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

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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 ⇒ 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

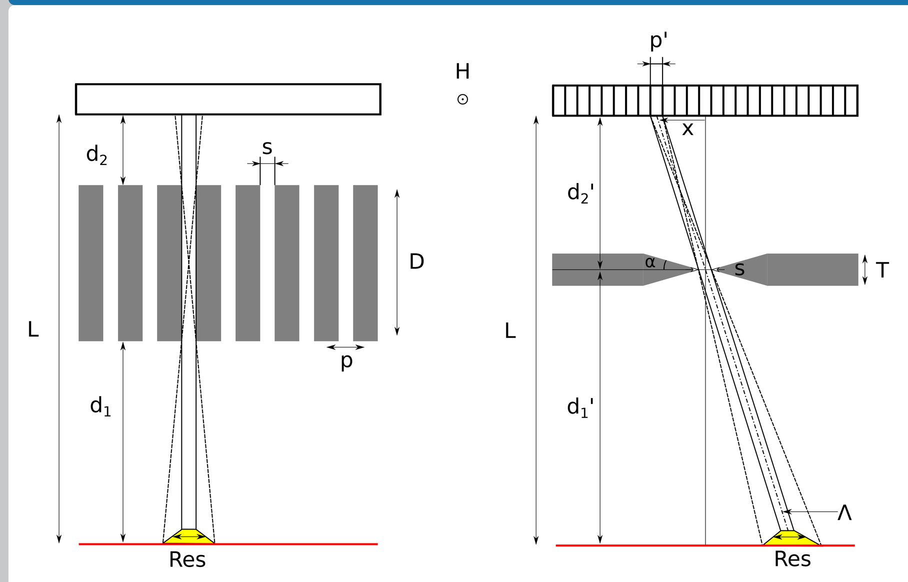

Figure 1: MPS (left) and KES (right) collimation. H: height. f: filling factor $((1-s)/p)$

	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 ⇒ 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)

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)

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

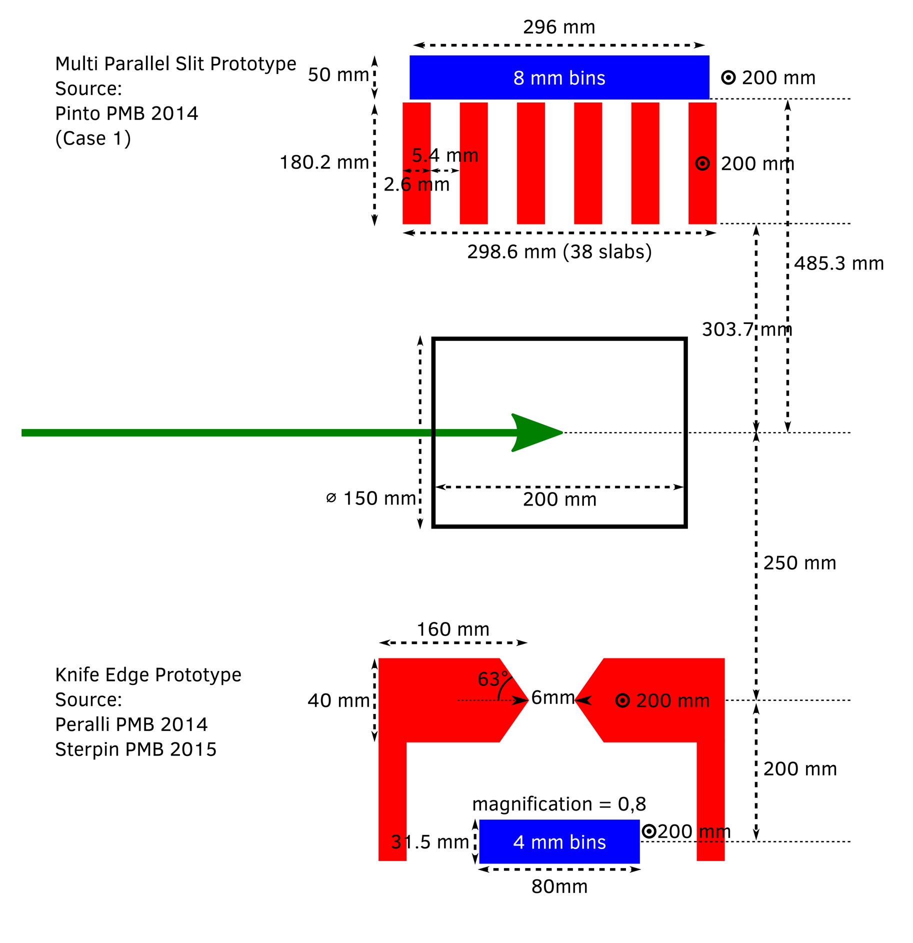

Figure 2: Prototypes representation

6. Figures of merit

- Detection efficiency (DE): #detected PG/#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

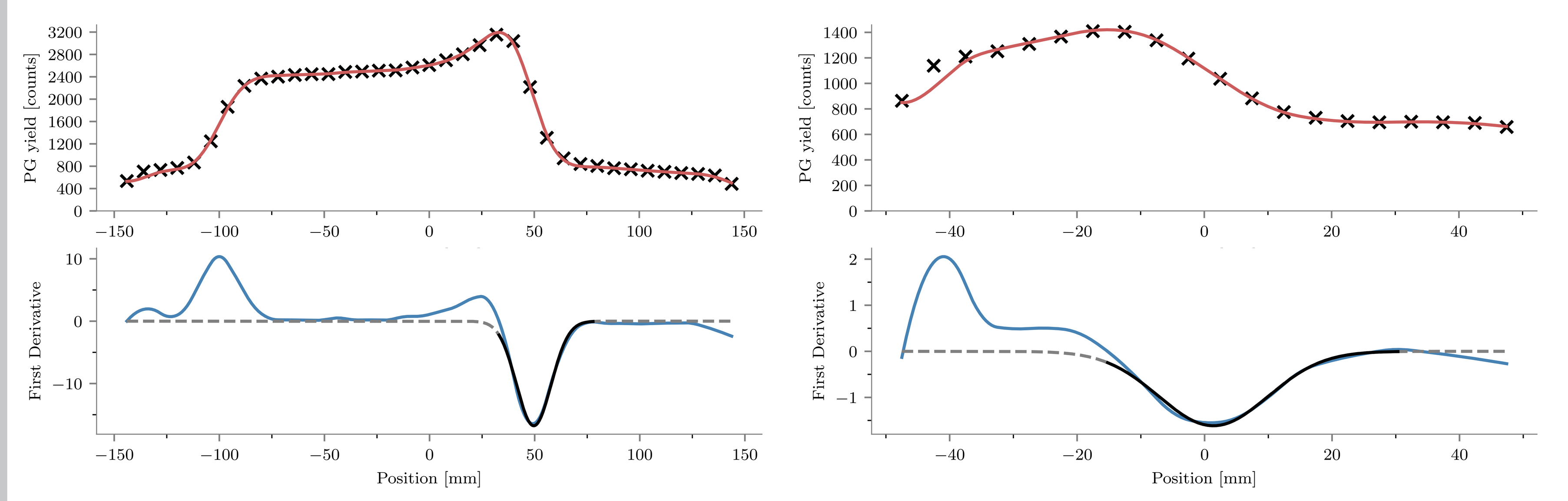

Figure 3: Top: PG profiles obtained with MPS (left) and KES (right). See column PC of Table 2 for the parameters. Bottom: first derivative of the PG profiles.

Fall-off Retrieval Precision

# protons	MPS			KES		
	FRP	FOW	DE	FRP	FOW	DE
10^9	0.32	19.4	1.04×10^{-3}	0.65	20.1	5.58×10^{-4}
10^8	1.05	19.4		1.80	20.1	
10^7	2.81	19.4		17.1	20.1	

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

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]
    - ⇒ Same DE and FOW with perfect collimators
    - ⇒ 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
  - ⇒ Better Fall-Off Retrieval Precision (FRP) with the MPS prototype
  - Precisions in agreement with the ones published in [2] and [3]

References

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