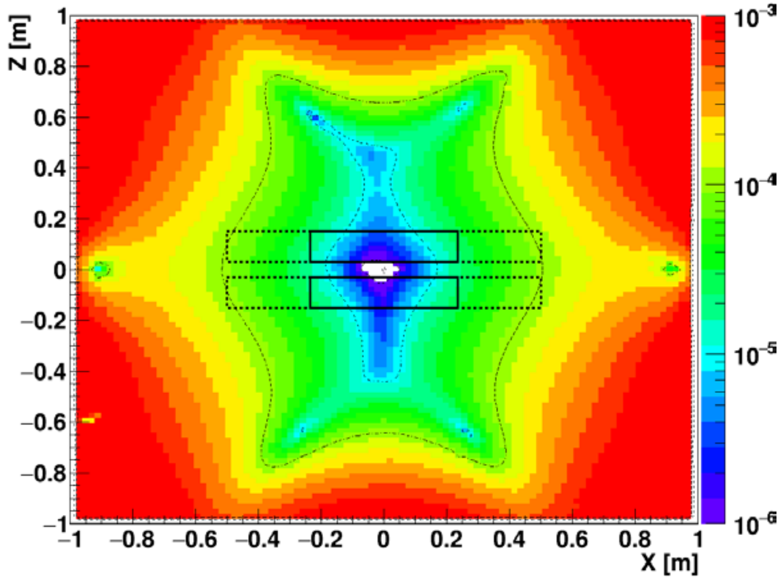
Design @LPC CAEN

adapted box-shape B0 coil which uses MSR as return yoke provides adequate homogeneity and stability via current stabilization

goal is uniformity better than 10^{-4}

Talk by
Pierrick Flaux

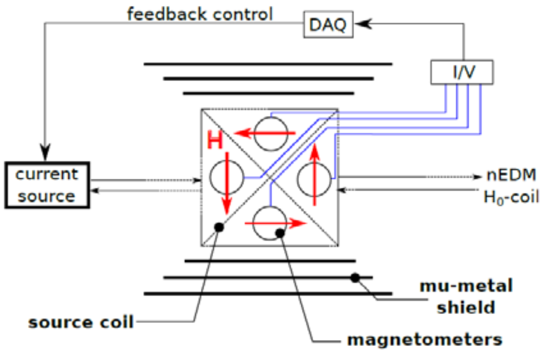
Field coil system - 1μT



Calculated B-field uniformity: XY at z=85cm
XZ at z = 0cm
circles: ID=47cm, ID=100cm
mu-metal included
no trim coils

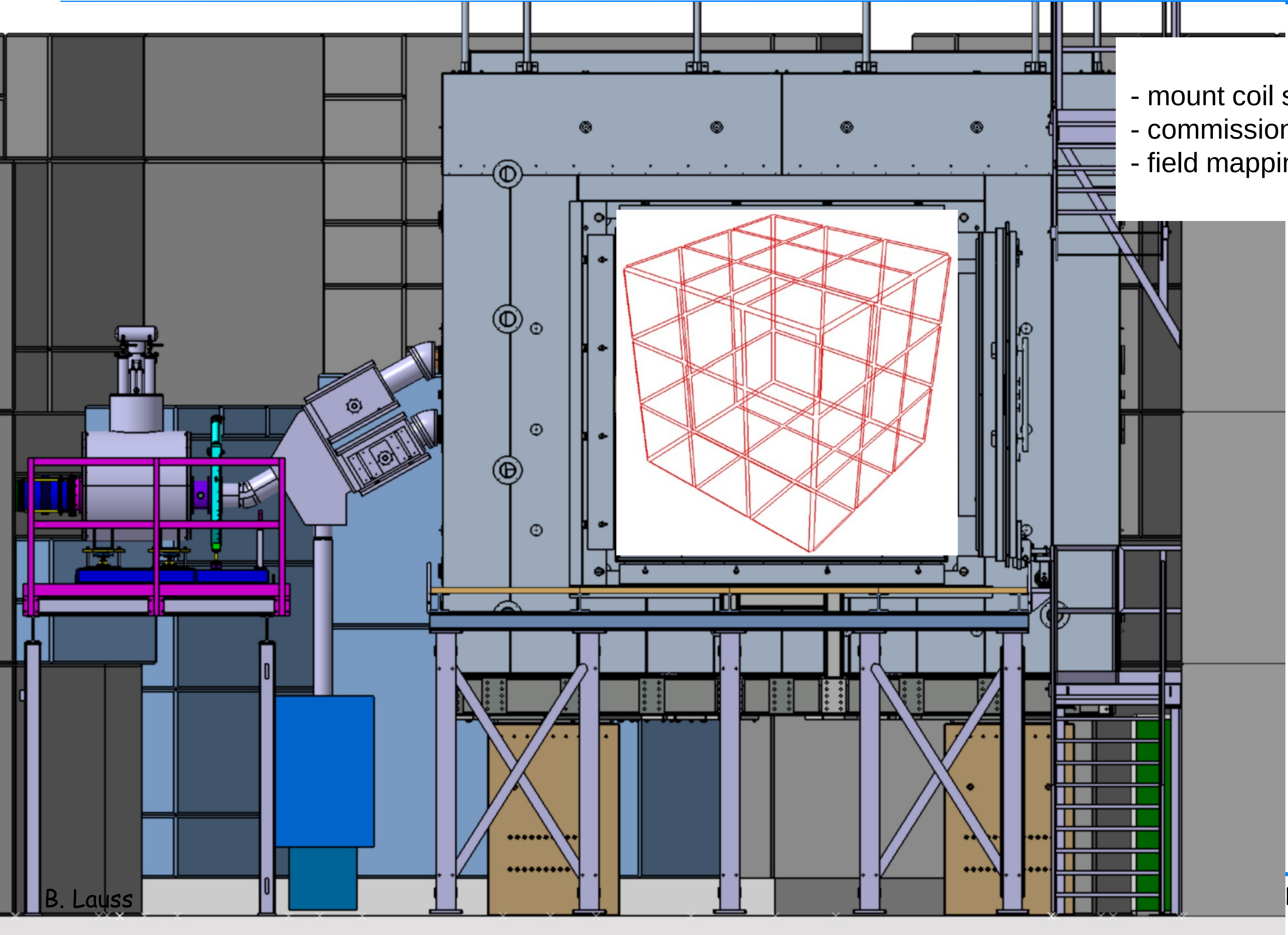
Talk by
Pierrick Flaux

Designing a low-noise current source with feedback stabilization via a magnetometer in a high homogeneity field.



P.Koss et al, IEEE Magnetics Letters 2017 2701771
demonstrated uniformity better than 10^{-3}

Trim coil system



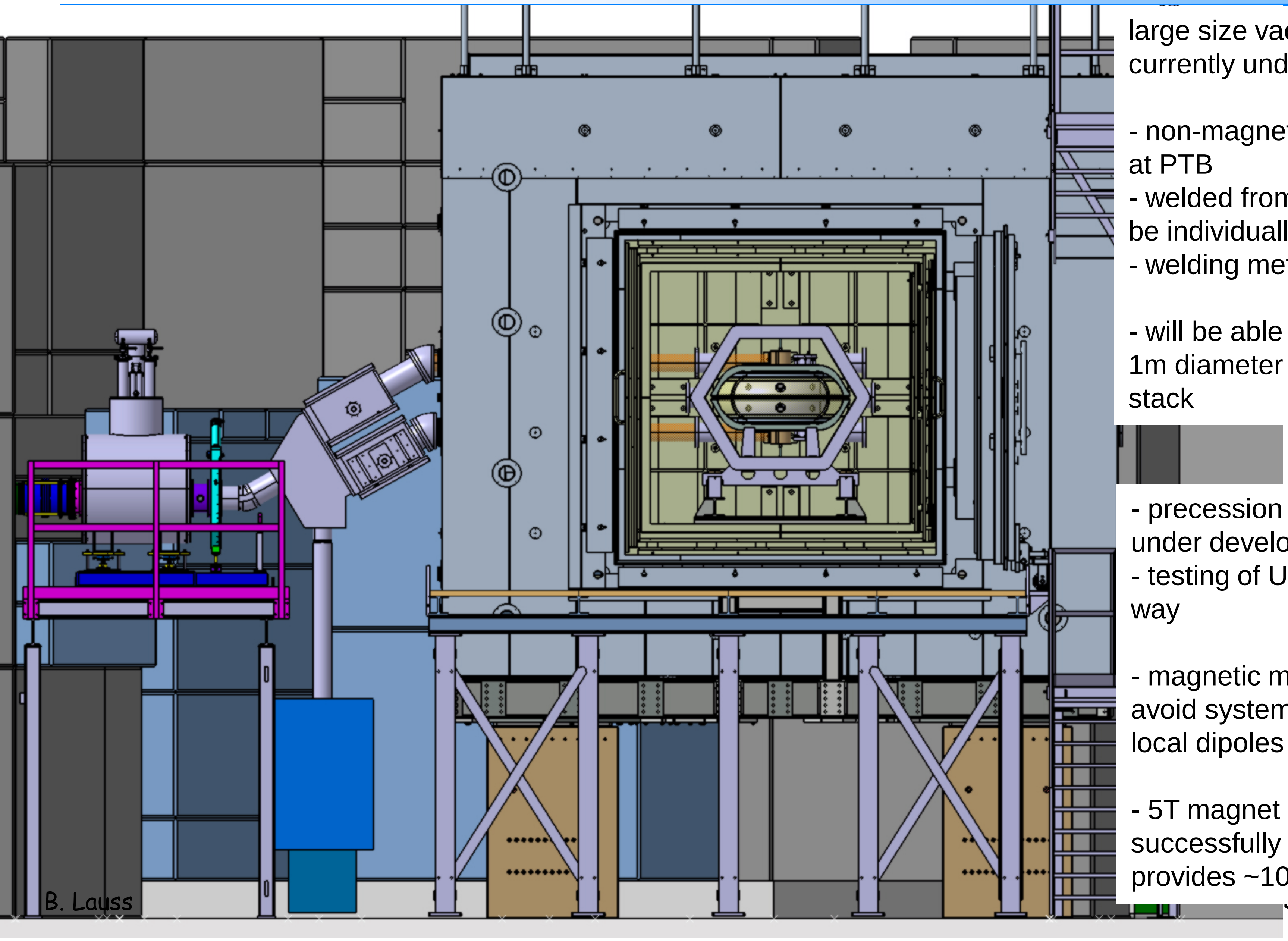
- mount coil system
- commission individual coils
- field mapping

bird cage compensation coil system to produce higher harmonics field contributions

see talk by Guillaume Pignol

target is a final field uniformity of better than 10^{-4}

Vacuum vessel



large size vacuum vessel currently under development

- non-magnetic parts checked at PTB
- welded from plates which can be individually checked
- welding methods checked

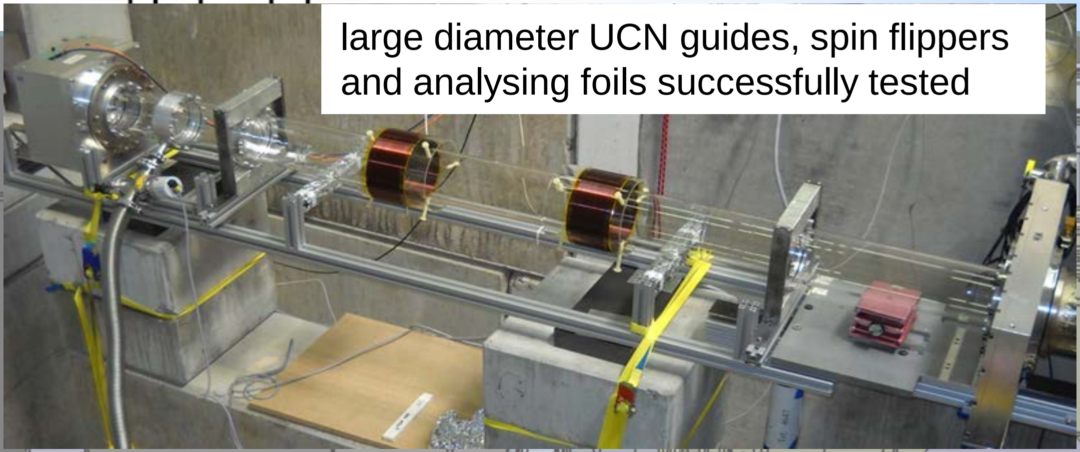
- will be able to house up to a 1m diameter UCN chamber stack

- precession chamber stack under development
- testing of UCN shutter under way

- magnetic materials check to avoid systematic effects from local dipoles

- 5T magnet polarizer operated successfully for several years, provides ~100% polarization

UCN guides and detection



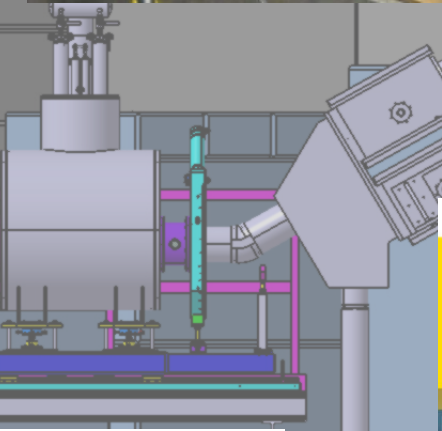
large diameter UCN guides, spin flippers and analysing foils successfully tested

UCN guides - glass tubes with ID = 130mm

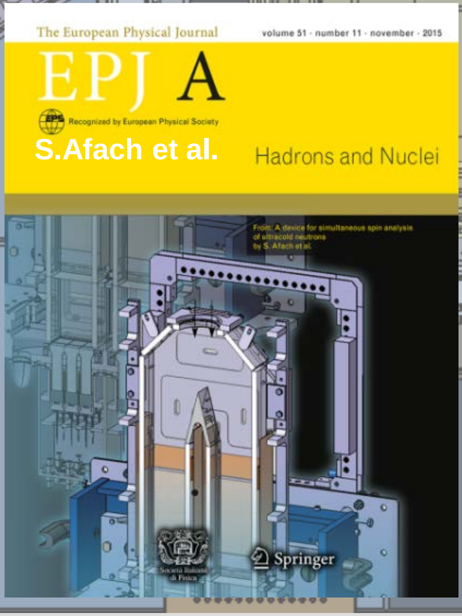
large facility ready for guide production with metal coatings

NiMo (^{58}NiMo) seems to be appropriate material

see
V.Bondar et al., Phys.Rev.C 96 (2017) 035205



improved gas-based large area detector under development at LPC Caen



The European Physical Journal volume 51 · number 11 · november · 2015

EPJ A

Recognized by European Physical Society

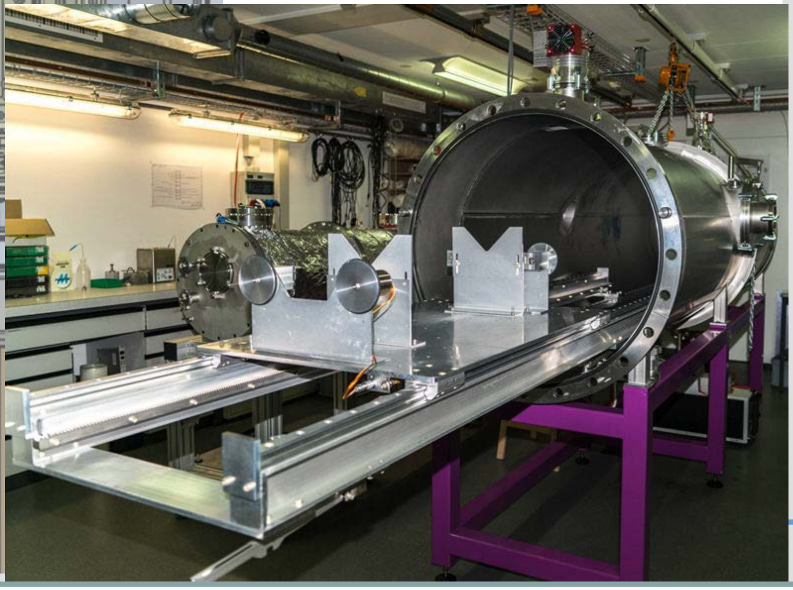
S.Afach et al.

Hadrons and Nuclei

From: A device for simultaneous spin analysis of ultracold neutrons by S. Afach et al.

Società Italiana di Fisica

Springer



B. Lauss

Selected requirements for the given statistics goal

Table 4 summarizes the requirements on magnetic field stability, uniformity, and measurement,

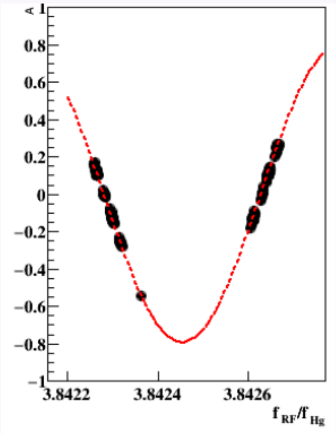
Related to statistical errors	
Vertical uniformity $\partial B_z/\partial z$	0.7 pT/cm
Horizontal uniformity $\partial B_z/\partial x, y$	8 pT/cm
G stability on hour timescale	0.1 pT/cm
B stability on minutes timescale	0.03 pT
Precision mercury co-magnetometer (per chamber)	0.03 pT

G fluctuation induce R fluctuations

must not limit neutron statistic (2% level)

Same frequency for the pi/2 pulses for both chambers:

Larmor frequency should be the same in both chambers. $\partial_z B_z$ must be small.



$\partial_{x,y} B_z$ should be small enough not to induce intrinsic depolarization of UCNs and decrease the visibility α.

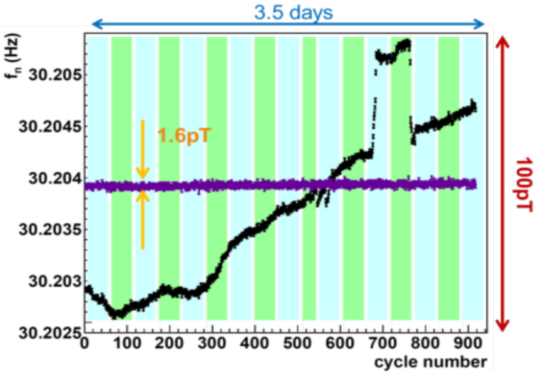
$$T_2^{hgr} \approx \frac{9\pi v}{D^3 \gamma_n^2 (\partial B_z/\partial x)^2}$$

talks by
Guillaume Pignol
and
by Georg Bison

Analysis: Frequency ratio $R = f_n/f_{Hg}$

$$\frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$$

$$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$$



$\overline{v_{\mathrm{Hg}}} \approx 160$ m/s vs. $\overline{v_{\mathrm{UCN}}} \approx 3$ m/s

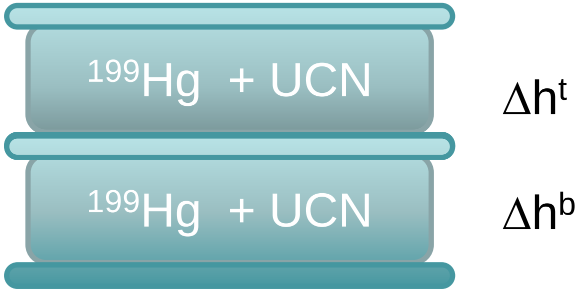
center of mass difference h

single chamber analysis - B and G fluctuations compensated by comagnetometer but gradient fluctuations introduce error term proportional to gravitational shift

$$R = \frac{\langle f_{\mathrm{UCN}}\rangle}{\langle f_{\mathrm{Hg}}\rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp}\rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}\right)$$

Analysis: based on R as function of dB/dz extrapolate to 0

Analysis: Frequency ratio $R = f_n/f_{Hg}$



double chamber - linear ∂B/∂z is almost perfectly compensated
but due to different h_t and h_b gradient fluctuations still cause an error on a lower level though

$$R^T - R^B = \frac{2E}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}} + \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(h^T - h^B\right) \frac{G}{B_0}$$

Analysis: based on (R^T - R^B) as function of dB/dz extrapolate to 0

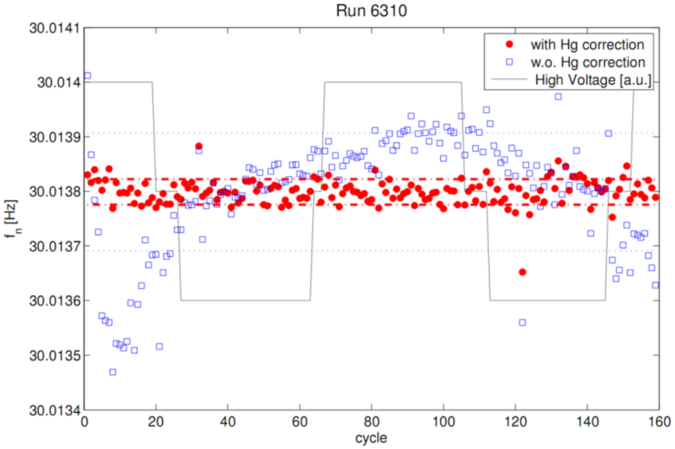
Laser-based Hg magnetometry

Correction: $$\omega_n^* = \omega_n - \frac{\gamma_n}{\gamma_{Hg}}\omega_{Hg}$$

Increase of the statistical error due to correction:

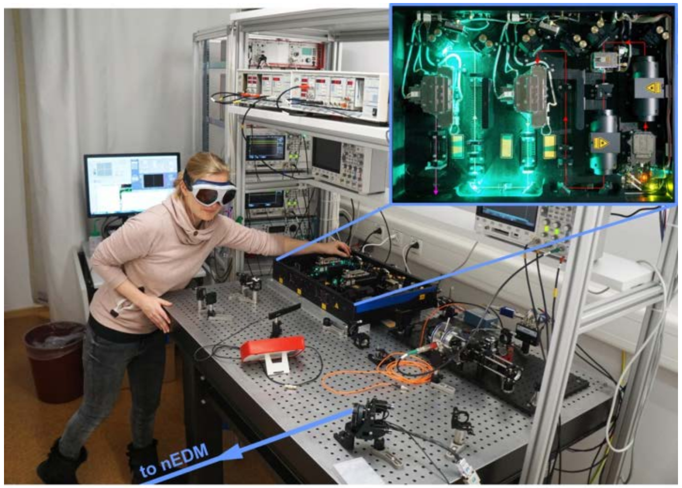
$$K = \sqrt{1 + \left(\frac{\Delta\omega_{Hg}/\omega_{Hg}}{\Delta\omega_n/\omega_n}\right)^2}$$

Systematics: no-lightshift effect due to stabilization at the 'no-lightshift' frequency point -> no systematic error contribution



required magnetometer resolution per cycle
(for d_n =2.3E-26/day): $\delta B = 24$ fT

see talk by Georg Bison



tested laser-based Hg readout
system with present apparatus

$\delta B = 5$ fT

Thesis Work of
M.Fertl 2013 and S.Komposch 2017
publication pending

Motional false EDM - mitigated by Hg to n

- Indirect effect, i.e. $d_{n\to Hg}^{False} = \frac{\gamma_n}{\gamma_{Hg}} d_{Hg}^{False}$
- Motional false edm $d_{Hg}^{False} = \frac{\hbar\gamma_{Hg}^2}{2c^2}\langle xB_x + yB_y\rangle$

G.Pignol & S.Roccia, Phys.Rev.A 85 (2012) 042105

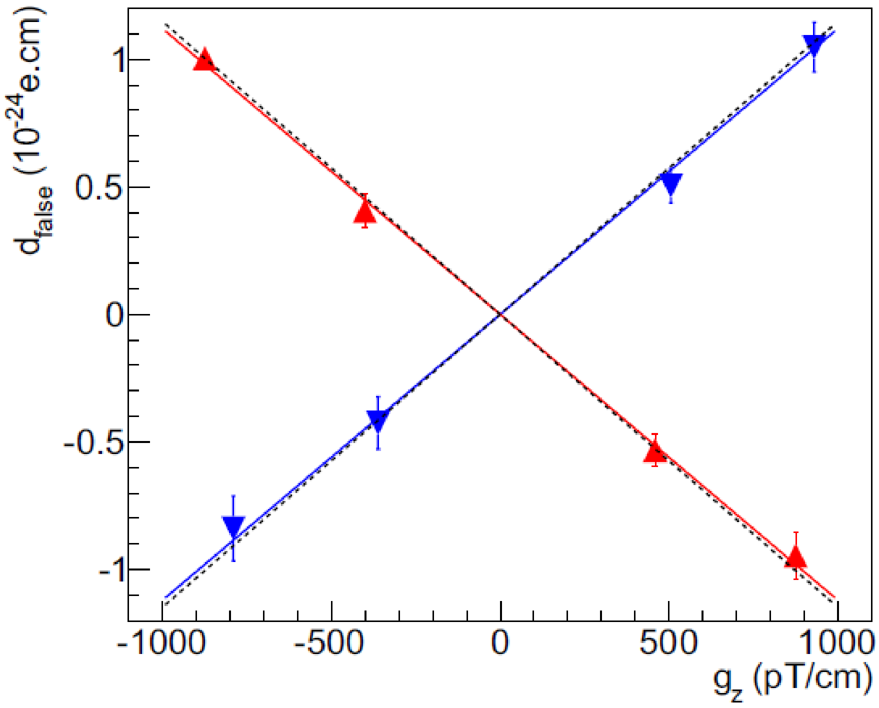


Fig. 5. Motional false mercury EDM versus the vertical gradient g_z for $B_0^{\uparrow}$ (red up triangles) and $B_0^{\downarrow}$ (blue down triangles). The solid lines correspond to a linear fit, and the dashed line to the theory discussed in Section 2. The horizontal error bars are smaller than the symbol size.

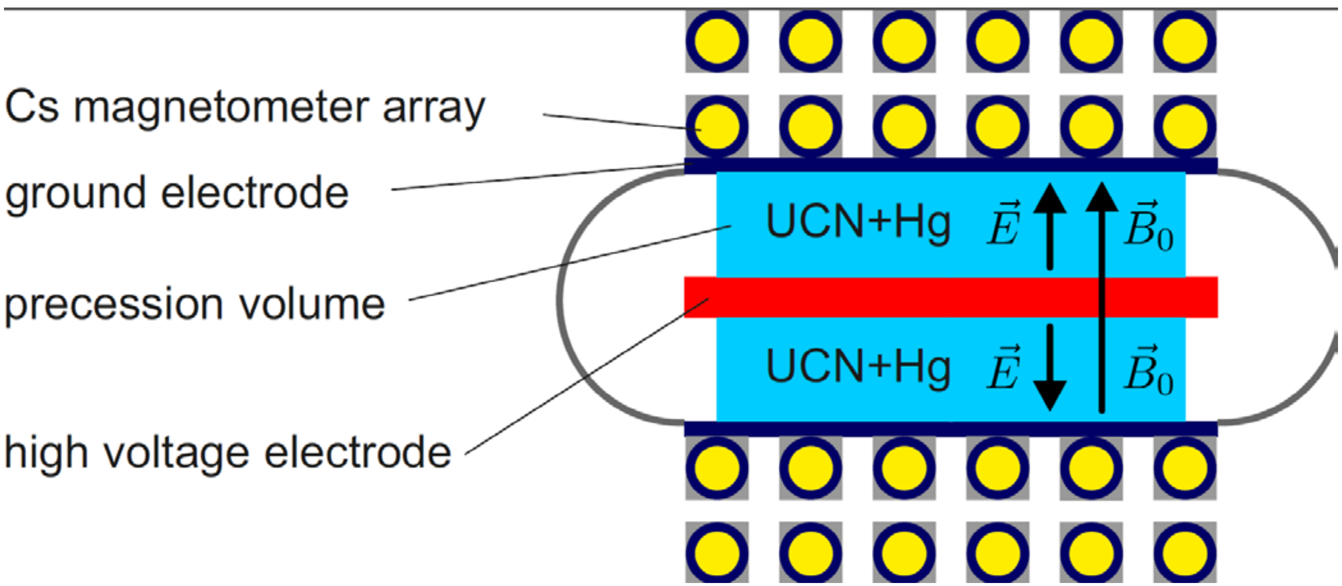
effect is ~proportional D^2 of chamber
expressions verified to 3% accuracy
with present apparatus

published in S. Afach et al., EPJ D 69 (2015) 225

demonstrated with laser-based system to higher gradient orders

see talk by Georg Bison

Cs magnetometer array

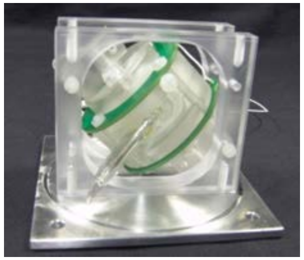


Cs magnetometer array

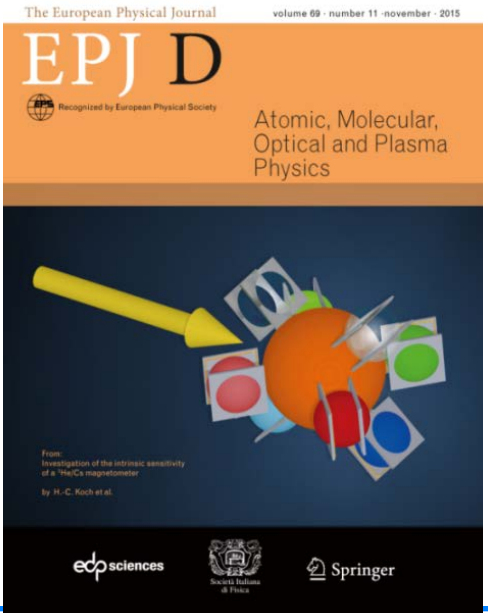
ground electrode

precession volume

high voltage electrode



Cs sensor



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EPJ D

Recognized by European Physical Society

Atomic, Molecular, Optical and Plasma Physics

From:
Investigation of the intrinsic sensitivity of a ^{3}He/Cs magnetometer

by H.-C. Koch et al.

edp sciences

Società Italiana di Fisica

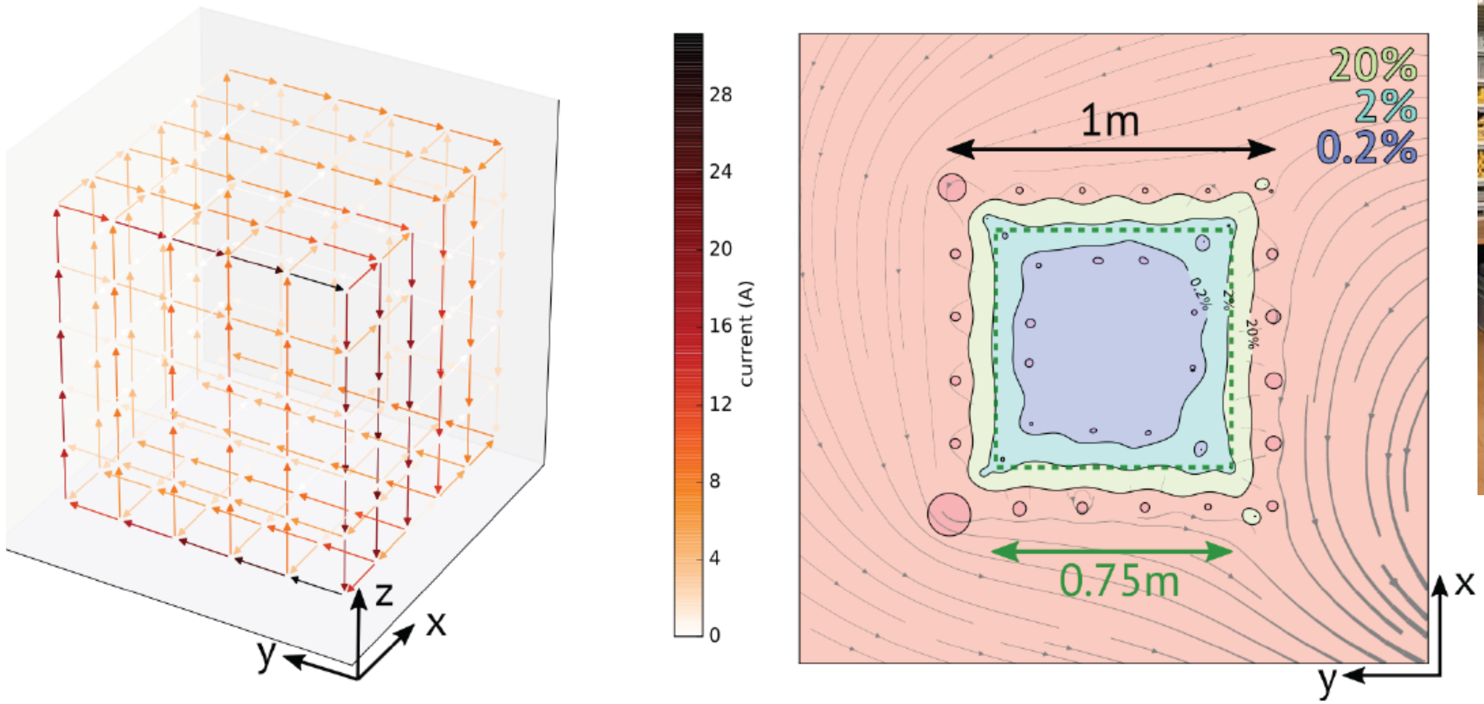
Springer

- homogenisation & control of B field
- (higher) gradient measurement and control in all directions
- measurement of correlations with E-fields
- crucial for systematics control

talk by Georg Bison

- develop ^{3}He magnetometry further for absolute B measurement and sensor calibration

Stabilization of surrounding B field and temperature



Scaled prototype operating at ETH

Surrounding field compensation system - talk by Michal Rawlik

In addition: air-conditioned environment to control T better than the 0.1K level

Timeline and Summary

- today started area cleaning and preparation for n2EDM apparatus
- magnetically shielded room is scheduled to be installed Feb. 2018
- all parts of the apparatus are under development and will be tested and commissioned in parallel in 3 experiment areas at PSI
- we plan to have the complete apparatus ready in 2020 (2018 and 2019 will only have short proton beam operation periods because of scheduled cyclotron and SINQ upgrades - but UCN testing will be possible)
- goal is to be back data taking in 2020 with at least a factor ~10 improved sensitivity, leading to an accumulated statistical sensitivity at or below $1\cdot10^{-27}$ ecm after 500 days of data taking
- simultaneously we are working on further increasing the UCN source intensity

Thanks to all my collaborators,
specifically Georg and Guillaume for figures,
inputs and many discussions and

Thanks to all of you
for your attention.