PLASMED-X: a compact light source for X-ray fluorescence imaging

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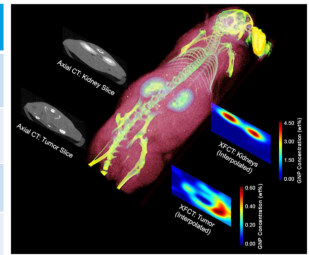
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Motivation for X-Ray fluorescence imaging

An imaging modality with advantageous properties

	PET	CT	MRI	XFI
Temporal resolution	poor	high	high	**high**
Spatial resolution	poor(4-5 mm)	high (1 mm)	high (1 mm)	**high (≤1 mm)**
Sensitivity	high	low	low	**high**
Dose exposure	moderate to high	high	none	**low**



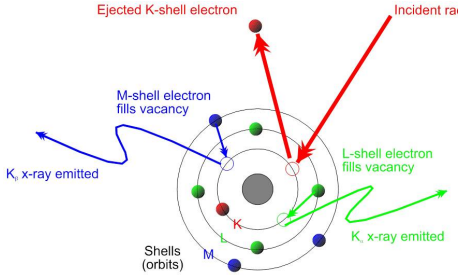
Grüner *et al.*, Sci. Rep. **8**, 16561 (2018)

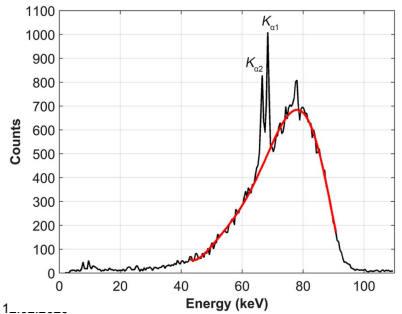
X-Ray Fluorescence Imaging

Unique advantages for functional imaging

Detection of flouresence photons from excited nanoparticles

- For gold nanoparticles (GNP) 81 keV photons needed
- Lower absorption of high X-Ray energies leads to decreased dose
- No Au in human body – no false positives
- GNPs can be attached to several peptides and antibodies
- GNPs are stable, so allow studies of pharmacokinetics
- Spatial resolution determined by the size of the X-Ray beam
- Narrow X-Ray bandwidth is beneficial, favouring synchrotrons/Thomson sources





Manohar *et al.*, Sci. Rep. **6**, 22079 (2016)

X-Ray Fluorescence Imaging

Possible X-ray sources

Conventional X-ray tubes:

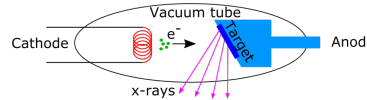
- Low-cost, small
- Large source size and divergence
- Broad spectrum (bremsstrahlung)

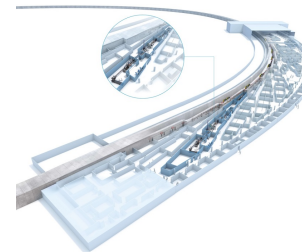
Synchrotrons

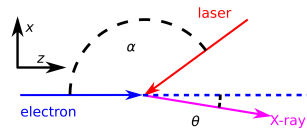
- High flux and repetition rate
- Small source size and divergence
- Large and expensive facilities

Thomson sources

- Small source size and divergence
- High repetition rate and flux
- Low bandwidth
- Compact, moderate cost





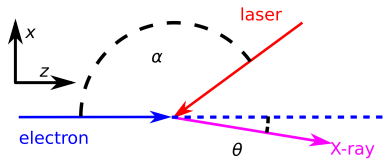


LWFA + Thomson scattering

Ideal source for XFI

XFI with GNPs requires source with:

- Low bandwidth ($< 15\%$)[1]: BW $\simeq 2{\sigma_\gamma}^2$
- Small source size and divergence: $\theta_S \sim \gamma^{-1}$
- Large flux and rep. rate: $N_X \propto Q N_{\text{osc}} a_0^2 \sigma(\theta_{\text{obs}})$
- Compactness and low cost
- X-Ray energy $\hbar\omega_X \sim 90\,\text{keV} \rightarrow \gamma \simeq 120$



$$\omega_X = \frac{2\gamma^2\,(1-\beta\cos\alpha)}{1+a_0^2/2+\gamma^2\theta^2}\,\omega_L$$

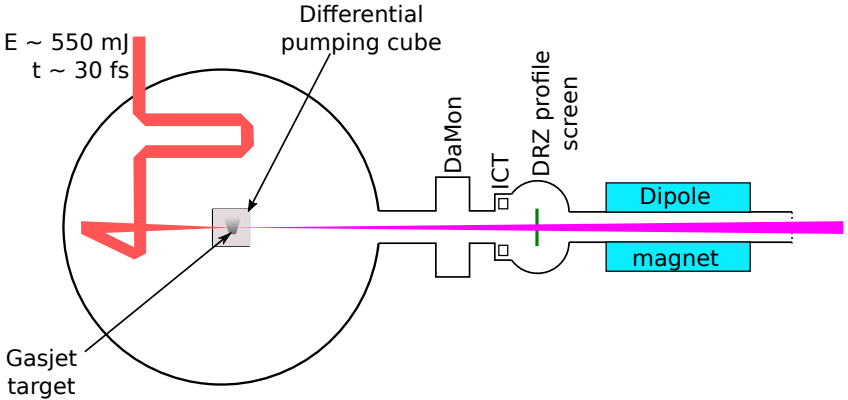
While X-Ray tubes are cheap & compact and synchrotrons have desirable beam parameters, only all-optical Thomson sources fulfill all criteria!

[1] Grüner *et al.*, Sci. Rep. **8**, 16561 (2018)

[2] Rykovanov *et al.*, PRAB **19**, 030701 (2016)

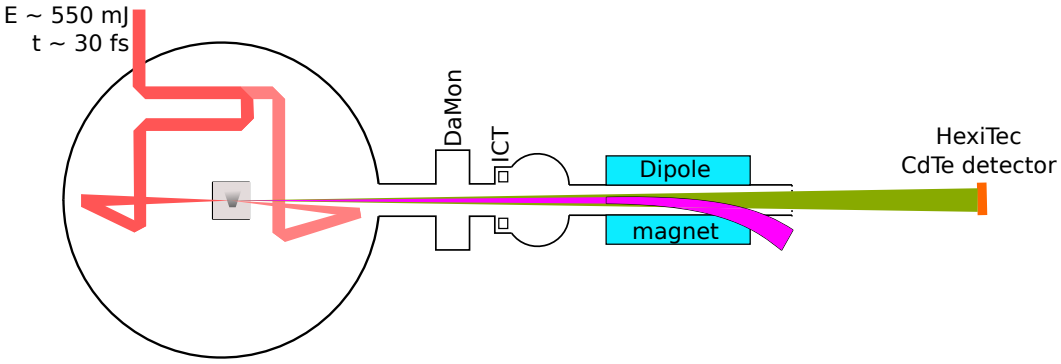
Experiments: setup, work done and future

Stable and reproducible electron source with II



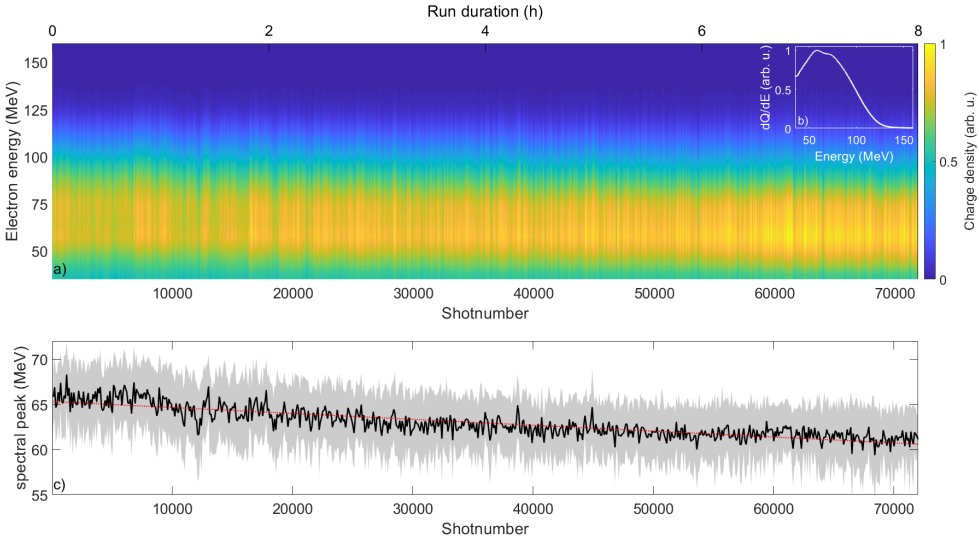
Experiments: setup, work done and future

First Thomson X-Rays measured



Stable electron beams

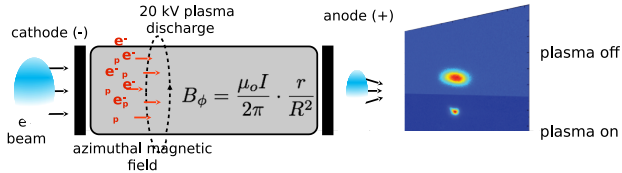
Ionisation injection (1% N_2) results in reliable electron source

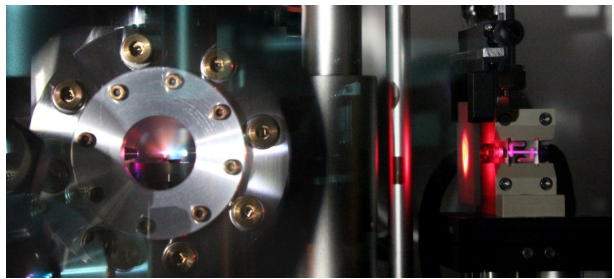


Active Plasma Lenses

Compact, aberration-free, high gradient electron beam optics

- Active plasma lenses[3,4,5] offer strong, axially symmetric focussing
- Up to kT/m gradients achievable
- Allows a large divergence electron beam to be refocussed





[3] van Tilborg *et al.*, PRL **115**, 184802 (2015)

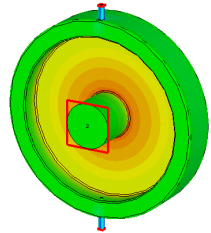
[4] Röckemann *et al.*, PRAB **21**, 122801 (2018)

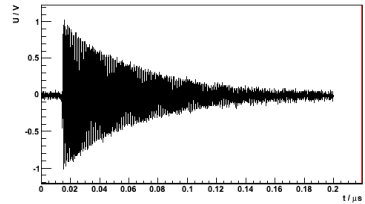
[5] Lindstrøm *et al.*, PRL **121**, 194801 (2018)

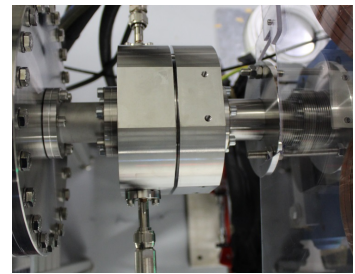
The Dark-current Monitor charge diagnostic

Cavity based non-destructive beam charge measurement device

- Stainless Steel cavity used as passive resonator[6]
- Frequency of first monopole mode (TM01) at 1.3 GHz[7]
- Induced TM01 mode used for charge measurement
- Amplitude of induced mode proportional to charge and independent of position
- Two readout channels for high dynamic range – 3 OoM per channel
- Clear aperture 35 mm





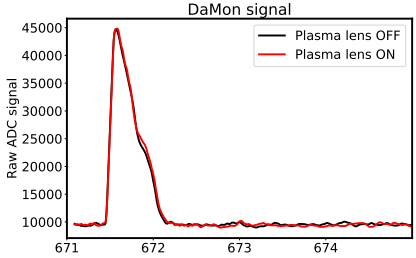


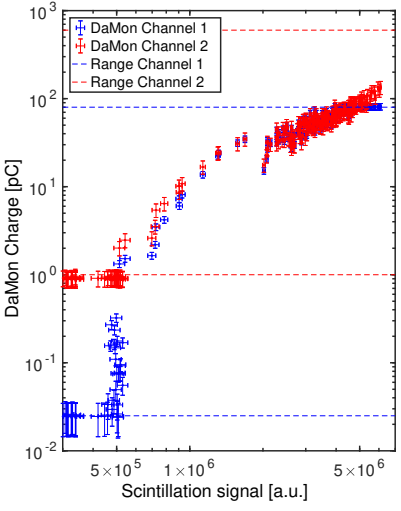
[6] D. Lipka *et al.*, Proc. of DIPAC 2011, Hamburg, WEOC03

[7] D. Lipka *et al.*, Proc. of IBIC 2013, Oxford, WEPF25

The Dark-current Monitor charge diagnostic

Femtocoulomb-level charge measurement and insensitive to EMP

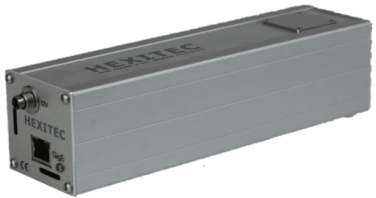


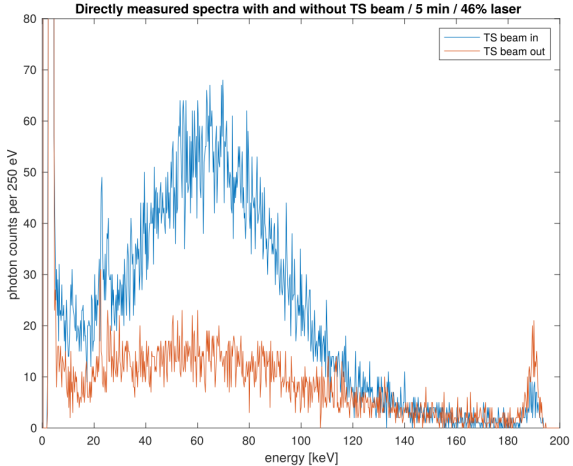


HexiTec CdTe pixellated detector

4-200 keV sensitivity with high spectral resolution

Hexitec[8,9] detector[10]: 0.8 keV energy resolution, 80×80 pixels $1 \times 0.25 \times 0.25$ mm





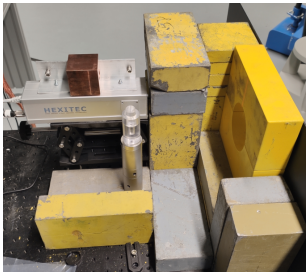
[8] Seller *et al.*, J Instrum. 6 (2011)

[9] Golovin *et al.*, Sci. Rep. **6**, 24622 (2016)

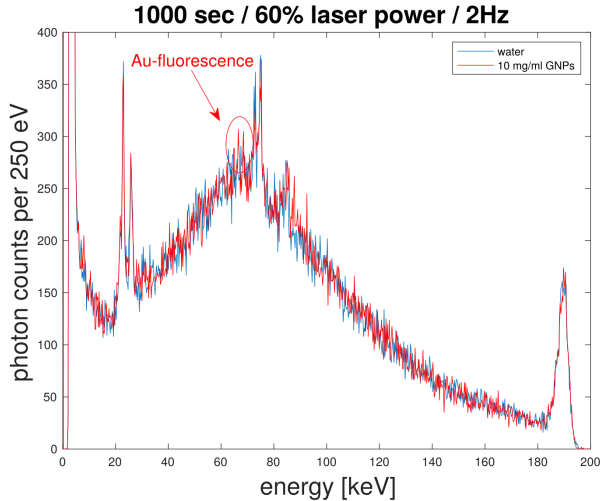
[10] Kindly loaned from CLF

XFI signal measured in 28m lab

Fluoresence of gold detected

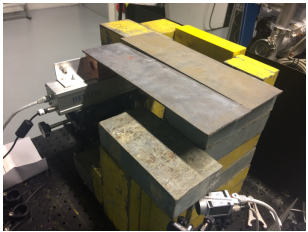


- 4 cm diameter PMMA-cylinder with 0.3 ml Eppendorf tube containing 10 mg/ml GNPs
- Target at 3.25 meters from interaction point
- Calculated significance $Z = \mathbf{5.4}$

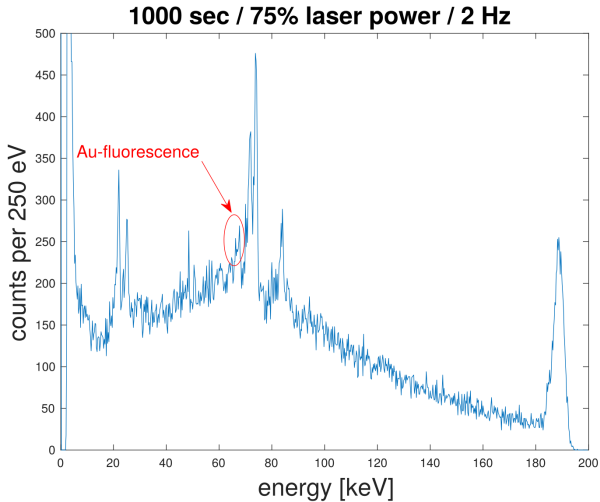


XFI signal measured in 28m lab

Shielding improvements reduce background and increase significance



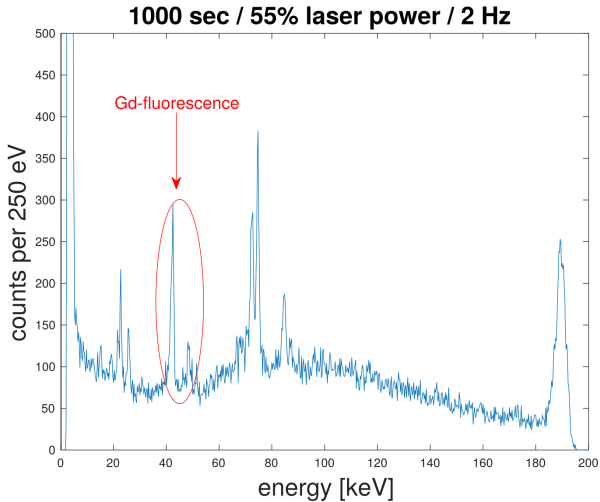
- 3 cm diameter PMMA-cylinder with 0.3 ml Eppendorf tube containing 18.87 mg/ml GNPs
- Improved lead shielding to reduce bremsstrahlung
- Target at 3.25 meters from interaction point
- Calculated significance $Z = \mathbf{8.3}$



XFI signal measured in 28m lab

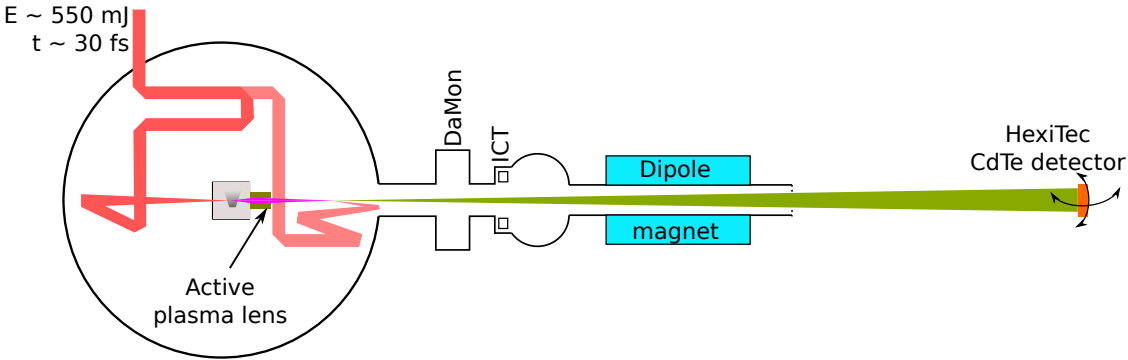
Shielding improvements reduce background and increase significance

- Gadolinium is used as contrast agent in magnetic resonance imaging
- 1 cm diameter Eppendorf tube containing 78 mg/ml Gd-solution
- Target (only Eppendorf tube, no surrounding phantom) at 3.25 meters from interaction point
- Calculated significance of fluorescence lines at 42.3 and 43 keV: $Z = \mathbf{32}$
- Even K_β-fluorescence at 48.7 keV visible



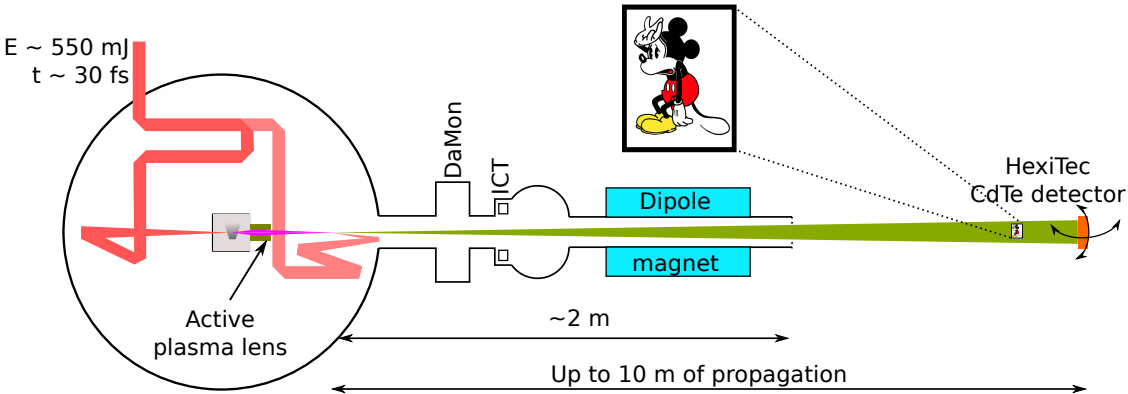
The future

Using APLs to increase and filter X-Ray yield



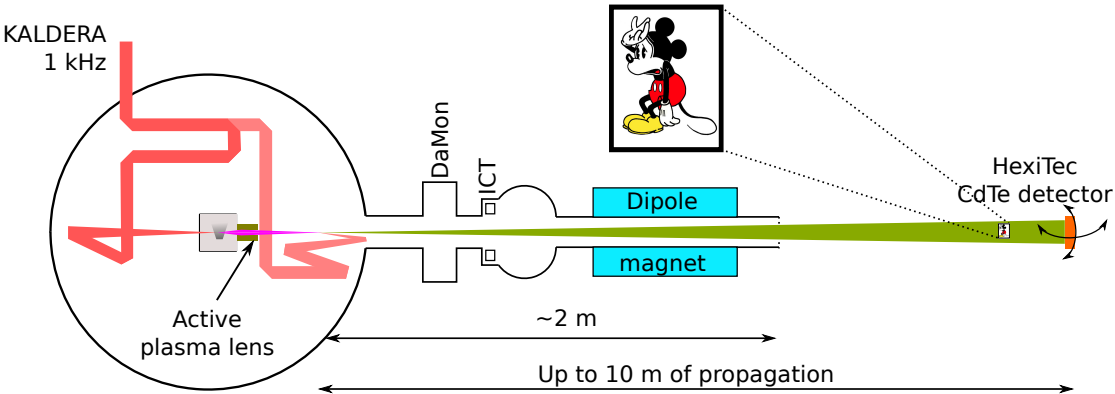
The future

Proof of principle XFI experiment with mouse phantom



The future

Move to KALDERA for high rep rate X-Ray source



Summary

Development of a very compact Thomson X-Ray source for XFI progressing well

- Stable and robust electron source commissioned
- First Thomson spectra and XFI signal measured
- Plasma lens implementation happening as we speak
- Future deployment at KALDERA for kHz X-Ray source