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

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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

Objectives

- Development 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 two MPS and KES prototypes developed by IBA and the CLaRyS collaboration, respectively.

The Analytical Model of MPS and KES collimations

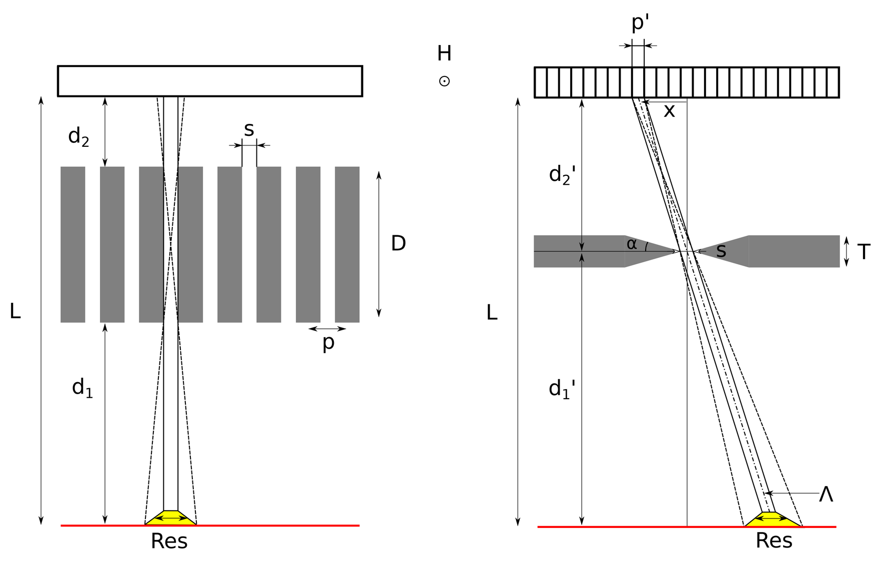

Figure 1: MPS (left) and KES (right) collimation

	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 (FOW) predicted by the analytical model. s_e: effective slit width ; T_e: Collimator effective thickness.

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 [5] (KES, $5\cdot10^{-7}$ counts per primary proton per 4 mm bin) and [2] (MPS, $2.5\cdot10^{-7}$ counts/incident proton and per 8 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

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), in particular the use of "perfect" collimators and detectors (full gamma absorption)

		AMV	PC
Absorber	MPS	LYSO	BGO
	KES		LYSO
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. For AMV, the PG source corresponds to the PG emitted along the beam direction during the PMMA irradiation

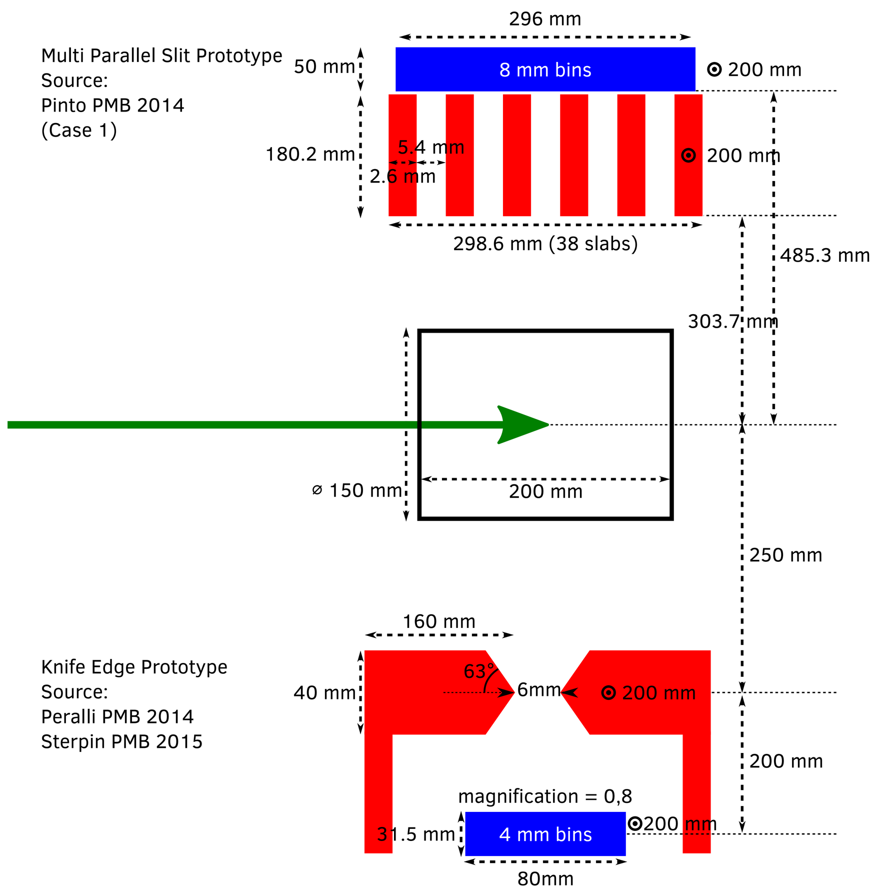

Figure 2: Prototypes representation

Figures of merit

- Detection efficiency: #detected PG/#emitted PG in the camera Field of View (FOV)
- Spatial resolution: the width of the PG profile fall-off, namely the FWHM of the peak resulting from the computation of the PG profile first derivative
- Fall-off Retrieval Precision (FRP): Standard deviation of the FOP distribution obtained with 50 MC simulation runs.

Results

AMV

	MPS		KES	
	AM	MC	AM	MC
FOW	14.52 mm	17.9 mm	13.5 mm	13.8 mm
DE	$6.66\cdot10^{-4}$	TODO	$1.06\cdot10^{-3}$	TODO

PG profiles detected by the prototypes

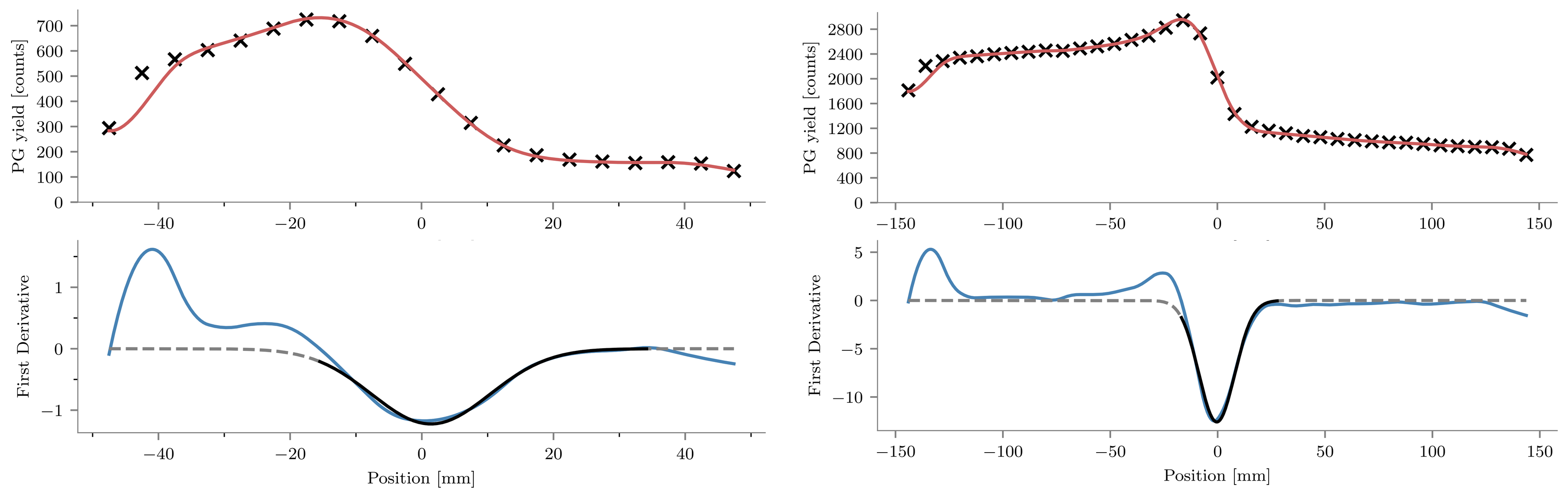

Figure 3: PG profiles: MPS (left), KES (right). See Table 2 for the parameters.

Fall-off Retrieval Precision

Time selection	ToF				None			
Energy selection (MeV)	>1		3–6		>1		3–6	
Camera	MPS	KES	MPS	KES	MPS	KES	MPS	KES
10^9 (# protons)	**0.37**	0.55	0.44	1.07	0.42	0.74	0.66	**1.32**
10^8	**1.35**	2.08	1.60	4.22	1.36	1.82	2.00	**9.70**
10^7	**4.41**	11.88	20.36	20.50	22.45	17.18	56.92	**19.39**

Table 3: TO VERIFY: Standard deviation of the FOP distribution. In bold, the cuts and ToF selections as proposed.

Discussion and conclusion

- Analytical Model (AM)
  - Good agreement in overall with MC
  - Unlike what can be concluded from previous studies [6, 7, 8], striking similarities between MPS and KES performances
    - ⇒ Same DE and FOW with perfect collimators
    - ⇒ With real collimators: slightly poorer DE for MPS and FOW for KES

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