Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

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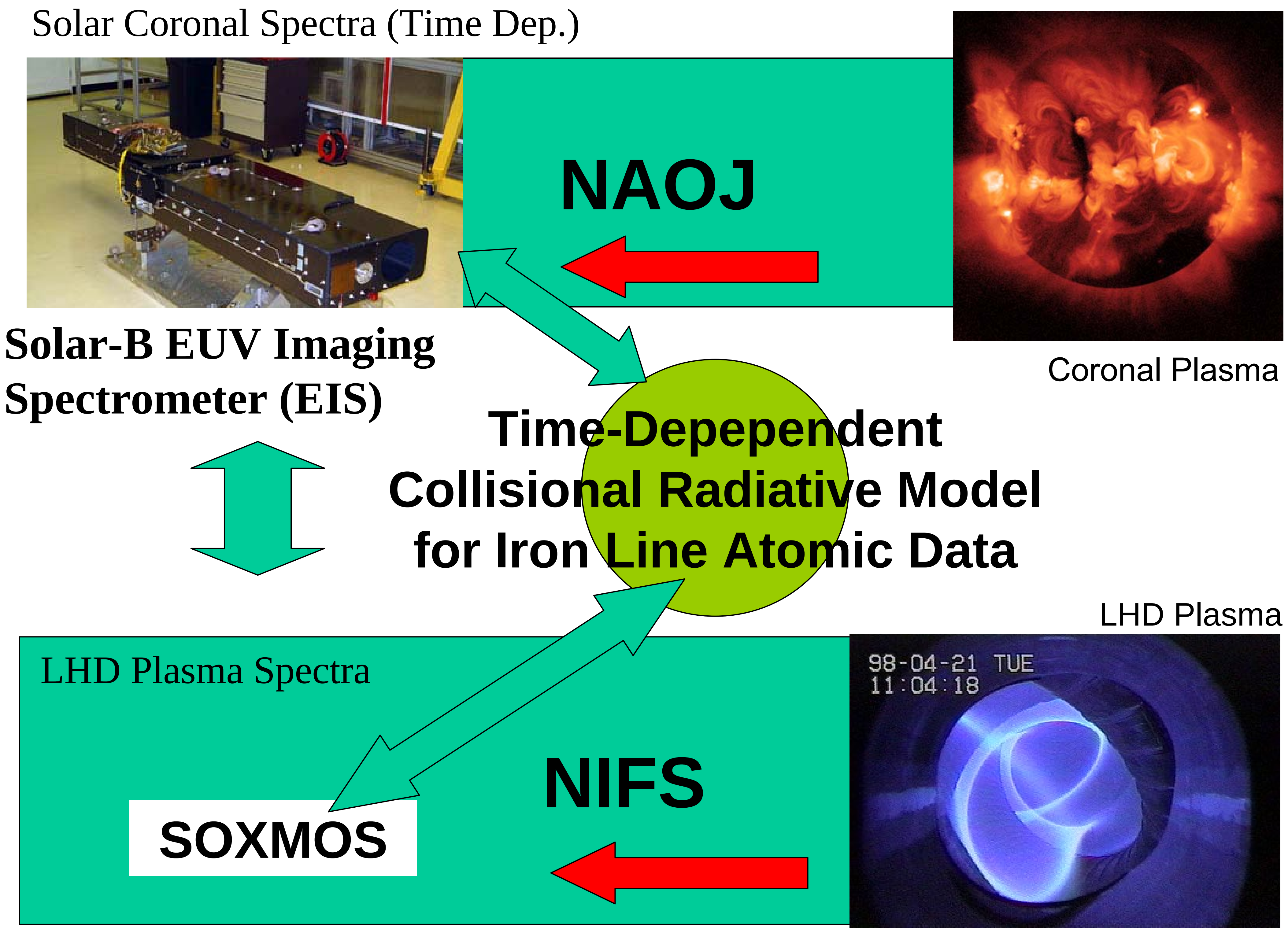

Solar Coronal Spectra (Time Dep.)
NAOJ
Coronal Plasma
Solar-B EUV Imaging Spectrometer (EIS)
Time-Depependent Collisional Radiative Model for Iron Line Atomic Data
LHD Plasma
LHD Plasma Spectra
98-04-21 TUE
11:04:18
NIFS
SOXMOS

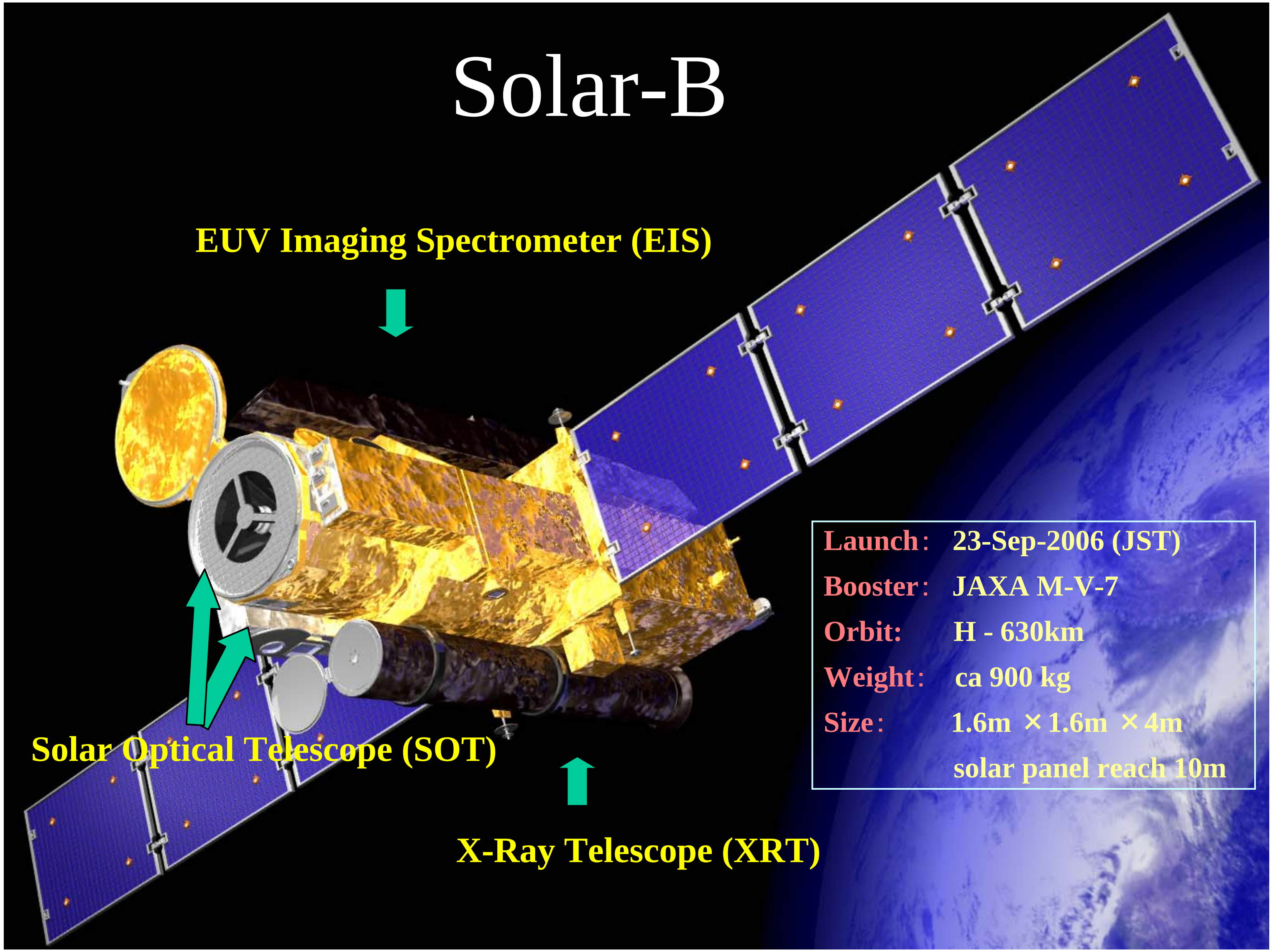
Solar-B (NAOJ) & Large Helical Device (NIFS) Iron M-shell Lines

- Solar-B EIS (NAOJ, JAXA/MSSL/BU/RAL/NRL/UO)
- Atomic Data Evaluation (NIFS)
- Time-dependent Collisional Radiative Model

  Theoretical Calculation (Yamamoto et al.)
- Atomic Data Generation

  EBIS/EBIT experiment (Sakaue et al.)

Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV



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EIS SOLAR-B

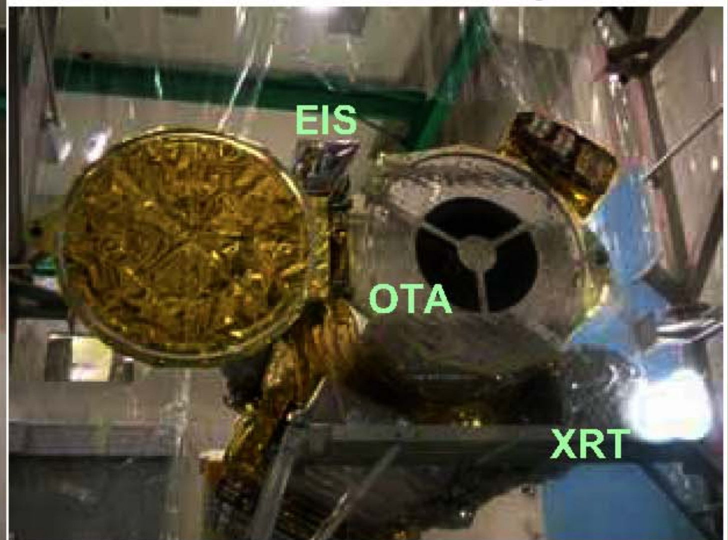
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

NINS NAOJ LHD NIFS

Launch : 23-Sep-2006 6:36am (JST)

OTA: Optical Telescope Assmbly

FPP: Focal Plane Package



XRT : X-ray Telescope

EIS : EUV Imaging Spectrometer

M-V Booster

Uchinoura Space Centre / JAXA

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Solar and LHD (Large Helical Device)
Plasma Diagnostics in EUV

Uchinoura Space Centre

Tetsuya Watanabe (NAOJ) et al.

Uchinoura Space Centre

Hinode (sunrise; “he-know-day”)

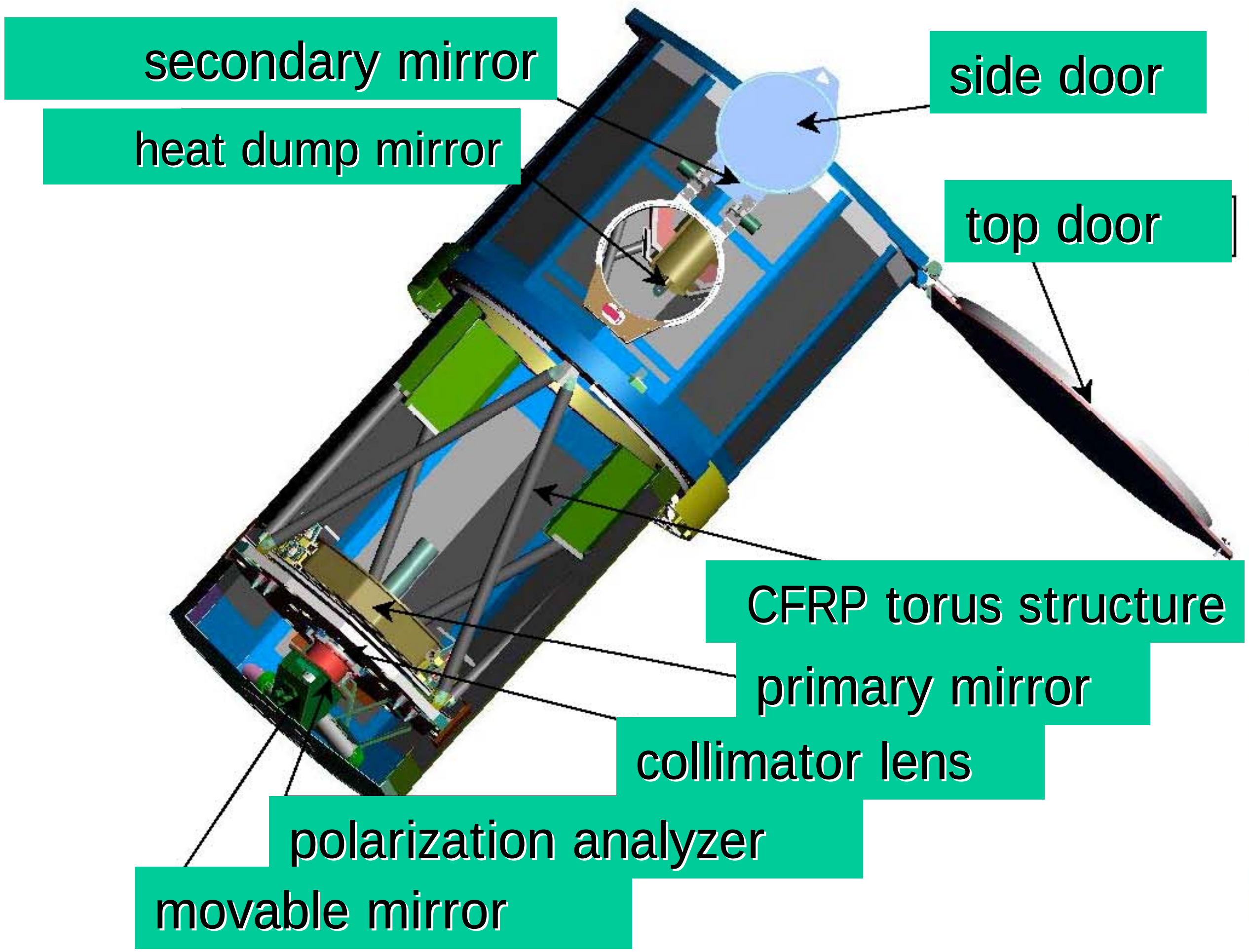
• Epoch:	2006/10/3 18:00:00UTC
• semi-major axis :	7059.706 km
• eccentricity :	0.0000
• inclination :	98.090 deg
• altitude of perigee :	678.452 km
• altitude of apogee :	684.682 km
• period :	98.387 min

Opening of Telescope Doors (schedule)

- SOT side door; 14-Oct – done!
  top door; 25-Oct
- XRT top door; 27-Oct
- EIS clamshell-front door; 27-Oct
  clamshell-rear door; 28-Oct

SOT

Optical Telescope Assembly (OTA)



SOT

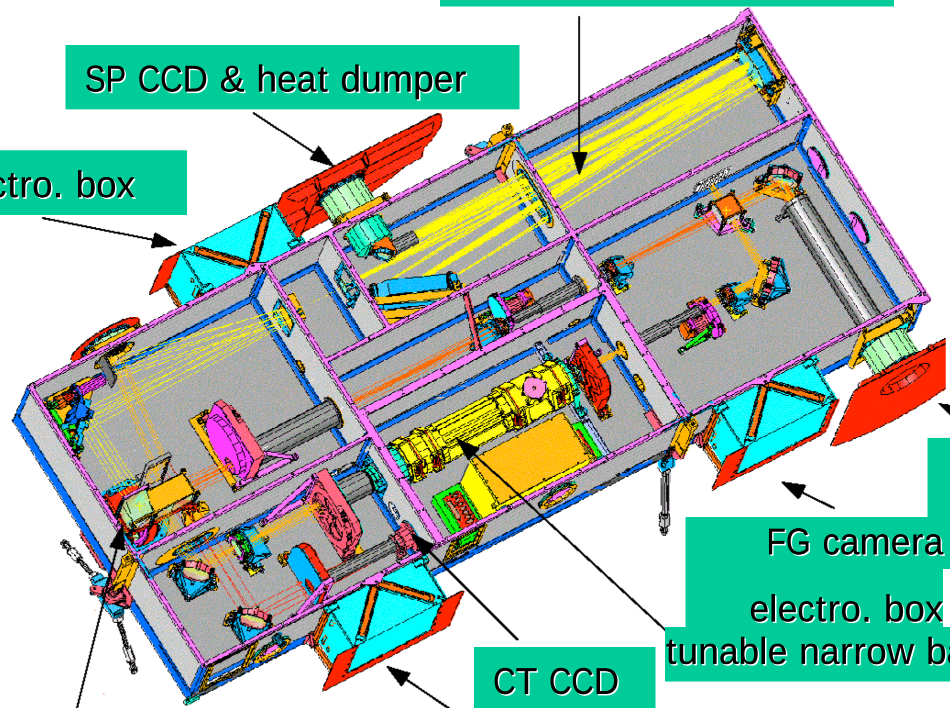
Focal Plane Package (FPP)

Filtergraph (FG)

high time-resolution 2D pictures + 3D magnetic fields in 12 wavelengths

Spectropolarimeter (FPP)

detailed spectro-polarimetry of FeI absorption line at 630nm for 3-D structures of photospheric magnetic fields



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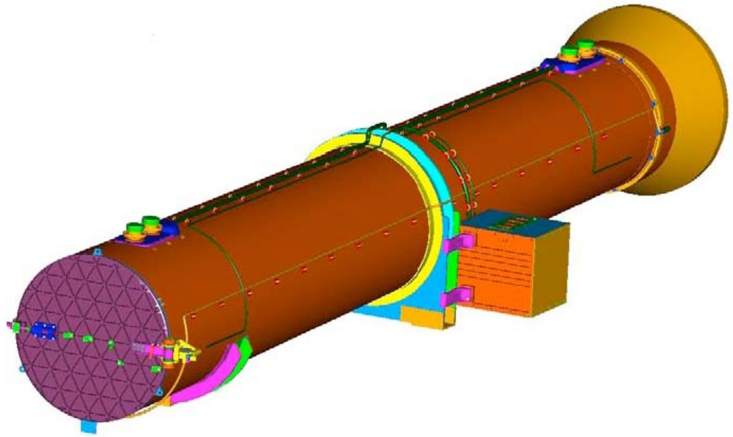
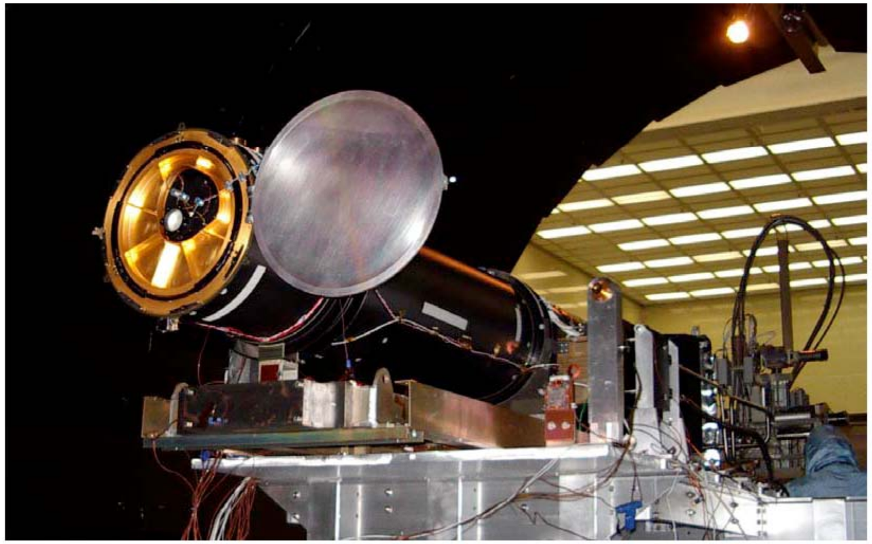
X-Ray Telescope (XRT)

Takes X-ray images of dynamically changing solar coronal structures



- grazing-incidence telescope + 2k x 2k – pixel CCD to take X-ray images of solar corona
- angular resolution 1” (x 3 better than *Yohkoh*
- Seeing plasma with temperatures 1 - 10 MK.



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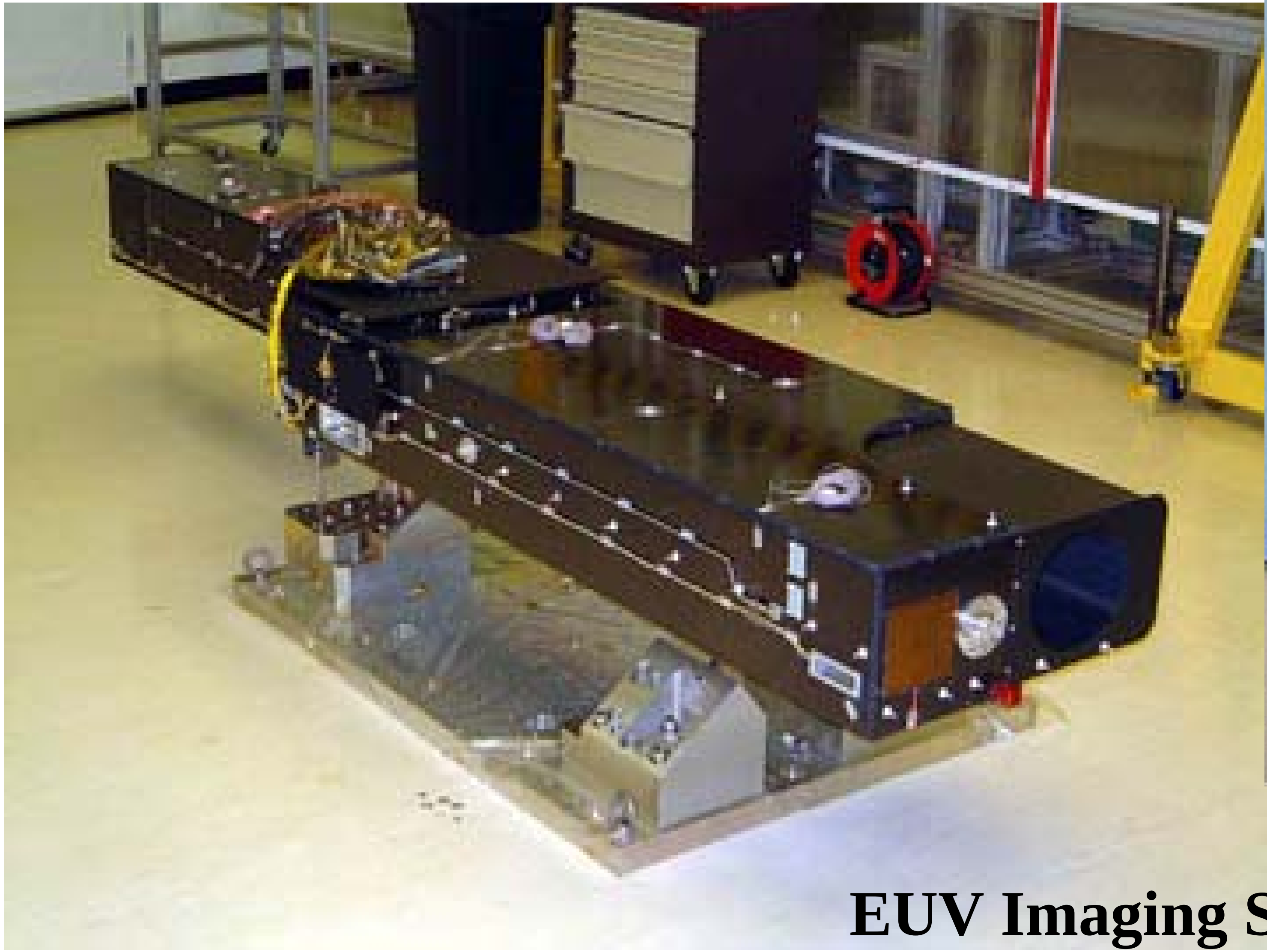

EUV Imaging Spectrometer（EIS）

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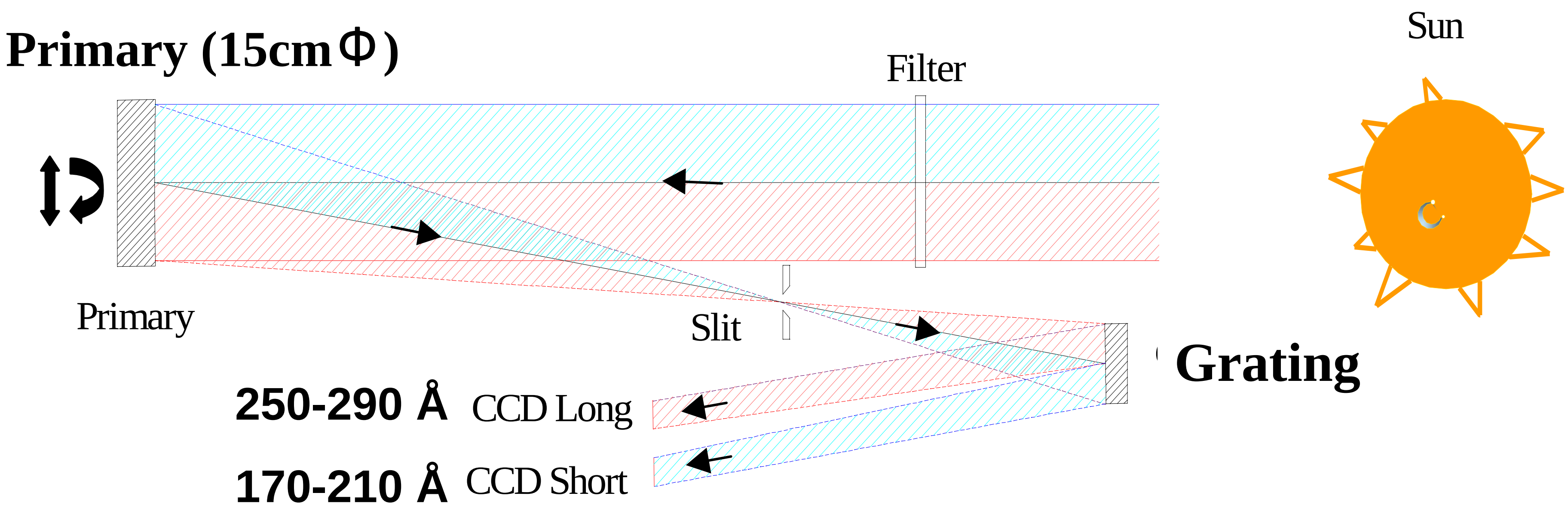
EIS Optical Path



Slit/slot; 1”, 2”, 40”, 250”

Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

FOV	Fine Mirror Scan 360 arcsec
	Slit/Slot 1”, 2 ”, 40 ”, 250” （4-positions）
	Slit length 512 arcsec (1pixel=13.5μm=1arcsec)
Min. Exp. Time	< 1 sec (sit&stare/overlappograph), ＜1.3sec
Wavelengths	170 - 210Å & 250 - 290Å
Temperature Range	$10^5 – 2 \times 10^{7\circ}$ K (via HeII ~ FeXXIV)
Density Diagnostics	$10^8 – 10^{12}$ cm^{-3} (via FeXII)
Velocity Field	Δv ~20 kms^{-1}/pix (250 – 290Å); 1000ph →
	$1kms^{-1}$ (line center) , $3kms^{-1}$ (line width)

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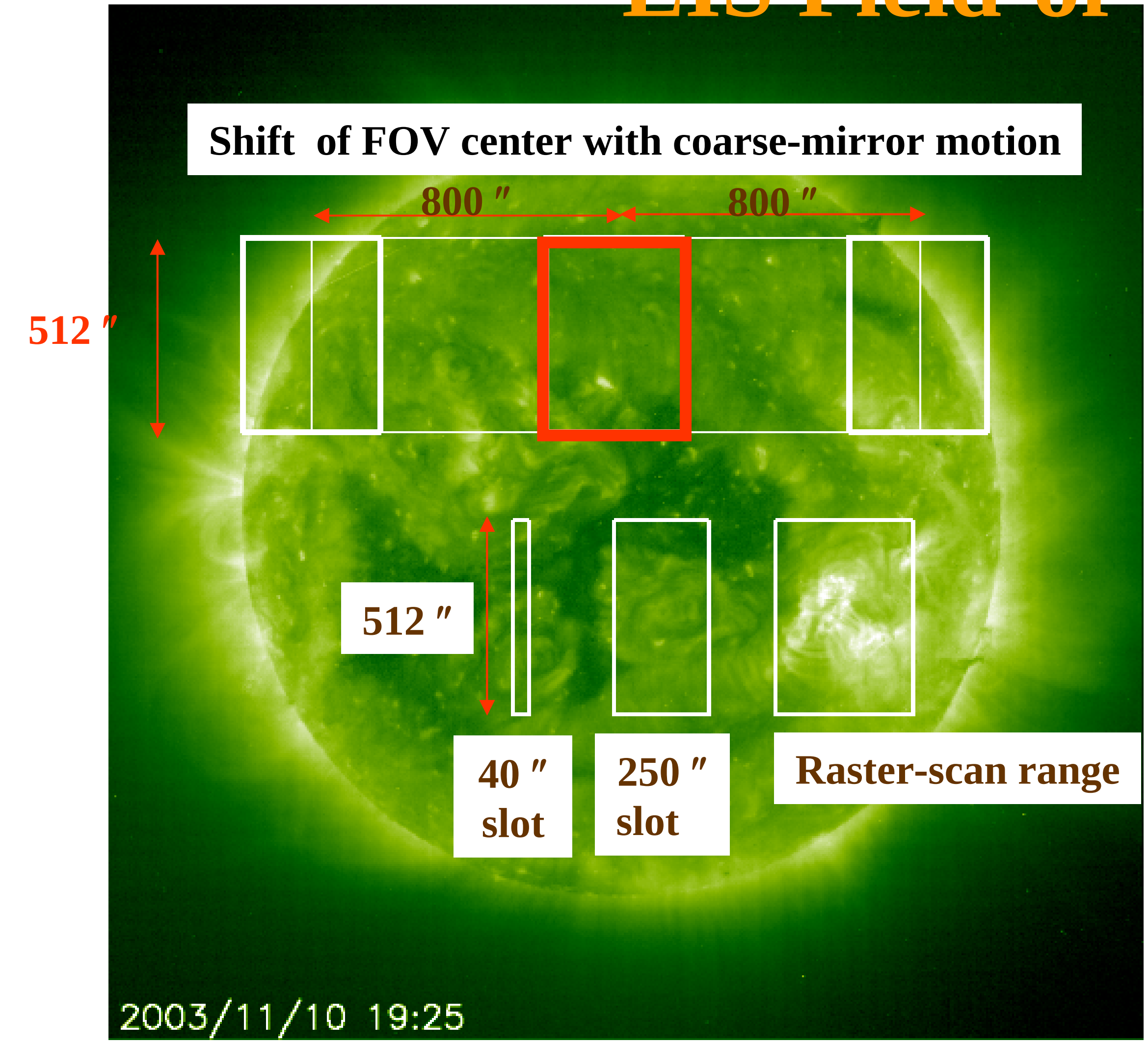
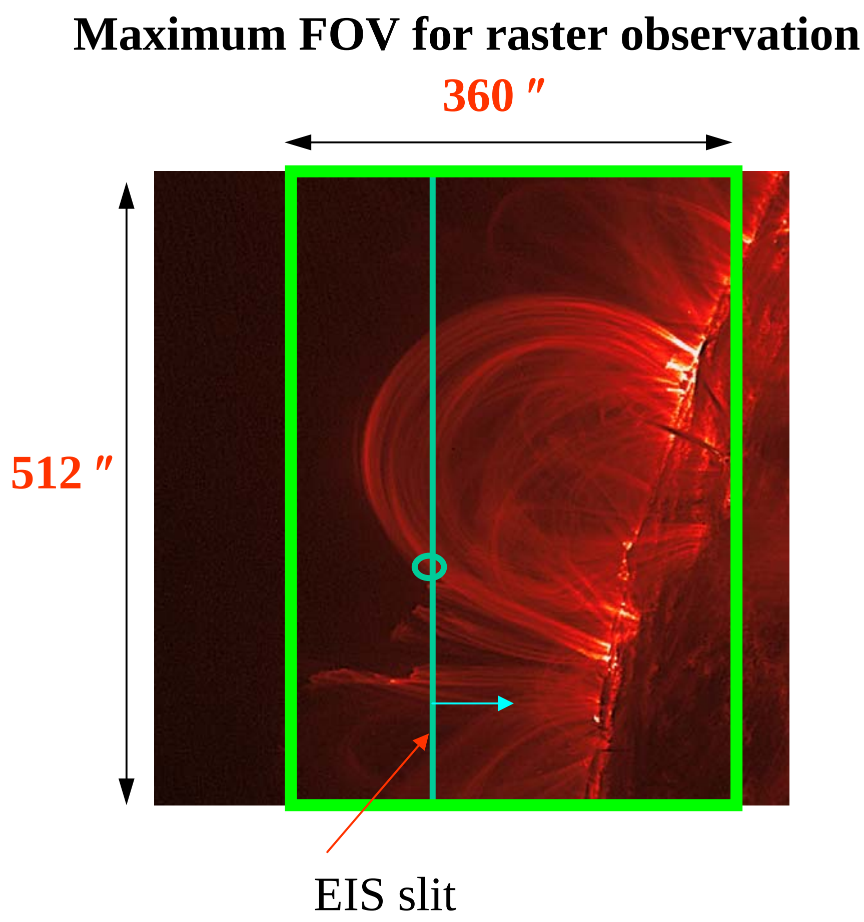
EIS Field-of-View (FOV)





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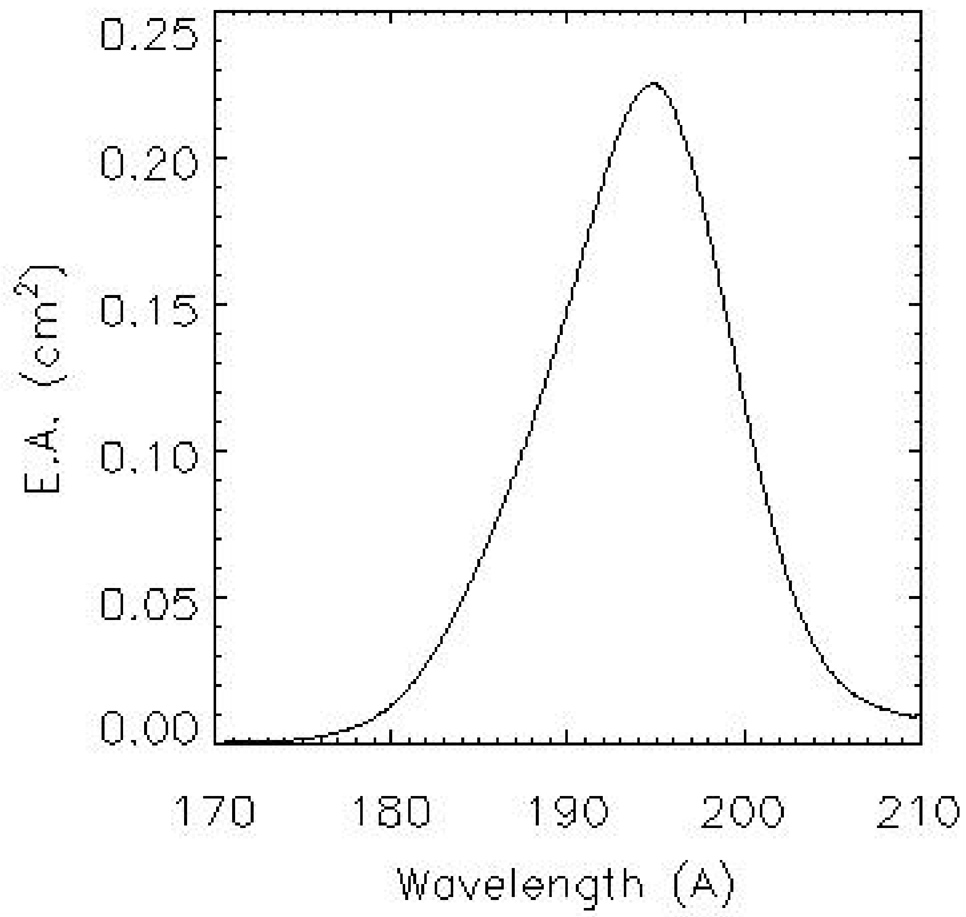
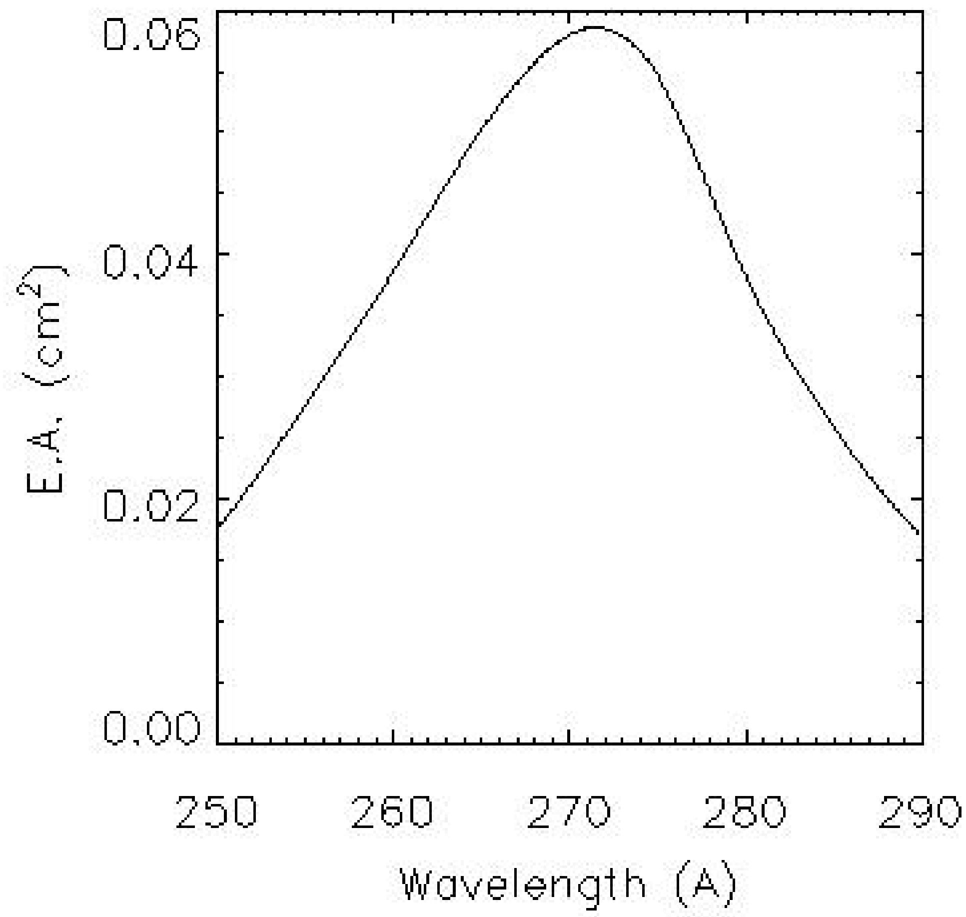
EIS Effective Area





Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

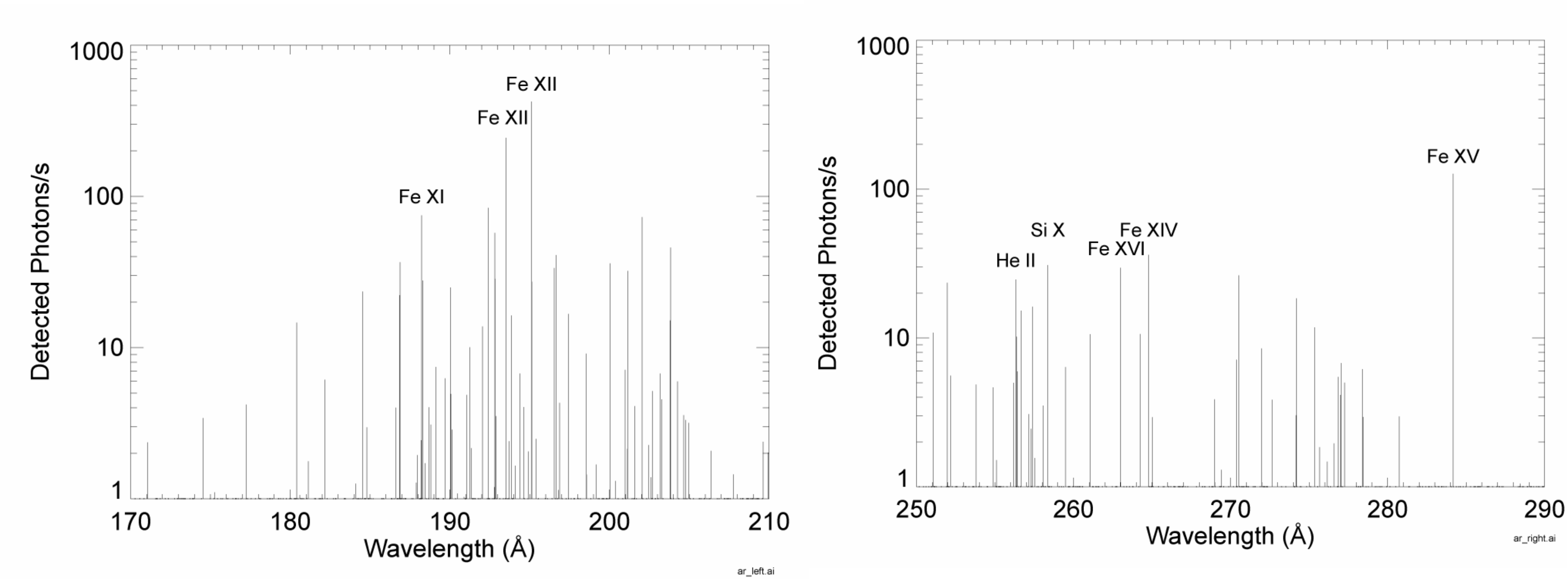
Ion	Wave	T	Incident	Detected
Short Wavelength Band				
Fe XI	180.41	6.11	690.49	14.62
Fe X	184.54	6.00	286.53	23.47
Fe XII	186.85	6.11	142.80	22.20
Fe XII	186.88	6.11	233.69	36.61
Fe XI	188.23	6.11	359.34	74.79
Fe XI	188.30	6.11	131.76	27.77
Fe X	190.04	6.00	89.48	24.95
S XI	191.27	6.20	31.00	10.04
Fe XXIV	192.04	7.30	39.46	13.78
Fe XII	192.39	6.11	233.45	83.94
Ca XVII	192.82	6.70	154.30	57.24
Fe XI	192.83	6.11	76.80	28.51
Fe XII	193.52	6.11	631.78	244.11
Ca XIV	193.87	6.51	41.57	16.31
Fe XII	195.12	6.11	1052.18	424.08
Fe XII	195.13	6.11	67.64	27.26
Fe XIII	196.54	6.20	86.19	33.58
Fe XII	196.65	6.11	105.45	40.83
Fe XIII	197.43	6.20	45.80	16.67
Fe XIII	200.02	6.20	155.95	36.00
Fe XIII	201.13	6.20	192.59	32.15
Fe XIII	202.04	6.20	591.85	72.96
Fe XIII	203.80	6.20	208.79	15.09

Ion	Wave	T	Incident	Detected
Fe XIII	203.83	6.20	638.82	45.80
Long Wavelength Band				
Fe XVI	251.07	6.40	188.12	10.84
Fe XIII	251.96	6.20	387.52	23.48
He II	256.32	4.70	328.81	24.69
He II	256.32	4.70	164.40	12.34
Si X	256.38	6.11	135.28	10.18
S XIII	256.68	6.40	199.87	15.23
Fe XIV	257.38	6.30	207.85	16.23
Si X	258.37	6.11	382.83	30.83
Si X	261.06	6.11	123.07	10.58
Fe XVI	262.98	6.40	331.16	29.55
S X	264.23	6.11	116.73	10.62
Fe XIV	264.78	6.30	394.57	36.15
Fe XIV	270.51	6.30	291.23	26.31
Fe XIV	274.20	6.30	241.91	18.46
Si VII	275.35	5.80	166.99	11.76
Fe XV	284.16	6.30	4063.11	126.55

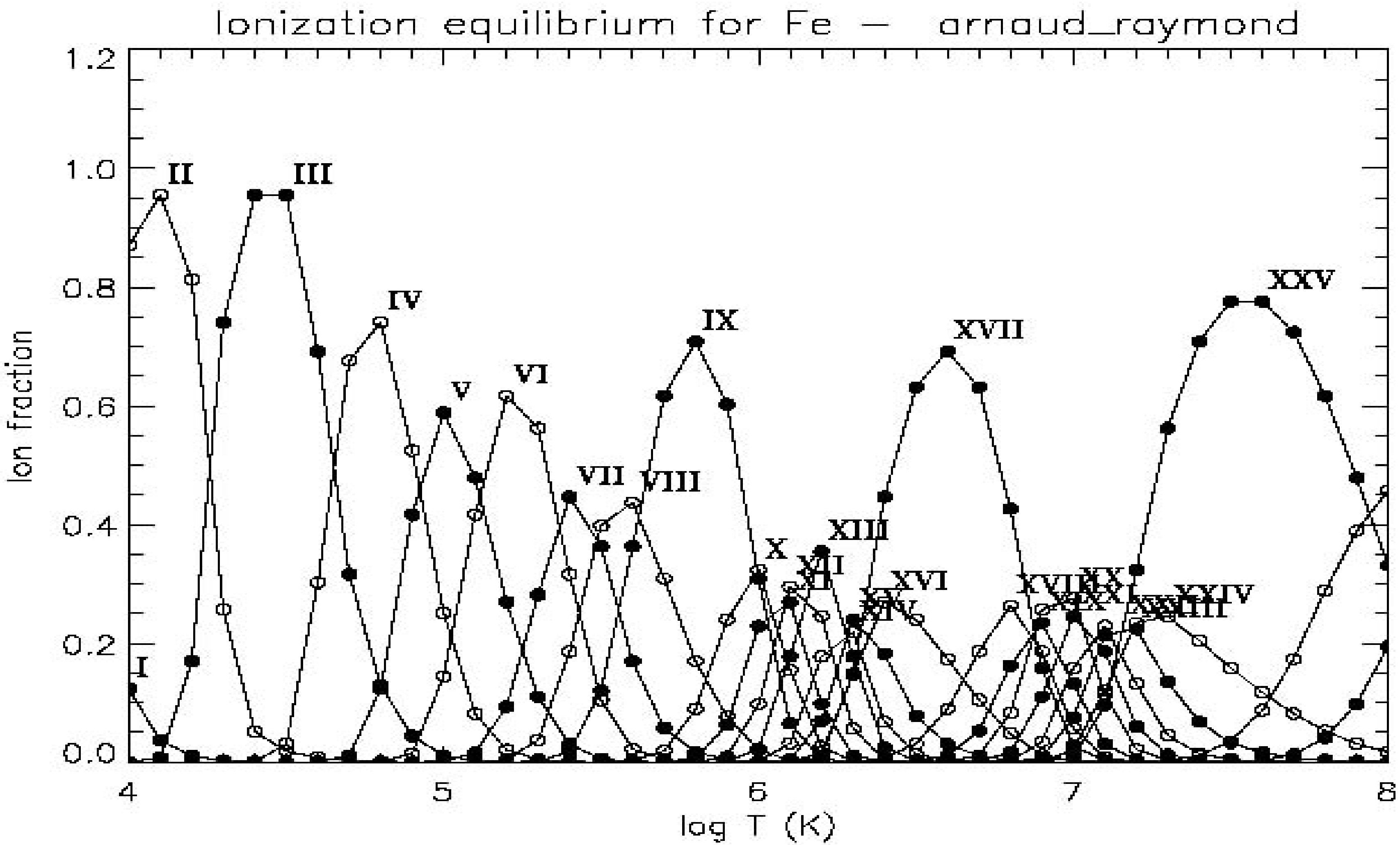
Active Region

Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Active Region



Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV



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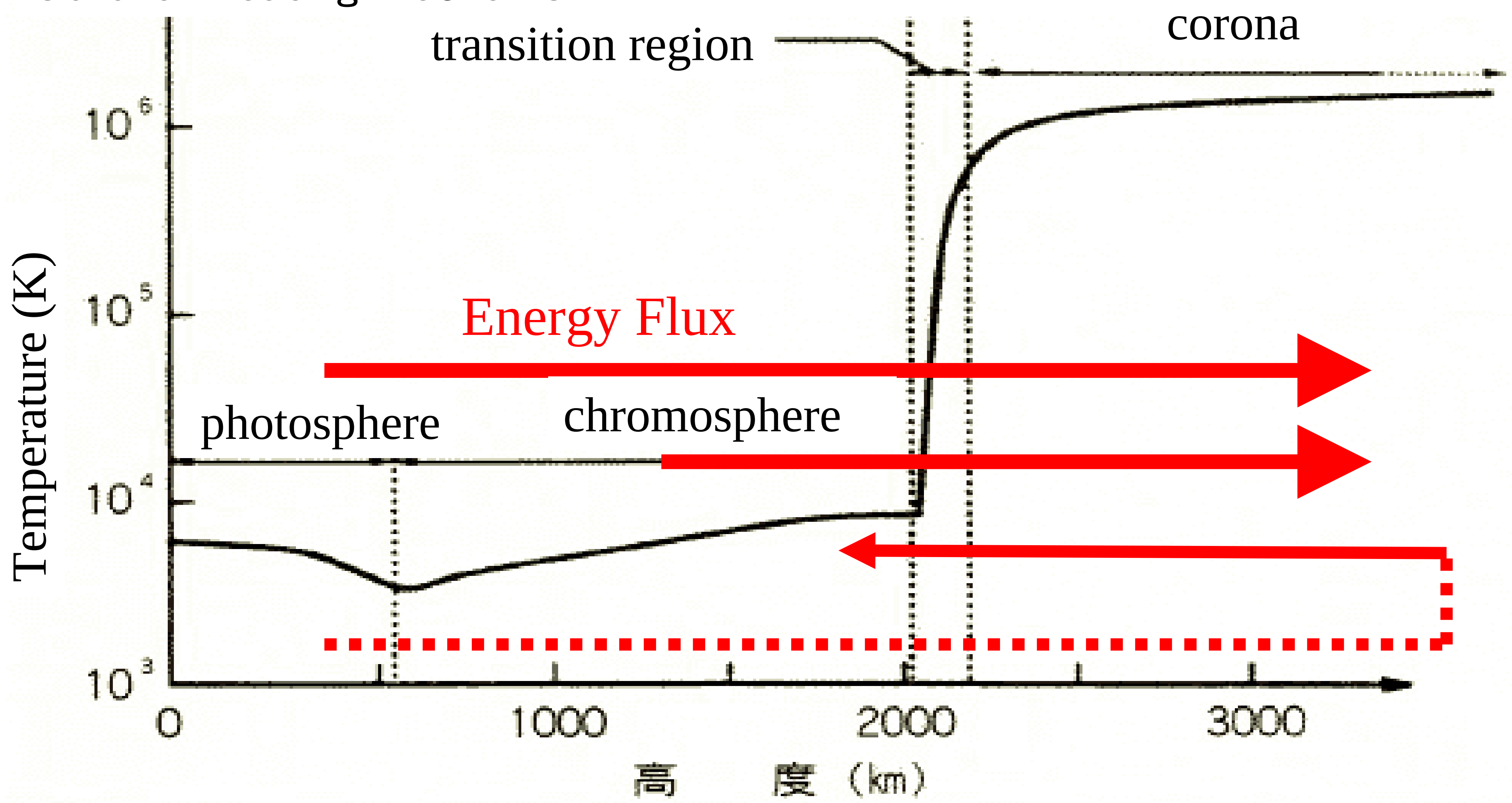
Coronal Heating Mechanism



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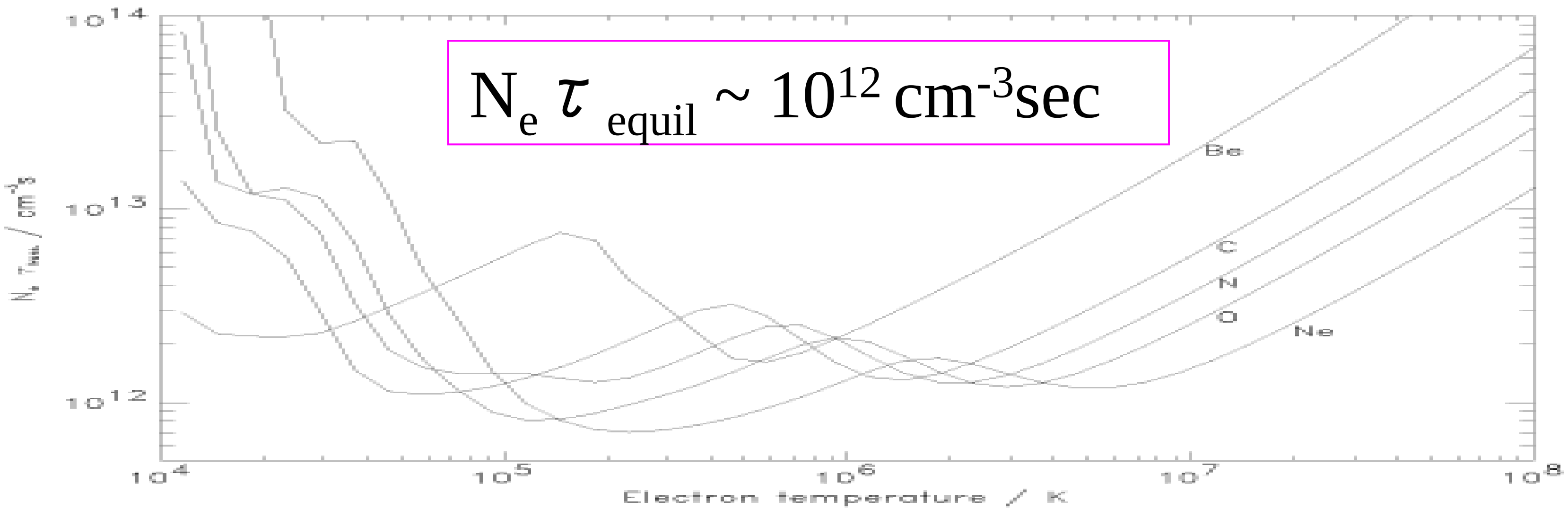
Ionization Equilibrium; Relaxation Time Scales



Brooks et al. (1999)

	$N_e (cm^{-3})$	$T_e (K)$	$\tau_{transient}$
upper chromosphere	3.7×10^{10}	2×10^4	$\sim 5 \rightarrow 6$ minutes
transition region	$1.3 \times 10^{10} \rightarrow 1.3 \times 10^9$	$5 \times 10^4 \rightarrow 5 \times 10^5$	$\sim 3 \rightarrow 20$ min utes
corona	5.4×10^8	1×10^6	~ 1 hour

Iron M-shell Line Atomic Data Evaluation

Fe X, Fe XI, Fe XIII

- Survey existing data
- Method of Calculation
- Pick up Recommended data
- Analytical fitting (only) for Fe XIII

FeXIII

Fawcett & Mason (1989)

SuperStructure, 48 levels, Distorted Wave

Gupta & Tayal (1998)

26 levels, Semirelativistic R-matrix (Breit-Pauli approximation) , partial waves with J ≦22.5, E<60Ryd

Tayal (2000)

26 levels, Breit-Pauli R-matrix, E<90Ryd, partial waves with J≦22.5, 0.005Ryd mesh

Aggarwal & Keenan (2005)

GRASP, 97 levels, Dirac Atomic R-matrix, E<120Ryd, partial waves with J≦39.5; 0.001-0.002Ryd mesh

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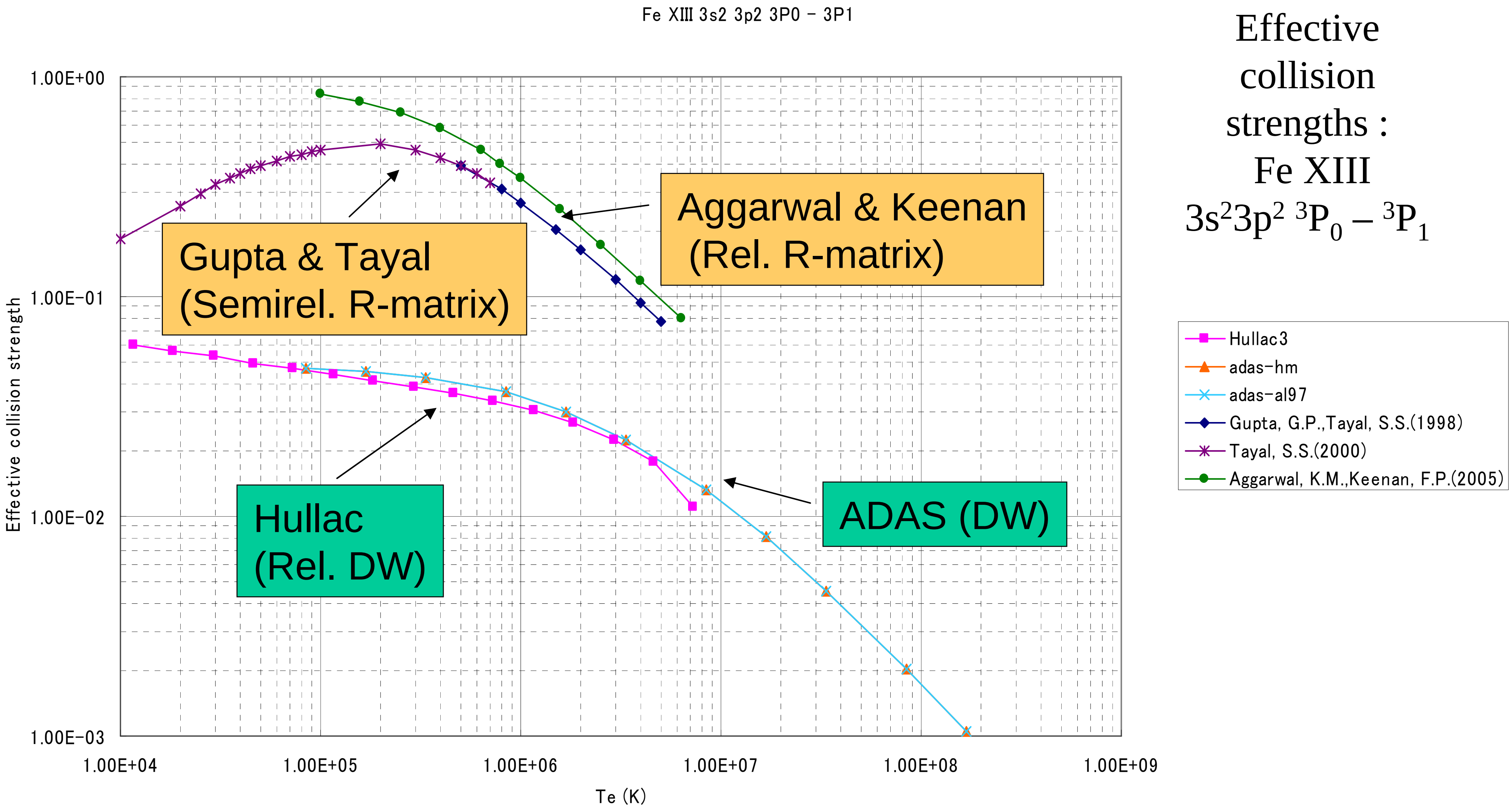

Effective collision strengths : Fe XIII $3s^2 3p^2\ ^3P_0 - {}^3P_1$

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RESULTS

Electron-Ion Collisions

Fe X

➢**Aggarwal, K. M., & Keenan, F. P., A&A, 439, 1215 (2005)**

fully relativistic approach based on GRASP code for the generation of wavefunctions, and the Dirac Atomic *R*-matrix Code (DARC) for the computations collision and effective collision strengths. Calculations are in the *jj* coupling scheme, and Breit and QED corrections have been included.

Advantages of this work:

- **significantly improved the accuracy of energy levels, radiative rates and collision strengths, by including extensive CI and performing the calculations in the *jj* coupling.**
- **improving the accuracy of Ω values by extending the range of partial waves and by achieving convergence in values of Ω at all energies and the energy range considered**
- **improving the Γ values by resolving resonances in a finer energy mesh and by including additional resonances**
- **extending the range of levels and including many of the desired levels among which the transitions have already been observed**

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Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Fe X

The results presented in paper Aggarwal & Keenan have obvious advantages in comparison with all earlier results.

In comparison with the work Bhatia & Doschek, these calculations have significantly improved the accuracy of energy levels, radiative rates and collision strengths, by including extensive CI and performing the calculations in the *jj* coupling.

In comparison to the work Tayal an overall improvement has been made by: (i) including additional CI in the generation of wavefunctions, and thus improving the accuracy of energy levels; (ii) extending the range of levels from 54 to 90, and hence including many of the desired levels among which the transitions have already been observed; (iii) improving the accuracy of Ω values, by extending the range of partial waves (from 20 to 39) and the energy range (from 90 Ryd to 210 Ryd); (iv) improving the Γ values by resolving resonances in a finer energy mesh and by including additional resonances; (v) performing the calculations in the *jj* coupling instead of the semi-relativistic approach in the *LSJ* coupling scheme.

Similarly, this work is an improvement over the work of Pelan & Berrington mainly by extending the range of levels (transitions) from 31 (465) to 90 (4005), and by achieving convergence in values of Ω at all energies.

We recommend to use for Fe X data of Aggarwal & Keenan.

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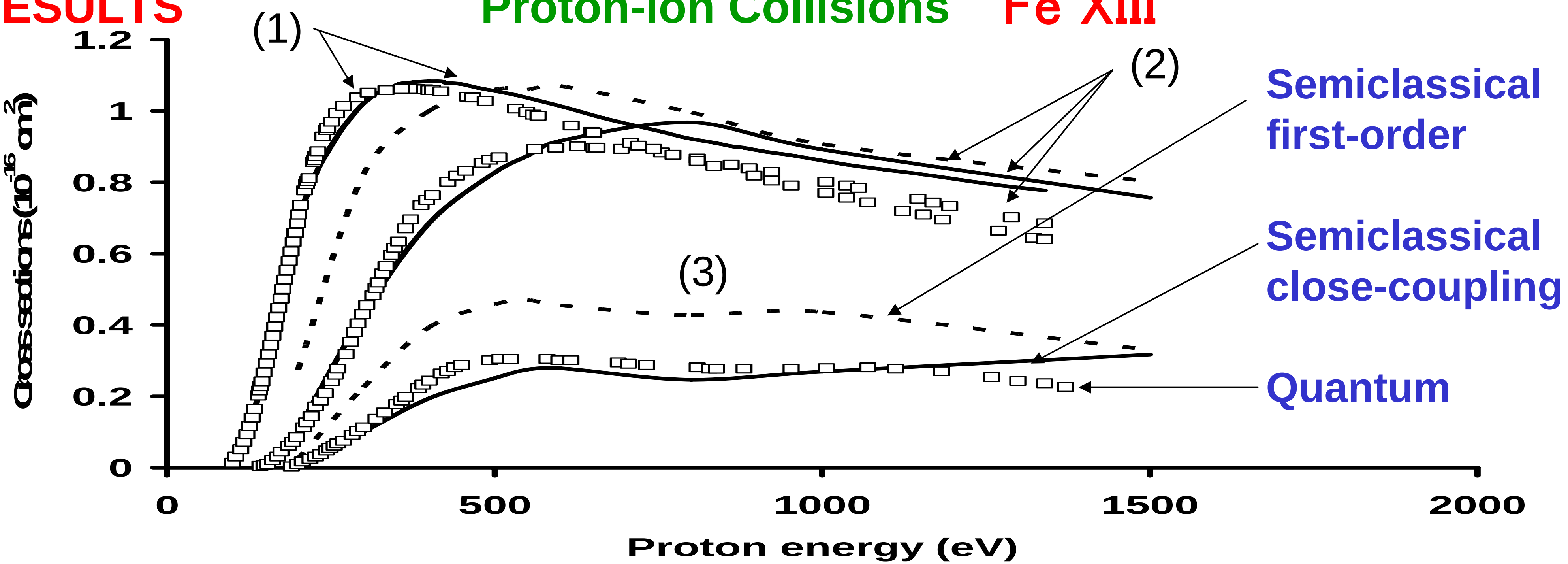
RESULTS

Proton-Ion Collisions Fe XIII



Proton excitation cross sections for transitions in Si-like Fe XIII: □ - quantum results [Faucher 1977], solid line - semi-classical results [1Landman 1975], dotted line – semi-classical results [Masnou-Seeuws & McCarroll 1972]; (1) – transition $^3P_0$-$^3P_1$, (2) – transition $^3P_1$-$^3P_2$, (3) – transition $^3P_0$-$^3P_2$.

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RESULTS Proton-Ion Collisions

General conclusion:

In **low density** plasma $N_e \leq 10^{16}$ cm^{-3} proton collisions are Important for ions: **Fe X, XI, XIII, XIV, XVII, XVIII, XIX, XX, XXI, XXII, XXIII.**

In **high density** plasma $N_e > 10^{16}$ cm^{-3} proton collisions are Important for ions: **Fe XV, XVII, XXII.**

$Np \sim Ne < A_i/C_i^e$

For Fe XII proton collisions are not important.

For all important transitions we have evaluated available numerical data and recommended data were fitted to analytical formula.

Collisional-radiative model -Atomic Processes &Energy Levels

Atomic Processes (*rate*)**:**

Excitation/de-excitation ($C^e N_e$) by e$^-$-impact,

Excitation/de-excitation ($C^p N_e$) by p-impact,

Ionization (SN_e) /three-body recombination ($\beta^t N_e^2$),

Radiative transition (A^r), Radiative recombination ($\beta^r N_e$)

Energy Levels (*configuration*)**: $2 \le n \le 5$**

Bare, H-like(*nl*), He-like(*1snl*), Li-like($1s^2nl$), Be-like(*2l'nl*), B-like($2s^2nl$, $2s2pnl$, $2p^2nl$), C-like($2s^22pnl$, $2s2p^2nl$, $2p^2nl$), N-like($2s^22p^2nl$, $2s2p^3nl$, $2p^4nl$), O-like($2s^22p^3nl$, $2s2p^4nl$, $2p^5nl$), F-like($2s^22p^4nl$, $2s2p^5nl$, $2p^6nl$), Ne-like ($2s^22p^5nl$, $2s2p^6nl$), Na-like($2s^22p^6nl$), Mg-like(*3l'nl*), Al-like($3s^2nl$, $3s3pnl$, $3s3dnl$, $3p^2nl$, $3p3dnl$), Si-like($3s^23l'nl$), P-like($3s^23p3l'nl$), S-like($3p^23l'nl$), Cl-like($3p^33l'nl$), Ar($3p^5nl$), K-like($3p^6nl$, $3p^53dnl$), Ca-like($3p^63dnl$)

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Collisional-radiative model (Yamamoto et al.)

Time-dependent Rate Equation:

$$\frac{dN_i(t,T_e,N_e)}{dt} = -N_i(t,T_e,N_e)\sum_j W_{ij}(T_e(t),N_e(t)) + \sum_j W_{ji}(T_e(t),N_e(t))N_j(t,T_e,N_e)$$

Quasi-steady State Solution:

$$N_i(t,T_e,N_e) = \sum_k r_i^{(k)}(T_e,N_e)N_eN_k(t,T_e,N_e)$$

Time-independent Rate Equation:

$$\frac{dr_i^{(k)}(T_e,N_e)}{dt} = -r_i^{(k)}(T_e,N_e)\sum_j W_{ij}(T_e,N_e) + \sum_j W_{ji}(T_e,N_e)r_j^{(k)}(T_e,N_e)$$

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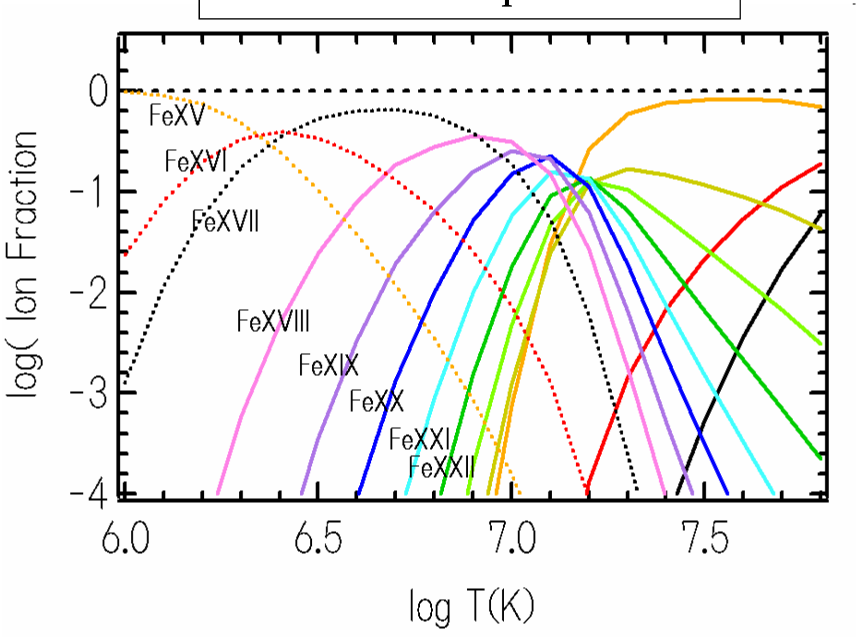
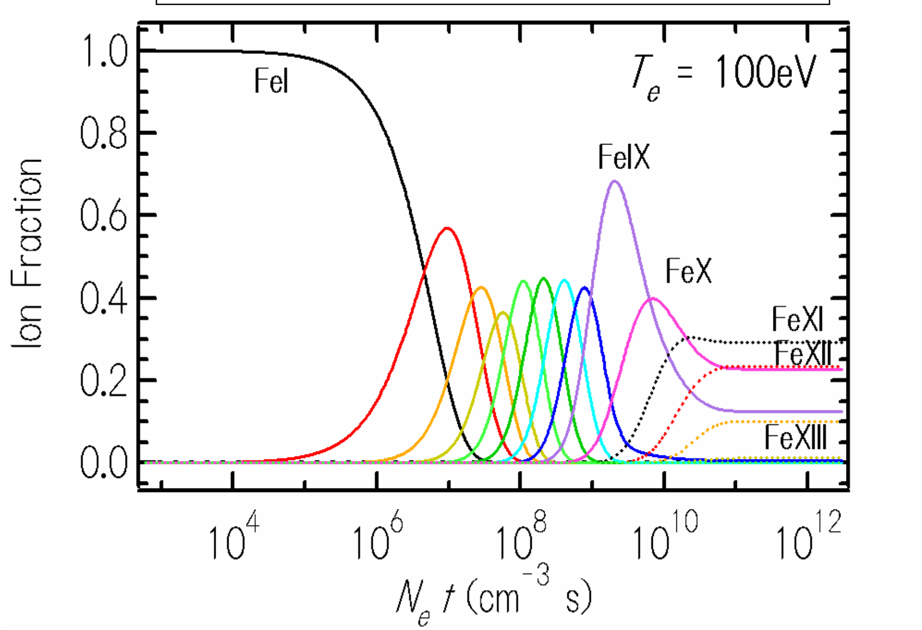
Ion Fraction N_k :

N_k is calculated to use total ionization and recombination rate coefficients, S and β, by Arnaud & Raymond (1992).

Ionization Equilibrium



Time Dependent (constant T_e)



Line Intensity $I(\lambda)$: $I(\lambda) = \sum_i N_i A^r_{ij} \Delta E_{ij} P_i(\lambda)$

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EIS SOLAR-B

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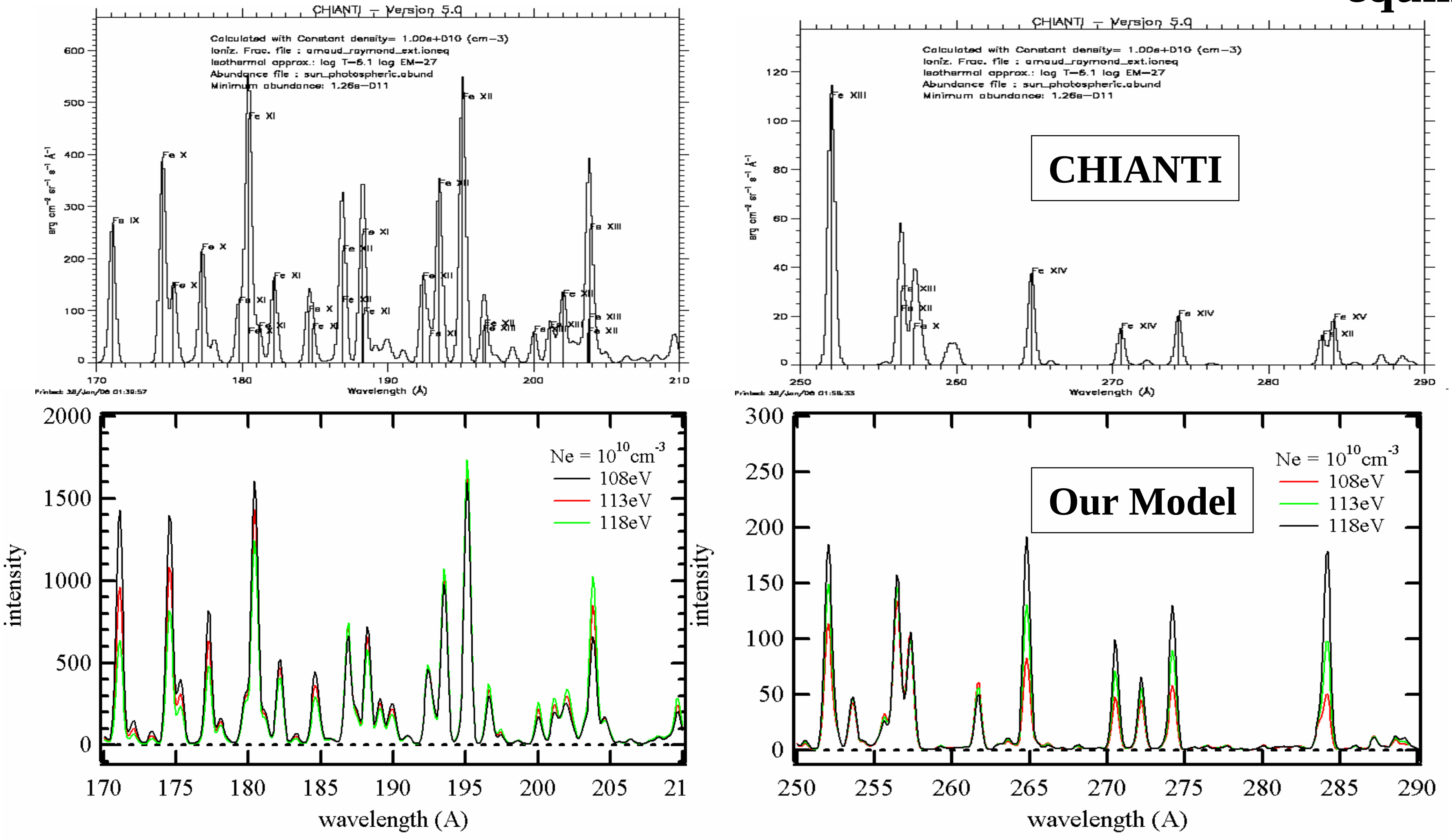
NINS LHD NIFS NAOJ

equilibrium



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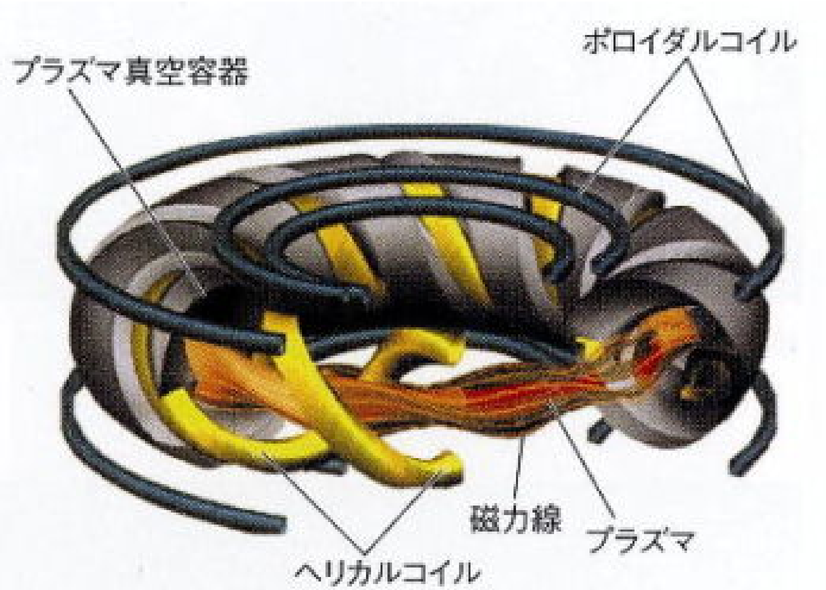
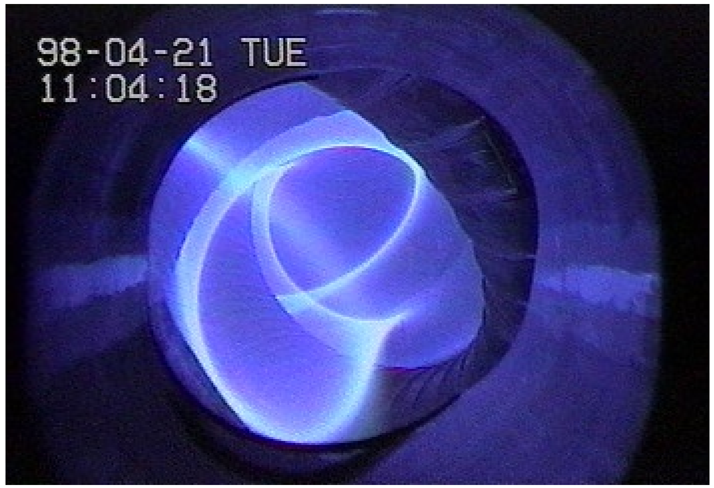


LHD experiment



Te, ne, V

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Diagnostics

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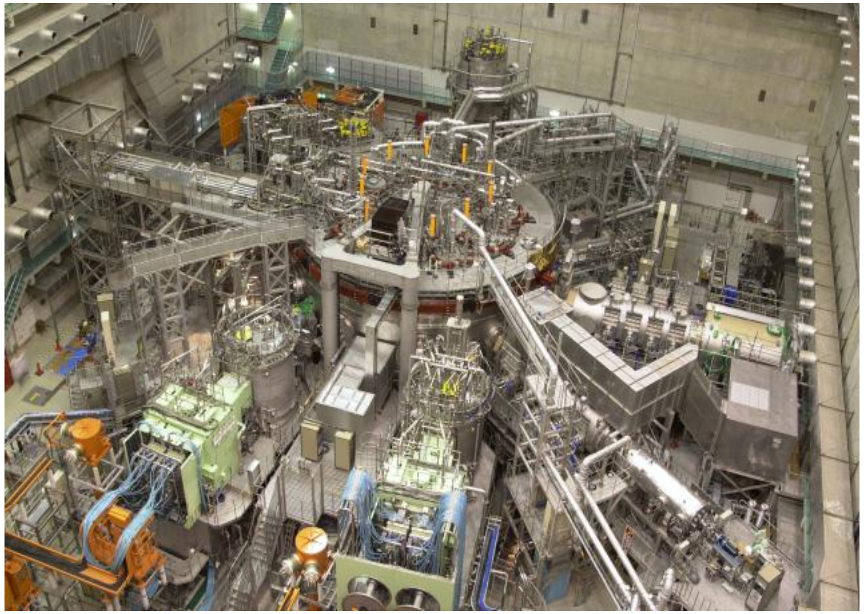

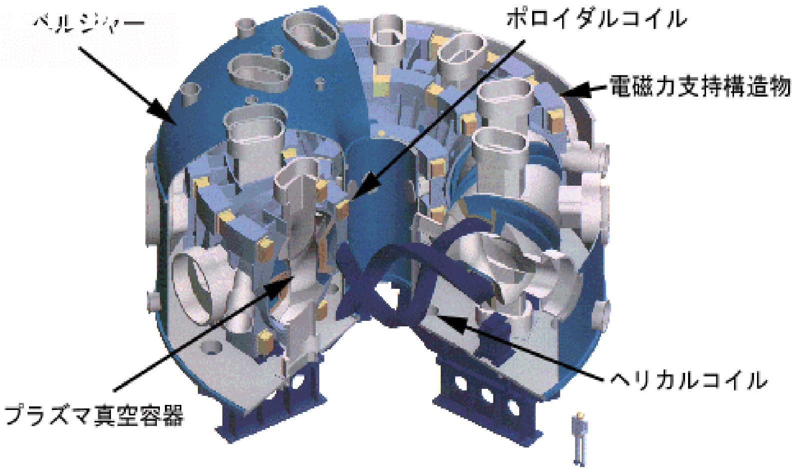

Plasma Source : Hydrogen
with *Fe-pellet* injection

Fe-TESPEL :
Polystyrene-shell Fe pellet
Pelet Radius: 780-820μm
Mass of Fe in the shell: 43-66μg
Mass of shell: 250-300μg
Injection Velocity: 300-400m/s
Injection Time: 1.0s

Plasma Heating :
NBI (neutral beam injection)
ECH (electron cyclotron resonance heating)
ICRF (ion cyclotron range-of-frequency)?

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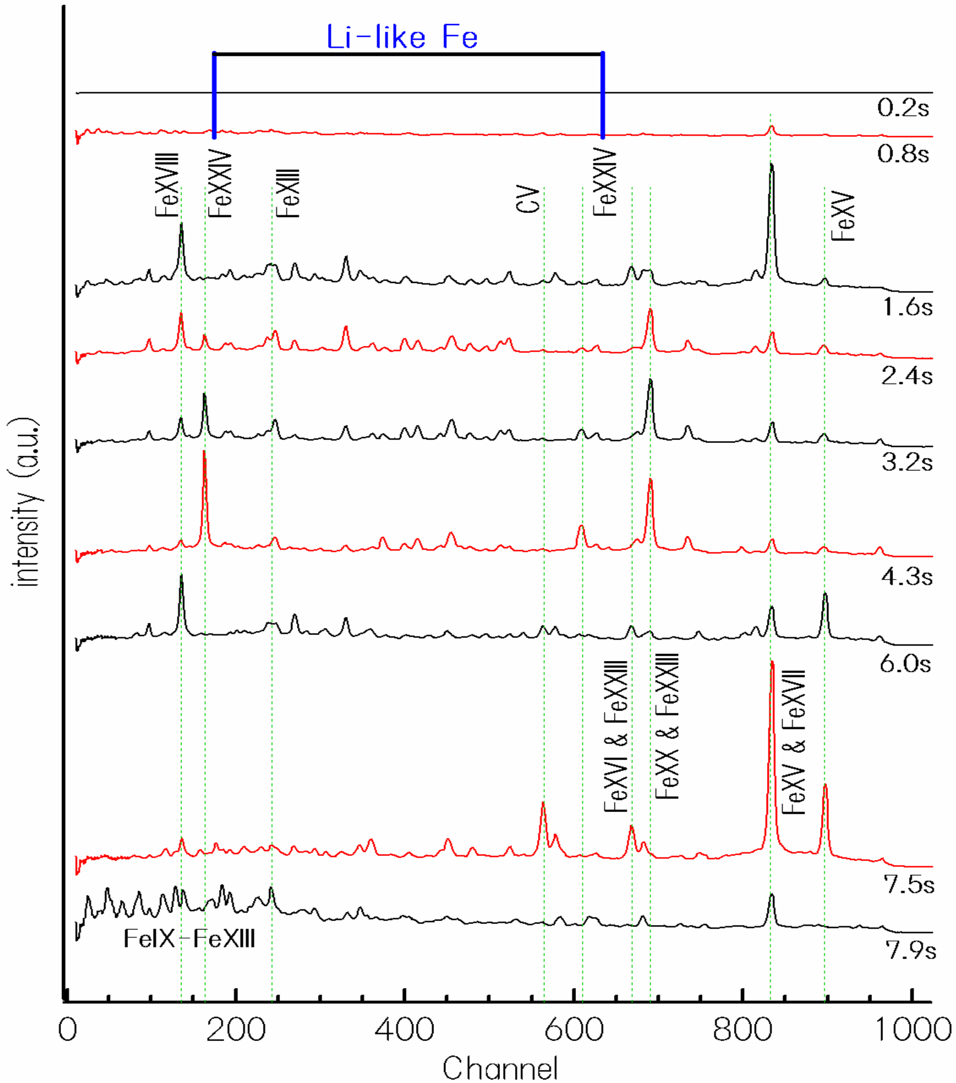
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV



Spectrometer:
- Time resolution: **0.1s**
- Wavelength resolution: **0.13A/ch**
- Total Frame: **80**
- Direction angle: **-0.1degree**
- Measurement band: **~165-300A**

Highest Temperature ?

Timing of Heating:
- ECH82.7: **0.0-1.0s**, ECH84: **5.5-6.0s**
- NBI#1: **7.0-11.0s**, NBI#2: **1.0-4.5s**,
- NBI#3: **4.0-7.0s**
- ICRF: ---

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5th ICAMDATA 17-Oct-2006

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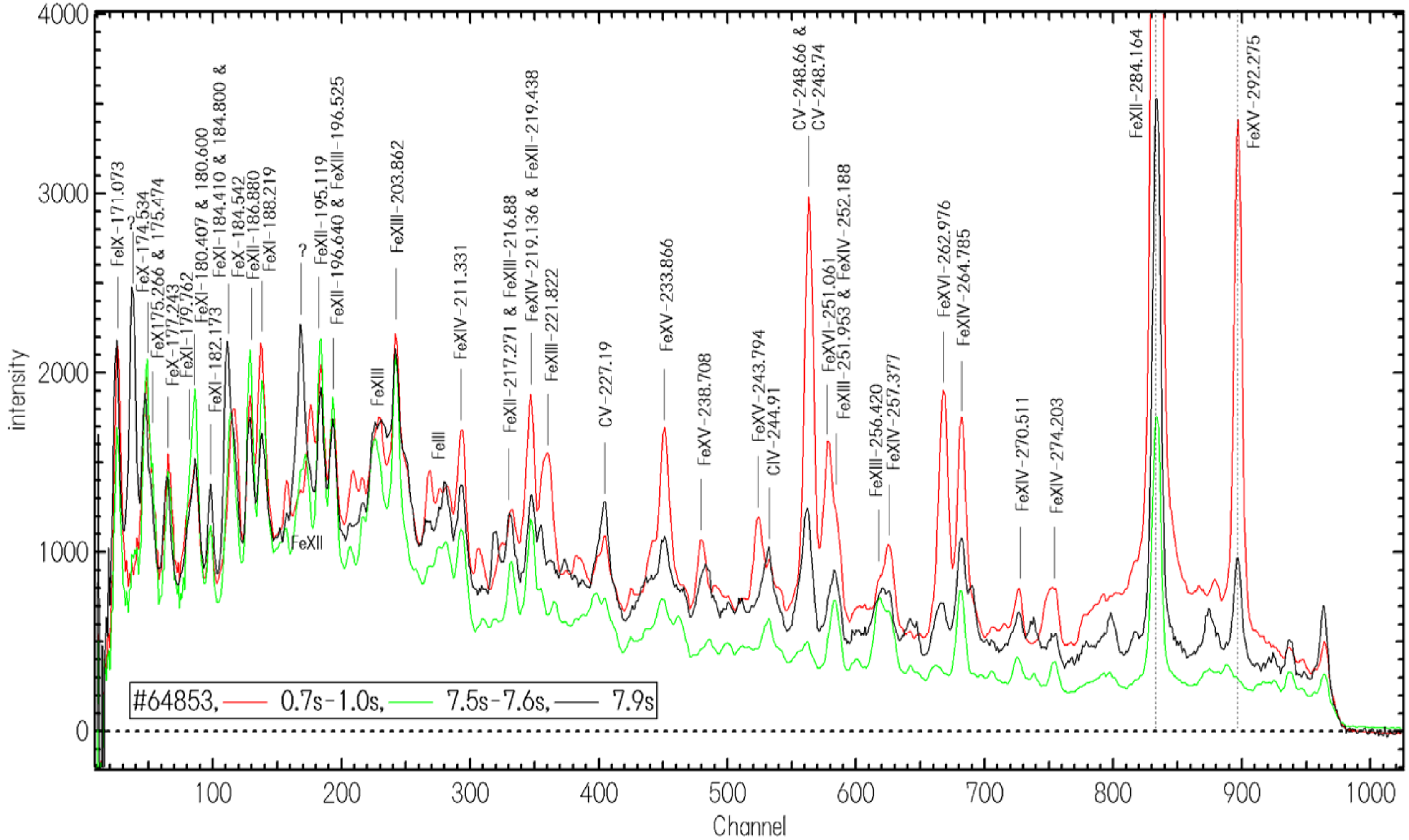
Spectra from Low temperature Plasma



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EBIT experiment for Fe M-shell transitions

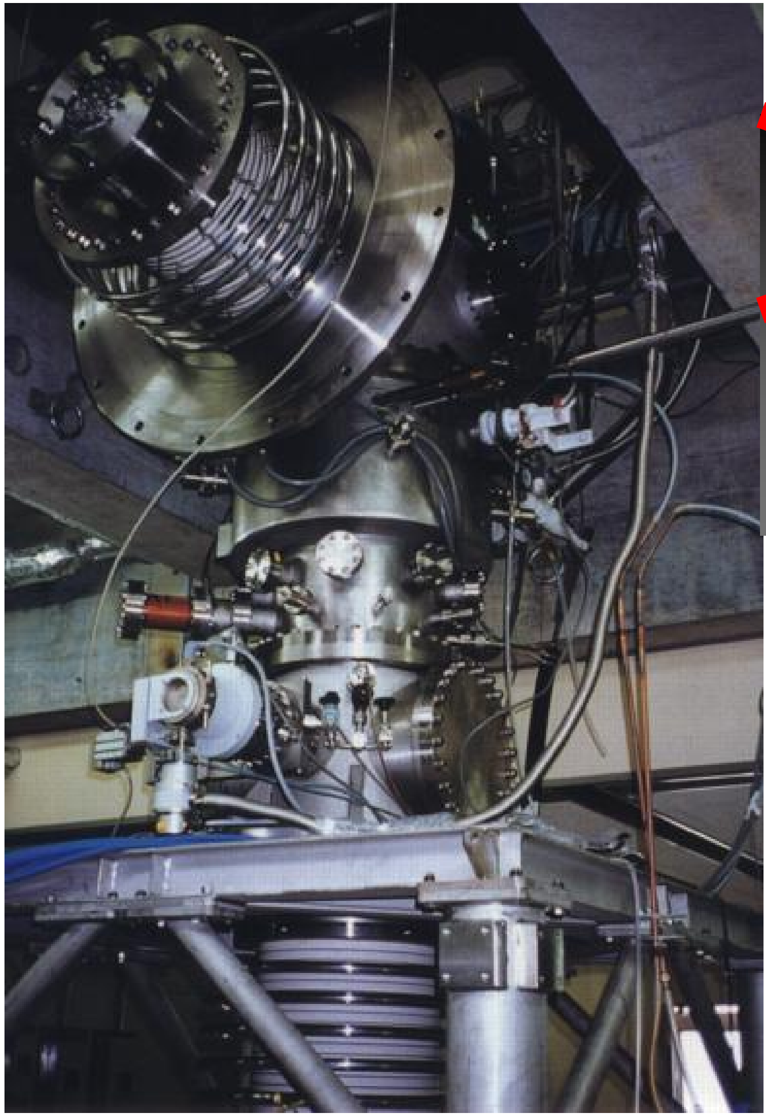
CO(ronal e)BIT project*

- N_e: 10^{12} cm^{-3}
- N_i: 10^{8-9} cm^{-3}
- E_e: mono-energetic 1-100 keV

Electron energy ⇔ ionization stage

*: kobito = dwarf

Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV



~~ANY ion can be produced!!!~~ (any charge state, any element)

Tokyo-EBIT

at The Univ. of Electro-Communications

Max. Ee: 200 keV (achieved)

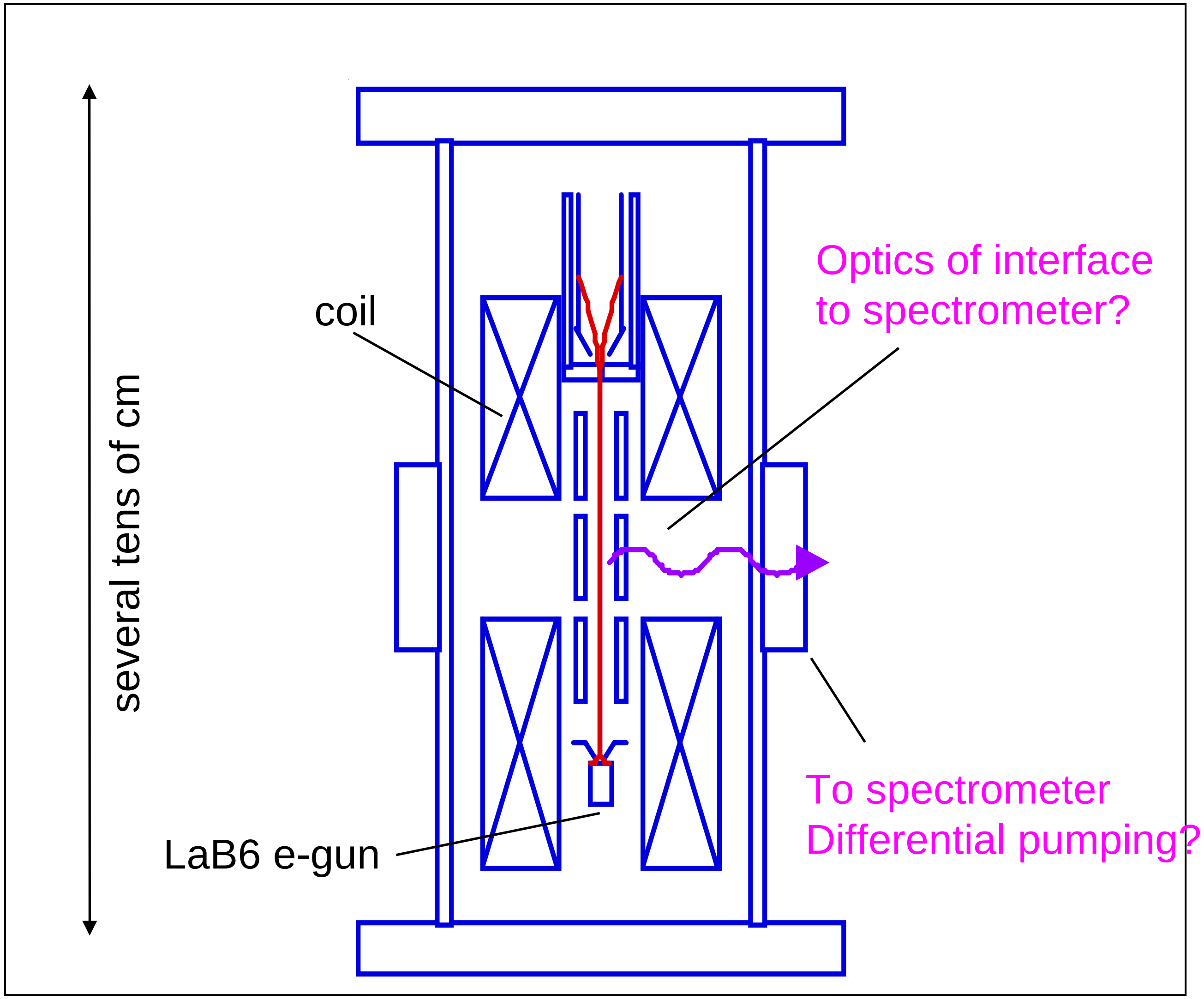
Max. Ie: 330 mA (achieved)

Ion trap

Middle of the trap

Tetsuya Watanabe (NAOJ) et al.

Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV



CoBIT (Coronal eBIT)

Ee: 0.1-1 keV
Ie: >10mA
B~0.1T
No cooling
or LN_2 cooled