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Spot Scanning Proton Beam Characterization via Plastic Scintillator Detector

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ABSTRACT

Spot scanning proton therapy steers a narrow pencil beam magnetically across the target volume, delivering highly conformal dose distributions layer by layer. This flexibility introduces a dosimetry problem: the beam is dynamic, the fields are small, and the dose gradients are steep — conditions that push conventional ionization chambers beyond their reliable operating range.

This work characterizes a Blue Physics plastic scintillation detector (PSD) in spot scanning proton fields at 100 and 200 MeV on a Varian ProBeam system, benchmarked against a PTW Bragg Peak Chamber and a TOPAS Monte Carlo model built on validated phase space files for the ProBeam nozzle.

In depth-dose measurements, the raw PSD signal tracked the Monte Carlo dose accurately through the entrance plateau but lost up to 44% of its signal at the Bragg peak due to ionization quenching. A Birks' law correction, using dose-averaged LET maps scored from TOPAS, fully recovered the Peak-to-Plateau Ratio at both energies, confirmed independently by the Bragg Peak Chamber.

Lateral spot profiles measured at Bragg peak depth agreed with simulation within clinical tolerance and captured the beam's intrinsic X-Y asymmetry, a feature that large-volume chambers cannot resolve.

These results demonstrate that the plastic scintillation detector, once quenching-corrected, is a viable high-resolution dosimeter for pencil beam scanning quality assurance, with energy-dependent geometric corrections identified as the primary remaining limitation.

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INTRODUCTION

The conformality of radiation therapy dose delivery has continued to improve with the introduction of various new technologies. Proton therapy offers a distinct advantage: protons deposit their energy at a specific depth near the end of their path—the Bragg peak—and then stop, thereby sparing tissue beyond the tumor.

Proton therapy has evolved from passive scattering to spot scanning, known as Pencil Beam Scanning (PBS), in which magnets steer a narrow pencil beam spot by spot without the need for patient-specific hardware. While PBS enhances conformality, it introduces challenges in dose measurement due to its high core dose and low-dose halo.

A standard Bragg peak ionization chamber is typically limited to relative dose measurements and captures only a restricted portion of the halo dose. Film dosimetry suffers some dose uncertainties.

Plastic scintillation detectors (PSDs), as used in this study, overcome these limitations with a sub-millimeter, water-equivalent, real-time active volume. However, they are affected by ionization quenching at the high-LET distal Bragg peak, where scintillation efficiency decreases and the detector under-reports dose exactly where it matters most clinically. This effect, described by Birks' Law, must be corrected for dose measurements.

METHODS AND MATERIALS

Measurements were performed on the Varian ProBeam system at the South Florida Proton Therapy Institute, with 100 and 200 MeV — sampling both ends of the clinical LET range. The Blue Physics PSD (1 mm scintillating tip) was mounted in a PTW 3D water phantom via a PTW SemiFlex holder, aligned to the beam axis using room lasers and a peak-signal scan.

Reference depth-dose curves were acquired with a PTW Bragg Peak Chamber (type 34070). PSD depth-dose scans used 2 mm steps; lateral spot profiles (X, Y) were acquired at the Bragg peak in 0.5 mm steps over ±21 mm.

A parallel TOPAS Monte Carlo model, built on validated ProBeam phase space files, modeled the PSD explicitly and scored dose-averaged LET for the Birks' law correction: QCF(z) = 1 + k_B·LET_D(z).

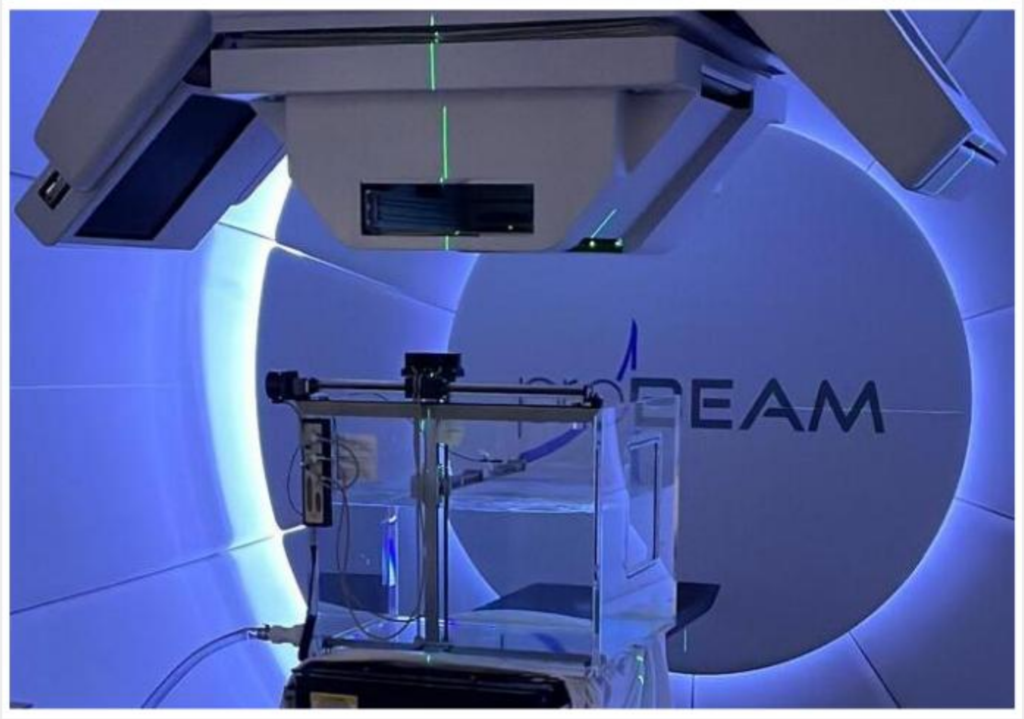

Figure 1. Experimental setup at SFPTI

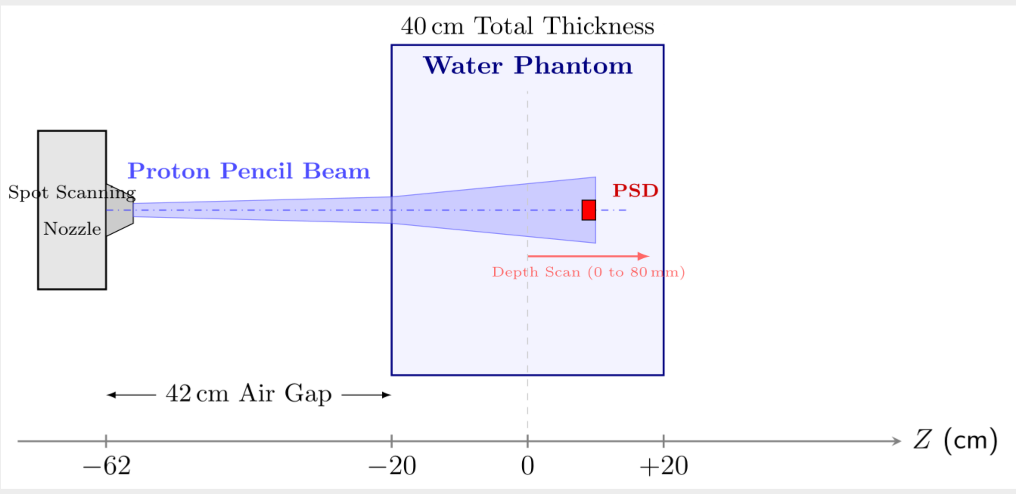

Figure 2. Schematic representation of the TOPAS simulation geometry for spot scanning proton therapy.

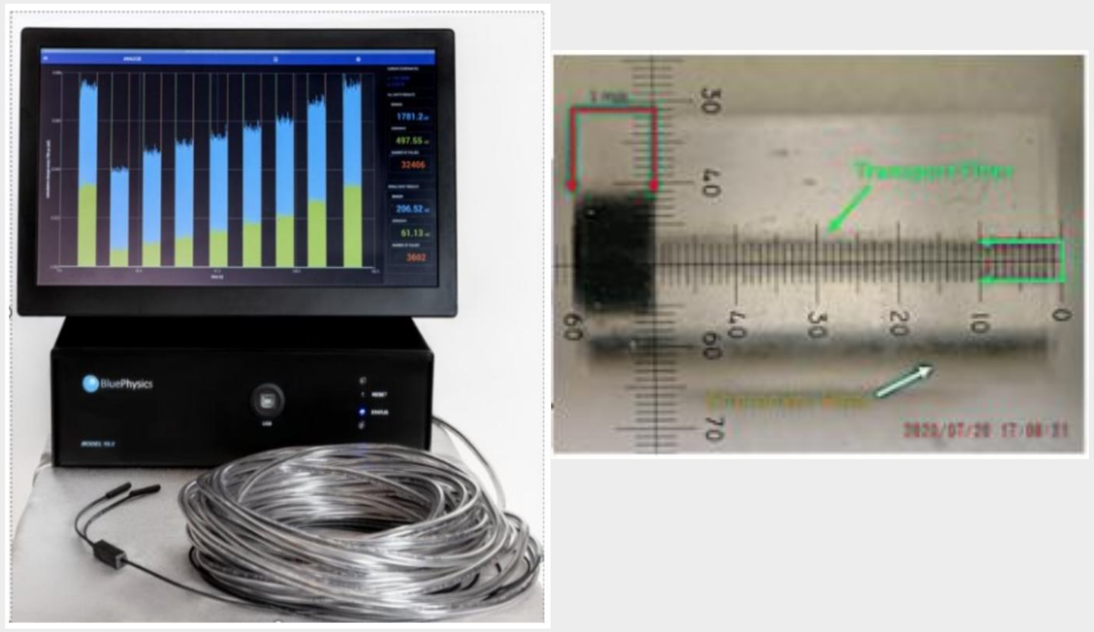

Figure 3. PSD acquisition system and detector dimensions

RESULTS

Raw PSD depth-dose measurements matched TOPAS Bragg peak position within ±2.0 mm at both energies. A +1.5 mm WET correction, derived at 100 MeV, brought 200 MeV agreement to within ±0.7–1.3 mm.

The raw signal was suppressed at the Bragg peak by 26% (100 MeV) and 44% (200 MeV) — ionization quenching (Figure 1). The Birks' law correction recovered the full Peak-to-Plateau (PPR) Ratio at both energies (Table 1), confirmed by the Bragg Peak Chamber (PPR = 3.1 ± 0.1 at 100 MeV).

Lateral spot sigma agreed with simulation within 1 mm at both energies — well inside the ±10% AAPM TG-185 tolerance (Table 1, figures below).

Table 1. Range, PPR, and spot profile (σ) agreement before/after correction.

Parameter	100 MeV	200 MeV
R_{100} offset, corrected	0.0 mm	−1.3 mm
PPR, uncorrected (deficit)	≈26% low	≈44% low
PPR, fully corrected	≈3.1	≈2.5
Spot σ (X), PSD / TOPAS	5.52 / 5.50 mm	6.41 / 7.29 mm
Spot σ (Y), PSD / TOPAS	5.52 / 5.69 mm	6.57 / 7.54 mm

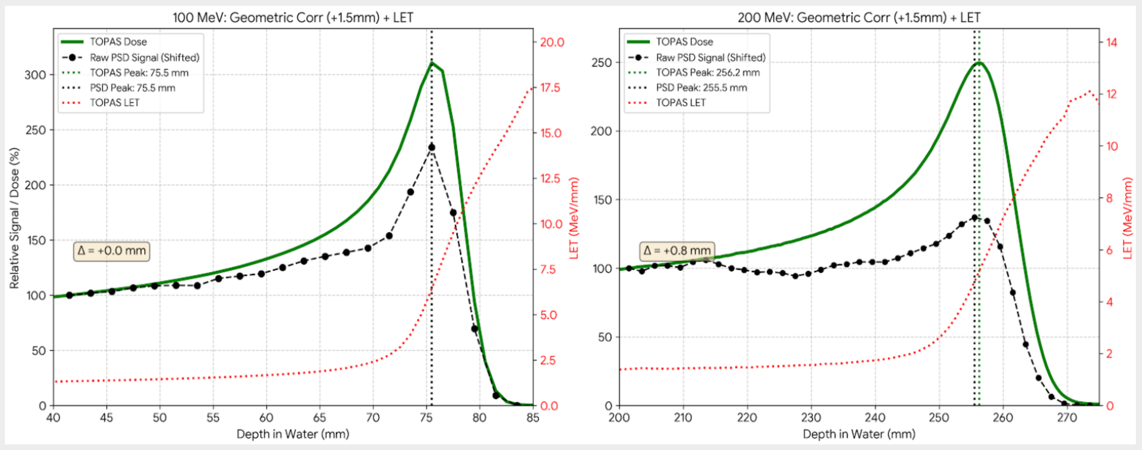

Figure 4. Geometric correction (+1.5 mm shift) to the PSD data for both 100 and 200 MeV.

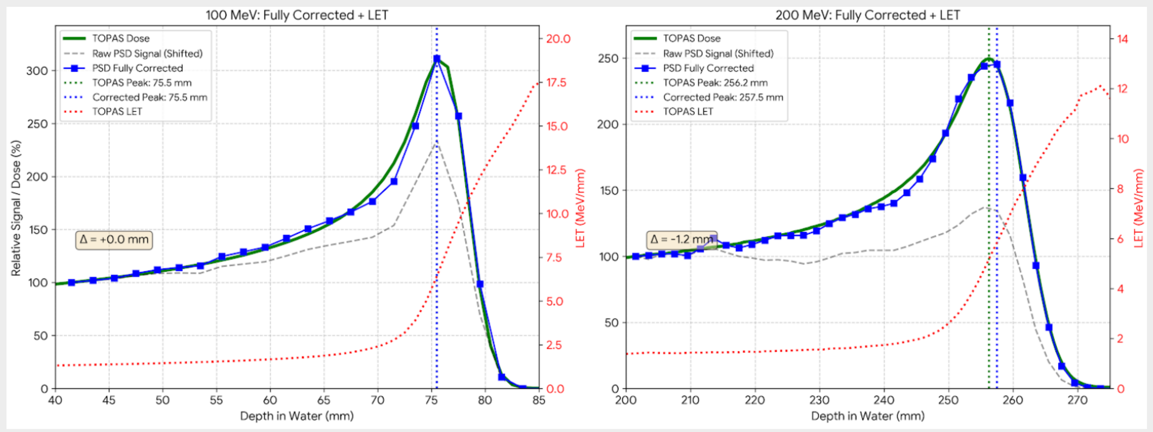

Figure 5. Quenching corrections calculated via Brik's law applied for both energies

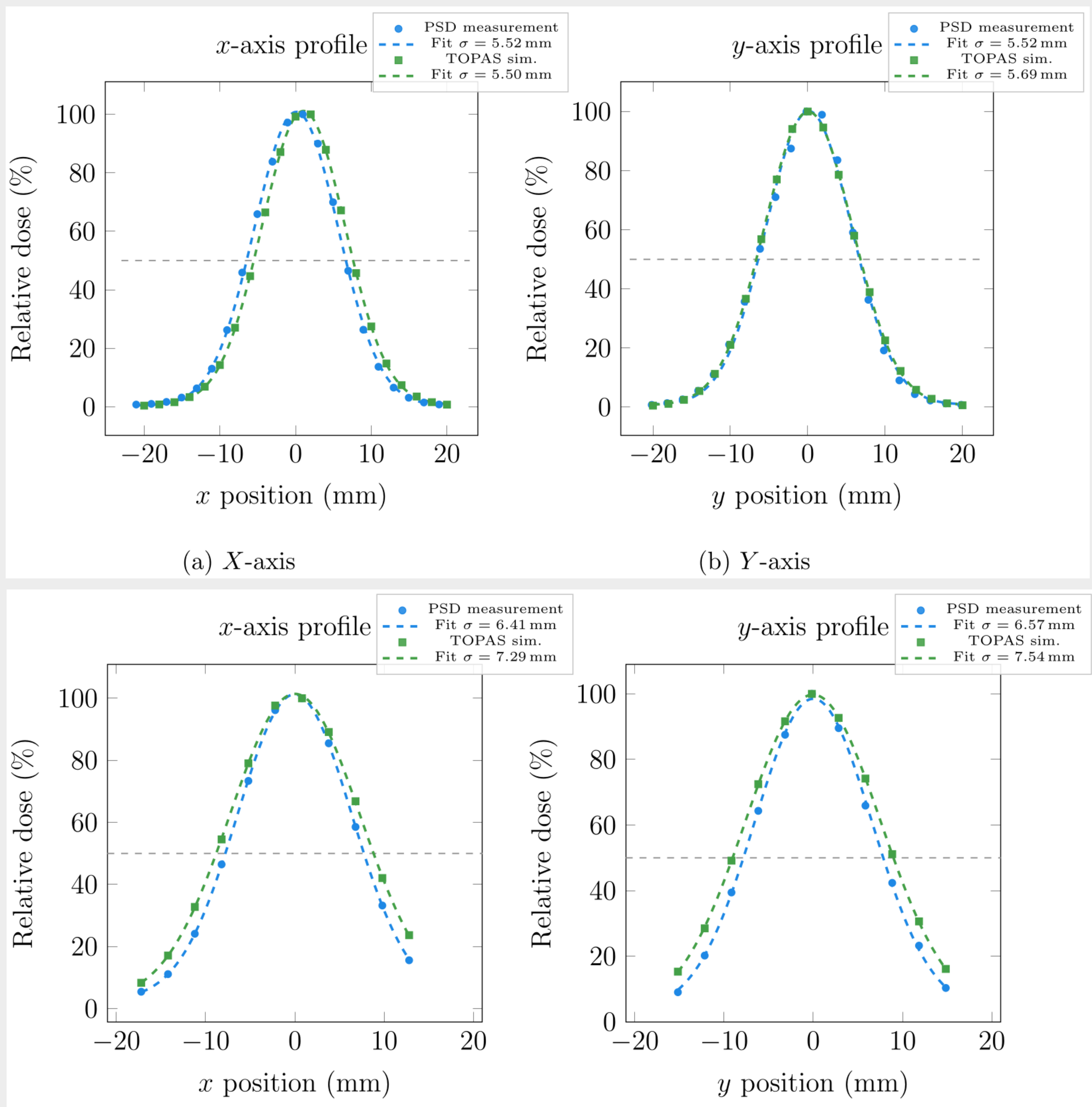

Figure 6. Spot profiles of the 100 MeV (top) and 200 MeV (bottom) proton beam measured with a PSD and simulated with TOPAS Monte Carlo.

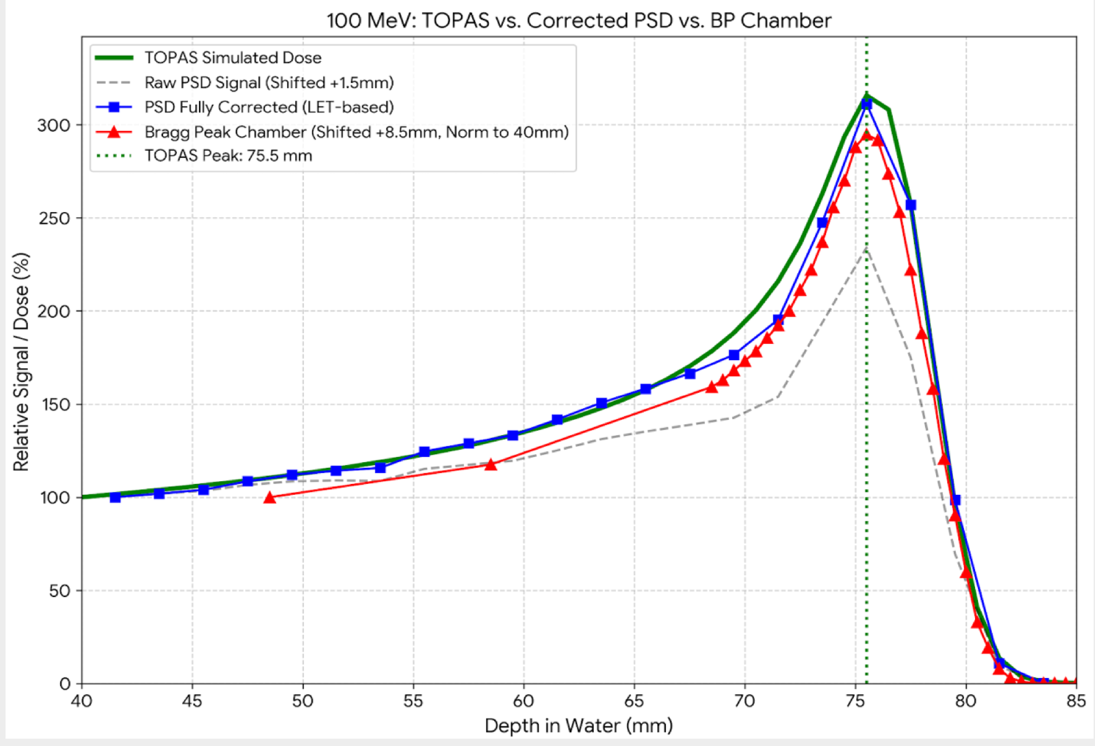

Figure 7: Normalised Integral Depth-Dose (IDD) curve acquired with the Chamber for the 100 MeV proton beam

Table 2. Gaussian fit parameters for the lateral dose profiles of the 100 MeV and 200 MeV proton beams.

Dataset	σ (mm)	$FWHM_G$ (mm)	$FWHM_I$ (mm)	$\Delta FWHM_G$ (mm)
100 MeV *proton beam*				
PSD meas. (x)	5.518	12.993	13.222	—
TOPAS sim. (x)	5.501	12.954	13.077	−0.038
PSD meas. (y)	5.519	12.996	13.116	—
TOPAS sim. (y)	5.694	13.409	13.462	0.413
200 MeV *proton beam*				
PSD meas. (x)	6.409	15.092	14.993	—
TOPAS sim. (x)	7.286	17.157	16.584	2.065
PSD meas. (y)	6.570	15.472	14.637	—
TOPAS sim. (y)	7.543	17.762	16.059	2.290

DISCUSSION

These results show the plastic scintillation detector (PSD) gives reliable spatial information and recovers accurate dosimetric amplitude once quenching-corrected. Several limitations remain.

Only two energies were tested; the ProBeam covers 70–220 MeV clinically, and the quenching correction is strongly LET-dependent. The Birks' constant here was fit to two points and should be verified at intermediate energies before broader use.

All data came from single sessions with no repeats, so reproducibility is unknown. AAPM TG-185 recommends at least three repeats per parameter for commissioning-grade data.

The +1.5 mm geometric correction, derived at 100 MeV, left a residual −1.3 mm offset at 200 MeV. The TOPAS model also simplified the detector to a bare polystyrene cylinder, omitting the fiber and housing, which likely explains part of this residual.

CONCLUSIONS

The Blue Physics PSD, combined with a TOPAS-derived Birks' law correction, produced results consistent with the Bragg Peak Chamber and Monte Carlo ground truth at 100 and 200 MeV. Range agreement was within ±2.0 mm and spot sigma matched simulation within tolerance. The LET-based correction reduced the PPR quenching deficit from 26–44% to approximately zero. Intermediate-energy validation and a complete detector model are priorities for future work.

REFERENCES

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For a small and short **plastic scintillation rod** (typically materials like EJ-200 or BC-408), Birks's law requires specific corrections to address **extreme delta-ray fluctuations** and **geometry-induced optical loss**. Because the rod is small, standard simulation defaults will heavily miscalculate your actual light output.

1. The Geometry and Optical Escape Correction

In a short rod, a significant fraction of scintillation light escapes through the sides or undergoes total internal reflection before reaching your photodetector. You must correct the raw Birks equation by multiplying it by a position-dependent light collection efficiency function, $\eta(x)$: [1]

$$\frac{dL}{dx} = \eta(x) \cdot \frac{S \frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

$\eta(x)$: Typically modeled as $\eta_0 \cdot e^{-\alpha x}$, where α is the bulk attenuation length of the plastic and x is the distance to the optical readout.

For short rods, boundary reflections dominate over bulk attenuation, requiring a dedicated optical transport simulation (such as GATE or GEANT4 optical physics) to establish the exact correction curve.

2. Standard Plastic Scintillator Parameters

When simulating or fitting your experimental data, do not use generic organic scintillator defaults. The standard, widely accepted empirical parameters for plastic rods are:

Birks's Constant (k_B): Generally ranges from 0.0075 cm/MeV to 0.012 cm/MeV for standard plastics like EJ-200 / BC-408.

Chou's Second-Order Correction (C): For heavily ionizing particles (e.g., low-energy protons or alpha particles), Chou's parameter is approximately $C \approx 1.0 \times 10^{-5}$ cm^2/MeV^2 to correct for the over-suppression of light at the Bragg peak.

3. GEANT4 Step-Size and Delta-Ray Correction

Because your rod is physically small, your simulation step sizes will naturally be constrained. Standard GEANT4 implementations of Birks's law can suffer from step-size artifacts because secondary electrons (delta rays) are produced below the production threshold.

The Fix: Enable the G4emSaturation tool. It automatically applies a correction factor to the step by evaluating the restricted energy loss rather than the unrestricted $\frac{dE}{dx}$. This prevents your simulation from over-predicting the quenching effect in tiny volumes.

4. Edge Quenching Effect

In small rods, particles passing very close to the outer surface deposit energy in a region where surface micro-scratches or wrapping materials (like Teflon or aluminized Mylar) alter the local light collection. This creates an artificial lower light yield that mimics an elevated k_B value. You must apply a geometric cut in your data analysis to exclude edge-striking events. [2]

Could you share:

What **type and energy of particle** (e.g., MeV-range protons, cosmic muons, beta electrons) are you firing at the rod?

Are you looking for a **mathematical formula** to apply to your raw data, or **code configuration** for a simulation? [3]

Knowing this will help me provide the exact numerical framework or script snippet you need.