A Geant4 tool for the simulation of contrast enhanced dual-energy mammography – Study of polychromatic versus quasi-monochromatic X-ray spectra and different contrast agents

Gianfranco Paternò[1], Paolo Cardarelli[1], Angelo Taibi[1,2]

[1] INFN division of Ferrara

[2] University of Ferrara, department of Physics and Earth Sciences

https://medical-physics.unife.it

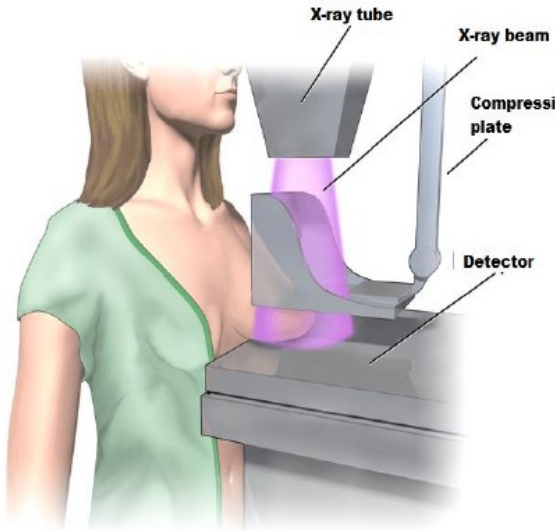
Outline

- Overview of X-ray diagnostic techniques for breast.
- A Geant4 tool for the simulation of Contrast Enhanced Dual-Energy (Subtraction) Mammography (CEDEM/CESM).
- CESM with quasi-monochromatic radiation vs the one based on conventional polychromatic sources.
- CESM with iodine contrast media vs the one based on gadolinium.

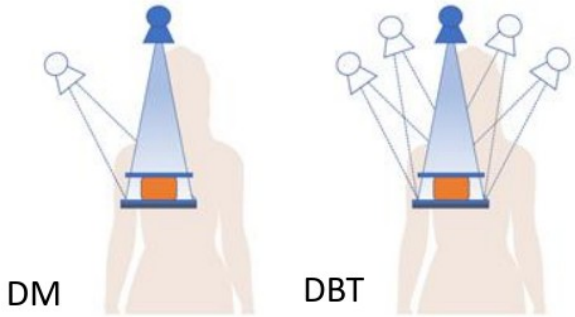
Diagnostic techniques for breast

Breast cancer is the most commonly diagnosed in female subjects (28% of cancers, 16% of deaths for cancer) -> early detection -> **first level screening** (**DM**, US)

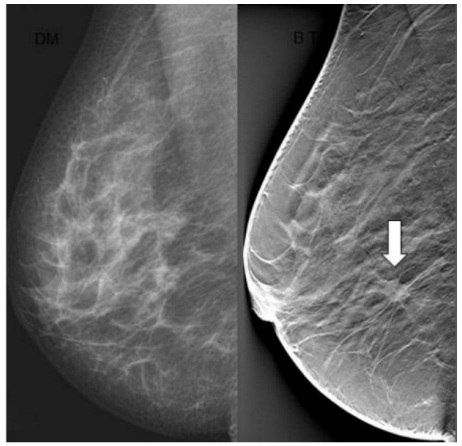
Second level techniques: 3D techniques (MRI, **DBT**, **BCT**) or contrast enhanced dual energy mammography (**CESM**) to avoid the overlap of tissues surrounding the lesion

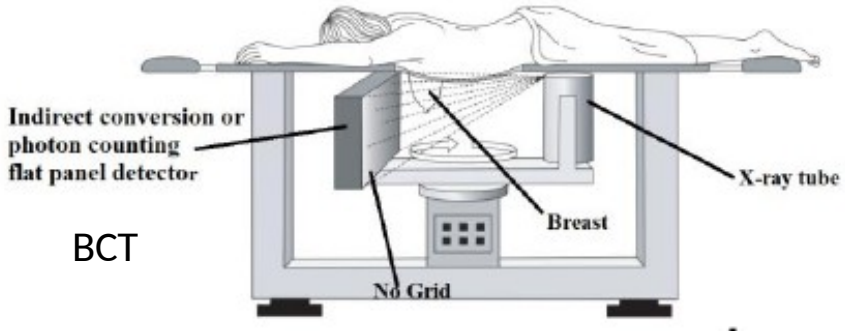


Indirect or a-Se direct conversion flat panel detector

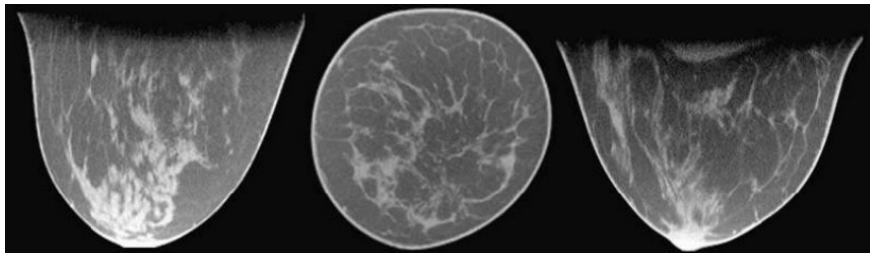


DM DBT





BCT



Examples of BCT acquired by J.M. Boone

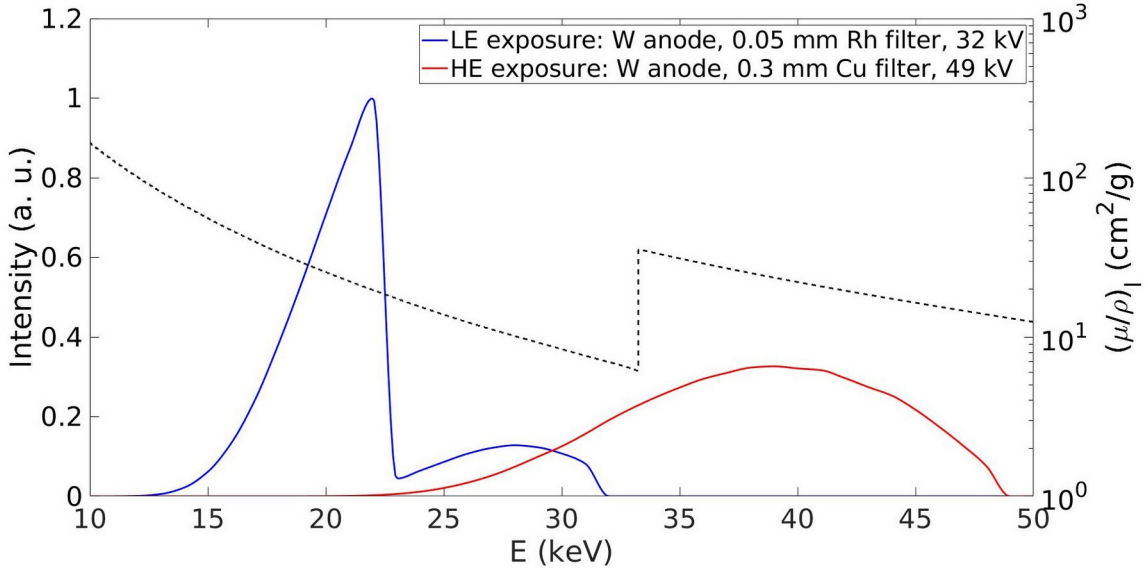
CESM

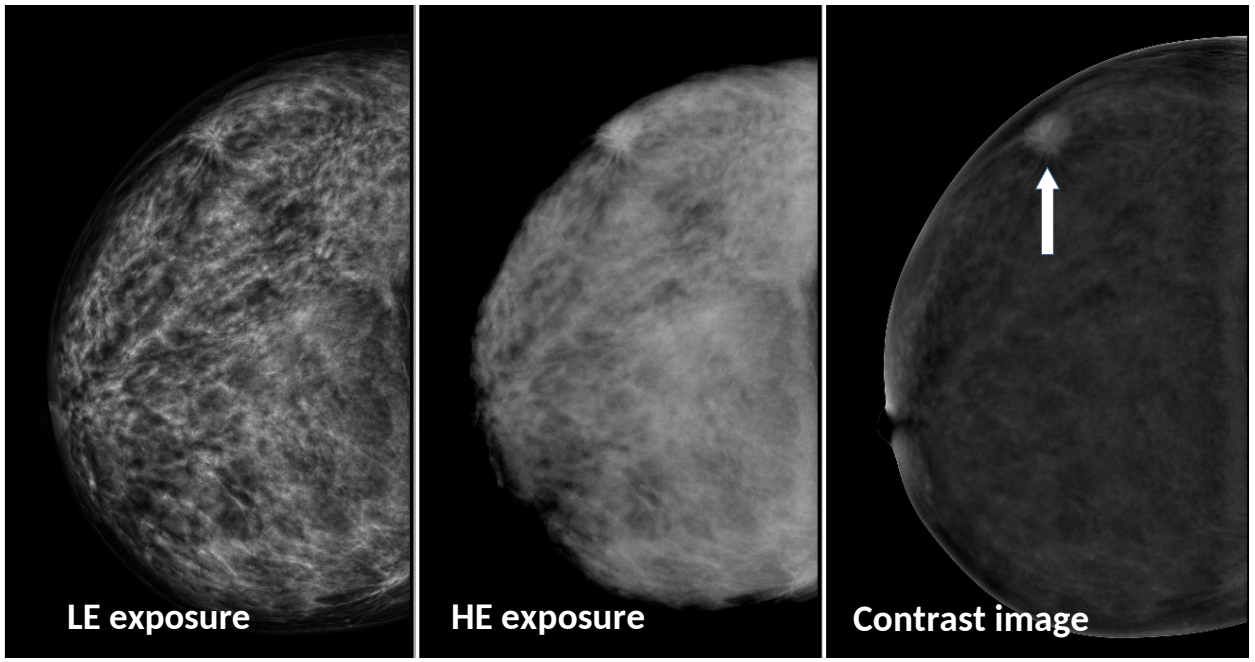
Weighted subtraction of 2 images acquired with spectra **straddling the K-edge** of a contrast medium (CM) injected to the patient → **enhancement of structures perfused with CM.**

Dual energy equations, in principle, are valid for monochromatic spectra and two materials, but are used also in **more general conditions, such as in CESM**, which is carried out using conventional polychromatic X-ray sources and involves more than 2 materials → **some issues → the aim of this study is to investigate other X-ray sources and CM to increase SNR and/or reduce MGD.**

$$(\rho t)_X = \frac{\left[\frac{\mu^-}{\rho}\right]_T C^+ - \left[\frac{\mu^+}{\rho}\right]_T C^-}{K_0}, \qquad C^\pm = \ln\left[\frac{N_0^\pm}{N^\pm}\right] = \left[\frac{\mu^\pm}{\rho}\right]_X (\rho t)_X + \left[\frac{\mu^\pm}{\rho}\right]_T (\rho t)_T,$$

$$(\rho t)_T = \frac{\left[\frac{\mu^+}{\rho}\right]_X C^- - \left[\frac{\mu^-}{\rho}\right]_X C^+}{K_0}, \qquad K_0 = \left[\frac{\mu^-}{\rho}\right]_T \left[\frac{\mu^+}{\rho}\right]_X - \left[\frac{\mu^+}{\rho}\right]_T \left[\frac{\mu^-}{\rho}\right]_X$$



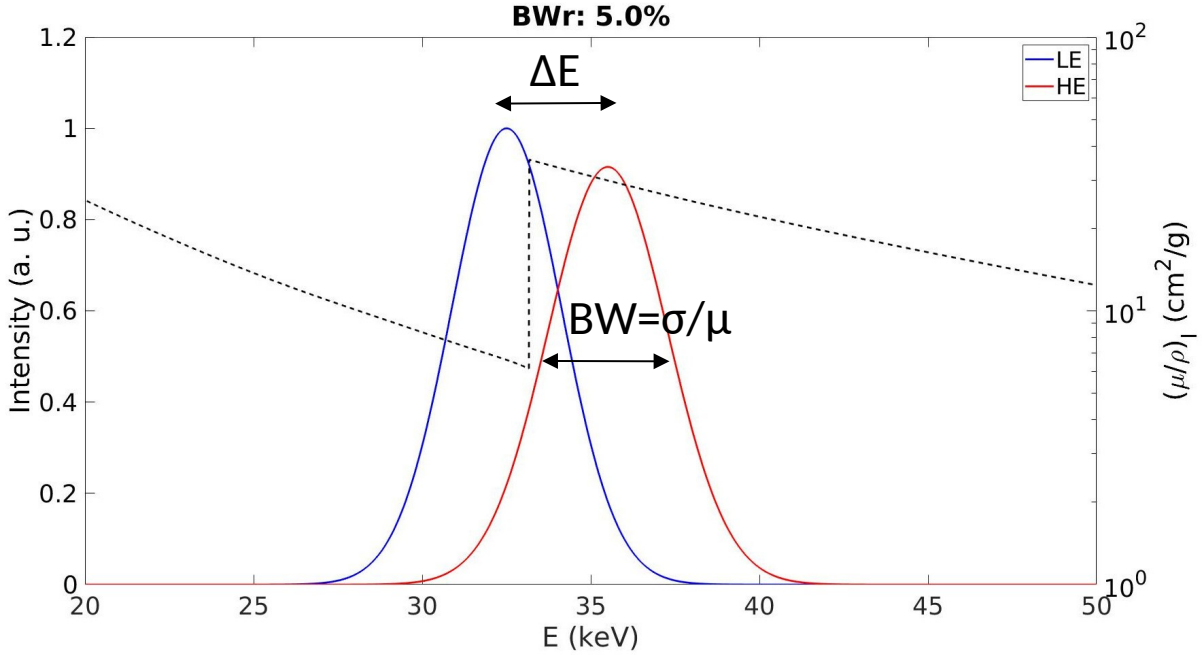


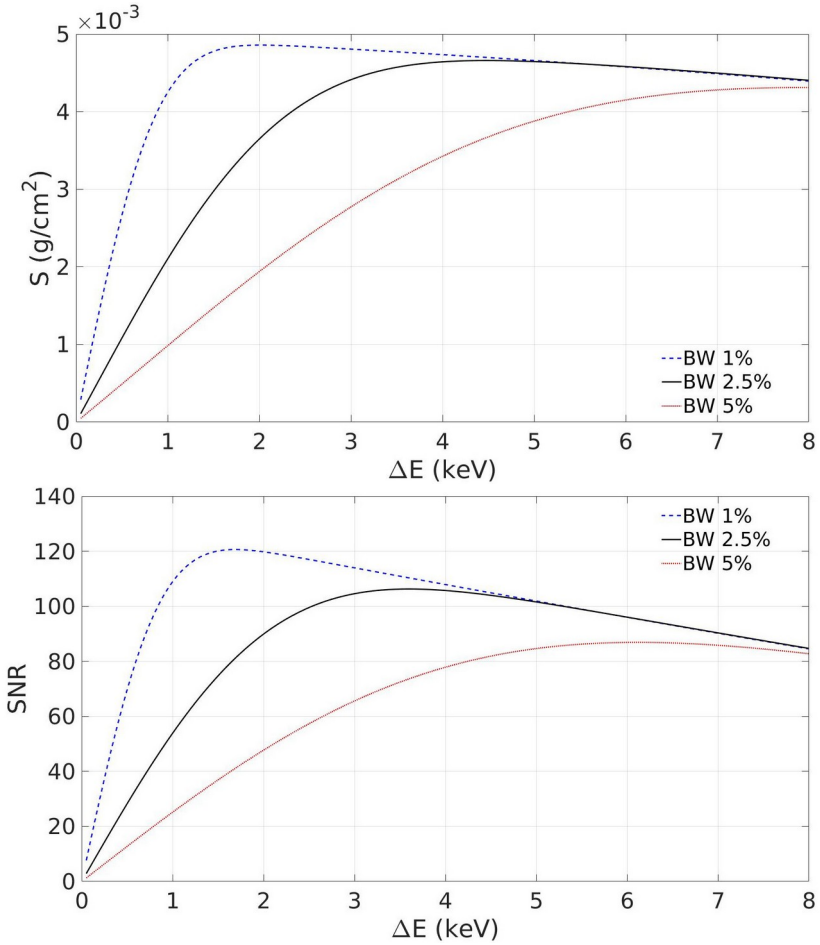
CESM: analytical signal reconstruction with Gaussian spectra → optimal energy separation (ΔE)

3 materials case: adipose, glandular, iodine CM (t_T = 5 cm, G=30%, expected S = 5 x 10^{-3} g cm^{-2}, detail 5 mm diam)

$$S = (\rho t_X)_D - (\rho t_X)_{BG}, \qquad SNR = \frac{S}{\sigma_{BG}} \qquad \sigma_{BG} = \sigma_P / \sqrt{n},$$

$$\sigma_P^2 = \frac{1}{K_0^2}\left(\left[\frac{\mu^-}{\rho}\right]_T^2 \frac{1}{N^+} + \left[\frac{\mu^+}{\rho}\right]_T^2 \frac{1}{N^-}\right) \qquad N^{\pm} = N_0^{\pm} \exp\left(-\sum_{i \neq CM} \mu_i^{\pm} t_i\right)$$





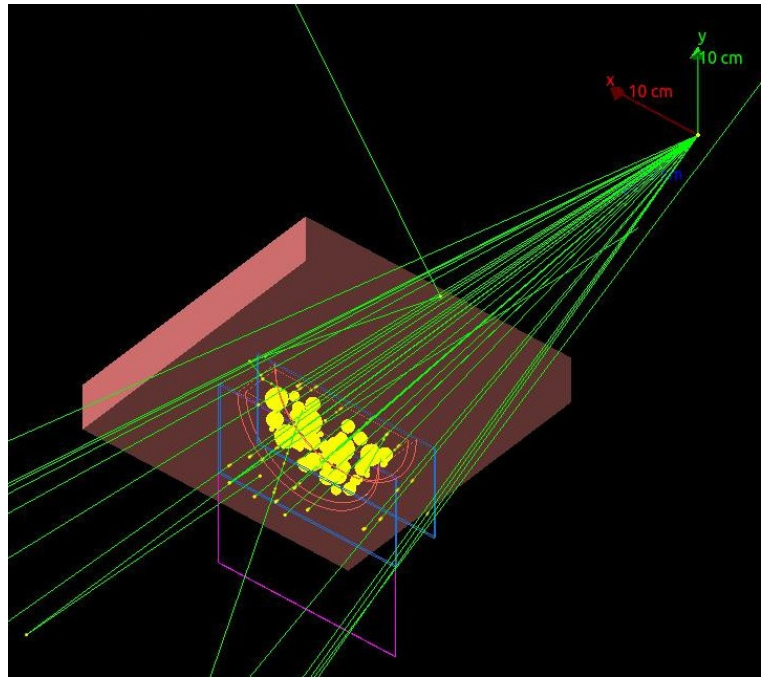
The *mammo* code

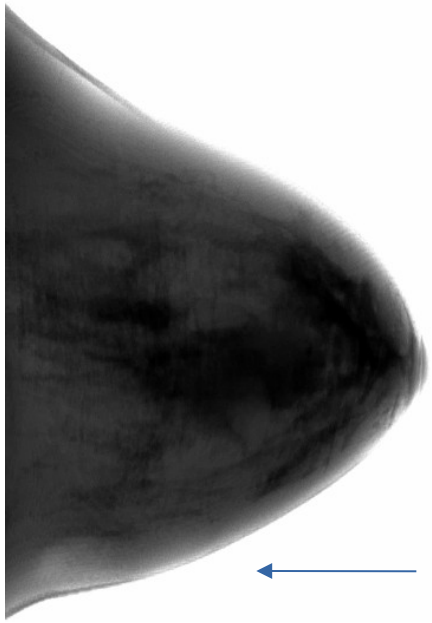
Project proposal for INFN CSN5 - Bando n. 21188
PI: Antonio Sarno, PhD, INFN Naples
AGATA
Advanced GeAnt4-based platform for virtual clinical Trials in X-ray breAst imaging

- A Geant4 application, *mammo*, has been developed.
- It allows us to simulate mammographic projections of both **geometric** and **personalized voxel phantoms** (it incorporates part of the code developed for the former INFN-AGATA project for Virtual Clinical Trials).
- Various **geometric configurations** (compressed or pendant breast), **X-ray imaging modalities** (DM, DBT, BCT, CESM) and **sources** (Gaussian or polychromatic beams, ICS) can be considered.
- The geometry (thorax, phantom, compression paddle, grid, detector, slits) and the associated materials can be set through **custom commands** (macro files).
- The photons impinging on the **detector** and the **energy deposited**, as well as the **phantom dose** are scored through the SteppingAction and a custom (voxel) scorer class.

Available at https://medical-physics.unife.it/downloads/geant4

Geometric phantom (used in this study about CESM)





Example of **DM** of a **Voxel phantom** (taken from the dataset described in A. Sarno et al. Medical Physics 48, no. 5 (2021): 2682-2693.)

X-ray source: Hologic Selenia Dimension (W anode, Rh filter) at 25 kV

10^{11} simulated events

Settings for our study on CESM with *mammo*

- **Phantom**:
- ➔ Semi-cylindrical (5 cm thick, 16 cm diam)
- ➔ Materials: adipose tissue, spheres of glandular tissue (G = 30%), µcalc (HA, 0.25 – 2 mm diam), skin (1.45 mm ICRU skin + 3.55 mm adipose)
- ➔ Spherical detail (5 cm diam) filled with CM (5 mg/ml of I or Gd)
- **Detector**: 20x20 cm^2, pixel area 0.3x0.3 mm^2, ideal photon counting and Edep scored in a 0.4 mm thick CsI layer.
- Focused **anti-scatter grid** (3 mm Pb) considered or not.
- **Physics list**: EM standard_option4 , 0.1 mm cuts, no e- tracking.

- It has been used the **Dual-energy reconstruction algorithm for 3 materials** (see, for instance, *A. Contillo et al, Medical Physics 43.6 Part1 (2016): 3080-3089*).
- 30 (45.5) keV and 36 (54.5) keV are the mean energies of the **Gaussian spectra** (5% BW) for LE and HE exposure, respectively, in the case of I (Gd) contrast medium.
- Used **polychromatic sources** are X-ray tube with W anode and proper filtration and voltage (see slide 4).
- 10^{10} photons impinging on the phantom ($4.5x10^4$ ph/px → MGD ∼ 0.02 mGy).

CESM: polychromatic vs quasi-monochromatic radiation (iodine CM)

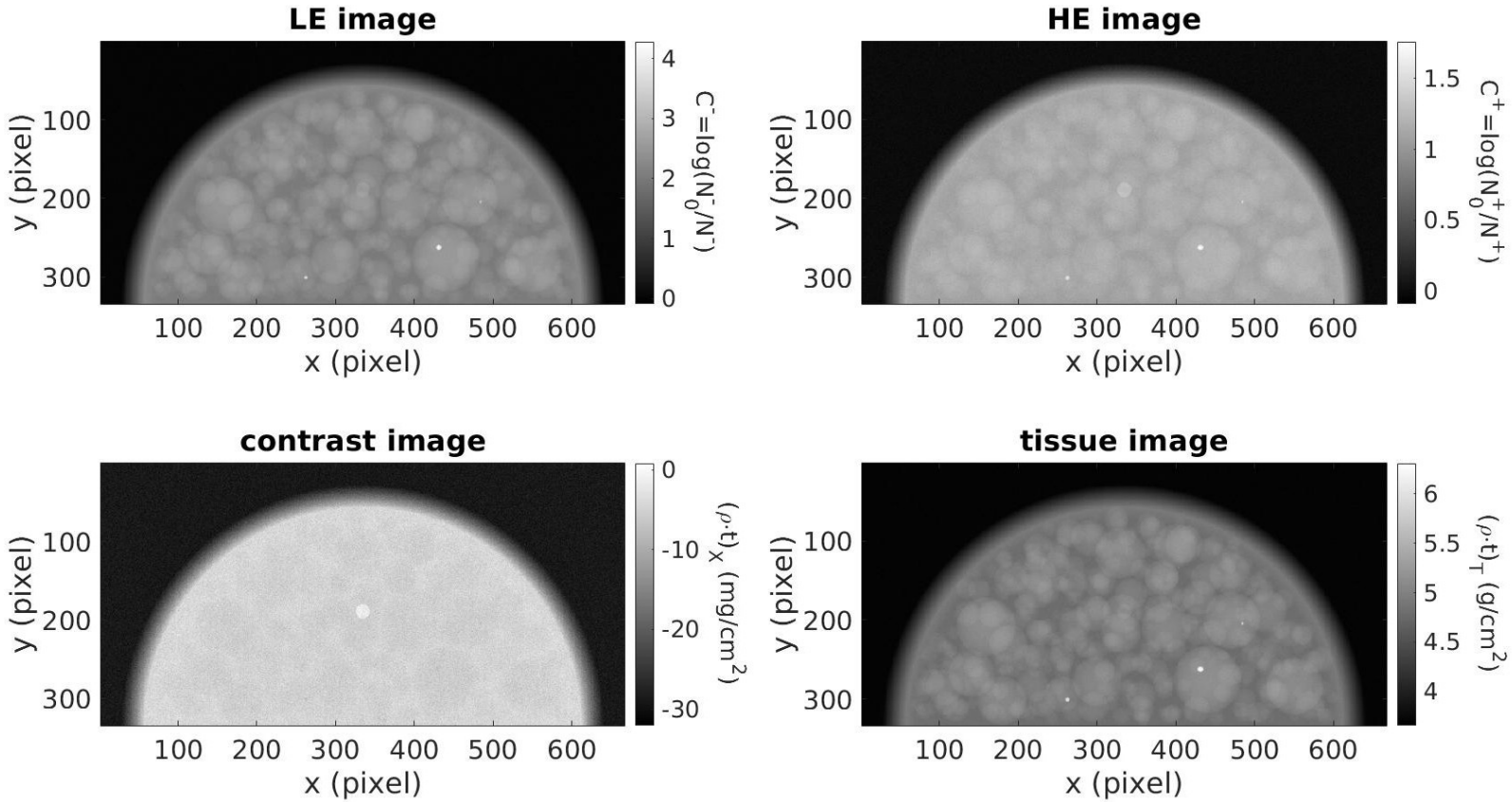
Example of CES images obtained with *mammo*: case of **polychromatic source** (with grid).

Signal for the **iodinated detail** and **other metrics** were calculated in **4 cases** (see the table below)

Results (FoM=SNR^2/MGD):

R_{grid} = FoM_{grid}/FoM = 1.49 and 3.87 for Gaussian (G) and polychromatic spectra (P), respectively.

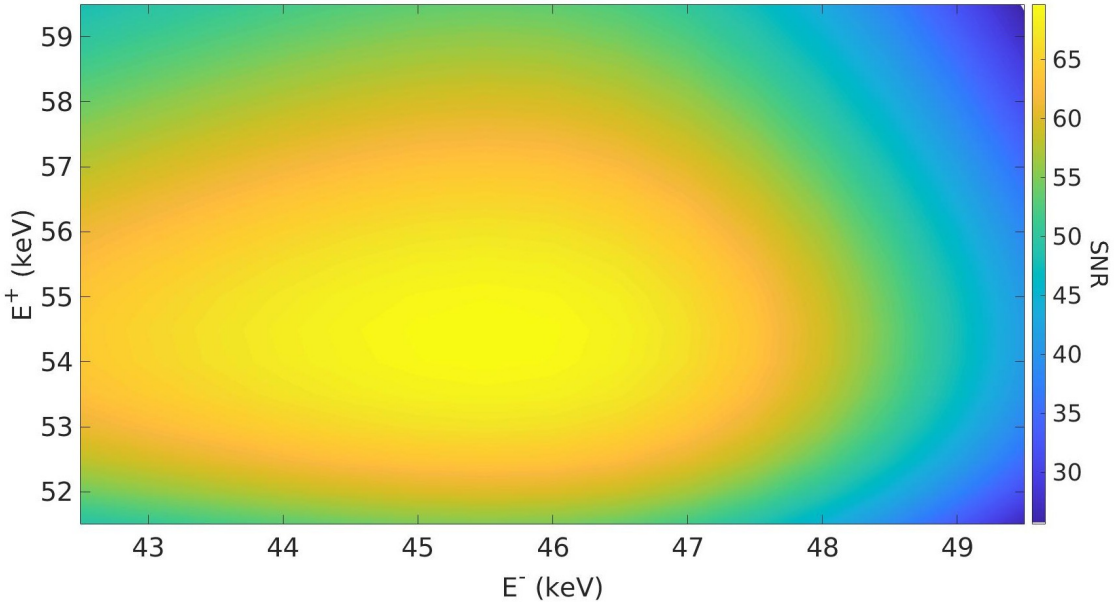
$R_{G,P}$ = FoM_G/FoM_P = 4.34 and 11.30 with and without grid, respectively.



X-ray spectra	CM	grid	E$^-$ (keV)	E$^+$ (keV)	S (mg/cm^2)	SNR	MGD (mGy)	FoM (mGy^{-1})
Polychormatic	I	no	24.0	39.0	1.67	20.56	0.0186	2.27E+04
Gaussian (5%BW)	I	no	30.0	36.0	3.00	67.22	0.0176	2.57E+05
Polychormatic	I	yes	24.0	39.0	3.35	40.46	0.0186	8.80E+04
Gaussian (5% BW)	I	yes	30.0	36.0	4.67	82.02	0.0176	3.82E+05

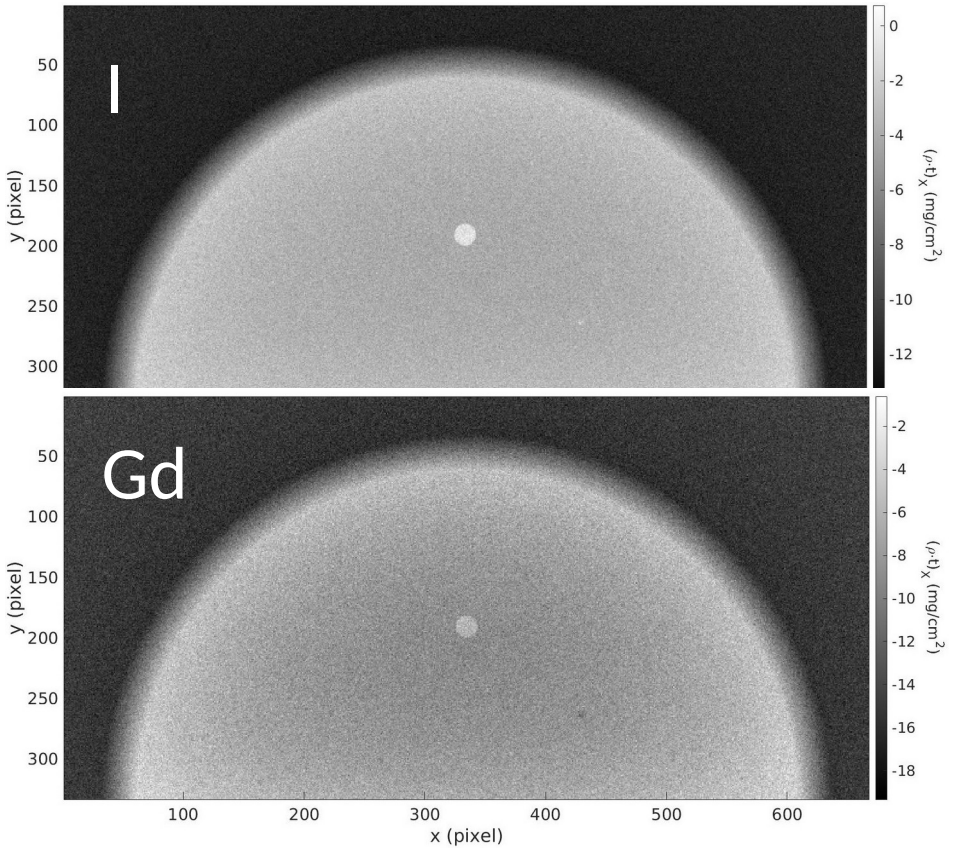
CESM: iodine vs gadolinium (quasi-monochromatic beams)

Selection of the **mean energy of the X-ray beams** in the case of Gd as contrast agent (analytical calculation)



X-ray spectra	CM	grid	E⁻ (keV)	E⁺ (keV)	S (mg/cm²)	SNR	MGD (mGy)	FoM (mGy⁻¹)
Gaussian (5%BW)	I	no	30.0	36.0	3.00	67.22	0.0176	2.57E+05
Gaussian (5%BW)	Gd	no	45.5	54.5	2.49	27.4	0.0131	5.73E+04

Contrast images obtained with *mammo*



$R_{I,Gd} = FoM_I/FoM_{Gd} = 4.48$ at the same CM concentration and input fluence.

Conclusions

- **A code has been developed in Geant4** for the simulation of **mammographic projections** using phantoms of various complexity and different sources.
- The use of **quasi-monocromatic** beams in CESM leads to typically double SNR at almost the same dose ($FoM=SNR^2/MGD > 4$) with respect to CESM with conventional polychromatic spectra.
- **Iodine contrast medium** leads to FoM more than 4 time higher than those obtained with Gadolinium.