MaMFIS

First experiments on deep ionization of Ir, Ce and Xe atoms in local ion trap at JINR

V. P. Ovsyannikov, E. D. Donets, E. E. Donets, D. E. Donets, S. I. Tytynnikov, V. I. Stegailov, A. Yu. Ramsdorf, A. Yu. Boytsov, D. N. Rassadov

Joint Institute for Nuclear Research, Dubna, Russia

A. V. Nefiodov

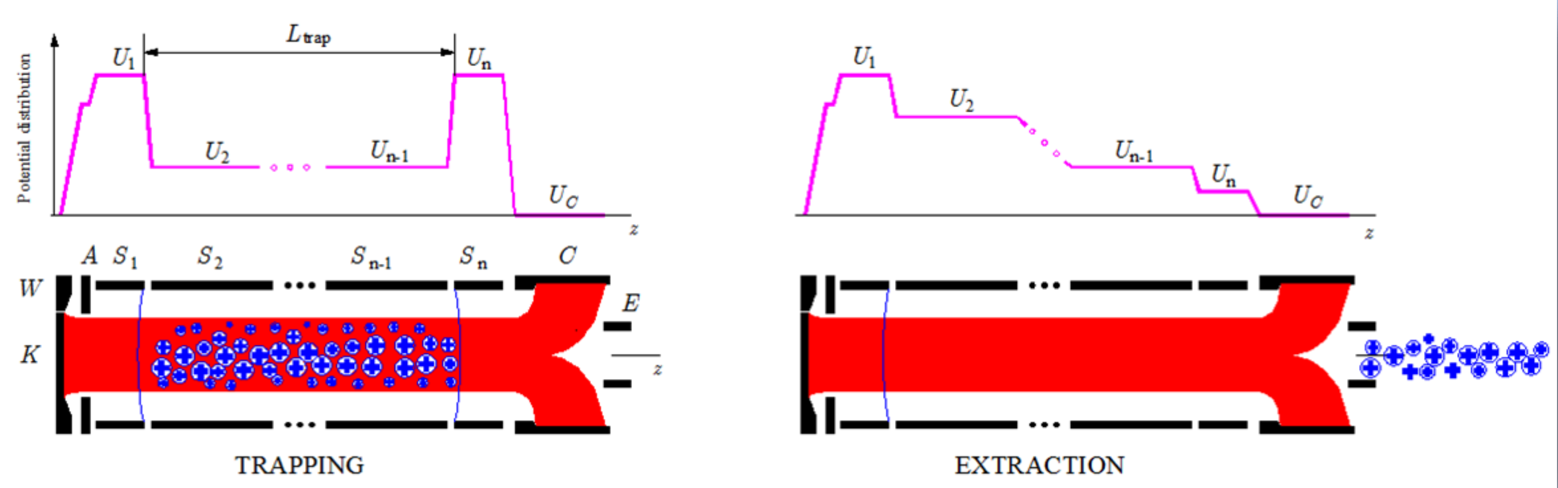
Petersburg Nuclear Physics Institute, St. Petersburg, Russia

A. A. Levin

MaMFIS Group, Hochschulstr. 13, D-01069 Dresden, Germany

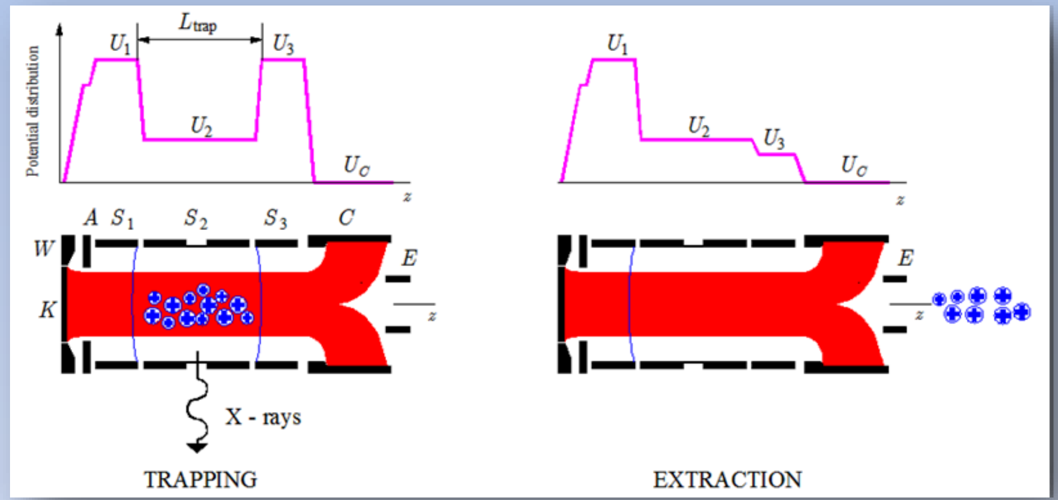
Production of highly charged ions in electron beams (history)

Electron Beam Ion Source (EBIS), E. D. Donets, Dubna, 1967

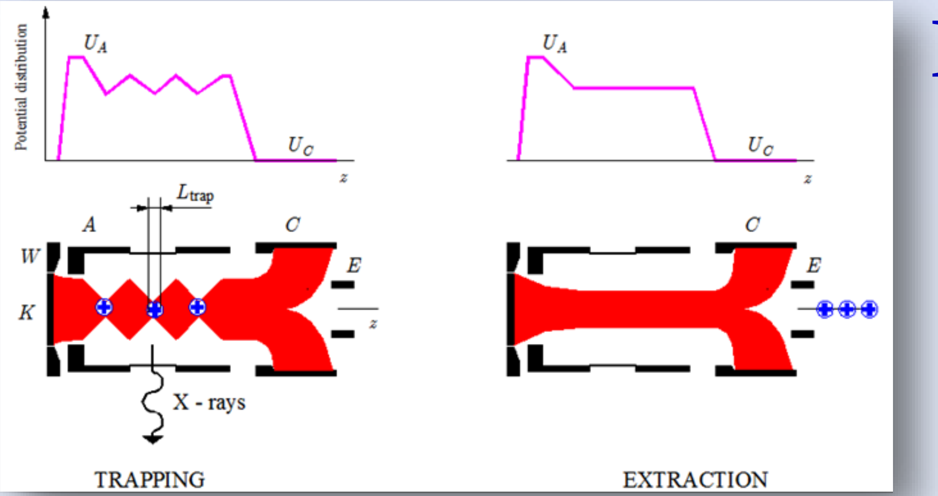


L_{trap}= 0.7 – 1.5 m, j_e ~ 500 A/cm^2

Electron Beam Ion Trap (EBIT), M. Levine, R. Marrs, LLNL, 1986



L_{trap}= 2 cm,
j_e ~ 2 kA/cm^2

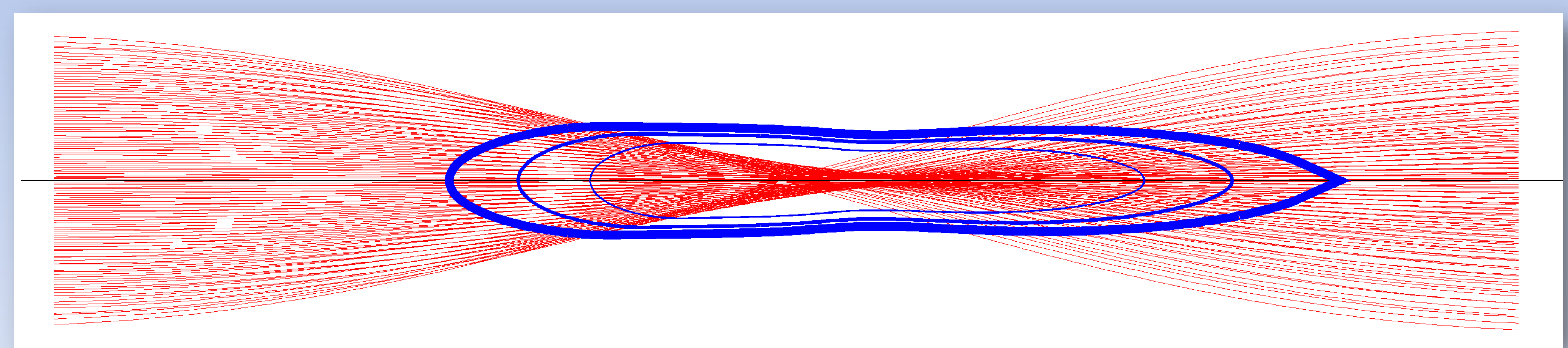


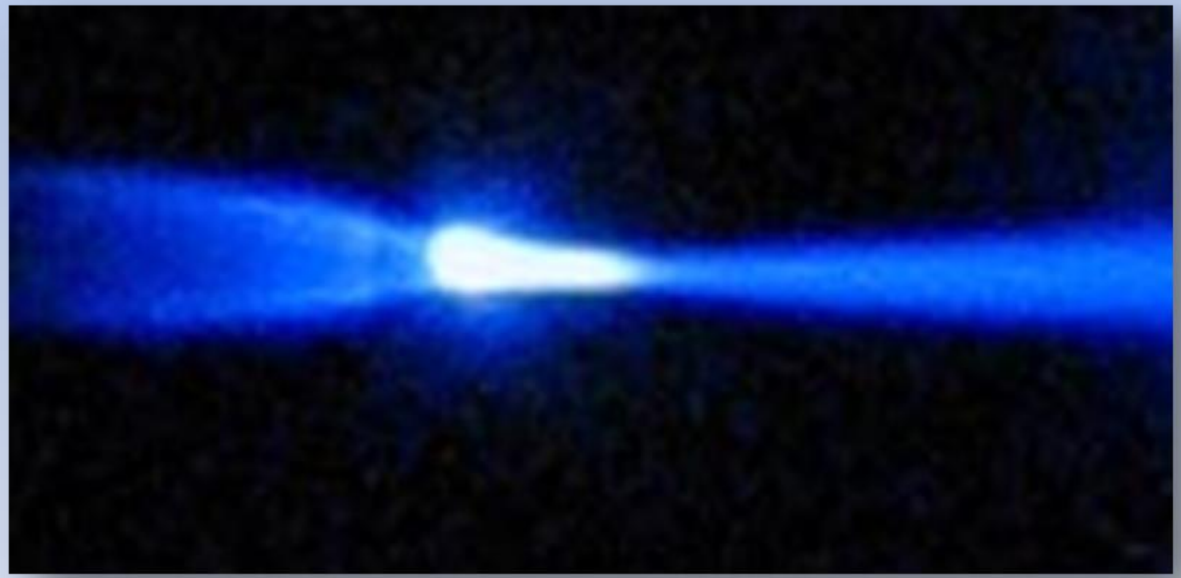
Main Magnetic Focus Ion Source (MaMFIS)

L_{trap}= 1 mm
j_e > 10 kA/cm^2

K, cathode
W, focusing (Wehnelt) electrode
A, anode
S_1, S_2,…, S_n, sections of drift tube
C, collector
E, extractor
z, axis of electron beam
j_e, effective electron current density
L_{trap}, trap length

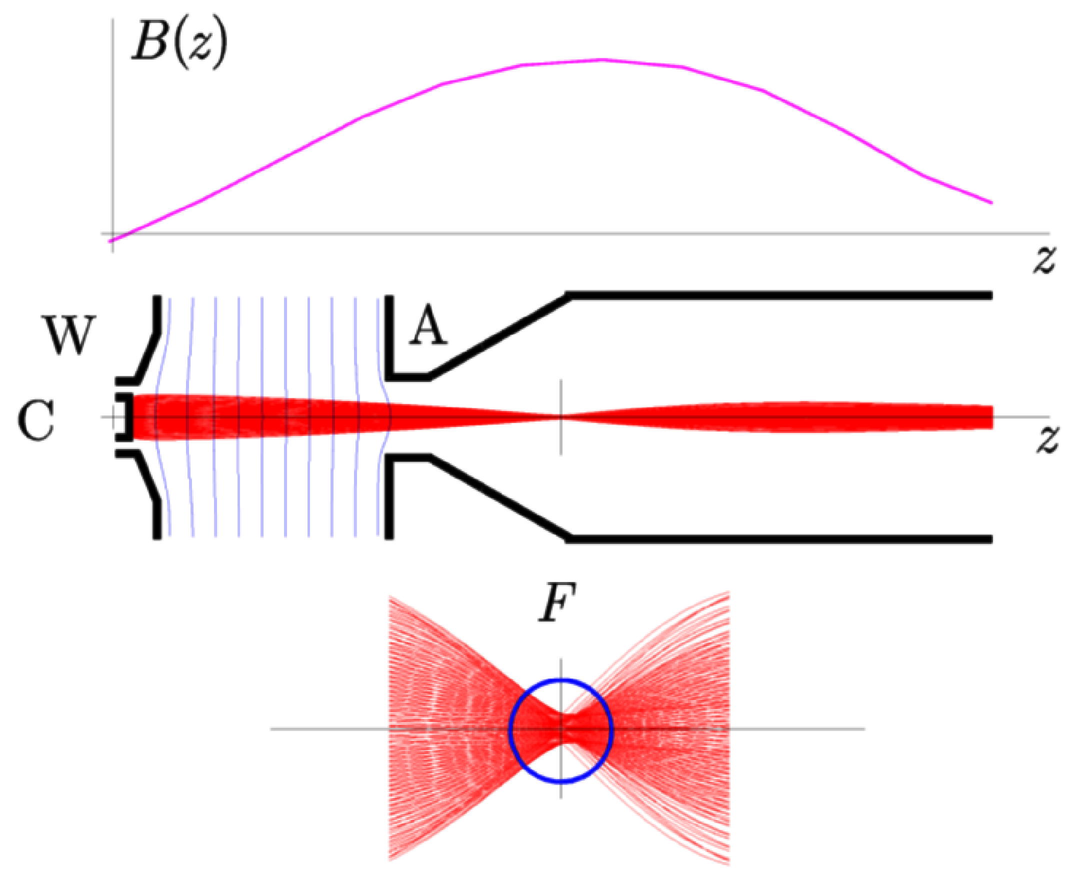
Main Magnetic Focus Ion Source (MaMFIS)





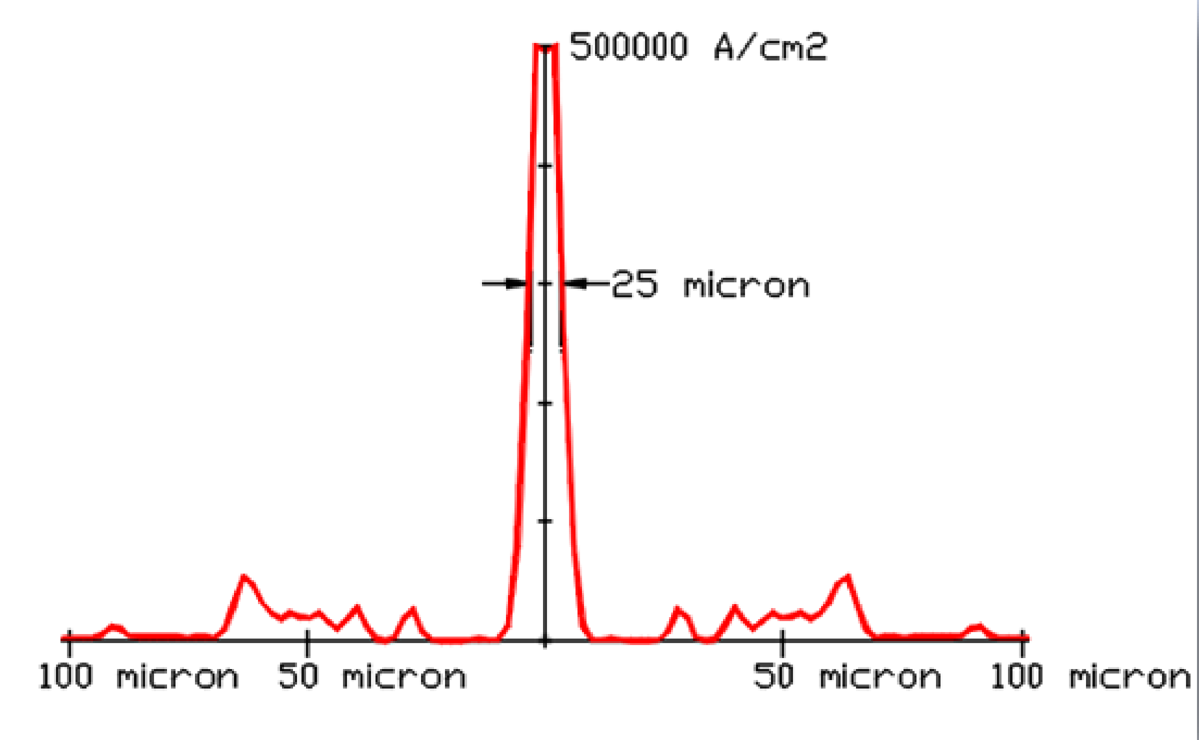
Electron current density j_e is the key quantity, because it determines the rate for production of highly charged ions

Operation principle of MaMFIS (Single Focus)



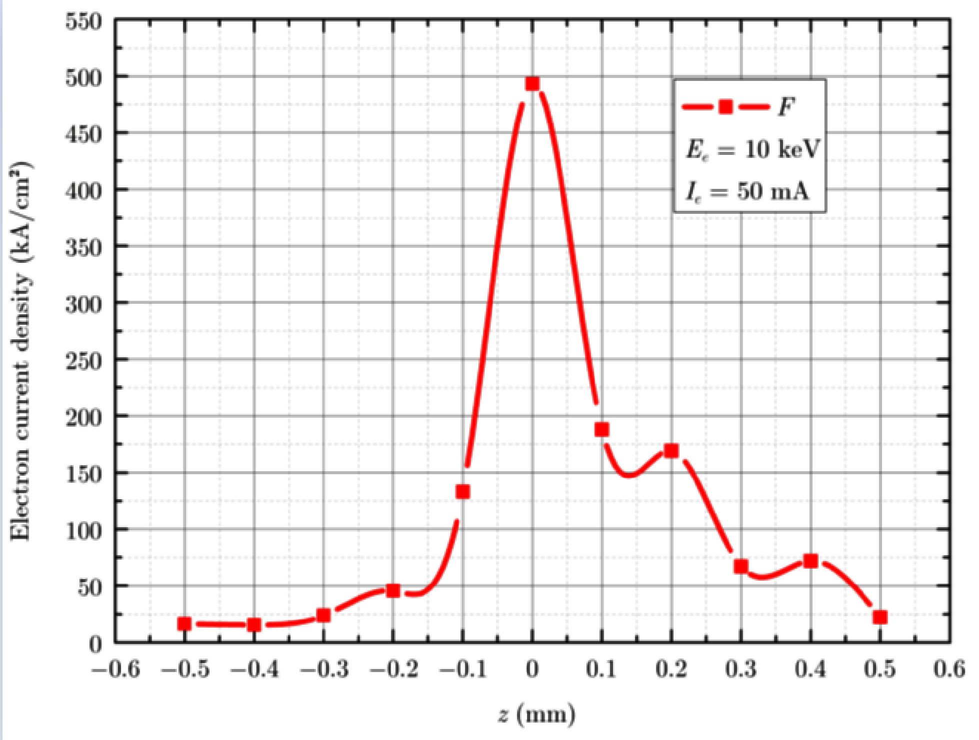
Electron beam trajectories for single-focus electron optics (theoretical estimation)

C, cathode
W, focusing (Wehnelt) electrode
A, anode
z, axis of electron beam
B(*z*), magnetic field distribution
F, magnetic focuses (local ion traps)

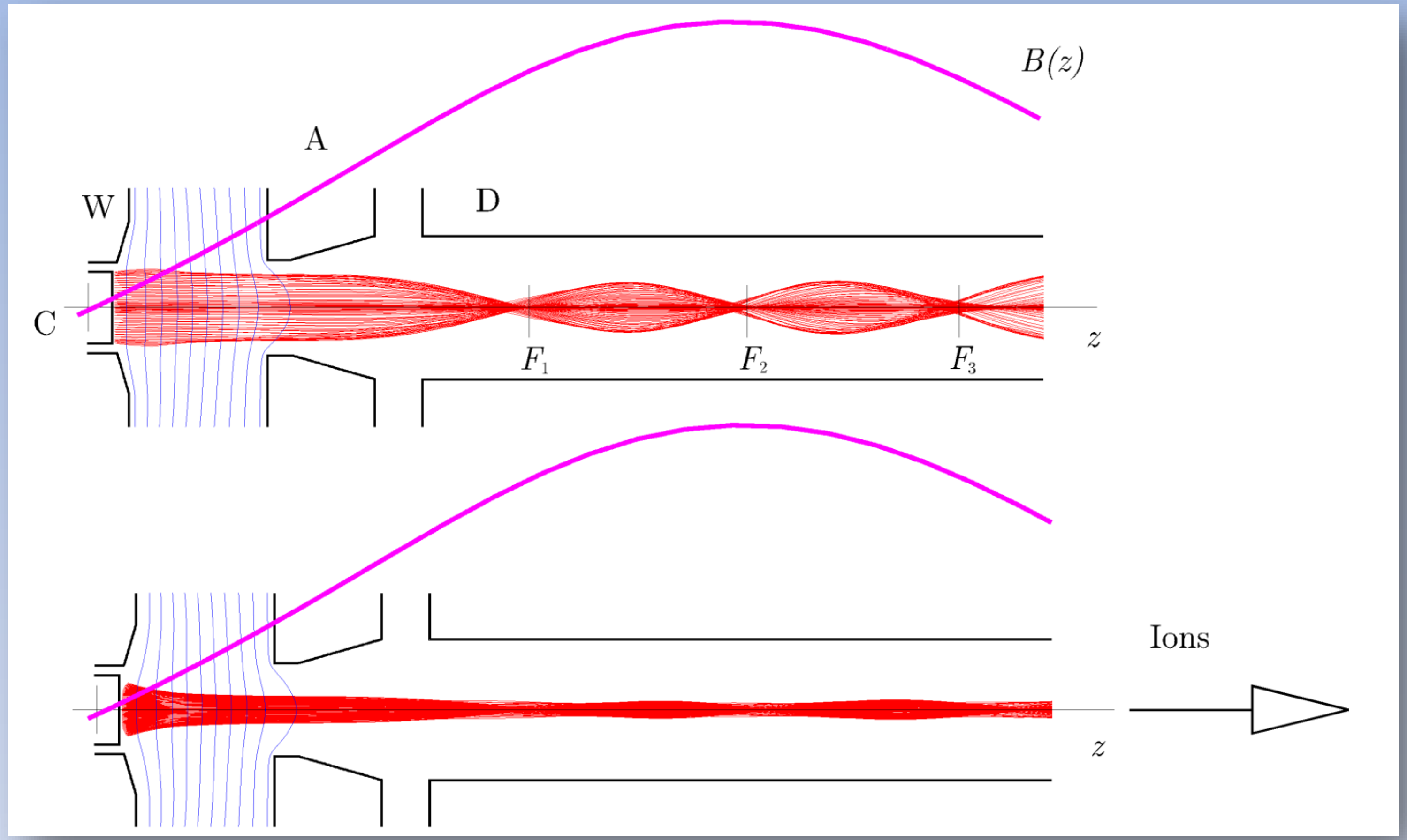


Radial (left fig.) and axial (right fig.) distributions of electron current density j_e near focus point *F*

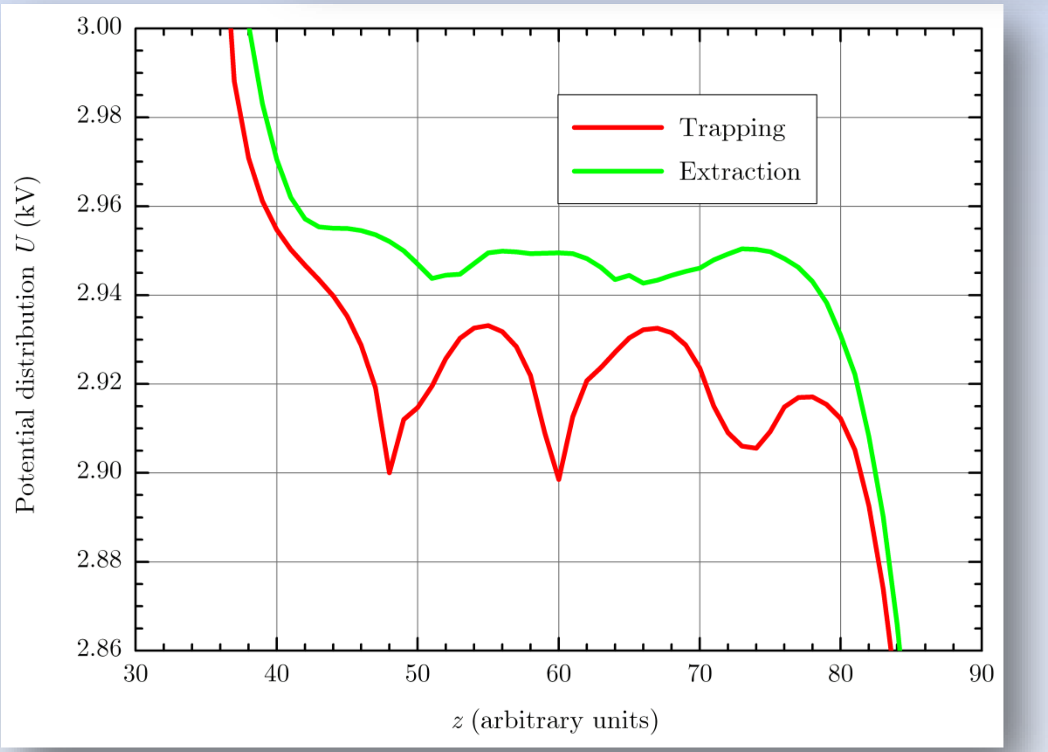
The electron current density in a single focus can be extremely high!



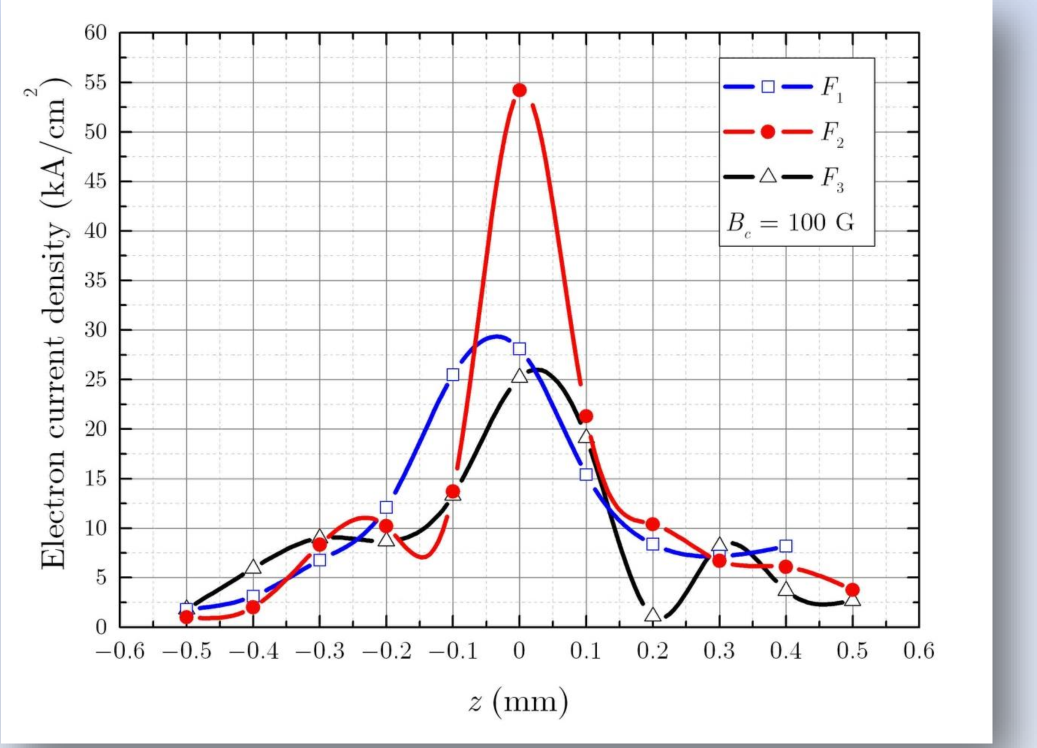
Operation principle of MaMFIS (Three Focuses)



C, cathode
W, focusing (Wehnelt) electrode
A, anode
D, drift tube
***z*, axis of electron beam**
***B*(*z*), magnetic field distribution**
F_1, F_2, F_3, magnetic focuses (local ion traps)
Effective electron current density j_e ~ 20 kA/cm^2



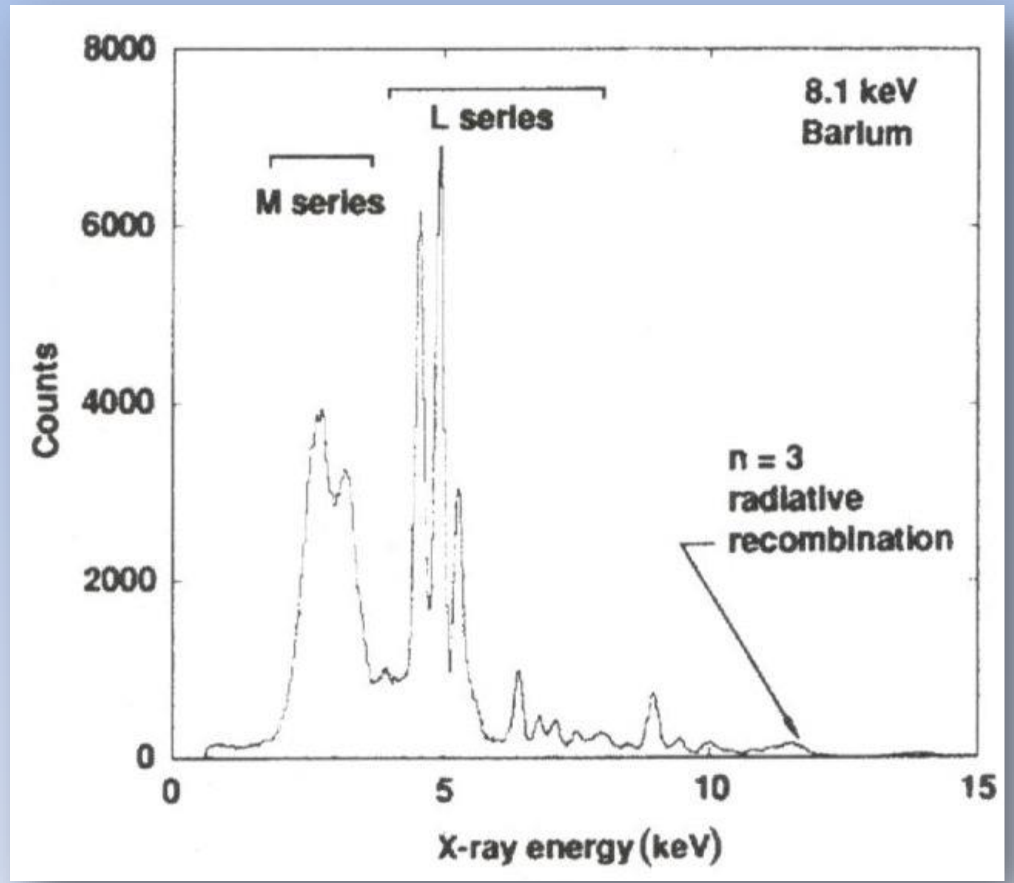
Local ion traps in a rippled electron beam

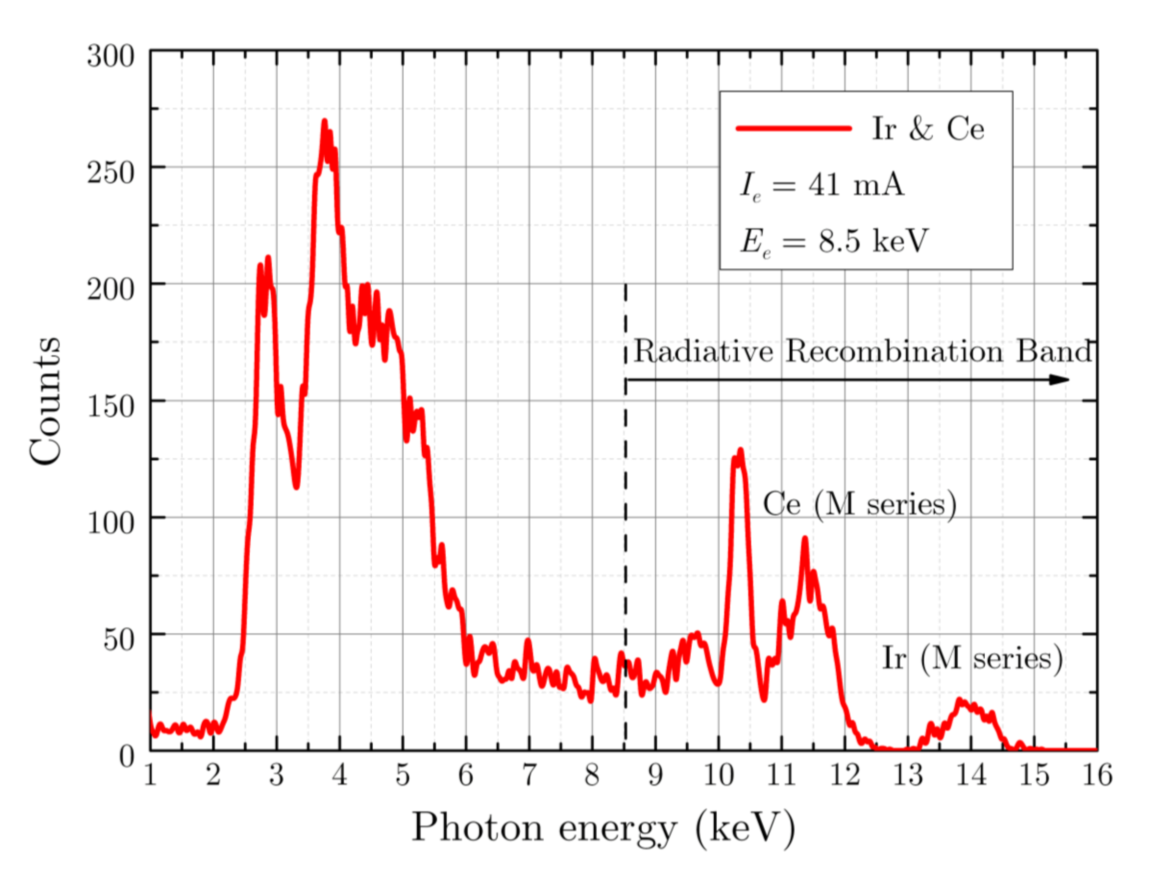


Axial distribution of electron current density on the length of 1 mm near focuses

MaMFIS-10 versus LLNL superconducting EBIT

X-ray spectra from cathode materials





LLNL EBIT

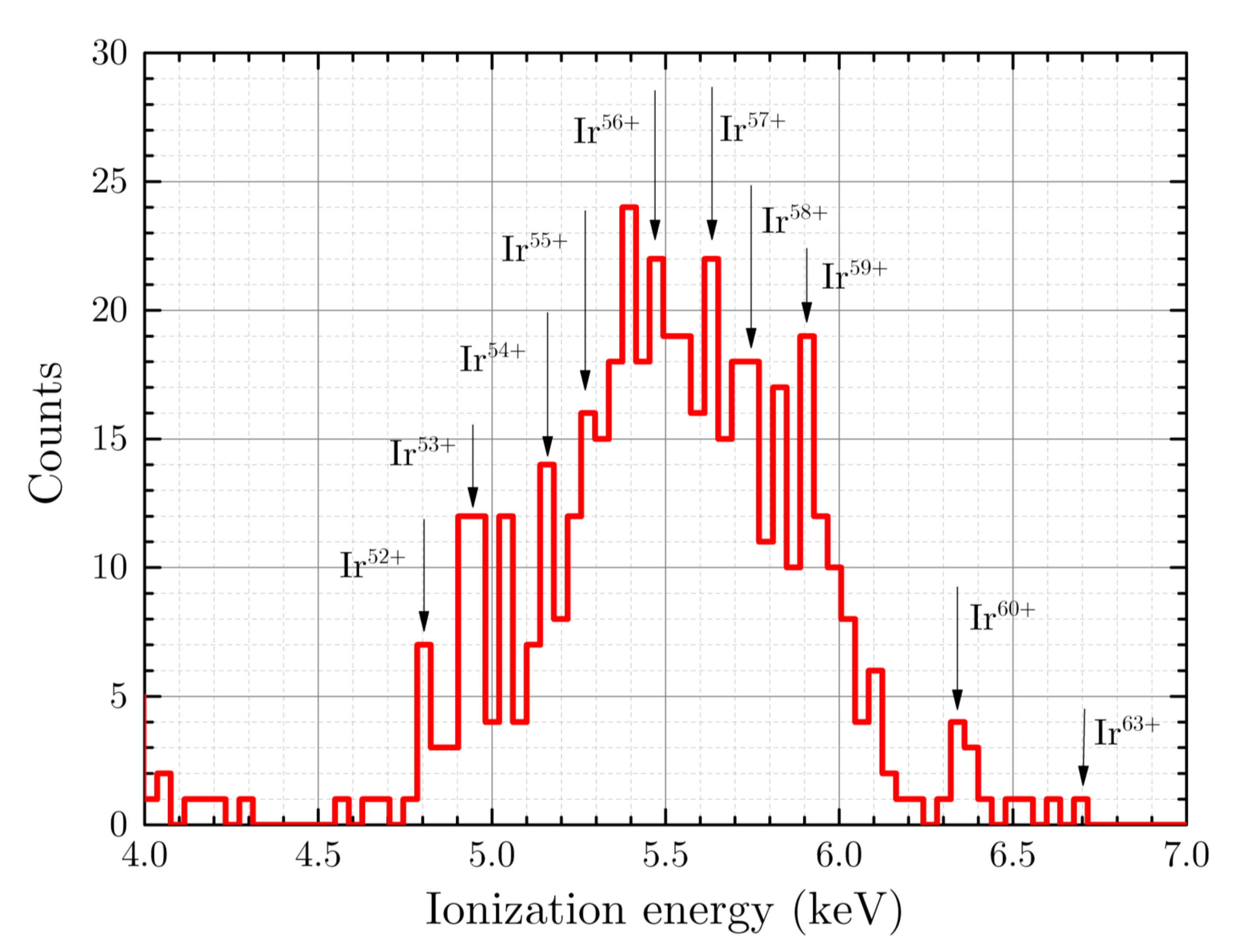
M.A. Levine, R.E. Marrs, J.R. Henderson, D.A. Knapp and M.B. Schneider, Phys. Scripta T22, 157 (1988)

V.P. Ovsyannikov and A.V. Nefiodov, Nucl. Instr. Meth. B 370, 32 (2016)

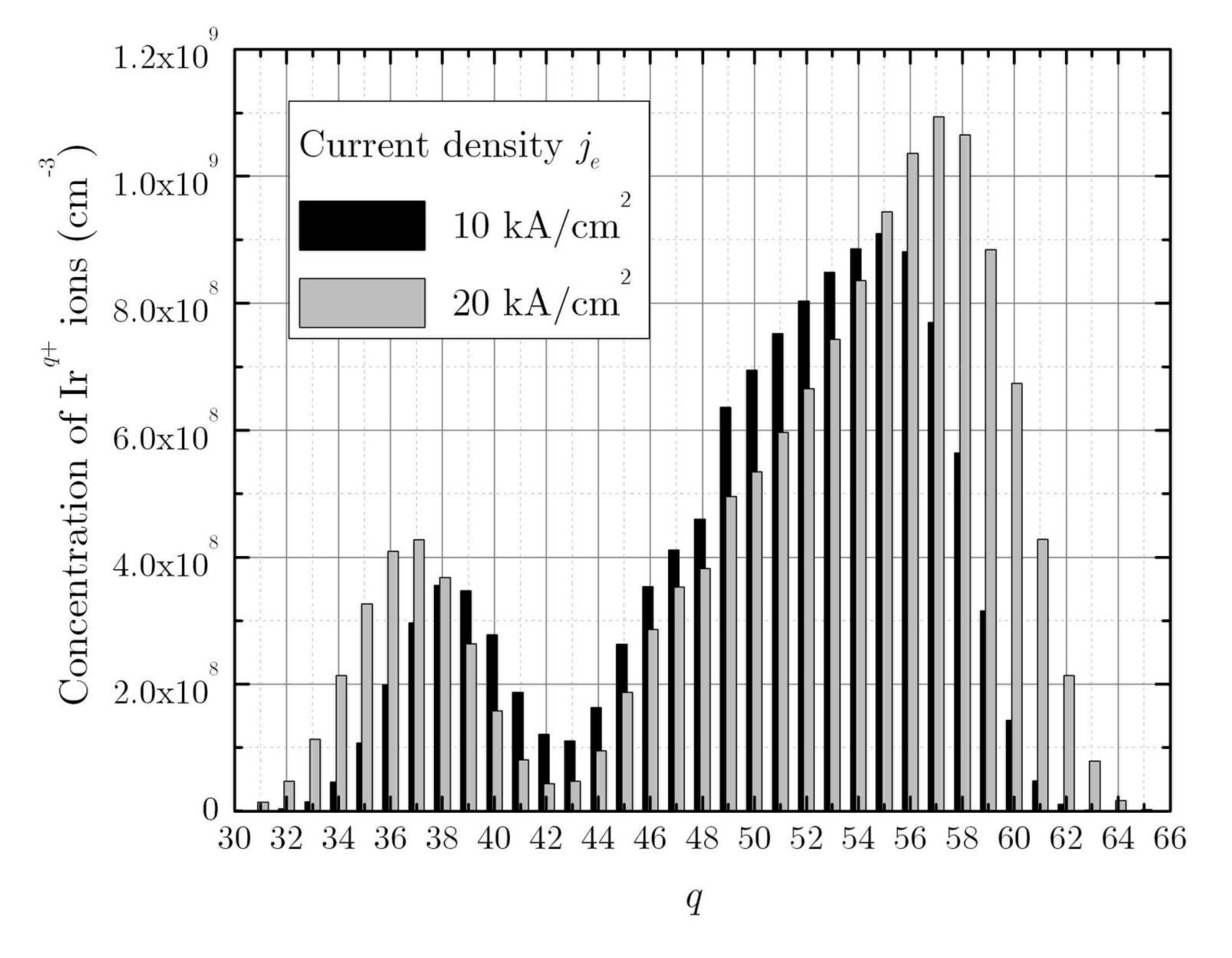
MaMFIS-10
E_e b 10 keV
I_e = 50 mA

First run: Justus-Liebig-University Giessen, 2013

MaMFIS-10: Estimation of electron current density



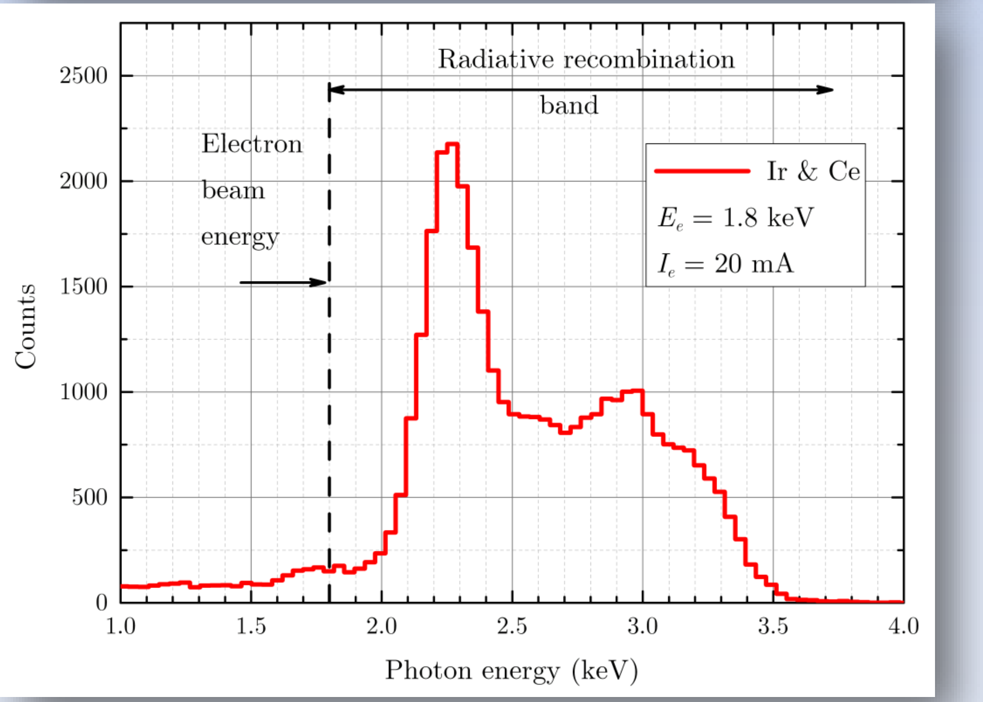
X-ray emission due to radiative recombination into the M-shell of Ir ions (experiment)



Charge-state distributions of Ir ions for different electron current density (computer simulation)

Electron current density is estimated to be j_e ~ (10 – 20) kA/cm^2

MaMFIS family developed until now



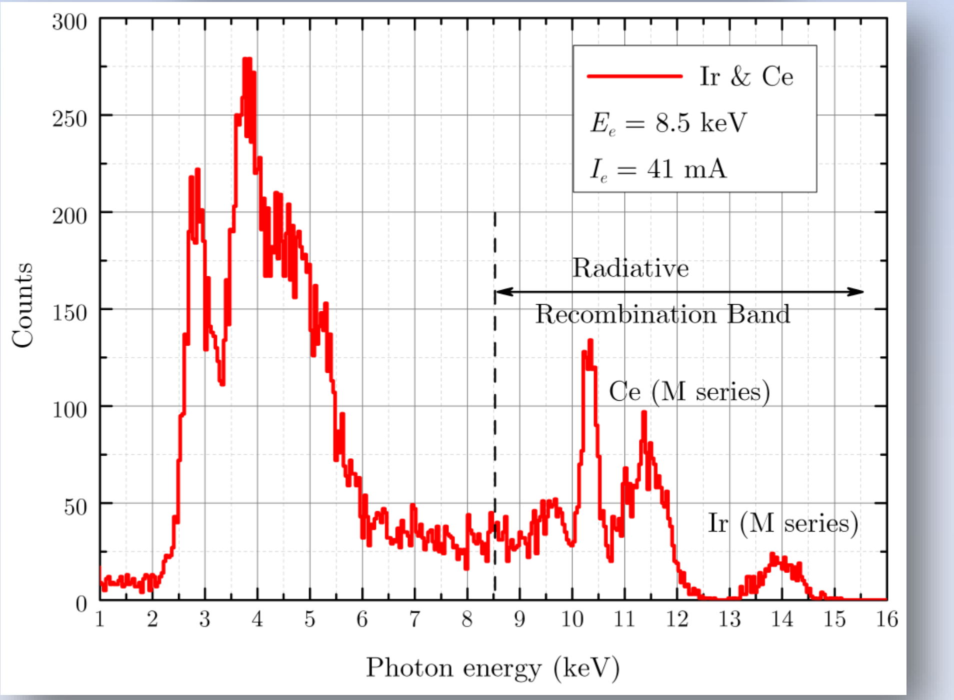
MaMFIS-4

E_e b 4 keV

Not yet tested

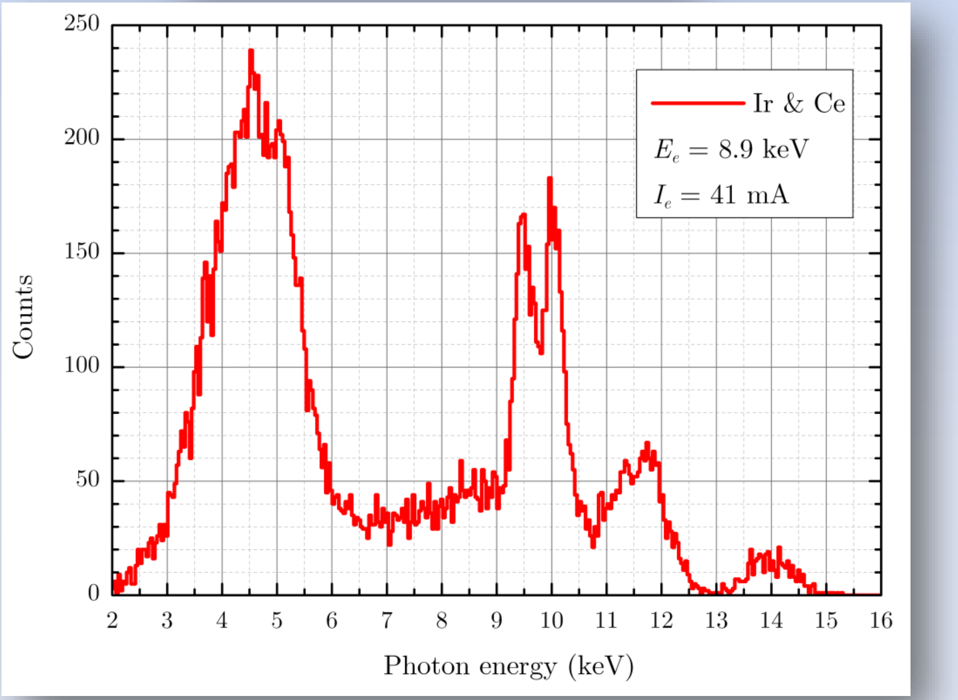
MaMFIS-8

E_e b 8 keV



MaMFIS-10

E_e b 10 keV



MaMFIS-30

E_e b 30 keV

MaMFIS-40 at JINR in Dubna

First assembling of MaMFIS-40D

Project parameters:

Electron energy E_e b 35 keV

Electron current density j_e b 20 kA/cm^2

Electron current I_e b 50 mA (DC-mode)

Realized parameters:

E_e b 40 keV

j_e b 20 kA/cm^2

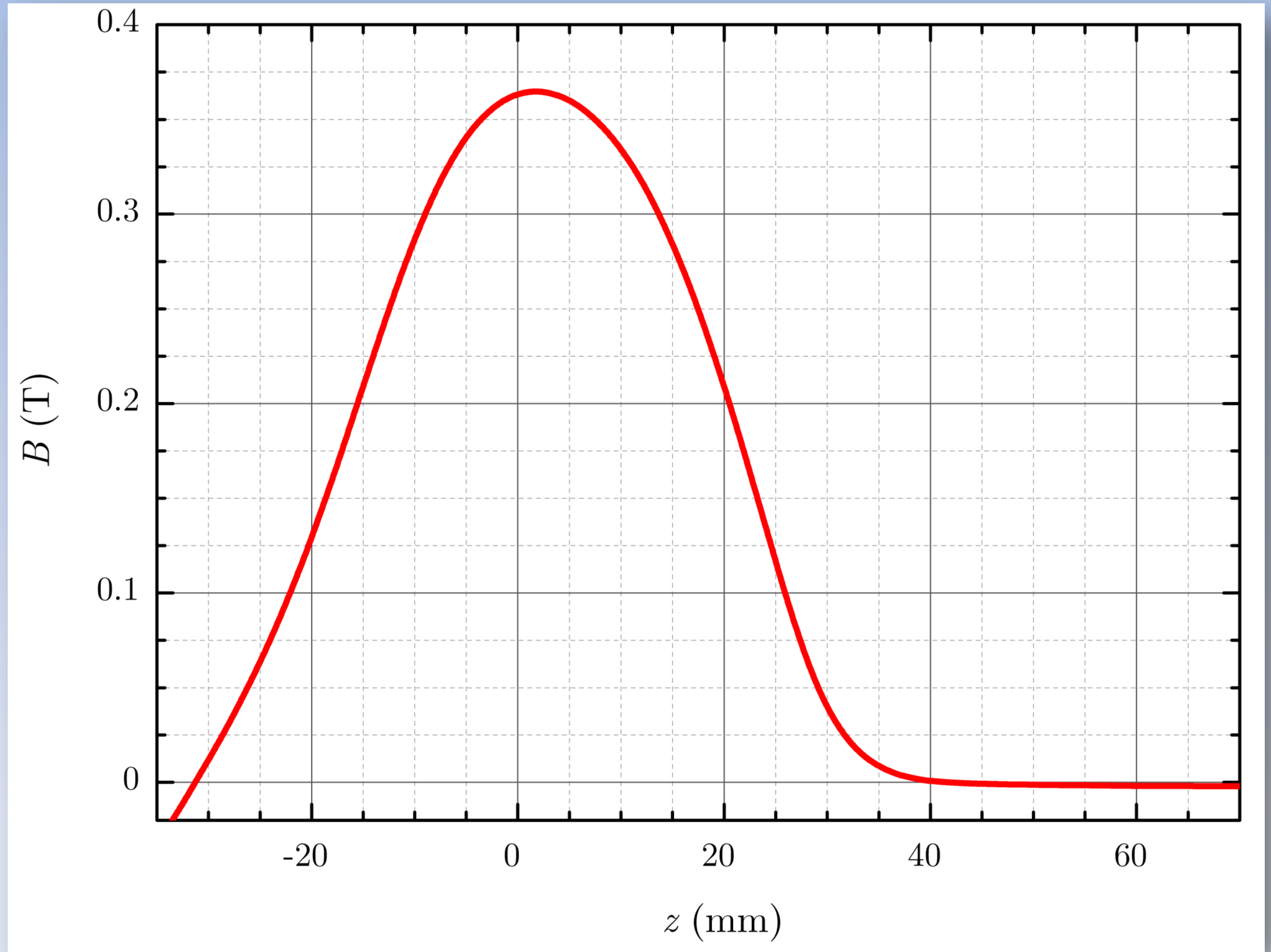
I_e b 50 mA

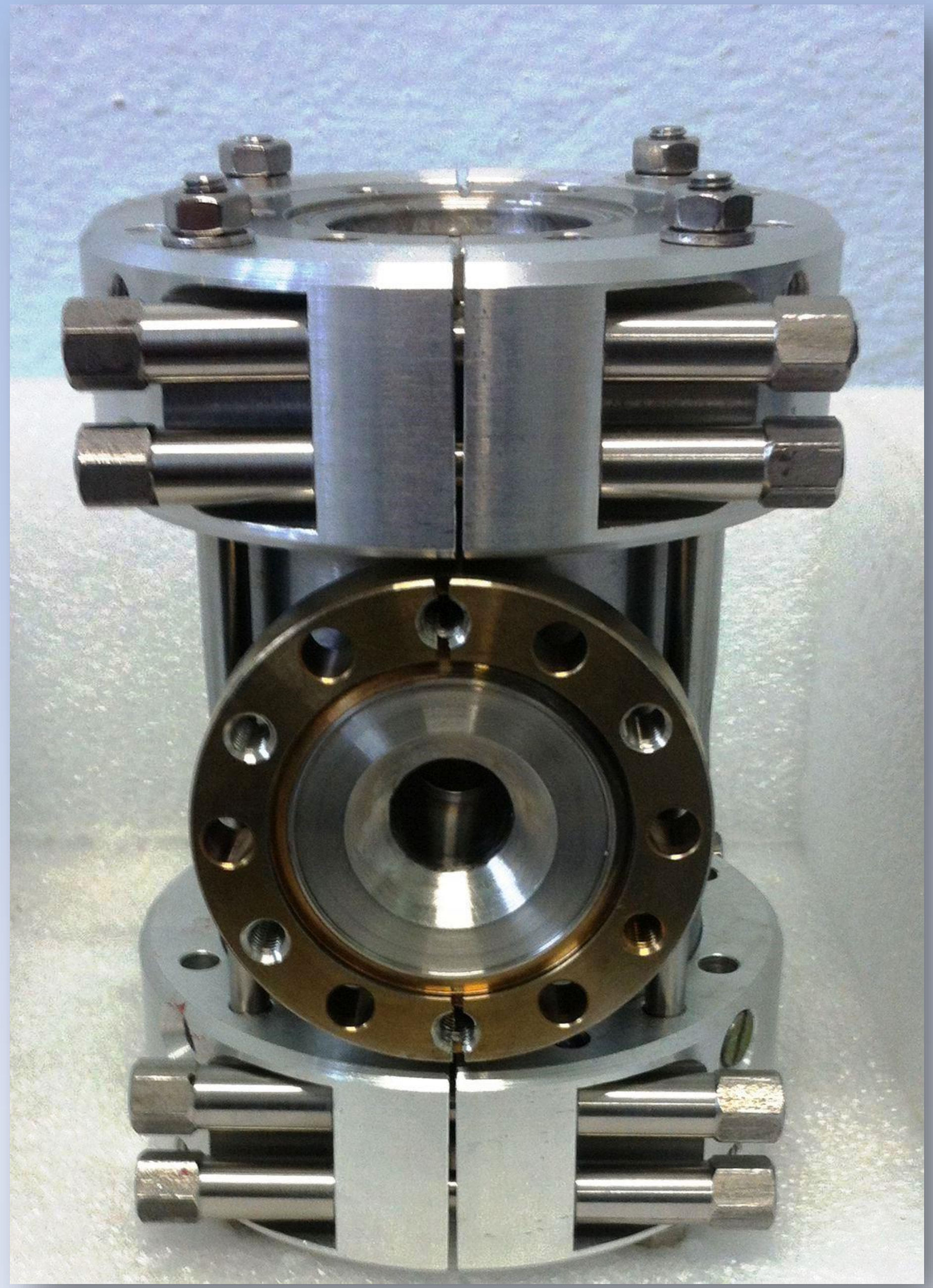
Aim of project:

Development of MaMFIS technology for production of highly charged ions of heavy elements

Assembling for extraction mode

Permanent magnet focusing system



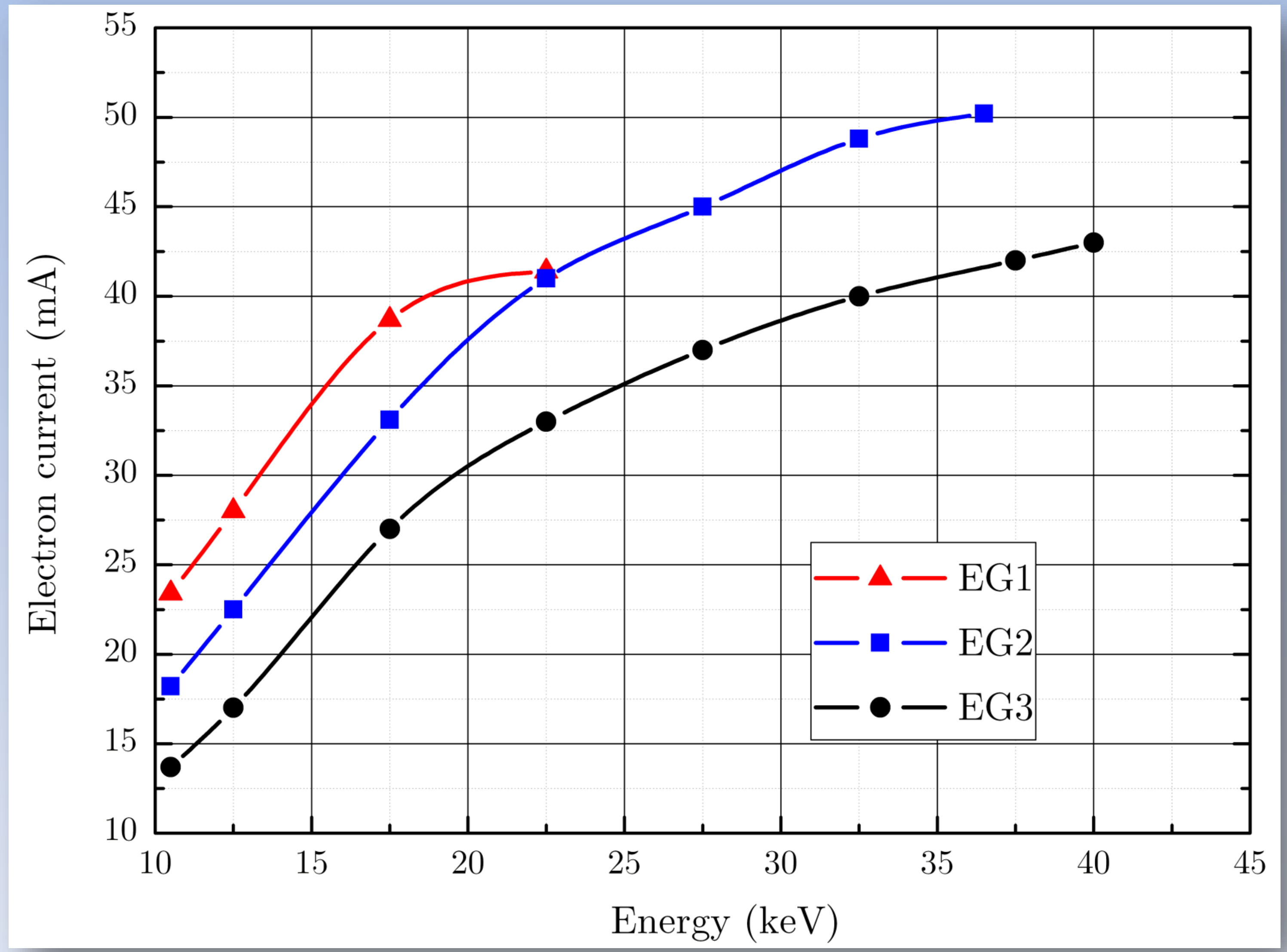


Focusing permanent magnets

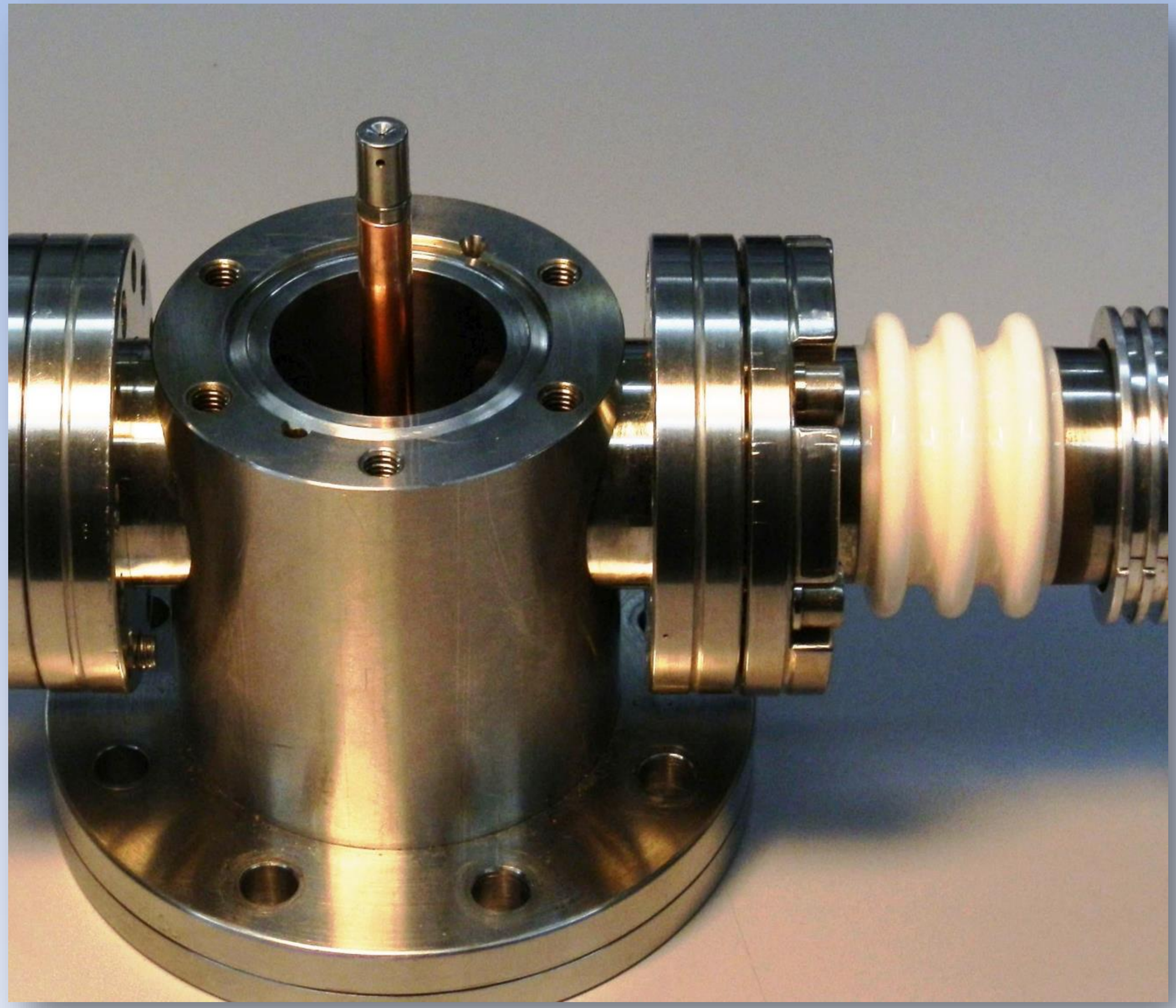
Magnetic field distribution

Focusing permanent magnets on ionization chamber

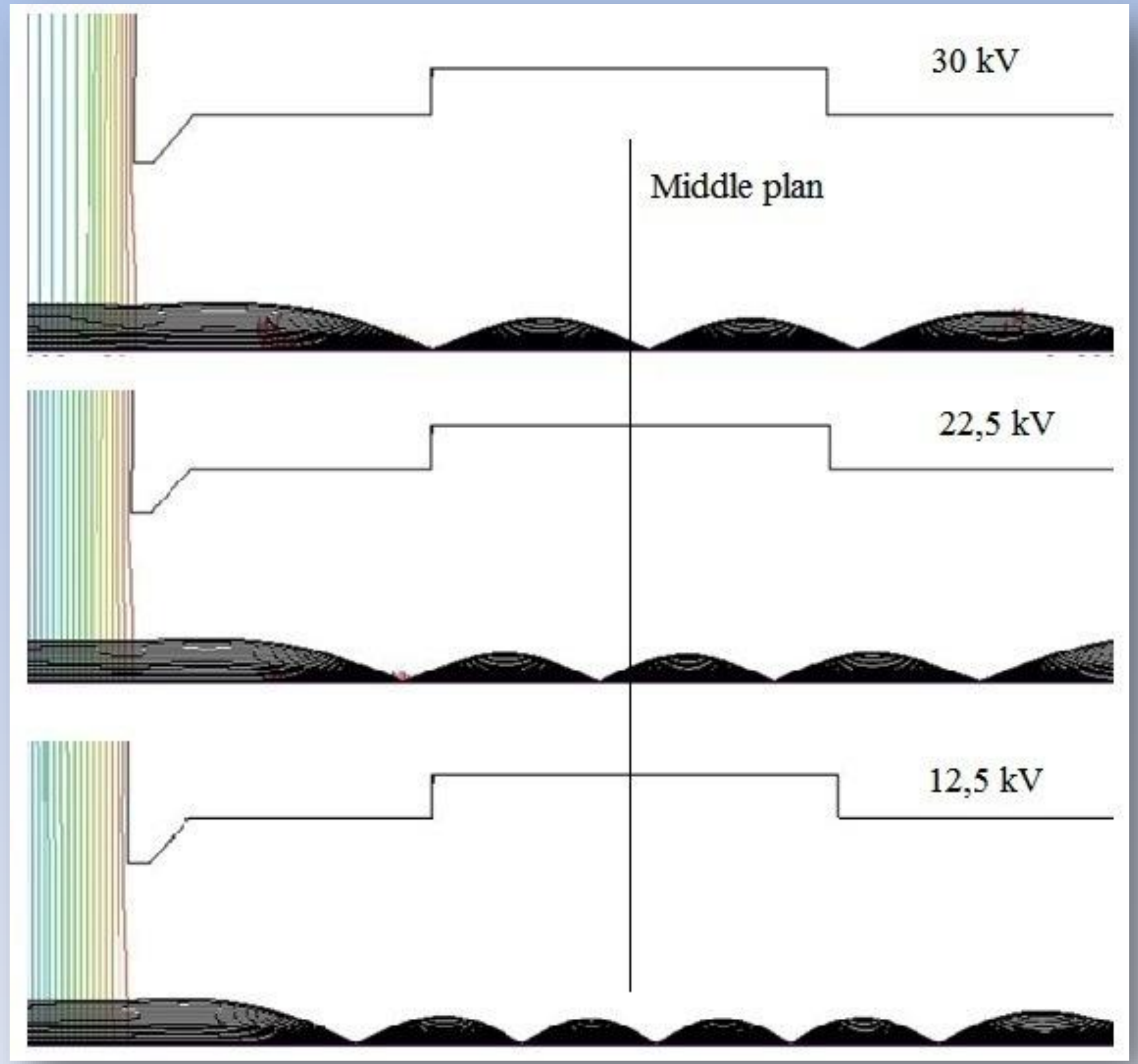
Electron gun and its characteristics



Volt-Ampere characteristics of electron guns (EG)

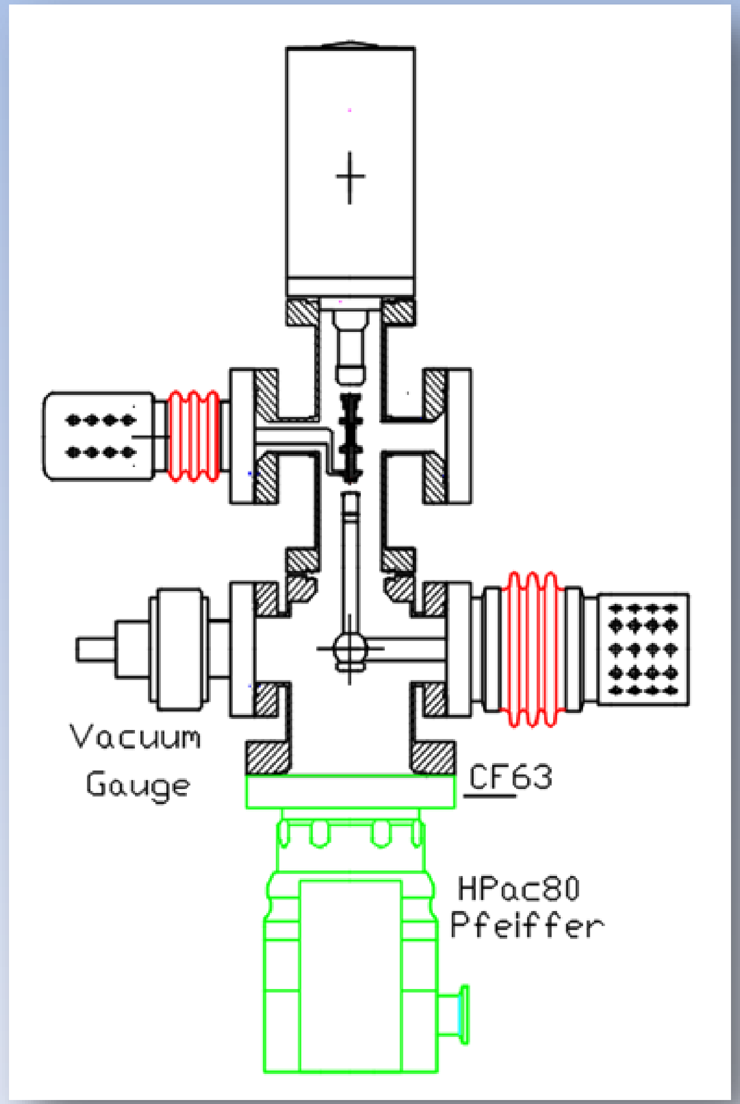


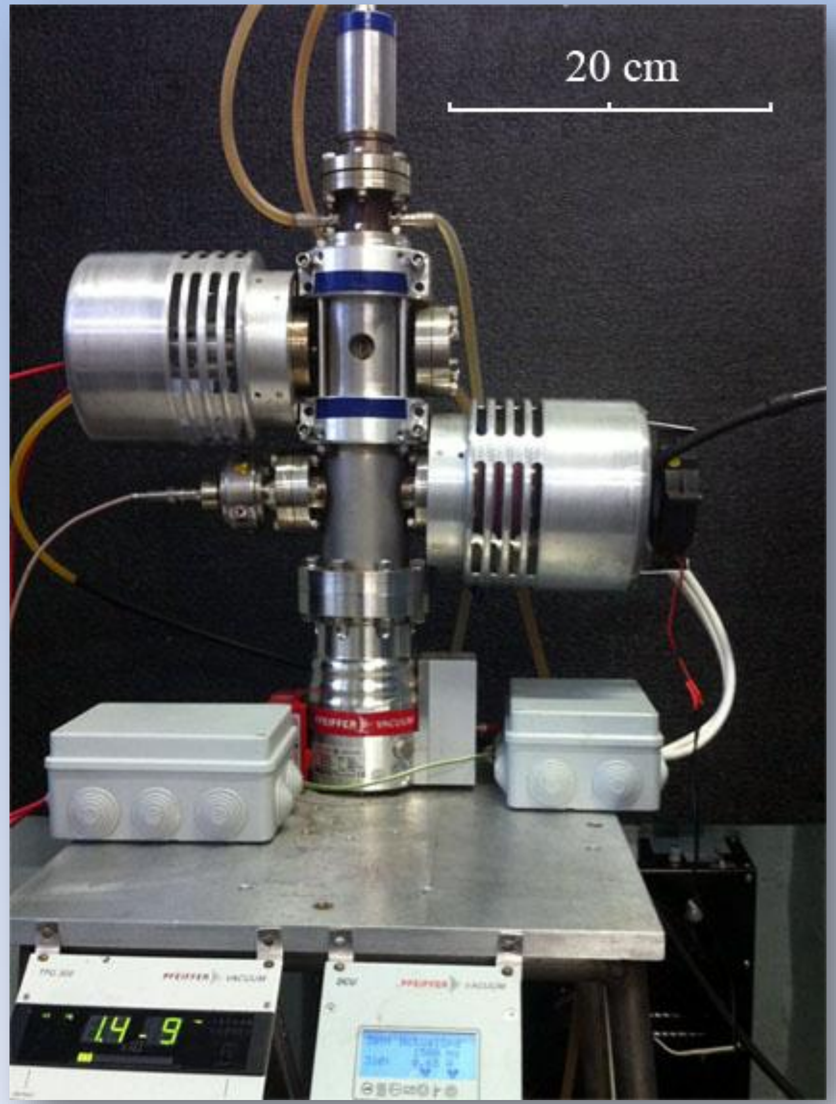
Cathode assembly of electron gun

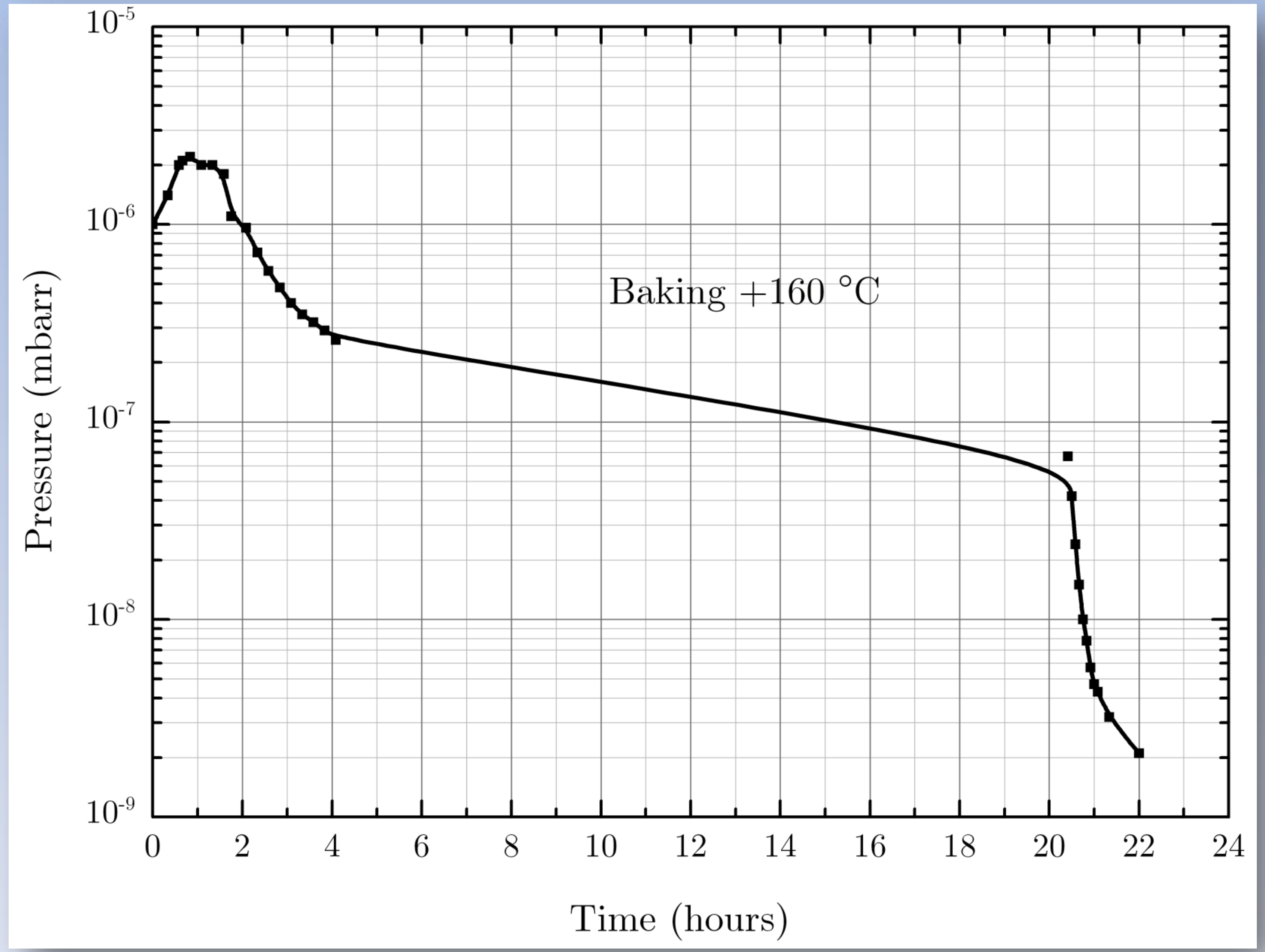


Electron beam trajectories vs. Electron energy E_e

Vacuum





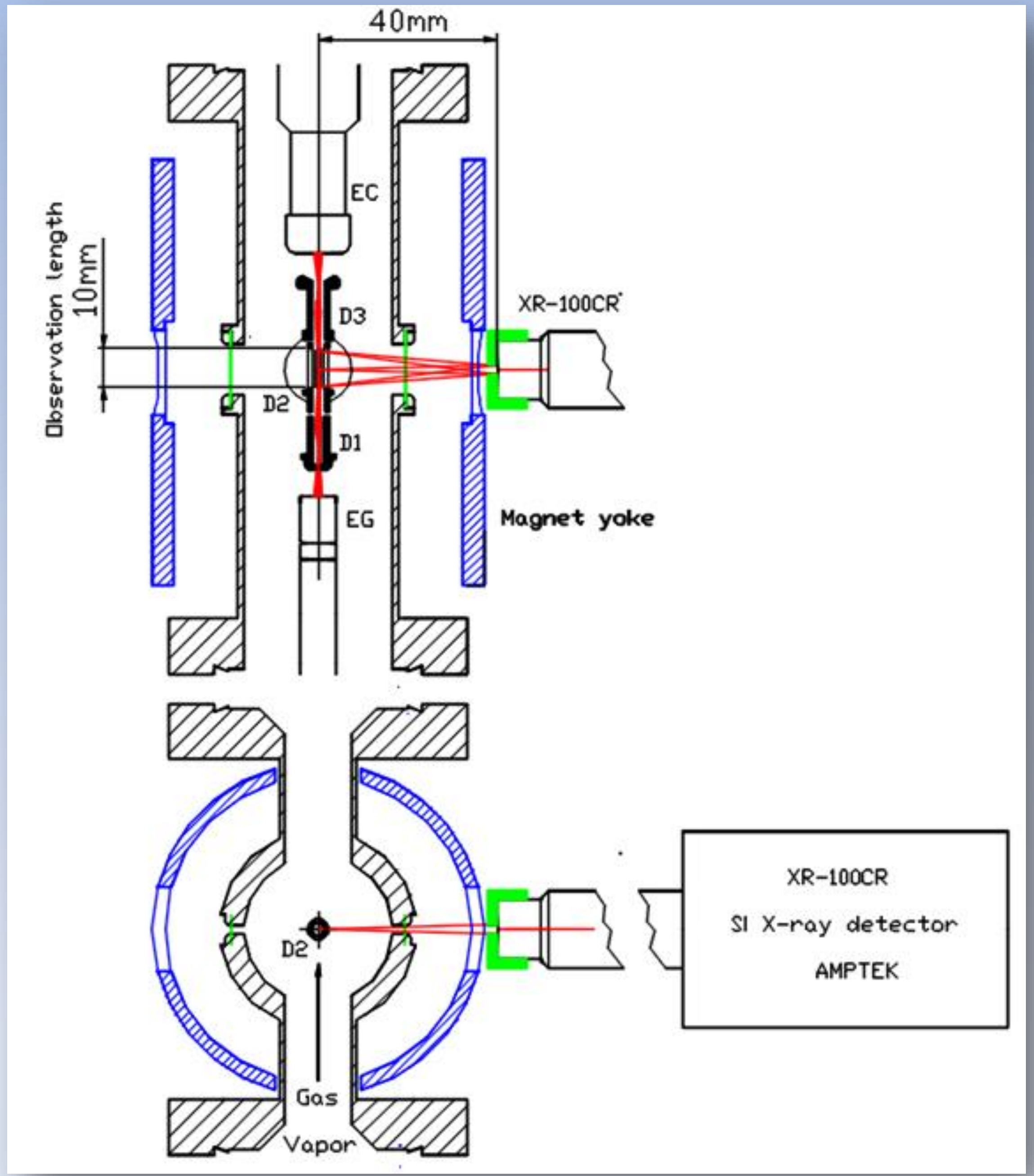


Vacuum volume < 1 litre

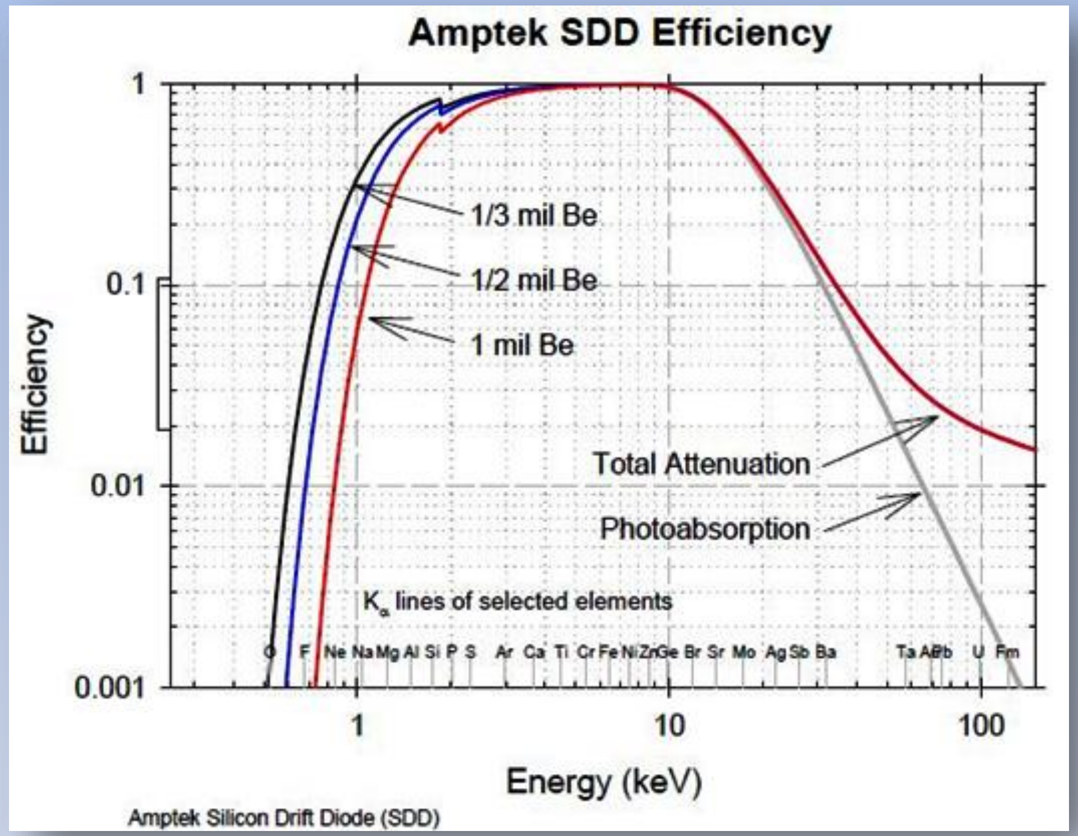
During operation vacuum ranges from 10^{-9} to 5×10^{-8} mbar

Baking procedure

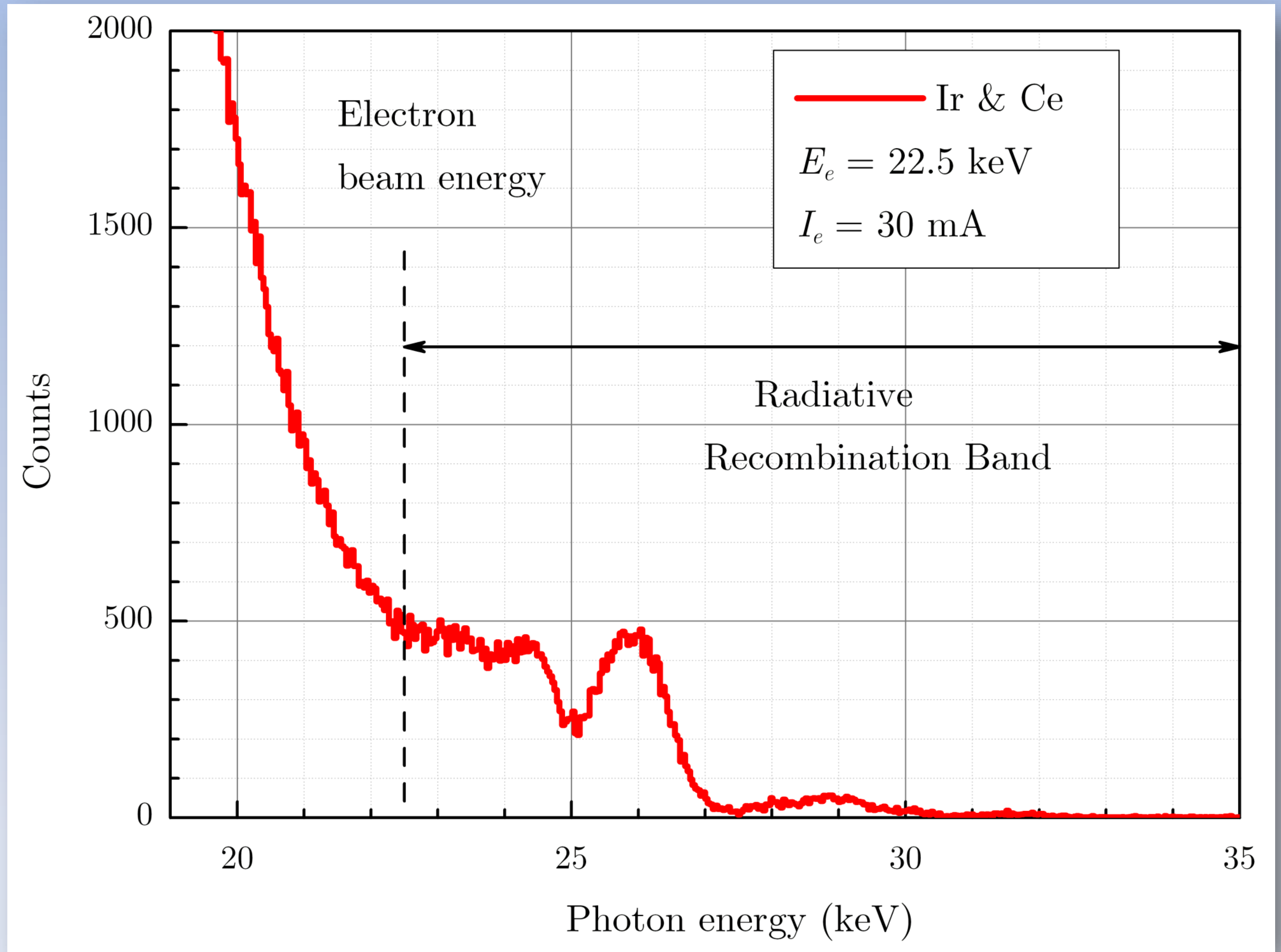
X-ray spectroscopy



Experimental scheme



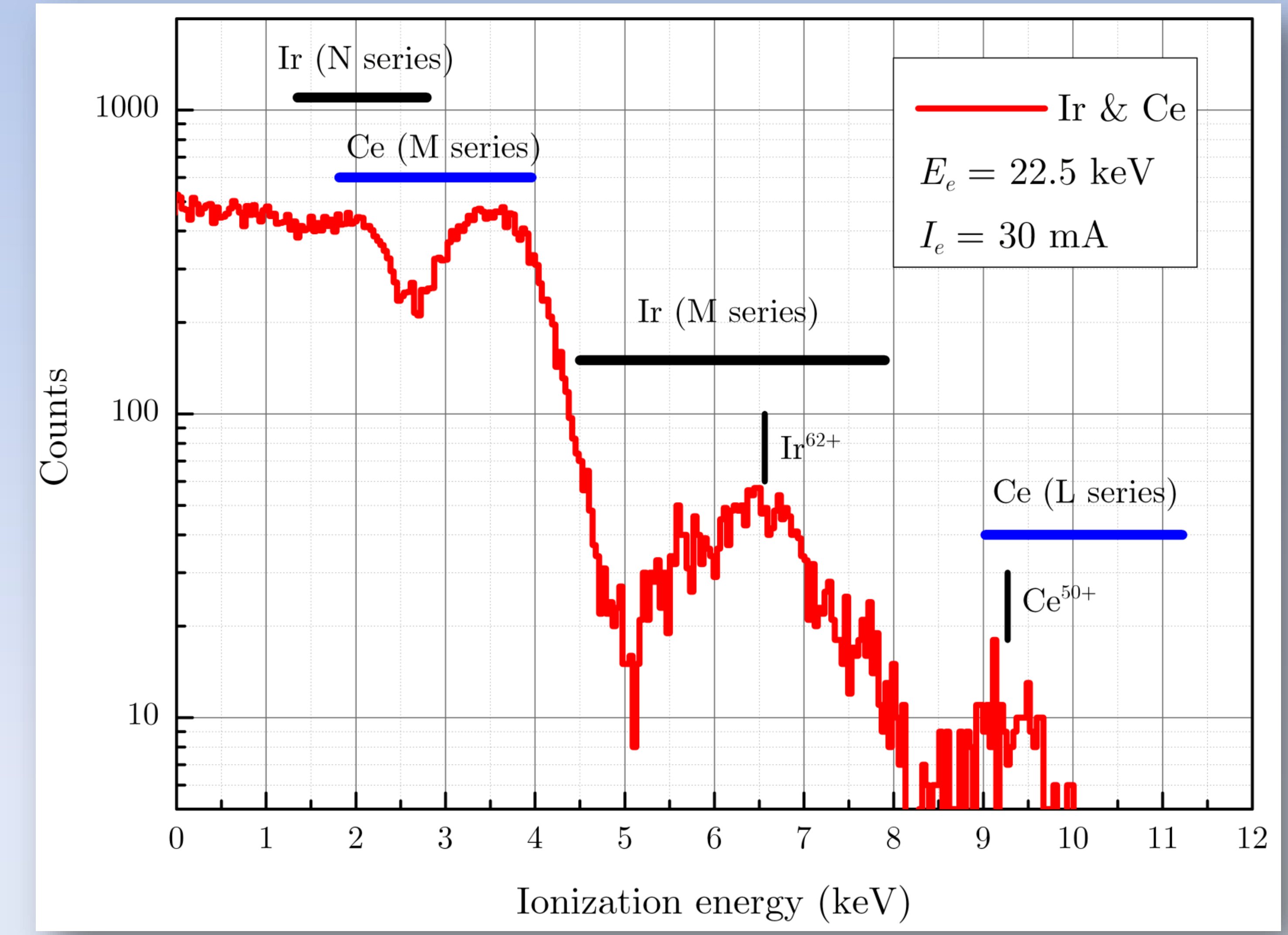
Efficiency of registration



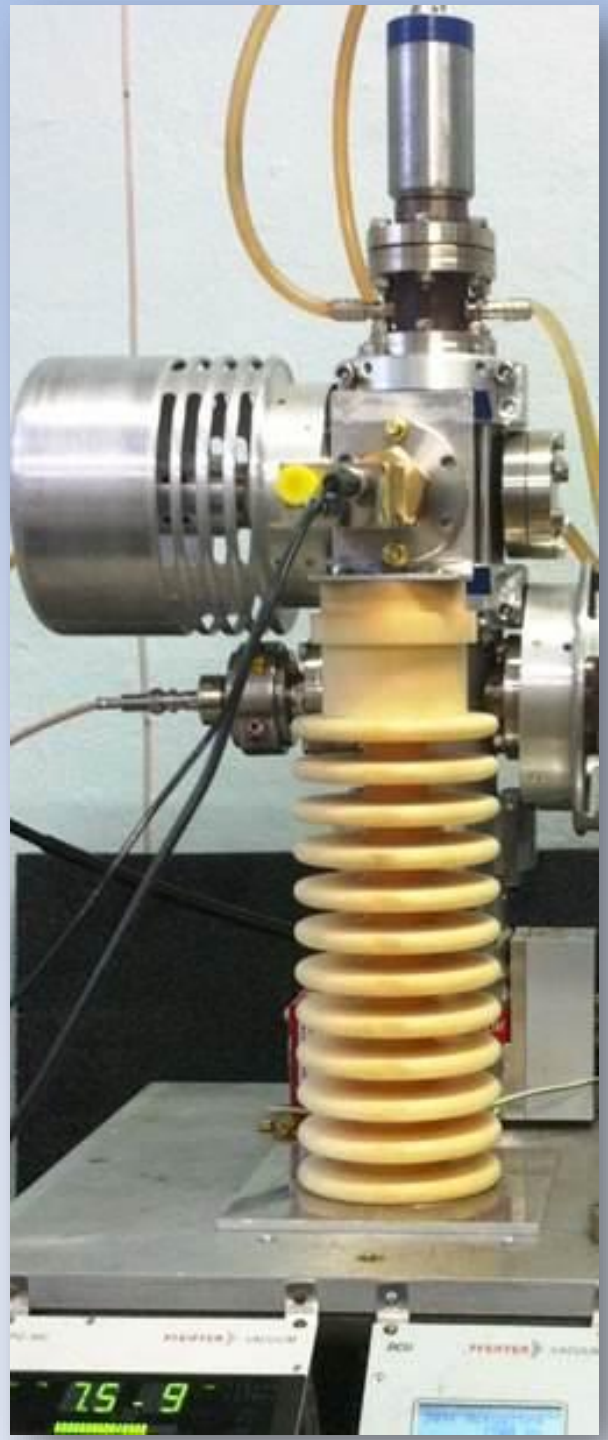
Radiation spectrum of cathode materials

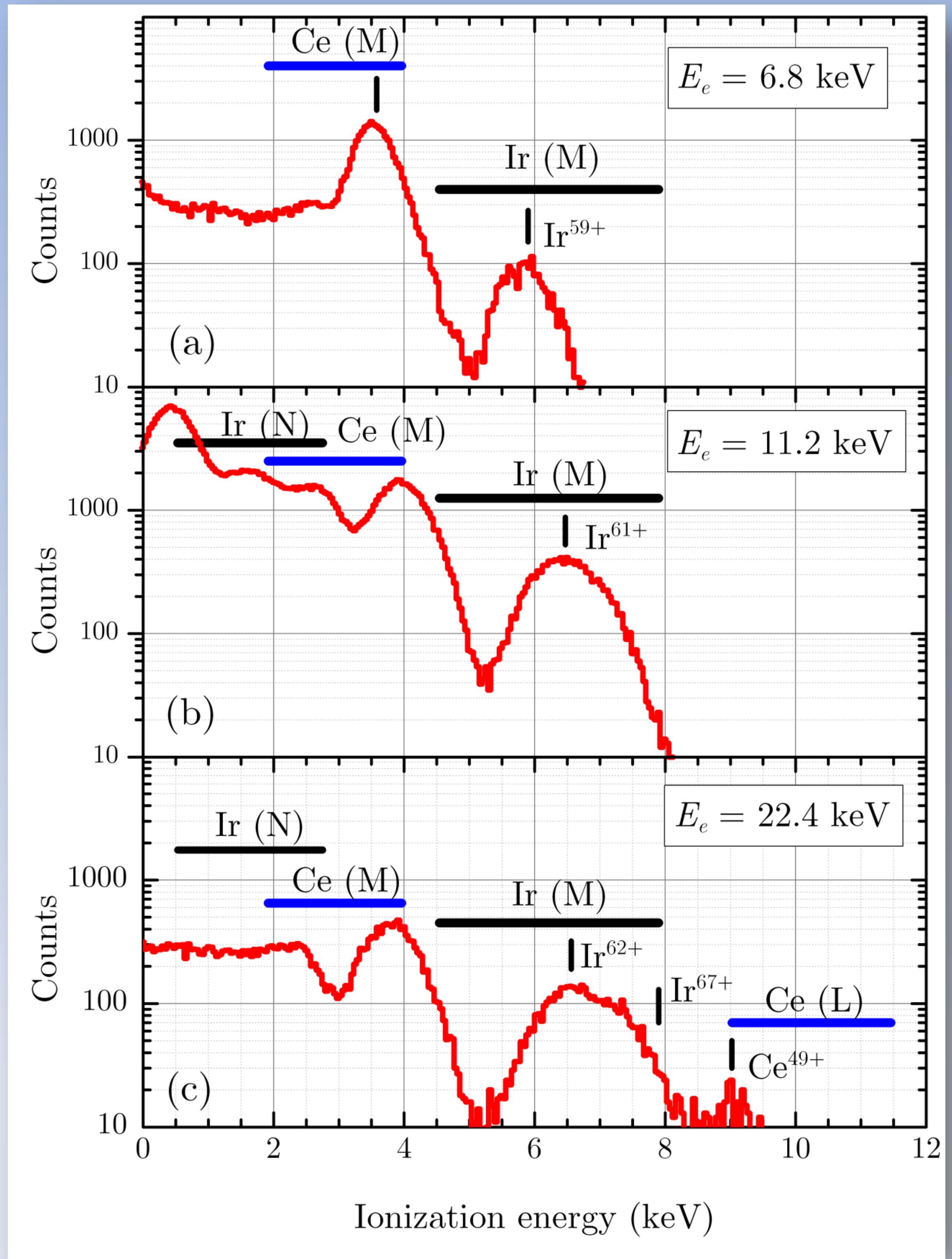
Radiative recombination continuum

Cathode materials (Ir & Ce)



RR spectrum for E_e= 22.5 keV

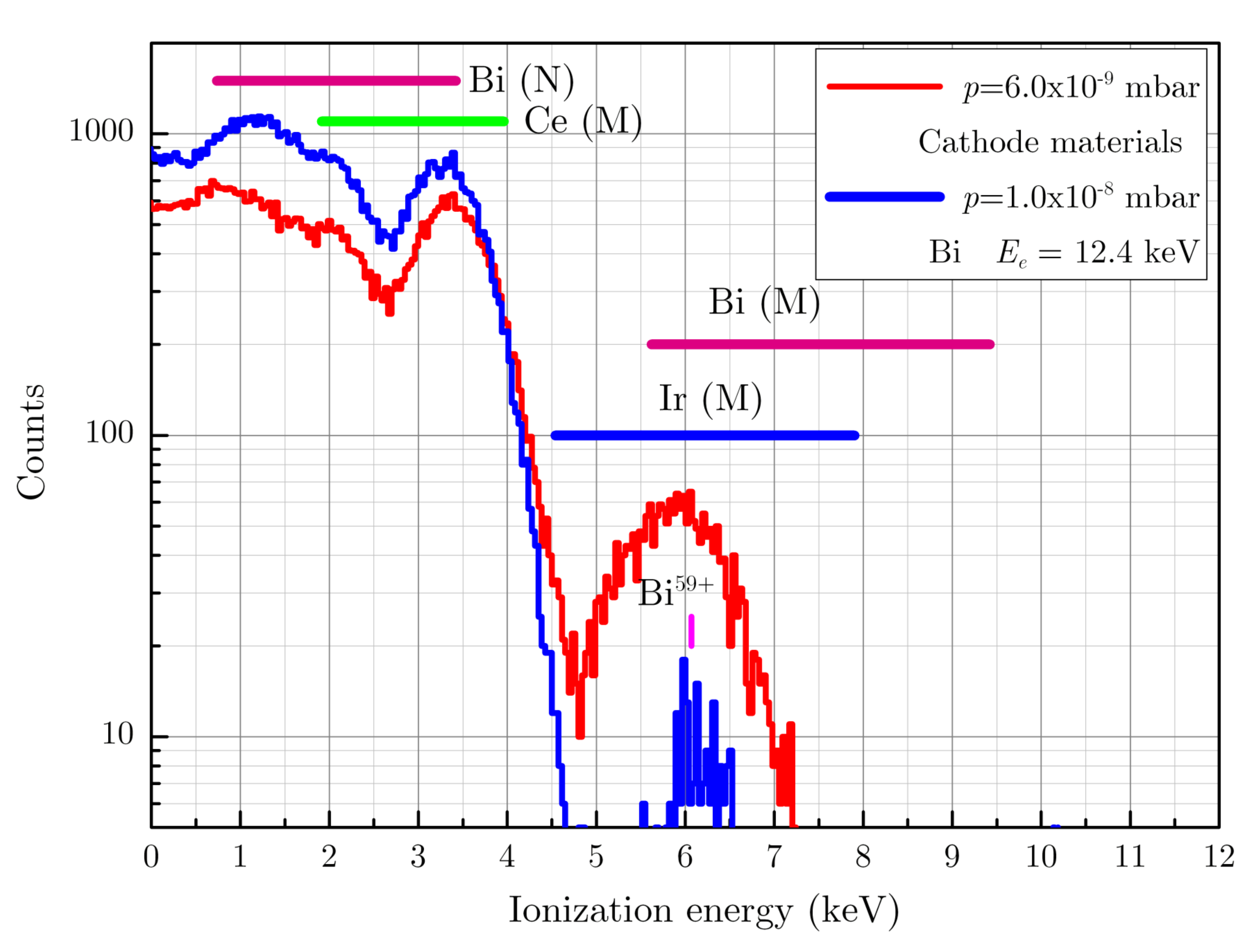




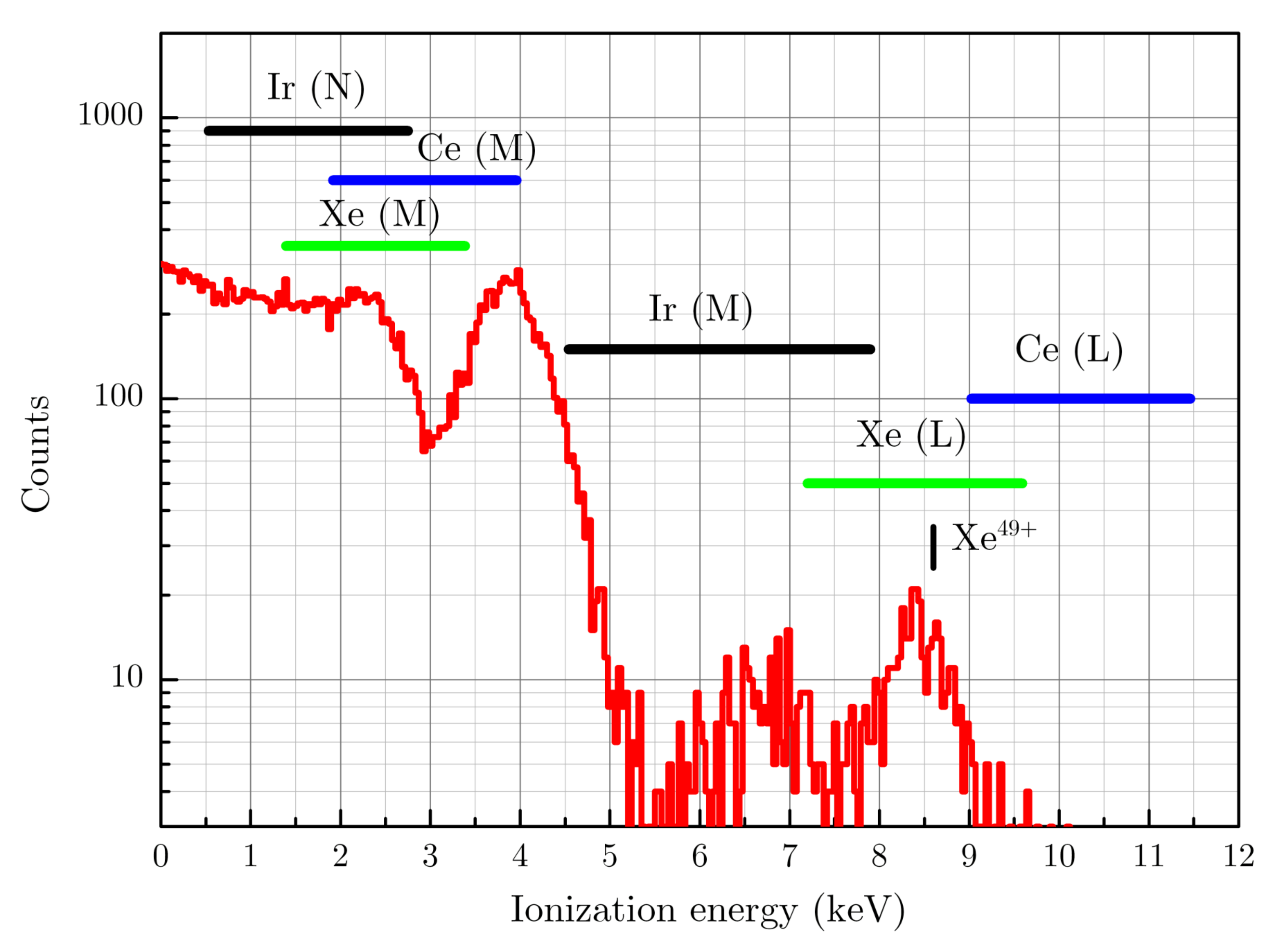
RR spectrum for different E_e

Radiative recombination continuum

Injected materials (Bi & Xe)



RR spectrum of bismuth (blue curve) compared to that of cathode materials (red curve)



RR spectrum of xenon

Features and applications of MaMFIS

Advantages:

- Highest ionization factor among the ion sources available around the world
- Minimum confinement time
- High-frequency operation

Disadvantage:

- low intensity in pulse

Applications

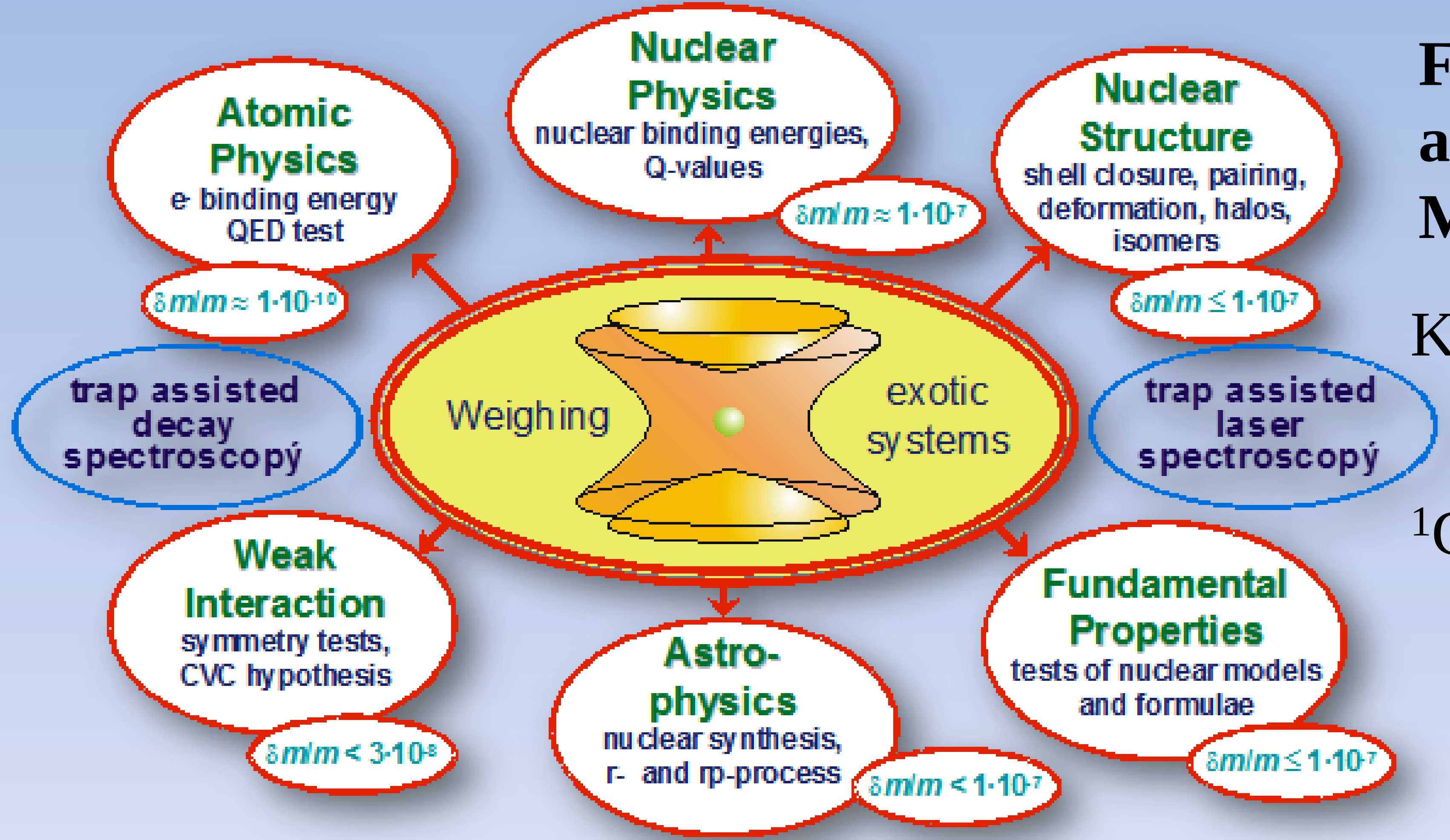
- Atomic physics (X-ray spectroscopy and ion-atom collisions)
- X-ray astrophysics and solar physics
- Plasma physics (magnetic fusion diagnostics)
- Interaction of highly charged ions with surface (secondary electron and ion emission)
- Secondary ion mass spectrometry
- Nanostructuring

Penning Trap experiments

MaMFIS as ion source for high-precision mass measurements

Resolution: $\frac{m}{Dm} \sim \frac{qB}{m}$

Intensity of ions > 1 ion/s



Future Penning Trap Experiments at GSI / FAIR – The HITRAP and MATS Projects

K. Blaum[1,2] and F. Herfurth[1] for the HITRAP and MATS Collaboration

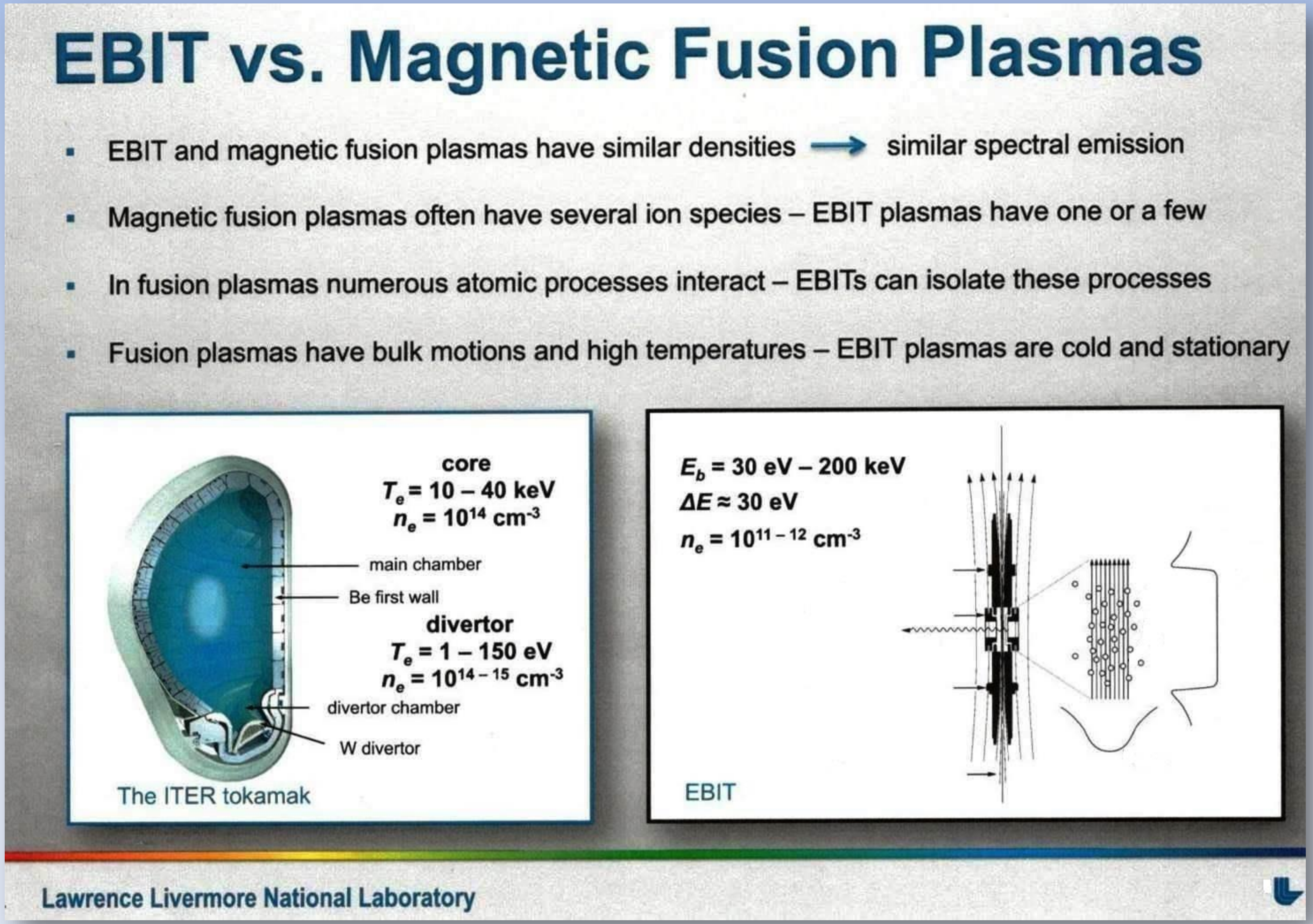
[1]GSI Darmstadt, [2]Johannes Gutenberg-University Mainz

MaMFIS technology perfectly fulfills the requirements

MaMFIS is a very efficient Charge Breeder with trap capacity of 10^5 – 10^6 charges, in particular, for short half-life radionuclides

"The radioactive beam intensity spans … from a few to over 10^{10} ions/s."
F. Wenander, *Charge breeding of radioactive ions with EBIS and EBIT*, Int. Symposium on Electron Beam Ion Sources and Traps, April 7th-10th 2010, Stockholm, Sweden

High-density microplasma research



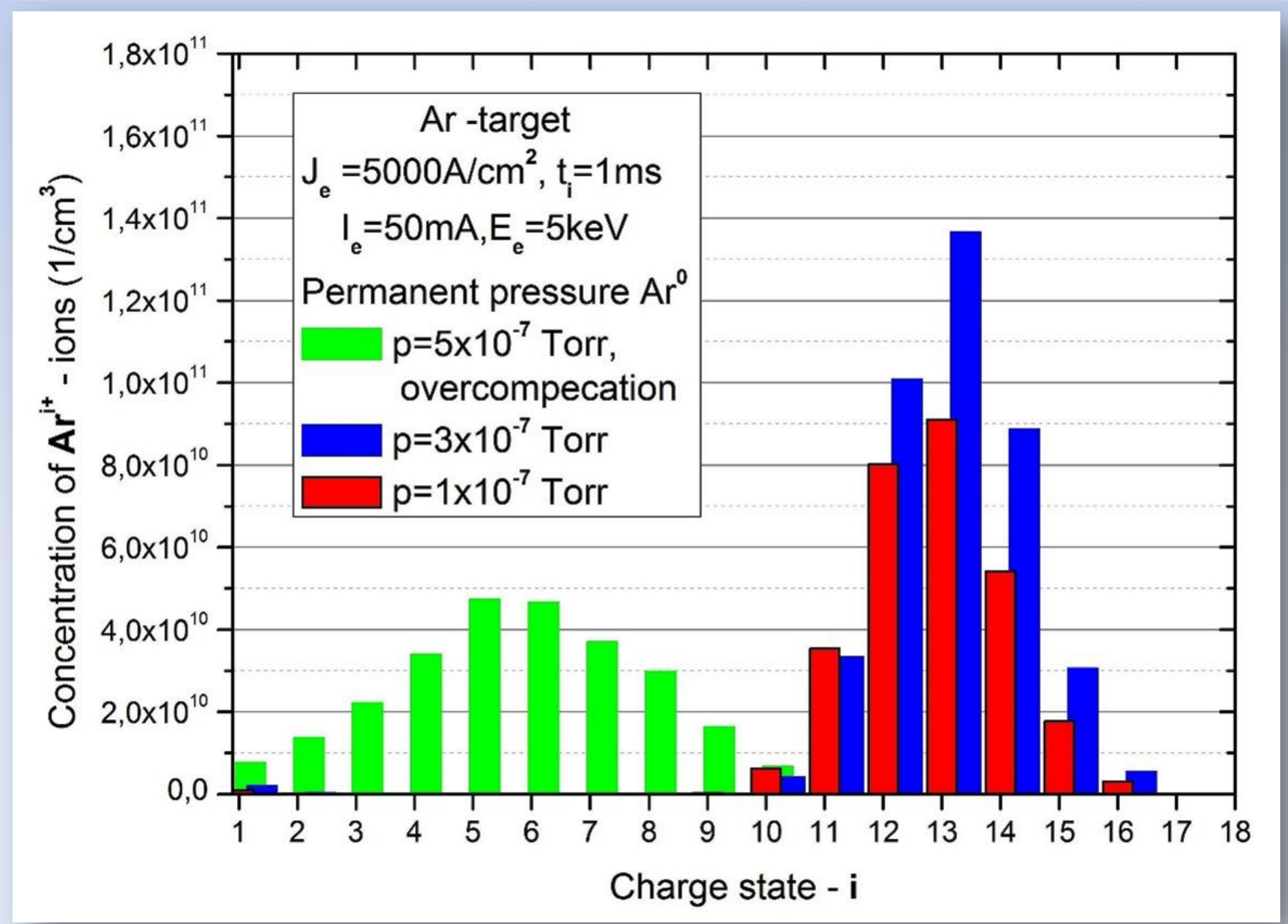
Joel Clementson, LLNL

MaMFIS:

$E_e \sim 10$ keV	$E_e \sim 40$ keV
$j_e \sim 20$ kA/cm^2	$j_e \sim 200$ kA/cm^2
$n_e \sim 2\times10^{13}$ cm^{-3}	$n_e \sim 10^{14}$ cm^{-3}

High-frequency accelerators

Accelerated ion	$^{16}O^{5+}$	$^{20}Ne^{6+,7+}$	$^{40}Ar^{12+,13+}$	$^{56}Fe^{17+,18+}$	$^{84}Kr^{25+,26+}$	$^{132}Xe^{36+ \div 39+}$	$^{184}W^{42+ \div 46+}$ *	$^{209}Bi^{48+ \div 53+}$
A/Z	3.2	3.67, 2.86	3.33, 3.08	3.29, 3.11	3.36, 3.23	3.38 ÷ 3.67	4 ÷ 4.38	3.94 ÷ 4.45
Yield, ions/s	$7\cdot10^7$	$8\cdot10^7$	$9\cdot10^7$	10^8	$3\cdot10^8$	$4\cdot10^8$	$4\cdot10^8$	$4\cdot10^8$



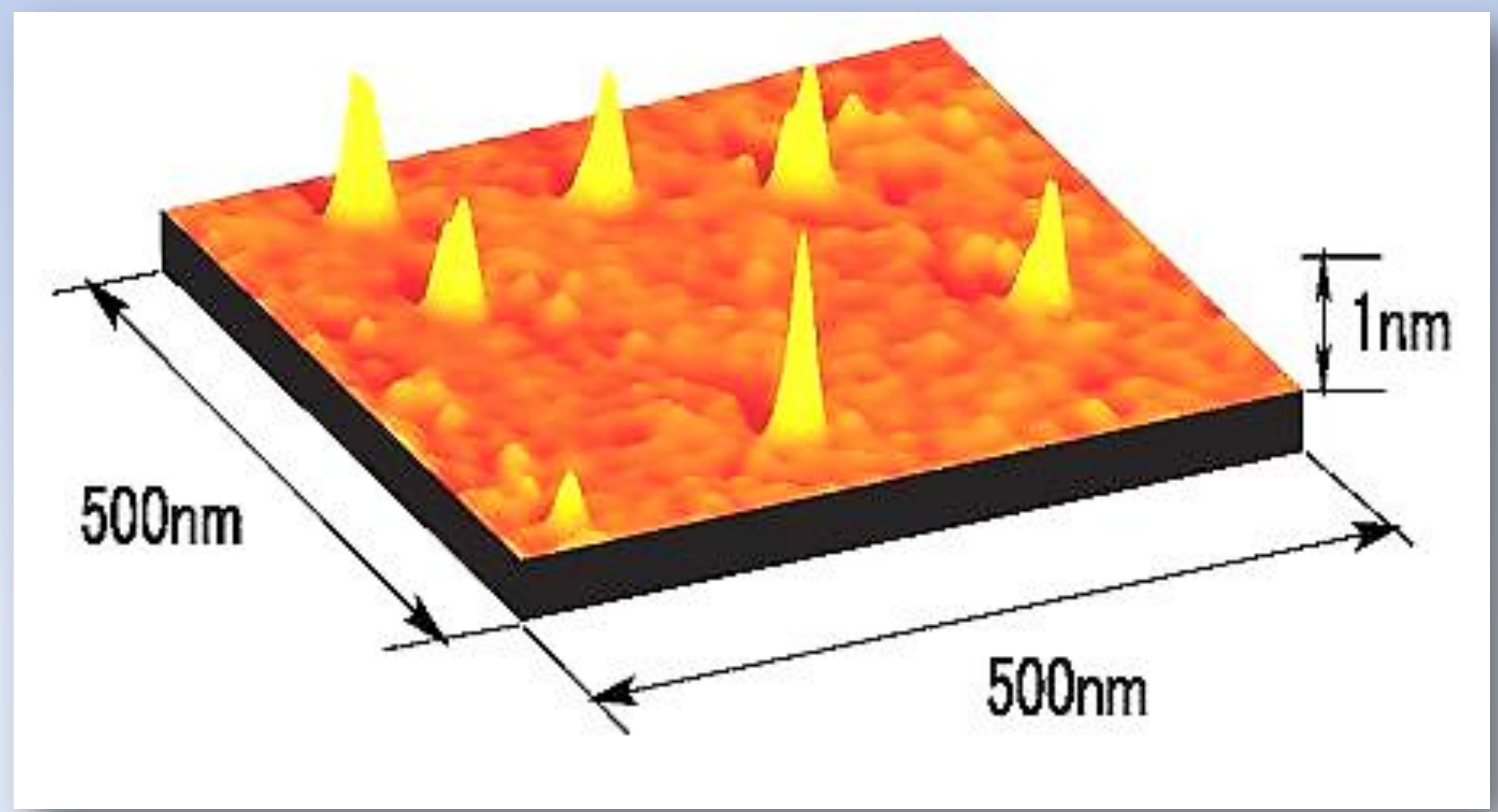
Low-intensity, high-charge state ion beams for special applications

Ion source of MaMFIS-10 type: expected yield of Kr^{25+} ~ 10^8 ions per second

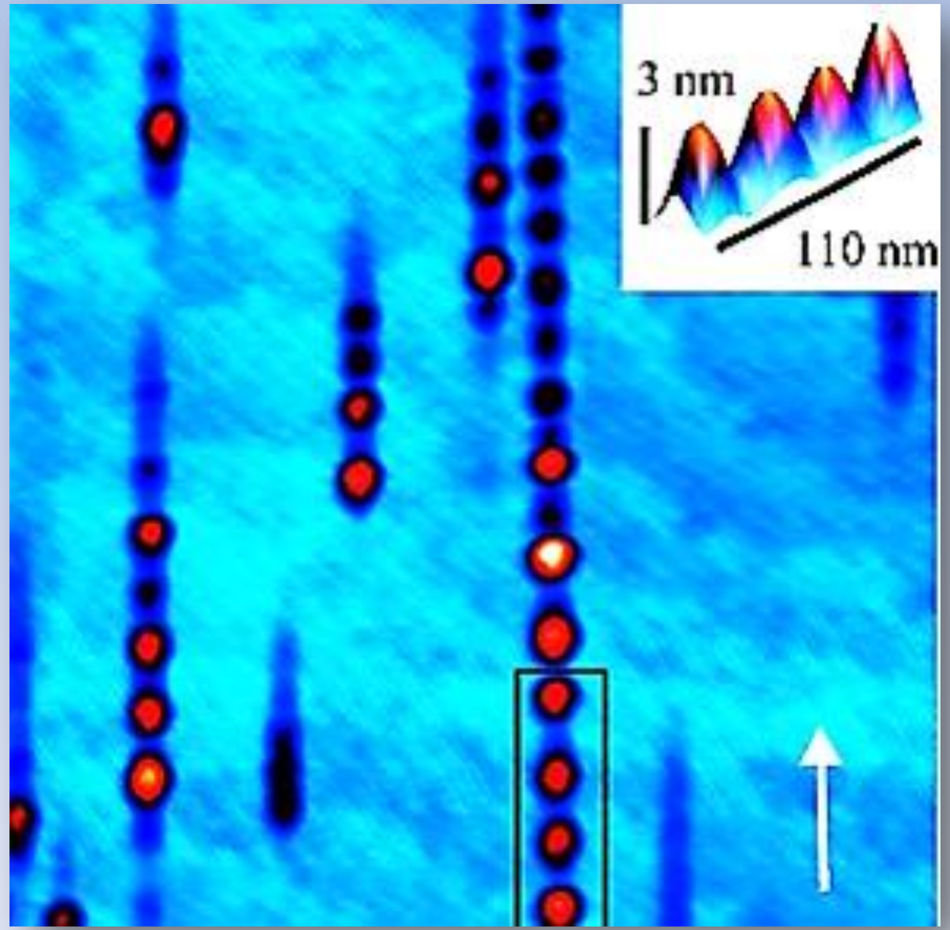
Nanostructuring

Basic idea – R. Schmieder, 1991

Basic research – University of California, Berkeley
Livermore EBIT was moved to Berkeley in 2001



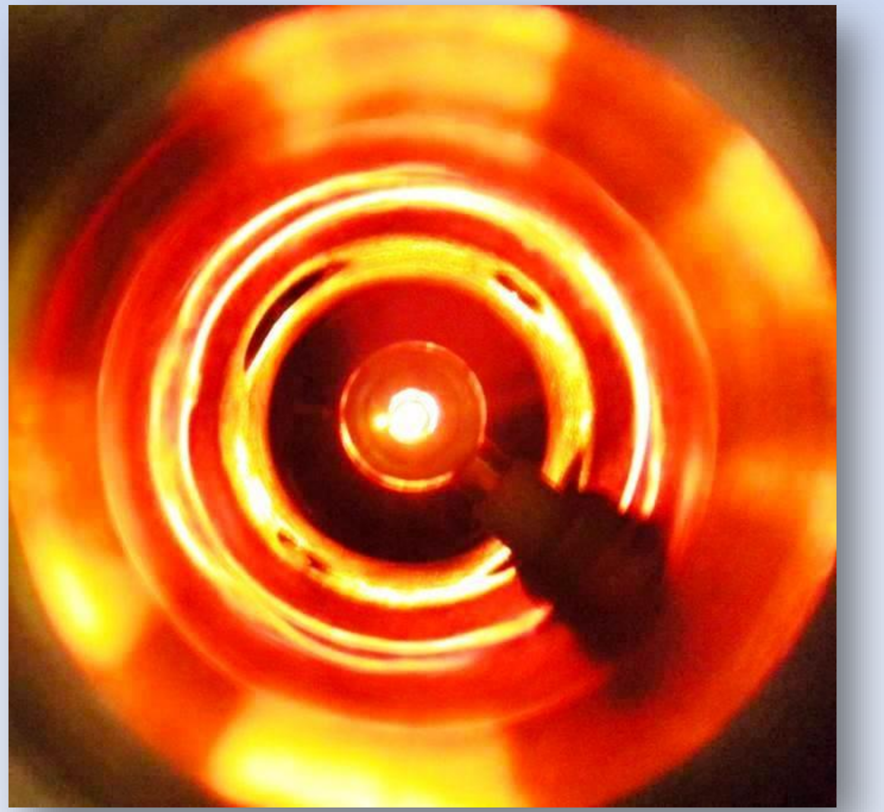
http://yebisu.ils.uec.ac.jp/surface.html



Prof. Dr. Marika Schleberger
University Duisburg-Essen
(Dresden EBIT)

Summary

- **Novel method for production of highly charged ions in a rippled electron beam is developed and confirmed experimentally at electron energies E_e b 22.5 keV**
- **Electron current density of about 20 kA/cm^2 is achieved**
- **X-ray radiation from highly charged ions of Ir^{67+} and Xe^{50+} is detected**
- **Method allows one to produce any ions of arbitrary elements of the periodic table up to U^{92+} ions in simple compact devices**
- **X-ray spectroscopy of all elements of the periodic table is feasible**



Acknowledgements

The authors express deep gratitude to
A. A. Smirnov and A. A. Karpukhin for help in the x-ray spectroscopic measurements,
A. Mueller for giving opportunity to test the first MaMFIS in Institute for Atomic and Molecular Physics at Justus-Liebig-University Giessen,
O. K. Kultashev for his contribution to creation of electron optics,
All members of Krion Group of Joint Institute for Nuclear Research in Dubna, who help in experiments

THANK YOU FOR YOUR ATTENTION !