プラズマ光源関連イオンのEBITによる分光

Emission spectroscopy of multiply charged ions related to plasma light sources with an EBIT

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NIFS

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2012 年 12 月 11-13 日

核融合科学研究所, 土岐市, 岐阜県

Outline

- ***Experimental setup***
  - Electron beam ion trap (EBIT)
  - EUV spectrometer
- ***Motivation & Results and discussion for…***
  - Sn ions
    - Semiconductor photo-lithography
    - Extreme ultra-violet (EUV) lithography
  - Gd ions
    - Beyond EUV lithography
  - Bi ions
    - Water window, Live cell imaging

    - *EBIT emission spectra*
    - Comparison with other emissions and Calc. (FAC)
- ***Summary and Outlook***

Principle of an EBIT

(Electron Beam Ion Trap)

Penning-like ion trap
+
High density electron beam

➔ ***Successive ionization***

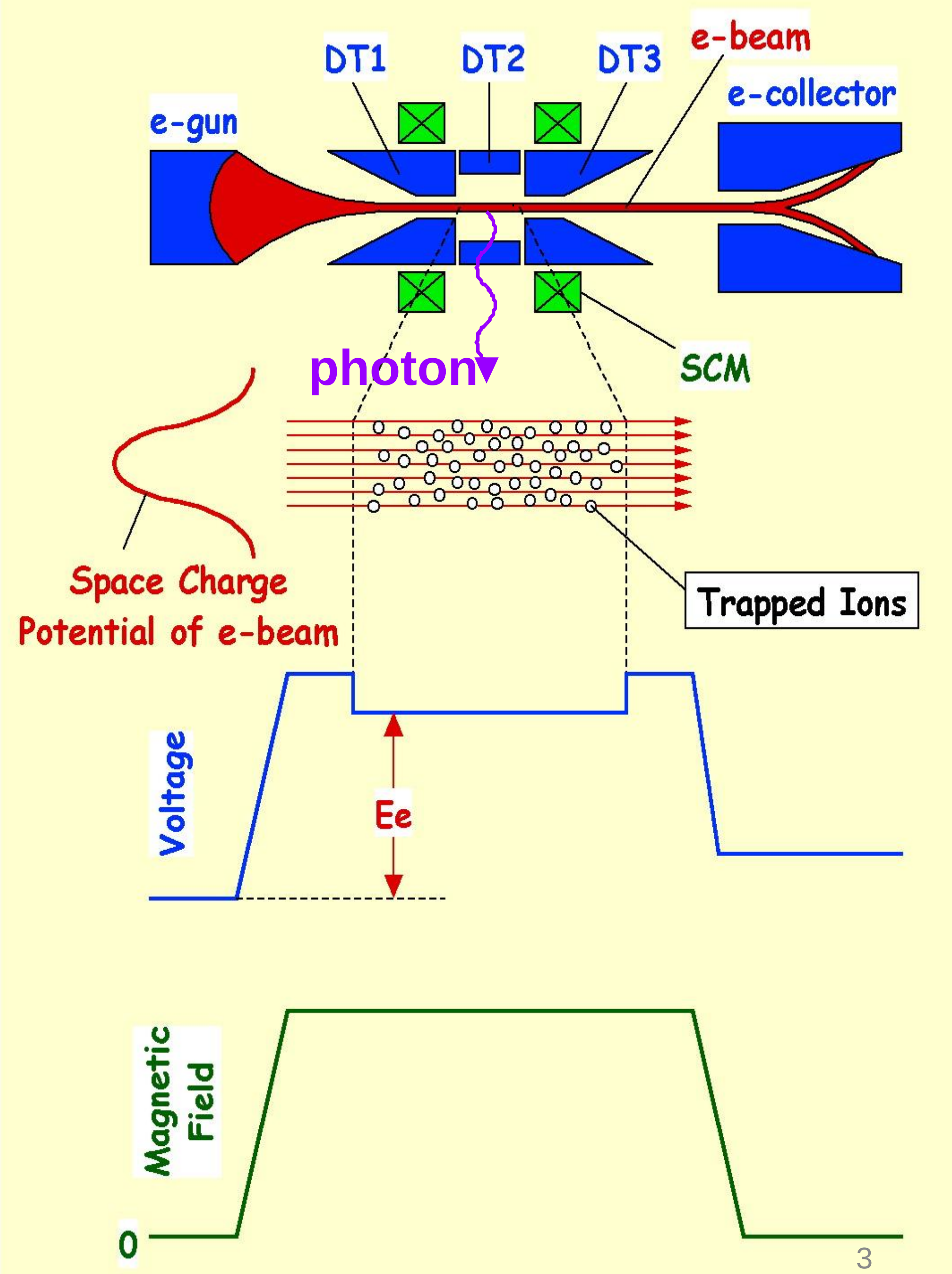
- **Ion trap**

  Well-type potential (DT1,2,3)
  + Space charge (e-beam)

- **High density electron beam**

  Superconductive magnets

- **Emission spectroscopy**
- **Ion extraction; collision expt.**

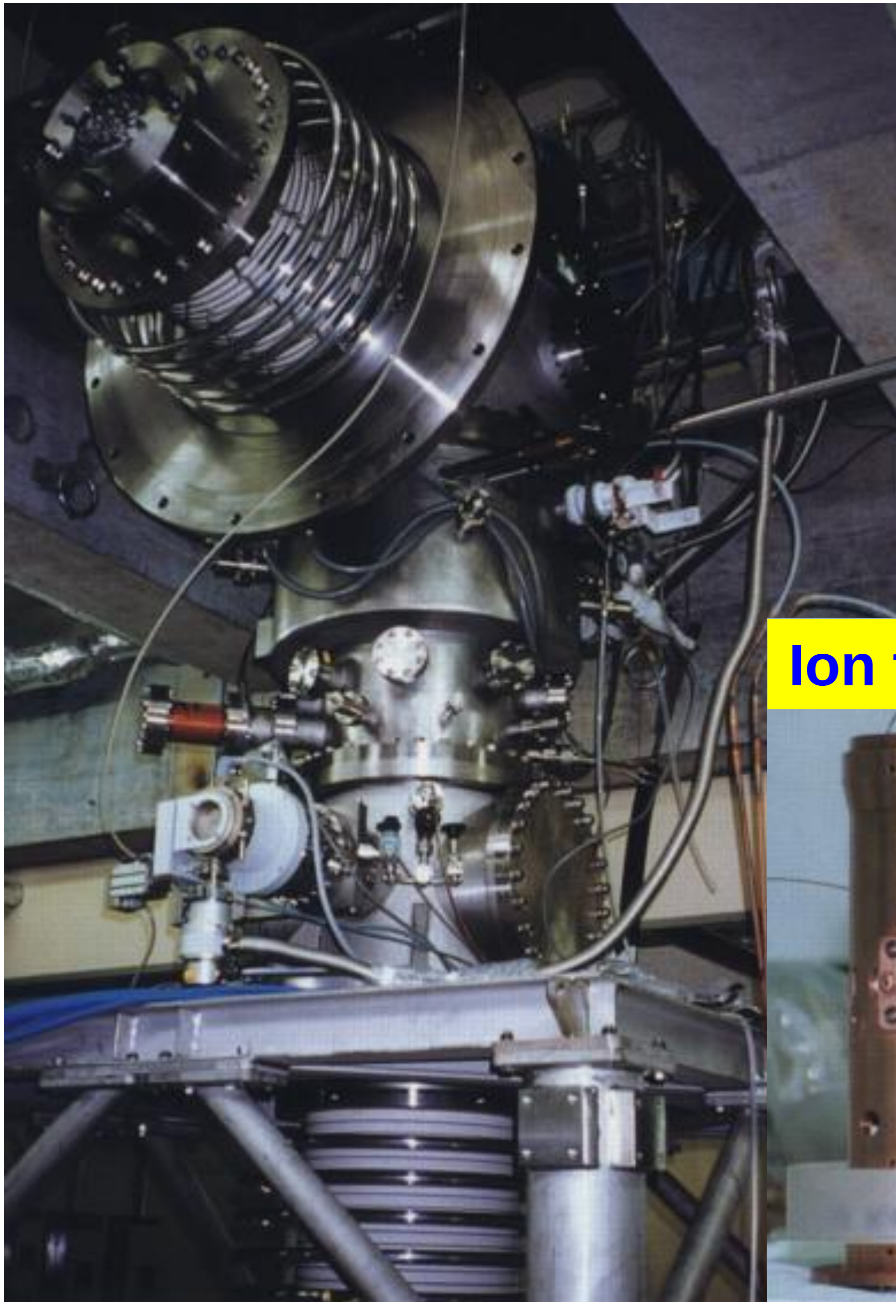


Two EBITs at UEC Tokyo

Tokyo-EBIT
since 1995

CoBIT
since 2007

Tokyo-EBIT

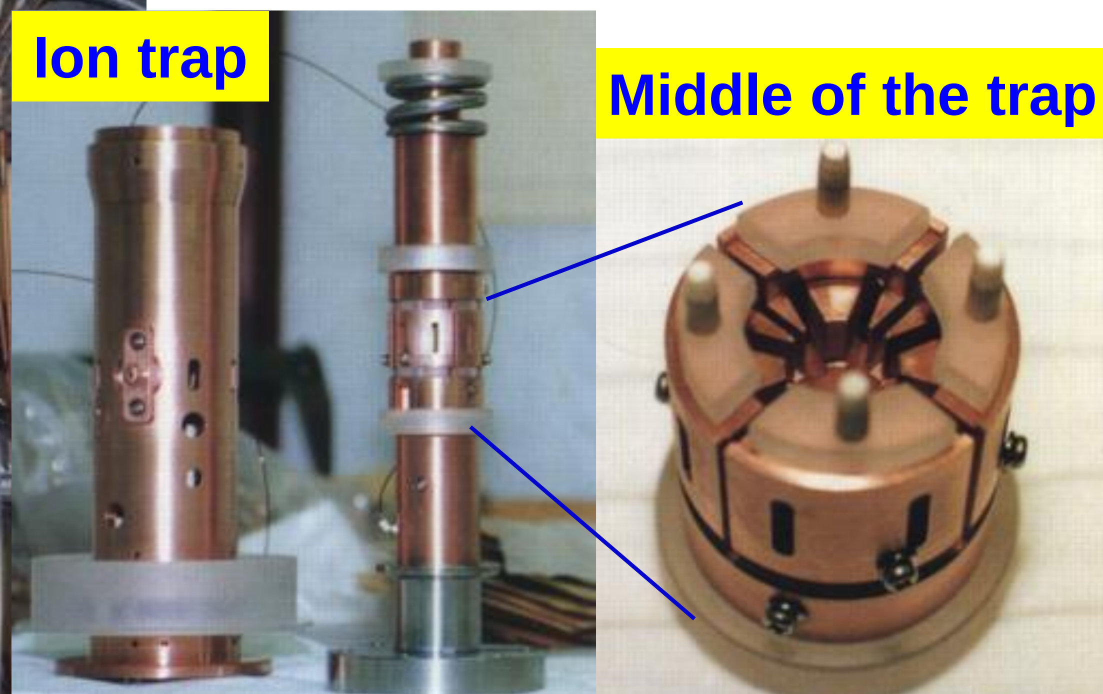


e-beam energy : 1 – 180 keV

e-beam current : 330 mA (max)

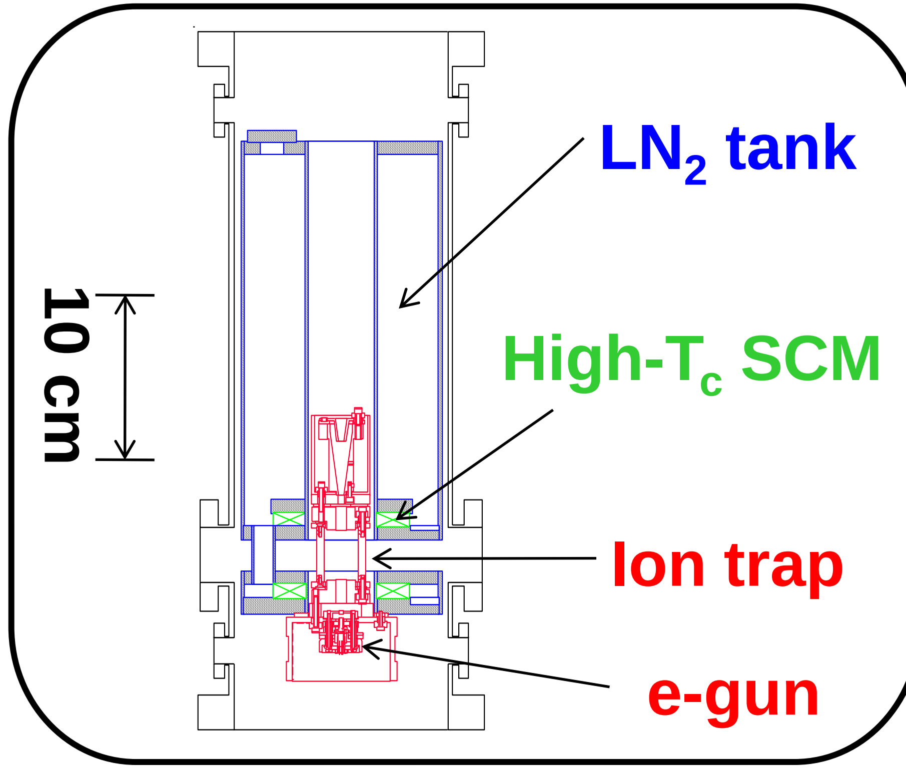
Magnetic field : 4.5 T (max)

Cryostat temp. : 4.2 K (LHe)



CoBIT (Compact, Corona, … EBIT)

N. Nakamura et al., Rev. Sci. Instrum., 79 (2008) 063104



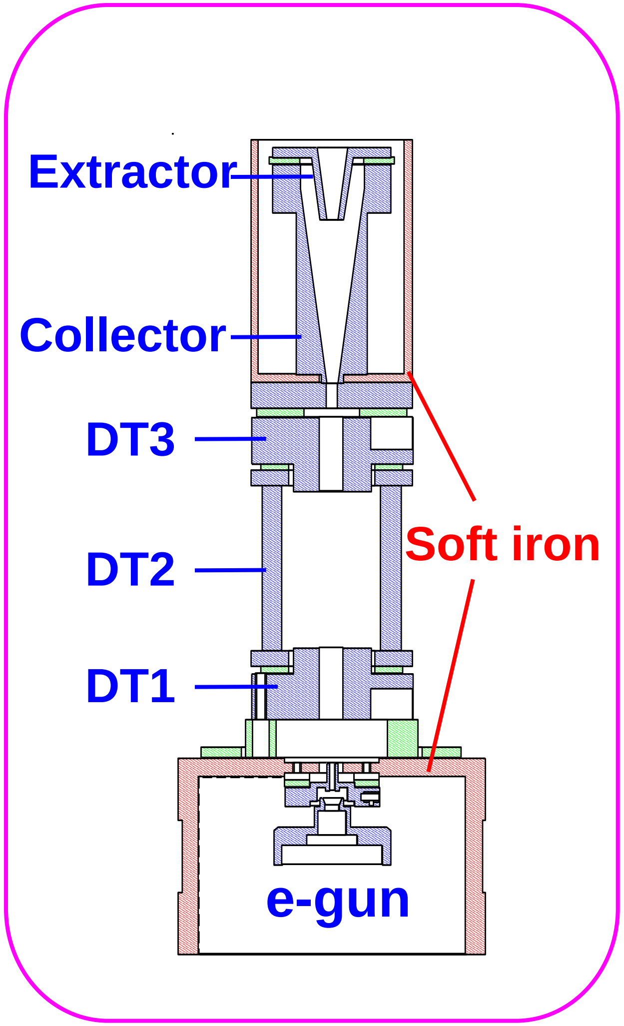
e-beam energy : 0.1 – 2 keV

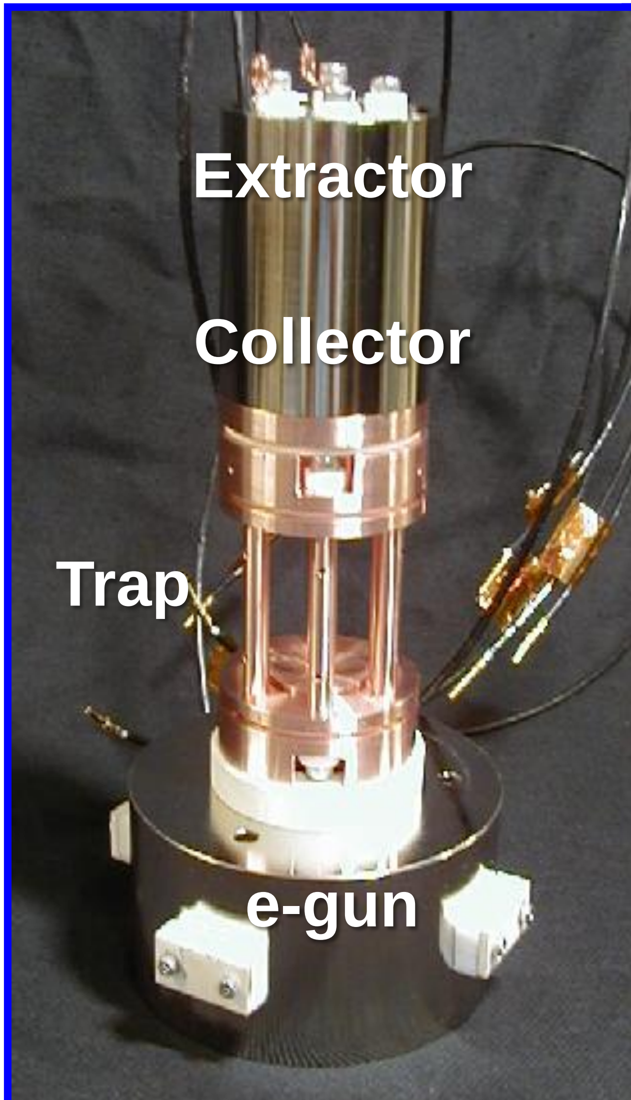
e-beam current : 20 mA (max)

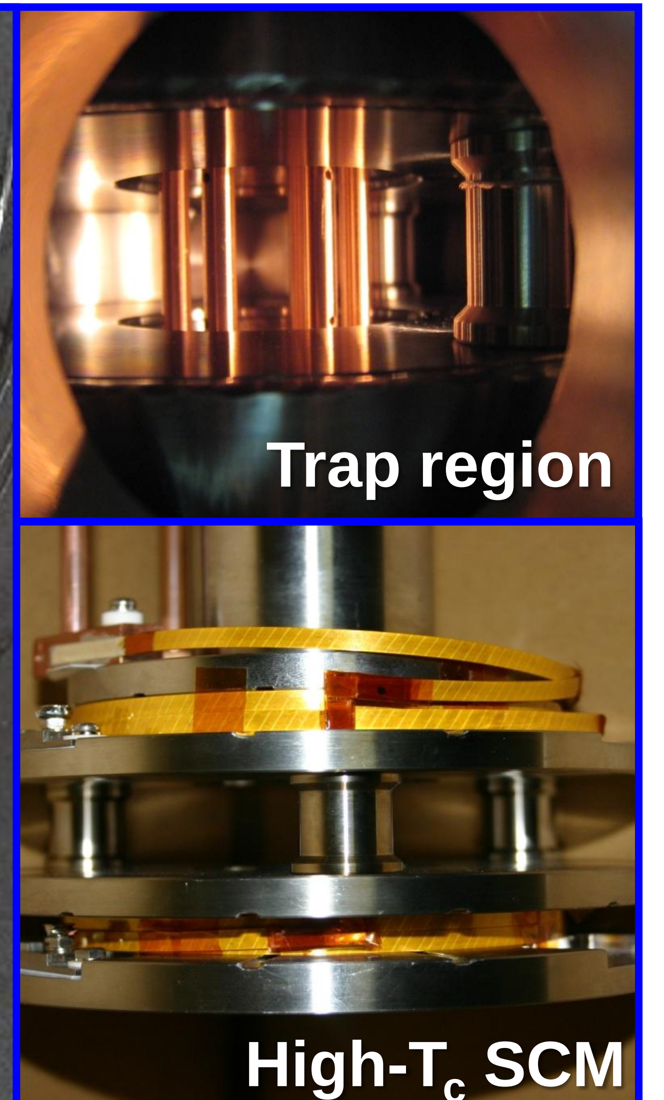
Magnetic field : 0.2 T (max)

Cryostat temp. : 77 K (LN_2)

The core of CoBIT



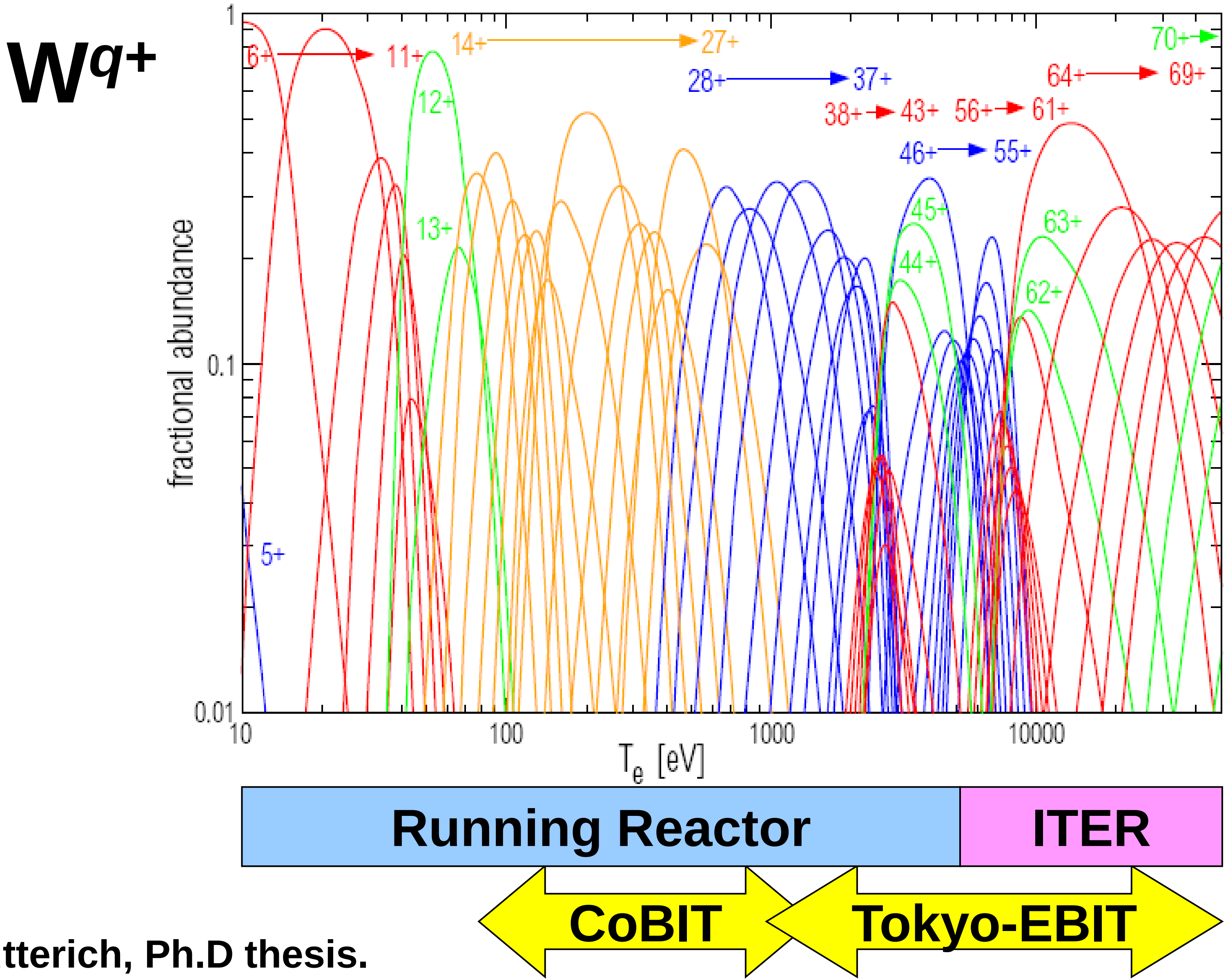




Comparison between two EBITs

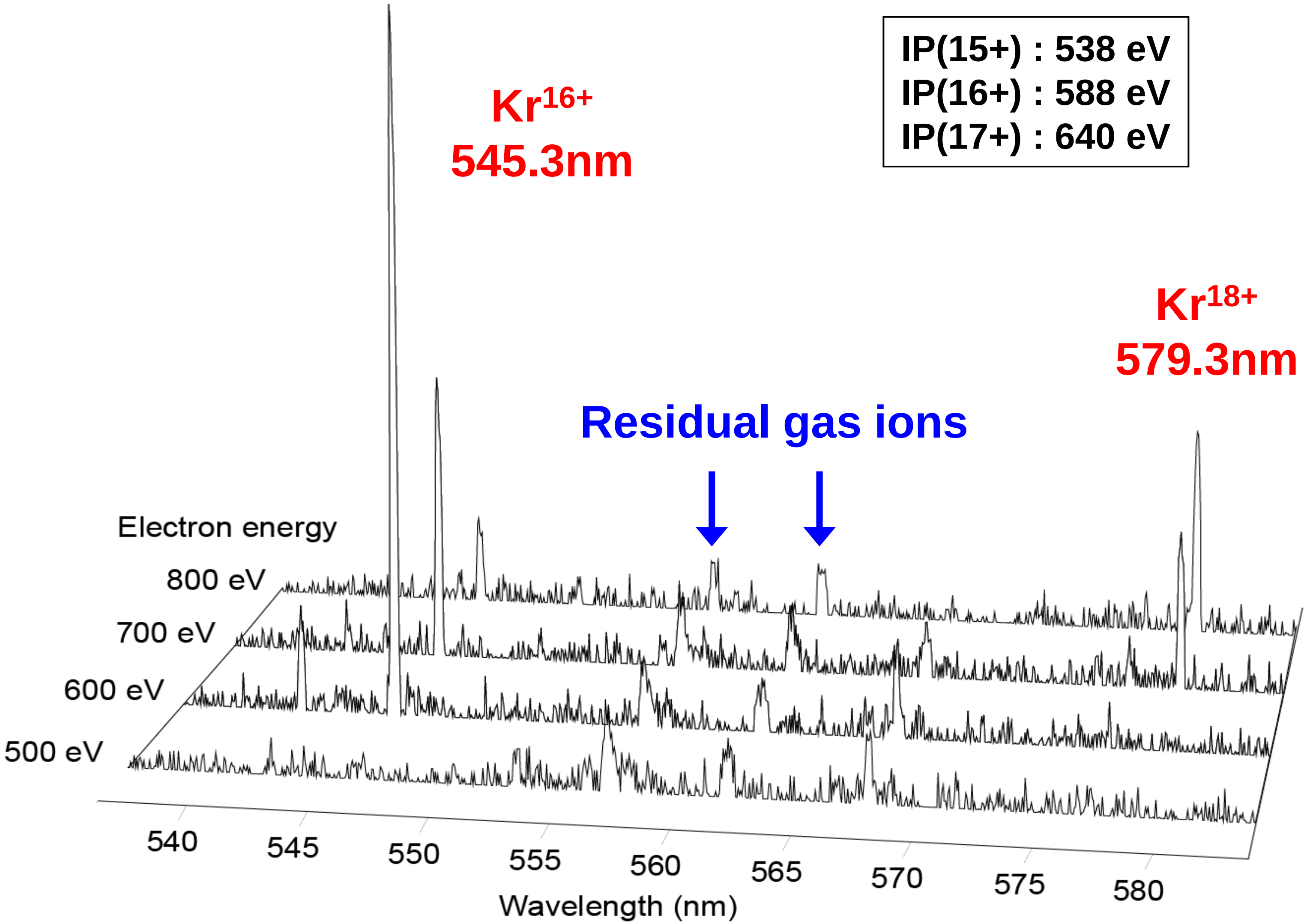
	Tokyo-EBIT	**CoBIT**
e-beam energy / keV	**1 – 180**	**0.1 – 2**
e-beam current (max) / mA	330	20
Magnetic field (max) / T	4.5 (typically 4.0)	0.2 (typically < 0.1)
Cryostat temp. / K	4.2	77
Coolant	**LHe**	**LN_2**
Height / m	~ 4	~ 0.4

Fractional abundance in hot plasmas



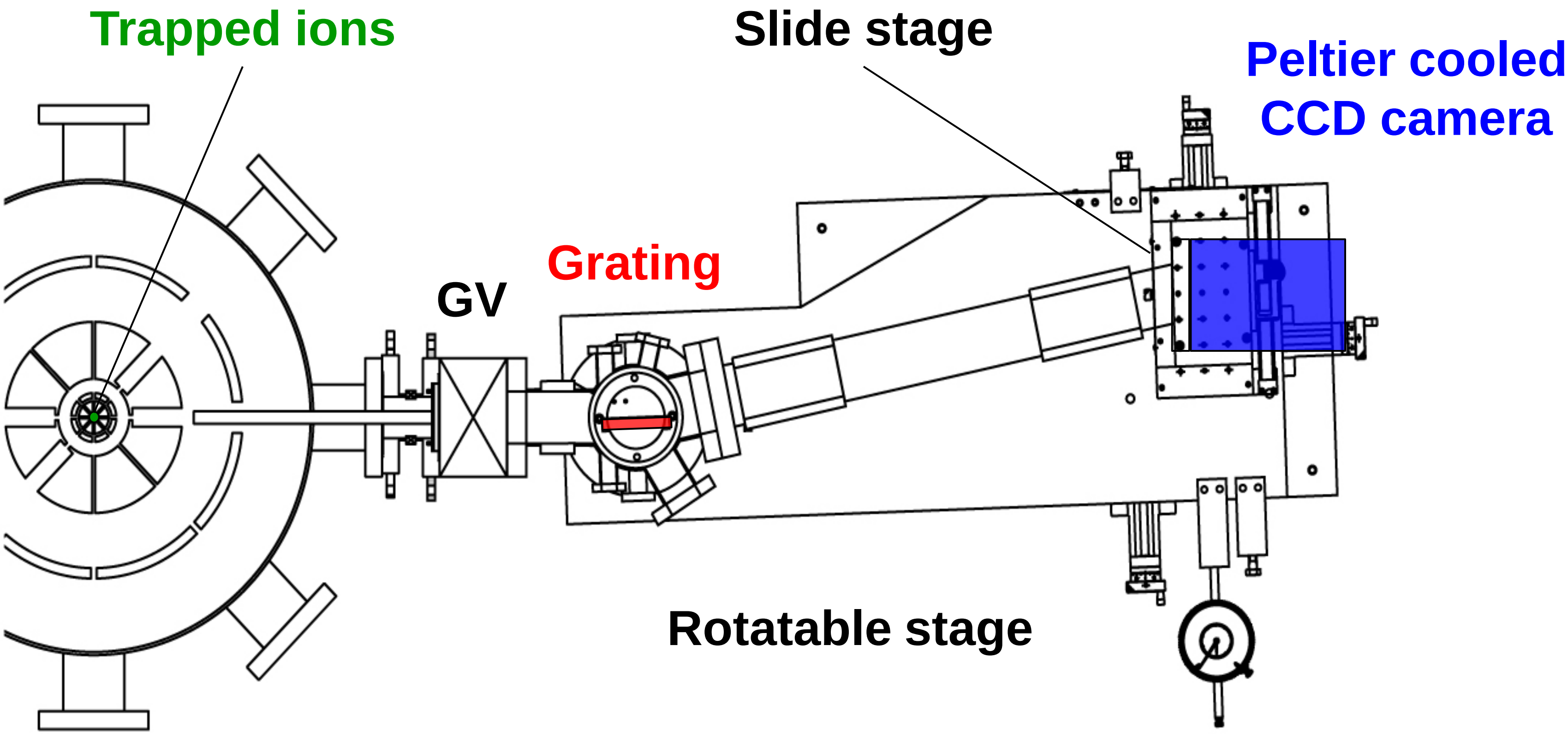
T. Pütterich, Ph.D thesis.

What we can do using an EBIT?



N. Nakamura *et al*., Rev. Sci. Instrum., 79 063104 (2008)

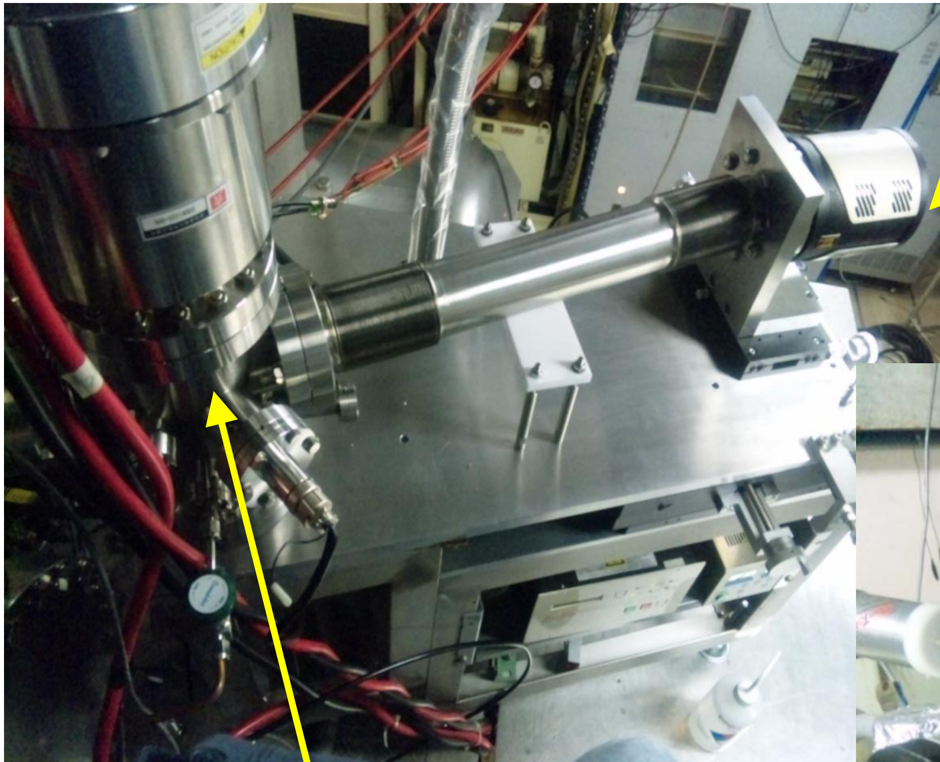
EUV spectrometer at the Tokyo-EBIT



Metallic Sn/Gd/Bi in a Knudsen cell @570–1100^{o}C

H. Ohashi *et al.*, Rev. Sci. Instrum. 82 083103 (2011)

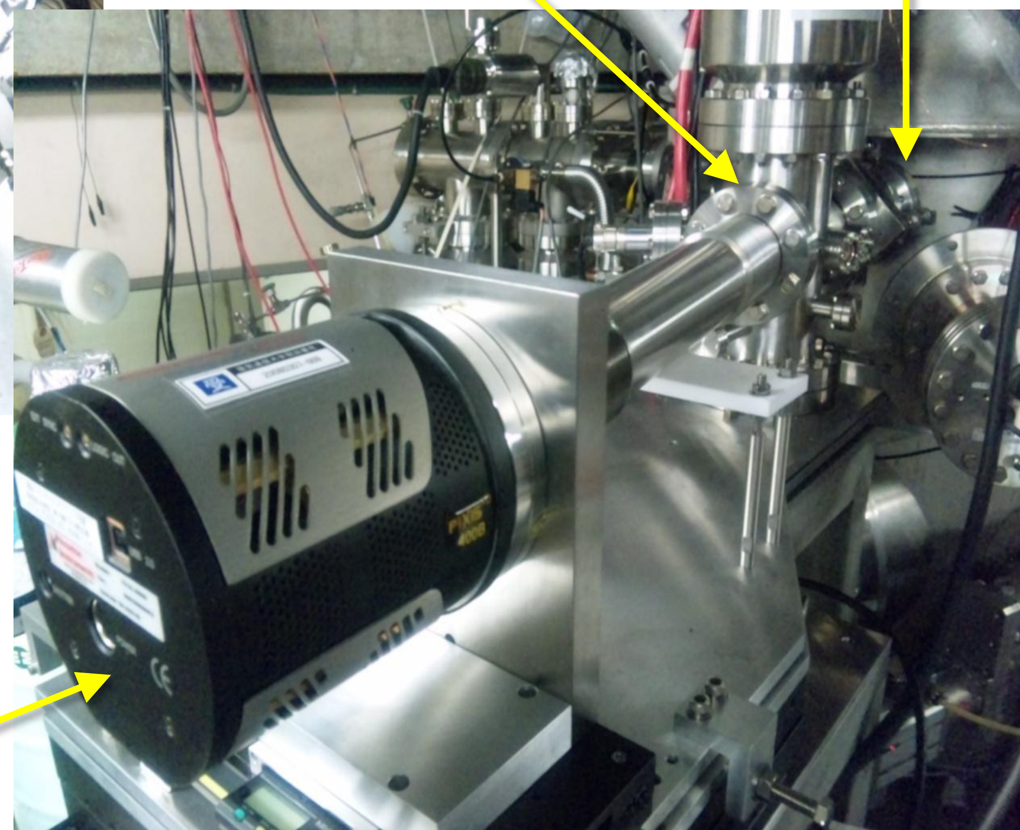
EUV spectrometer at the Tokyo-EBIT



Back-illuminated CCD

Tokyo-EBIT

Grating chamber

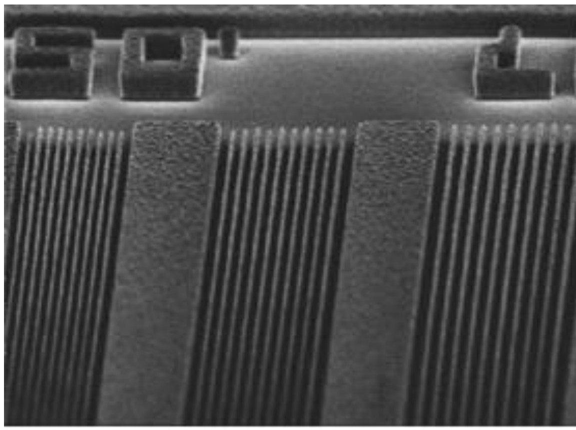


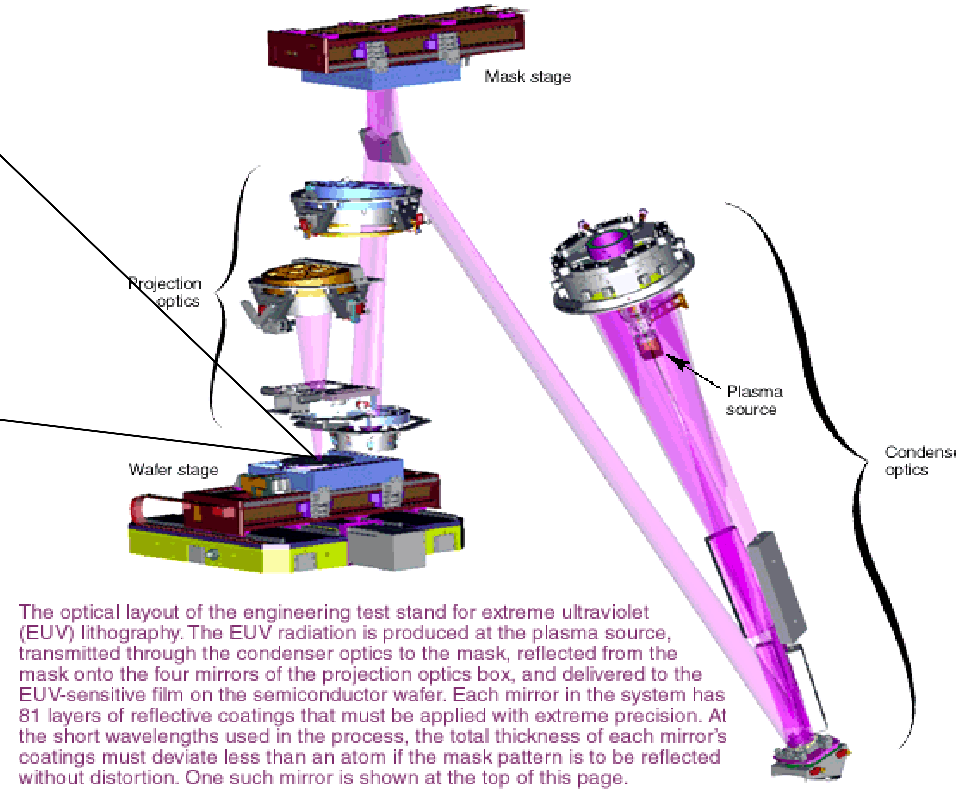
Grating chamber

Back-illuminated CCD

Sn ions

Semiconductor Photo-Lithography





The optical layout of the engineering test stand for EUV lithography.

http://www.llnl.gov/str/Sween.html

Resolution

$\propto$ Exposure light wavelength

Shorter wavelength

➔ Highly integrated

Developments of the exposure light wavelength

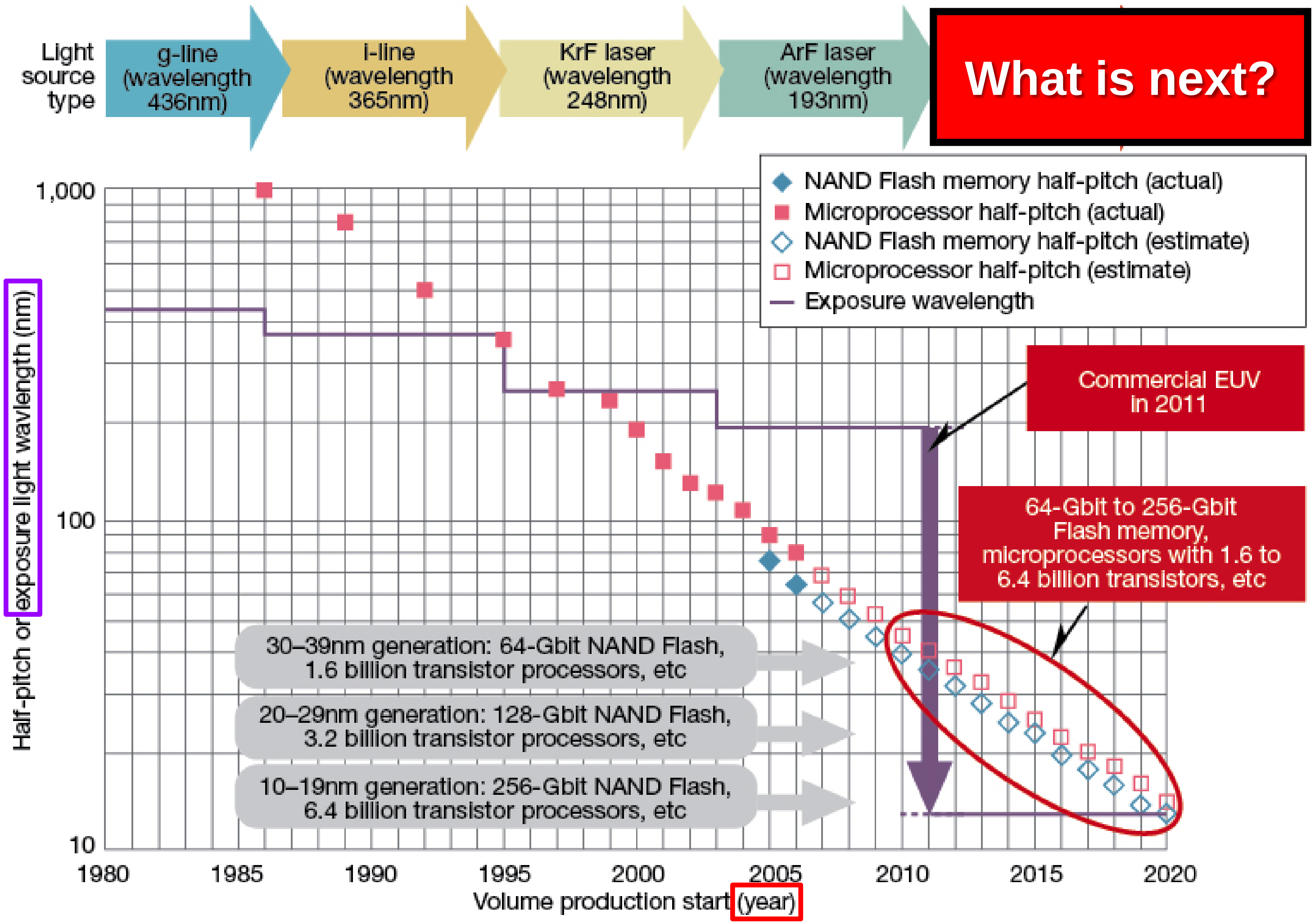


Fig 1 Slashing Lithography Wavelength to Drive Further Geometry Shrink EUV lithography has been pegged as a technology for the future, but it is approaching practical use fast. Diagram by *Nikkei Electronics* based on material from Intel, International Technology Roadmap for Semiconductors (ITRS), etc.

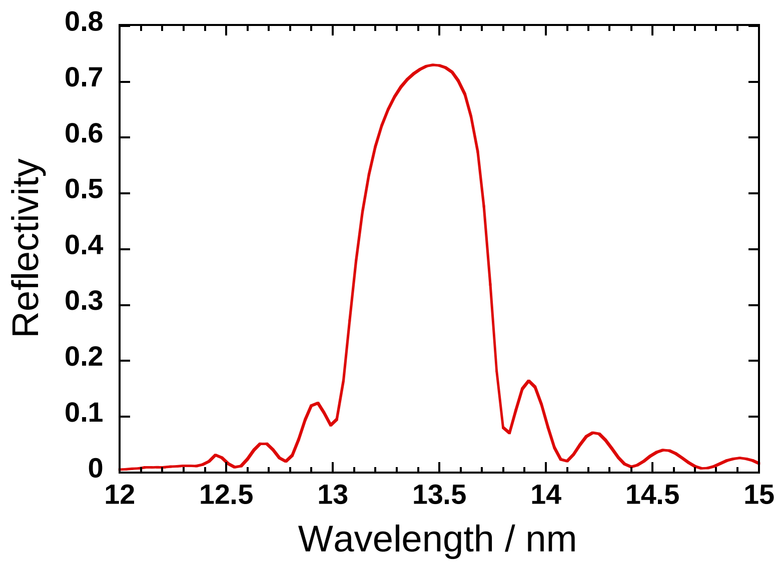
http://techon.nikkeibp.co.jp/article/HONSHI/20070926/139712/

Extreme Ultra-Violet (EUV) Lithography

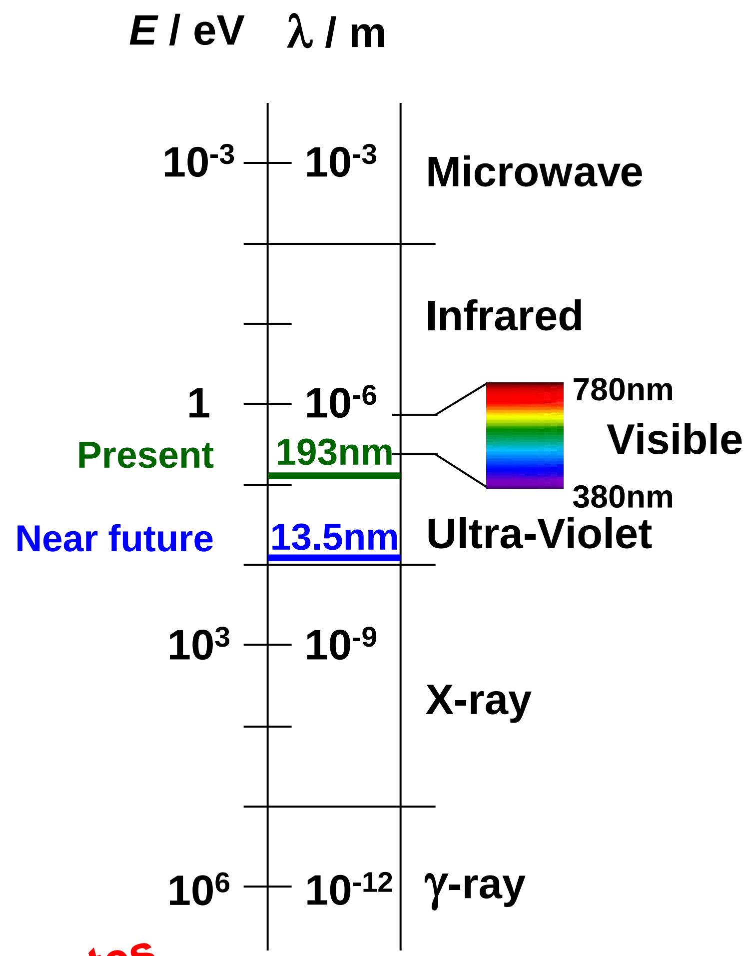
Exposure light Wavelength

Light Source ⇔ Optical Mirror

Decided !



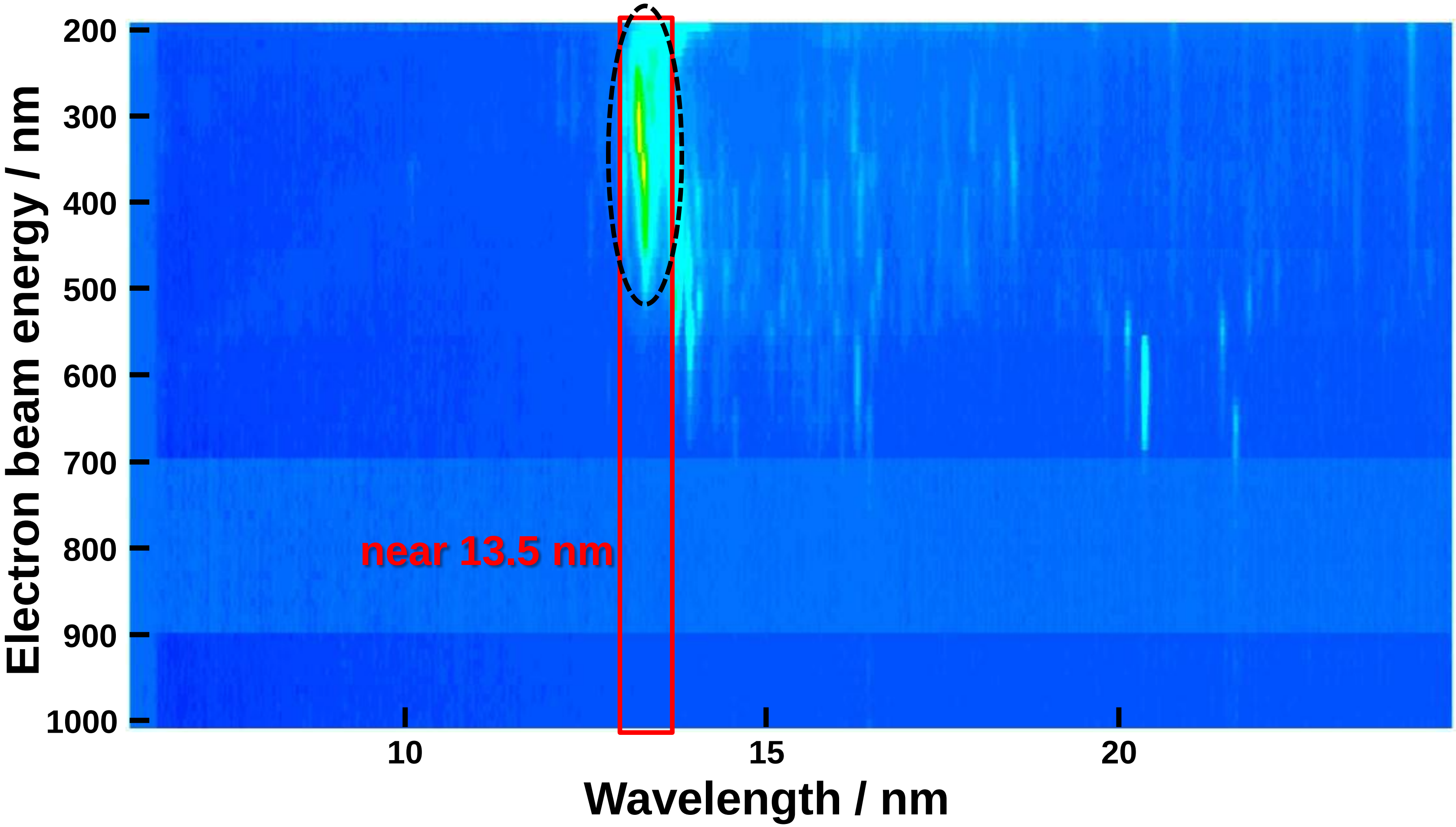
Reflectivity of Mo/Si multi-layer mirror (MLM) for EUV lithography.



➔ λ = 13.5 nm (91.9 eV) ➔ ***Candidates*** **$_{3}$Li, $_{50}$Sn and $_{54}$Xe plasmas**

EUV emission spectra of Sn ions

Unresolved transition array (UTA) of 4d-4f and 4p-4d transitions

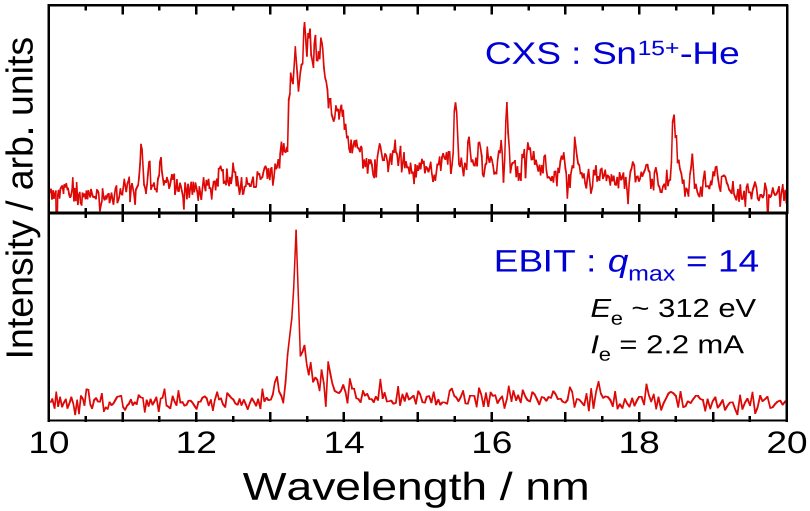


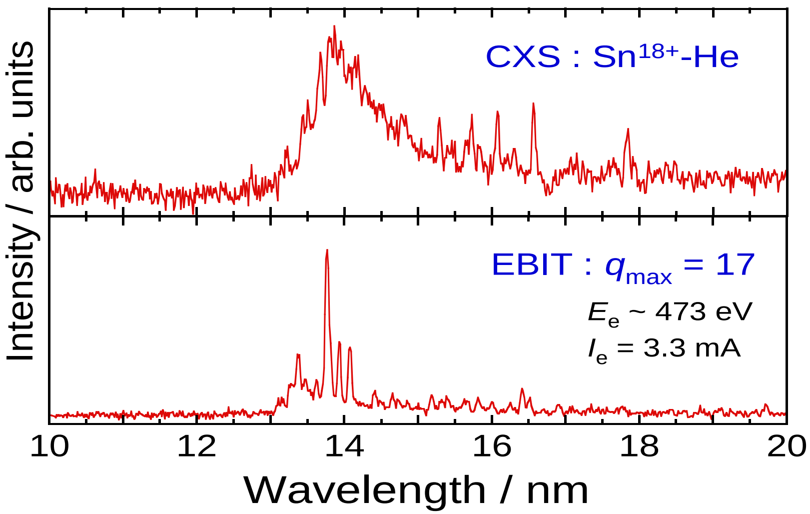
IPs to produce each charge state / eV

10+ : 184
11+ : 208
12+ : 232
13+ : 258
14+ : 282
15+ : 379
16+ : 407
17+ : 437
18+ : 466
19+ : 506
20+ : 537
21+ : 608
22+ : 642
23+ :1130

J. Yatsurugi *et al.*, Phys. Scr., T144 014031 (2011)

Complementary spectroscopy of Sn ions





Charge exchange collision (CXS)

- → **Resonance line**
- → ***Transition between excited states***

EBIT : electron impact

- → **Resonance line**

EBIT ⇔ Charge exchange

→ *Complementary Expt.*

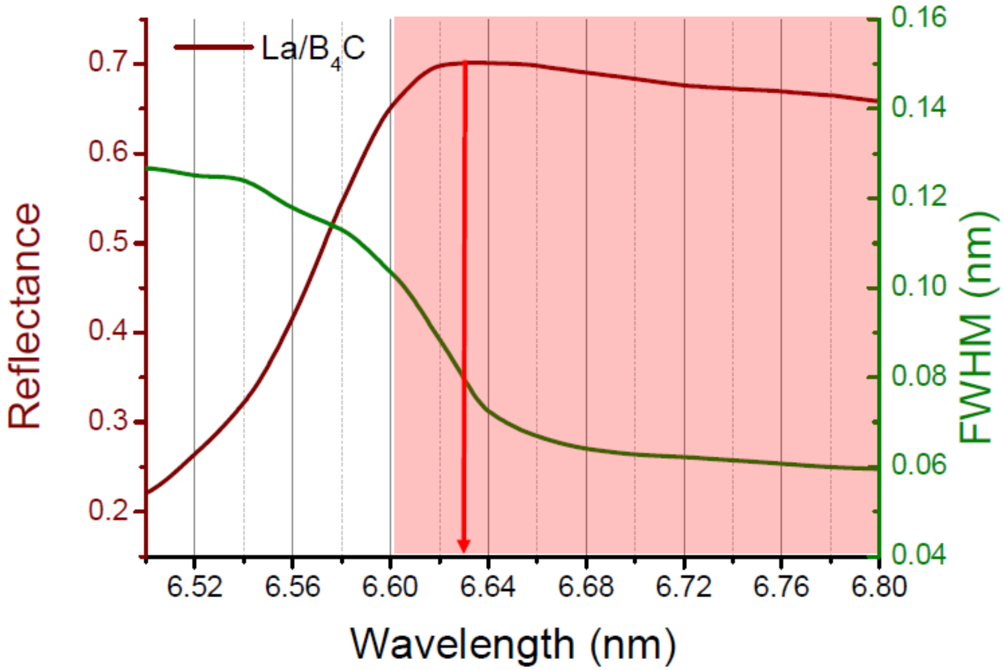
H. Ohashi *et al.*, J. Phys. Conf. Ser., 163 012071 (2009)

Gd ions

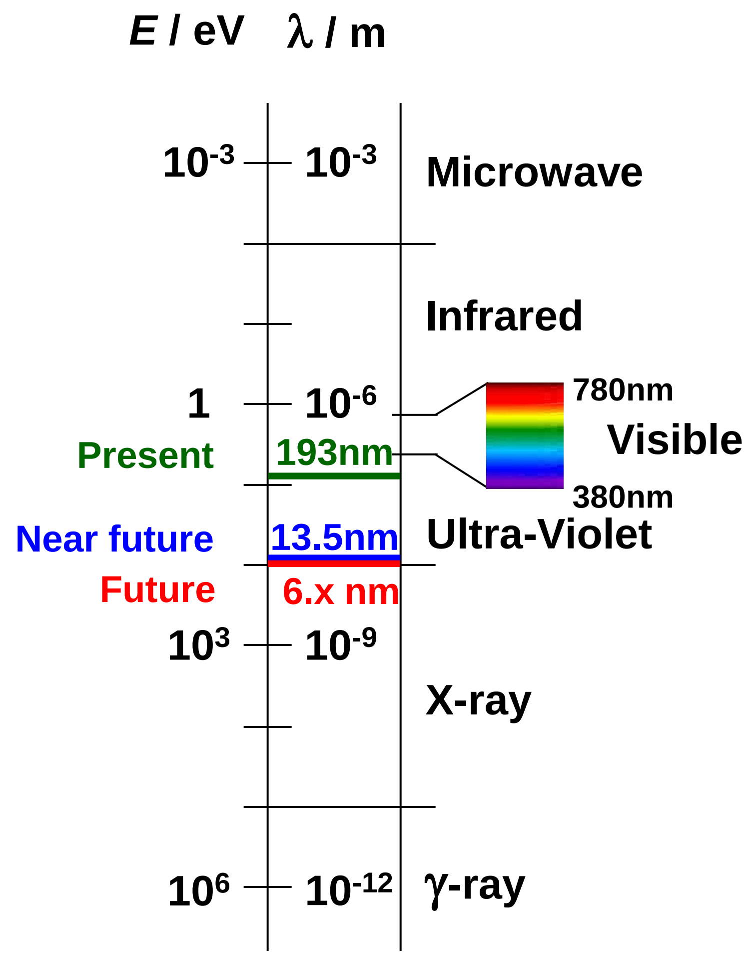
Beyond Extreme Ultra-Violet (EUV) Lithography

Exposure light Wavelength

Light Source ⇔ Optical Mirror



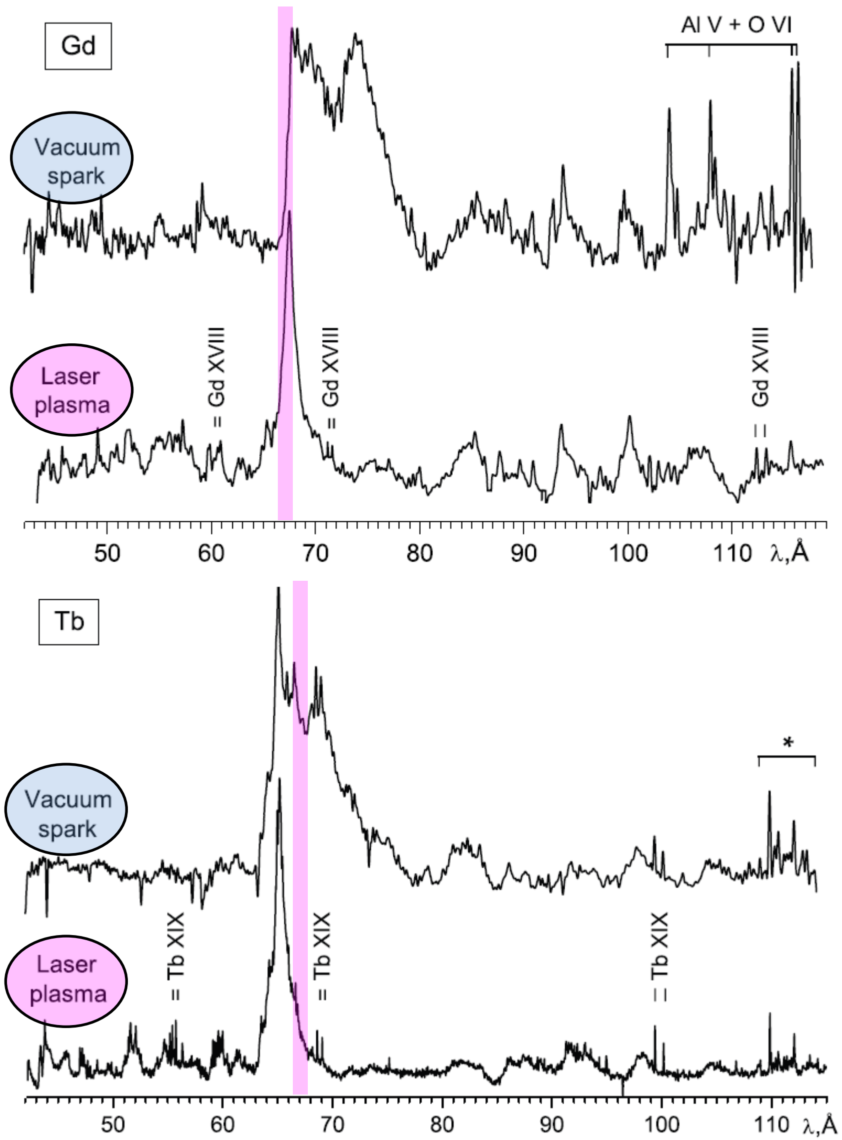
Calculated normal incidence reflectance and band width[1, 2]



➔ **λ = 6.x nm** ➔ **Candidates** **$_{64}$Gd and $_{65}$Tb plasmas**

R. Soufli *et al.*, Appl. Opt., 47 25 (2008). M. Fernandez-Perea *et al.*, J. Opt. Soc. Am. A, 24 12 (2007).

Next-Generation EUV Lithography at 6.x nm



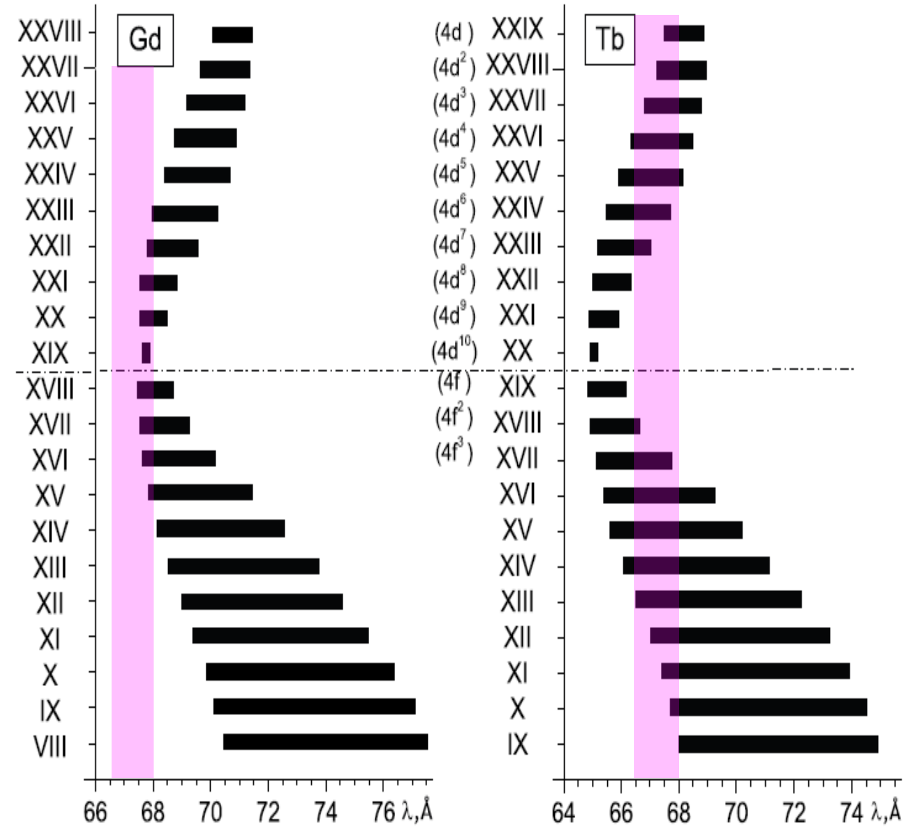


Figure 3. The calculated wavelength bands of the most intense 4–4 transition in the spectra of the rare-earth 4d- and 4f-ions.

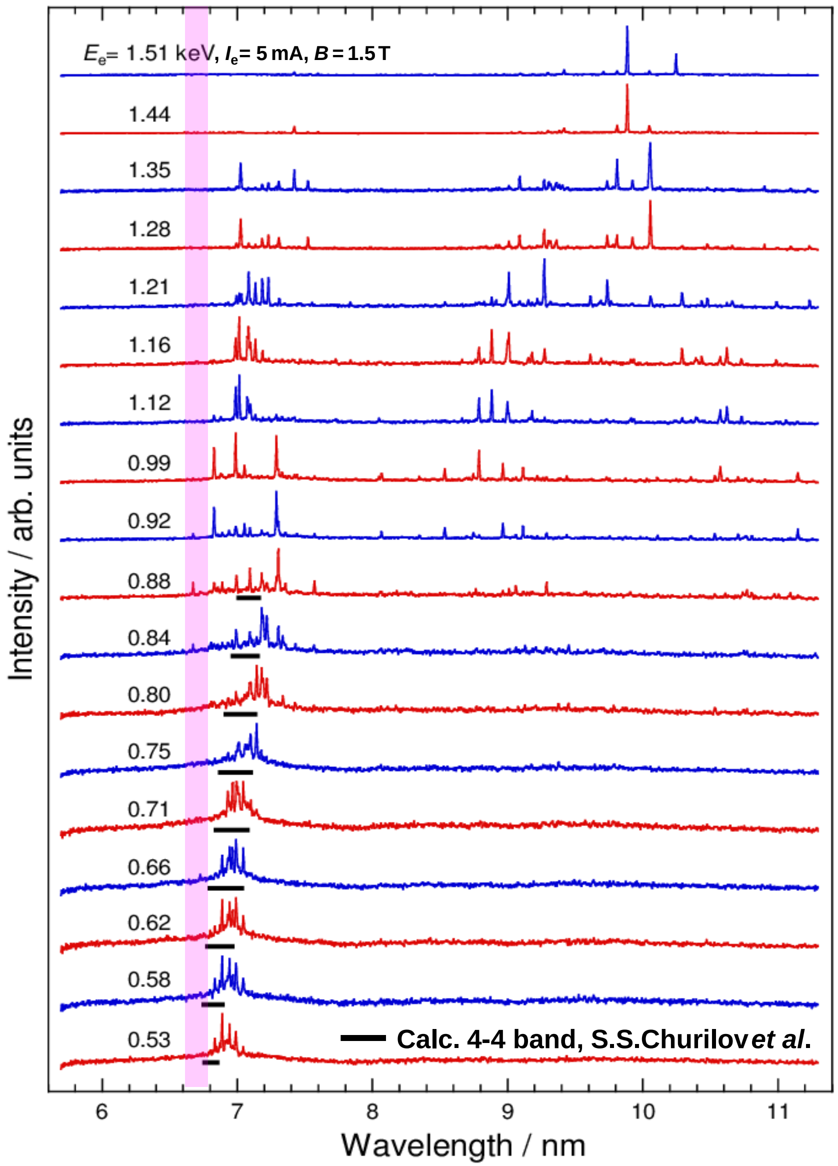
Atomic data for each charge state is needed to understand and optimize the plasma!!

Atomic data accumulation!!

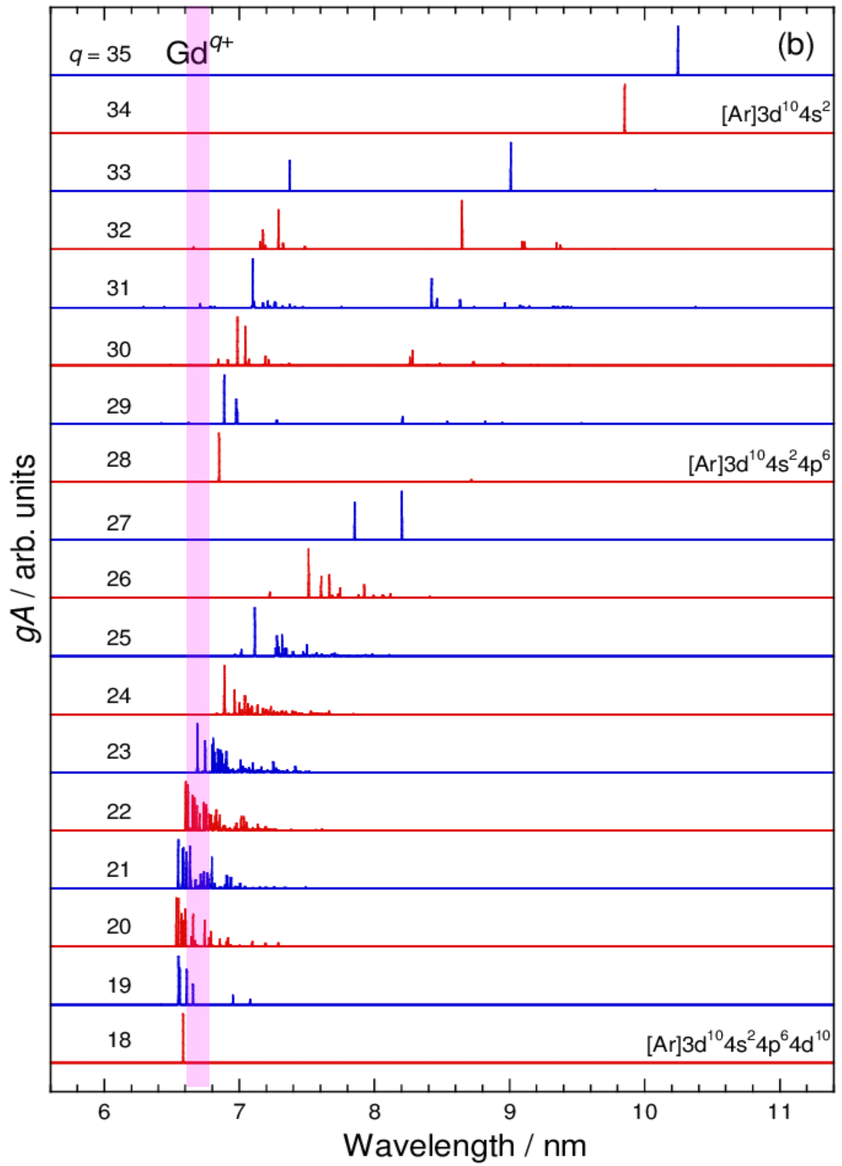
S.S.Churilov *et al.*, Phys.Scr. 80 045303 (2009)

Electron beam energy dependence

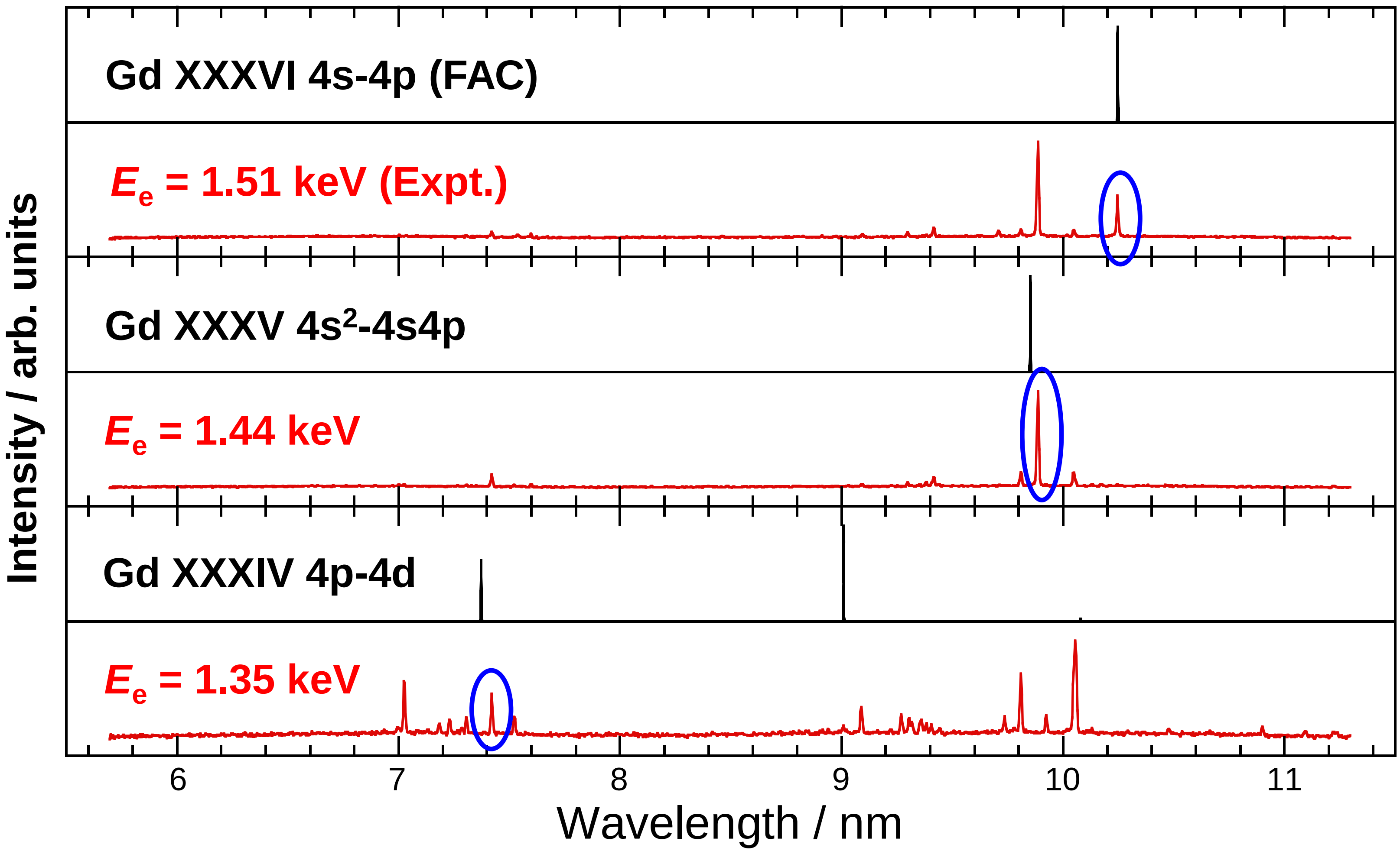
Expt.



Calc. with FAC



Identification of observed lines with FAC



Identification of observed lines with FAC

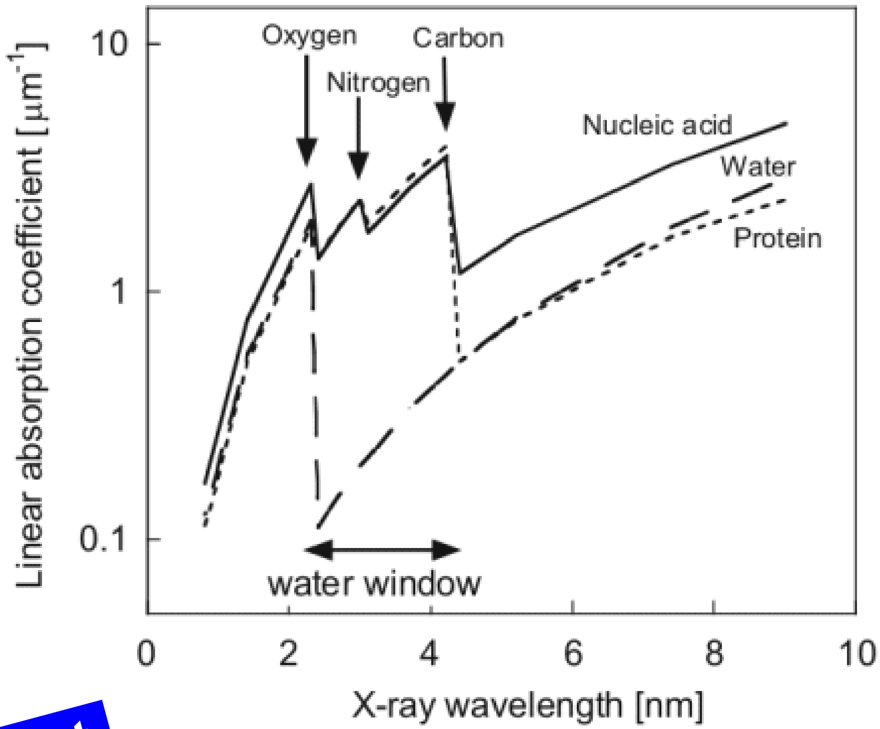
Ion	Sequence	Lower level		Upper level		Expt.wavelength / nm		Calc. / nm
		Conf.	State	Conf.	State	This work	Previous	FAC
Gd^{35+}	Cu-like	4s	$4s_{1/2}$	4p	$4p_{3/2}$	10.246	10.2497(15)[1] 10.2459(15)[2] 10.243(3)[3]	10.246
Gd^{34+}	Zn-like	$4s^2$	$(4s^2)_0$	4s4p	$(4s4p)_1$	9.887	9.8824(20)[4] 9.8831(10)[5] 9.887(2)[6]	9.850
Gd^{33+}	Ga-like	$4s^24p$	$4p_{1/2}$	$4s^24d$	$4d_{3/2}$	7.421	7.414(20)[7]	7.382

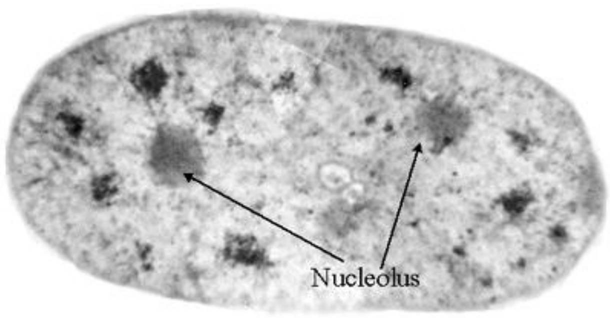
Under identification **for other observed emission lines.**

[1] J. Reader and G. Luther, Phys. Scr., 24 732 (1981)
[2] G. A. Doschek *et al*., J. Opt. Soc. Am. B, 5 243 (1988)
[3] J. F. Seely *et al*., Phys. Rev. A, 40 5020 (1989)
[4] C. M. Brown *et al*., At. Data Nucl. Data Tables, 58 203 (1994)
[5] N. Acquista and J. Reader, J. Opt. Soc. Am. B, 1 649 (1984)
[6] J. Reader and G. Luther, Phys. Rev. Lett., 45 609 (1980)
[7] K. B. Fournier *et al*., Phys. Rev. A, 50 2248 (1994)

Bi ions

Water window &
X-ray microscopy for live cell imaging





In vivo!!

http://www.lbl.gov/Science-Articles/Archive/xray-inside-cells.html

Present

Light Source: Synchrotrons or Free Electron Laser (FEL)
→ Too big and not easy to use

Future

Table-top (laboratory-scale) broadband emission source

LPP spectra of Bi ions

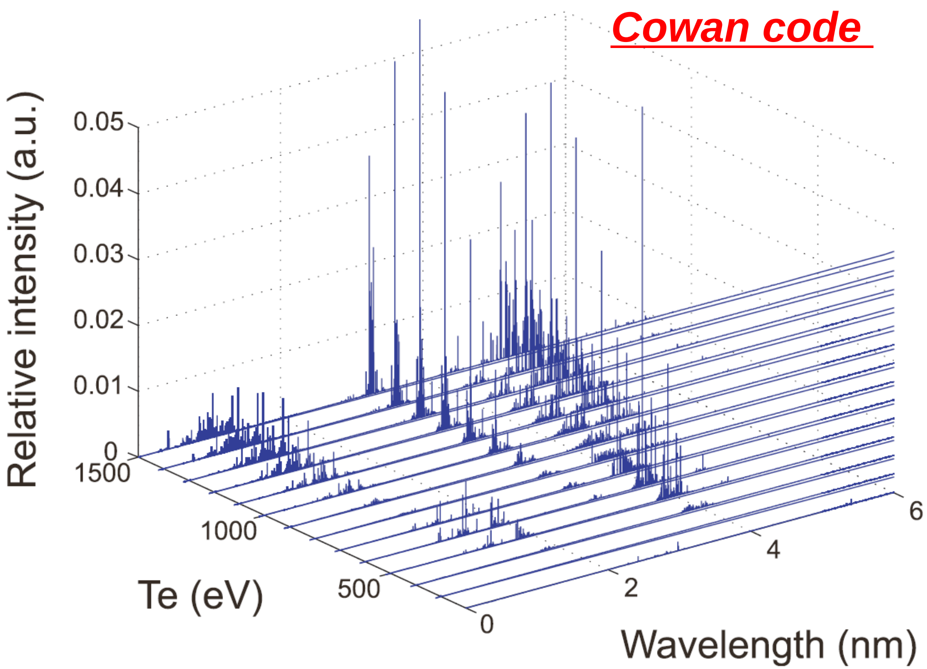


FIG. 2. (Color online) Calculated spectral variation as a function of electron temperature.

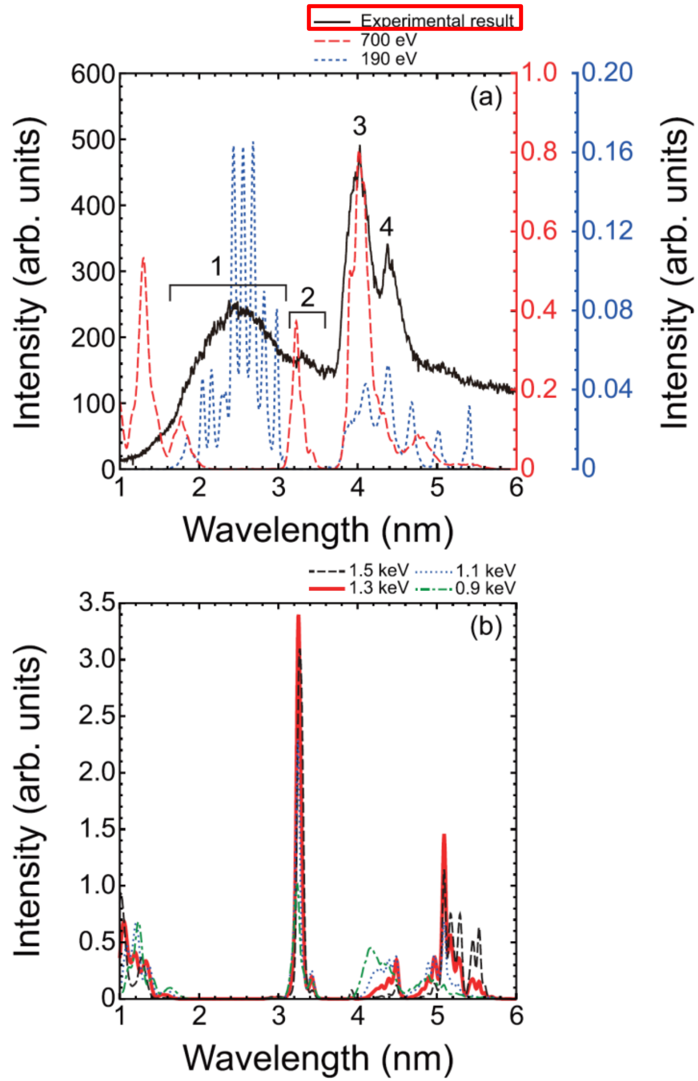


FIG. 4. (Color online) (a) The comparison between the observed spectrum with numerical calculation under assuming steady-state electron temperatures of 190 and 700 eV, respectively. (b) Calculated spectra for electron temperatures higher than 900 eV.

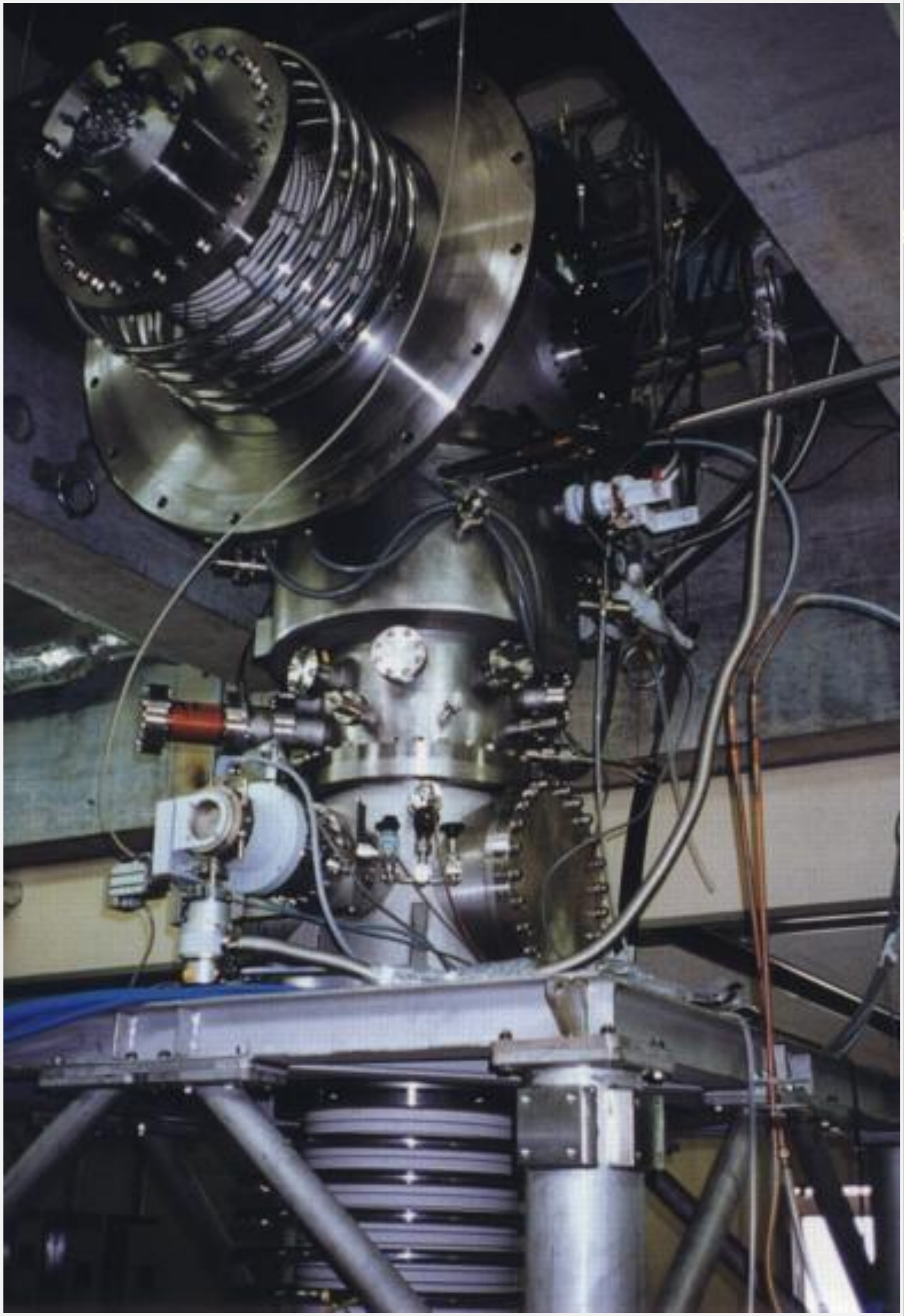
T. Higashiguchi *et al.*,
Appl. Phys. Lett., 100 014103 (2012)

Summary

- **EUV emission spectroscopy of $_{50}$Sn, $_{64}$Gd and $_{83}$Bi ions with an EBIT.**
- **UTA of 4d-4f and 4p-4d transitions contribute to main emissions for EUV light sources.**
- **FAC Calc. for line identification**
  - **discrepancy between Expt. and Calc.**
- **Comparison with other emission spectra in different Expt.**

Outlook

- **Identification of observed emission lines**
- **Lower energy Expt. using CoBIT (→ Lower charge states)**
- **Charge exchange spectroscopy**
  (→ Including transitions between excited states)
- **Terbium($_{65}$Tb) for BEUVL, Zirconium ($_{40}$Zr) for water window**



Thank you for your attention!!