

Analytical and Monte-Carlo modeling of Multi-Parallel Slit and Knife-Edge Slit Prompt Gamma Cameras

E. Testa¹, B.F.B. Huisman^{1,2}, D. Dauvergne³, J. M. Létang², D. Sarrut²

¹Université de Lyon, Université Claude Bernard Lyon 1, CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, 69622 Villeurbanne, France, ²CREATIS, Université de Lyon; CNRS UMR5220; INSERM U1044; INSA-Lyon; Université Lyon 1; Centre Léon Bérard, Lyon, France, ³Université Grenoble Alpes, Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3, Grenoble, France

1. Introduction

Ion-range verification during hadrontherapy

- Major challenge to fully take benefit from ion beam ballistic properties
- Main imaging modalities under study: prompt gammas (PG) detection [1] with non-imaging systems (such as PG Timing, PG Spectroscopy and PG Peak Integral) and imaging systems, namely physically-collimated or electronically collimated cameras (Compton cameras)

PG collimated cameras

- 2 main collimator configurations: Multi-Parallel Slit (MPS) [2] and Knife-Edge Slit (KES) collimators [3] (Figure 1)
- No theoretical considerations have been proposed for the specific 1D collimation systems developed for PG detection

2. Objectives

- Development of an analytical model (AM) of MPS and KES collimations \Rightarrow main intrinsic features of each collimator
- Verification of the AM by means of Monte Carlo (MC) simulations
- Comparison the MPS and KES prototypes developed by the CLaRyS collaboration [2] and IBA [3], respectively.

3. The Analytical Model of MPS and KES collimations

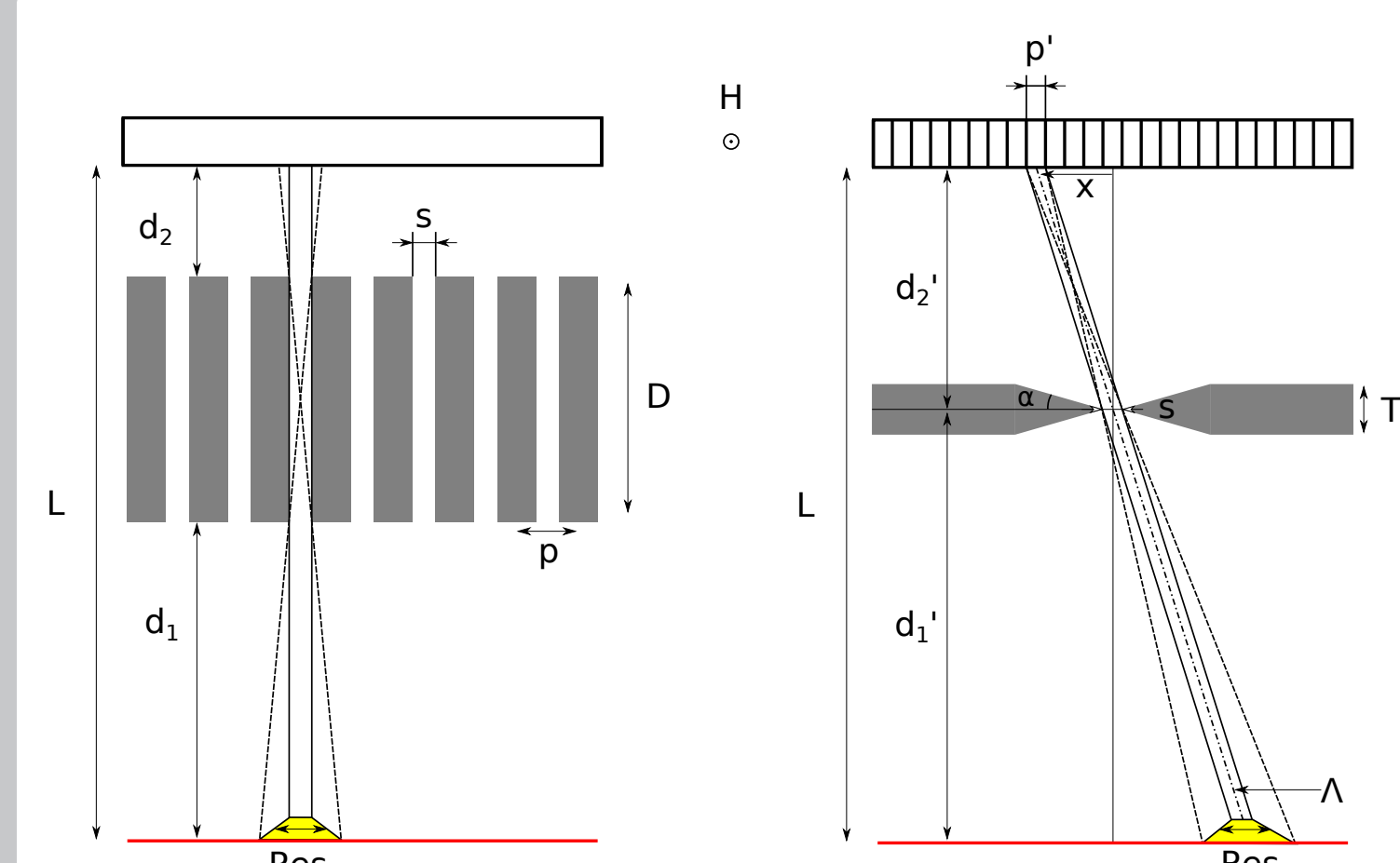


Figure 1: MPS (left) and KES (right) collimation. H : height. f : filling factor $((1 - s)/p)$

	MPS	KES
s_e	s	$s + \frac{\ln(2)}{\mu \tan(\alpha)}$
FOW	$s \left(1 + \frac{d_1}{D}\right)$	$s_e \left(1 + \frac{d_1}{d_2}\right)$
DE	$\frac{Hs}{4\pi LD} (1 - f)$	$\frac{Hs_e}{4\pi Ld_2} \left(1 + \frac{x^2}{d_2^2}\right)^{-3/2}$
T_e	$D \times f$	T

Table 1: Detection efficiencies (DE) and spatial resolution (Res=FOW) predicted by the analytical model. FOW: Fall-Off Width of the PG profile (see section "Figures of merit"); s_e : effective slit width; T_e : effective thickness.

4. Monte Carlo simulations & PG profile analysis

- Monte Carlo simulations
 - 2-stage simulation with Gate 7.2 (Geant4 4.10.02)
 - First stage: target irradiation (QGSP_BIC_HP_EMY physics list)
 - Optimization: vpgTLE variance reduction method \Rightarrow gain of $\sim 10^3$ [4]
 - Second stage: photon propagation in the geometry (emlivermore physics list)
- PG profile analysis
 - Background (BKG) modeling:
 - Estimates of background counts in the detector (mainly due to secondary neutrons) are taken from [2] (MPS, 2.5×10^{-7} counts/incident proton and per 8 mm bin) and [5] (KES, 5×10^{-7} counts per primary proton per 4 mm bin) which are both based on measured data
 - Fall-Off Position (FOP): position corresponding to the half FO amplitude in the spline-fit to the PG profile
 - Fall-Off Width (FOW): width of the PG profile fall-off, namely the FWHM of the peak resulting from the computation of the PG profile first derivative (see bottom row of Figure 3)

6. Figures of merit

- Detection efficiency (DE): $\# \text{detected PG} / \# \text{emitted PG}$ in the camera Field of View
- Spatial resolution (Res) = FOW (Fall-Off Width)
- Fall-off Retrieval Precision (FRP): Standard deviation of the FOP distribution obtained with 50 MC simulation runs.

7. Results

AMV

	MPS		KES	
	AM	MC	AM	MC
FOW (mm)	14.5	16.9	13.5	13.8
DE	6.66×10^{-4}	6.47×10^{-4}	1.06×10^{-3}	8.7×10^{-4}

PG profiles detected by the prototypes

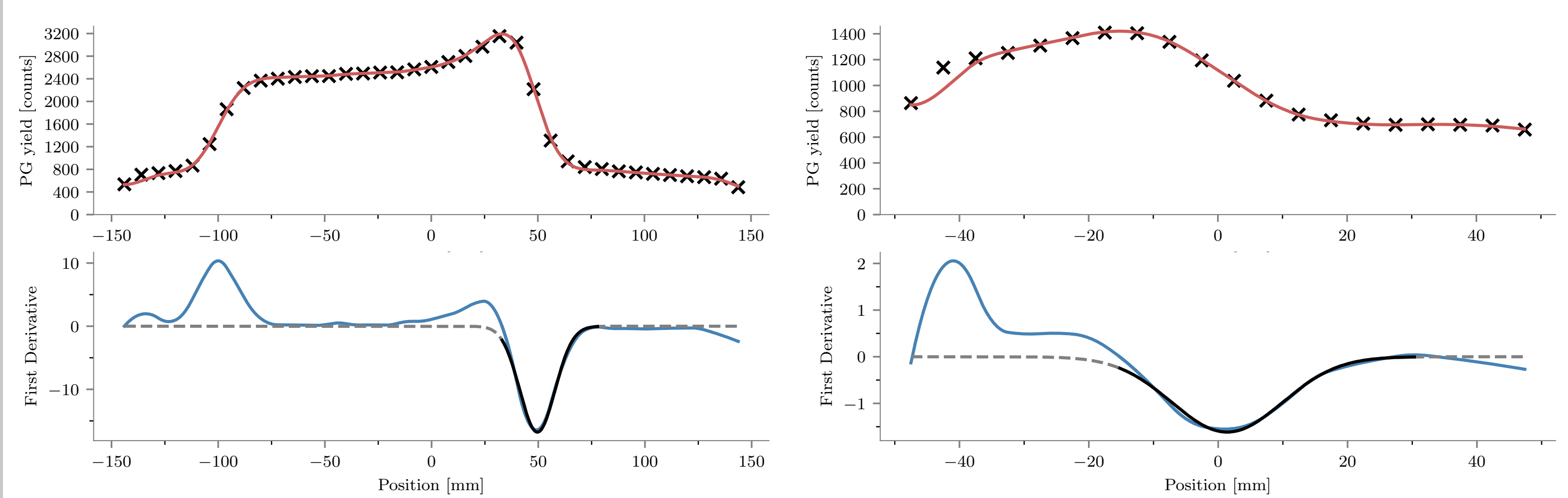


Figure 3: Top: PG profiles obtained with MPS (left) and KES (right). See column PC of Table 2 for the parameters. Bottom: first derivative of the PG profiles.

Fall-off Retrieval Precision

# protons	MPS	KES
10^9	0.32	0.65
10^8	1.05	1.80
10^7	2.81	17.1

Table 3: Standard deviations (in mm) of the FOP distributions. See column PC of Table 2 for the parameters.

5. Simulated geometries

- 2 configurations (Table 2):
 - The prototypes as they are published (Figure 2)
 - The prototypes with some alterations for the Analytical Model Verification (AMV)

Absorber	MPS	AMV	PC
KES	Perfect	Perfect	BGO
Collimator	Perfect	Perfect	LYSO
Energy selection	MPS	> 1 MeV	> 1 MeV
KES	> 1 MeV	> 1 MeV	3–6 MeV
TOF selection	MPS	no TOF	TOF
KES	no TOF	no TOF	no TOF
BKG	No modeling	No modeling	Exp. data based
Target	No	No	Yes
Beam	160 MeV proton		

Table 2: AMV: Analytical Model Verification – PC: Prototypes Comparison. "Perfect" collimators and detectors: gamma full absorption. For AMV, the PG source corresponds to the PG emitted along the beam direction during the PMMA irradiation

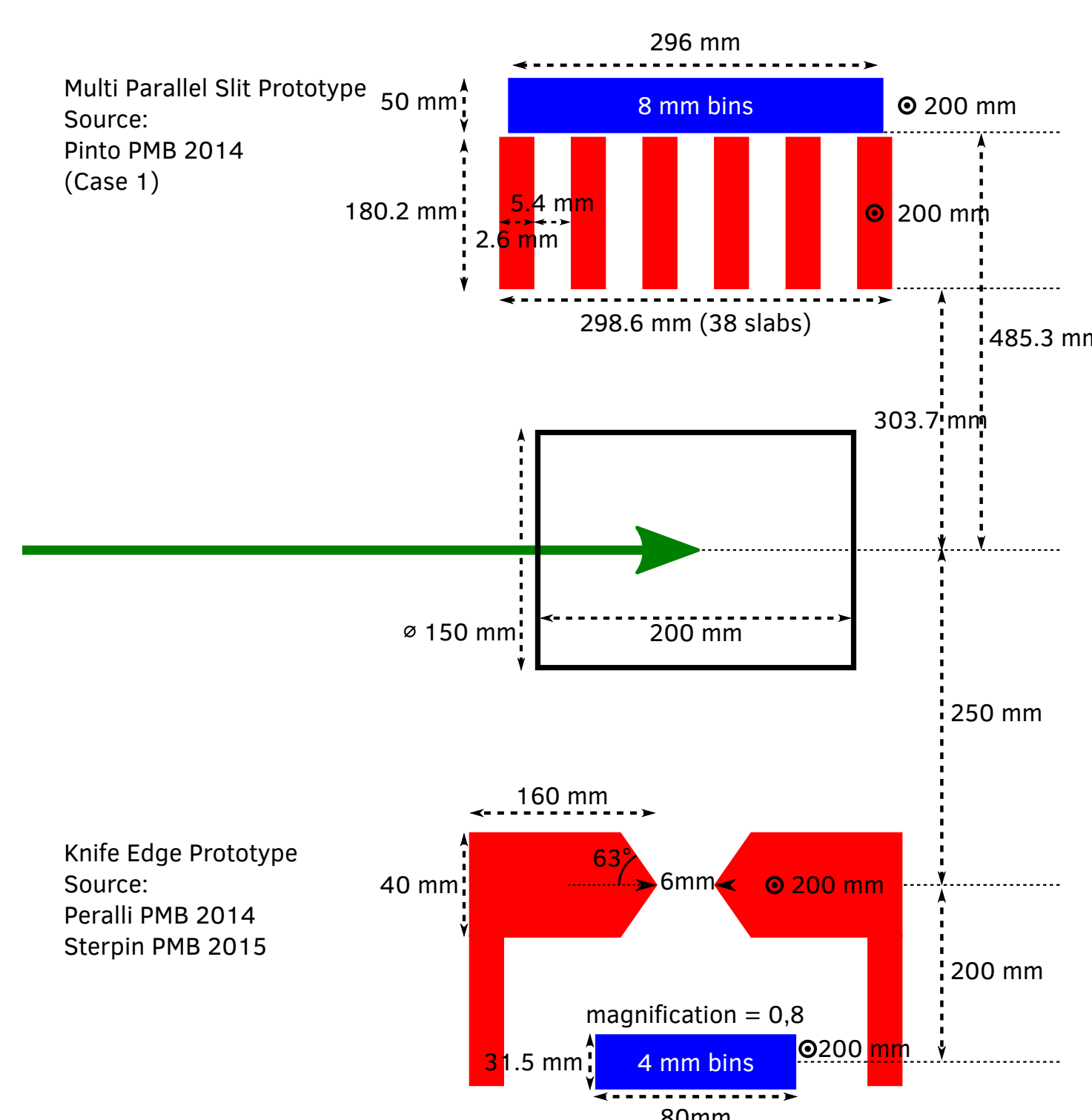


Figure 2: Prototypes representation

8. Discussion and conclusion

- Analytical Model (AM)
 - Good agreement in overall with MC
 - Striking similarities between MPS and KES performances, unlike what can be concluded from previous studies [6, 7, 8]
 - \Rightarrow Same DE and FOW with perfect collimators
 - \Rightarrow With real collimators: slightly poorer DE for MPS and FOW for KES
 - Note that the MPS prototype allows for the detection of the whole PG profile: the field of view of the MPS and KES prototypes are of 30 cm and 10 cm, respectively
- Prototypes comparison
 - PG profiles: MPS prototype with larger fall-off amplitude and lower BKG level thanks to wider energy selection and TOF selection, respectively
 - \Rightarrow Better Fall-Off Retrieval Precision (FRP) with the MPS prototype
 - Precisions in agreement with the ones published in [2] and [3]

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