nEDM with Spallation UCN Source of He-II

Y. Masuda (KEK), April 15, 2016,
Mainz

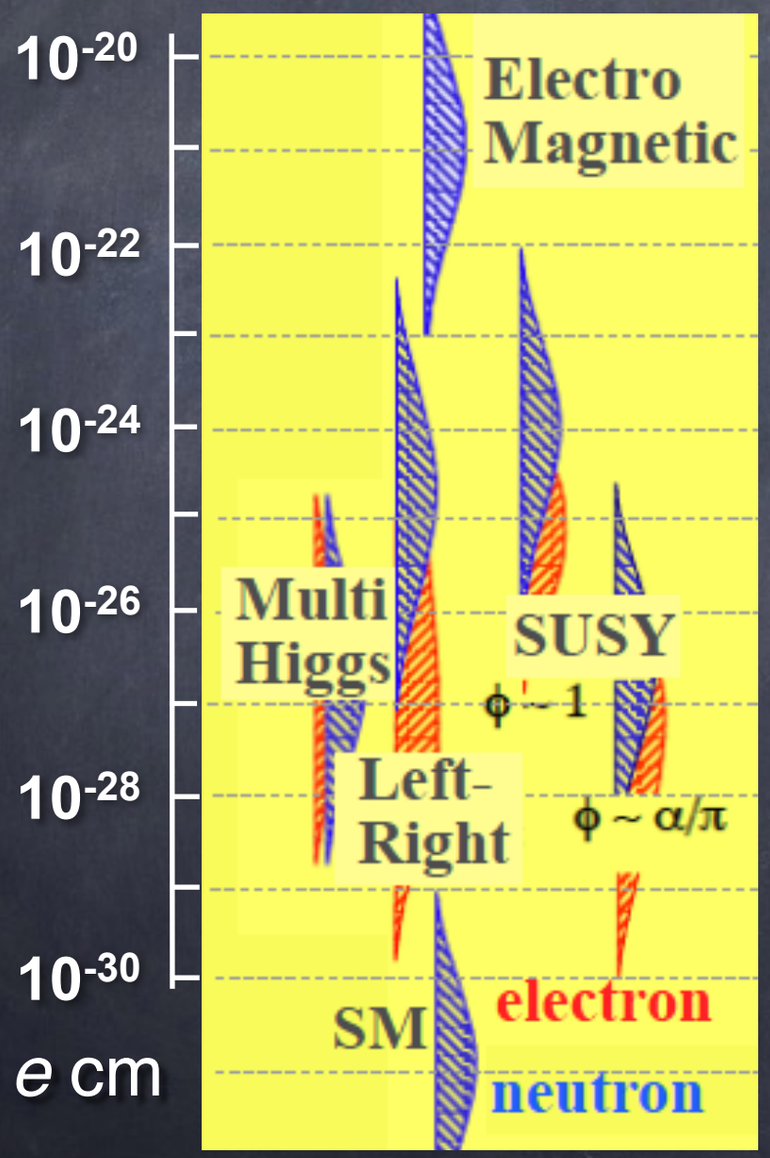
CP violation
shifts
charge distribution

EDM cell

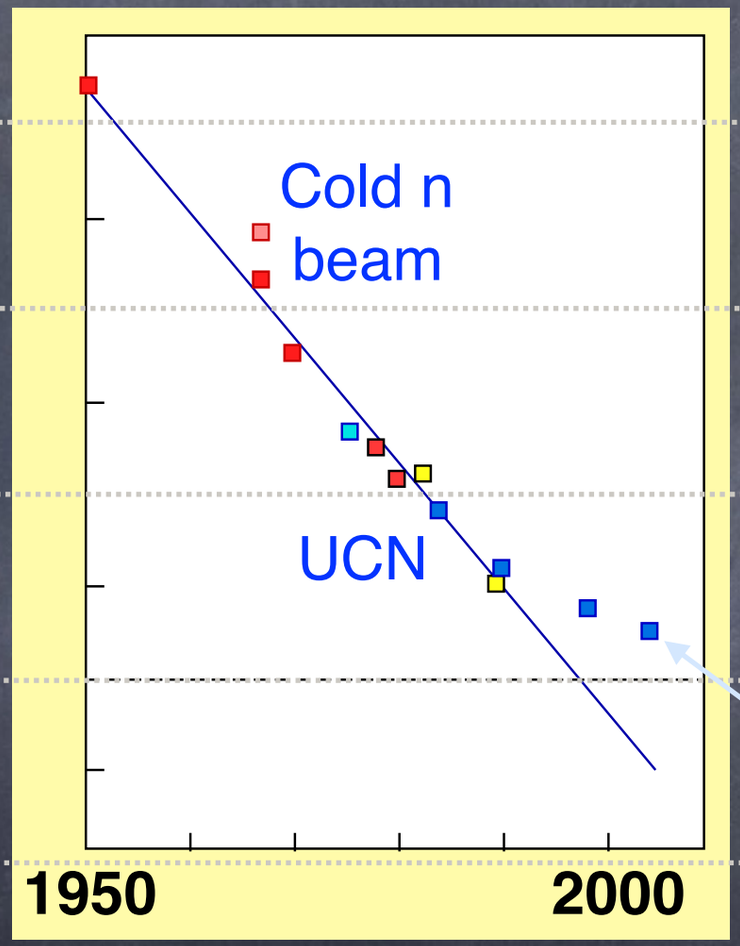
Nuclei in matter

nEDM

Theoretical predictions



History



upper limit of nEDM

10-20

10-22

10-24

10-26 *e* cm

ρ = 1 UCN/cm³

↓

800 UCN/cm³

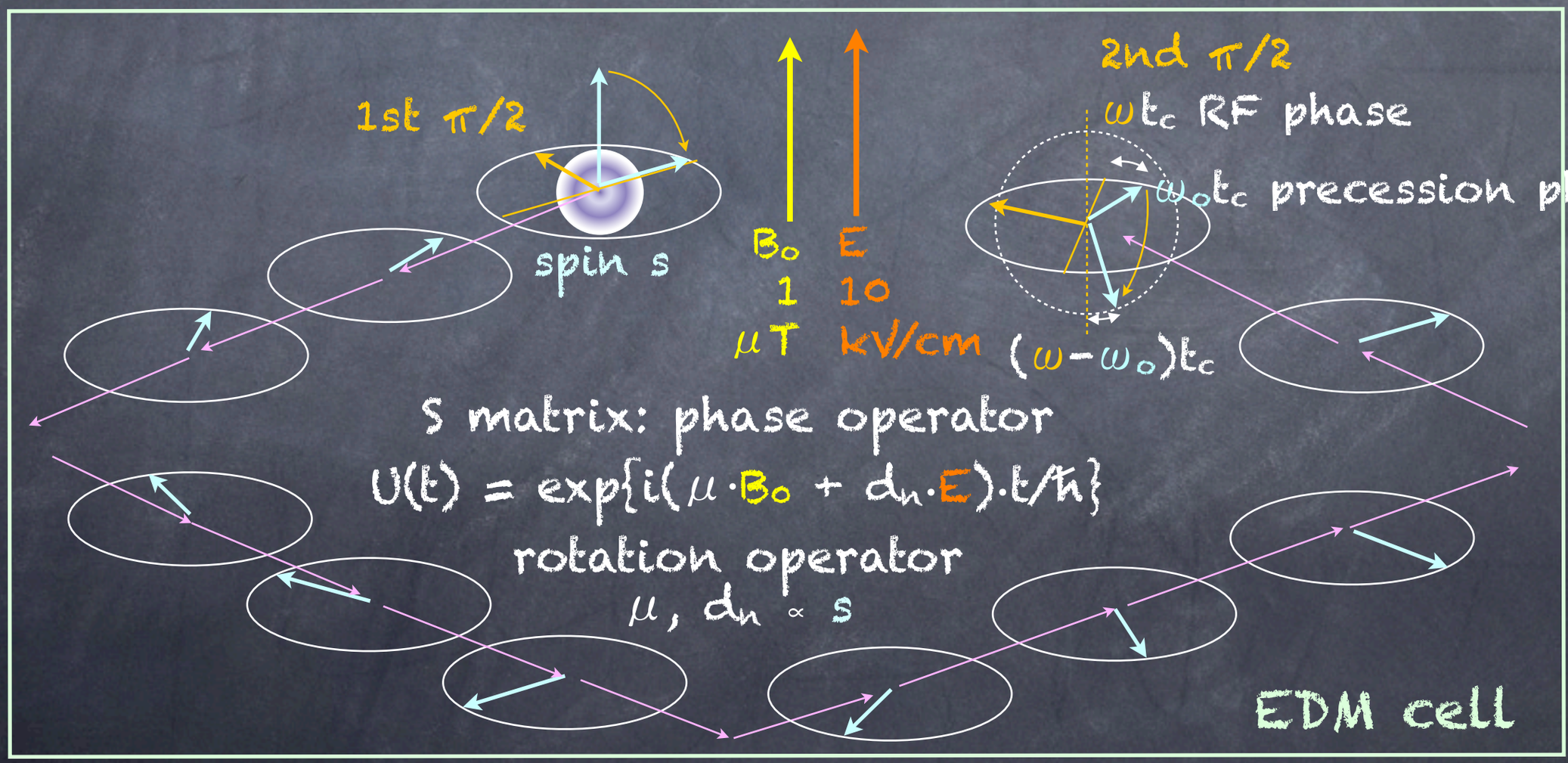
A He-II UCN source

Our EDM measurement

The difference $(\omega-\omega_o)t_c$ is measured by polarimetry: $\delta d_{sta} = \hbar/\{2P_n E t_c \sqrt{N}\}$

Statistical error: 1. *N*, He-II spallation UCN source → 10^{-27}~10^{-28} *e* cm
2. P_n, Magnetic extraction of UCN from He-II

Systematic error: 3. B_0 monitor, ^{129}Xe co-magnetometer → 10^{-27} *e* cm



Our nEDM apparatus

2. Magnetic extraction of UCN

μB_0(3.5T) = 210 neV > V_F(Al)=54 neV

3. ^{129}Xe co-magnetometer

Ramsey resonance
EDM cell

B_0 E

UCN valve is closed during production

SCM

Vacuum

He-II

Al foils

Polarized UCN
P_{UCN}~100%

Rotary valve

Spin analyzer

V_F(guide)= 210 neV

10K D_2O

12L He-II

300K D_2O

Target

proton beam

1. UCN production in He-II

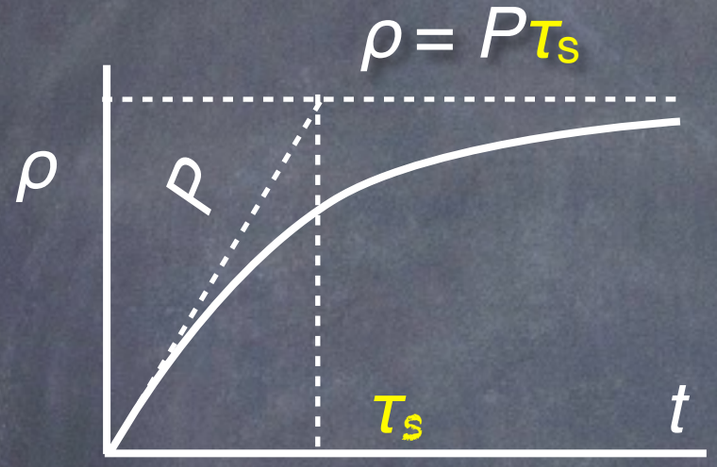
$N \propto$ production rate $\propto E_p \times I_p$

$N \propto$ production time $\propto \tau_S$

$\delta d_{sta} = \hbar/\{2P_n E t_c \sqrt{N}\}$

P = 200 UCN/cm³/s, τ_s = 100 s in 12 L He-II at E_c = 210 new

ρ_{pol} = 800 UCN/cm³ in EDM cell of E_c = 90 neV



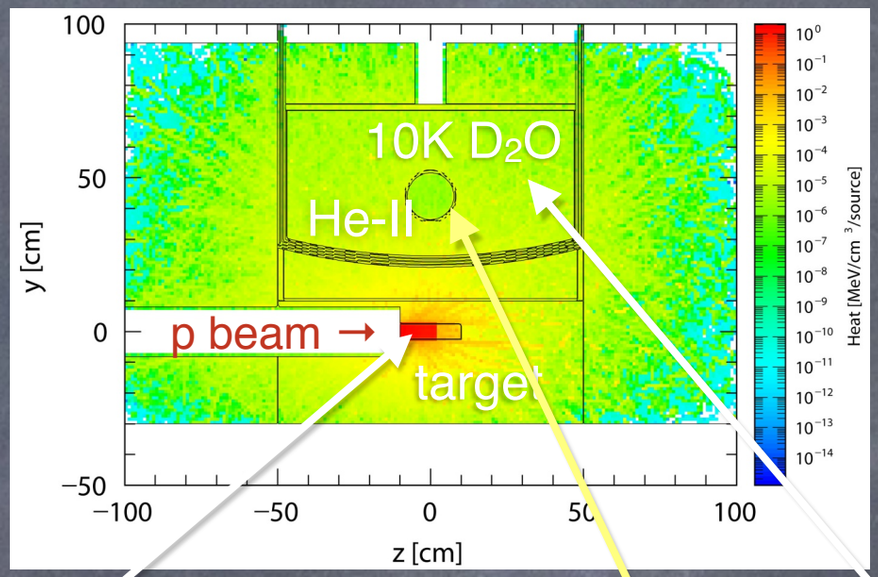
P (production rate)

$= \iint dE_{in} dE_{UCN}$

$N\sigma(E_{in} \rightarrow E_{UCN}) d\Phi_n(E_{in})/dE_{in}$

$\propto E_p \times I_p$

Energy deposit upon spallation reaction



	Target	He-II	10K D_2O
Proton beam power			
400MeV×1μA		0.1 W	4.4 W
400MeV×10μA		1 W	44 W
500MeV×40μA (our goal)		5 W	220 W

He-II bottle wall is dominant

Longer UCN production

τ_{ph} = 600 s at 0.8 K

τ_s (UCN lifetime)

$= 1/\{1/\tau_\beta + 1/\tau_{3He} + 1/\tau_w + 1/\tau_{ph}\}$

= 174 s

τ_β = 886 s (β decay)

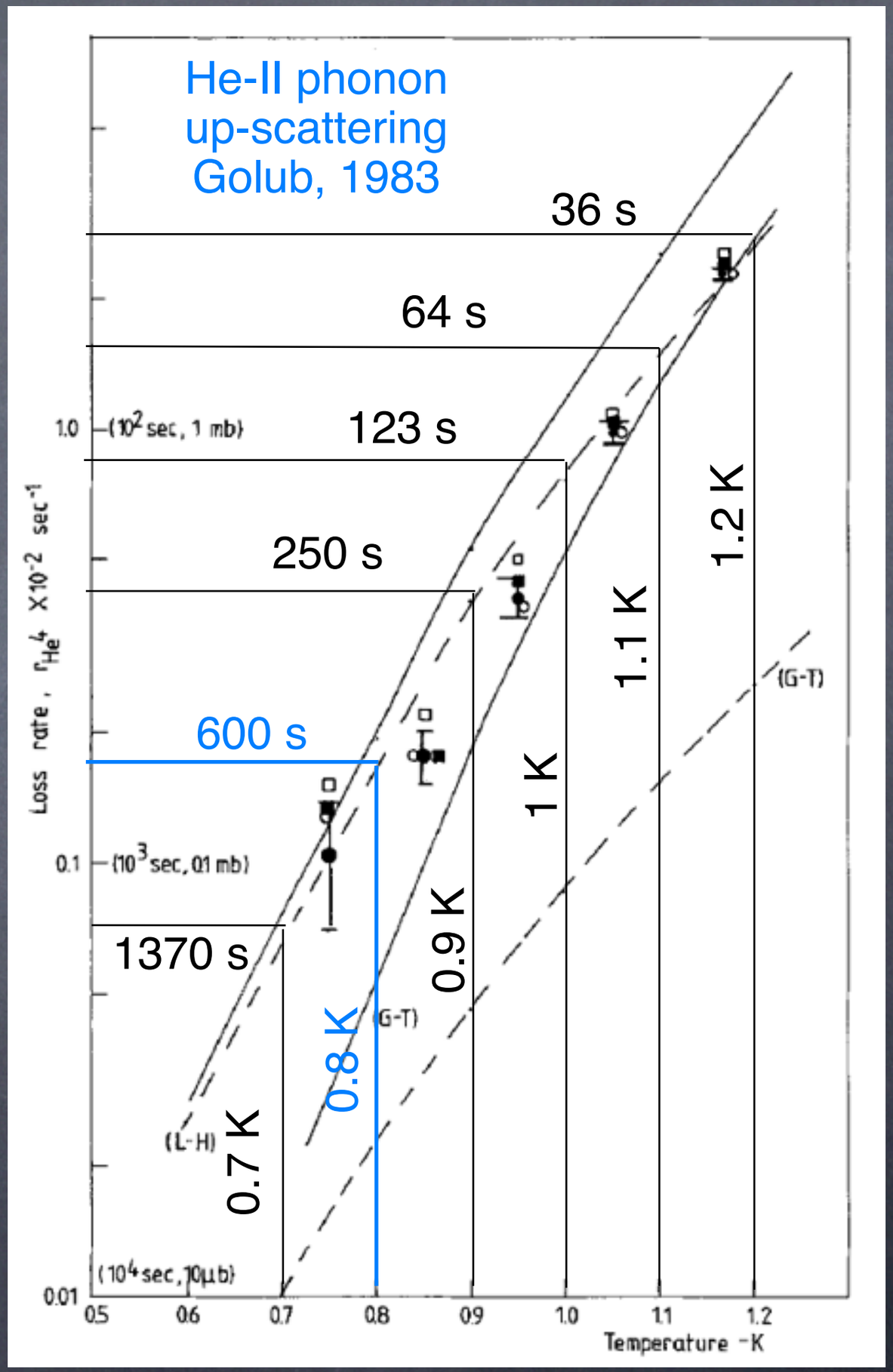
τ_{3He} = 28 ms at $^3He/^4He = 1.4\times10^{-6}$

= 3900 s at $^3He/^4He = 10^{-11}$

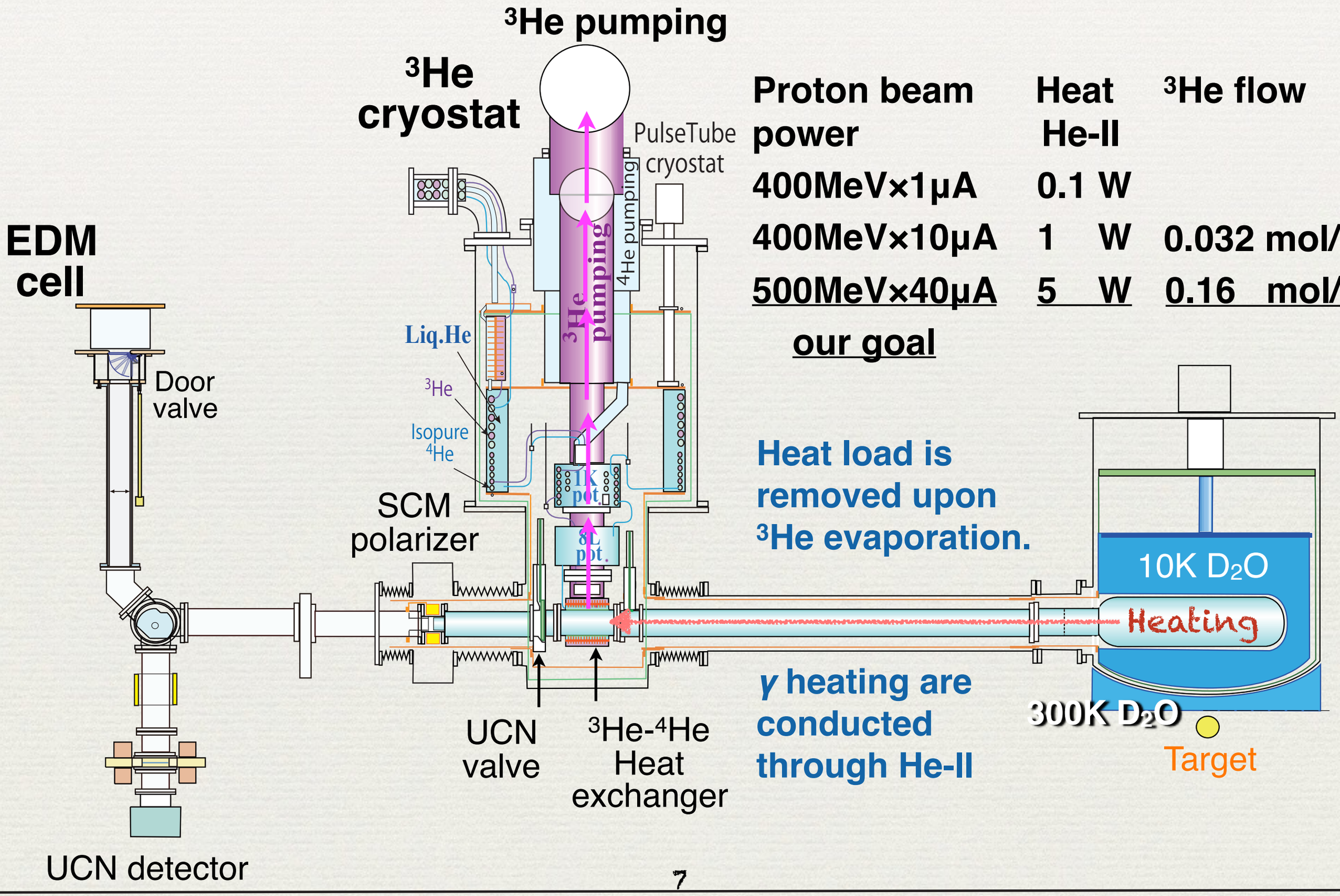
τ_w = 246 s (wall loss)

Z. Phys. B59(1985)261

We are aiming at τ_s = 100 s



He-II cooling at 0.8 K



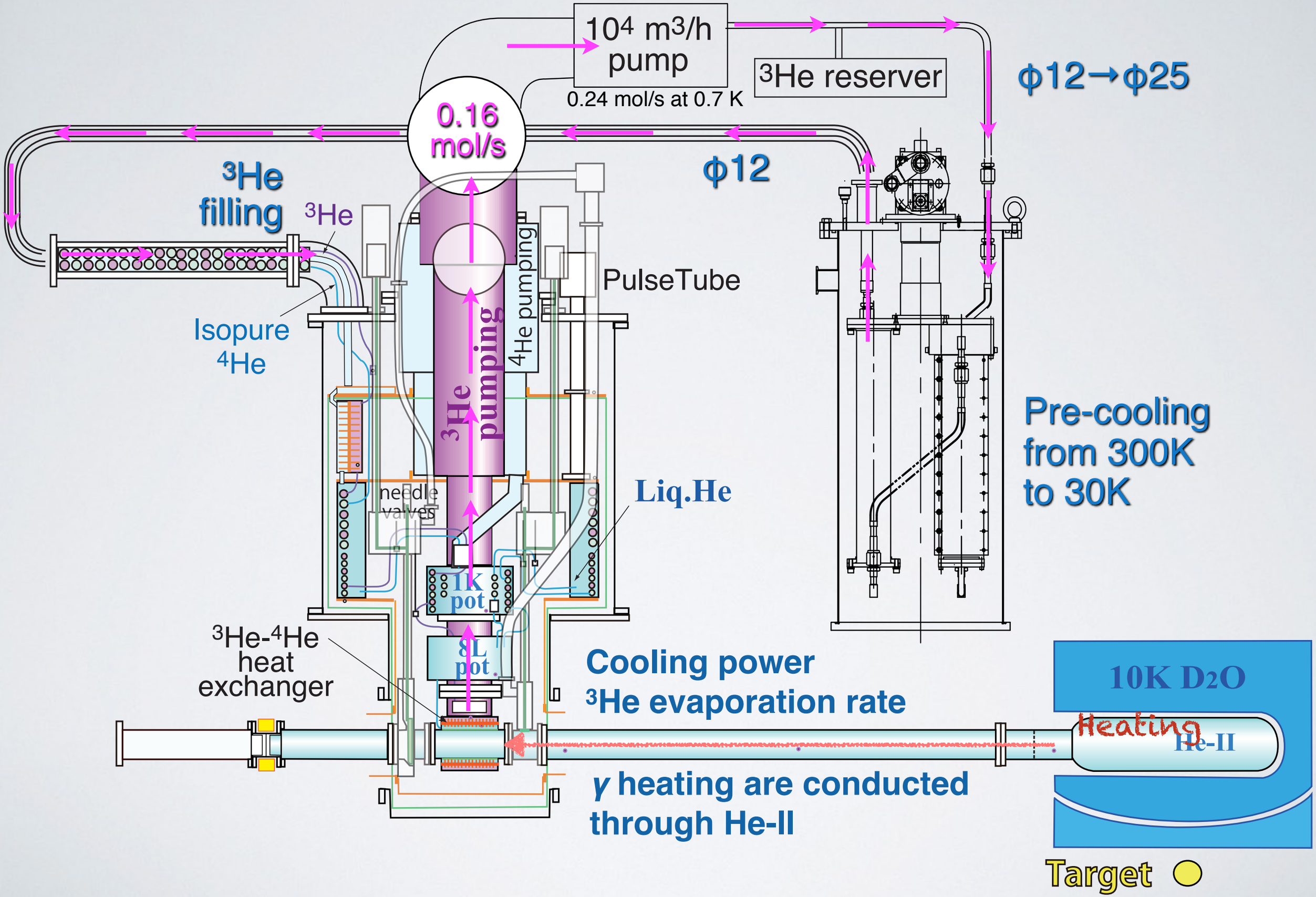
Proton beam power	Heat He-II	³He flow
400MeV×1μA	0.1 W	
400MeV×10μA	1 W	0.032 mol/s
500MeV×40μA	5 W	0.16 mol/s

our goal

Heat load is removed upon ³He evaporation.

***γ* heating are conducted through He-II**

^{3}He of 0.16 mol/s at $E_p \times I_p$ = 20 kW is returned to cryostat



Present status of our UCN source

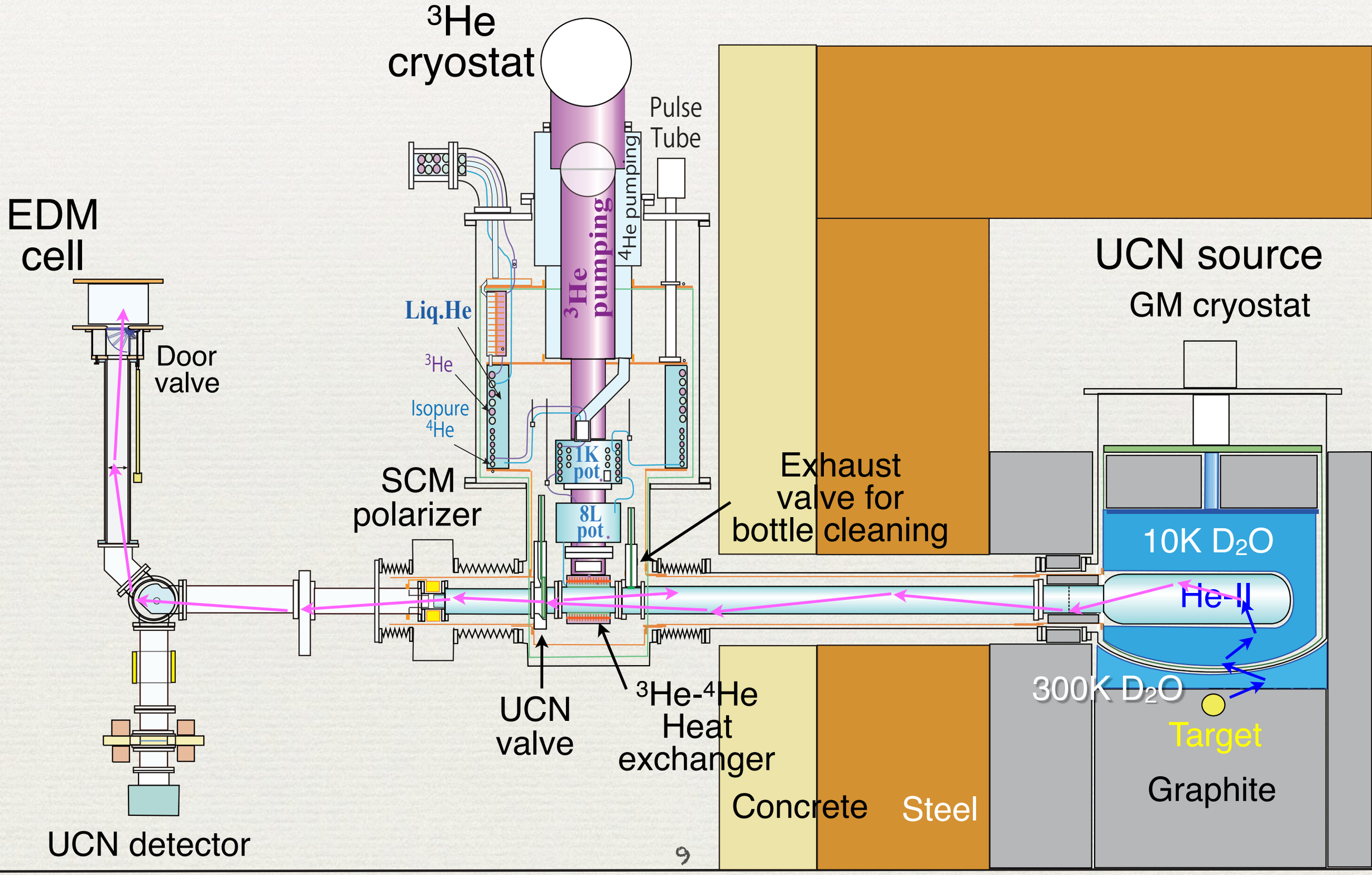


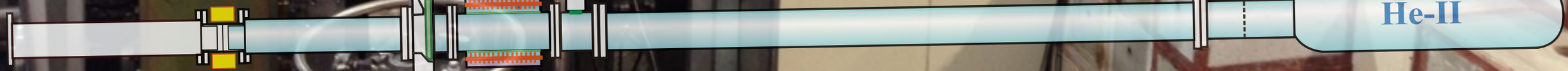
Photo of our UCN source

^{3}He cryostat

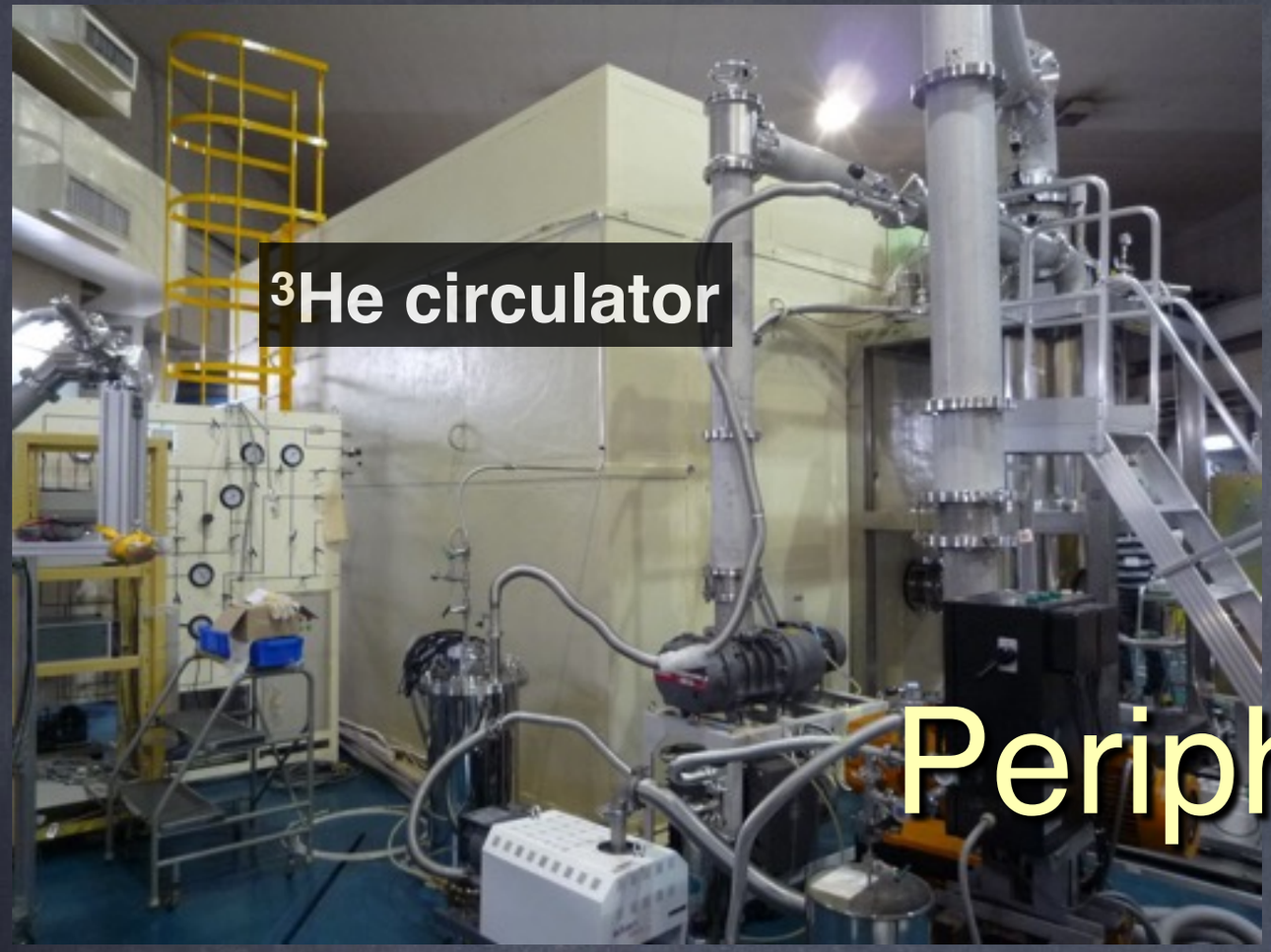
Superconducting magnet

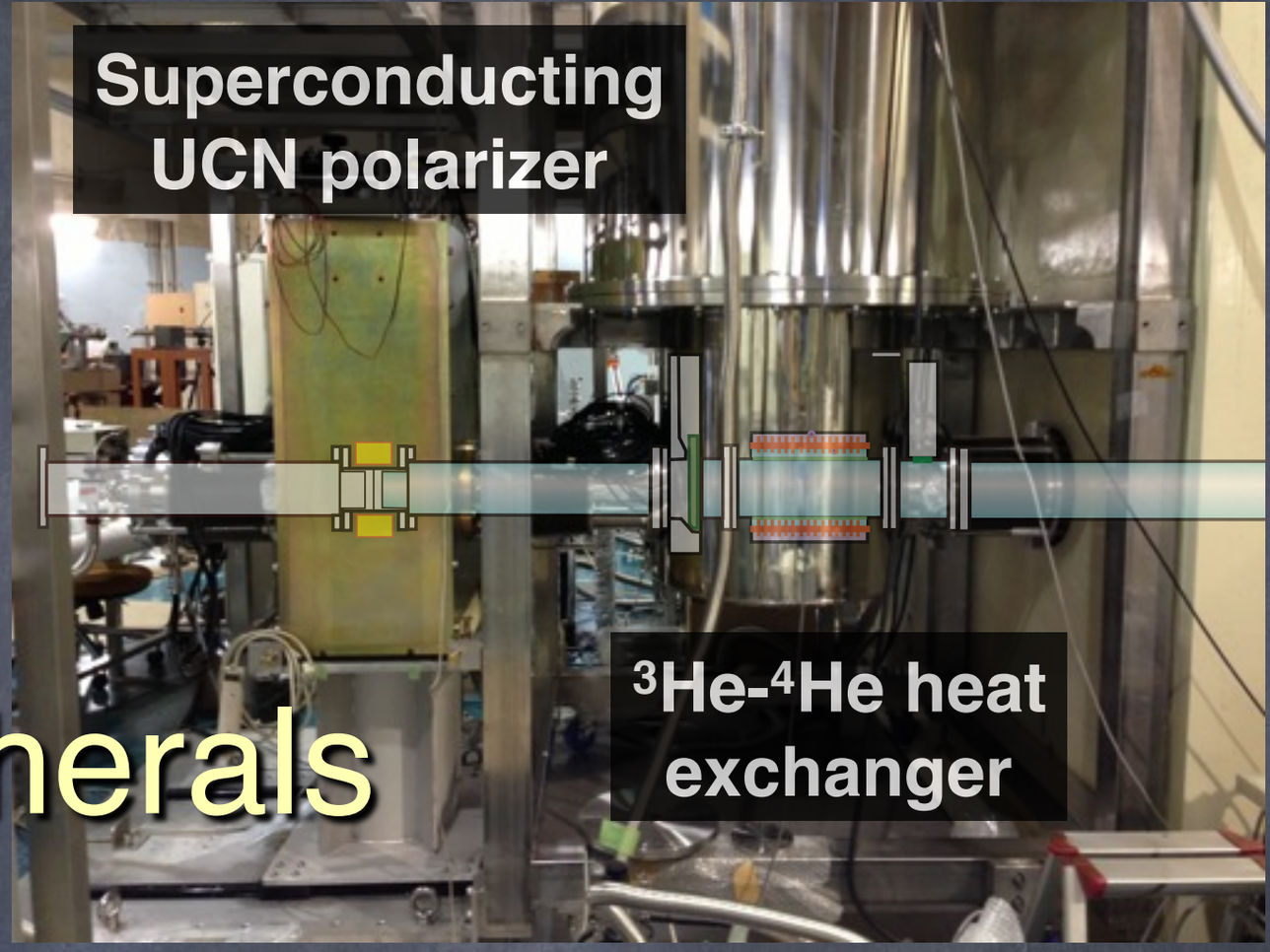
Heat exchanger

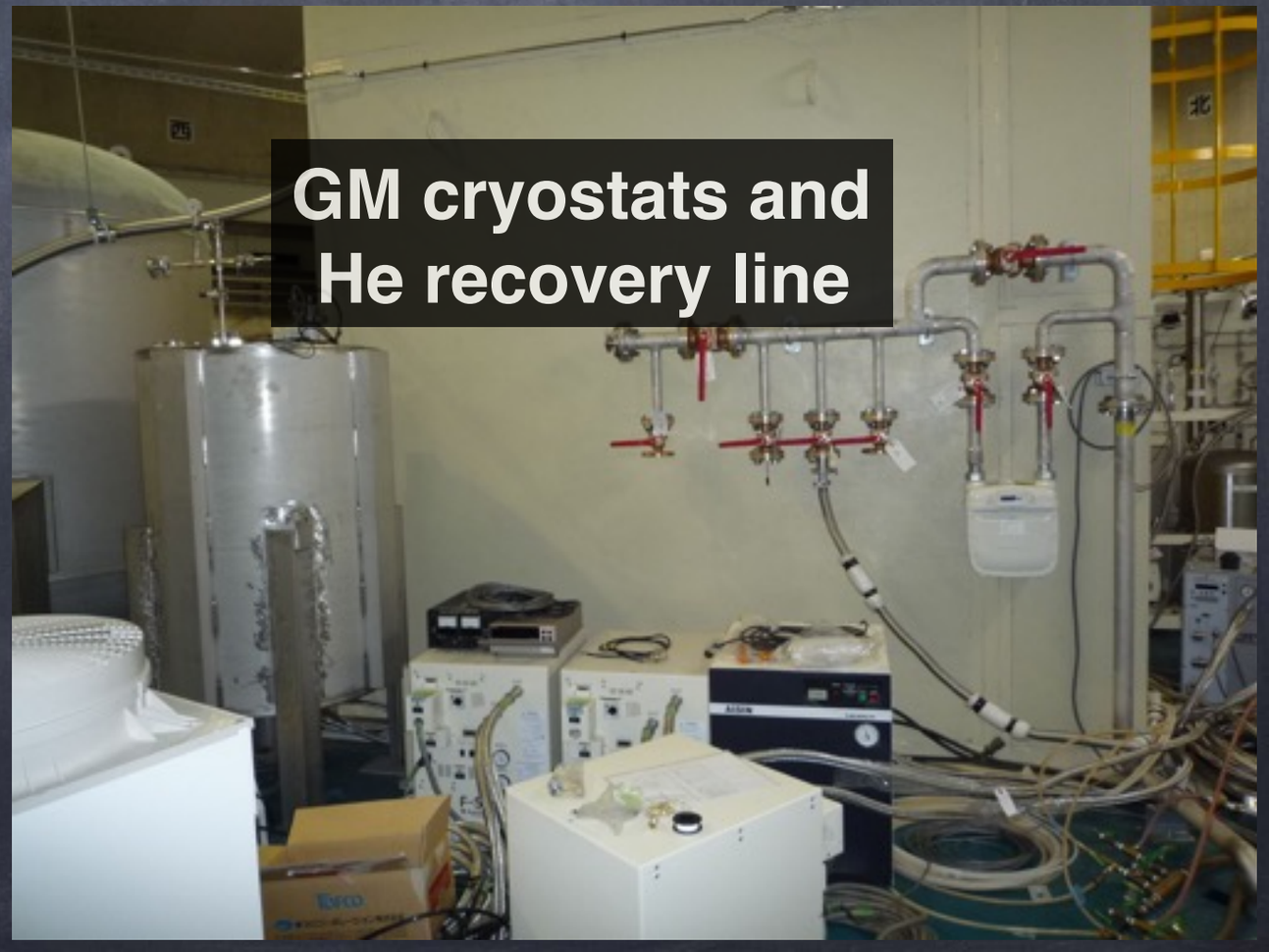
UCN source



Peripherals



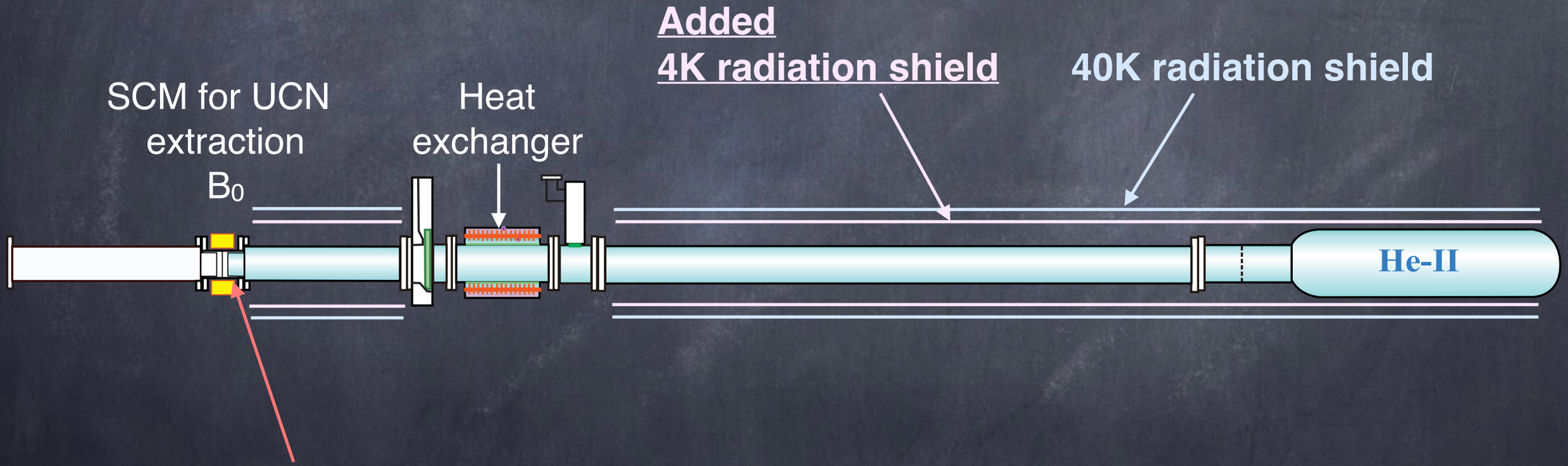




Heat load from outside

to the horizontal UCN guide and the UCN extraction part,

was 1 W ⟶ 0.3 W ⟶ 0.2 W



Replaced Be-Cu with stainless steel for better thermal insulation

Increasing UCN production rate from 4 to 200 UCN/cm³/s at E_c = 210 neV

^{3}He pumping of 2000 m³/h → 10000 m³/h for 5W (10 W)

$E_p \times I_p$ = 20 kW

^{3}He cryostat

We have achieved
cooling power of 1 W at 0.7 K (2 W at 0.8 K)

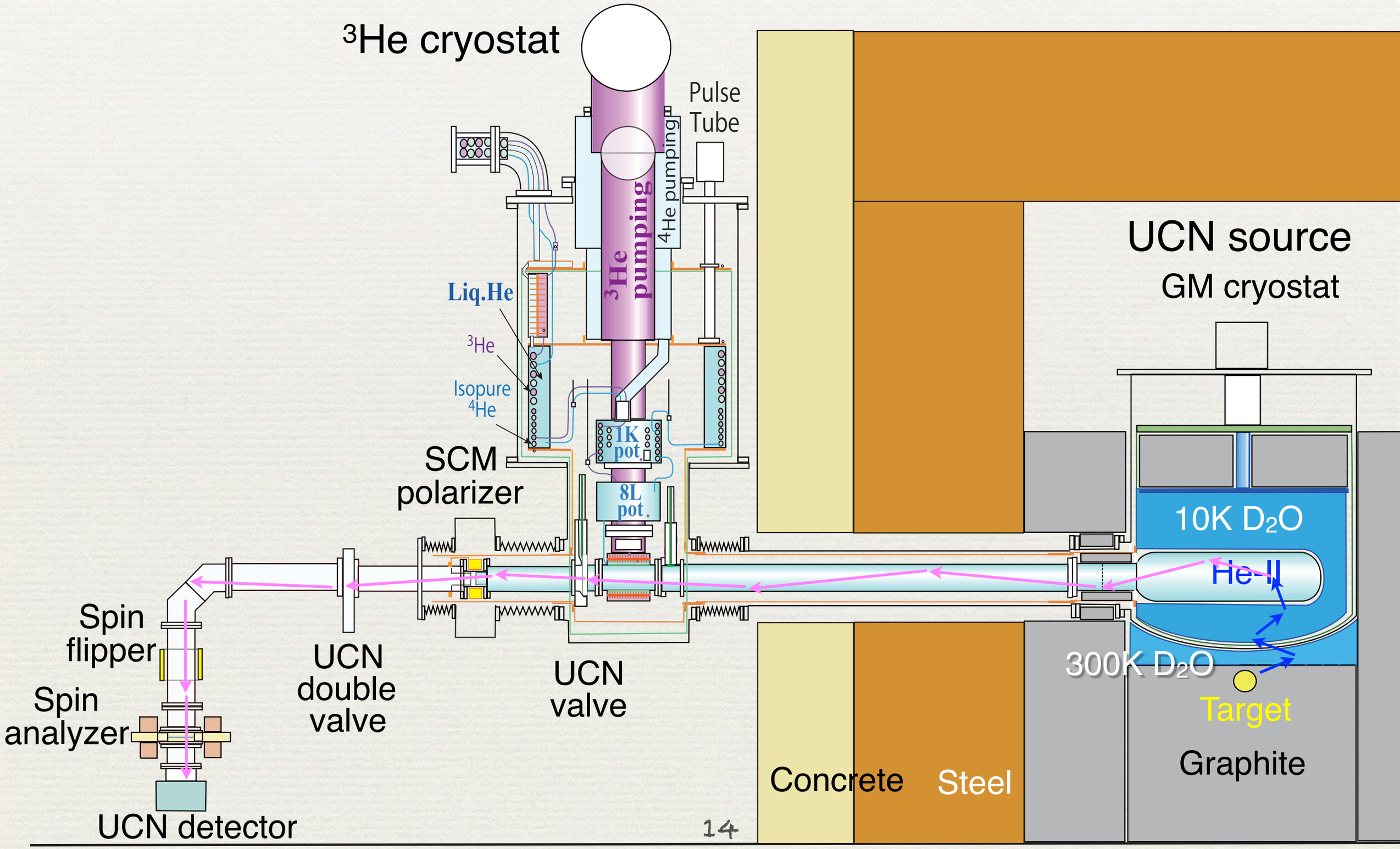
UCN source

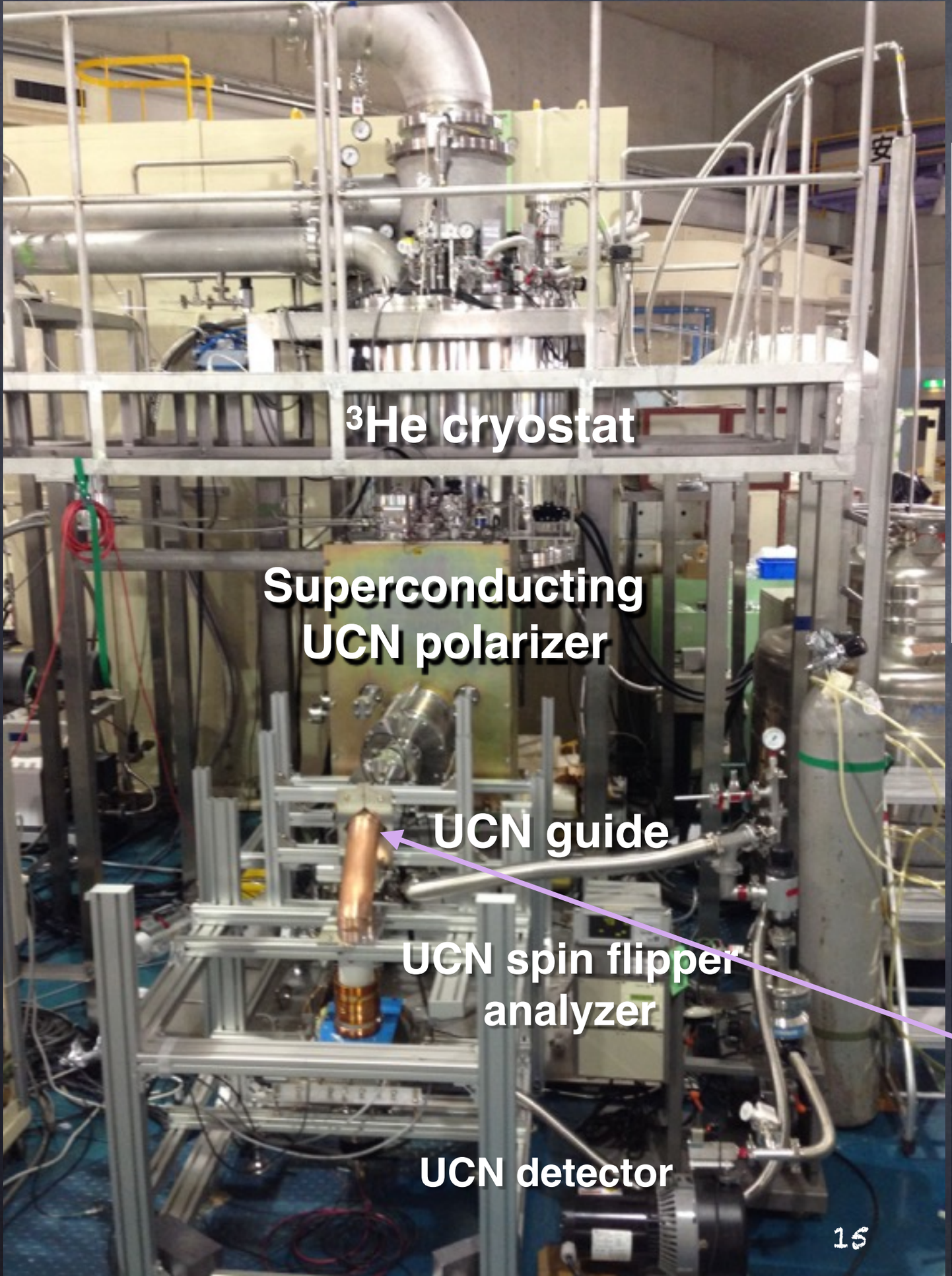
$E_p \times I_p$ = 4 kW (8 kW)

Heat load on He-II	1 W	0.3 W	0.2 W
^{3}He evaporation	32×10^{-3} mol/s	9.6×10^{-3} mol/s	6.4×10^{-3} mol/s
He-II temperature	0.7 K	0.6 K	0.58 K

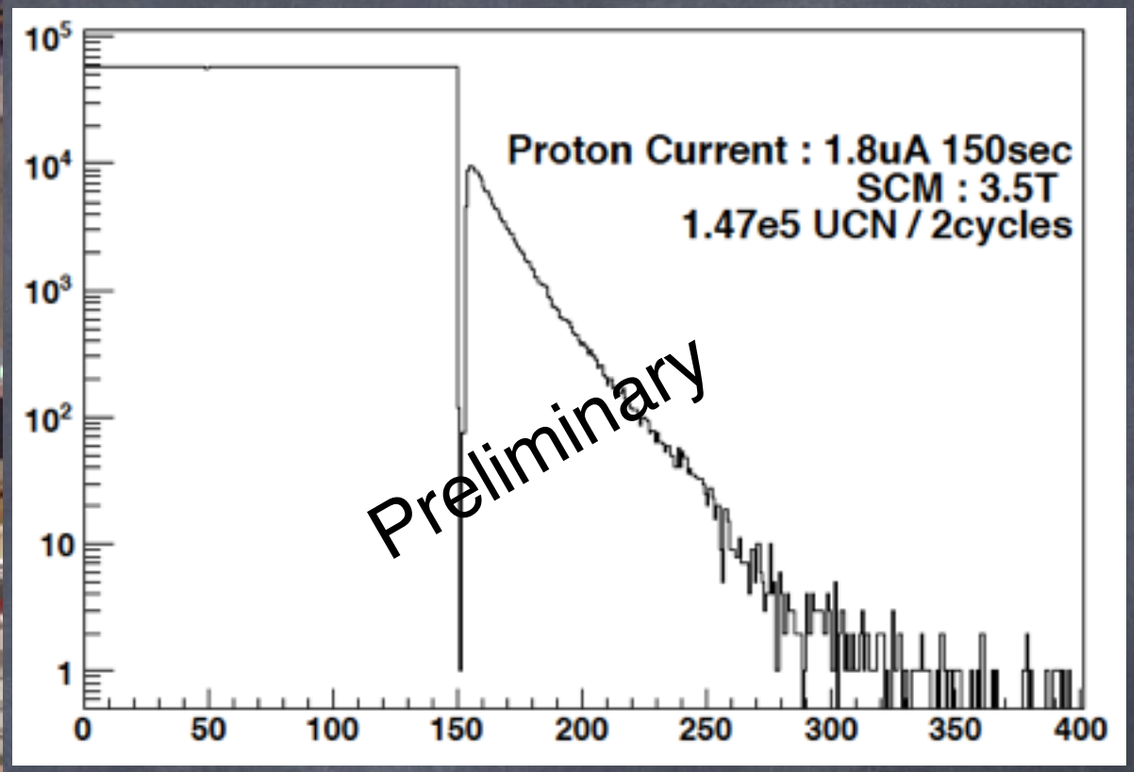
Superconducting magnet

UCN production and polarized UCN extraction

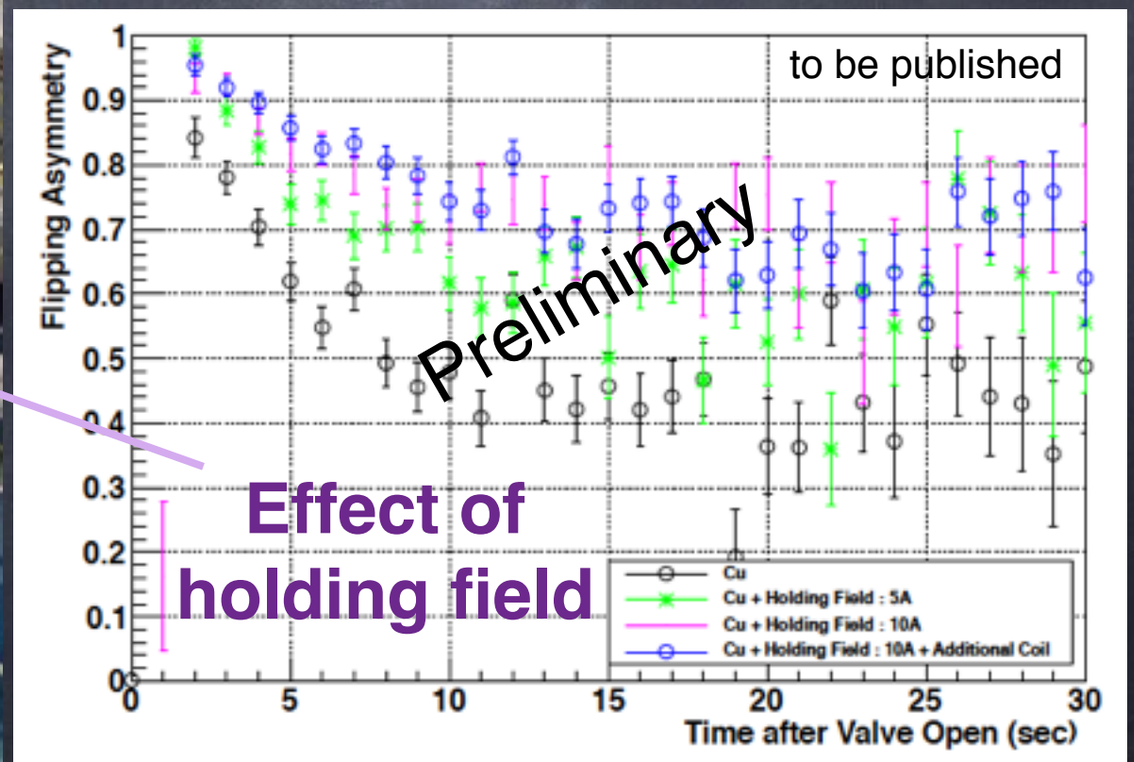




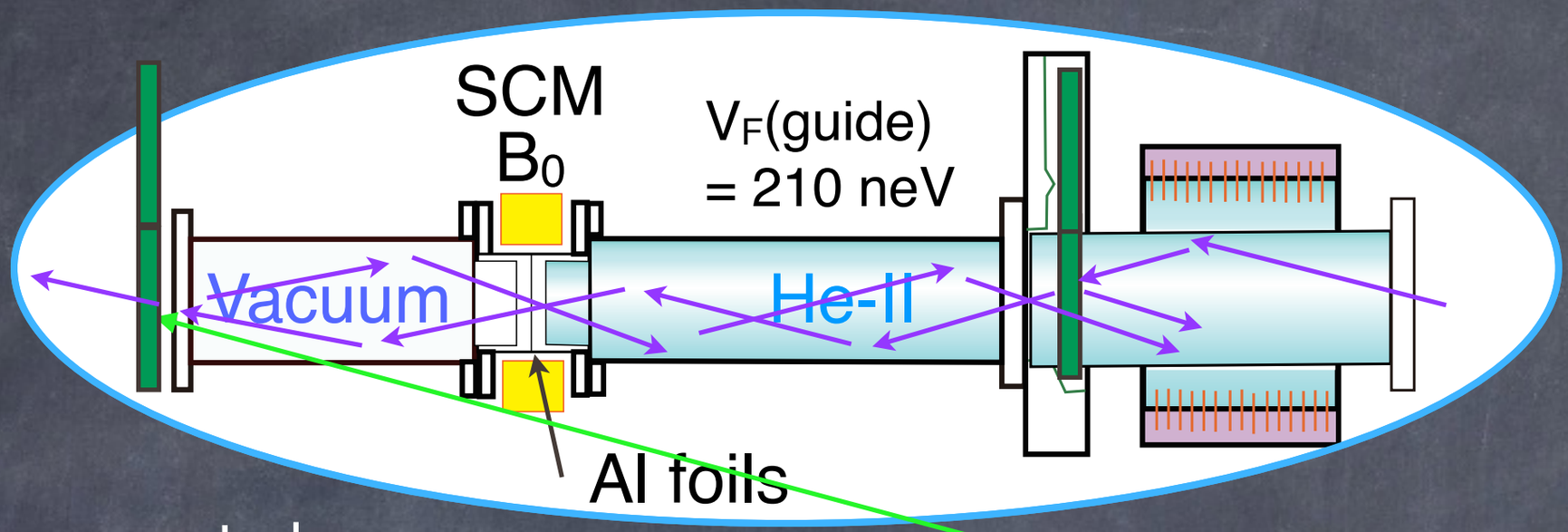
UCN production



UCN polarization

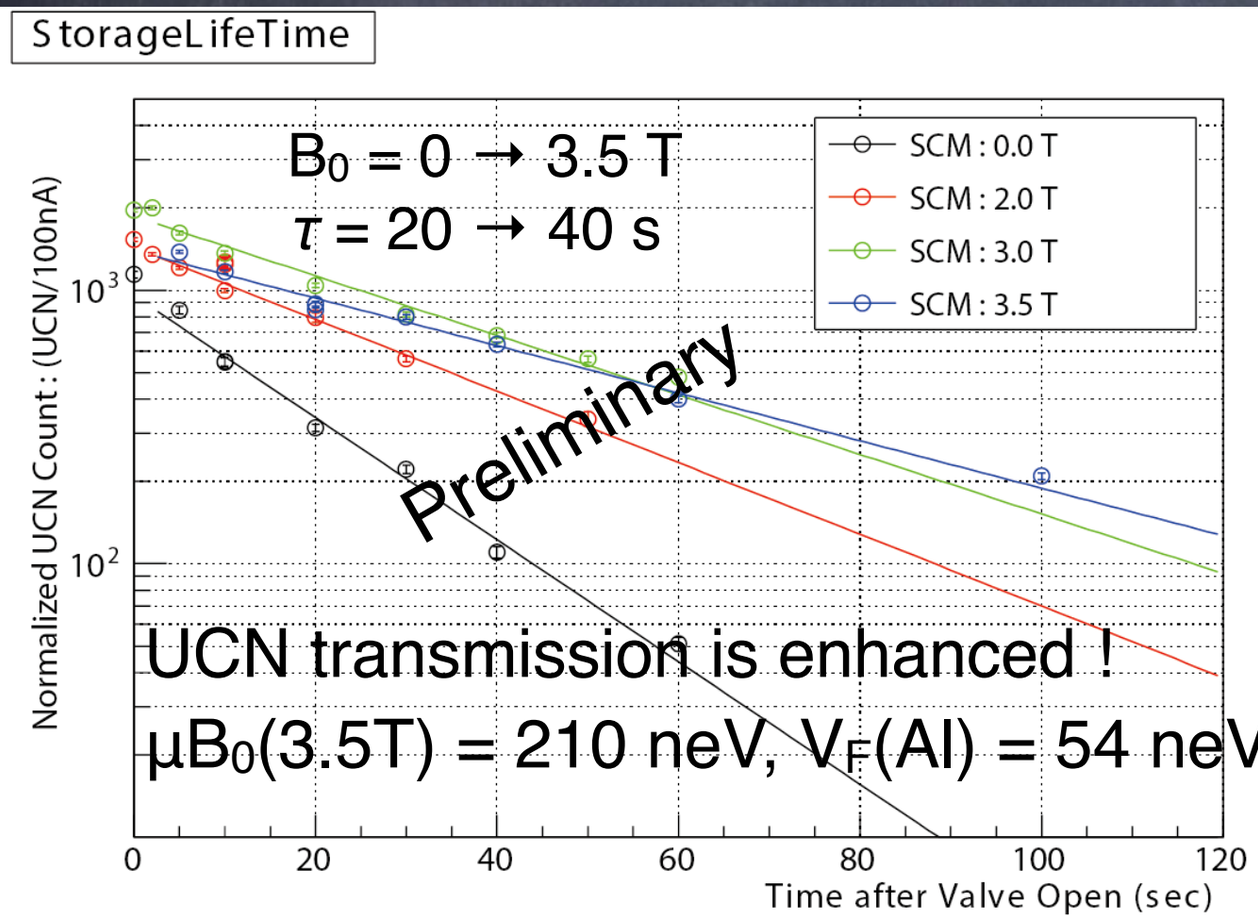


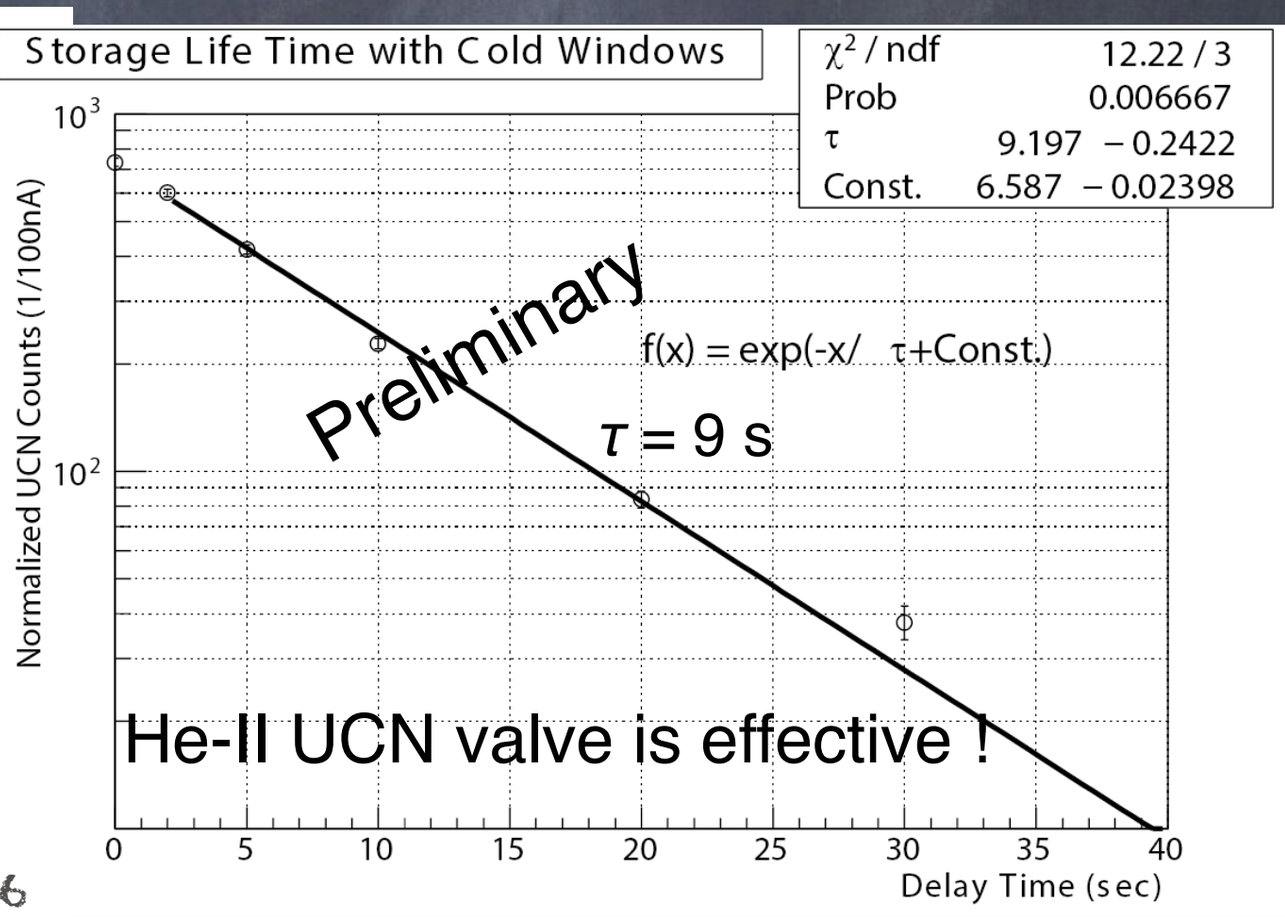
UCN storage lifetime in He-II



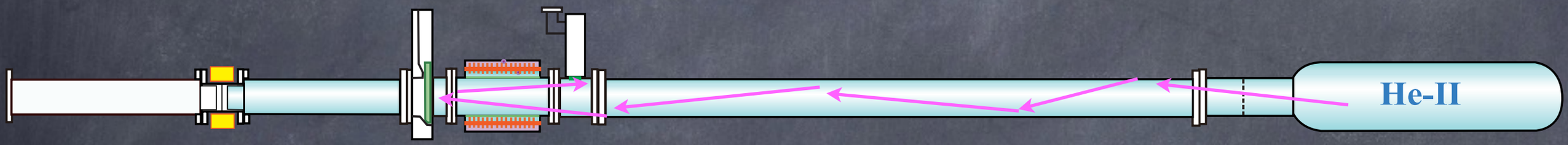
UCN was counted
as a function of valve opening time

Including Al foils





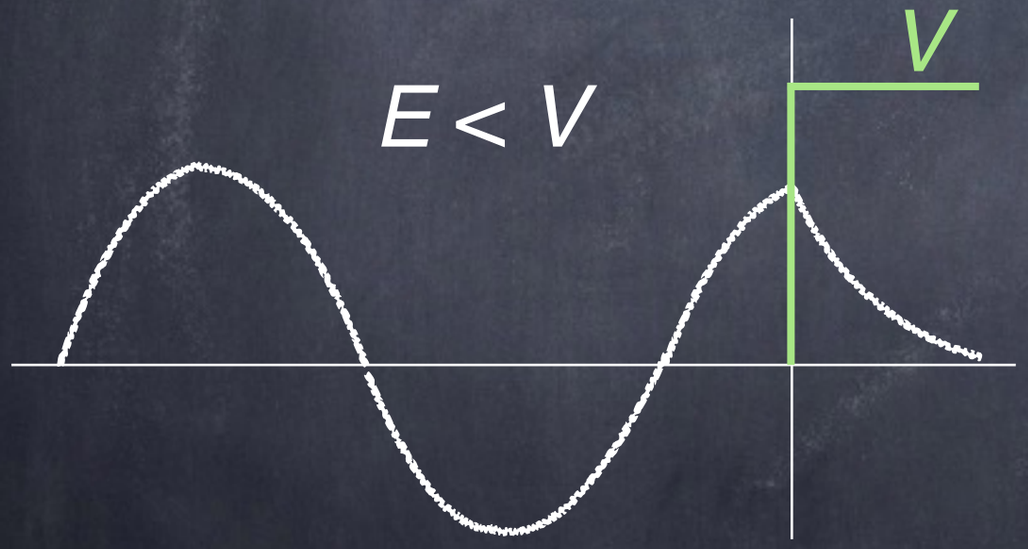
Increasing UCN storage lifetime to <u>100 s</u>



^{3}He absorption: $\tau_{^3He}$ = 3900 s at $^3He/^4He = 10^{-11}$

Wall loss

loss/collision: $\mu = 2f \int\{E\cos^2\theta/(V\text{-}E\cos^2\theta)\}^{1/2} \cos\theta\, d(\cos\theta)$



$f = W/V$

optical potential

$U = V - iW$

$= 2\pi\hbar^2/m\, N\,(a_r - ia_i)$

$\mathrm{Im}\, f(0) = k/4\pi\, \sigma_{tot}$

$\sigma_{tot} = \sigma_{inela} + \sigma_a$

We need material of low absorption and high Fermi potential

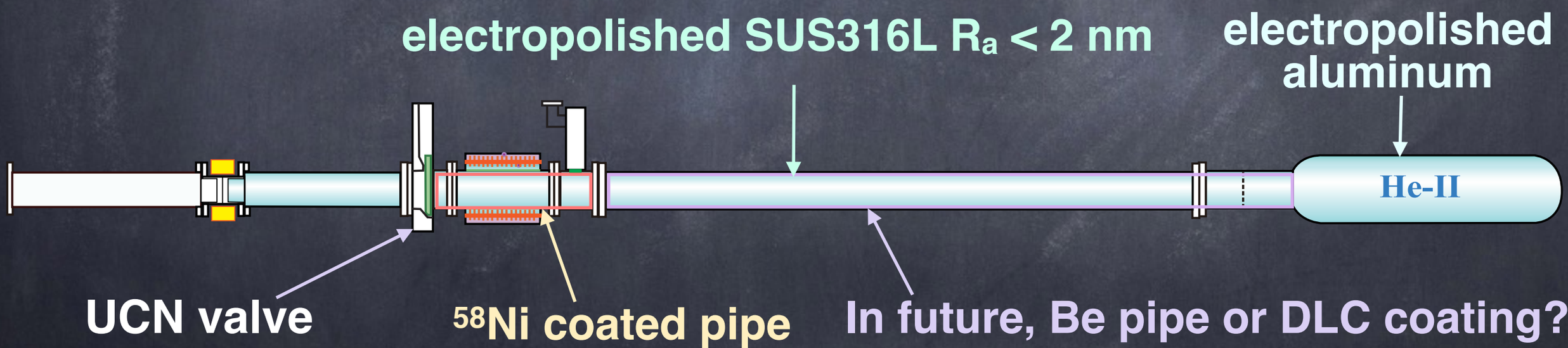
Suitable wall material

for $\tau >$ 100 s

We need material of lower $f = W/V$!

The material should sustain at the low temperature !

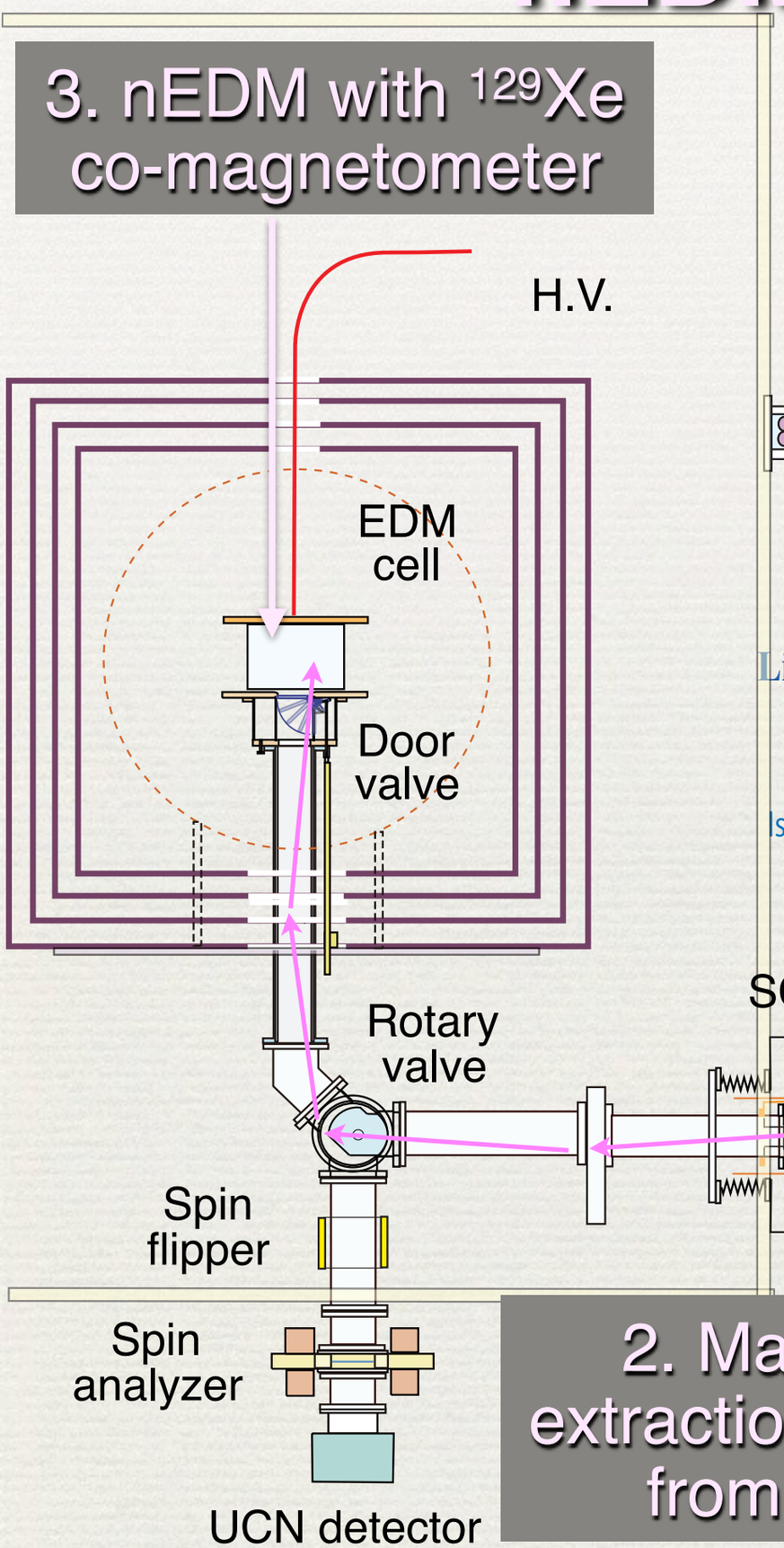
NiP → ^{58}Ni → Be pipe or DLC coating?

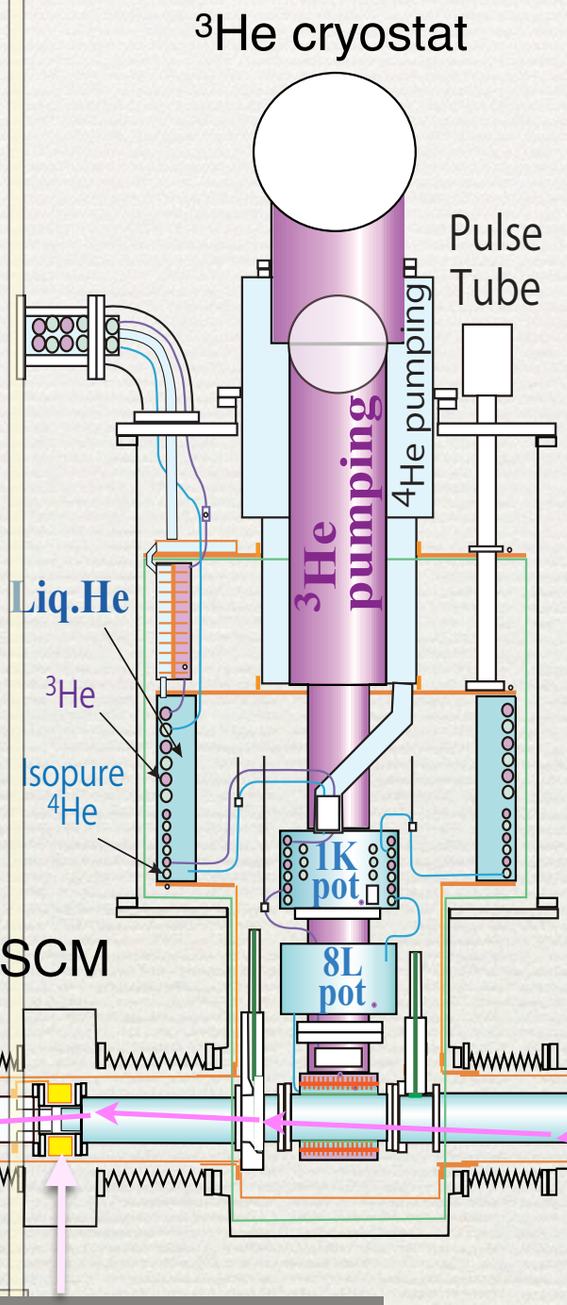


good heat conduction

nEDM, KEK-Osaka-RCNP

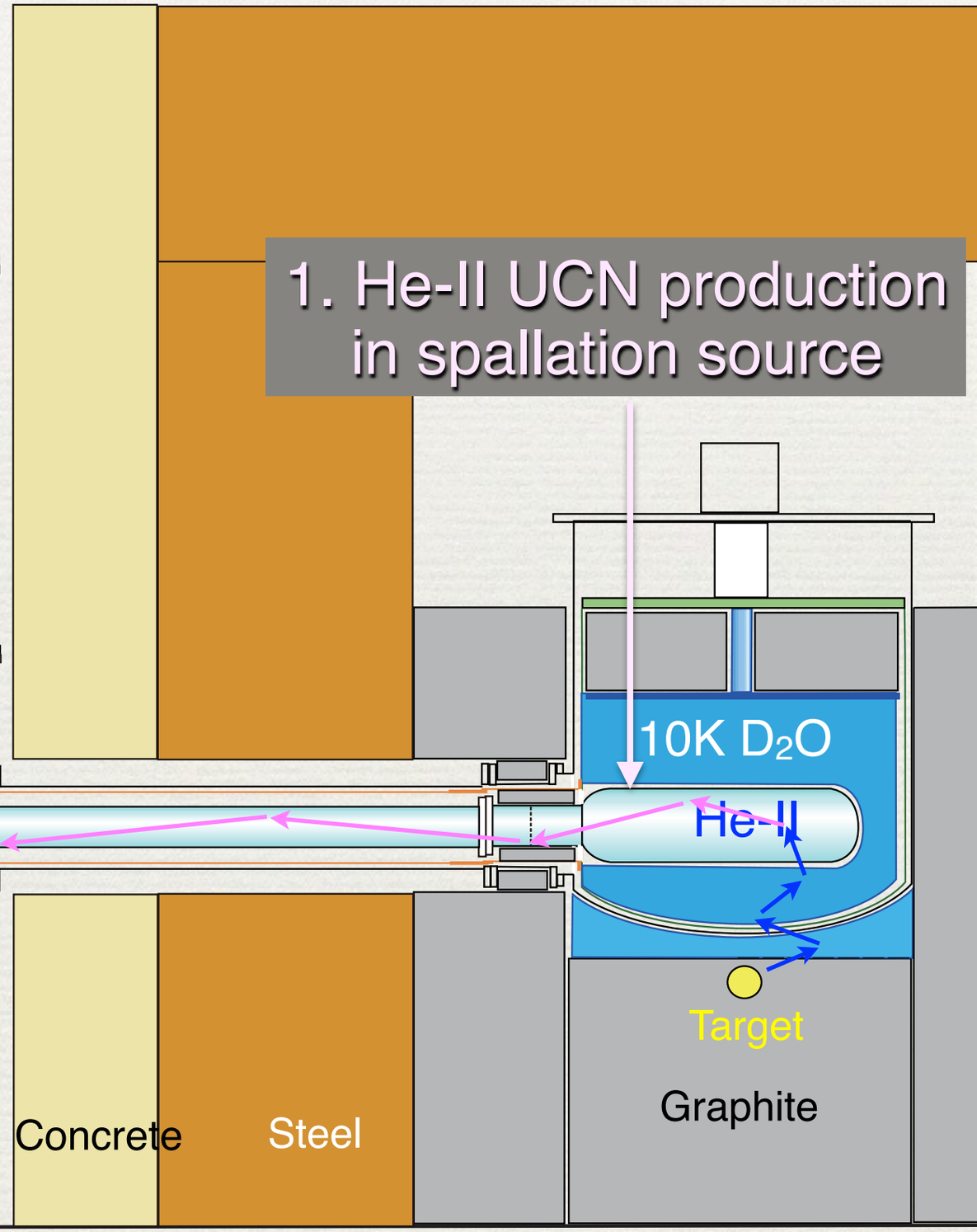
3. nEDM with ^{129}Xe co-magnetometer



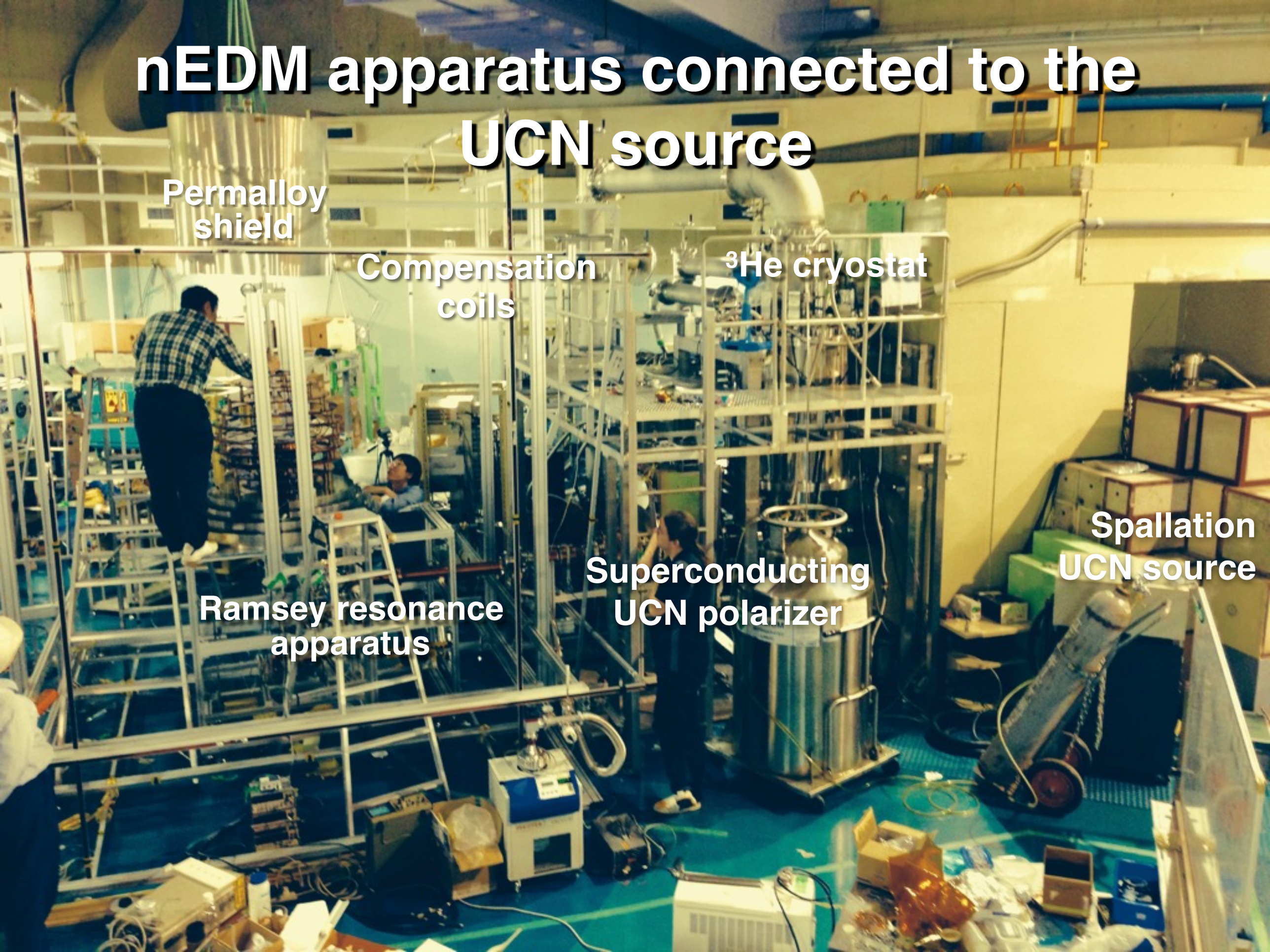


2. Magnetic extraction of UCN from He-II

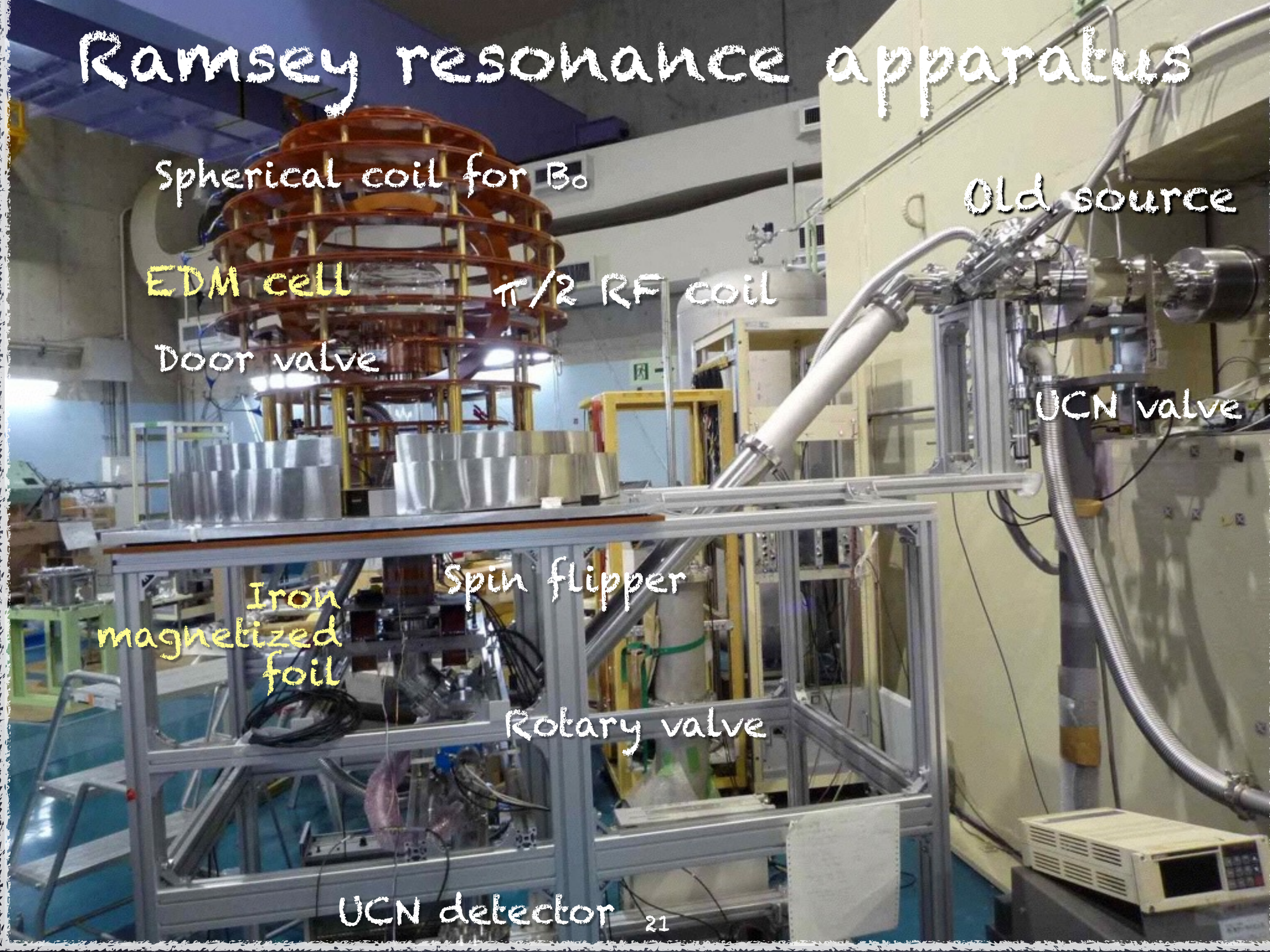
1. He-II UCN production in spallation source



nEDM apparatus connected to the UCN source



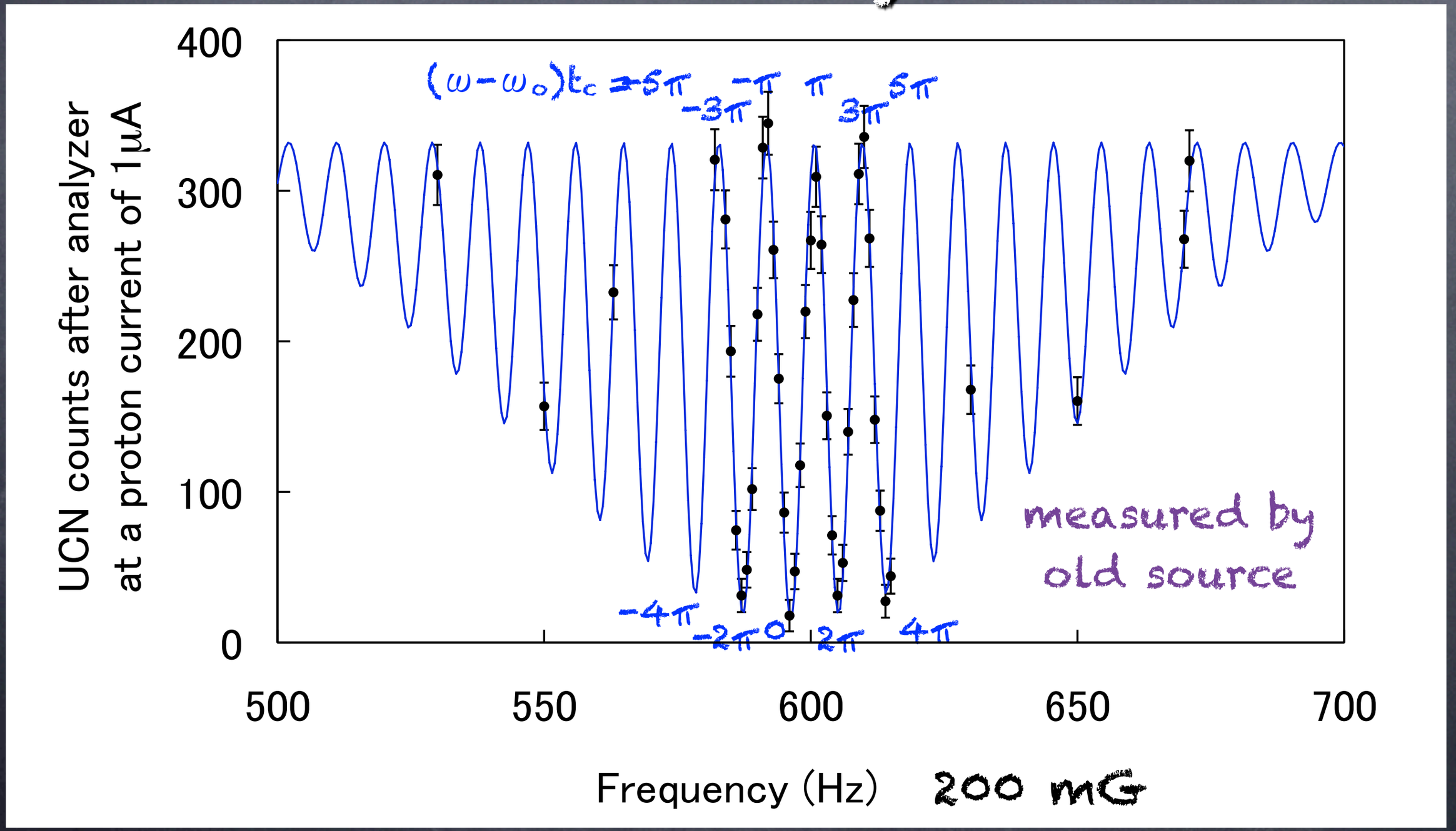
Ramsey resonance apparatus



Ramsey resonance

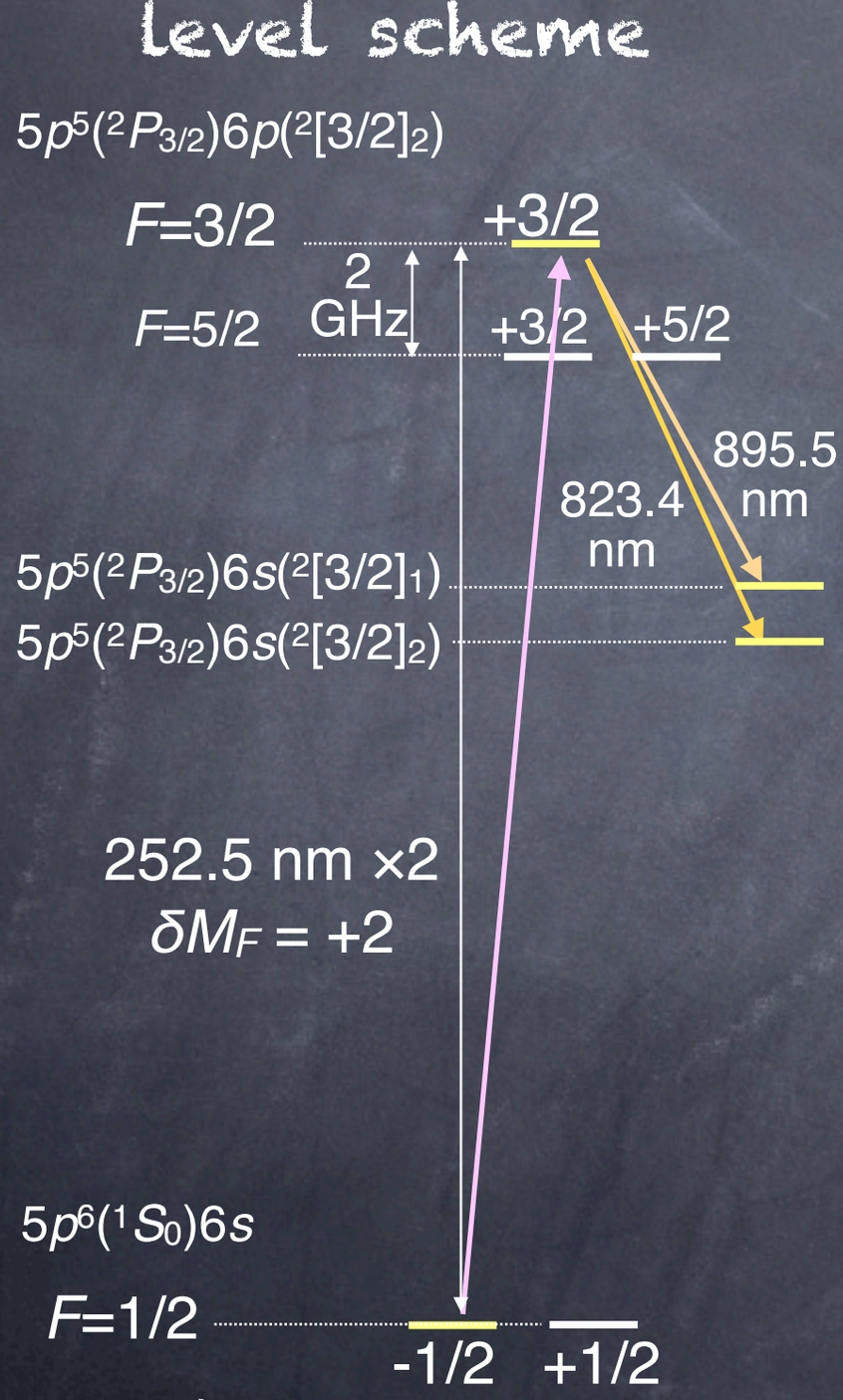
nEDM is measured from shift upon E reversal

B_0 stability



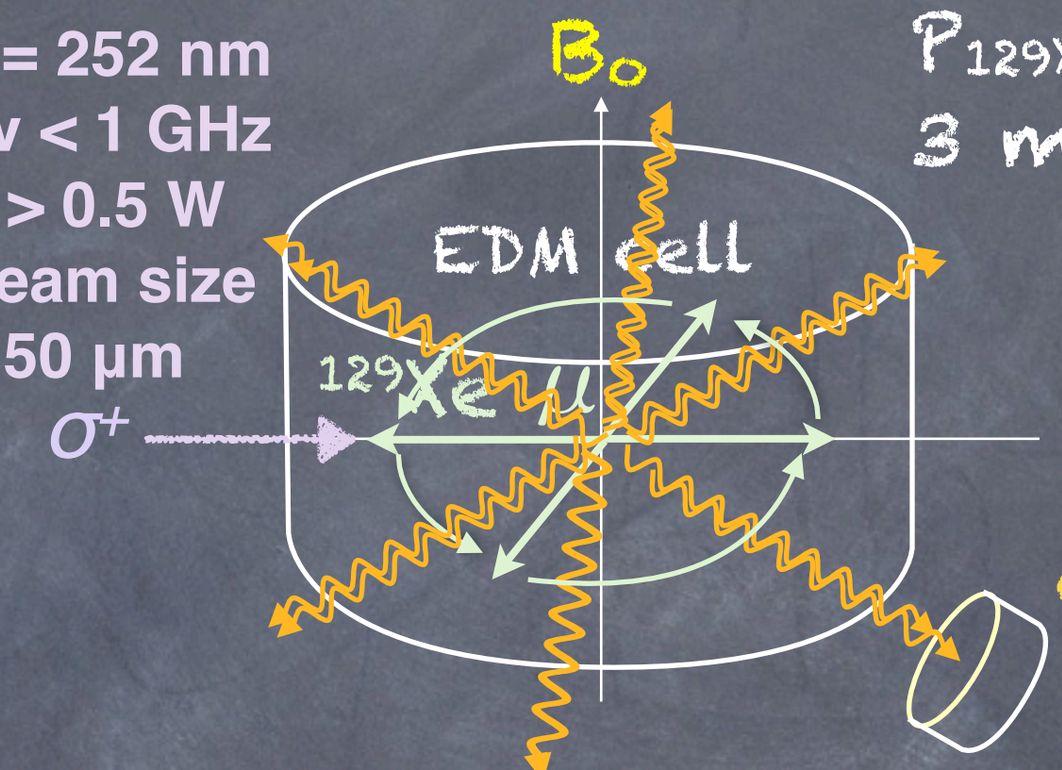
B_0 monitor: ^{129}Xe spin precession

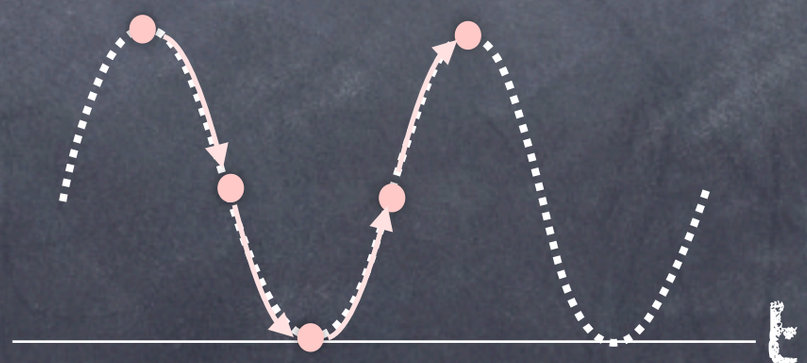
^{129}Xe level scheme



T. Chupp

λ = 252 nm
δν < 1 GHz
P > 0.5 W
Beam size
< 50 μm





$P_{^{129}Xe}$ = 3 mmTorr

5 days of measurement

δB_0 = 0.3 fT

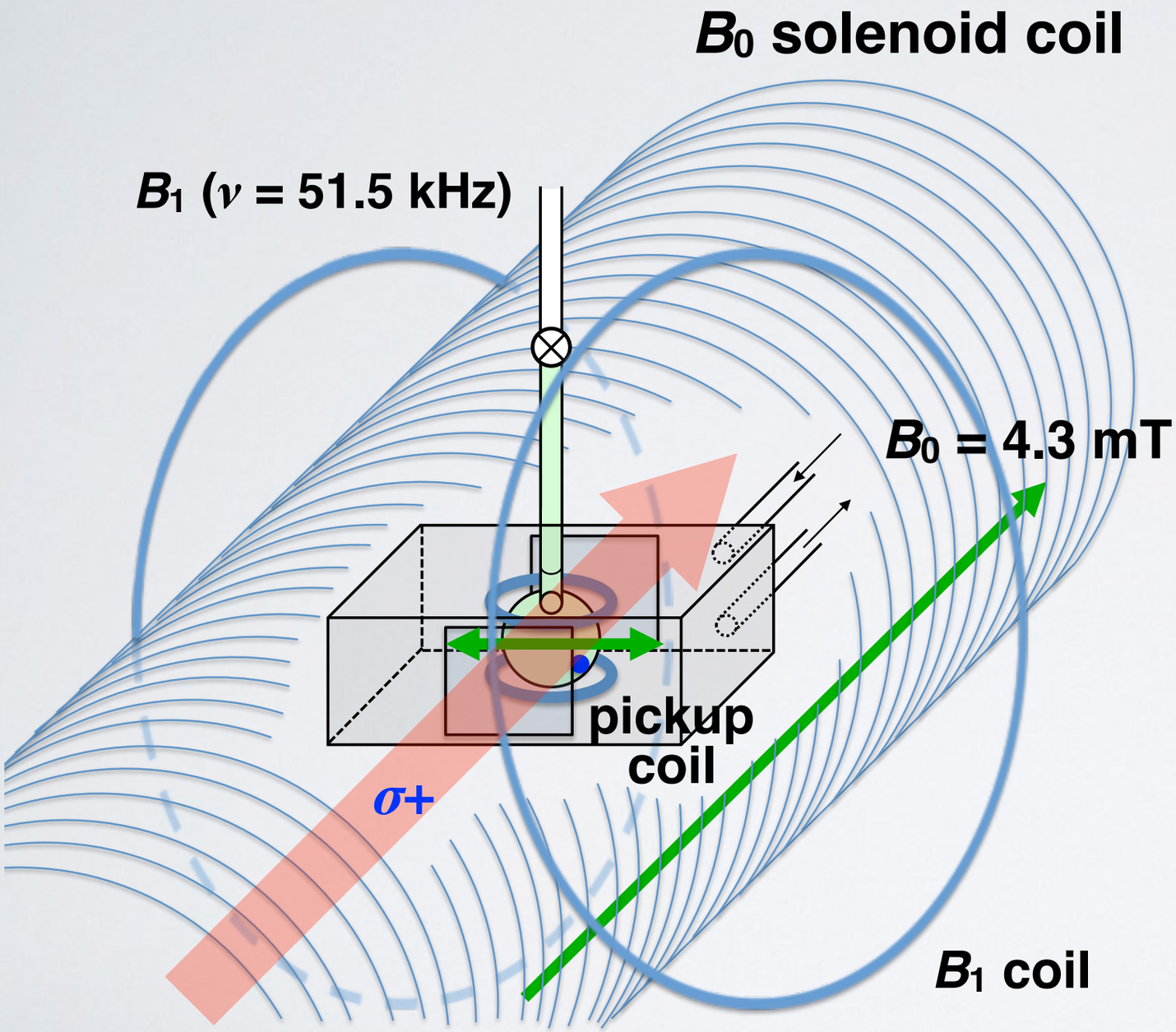
↓

10^{-27} *e* cm

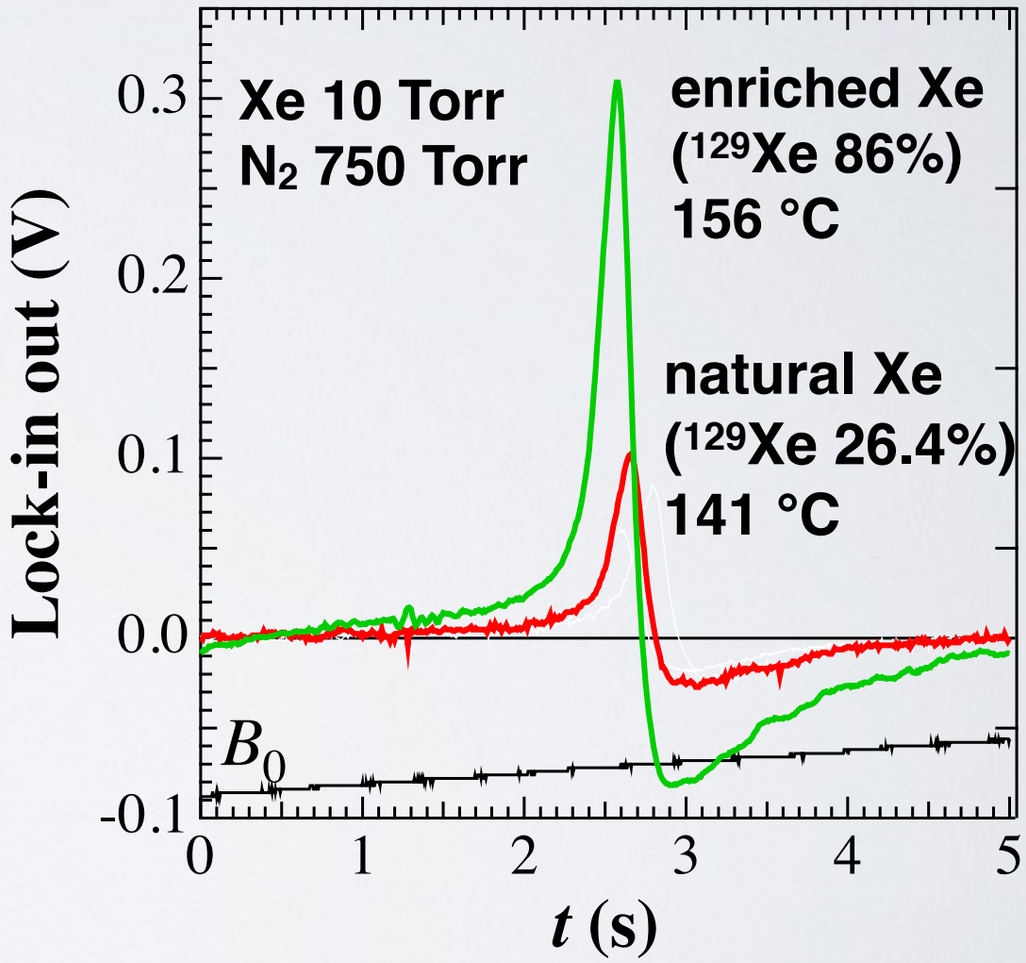
M. Mihara

Rb-Xe spin exchange optical pumping

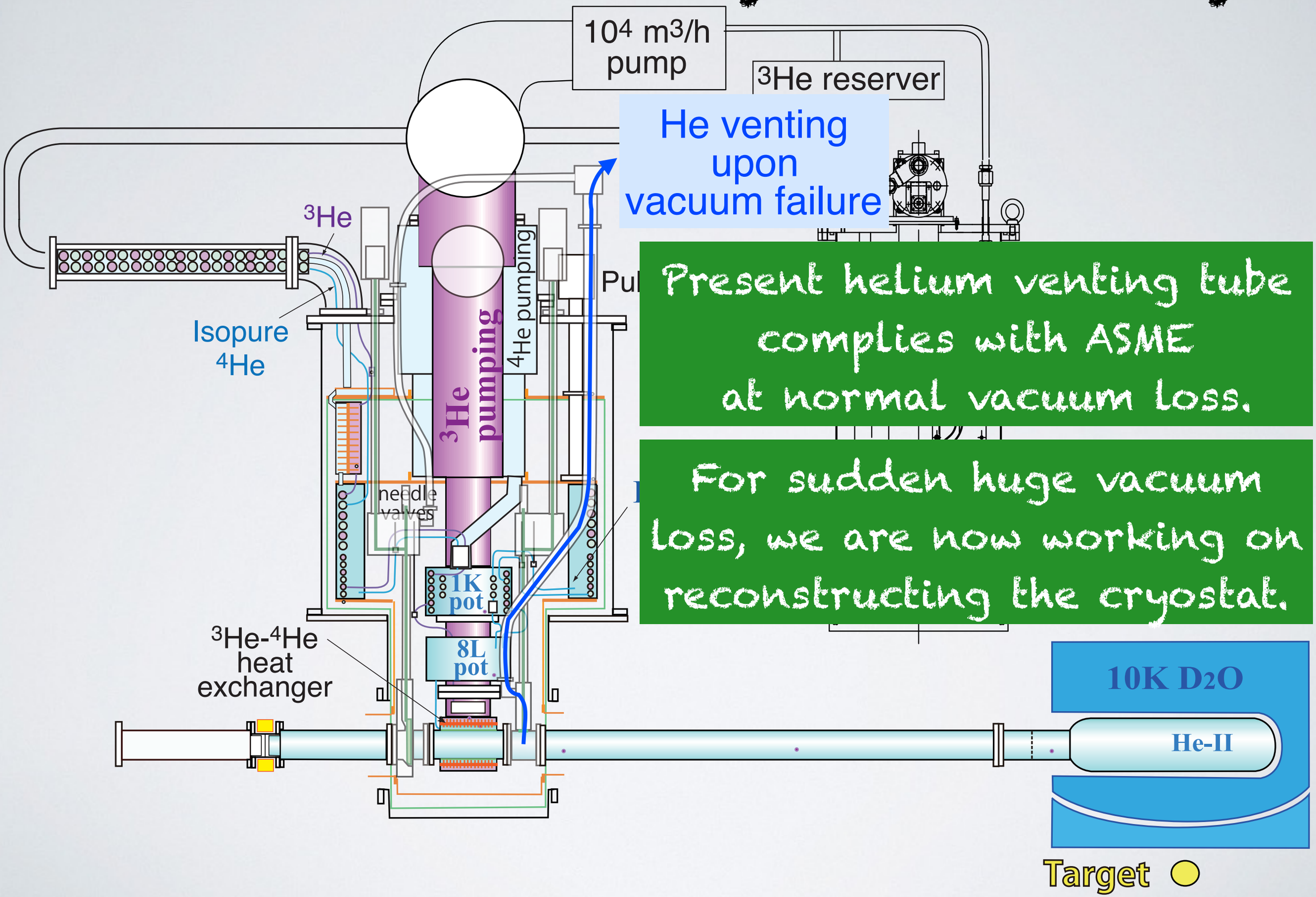
Happer



We have achieved
^{129}Xe polarization of 70%



We are remodeling cryostat for safety



Present helium venting tube complies with ASME at normal vacuum loss.

For sudden huge vacuum loss, we are now working on reconstructing the cryostat.

Our nEDM

Statistical error: 10^{-27}~10^{-28} e cm

1. **He-II UCN production in spallation n source**

   P = 4 UCN/cm^3 · s at E_c = 210 neV, $E_p \times I_p$ = 0.4 kW (2012)

   → 200 UCN/cm^3 · s in 12 L He-II 20 kW

   τ_s = 81 s (2012)

   → 100 s

   ρ_{pol} = 800 UCN/cm^3 in the EDM cell of E_c = 90 neV

2. **Magnetic extraction of UCN from He-II**

   P_{UCN} = 90% at the EDM cell

   visibility α = 83 %

Systematic error: 10^{-27} e cm

3. **^{129}Xe co-magnetometer**

Thanks