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Thermomechanical design of a static gas target for electron accelerators

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ABSTRACT

Gas targets are often used at accelerator facilities. A design of high-pressure gas cells that are suitable for hydrogen and helium isotopes at relatively high electron beam currents is presented. In particular, we consider rare gas targets, $^3H_2$ and ^3He. In the design, heat transfer and mechanical integrity of the target cell are emphasized. ANSYS 12 was used for the thermo-mechanical studies of the target cell. Since the ultimate goal in this study was to design a gas target for use at the Jefferson Laboratory (JLab), particular attention is given to the typical operating conditions found there. It is demonstrated that an aluminum alloy cell can meet the required design goals.

1. Introduction

Since the electromagnetic interaction is relatively weak, a relatively large luminosity is necessary for electron scattering experiments. The problem addressed here is developing an experiment design that makes optimal use of rare target gases such as $^3H_2$ and ^3He. The presence of tritium gas places numerous stringent requirements on the target cell. Recently, two proposals [1,2] that make use of a tritium target have been assigned high priority and recommended for approval by the Jefferson Lab Program Advisory Committee. Tritium targets have been used at a number of electron accelerators: the Stanford High Energy Physics Laboratory [3], the MIT-Bates Electron Accelerator Center [4,5], and the Saclay Electron Accelerator Lab [6]. The general characteristics of these targets are given in Table 1.

The targets that we consider in this study are hydrogen, deuterium and tritium gas targets that are 10 bar in pressure at room temperature and 40 cm long. A ^3He target of the same length but at 20 bar is also considered. Both stainless steel and aluminum target cells were studied. An electron beam in the GeV region and a current of 20 μA with a rastered spot size of 3 mm in diameter was assumed for this study. The beam was assumed to be uniform over the entire spot size. With these assumptions, the characteristics of this target are compared with the previous targets in Table 1 in the entry under JLab. In terms of luminosity this target is competitive with previous targets, but makes use of the smallest inventory of tritium, only 43.3 TBq (1.17 kCi), of the previous targets.

There have been studies of static and circulating gas targets at ion beam facilities. In particular a study of the reduction in the gas target density was performed for a few-mm diameter proton or heavy-ion beam incident on static and circulating hydrogen gas targets. It was found [7,8] that the threshold in beam power per unit length in the gas to induce density fluctuations is 10 mW/mm. For the hydrogenic targets considered here and a 20 μA electron beam, the linear power density is approximately 9.5 mW/mm, while that for the ^3He target is approximately 19 mW/mm. According to Gorres et al. [7] this would result in a negligible reduction in the hydrogenic target thicknesses and about a 10% reduction in the ^3He target thickness. Of course, the density correction factors can be determined from beam current scans during the actual experiment. Unlike low-energy proton or heavy-ion beams, the high-energy electron beam loses a relatively small amount of energy in the thin windows and target gas. It is essentially a nearly constant energy loss over the length of the target cell. At Jefferson Lab in particular, the beam shape, diameter and current are quite stable. The actual beam has a diameter between 50 and 100 μm. The beam is rastered to a size of about 3 mm on the target and thus has essentially a rectangular spatial distribution. The effects of density fluctuations due to beam-induced target gas heating can be measured periodically during the experiment, say with each electron beam energy change, by measuring the target scattering rate as a function of the electron beam current.

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2. Mechanical design and cooling

The objective is to design high-pressure static gas cells that contain hydrogenic and helium gases that can be used as a target at a relatively high beam current at an electron accelerator facility. Since one of the gases is tritium, a large safety factor is necessary. The design parameters are demanding and sometimes conflicting.

The design criteria for the target were

- The amount of rare gas should be optimized.
- The target cell material must be compatible with tritium storage.
- Any possibilities for leaks (seals) should be minimized.
- The target cell must reside in vacuum.
- A reasonably high density of target gas should be achieved with a cell less than 400 mm in length and a diameter of at least 12.5 mm.
- Electron beam entry, exit and side windows should be no thicker than 0.46 mm of Al to preserve a reasonable signal to background ratio based on a GEANT4 simulation.
- At least four target cells plus an empty cell for background measurements should be provided.
- With a 20 μA electron beam, the warmest part of the cells with hydrogenic gases should not exceed 180 K, the threshold for electron beam-induced corrosion of aluminum.
- The cell should have a high safety factor and survive off-normal operation such as loss of coolant or beam raster for much longer than the time for an interlock to turn off the beam.

After realizing that the thermo-mechanical properties of stainless steel were not sufficient for this application, we investigated aluminum 2219-T851 because Al is compatible with tritium usage [9] and because this high strength alloy is weldable. The use of welded joints rather than flanges with seals would reduce the potential for possible leaks as well as permit accurate heat transfer simulations. When developing the mechanical design for this target, the emphasis was placed on minimizing the material in the path of the beam (the endcaps of the cell) while maintaining a high factor of safety. Further consideration was given to minimizing the thickness of the side walls of the cell through which scattered particles must traverse.

A top view of overall setup of the target, electron beam and spectrometers is given in Fig. 1. The target cell assembly is located inside an evacuated scattering chamber as indicated in the figure. The scattering chamber is completely isolated from the beam line and serves as secondary containment for the tritium gas target cell. The most vulnerable components in the target cell assembly are the endcaps where the primary electron beam enters and exits the target. It is desirable to keep these as thin as possible but when the beam is running they will experience the most heating in the central portion. Since the rastered beam has a diameter of 3 mm, we designed an endcap with a thin central diameter of 8 mm. Outside this area the thickness was increased significantly in order to optimize heat conduction. Given the mechanical and heat transfer properties of Aluminum 2219-T851, a central thickness of 0.46 mm, increasing to 1.5 mm outside of this area, was found to be acceptable. A flange was included in the design in order to facilitate welding and the overall height of the endcap was chosen to be 11.5 mm in order to place the welds far away from the heat generated in the central portion as indicated in Fig. 2. Although Al 2219-T851 can be age hardened after welding, the material strength does not return fully to the pre-welded conditions.

Table 1
Characteristics of tritium targets that have been used at electron accelerators. The last entry represents properties of a possible target for Jefferson Lab.

Lab	Year	Quantity (PBq)/(kCi)	Thickness (g/cm^2)	Current (μA)	Luminosity (μA g/cm^2)
Stanford	1966	0.93/25	0.8	1	0.8
MIT-Bates	1985	6.7/180	0.3	20	6.0
Saclay	1985	0.37/10	1.2	10	12.0
JLab	–	0.04/1.17	0.1	20	2.0

For this application five target cells are necessary, one for each of the gases of hydrogen, deuterium, tritium and ^{3}He and one empty cell for background measurements. The main bodies of all five target cells will be machined out of a single piece of aluminum. The maximum thickness will be approximately 41 mm. Along the axis of each target cell a wedge of material will be removed on each side in order to reduce the wall thickness within the field of view as shown in Fig. 3. Use of a single piece will allow the individual targets to be passively cooled. A large heat sink block, integral to the target array, will be actively cooled. The ends of the targets will contain counterbores designed to fit the flanges on the endcaps and provide access for e-beam welding. A hole will be drilled into the thick portion of the target array. This will provide a “parking position”, as indicated in the figure, and allow running the beam for background studies without any targets or heat generation. This position is distinct from the empty target cell since the empty target cell will be used to measure background scattering from the cell entrance and exit windows. Thermal analysis shows that this configuration will prevent the individual target cells and endcaps from overheating. The hydrogenic targets which have the most stringent temperature requirements will be placed nearest to the heat sink block.

The target lengths can be determined from 3-D measurements of the entire assembly on a coordinate measurement machine at various cell pressures. Comparison between inner, outer, and cell wall dimensions can give dimensions accurate to 0.1 mm. The target gases are expected to be greater than 99.5% isotopically pure. The fill temperature and pressure in the cell will be monitored to 0.3% at 1 Mpa. The total uncertainty in the cell length is expected to be less than 2%.

Fig. 3 also shows the overall assembly. Four valves will be mounted to the sides of the target array, out of the field of view, in order to fill and seal the individual cells. These are tritium-compatible stainless-steel valves. Since the target array will be aluminum, an aluminum-to-stainless transition piece will be used to join these parts. The target cells are located 70 mm apart. This

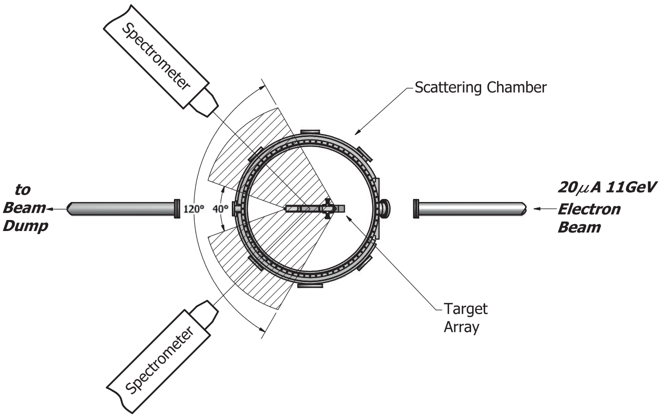

Fig. 1. Schematic diagram of the top view of the experiment indicating the location of the target cells with respect to the beam and spectrometer. The evacuated scattering chamber also serves as secondary containment for the tritium target.