INTERNAL TARGETS

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Abstract
Storage-ring operation with the combination of thin internal targets and phase-space cooling of the stored beams allows high-precision experiments to be made under very clean conditions. Here we will discuss the advantages and drawbacks of the internal-target systems currently in use or under development.

1. INTRODUCTION

The operation of internal targets in multi-pass experiments dates back to the seventies when gas-jet targets were used in the high-energy accelerators at Serpukhov and Fermilab [1-3]. These targets, later also used at Brookhaven [4], were pulsed and produced strong pressure bumps close to the target. In the late seventies, the coninuous operation of thin internal targets, compatible with the vacuum requirements in storage rings, was investigated at the CERN accelerators LEAR, ISR and SPS. The proposals at ISR [5] and SPS [6] in 1980 led to the construction and installation of so-called cluster-jet targets for high-energy physics experiments. The early plans for an internal target at LEAR and a thorough discussion of the merits of internal-target operation in conjunction with phase-space cooling of the stored beams may be found in the report by Kilian et al. [7]. By this time, Garçon et al. [8] had installed a cluster-jet target at the Saturne accelerator at Saclay. A light-ion storage ring with internal targets and electron cooling, intended mainly for intermediate-energy physics experiments, was proposed in 1980 by Pollock et al. [9] at IUCF, Indiana. This Indiana Cooler ring has been followed by a large number of cooler storage-ring projects for internal-target experiments with light and heavy ions, i.e. at Aarhus, Darmstadt, Heidelberg, Jülich, Osaka, Stockholm, Tokyo and Uppsala. There is now a rapidly growing interest in using the technique of internal targets also at electron accelerators and stretcher rings, eg. at Amsterdam, Cambridge, Frascati, Hamburg and Saskatchewan following initial experiments at Novosibirsk [10].

The use of internal targets in storage rings has been discussed at several conferences and workshops, eg. [11-22], to which here frequent references will be given. The present paper is an updated version of the internal-target contribution [23] to the CERN Accelerator School at Uppsala in 1989.

Following some general physics-experiment considerations we will here discuss the requirements on internal targets in storage-ring environement, and in some detail the techniques and advantages of gas-jet targets, polarized targets and solid targets.

2. PHYSICS EXPERIMENTS

When building accelerators and targets it is important to remember that the main goal is to optimize the conditions for the *physics experiments* to be made. The figure of merit for physics experiments is usually the luminosity, i.e. the target thickness (number of target atoms per cm^2) times the particle-beam intensity (number of projectiles passing through the target per second). The total reaction rate in the target is then given by the product of the luminosity and the total cross section for all reactions. In a given experiment, one is normally interested in only one specific channel. The detected count rate for this channel is obtained as the product between luminosity, differential cross section, detector efficiency and the solid angle covered by the detector. The quality of the experiment is, however, not only given by the count rate, but is very much dependent on other factors like background from other sources, energy resolution and angular resolution. These factors become of increasing importance in high-sensitivity experiments like on rare reactions and rare decays, and in high-precision experiments. In designing an experiment, one has to consider seriously these factors in addition to the general figure of merit, the luminosity.

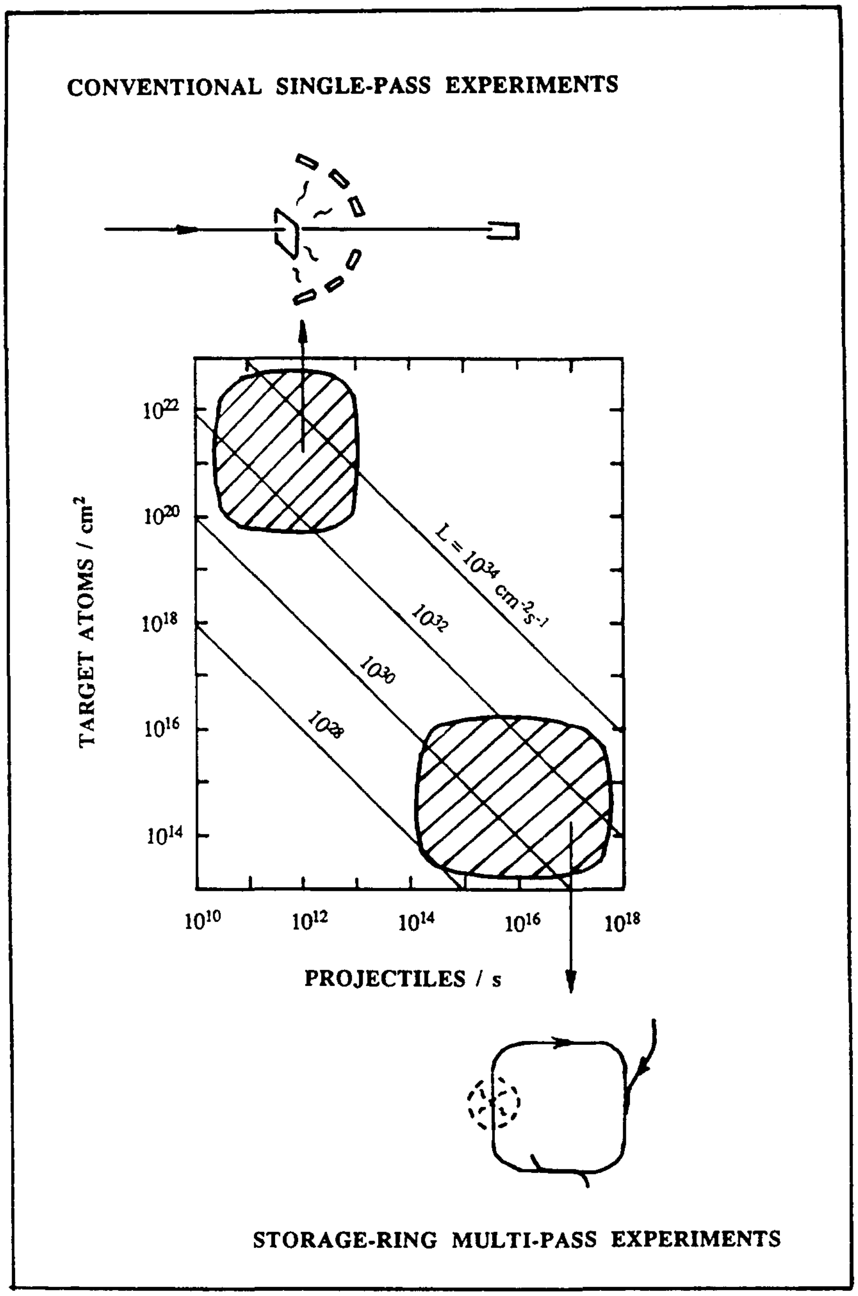

Fig. 1 Target thickness - beam intensity diagram showing the regions for conventional single-pass experiments and storage-ring multi-pass experiments. Lines of equal luminosity are indicated.

3. COMPARISON BETWEEN CONVENTIONAL AND INTERNAL-TARGET EXPERIMENTS

It is of interest to compare conventional single-pass experiments with storage-ring multi-pass experiments. In the diagram shown in Fig. 1 is given the target thickness as a function of particle-beam intensity. Lines of equal luminosity are indicated. The conventional single-pass experiments are made with extracted beams of 10^{10} - 10^{13} projectiles/s, i.e. currents of 1.6 nA - 1.6 μA singly-charged particles, from the accelerator passing through a rather thick target of 10^{20} - 10^{23} atoms/cm^2, i.e. 0.16 mg/cm^2 - 0.16 g/cm^2 single-nucleon target thickness. We are thus in the upper left corner of the diagram with luminosities in the range 10^{30} - 10^{35} cm^{-2}s^{-1}. Comparable or somewhat lower luminosities may be obtained in storage-ring multi-pass experiments with a stored beam interacting with an internal target. The intensity of the stored beam is given by the number of projectiles times the revolution frequency which is typically 1 MHz in small rings. Phase-space cooling is generally included to balance the beam heating and to improve on the beam properties. In the lower left corner the combination of beam intensity and target thickness gives too low luminosity for a realistic experiment, whereas in the upper right corner, these high intensities are not available for conventional experiments, and the high target thickness would directly kill the circulating beam in a storage-ring experiment.

The comparison shows that the two types of experiments are working at about the same luminosity but at quite separate regions of the target-thickness beam-intensity diagram. The storage-ring operation is, however, considered to be superior to the conventional experiments in several respects.

Efficient use of the particle beams from the accelerator.

Storage-ring experiments allow parallel operation since only a fraction of the beam from the accelerator is used, injected periodically into the ring. The particles make typically 1 million revolutions per second in small rings, and since the target is extremely thin, particles which do not interact strongly in the target or are scattered out of the ring acceptance, are recirculated and used again, maybe after cooling to retain their beam properties.

High energy and angular resolutions.

The high energy resolution of the cooled particle beams may be fully utilized in the experiments thanks to the small target thickness. The angular resolution profits from the small, well defined intersection point between particle beam and target.

Undisturbed reaction products.

The reaction products may be detected more or less without energy loss in the thin target. The detectors are placed either inside the scattering chamber or outside behind thin foil windows.

No background from target container or beam dump.

This is evident, since neither target container nor beam dump are required when using internal targets in a storage ring.

Possibility for use of special targets.

Here can be mentioned atomic-beam targets of almost 100% polarization.

High luminosities and count rates.

As shown above, the luminosities in storage-ring experiments are comparable or somewhat lower than those in conventional experiments. For a given energy resolution they are of course superior.

4. REQUIREMENTS ON INTERNAL TARGETS

The internal targets to be used in storage-ring experiments have to fulfil a number of requirements. They should be thick enough to give sufficient count rate, and at the same time thin enough not to degrade the circulating beam too rapidly. They should also be thin enough to allow heavy recoil products to escape and be detected. From the experimental point of view, a wide choice of target material is desirable. To reduce the risk of background from non-target material, like narrow collimators, the region around the target should be wide enough. The disturbance to the ring vacuum should of course be kept at a minimum. For the detector arrangements, a large solid angle should be available around the target. Finally, most experiments require a well defined reaction vertex.

All these requirements are of course impossible to meet at the same time, and in building different target systems, a trade-off between different requirements is common, in order to meet the needs of a specific experiment.

5. CHOICE OF INTERNAL TARGETS

There is a wide range of potential internal targets to be used in storage-ring experiments. They may be divided schematically into gas targets and solid targets. The main advantage with gas targets is that the target beams are well matched to the ion beams, both in dimensions and thickness, whereas the disadvantage is the pressure bump around the target beam. The solid targets are locally very thick, but they occupy on the other hand only a small fraction of the area of the stored beam. Limited beam lifetimes and low duty factors are seen as the main drawbacks in using these targets.

There are three types of molecular-beam targets. If we assume a distance of 25 cm between the nozzle and intersection point between target beam and circulating beam, to allow for the differential pumping, we may reach a target thickness of the order 10^{10} atoms/cm^2 in the case of molecular effusion through a nozzle. At higher input pressures we get a supersonic gas jet which at room temperature reaches thicknesses of 10^{13} atoms/cm^2. Another factor of 10 may be obtained in the so-called cluster jet, obtained by cooling the nozzle.

Polarized atomic-beam targets may be obtained for hydrogen and deuterium using multipole magnets and rf-transitions, or by spin exchange, and for ^{3}He and the alkali metals using laser light. In optimized systems, target thicknesses of 10^{13} atoms/cm^2 are foreseen. To increase further the target thickness a factor of 10, storage cells for the gas have been developed. Special attention is given to the wall material, the temperature and the openings of the storage cells.

The solid targets to be used in storage-ring experiments may be of different materials and forms. We have thin fibers or micro-ribbons mounted on some fork-structure and introduced into the circulating beam. Microparticles (dust) may be enclosed in a cell, like in the case of gas storage-cell, or prepared in the form of a beam, crossing the stored beam and collected in a beam dump. Frozen droplets, so-called pellets, may be seen as a special case of the microparticle-beam target. The solid targets are, as mentioned above, locally very thick, but the *effective target thickness*, taking into account the area of the stored beam occupied by the target, may be adjusted to optimum values of the order 10^{14}-10^{15} atoms/cm^2. In fact, a main problem is to come down to this effective values without reducing the duty factor by keeping the target outside the beam part of the time.

In Table I is collected the status of the internal-target systems at different hadron and electron accelerators, realizing that the border lines between plans, developments, tests and experiments may be rather floating. It is mainly the gas-jet and cluster-jet targets which are used regularly for data taking, while the other target systems are at different stages of development.

Table I. Compilation of internal targets under development (dev), test (test) and data-taking (exp) at different hadron and electron accelerators. Activities no longer being pursued are given within parentheses.

Target / Accelerator	Gas target				Solid target		
	Gas jet	Cluster jet	Pol. beam	Pol. cell	Fiber	Dust	Pellet
Main Ring, FNAL	(exp)						
Accum. Ring		exp					
AGS, BNL	exp						
ISR, CERN		(exp)					
SPS		exp	dev				
LEAR		exp		dev			
UNK, Serpukhov			dev				
SATURNE, Saclay		(exp)					
COOLER, IUCF Indiana	exp			dev	test	test	
CELSIUS, TSL Uppsala		exp			test		dev
ESR, GSI Darmstadt	test						
TSR, MPI Heidelberg				test			
COSY, KFA Jülich		dev			dev	(dev)	
TARN, INS Tokyo					dev	(dev)	
NIKHEF, Amsterdam	dev			dev			
VEPP, Novosibirsk			(exp)	exp		exp	
ADONE, Frascati		exp					
HERA, Hamburg				dev			
Bates, MIT	dev			dev			
Saskatchewan	dev						

The techniques, advantages and drawbacks of different target systems will be discussed briefly below, starting with the gas-jet targets.

6. GAS-JET TARGETS

A review on the use of gas-jet targets in storage rings was given by Macri [24] at the CERN Accelerator School at Geneva in 1983. Various source configurations for beam production were discussed as well as the implementation of gas-jet targets in storage rings and the influence on stored beams. As examples, the cluster-jet targets at ISR [5, 25] and SPS [6, 26] at CERN were described in some detail. Here, we will present briefly some developments made and systems put into operation since 1983.

6.1 Supersonic gas-jet targets

Supersonic gas-jet targets are being used for experiments at extracted beams at a number of low-energy accelerators (cf. eg. Ref. 14). In these set-ups, different gases may be pressed through a tube and nozzle, passing a skimmer and being collected in a catcher. There is a very narrow space for the ion beam to pass between the skimmer and catcher, and the detectors occupy only a small solid angle in the horizontal plane. The target thicknesses are very large, 10^{17} atoms/cm^2, thanks to the closeness to the nozzle exit. The pressure in the target region is on the other hand very large, of the order 10^{-4} mbar, which of course is not compatible with storage-ring operation. To cure this situation and reach acceptable ring pressures, a number of differentially pumped stages on each side of the target region has to be added. The differential pumping along the circulating beam, using narrow tubings, of course increases the problem of background count rates, and reduces the flexibility of mounting external detectors. Also, the broad gas distribution gives a less defined reaction vertex and contributes to the background.

A supersonic gas-jet target has been constructed by Sperisen et al. [27, 28] at the Indiana Cooler ring at IUCF, Bloomington, and successfully used in measurements of the total cross section for the reaction $p+p \rightarrow p+p+\pi^0$ close to threshold by Meyer et al. [29, 30]. In the experiments, the target beam was produced by a flow of about 2 mbar l/s of hydrogen molecules through a 0.11 mm diameter nozzle cooled to 40 K. A catcher with a 23 mm diameter opening located 14 mm from the nozzle pumped away about half of the gas flow, the rest being removed in a three-stage differential pumping along the circulating beam. About 60% of the total target thickness of 7×10^{15} atoms/cm^2 was due to the target beam with a FWHM of 3.3 mm at the intersection point. The main contribution to the remaining 40% of the target thickness came from the pressure in the first pumping stage along the 164 mm beam path through the chamber. The target system may be installed at three different positions in a general-purpose scattering chamber. The forward scattering angles are determined by a 260 mm diameter foil window with a central tube for the circulating beam. The maximum and minimum angles are 13.6° and 1.7° when the target is mounted at the central position. The maximum angle may be increased to 22° with the target in the downstream position, and the minimum angle decreased to 1.1° in the upstream position.

At the Experimental Storage Ring (ESR) at GSI, Darmstadt, a gas-jet target has been installed by Gruber et al. [31]. The target is designed to deliver a molecular density of 10^{11} - 10^{14} atoms/cm^3 within an interaction length of 3 - 5 mm. The strong vacuum requirements in the ring and the scattering chamber are satisfied by a differential pumping in four stages along the target beam, both at the injection side and the beam-dump side. By adjusting the gas-input parameters, cluster formation in the target beam is avoided. This is important since the high power deposition in the clusters from the high-Z projectiles traversing the target beam will cause evaporation of the clusters. A recirculation and cleaning system will be used to handle more economically the large throughput of gas. The differential pumping along the target beam, instead of along the circulating beam, allows detectors to cover almost the whole horizontal plane and vertical angles between ±10°.

Internal-target experiments are being planned at the pulse stretcher/storage rings at the electron accelerators at MIT-Bates [32], NIKHEF, Amsterdam [33] and at Saskatchewan using gas-jet targets with thicknesses of the order 10^{17} - 10^{18} atoms/cm^2 [19, 34]. In order to reach these target thicknesses the focusing properties of slit nozzles will be utililized. Additional development work is, however, needed to understand the influence on the beam formation of parameters like slit length, width and opening angle, nozzle temperature, input pressure and type of gas.

6.2 Cluster-jet targets

The cluster-beams are formed by pressing a gas through a trumpet-shaped nozzle with temperature and pressure conditions close to the phase transition to liquid. The central part of the target beam is forming large molecules, so-called clusters, with typically 10^5 atoms. The technique was invented by Becker et al. [35] at Karlsruhe, and the dependence of the cluster formation on different input parameters has been studied in detail by Hagena and Obert [36]. The technique has been used to produce target beams of hydrogen for high-energy physics experiments at CERN [25, 26] and Saclay [8]. A cluster-jet target, similar to the one used at the UA6 experiment at the SPS at CERN [26], has been installed at the CELSIUS storage ring at Uppsala [37-39]. It is being used also for heavier gases like deuterium, nitrogen and argon.

Figure 2 shows the central part of the cluster-jet target at Uppsala, with the differentially pumped beam source, the interaction region and the target-beam dump. For the target-beam production a gas is pressed by a few atmospheres through the nozzle, which may be cooled down to 20 K by a two-stage cryogenerator. A cluster beam is formed which is made to pass a skimmer and a set of collimators, giving an intense beam with a well bounded intensity profile. The cross section of the target beam at the intersection with the circulating CELSIUS beam, 250 mm from the nozzle, is oval-shaped, defined by the oval skimmer, with a length of 8 mm along the circulating beam and 5 mm across. At the bottom, the target beam is collected in a cryogenic beam dump which has to be regenerated after typically 40 hours of running. A gas recirculation and cleaning system is currently under construction.

In Table II is given a compilation of running conditions and target thicknesses for the gases hydrogen, nitrogen and argon, taken when the pressure in the scattering chamber reached 2×10^{-7} mbar. The target thicknesses, measured by a compression tube, are all of the order 1 ng/cm^2 or ranging from 3×10^{14} to 2.4×10^{13} atoms/cm^2 between hydrogen and argon. A wide range of of pressure-temperature combinations, certainly, will give similar target thicknesses.

Life-times of the proton beam at CELSIUS have been measured at different energies with cluster-jets of hydrogen, nitrogen and argon. The target-related partial half-lives are collected in Table III and compared with calculated half-lives due to multiple Coulomb scattering [40] using an acceptance of the CELSIUS ring of 100π mm mrad and, in the case of hydrogen, the target thickness of Table II. For nitrogen and argon, the target thicknesses used were determined from triple-coincidence measurements of scattered protons in a monitor telescope. There is a good agreement between the experimental and calculated half-lives, as well as between the target thicknesses of nitrogen and argon measured by the two methods of Table II and III.

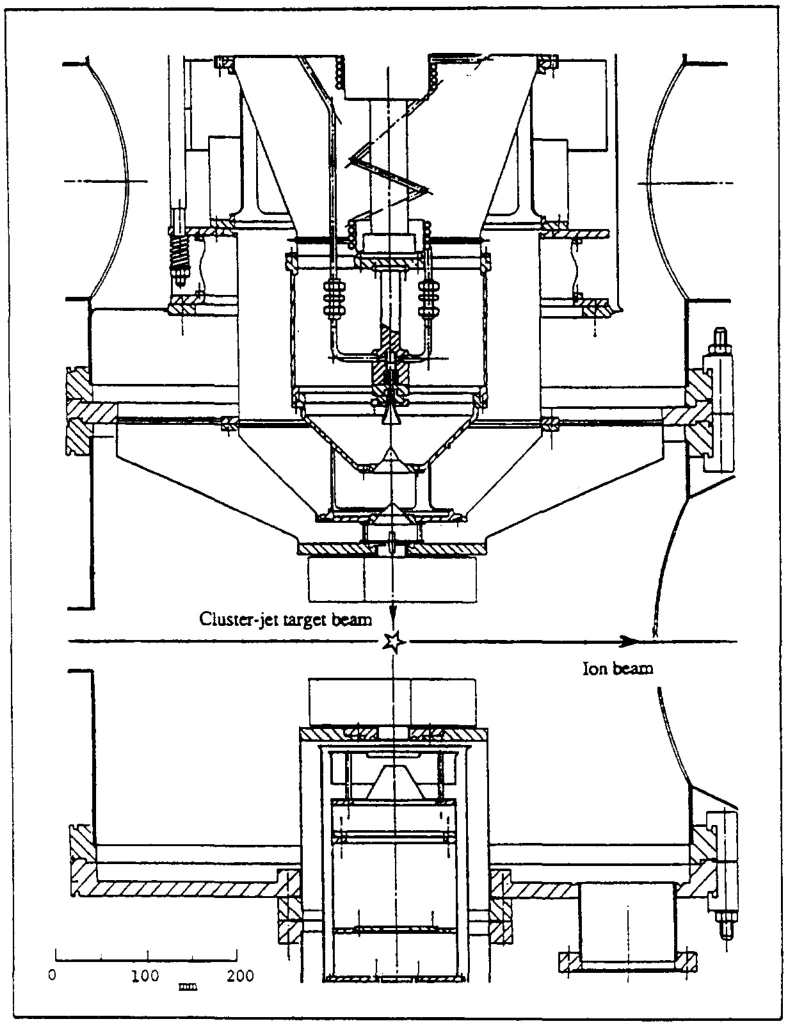

Fig. 2 Vertical cross section of the central part of the cluster-jet target at the CELSIUS ring, showing, in the upper part, the differentially pumped beam source with the cooled nozzle, skimmer and collimators, the central scattering chamber, and, in the lower part, the cryogenic target-beam dump.

Table II. Input parameters and target thicknesses for different gases in the cluster-jet target.

Gas	Z	A	Input pressure [bar]	Nozzle temp. [K]	Gas flow [mbar l/s]	Target thickness [atoms/cm^2]	[g/cm^2]
Hydrogen	1	1	1.5	34	10.0	3.0×10^{14}	0.5×10^{-9}
Nitrogen	7	14	7.0	160	9.5	5.0×10^{13}	1.2×10^{-9}
Argon	18	40	2.0	130	2.5	2.4×10^{13}	1.6×10^{-9}

Table III. Comparison between experimental and theoretical partial half-lives of proton beams of different energies traversing cluster-jet targets of hydrogen, nitrogen and argon.

Gas	Target thickness [atoms/cm^2]	Partial half-life of proton beam					
		48 MeV		72 MeV		600 MeV	
		Exp.	Theor.	Exp.	Theor.	Exp.	Theor.
Hydrogen	3.0×10^{14}			2 min	1 min	21 min	20 min
Nitrogen	3.6×10^{13}	22 s	27 s			20 min	22 min
Argon	2.0×10^{13}	21 s	9 s				

It is here appropriate to discuss some conditions for internal and external detection of the reaction products. The cluster-target systems, with the differential pumping made along the target beam, instead of along the circulating beam, allow for an open construction with possibilities for valves both towards the beam source and the beam dump, and for wide-angle detection. The scattering chamber of the CELSIUS cluster-jet target is equipped with a number of cones on which are mounted flanges with thin stainless-steel windows. A large fraction of the horizontal plane is accessible for external detection, as shown in Fig. 3, the forward cone covering the range 5° - 24°. The deuteron break-up by protons of 1.15 GeV has been studied with a hodoscope and absorbers in the forward direction and CsI crystals located at 55° and 80° to the beam [41].

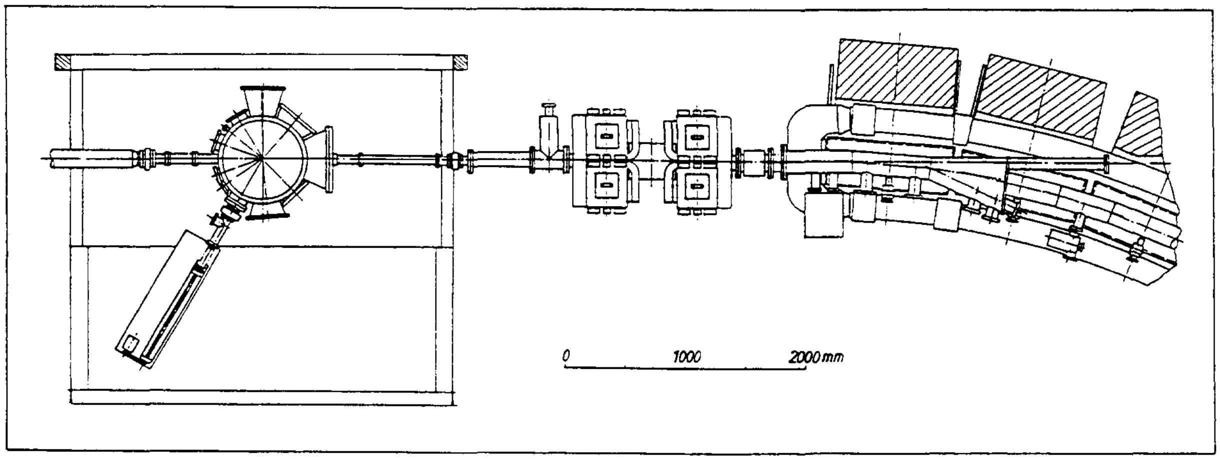

Fig. 3 Target section and part of the magnet quadrant at the CELSIUS ring, showing the possibilities for external detection around the common cluster-jet and fiber-target scattering chamber, internal detection inside the chamber, and also small-angle detection in the quadrant vacuum chamber.

For the detection of slow reaction products, not penetrating the thin windows, a rail system for mounting internal detectors inside the scattering chamber has been constructed. The detection of small-angle reaction products are being made in a specially constructed vacuum chamber located in the magnet quadrant following the target section, using the ring magnets as a spectrometer (cf. Fig. 3). A new detector chamber is also being prepared for installation at the straight section following the magnet quadrant.

The present trend in several internal-target experiments at CELSIUS is to go in the direction of wide-angle detection. The fiber target and the pellet target, to be discussed in detail below, are meeting the requirements of close to 4π detection. The cluster-jet target at CELSIUS is more restricted in this sense, but the construction of a new scattering chamber will substantially increase the angular range covered by external detectors, at the expense, however, of reduced target thickness and higher pressure in the scattering chamber. The new chamber is schematically given in Fig. 4. It consists of three parts; two permanent chambers including the valves towards the beam source and the beam dump, and an exchangeable central chamber. The central chamber to be used by the WASA/PROMICE collaboration at CELSIUS allows a large fraction of the horizontal plane and ±35° vertically to be covered by external detectors outside the thin-walled central cylinder, and between 3° and 25° for external forward detection by using a thin-walled forward window. The advantage of the new construction is the possibility to rapidly exchange central chambers, tailor-made for specific experiments. The heavy-ion collaboration CHIC at CELSIUS is constructing a central chamber covering both external and internal detection, and with the possibility to introduce the fiber target as a complement to the cluster-jet target.

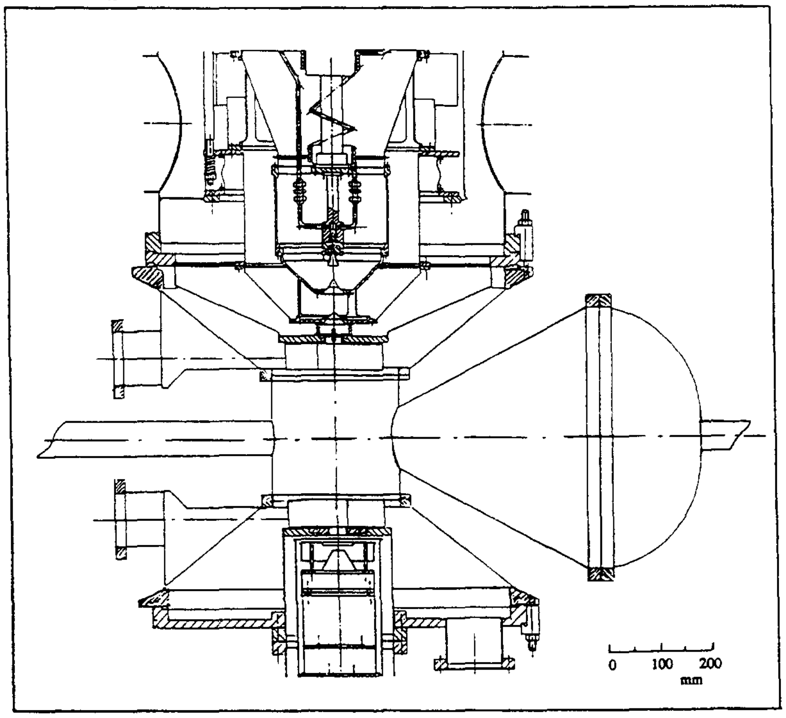

Fig. 4 Schematic view of the new scattering chamber connected to the cluster-jet target at the CELSIUS ring.

The properties of cluster-beams of being intense and highly directive are fully utilized in the JETSET experiment [42-44] at the Low-Energy Antiproton Ring (LEAR) at CERN. The antiprotons in LEAR are interacting with the protons in a hydrogen target beam, and the reaction products are detected in a close to 4π detector system. To allow for the installation of the detector system, the distance between the beam production and beam dump is about 2 m. A target thickness of $3x10^{13}$ atoms/cm^2 and a beam diameter of 8 mm (FWHM) at the intersection have been reported [44]. Preparations are being made to decrease the distance of 1.1 m between the beam source and the interaction region in order to reach higher values of the target thickness.

The charmonium spectroscopy experiments at the CERN-ISR [25], using the antiproton beam and the hydrogen cluster-jet target, are being continued at the Fermilab antiproton Accumulator Ring [43, 45] at a factor of 10 higher luminosity and a factor of 5 larger acceptance. The hydrogen cluster-jet target, having a distance of 36 cm between the nozzle and the intersection point, produces a target thickness of 10^{14} atoms/cm^2. The vacuum requirements of 10^{-10} mbar in the Accumulator Ring is met by strong pumping of the target and the interaction region.

In addition to the cluster-jet targets at ISR, LEAR and FNAL, the productive Genova group has constructed a cluster target for heavy gases [46] to produce tagged photon beams at the ADONE electron accelerator at Frascati. A target thickness of 1.5×10^{14} atoms/cm^2 of argon has been obtained by pressing the gas of 20 bar through a room-temperature nozzle with 0.07 mm diameter opening. The beam diameter at the intersection point, 25 cm from the nozzle, is 5.4 mm. Tests with cluster beams of argon and krypton have shown good agreement with the law of corresponding jets [47, 36]. The facility has been updated with a cooling device to cool the nozzle down to 90 K. The effects of the cluster-jet target on the beam quality of the stored electrons in the ADONE ring are described in Ref. 48.

A hydrogen cluster-jet target for internal-target experiments at the COSY storage ring at KFA, Jülich, is under construction at the University of Münster [49]. The design is based on the experience from previous investigations of cluster beams at Münster [50]. The target system will be located in the narrow space between a quadrupole and dipole magnet (cf. eg. Fig. 3) in the COSY ring, using the dipole magnet as a spectrometer for the reaction products. The special location requires a narrow construction and a distance of about 1.5 m between the beam source and the beam dump. The design value of the target thickness is 10^{14} atoms/cm^2. To meet the vacuum requirements of the COSY ring several differential pumping stages along the cluster beam will be installed using cryopumps with specially constructed cold surfaces.

A new nozzle design for cluster-jet target beams has been proposed by Varentsov [51] at St Petersburg. The target beam emanates from a narrow central tube inside the nozzle whereas a carrier gas is injected in the outer part of the nozzle orifice. The main advantage of the construction is the reduced consumption of target material, of particular importance in the cases of expensive gases.

7. POLARIZED TARGETS

Important additional information on the nuclear interactions may be obtained in experiments using polarized targets and polarized beams. A general problem, however, is to reach the luminosities available in non-polarized experiments. The polarized atomic-beam targets may be obtained either by state selection in multipole magnets or by optical pumping induced by laser light, either directly or through spin exchange. To increase the target thickness, the polarized target atoms may be introduced into a storage cell. Reviews on free and stored atomic beams as internal polarized targets have been given by eg. Grüebler [52] and Haeberli [53].

7.1 Atomic-beam targets

The nuclear polarization is generally obtained by electron-spin polarization which through the hyperfine interaction affects the nuclear spin projection. The hyperfine structure (hfs) diagrams of hydrogen and deuterium are shown in Fig. 5.

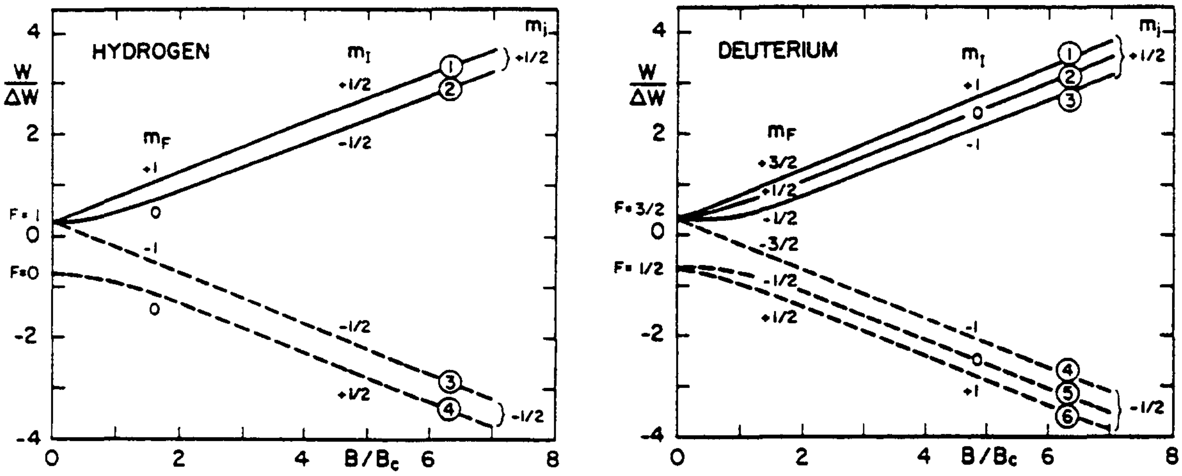

Fig. 5 Energy level diagrams of hydrogen and deuterium in an external magnetic field. The energies are given in units of ΔW = 1420.4 MHz and 327.4 MHz, respectively, and the magnetic fields in units of B_c = 507 G and 117 G. From Ref. 52.

In the case of hydrogen we have a simple atomic system with both nuclear and electronic spin equal to 1/2. The resulting hyperfine levels with F = 1 and 0 are split up into magnetic substates by an external magnetic field. In the strong-field limit there are two groups characterized by the electron spin projections $m_J = \pm 1/2$. The proton spin projections, which are the ones of interest in the experiments, are here $m_I = \pm 1/2$ in the two groups. The proton polarization is given by $P_z = N_+ - N_-$, the difference in number of protons in $m_I = +1/2$ and -1/2, with the total number of particles normalized to 1. The quantization axis is normally chosen along the magnetic field, resulting in vanishing components P_x and P_y of the vector polarization. The states 1 and 3 are pure in m_I, +1/2 and -1/2, with a polarization $P_z = +1$ and -1, respectively, independent of the external magnetic field. In the mixed states 2 and 4, the polarization depends on the strength of the field, $P_z = -1$ and +1, respectively, in strong fields, going down to 0 in weak fields. In the case where several states are occupied, the polarization is given by the weighted mean value.

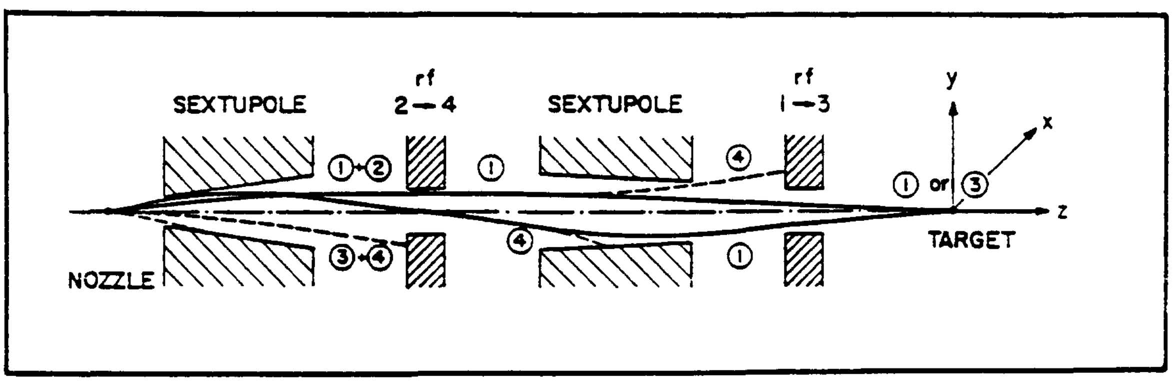

Fig. 6 Schematic diagram of a polarized atomic-beam target system with multipole magnets and rf-transitions to produce single substates. The trajectories of hydrogen atoms in different magnetic substates, cf. Fig. 5, are indicated. From Ref. 52.

A polarized beam of atomic hydrogen may be obtained by state selection in inhomogeneous magnetic fields and rf-transitions between the hyperfine states (cf. Fig. 6). Molecular hydrogen is dissociated by an rf-discharge to give a beam of atomic hydrogen. The first sextupole focus atoms in the states 1 and 2 with $m_J = +1/2$, while atoms in 3 and 4 are defocused and lost. In the central field, an rf-transition is induced between the states 2 and 4, so, at the entrance of the second sextupole we have atoms in the states 1 and 4. In this magnet, atoms in the state 4 are again defocused, and we have a remaining hydrogen beam of state 1 atoms focused to the intersection with the circulating beam. The proton polarization is here $P_z = +1$, since all atoms are in the state 1 with $m_I = +1/2$. An rf-transition between the states 1 and 3 directly after the second magnet provides a rapid switching between the polarizations $P_z = +1$ and -1.

Deuterium, with a nuclear spin I = 1, has a hfs diagram similar to hydrogen (cf. Fig. 5). The m_I components are here 1, 0 and -1, and the polarization of the deuteron may be described by a vector polarization, $P_z = N_+ - N_-$, the difference in number of deuterons in $m_I = +1$ and -1, and a tensor polarization $P_{zz} = 1 - 3N_o$, where N_o is the number of deuterons in states with $m_I = 0$. The only pure states are 1 and 4 with $P_z = \pm 1$ and $P_{zz} = 1$. For the other mixed states, the vector and tensor polarizations depend on the strength of the external field. By state selection and rf-transitions one may obtain deuterium beams with different combinations of the deuteron vector and tensor polarizations.

An atomic-beam target consists essentially of the atomic-beam part of a polarized ion source, for which over the years large efforts have been put into increasing the intensity. In a series of papers, Singy et al. [54-56] at ETH, Zürich, are discussing the influence of cooling, surface recombination and magnet system in the production of intense polarized hydrogen atomic beams. An intensity of 10^{17} atoms/s and a density of 2×10^{12} atoms/cm^3 at the exit of the atomic-beam stage have been obtained using a slow atomic beam (T = 35 K) and an optimized magnet system with tapered electromagnetic sextupoles. High-field permanent sextupole magnets are also very efficient for state selection in atomic-beam sources [57]. They are being used in the atomic-beam stage feeding a storage cell in the FILTEX experiment, to be discussed separately below.

At CERN an optimized system with cooled beams and superconducting magnets has been studied by Dick and Kubischta [58]. The calculations give target thicknesses of 9×10^{12} polarized hydrogen atoms per cm^2 with a target length of 30 mm and width of 15 mm, using a slit source 2 x 14 mm, cooled to 30 K, with a gas input of 2 mbar l/s. The required high angular acceptance may be met by using superconducting sextupole magnets. Apertures and pole-tip fields of up to 107 mm and 4.7 T, respectively, are foreseen [59]. Experiments have been proposed at the UA6 facility at SPS, and preparations are being made for projects at LEP and at the proposed LHC at CERN.

A conventional jet target for polarized hydrogen and deuterium atoms is being developed at Dubna [60] for use at the UNK accelerator at Serpukhov. The estimated target thickness is 10^{12} atoms/cm^2 with a target diameter of 1 cm at the interaction point.

A Michigan-MIT Collaboration [61, 62] is developing an ultra-cold polarized atomic hydrogen jet target for experiments at the UNK proton accelerator at Serpukhov. Microwave-induced extraction of polarized hydrogen atoms stored at 0.3 K and 5 T in a dilution refrigerator is expected to give a target beam with a thickness of 10^{14} atoms/cm^2. In a similar system at Dubna [63], the extraction by spin separation in the gradient of a high magnetic field is being studied. Both techniques are discussed in Ref. 22.

7.2 Storage-cell targets

A way to increase the target thicknesses, particularly in the case of polarized atomic-beam targets, is to feed a storage cell, through which the circulating beam will pass. A schematic drawing of a storage cell is given in Fig. 7.

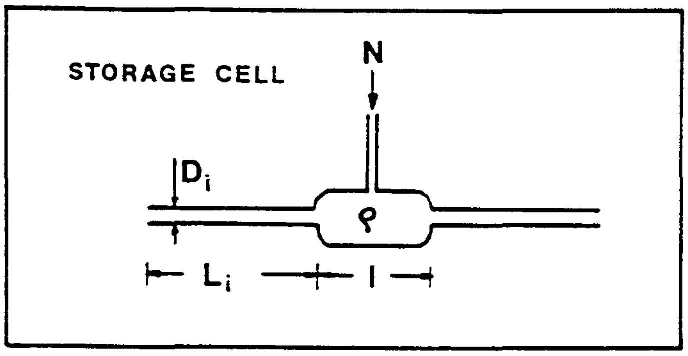

Fig. 7 Schematic diagram of a storage-cell target with openings for the gas injection and for the circulating beam.

The average density in the storage cell is the feed rate divided by the total conductance of the constrictions.

$$\rho = N/C$$

ρ	average density in the storage cell [atoms/cm^3]
N	feed rate [atoms/s]
C	total conductance of the constrictions [cm^3/s]

The target thickness is as usual given by the density times the length of the target along the circulating beam.

$$t = \rho\, l$$

t	average target thickness [atoms/cm^2]
l	length of the storage cell [cm]

The conductance depends on the square root of the temperature of the system divided by the molecular weight of the target gas, and the sum of the constrictions with diameter in cube divided by the length.

$$C = 3.81\text{x}10^3 \sqrt{\frac{T}{M}} \sum_i \frac{D_i^3}{L_i + 1.33 D_i}$$

T	absolute temperature [K]
M	molecular weight of the target gas
D_i	diameter of a constriction [cm]
L_i	length of a constriction [cm]

Combining these equations we get an expression for the target thickness in the storage cell. From the simplified relation below it is evident that high target thicknesses require a large feed rate, a long storage cell, a heavy gas at low temperature, and few, long and narrow constrictions.

$$t \propto N\, l \sqrt{\frac{M}{T}} \sum_i \frac{L_i}{D_i^3} \qquad L \gg D$$

In a typical case we have feed rates of 10^{17} atoms/s, a cell of 10 cm length, three constrictions of 10 cm length and 1 cm diameter. For atomic hydrogen at room temperature the target thickness will be 6×10^{13} atoms/cm^2 and at 20K 2×10^{14} atoms/cm^2. This can be compared with the value 10^{12} atoms/cm^2 for a free atomic beam of 10^{17} atoms/cm^2 s and the velocity 10^5 cm/s. The gain a factor of 100 has to be paid by the narrow constrictions which may cause background problems, the target length which results in an undefined reaction vertex, and the cell walls which may disturb the reaction products. Special attention has also to be paid to the wall coating and the cooling to keep recombination and depolarization at low values.

A storage-cell target for polarized hydrogen has been constructed by a collaboration from Heidelberg, Marburg, Munich and Madison [64, 65]. It is based on an atomic-beam source with high-field permanent sextupole magnets and rf-transitions of the kind described above giving so far about 3×10^{16} atoms/s of polarized hydrogen in one substate. This results in a target thickness of about 2.5×10^{13} atoms/cm^2 in the storage cell of 250 mm length and cooled to 100 K. An improvement of a factor two will be obtained by using two short tapered magnets as the first sextupole. The storage-cell system will be used to produce polarized beams in the so-called FILTEX experiments at the test storage ring (TSR) at Heidelberg for protons and at LEAR, CERN for antiprotons. The installation at TSR is planned for the spring 1992. A similar system, the HERMES storage-cell target, is proposed for the study of reactions between polarized electrons in the HERA ring at Hamburg and polarized target nuclei. Scaling to the HERMES parameters indicates that the required target thickness of 10^{14} atoms/cm^2 will be reached. The HERMES configuration is planned to be tested early in 1992 with external alpha beams at MPI, Heidelberg. Alternative polarized sources feeding the HERMES storage cell are the spin-exchange optical pumping source and the ^{3}He source discussed below.

In a series of experiments, an Argonne-Novosibirsk collaboration is measuring the tensor analyzing power in electron-deuteron elastic scattering using a polarized deuterium storage-cell target in the VEPP-3 electron storage ring at Novosibirsk. It is a continuation of the initial measurements [66] made at the VEPP-2 ring at a target thickness of 10^{11} atoms/cm^2 from a polarized deuterium gas-jet target [67]. The first storage-cell measurements [68] were made at a target thickness of about 3×10^{12} atoms/cm^2 with a storage cell of 940 mm length, the cell being fed by polarized deuterium from the atomic-beam source [67]. An improved storage cell of 570 mm length with a clam-shell mechanism to open during electron-beam filling of the ring and to close during data taking is expected to give a target thickness of 10^{13} atoms/cm^2 [69]. A major improvement will be made by exchanging the atomic-beam source with a laser-driven source feeding the storage cell with deuterium polarized through spin exchange with optically pumped alkali atoms [69, 70]. By performing the optical pumping and the spin exchange at high magnetic fields, intensities of 4×10^{17} atoms/s and polarization P_{zz} of 0.54 are expected. The target thickness in the clam-shell storage cell will then be about 4×10^{14} atoms/cm^2.

A storage-cell target for polarized ^{3}He has been proposed by Milner et al. [71] at Caltech. The system consists of two stages; a cell fed by helium gas and polarized by laser light and the storage-cell target fed by the polarized helium through a capillary tube. In the first cell, the $^3S_1$ metastable state is populated by a discharge and polarized through optical pumping by polarized laser light to the $^3P_0$ state. The $^1S_0$ ground-state atoms are then polarized through exchange collisions. A flow of 10^{17} polarized ^{3}He atoms per second are expected to enter the storage cell through the capillary tube. The target thickness is of course dependent on the geometry of the storage cell, but assuming the same dimensions as discussed above, it will reach about 10^{14} atoms/cm^2. A storage-cell target of this kind has been developed at MIT for use at the MIT-Bates South Hall Ring [19, 32].

A feasibility study of a storage-cell target in the IUCF Cooler has been performed using variable apertures as well as a storage cell with 240 mm length and 8 mm diameter [72]. The tests with 185 MeV protons and targets of hydrogen and helium showed positive results with respect to attainable luminosity and to low-background detection. The MIT polarized ^{3}He target is planned to be installed for the investigation of the ^{3}He wave function by quasi-free scattering [73].

Spin physics with polarized electron beams and polarized internal targets is being planned within the SPITFIRE program at the AmPS ring at NIKHEF, Amsterdam [74].

8. SOLID TARGETS

We will now turn to the solid targets and start by looking at some characteristics, Table IV. Fibers of the refractory elements carbon, molybdenum and tungsten, with diameters 7, 13 and 4 μm, microparticles in the form of 1 μm nickel-dust and 25 μm frozen hydrogen pellets, all have target thicknesses of the order 10^{19} atoms/cm^2. They are locally very thick, but taking into account the ratio between the target area and stored-beam area, the effective target thicknesses come into the range acceptable for storage-ring operation. A reduction of the effective target thickness may also be obtained by a periodic sweeping of the beam over the target or reversely the target over the beam.

Table IV. Characteristics of some solid targets.

	Fibers			Microparticles	
				"dust"	"pellet"
	^{12}C	"96"Mo	"184"W	"59"Ni	^{1}H
Fiber diameter [μm]	7	13	4		
Microparticle diameter [μm]				1	25
Mass density [g/cm^3]	2.27	10.2	19.3	8.9	0.07
Target thickness [mg/cm^2]	1.3	10.5	6.1	0.55	0.11
- " - [10^{19} atoms/cm^2]	6.3	6.5	2.0	0.6	6.6

8.1 Fiber targets

The use of thin fibers as internal targets in storage-ring experiments has the advantages of simple target construction, good vacuum conditions and the possibility for close to 4π detection of the nuclear reaction products. Limited number of fiber materials and the problems connected with the manufacture and mounting of sufficently thin fibers (not to degrade the circulating beam too rapidly) are seen as the main drawbacks in using fiber targets. Furthermore, the detection of heavy recoils is prevented by the large local target thickness of the order of mg/cm^2 of fibers with μm diameters (cf. Table IV).

Commercially available fibers of refractory materials in the μm range have been tested [37] in simulated CELSIUS experiments to determine the luminosity limits. Fibers of the elements carbon, molybdenum and tungsten of the diameters given in Table IV were shown to withstand luminosities of 10^{32} $cm^{-2}s^{-1}$. Carbon fibers impregnated by different elements like cobolt, lanthanum, thorium and uranium to form low vapour-pressure carbides further increase the number of available target materials [37].

Measurements of position, profile and lifetime of the stored proton beam at CELSIUS have been made with 7 μm diameter carbon fibers in combination with pick-up electrodes in the ring and a spectrum analyzer. At the energies 72 and 600 MeV the lifetimes were determined to be 30 and 270 ms, respectively, the latter value a factor 6 lower than the calculated one. The effective target thickness of a 7 μm carbon fiber in a 9 mm wide beam, $5x10^{16}$ atoms/cm^2, is evidently too high to give useful lifetimes for storage-ring experiments at CELSIUS [39].

The effective or time-averaged target thickness may be decreased by sweeping the fiber periodically over the beam or conversely the beam over the target. This has been demonstrated by Meyer et al. at the Indiana Cooler, IUCF, in a sequence of experiments using different sweeping mechanisms. In the latest version [75], the fiber is mounted in a frame suspended from springs and excited via permanent magnets in the alternating field of two coils. The amplitude of the fiber motion determines the time-averaged target thickness, which is thus easily adjustable. Test experiments at the Cooler [75] have been made with so-called micro-ribbon targets of carbon, 43 μm wide and 8 $\mu g/cm^2$ thick [76], swept over the beam to give average target thicknesses in the range 10^{14} - 10^{15} atoms/cm^2. Beam lifetimes and energy spreads of 185 MeV protons were determined as a function of target thickness. For comparison, the measurements were repeated using a homogeneous nitrogen gas target. At a target thickness of $4x10^{14}$ atoms/cm^2, the lifetime was about 17 s with the nitrogen target and a factor 7 shorter with carbon. The difference increases for lower target thicknesses and decreases for higher ones. Monte Carlo calculations reproduce the data for nitrogen while they fail for carbon. The same is true for the beam energy spread, increasing from 6 keV FWHM without target to 7 keV with a $4x10^{14}$ atoms/cm^2 nitrogen target, whereas it is 14.8 keV and develops a long tail towards the low-energy side of the peak with a carbon target of the same average thickness.

Ribbon targets of 40 $\mu g/cm^2$ carbon and 200 $\mu g/cm^2$ gold, suspended from a support at the top, have been tested at different accelerators by Koch et al. [77] at Jülich. An average luminosity of $3x10^{32}$ $cm^{-2}s^{-1}$ was obtained with 10^{11} protons of 150 MeV in the SATURNE ring at Saclay and the carbon-ribbon target. The proton beam half-life was 15 ms. In the case of gold ribbons, the average luminosity was $1x10^{31}$ $cm^{-2}s^{-1}$ with 10^{11} protons of 300 MeV giving a half-life of 1.2 ms. A theoretical account of the use of thin ribbon or foil targets in cooler-ring experiments has been given in Ref. 77 and by Noda et al. [78] at Tokyo. Proton energies around 1 GeV are evidently required to give lifetimes of the order 100 ms.

8.2. Microparticle targets

There are different ways of introducing microparticles into the circulating beam. These so-called dust targets may be used in a storage cell, much the same as the storage cells discussed in connection with the polarized gas targets. The problems with the charging and the uncontrollable diffusion of dust out of the cell have, however, turned the attention to producing microparticle beams instead. So-called dust guns have been developed as well as systems for beams of gas-particle mixtures where the gas is differentially pumped away to give a beam of microparticles. The advantages of the microparticle target are that the material is commercially available for many elements, there is a very small target heating, the target thickness can be matched to optimum storage-ring operation, and that there are no special vacuum problems, except of course for the differentially pumped system.

A dust gun for microparticle beams has been developed by Tanabe et al. [79] at Tokyo. The technique is based on contact-charging dust particles in electric fields on metal surfaces, followed by extraction and acceleration to prepare a dust beam. They used 1 μm Ni-particles collected in a cup, measuring the current. The target thickness of the dust beam was shown to be 10^{14} - 10^{16} atoms/cm^2 by bombarding with a 65 MeV alpha beam and detecting the elastically scattered alpha particles. Meyer et al. [80] at IUCF have put much effort into developing a dust-gun system, but the technique was later abandoned because of problems to get sufficient target thickness in a reliable and reproducible way. Prasuhn et al. [81] at Bonn have improved the dust-gun system by shaking the dust on a foil with an electromagnet, and optimized the geometry of the extraction and focusing elements. It seems, however, that the dust-gun activities of all three goups above have been discontinued.

A microparticle-target concept, shown to work successfully in storage-ring environment, has been developed by Meyer et al. [82] at IUCF. It is based on a gas-microparticle mixture introduced into vacuum through a capillary after which the carrier gas is removed by differential pumping giving a microparticle beam. The beam is crossed with the stored beam and collected in a catcher. Following an extensive development period a microparticle target has been tested at the Indiana Cooler with graphite particles of 3 μm average size mixed with nitrogen at atmospheric pressure. In a capillary of 610 mm length and 0.41 mm diameter the particles are accelerated to about 200 m/s and collimated to a beam with divergence of about 4° full angle. The carrier gas of 2.9 mbar l/s is to a large extent removed in two differentially pumped stages, giving a pressure in the target box of 5.7×10^{-7} mbar. After passing the interaction region the microparticle beam is collected in a catcher, consisting of a series of glass cones to slow down and catch the target particles. The catcher efficiency was shown to be higher than 99%. By varying the the membrane excitation of the mixer the time-averaged target thickness may be adjusted. The test covered the range 3×10^{13} to 2×10^{15} atoms/cm^2 as determined by proton scattering using a cooled proton beam of 120 MeV in the Cooler. The intensity of the proton beam decreased with a life-time from about 30 s to 0.4 s in this range. The mass flow at the higher thickness corresponds to about 0.15 mg/s. The test has clearly shown the feasibility of microparticle internal targets, providing a wide range of target materials. A worry, however, still remains of the effects on sensitive parts of the accelerator vacuum system in extended experimental periods with microparticles.

A differentially pumped gas-microparticle target has been used for experiments by Voitsekhovskii et al. [83] at the VEPP-2 electron storage ring at Novosibirsk. Nickel particles of 2 μm diameter were mixed with CO_2 as carrier gas. A gas flow of 6.5 mbar l/s and a Ni-particle flux of 0.1 mg/s through a 50 mm capillary of 0.5 and 0.1 mm entrance and exit diameters, respectively, gave a target thickness of about 10^{14} atoms/cm^2.

8.3 Pellet targets

The elementary-particle physics program of the WASA (Wide Angle Shower Apparatus) collaboration [84] at the CELSIUS storage ring at Uppsala is intended for detailed decay studies of light mesons to determine the branching ratios of rare decay modes. The target system to be used in the WASA experiments has to fulfil a number of stringent requirements. It has to produce a pure hydrogen target, giving luminosities above 10^{32} $cm^{-2}s^{-1}$, access to close to 4π detection, a good spatial vertex definition, tagging possibilities, acceptable pertubation to the stored beam and acceptable gas load on the ring. These requirements may be met by the so-called pellet-target system, letting frozen micro-spheres of hydrogen pass through the circulating proton beam under well controlled conditions.

A pellet-target system, based partly on the design of the pellet generator developed by Foster et al. [85] for refueling of fusion tokamak reactors, is currently being built up at Uppsala by Trostell and collaborators [86]. A vertical cross section of the pellet generator is shown in Fig. 8. Hydrogen gas is liquified in a heat exchanger, connected to the cold head of a two-stage cryogenerator, and pressed through a glass nozzle with a 15 μm diameter at conditions close to the triple point; 14 K and 72 mbar. The liquid hydrogen jet is broken up into uniformly sized and spaced droplets by an acoustical excitation induced by a piezo-electric transducer connected to the nozzle. Droplets of 20 μm diameter with a velocity of 10 m/s are produced at a rate of $2x10^5$ s^{-1}. In the droplet chamber, kept at a pressure slightly below the triple point value, the droplets develop a frozen shell by partial evaporation. The droplet production may be observed by stroboscopic diagnostics using a microscope and triggered flash lamp.

The behaviour of the pellet train during the injection into vacuum has been calculated by Tinoco [87] assuming different geometries and dimensions of the vacuum-injection nozzle. The proposed design contains a contraction region followed by a 50 mm long capillary of 0.2 mm diameter. The capillary diameter is shown to be the most important parameter in determining the gas flow and pellet motion. The 20 μm diameter pellets of velocity 10 m/s and temperature 14 K, will reach the values 90 m/s and 12 K, respectively, at the exit of the capillary. The pellet train from the production nozzle may be adjusted in position and angle to enter along the axis of the capillary. The focusing force in the capillary concentrates the pellets to the axis and thus reduces the angular spread. An angular deviation of less than 0.05° is required for the pellets to hit the 3 mm proton beam at a distance of 2 m. To meet the requirement of one single pellet at a time in the 3 mm proton beam, 5 out of 6 pellets have to be deflected away, reducing the pellet rate to $3.5x10^4$ s^{-1}. This will give a luminosity of 10^{32} $cm^{-2}s^{-1}$, assuming 10^{10} stored protons in CELSIUS. To reduce the load on the proton beam and on the ring, the pellet train will be introduced to the beam only during data-taking. The thermodynamics of hydrogen pellets as internal targets in storage rings has been calculated by Trostell [88], giving a gas load rate of a few times 10^{-3} mbar l/s and a pressure of about 10^{-5} mbar in the scattering chamber .

The droplet production has been demonstrated in the test set-up and injection into vacuum has been observed, however, so far only in non-optimized conditions. An interesting phenomena occurs when injecting directly into vacuum with the vacuum-injection capillary removed. During these conditions a hydrogen fiber is developed, extending 1.5 m along the vacuum system. The fiber is stable within millimeters in lateral position for periods of hours. The phenomena will be the subject of further studies.

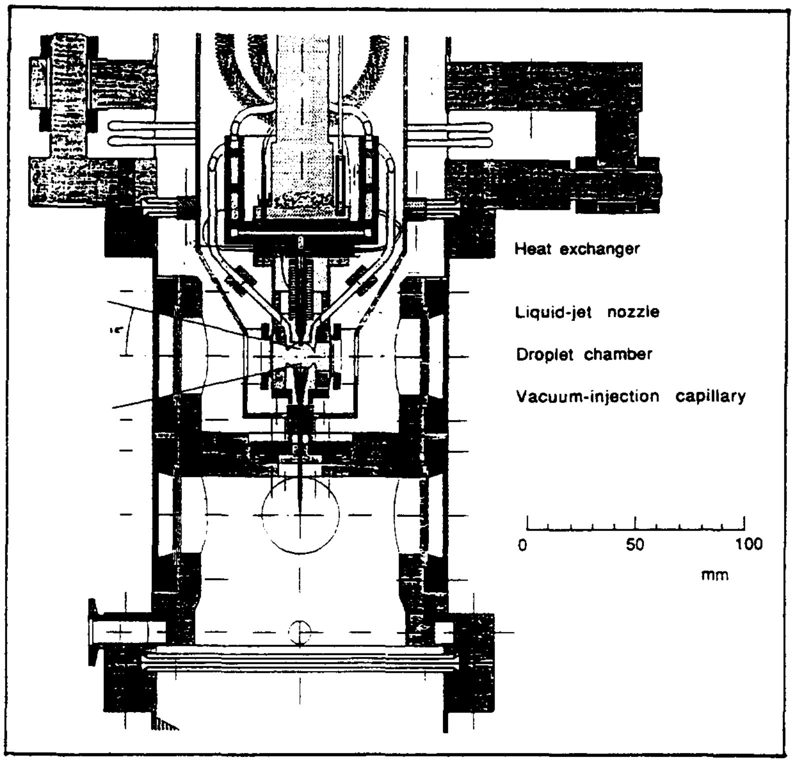

Fig. 8 Vertical cross section of the central part of the pellet generator, showing the heat exchanger connected to the cryogenerator cold head, the liquid-jet nozzle and the vacuum-injection capillary. Observation windows are used for diagnostics of the droplet and pellet trains.

A positive outcome of the hydrogen pellet-target developments will certainly lead to a wider application using other gases and liquids. This will add to the long list of advantages given above. The high gas load in the interaction region, however, will probably reduce the use of pellet targets to light-ion experiments in the ring. Also, the high local target thickness will prevent the detection of heavy recoil products.

9. SUMMARY AND CONCLUSION

In Table V is given a comparison of some characteristics of different target systems used or to be used in internal-target experiments. In gas-jet targets the distance between nozzle and catcher is generally very small giving high target thicknesses but also high pressures around the target. The differential pumping along the circulating beam reduces the space available for detection. In cluster-jet targets, with differential pumping along the target beam instead, the lower pressure and better space for internal and external detection have to be paid for by a lower target thickness. Among the polarized targets, the atomic beams give good detection possibilities while storage-cells, with their higher target thickness, however, are more restricted in this sense. The solid targets, fiber, dust or pellet of micrometer dimensions, have all very large local target thicknesses preventing the detection of slow heavy recoil products. The effective target thicknesses may, however, be optimized for storage-ring experiments. The space for detection is very good for fibers and pellets, while it is more reduced in the dust-target system. The vacuum conditions are very good for the fiber targets, and by the use of sub-micron fibers recoil detection may also come into reach.

Table V. Summary of characteristics of different target systems of importance in experimental considerations. The target thicknesses and pressure values given should be regarded only as order-of-magnitude values.

Characteristics / Target	Target material	Target thickness [at/cm^2]	Pressure around target [mbar]	Space for detection	Recoil detection
GAS JET	Gases	$<10^{17}$	10^{-4}	-	+
CLUSTER JET	Gases	$<10^{14}$	10^{-7}	+	+
POLARIZED (atomic beam)	H, D, alkalis	$<10^{13}$	10^{-7}	+	+
POLARIZED (storage cell)	- " - , ^{3}He	$<10^{14}$		-	(+)
FIBER	Refractory materials	$\approx 10^{19}$	10^{-9}	+	(-)
DUST (gas driven)	Wide range	$\approx 10^{19}$	10^{-7}	-	-
PELLET	Gases Liquids	$\approx 10^{19}$	10^{-5}	+	-

There is currently a strong development in the field of internal targets to be used in storage-ring experiments as evidenced by the large number of publications during the last few years. It is however important to be aware of the advantages and drawbacks of the different target systems. There is obviously no general-purpose system available, but one has in each case to choose and optimize the target in order to meet the specific needs of the experiment to be done.

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