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/cm³ 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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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

High resolution beamline matching dispersion with Grand Raiden

WS Beam Line and Two-Arm Spectrometers at RCNP

RCNP AVF Cyclotron K=400MeV
Ring Cyclotron K=400MeV
Operating statistics

- AVF cyclotron was commissioned
- Ring cyclotron was commissioned
- Developments were started to enhance the intensity of the beams

Operating statistics

Total: 6100 hours

- Proton 3230-15mm: 42h 57min
- 11-B: 113h 43min
- 40-Ar: 108h 20min
- 18-O: 237h 17min
- 15-O: 56h 20min
- 8-Li: 193h 42min

- D: 60h 33min
- 7-Li: 128h 15min
- 16-O: 35h 47min
- 6-He: 51h 46min

- p: 52h 10min
- He (p): 4653h
- H (p): 1447h

Bypass & diagnostic beam line

Emittance monitor: Profile measurement
Emittance monitor: Silt
Vertical Alignment system

Development of HTS magnets

(next generation particle radiotherapy device)

The National Cancer Center (Chiba)

- C230 Cyclotron
- Irradiation control room
- Fixed port
- Gantry

Size of a proton therapy system is limited by gantries.

Diameter: 10~12m
Compact irradiation system is required
AC loss measurement

Cu-oxide HTS materials

1986: discovery of (La1−xBax)2CuO4
J.G. Bednorz and K.A. Müller

1st generation HTS wires (Tc = 110 K)
Bi2Sr2CaCu2O8 (Bi-2223)

2nd generation HTS wires (Tc = 95 K)
YBa2Cu3O7 (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 superconducting wires

- $Q_H$: hysteretic losses (in the superconductor)
  \[ Q_H = \frac{1}{2} M \frac{d}{dt} H - \mu_0 \frac{1}{2} i M \frac{d}{dt} \left( \frac{1}{3} H \right) \]
- $Q_C$: dynamic resistance losses caused by the flux flow
- $Q_L$: coupling losses (between filaments)
- $Q_S$: eddy current losses in the metallic sheath/substrate and supporting structures
- $Q_C$: current sharing in metallic sheath (I=IC)

Bi2Sr2CaCu2O8
(Bi-2223)

Histeretic losses of wire

\[ H_1 = \frac{j}{\pi} \left[ \frac{\tanh H_1}{H_1} - 2 \tanh \frac{H_1 - \tanh H_1}{2H_1} \right] \]
\[ H_2 = \frac{j}{\pi} \left[ \frac{\tanh H_2}{H_2} - 1 \tanh \frac{H_2 - \tanh H_2}{2H_2} \right] \]
\[ P = \mu_0 \frac{1}{2} M H_1 + 4 \kappa \frac{1}{2} M H_1 + \frac{1}{2} M H_1 - \frac{1}{2} M H_1 \]
\[ f(x) = 2 \ln \cosh x - x \tanh x \]

E.H. Brandt and M. Henderston,
AC losses per cycle of HTS conductors

- $Q_1 \propto I^{1.3}$
- $Q_2 \propto f^2$
- $Q_3 \propto f \cdot I^2$
- $Q_4 \propto I^2$

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

Design parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Critical current at 77 K</td>
<td>40 A</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>40 K</td>
</tr>
<tr>
<td>Cooling method</td>
<td>Conduction cooling by two Gd refrigerants</td>
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<tr>
<td>Thermal insulation</td>
<td>Vacuum insulation, 100 K K-type kapton insulation</td>
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<tr>
<td>Cooling power</td>
<td>0.5 kW at 77 K</td>
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<tr>
<td>for Gd refrigerant</td>
<td>10 W at 40 K</td>
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</tbody>
</table>

Critical current ($I_c$) of coils at 77 K

<table>
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<tr>
<th>Coil No.</th>
<th>Length (cm)</th>
<th>$I_c$ (A)</th>
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<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>322</td>
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<tr>
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<td>289</td>
</tr>
</tbody>
</table>

Cooling performance of a coil

- Temperature of the front shield
- Temperature of the backside
- Resistance of the coil
Magnetic field distributions on the axis

AC loss measurements at 20 K

AC losses at 20 K Comparison with calculations

3D calculation model

3T dipole magnet
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

Specification of HTS coils
- Wire: DI-BISCO Type-HT(SS20)
  - 0.46 × 0.36
  - 12.5μm polysilide (Half wrap)
- Winding: 500 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

History of nEDM measurements

Proto type UCN source

Ramsey resonance for EDM

Existence of the Electric Dipole Moment of a particle violates P invariance as well T and so CP violation.
Thank you for your attention