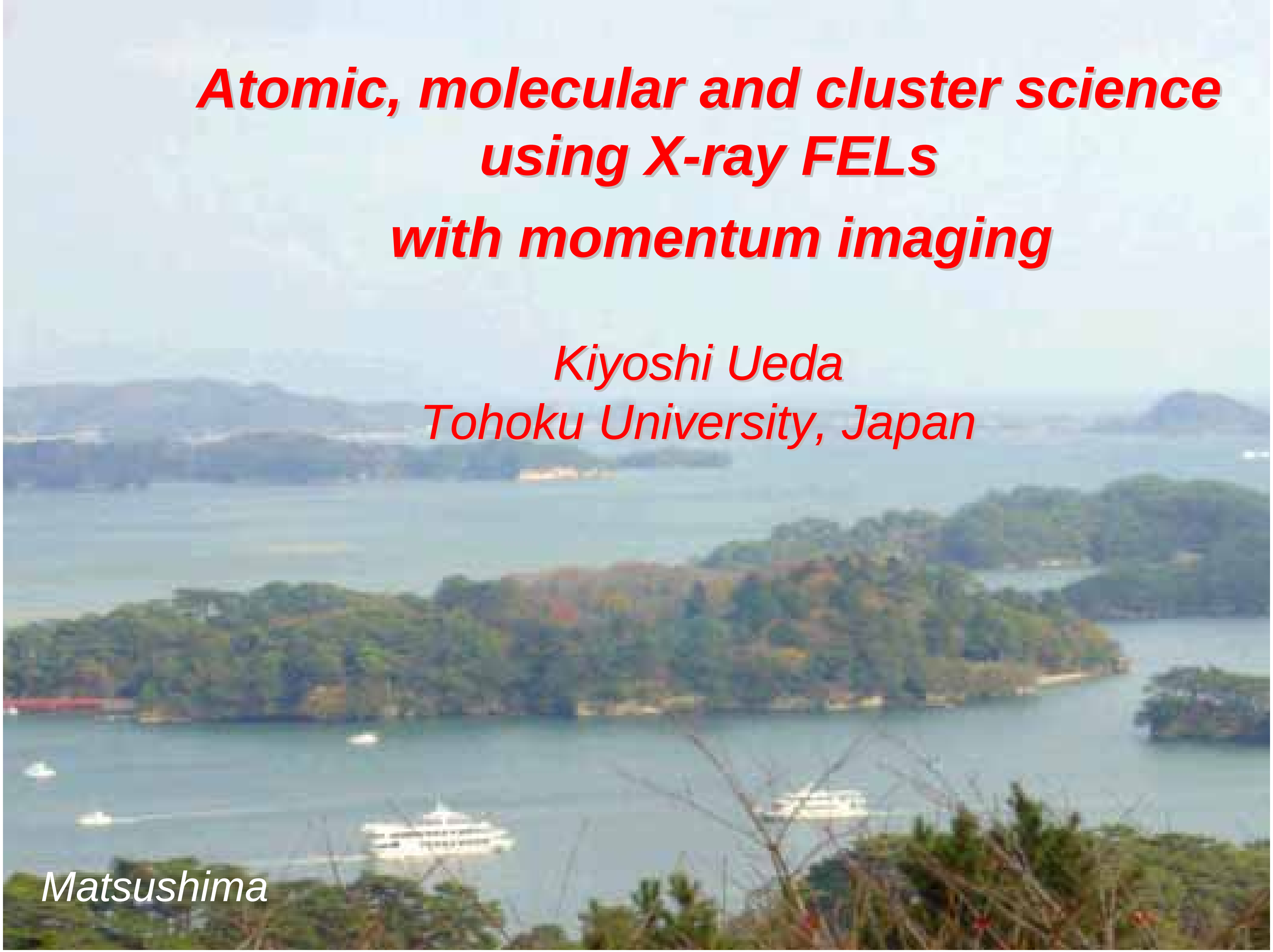
Atomic, molecular and cluster science using X-ray FELs
with momentum imaging

Kiyoshi Ueda
Tohoku University, Japan



X-FEL and EUV-FEL Facility in Japan

X-FEL (will be in operation in 2010)

EUV-FEL
(in operation)

SPring-8

Outline

1. Introduction to ion momentum imaging

Historical background

Towards zero dead-time detections

Apparatus for ion momentum imaging

2. EUVFEL experiments

3-1. Higher harmonics probed by He recoil momentum spectroscopy

3-2. Sequential double and triple ionization of atoms and diatoms

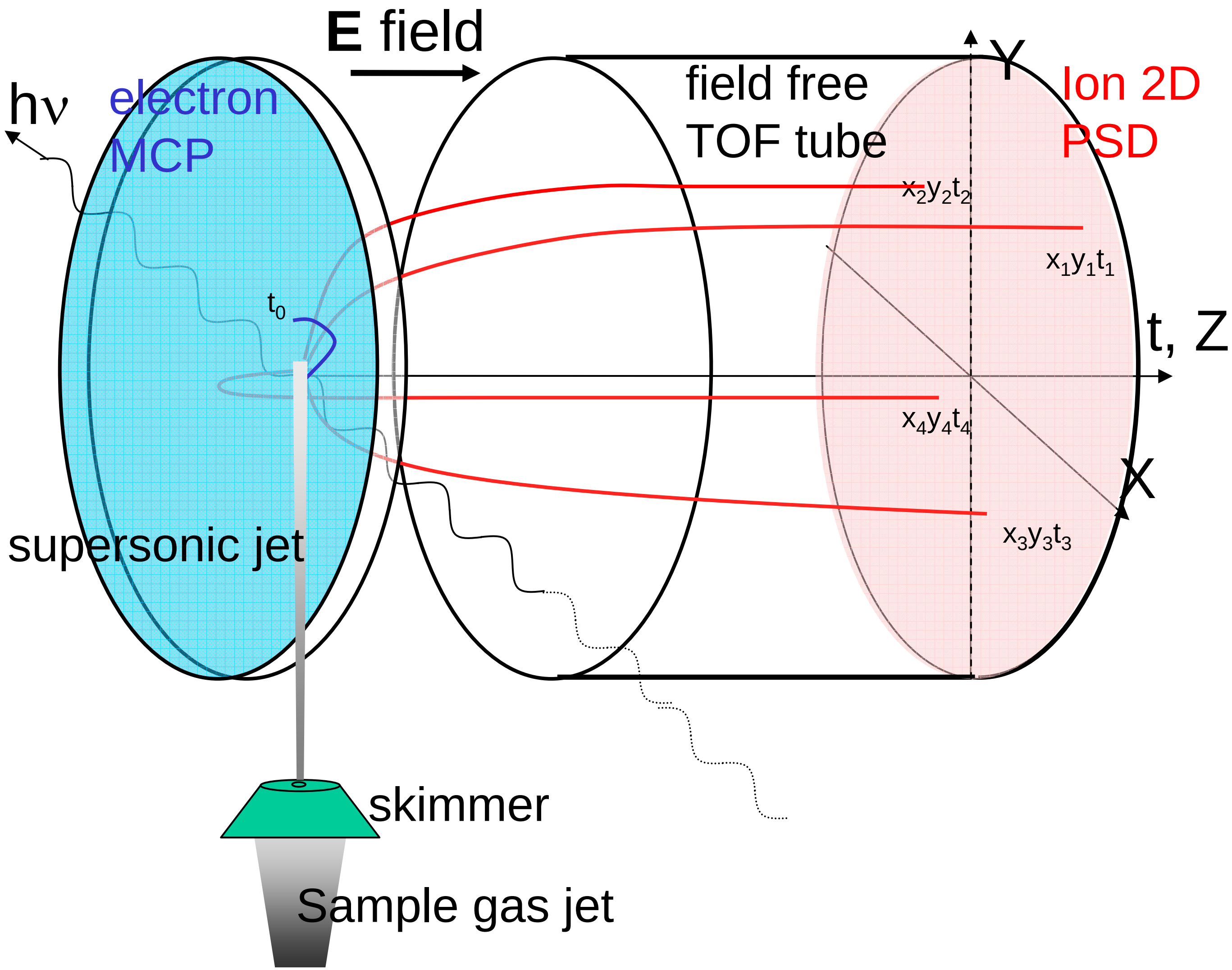
3-3. Step-wise multiple ionization of rare-gas clusters

3. Toward future, toward XFEL experiments

Apparatus for e and ion momentum imaging

Comments on single-shot X-ray diffraction microscope

Multiple-ion coincidence imaging setup



position & time of flight (x,y,t) → *3D momentum of each particle*

History of developments for momentum imaging techniques

Combining PSD with TOF technique –> momentum imaging

Multi-anode PSD: multi-hit capability

F. Heiser, U. Becker (FHI, Germany), M. Lavollée (LURE, France)

Delay-line anode PSD:

J.H.D. Eland (Oxford, UK)

O. Jagutzki, H. Schmidt-Böcking (Frankfurt, Germany)

Dead-time problem – solved by the development of HEX anode

(resort routine: by Achim Czasch)

Electronics:

TDC (for SR and high rep. rate laser experiments)

Multi-channel (16ch) multi-hit (up to 8 or more), common stop capability

TDC-8 (Roentdek) developed by J. Eland

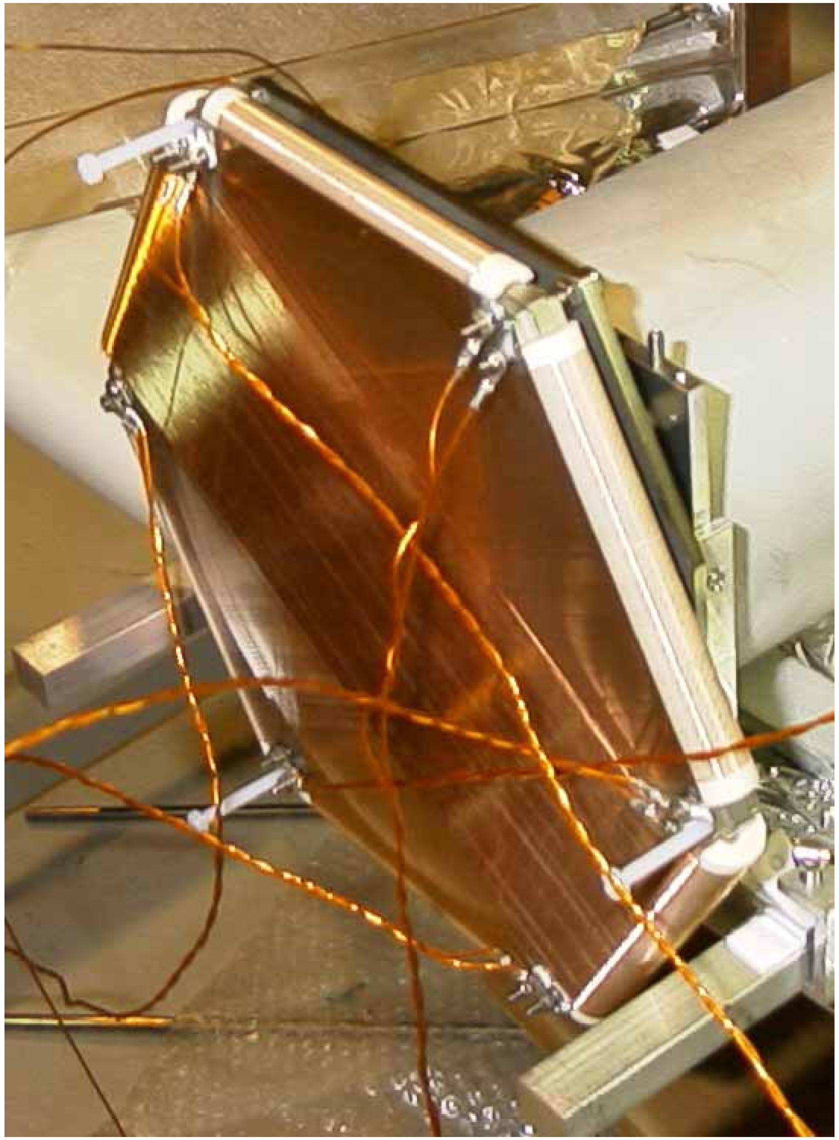
(Multi-channel TAC/TDC developed in Japan)

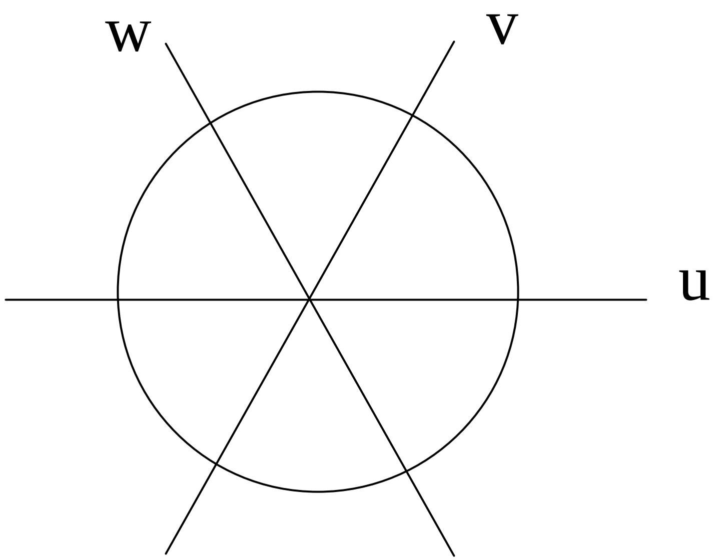
New TDC-8HP (by Till Jahnke)

Digitizer (for FEL)

Soft-CFD (by Lutz Faucer, Achim Czasch)

Hexagonal delay-line anode

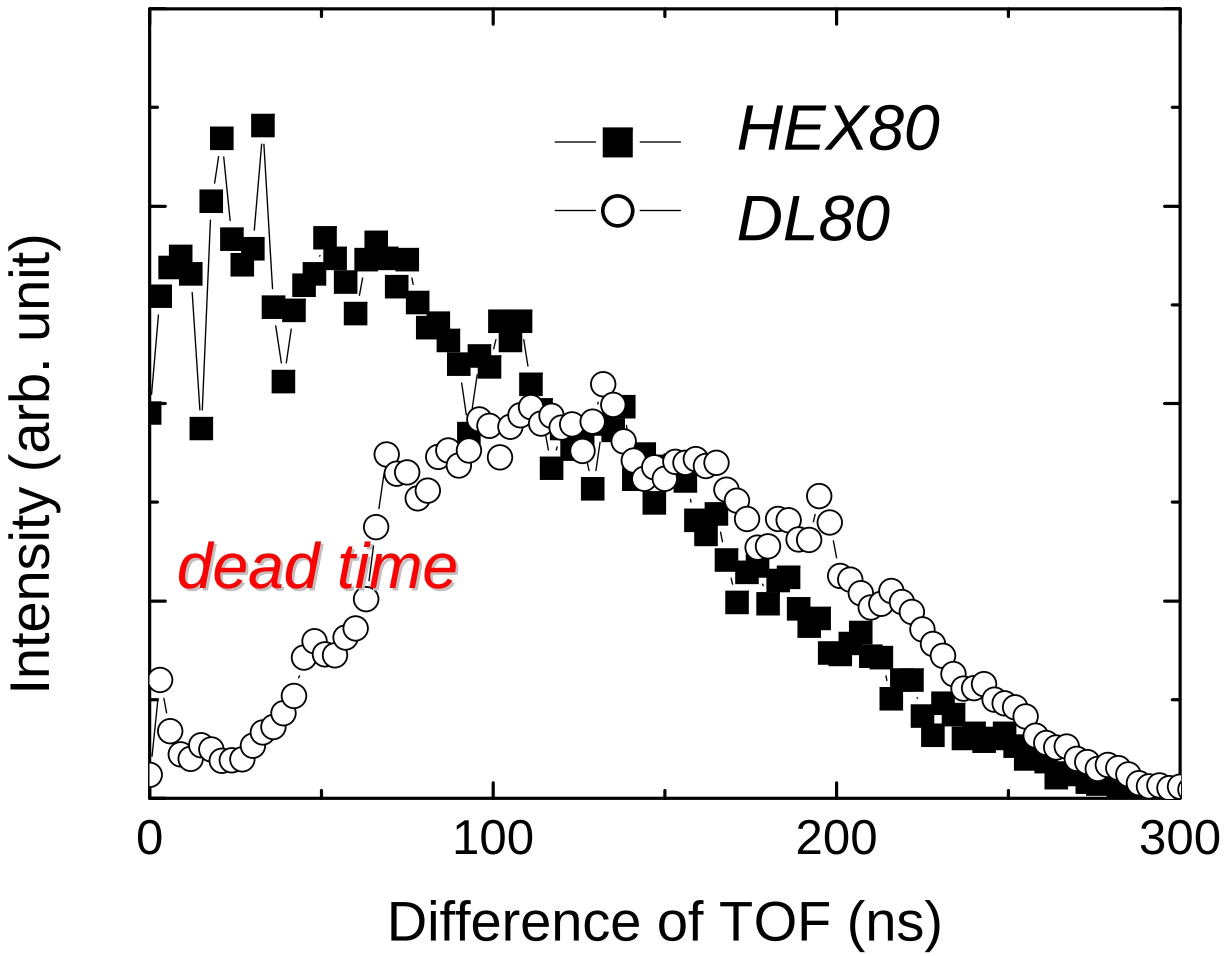




Redundant information from a three-layer delay line anode and a sophisticated logic is necessary to reconstruct time and positions for more than one "hit"s in 100 ns.

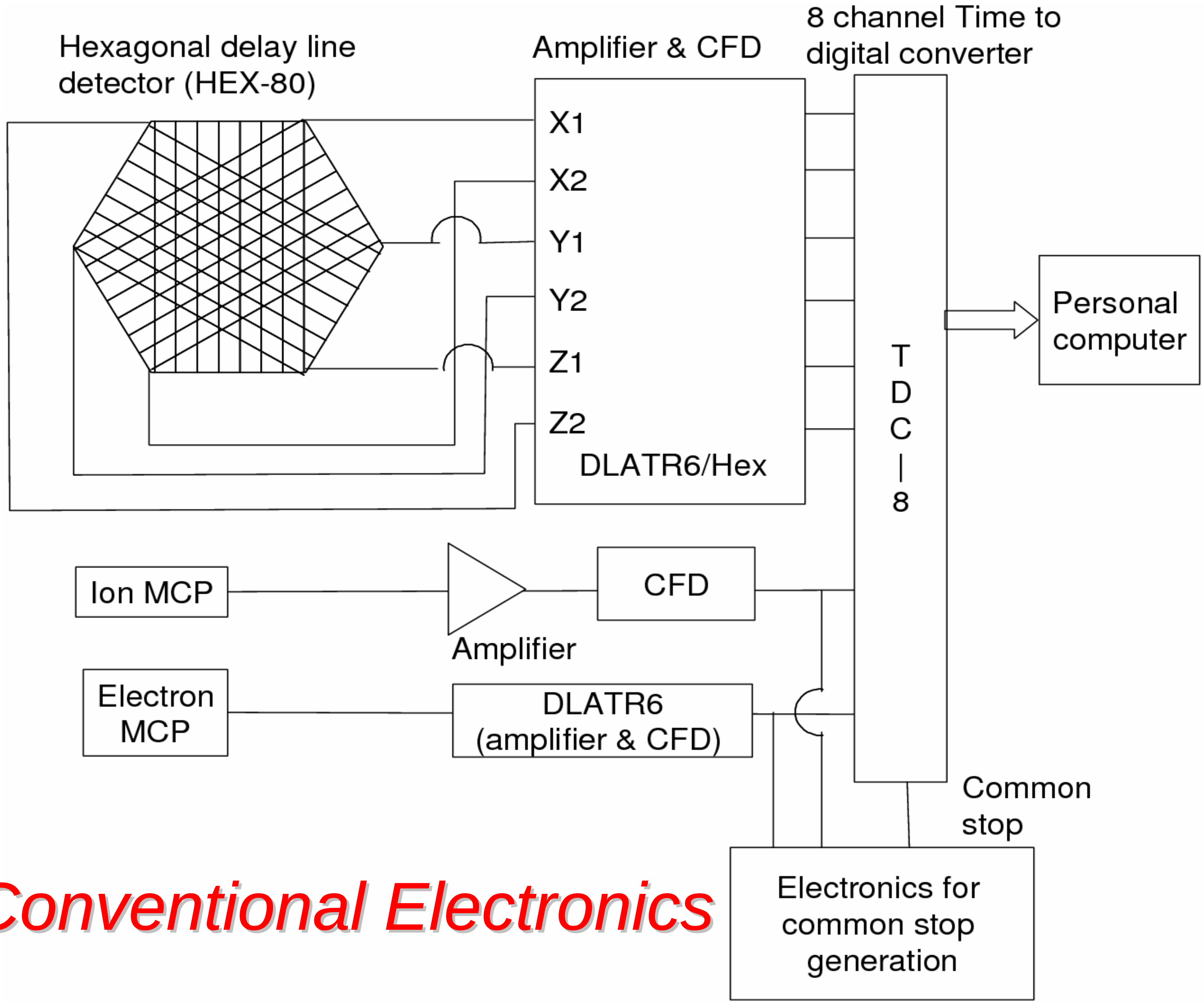
Roentdek, A. Czasch

Towards zero dead time detection



Distribution of events as a function of the TOF difference of the two O^+ ions produced from CO_2^{++}

N. Saito

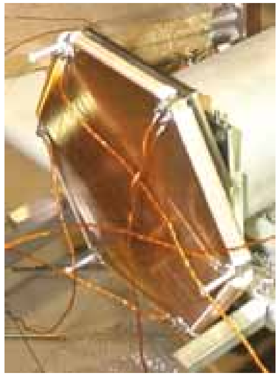


Conventional Electronics

Towards zero dead-time detection system

Digitizer +software CFD

L. Faucar



HEX detector

Digitizer
Acqiris DC282 x2
8 GS/s 10 bit

PC

software CFD

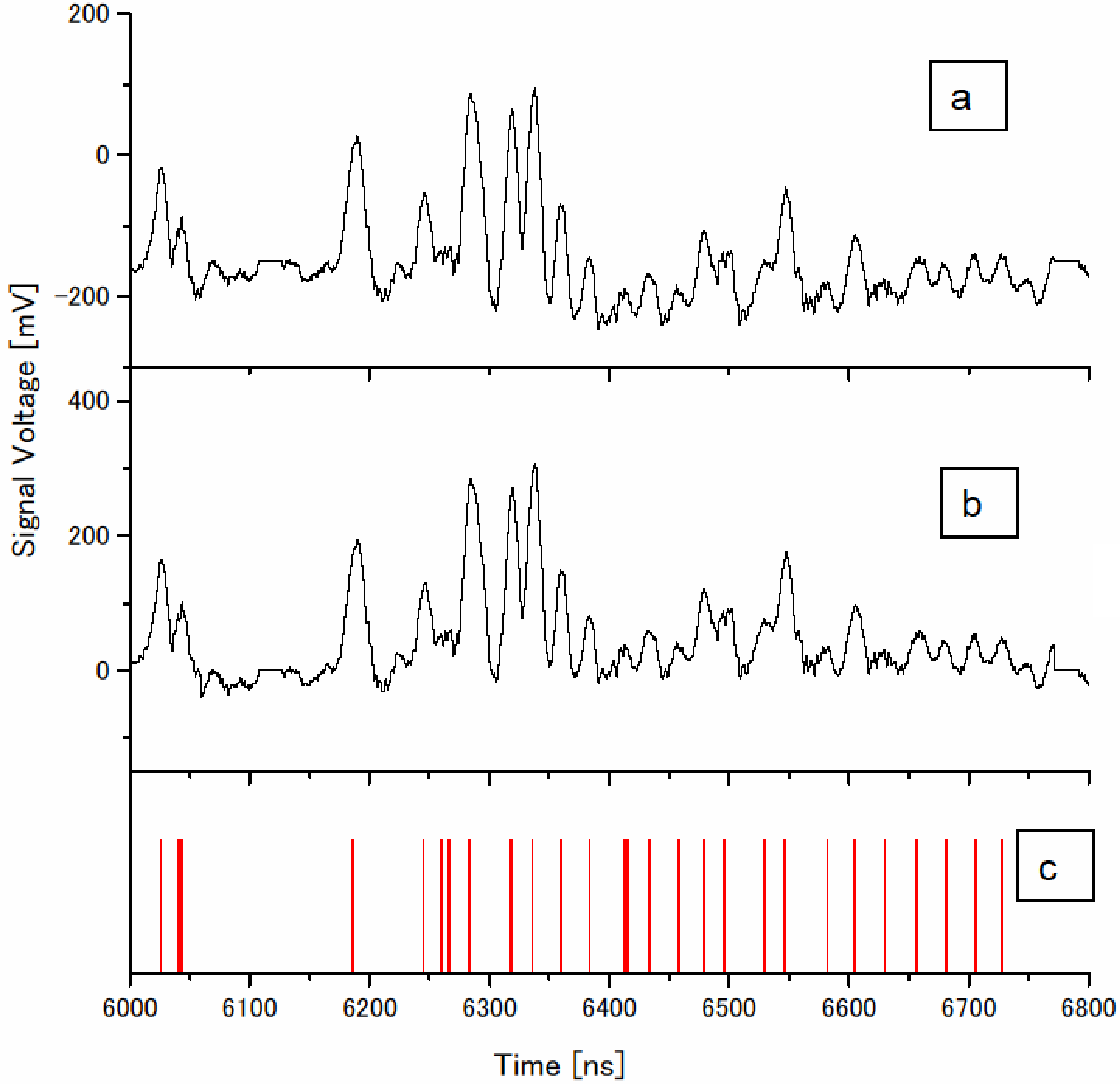
Extraction of the time information from the waveform

- TOF spectrum
- Position
- Momentum

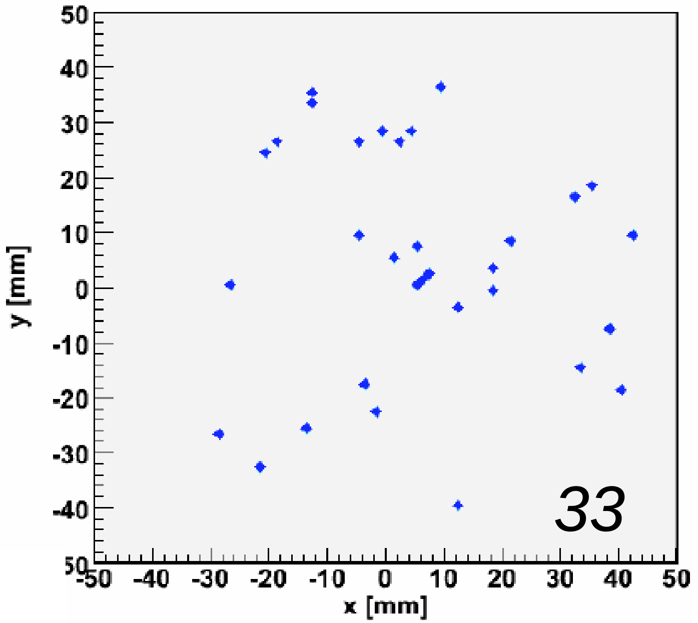
Analog signals are fed to PC

Software CFD

Kr⁺ via Coulomb explosion of Kr clusters irradiated by FEL



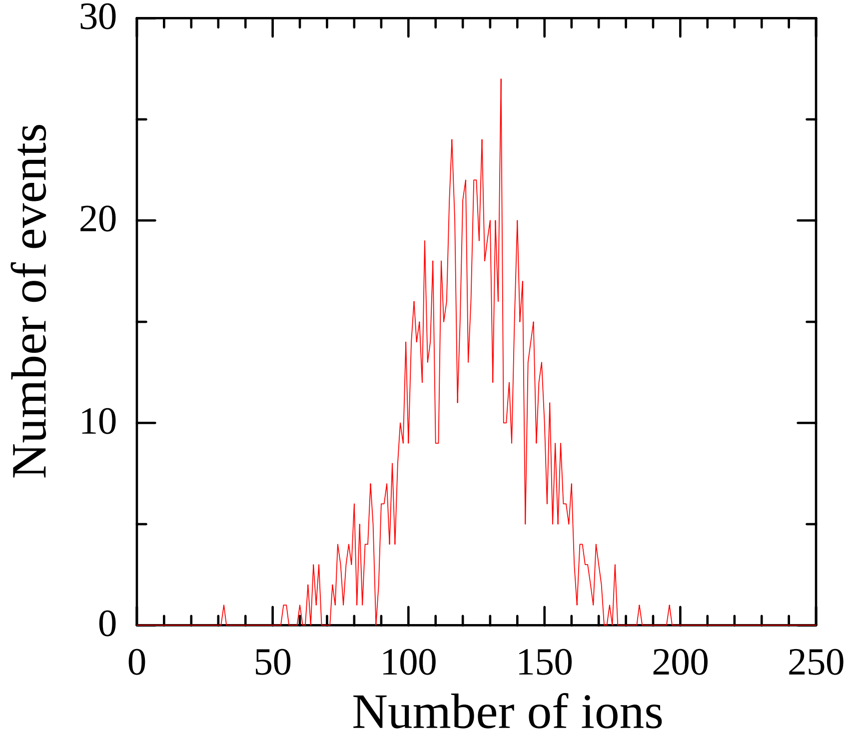
27

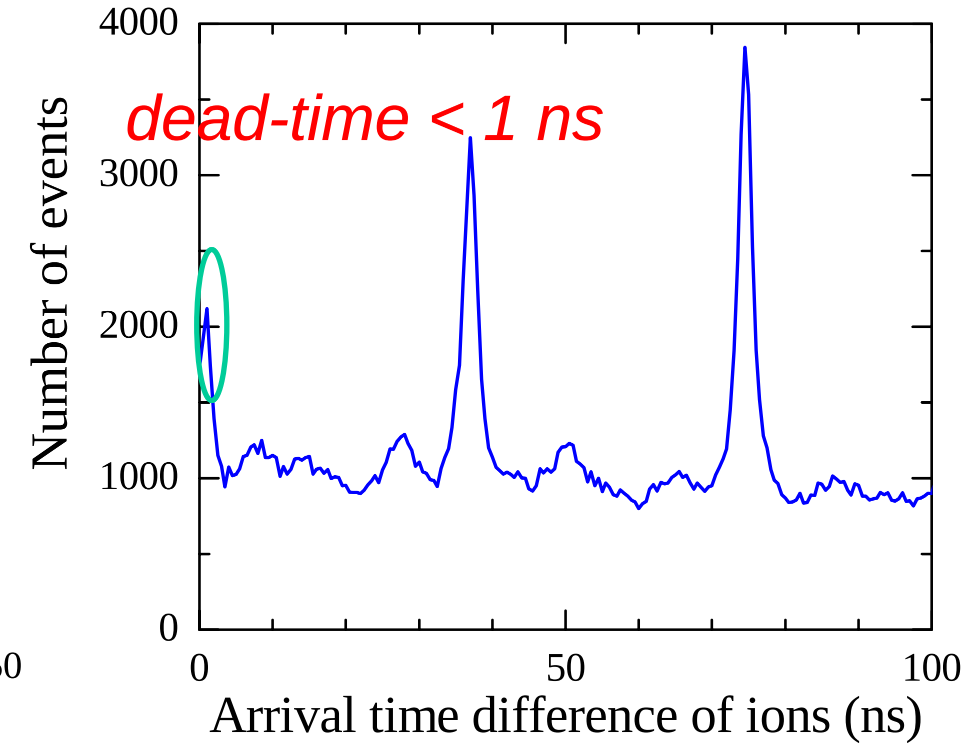


Motomura et al

Zero dead-time measurements

Coulomb explosion experiment of Kr clusters by FEL

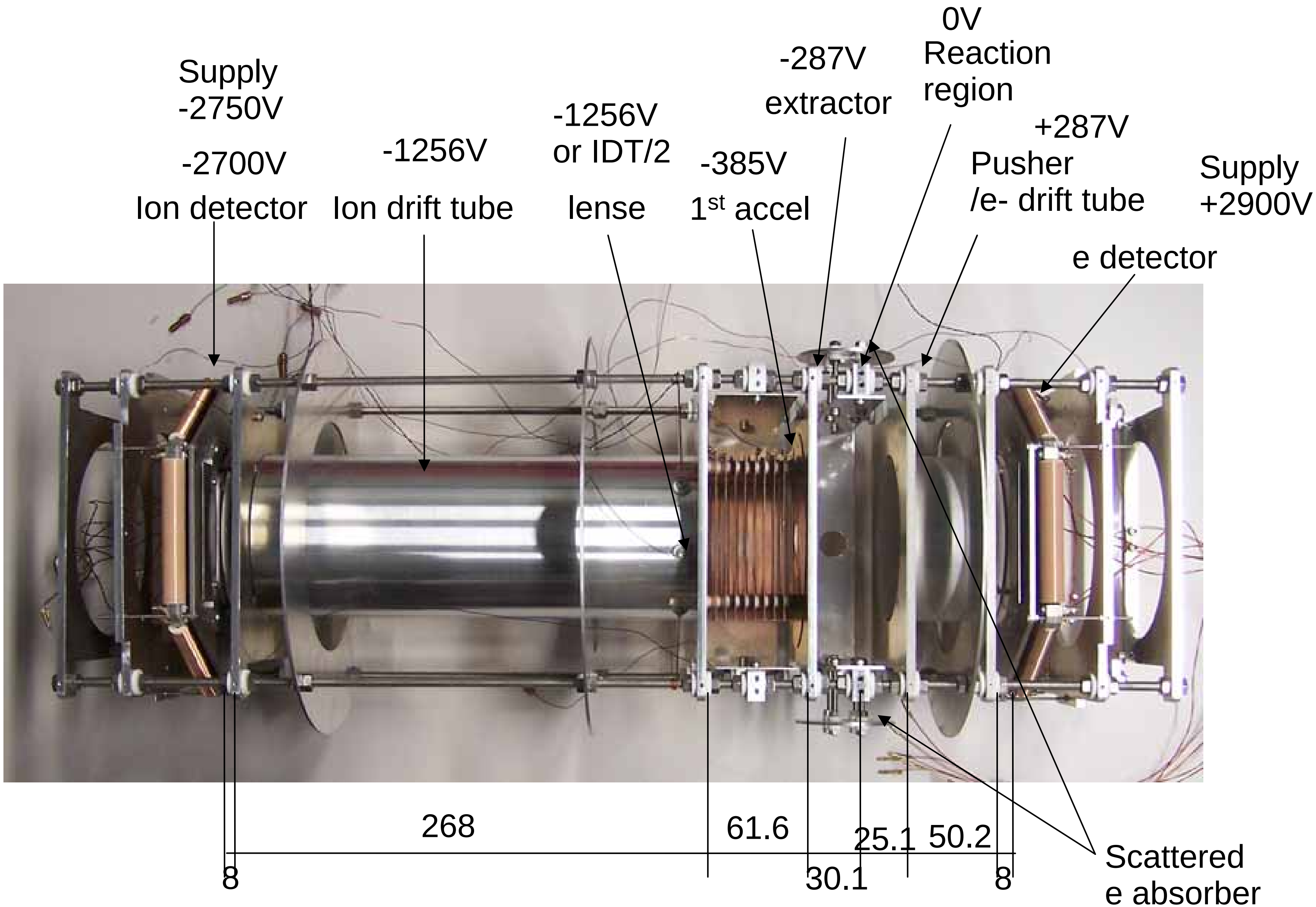




Motomura, Czasch, Faucar et al

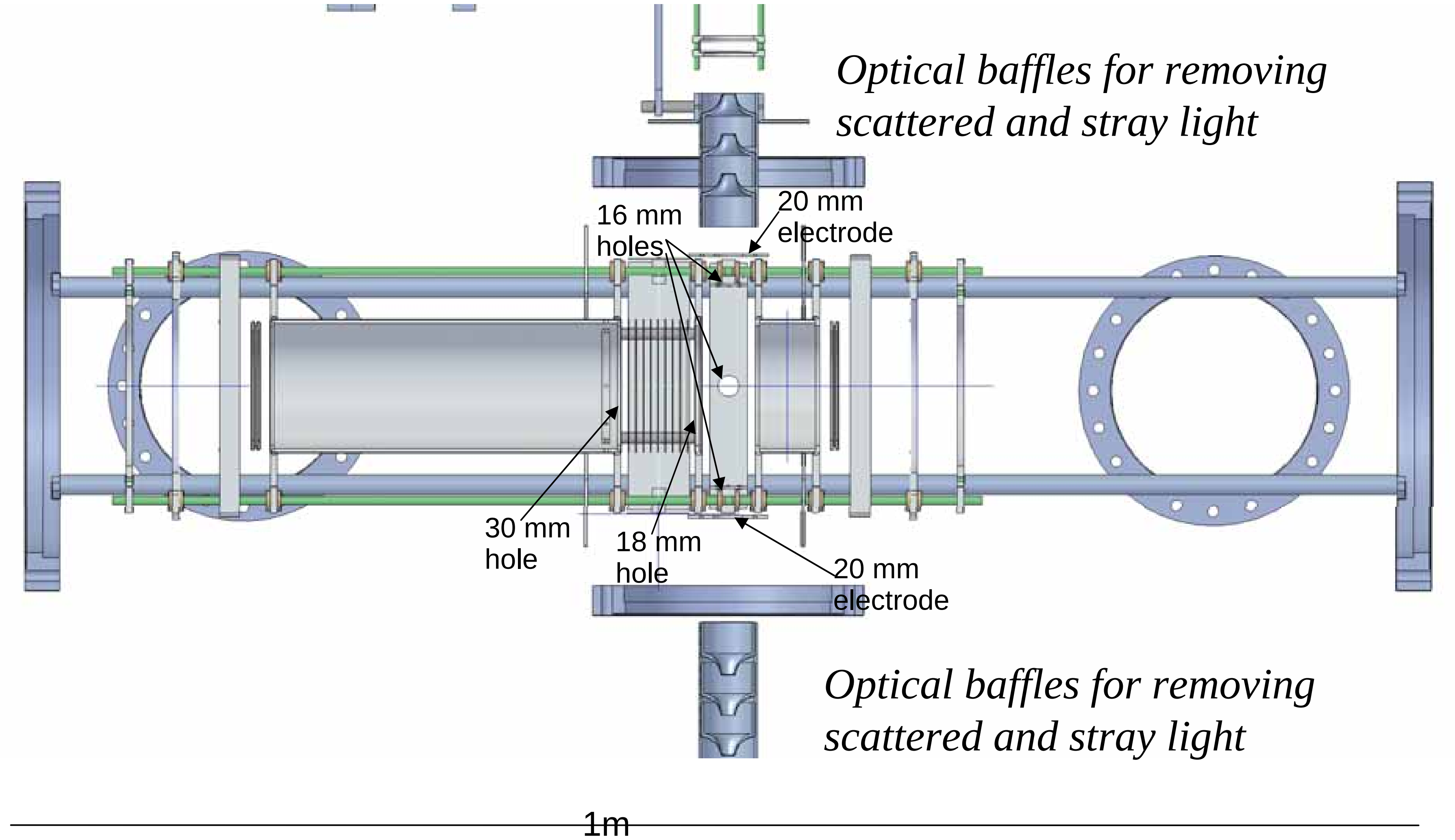
Spectrometer and typical voltage conditions

Two-stage acceleration + velocity focusing optics



Liu et al

Spectrometer mounted in the chamber



Liu, pruemer et al

EUV-FEL Experiments :

Mar 10 – Mar 21, 2008

Setup version 1.0

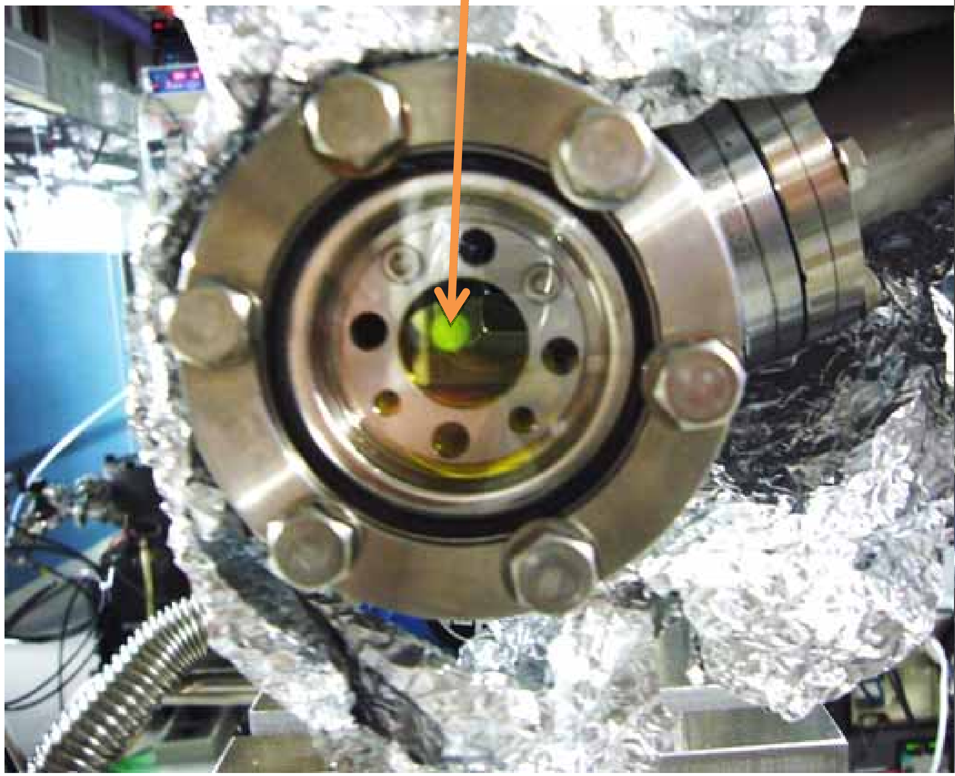
May 26 – June 6, 2008

Setup version 1.1

Sep 29 – Oct 3, 2008

Setup version 2.0

EUV-FEL light



Multiple ionization of rare gas clusters by intense EUV-FEL at SPring-8

Tohoku U.
H. Fukuzawa
X.J. Liu
G. Pruemper
M. Okunishi
K. Shimada
K. Ueda
Apparatus& Measurements

Tohoku U.
T. Harada
M. Toyoda
M. Yanagihara
M. Yamamoto
Optics

Kyoto U.
H. Iwayama
K. Nagaya
M. Yao
Cluster source

AIST
K. Motomura
N. Saito
Analysis software

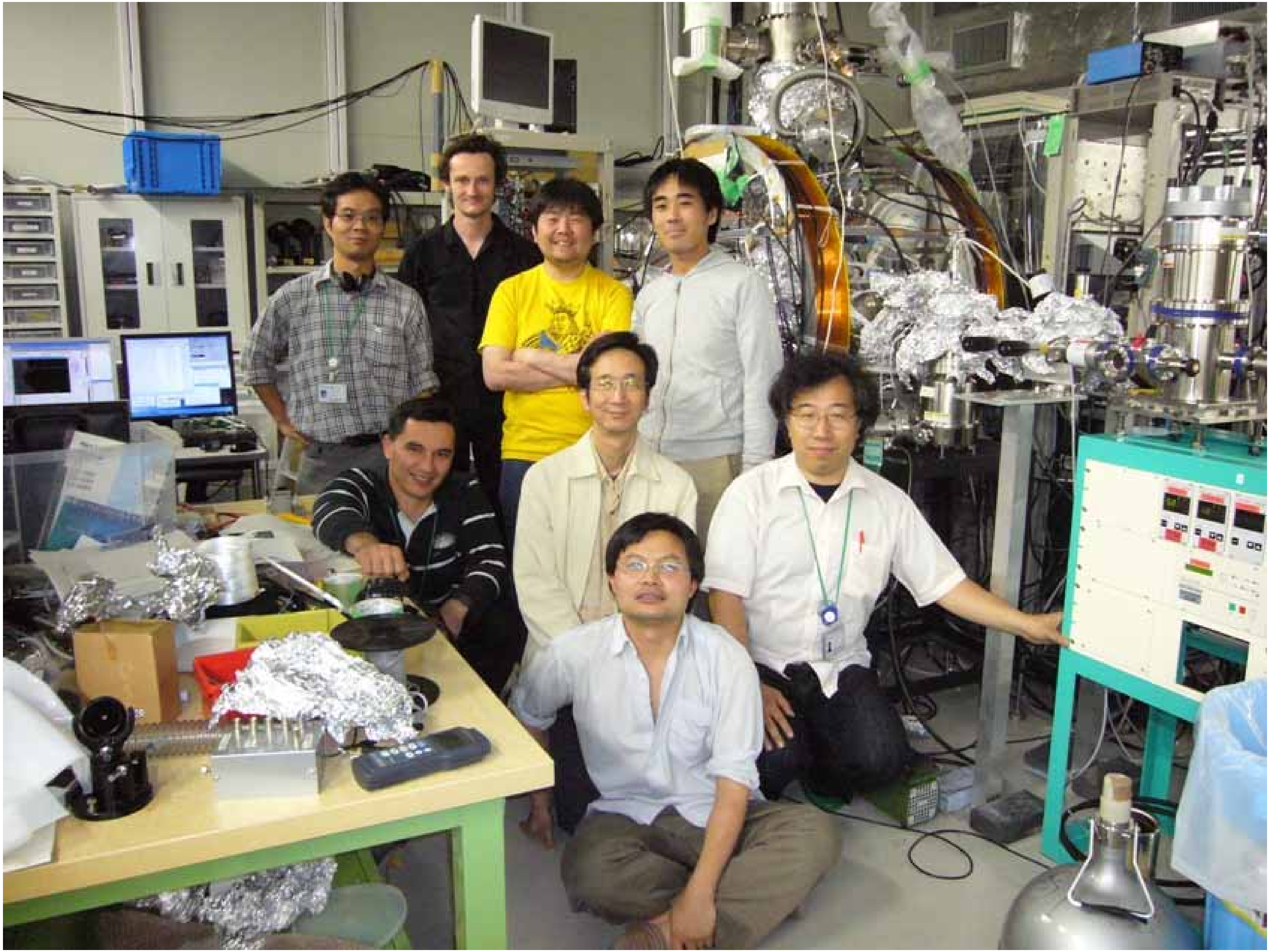
MPI Heidelberg
A. Rudenko
J. Ullrich
Measurements

Frankfurt U.
L. Foucar
A. Czasch
R. Doerner
Acquisition software

RIKEN
M. Nagasono
A. Higashiya
M. Yabashi
T. Ishikawa
R. Tanaka
Light source

RIKEN/JASRI
H. Kimura
H. Ohashi
Beam line

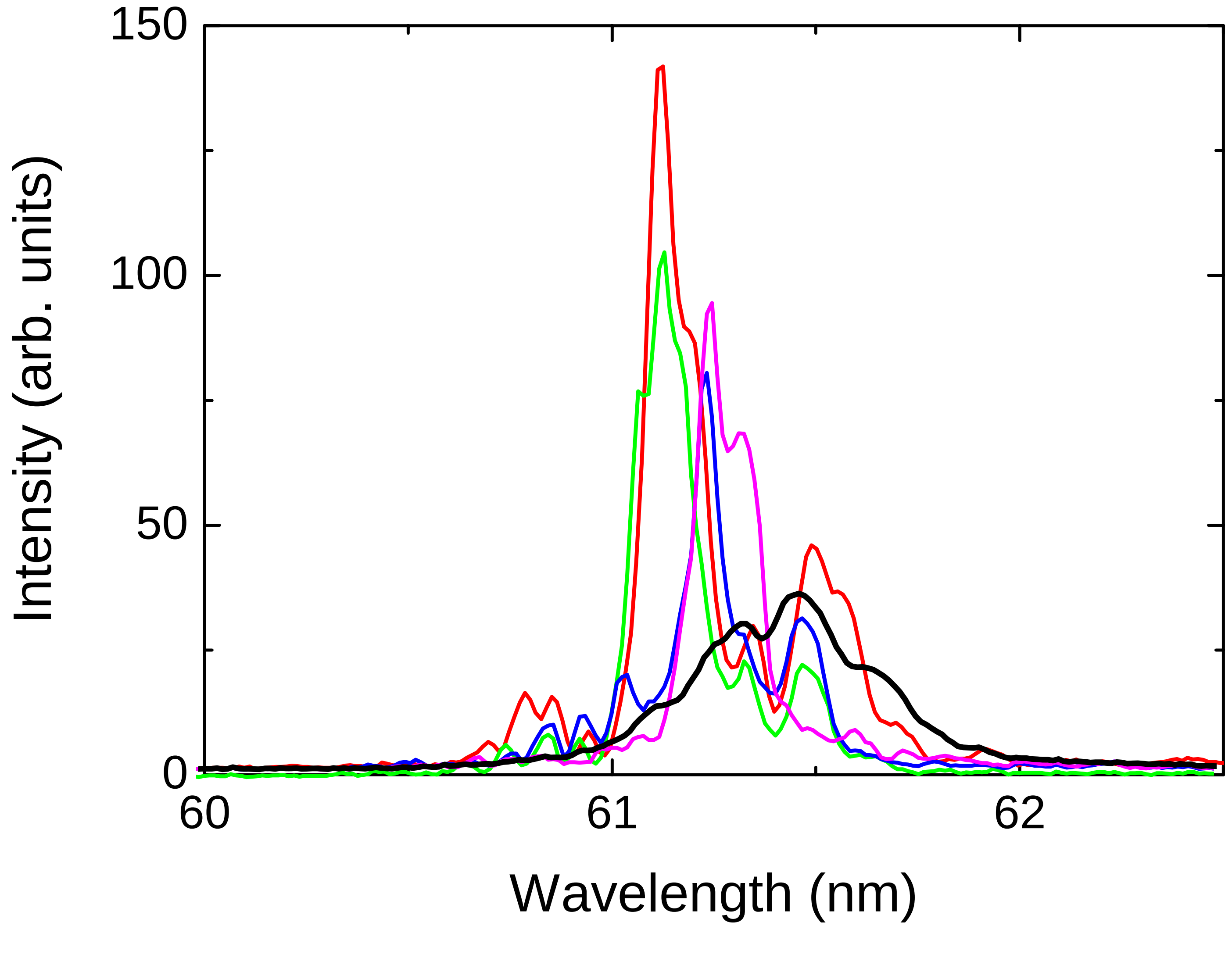
Special Thanks
RIKEN SCSS test accelerator operation group
IMRAM technical service section, Tohoku U.
A. Belkacem & LBL optics group
Budget support: MEXT, JSPS, MPG



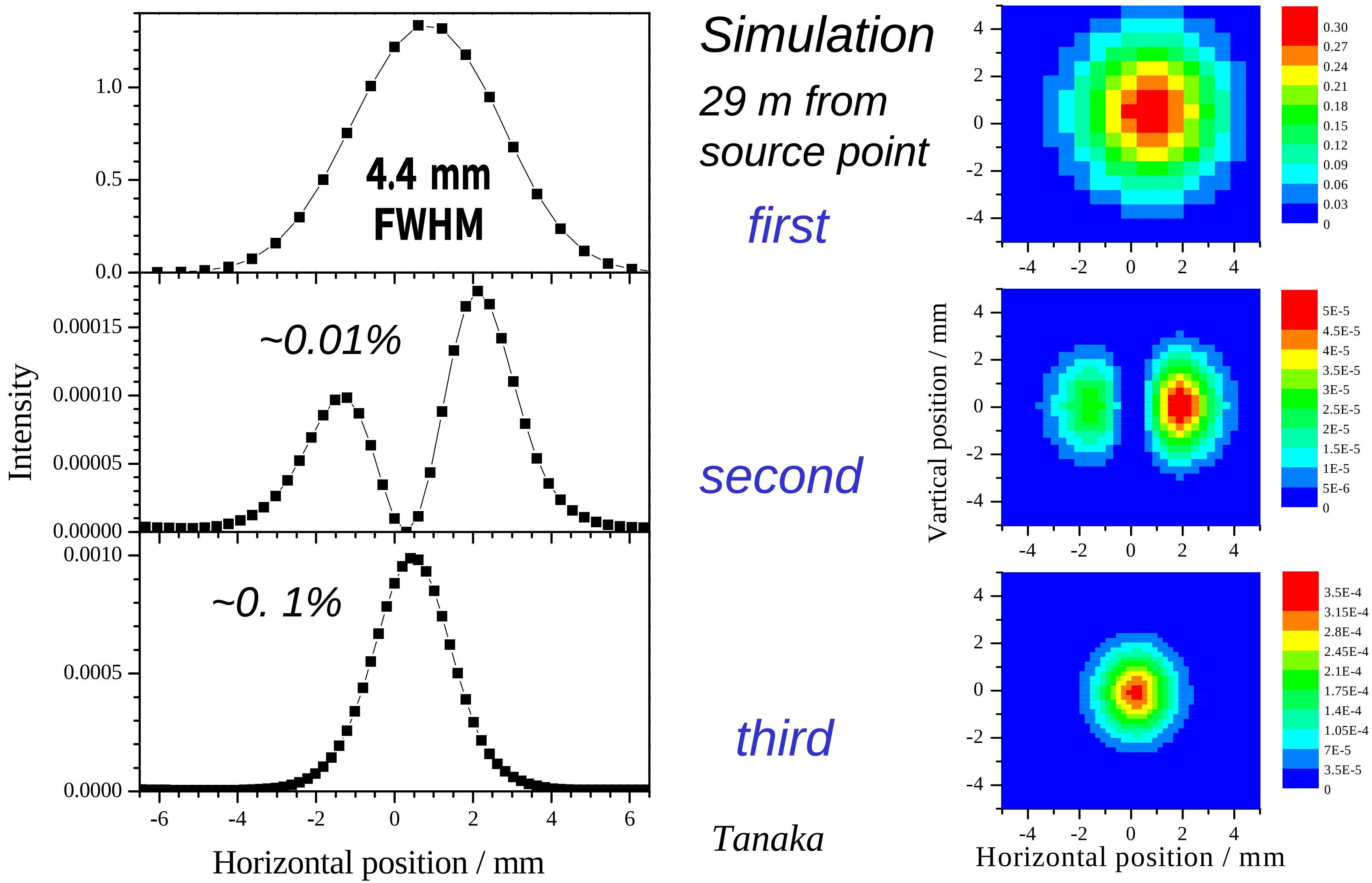
Characteristics of EUV-FEL

Energy range	**51 - 61 nm (20 - 24 eV)**
Band width	< 1 %
Pulse Energy	> 10 μJ at 61 nm
Stability of pulse energy	< 20 %
Pulse width	~ 100 fs
Period of Bunch	10 Hz (60 Hz in future)
Polarization	Horizontal (> 99 %)
Higher harmonics at 54 nm	Second < 0.1 % Third < 1 %

Example of EUV-FEL spectra

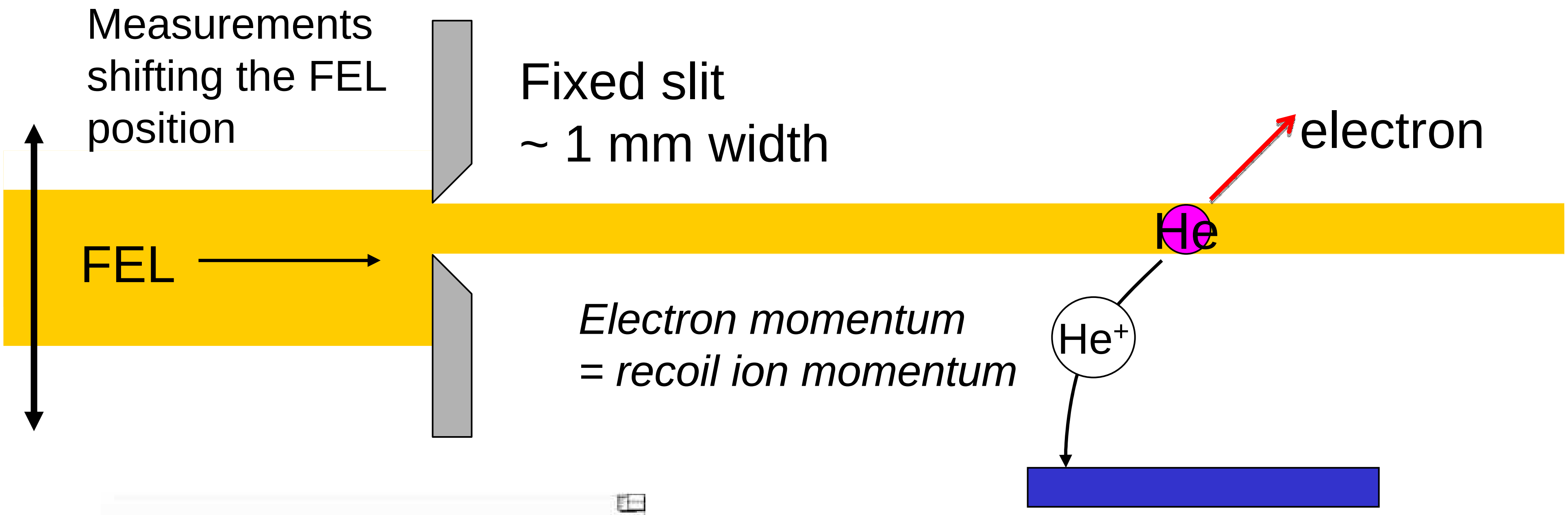


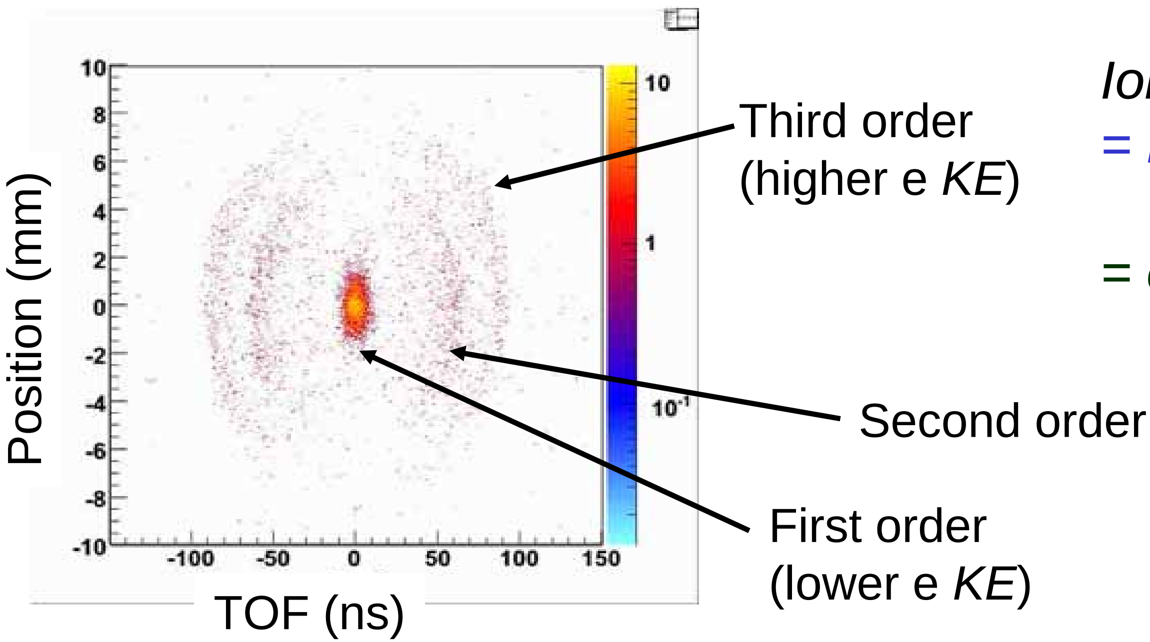
Higher order harmonics



Task: measurements of relative intensities and spatial distributions

Intensity distribution measurements for the higher order lights



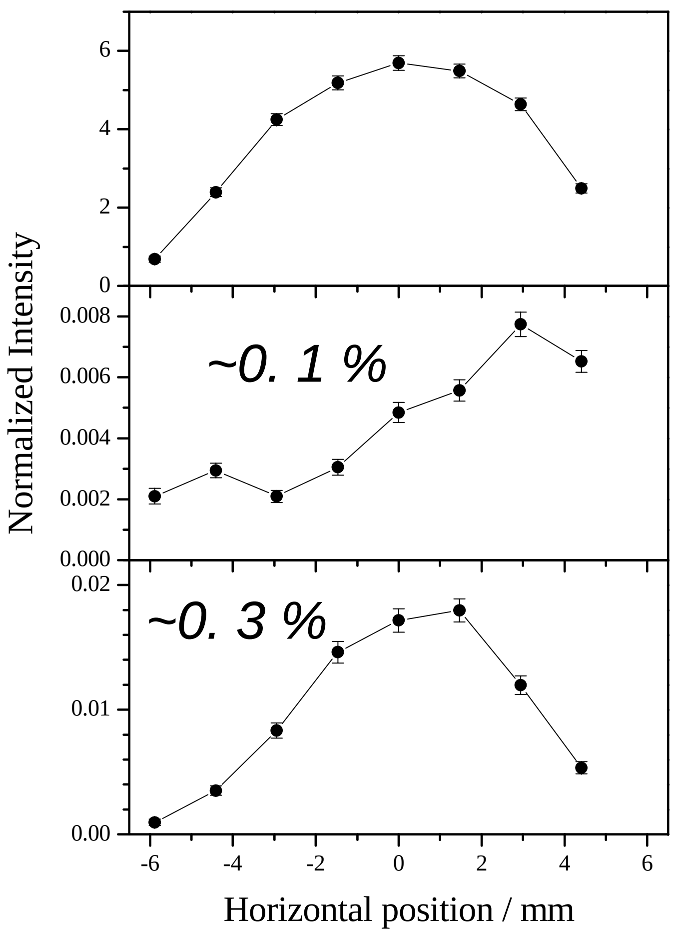


Ion momentum imaging
= Recoil-ion momentum spectroscopy
= energy-resolved electron angular-distribution measurements

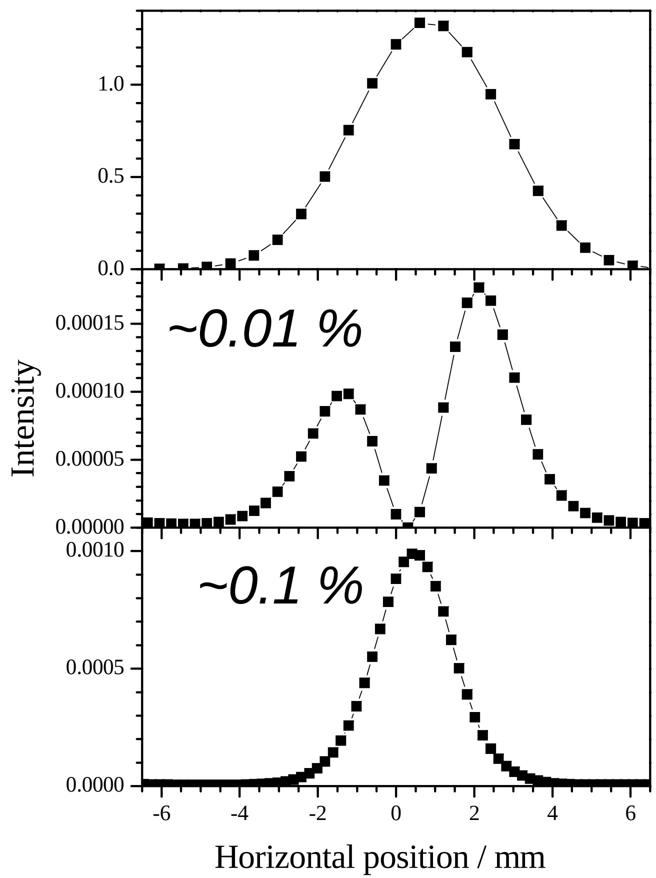
Liu et al

Intensity distributions for the higher order lights

measured



simulated

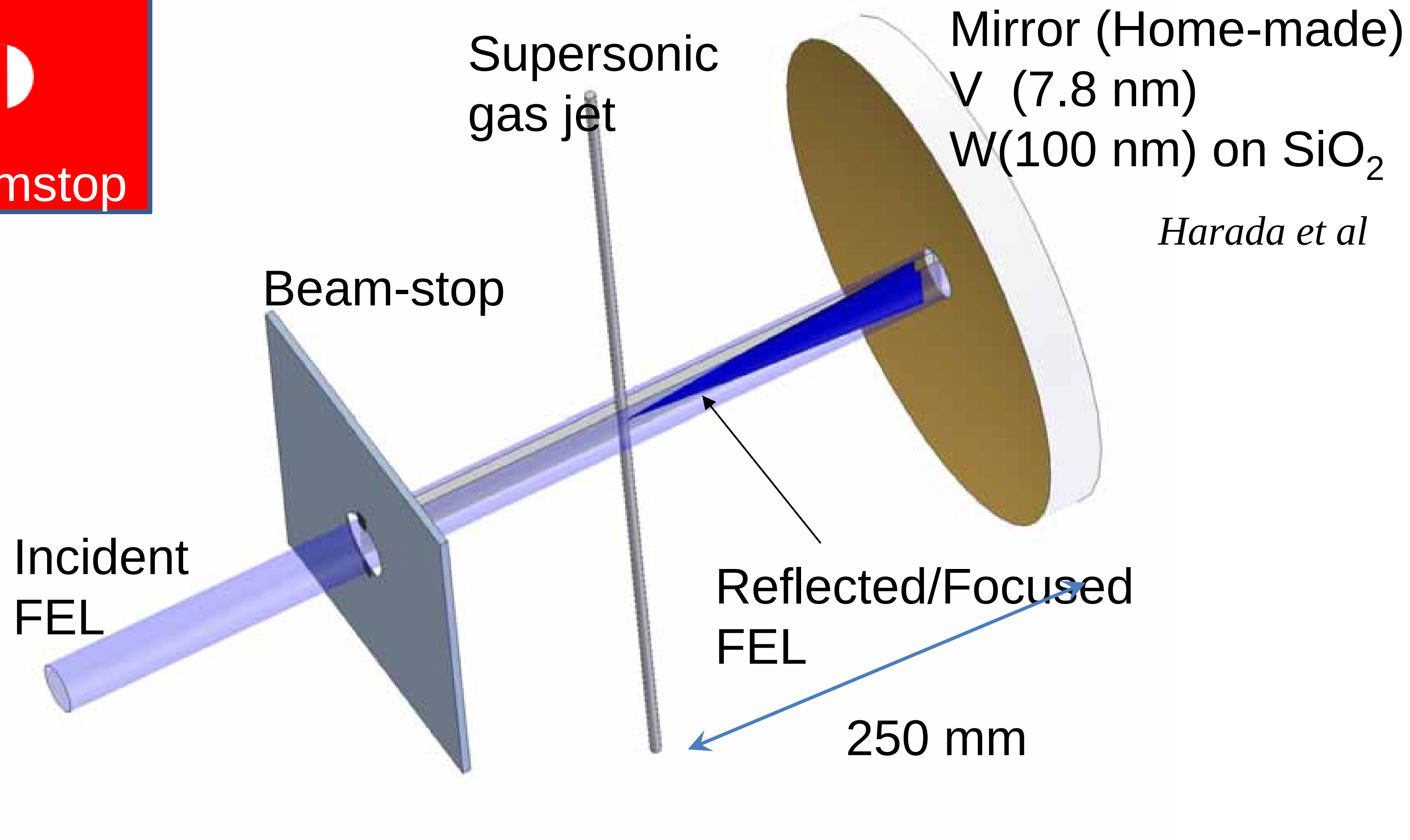


FEL beam is broader than expected

Contributions from the second order light is one order more than expected

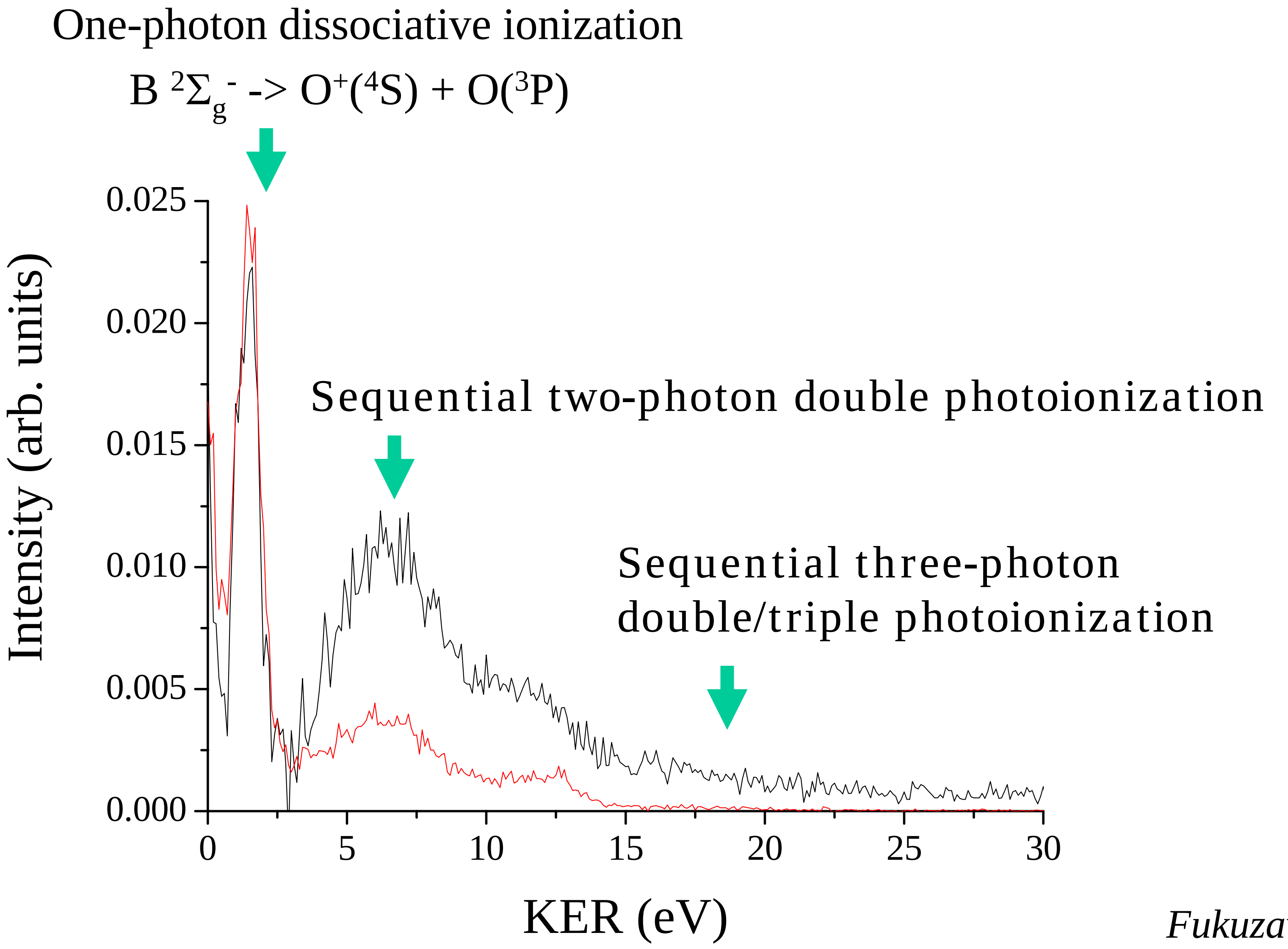
The electron beam may not be completely focused: Instability of the electron beam?

Focusing the FEL

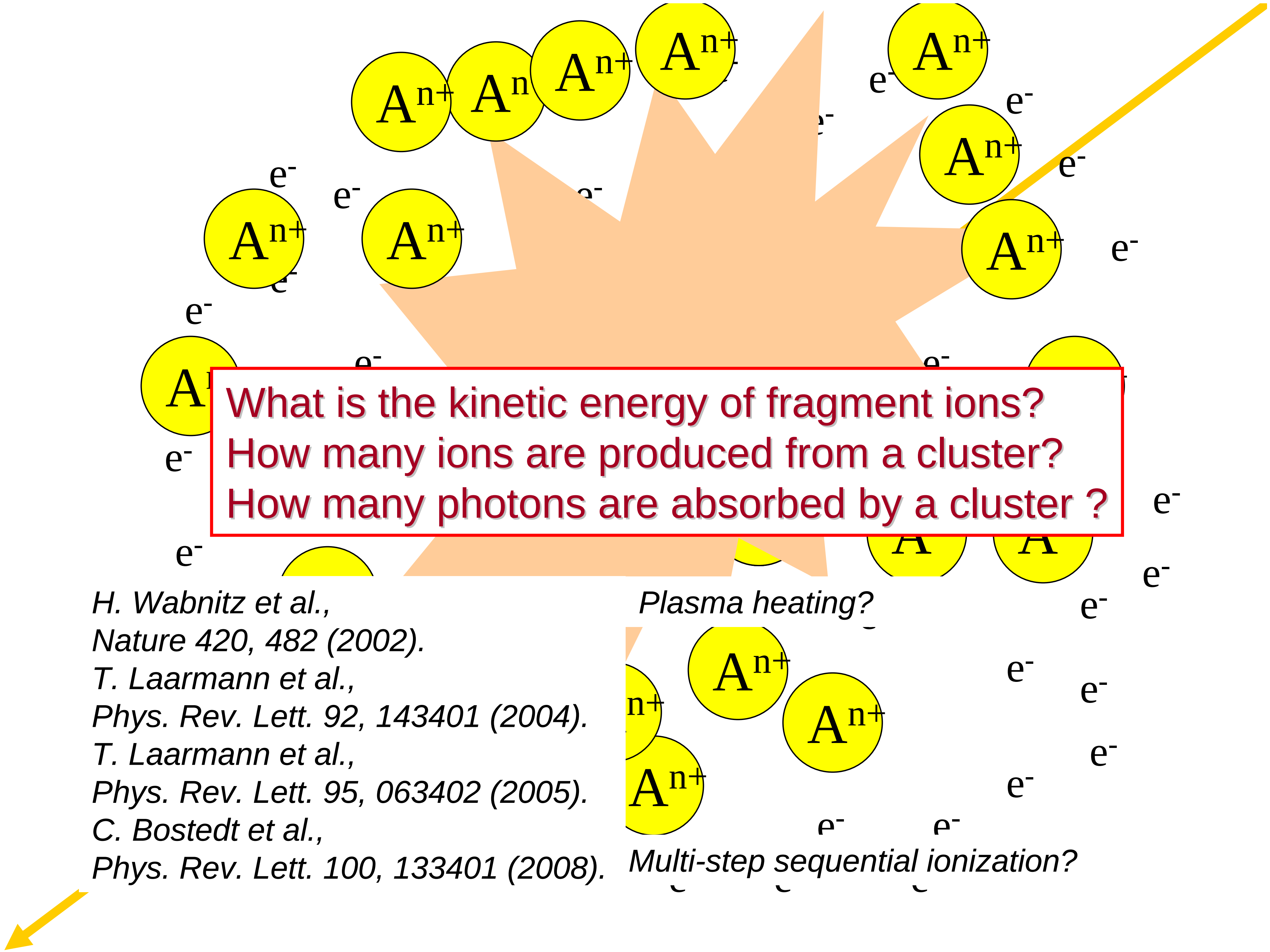


Beam-stop cuts the FEL along the gas jet so as not to cross the gas beam.

Laser power dependence of KER distributions for O_2 irradiated by 51 nm fEL



Fukuzawa et al



What is the kinetic energy of fragment ions?
How many ions are produced from a cluster?
How many photons are absorbed by a cluster ?

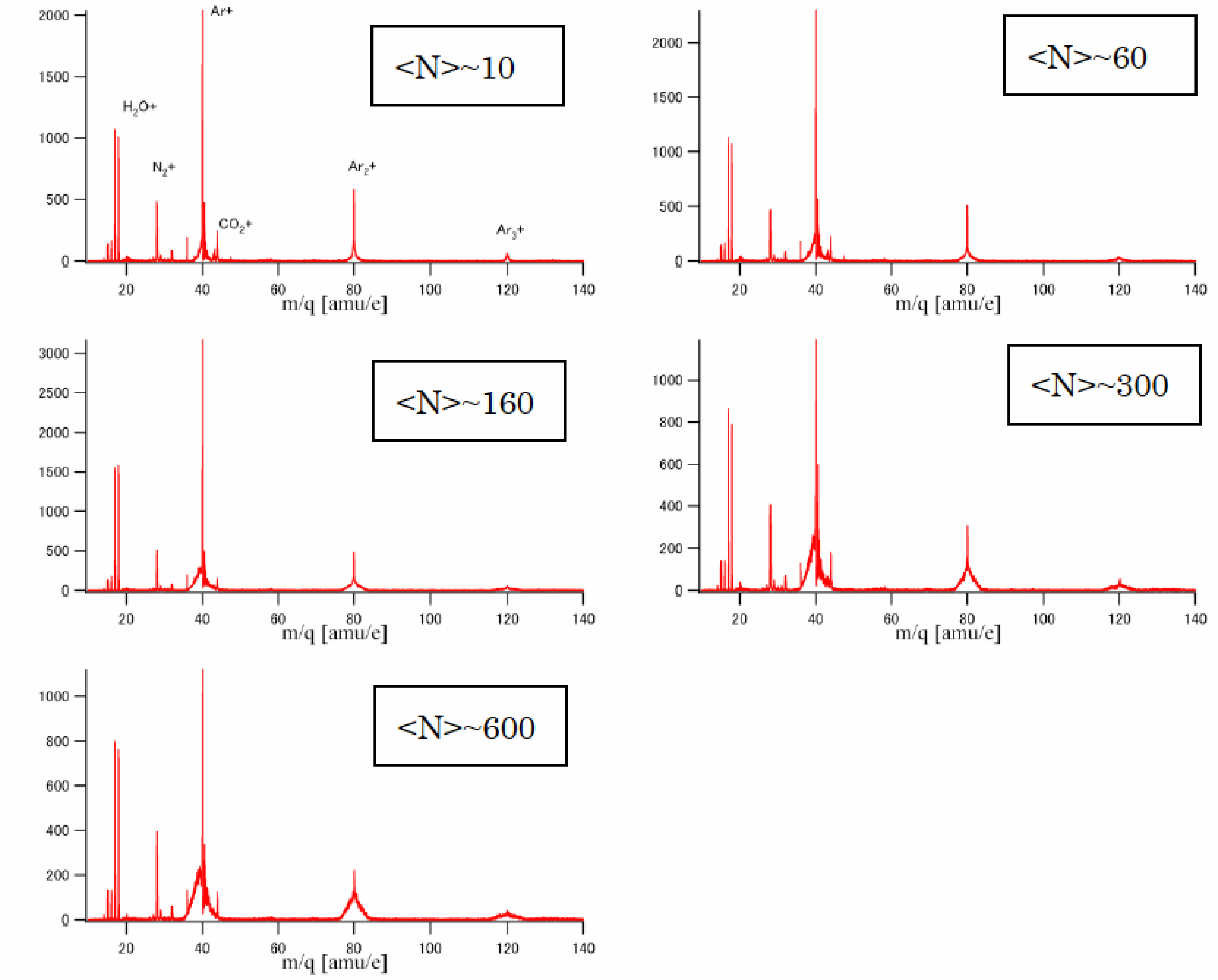
Plasma heating?

Multi-step sequential ionization?

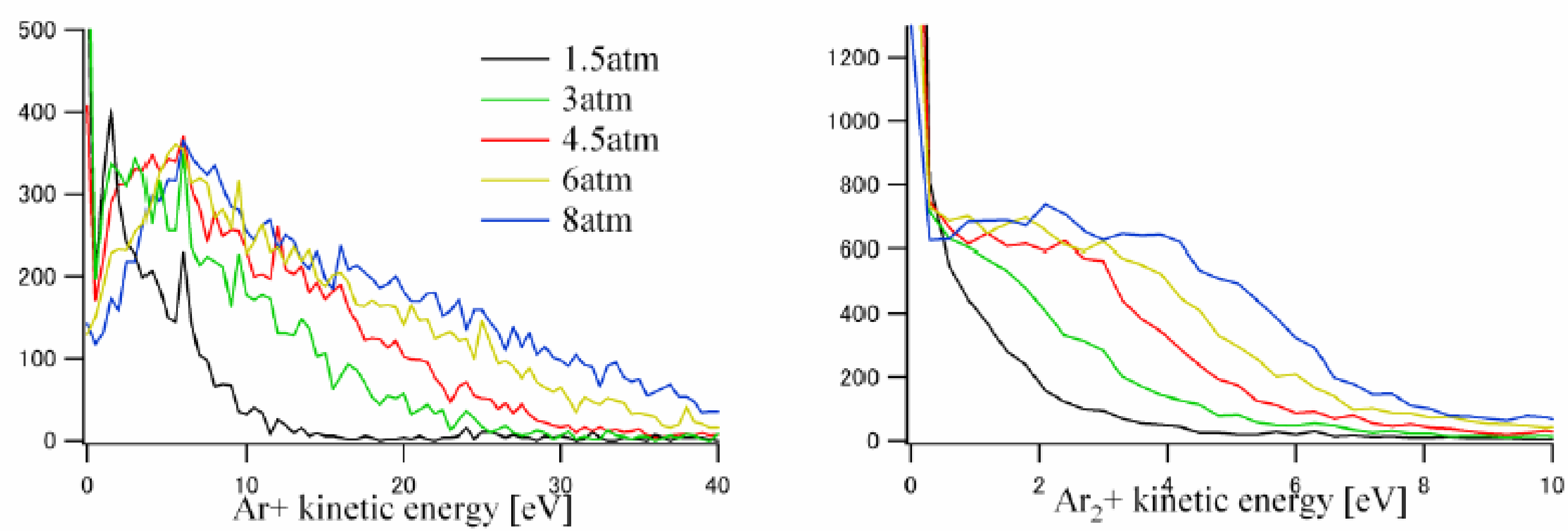
H. Wabnitz et al.,
Nature 420, 482 (2002).
T. Laarmann et al.,
Phys. Rev. Lett. 92, 143401 (2004).
T. Laarmann et al.,
Phys. Rev. Lett. 95, 063402 (2005).
C. Bostedt et al.,
Phys. Rev. Lett. 100, 133401 (2008).

Ar cluster mass spectra vs cluster size at 60 nm

Time-of-flight spectra



Kinetic energy distributions of Ar^+ and Ar_2^+ ions vs. cluster size measured at 60 nm



If the number of absorbed photons increases with an increase in the cluster size, then the charge state of the ion parent cluster and thus the kinetic energy release by Coulomb explosion increase.

Iwayama et al

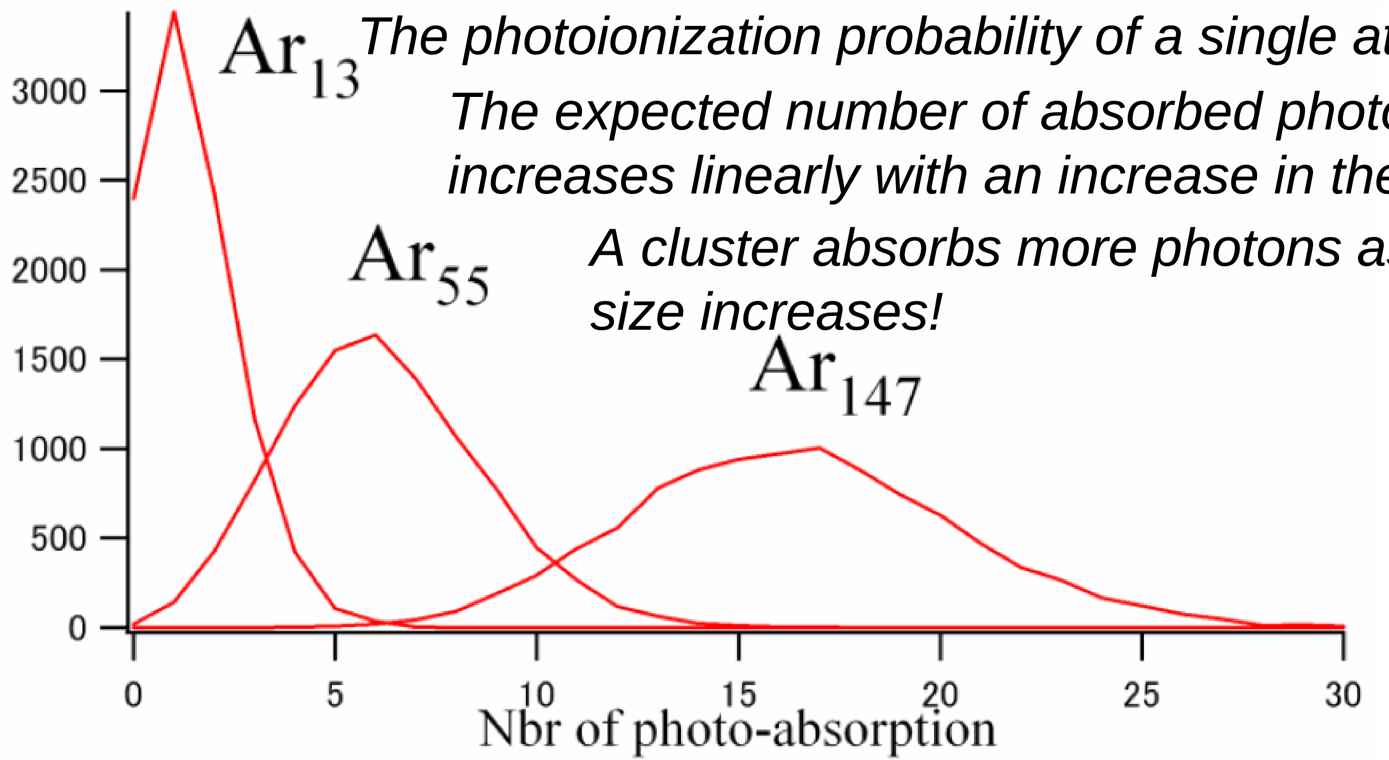
Estimates for number of photons to be absorbed by a single cluster: cluster size dependence

FEL pulse duration : 100fs

Laser power :$1*10^{11}$ [W/cm^2]

wavelength=60nm

cross section for 3p ionization : 35.7Mbarn



The photoionization probability of a single atom is ~0.1.

The expected number of absorbed photons increases linearly with an increase in the cluster size.

A cluster absorbs more photons as the cluster size increases!

Iwayama et al

Kinetic energy distributions of Xe^+ ions Xe_{150} vs. laser power density, measured at 60 nm

Laser power density:
1 x10^{11} W/cm^2
4 x10^{11} W/cm^2
10 x10^{11} W/cm^2

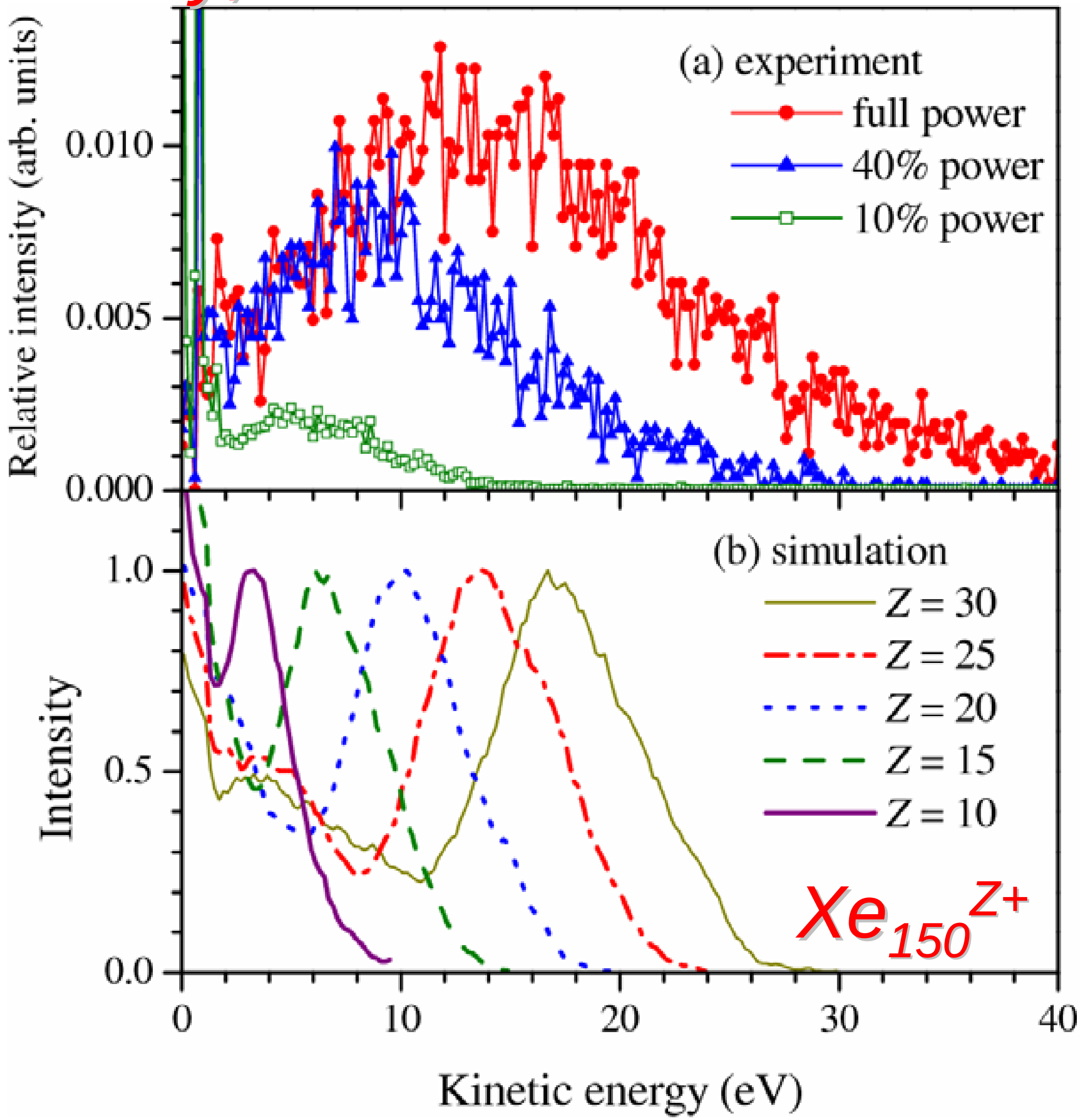
Photoionization probability of an Xe atom:
P=0.095, 0.33, 0.63

Expected number N of absorbed photons by Xe_{150}:
N=14, 50, 95

Z/N = 1, 2/5, 1/4 <1

Z/N <1
Suppression of cluster direct ionization

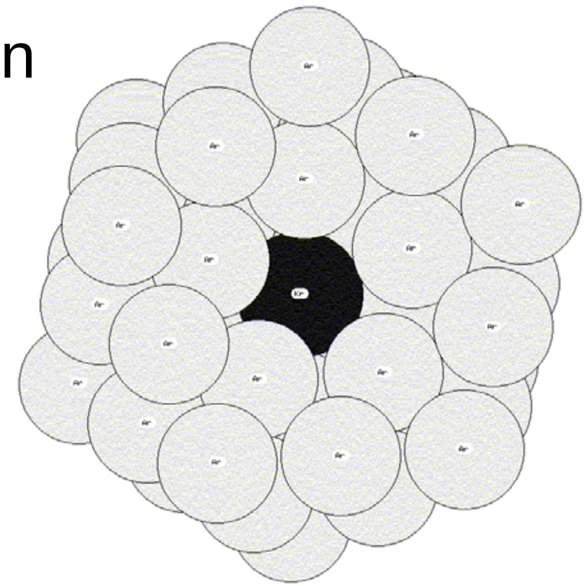
Photoabsorption of the individual atoms causes inner ionization at high Z.



Fukuzawa et al

MD simulation for estimates of initial kinetic energy distributions from given charged states

- Cluster structure of Xe_{150} is constructed by adding 3 atoms on a perfect icosahedron structure of Xe_{147}
- Randomly selected z atoms are singly charged ions (Xe_n^{z+})
- Direct Coulomb potential and Lennard-Jones potential are taken into account
- Classical Molecular Dynamics simulation



X-FEL and EUV-FEL Facility in Japan

X-FEL will be in operation in 2010!

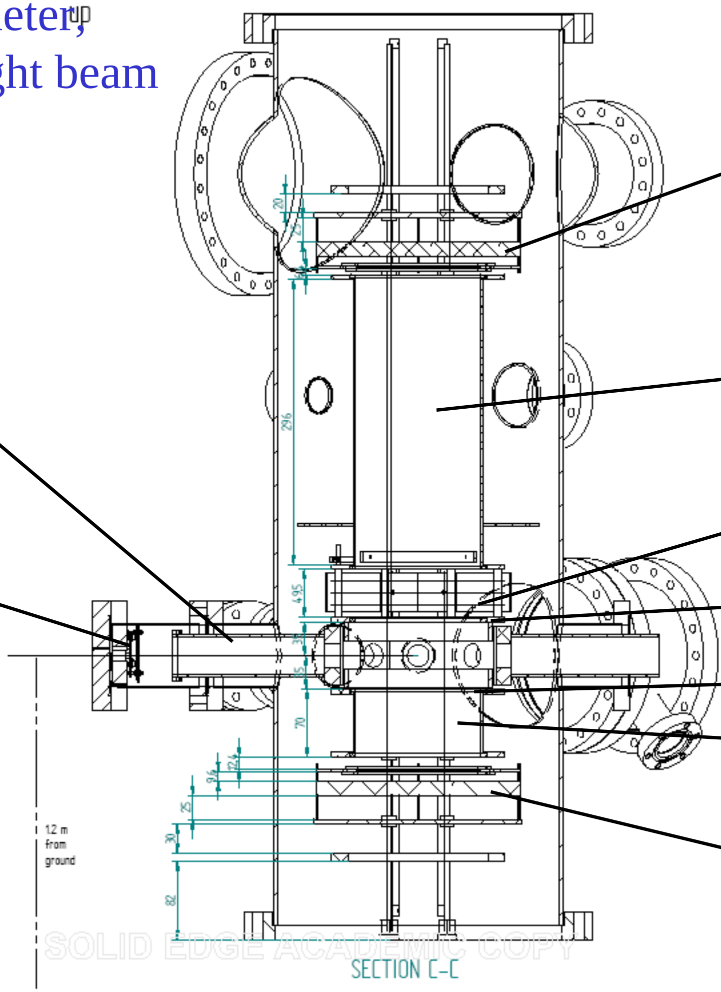
Electron-ion momentum imaging apparatus for X-FEL

tested by laser 800nm, lens 50 mm focus outside chamber

4 x simple
electron TOF spectrometer,
2 x perpendicular to light beam
2 x at magic angle
(forward, backward)

ion detection
pusher +320V
extractor -320V
ion drift tube -1000V

120 mm diameter
ion detector,
hexagonal



ion drift tube
+ focussing lens

4 x 50 mm diameter
MCP stack

acceleration region
0.75 Extractor +
0.25 drift tube

extractor

pusher

e-imaging:
pusher +20V
extractor -20V
(electron DT -20V)
B-field : 450 µT

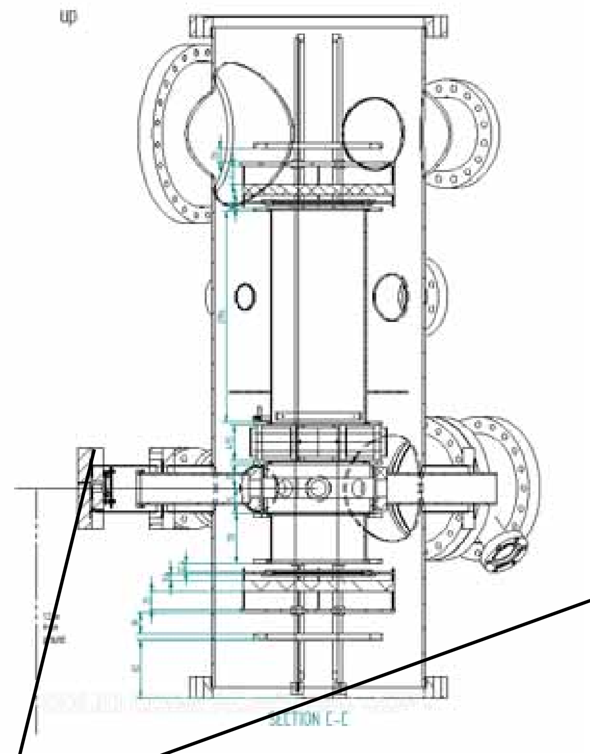
electron
drift tube

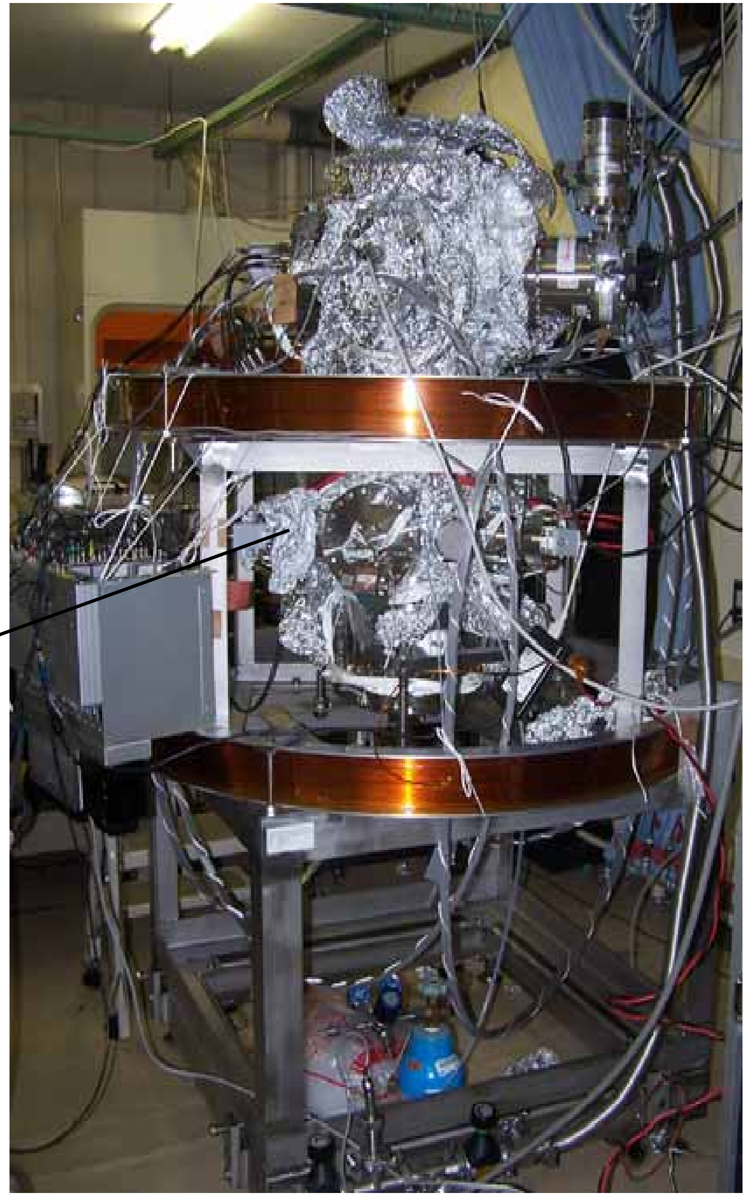
80 mm diameter
electron detector,
hexagonal

dimensions: pusher - extractor 75 mm, electron DT 70 mm
extractor - ion DT 40.5 mm, ion drift tube 296 mm

Electron TOF spectrometer

field free conditions 0V/cm   B<5μT



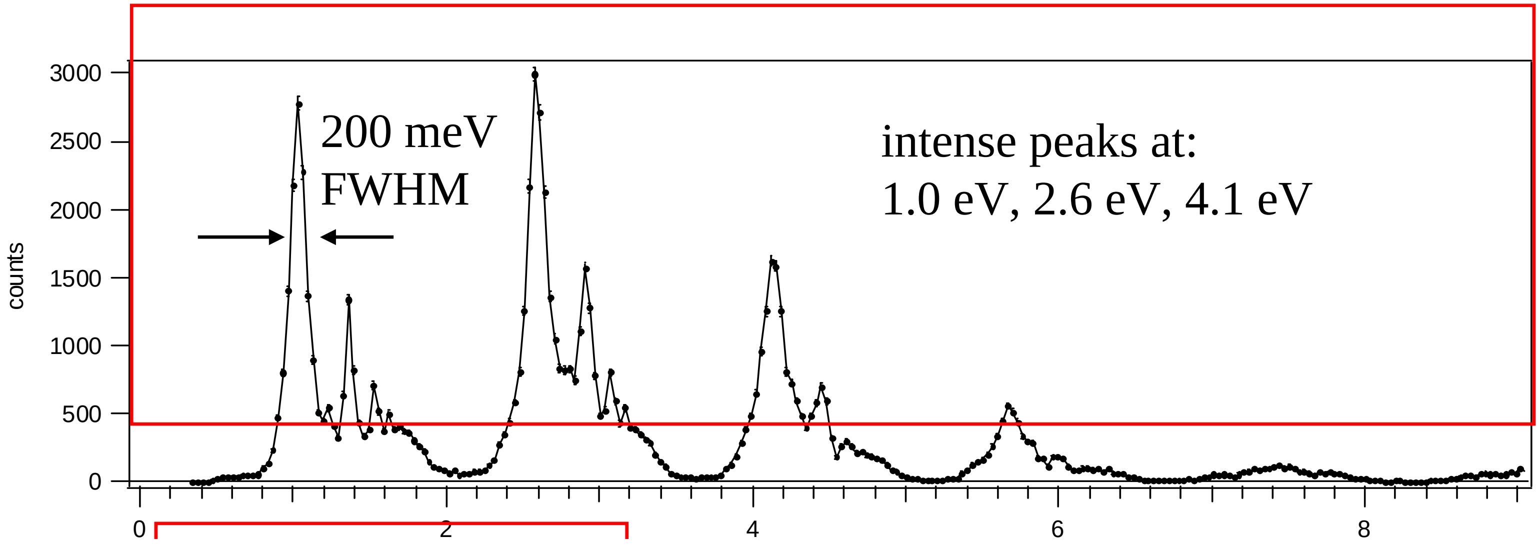


High-resolution
High-intensity
measurements

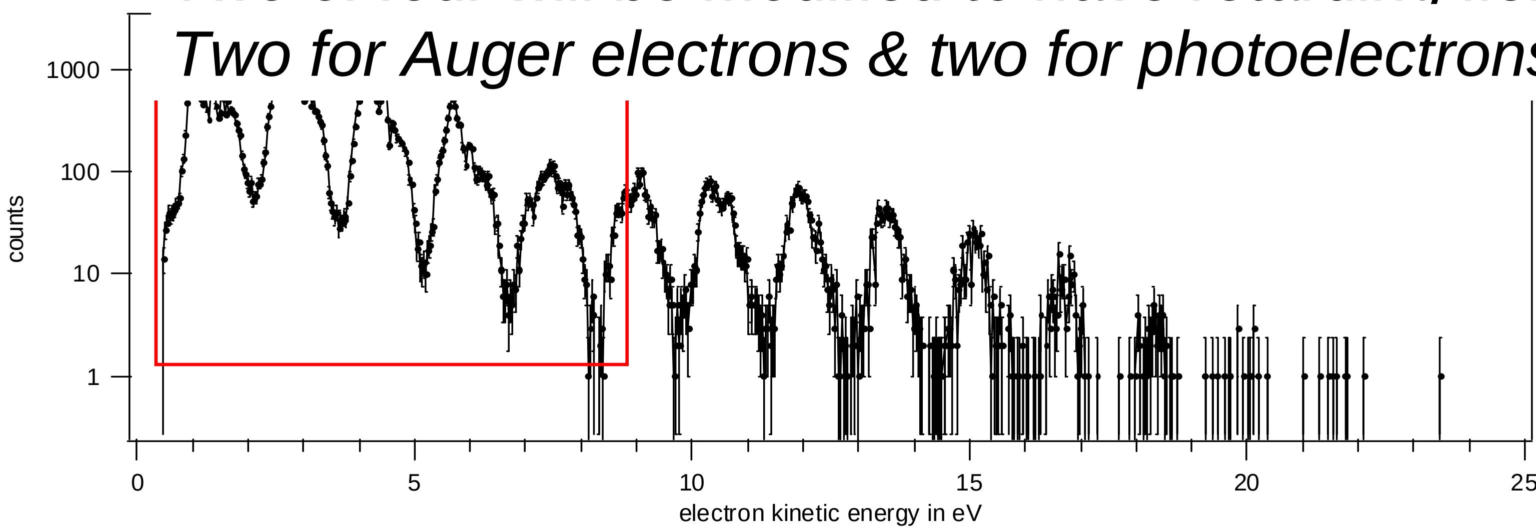
4 directions at the
same time.
counting mode or 1 spectrum per shot mode

ATI electron spectrum of Xe by 800nm, 40 mW laser pulses

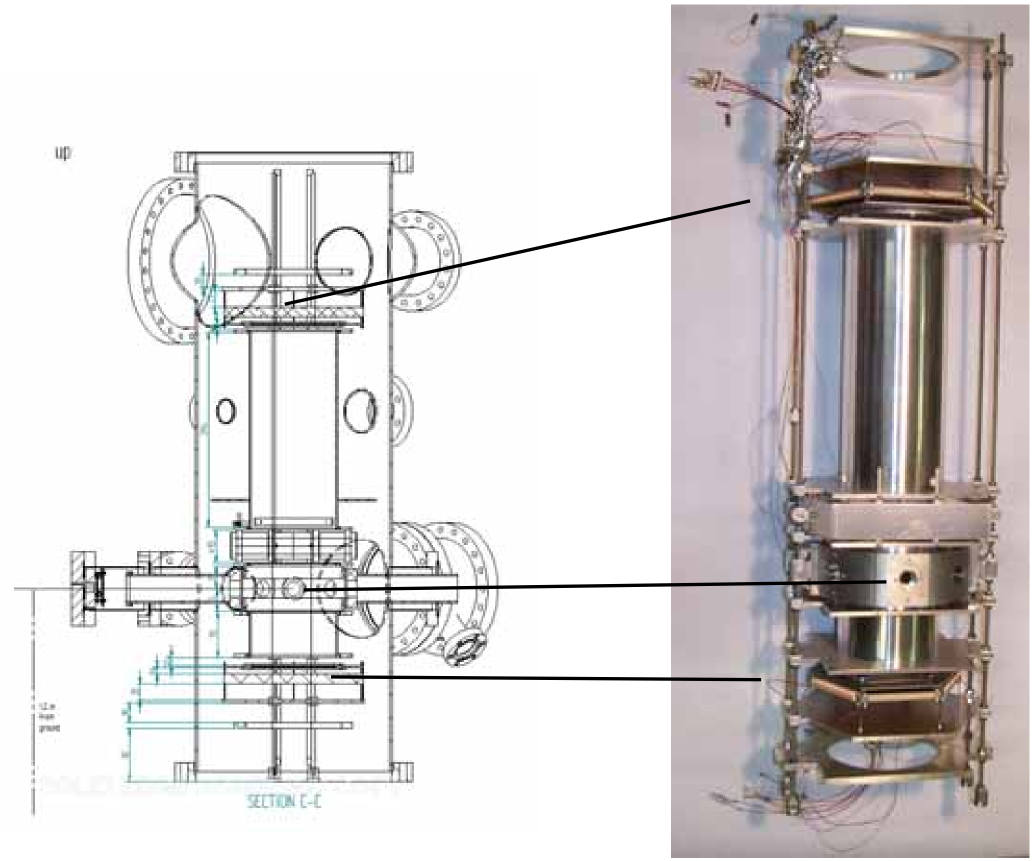
recorded by one of TOF spectrometers (limited acceptance angles) under the field-free conditions. Freeman resonances appear. The spectrum shows good resolution, good energy range.



Two of four will be modified to have retarding fields.
Two for Auger electrons & two for photoelectrons.



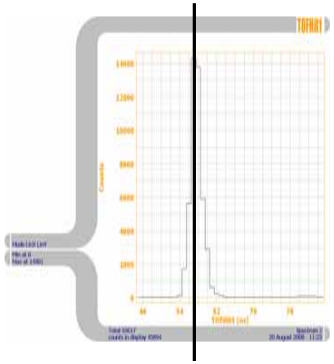
Electron & ion momentum imaging spectrometers



ion imaging

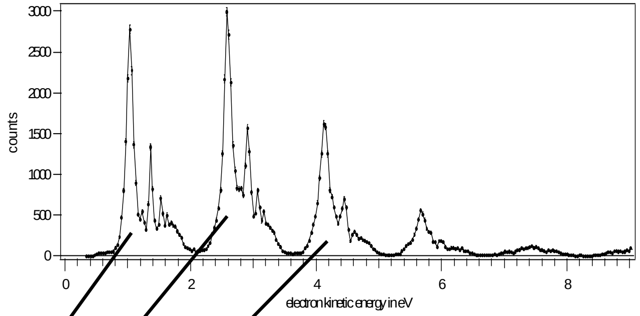
electron imaging

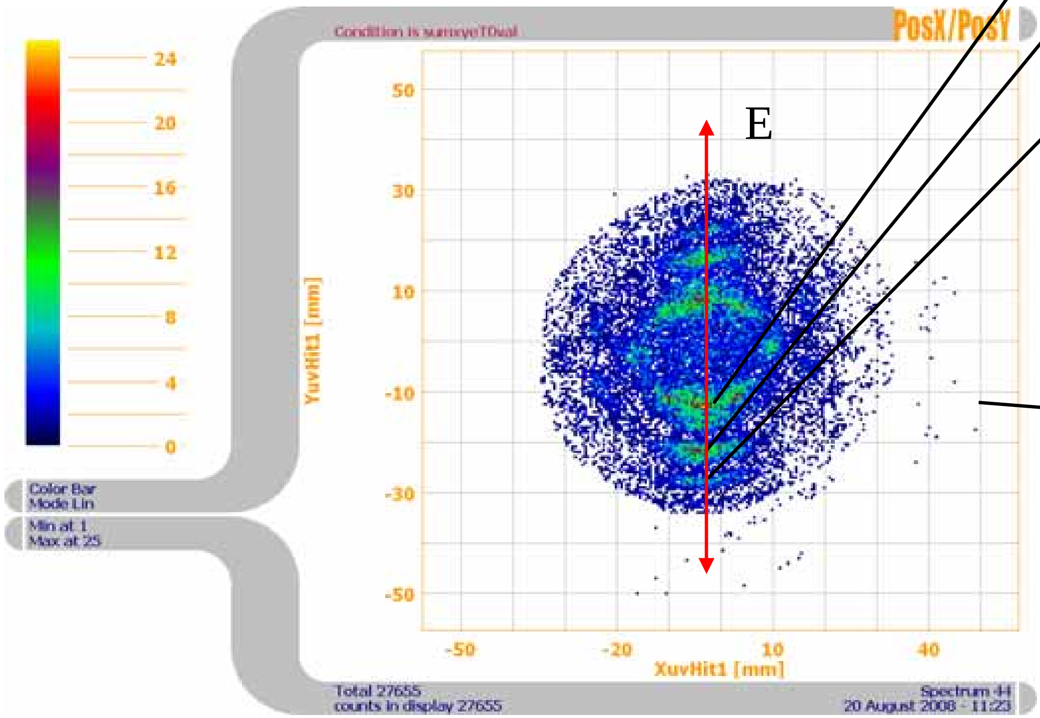
Electron 2D imaging with DC-extraction field



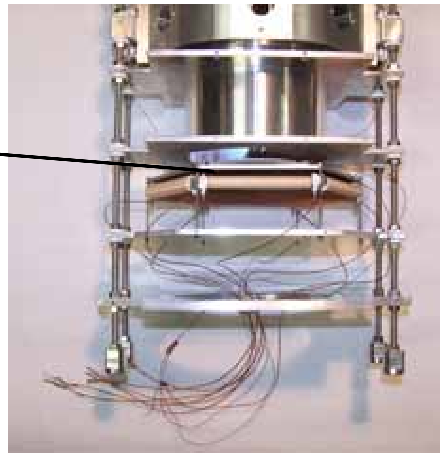
cut in electron TOF,
Momentum (p_x, p_y)
only perpendicular to detector

laser: horizontal polarization





+-100V at pusher / extractor
get all electrons up to 8 eV
without magnetic field

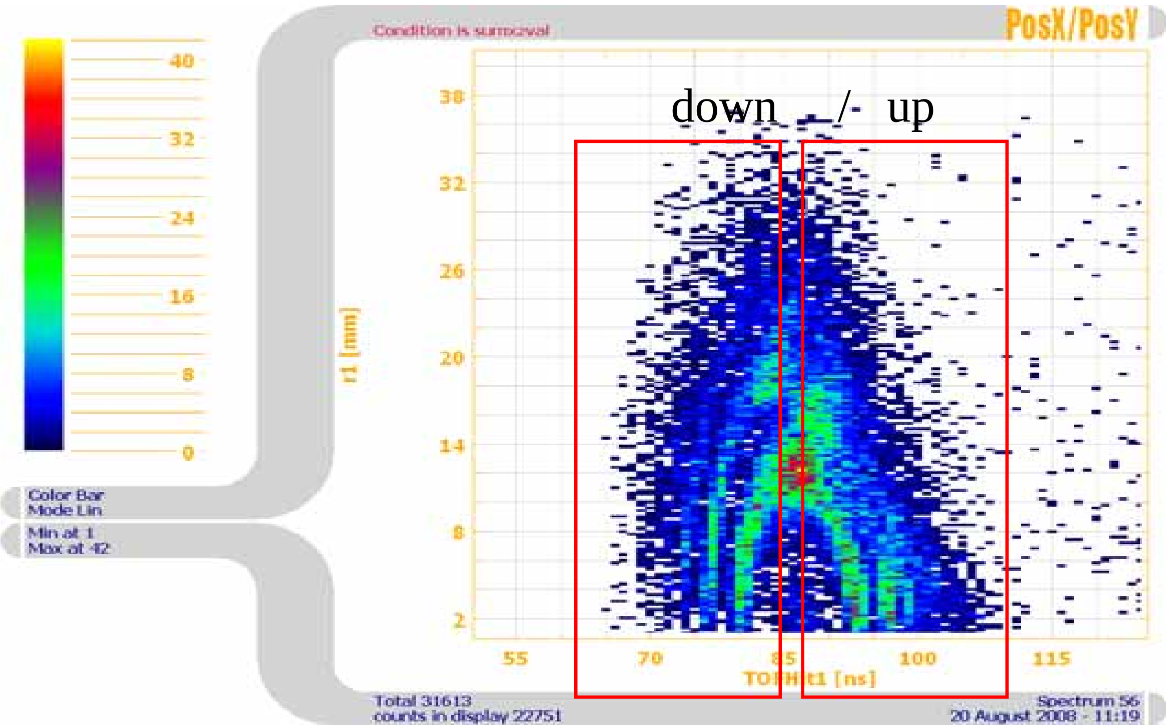


Can be used for molecules and clusters (for e-ion coincidence)

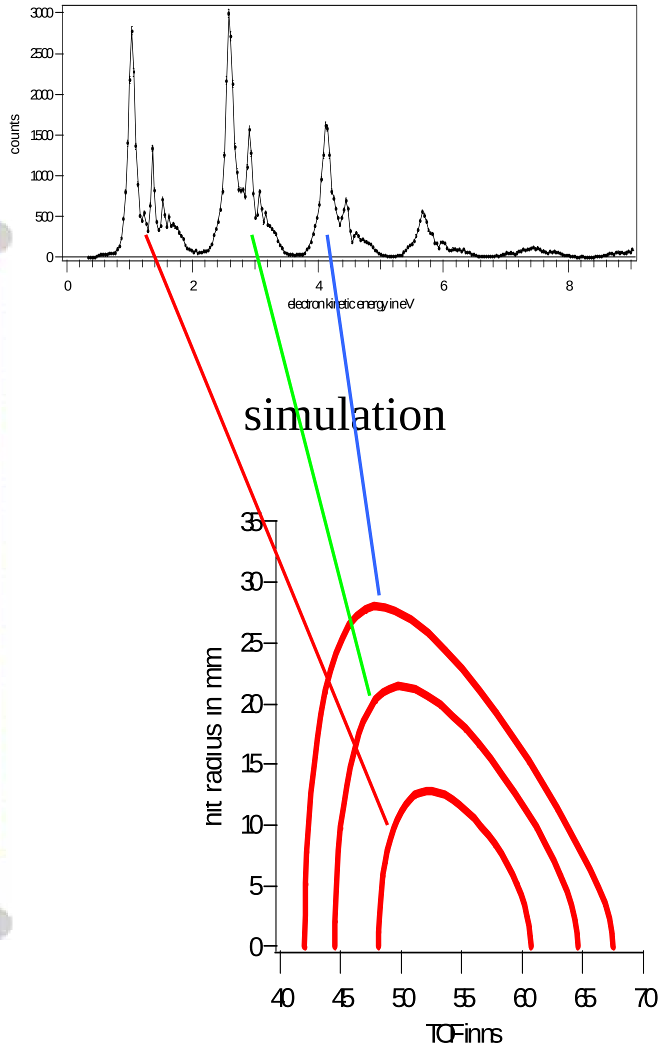
Electron 3D imaging (2D imaging+ TOF)

4 π detection efficiency
moderate resolution, 1 or more electrons per shot
+-20V at pusher / extractor,   450 μT (4.5 G)
get all electrons up to 5 eV,
all direction with reasonable resolution

intense peaks at:
1.0 eV, 2.6 eV, 4.1 eV

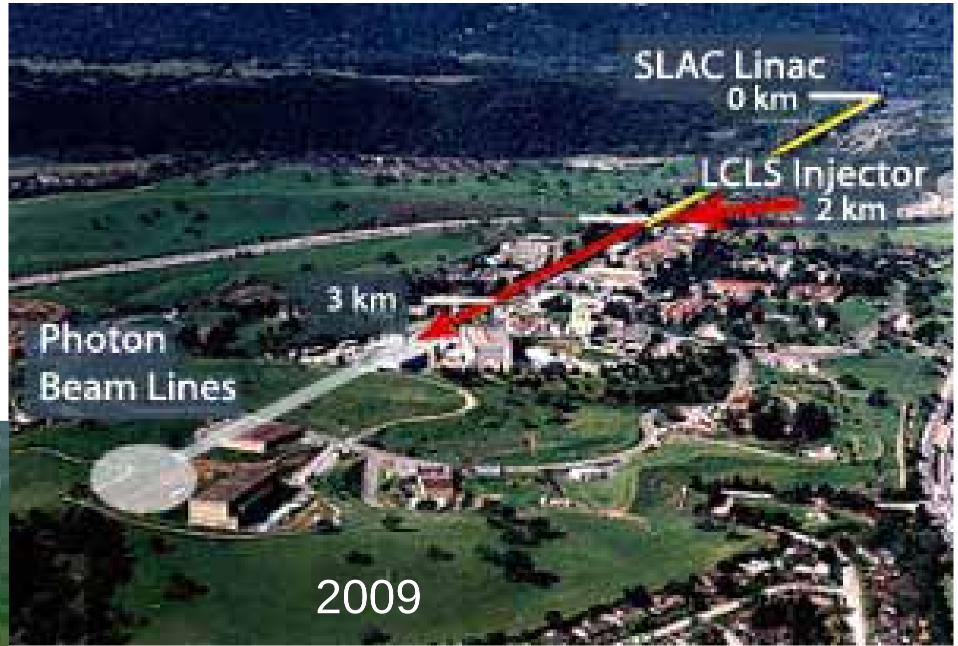


(laser: horizontal + vertical polarization)



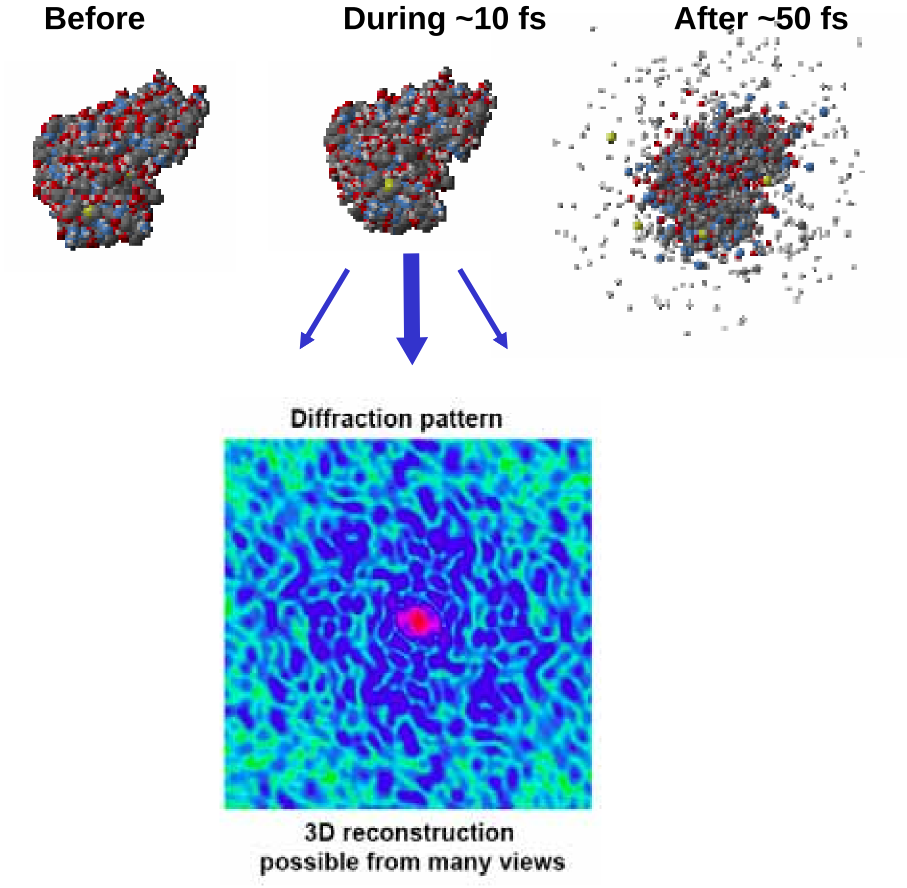
Can be used for (He and) Ne recoil momentum coincident with e

Single-shot imaging by X-FEL



Structure analysis for a single biomolecule

Neutze, Wouts, van der Spoel, Weckert, Hajdu   Nature 406, 752 (2000)



Should record the X-ray diffraction pattern before Coulomb explosion….
Change of the electron density may be even faster….
Developing the X-ray detectors is the most important issue….

The end

Thank you very much for your attention!

Sendai in summer

Tanabata festival