Symposium: Innovations for sustainable tomorrow

Proof-of-Concept Particle Counter for Heavy Ion Beams: Radiation Hardness, Sustainability and Single-Ion Sensitivity

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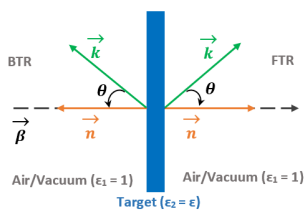
We demonstrate a proof-of-concept fast single-ion counter for heavy-ion beams. The detector geometry is simple: a thin aluminium-foil stack in atmospheric air, read out by a single PMT. Two known UV–VIS emission channels drive the signal – beam-induced air fluorescence and transition radiation at the foil–air interfaces – and both are read out directly by the same phototube. Experimental studies with a slow-extracted U^{73+} beam at the high-energy beam transport line at GSI–FAIR confirm single-ion sensitivity, with prototype detection efficiencies up to 99.5%. Because the detector has no luminescence mechanism to radiation-damage, we propose – as a **working hypothesis, not yet demonstrated** – that it is inherently more radiation-hard and materially simpler than traditional scintillator-based single-ion counters, offering a possible sustainability co-benefit alongside the physics performance for which it was designed.

Fluorescence and Transition Radiation

Air Fluorescence: Systematic measurements with electrons over energy range of 500 keV to 50 GeV, with protons at 120 GeV, and with 0.3–5.1 MeV α-particles, reports yield of ≈ 20 photons in 300-420 nm per MeV of energy deposited in air at Normal Temperature and Pressure (NTP), with most $\approx 6-7$ photons at 337 nm band (2P(0,0)).[1]

- Beam-Induced Air Fluorescence at atmospheric pressure is mostly dominated by second positive (2P) system of molecular N_2 followed by a very small contribution from first negative (1N) system of ionic N_2^+ which includes 391 nm band (1N(0,0)).
- In air, increasing pressure raises the fluorescence yield through higher molecular density, but collisional quenching competes with radiative decay. For 2P system, quenching is further compensated by N_2^+ contributing to excited N_2.
- Quenching reduces the lifetime of 2P system to sub-nanosecond values. For example 2P(0,0) 337 nm have 0.57 ns lifetime in air at atmospheric pressure.[2]

Transition Radiation: The double-differential backward transition radiation (BTR) photon yield, for a particle of charge Ze and velocity $\vec{\beta} = \vec{v}/c$ crossing at normal incidence from vacuum ($\varepsilon_1 = 1$) into a target medium with dielectric constant $\varepsilon_2 = \varepsilon$ can be written, as function of wavelength λ and observation angle θ as [3]:



$$dN(\lambda,\theta) = \frac{Z^2 e^2 \beta^2 \sin^3\theta \cos^2\theta |1-\varepsilon|^2}{\pi\varepsilon_0 hc\lambda \left(1-\beta^2\cos^2\theta\right)^2} d\lambda\, d\theta \times \left| \frac{\left(1+\beta\sqrt{\varepsilon-\sin^2\theta}-\beta^2\right)}{\left(1+\beta\sqrt{\varepsilon-\sin^2\theta}\right)\left(\sqrt{\varepsilon-\sin^2\theta}+\varepsilon\cos\theta\right)} \right|^2$$

Photon Yield for a charge crossing a surface normally

Note: The forward TR (FTR) formula follows by the usual substitution $\beta \to -\beta$.

Approximate yields for two processes in (300–700 nm) for U^{92+}.

T (MeV/u)	Energy deposited (MeV/mm)	Fluorescence photons (mm^{-1})	TR photons per surface
300	≈3.2	≈63	≈7.9
500	≈2.5	≈49	≈12.4
700	≈2.2	≈44	≈16.4

Experiment

- Goal: Proof-of-concept single-ion counting via UV–VIS emission.
- Detector A (Air Fluorescence): Paper box $5\times5\times5$ cm, with 1×3 cm observation window.
- Detector B (TR): $100\times$ Al foils (18 µm) with 0.1 mm gaps (Chosen so that OTR dominates air fluorescence).
- Readout: R6427 PMT & BC400 scintillator (coincidence); MSO58 oscilloscope.

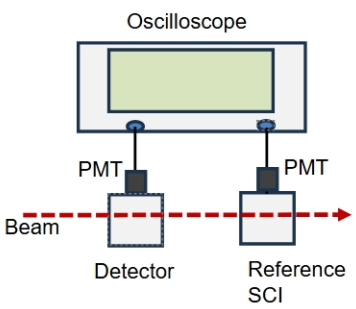


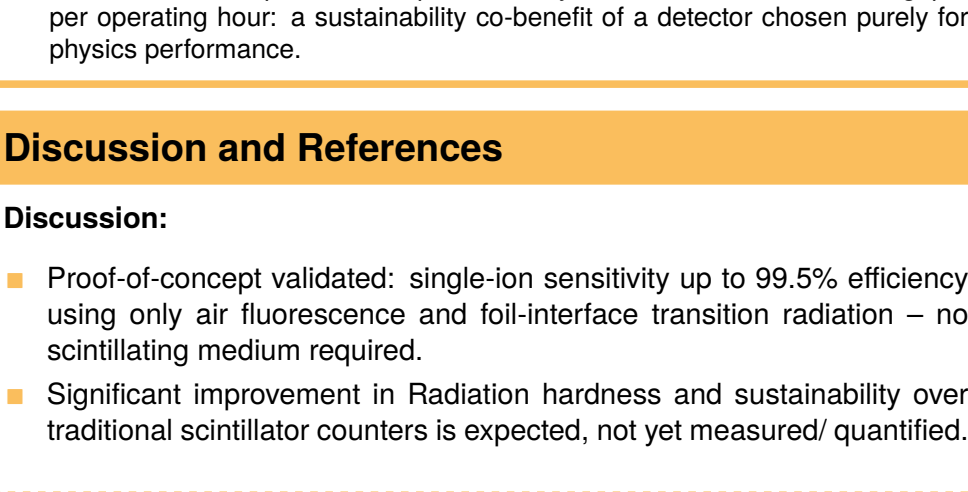
Figure shows the schematic of the experimental setup. The detector combined with Hamamatsu R6427 PMT was employed for counting single ions in coincidence with standard BC400 Scintillator (trigger signal). The signals were recorded with a Tektronix Oscilloscope MSO58 in Fast Frame mode. 4 photons on average produce one pulse of 30 mV at the PMT settings.

Acknowledgements

This work is supported by the STFC Liverpool Centre for Doctoral Training for Innovation in Data Intensive Science (LIV.INNO) under grant agreement ST/W006766/1, and by the GSI/FAIR Innovation Fund for Technology Transfer Projects. We would like to thank Marco Biljan and Michael Müller for their help during the preparation of the experiment, and Peter Forck for valuable discussions.

Signal Amplitudes and Detection Efficiency

- For Detector A, the single-ion *detection efficiency* exceeded 99.5% at all energies.
- Both the mean of signal amplitudes and its standard deviation increased with beam energy.
- For Detector B, the efficiency increases from 68.1% to 93.7% for experimental energies. (Most of the signal is lost to multiple reflections.)



Signal amplitude distributions for Detectors A (left) and B (right). Insets: Typical detector and trigger waveforms for a single ion.

Sustainability Hypothesis: Radiation Hardness

The radiators in the detector are Al foils and air rather than a specialized material such as a scintillator. Foils have no luminescence mechanism to radiation-damage; scintillator light yield, by contrast, is well documented to degrade under dose[4,5,6]. This motivates a hypothesis we have **not yet tested** for our own detector:

- Foil-based Detector *may* tolerate higher integrated dose before replacement than a scintillator-based equivalent – untested for our stack. The fluorescence signal from atmospheric air, unlike a solid scintillator, does not itself degrade with accumulated dose (the gas is continuously replenished).
- Bulk Al foil is a cheaper material class than doped scintillator crystal/polymer – no costed comparison performed.
- If both hold, this implies fewer replacement cycles and lower material throughput per operating hour: a sustainability co-benefit of a detector chosen purely for physics performance.

Discussion and References

Discussion:

- Proof-of-concept validated: single-ion sensitivity up to 99.5% efficiency using only air fluorescence and foil-interface transition radiation – no scintillating medium required.
- Significant improvement in Radiation hardness and sustainability over traditional scintillator counters is expected, not yet measured/ quantified.

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