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

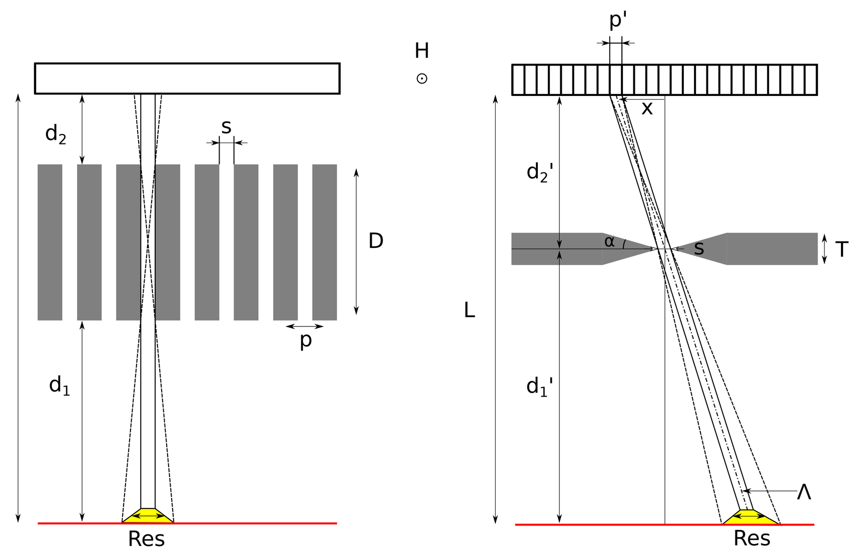

Figure 1: MPS (left) and KES (right) collimation

	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	$\frac{Hs}{4\pi LD}(1-f)$	$\frac{Hs_e}{4\pi L d_2'}\left(1+\frac{x^2}{d_2'^2}\right)^{-3/2}$
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 $\sim \mathbf{10^3}$ [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, $\mathbf{5 \cdot 10^{-7}}$ counts per primary proton per 4 mm bin) and [2] (MPS, $\mathbf{2.5 \cdot 10^{-7}}$ 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)

		AMV	PC
Absorber	MPS	LYSO	BGO
	KES		LYSO
Energy selection	MPS	$> \mathbf{1}$ MeV	$> \mathbf{1}$ 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

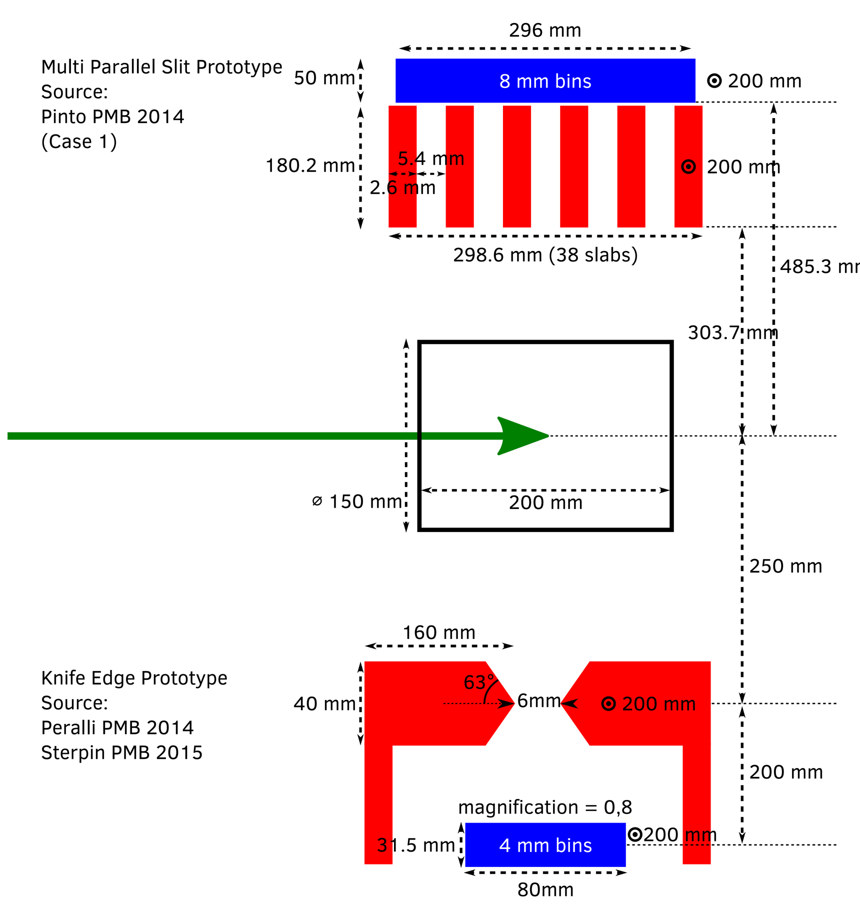

Figure 2: Prototypes representation

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 (mm)	14.5	17.9	13.5	13.8
DE	$\mathbf{6.66 \cdot 10^{-4}}$	$\mathbf{6.35 \cdot 10^{-4}}$	$\mathbf{1.06 \cdot 10^{-3}}$	$\mathbf{7.54 \cdot 10^{-4}}$

PG profiles detected by the prototypes

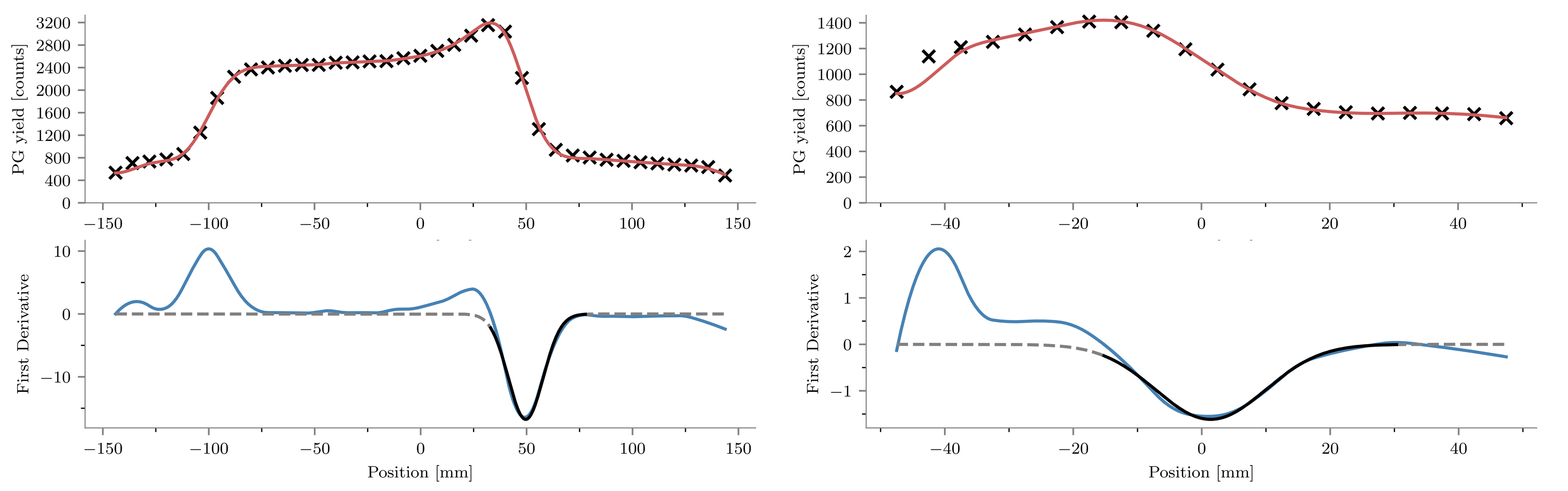

Figure 3: PG profiles: MPS (left), KES (right). See column PC of Table 2 for the parameters.

Fall-off Retrieval Precision

# protons	MPS	KES
$\mathbf{10^9}$	0.32	0.65
$\mathbf{10^8}$	1.05	1.80
$\mathbf{10^7}$	2.81	17.1

Table 3: Standard deviation of the FOP distribution. See column PC of Table 2 for the parameters.

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
- Prototypes comparison
  - PG profiles: MPS prototype with larger FO amplitude and lower BKG level thanks to larger energy selection and TOF selection, respectively
  - ⇒ Better Fo Retrieval precision with the MPS prototype

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