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A Dual 6T Persistent-Mode SC Solenoid Ion-Optical System for Radioactive Nuclear Beam Research

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Abstract - **A unique ion-optical system for the production of high-intensity, short-lived radioactive nuclear beams has been designed, constructed and put into operation at the Nuclear Structure Laboratory at the University of Notre Dame as a joint project between the University of Michigan and NSL-UND. The system consists of a matched in-line pair of large-bore (30 cm) 6T sc solenoid magnets which act as high-effeciency collectors and magnetic filters of secondary radioactive nuclear beam products (RNB). The latter are brought to a focus on a secondary target and nuclear reactions using the RNB studied. These are primarily reactions of interest in Big-Bang nucleosynthesis and stellar helium burning and involve the production of ^{6}He,^{7}Be,^{8}B and similar beams. A number of unique features were incorporated in the magnet design to permit use as a precise ion-optical device in the RNB mode. To our knowledge this is the only large-scale in-beam ion-optical system to operate primarily in persistent mode. A similar device will be built at the University of São Paulo also for RNB research.**

Index Terms – **Superconducting solenoid ion-optical system, radioactive nuclear beam apparatus.**

I. Introduction

Traditionally, short-lived secondary nuclear ion beams such as pions, muons, etc. have been made using quadrupole and dipole magnets as the primary ion-optical elements. In this case, the angular acceptance of the dipole magnet often limits the collection efficiency and hence intensity of the secondary ions. With regard to the latter a solenoid "lens" is preferable due to its large acceptance and *a priori* double-focussing properties. However, only with the advent of large superconducting-magnet technology could solenoids be effectively used as ion-optical devices for the production of secondary nuclear beams. This was demonstrated, for example, in our earlier radioactive nuclear beam (RNB) apparatus which was installed at the UND 9MV tandem accelerator 1987-1997 [1]. This apparatus utilized a single 20 cm bore, 3.5 T air-core aluminum-cryostat sc IGC solenoid obtained surplus from the DoE fusion-energy program. A larger, 40 cm-bore 7T solenoid was subsequently built (DoE funded) and installed at the Michigan State University National Superconducting Cyclotron Laboratory (NSCL) 1992-1998 [2]. Based on the success of these devices, we proposed to design and construct a dual 30 cm bore, 6T RNB apparatus which was subsequently funded as part of the NSF ARI grant program as a joint UM-UND project. The magnets were successfully built [3], tested, installed [4], and have been in operation at UND since the fall of 1996. In this paper we describe some of the technical design features of the magnets. Other aspects of the RNB research program using the magnets may be found elsewhere [5-8].

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II. Solenoid Ion-Optical System

A. RNB production

Many features of the magnets' design (Table 1; Figs 1-5) are dictated by the ion-optical configuration needed to produce, collect, magnetically select, purify and refocus the secondary RNBs onto a reaction target. The layout for the twin-magnet system ("TwinSol") is shown in Fig. 1. The primary production beam is typically $^{6,7}Li^{3+}$ at one or more microamps current, E ≈ 30 MeV. This beam impinges on a thin beryllium foil or a ^{3}He gas production target to produce short-lived beams of ^{6}He, ^{8}Li, ^{7}Be, ^{8}B etc. These are collected by the first solenoid, which has a typical aperture of ± 2° to ± 8° in angle (Fig. 1). This is typically x4 to x50 that of a dipole-based system.

The secondary ions are brought to an intermediate focus (typically a few mm^2) between the two magnets, where a suitable aperture and mid-plane energy-loss absorber are used to better select and purify the RNBs). The RNB is then brought to another focus on a secondary target in the back scattering chamber (Fig.1) where the RNB-induced reaction is studied [5-8].

Like most ion-optical systems the alignment of the magnetic axes of the two magnets is quite critical especially with the long ca. 6m total flight path. Thus the solenoid coils were designed to be mounted in their cryostats to close tolerances (±2 mm or less) without movement at different field settings. The latter includes movement due to the coil-to-coil forces on the magnets so suitable internal bracing for these forces (Table I) was designed and successfully employed [3].

Initial adjustment of the magnetic axes is done using external XYZ mounts on the cryostats. These in turn are mounted on aluminum optical-bench rails (Fig. 5) to permit changes in the image/object distances for the solenoid "lens" optics (magnification and angular divergence). Thus, the magnets utilize aluminum cryostats to minimize their overall weight.

The maximum field (6T) and coil length (60 cm) is designed to match the highest magnetic rigidity of the secondary beams available at UND with reasonable image/object distances (Fig.1).

B. Neutron activation and neutron heating

Given the intense primary beams, which must be stopped in a faraday cup after the production target (Fig. 1), neutron activation of the cryostat and neutron heating of the solenoid coil were of concern. To minimize neutron activation, the cryostats are made of aluminum rather than stainless steel. Also, we use large-bore magnets so that they may be situated relatively far from the production target and faraday cup. This also minimizes neutron heating of the sc coils which has been a problem in other sc ion-optical magnets. After ca. 2 years of operation, there has been no significant activation of the cryostats nor beam-induced magnet quenches.

C. Low-loss cryostats

Another design constraint was the lack of a LHe system or even a He gas recovery system at the UND accelerator lab. LHe cost was therefore a major concern together with the inconvenience imposed by frequent batch-fills. The cryostats were therefore designed for minimal LHe consumption and hence long hold time (Table I). This was primarily accomplished by the use of a "40K" shield intermediate to the LHe vessel and LN shield together with suitable low-loss G10 straps and ss tubing to provide the necessary coil support. Retractable power leads (Fig. 2) were also utilized but even when retracted they have little impact on LHe consumption when not powered, so they are generally left inserted. Retractable leads were specified in part so should a lead fail e.g. from loss of LHe vapor cooling during powered operation (see below), an individual lead could likely be replaced without cutting open the cryostat.

To further reduce LHe consumption, the magnets run primarily in persistent mode. As a result, much of the LHe consumption appears to come from eddy-current heating during power up and power down together with I^2R losses in the leads when powered. Quiescently, in persistent mode, the LHe consumption is typically <100ml/hr per magnet which results in a hold time of ca. 3 months or more (Table I). Thus, the magnets are kept continually at LHe temperatures. An added benefit of persistent-mode operation is the exceptional field and ion-optical stability of the system (Table I). This has proven very beneficial due to the sensitivity of the secondary beam focus on slight changes in field (e.g. one part in 10^4).

The cryostats are protected by Lexan™ panels which enclose the cryostats (Fig.5). These are designed to protect personnel working near the magnets in the unlikely case of a cryostat failure during a quench. Also, they prevent ferromagnetic objects from impinging on the cryostats and perhaps causing a quench or damage.

The beam line is primarily assembled from ISO 100, 200 and 250 aluminum or stainless steel components (Fig. 5).

III. Coil Design and Protection Circuitry

The coil circuit is shown in Fig. 3. Each solenoid consists of ten concentric coils individually protected with diodes and resistors internal to the cryostat to provide over-voltage protection in a quench. In addition, with the power leads inserted (per normal operation) the coil is protected externally by the quench-detect circuit and energy absorber in the magnet power supply [3]. This supply will also provide a safe ramp down of the magnet in case of AC line failure when operating in non-persistent mode. This same feature is provided for a loss of vapor cooling to the magnet leads, where the latter is detected by monitoring the voltage drop (i.e. resistance) across the leads via suitable voltage taps (Fig. 3).

IV. System Monitoring

The LHe boil-off rate is monitored ca. 100m away in the accelerator control room together with other critical parameters: LHe and LN levels; coil, intermediate-shield and LN-shield temperature; coil current and magnetic field at the cryostat face; etc. These are monitored (with suitable alarms) using a Fluke™ Hydra data logger which also sends the data to a computer for archiving (Fig. 3). The data is also available offsite via remote connection to the computer.

V. Performance

The system (Fig. 5) has been in operation since the fall of 1996 and has met or exceeded all of its design specifications and in particular LHe consumption (<0.1 l/hr per magnet). This has permitted the system to remain continuously available at LHe temperatures despite lack of an on-site He liquifier or gas recovery system.

The ion-optics, particularly in persistent mode, have been very stable and reproducible. Due to the lack of a steel yoke or other steel components in the support structure there is no hysteresis so the magnet current alone determines the focal properties of the system, and the field scales linearly with current. This minimizes the time needed to tune a secondary beam to a good focus, or to reproduce a previous tune as there is only a single "knob" for each magnet, the magnet current.

A number of experiments using secondary beams (10^4-10^6/s) of ^{6}He, ^{8}Li, ^{7}Be and ^{8}B, E=20-36 MeV have been successfully completed and published [e.g. 5-8]. A system similar to the one described here is under construction at the nuclear accelerator laboratory in São Paulo, Brazil.

Further details about the TwinSol apparatus and recent work with it may be found at www.physics.lsa.umich.edu/twinsol/

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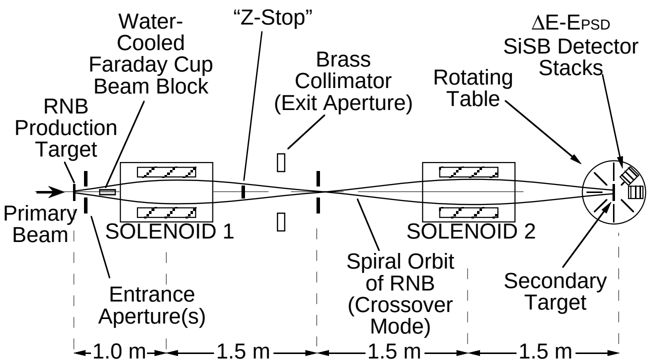


Fig. 1 Ion-optical layout of TwinSol RNB apparatus

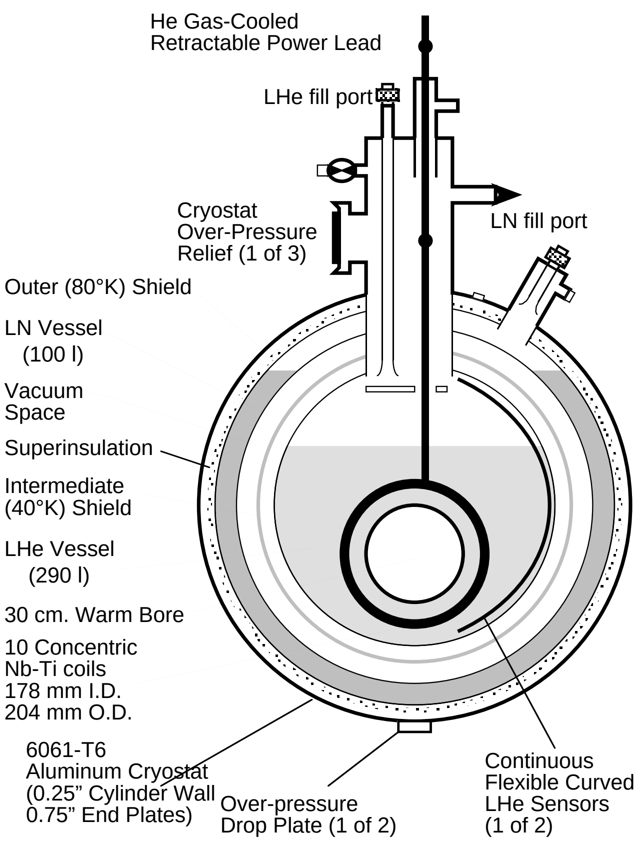


Fig. 2 Cross-sectional diagram of a TwinSol magnet.

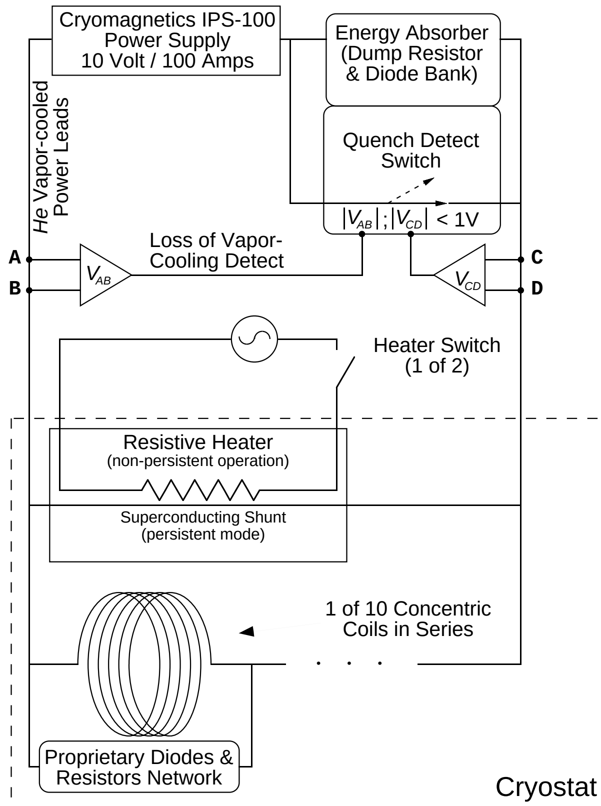


Fig. 3 Coil circuit, quench protection and monitor circuits.

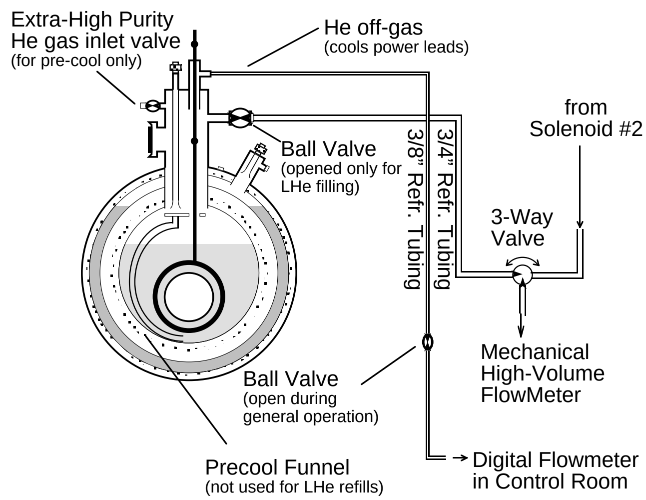
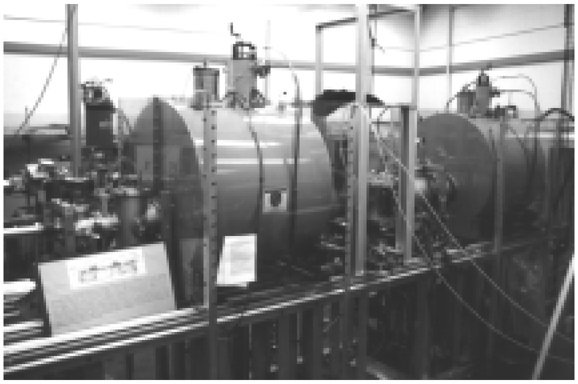


Fig. 4 Gas-handling system diagram



Design Specifications		Actual
NbTi Coil		
Field strength	6 tesla @ 100 A	6 tesla @ 98.7 A
Field integral	3.6 T-m @ 100 A	
Radial symmetry	one part in 10^4	satisfactory
Alignment of axes	< +/- 2mm	satisfactory
Inductance	200 henries	218 henries
Field persistence		< 0.1% field decay / week
Stored coil energy	1 MJ	1.1 MJ
Dimensions	(see below)	
Length		60.0 cm
Inner Radius		17.8 cm
Outer Radius		20.4 cm
Intersolenoidal force @ 3 m CL to CL		1278 newtons (6 T)
Cryostat		
Material	Aluminum	6061-T6
LHe capacity	300 liter	290 liter
LN capacity	100 liter	100 liter
LHe boil-off	< 0.30 liter/ hr	0.09 liter/ hr
LHe Hold time	> 1 month	~ 3 months
Dimensions		
Overall Length	< 1 m	0.99 m
Diameter	~ 1 m	1.12 m
Warm Bore	30 cm	30 cm
Weight	< 1000 kg	~680 kg (empty)

Fig. 5 The TwinSol RNB apparatus installed at the UND accelerator laboratory

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