EBIT spectroscopy of highly charged heavy ions relevant to hot plasmas

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Collaborators

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- Chubu Univ.
  H. Watanabe, N. Yamamoto
- Kitasato Univ.
  F. Koike

Contents

- Electron beam ion trap (EBIT)
  - Tokyo-EBIT and CoBIT
  - Spectrometers
- Spectroscopic data of
  - Tungsten (ITER related)
  - Iron (astrophysical interest)
  - Gadolinium (lithography related)
- Summary

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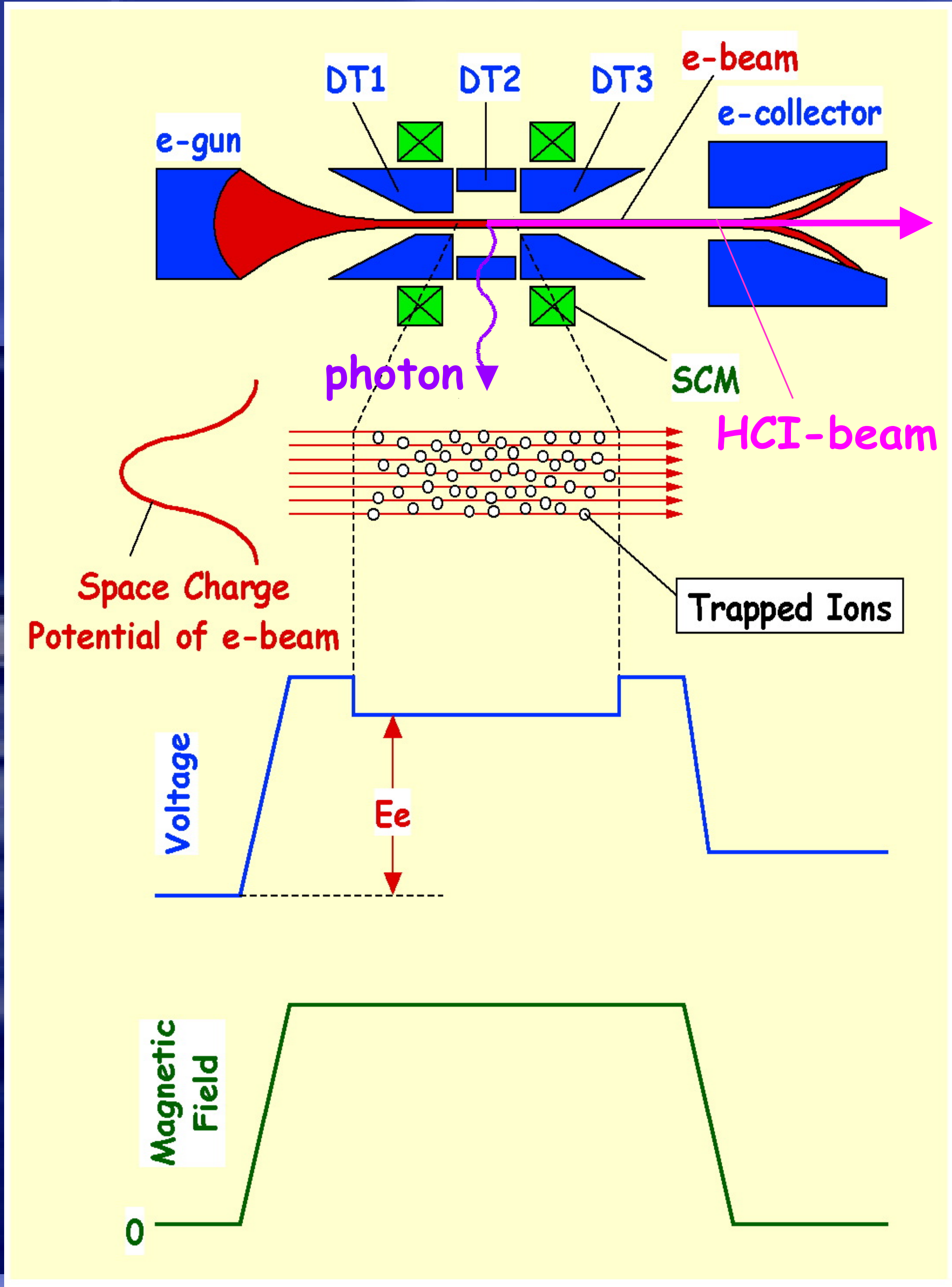
Electron beam ion trap (EBIT)

- A Penning-like trap
  + a high energy e-beam.
- Axial potential applied to the drift tube (DT) and the space charge of the electron beam confines the ions.
- Highly charged ions are produced through successive electron impact ionization with a high density electron beam compressed by a strong magnetic field.
- Radiation from the trapped ions can be observed through the observation slits opened at the middle of the ion trap.
- The ions can be extracted axially through the electron collector.

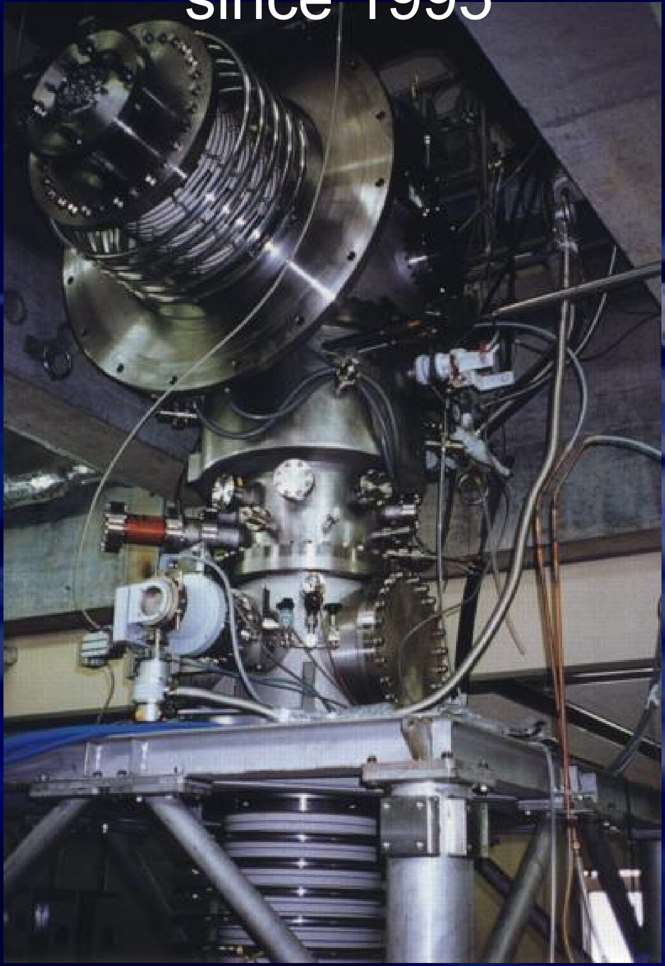


EBIT Spectroscopy

- **Interaction with an unidirectional and mono-energetic electron beam** *-in contrast with plasma spectroscopy*
  - **Charge state can be controlled by electron energy**
  - **Electron density can be controlled by current and B-field**
  - **"Well-defined plasma" → good benchmark for model calculation**
  - **Dependence on electron energy**
    excitation function, resonant processes
  - **Non-thermal radiation (anisotropy), polarization**
  - **Thin line-shape source → slit-less spectrometer**
- **Radiation from trapped ions** *-in contrast with beam-foil spectroscopy*
  - **Doppler-shift free**
  - **Small Doppler broadening**

Two EBITs at UEC Tokyo

Tokyo-EBIT
since 1995



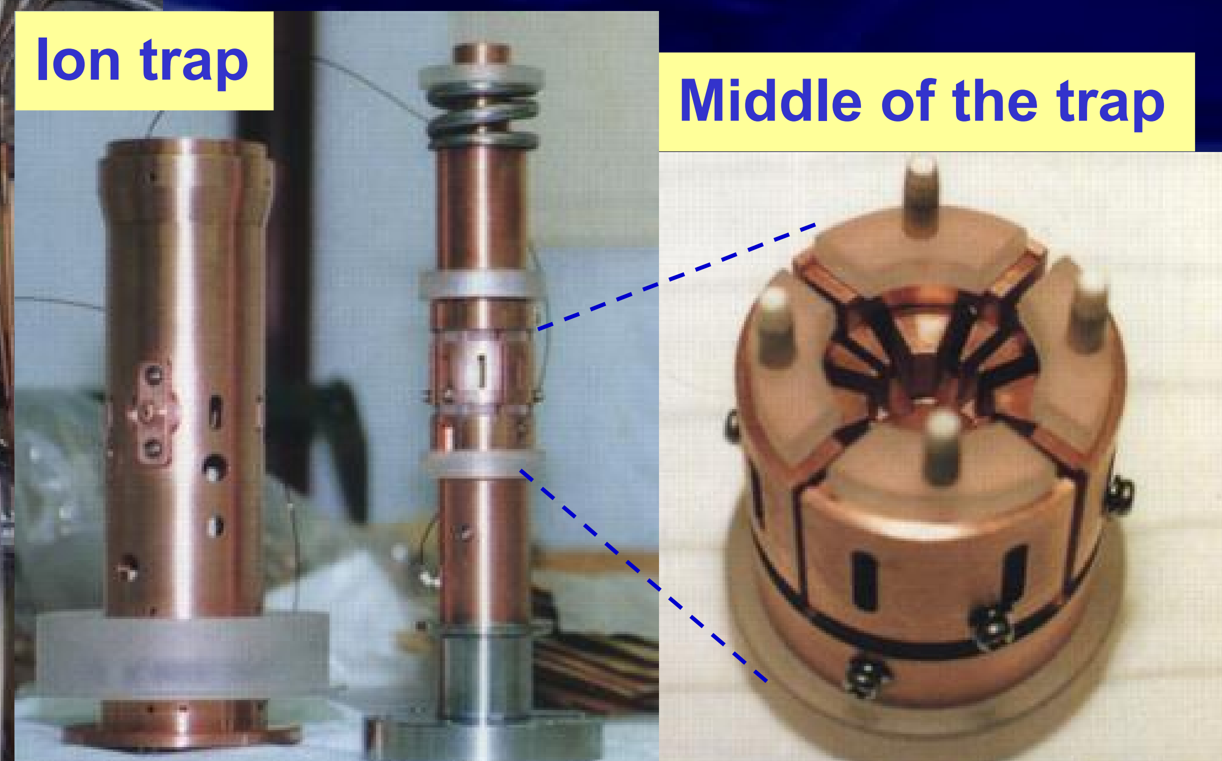
CoBIT
since 2007

(Another CoBIT has been installed at NIFS recently.)

Tokyo-EBIT

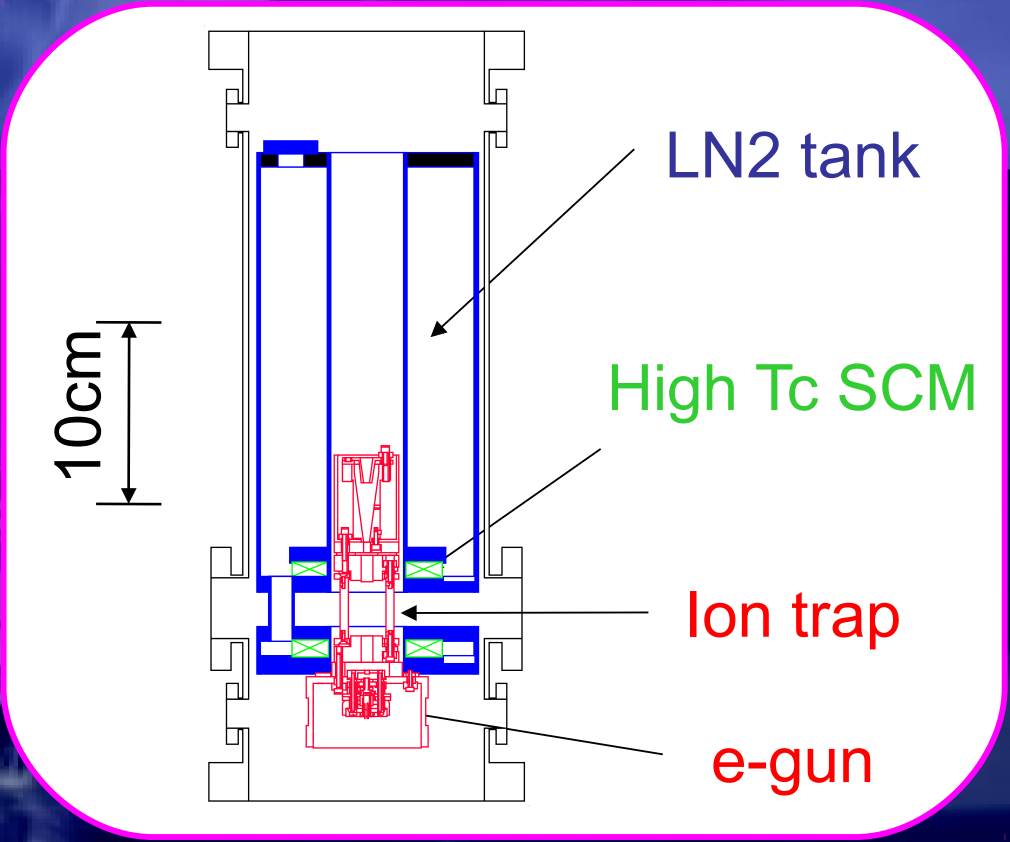
Achieved max. Ee: 180 keV

Achieved max. Ie: 330 mA



CoBIT (Compact, Corona, … EBIT)

N.Nakamura et al., RSI 79 (2008) 063104



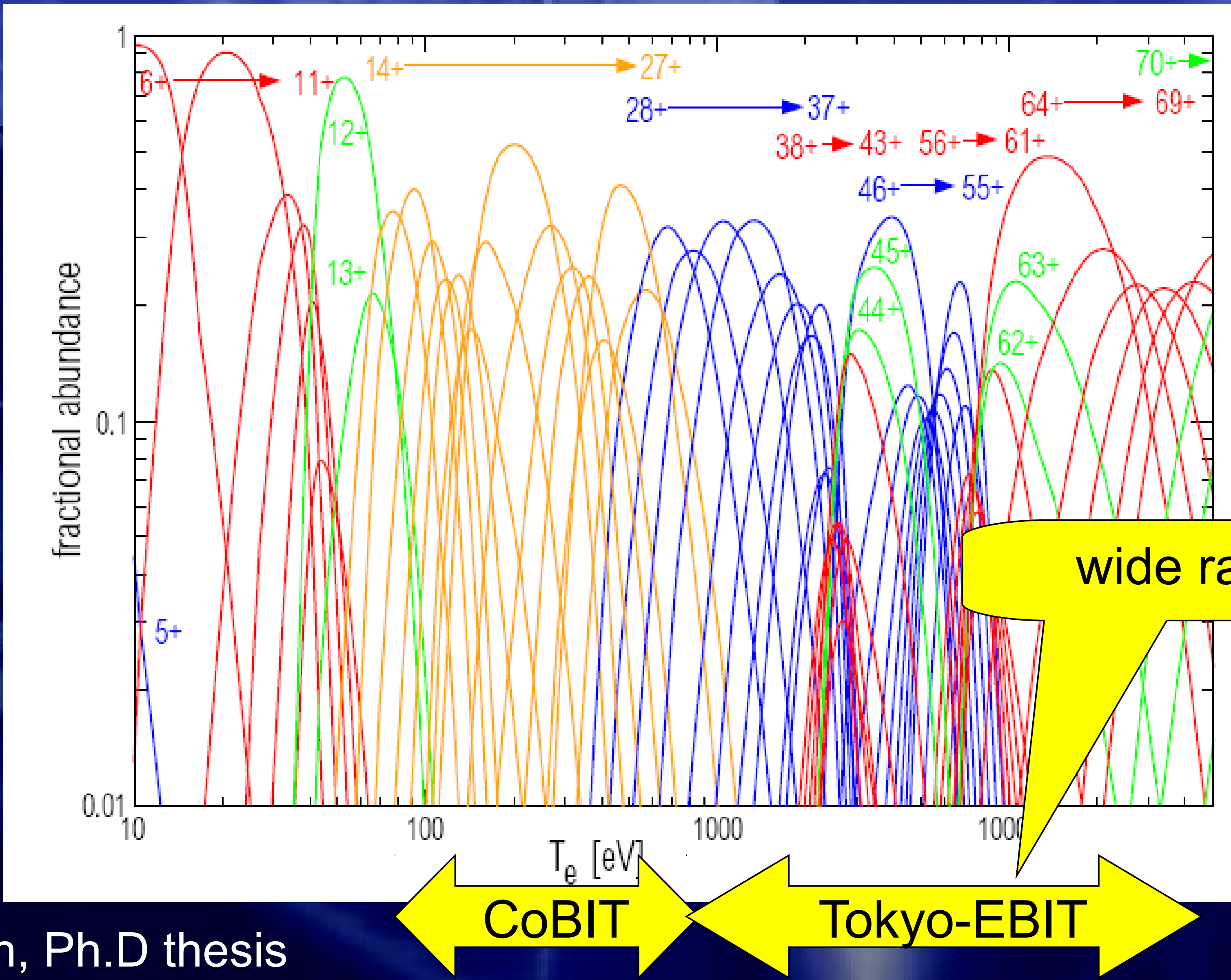
Specifications

e-beam energy	100 – 2500 eV
e-beam current	20 mA (max)
Magnetic field	0.2 T (max)
Temperature	77 K (High-Tc SCM)

Comparison between two EBITs

	Tokyo-EBIT	CoBIT
Max. electron energy (keV)	180	2.5
Max. electron current (mA)	330	20
Max. magnetic field (T)	4.5 (typically 4.0)	0.2 (typically <0.1)
Cryostat temp. (K)	2.3 (typically 4.2)	77
Coolant	LHe	LN2
Height (m)	~4	~0.4
Ions	Bi^{82+}, Xe^{54+}	W^{35+}, Fe^{16+}

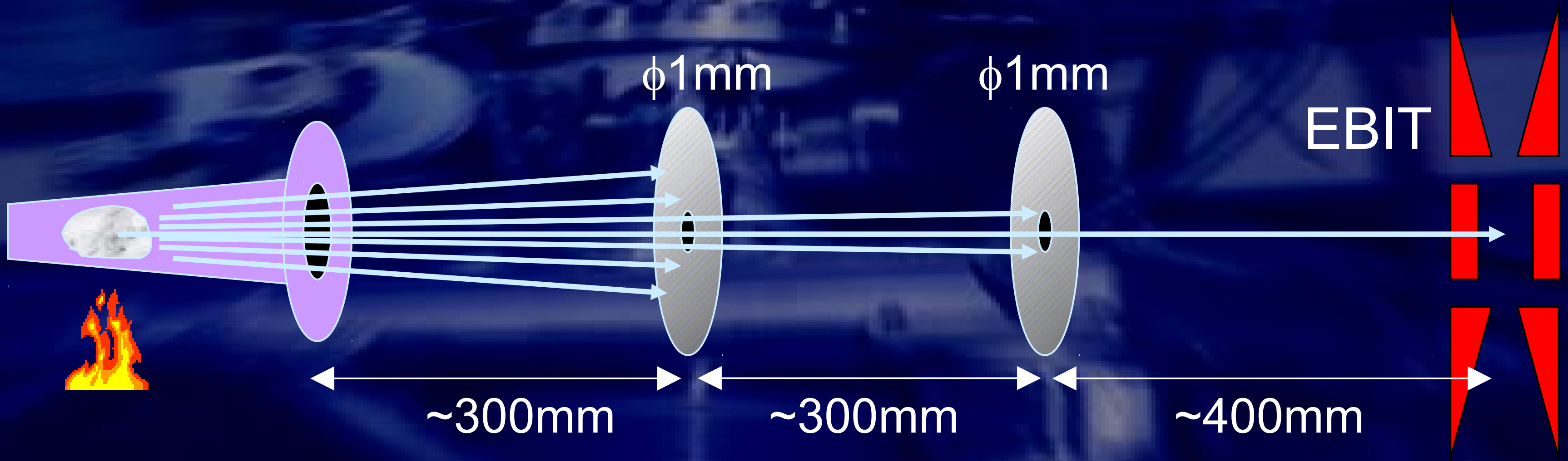
Fractional abundance in hot plasmas



Pütterich, Ph.D thesis

Injection of various elements

- Ordinary gas injector
  - $W(CO)_6$ for W, $Fe(C_2H_5)_2$ for Fe
- Effusion cell (Knudsen cell, K-cell)
  - Gd (1100 °C)



Yamada et al., RSI 77 (2006) 066110

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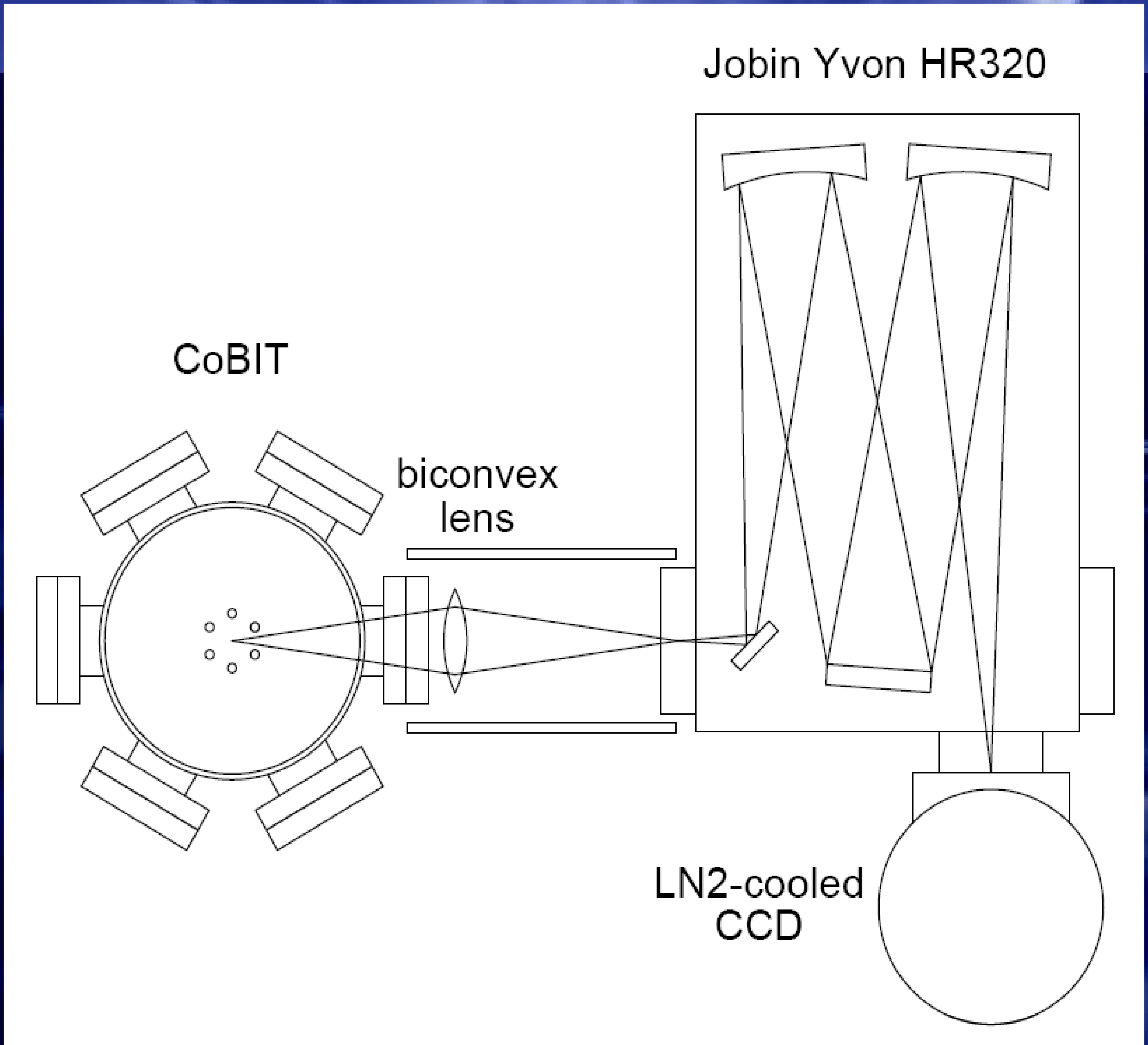
Experimental setup for visible spectroscopy



Sakoda et al., Phys. Scr. T144 (2011) 014011

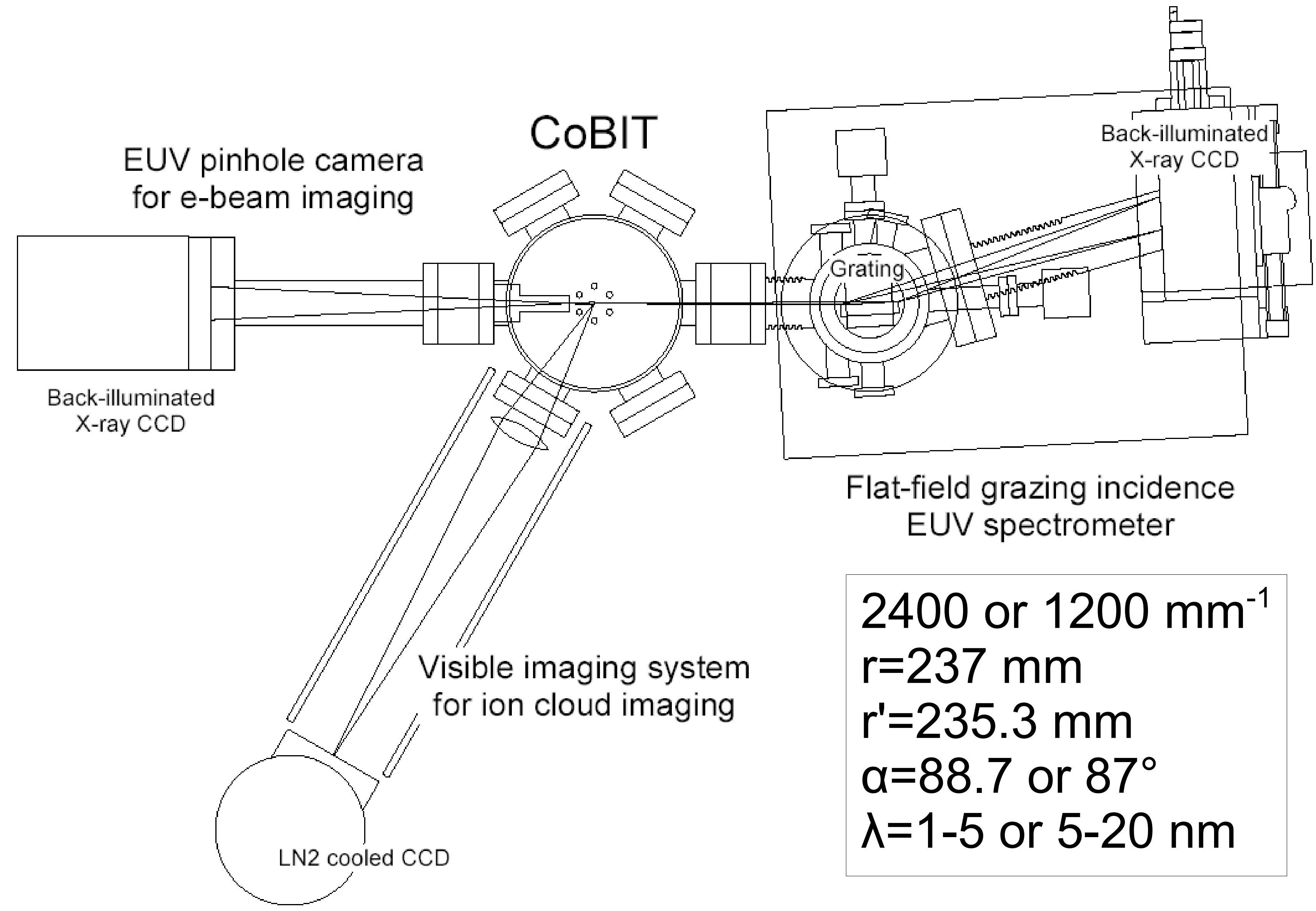
grating1:
- 1200 g/mm
- brazed at 400 nm

grating2:
- 300 g/mm
- brazed at 500 nm

biconvex lens: f=62.3 mm

CCD: Roper LN/CCD-1100PB

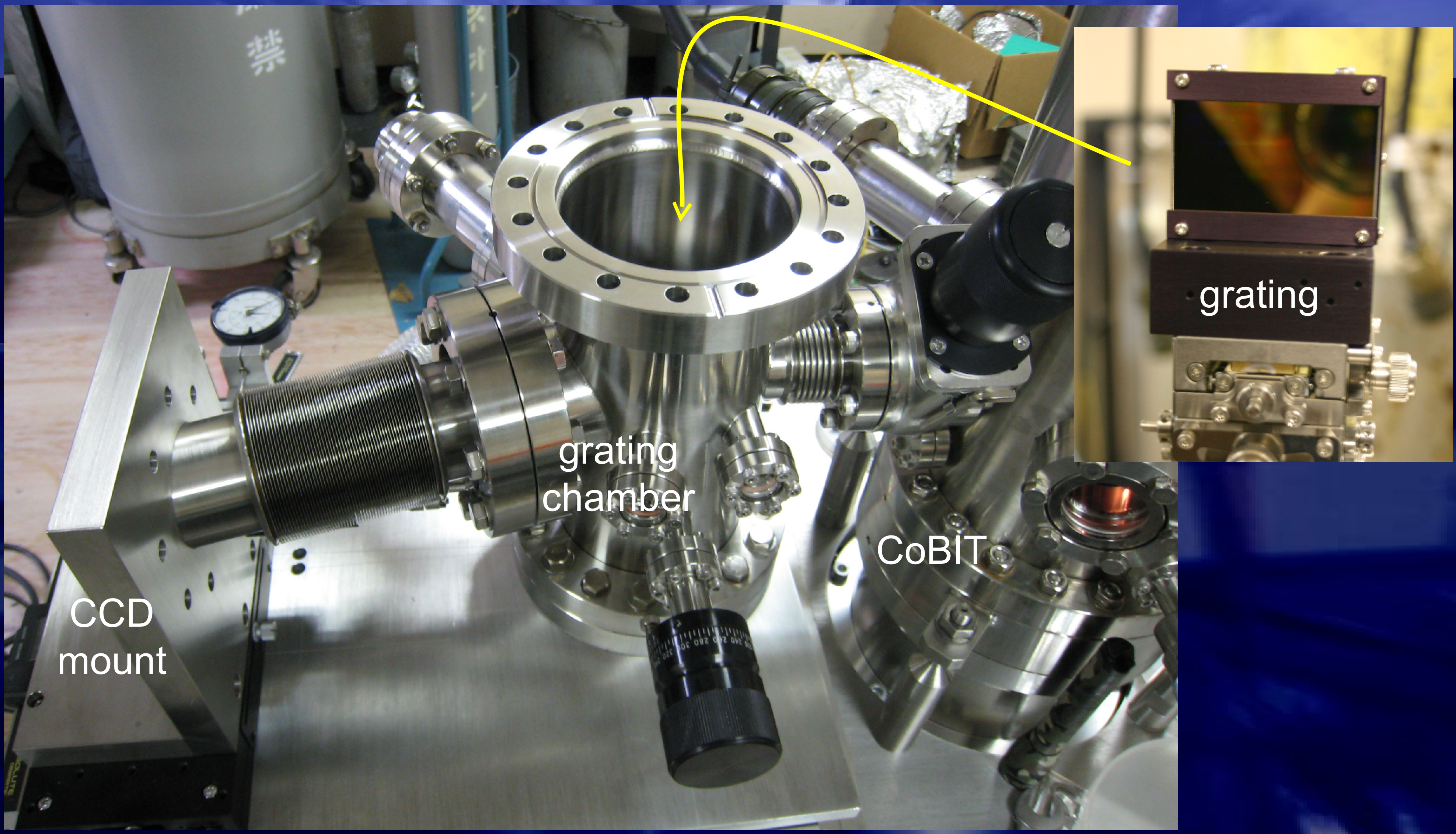
EUV spectrometer for CoBIT



2400 or 1200 mm^{-1}
r=237 mm
r'=235.3 mm
α=88.7 or 87°
λ=1-5 or 5-20 nm

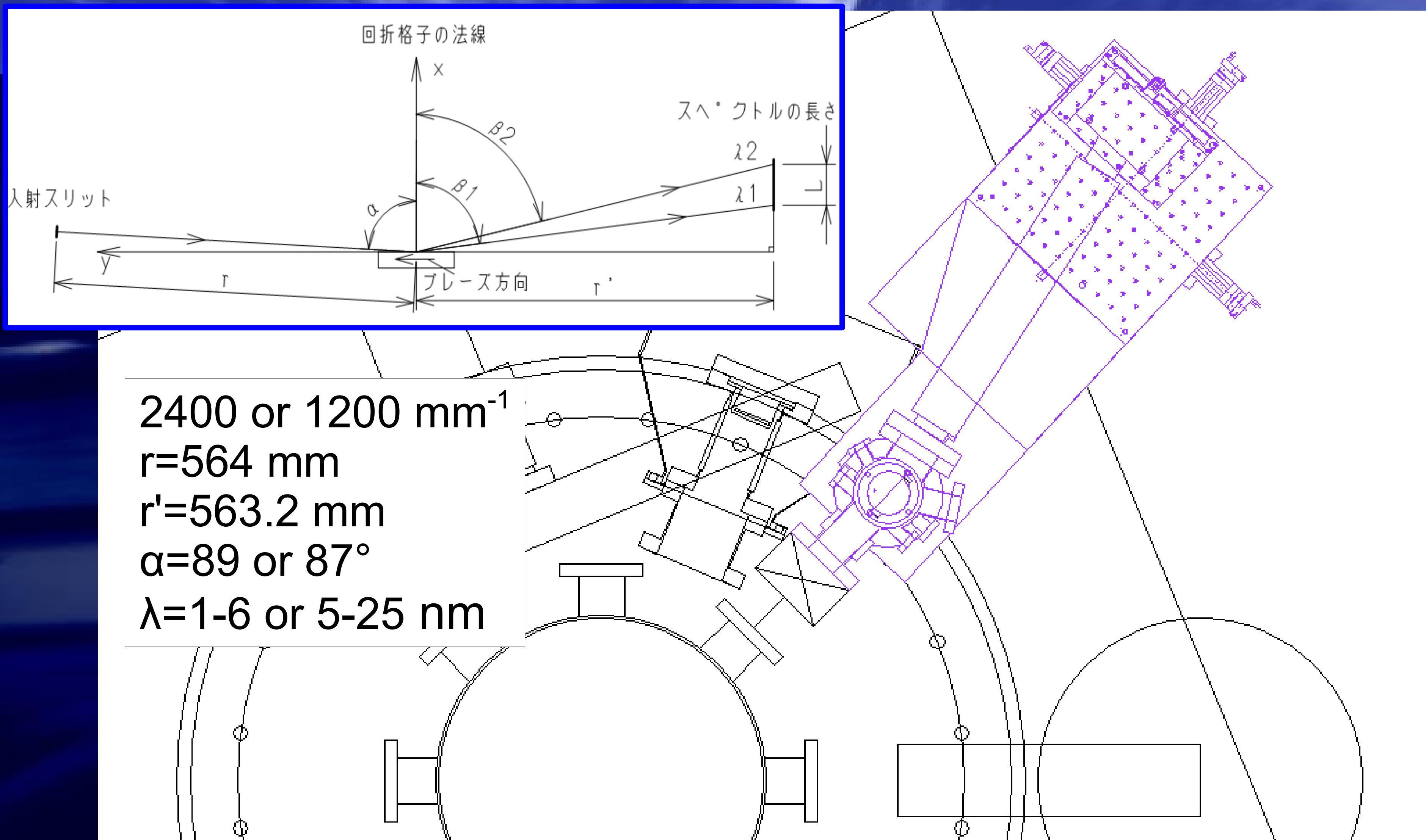
Nakamura et al., ApJ 739 (2011) 17

EUV spectrometer for CoBIT



Nakamura et al., ApJ 739 (2011) 17

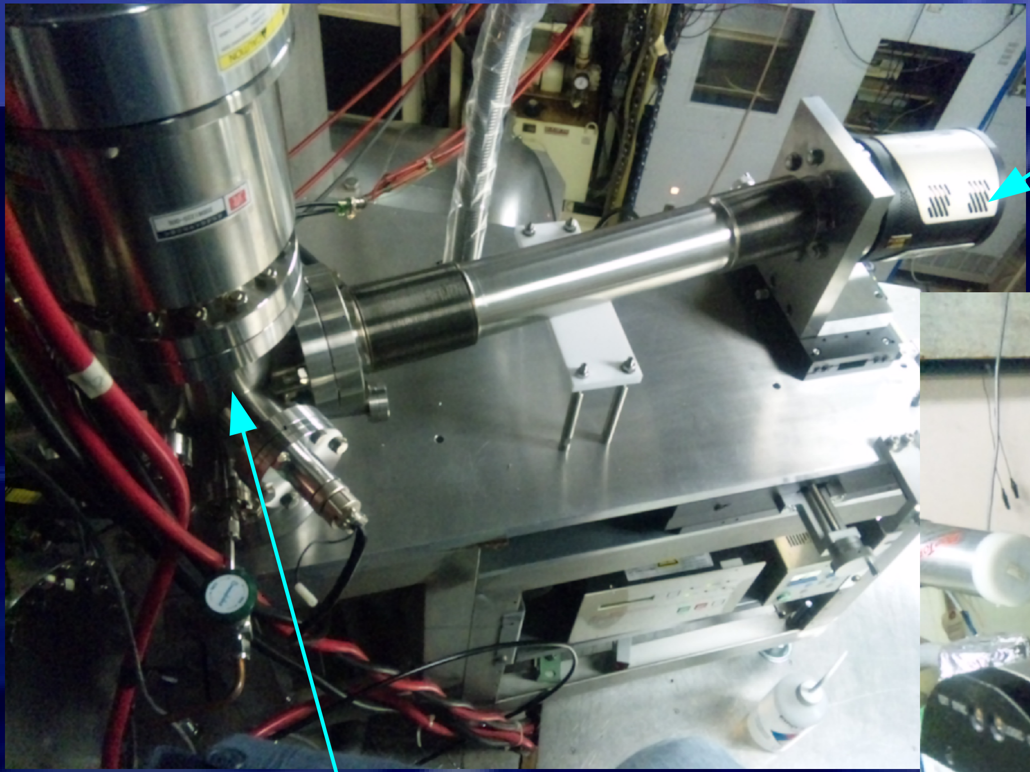
EUV spectrometer for the Tokyo-EBIT

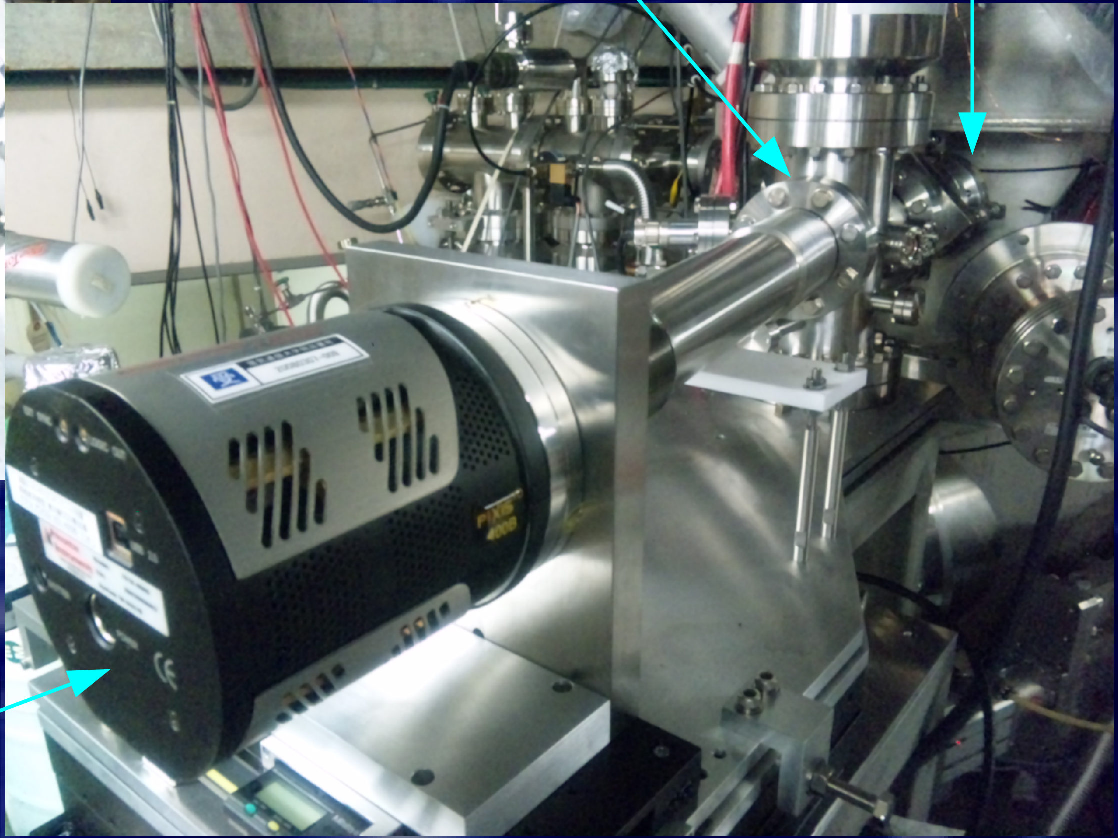


2400 or 1200 mm^{-1}
r=564 mm
r'=563.2 mm
α=89 or 87°
λ=1-6 or 5-25 nm

H. Ohashi et al., RSI 82 (2011) 083103

EUV spectrometer for the Tokyo-EBIT





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Atomic data needs for W ions

summarized by C.H. Skinner (CJP86, 285)

- Search for W emission lines **in the visible region**
- Search for W emission lines from charge states **below W26+**
- Identification of emission lines from neon-like tungsten
- Improvements to the existing codes
- ***More identified lines needed!***

Visible lines of W registered in the NIST DB

NIST Atomic Spectra Database Lines Data

W III-LXXIV: 1 Line of Data Found

Ion	Observed Wavelength Air (nm)	Ritz Wavelength Air (nm)
W LIII	362.713	362.713

Ti-like W^{52+} $3d^4$ ^5D_J (J=3-2)

Contribution from metastable states

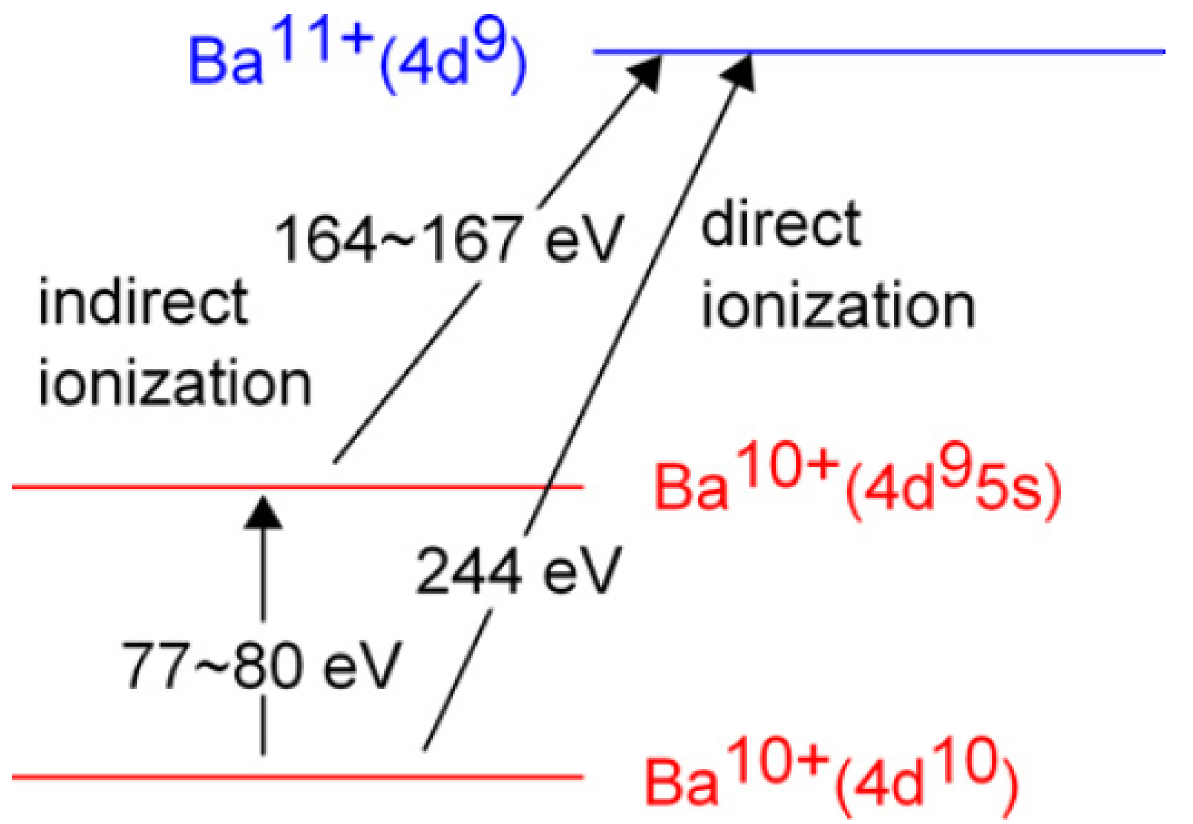

Figure 4. Energy levels of Ba^{10+} and Ba^{11+} [4, 5].

Sakoda et al., Phys. Scr. T144 (2011) 014011 (HCI2010 proceedings)

Detailed identification for some lines of W^{26+}

Table 3. The magnetic-dipole (M1) and electric-quadrupole (E2) transitions in visible region of ground state multiplets of W^{26+} ions. The gf means the weighted oscillator strength. The number in the format of $a(b)$ represent $a \times 10^b$.

Upper - Lower	$\lambda_{The.}$(nm)	$\lambda_{Obs.}(nm)$	Type	Rate(s^{-1})	gf
$^3H_5 \rightarrow ^3H_4$	388.43	389.41	M1	3.94(2)	9.80(-6)
			E2	1.69(-3)	4.21(-11)
$^3H_6 \rightarrow ^3H_5$	467.79	464.41	M1	2.05(2)	8.75(-6)
			E2	3.31(-4)	1.41(-11)
$^3F_3 \rightarrow ^3F_2$	501.80	501.99	M1	1.75(2)	4.62(-6)
			E2	7.28(-5)	1.92(-12)

X.B. Ding et al., JPB 44 (2011) 145004
Komatsu et al., Phys. Scr. T144 (2011) 014012

cf) Recent studies on W27+
(TH) X.B. Ding et al., J. Phys. B 45 (2012) 035003
(TH+EX from Shanghai) Poster 3a (p.77)

Lines from highly charged tungsten ions observed in the visible region between 340 and 400 nm

Hirofumi Watanabe, Nobuyuki Nakamura, Daiji Kato, Hiroyuki A. Sakaue, and Shunsuke Ohtani

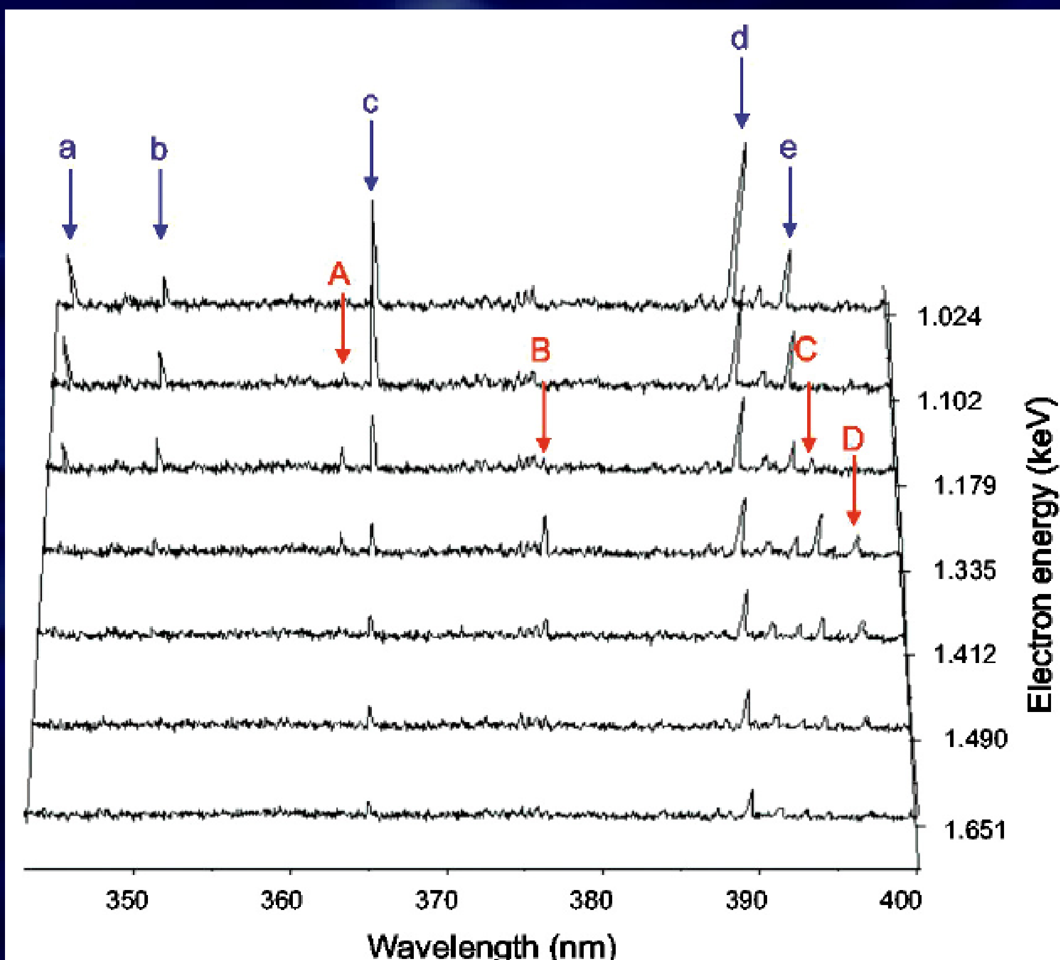

Table 1. Summary of wavelengths and threshold electron energies at which the observed lines emerge.

Label	Ion and transition	Threshold electron energy (keV)	Wavelength (nm)
A	W^{29+}	1.063(77)	363.12(3)
B	W^{30+}	1.141(77)	376.54(3)
C	W^{30+}	1.141(77)	394.41(3)
D	$W^{31\text{–}33+}$	1.257(116)	397.04(3)
a	$W^{27,28+*}$	—	344.40(4)
b	$W^{28,27+*}$	—	350.74(3)
c	$W^{27,28+*}$	—	365.18(3)
d	W^{26+} $(4f_{5/2}^2)_{J=4} - (4f_{5/2}4f_{7/2})_{J=5}$	—	389.35(3)
e	$W^{27,28+*}$	—	392.99(3)

*If lines a, c, and e came from W^{27+}, line b was from W^{28+}. If lines a, c, and e came from W^{28+}, line b was from W^{27+}.

H. Watanabe et al.,
Can. J. Phys. 90: 497-501 (2012)

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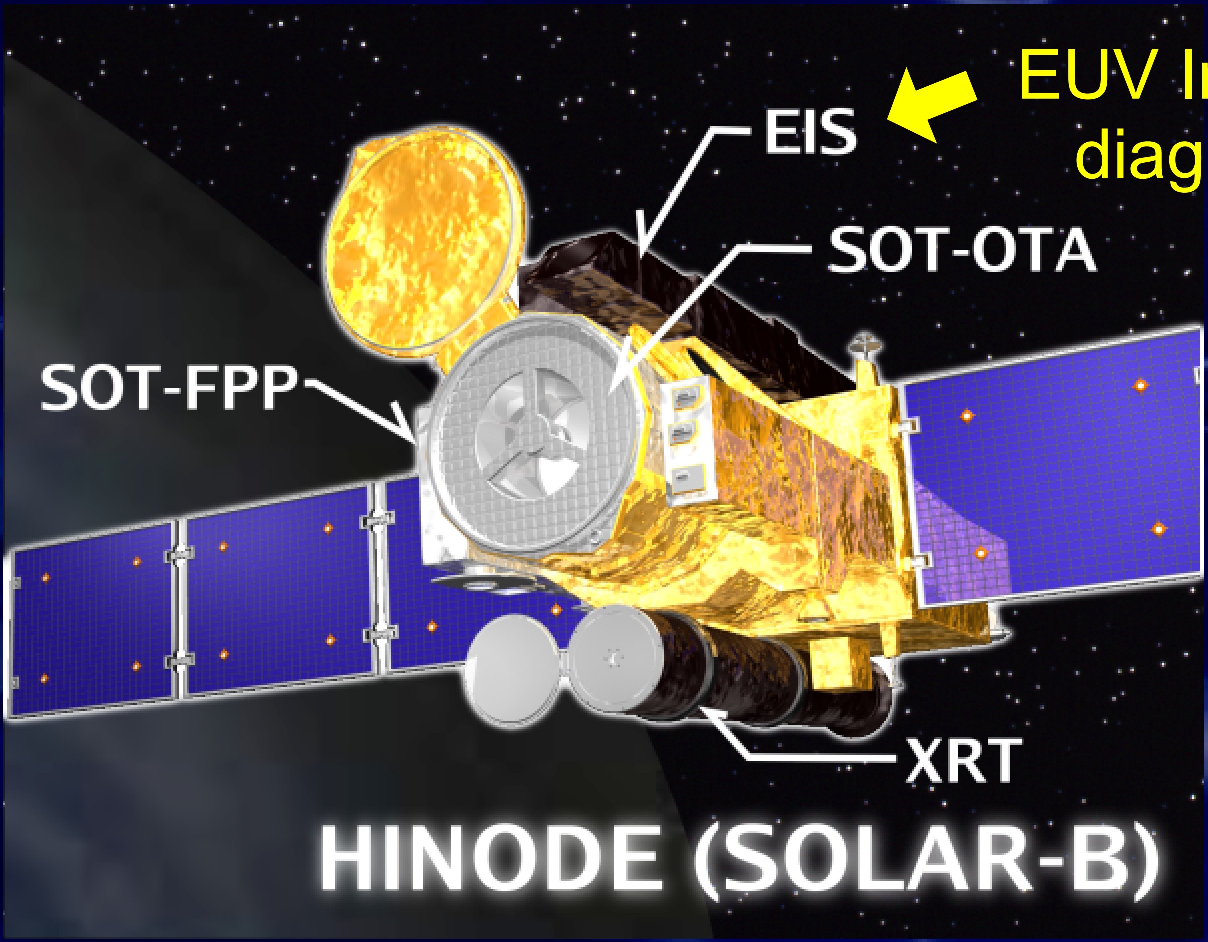
Solar observation satellite HINODE



EUV Imaging Spectrometer diagnostics for $T_e=10^5$-10^7 K.

↓

E_e= 10-1000 eV

Density diagnostics through intensity ratio observation

FeXIII spectrum by HINODE

T. Watanabe et al., ApJ (2009)

Fe XIII LINE DIAGNOSTICS

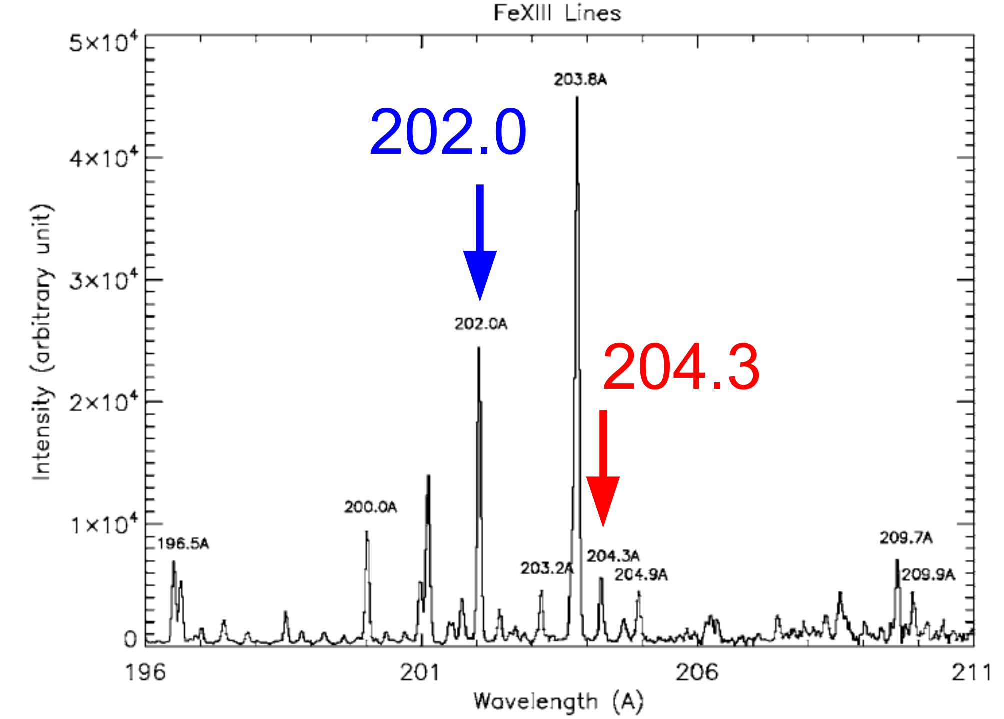
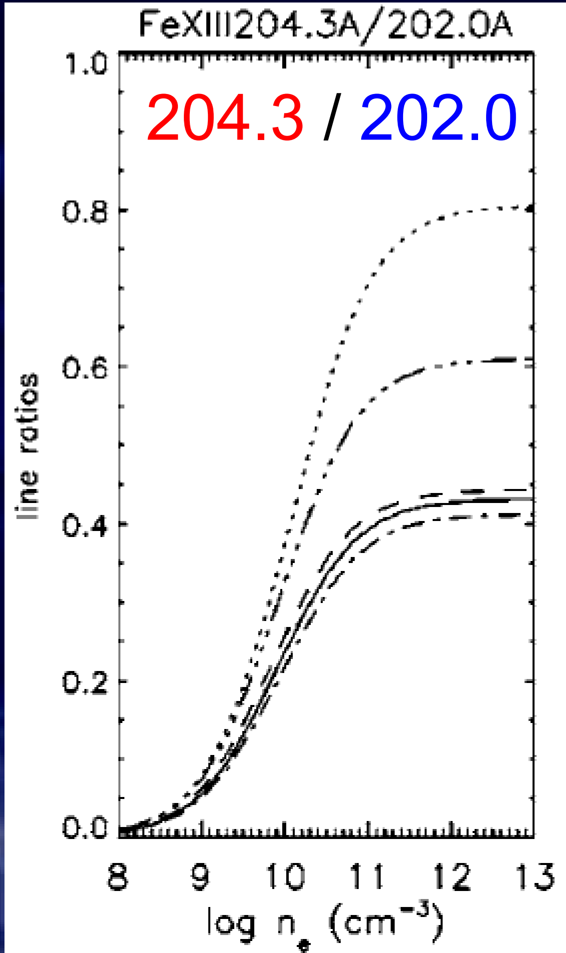
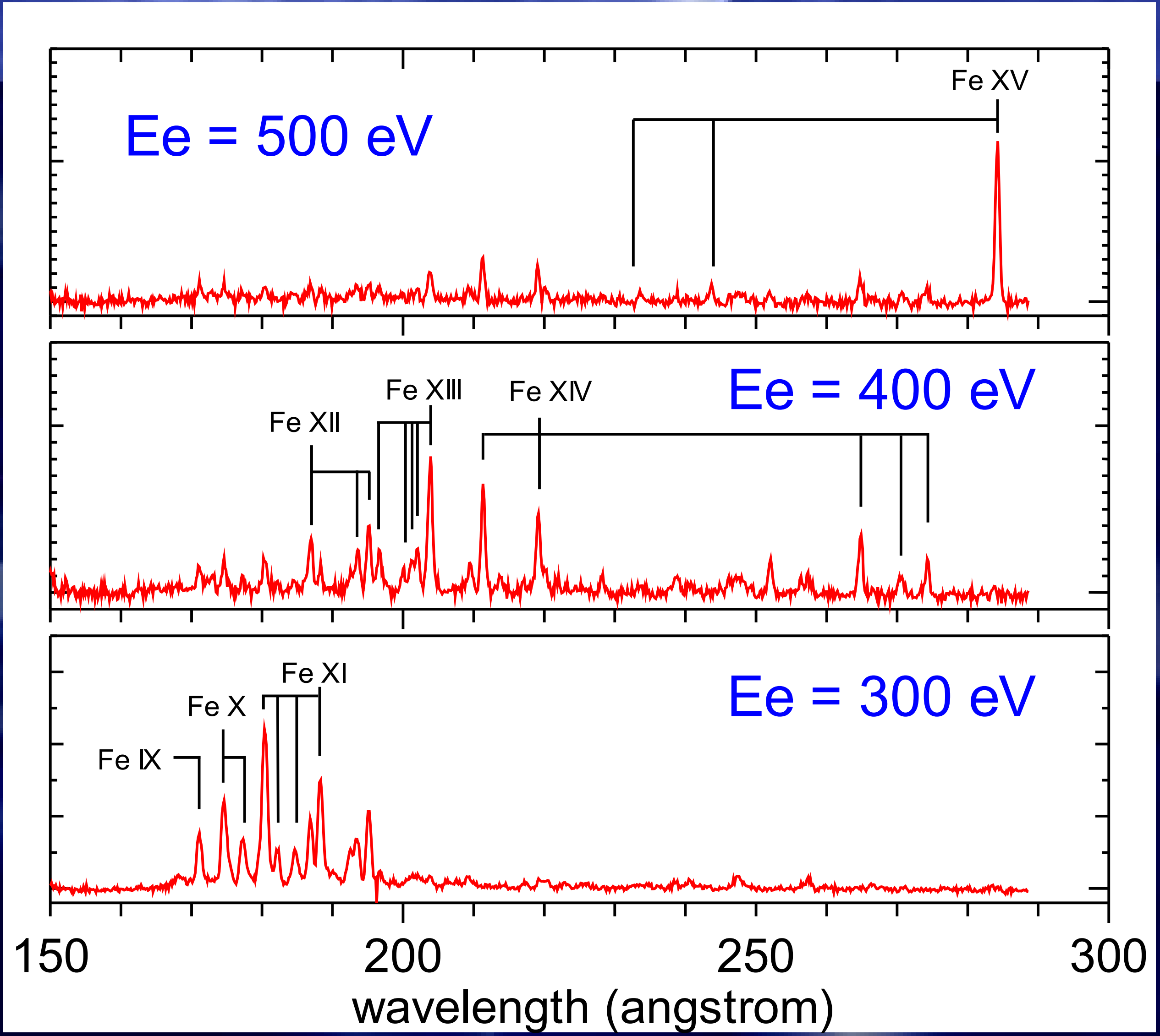


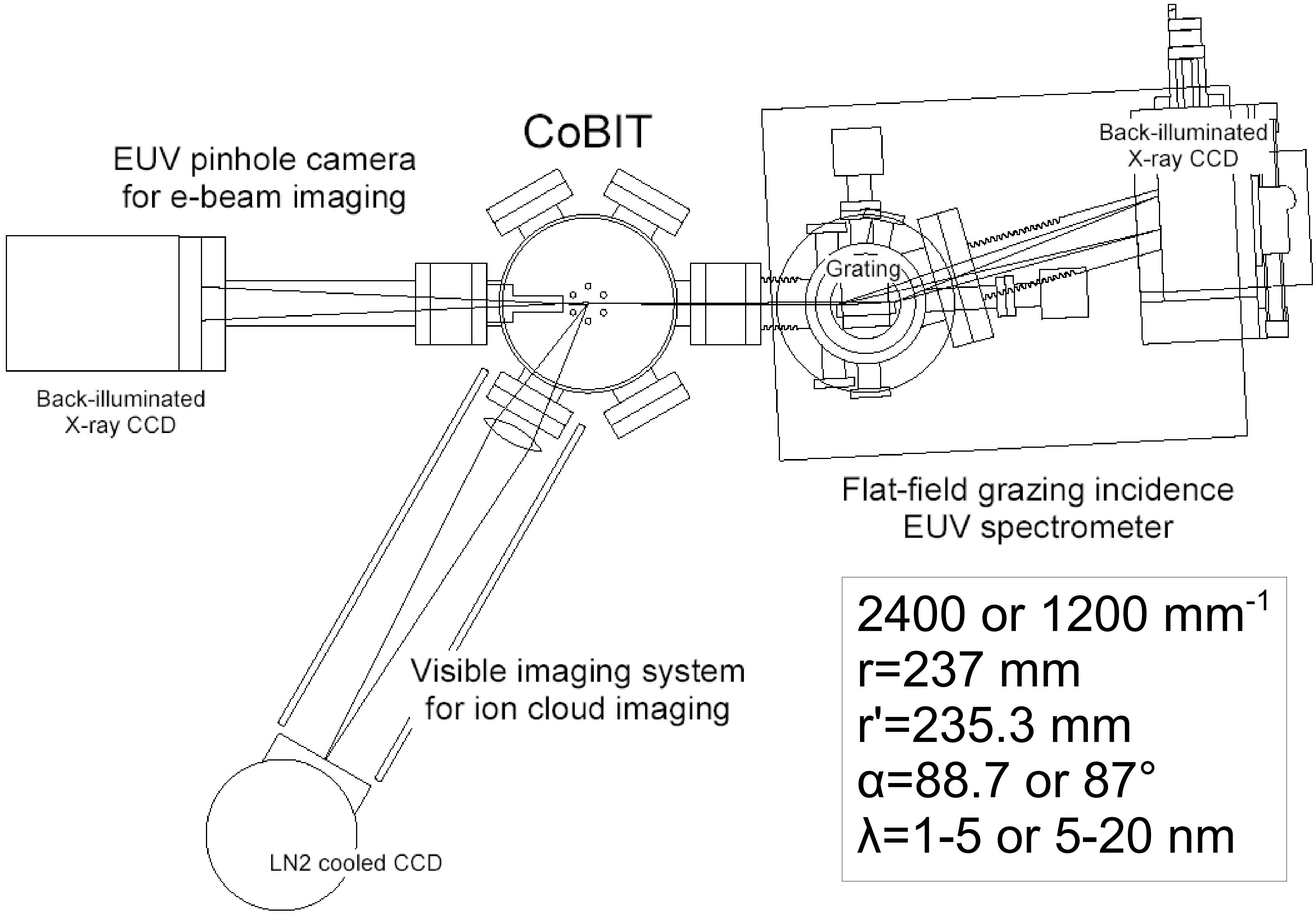
Figure 1. Active region spectrum in the wavelengths of 196–211 Å: strong Fe XIII emission lines are indicated.



Typical EUV spectra of iron obtained with CoBIT



Experimental setup



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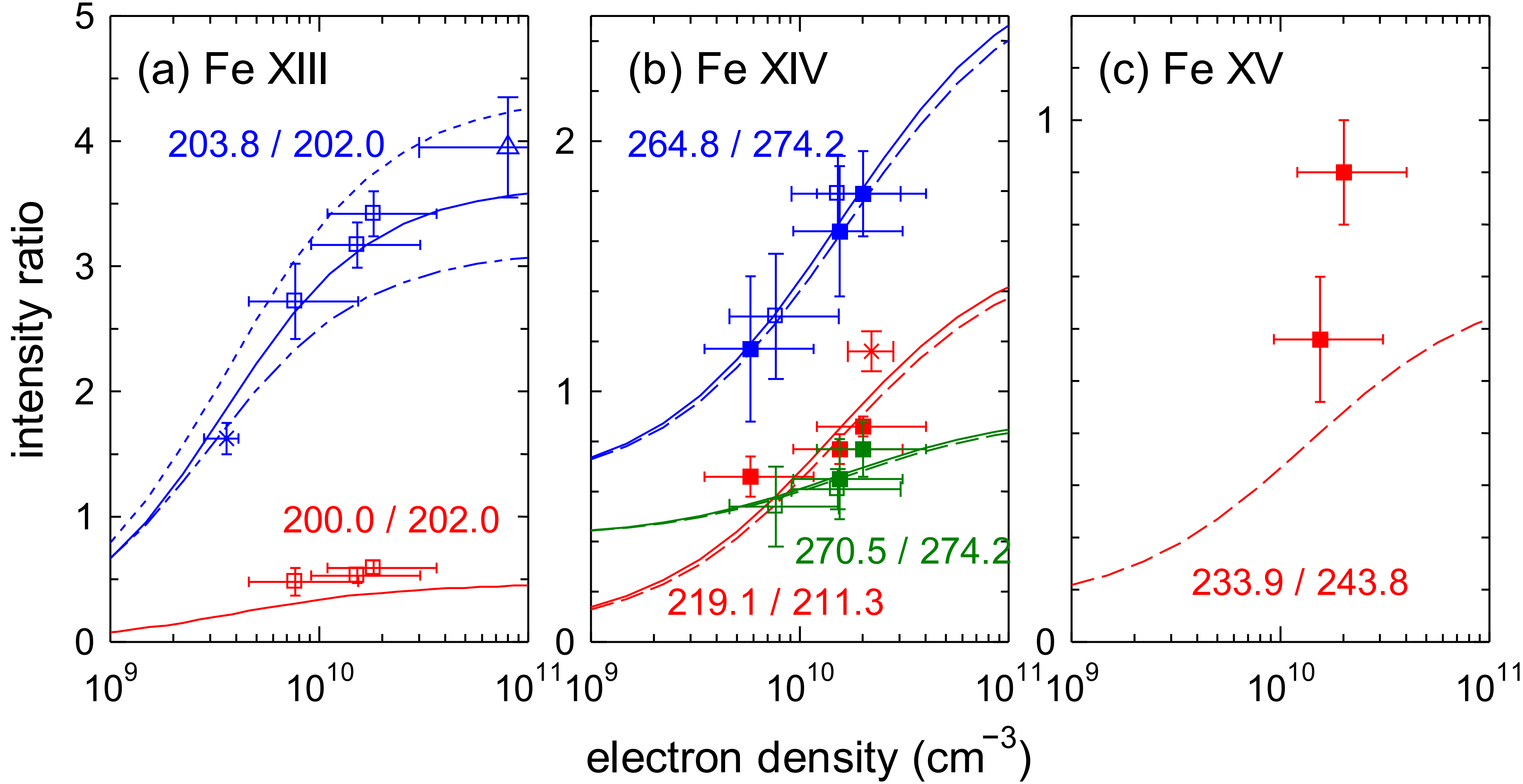
α=88.7 or 87°
λ=1-5 or 5-20 nm

Nakamura et al., ApJ 739, 17

Density dependence of intensity ratio



N. Nakamura et al., Astrophys. J. 739 (2011) 17

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Summary

- Electron beam ion trap
  - Versatile device to study radiative and collisional processes of highly charged ions
- The complementary use of the Tokyo-EBIT and CoBIT
  - A wide range of charge states of a wide range of atomic numbers can be studied.
  - Spectra of hot plasma related ions (W, Fe, Gd) has been systematically investigated.