Nuclear Inst. and Methods in Physics Research, A 866 (2017) 207–212

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

# First beam test of a liquid Cherenkov detector prototype for a future TOF measurements at the Super-FRS

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A R T I C L E I N F O

*Keywords:*
Cherenkov detector
Time-of-Flight detector
Super-FRS
Timing accuracy
Detection efficiency
Heavy ions

A B S T R A C T

In order to separate and identify fragmentation products with the Super-Fragment Separator (SuperFRS) at FAIR a high resolving power detector system is required for position and Time-Of-Flight (TOF) measurements. The TOF detector is used to measure the velocity of the particles and hence, in conjunction with their momentum or energy, to determine their mass and hence their identity. Aiming to develop a system with a precision down to about 50 ps in time and resistant to a high radiation rate of relativistic heavy ions of up to $10^7$ per spill (at the second focal plane), we have shown a conceptual design for a Cherenkov detector envisioned for the future TOF measurements employing Iodine Naphthalene ($C_{10}H_7I$) as a fluid radiator. The application of a liquid radiator allows the circulation of the active material and therefore to greatly reduce the effects of the degradation of the optical performance expected after exposure to the high ion rates at the Super-FRS. The prototype of a TOF-Cherenkov detector was designed, constructed and its key-properties have been investigated in measurements with heavy ions at CaveC at GSI. These measurements were performed with nickel ions at 300–1500 MeV/u and ion-beam intensities of up to $4 \times 10^6$ ions/spill of 8 s. As a first result a maximum detection efficiency of 70% and a timing resolution of 267 ps ($\sigma$) was achieved. We report the first attempt of time measurements with a Cherenkov detector based on a liquid radiator. Further optimization is required.



## 1. Introduction

At the in-flight Super-Fragment Separator [1] (Super-FRS) at the Future Antiproton and Ion Research (FAIR) facility a wide range of ions with energies up to 1.5 A GeV will be used for the production of isotopes by projectile fragmentation and fission. The SuperFRS is currently under construction and is superior to the present FRS [2] installation due to major enhancements: higher intensity of the primary beams, increased transmission for fission fragments produced by uranium projectiles, improved transmission of fragments to the dedicated experimental areas and larger acceptance of fragments by the storage-cooler ring. Altogether these improvements will result in higher luminosity of the secondary beams produced and particle rates for the future physics experiments of up to 10 MHz. The SuperFRS will consist of a two-stage magnetic system: the pre- and the main-separator, both equipped with a degrader. Both separator stages use the $(B\rho)_1$-$\Delta E$-$(B\rho)_2$ method [2] where a two-fold magnetic rigidity analysis is applied in front and behind a specially shaped energy degrader. $\rho$ is the radius of the particle path in the magnetic field $B$, the quantity represented by $B\rho$ is called the magnetic rigidity of the beam and $\Delta E$ is the atomic energy loss in the thick degrader.

The main-separator part at the first 'FMF1', central 'FMF2' and final focal planes will be equipped with high resolving-power detection systems for position and time-of-flight measurements. These detectors are used for the identification of the nuclei before and after the secondary reactions. The system will identify the nuclear-charge number $Z$ and the mass number $A$ of nuclei. Identification of fragments is performed by applying the so called $\Delta E$-$(B\rho)_2$-$TOF$-method, measuring the energy loss ($\Delta E$) in an ionization chamber [3] as well as the magnetic rigidity $(B\rho)_2$ by determining the position at the central focal plane as well as the time-of-flight (TOF) [4] in the second half of the spectrometer.

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http://dx.doi.org/10.1016/j.nima.2017.06.010
Received 10 January 2017; Received in revised form 2 June 2017; Accepted 6 June 2017
Available online 10 June 2017

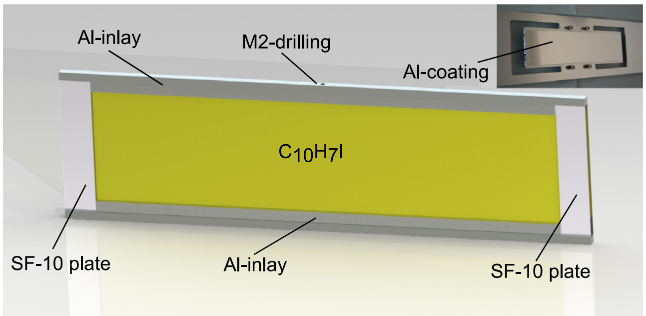


**Fig. 1.** 3D view of the cuvette filled with an active fluid. Aluminium inlays at the top and bottom of the cuvette provide stability and sealing. SF-10 glass plates bridge the photons from the cuvette to light guides. Front and back windows are made out of borosilicate glass of 0.5 mm thickness. The sensitive thickness of the cuvette filled with the liquid is 2 mm. The whole cuvette is coated with 0.15 μm of Aluminium (see inset picture).

A high performance TOF detector is one of the key detectors employed in such a system. It is used to measure the velocity of the particles and hence, in conjunction with their momentum or energy, to determine their mass and hence their identity ($m/q$) ($q = Z.e$). For example in order to separate the heaviest ions with masses of 200u and 201u at an energy of about 1 GeV/u over the distance of 52 m from the middle plane FMF2 to the final plane FMF4 of the SFRS a detection system with a timing resolution of 54 ps $\sigma$ is required. Along with a fast timing response the high radiation dose due to the high primary-beam intensity in the Super-FRS requires special considerations for the layout and the design of the components used there.

## 2. Working principle

### 2.1. TOF detector design

In the prototype Cherenkov-detector design, the fluid is kept in a cuvette made from an aluminium frame and walls made of borosilicate glass (BK7). The walls of the cuvette have to be kept as thin as possible in order to minimize the energy loss of the ions. The entrance and exit glass walls are of 0.5 mm thickness with an active area of $170 \times 50$ mm$^2$. They are coated with 0.15 μm of aluminium to provide reflection of Cherenkov photons. The top and bottom sides of the cuvette are sealed with Aluminium-inlays for stability. SF-10 glass plates [5] ($n$ = 1.728@586 nm) (10 mm × 2 mm × 50 mm) are bonded to the right and left sides of the cuvette with an epoxy adhesive [6] in order to provide smooth transition of Cherenkov photons to the light guides (Fig. 1). A conceptual design for the Cherenkov detector as it was used in the measurements with heavy ions is shown in Fig. 2. The light produced in the liquid is read out at each side by strip-type light guides made out of UV-transmissive polymethylmethacrylat (PMMA). The photomultiplier tubes (PMT) of type H2431 (R2083) made by Hamamatsu Photonics [7] are attached to them with optical grease [8]. The PMTs have an active diameter of 46 mm and a Transit-Time-Spread (TTS) of 0.157 ns ($\sigma$). Due to the smaller diameter of the light guides the photocathode area was not fully illuminated during the measurements, reducing the effective TTS

The light tight box housing the cuvette as well as the light-guides is sealed with entrance and exit windows made from 114 μm thick black poly-olefin foils. The cuvette itself consists of two borosilicate walls with the thickness of 0.5 mm each, containing the active liquid with a thickness of 2 mm in beam direction.

### 2.2. Choice of radiator material

In many relativistic heavy ion experiments gaseous [9] or solid [10–12] materials are commonly used as Cherenkov radiators for particle identification and energy measurements. The circulation of gaseous

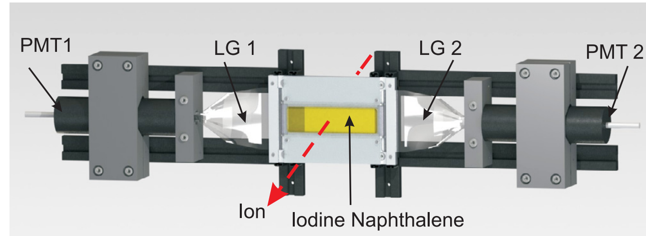


**Fig. 2.** Conceptual design of the TOF detector as it was used in the measurements with nickel ions. The cuvette filled with the active fluid radiator is read out at the horizontal sides via strip-type light-guides (LG) and Photomultipliers (PMT).

or liquid active materials allows regular refreshing and can greatly reduce the performance degradation due to ageing after exposure to high ion rates. Other advantages of fluid over TOF systems based on solid-state materials, including small area diamond [13–15] or silicon [16] are the virtually unlimited radiation hardness of the fluid (through recirculation or replacement), and the relative simplicity of the PMT-based readout electronics.

Typical refractive indices of a gases at ambient temperature and pressure are around $n = 1.0003$ (with corresponding Cherenkov thresholds around $\beta = 0.99$). This is inapplicable in our application where future measurements will need to cope with lowest primary particle energies of ~220 MeV/u, with a corresponding Cherenkov threshold of $\beta = 0.99$, requiring a radiator refractive index of around $n = 1.7$.

Consequently, for a future TOF detector based on a liquid medium, e.g. an Iodine-Naphthalene liquid ($C_{10}H_7I$) radiator is proposed. The high refractive index of this fluid of $n = 1.7003$ at 589 nm and its nevertheless relatively low density of $\rho = 1.738$ g/cm$^2$ makes it suitable for a continuous flow of the material.

The variation (dispersion) of refractive index with light wavelength $\lambda$ is described according to the Sellmeier equation. The commonly used form of the equation is given by

$$n(\lambda) = \sqrt{1 + \frac{B_1 \cdot \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \cdot \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \cdot \lambda^2}{\lambda^2 - C_3}} \quad (1)$$

where $B_i$ and $C_i$ are the experimentally determined Sellmeier coefficients.

The dispersion curve of the Iodine Naphthalene fluid was measured in the wavelength range from 400 to 1600 nm [17]. As a result of the measurements Sellmeier coefficients to the Eq. (1) have been obtained: $B_1 = 0.9691$, $B_2 = 0.7629$, $B_3 = 0$, $C_1 = 0.0488$, $C_2 = 0.00011$ and $C_3 = 776.5758$.

Fig. 3 illustrates the variation of the refractive index with the wavelength for several materials including $C_{10}H_7I$ with the corresponding threshold velocity. A series of measurements observing the Cherenkov radiation in Iodine Naphthalene with cosmic radiation and the change of the optical properties of the fluids are documented in [18].

The number of Cherenkov photons emitted during the penetration of an ion with a charge $z$ in an optical spectral range $\lambda_1 \div \lambda_2$ is estimated according to the standard formulae based on the Tamm–Frank theory [19]:

$$\frac{dN_{Ch}}{d\lambda dx} = \frac{2\pi}{137} z^2 \cdot \left(1 - \frac{1}{n(\lambda)^2 \beta_0^2}\right) \frac{1}{\lambda^2} \quad (2)$$

where $dx$ is the radiator thickness and $\beta_0$ is initial ion velocity. This theory ignores decreasing of particle velocity due to ionization energy loss. Authors [20,21] established a more refined approach, which includes the calculation of the energy loss and ion velocity depending on the ion penetration depth in the solid radiator. In the calculations the thickness of the radiator $L$ is divided into $N$ number of segments and the energy loss at each segment length $\triangle x = L/N$ is estimated.