Neutron Electric Dipole Moment search with a superthermal spallation Ultracold Neutron source at RCNP/TRIUMF

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Outline

- The neutron Electric Dipole Moment (nEDM) and the particles used: the UltraCold Neutrons (UCN)
- The new He-II superthermal UCN source at RCNP
- Development on the nEDM experiment
- Outlook

The neutron EDM group

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(KEK, U. of Winnipeg, U. of Manitoba, TRIUMF, NCSU,

RCNP, UNBC, UBC, Osaka University)

The neutron Electric Dipole Moment

Baryon asymmetry of the Universe

$$\eta_{EW-SM} \sim 10^{-18} \text{ and } \eta_{exp} \sim 6 \times 10^{-10}$$ [WMAP (2003)]

Sakharov's conditions for baryogenesis [JETP letters **5**, 24 (1967)].

- B-Violation
- C & CP violation
- non equilibrium

Known CP violation (B - K^0) insufficient
$\rightarrow$ New CP violations needed

The neutron Electric Dipole Moment

The EDM of a particle

$$\vec{d} = d\frac{\vec{s}}{s}$$

$$\hat{H} = -\vec{d}\cdot\vec{E} = -d\frac{\vec{s}}{s}\cdot\vec{E}$$

	C	P	T
$\vec{s}$	$\vec{s}$	$\vec{s}$	$-\vec{s}$
d	$-d$	d	d
$\vec{E}$	$-\vec{E}$	$-\vec{E}$	$\vec{E}$
$\hat{H}$	$\hat{H}$	$-\hat{H}$	$-\hat{H}$

C, P, T symmetries

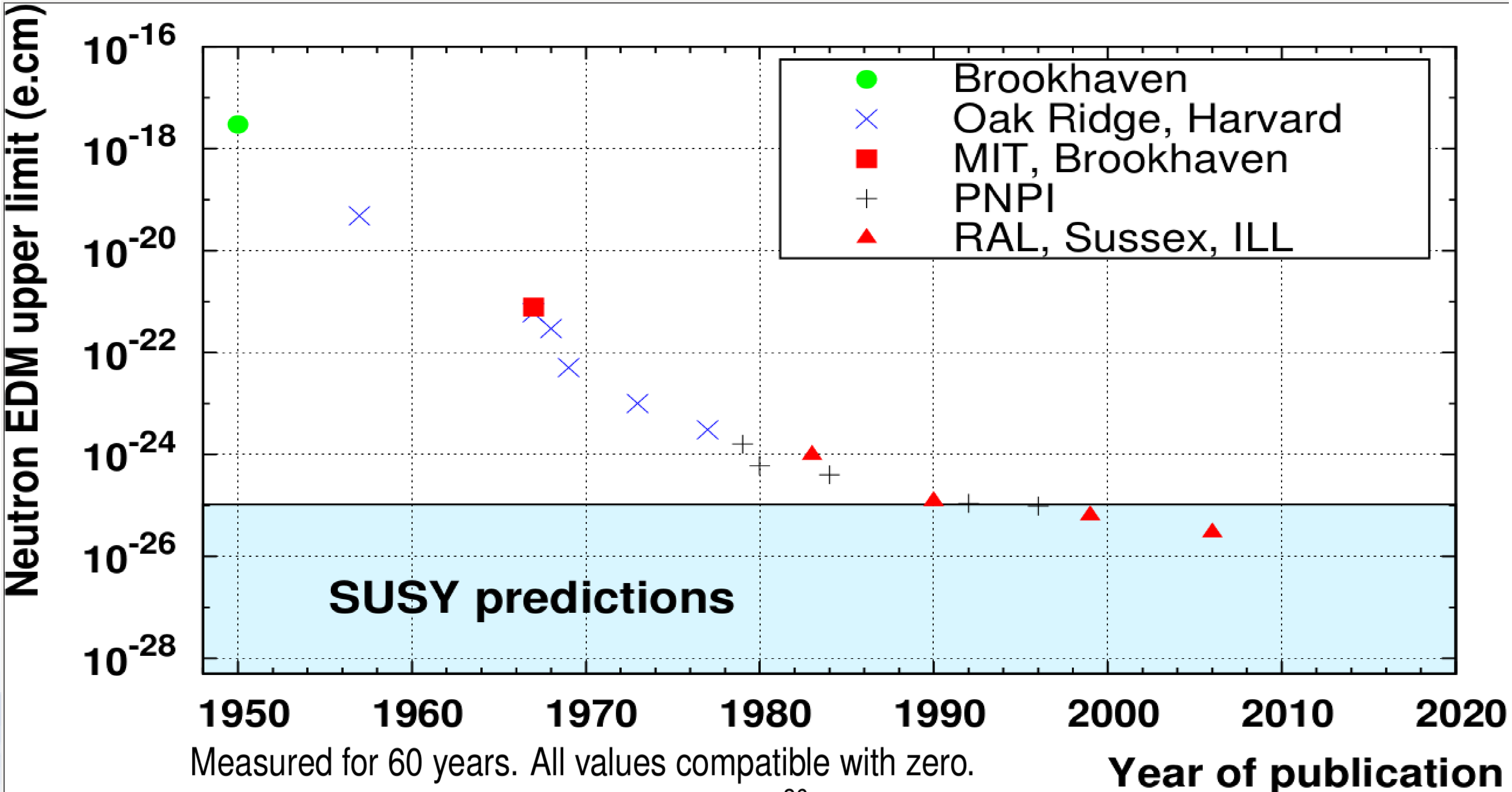
- C: charge conjugation ($q \to -q$)
- P: parity inversion ($\vec{r} \to -\vec{r}$)
- T: time reversal($t \to -t$)

Assuming CPT conservation

$\hat{H}$: P-odd and T-odd

$\Rightarrow$ Non zero d violates CP and T

nEDM: status of the art

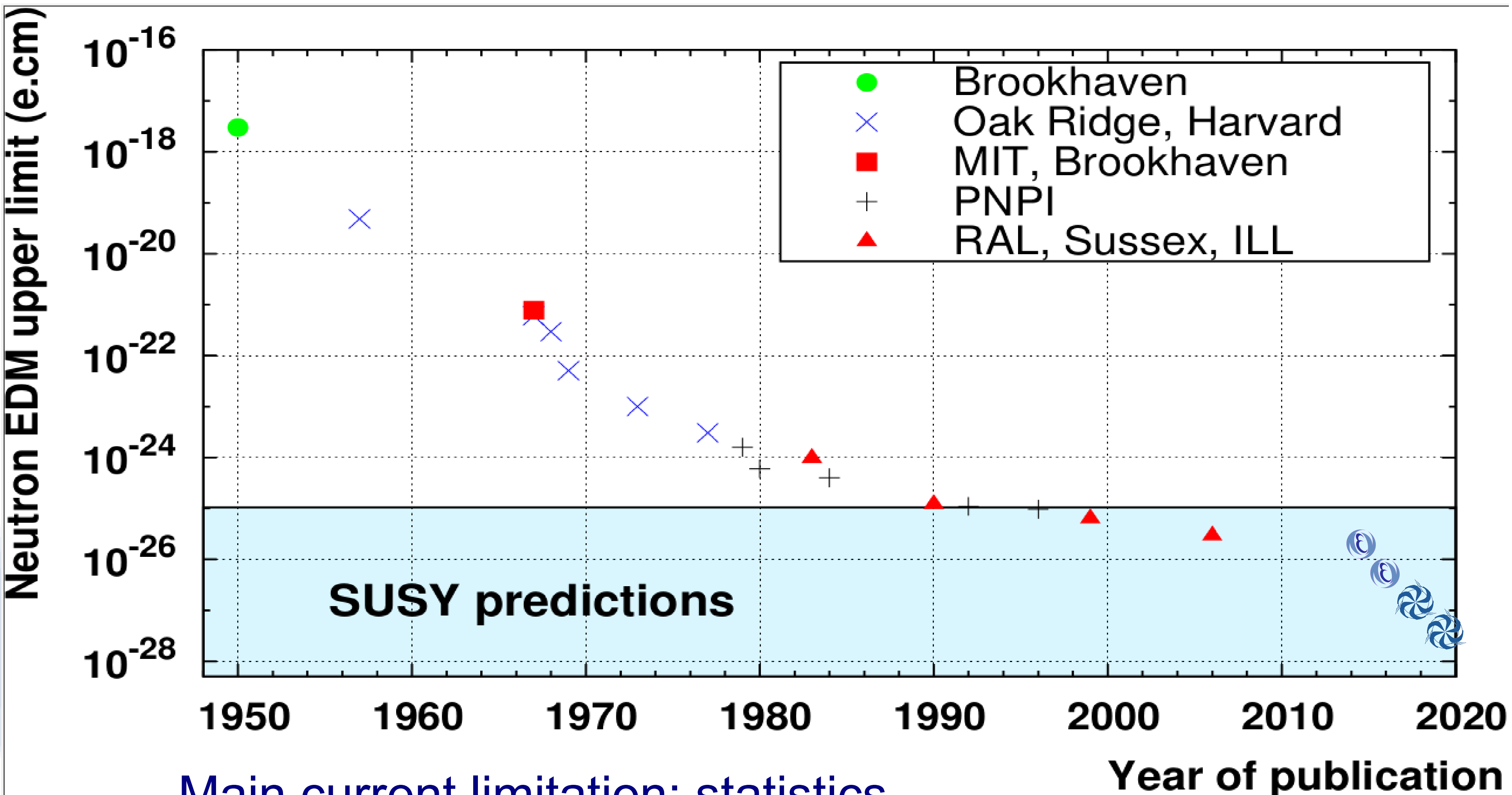


Measured for 60 years. All values compatible with zero.

$$d_n = 0.2 \pm 1.5\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) 10^{-26}\ e\ \mathrm{cm}$$

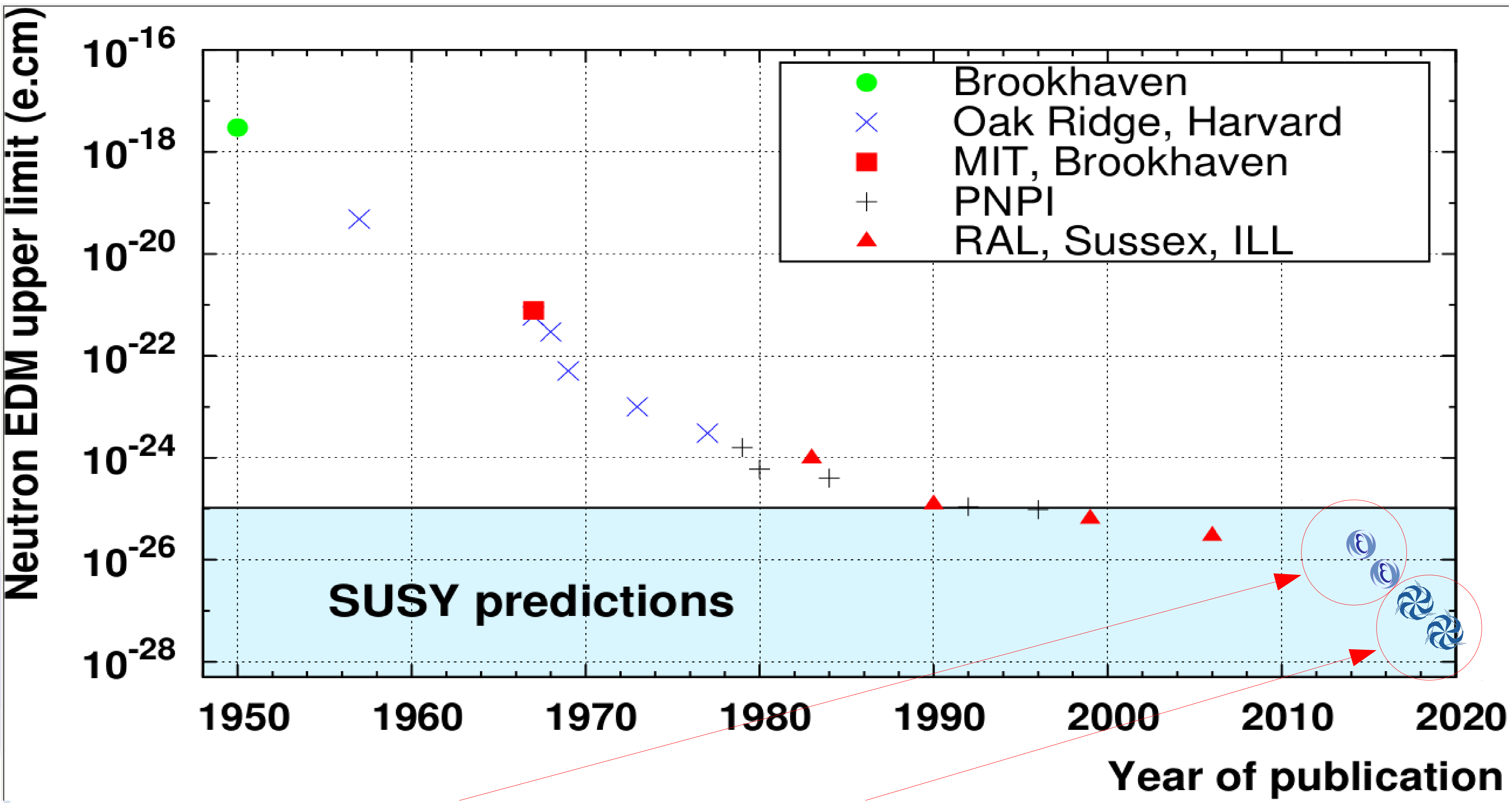
[C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)]

nEDM: predictions



Main current limitation: statistics

nEDM: predictions

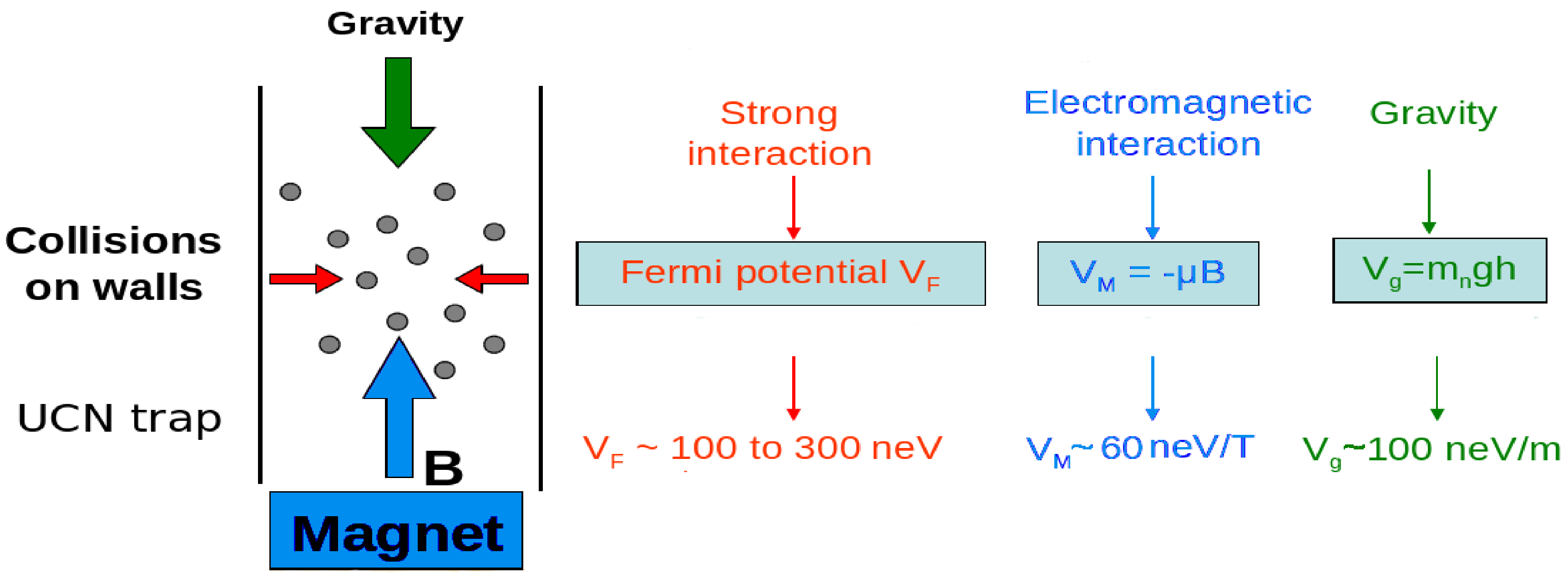


First phases in Japan
2014 to 2016

Experiment in Canada
2016 to 2020

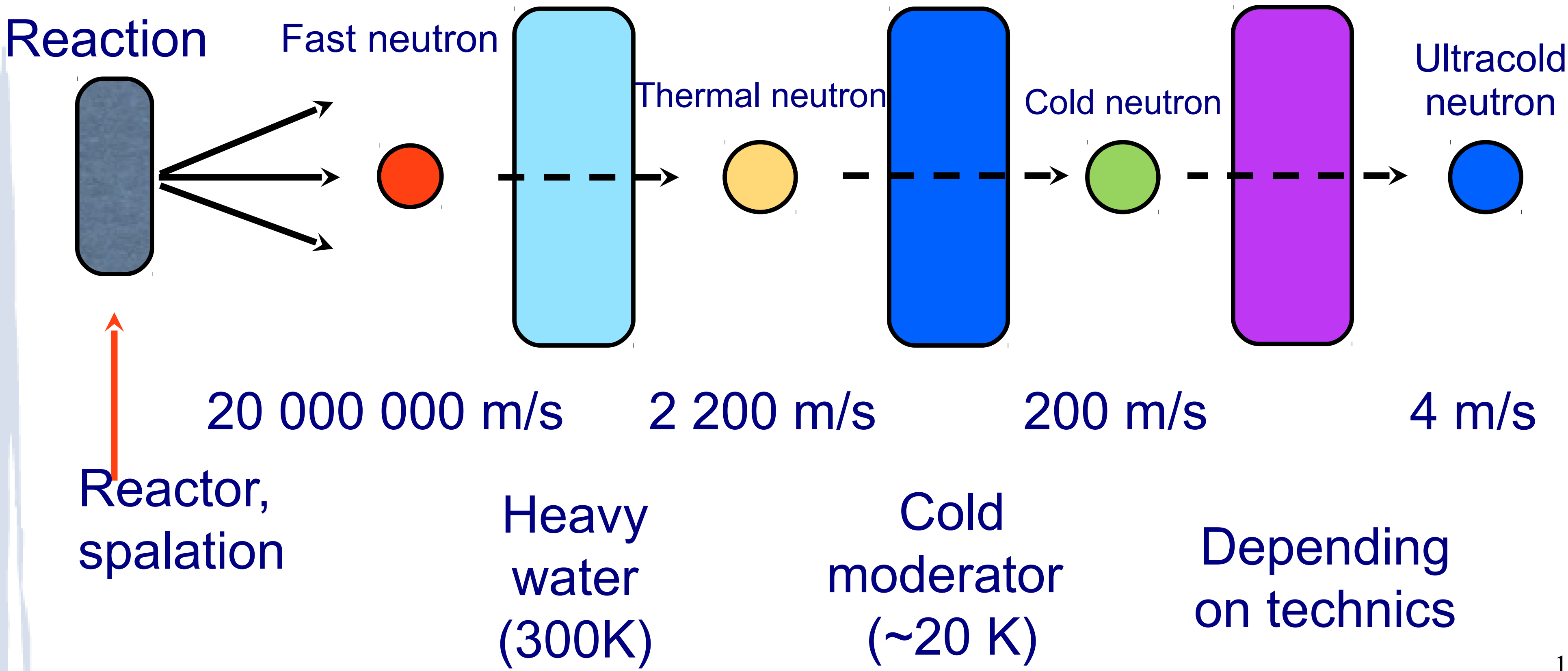
UltraCold Neutrons (UCN)

- ~100 neV energy neutrons
- All the interactions: same order of magnitude
- Can be trapped using physical walls!



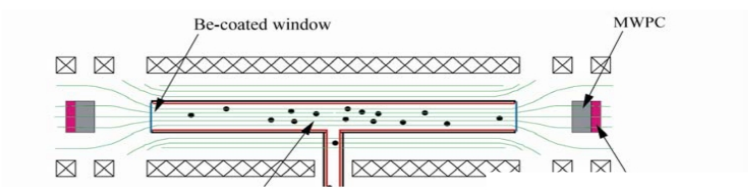
How to produce UCN

Neutrons are moderated by passing through different materials with different temperatures

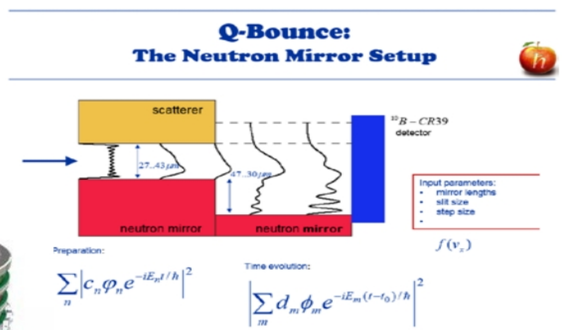


Experiments with UCN

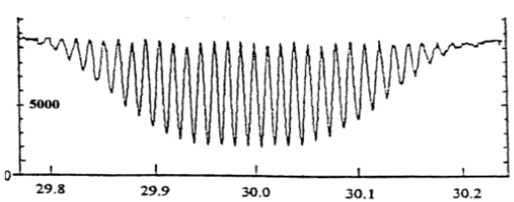
- Long storage time: many applications for fundamental physics
- n decay, gravity, lifetime, electric charge...



Neutron decay: UCNA

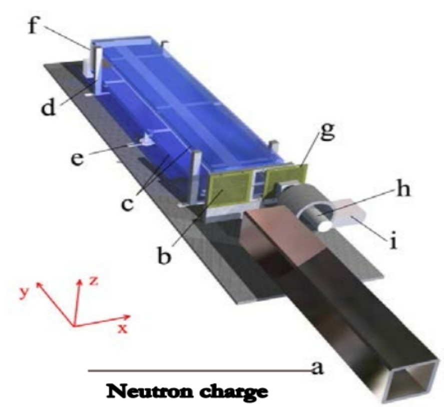


Gravity: Q-Bounce



EDM: Ramsay fringes

Lifetime: PENeLOPE

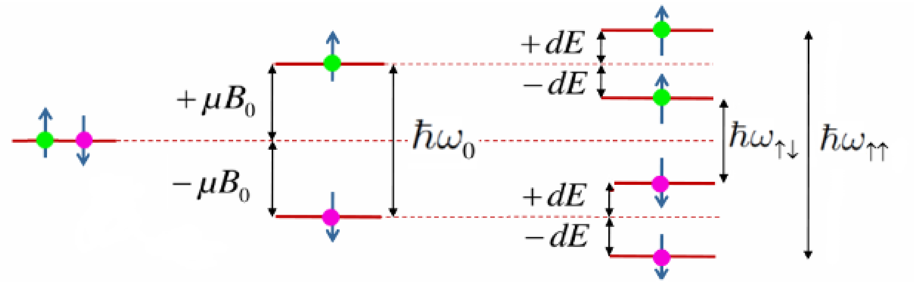


Neutron charge

How to measure the nEDM

Interaction Hamiltonian

$$\hat{H} = -\vec{d}\cdot\vec{E} - \vec{\mu}\cdot\vec{B} = -\frac{d}{s}\vec{s}\cdot\vec{E} - \frac{\mu}{s}\vec{s}\cdot\vec{B}$$



d_n extraction

$$d_n = -\frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) + \frac{\mu}{2E}(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})$$

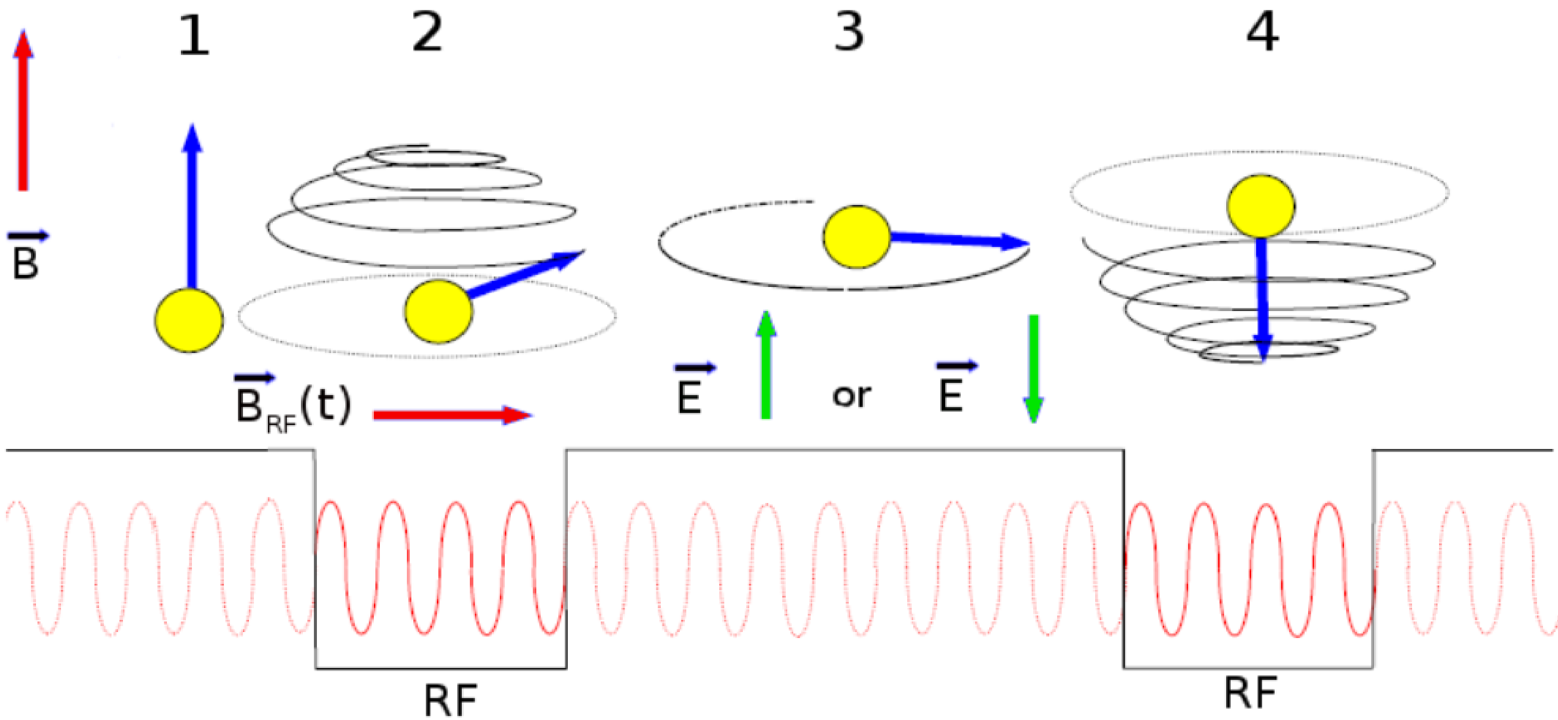
- parallel $\vec{B}$ and $\vec{E}$ fields: $\hbar\omega_{\uparrow\uparrow} = 2(\mu B_{\uparrow\uparrow} + dE_{\uparrow\uparrow})$
- antiparallel $\vec{B}$ and $\vec{E}$ fields: $\hbar\omega_{\uparrow\downarrow} = 2(\mu B_{\uparrow\downarrow} - dE_{\uparrow\downarrow})$

$B_{\uparrow\uparrow} - B_{\uparrow\downarrow}$ contribution must vanish.
High control on B fluctuations and spin handling needed.

Co-magnetometer needed!

How to measure the nEDM: the Ramsey's method

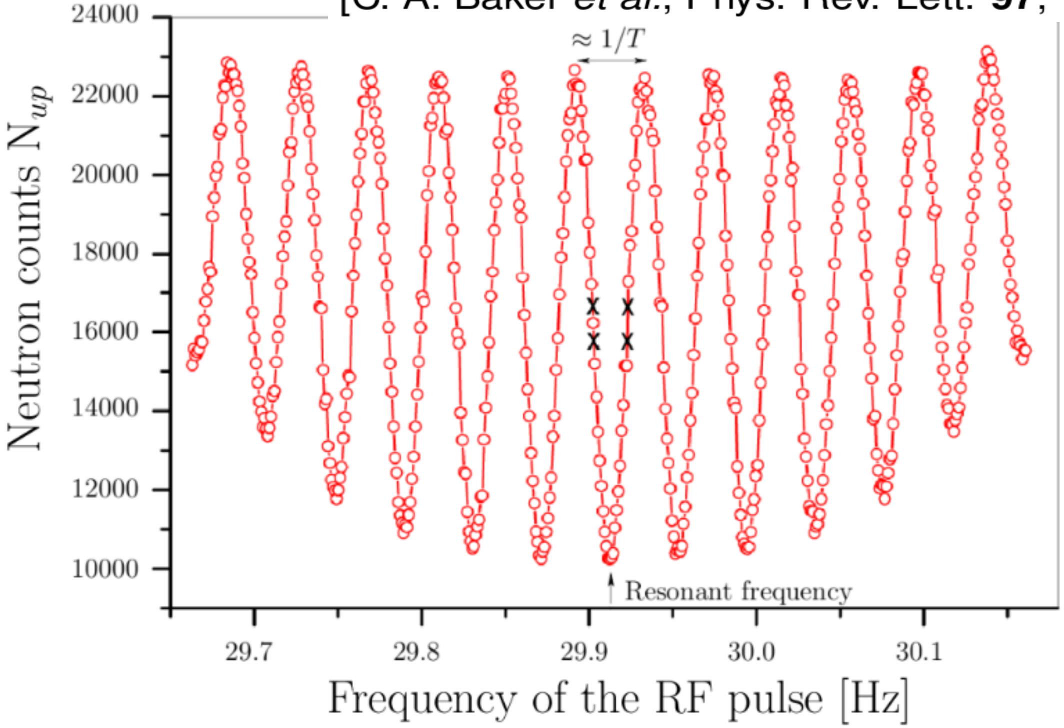
N. F. Ramsey, Phys.Rev.**76** 996 (1949) $\Rightarrow$ **Nobel Prize 1989**



1. Initially spin $\parallel \vec{B}$, $\vec{E} \uparrow$ or $\downarrow$ field applied
2. First $\pi/2$ RF pulse to place the spin $\perp \vec{B}$ (2s)
3. Free precession time T
4. Second $\pi/2$ RF pulse (2s)

How to measure the nEDM: the Ramsey's method

[C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)]



4 measurements points: $\Delta\omega \approx \frac{\pi}{2T} - \frac{N_{down} - N_{up}}{\alpha T (N_{up} + N_{down})}$

$N_0 = N_{up} + N_{down}$
$\Delta N = N_{up} - N_{down}$
α: visibility
$\alpha = \frac{N_{res} - N_{off}}{N_{res} + N_{off}}$

$$\rightarrow d_n = -\frac{\hbar(\Delta N_{\uparrow\uparrow} - \Delta N_{\uparrow\downarrow})}{4\alpha T E N_0}$$

Expected statistical sensitivity

$$\sigma_d = \frac{h}{2\alpha E t_c \sqrt{N}}$$

$\alpha = 0.95 \exp(-t_c/T_2) = 0.83$
$E = 10$ kV/cm
$t_c = 130$ s

10 μA @RCNP

$N = (7.5\mathrm{x}10^5$ UCN/batch$) \exp(-t_c/\tau)$
x 144 batch/day = 7.1 x10^7 pol. UCN

$\frac{3600s \times 24}{600s}$ assuming 10 minutes cycle

1 μA @RCNP $\sigma_d = 1.1 \times 10^{-25}$ ecm/day
10 μA @RCNP $\sigma_d = 3.6 \times 10^{-26}$ ecm/day
40 μA @TRIUMF $\sigma_d = 1.6 \times 10^{-26}$ ecm/day
More improvements @TRIUMF $\sigma_d = 3.0 \times 10^{-27}$ ecm/day

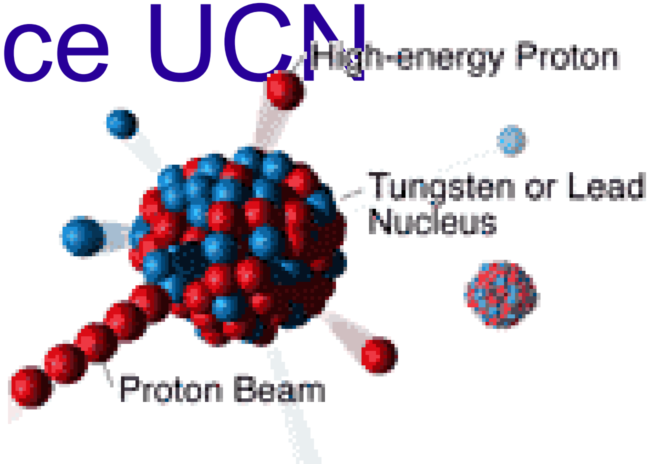
Expected statistical sensitivity

- Such N not achievable with the UCN sources used during 2006 experiment.
- This was already know for a long time...

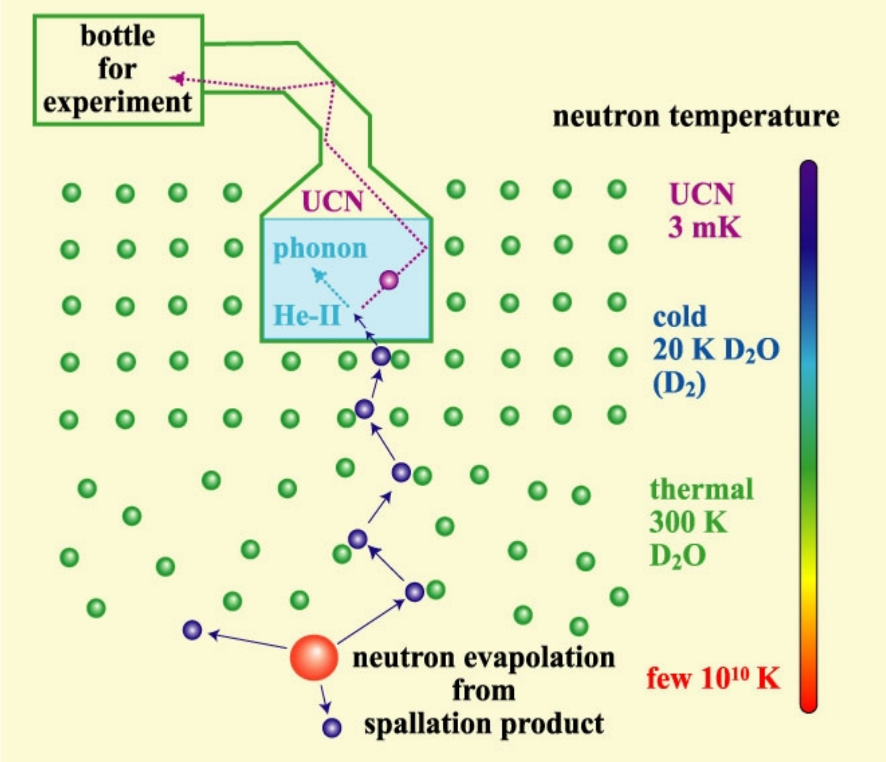
  Golub and Pandlebury, Contemporary Physics 13, 519 (1972) Review on neutron EDM:

  “If no effort were to be spared, an nEDM error of 2×10^{-27} e cm might ultimately be achieved”
- New UCN sources must be developed

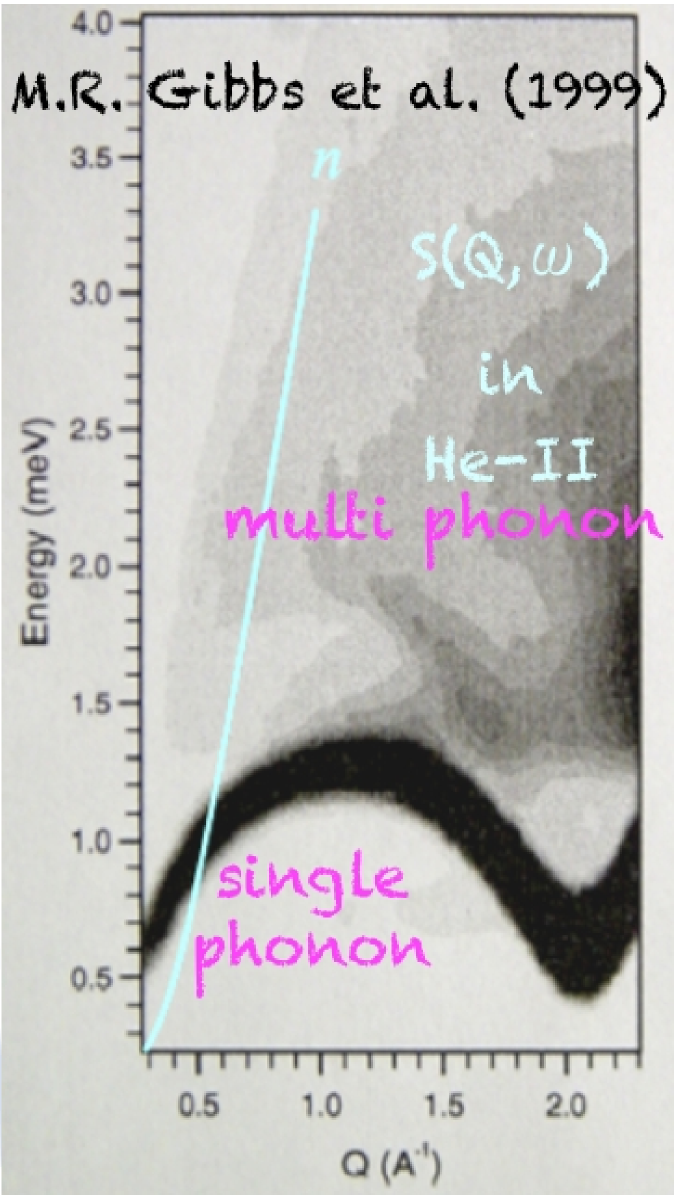
The new way to produce UCN

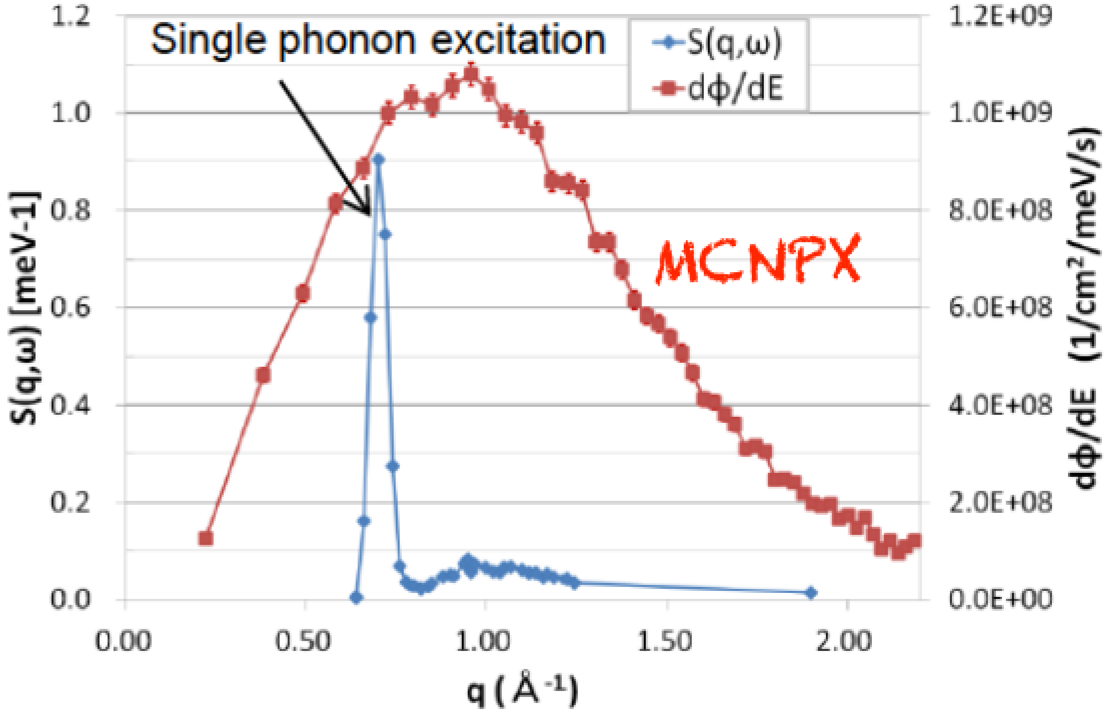


- Liberate neutrons by proton-induced spallation.
- Moderate (thermalize) in cold (20 K) D_2O.
- Cold neutrons then “downscatter” to near zero energy (4 mK) in superfluid helium through phonon production.



He-II superthermal source concept





$$P = \int p(E_u)dE_u = N_{\mathrm{He}} 4\pi b^2 \left(\frac{\hbar}{m_n}\right)^2 \frac{k_c^3}{3}\left[\int \frac{d\Phi(q)}{dE} S\left(q, \hbar\omega = \frac{\hbar^2 q^2}{2m_n}\right) dq\right]$$

From MC simulations (R. Matsumiya)
P=14 UCN/cm^3/s at 20 K
P=6 UCN/cm^3/s at 50 K
P=4 UCN/cm^3/s at 80 K

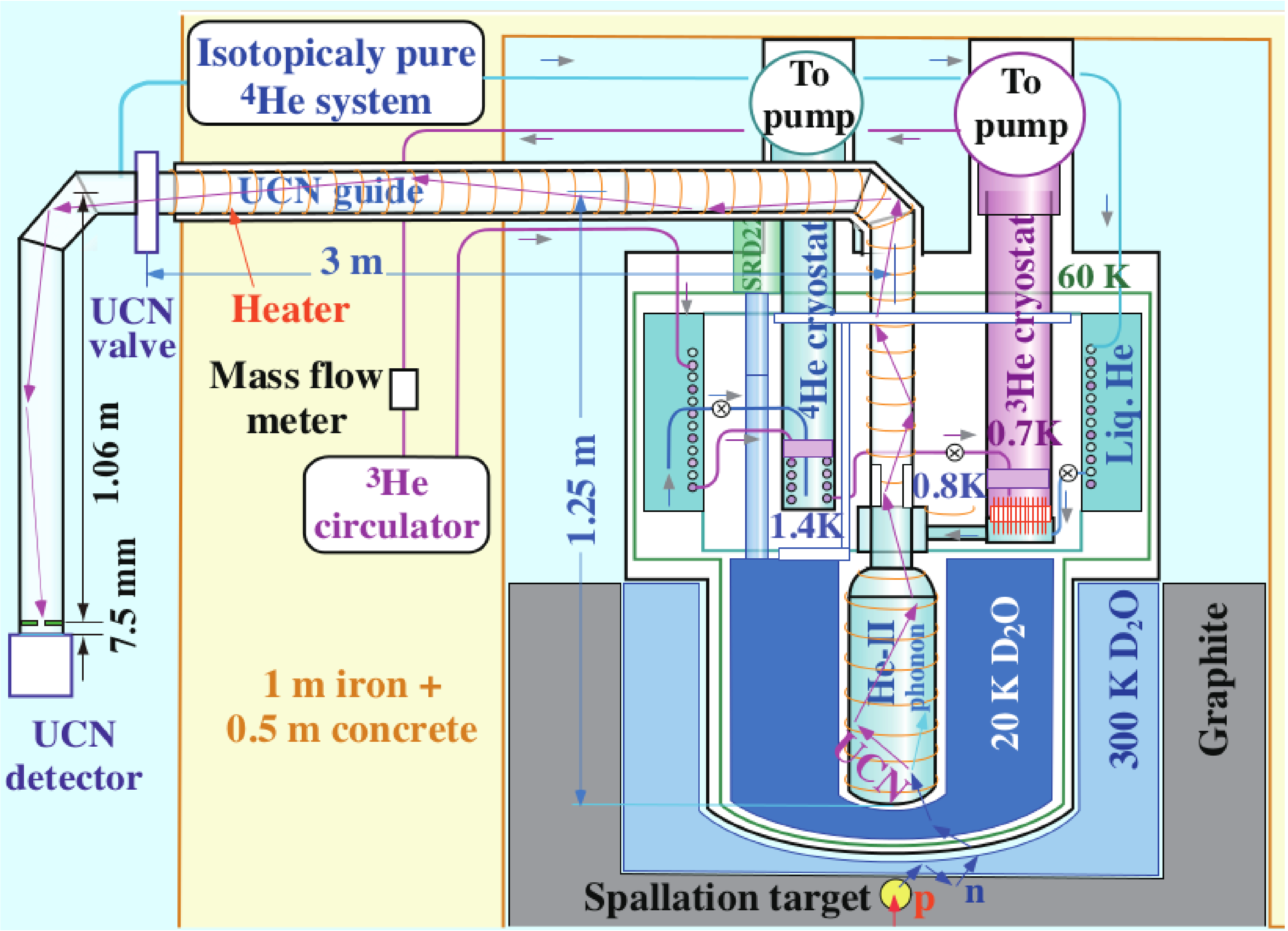
UCN losses within He-II

- Upscattering: depends on temperature $\tau \sim T^{-7}$. For T=0.8K (reached during last November experiment!), we have $\tau \sim 600$ s.
- Absorption with ^{3}He (σ_{abs}=5333 b). Natural abondance: $\tau \sim 30$ ms. Isopure ^{4}He needed. With 10^{-10} ^{3}He impurity, $\tau \sim 300$ s.
- Neutron lifetime: $\tau \sim 886$ s.
- Losses during wall collisions: $\tau \sim 250$ s.
- Global storage lifetime reachable: $\tau \sim 150$ s.

UCN losses within He-II

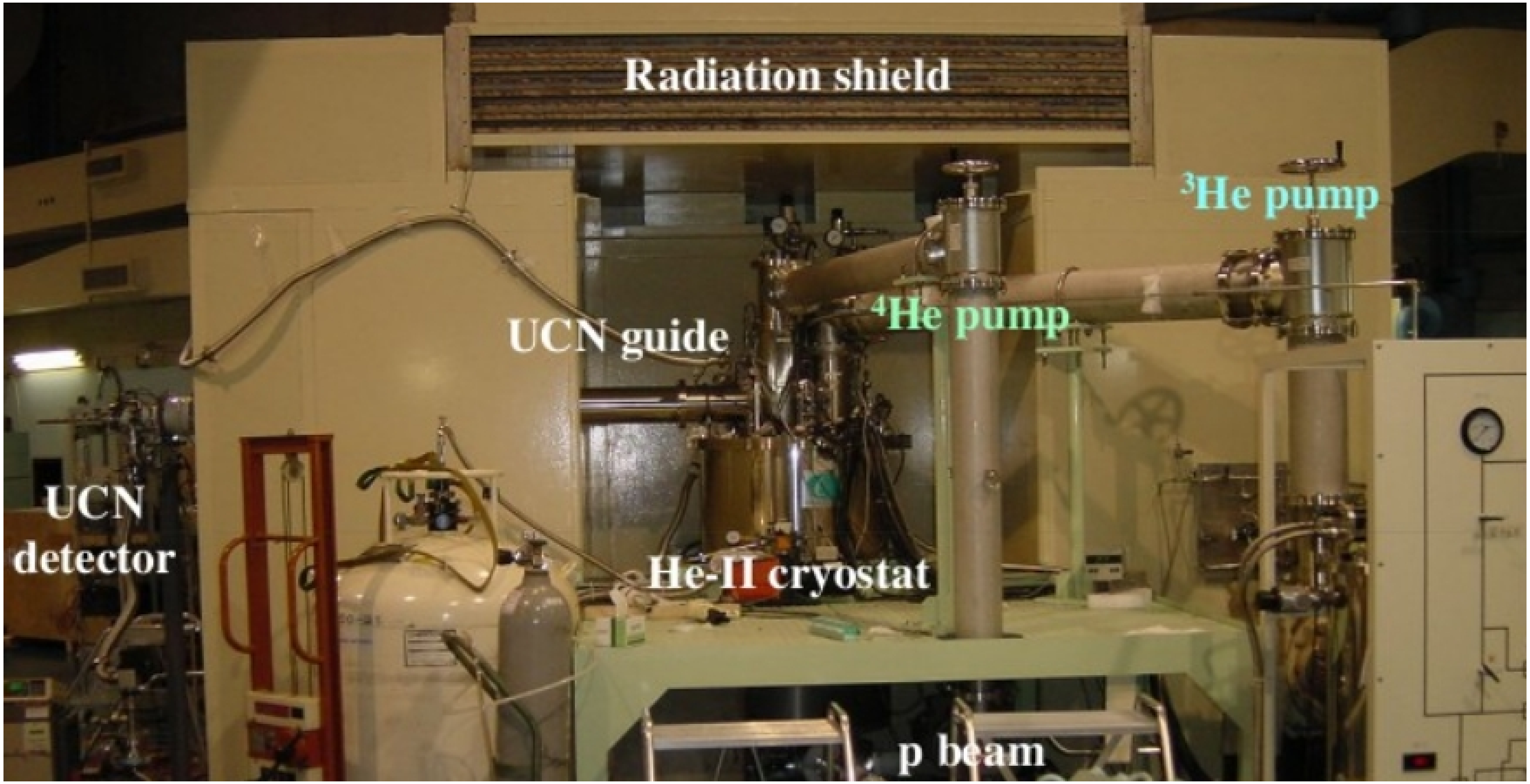
- Upscattering: need low temperature
- Absorption with ^{3}He: need isopure Helium
- Neutron lifetime: intrinsic
- Losses during wall collisions: need high cleaning of the walls

First prototype source: vertical extraction

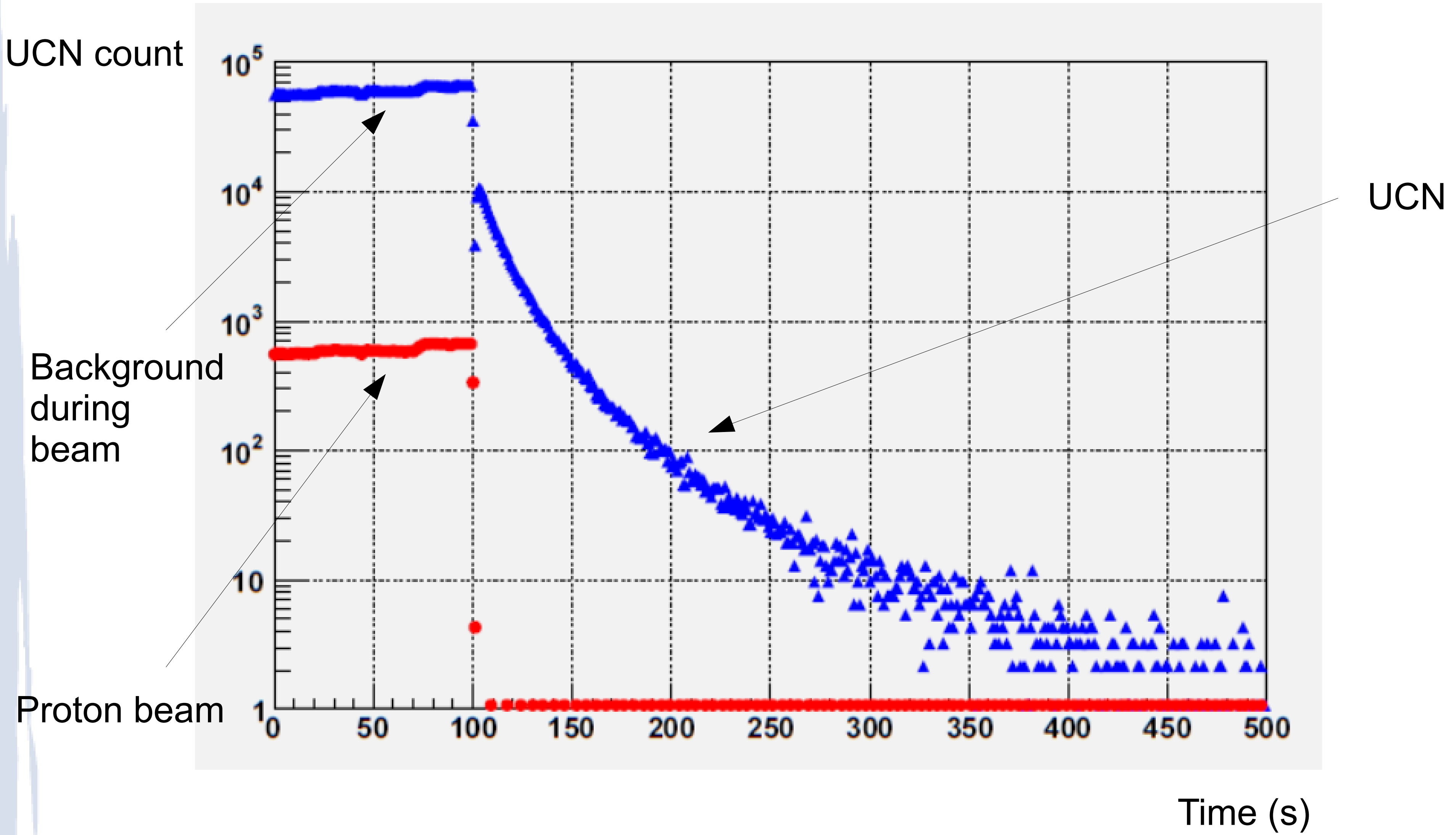


Y. Masuda

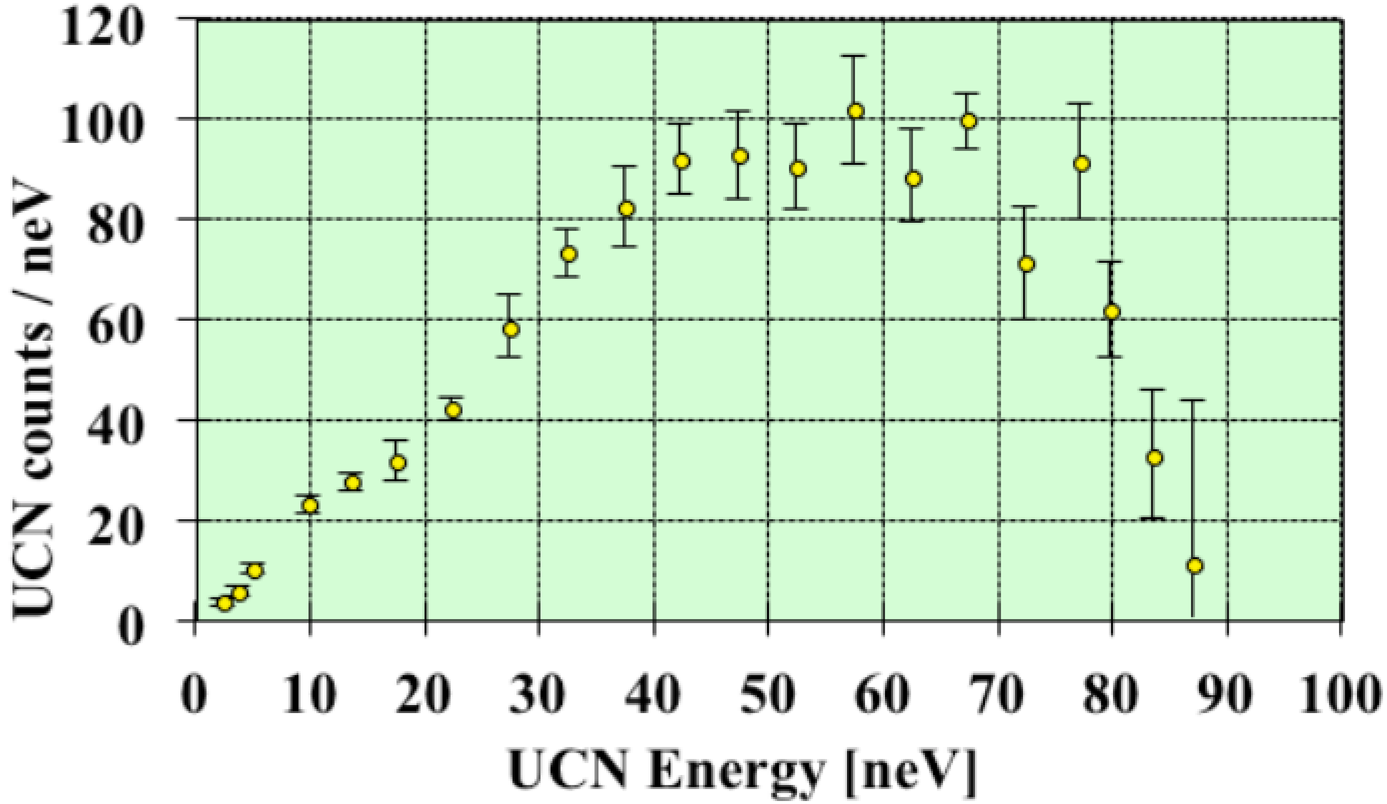
First prototype source: vertical extraction



Vertical source: UCN production

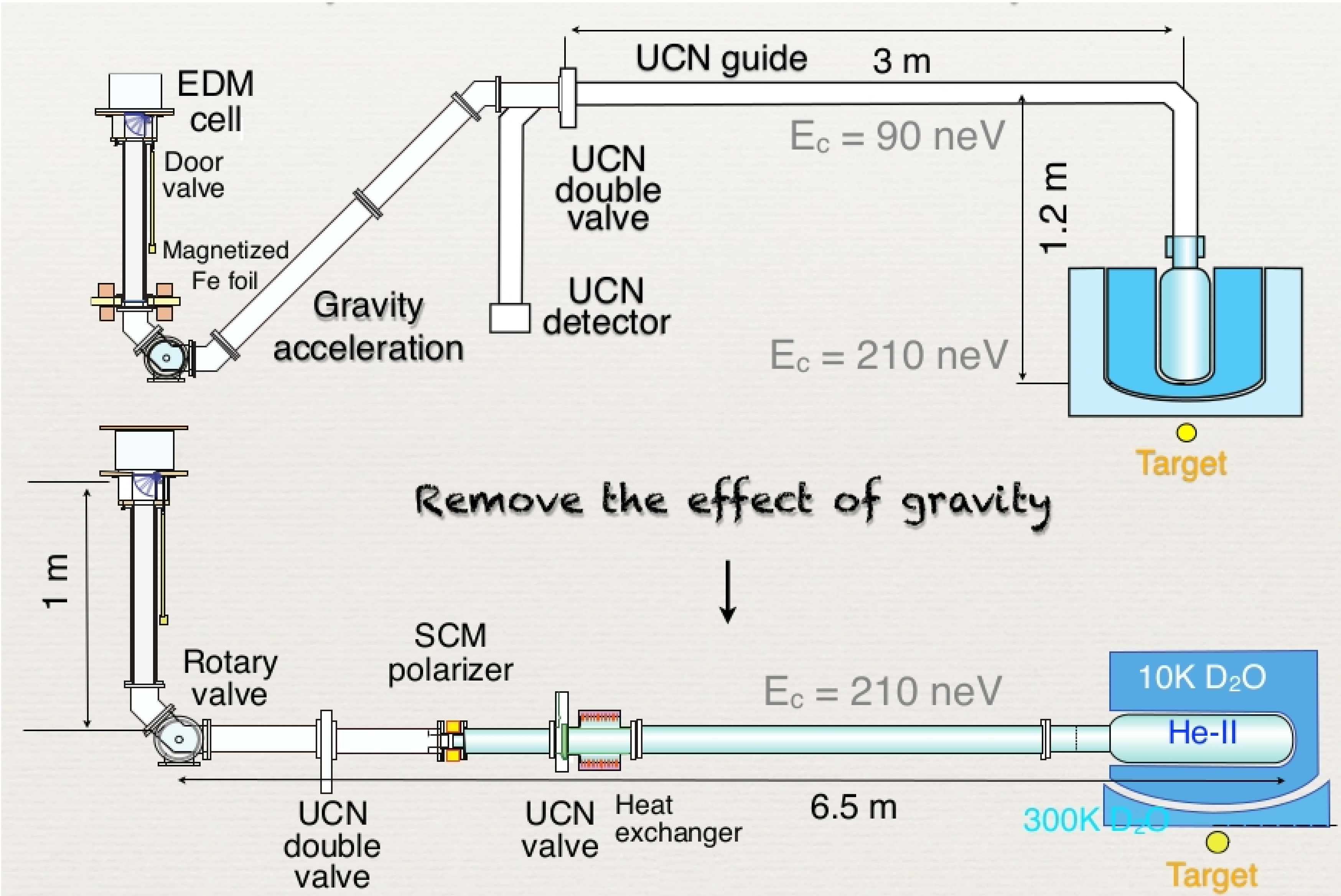


Vertical source issue: energy spectrum



Gravity reduces number of UCN which can reach the experimental setup

New concept: horizontal extraction



Y. Masuda

Expected UCN number for the new horizontal source

- $N = P\tau_s \varepsilon_d V$
- Vertical UCN source: P=4 UCN/cm^3/s

  26 UCN/cm^3 at E_c=90 neV

  Phys. Rev. Lett. 108(2012)134801
- Horizontal: dilution factor (V ratio): x6/9.9

  cold n flux: x1.2

  UCN production volume: x1.4

  beam current upgrade: x10

  storage lifetime: x2

Expected number of UCN at RCNP (10 μA beam current): N=7.5x10^5

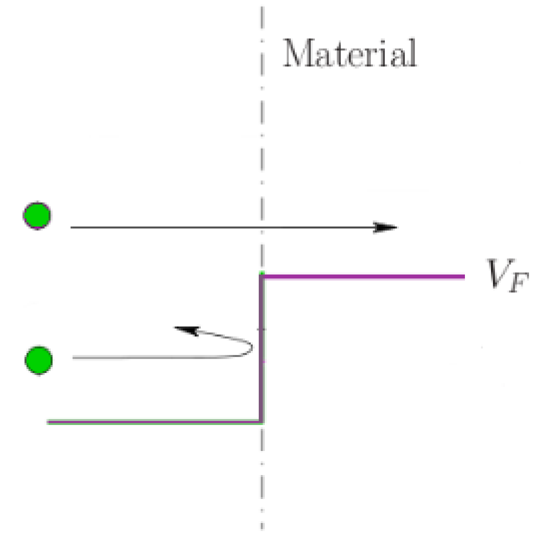
New source: a source of polarized UCN

Goal: select and keep the polarization along the experimental setup.
Interaction UCN - material wall:

Fermi potential

$V = V_F$

Potential spin independent.

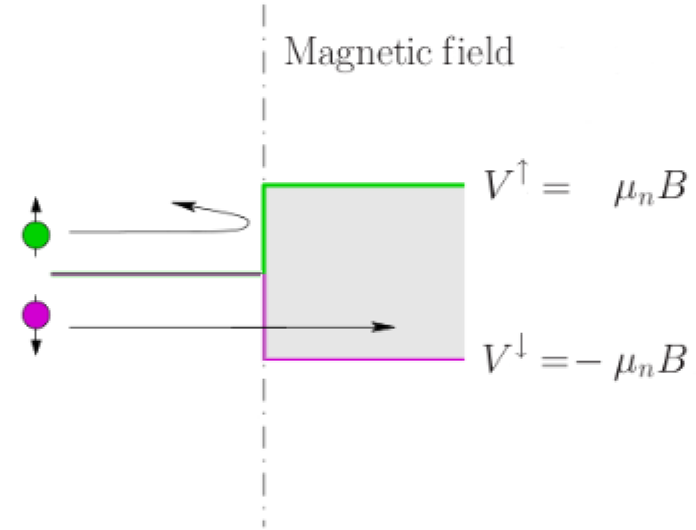


New source: a source of polarized UCN

Magnetic potential

$$V = \mp \vec{\mu}_B \cdot \vec{B}$$

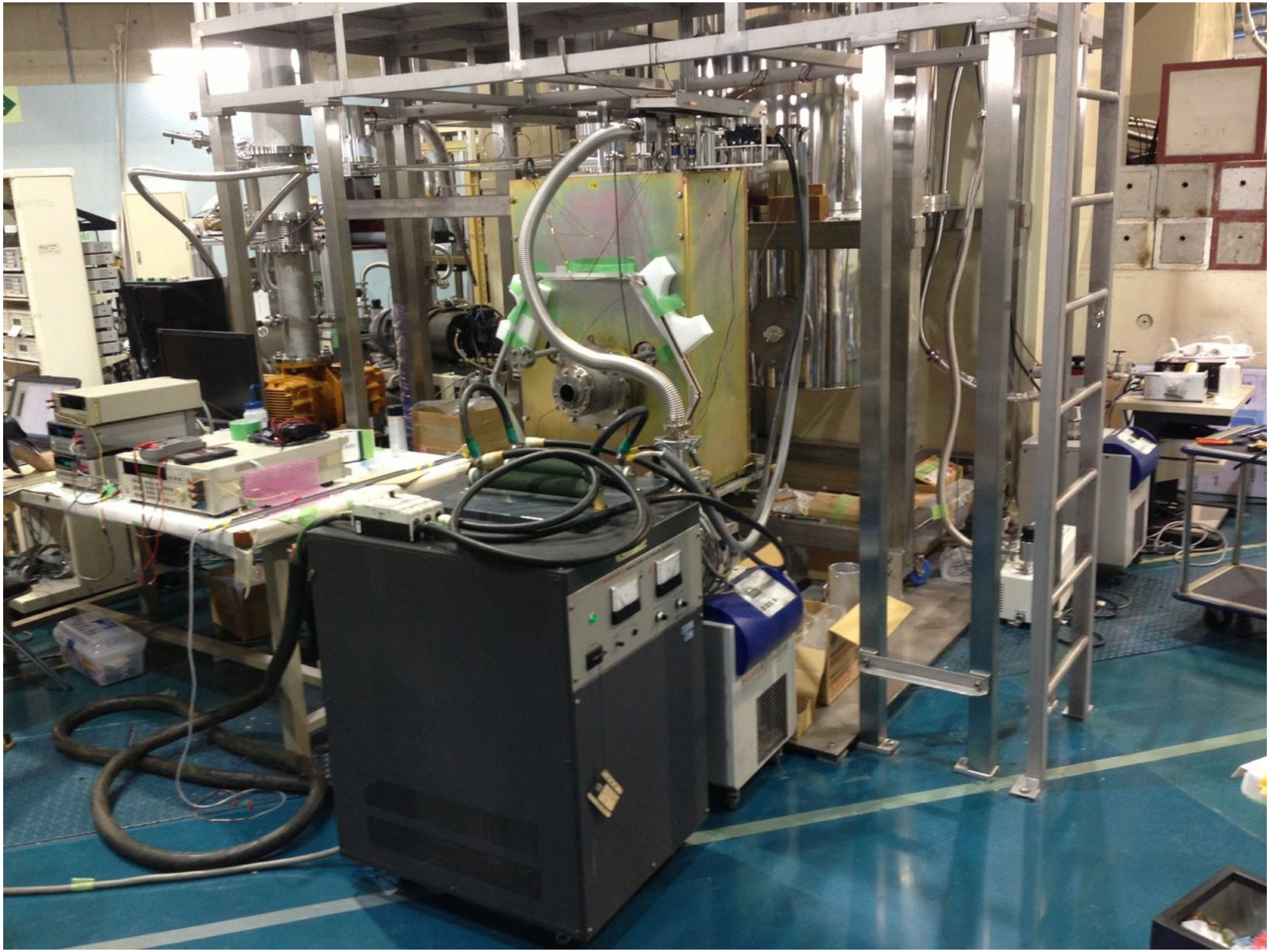
Potential spin dependant.



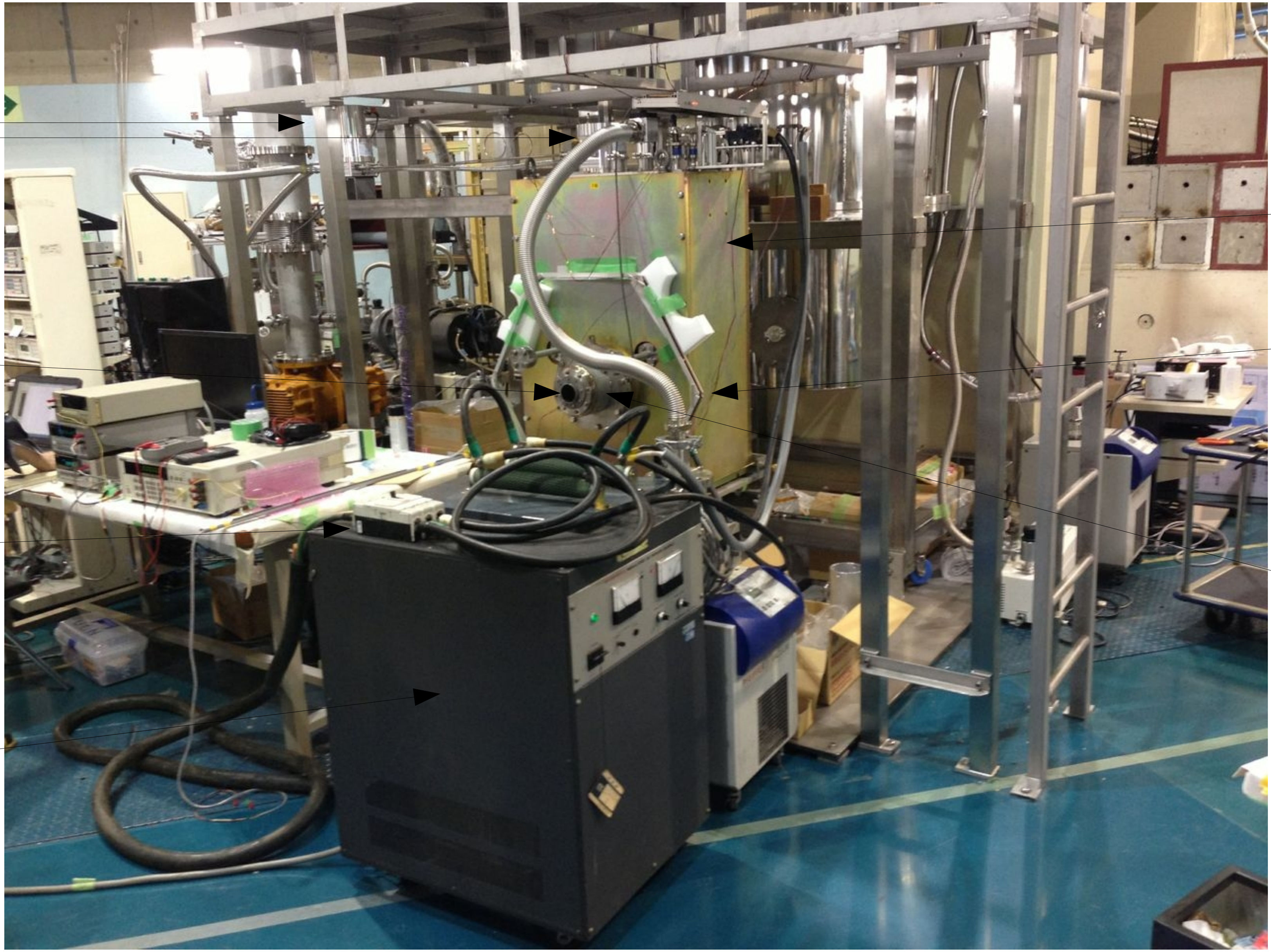
B =3.5 T$\rightarrow \vec{\mu}_B \cdot \vec{B} = 210$ neV.
Polarizable energy range:
0-210 neV.
Only one spin state can pass.

But we have to be careful to do not depolarize UCN during transport

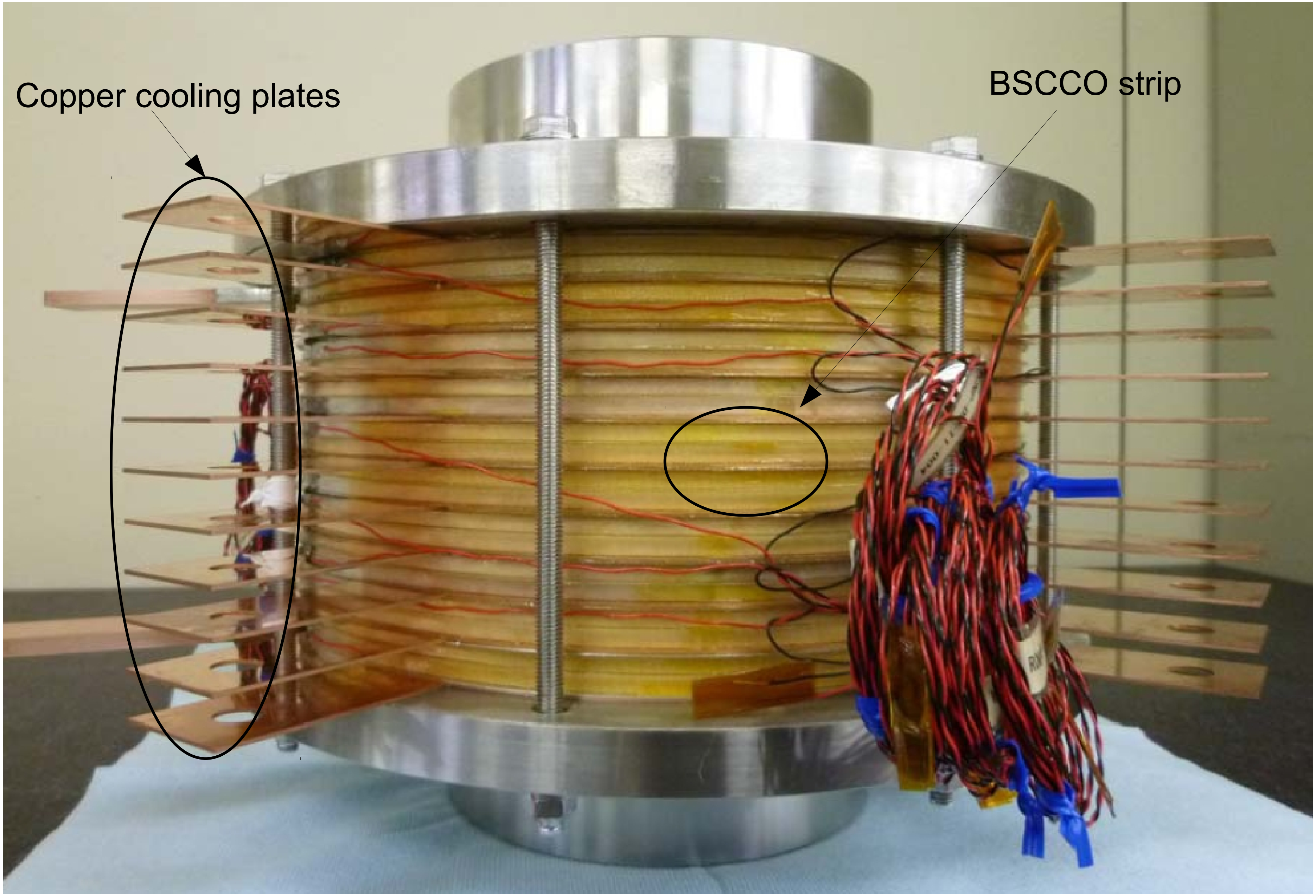
SC magnet at RCNP



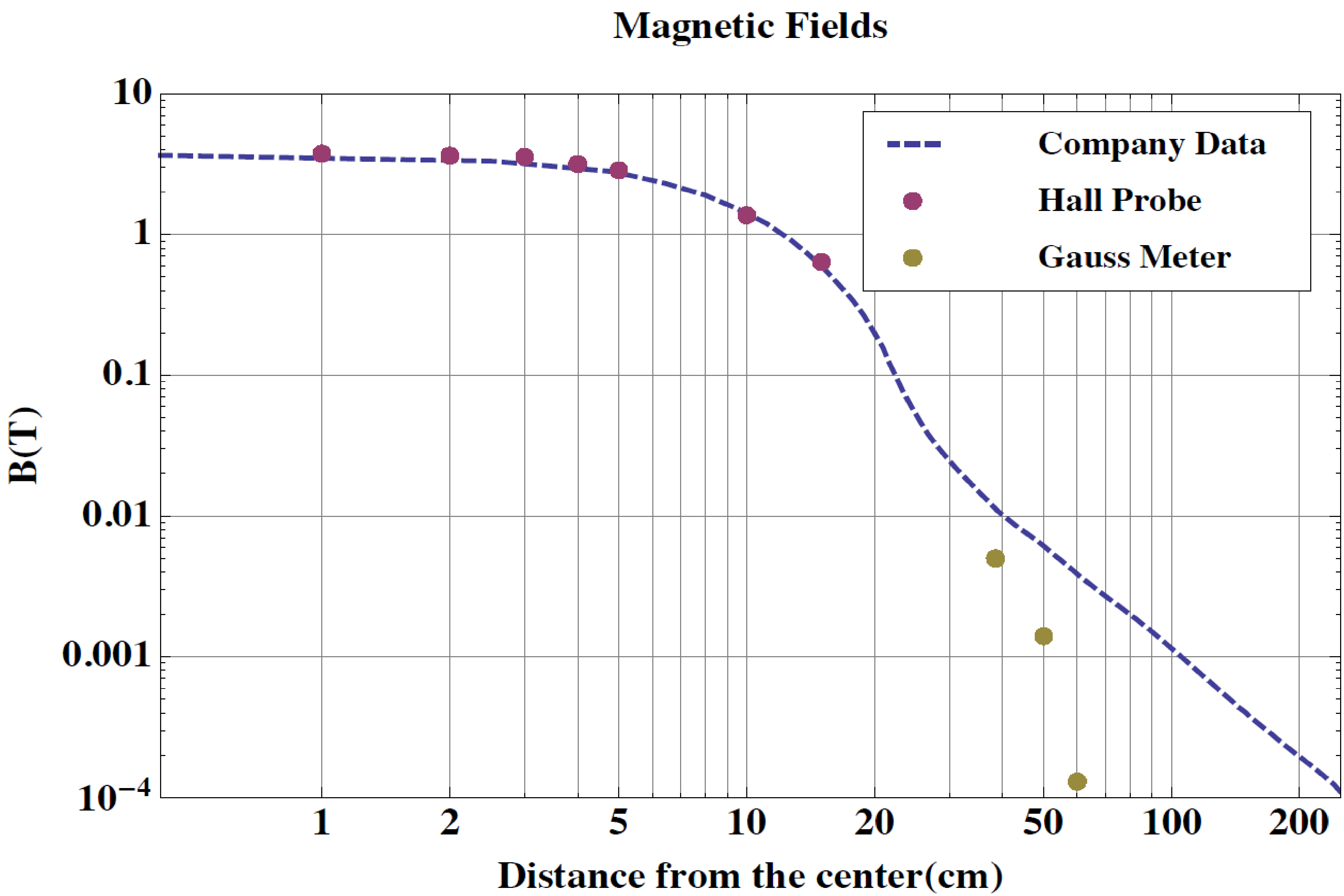
SC magnet at RCNP



SC coil

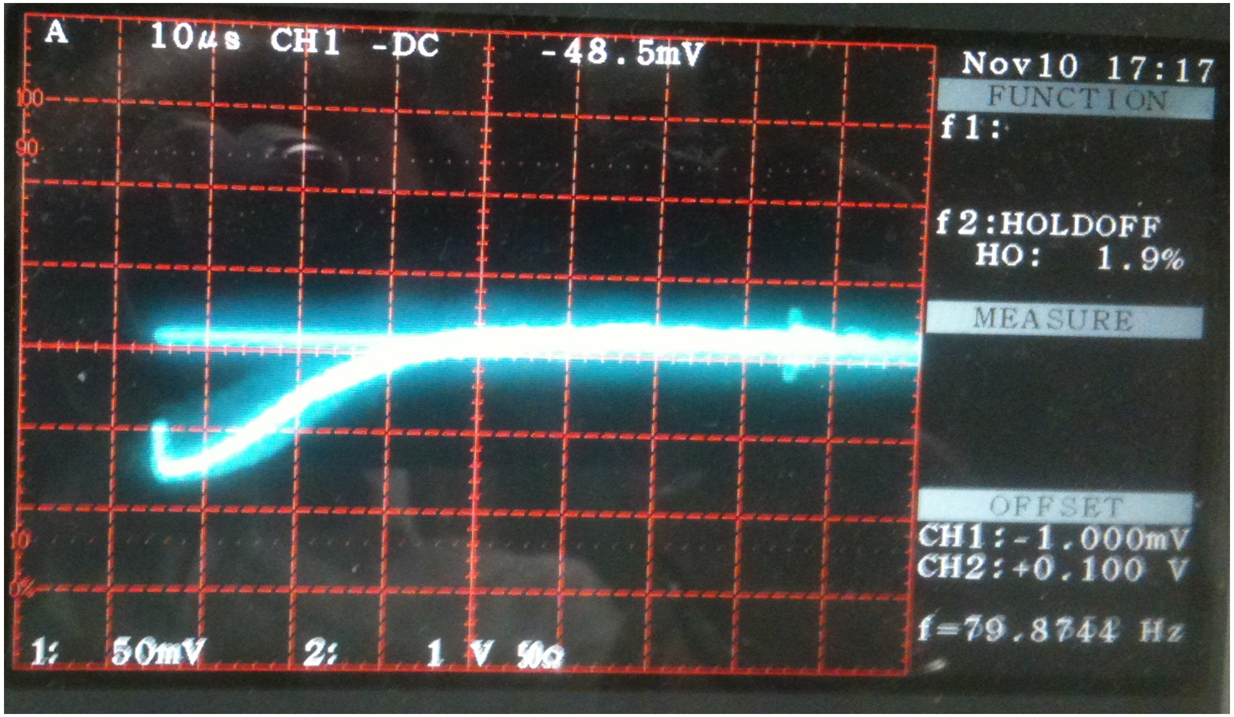


Magnetic field check on axis



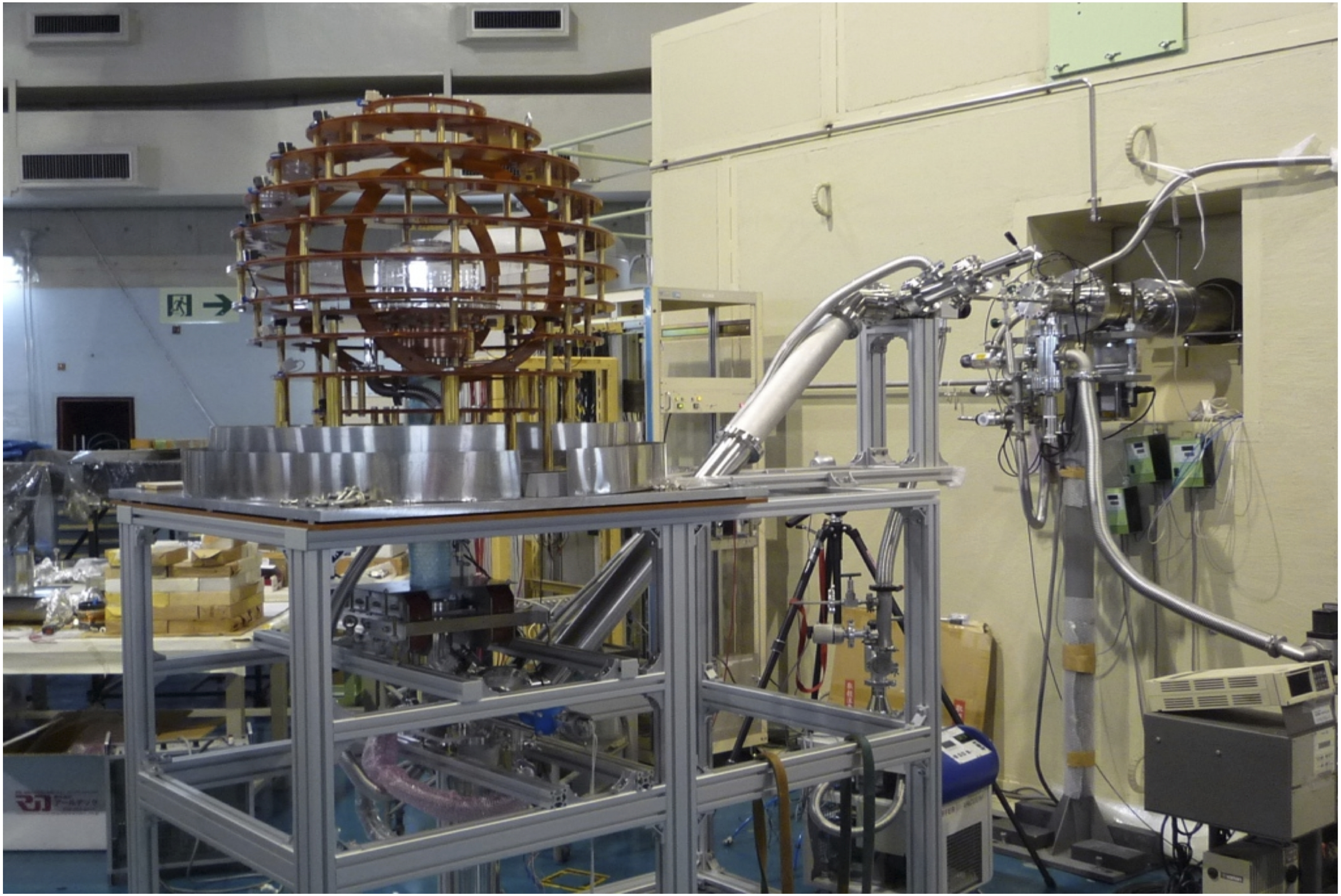
Horizontal source

- We got first polarized UCN during last November!



- Analysis currently on going.

The nEDM experiment



Many nEDM experiments!

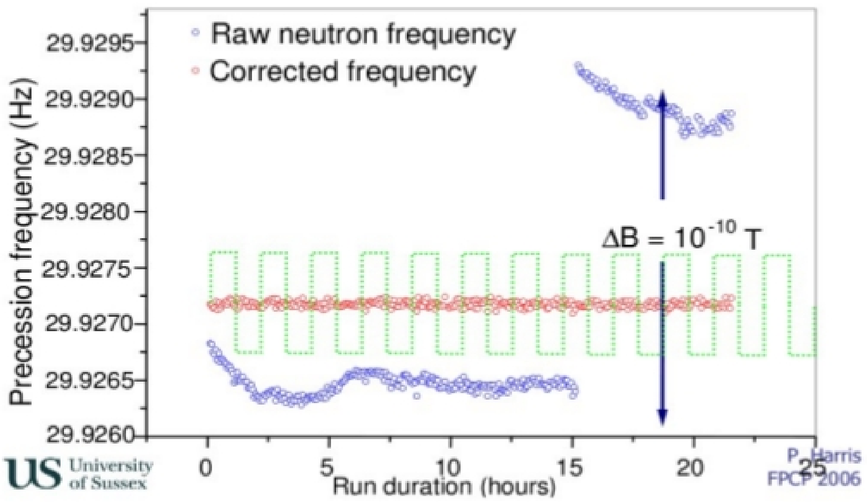
	RAL/ SUSSEX /ILL (Grenoble, FR)	PSI (Villigen, CH)	TUM (Munich, DE)	SNS EDM (Oakridge, US)	CryoEDM (Grenoble, FR)	Russian (Grenoble, FR ⇒ Dubna, RU)	TRIUMF (Vancouver, CA)
temp	RT	RT	RT	0.7 K	0.7 K	RT	RT
comag	Hg	Hg	Hg	^{3}He	none	none	Xe+Hg
source	reactor, turbine	spall., sD_2	reactor, sD_2	spall, internal ^{4}He	reactor, internal ^{4}He	reactor, turbine, (^{4}He)	spall., ^{4}He
nr of cells	1	2	2	2	4	>1	1-2
goal [ecm]	$3{\cdot}10^{-26}$	$5{\cdot}10^{-28}$	$5{\cdot}10^{-28}$	$3{\cdot}10^{-28}$	$1.6{\cdot}10^{-27}$	$3{\cdot}10^{-28}$	10^{-28}
date	2006	2018	2019	2020	2015	2018	2019

R. Picker

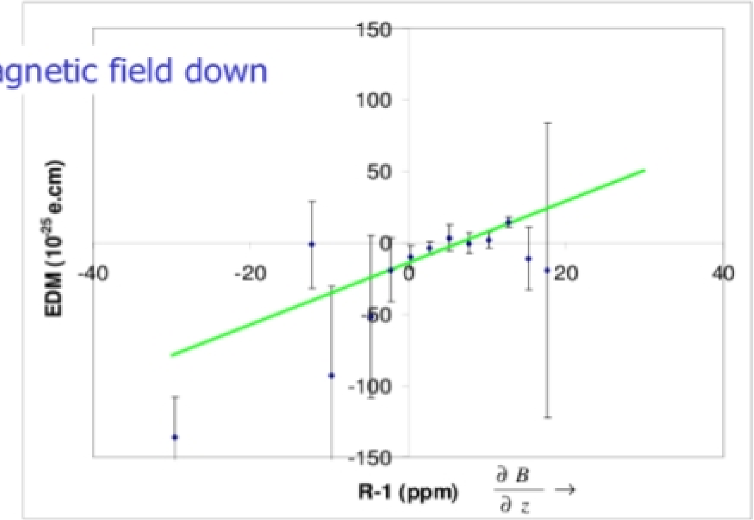
nEDM systematics

- magnetic field variations
- leakage currents
- geometric phase effect
  - false EDM arising from B-field inhomogeneity and E x v.

(co)magnetometry



comagnetometry



false EDM (GP) effect

nEDM systematics

Best nEDM limit so far (ILL/RAL/SUSSEX): 2.9 ·10^{-26} e·cm

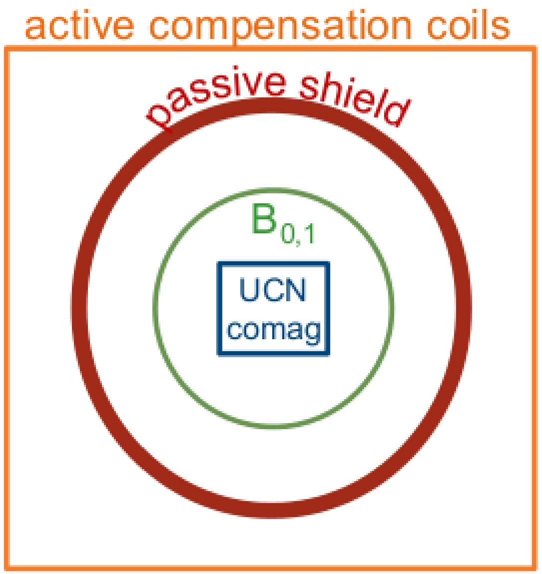
TABLE I. Systematic errors and uncertainties ($10^{-27} e$ cm).

Effect	Shift	σ
Door cavity dipole	−5.6	2.0
Other dipole fields	0.0	6.0
Quadrupole difference	−1.3	2.0
$\mathbf{v} \times \mathbf{E}$ translational	0.0	0.03
$\mathbf{v} \times \mathbf{E}$ rotational	0.0	1.0
Second-order $\mathbf{v} \times \mathbf{E}$	0.0	0.02
ν_{Hg} light shift (geo phase)	3.5	0.8
ν_{Hg} light shift (direct)	0.0	0.2
Uncompensated B drift	0.0	2.4
Hg atom EDM	−0.4	0.3
Electric forces	0.0	0.4
Leakage currents	0.0	0.1
ac fields	0.0	0.01
Total	−3.8	7.2

PRL **97,** 131801 (2006)

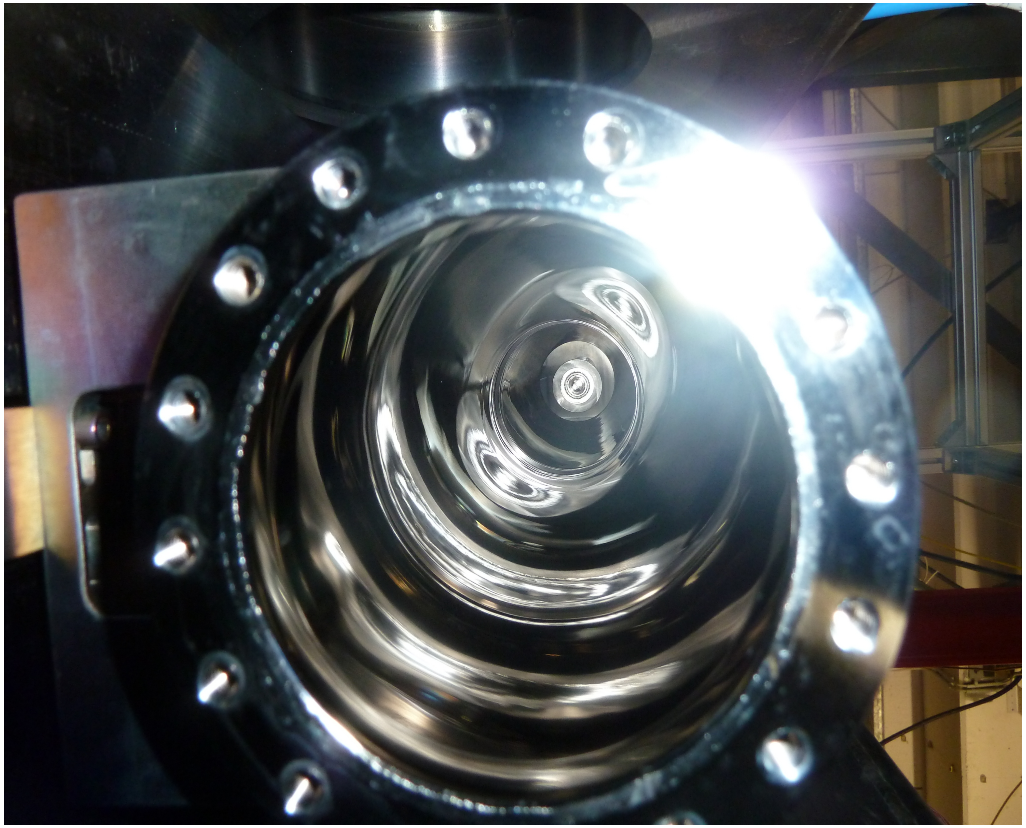
Requirements for 10^{-27} ecm

- B_0 ca 1 μT
- Homogeneity < nT/m
  - ⇒ < 100 pT across the cell
- Stability controlled to < pT



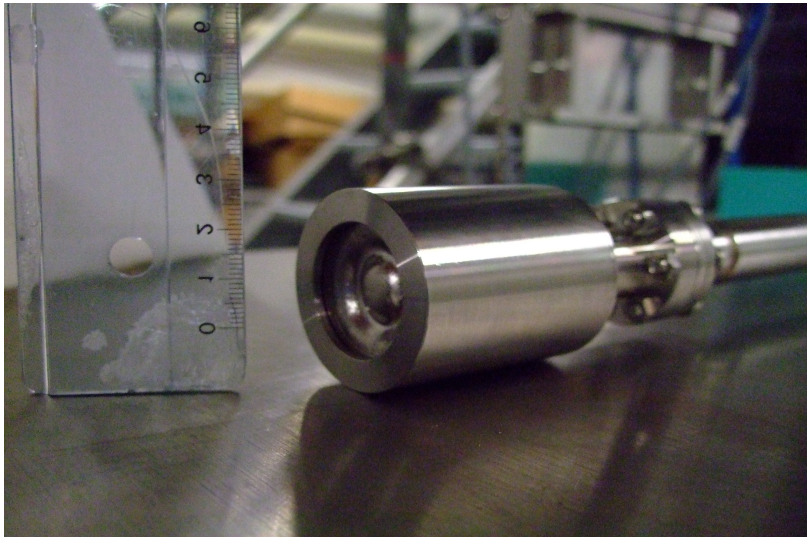
Some developments for the nEDM experiment

- New UCN guides for high polarization
- Non magnetic NiMo coating



Some developments for the nEDM experiment

- New UCN guides for high polarization
- Non magnetic NiMo coating
- Successfully coated at TUM (Munich) last summer



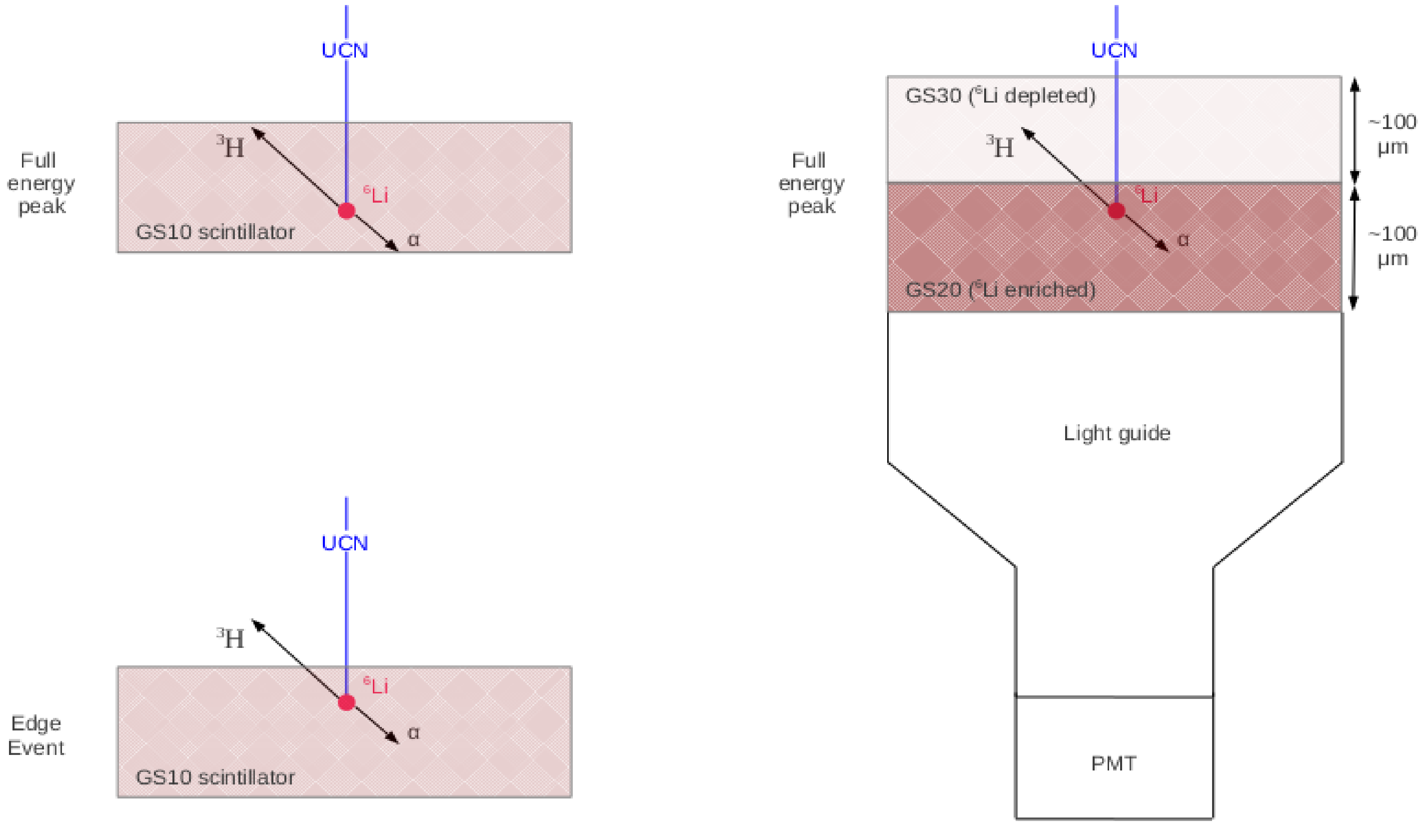
Magnetron sputtering, T. Lauer

Some developments for the nEDM experiment

- New UCN guides for high polarization
- Non magnetic NiMo coating
- Successfully coated at TUM (Munich) last summer
- Should increase polarization from 20% to 99% compared to stainless steel!

Some developments for the nEDM experiment

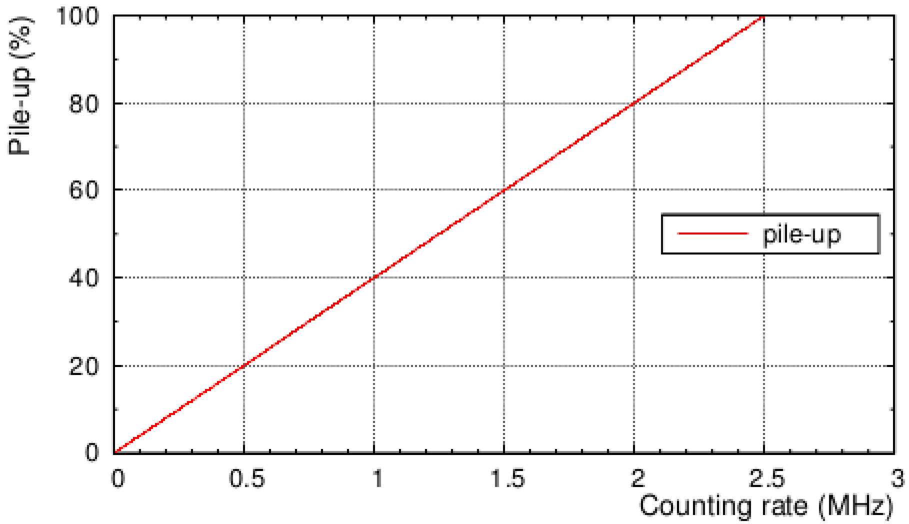
- New high efficiency UCN detector based on neutron capture on Lithium 6

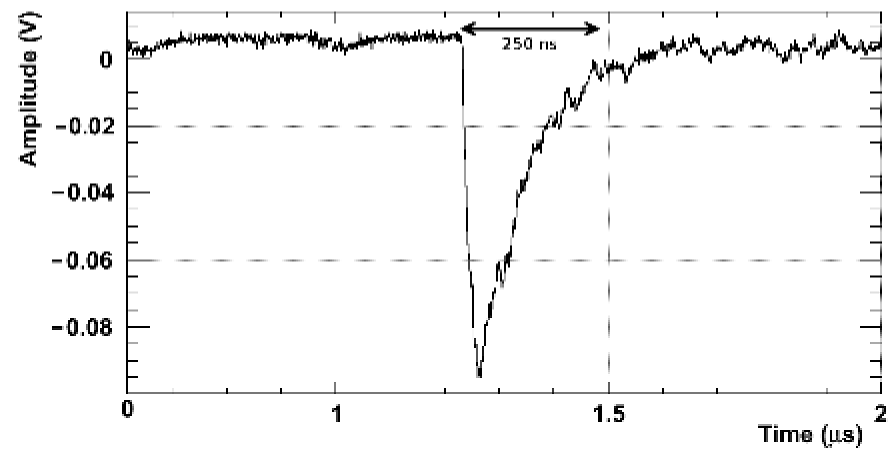


[1] G. Ban, E. Pierre *et al.*, Nucl. Instr. and Meth. A **611**, 280 (2009)

Some developments for the nEDM experiment

First order pile-up calculation (pulse lenght: 250 ns):



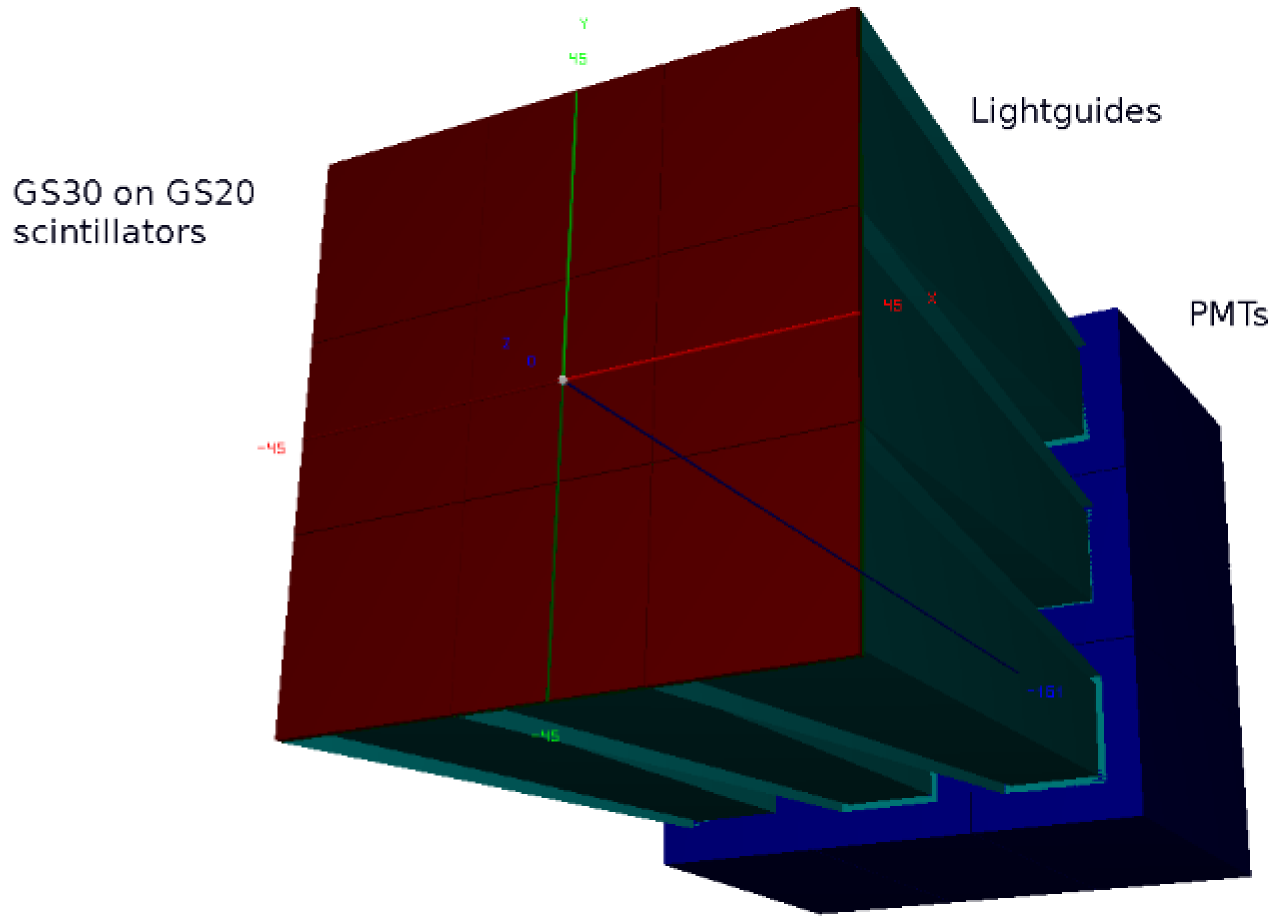


Expected $\sim$ 30 % pile-up at TRIUMF commissioning.

$\rightarrow$ Segmentation needed.

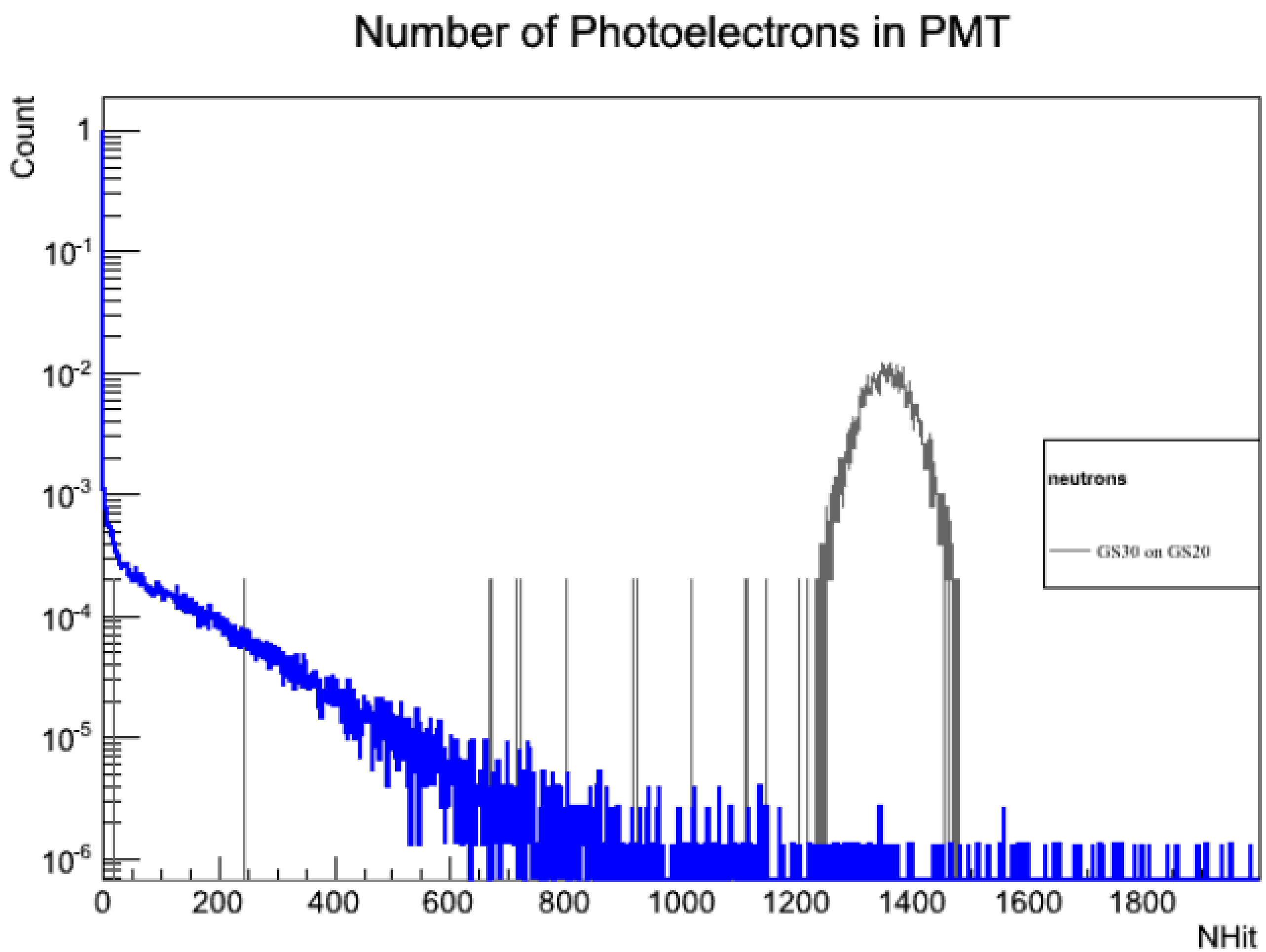
Some developments for the nEDM experiment

- G4 model

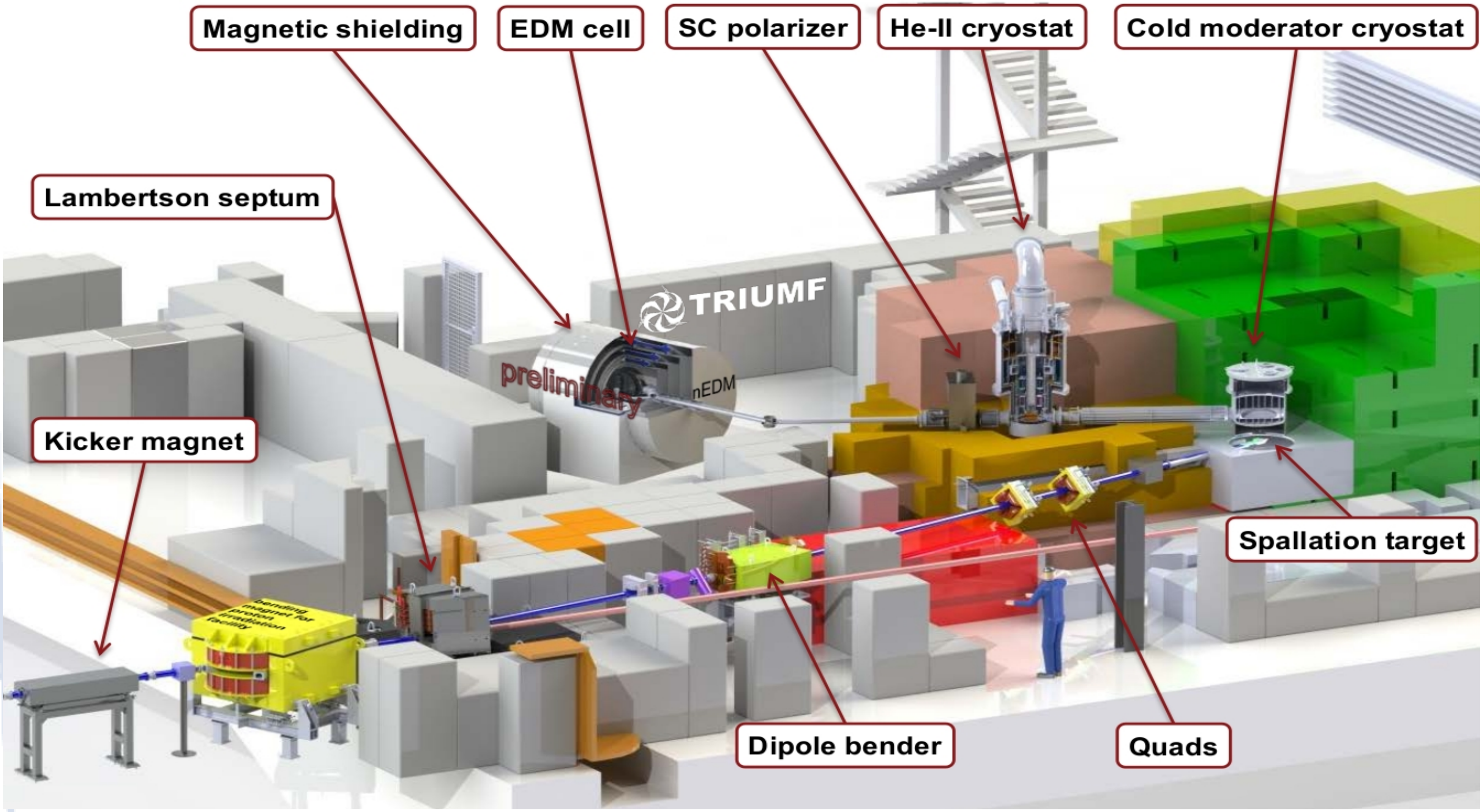


Some developments for the nEDM experiment

- Background study



The future experiment at TRIUMF



Outlook

- The new horizontal source has been tested successfully two months ago
- Focusing on nEDM developments during 2014 such as UCN detector tests with real UCN, magnetic fields and high voltage
- Expected publishable new nEDM limit for 2016 in Japan, just before moving the experiment to Canada

Thank you