Development of HTS magnets and UCN source at RCNP

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The Research Center for Nuclear Physics (RCNP) cyclotron cascade system has been operated to provide high quality beams for various experiments in nuclear and fundamental physics and applications. The accelerator cascade consists of an injector Azimuthally Varying Field (AVF) cyclotron (K=140) and a ring cyclotron (K=400). Sophisticated experimental apparatuses are equipped like a pair spectrometer, a neutron time-of-flight facility with a 100-m-long tunnel, a radioactive nuclei separator, a super-thermal ultra cold neutron (UCN) source, a white neutron source, and a RI production system for nuclear chemistry. In my talk, I will present the development of the High Temperature Superconducting (HTS) magnets and the UCN source.

More than two decades have passed since the discovery of HTS materials in 1986. Significant effort went into the development of new and improved conductor materials and it became possible to manufacture relatively long HTS wires of the first generation. Although many prototype devices using HTS wires have been developed, these applications are presently rather limited in accelerator and beam line facilities. It is inevitable to downsize the system in order to install it in a town hospital. There have been a lot of efforts to make accelerators compact. However, it is well known an accelerator is not the main part to determine the size of a particle radiotherapy facility. A beam delivering system becomes large and heavy for a heavy ion therapy system. For example, the gantry of the HIT facility at Heidelberg is 13m in diameter and 25m long. The total weight of rotating parts amounts to 570t. At RCNP, we have developed HTS magnets as a key device of the next generation particle radiotherapy system. Performance of the fabricated scanning magnet is discussed. A 3T dipole magnet is designed and under fabrication utilizing HTS wires. The magnets can be excited by alternating currents to study the applicability to synchrotron magnets as well as gantry magnets.

The present UCN source is placed in a 400MeV proton beam line. Spallation neutrons are evaporated from the lead target and are moderated to cold neutrons by the room temperature heavy water and 10K heavy ice. Cold neutrons are cooled to UCN by exchanging phonons and rotons in superfluid helium (He-II) at 0.8K. We achieved UCN density of 19/cm^3 at 90neV. We are preparing for the measurements of the neutron electric dipole moment (nEDM). Ramsey fringe was successfully observed at the magnetic field of 2μT and the correlation time of 30s. Efforts are being continued to improve the T1 relaxation time and to apply the electric field to the EDM cell.

We expect the collaboration with researches at the Indiana University will be very beneficial to promote developments in both the accelerator and neutron physics.

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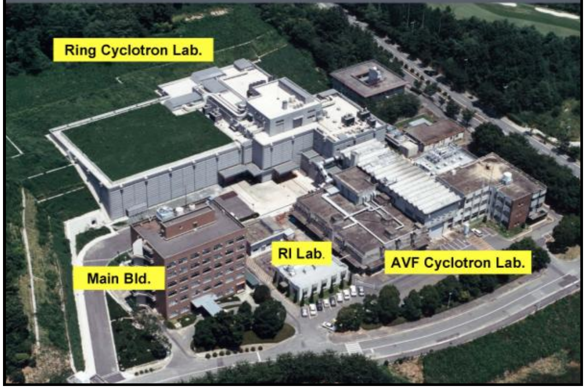
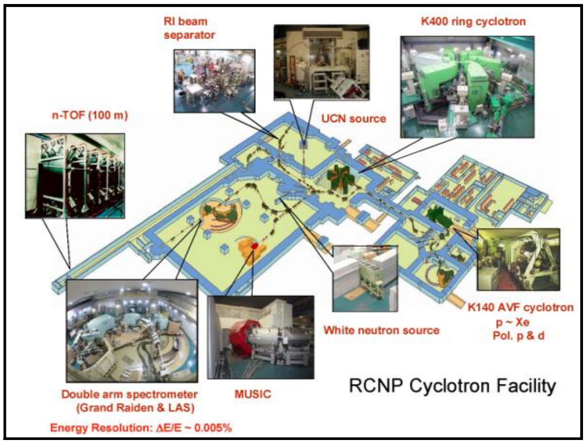
Indiana University

Outline

1. Overview of the RCNP cyclotron facility
2. High Temperature Superconducting magnets
   Scanning magnet
   Dipole magnet
   (Accelerator physics)
3. Ultra Cold Neutron Source
   (Fundamental physics)

RCNP Cyclotron Facility



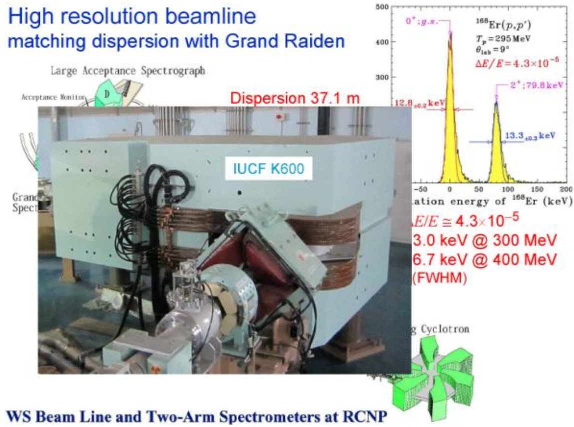


RCNP Cyclotron Facility

Energy Resolution: ΔE/E ~ 0.005%

High resolution beamline

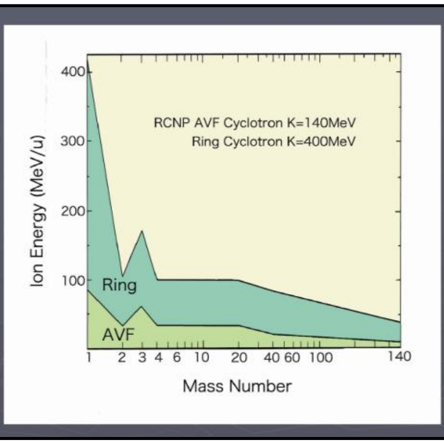
matching dispersion with Grand Raiden

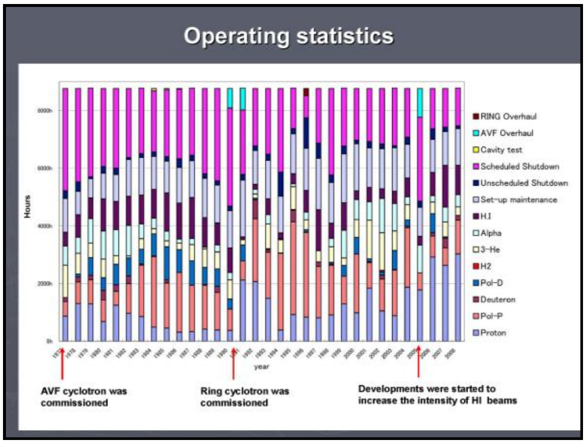


Dispersion 37.1 m

$E/E \cong 4.3\times10^{-5}$
3.0 keV @ 300 MeV
6.7 keV @ 400 MeV
(FWHM)

WS Beam Line and Two-Arm Spectrometers at RCNP



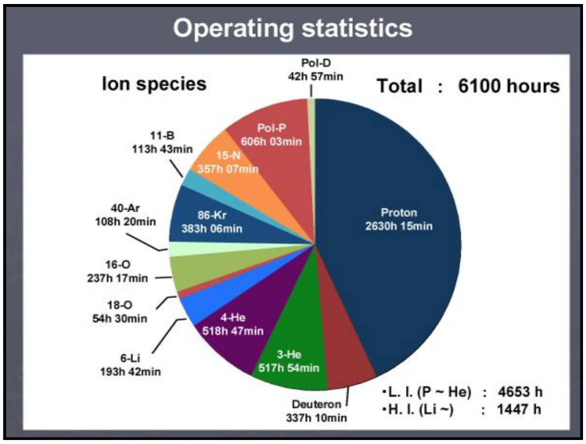


Operating statistics

AVF cyclotron was commissioned

Ring cyclotron was commissioned

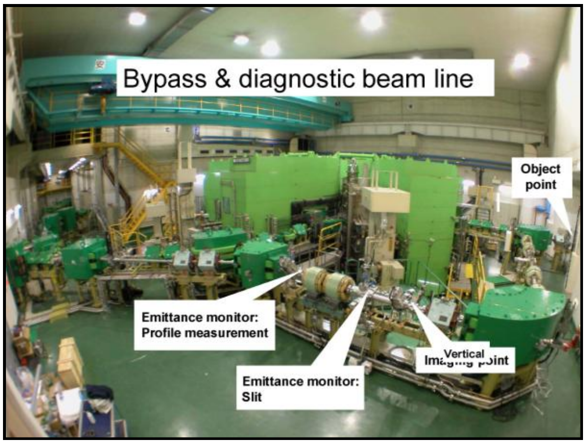
Developments were started to increase the intensity of HI beams



Operating statistics

Total : 6100 hours

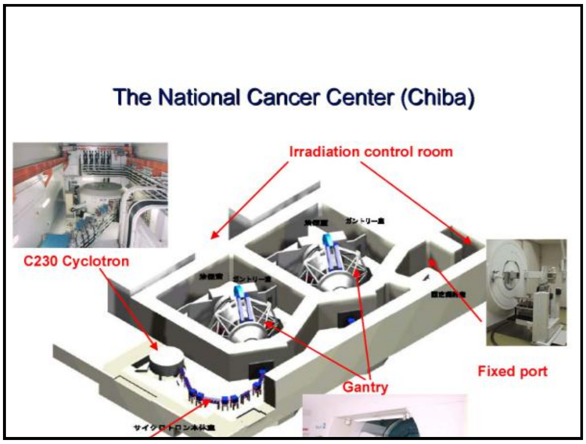
- L. I. (P ~ He) : 4653 h
- H. I. (Li ~) : 1447 h



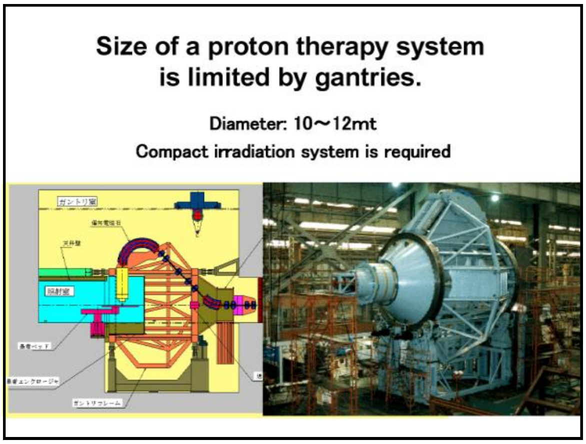
Bypass & diagnostic beam line

Development of HTS magnets

(next generation particle radiotherapy device)



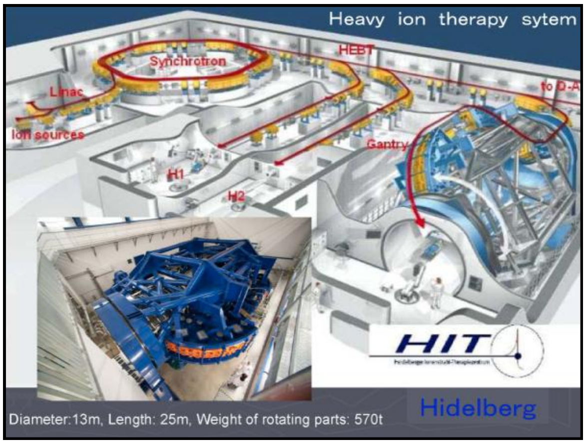
The National Cancer Center (Chiba)



Size of a proton therapy system is limited by gantries.

Diameter: 10〜12mt

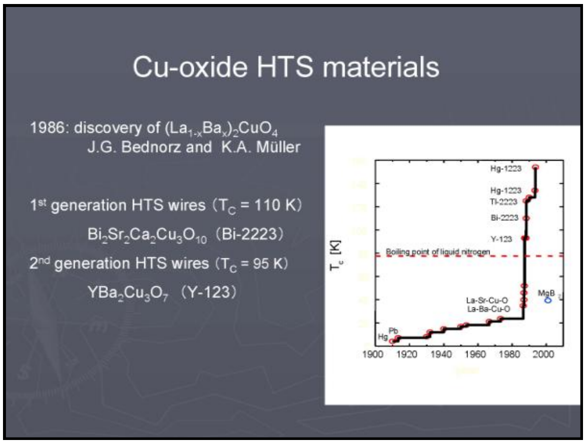
Compact irradiation system is required



Heavy ion therapy sytem

Diameter:13m, Length: 25m, Weight of rotating parts: 570t

AC loss measurement



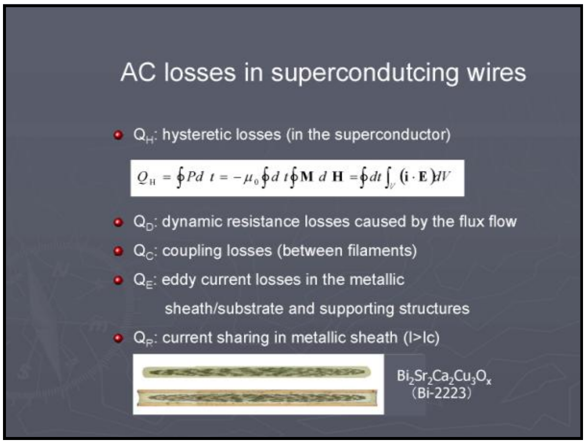
Cu-oxide HTS materials

1986: discovery of $(La_{1-x}Ba_x)_2CuO_4$
J.G. Bednorz and K.A. Müller

1st generation HTS wires（T_C = 110 K）
$Bi_2Sr_2Ca_2Cu_3O_{10}$（Bi-2223）
2nd generation HTS wires（T_C = 95 K）
$YBa_2Cu_3O_7$（Y-123）

Application of HTS conductors to magnets

- Compact system
- Simple cooling system (No liquid He is required)
  cryogenic refrigerators and conduction cooling
- A wide temperature range of the operation
- A large margin in operating temperature
  application to AC magnets as well as DC magnet
  for example,
    cyclotron, synchrotron, beam line magnets
    gantry magnets for the cancer treatment
    scanning magnets for ion planting or therapy



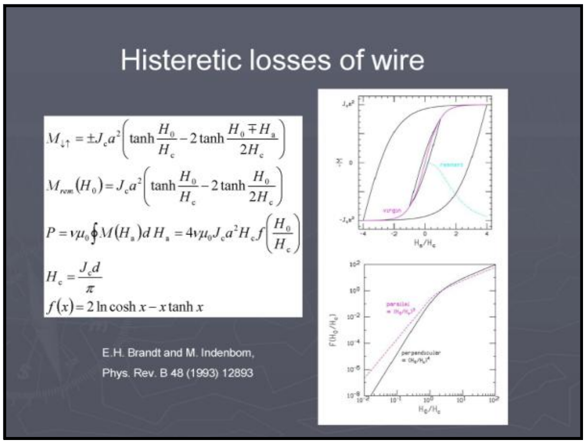
AC losses in supercondutcing wires

- Q_H: hysteretic losses (in the superconductor)

$$Q_H = \oint P\,dt = -\mu_0 \oint dt \oint \mathbf{M}\, d\mathbf{H} = \oint dt \int_V (\mathbf{i}\cdot\mathbf{E})\,dV$$

- Q_D: dynamic resistance losses caused by the flux flow
- Q_C: coupling losses (between filaments)
- Q_E: eddy current losses in the metallic
  sheath/substrate and supporting structures
- Q_R: current sharing in metallic sheath (I>Ic)

$Bi_2Sr_2Ca_2Cu_3O_x$
（Bi-2223）



Histeretic losses of wire

$$M_{\downarrow\uparrow} = \pm J_c a^2\left(\tanh\frac{H_0}{H_c} - 2\tanh\frac{H_0 \mp H_a}{2H_c}\right)$$

$$M_{rem}(H_0) = J_c a^2\left(\tanh\frac{H_0}{H_c} - 2\tanh\frac{H_0}{2H_c}\right)$$

$$P = \nu\mu_0 \oint M(H_a)\,dH_a = 4\nu\mu_0 J_c a^2 H_c f\left(\frac{H_0}{H_c}\right)$$

$$H_c = \frac{J_c d}{\pi}$$

$$f(x) = 2\ln\cosh x - x\tanh x$$

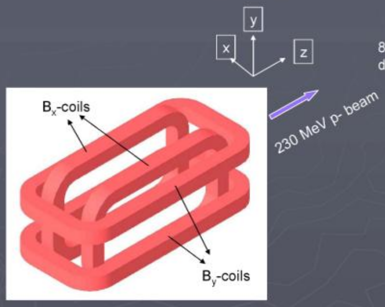
E.H. Brandt and M. Indenbom,
Phys. Rev. B 48 (1993) 12893

AC losses per cycle of HTS conductors

- $Q_H \propto I^{3-4}$
- $Q_D \propto I^2$
- $Q_C \propto f \cdot I^2$
- $Q_E \propto f \cdot I^2$
- $Q_R \propto I^2$

Studies have been limited to such simple structures as tapes, cables and simple coils in both experimental and theoretical points of view.

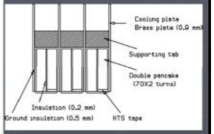
A scanning magnet



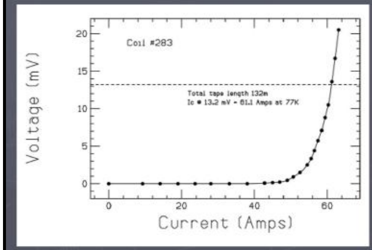
80 mrad deflection

Design parameter

Coils	Inner size	B_x: 150 mm × 300 mm, B_y: 150 mm × 380 mm
	Cross section	30 mm × 30 mm
	Separation	70 mm
	Max. field	0.6 T
	Superconductor	Bi-2223/Ag alloy wire
	Total length	B_x: 412 m × 2, B_y: 460 m × 2
	Number of turns	420 × 2 coils for both B_x and B_y
	Winding construction	3 double pancakes/coil
	Inductance of single coil	B_x: 75mH, B_y: 92 mH
	Critical current at 77 K	40-43 A
	Rated current	200 A
	Operating temperature	20 K
Cryostat	Cooling method	Conduction cooling by two GM refrigerators
	Thermal insulation	Vacuum isolation, 80 K shield, super-insulation
	Cooling power of the GM refrigerator	45 W at 20K 53 W at 80 K

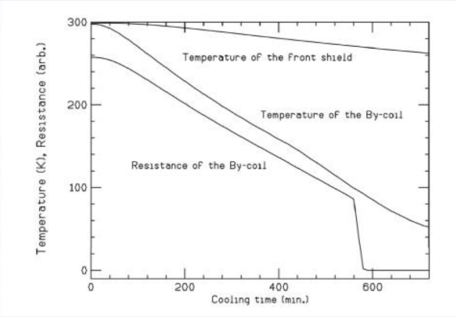


Critical current (I_c) of coils at 77 K

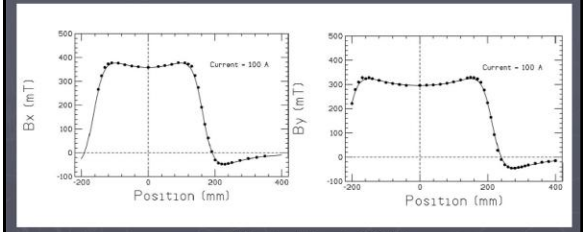


Coil No.	Length (m)	I_c (A)
278	132	56.1
280	132	57.0
283	132	61.1
285	132	58.0
286	132	62.2
288	132	57.4
290	162	60.6
296	162	58.7
298	162	59.8
300	162	60.5
304	162	61.1
306	162	59.0
Bx_1	396	40.8
Bx_2	396	41.1
By_1	486	42.7
By_2	486	42.9

Cooling performance of a coil

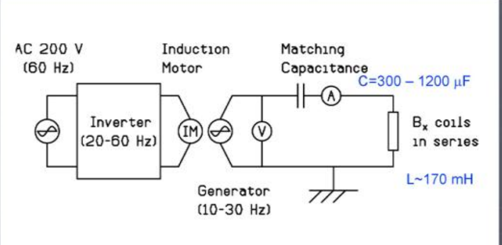


Magnetic field distributions on the axis



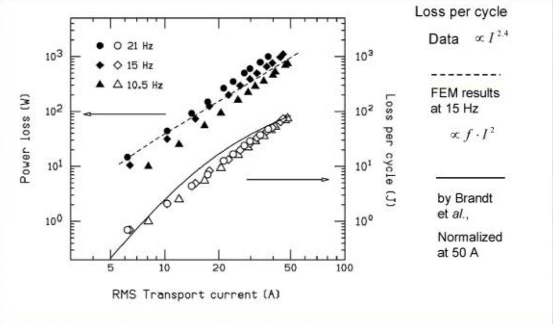
FEM calculations by TOSCA

AC loss measurements at 20 K



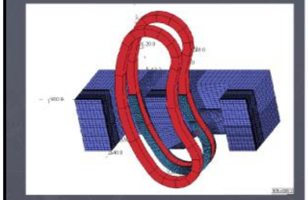
Schematic set-up of measurements.

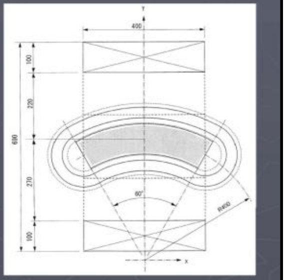
AC losses at 20 K
Comparison with calculations

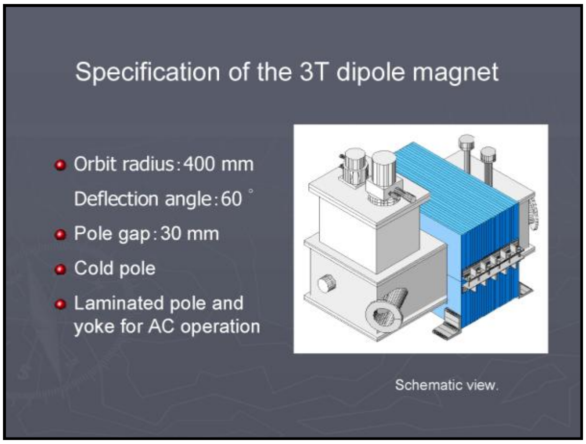


3T dipole magnet

3D calculation model



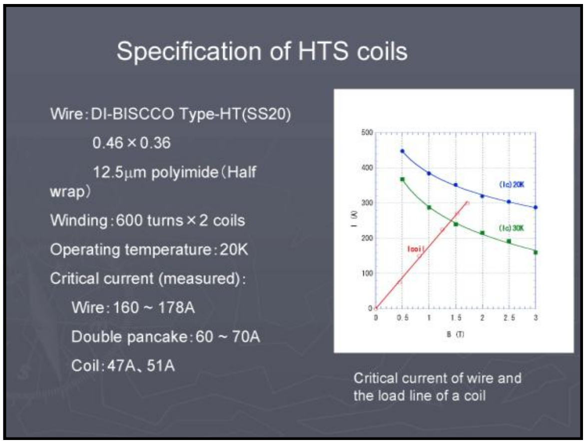




Specification of the 3T dipole magnet

- Orbit radius : 400 mm
  Deflection angle : 60 °
- Pole gap : 30 mm
- Cold pole
- Laminated pole and yoke for AC operation

Schematic view.



Specification of HTS coils

Wire : DI-BISCCO Type-HT(SS20)

0.46 × 0.36

12.5μm polyimide（Half wrap）

Winding : 600 turns × 2 coils

Operating temperature : 20K

Critical current (measured) :

Wire : 160 ~ 178A

Double pancake : 60 ~ 70A

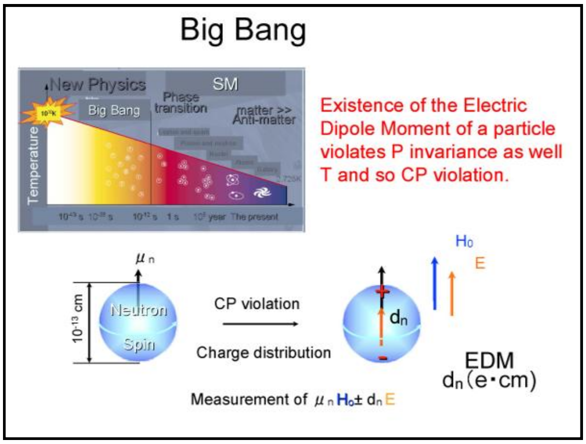
Coil : 47A、51A

Critical current of wire and the load line of a coil

Super-thermal UCN source

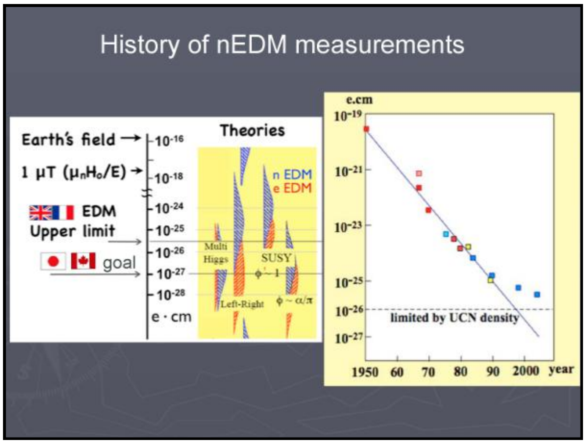
and

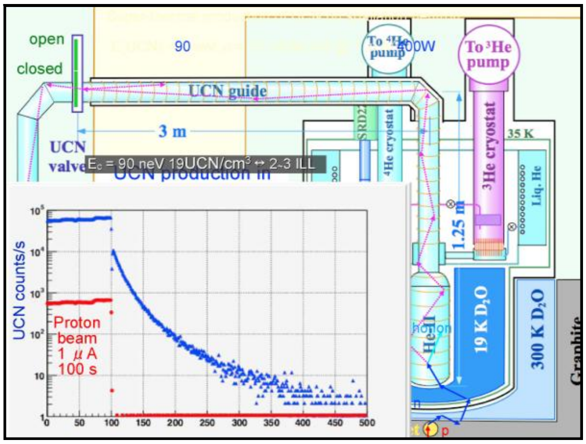
nEDM measurement

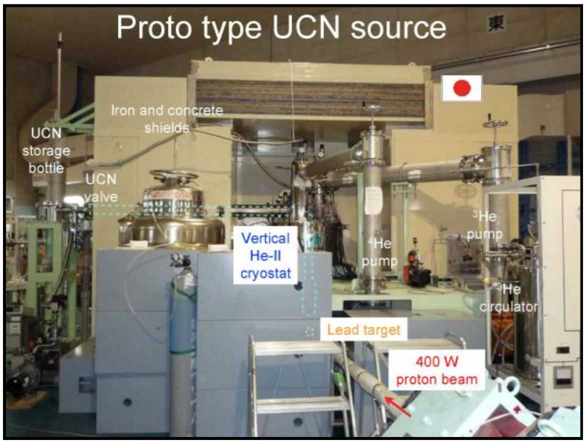

Big Bang

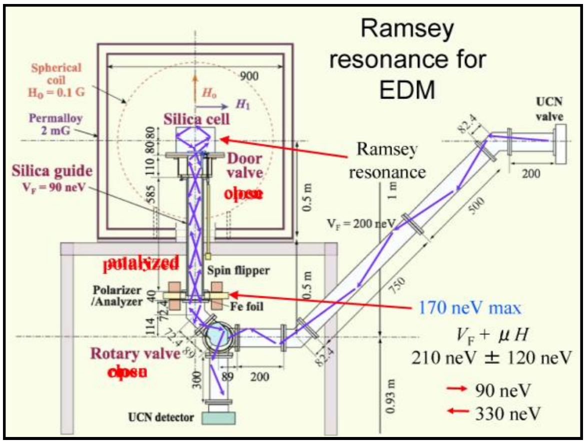
Existence of the Electric Dipole Moment of a particle violates P invariance as well T and so CP violation.

Measurement of $\mu_n H_0 \pm d_n E$


History of nEDM measurements


E_c = 90 neV 19UCN/cm^3 ↔ 2-3 ILL


Proto type UCN source


Ramsey resonance for EDM

170 neV max

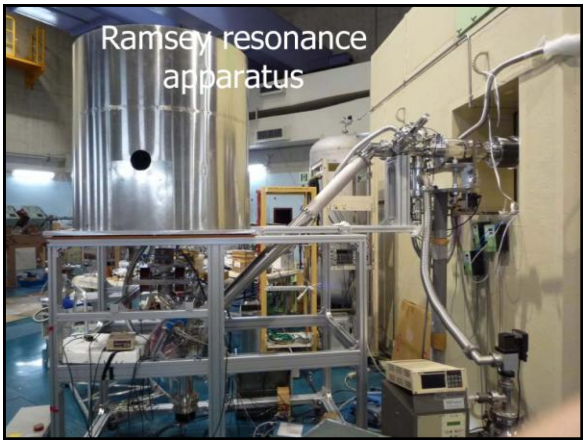
$V_F + \mu H$

210 neV ± 120 neV

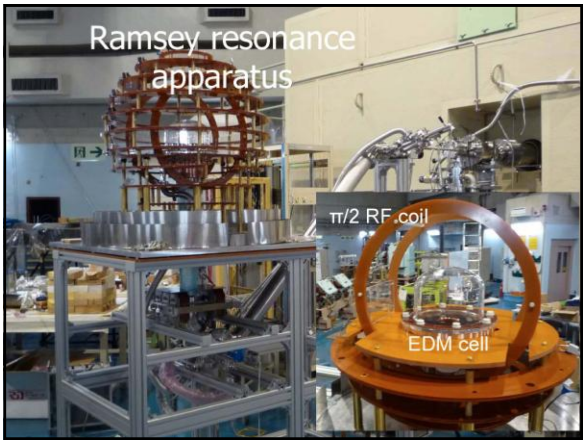
→ 90 neV

← 330 neV

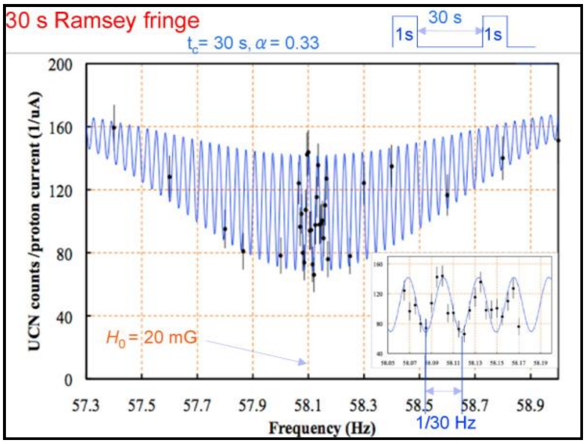
Ramsey resonance apparatus



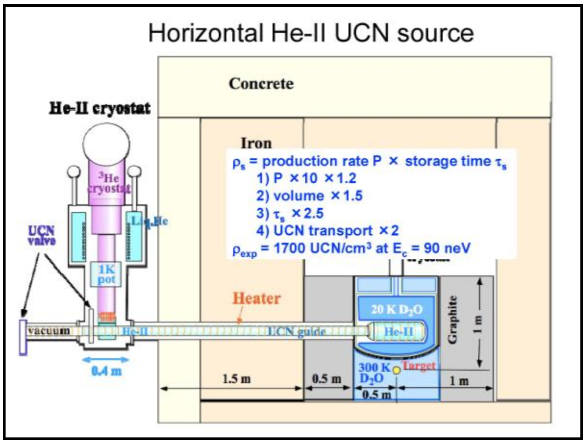
Ramsey resonance apparatus



30 s Ramsey fringe



Horizontal He-II UCN source



ρ_s = production rate P × storage time τ_s

1) P ×10 ×1.2
2) volume ×1.5
3) τ_s ×2.5
4) UCN transport ×2

ρ_{exp} = 1700 UCN/cm³ at E_c = 90 neV

Thank you for your attention