Beam Hardening and Scatter Removal with Empirical Cupping Correction for Primary Modulation (ECCP)

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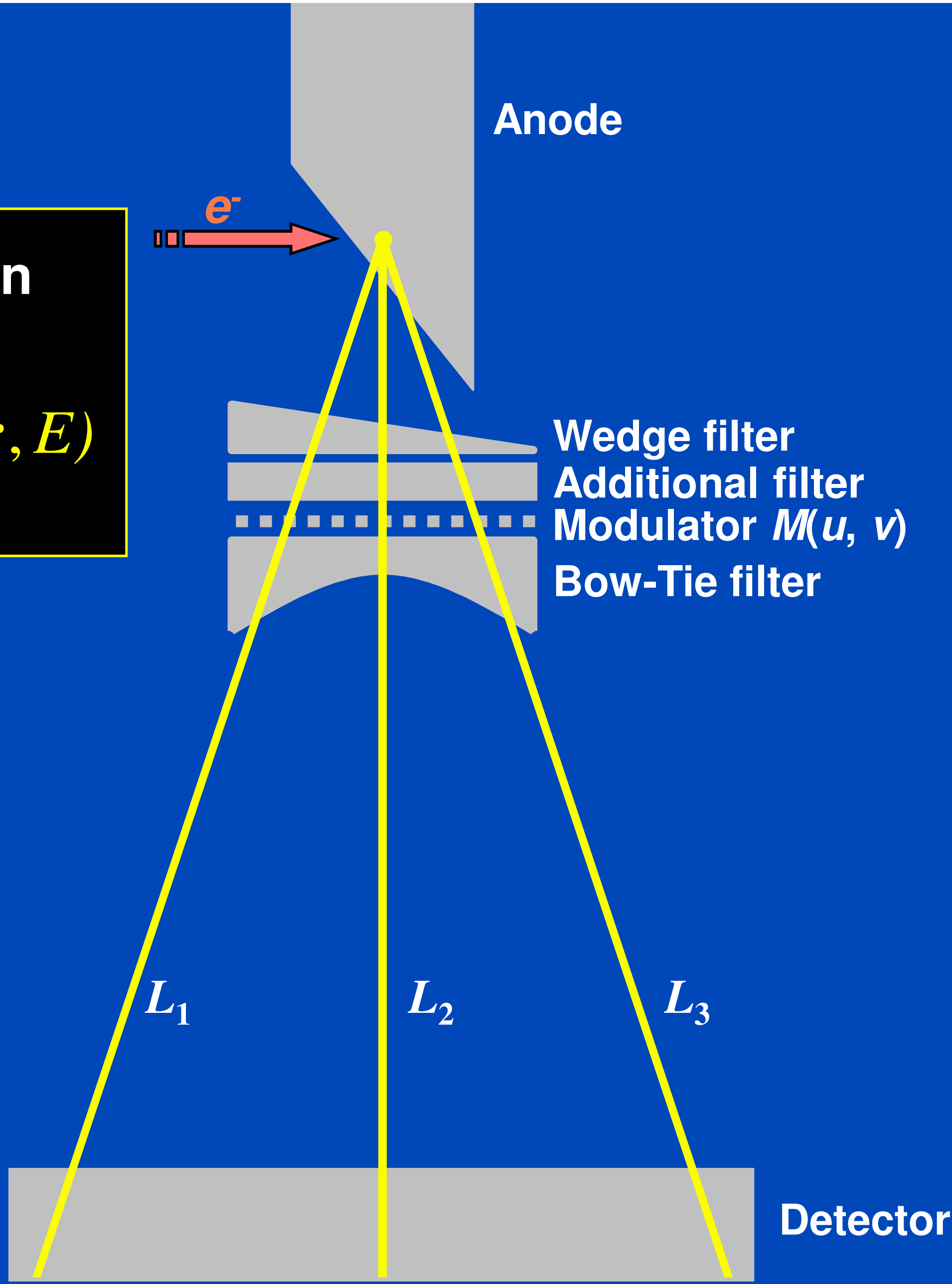
Aim

- To reduce scatter using the technique of primary modulation
- To correct for beam hardening artifacts in case of spatially strongly varying x-ray spectra

The detected spectrum is a function of the line of integration *L*:

$$q(L) = -\ln \int dE\, w(L,E)\, e^{-\int dL\, \mu(\mathbf{r},E)}$$



Primary Modulation Scatter Estimation (PMSE)
Basic Idea

Key hypothesis: “Low-frequency components dominate the scatter distribution even if high-frequency components are present in the incident x-ray intensity distribution.“

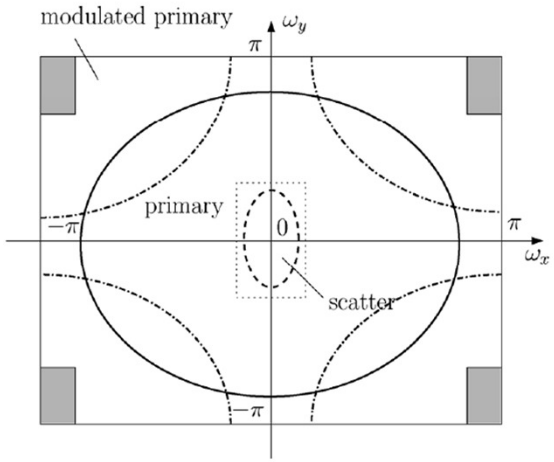


Fig. 3. Conceptual illustration of the primary and scatter distributions in the Fourier domain, with the primary modulator in place. The solid line indicates the primary distribution before modulation; the dot-dashed line indicates the modulated primary; the dashed line around the origin indicates the scatter distribution, which is mainly concentrated in the low-frequency region before and after primary modulation; the center region encompassed by the dotted line indicates the support of the low-pass filter used in Step 3.3 of the scatter correction algorithm proposed in Section II-D; the shaded region indicates the support of the high-pass filter used in Step 3.4.

The measurement with a modulator can expressed in Fourier space with:

$$P'(\omega) = \frac{1+\alpha}{2}P(\omega) + \frac{1-\alpha}{2}P(\omega - \pi) + S(\omega), \qquad (1)$$

where P and S denote the Fourier transforms of primary and scatter, respectively, and $\omega \in [-\pi, \pi] \times [-\pi, \pi]$ is the 2D coordinate of (ω_x, ω_y) in the Fourier domain. Parameter $\alpha \in (0, 1)$ is the transmission factor of the modulator blocker,

Scatter S can be estimated by

$$S_{\text{est}}(\omega) = P'(\omega)H(\omega) - \frac{1+\alpha}{1-\alpha}P'(\omega - \pi)H(\omega). \qquad (8)$$

with H(ω) being a low-pass filter

Zhu, Bennett, Fahrig. Scatter correction method for X-ray CT using primary modulation: Theory and preliminary results. IEEE TMI 25(12):1573 – 1587, 2006.

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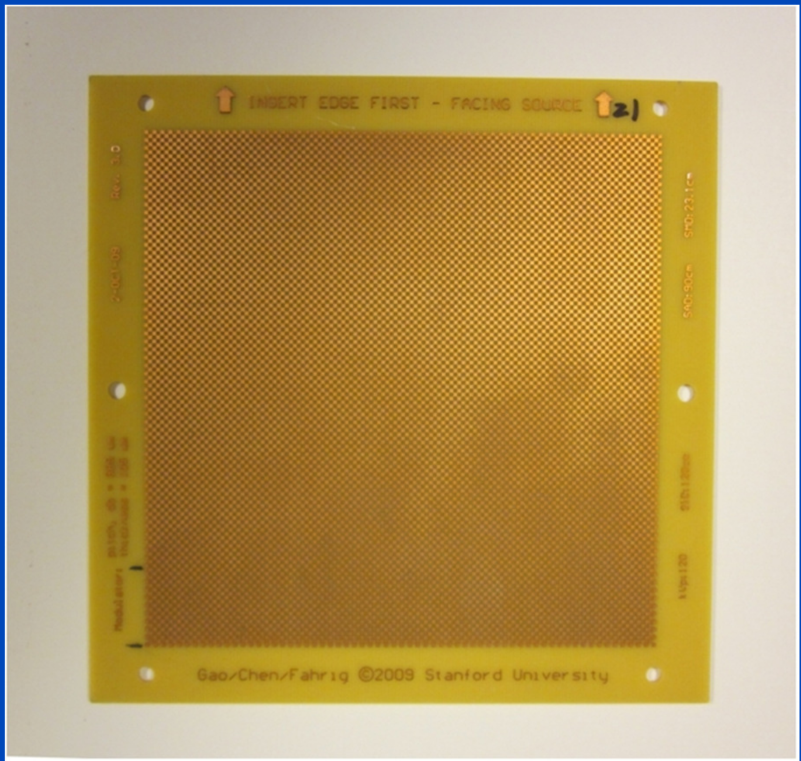
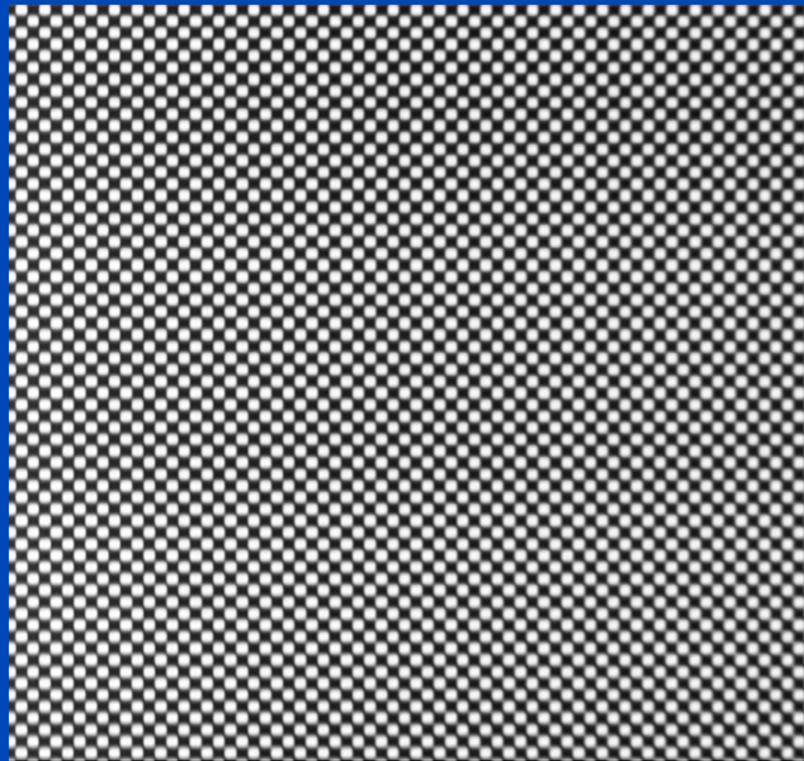
Modulator



Photograph of the copper modulator

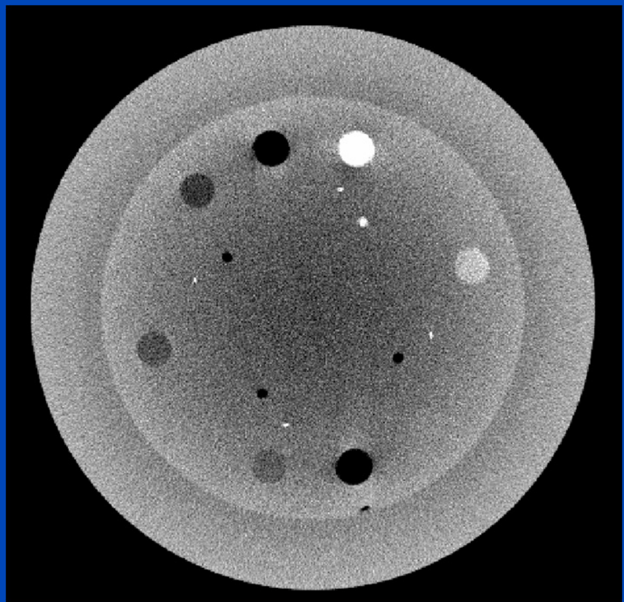
$$M(u,v)$$



Projection image of the modulator

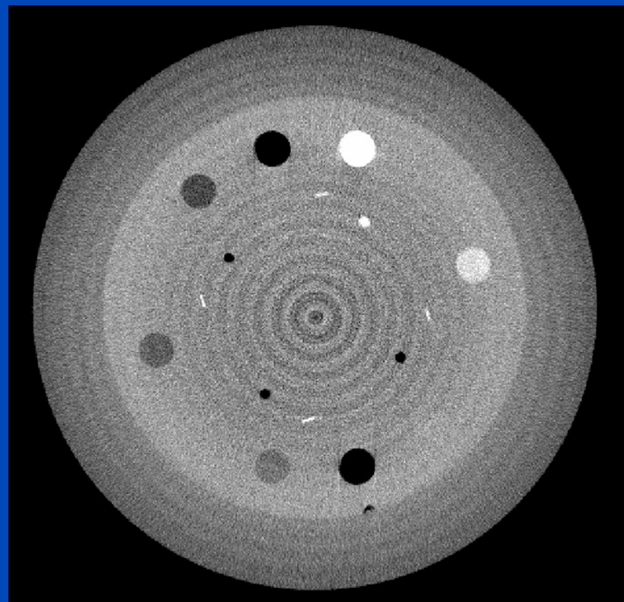
Primary Modulator Introduces Beam Hardening

- The primary modulator introduces high frequency variations of the incident x-ray spectrum.
- These variations show up as ring artifacts in the reconstructed images[1,2,3].



Scan without modulator, no scatter correction

(0 HU, 500 HU)



Scan with modulator, after PMSE correction

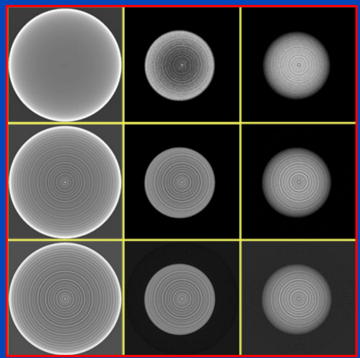
[1] Gao et al. MedPhys 37(2):934-946, 2010. [2] Gao et al. Proc. SPIE 7622, 2010. [3] Gao et al. MedPhys 37(8):4029-4037, 2010.

ECCP Calibration Procedure

- **Beam hardening can be corrected as**

$$p(\alpha,u,v)=\sum_{ij} c_{ij}\, M^i(u,v)\, q^j(\alpha,u,v)$$

- **Let us define basis volumes as**



$$f_{ij}(\boldsymbol{r})=\mathsf{R}^{-1}\, M^i(u,v)\, q^j(\alpha,u,v)$$

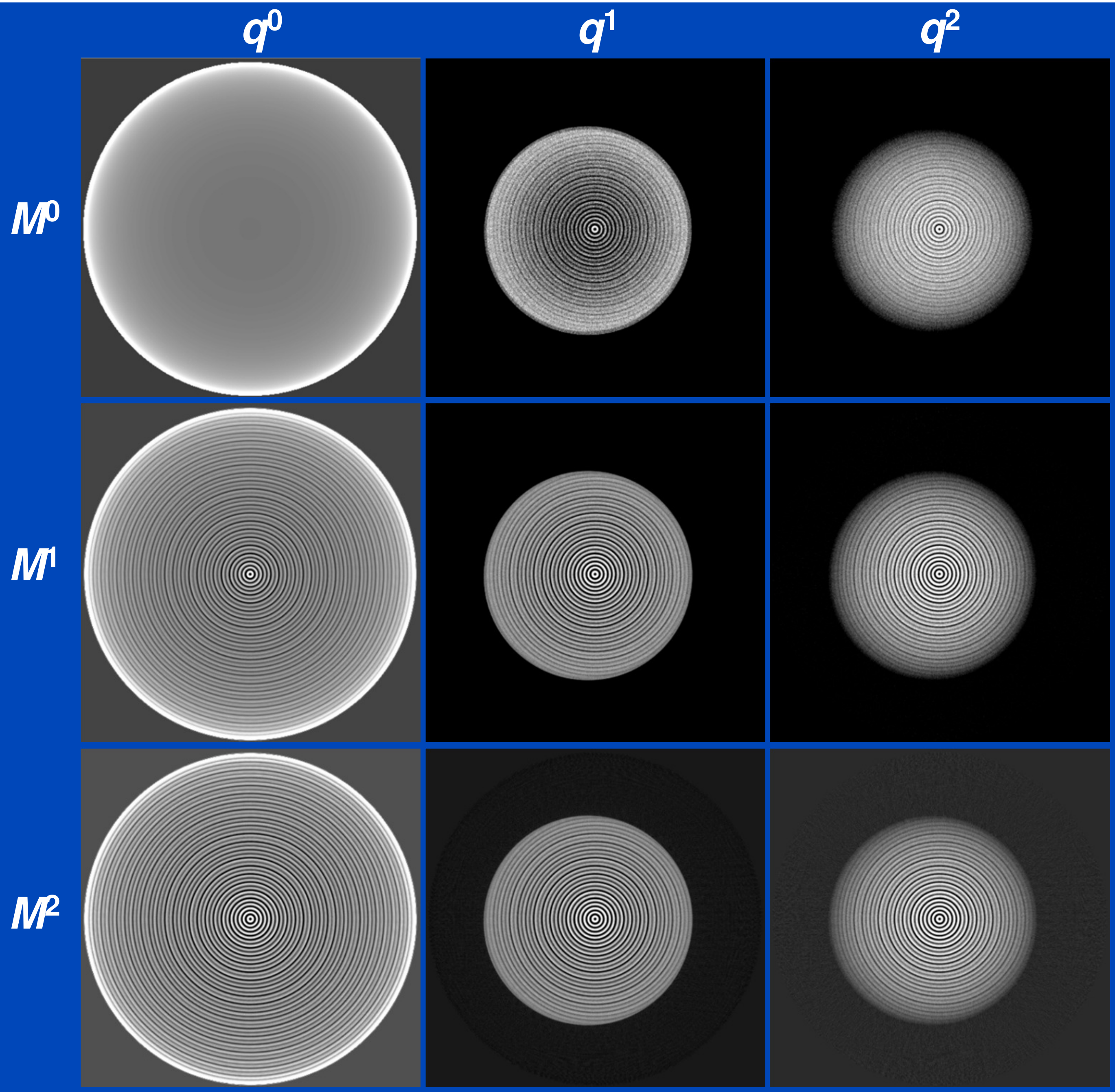
such that

$$f(\boldsymbol{r})=\sum_{ij} c_{ij} f_{ij}(\boldsymbol{r})$$

- **To determine c_{ij} minimize**

$$\int d^3r\, w(\boldsymbol{r})\big(f(\boldsymbol{r})-t(\boldsymbol{r})\big)^2$$

which is the weighted distance between the volume *f*(*r*) and a template volume *t*(*r*), that is a binary version of the uncorrected calibration phantom.

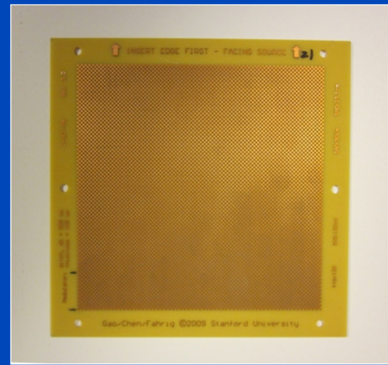


Central slices through nine different basis volumes

$$f_{ij} = \mathrm{R}^{-1}\, M^i\, q^j$$

Materials

- **Acquisition with a tabletop system**
  - Water Phantom (calibration)
  - Catphan Phantom (slightly larger)
  - Thorax Phantom (significantly larger)
- **Measurement with and without primary modulation (0.21 mm thick copper checkerboard pattern)**
- **Applying ECCP and PMSE**
- **Compare to a slit scan measurement**

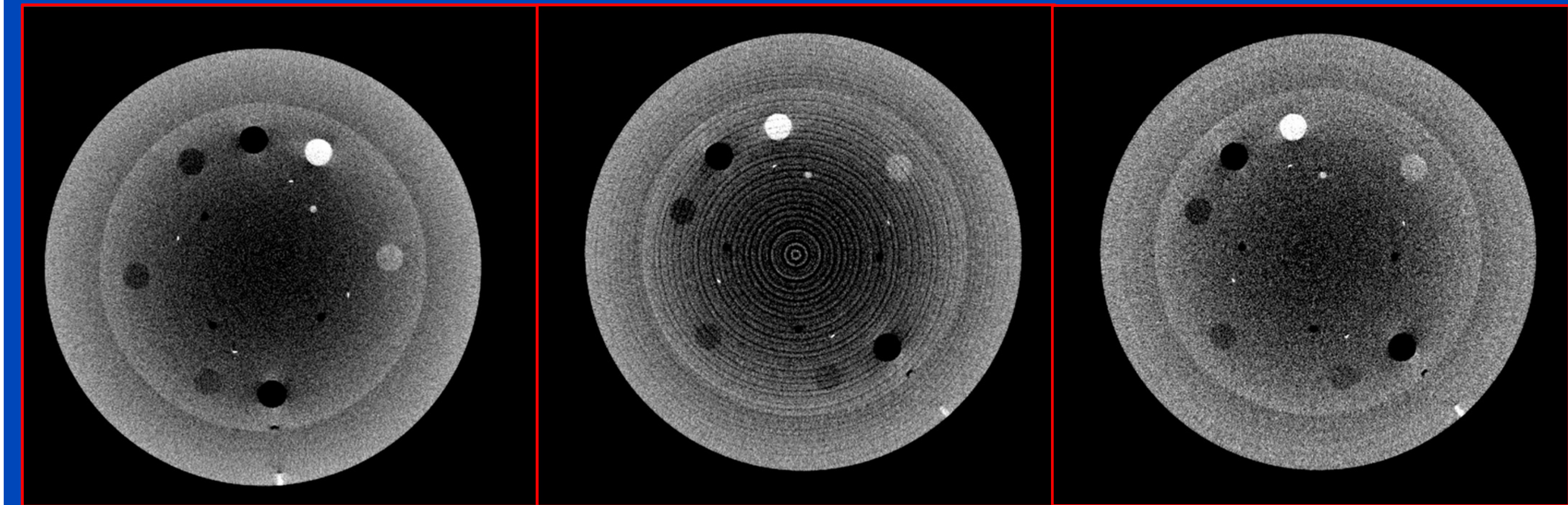


Picture of the copper modulator

Projection image of the modulator

Results
Correction of the Catphan Phantom

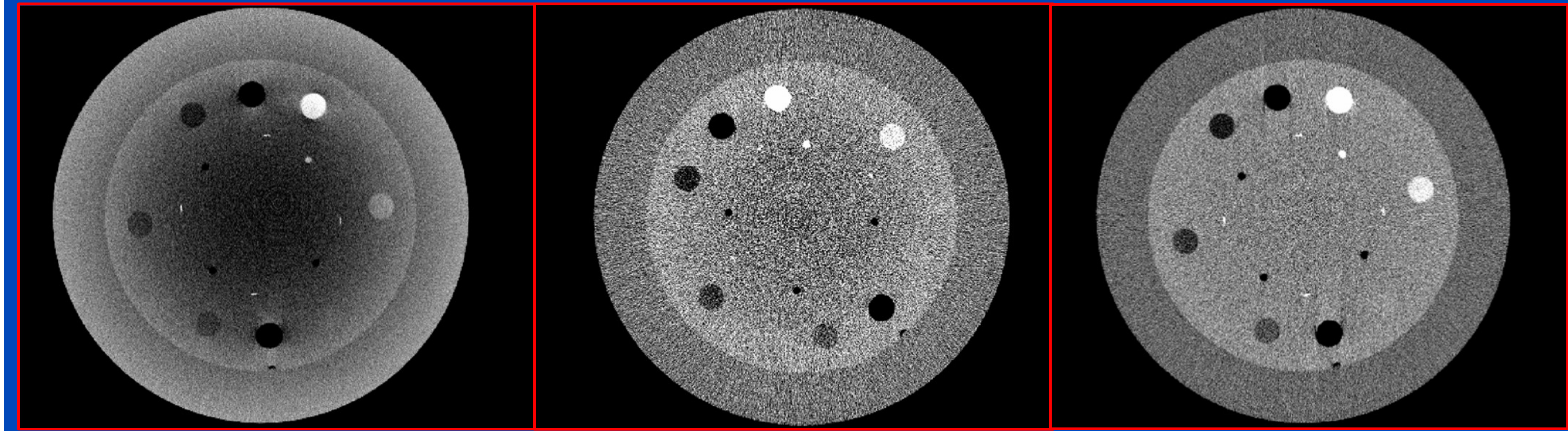
Measurement without Modulator	Measurement with Modulator	ECCP–corrected



C = 0 HU, W = 500 HU

Results
Combined correction with PMSE and ECCP

Measurement without Modulator	PMSE+ECCP–corrected	Slitscan without modulator



C = 0 HU, W = 500 HU

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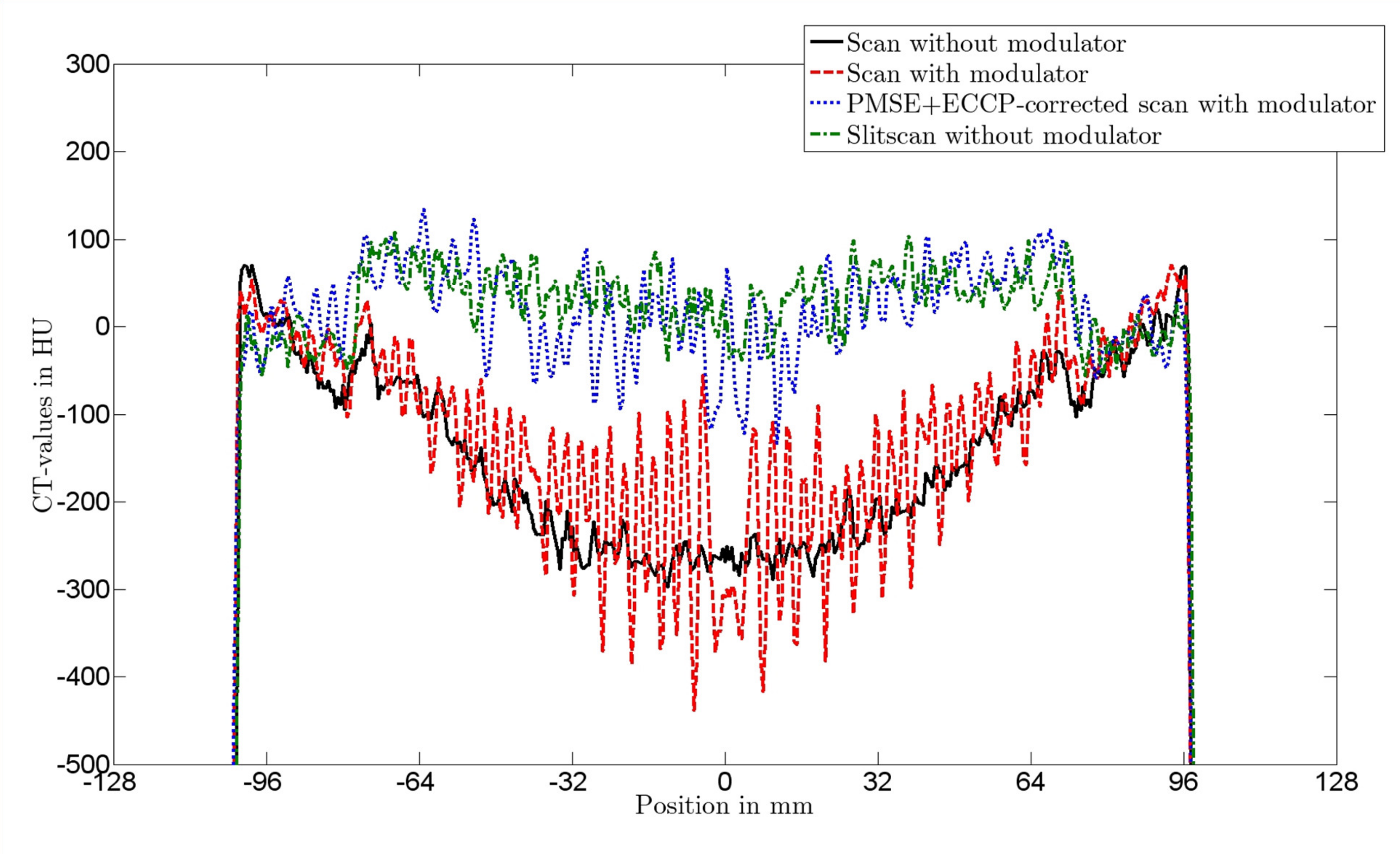
Results
Combined correction with PMSE and ECCP



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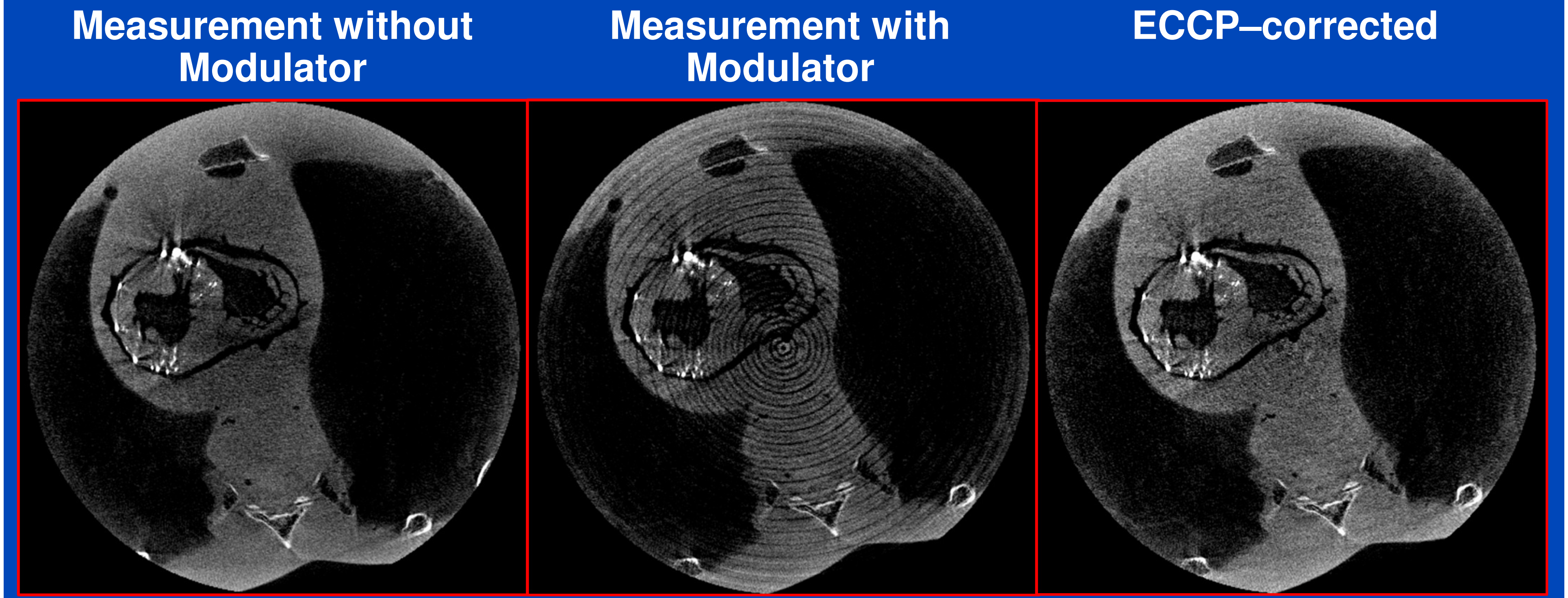
Results

Correction of the Thorax Phantom



C = 0 HU, W = 1000 HU

Conclusions on ECCP

- ECCP is dedicated to rapidly varying spectra, e.g. as caused by
  - primary modulators
  - the heel effect
  - wedge filters
  - scratches in the filtration
  - varying sensitivity of the detector pixels
  - .....
- ECCP is an efficient and simple way to correct for first order beam hardening.
- ECCP can be combined with PMSE to nearly completely eliminate beam hardening and scatter artifacts.

Thank You!

This study was supported by the AiF under grant KF2336201FO9.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany