

# Operations with Internal Targets and Electron Cooling at CELSIUS

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## Abstract

CELSIUS is a storage ring for intermediate energy nuclear and particle physics with light and heavy ions from the Gustaf Werner cyclotron in Uppsala, Sweden. The ring features extremely thin internal targets and an electron cooling system. The internal target which has been used so far for physics is a cluster-jet target. It has been operated with target beams of hydrogen, deuterium, nitrogen, and argon. An advanced target facility using frozen hydrogen micro-spheres of about 20  $\mu\text{m}$  diameter is under development. Carbon fibres with 7  $\mu\text{m}$  diameter have also been tested as targets. They do, however, give beam lifetimes which are too short to be useful in the physics experiments. Much thinner carbon fibres will be tried in the near future.

## 1. THE CELSIUS RING

CELSIUS [1-3] consists of four 90° arcs and four straight sections, see fig. 1. This figure shows the planned layout, when the WASA detector [4] comes into place in 1994-1995.

One straight section is used for injection into the ring [5]. WASA will be placed on the second straight section. This straight section is presently filled with beam diagnostics equipment [6], but later during this spring (1992) a special scattering chamber with fibre targets will be put there, to be replaced in two and a half years with the WASA equipment. The third straight section holds the electron cooler and also a radio frequency cavity [7], and the fourth straight section holds the cluster-jet target [8].

### Some parameters of the CELSIUS ring

Circumference	82 m
Max. magnetic field	1.0 T (1.2 T planned)
Max. momentum	2.1xZ GeV/c (at present)
Max energy (protons)	1.36 GeV (at present)
Max. energy ( $Z/A = 1/2$ )	470xZ MeV (at present)
$Q_x, Q_y$	1.630, 1.833
$\beta_x, \beta_y$ at internal targets	1.4 m, 1.5 m
Electron beam voltage	5-300 kV
Electron beam current	0-3 A
Electron beam diameter	2 cm

### Achieved intensities

Proton intensity	$1 \times 10^{11}$
Deuteron intensity	$1 \times 10^{10}$
$\alpha$ -particle intensity	$1 \times 10^{10}$
$^{16}\text{O}$ intensity	$3 \times 10^8$

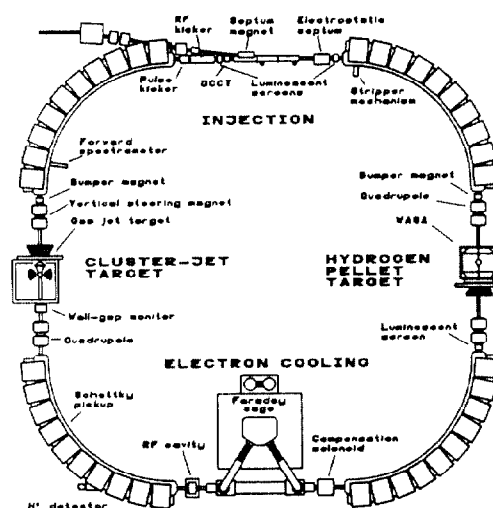


Fig. 1. Planned layout of CELSIUS

## 2. MODES OF OPERATION

CELSIUS can be operated in static mode or in cycles. In the static mode the machine parameters have constant values, and the energy of the stored beam remains at the value at injection. During operation in the cyclic mode, the beam may be accelerated or decelerated. The variation of the magnetic field during a typical cycle is illustrated in fig. 2.

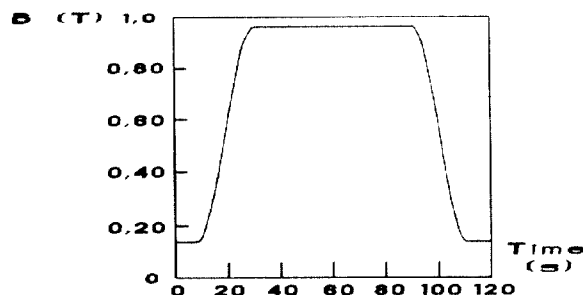


Fig. 2. Variation of the main magnetic field in CELSIUS during a cycle with acceleration of protons to 1.3 GeV.

Since the dipole magnets of CELSIUS are not laminated [9] the acceleration is performed slowly; the standard period used for acceleration is 22 s so far. This is consistent with the use of the ring for experiments with ultra-thin internal targets, even though the overhead time per machine cycle typically to-

tals 60 s the duty factor is acceptable, 50 % in two-minute cycles and 80 % in five-minute cycles.

So far cycles have been developed for acceleration of protons to several final energies between 200 MeV and 1300 MeV, and for experimental situations where a slow ramping of the proton energy is performed during the "flat" top. Examples of such slow ramps are from 270 to 310 MeV ( $\pi^0$  threshold in  $p+p$  reactions) and from 1230 to 1300 MeV ( $\eta$  threshold in  $p+p$  reactions). The maximum intensity after acceleration obtained so far is  $5 \times 10^{10}$  protons at 1150 MeV and  $1 \times 10^{10}$  protons at 1300 MeV.  $\alpha$ -particles have been accelerated to 600 MeV, and deuterons to several final energies up to 783 MeV where they ( $1 \times 10^{10}$ ) have also been cooled (measured  $\Delta p/p = 3 \times 10^{-5}$ ).

The electron cooling system can be used in order to build up the intensity [5] in cases when what is achieved with a single ordinary injection is much less than what corresponds to the stability limit of the ring. It can also be used to shrink the transverse beam size, and improve the momentum spread in the beam after acceleration, provided that the velocity of the ions is within the velocity range of the electrons, i.e. for protons up to 550 MeV and for heavy ions up to the maximum energy.

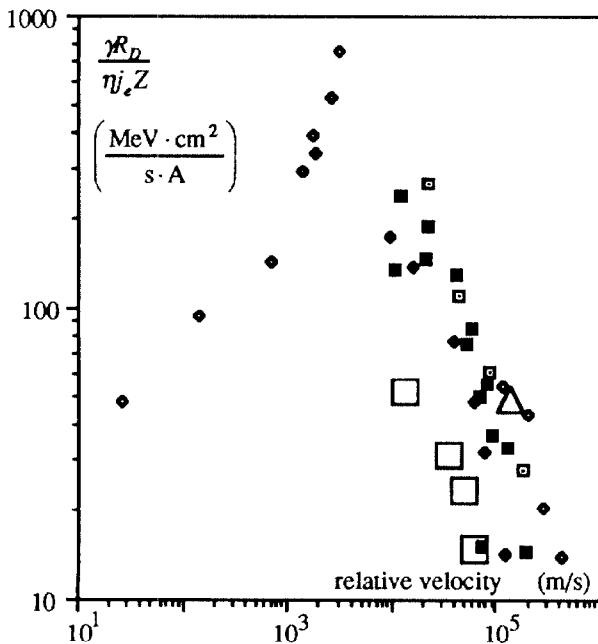


Fig. 3. Comparison between measured drag rates at LEAR (49 MeV p)  $\blacksquare$ , NAP-M (65 MeV p)  $\bullet$ , FNAL (203 MeV p)  $\blacksquare$ , IUCF (45 MeV p)  $\blacklozenge$ , INS (20 MeV p)  $\blacksquare$ , and CELSIUS with 783 MeV deuterons  $\square$ , and 296 MeV oxygen ions  $\triangle$ .

### 3. ELECTRON COOLING SYSTEM

Electron cooling has been studied at the injection energies (using stripping injection) of protons (48 MeV), deuterons (24 MeV), oxygen ions (292 MeV), as well as after accelera-

tion with 275 MeV protons and with 390 MeV, 600 MeV, and 780 MeV deuterons.

The longitudinal drag rate has been measured with coasting beams of protons, deuterons, and oxygen ions with several energies. The measurement technique has been to step the output voltage from the electron cooler high voltage supply, and to measure how the revolution frequency of the ions changes as a function of time after the step. Fig. 3, shows several measured scaled drag rates for 783 MeV deuterons and a single measured point for 296 MeV oxygen ions together with measured scaled drag rates from several other laboratories [10,11].

Measurements of the longitudinal cooling time have been performed with bunched beams, where the momentum spread is proportional to the time spread in the bunch (unless space charge effects are important). One such measurement is illustrated in fig. 4

The horizontal size of a cooled beam of protons at 275 MeV has been measured with a 7  $\mu\text{m}$  carbon fibre at the target position. Measurements were done both with and without voltage on the rf cavity. The beam size is smallest when the rf voltage is zero. Then the FWHM of the cooled beam was measured to be 2.5 mm, corresponding to a transverse rms. emittance of  $0.8\pi \mu\text{m}$  (for  $\beta_x = 1.4 \text{ m}$ )

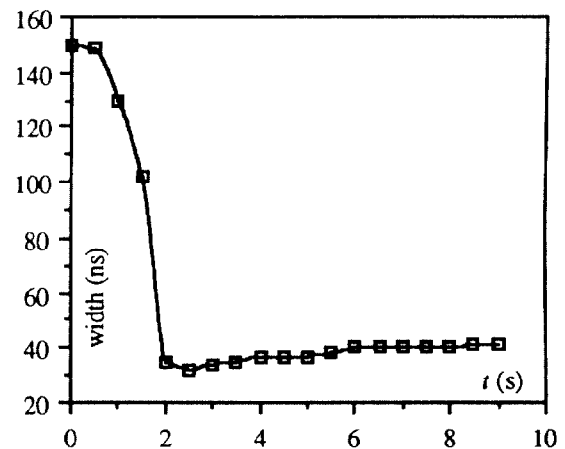


Fig. 4. Measured FWHM time spread of a bunch of 275 MeV protons during cooling with 410 mA of electrons.

A phenomenon, which is not yet understood, is that there is an apparent "heating" of the stored ion beam by the electron beam as soon as the electron beam is put together with the ion beam. This heating causes a dramatic drop in lifetime of the stored ion beam, particularly when the ion beam has a low energy [2]. This heating is more than compensated for by the electron cooling when the ion beam and the electron beam are well enough matched in velocity and direction. The heating seems to be always present, also when the beams have large relative velocity. It is suspected that the heating is due to excitation of resonances by non-linear electrical fields created by the electron beam. On the other hand, the tune shifts induced on the ion beam by the electron space charge is close to its theoretical values, so there does not appear to be any large un-

expected stored charge due to trapped ions or electrons in the electron beam.

#### 4. INTERNAL TARGETS

##### 4.1 The cluster-jet target

The cluster-jet target system [8] has been in operation for experiments since 1989 using target beams of hydrogen, deuterium, nitrogen, and argon.

Target thicknesses of  $3 \times 10^{14}$  atoms/cm<sup>2</sup> for hydrogen and deuterium,  $4 \times 10^{13}$  atoms/cm<sup>2</sup> for nitrogen, and  $2 \times 10^{13}$  atoms/cm<sup>2</sup> for argon have been obtained. When the system is running with these target thicknesses the pressure in the scattering chamber becomes  $2 \times 10^{-7}$  mbar.

Life-times of the proton beam at CELSIUS have been measured at different energies with cluster-jet target beams of hydrogen, nitrogen, and argon. An example of such a measurement is given in fig. 5, which shows, in a logarithmic scale, the intensity of the stored proton beam during a cycle with acceleration to 200 MeV, with and without an argon target with thickness  $2 \times 10^{13}$  atoms/cm<sup>2</sup>. The natural  $e^{-1}$  lifetime (8.7 dB) of the beam is 85 s with target on. With formulae in [12] we calculate that this is consistent with a circular acceptance of  $40\pi \mu\text{m}$  if the horizontal and vertical  $\beta$ -values at the target are 1.5 m. This must be compared with the geometrical vacuum chamber acceptance of  $125\pi \mu\text{m}$ .

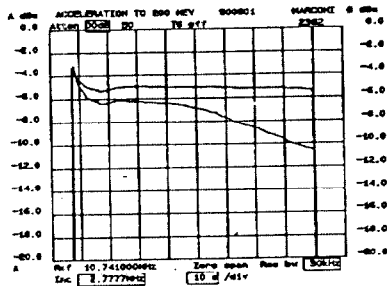


Fig. 5. Proton intensity measured with a pickup electrode during a cycle which includes acceleration to 200 MeV. The intensity was measured with and without an argon target with thickness  $2 \times 10^{13}$  atoms/cm<sup>2</sup>.

##### 4.2 Fibre targets

The use of thin fibres as internal targets has the potential advantages of good vacuum conditions and the possibility of close to  $4\pi$  detection of the nuclear reaction products.

The life-time of stored proton beams in presence of carbon fibres with  $7 \mu\text{m}$  diameter has been studied. A prediction that the stored beam lifetime is longer when the fibre is placed right on the position of the closed orbit than if it is displaced from this position has been confirmed [2].

The stored beam lifetime with the  $7 \mu\text{m}$  carbon fibres, which presently have been tested, are too short to be useful for nuclear physics experiments. At IUCF, 'micro-ribbons' of carbon, which represent two orders of magnitude less material per unit length than the  $7 \mu\text{m}$  carbon fibres have been developed [13]. We will have opportunity to try this kind of fibres

later during the spring of 1992. The fibres have been kindly supplied by IUCF, and will be tested in a small scattering chamber, which will be temporarily installed in the ring, at the place where the WASA detector will be installed later.

##### 4.3 The pellet target

The elementary particle physics programme of the WASA collaboration [4] is intended to determine the branching ratios of rare decay modes of mesons. Their target system has to fulfil a number of strict requirements. It has to produce a pure hydrogen target, giving a luminosity above  $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ , possibility of close to  $4\pi$  detection, a good spatial vertex definition, tagging possibilities, acceptable perturbation to the stored beam and acceptable gas load to the vacuum system of the ring. These requirements will be met by the so-called pellet target system, in which frozen droplets of hydrogen pass through the circulating proton beam under well controlled conditions [14].

The production of frozen hydrogen pellets and their injection into vacuum has been demonstrated during 1991.

An interesting phenomenon occurs when injecting directly into vacuum with the vacuum injection nozzle removed. During operation with these conditions a hydrogen fibre is developed. The fibre extends 1.5 m along the vacuum system, and is stable within millimeters for periods of hours. The hydrogen fibre is another possible internal target for CELSIUS.

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