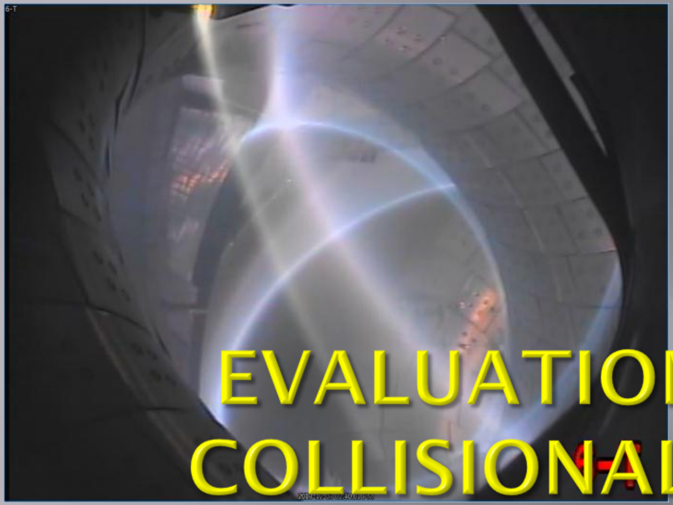
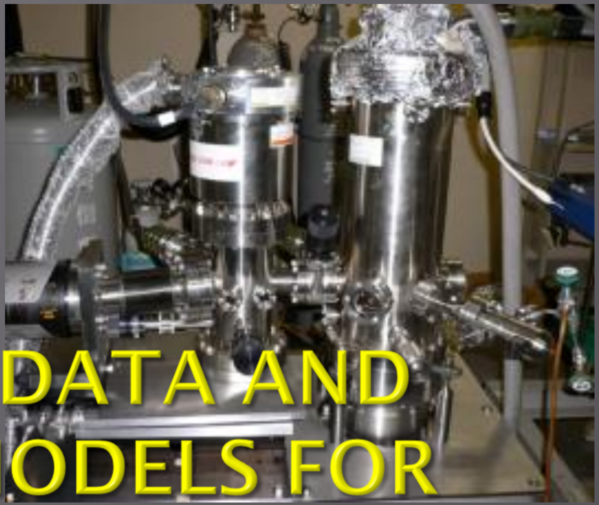




EVALUATION ON ATOMIC DATA AND COLLISIONAL-RADIATIVE MODELS FOR SPECTROSCOPIC DIAGNOSTICS AND COLLABORATION NETWORK IN JAPAN

I.Murakami[1,2], D. Kato[1,2], H. A. Sakaue[1], N. Nakamura[3], N. Yamamoto[4], T. Watanabe[5,2]

1. National Institute for Fusion Science, NINS, Toki, Gifu, Japan
2. SOKENDAI (The Graduate University for Advanced Studies), Hayama, Kanagawa, Japan
3. Institute for Laser Science, The University of Electro-Communications, Tokyo, Japan
4. Chubu University, Kasugai, Aichi, Japan
5. National Astronomical Observatory of Japan, NINS, Mitaka, Tokyo, Japan

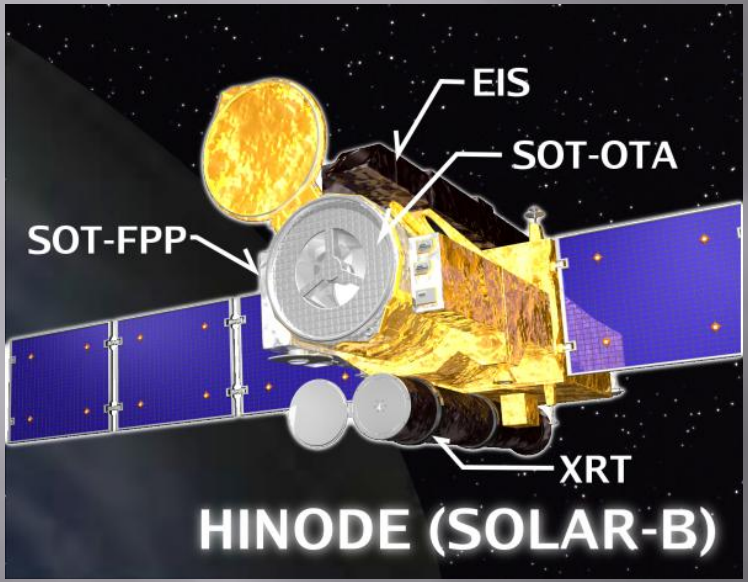
Outline

- Introduction
- Evaluation of the Collisional-Radiative Model and Atomic Data for Fe ions
- Collaboration Network with AM physicists
- Summary

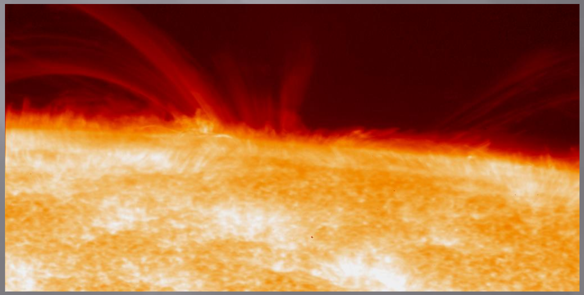
Introduction

- Spectroscopic diagnostics requires reliable atomic model (eg. a collisional-radiative (CR) model) and reliable atomic data to get good information from plasmas.
- Evaluation of atomic data and CR model with laboratory measurements is important.
- We have carried out evaluation of **CR model and atomic data for Fe ions** related to spectroscopic diagnostics for the Sun by EUV Imaging Spectrometer (EIS) on Hinode Solar Satellite.
- Collaboration network with experimentalists and theorists on AM physics is important and works well.

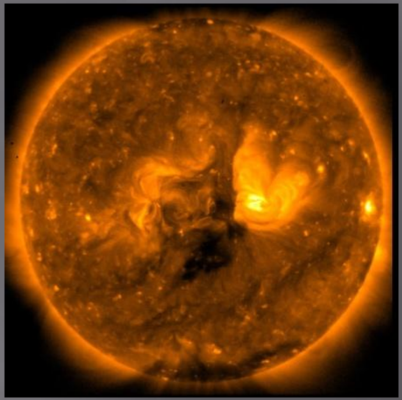
The *HINODE* solar observational satellite, on orbit since 22 Sep., 2006



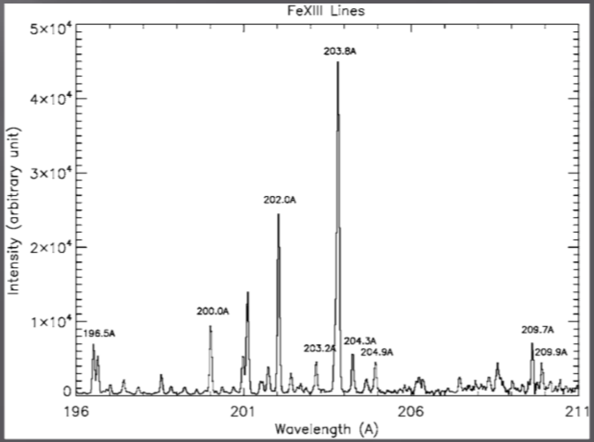
The HINODE is equipped with Solar Optical Telescope (SOT),
X-Ray Telescope（XRT), and
EUV Imaging Spectrometer（EIS), to observe solar magnetic fields and high temperature region to reveal the heating mechanism and dynamics of the active solar corona.



SOT observed dynamic flare near sunspot.



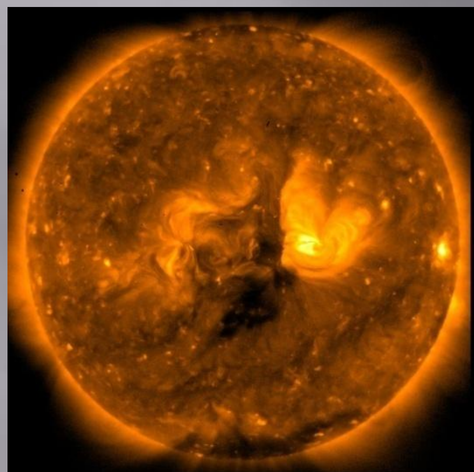
X-ray image of the Sun



Spectrum taken by EIS

Collaboration started in 2006 to evaluate atomic data and CR model for Fe ions by experiments with LHD and EBIT /CoBIT

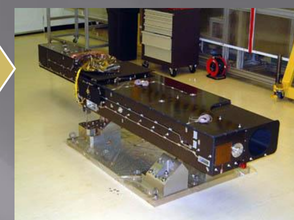
Solar spectrum



Plasma similarity

NAOJ

EIS / HINODE



Univ. Electro-comm.／NIFS

CoBIT・EBIT

Collisional-Radiative Moldel
Fe ion atomic data

Atomic data measurements

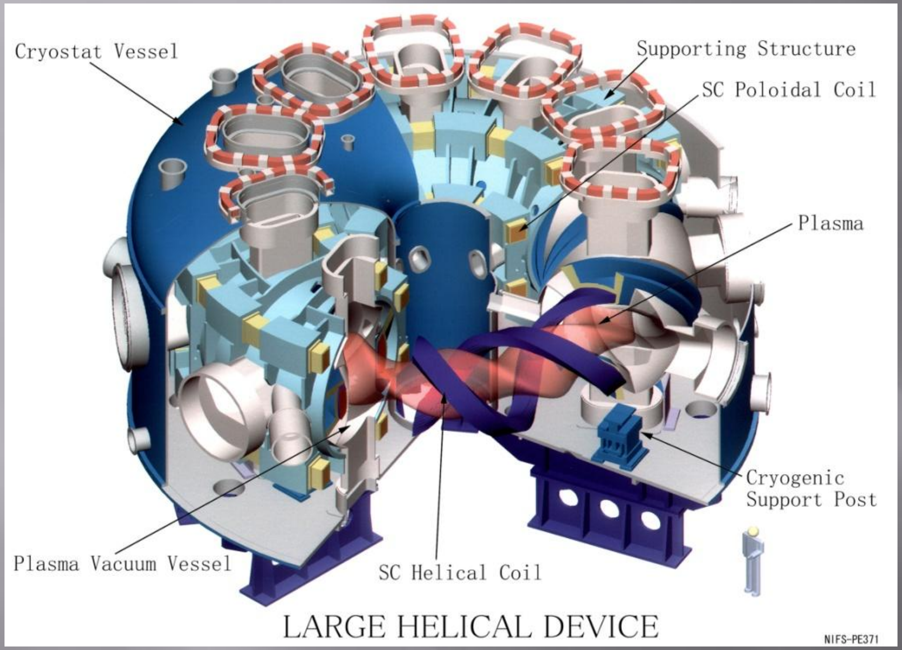
LHD spectrum

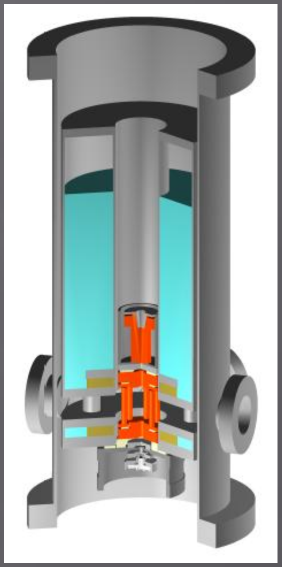
SOXMOS／EUV spectrometer

NIFS

CoBIT was developed under this collaboration <u>supported by NINS</u>.

Validation of atomic data and spectroscopic model by using LHD and CoBIT





- LHD can hold plasma stably with impurity input by pellets/TESPELs.
- Electron temperature and density can be measured independently.
- Plasma with similar electron temperature to the solar transition region can be produced.

- Compact EBIT (CoBIT) produces plasma with low electron density (~10^{10}cm^{-3}).
- CoBIT can control charge state distribution by electron beam energy (200eV – 2keV). It is easy to identify spectral lines.

Spectroscopic model for Fe ions
< Collisional-Radiative model >

- We have constructed a collisional-radiative (CR) models for Fe ions to analyze Fe spectra.
- Atomic data used in the CR model is mainly calculated by HULLAC code. We also use evaluated published data. Proton-impact excitation rate coefficients were evaluated.
- Electron-impact excitation rate coefficients are calculated from the cross section with Maxwellian velocity distribution for LHD plasmas and mono energy for EBIT plasmas.
- Rate equations for population densities of excited states $n(p)$ are solved with quasi-steady state assumption. (Recombination processes are ignored.)

$$\frac{dn(p)}{dt} = \Gamma_{in} - \Gamma_{out} = 0$$

$$\Gamma_{in} = \sum_{q<p} \{C(q,p) n_e n(q) + C^P(q,p) n_P n(q)\} + \sum_{q>p} \{F(q,p) n_e + F^P(q,p) n_P + A(q,p)\} n(q)$$

Electron-impact excitation

Proton-impact excitation

De-excitation

Radiadive decay

$$\Gamma_{out} = [S(p) n_e + \sum_{q>p} \{C(p,q) n_e + C^P(p,q) n_P\} + \sum_{q<p} \{F(p,q) n_e + F^P(p,q) n_P\} + A(p,q)] n(p)$$

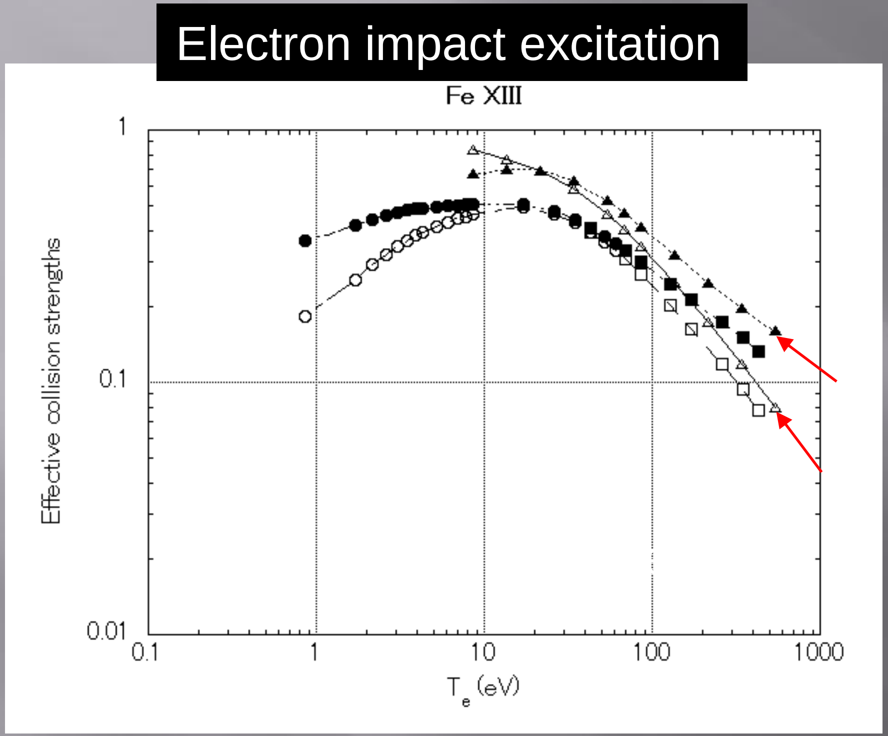
Electron-impact ionization

CR model for Fe ions was constructed
N. Yamamoto et al. Ap. J. 689, 646 (2008)

- Atomic data were calculated with HULLAC code.
- Proton-impact excitation processes were included, which data were evaluated.

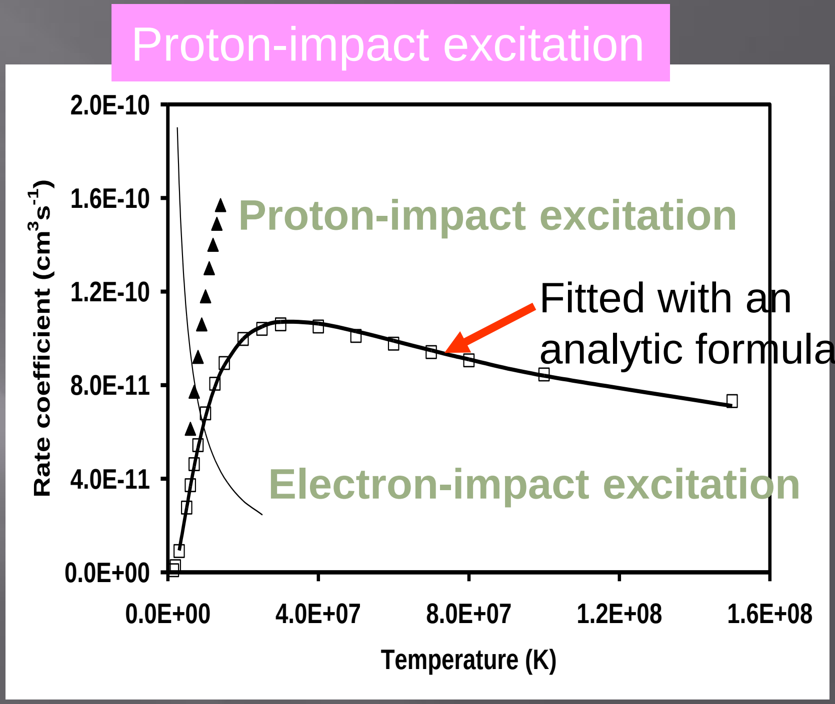
- *H-like : 1s, 2s, 2p, …, 5p, 5d, 5f, 5g* ($n \leqq 5, l \leqq 4$) *25 states*
- *He-like : $1s^2$, 1s2s, 1s2p, …, 1s5d, 1s5f, 1s5g* ($n \leqq 5, l \leqq 4$) *49 states*
- *Li-like : $1s^22s$, $1s^22p$, …, $1s^25d$, $1s^25f$, $1s^25g$* ($n \leqq 5, l \leqq 4$) *24 states*
- *Be-like : $1s^22s^2$, $1s^22snl$, $1s^22pnl$* ($n \leqq 5, l \leqq 4$) *166 states*
- *B-like : $1s^22s^22p$, $1s^22s^2nl$, $1s^22s2pnl$, $1s^22p^2nl$* ($n \leqq 5, l \leqq 4$) *513 states*
- *C-like : $1s^22s^22p^2$, $1s^22s^22pnl$, $1s^22s2p^2nl$, $1s^22p^3nl$* ($n \leqq 5, l \leqq 4$) *1004 states*
- *N-like : $1s^22s^22p^3$, $1s^22s^22p^2nl$, $1s^22s2p^3nl$, $1s^22p^4nl$* ($n \leqq 5, l \leqq 4$) *1204 states*
- *O-like : $1s^22s^22p^4$, $1s^22s^22p^3nl$, $1s^22s2p^4nl$, $1s^22p^5nl$* ($n \leqq 5, l \leqq 4$) *994 states*
- *F-like : $1s^22s^22p^5$, $1s^22s^22p^4nl$, $1s^22s2p^5nl$, $1s^22p^6nl$* ($n \leqq 5, l \leqq 4$) *480 states*
- *Ne-like : $1s^22s^22p^6$, $1s^22s^22p^5nl$, $1s^22s2p^6nl$* ($n \leqq 5, l \leqq 4$) *157 states*
- *Na-like ($1s^22s^22p^6$) : 3s, 3p, … nl* ($n \leqq 5, l \leqq 4$) *21 states*
- *Mg-like ($1s^22s^22p^6$) : $3s^2$, 3snl, 3pnl, 3dnl* ($n \leqq 5, l \leqq 4$) *243 states*
- *Al-like ($1s^22s^22p^6$) : $3s^23p$, $3s^23d$, $3s3p^2$, 3s3p3d, $3p^3$, $3p^23d$, $3s3d^2$, $3p3d^2$, $3d^3$, $3s^2nl$, 3s3pnl* ($n \leqq 5, l \leqq 4$) *332 states*
- *Si-like ($1s^22s^22p^6$) : $3s^23p^2$, 3l3l′3l″nl* ($n \leqq 5, l \leqq 4$) *917 states*
- *P-like ($1s^22s^22p^6$) : $3s^23p^3$, 3l3l′3l″3l‴nl* ($n \leqq 5, l \leqq 4$) *1287 states*
- *S-like ($1s^22s^22p^6$) : $3s^23p^4$, 3l3l′3l″3l‴3l″″nl* ($n \leqq 5, l \leqq 4$) *1189 states*
- *Cl-like ($1s^22s^22p^6$) : $3s^23p^5$, 3l3l′3l″3l‴3l″″3l″‴nl* ($n \leqq 5, l \leqq 4$) *1084 states*
- *Ar-like ($1s^22s^22p^6$) : $3s^23p^6$, 3l3l′3l″3l‴3l″″3l″‴3l″″″nl* ($n \leqq 5, l \leqq 4$) *1073 states*
- *K-like ($1s^22s^22p^6$) : $3s^23p^63d$, 3l3l′3l″3l‴3l″″3l″‴3l″″″3l″″‴nl* ($n \leqq 5, l \leqq 4$) *1301 states*
- *Ca-like ($1s^22s^22p^6$) : $3s^23p^63d^2$, 3l3l′3l″3l‴3l″″3l″‴3l″″″3l″″‴3l″″″″nl* ($n \leqq 5, l \leqq 4$) *1089 states*

Atomic data evaluation of published data for electron-impact excitation and proton-impact excitation rate coefficients



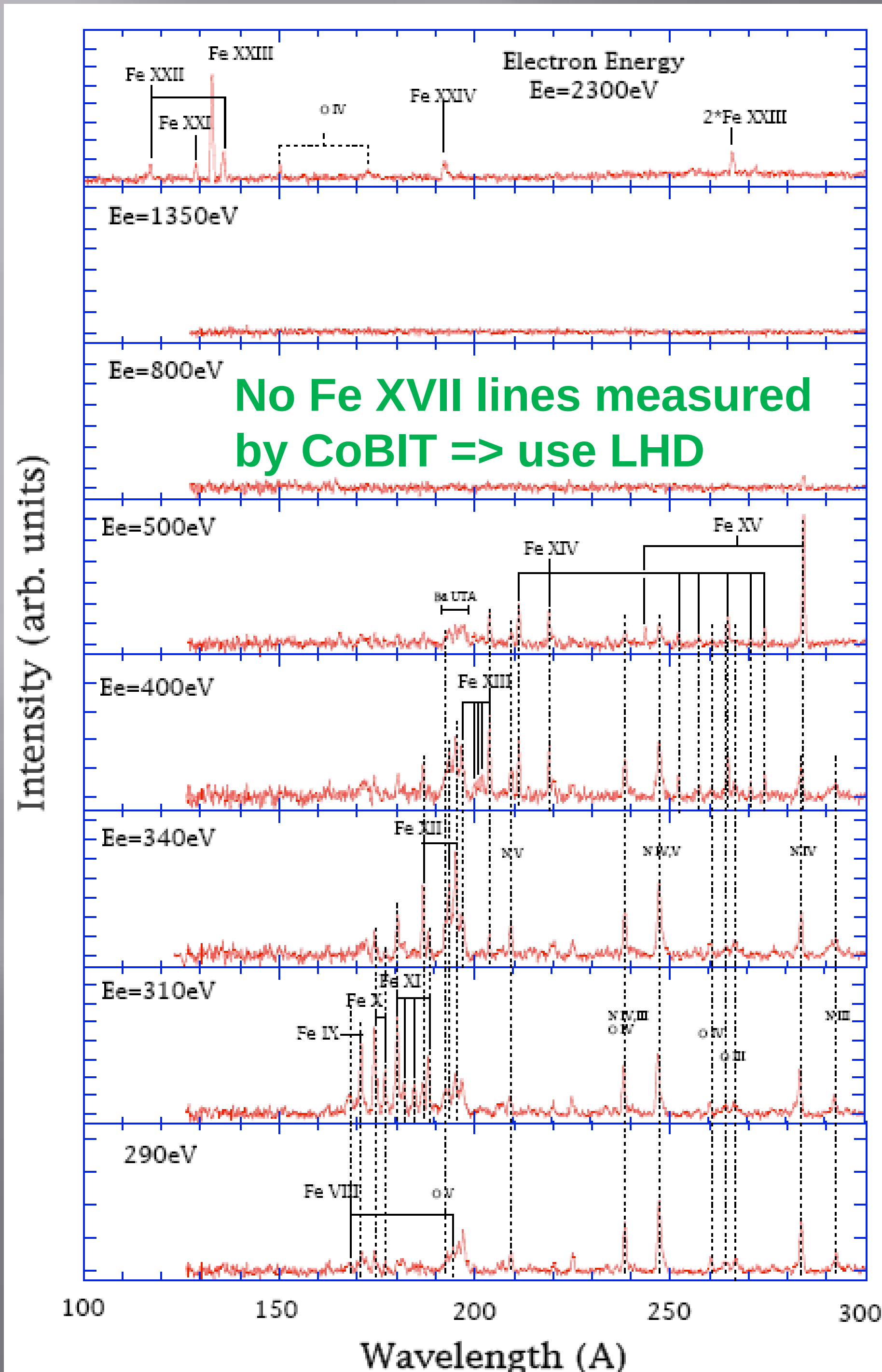
Effective collision strengths of the Fe XIII $3s^23p^2\ {}^3P_0 - 3s^23p^2\ {}^3P_1$ (open symbols) and the $3s^23p^2\ {}^3P_0 - 3s^23p^2\ {}^3P_2$ (filled symbols) transitions obtained by Gupta and Tayal (1998) (squares) , Tayal (2000) (circles), and Aggarwal and Keenan (2005) (triangles) as a function of electron temperature.

Murakami et al. (2011)



Collisional excitation rate coefficients for transition $2s^22p^2\ {}^3P_1 - {}^3P_2$ in C-like Fe ions (Fe XXI): solid thick line – formula (1) for protons, solid thin line – electrons [Butler & Zeippen 2000], ▲data [Faucher 1977], ☐ - data [Ryans et al. 1999; relativistic treatment].

Skobelev et al., (2010) A&A,511, A60



Fe spectra searched by CoBIT

By changing electron beam energy, ion charges are tunable. We measured Fe VIII – Fe XXIII lines in 100-300 Å region.

We also used LHD for Fe spectra measurements by injecting a pellet.

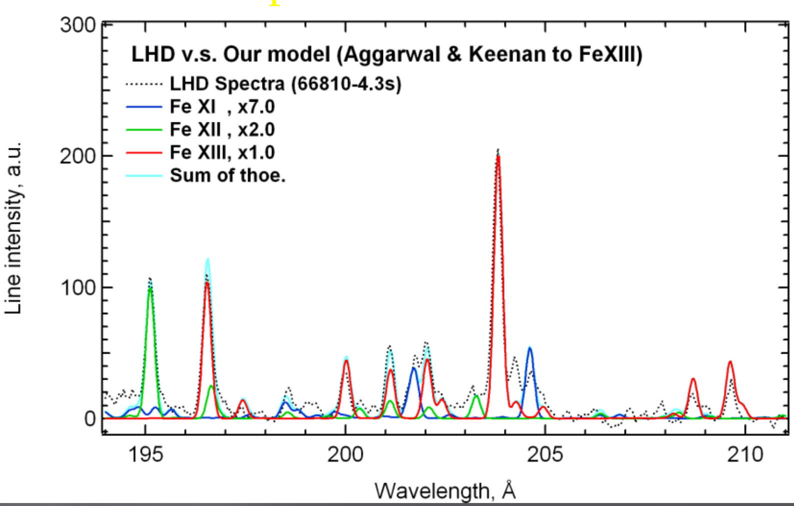
Fe XXII : Sakaue et al. (2011) (EBIT & LHD)
Fe XXI : Murakami et al. (2010) (LHD)
Fe XVII : Murakami et al. (2014) (LHD)
Fe XV : Shimizu et al. (2015)
Fe XIII, XIV, XV: Nakamura et al. (2011)
Fe XIII : Yamamoto et al. (2008) (LHD)
Fe X, XI, XII : in preparation

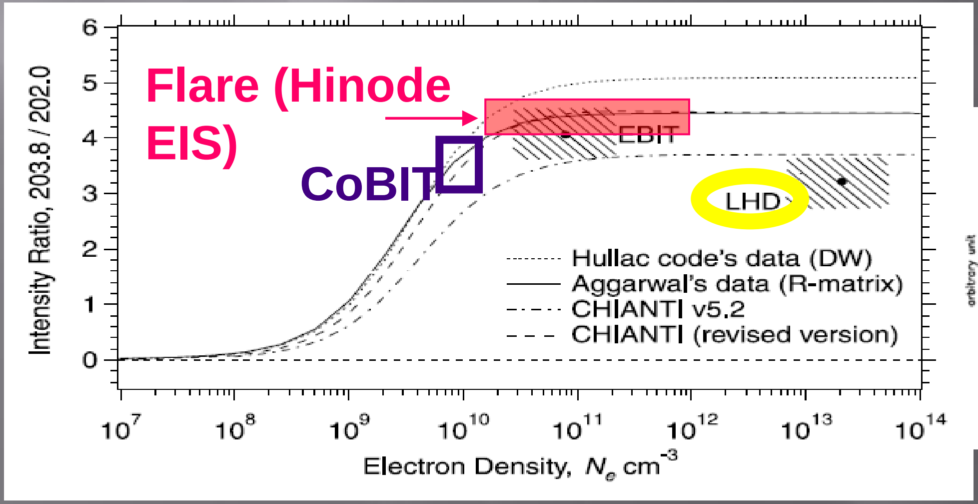
Validation of CR model for Fe XIII by using LHD and EBIT, then apply to the analysis of EIS spectra

N. Yamamoto et al. Ap. J. 689, 646 (2008),
T. Watanabe et al. Ap. J.692, 1294 (2009)

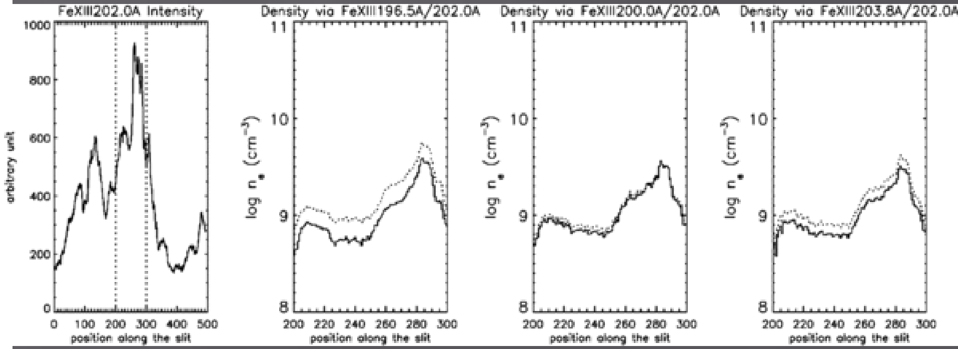
1. Electron density dependence of Fe XIII lines were examined with LHD and EBIT (LLNL) to select valid atomic data.
2. Apply the model to analyze the solar spectra measured by EIS. Electron density distribution of the sun transition region was estimated by using the density dependence of line ratios.

EUV spectrum of LHD





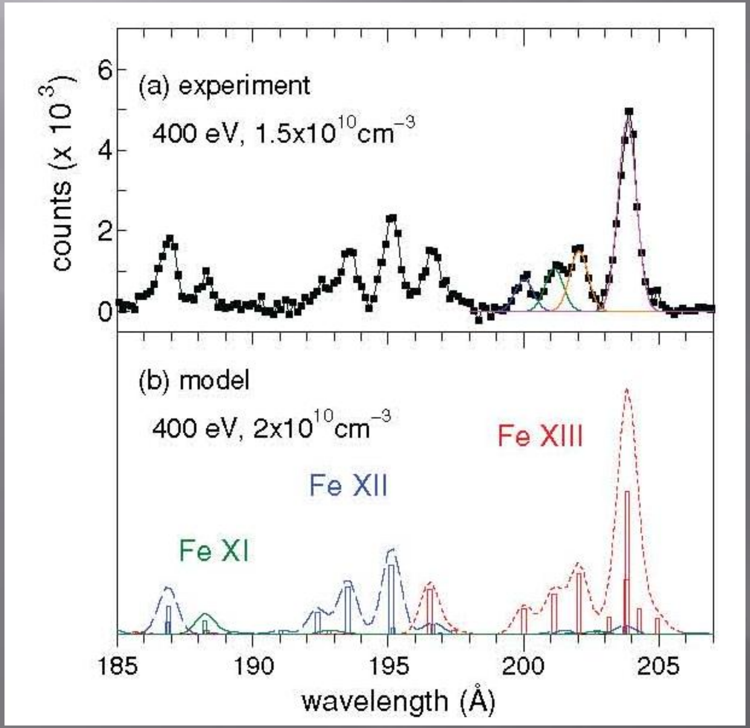
Electron density distribution of the sun



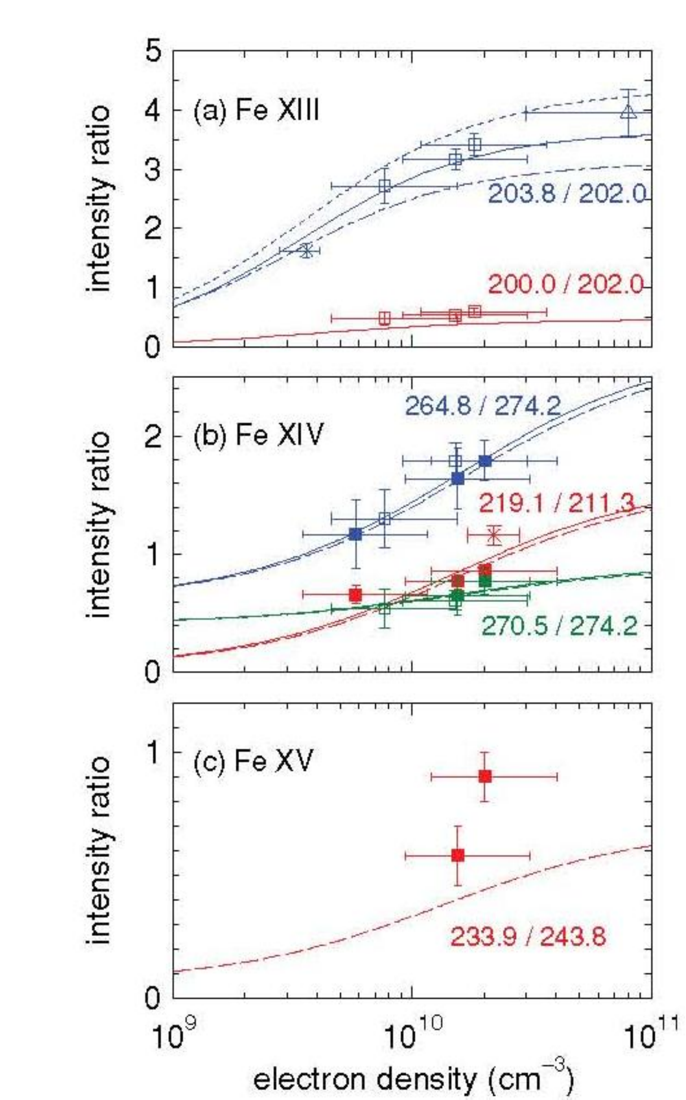
Validation of CR models for Fe XIII – XV by using CoBIT

N. Nakamura et al. ApJ 739, 17 (2011)
E. Shimizu et al., J. Phys. Conf. Ser. 583 (2015) 012019

Line ratios of Fe XIII, Fe XIV, and Fe XV were measured by CoBIT and compared with the calculations of the CR model. Good agreement for Fe XIII and Fe XIV.



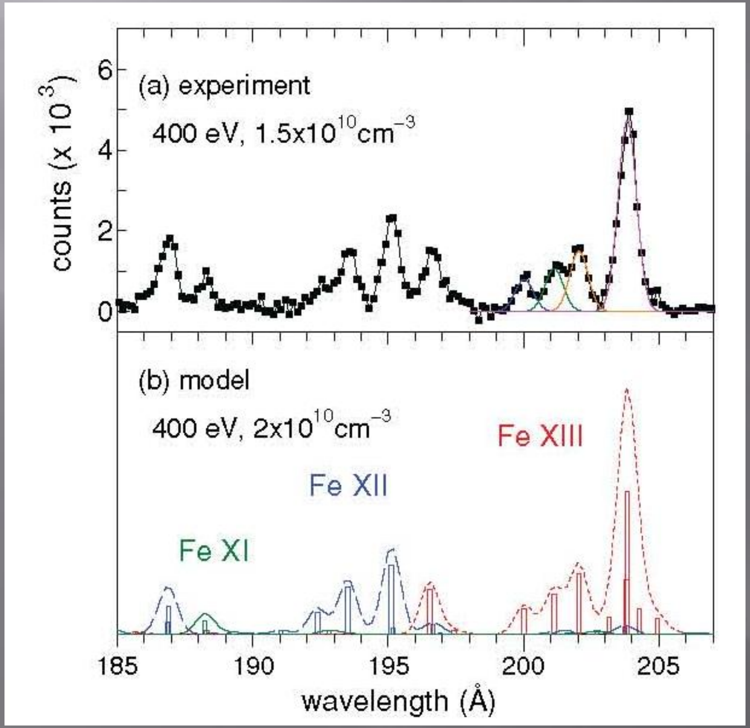
Discrepancy for Fe XV ratio indicates needs to check the CR model and the atomic data, as well as further measurements.



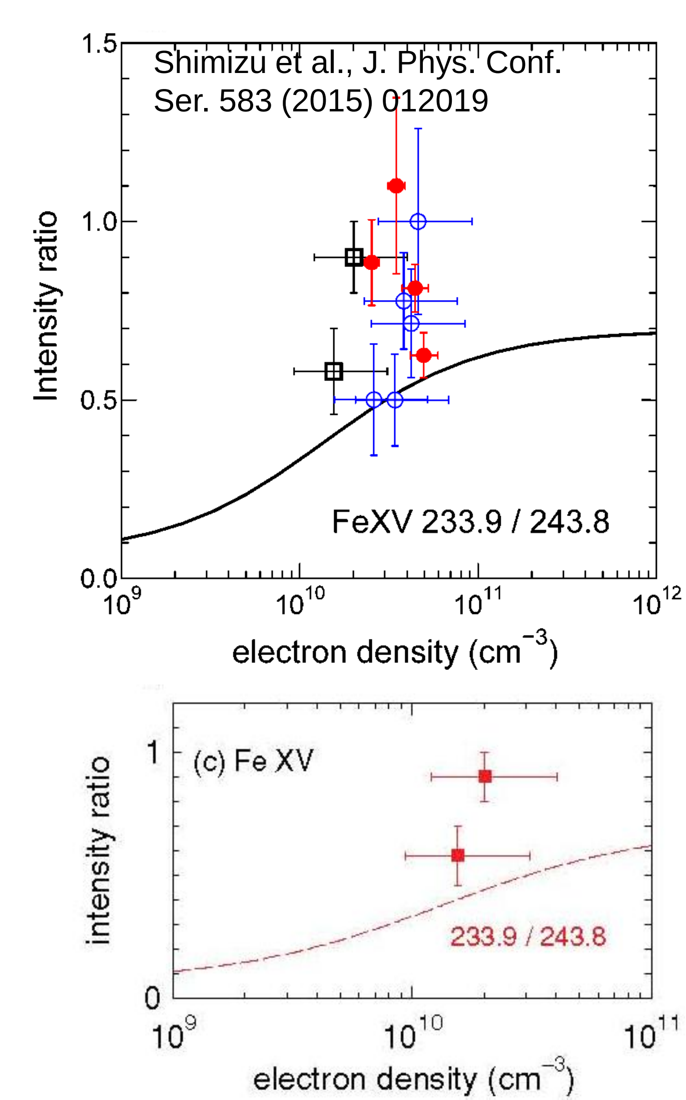
Validation of CR models for Fe XIII – XV by using CoBIT

N. Nakamura et al. ApJ 739, 17 (2011)
E. Shimizu et al., J. Phys. Conf. Ser. 583 (2015) 012019

Line ratios of Fe XIII, Fe XIV, and Fe XV were measured by CoBIT and compared with the calculations of the CR model. Good agreement for Fe XIII and Fe XIV.



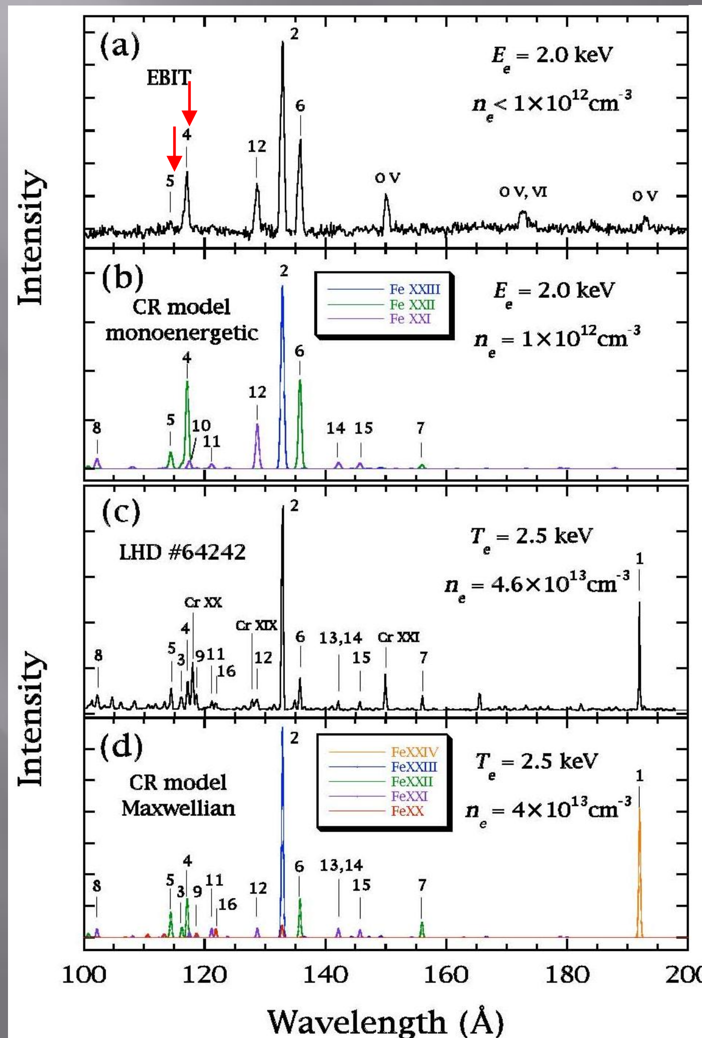
Discrepancy for Fe XV ratio indicates needs to check the CR model and the atomic data, as well as further measurements.

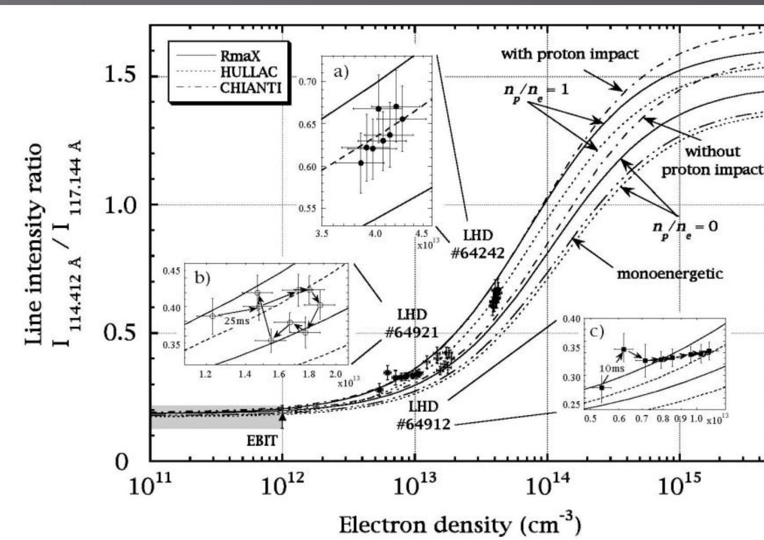


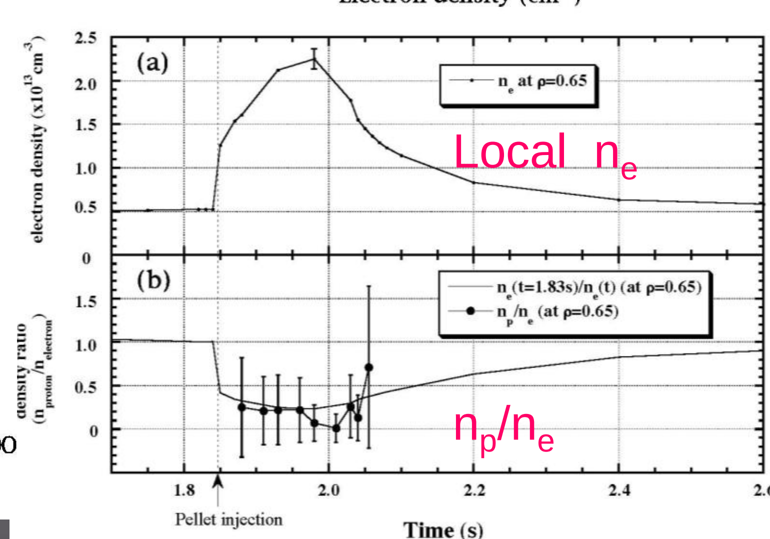
Analysis of Fe XXII line ratio for EBIT and LHD

H. A. Sakaue et al., J. Appl. Phys., 109, 073304 (2011)

- Fe XXII 114Å/117Å ratio was measured for EBIT and LHD.
- Measurements agreed with the CR model calculation.
- Detailed comparison indicates time variation of local proton density relative to electron density.







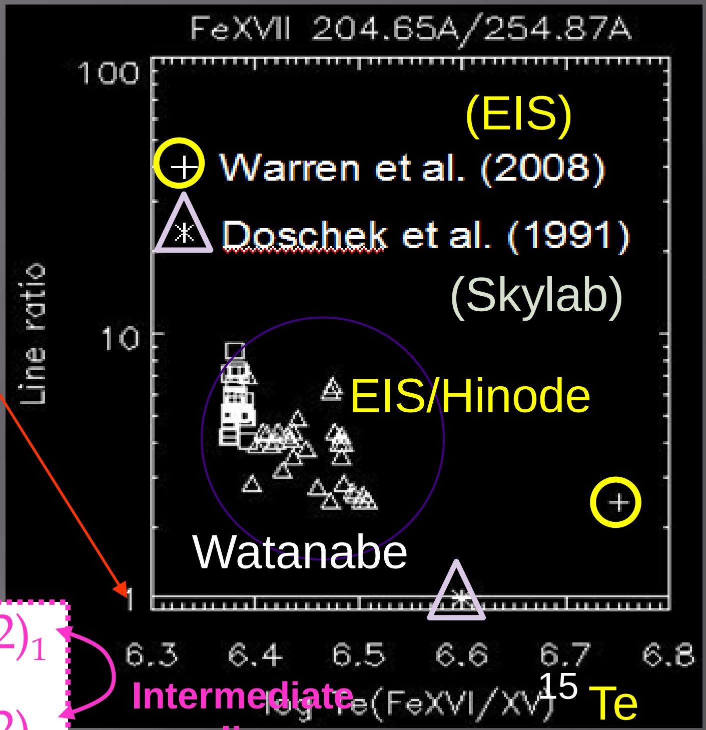
Problems of Fe XVII line diagnostics

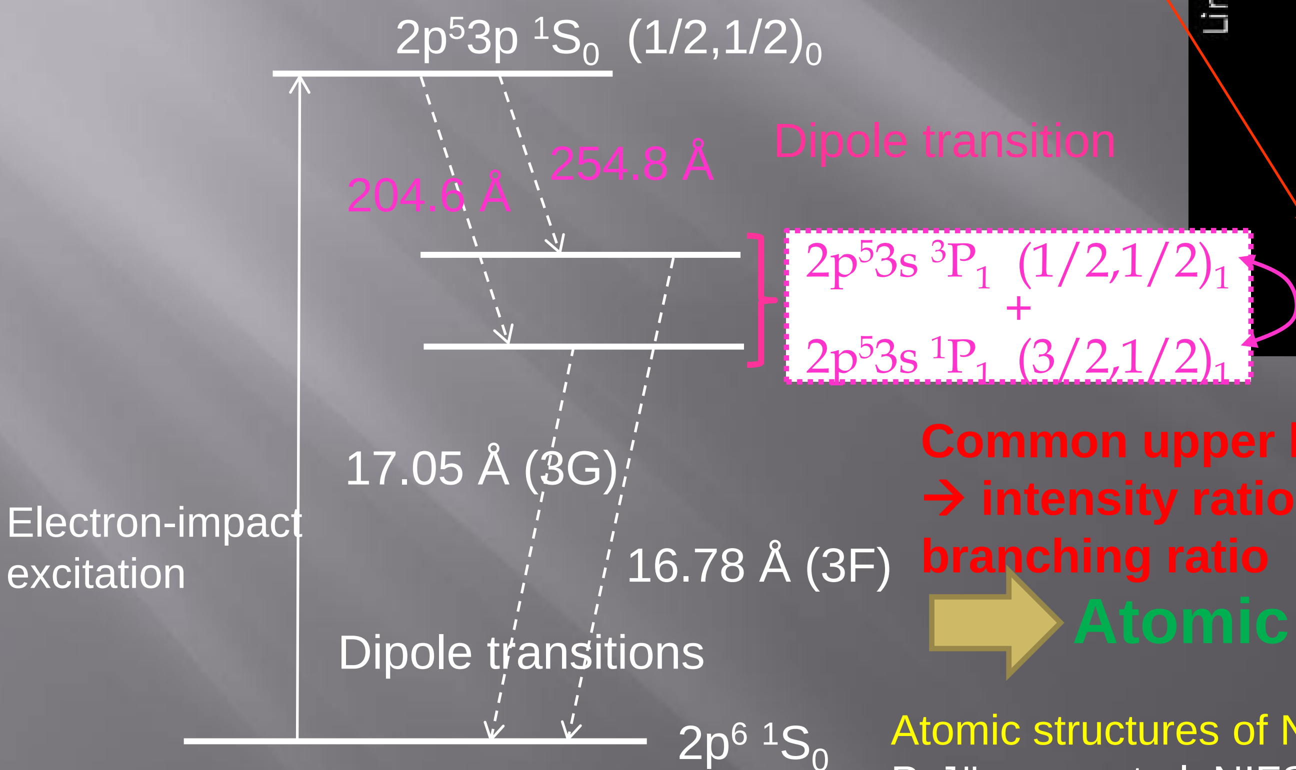
I. Murakami et al. Plasma and Fusion Research, 9, 1401056 (2014)

- EIS/Hinode measurements indicated discrepancy between observations and theoretical predictions.

Fe XVII
204/254

Theoretical calculation





Common upper level
→ intensity ratio is determined by the branching ratio

Atomic physics

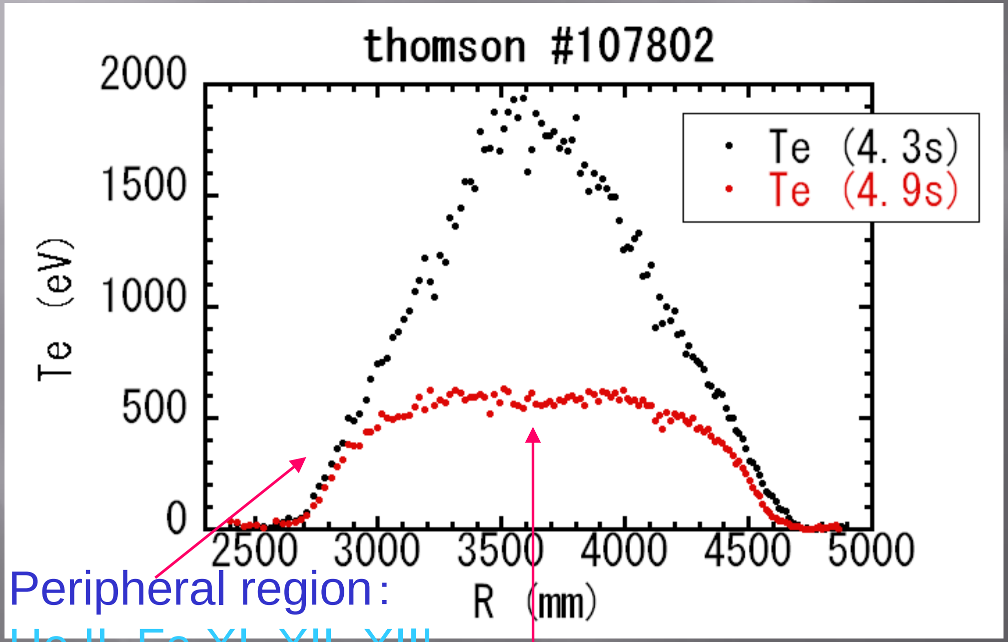
Atomic structures of Ne-like ions were re-examined:
P. Jönsson et al. NIFS-DATA-113 (2011); ADNDT 100 (2014) 1

Fe EUV spectroscopic measurements in LHD

I. Murakami et al. Plasma and Fusion Research, 9, 1401056 (2014)

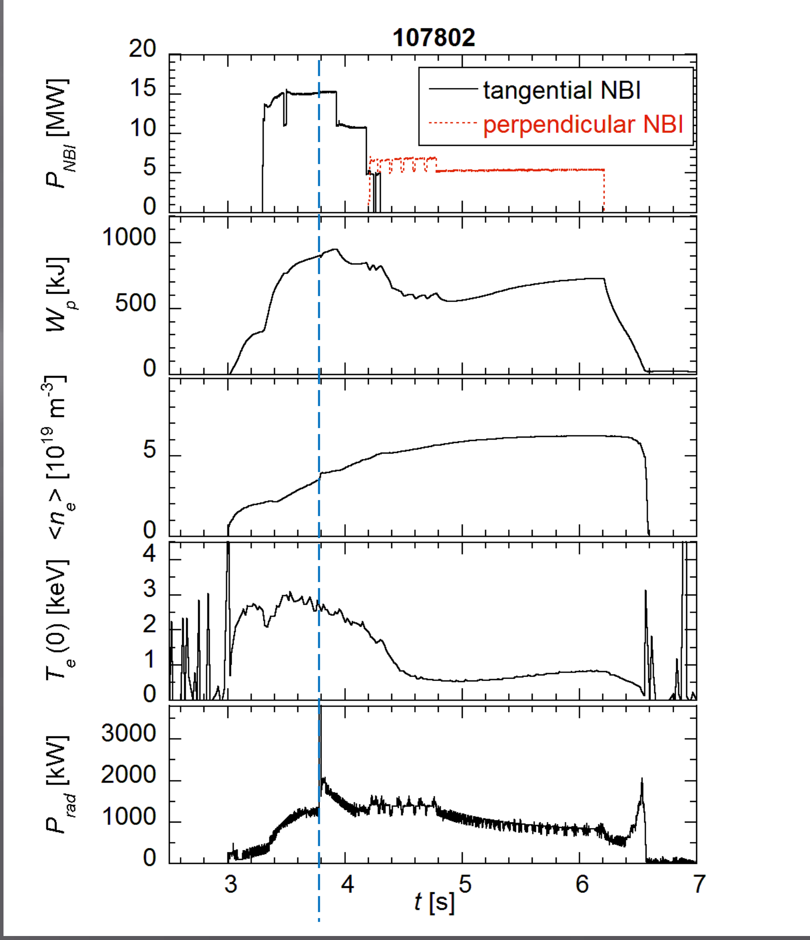
EUV spectra were measured for LHD plasmas in which small amount of Fe is injected using a tracer encapsulated pellet (TESPEL).
By controlling NBI injections, stable plasmas with central electron temperature less than 700eV were achieved, which are suitable for Fe XVII ion measurements.

Electron temperature distribution



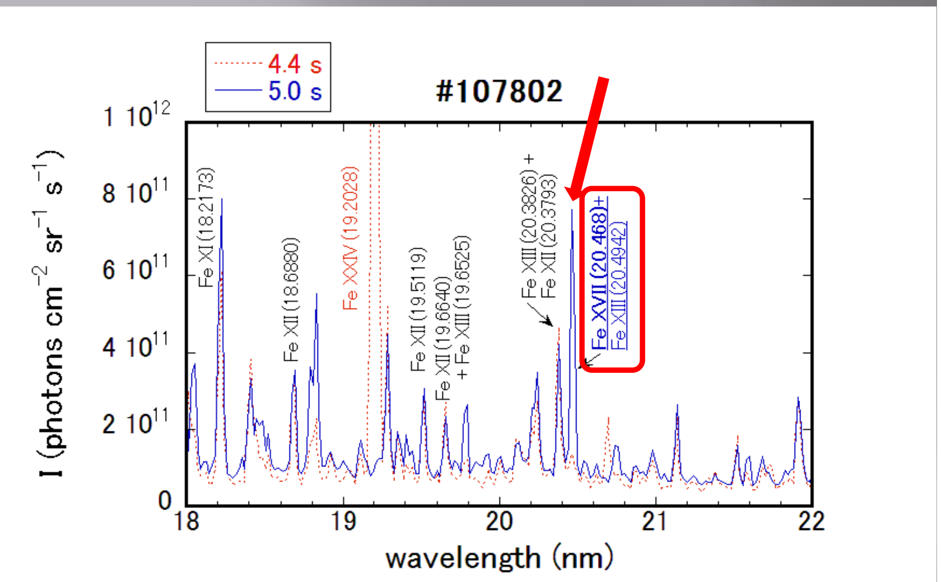
Peripheral region:
He II, Fe XI, XII, XIII

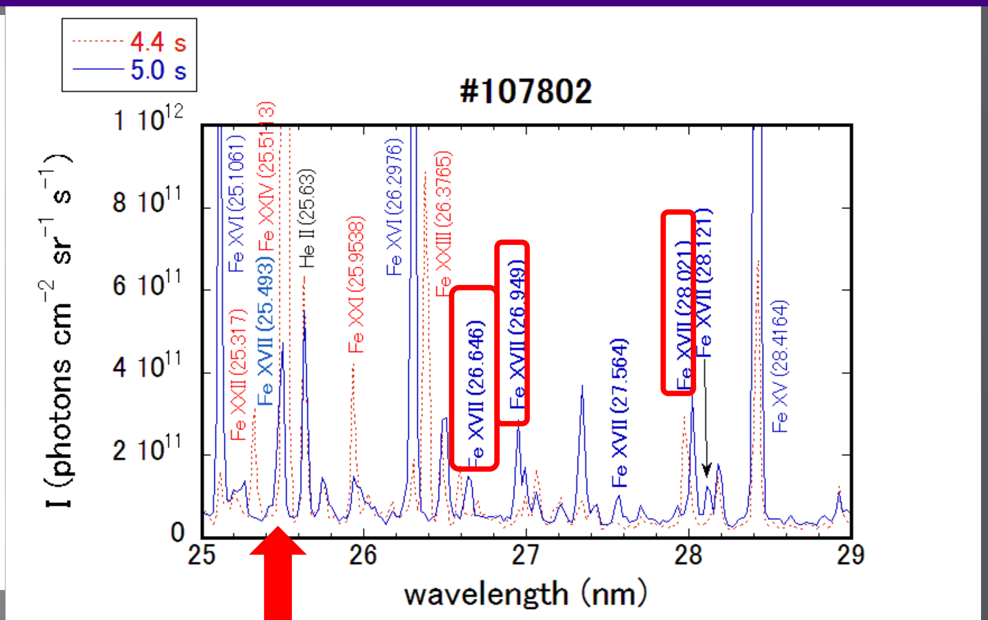
Core: Te>1keV（t<4500ms) =Fe XXIV, XXIII, XXII
Te<1keV (t>4500ms)=Fe XVII, XVI, XV

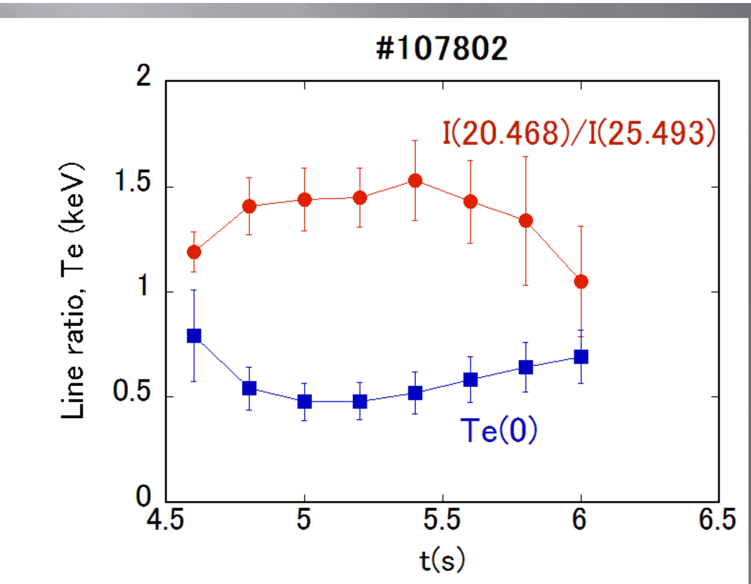


TESPEL injection at 3.8s

Fe XVII 204.6Å and 254.9Å lines were measured



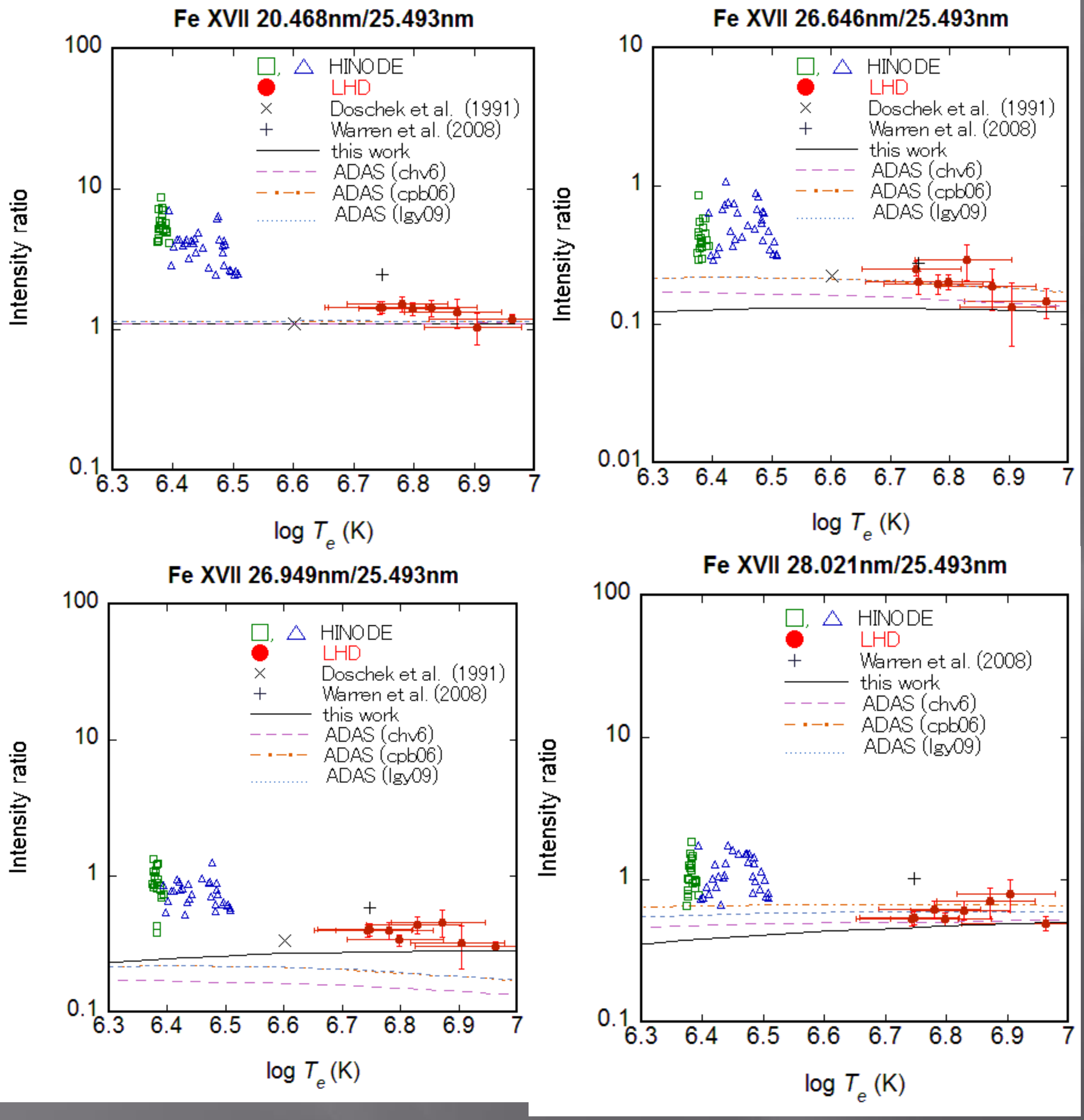




- Fe XVII lines and other Fe ion lines were measured and examined the line ratios.
- Fe XVII 20.468nm is blended with Fe XIII 20.49nm line. Subtracting the contribution of Fe XIII line with help of other Fe XII and Fe XIII lines, the average Fe XVII line ratio becomes ~ 1.12 (Watanabe et al., 2017).
- Temperature dependence is still remained and this suggests other contamination of lower temperature Fe lines.

Other Fe XVII intensity ratios

I. Murakami et al. Plasma and Fusion Research, 9, 1401056 (2014)



- Spectroscopic measurements of Fe XVII line ratios in LHD plasmas are consistent with theoretical predictions.

- Thus, the discrepancy of Hinode is not the problem of atomic physics.
  → The EIS team re-examined the sensitivity calibration (Del Zanna 2013, Warren et al. 2014)
  → The discrepancy of EIS measurements of 204/254 could be caused by the degradation of pre-flight sensitivity calibration with time.

Collaboration Network with AM physicists

- National Institute for Fusion Science (NIFS) and National Institutes of Natural Sciences (NINS) have domestic and international collaboration programs with some budgets. These help various activities related to fusion science, i.e. plasma physics, material science, PWI, atomic and molecular (AM) physics, reactor design, fusion engineering, safety study etc.
- Domestic programs support budgets on travels in Japan and some equipments. International programs support only for travels.
- We organize several collaboration projects on AM data, spectroscopy, and PWI for fusion science, astrophysics, and applied physics.

Collaboration Network

Spectroscopy with EBIT
Univ. Electro-Communications.
Toyama Univ.

Atomic structure (theory)
Sophia Univ., NWNU (China),
Vilnius Univ. (Lithuania)
Malmö Univ. (Sweden)

CX Cross Sec.
Tokyo Metropolitan Univ.,
Niigata Univ., Kyoto Univ.,
Kinki Univ., Nara Women's Univ.

CX Cross Sec. (theory)
Lebedev (Russia)
IAPCM Beijin (China)

CR model
Shinshu Univ., QST
NWNU (China)

Dissociation Cross Sec.
Toho Univ., Nara Women's Univ.

NIFS

e + Molecule Cross Sec.
Sophia Univ.

Plasma Spectroscopy
Kyoto Univ., QST
ASIPP, SWIP (China)

Sputtering, reflection
Toho Univ., Toyo Univ.,
Doshisha Univ., Kobe Univ.

Laser Plasma Spectroscopy
Utsunomiya Univ., Osaka Univ.
Univ. Coll. Dublin (Ireland)

H permeation of SUS
Toho Univ.

AM database update
Tokyo Inst. Tech.
+ many

Summary

- Evaluation on atomic data and CR models are important. We have carried out the evaluations for Fe ions by experiments using CoBIT and LHD under domestic collaboration projects and by theoretical studies as international collaboration.
- Collaboration network with AM physicists and plasma physicists have been established even with small budgets from NIFS/NINS. Collaboration programs are helpful to keep activities on AM data production and evaluation.

Thank you for your attention.