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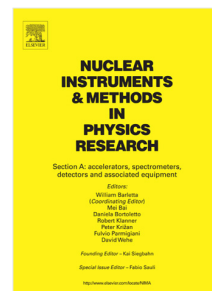
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Hybrid Monte Carlo and deterministic simulation approach for modeling a computed radiography imaging chain from X-ray exposure to optical readout

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Abstract: Simulation of radiographic inspection is of great interest for experimental outcomes prediction and optimal operating condition determination. As concerns computed radiography (CR), the use of photo-stimulable imaging plates and laser scanners, implies modeling the behavior of a multi-stages detector. As a consequence, both the X-ray and the optical system responses have to be handled. Moreover, for high energy X-rays, two issues often trouble CR simulation: long running time and X-ray scattering image contribution, which should not be neglected. To overcome these issues, we have developed a complete hybrid model which is the first available one at such energies. In our approach, the imaging process is decomposed into three independent successive stages: X-ray attenuation by an object, X-ray latent image generation, and optical readout. A deterministic code is applied to obtain rapidly the transmitted X-ray image emerging from a complex object. The energy deposition is then simulated by a convolution of the transmitted X-ray image with a CR detector response model, which was obtained off-line by a Monte Carlo tool. Then, optical readout is modeled using the same hybrid approach, where the optical response (laser light spreading in the imaging plate) was obtained by Monte Carlo and laser scanning is modeled analytically. A good agreement has been observed between the proposed hybrid model and a full Monte Carlo approach for the X-ray energy deposition stage. A realistic X-ray inspection case study has been chosen to emphasize the interest of this complete hybrid model. The comparison of three different detector configurations and the influence of readout laser power are illustrated.

Keywords : Computed Radiography, Imaging Plate, Monte Carlo simulation, deterministic simulation, optical readout modelling

1 Introduction

For over a century, film-based radiography has been used for industrial inspection. Recently, the NDT community started considering alternative digital techniques [1]. Computed radiography

37 (CR), as the first standardized digital radiographic imaging technique, is an interesting alternative
38 [2], as it employs a flexible (i.e. which can be bent and cut) storage phosphor imaging plate (IP)
39 as digital detector, which shares the same advantages in terms of handling as film. However, the
40 performance of standard CR systems is not as good as film-based radiography at high energies
41 (i.e. several hundred keV up to MeV). For the inspection of high attenuation specimens (e.g.
42 pipeline welding), high energy gamma sources, such as isotopes Iridium-192 and Cobalt-60, are
43 often required. Therefore, the unsatisfied CR performance at high energies is an issue to be
44 overcome in industrial applications.

45 The performance improvement of CR can be achieved by means of introducing appropriate filters
46 and thin metallic screens in the system. Current international standards, concerning NDT
47 radiography with digital detectors, address general metallic screen employment guidelines to
48 ensure a good imaging quality [2-4]. However, the type and thickness of such screens are not
49 clearly defined and a large panel of possible configurations does exist. Experimental studies on the
50 CR image quality [1,5-7], indicate that CR cannot fulfill the requirements in all NDT cases, due
51 to the IP response and optical readout process.

52 Apart from experimental studies, computational simulation is also an important tool for physical
53 phenomena comprehension and system performance optimization [8-9]. It makes it possible to
54 study how the relevant operating parameters affect the X-ray image without actually testing it in
55 real life. At present, Monte Carlo and deterministic techniques are widely used to simulate
56 radiation transport. Monte Carlo simulation is well accepted as the most accurate method [10]. It
57 can give insight on physical phenomena but due to its random nature, a large amount of
58 computational time is required, especially for complex geometry simulation [9-10]. Deterministic
59 methods, on the other hand, can handle easily complex geometries, and are quite computationally
60 efficient, but the estimation of scattering and fluorescence effects is quite difficult.

61 In prior works, many CR modeling and simulation studies were dedicated to medical applications
62 [11-20]. Vedantham and Kazellias have developed a complete (from X-ray exposure to digital
63 readout) analytic CR model to analyze the system performance factor propagation during image
64 formation process such as detective quantum efficiency (DQE) and modulation transfer function
65 (MTF) [11]. This model is based on a cascaded linear system approach [17,18], and based on the
66 assumption that the X-ray scattering effect is negligible. However, for high energy CR, where the
67 scattering effect becomes dominant, this assumption is not appropriate. A more precise model is
68 needed for scattering effect estimation. In [19] and [20], E.M. Souza et al. proposed a
69 methodology for computed radiography simulation for industrial applications using Monte Carlo
70 code MCNP taking into account the energy-dependent response of imaging plate (IP) and the
71 digitization effect. But in their approach, the spatial degradation due to X-ray interaction in the
72 detector has not been considered. Full Monte Carlo simulation could be the solution to overcome
73 the mentioned issues. However, due to its random nature, the computation time might be
74 extremely long.

75 In this paper, we propose a CR model which combines the use of both Monte Carlo and
76 deterministic codes. Such a complete hybrid model is the first available one to our knowledge.
77 The CR imaging process is split into three successive stages: i) X-ray attenuation by the object;
78 ii) energy deposition resulting in X-ray latent image generation; iii) optical readout resulting in
79 the final digital image generation. The first stage is based on a deterministic code which provides
80 a realistic radiant image of a complex-shape object in a short time (typically 0.1 s) based on the
81 object CAD model. The second stage is based on an offline CR detector response model which is
82 obtained by means of off-line MC simulations accounting for all physical effects such as
83 fluorescence, scattering and electrons interactions. The response function is then convolved with
84 the object radiant image. A database of several detector systems has been built in order to cover
85 all the industrial application range. As concerns the optical readout (third stage), the laser
86 spreading distribution function is obtained off-line by a dedicated optical MC tool developed on
87 purpose, while the laser scanning operation is modeled by an analytic function. Thus, we obtain a
88 complete model which is able to simulate a realistic inspection case study in a reasonable time,
89 while taking into account all physical effects both for X-ray and optical photons effects. It is
90 worth noting that the presented model allows to determine mean values and obviously does not
91 include noise. This approach allows to add noise afterwards while keeping a reasonable
92 computation time, even for a complex shape object. Thus, all Monte Carlo simulations are carried
93 out off-line, allowing to model all physical effects in the form of response functions.

94 In the following, the CR principle is briefly reminded in section 2, together with an overview of
95 the model, then a detailed description of the different simulation stages is given in section 3.
96 Section 4 and 5 show some results, before concluding in section 6.

97

98 **2 CR principle and general overview of the modelling approach**

99

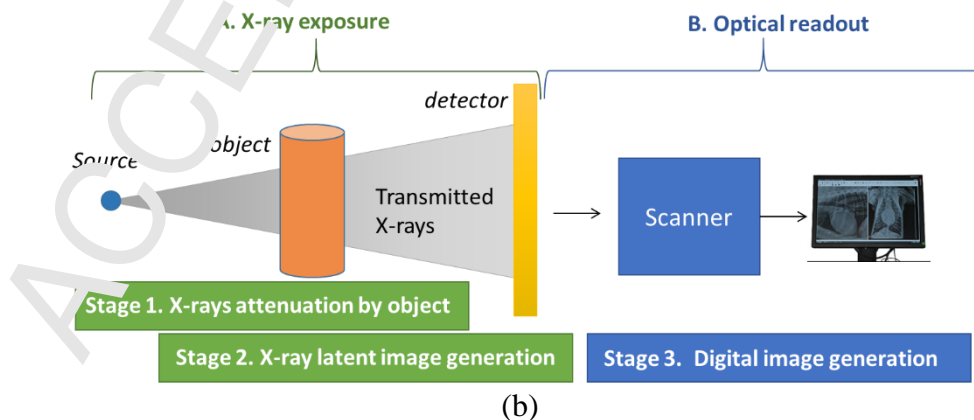
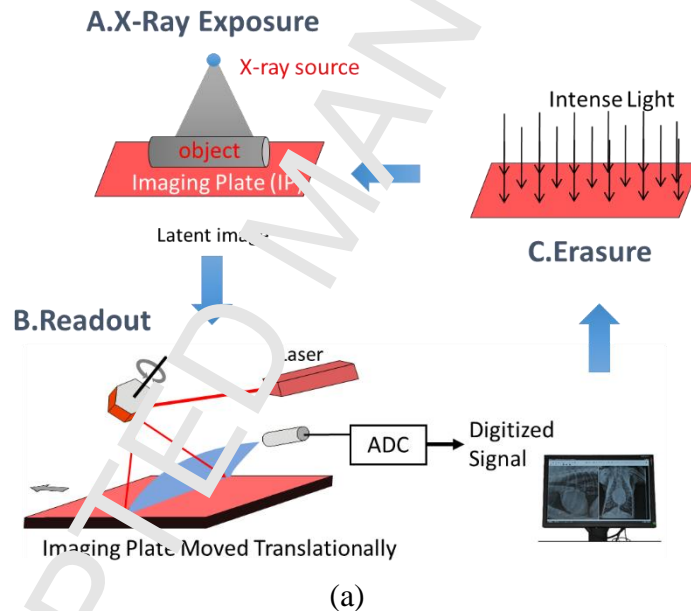
100 **2.1 CR principle**

101 As illustrated in Figure 1a, CR imaging consists first in the X-ray exposure itself (A), where the
102 energy transmitted by an object is deposited in the detector. The particularity of CR yields in the
103 type of detector, a photo-stimulable imaging plate (IP), in which the deposited energy allows to
104 create electron/hole pairs in the material. Some of these charges are trapped in the material,
105 forming a latent image which is stable during several hours. The second step (B) consists of
106 reading the latent image. A laser beam allows to excite the storage centers and light is emitted
107 (photo-stimulation mechanism). The third step is the erasure of the plate which makes the
108 detector available for a new image (C).

109 Only some specific materials present this photo-luminescence effect with sufficient stability of
110 the trapped electrons yielding a useful latent image. The most common material is BaFBr:Eu^{2+} ,

111 available in the form of grains in a binder. Since the discovery of the photo-stimulability of
 112 BaFBr:Eu²⁺, several works have been done attempting to find out the physical mechanisms
 113 occurring during X-ray radiation. Present day's well accepted electron/hole production
 114 mechanism is proposed by Koschnick et al. [21,22]. It is worth noting however that those
 115 mechanisms are extremely complex and not fully understood.

116
 117 BaFBr:Eu²⁺ imaging plates are successfully used in the medical field, because the X-ray energy
 118 range gives rise mainly to photoelectric effects in the material. For higher energies (such as
 119 Cobalt or Iridium sources), the efficiency of imaging plates is known to be poor. To improve
 120 performances, NDT standards [2] require the use of metallic screens to be used together with IP
 121 (front and back screens), such as what is done for radiographic films. However, unlike films
 122 where the use of screens yields sufficient imaging performance at high energy, in CR, the optimal
 123 nature and thickness of screens is still to be found, such as optical properties of the IP itself. This
 124 is the reason why simulation can be interesting, to understand the physical mechanisms during
 125 image formation, and find optimal combinations of IP/screen.



126

127 **Figure 1: (a) CR principle with the acquisition procedure highlighted: A. X-ray exposure**
 128 **which yields a latent image, B. Optical readout of the latent image, and C. Erasure of the**
 129 **image; (b) only part A and B are simulated, sub-divided into three stages.**

132 2.2. Overview of the simulation approach

133 During X- or gamma-ray exposure, the radiation beam first interacts with the object, and owing
 134 to the object attenuation, only part of the beam can arrive at the CR detector¹. This transmitted
 135 beam carries the object pattern, which is received by the CR detector; a portion of the transmitted
 136 beam penetrates through the detector and escape from the system, while the other portion
 137 interacts with the detector resulting in a latent image. The CR image formation is viewed as a
 138 three-stage process (Figure 1b): X-ray attenuation, latent image generation and digital image
 139 generation. Different simulation methods (Monte Carlo or Deterministic) are applied to different
 140 stages. The CR simulation method is summarized as follows.

141
 142 Stage 1: X-ray attenuation by an object (X-ray beam \rightarrow attenuated X-ray beam). In this step, the
 143 source beam interacts with an object resulting in an object image. In this paper, the Virtual X-
 144 ray Imaging (VXI) software, a deterministic code for fast complex imaging [23], [24], is used.
 145 The output image should contain the energy information, namely a spectral image, here
 146 denoted $Obj(E,x,y)$.

147 Stage 2: X-ray latent image generation (X-ray photons incoming the CR detector \rightarrow storage
 148 centers in IP). This stage is split into two sub-steps.

149 (a) X-ray/detector interaction (X-ray photons incoming the detector \rightarrow deposited energy in IP),
 150 via the detector response model (denoted PSF_{det}) resulting in a 3D deposited energy image.
 151 The detector response model is obtained by means of an off-line Monte Carlo simulation.

152 (b) Latent image formation (deposited energy in IP \rightarrow storage centers in IP). The latent image is
 153 in fact the map of storage center distribution in IP. At present day, the latent image formation
 154 mechanism is not clearly understood. Hence this step is modeled as conversion factor, denoted
 155 g_{sc} .

156 The entire Stage 2 is modeled by a convolution-based operator HI :

$$157 \quad Li ng(x,y,z) = HI(Obj; PSF_{det}) \quad (1)$$

158
 159 Stage 3: Digital image generation (storage centers \rightarrow gray levels). This stage is also split into two
 160 sub-steps.

161 (a) Optical readout (storage centers \rightarrow photo-stimulated luminescence (PSL) photons). In CR, the
 162 latent image is readout by a scanning laser. Due to the IP's granular property, the laser light
 163 spreads out in IP; storage centers within the laser volume can be released resulting in PSL.
 164 The laser spreading is simulated with a Monte Carlo tool developed on purpose. This tool
 165 outputs a laser distribution function $f(x,y,z)$. The scanning is then modelled analytically, based
 166 on the scanning parameters i.e. laser power P_{laser} , scanning speed v_{scan} and pixel size l_{pxl} .

167 (b) Signal collection, amplification and digitization (PSL photons \rightarrow gray levels).

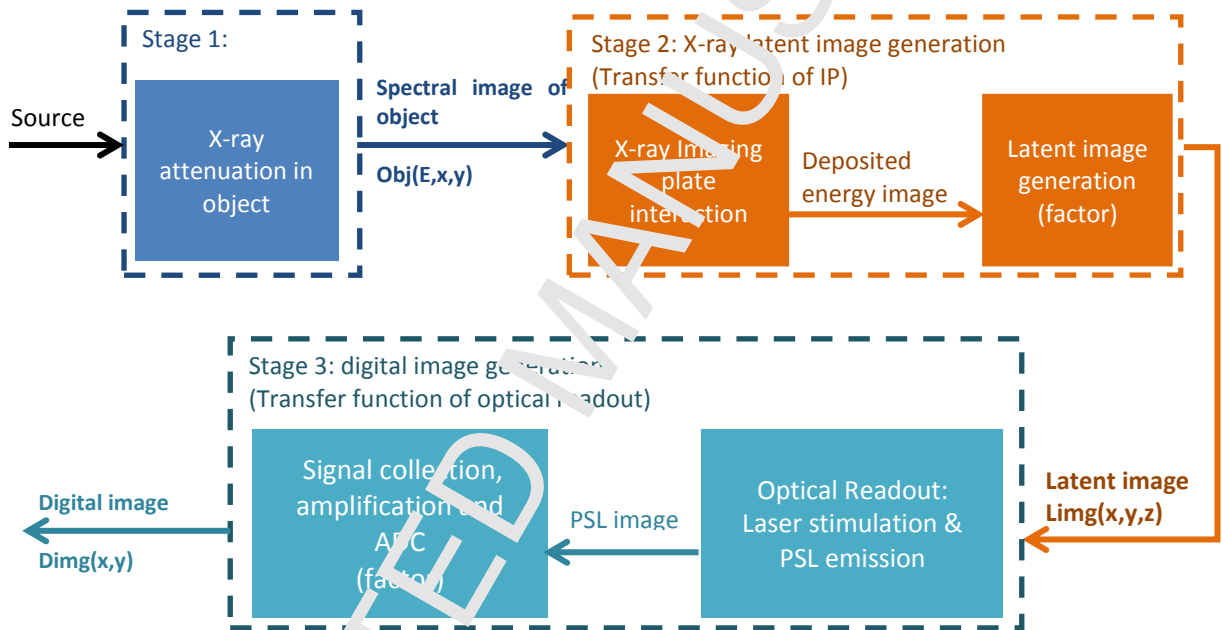
¹In the following, the term “detector” should be understood as the complete system including the IP itself and front and back screens, which are metallic screens as recommended in the international standards.

168 In this sub-step, the emitted PSL is collected by a light guide, then detected and amplified by a
 169 photo-multiplier tube and finally digitized with an analog-to-digital converter. A PSL to gray
 170 level conversion factor g_{psl} can be applied.

171
 172 Stage 3 is modeled by an operator $H2$:

$$173 \quad Dimg(x,y) = H2(Limg; f; \text{scanning parameters}) \quad (2)$$

174
 175 To summarize, as represented in Figure 2, the presented method allows to simulate the complete
 176 CR imaging chain, in which all the operating parameters such as source, detector configuration
 177 and optical readout parameters are taken into account through the operators $H1$ and $H2$.



179
 180 **Figure 2: Schematic representation of the simulation of the entire CR imaging chain**

181
 182 Before introducing the details of the model, let's introduce the assumptions adopted:

- 183
- 184 • As concerns the X-ray exposure, the CR detector is considered as a linear system, so that
 185 the convolution operator $H1$ can be applied to obtain the X-ray detector response to any
 186 object spectral image obj .
 - 187 • The electrons emerging from the object are neglected. Our approach deals with high
 188 attenuation object (i.e. high thickness); therefore, the fraction of electrons in the radiation
 189 emerging from the object is very small. Moreover, before arriving at the detector, a great
 190 part of the electrons are absorbed by air and cassette (normally the CR detector is handled
 191 in a cassette). Be aware that the electrons produced by metallic screens and IP are not
 neglected, and are taken into account in the detector model obtained by MC simulations.

- 192 • Normal incidence of radiation on the detector. In reality, the transmitted X-ray photons
 193 arrive at the CR detector with a certain incident angle. In our model, we assume the X-ray
 194 photons travel forwardly, with a normal incidence on the detector.
 195 • Normal incidence of laser beam on the imaging plate during the readout process.
 196

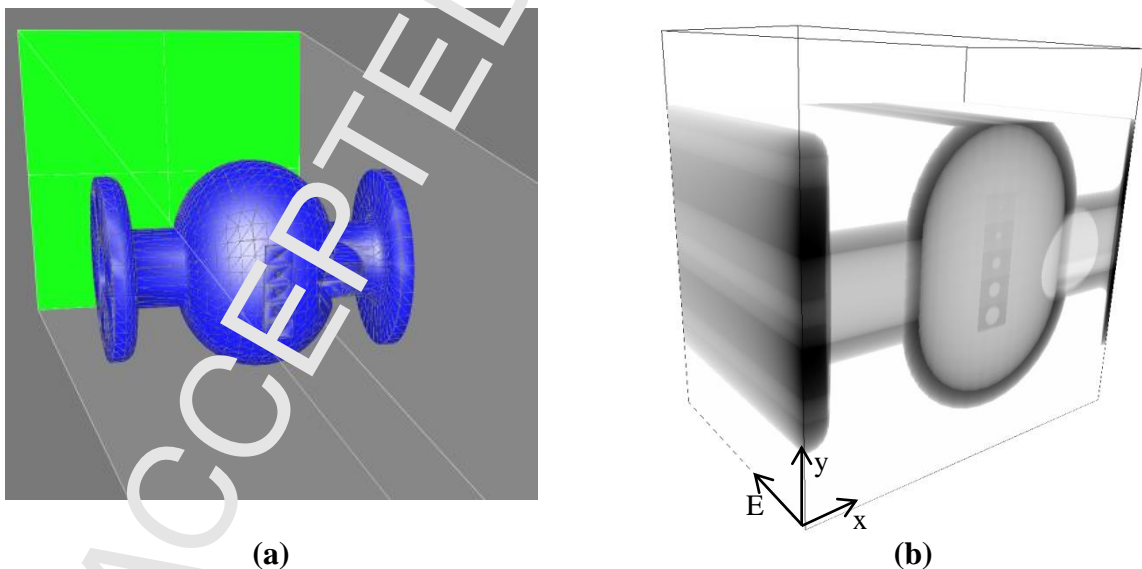
197 3 Detailed description of the model

198 3.1 Object image generation (spectral image)

199 In this step, to generate $Obj(E,x,y)$, a deterministic code for simulating complex imaging set-up is
 200 preferred since it can offer a realistic object image in a short time.

201 To generate $Obj(E,x,y)$, a virtual detector is used and placed at the actual detector plane. This
 202 virtual detector is divided into $M \times N$ pixels to record the spatial distribution of the incident
 203 photons. Each pixel pitch counts the incident photon number, and classifies the photons into
 204 different energy channels. The direct output of this virtual detector is the photon number per
 205 energy channel per pixel pitch, and the $Obj(E,x,y)$ should be the output value divided by the pixel
 206 pitch surface. Figure 3 is an example of the object image generation: (a) is a geometry set-up
 207 generated using VXI software [23,24], where a virtual detector (in green) is placed at the actual
 208 detector plane; and (b) is the spectral image detected by the virtual detector $Obj(E,x,y)$.

209



210 **Figure 3: Spectral object image: (a) geometry setup and (b) illustration of a spectral image.**
 211 **The example here is obtained with VXI software [23, 24]**

212

213 3.2 Detector dose response model generation

214 The detector dose response model, denoted $PSF_{det}(E, x, y, z)$, is the second input required by the
 215 operator HI .

216 The detector considered in this study is a multiple-layered structure, in which the imaging plate is
 217 sandwiched between metallic screens (Figure 4a). The imaging plate also consists of multiple
 218 layers such as overcoat and phosphor layer. The phosphor layer is the effective medium which
 219 stores the latent image, and will be later readout by CR scanner. Hence the PSF here is a 3D
 220 energy absorption efficiency map within the IP's phosphor layer. A Monte Carlo simulation tool
 221 [25], based on the use of PENELOPE [26], has been developed to characterize the CR detector
 222 response at different energies. In order to record the PSF , a uniform three-dimensional grid is
 223 applied to the phosphor layer. As shown in Figure 4a, we send a mono-energetic pencil beam (E_i)
 224 to strike the detector det . The raw output $DEP(x, y, z)$ of the simulation is illustrated in Figure 4b,
 225 which is the deposited energy map (absorbed energy per unit volume $\text{keV}\cdot\text{cm}^{-3}$) within the
 226 phosphor layer. The PSF is obtained with:

227

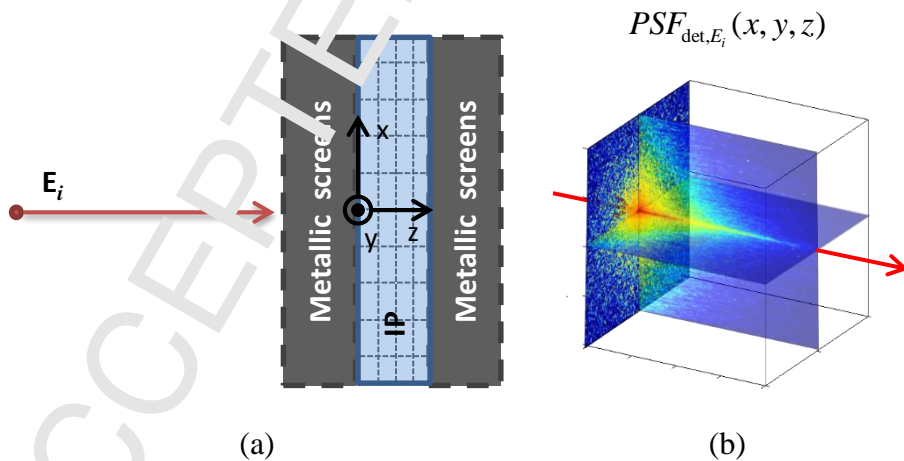
$$PSF_{det, E_i}(x, y, z) = \frac{DEP(x, y, z)}{N_i E_i} \quad (3)$$

228 where N_i is the number of the incident photons. As a Monte Carlo calculation contains statistical
 229 noise, the incident photon number should be as large as possible to limit this noise. The impulse
 230 response is of cylinder symmetry around z -axis, hence we also apply a radial averaging to the
 231 PSF to reduce the noise, and the PSF is reduced to a 2D function.

232 In such a way, the storage space can be saved. The storage digits can be further reduced by
 233 applying an analytic fitting function to each 1D profile at different z .

234

235



236 **Figure 4: Impulse response of a detector: (a) Geometry configuration and, (b) 3D energy**
 237 **deposition map; the red arrow indicates the beam propagation direction which is also the**
 238 **IP depth direction.**

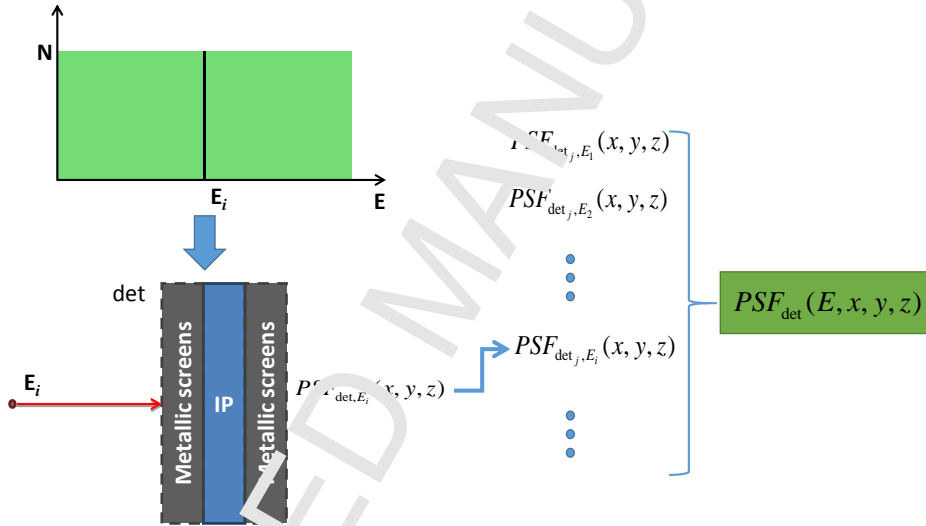
239

240 The second step of detector response model generation is to repeat the previous operations (i.e.
 241 raw PSF simulation and radial averaging) by scanning all energies (see Figure 5). Different

242 energies ranging from E_{min} to E_{max} are sampled to excite the detector det . After the radial
 243 averaging operation, we have a set of PSF, and all these PSFs make up the response model of the
 244 detector det . In order to cover the energy range of common NDT radiation sources (such as Ir192
 245 and Co60), E_{min} is assigned 0 keV, and E_{max} 1400 keV.

246
 247 In order to build a database of detector models, several detector configurations have been
 248 simulated. At present, we have covered all the metallic screens (front/back) combinations
 249 proposed in the standards EN ISO 16 371-2 [2] and ISO17634-2 [3] as well as other screens, for
 250 different thicknesses and properties of BaFBr imaging plates to form a database of 128
 251 configurations.

252



253

254 **Figure 5: Generating the detector dose response function of a fixed detector det .**

255

256 3.3 Latent image computation

257 The latent image generation involves the energy deposition and storage center formation. Only a
 258 portion of the deposited energy is stored in the form of storage centers. At present day, the
 259 storage center forming mechanism is still not clearly understood [27–29]; moreover, it is different
 260 from one to another material. Therefore, the latent image (storage center) formation process is
 261 simply modeled as a conversion factor g_{sc} (unit: keV^{-1}). In the review of Rowlands[28], the
 262 absorbed X-ray energy to storage center ratio in BaFBr is 2.4 keV^{-1} ; while in [29], a different
 263 ratio 7.98 keV^{-1} is reported. In the following, we assign the normalized value 1 keV^{-1} to g_{sc} .

264

265 Equation (4) gives the operation realized.

$$\begin{aligned}
Limg(x, y, z) &= H1(Obj, PSF_{det}) \\
&= g_{sc} \int_E (E Obj(E, x, y) * PSF_{det}(E, x, y, z)) dE \\
&= g_{sc} \int_E E \left(\iint_{u,v} Obj(E, u, v) PSF_{det}(E, x - u, y - v, z) du dv \right) dE
\end{aligned} \tag{4}$$

266 where:

- 267 - $H1$ represents the latent image generation model which is a 2D spatial convolution (along
- 268 x and y), at a given depth z , integrated over all energies, and finally multiplied by the
- 269 conversion factor g_{sc} ;
- 270 - g_{sc} represents the absorbed X-ray energy to storage center conversion efficiency (unit:
- 271 keV^{-1});
- 272 - $Obj(E, x, y)$ is the spectral object image, namely the number of photons per unit surface per
- 273 energy channel (unit: $\text{cm}^{-2} \cdot \text{keV}^{-1}$);
- 274 - $PSF_{det}(E, x, y, z)$ is the detector model, which is in fact a set of point spread functions (unit:
- 275 cm^{-3}) for all energies;
- 276 - E is the X-ray photon energy (unit: keV);

277
278 The term which is multiplied by g_{sc} represents the deposited energy distribution (unit: $\text{keV} \cdot \text{cm}^{-3}$).

279 Multiplying by g_{sc} allows to convert this energy into a storage center distribution i.e. latent

280 image.

281

282 Numerically, this equation is realized energy by energy. For each energy channel, we compute

283 the storage center distribution at different depths; by summing the latent images obtained for all energy

284 channels, we get the final output latent image.

285

286 The corresponding computation algorithm is:

287

```

288 Initialize the latent image array  $Limg(x, y, z) = 0$ .
289 for each energy channel  $E_i = 0$  to  $E_{max}$  do
290   for each depth:  $z_j = 0$  to  $d$  do
291     Compute the latent image at depth  $z_j$  given by photons of energy  $E_i$ 
292      $\Delta Limg(x, y, z_j) = g_{sc} \cdot [Obj_{E_i}(x, y) * PSF_{E_i, z_j}(x, y)]$ ;
293     Accumulate  $\Delta Limg(x, y)$  to the corresponding depth slice  $z_j$  in latent image
294     array
295      $Limg(x, y, z_j) = Limg(x, y, z_j) + \Delta Limg(x, y, z_j)$ .
296   end
297 end

```

298

299 Note that the numerical convolution requires the pixel size matching between Obj and PSF_{det} . In

300 this paper, the sampling match is achieved by means of interpolation.

301 The algorithm output is a 3D latent image. We keep the information along detector depth (z)

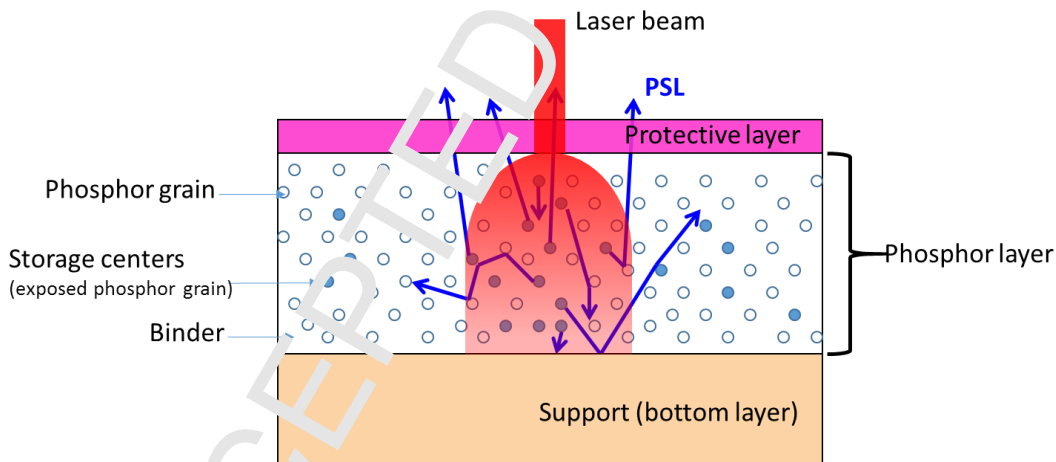
302 direction, because the latent image is read by a scanning laser, the laser power modifies the

303 penetration of the laser light, and thus the deep storage centers have less contribution to the
 304 readout image. With this in mind, we choose to keep the information along z .
 305

306 3.4 Optical readout

307 Readout is a crucial process that affects the final image quality (e.g. efficiency, contrast and
 308 spatial resolution). As shown previously in Figure 1a, the basic principle of CR readout is the
 309 “flying spot”: via a rotating mirror, the finely focused stimulating laser beam scans horizontally
 310 the imaging plate (IP). Together with a continuous translation of IP, the stored information can be
 311 released line by line through the whole imaging plate. This scanning process is usually called
 312 raster scan (or raster scanning).

313 The imaging plate has a multiple-layered structure which basically consists of a protective layer,
 314 a photo-stimulable phosphor (PSP) layer (the phosphor grains are embedded in polymer binder)
 315 and a support layer. Sometimes, a reflective or an absorbing layer is added between PSP layer
 316 and support layer. Concerning the optical readout simulation, we are only interested in the PSP
 317 layer and the two layers in contact with it. The reason is that the optical photons are much less
 318 energetic comparing with X- or γ -rays, thus the effects of the 'outer layers' can be neglected.
 319 Therefore in this part, we simulate the light transport problem in a three-layered structure (see
 320 Figure 6): top layer (e.g. protective layer), PSP layer and bottom layer (e.g., reflective layer or
 321 support layer). The top and bottom layers are considered to be clear media where the laser light
 322 travels in a straight line, while the PSP layer is modeled as granular layer where the scattering
 323 effect is pronounced.
 324



325
 326 **Figure 6: Optical effects within imaging plate. A three-layered structure is considered: a**
 327 **top layer, a PSP layer and a bottom layer, where the top and bottom layer are clear media,**
 328 **and the PSP layer is granular. The laser beam (red) strikes perpendicularly the front side of**
 329 **IP; it first passes through the top layer without expanding the beam size; in the PSP layer,**
 330 **the laser light diffuses along its traveling path; at the interfaces, top-PSP and PSP-bottom,**
 331 **the laser photons might be absorbed or reflected. Part of the storage centers within the red**
 332 **volume will be stimulated by laser photon resulting in PSL (blue arrows), which also suffers**
 333 **multiple scattering effect; only a fraction of the emitted PSL could reach the front surface**
 334 **and be detected contributing to the final image**

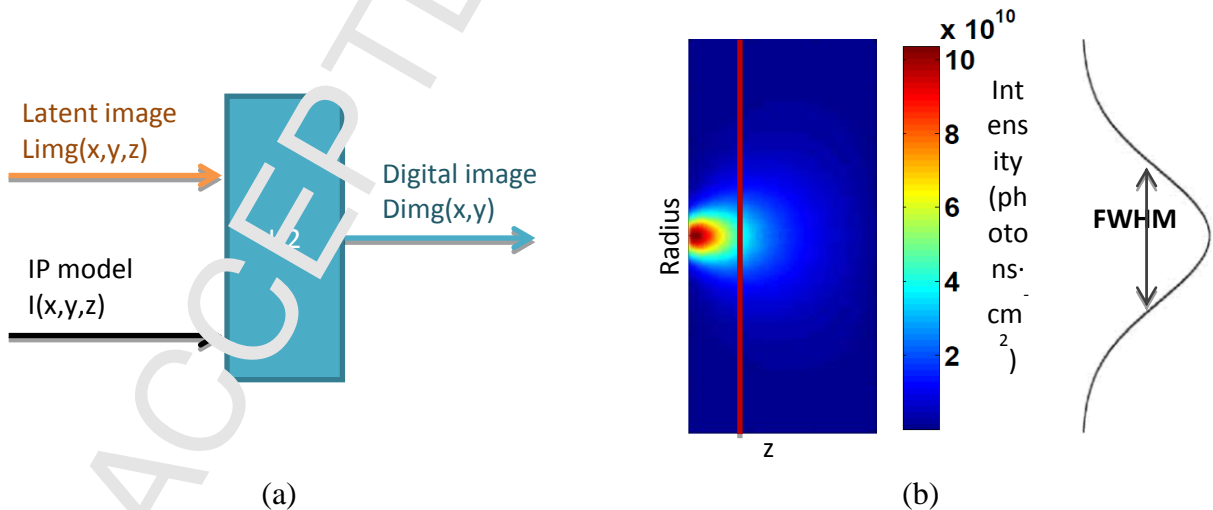
335

336 The optical readout process is viewed as a transfer function H_2 (Figure 7a), which also requires
 337 two inputs: latent image and IP optical response model. Flying spot scanner is the most common
 338 CR reader: a finely focused laser is used to scan and release, line by line, the latent image; the
 339 latent image is modified while the laser spot traverses the IP [22]. Thus, unlike the previous
 340 operator H_1 , H_2 is a modified convolution operation. The final digital image is computed using
 341 the following equation, where x_m, y_n denotes the coordinates of pixel m, n in the image (x and m
 342 referring to the laser scan direction, while y and n to the IP translation direction):
 343

$$\begin{aligned} Dimg(x_m, y_n) &= H_2(Limg, f, \text{scanning parameters}) \\ &= \int_z P(z) dz \iint_{x,y} Limg^{(m,n)}(x, y, z) \{1 - \exp[-\sigma \cdot f(x - x_m, y - y_n, z) \cdot P_{laser} t_{scan}]\} dx dy \end{aligned} \quad (5)$$

344
 345 where $Limg^{(m,n)}(x, y, z)$ is the scanning modified latent image at reading point (x_m, y_n) , whose
 346 formula is given in relation (6). $f(x, y, z)$ is the IP optical impulse response to a laser beam, $P(z)$ is
 347 the probability that a photon (emitted at z) could escape from the front side of IP, σ is the optical
 348 cross section of photo-stimulation, P_{laser} is the laser power and t_{scan} is the dwell time of laser spot
 349 at (x_m, y_n) . This formula (5) is based on the laser latent image interaction model in the work of
 350 Thoms [30].
 351

352 The IP optical response model $f(x, y, z)$ is usually obtained through the Monte Carlo method. A
 353 specific Monte Carlo code has been programmed on purpose in Matlab to simulate the light
 354 propagation problem in IP [31]. Some physical models of light/IP interaction adopted in the code
 355 are based on [32] and [33]. Figure 7b shows an example of IP response to a normal incident laser
 356 beam, for which 2×10^6 photons have been generated to strike the imaging plate.



357 **Figure 7: a) Generation of the digital image using the optical readout transfer function H_2 ;**
 358 **b) an example of IP model (impulse response of IP to laser light).**

359 It is worth noting that the value of $Limg^{(m,n)}(x, y, z)$ is modified by the laser scanning process, i.e. it
 360 is changed while the laser spot moves from one position to another. For this reason, we

361 emphasize that $Limg^{(m,n)}(x,y,z)$ here refers to the storage center distribution right *before* the laser
 362 beam arrives at pixel (m, n) . In order to obtain $Limg^{(m,n)}(x,y,z)$, namely the scanning modified
 363 latent image at reading point (x_m, y_n) , the following formula is applied. More details can be found
 364 in [31].

$$\begin{aligned}
 Limg^{(m,n)}(x,y,z) &= Limg(x,y,z) \exp \left\{ - \left[\sum_{j=0}^{n-2} \sum_{i=0}^{M-1} f(x - i \cdot l_{pxl}, y - j \cdot l_{pxl}, z) \right. \right. \\
 &\quad \left. \left. + \sum_{k=0}^{m-1} f(x - k \cdot l_{pxl}, y - (m-1) \cdot l_{pxl}, z) \right] t_{laser} t_{scan} \cdot \sigma \right\} \quad (6)
 \end{aligned}$$

365

366 with l_{pxl} being the optical readout output pixel size.

367 The corresponding computation algorithm is:

368

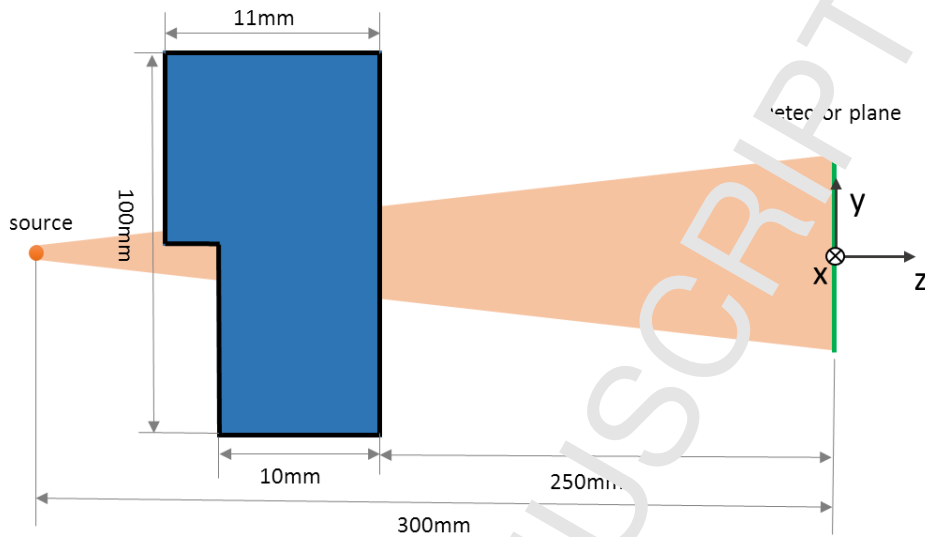
```

369 Initialize the digital image array  $Dimg(x,y) = 0$ .
370 for each line:  $n = 1$  to  $N$  do
371     for each pixel:  $m = 1$  to  $M$  do
372         Update the latent image  $Limg^{(m,n)}(x,y,z)$ 
373         Compute the output signal of the current pixel  $Dimg(x_m, y_n)$ 
374     end
375 end

```

376 4 Comparison with full Monte Carlo simulation

377 Monte Carlo method is commonly considered as the reference for radiation transport simulation.
 378 The MC simulation package PENELOPE [26] containing detailed physical models of both x-
 379 ray/matter and charged particle/matter interactions, is used here. Since it takes into account all
 380 kinds of interactions, the simulation running is slow. As a first step to validate our model, we
 381 have chosen a very simple imaging set-up to compare the simulation results obtained with a full
 382 Monte Carlo code and our model, comparing only the X-ray exposure part (i.e. without the
 383 optical readout), in order to validate the H1 operator.



384

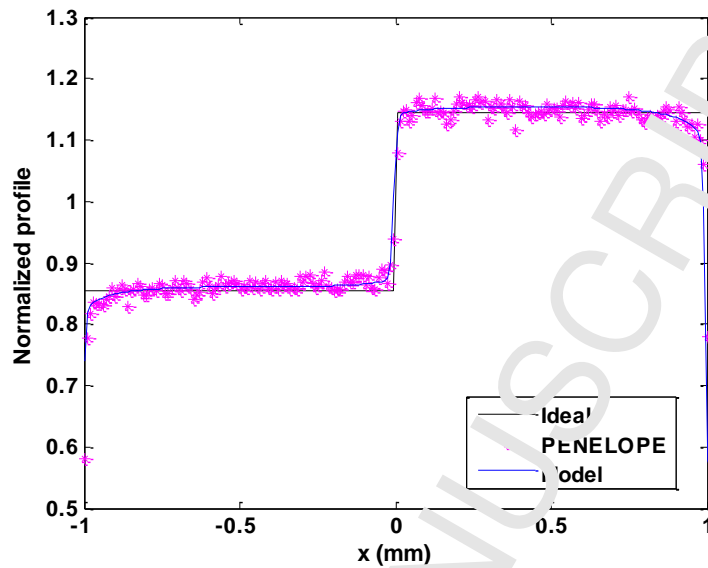
385 **Figure 8: Geometric set-up of the comparison simulation. The object is a two-step iron step-**
 386 **wedge. The detector is a $2\text{ mm} \times 2\text{ mm} \times 0.150\text{ mm}$ imaging plate. The beam aperture was**
 387 **set $2/300\text{ rad}$.**

388 We have simulated the imaging set-up as presented in Figure 8 with a full PENELOPE
 389 simulation and our model H1. The source used was a fixed energy cone beam. The energy was
 390 100 keV, and the beam aperture was set to $2/300\text{ rad}$. The number of the incident photons was
 391 10^9 . The PENELOPE simulation running took about 64 hours, we see that the object profile is
 392 still noisy, while our H1 model takes about 1 hour including VXI running time and H1 operation
 393 time. Note that the comparison was done on a fine scale in order to see the accuracy. Thus, a very
 394 fine sampling was used both in spectral and spatial domain: 1 keV energy sampling step and a
 395 spatial IP sampling with a $100 \times 100 \times 100$ grid for x, y, and z directions for a $2\text{ mm} \times 2\text{ mm} \times$
 396 0.150 mm imaging plate.

397

398 Figure 9 presents the object profiles across the iron steps. All profiles have been normalized by
 399 their mean signal value. The black one is the object ideal profile. The profile obtained with our
 400 *H1* model (blue) agrees perfectly with that obtained with PENELOPE (magenta). The H1
 401 operator being a convolution operator, the profile obtained with our model does not contain any
 402 noise, which is normal. This comparison allows to show that the contrast due to the 1 mm step is
 403 well modelled by the H1 operator, in comparison with a full MC simulation.

404



405

406 **Figure 9: Object grey-level profiles obtained with our *HI* model compared with a full MC**
 407 **simulation (PENELLOPE).**

408

409 **5 Result: complex imaging set-up simulation**

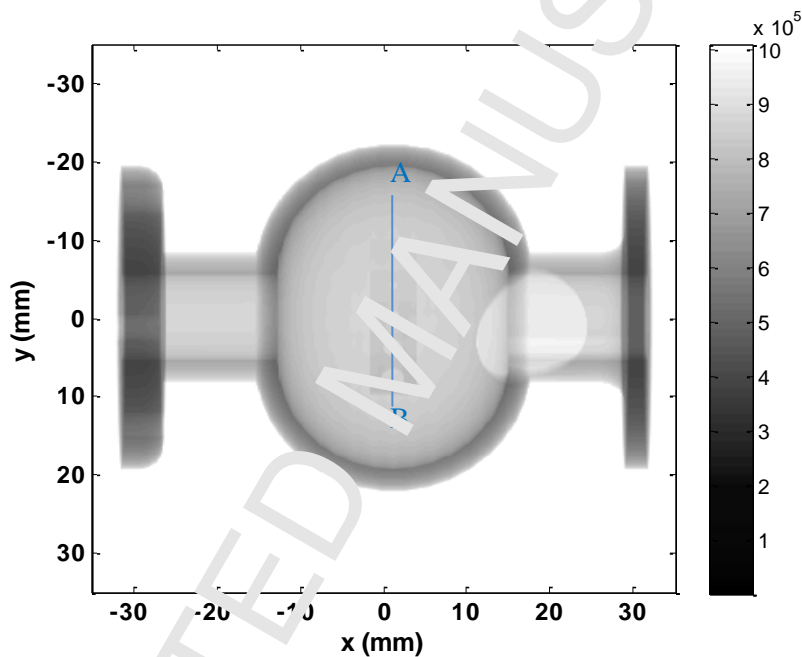
410 The model has then been applied to simulate the responses of different detector configurations to
 411 the same geometric set-up as illustrated in Figure 3a. A complex shape object with an image
 412 quality indicator (IQI) was irradiated by a monochromatic (100 keV) point source. This
 413 constitutes a realistic inspection case study where the IQI allows to quantify the image quality in
 414 terms of contrast resolution for different hole sizes. The virtual detector was set to $70 \times 70 \text{ mm}^2$ in
 415 size with a pixel size of $10 \times 10 \text{ }\mu\text{m}^2$. The photon energy was stored into different energy channels
 416 from 1 keV to 100 keV with a channel width of 1 keV.

417 The detector was modeled as an imaging plate sandwiched between metallic screens. The
 418 imaging plate was seen as a multiple-layered structure which consists of, in sequence: a $6 \text{ }\mu\text{m}$
 419 protective layer, a $150 \text{ }\mu\text{m}$ phosphor layer, a $254 \text{ }\mu\text{m}$ support layer and a $25.4 \text{ }\mu\text{m}$ backing layer.
 420 The materials of these layers are respectively Mylar for the protective and support layers,
 421 BaFBr:Eu²⁺ for the phosphor layer and polycarbonate for the backing layer.

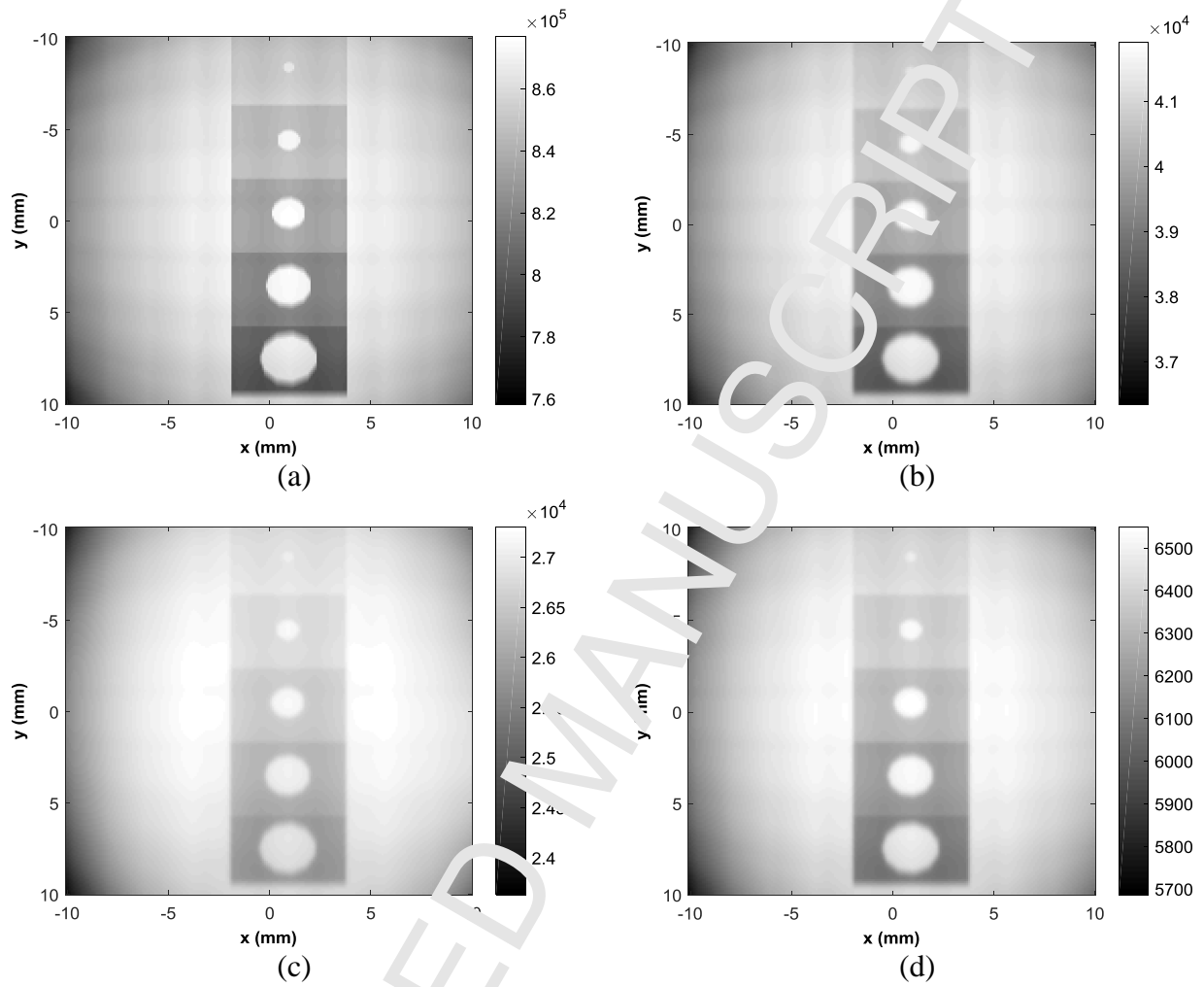
422 The responses of the following detector configurations were compared: a) IP alone; b) IP with
 423 0.2 mm Pb screens on both sides (denoted as IP+0.2Pb) and c) IP with 0.2 mm Pb and 0.8 mm Sn
 424 screens on both sides, where Sn is in contact with IP (denoted as IP+0.2Pb0.8Sn).

425 Figure 10 presents the full object image accounted by the virtual detector, i.e. the image $Obj(x,y)$.
 426 We see the object shape, and the image quality indicator (IQI) in the image center. Then we apply
 427 our *HI* model, to obtain the latent image detected with the three detector configurations,

428 $Limg(x,y,z)$. In order to have a better comparison, we only illustrate the region of interest
 429 containing the IQI. Figure 11 compares the IQI zone images obtained using different detectors,
 430 where $Limg(x,y)$ is obtained by summing $Limg(x,y,z)$ over z . Owing to the response of the
 431 detector, the signal level drops and the resolution decreases. With the three detectors, the smallest
 432 hole can still be identified; however, the sharpness of IP+0.2Pb is not as good as IP alone and
 433 IP+0.2Pb0.8Sn. In order to compare the images sharpness, we have normalized the four images
 434 to their maximum value. We plot the normalized profiles along AB (see Figure 10) in Figure 12.
 435 The sharpness of IP alone is very close to the ideal detector, except for a small contrast loss at high
 436 spatial frequency (difference at sharp edges). With IP+0.2Pb, the image sharpness is the worst.

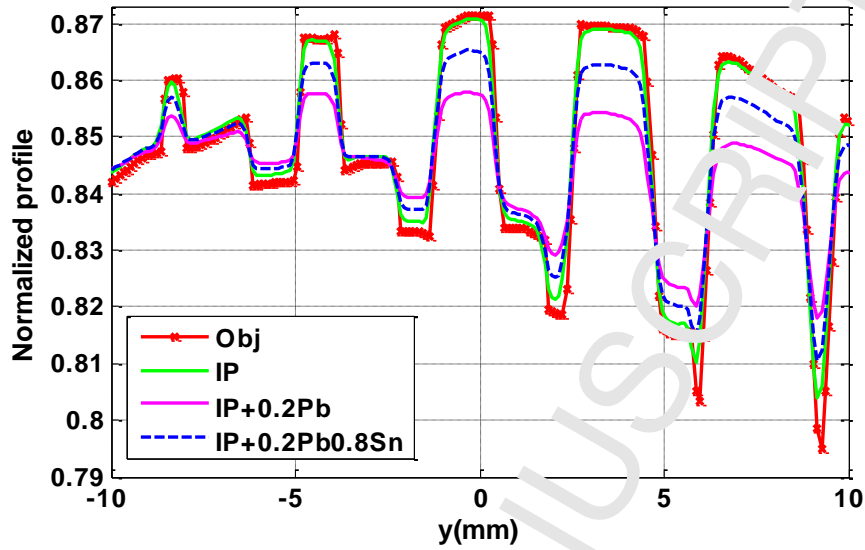


437
 438 **Figure 10: X-ray image obtained with VXI. This 2D illustration is obtained by summing the**
 439 **X-ray image $Obj(E,x,y)$ along its energy axis.**



440

441 **Figure 11: Comparison of the detected image using different detector configurations: a) is**
 442 **the X-ray image $obj(x,y)$ b) is the latent image $Ling(x,y)$ detected by IP alone using a**
 443 **summation over z direction; c) is the latent image detected by IP with lead screens; and d)**
 444 **is the latent image detected by IP with lead and tin screens.**



445

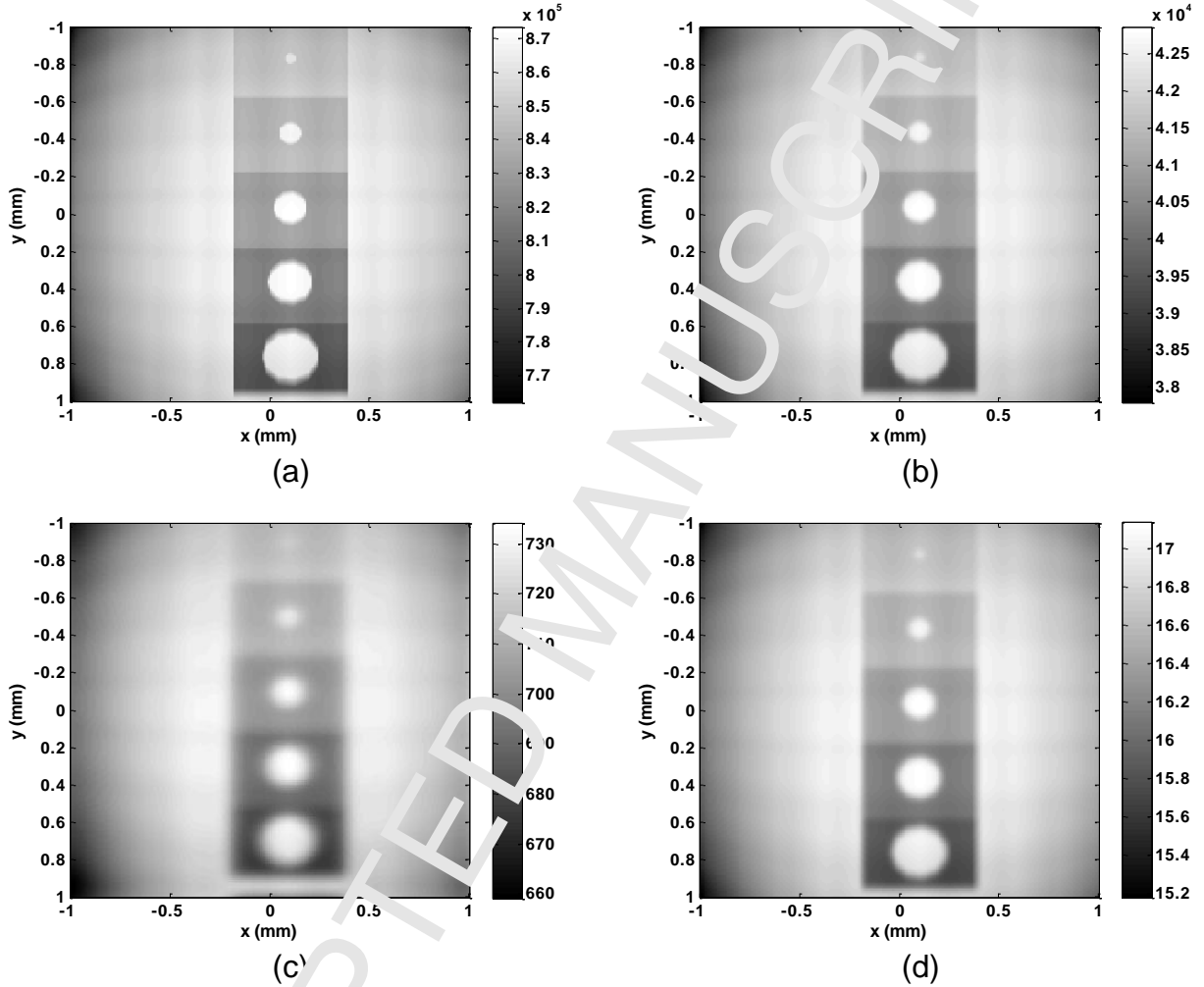
446 **Figure 12: Normalized profiles along the IQI holes (AB line in figure 10): the red curve**
 447 **corresponds to the X-ray image $obj(y)$ at the tx, z (AB) position; the green, pink and blue**
 448 **curves correspond respectively to the latent image profiles $Limg(y)$ obtained with the three**
 449 **detector configurations IP, IP+0.2Pb and IP+0.2Pb0.8Sn.**

450 We then investigated the influence of the readout process on image quality, for one detector
 451 configuration. The readout signal depends on the product of the laser power P_{laser} and dwell time
 452 t_{scan} , therefore, in the following, we simply use their product as a readout factor $p_{read} = P_{laser} \cdot t_{scan}$.
 453

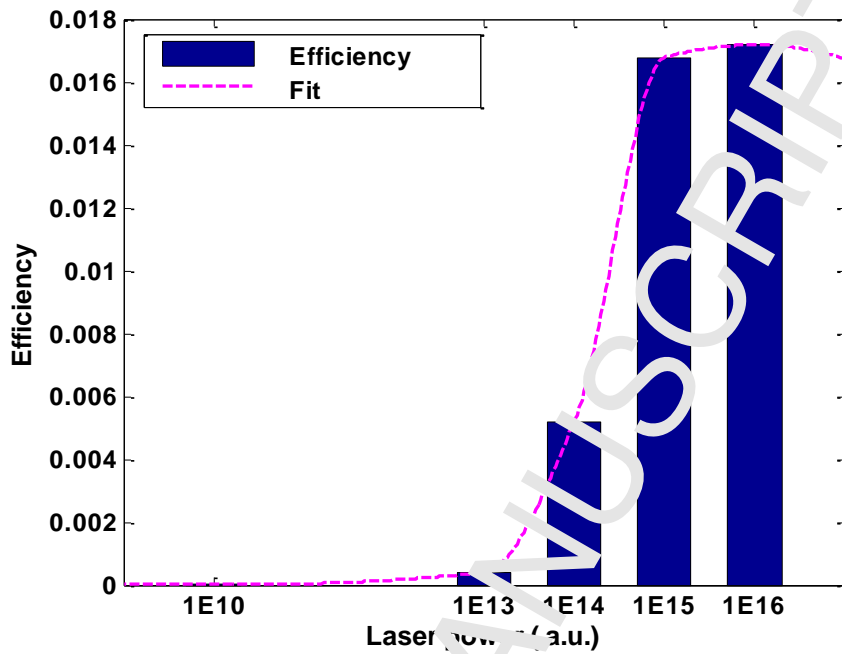
454 Figure 13 shows the effect of the optical readout. The images in the upper half are the object
 455 image $Obj(E, x, y)$ and the energy deposition image in IP alone $Limg(x, y, z)$ shown in Figure 11 a&b
 456 which are reminded here for a better visual comparison. Only a fraction ($\sim 5\%$) of the object
 457 image is detected by IP. In the lower half, we show the readout images using two different
 458 reading factors $p_{read} = 10^{16}$ and $p_{read} = 10^{10}$. With large values of reading power, most of the
 459 storage centers can be released (not all the released storage center can contribute to the final
 460 image), however a visible shift is observed (comparing Figure 13c&d) due to the scanning
 461 process. We focused then on the dependency between the reading efficiency (output signal over
 462 input signal) and the laser power (Figure 14). It was observed that the efficiency increases slowly
 463 at low laser power, while a significant rise was pointed out between 10^{13} and 10^{15} p_{read} values;
 464 and at 10^{16} the curve starts to reach its maximum. One may notice that the maximum efficiency
 465 does not equal to one. Indeed, a high power increases the photoluminescence, but the photons are
 466 emitted isotropically and only a small fraction can escape from the front surface of IP and
 467 contribute to the final image. In order to compare the image sharpness, the images have been
 468 normalized by their maximum values. In Figure 15, profiles along the IQI are presented, along
 469 the y direction corresponding to the IP translation direction (with the notations of equations (5)).
 470 The red curve refers to the latent image profile. The curves of the first 2 powers overlap each
 471 other, then we lose contrast by increasing the power. Comparing the profiles, we also see an
 472 obvious shift between the black and the red curves in the IP translation direction due to the
 473 scanning process modeled by equation (6).

474 Thus, the optimum choice of the p_{read} parameter represents a compromise between the need of a
 475 large reading efficiency and the care on not degrade the spatial resolution by affecting the
 476 neighboring pixels during readout process.

477



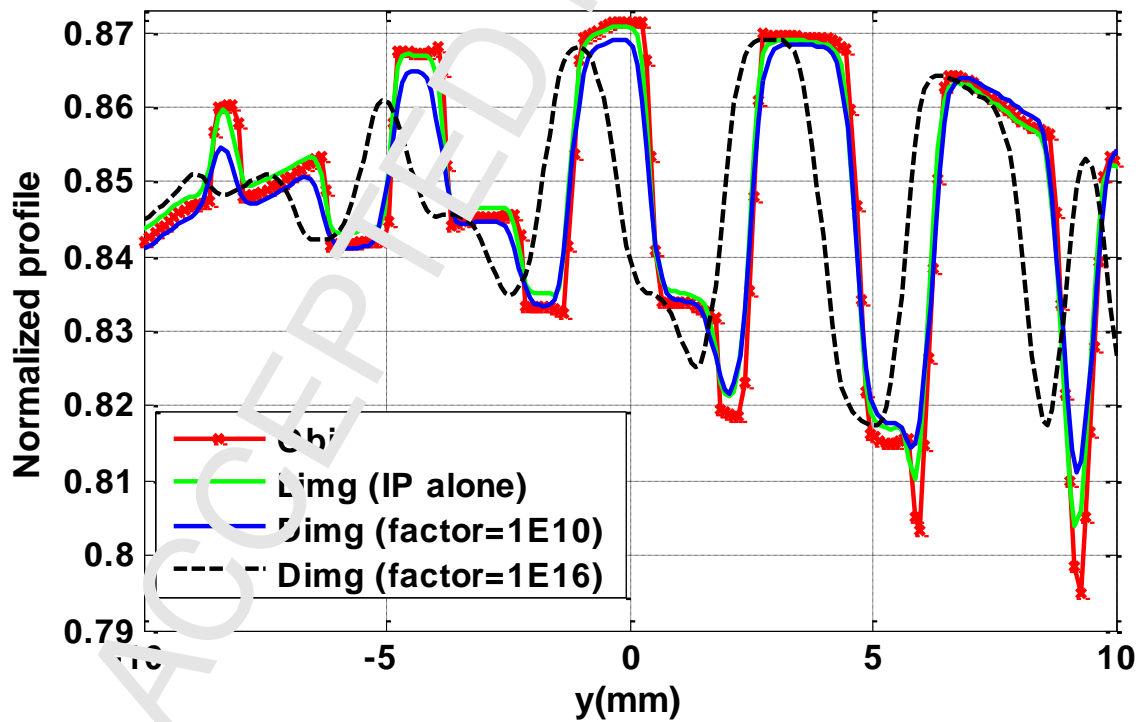
478
 479 **Figure 13: Simulation result: a) object image $obj(E,x,y)$, b) latent image $Lim(x,y)$ obtained**
 480 **with IP (same as Figure 11b), c) final $Dimg(x,y)$ image with a readout factor $p_{read}=10^{16}$, d)**
 481 **readout factor $p_{read}=10^{10}$.**



482

483

Figure 14: Readout efficiency versus laser power.



484

485

Figure 15: Normalized profiles along IQI (line AB shown on figure 10).

486

487 6 Discussion and conclusion

488 This paper presents a CR system model, where the CR detector and the optical readout are
 489 modeled as two different transfer functions. As concerns the X-ray exposure part, which is the
 490 most crucial step because it conditions the greater part of the final image, the comparison of *H1*
 491 operator with the full MC simulation using PENELOPE shows a very good accordance. More
 492 details are given in [31] about the optical part simulation which is in good correspondence with
 493 [33].

494
 495 A realistic inspection case study has been defined to illustrate the interest of this full model. As
 496 an example, the performances of three different detectors were compared in this particular
 497 inspection case. By comparing the obtained images, one can determine the most appropriate
 498 detector configuration. Then, different readout factors have been simulated (representing either a
 499 change in laser power or a different scanning time), showing the influence on the final image.
 500 Increasing the laser power allows to obtain greater signal, although at the expense of spatial
 501 resolution. The effect of scanning has been modelled analytically for the first time to our
 502 knowledge, and appears as a translation of the image when the readout factor is important.

503 With this method, one can simulate the complete CR image formation, and take into account the
 504 operating factors such as source parameters (in the first step), detector configuration (in the
 505 second step) and scanning parameters (in the last step). This full model is “*user-driven*”, which
 506 means that special emphasis has been taken to the selection of parameters which are accessible to
 507 the user (such as laser power). Also a database of 128 detectors has been built thanks to the MC
 508 off-line tool, with all physical effects up to energy of 1.4 MeV, which has never been done
 509 before. This represents a huge number of simulation hours.

510
 511 It has to be noted that the application of *H1* and *H2* operators requires the sampling match of *Obj*
 512 with *PSF_{det}* and *Limg* with *f*. Interpolation can be used for this purpose. The computation
 513 efficiency strongly depends on the array size of *Obj(E,x,y)*, *Limg(x,y,z)*, *PSF(x,y,z)* and *f(x,y,z)*.
 514 Great accuracy requires a small sampling size, and thus a large array size, which makes the
 515 simulation slower. The total simulation time varies from minutes to several tens of minutes or
 516 even more. It is worth noting that this model does not include noise and allows reasonable
 517 simulation time. The user can thus optimize parameters for contrast optimization even for
 518 complex shape objects without using noise. However, noise can be added afterwards for a
 519 complete image quality assessment.

520
 521 To summarize, the interests of this global model are:

- 522 • Reducing simulation time. The detection efficiency of CR detector at high energy (>
 523 hundreds keV) is very small (<1%), therefore, to obtain the same SNR level, a full MC
 524 simulation including detector effects would need to generate hundreds times more
 525 incident photons than our model *H1*. Thus, the running is accelerated by at least 100 times.

526 Using a deterministic code to simulate the object image also reduces the global simulation
527 time.

- 528 • Avoiding repeating simulation running. With a full MC simulation, one needs to rerun the
529 MC code for each detector configuration in order to determine the optimal conditions.
530 Thanks to the detector transfer functions, no MC run is needed during the current
531 simulation, as the MC codes are run off-line.
- 532 • 3D deposited energy distribution within IP. The CR optical readout is a crucial process
533 that limits the system sharpness and efficiency. The light diffuses along its penetrating
534 depth, hence knowing the 3D deposited energy distribution is important.

535 The presented simulation code has been successfully applied in a realistic case study with
536 Selenium gamma source in order to compare the image quality obtained using different screens
537 [34].

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626

ACCEPTED MANUSCRIPT

Highlights :

We have developed and implemented a novel simulation tool for computed radiography, including not only the X-ray exposure part, but also optical readout.

In order to keep reasonable computing time, all physical effects have been modeled using Monte Carlo code off-line. Two operators have been introduced to then simulate the complete process in an analytic way.

A database of 128 imaging systems (comprised of the phosphor imaging plate and front and back metallic screens) have been modeled.