Time-of-flight Identification of Ions in CESR and ERL

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The accumulation of ion densities in the beam pipe of an electron beam accelerator can disturb the beam's dynamics. Efforts to clear this ion cloud from the beam pipe rely on assumptions about its composition, and this work concerns the construction of a detector to determine the concentration of different ion species and charge states in the CESR and ERL beam pipes. This report describes the detector's assembly and its test with a low energy electron beam.

I. INTRODUCTION

The plan for construction of an Energy Recovery Linac (ERL) at Cornell necessitates a thorough study of the effects of ion densities that accumulate in the beam pipe of such an accelerator. In an ERL, the desire to achieve unprecedentedly controlled beam dynamics renders these densities undesirable, and they need to be understood and avoided where possible.

These densities result from scattering by the electron beam on the dilute gas of the beam pipe. The interaction between accumulated ion densities and the electron beam has a number of deleterious effects on the beam, and the reader is referred elsewhere for detailed investigations (e.g., see [1, 2]).

In some manner the ion densities that will accumulate must be removed, and the particular composition of the ion cloud both determines the efficacy of the clearing methods and gives information necessary to compute the effects of ions that cannot be removed. This work concerns the assembly of a detector to characterize the concentration of different species and charge states in the beam pipe. In particular, this project encompasses the assembly and initial calibration of a time-of-flight detector that can be mounted on an accelerator beam pipe to perform *in-situ* measurements of the ion densities. The entire system contains three main elements: the detector, the measurement system, and a test assembly or low energy beam source. This paper describes the assembly and calibration of these three elements through testing with the low energy electron beam.

II. THEORY

A general theory for time-of-flight measurements is outlined here for completeness. A "time-of-flight" scheme operates by imparting an equivalent potential V to a number of particles with masses $m_1, m_2, \ldots, m_N$ and charge $q_1, q_2, \ldots, q_N$ then measuring the corresponding velocity distribution of the particles. For a particle of mass m and charge q,

$$\frac{1}{2}mv^2 = qV \tag{1}$$

$$v = \sqrt{\frac{2qV}{m}}. \tag{2}$$

So $v \propto \sqrt{\frac{q}{m}}$ and this relation will allow identification of the relative concentration of ions using measurements of the velocity distribution of the ion cloud. The velocities are measured by letting the ions drift along a tube of length l and measuring the corresponding "time-of-flight." For,

$$v = \sqrt{\frac{2qV}{m}} \text{ where } v = \frac{l}{t} \text{ so that} \tag{3}$$

$$t = \frac{l}{\sqrt{2V}}\sqrt{\frac{m}{q}}. \tag{4}$$

Ions with mass-to-charge ratio $r_1, r_2, \ldots, r_i$ have a time-of-flight $t_1, t_2, \ldots, t_i$ respectively, and we perform the measurements to count the number n_j of signals in the interval $\Delta t_j = [t_j - \delta, t_j + \delta]$. We then expect, where $\mathcal{N} = \sum_j n_j$ counts all ion signals, $\lim_{\mathcal{N}\to\infty} \frac{n_j}{\mathcal{N}} = \rho_j$ where ρ_j is the relative concentration of the ion with mass-to-charge ratio r_j. Simulations of the ion cloud in the beam pipe determine the proportion p of the ions that are measured by the detector $\mathcal{N} = pN_{total}$, and we obtain $N_j = \rho_j \frac{\mathcal{N}}{p}$ for the number of ions in the beam pipe of mass-to-charge ratio r_j.

These simple relations encapsulate the general theory necessary to perform time-of-flight measurements and identify the ions - the rest concerns details of measurement. For example, we'll need a well-defined drift length l and zero of the time-of-flight t_0 in order to differentiate between ions. The resolution in the time measurements Δt necessary to resolve ions differing by $\Delta m \ll m$ can be written, to first order in $\frac{\Delta m}{m}$, as

$$\frac{1}{2}(m + \Delta m)v^2 = qV \tag{5}$$

$$\frac{l}{t + \Delta t} = \sqrt{\frac{2qV}{(m + \Delta m)}} \tag{6}$$

$$\big(1 + \frac{\Delta m}{m}\big)^{\frac{1}{2}} l = (t + \Delta t)\sqrt{\frac{2qV}{m}} \tag{7}$$

$$\big(1 + \frac{1}{2}\frac{\Delta m}{m}\big) l = (t + \Delta t)\sqrt{\frac{2qV}{m}} \tag{8}$$

$$\Delta t = \big(\frac{l}{2}\sqrt{\frac{m}{2qV}}\big)\frac{\Delta m}{m}. \tag{9}$$

Table I lists exemplative time-of-flights for ions expected in measurements on CESR and ERL.

TABLE I: Sample of time-of-flights of various ions assuming each molecule is once ionized, q=$1.6 \cdot 10^{-19}$ C, and from inserting the detector specifications $V = 400$ Volts, $l = 5.08$ cm.

Ion	Mass/Ion (kg)	TOF (μs)
H_2O	$2.99 \cdot 10^{-26}$	0.78
Ne	$3.32 \cdot 10^{-26}$	0.82
Ar	$5.32 \cdot 10^{-26}$	1.04
N_2	$7.31 \cdot 10^{-26}$	1.21

III. EXPERIMENTAL SETUP

The TOF spectrometer is analyzed by a test assembly. This test assembly generates a low energy electron beam to ionize the dilute gas and provide an ion source for the detector. The detector contains the drift tube for the time-of-flight scheme and produces signals when the ions arrive at the end of the drift tube. The measurement apparatus encompasses an array of electronics used to receive the incoming signals from the detector and operate sufficiently rapid measurements.

A. Test assembly

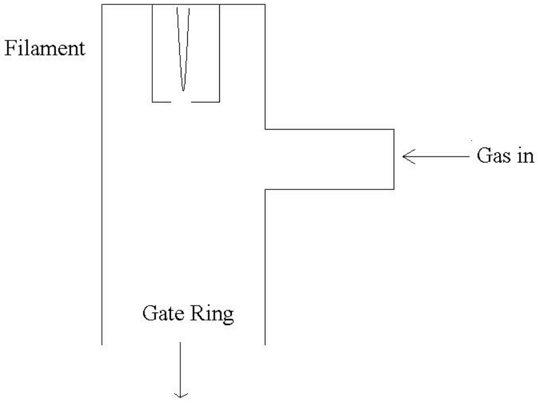

FIG. 1: A sketch of the test assembly setup.

The test assembly, as shown in Fig. 1, constitutes the first phase of operation of the detector to test its functionality and to calibrate it before installation on the CESR ring. It is designed to be a low energy electron beam source to scatter on either the dilute gas that is in the vacuum system inadvertently or on gases leaked into the chamber for the test. It consists of a tungsten filament that is heated by a current to emit electrons, a leak valve, and a region for the electrons to ionize the gas.

The filament is operated between 2 - 2.5 Amps and biased at voltages < 100V. This biasing is accomplished by floating the ground of the filament power supply while isolating it from the ground of the chamber walls by using an isolating transformer. The energy imparted to the electrons propels them into an ionization region to scatter on the dilute gas (at pressure approximately 10^{-6} Torr). The ions are shielded from the filament bias by a grounded plate mounted in front of the filament. The resultant ion cloud is used to test and calibrate the detector and resembles the ion cloud in an accelerator such as CESR or the ERL.

B. Detector

Components of the detector as shown in Fig. 2 are the gate ring, the focus ring, the drift tube, and an electron multiplier. The gate ring gates the flows of ions into the drift tube by maintaining a positive voltage and quickly switching to ground or negative voltage.

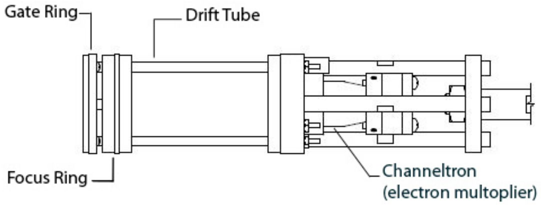

FIG. 2: A schematic of the detector showing, from left to right, the gate ring, focus ring, drift tube, and channeltron.

This switching constitutes the t_0 of the times-of-flight of the ions. A grounded plate, though not part of the detector *per se*, is mounted in front of the gate ring to simulate the beam pipe in CESR or the ERL. It is assumed the ions begin as a homogenous mixture in the region outside of this ground plate. The focus ring operates at -200V and focuses the ions into the drift tube once the gate is switched. The drift tube is 5.08cm and operates per the time-of-flight measurement scheme described above. The electron multiplier, in our case a “Channeltron,” operates at -2kV and, *via* secondary emission processes, amplifies the individual ion signals.

C. Measurement apparatus

The Channeltron produces a signal of amplitude ∼10-30 mV for an individual ion arrival, and this signal is run through a pre-amplifier to transform it into a narrow, negative pulse of amplitude 2-5 V. The gate ring voltage is controlled by a simple operational amplifier circuit that switches between a supply at positive voltage V_+ and a negative voltage V_-. As shown in Fig.3, the circuit receives a pulse of width w from a pulser and switches from V_+ to V_- for a time interval of duration w. The arrival of the pulse at the gate ring circuit determines the t_0 of the time-of-flight measurements.

This signal is simultaneously sent to a time-to-amplitude converter as the start signal. The stop signal is then the ion signal as detected on the Channeltron. The time-to-amplitude converter produces a pulse of voltage $V_{out} = \frac{t_{range} - t_{ion}}{t_{range}} V_{max}$ where t_{range} and t_{ion} are the selected range of the time-to-amplitude converter and $[t_{stop} - t_{start}]$, respectively (V_{max} is the maximum output voltage of the time-to-amplitude converter). Thus we determine the time-of-flight $t_{stop} - t_{start} = t_{ion} = \frac{V_{out}}{V_{max}} t_{range}$ precisely from the voltage produced by the time-to-amplitude converter. To investigate different regions of the time domain, we can delay the start signal from the pulser, using an Ortec gate and delay generator module, by a time t_{delay} and the time-of-flight is then $t_{delay} + t_{ion}$.

A computer running an Ortec program, MCA32, operates as a multi-channel analyzer that measures and counts the pulses of amplitude V_{out} produced by the time-to-amplitude converter. In this manner, we construct the desired histogram that, through a sequence of relations from the voltage to the mass-to-charge ratio, provides the information necessary to reconstruct the relative concentrations of ion species in the beam pipe.

The histograms that have been obtained so far have been inconclusive. As seen in Fig. 4, a Gaussian type peak develops, but it cannot be concluded if this lineshape corresponds to interference or unresolved ion signals.

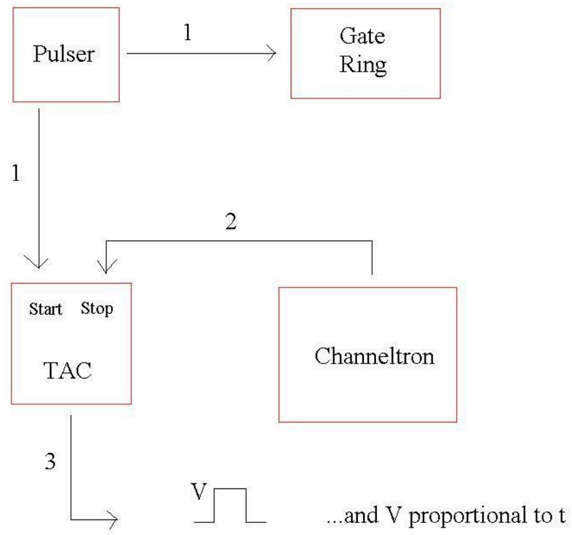

FIG. 3: Diagram for the measurement process.

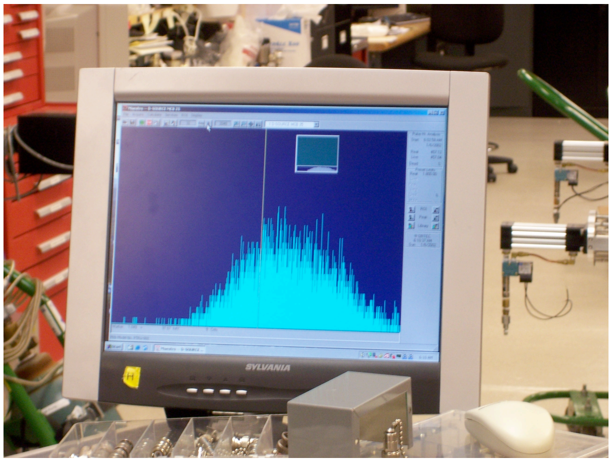

FIG. 4: Photo of the histogram readout in MCA32 on a computer taking inputs from the time-to-amplitude converter.

IV. FUTURE WORK

Future work for this project consists of completion of the test assembly phase and installation on CESR and the ERL.

The present experimental setup does not yet produce histograms that allow us to make conclusions about the character of the ion densities in the test assembly. Three modifications are discussed here that may be made to improve the resolution and to conclude the test assembly phase.

First, the low energy beam of the test assembly produces electrons that can be attracted by the positive voltage on the gate ring, which will not be the case in either CESR or ERL. These electrons have a long mean-free path inside the test assembly-detector chamber so that some number arrive at the gate ring voltage and are attracted into the detector resulting in noise. This problem can be avoided, however, by ionizing in a region and then clearing the electrons. The solution requires only slight modification of the current test assembly structure and provides a pure ion source to the detector, which will resemble ion densities in CESR and the ERL more closely.

Second, radio-frequency noise currently disallows starting the time-to-amplitude converter on the ions signals, and reflections affect the shape of the gate ring voltage (smears the edges of the square wave). There exist various methods for eliminating or reducing RF noise that need to be implemented. If one can decouple the signal on the collector wire from the noise, then that is most desirable. But if the noise persists, one might run the Channeltron at higher voltages to increase the weakest ion signals to a threshold of, say, 15mV. Then the RF noise problem need not be totally eliminated, only reduced so that the noise has amplitude < 15mV and can be reliably filtered from the ion signals.

Third, it would be helpful to enhance the switch rate to reduce ambiguity in t_0.

V. ACKNOWLEDGMENTS

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[1] G.H. Hoffstaetter, M. U. Liepe, Nuclear Instruments and Methods in Physics Research A 557, 205-212 (2006)

[2] G.H. Hoffstaetter, C. Spethmann, Physical Review ST-AB 11, 014001 (2008)