Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

CFEL SCIENCE

DESY.

X-Ray Fluorescence Imaging with a Laser-Wakefield Thomson X-Ray Source

Theresa Staufer[1], Simon Bohlen[2], Martin Meisel[2], Kristjan Poder[2], Theresa Brümmer[2], Florian Blumendorf[1], Oliver Schmutzler[1], Matthew C. Veale[3], Jens Osterhoff[2], Florian Grüner[1]

[1] University of Hamburg, Luruper Chaussee 149, 22761 Hamburg
[2] Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg
[3] STFC Rutherford Appleton Laboratory, Didcot, Oxon, UK

PLASMED X

DESY Strategy Fund.

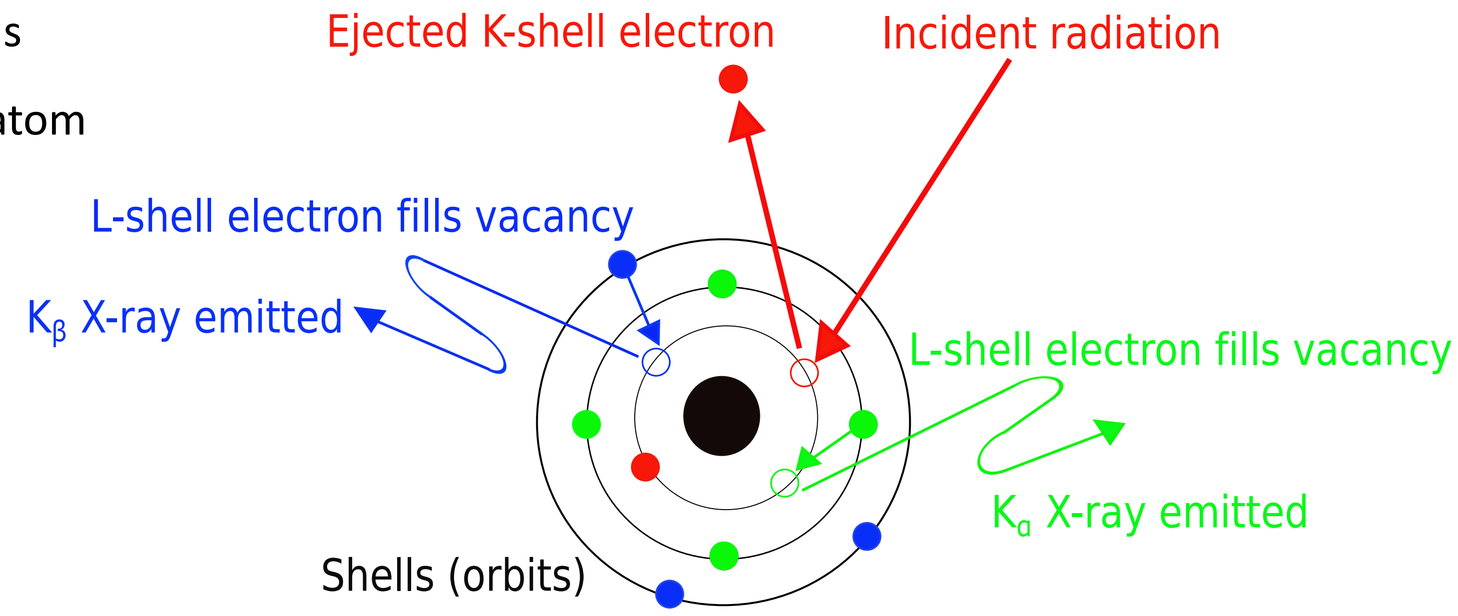
Theresa Staufer, PhD student
theresa.staufer@desy.de
EAAC 2019, Isola d'Elba

Bundesministerium für Bildung und Forschung

CONTENTS

X-RAY FLUORESCENCE IMAGING (XFI)

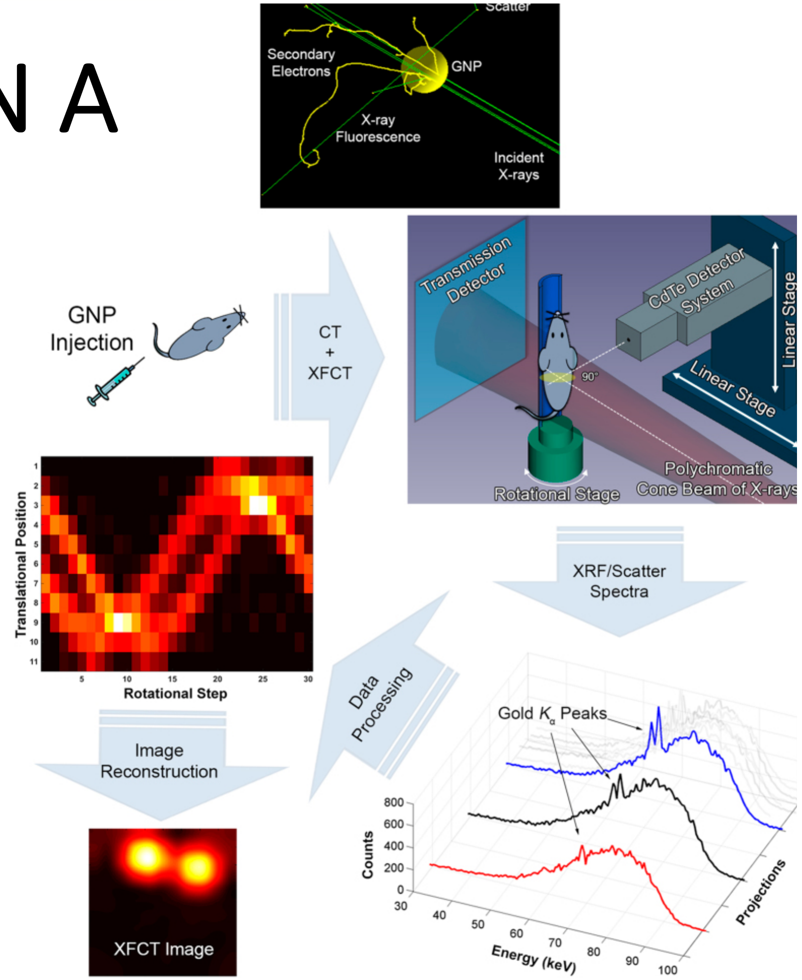
- Incident X-ray beam displaces electrons from inner orbital shells of the target atom
- Vacancies are filled by electrons from higher orbits
- Energy difference is released in form of characteristic X-rays
- Potential use for medical imaging with high-Z elements



Taken and modified from www.bruker.com

PREVIOUS IMAGING OF GNPs IN A TUMOR- BEARING MOUSE

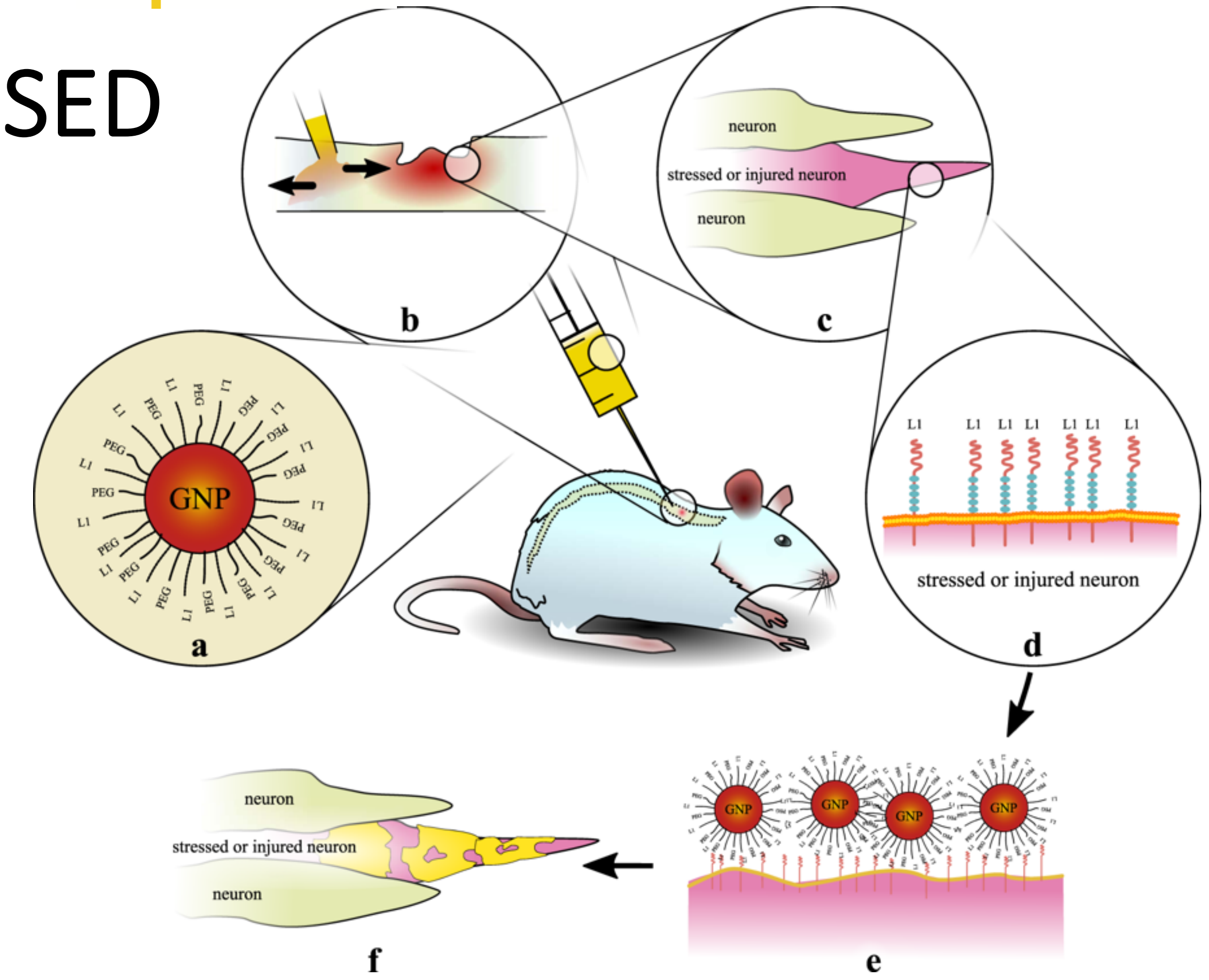
- Mouse injected with small amounts of gold nanoparticles (GNPs)
- Benchtop setting with polychromatic X-ray source
- Detect characteristic gold fluorescence signals
- Translation of the detector in order to obtain tomographic images



Scientific Reports 2016, 6:22079, Manohar et.al.

LOCALISING FUNCTIONALISED GOLD-NANOPARTICLES

- GNPs functionalised with L1-peptides injected into murine spinal cord → bind to stressed neurons
- XFI-scans localise regions with bound GNPs
- Gold masses down to 72 pg could be detected
- Close agreement to inductively coupled plasma mass spectrometry (ICP-MS) results



Scientific Reports 2018, 8:16561, F.Grüner et. al.

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK UND NATURWISSENSCHAFTEN

DESY Strategy Fund.

Bundesministerium für Bildung und Forschung

CFEL SCIENCE

DESY.

CONTENTS

- Principle of X-ray fluorescence imaging (XFI)
- **Requirements on the X-ray source & necessary improvements**
- Laser-wakefield acceleration (LWFA)
- Thomson scattering (TS)
- First proof-of-principle experiment and results
- Optimisation of the setup

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

DESY
Strategy
Fund.

Bundesministerium
für Bildung
und Forschung

CFEL SCIENCE

DESY.

NECESSARY IMPROVEMENTS & REQUIREMENTS

- Surface-functionalisation of GNPs
- Development of large-area, pixelated, spectroscopic detectors
- Development of compact, hard X-ray sources (80 – 100 keV) with high brilliance, flux and repetition rate
- Small source size
- Inexpensive realisation
- Effective background reduction with advanced filtering scheme and collimators

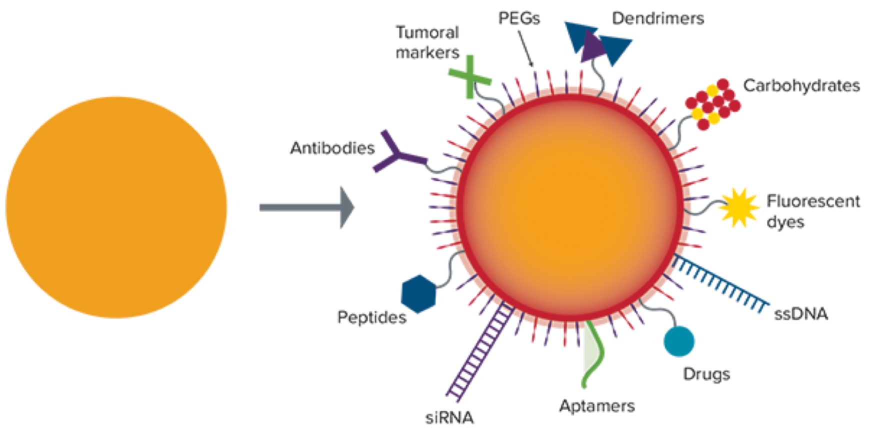
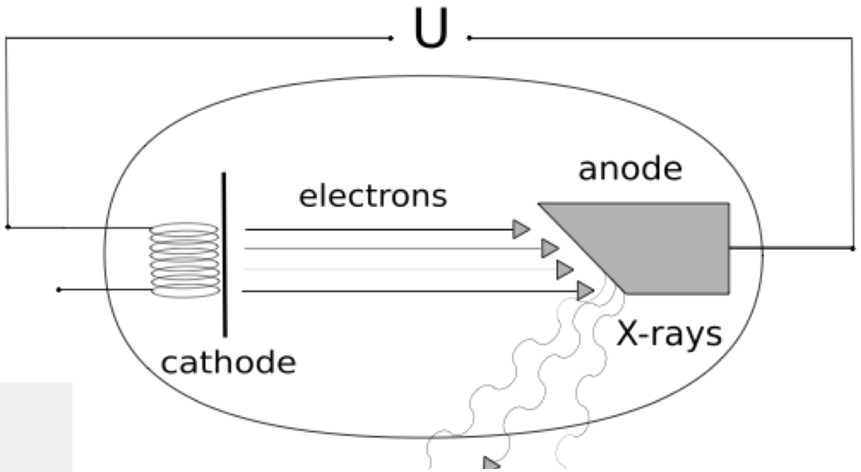


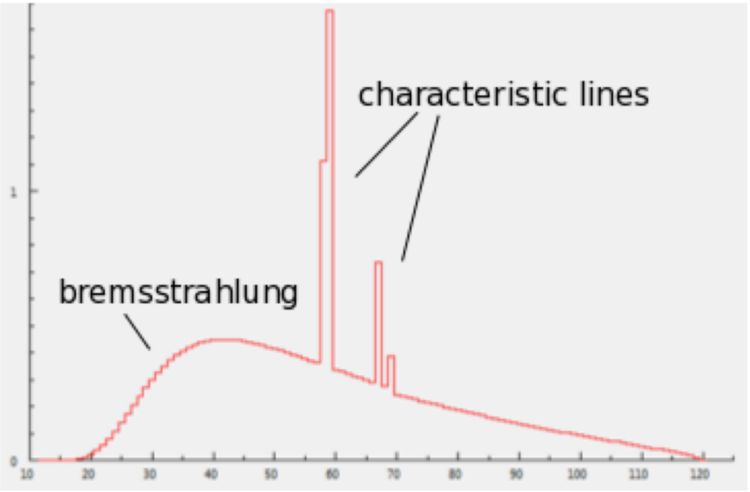
Diagram of surface functionalisation of nanoparticles from www.moleculardevices.com

Pixelated Hexitec detector from www.quantumdetectors.com

CLINICAL SOURCES TODAY: X-RAY TUBES

- Electrons are discharged and accelerated
- Collisional and radiative energy transfer
- Bremsstrahlung and characteristic X-rays
- 1% of the energy : X-rays
- 99% of the energy: heat



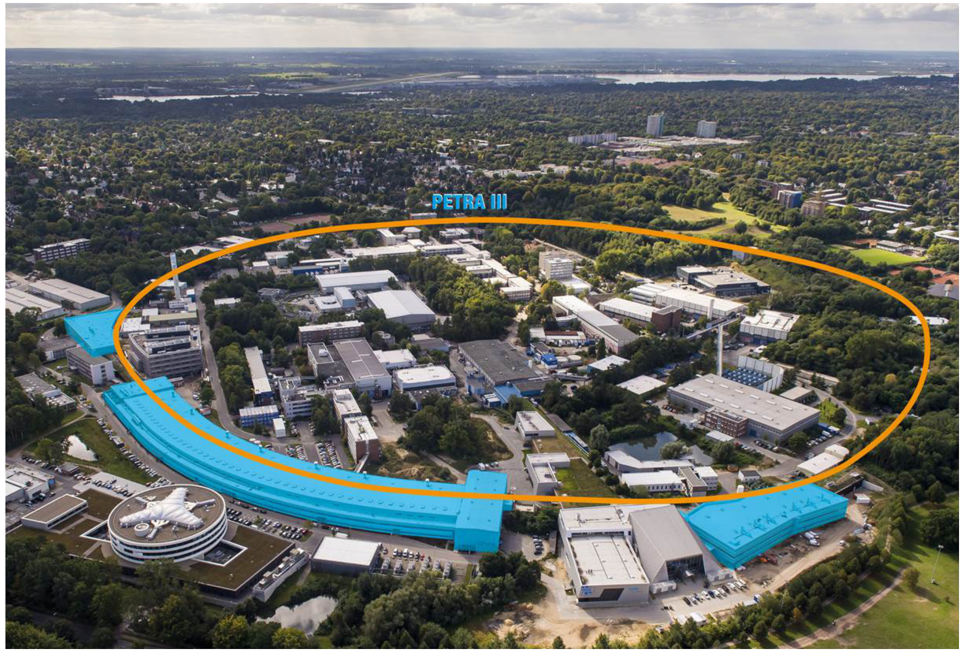


SYNCHROTRONS

- Modern synchrotrons provide high energy and brilliance photons
- Circumferences in the order of kilometers and large numbers of bending magnets

→ huge and expensive

- Not suitable for medical applications (except at research centers)



Aerial view of the PETRA III synchrotron at DESY in Hamburg (http://photon-science.desy.de)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

DESY
Strategy
Fund.

Bundesministerium
für Bildung
und Forschung

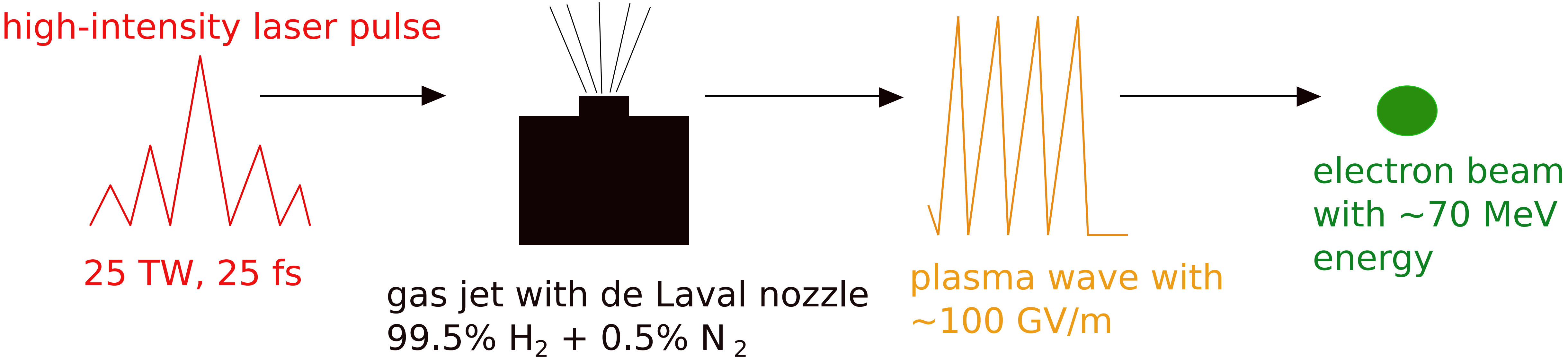
CFEL
SCIENCE

DESY.

CONTENTS

- Principle of X-ray fluorescence imaging (XFI)
- Requirements on the X-ray source & necessary improvements
- **Laser-wakefield acceleration (LWFA)**
- Thomson scattering (TS)
- First proof-of-principle experiment and results
- Optimisation of the setup

LASER-WAKEFIELD ACCELERATION (LWFA)



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

DESY
Strategy
Fund.

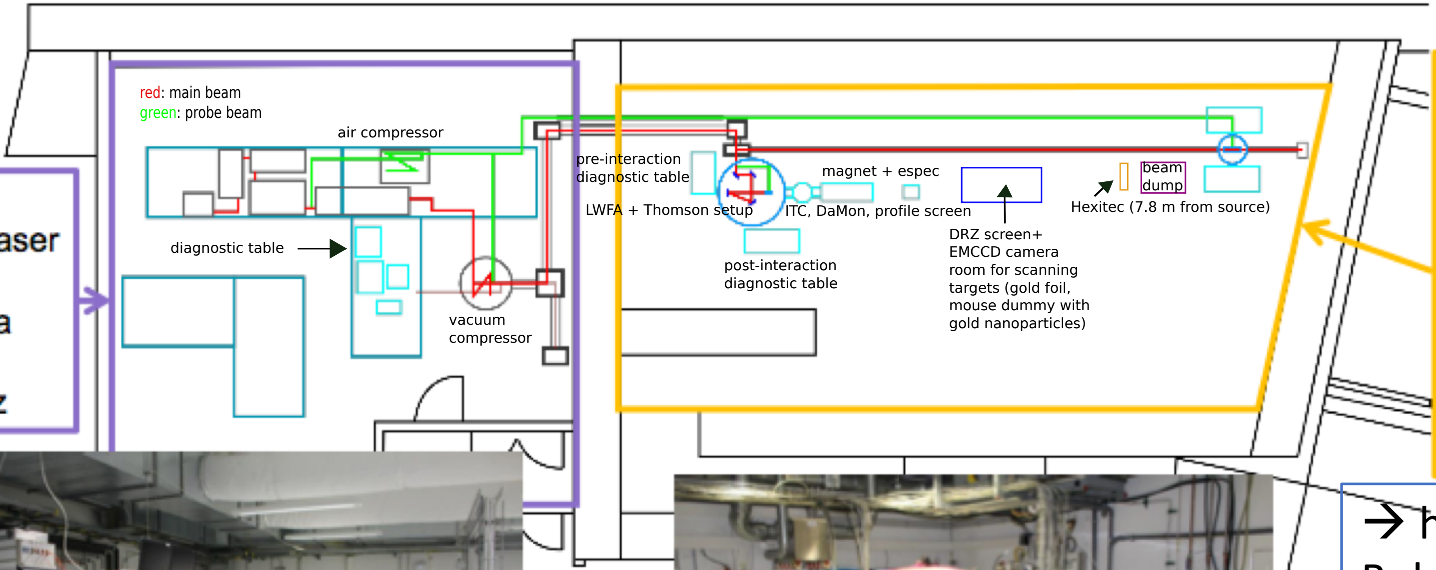
Bundesministerium
für Bildung
und Forschung

CFEL
SCIENCE

DESY.

LAB SETUP @DESY/HAMBURG

Laser lab:
- Amplitude laser system
- 25 TW Ti:Sa Laser
- 25 fs, 10 Hz



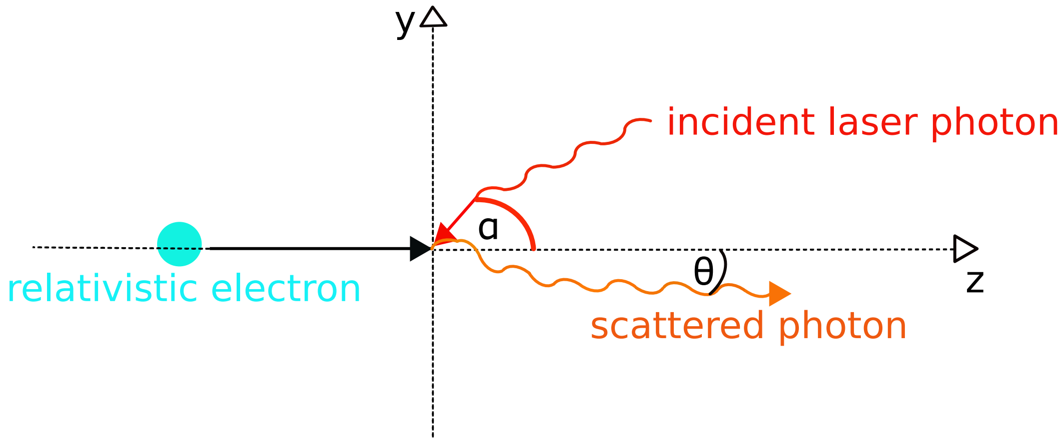
Experimental lab:
- LWFA setup to test diagnostics and concepts
- Ionisation test setup to study ionisation properties

→ hear also talk of Mr. Simon Bohlen: *"Development and characterisation of non-invasive diagnostics for plasma acceleration"* (tomorrow, 16:00, WG5)

CONTENTS

- Principle of X-ray fluorescence imaging (XFI)
- Requirements on the X-ray source & necessary improvements
- Laser-wakefield acceleration (LWFA)
- **Thomson scattering (TS)**
- First proof-of-principle experiment and results
- Optimisation of the setup

THOMSON SCATTERING (TS)



Simple schematic of the Thomson scattering process

Energy of scattered photons:

$$E_\gamma \propto \frac{\gamma^2 E_L}{1 + \frac{a_0^2}{2} + \gamma^2\theta^2}$$

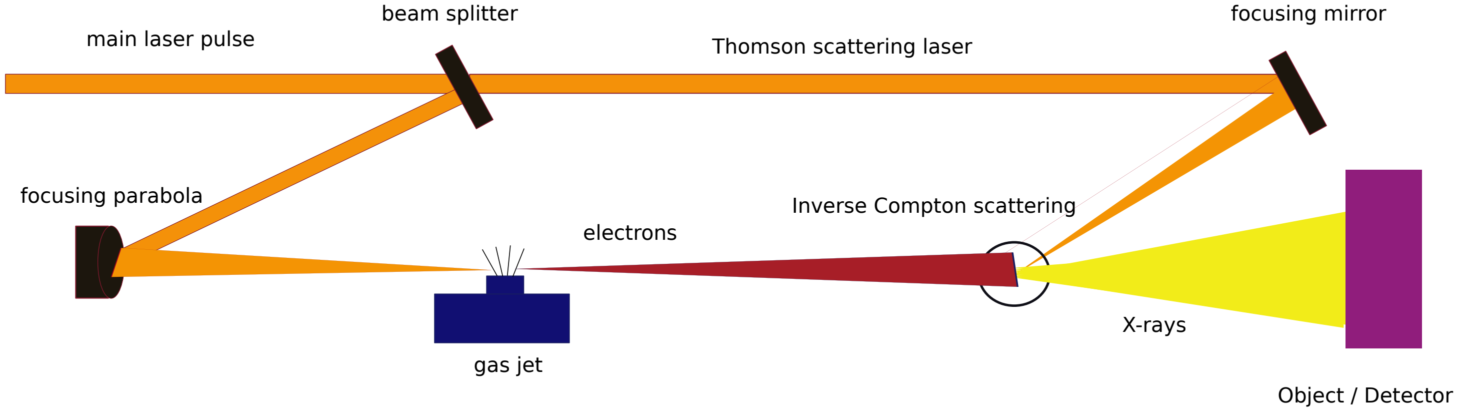
Opening angle:

$$\theta_S \sim \frac{1}{\gamma}$$

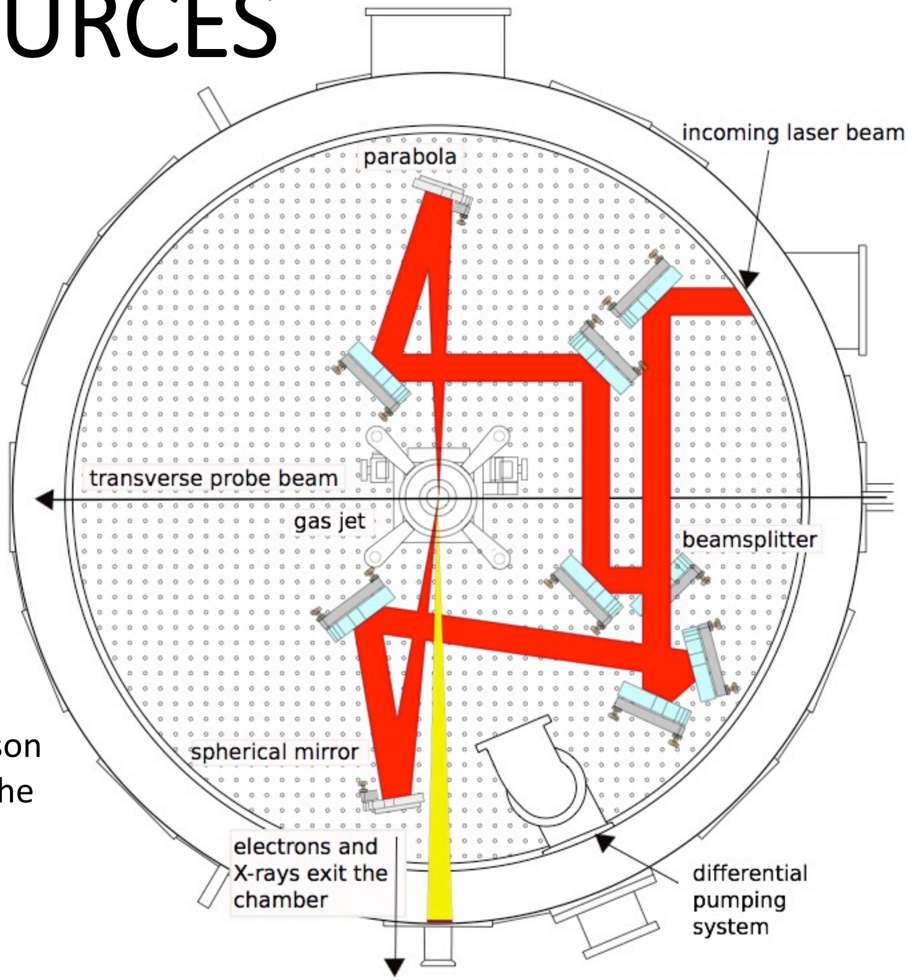
Photon number:

$$N_\gamma \sim Q_{bunch}\tau_{laser}a_0^2\sigma(\theta_{obs})$$

THOMSON SCATTERING X-RAY SOURCES



Schematic of the Thomson scattering setup



Sketch of the Thomson scattering setup in the vacuum chamber

CONTENTS

- Principle of X-ray fluorescence imaging (XFI)
- Requirements on the X-ray source & necessary improvements
- Laser-wakefield acceleration (LWFA)
- Thomson scattering (TS)
- **First proof-of-principle experiment and results**
- Optimisation of the setup

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

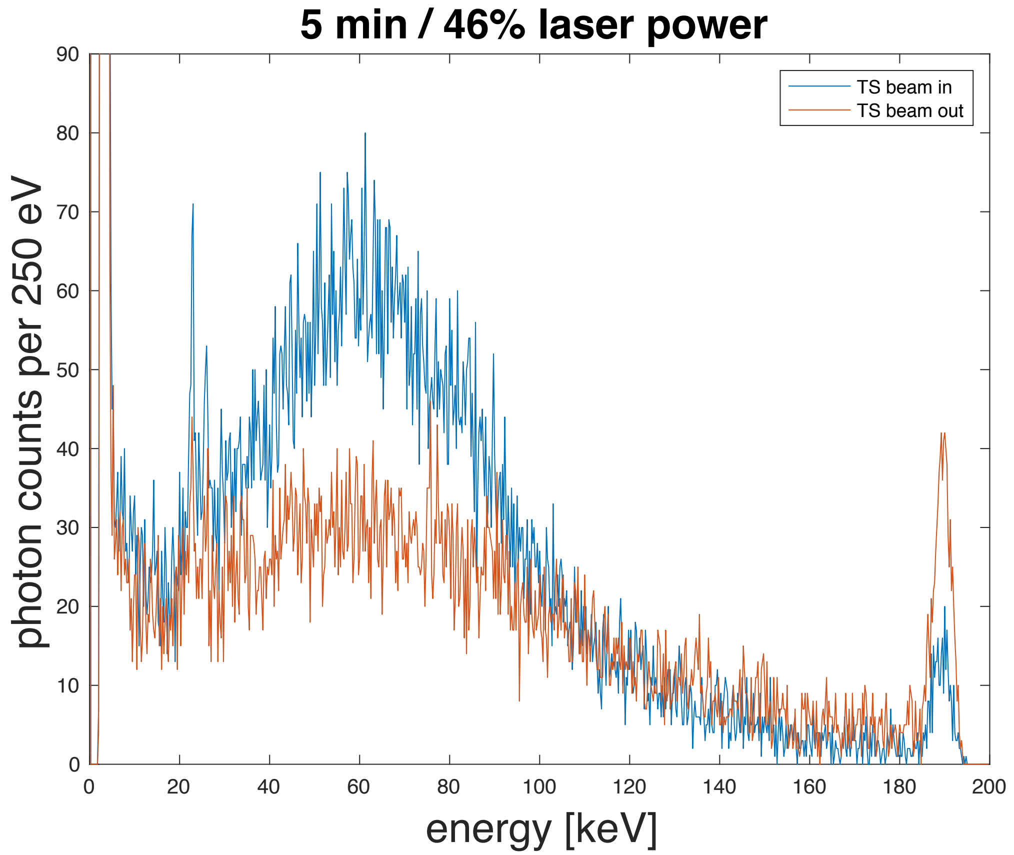
DESY
Strategy
Fund.

Bundesministerium
für Bildung
und Forschung

CFEL
SCIENCE

DESY.

FIRST PROOF-OF-PRINCIPLE EXPERIMENT

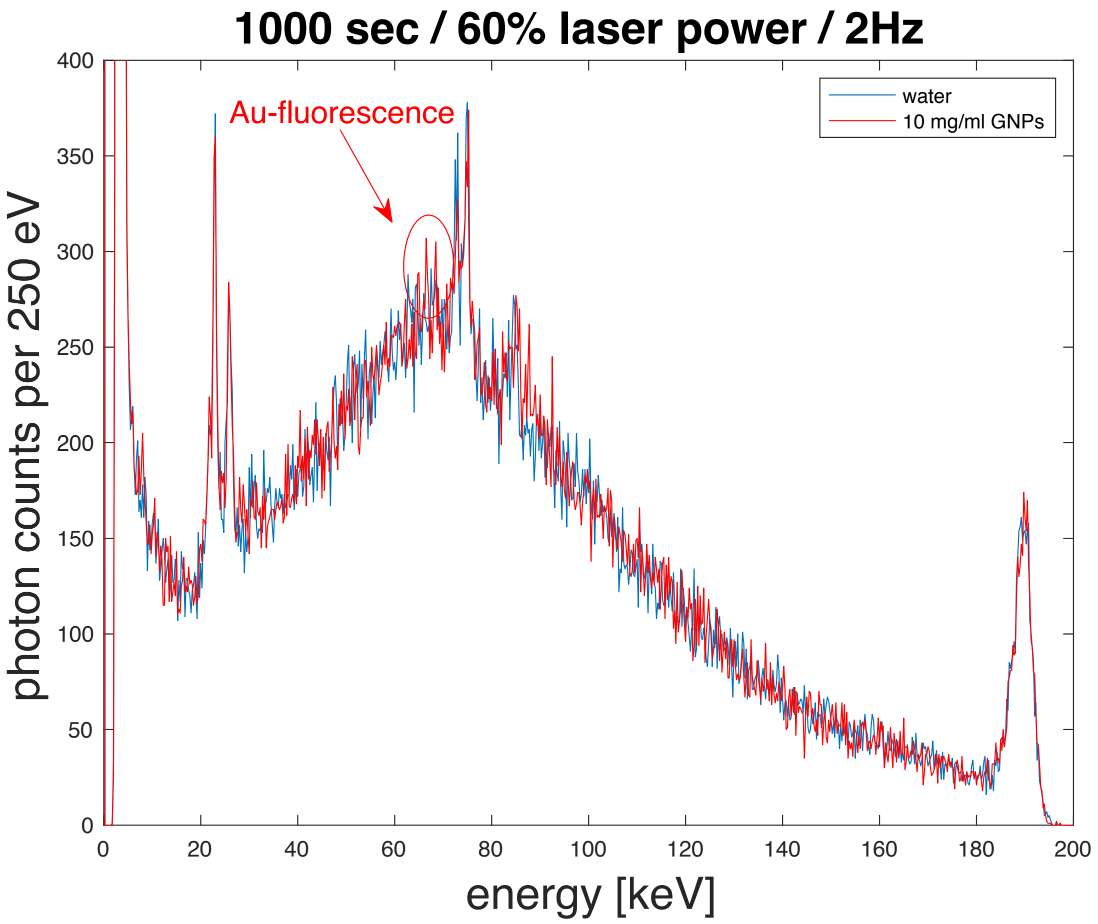


- Hexitec detector[1] at 8 meters distance from the interaction point
- 5 minutes measurement duration
- 46% laser power (2-3 pC charge, 60 MeV mean electron energy)
- Clear difference with / without Thomson scattering laser

[1] kindly loaned from CLF

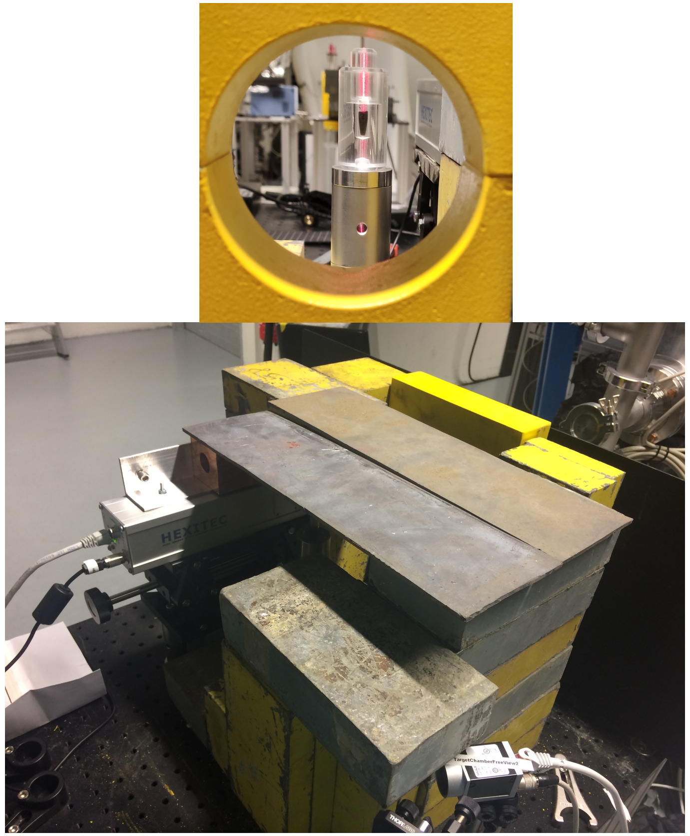
UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG
FAKULTÄT FÜR MATHEMATIK, INFORMATIK UND NATURWISSENSCHAFTEN
DESY Strategy Fund.
Bundesministerium für Bildung und Forschung
CFEL SCIENCE
DESY.

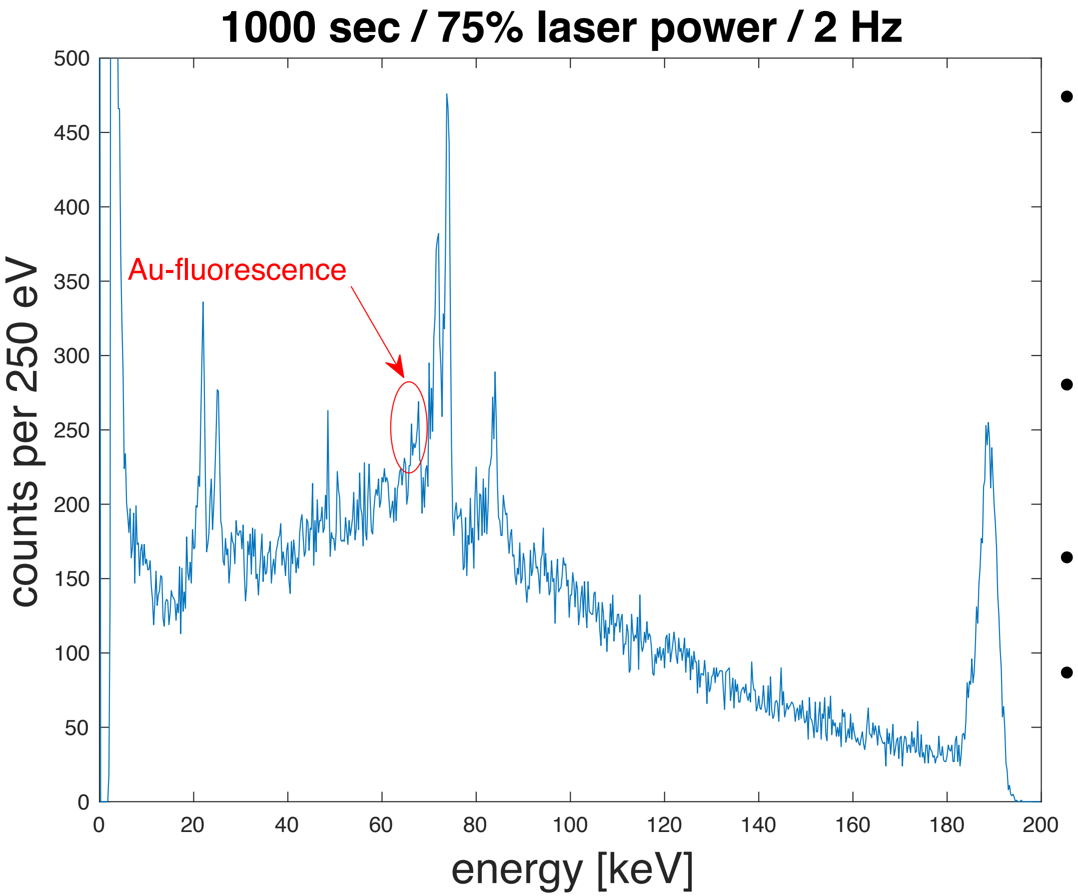
IMAGING OF GNPs IN A MOUSE PHANTOM



- 3 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 = 5.4**

IMAGING OF GNPs IN A MOUSE PHANTOM

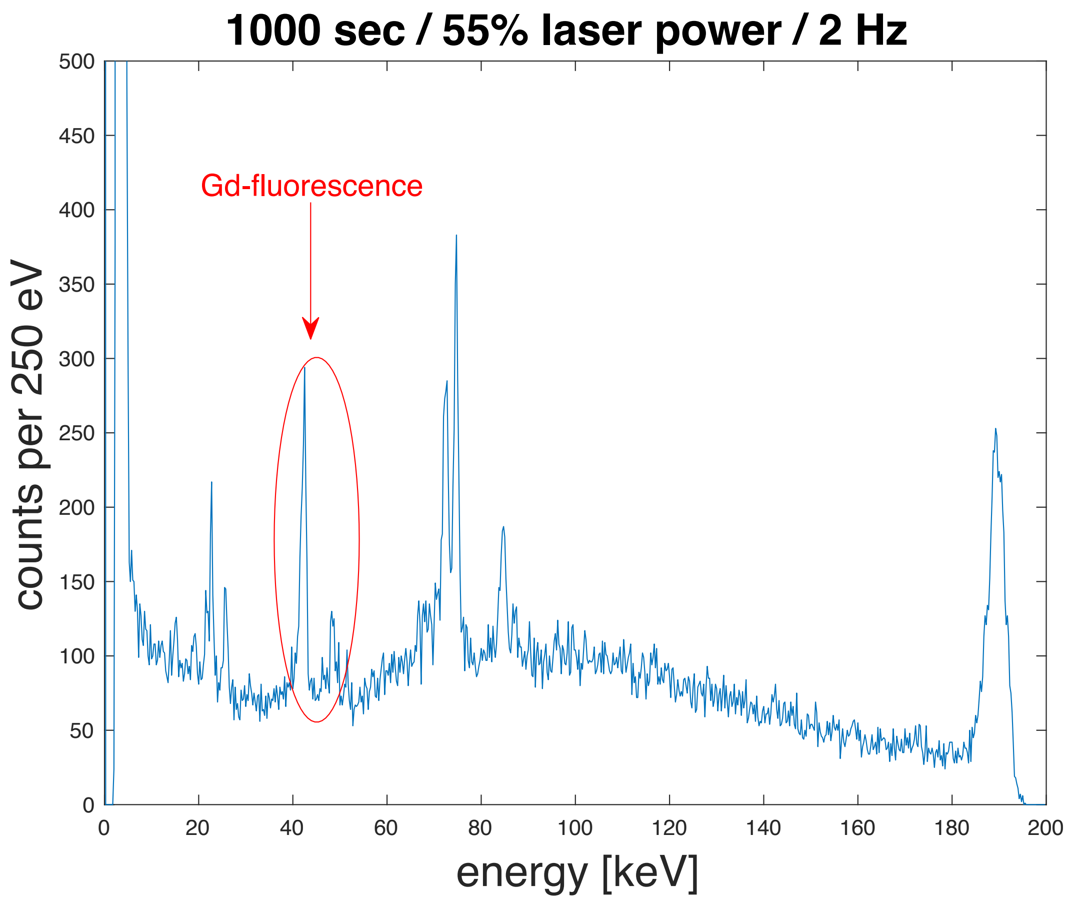




- 3 cm diameter PMMA-cylinder with 0.3 ml Eppendorf tube containing **18.87 mg/ml** GNPs
- Improved lead shielding to reduce Bremsstrahlung
- Target at 3.25 meters from interaction point
- Calculated significance **Z = 8.3**

IMAGING OF Gd-SOLUTION

- 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 = 32**
- Even K_{β}-fluorescence at 48.7 keV visible



CONTENTS

- Principle of X-ray fluorescence imaging (XFI)
- Requirements on the X-ray source & necessary improvements
- Laser-wakefield acceleration (LWFA)
- Thomson scattering (TS)
- First proof-of-principle experiment and results
- **Optimisation of the setup**

OPTIMISATION OF THE SETUP

- Improving the electron parameters:

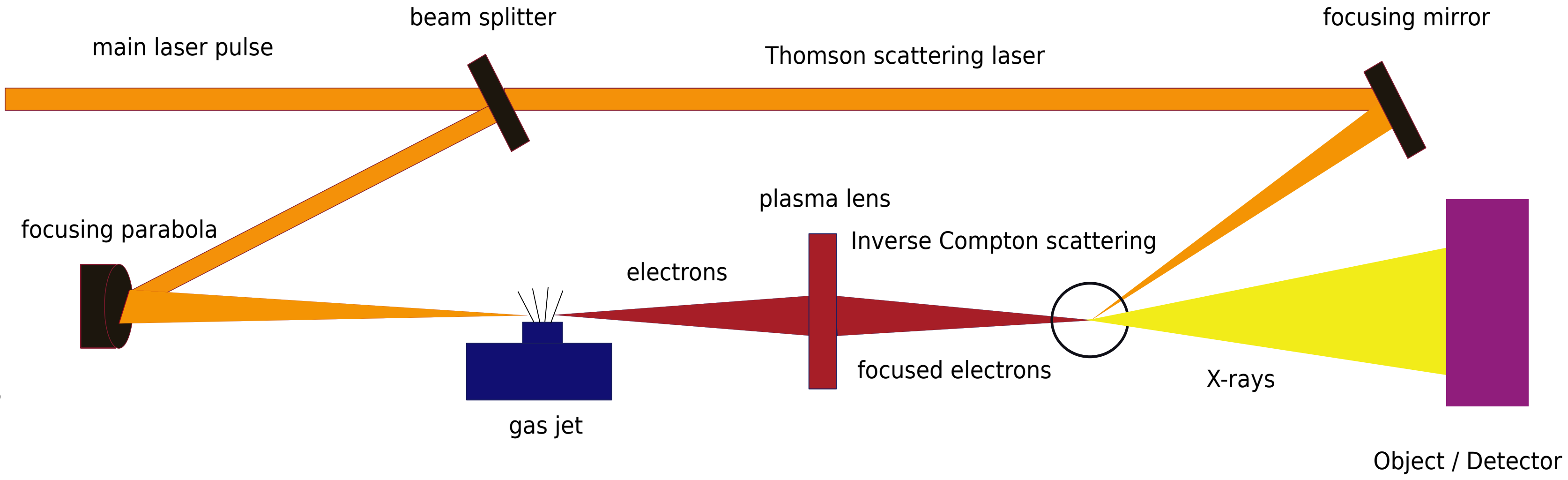
  Active Plasma Lenses
- Improving the laser parameters:

  maximising X-ray gain by

  varying laser focus and length
- Simulated result: 80 000 photons

  per shot in **90 keV ± 15 % FWHM**

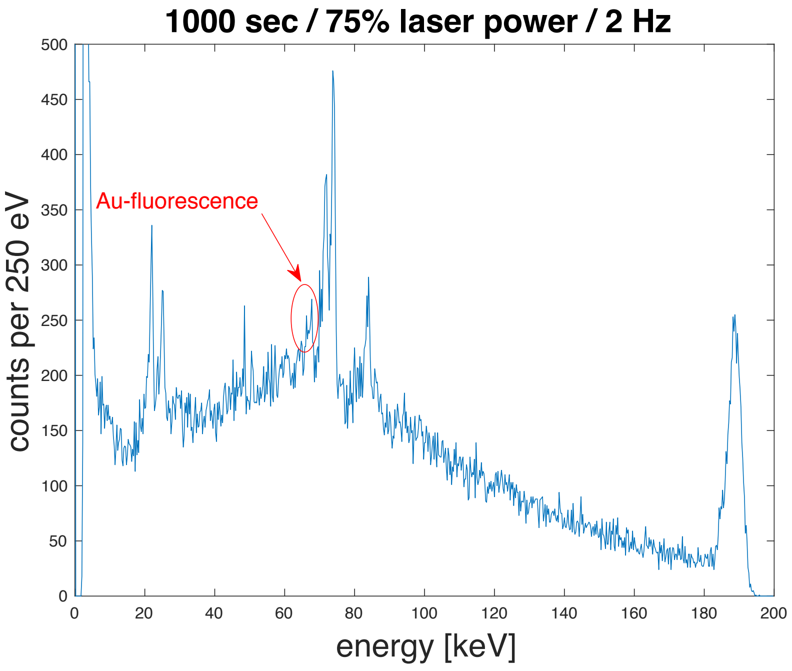
  (ideal parameters for XFI)



Schematic of the optimised setup with an active plasma lens

SUMMARY

- XFI is a new medical imaging modality with applications e.g. in pharmacokinetics or tumor diagnostics
- Developments in accelerator technologies enable to build compact and high-brightness X-ray sources
- Thomson scattering with laser-wakefield acceleration is an excellent driver for XFI with desired properties



- Proof-of-principle experiments demonstrated XFI measurements with a laser-driven Thomson X-ray source
- Implementation of active plasma lens will optimise incident Thomson spectrum for XFI by reducing effective spectral width of electrons