High-Z ions for Magnetic Fusion Diagnostics

Charles Skinner
Princeton Plasma Physics Laboratory

"20 Years of Spectroscopy with EBIT"
Workshop Nov 12-16, 2006, Berkeley, California.

- ITER status, schedule, expected plasma conditions, plasma facing materials, fuel and impurity gases.
- ITER diagnostics in general, special constraints of diagnostic environment.
- ITER spectroscopic diagnostics, plasma parameters needed, current suite of spectrometers planned.
- Supporting spectroscopic information needed
  - potential role of EBIT.

Acknowledge very helpful discussions with M Putterich, R Neu, D Stuttman, P Beiersdorfer, D Stotler, K Hill

PPPL PRINCETON PLASMA PHYSICS LABORATORY

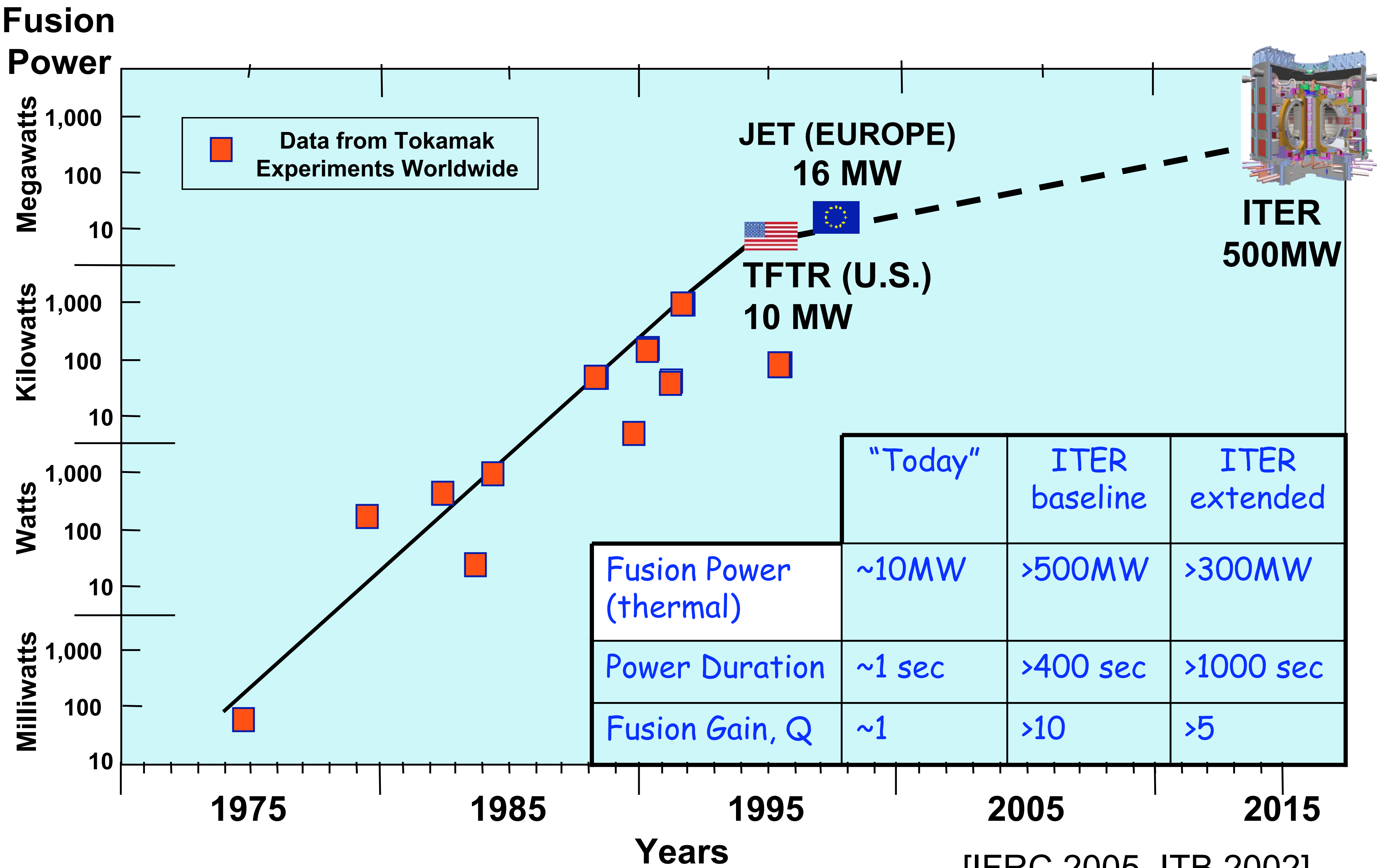
ITER - the essential next step in magnetic fusion

- Worlds biggest fusion energy research project.
- Objective: to demonstrate the scientific and technological feasibility of fusion power.
- Plasma to make 10x more power (500 MW) than needed to run it.
- Cost about 5 billion EU to construct and 5 billion EU to operate over 20 years and decommission.

Cadarache, France Site *(artists impression)*

- Involves virtually all the most developed countries, representing over half of today world's population

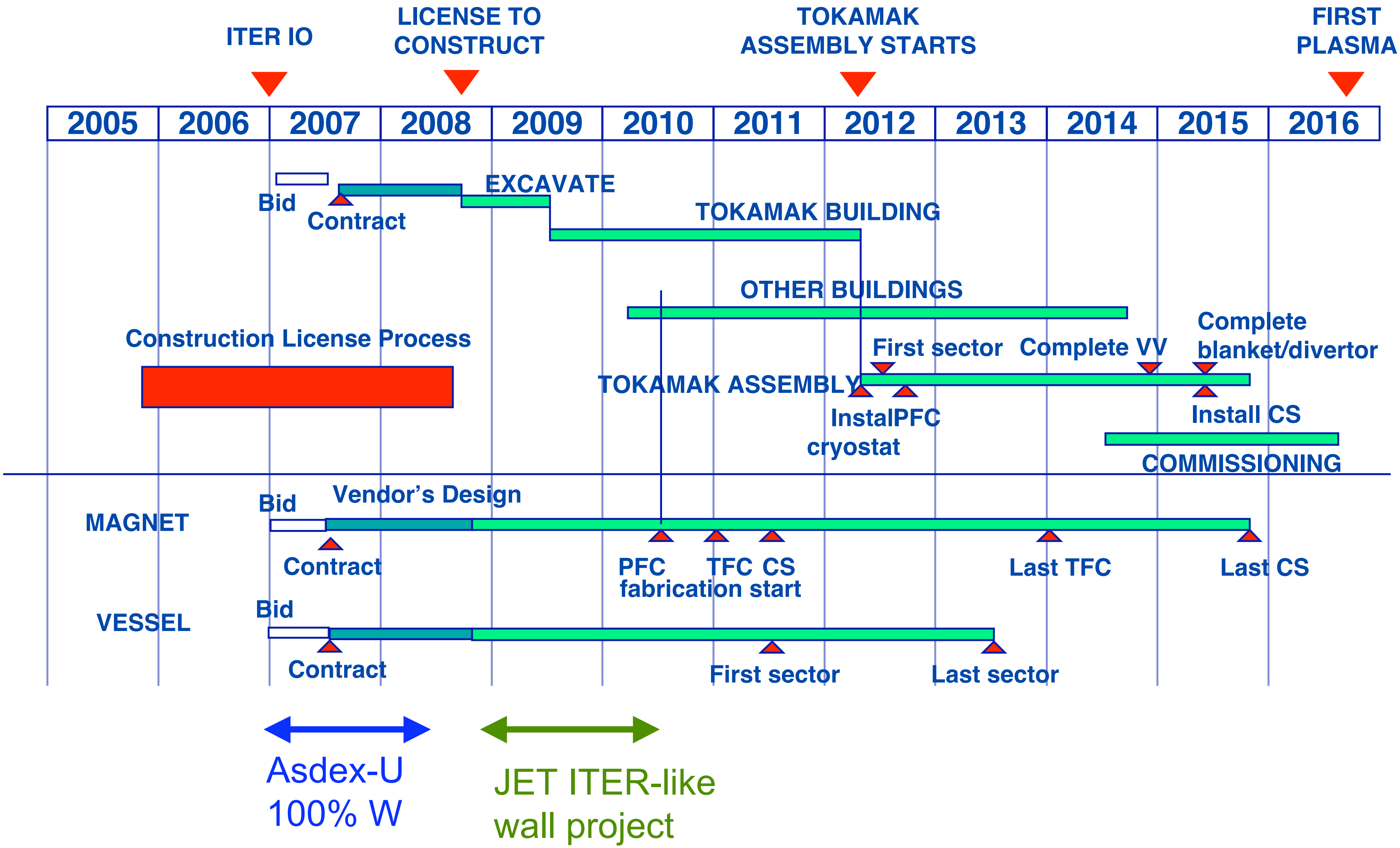
ITER's Fusion Performance in context.



	"Today"	ITER baseline	ITER extended
Fusion Power (thermal)	~10MW	>500MW	>300MW
Power Duration	~1 sec	>400 sec	>1000 sec
Fusion Gain, Q	~1	>10	>5

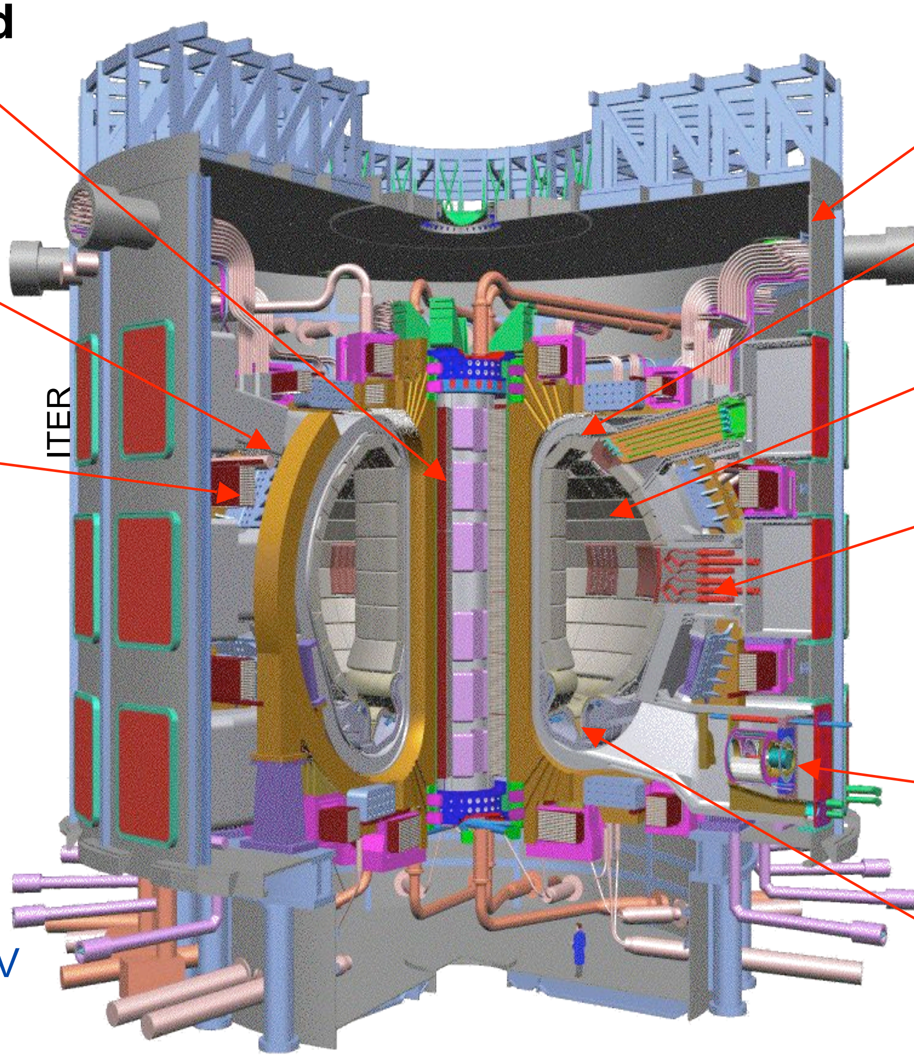
[IFRC 2005, ITB 2002]

ITER Project Schedule



N. Hotlkamp, SOFT Symposium, Warsaw 2006

The core of ITER



Major plasma radius 6.2 m

Plasma Volume: 840 m^3

Plasma Current: 15 MA

Typical Density: 10^{20} m^{-3}

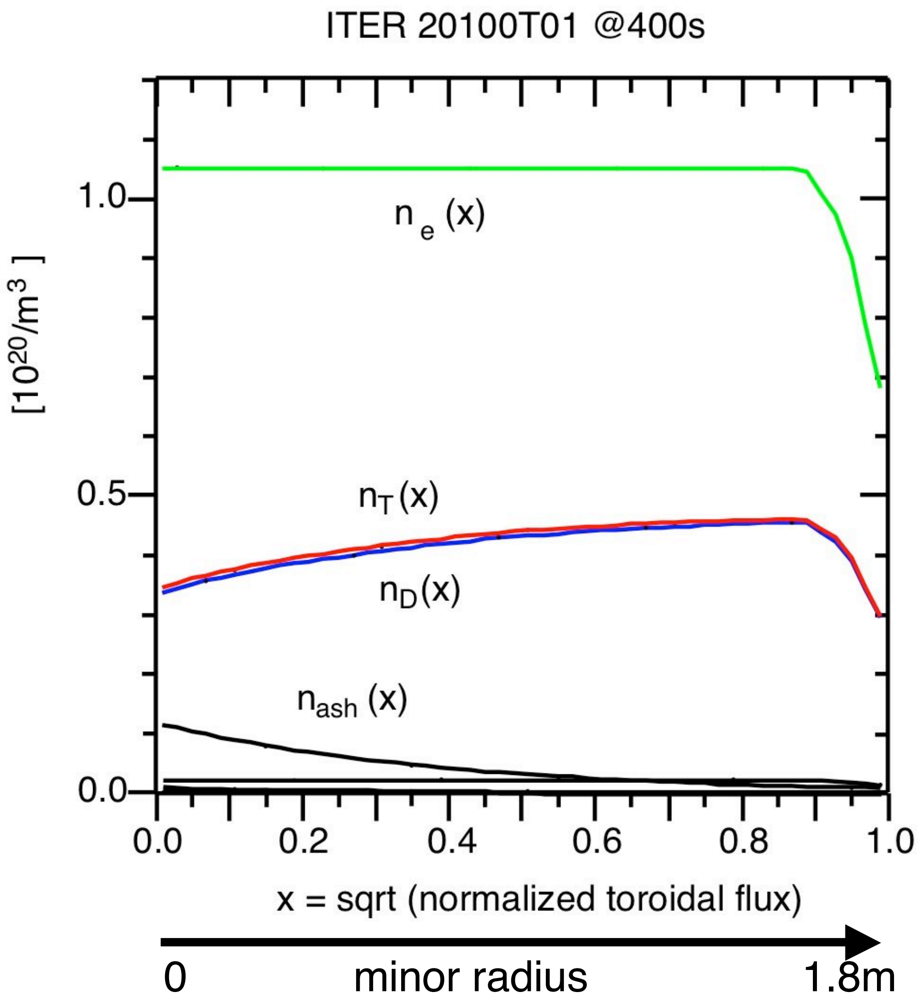
Typical Temperature: 20 keV

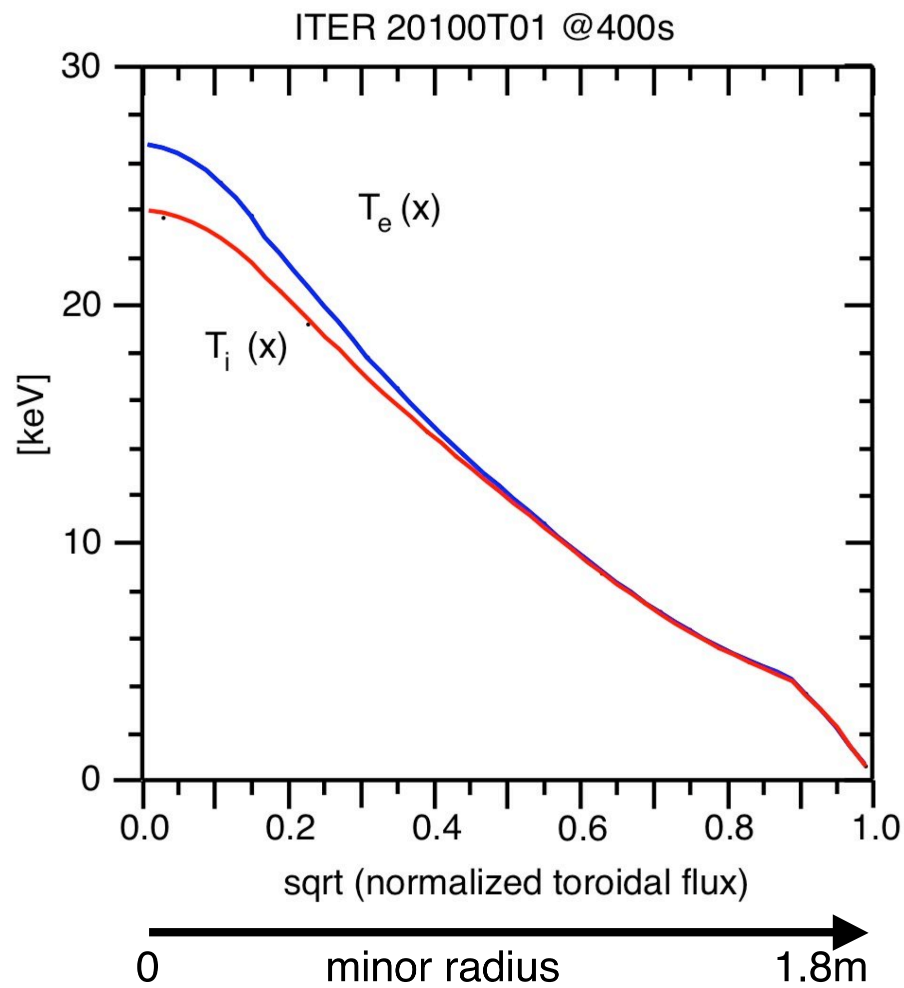
Fusion Power: 500 MW

Machine mass: 23350 t (cryostat + VV + magnets)
- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

D. Johnson

Radial profile of core ITER plasma parameters:





R Budny, Plasma Science and Technology in press

ITER divertor plasma

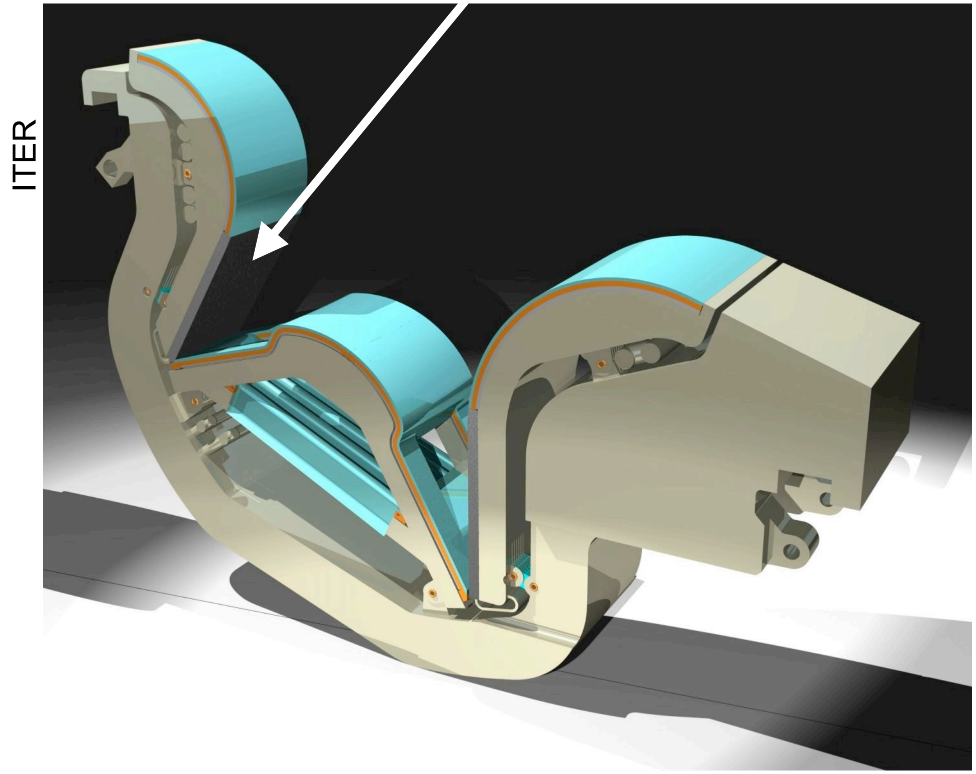
- Divertor moves plasma-wall interactions away from the core plasma.
- Facilitates He ash pumping
- But complicates power handling.

Fusion Reaction:

D+T -> 3.5MeV He + 14 MeV neutron

- At Q=10, Fusion Power = 500 MW. =100 MW He alphas + 50 MW NBI
- Heat flux similar to rocket nozzle needs to be dissipated.
- 75% radiated by C + Ar -> 10 MW/m2 on carbon divertor plate
- Too much radiation reduces plasma confinement and fusion power
- Too little radiation could result in damage to plate

Carbon divertor target plate



Divertor spectroscopy needed to control argon injection and power flowing to divertor plates
Divertor plasma parameters:

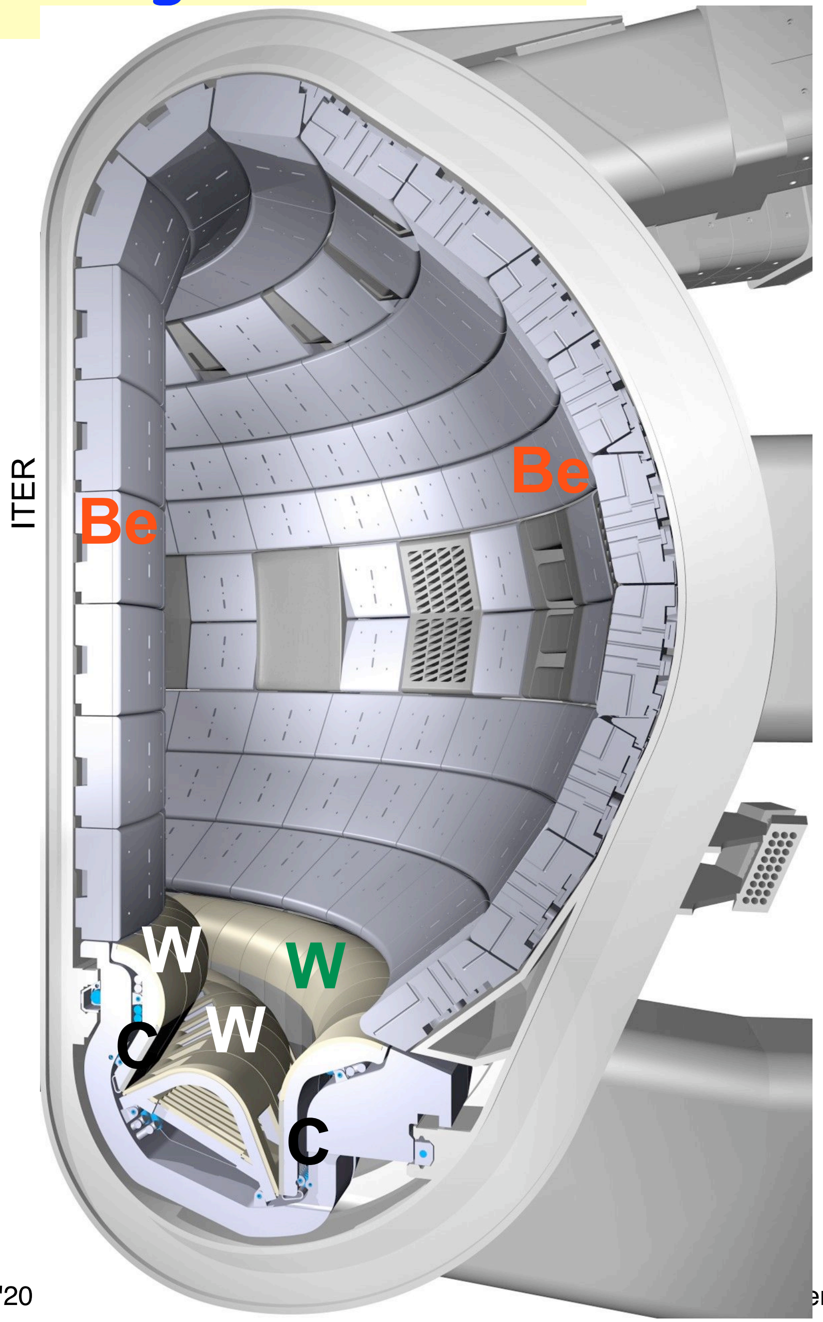
$Ne = 10^{20} - 10^{21}\ m^{-3}$, Te - 0.1 - 100eV

ITER plasma facing materials

Beryllium wall
(low Z = low radiation losses, oxygen getter, but low melt temperature)

Tungsten baffle and dome (high melt temp, low erosion, low T retention, but high rad. losses)

Carbon divertor target (does not melt, good radiator for plasma detachment, but T retention is major issue)



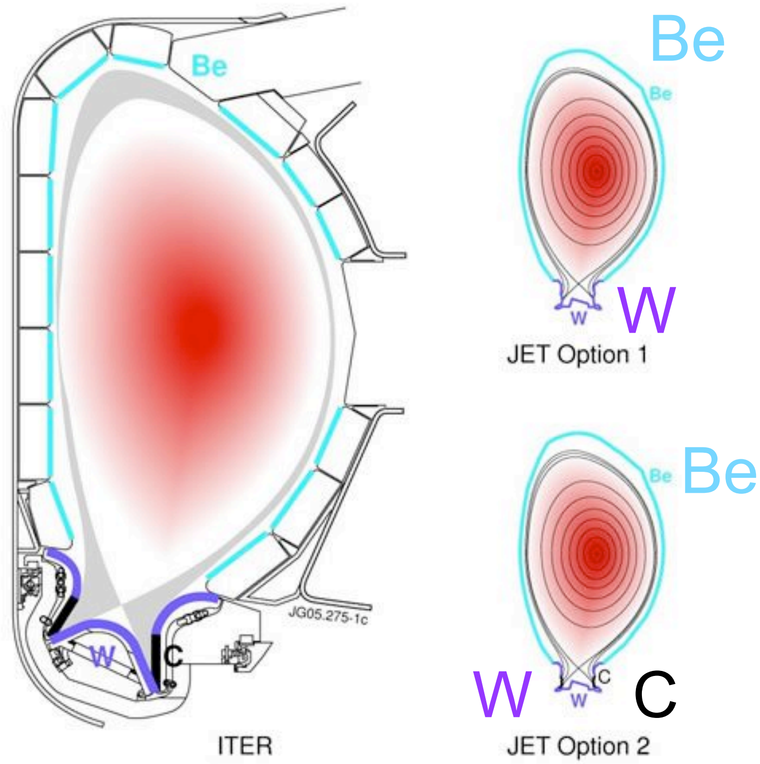
Plasma:
- Hydrogen initially, then
- Deuterium+ Tritium
- Argon ≈ 0.12% of electron density to control detachment
- Ne, N_2 also possible
- Be impurities est. ≈ 3% of Ne
- Core He ash 15%
- Zeff < 1.6

Important to track the creation of mixed material surfaces:
Be on W, W on Be etc.

Be is backed by copper so spectral information on Cu important too.

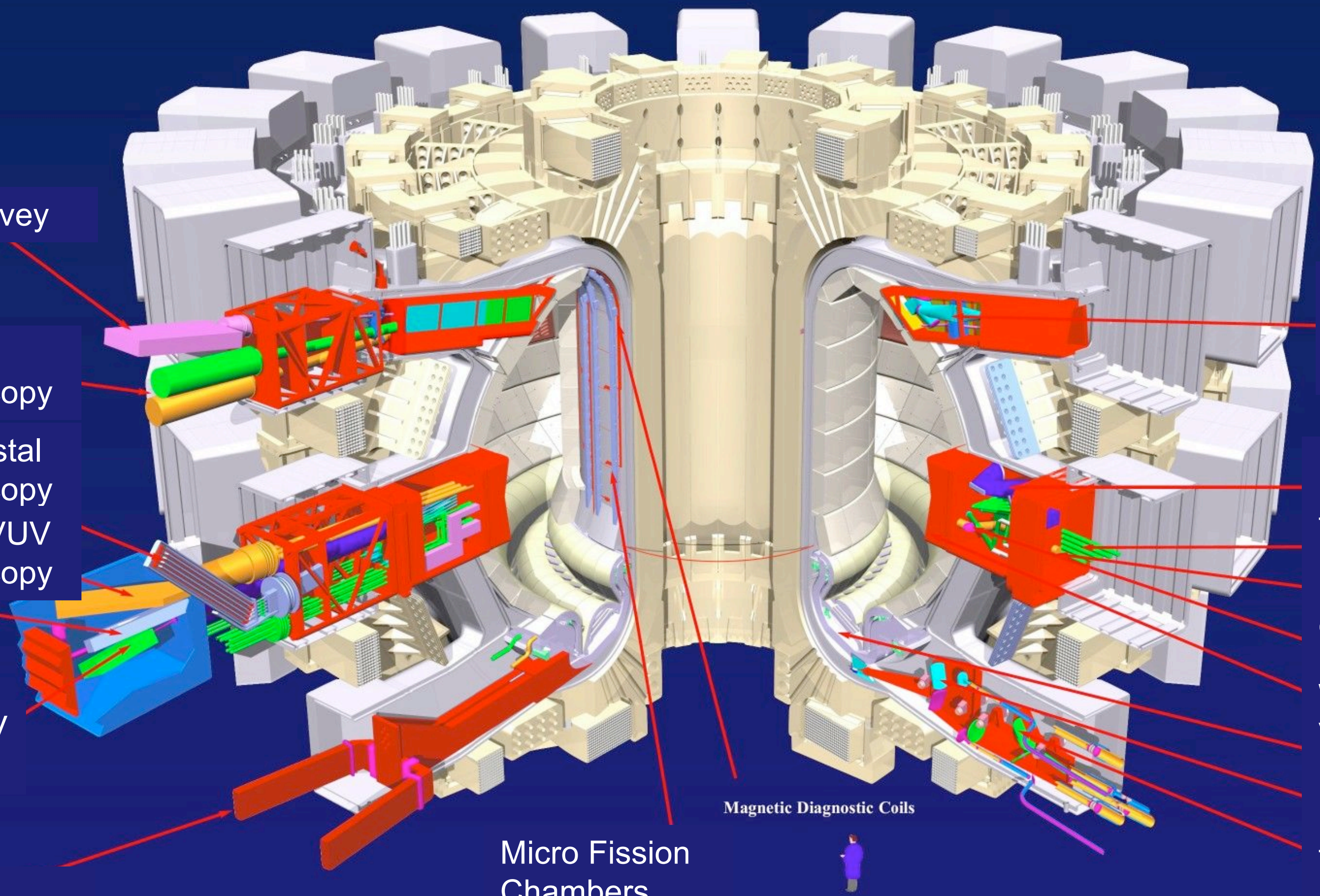
Near Term: 100% W Asdex-U, JET ITER-like wall

Asdex-U (R Neu PSI-17)



- Clearly important to get advance experience with ITER PFC materials.
- Asdex-U is completing conversion to 100% W PFCs - operations in 2007
- JET is implementing an ITER-like wall project - first W/Be then W/Be/C; operations in 2009

ITER diagnostics



ITER diagnostics

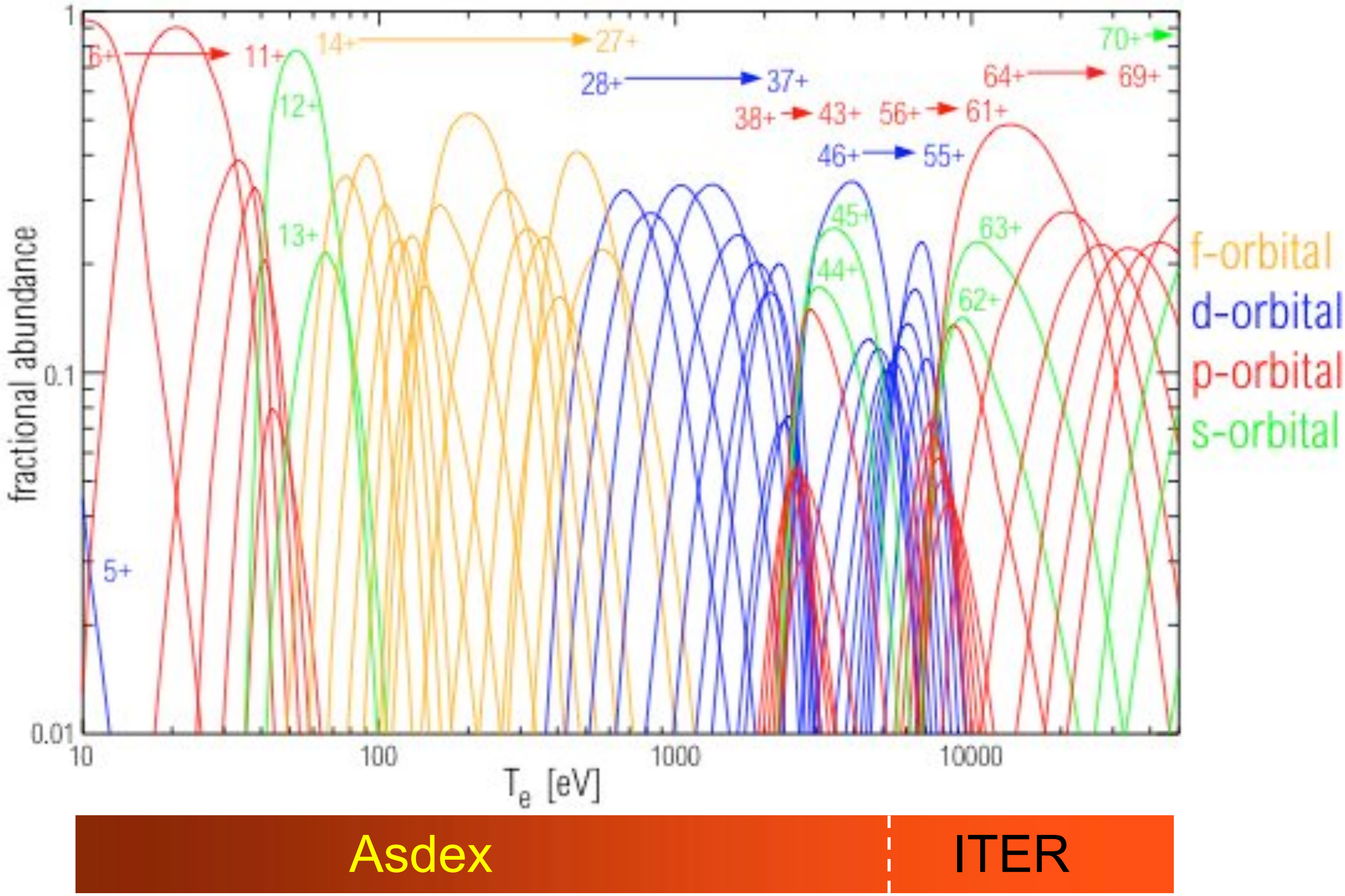
- Essential for plasma operations and physics goals:
- 40 measurement systems include magnetics, neutron, optical, spectroscopic, bolometry and microwave systems.
- Provide
  - Input for real time machine protection systems and plasma control.
  - Data for understanding of plasma behavior.
  - Optimization of plasma performance.

PID p.329 “The machine is unable to operate without a working diagnostic providing every group 1a parameter (1b for advanced operation).’

A Costley, Fus. Eng. Des. 74 (2005) 109

- Physics of diagnostics instruments typically established on present machines but application to ITER poses difficult challenges:
  - High reliability and accuracy required for real time plasma control.
  - Stability and longevity required for long pulse length and high duty cycle
- Severe Environment:
  - < 3e18 n/m2s (10x present machines)
  - <2e3 Gy/s (10x present machines)
  - 500kw/m2 plasma radiation
  - Radiation Induced Conductivity
  - Radiation Induced EMF
  - T containment, vacuum integrity
  - Minimal activation
  - Remote maintenance
  - Limited views

Tungsten will be principal high-z impurity

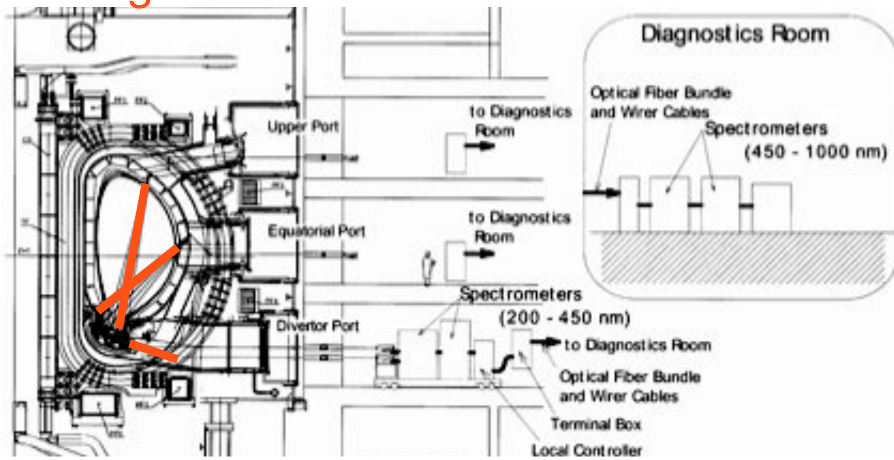


T Putterich

ITER spectroscopic diagnostics (fiberoptic coupled):

- Will identify impurity species C, W, Be, Cu, Ne, Ar, Kr.
- Measure 2D distributions of impurity density and influx.
- Measure ionization front and He ash density.
- Measure impurity ion temperature and flow velocity from Doppler effect.

Sightlines in red



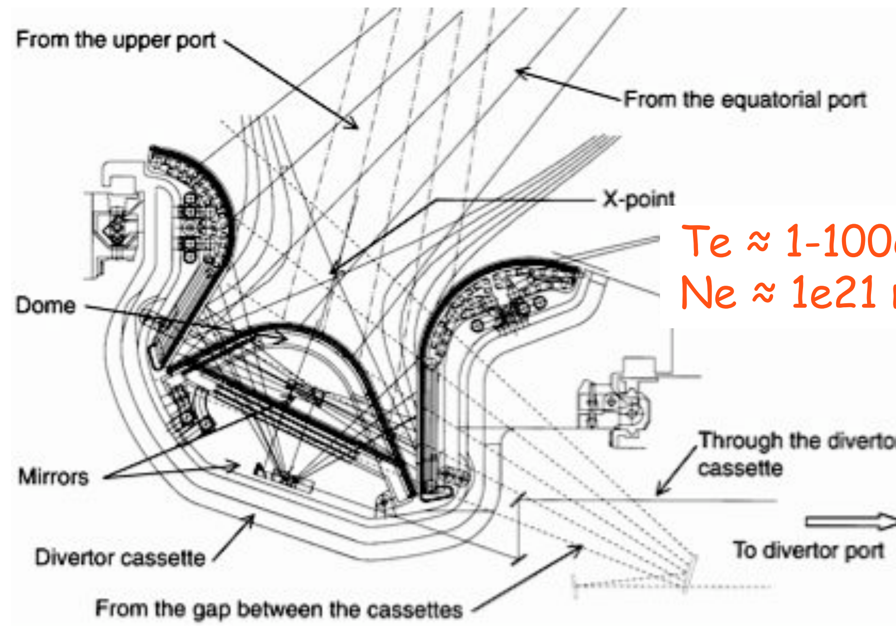
Four visible survey spectrometers
200-1000 nm. 0.1nm resolution, 10 ms time resolution, 10 cm spatial resolution.

Three high dispersion spectrometers
(Echelle) 200-1000nm, 0.01nm resolution, 10 ms, 10 cm

+ filter spectrometers.

Spectrometers for 200-450 nm are close in to minimise fiber optic losses but will experience neutron noise.

Responsible Party: Japan



Te ≈ 1-100eV, Ne ≈ 1e21 m^{-3}

T. Sugie et al., J. Plasma Fusion Res. 79 (2003) 1051

Recommendation:

- At present W influx gauged by W I 400.8 nm line with known photon efficiency (S/XB) but there is potential interference from WII line at nearly same wavelength
- Ionized tungsten has small gyro radius so major fraction is promptly recycled back to wall on the first gyro orbit after ionization.
- NIST Database for 450-1000 nm shows 2186 lines for W1, 35 lines for WII but remarkably nothing for W III and up at any wavelength.

Recommend:

1. Search for emission lines > 450 nm
2. Identifying emissions of charge states for ionization states below about W^{26+}
3. Corresponding S/XB (emission /mass loss) measurements.

Forbidden Lines

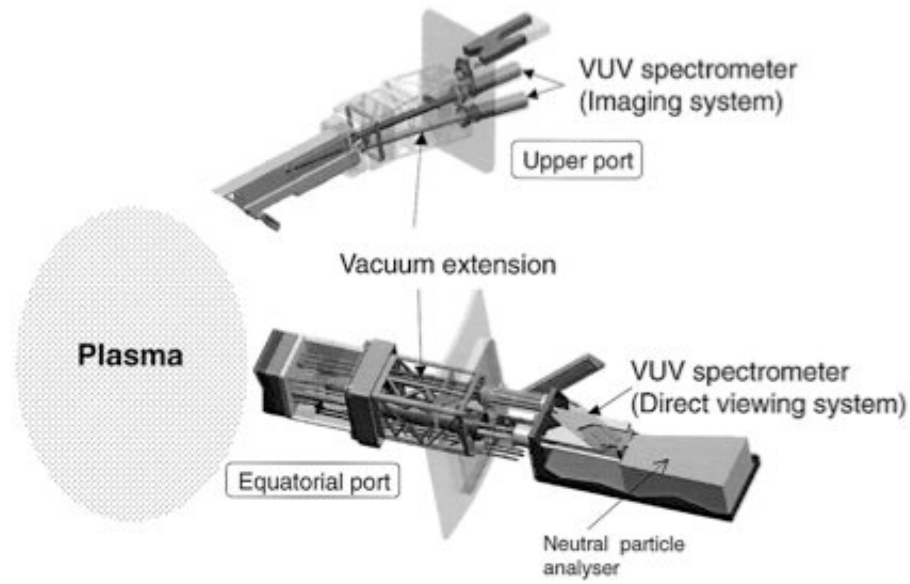
- Line of sight from upper port passes through plasma core.
  - potential to observe forbidden lines in 450-1000 nm region.
  - Could temperature and density of highly charged ions be conveniently obtained using high throughput visible region spectrometers / fiber optics ?

- First observation Fe+19 n=2 M1 line at 2665.1Å on the PLT tokamak in 1978 (Suckewer PRL 41 (1978) 756).
- Observations of forbidden lines in Cu, Zn, Ga, Ge, As, Se, Kr, Sr, Zr, Nb, Mo, Y on PLT, TEXT & Alcator followed.
- Visible forbidden transitions observed on SuperEBIT from Kr +21, Kr +22, Mo +28...... (Trabert, Utter, Beiersdorfer, Crespo Lopez-Urrutia)
- Ti-like Tungsten^{+52} M1 transition at 3627.13Å reported by Utter, Beiersdorfer & Brown (PRA 61 (2000) 030503(R))
  - (not seen so far on Asdex but maybe insufficient Te).

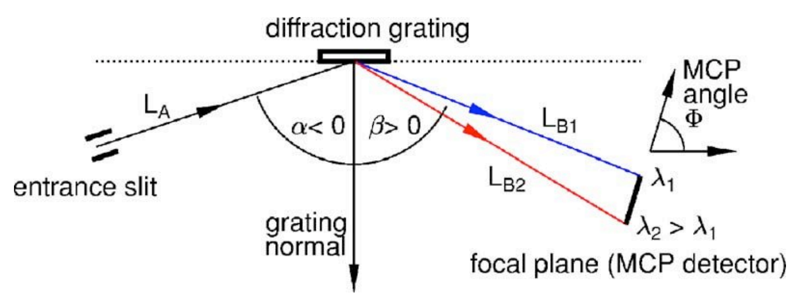
- Recommendation:
  Search for MI emission lines from highly ionized tungsten (up to Li-like).

ITER VUV spectroscopic diagnostics:

- Spectral region 1 - 100 nm
- VUV spectrometers in upper port and equatorial port (includes mirror to view divertor)
- Potential application of new high efficiency XUV spectrometer developed for W7-X (HEXOS).



T. Sugie et al., J. Plasma Fusion Res. 79 (2003) 1051



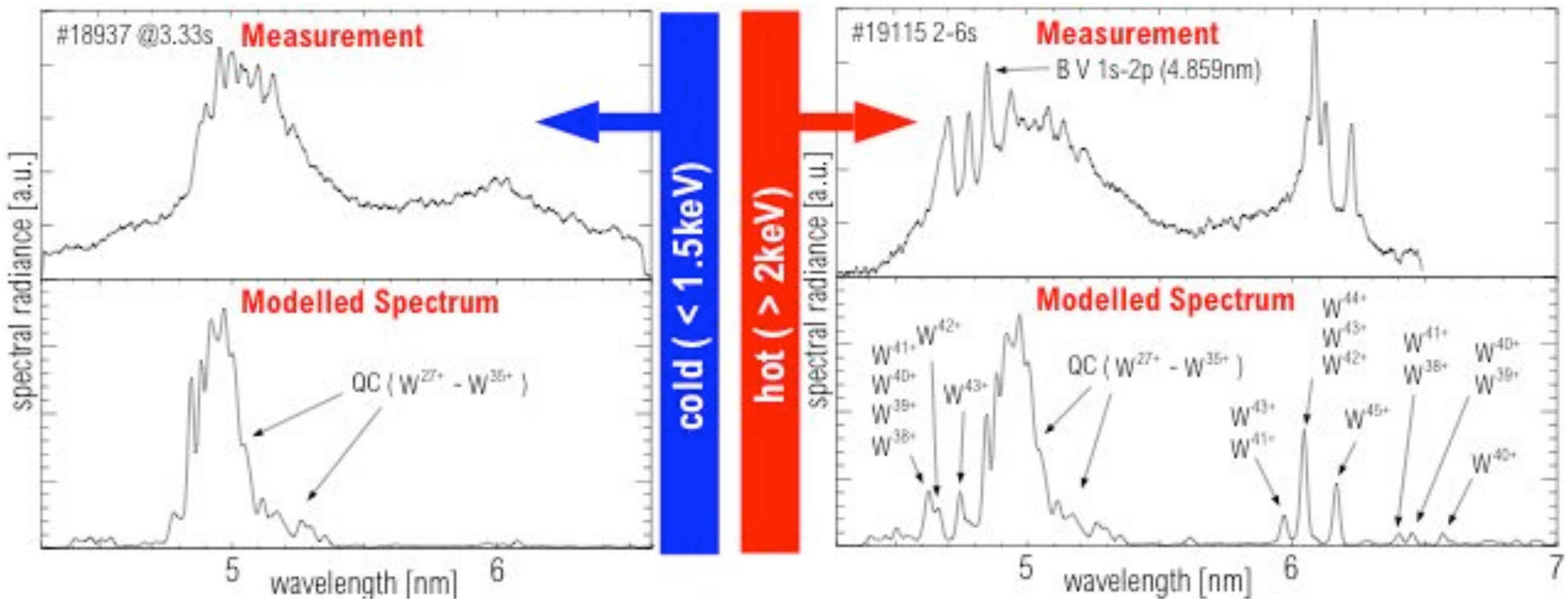
Responsible Party: Korea

HEXOS Biel et al., RSI 77 10F305 (2006)

Impurity density

- High number of W emission lines modeled in ADAS code and compared to experiment (rather than comparison of individual lines)
- More identified lines always desirable to identify W density gradients and transport barriers.
- Charge exchange processes may add to emission spectrum

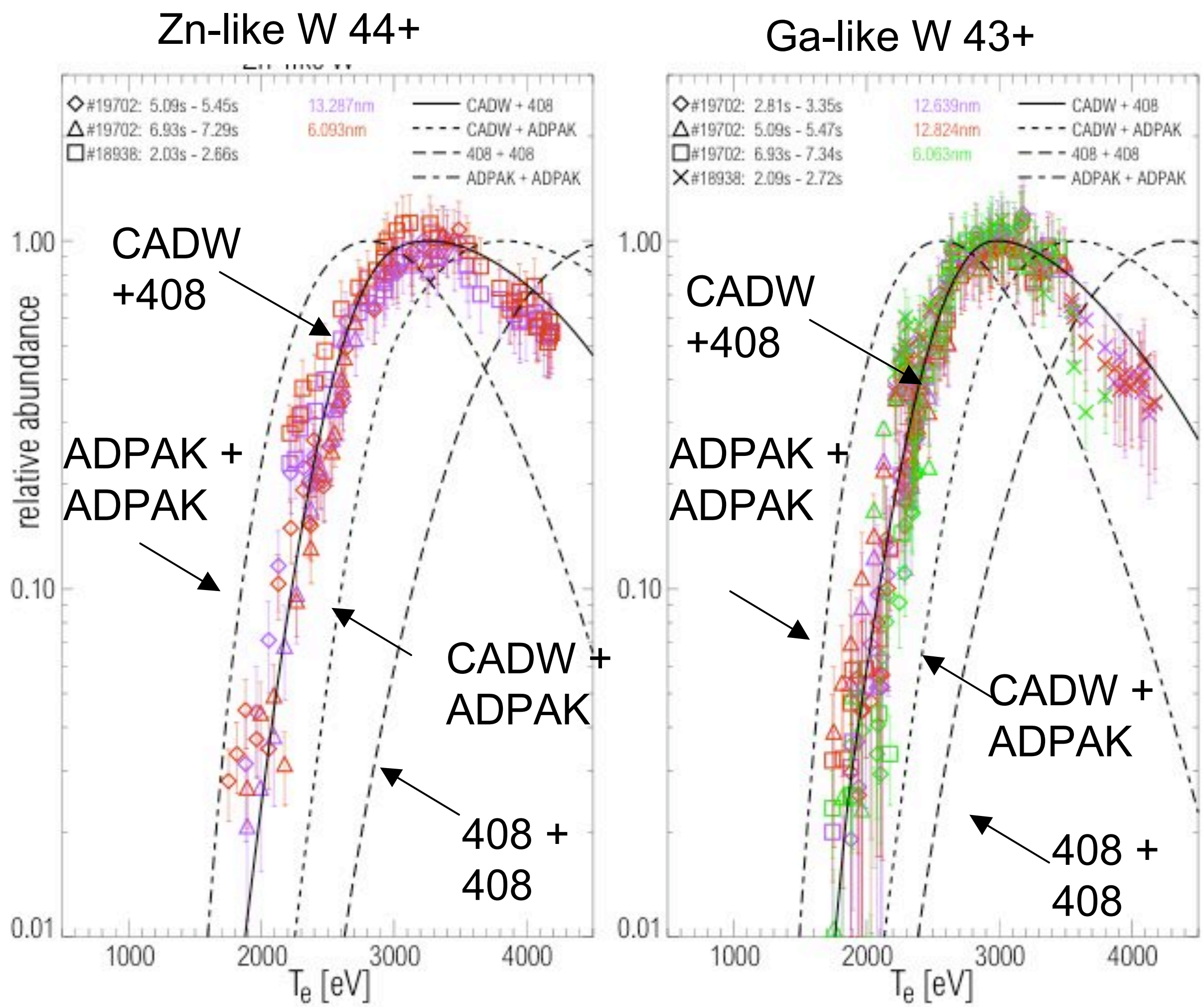
Putterich Asdex-U data



See also O'Mullane et al., RSI 77 10F520 (2006) for JET plans

Ionization Balance data needed.

- Ionization balance needs improvement (Putterich)
- Baseline ADAS (408 + 408) not good enough.



Putterich Asdex-U data

ITER x-ray spectroscopic diagnostics:

- Survey spectrometer 0.05 - 10 nm
  Equatorial port 11
  Single chord 0.1 - 10 nm
  $\lambda/\partial\lambda \sim 500$
- High resolution spectrometer for
  Doppler ion temperatures and velocities
  from Ar, Kr.
  Equatorial port 3, Upper port 9
  Imaging of minor radius
  ~ 1% bands between 0.1 and 0.4 nm
  $\lambda/\partial\lambda \sim 10{,}000$

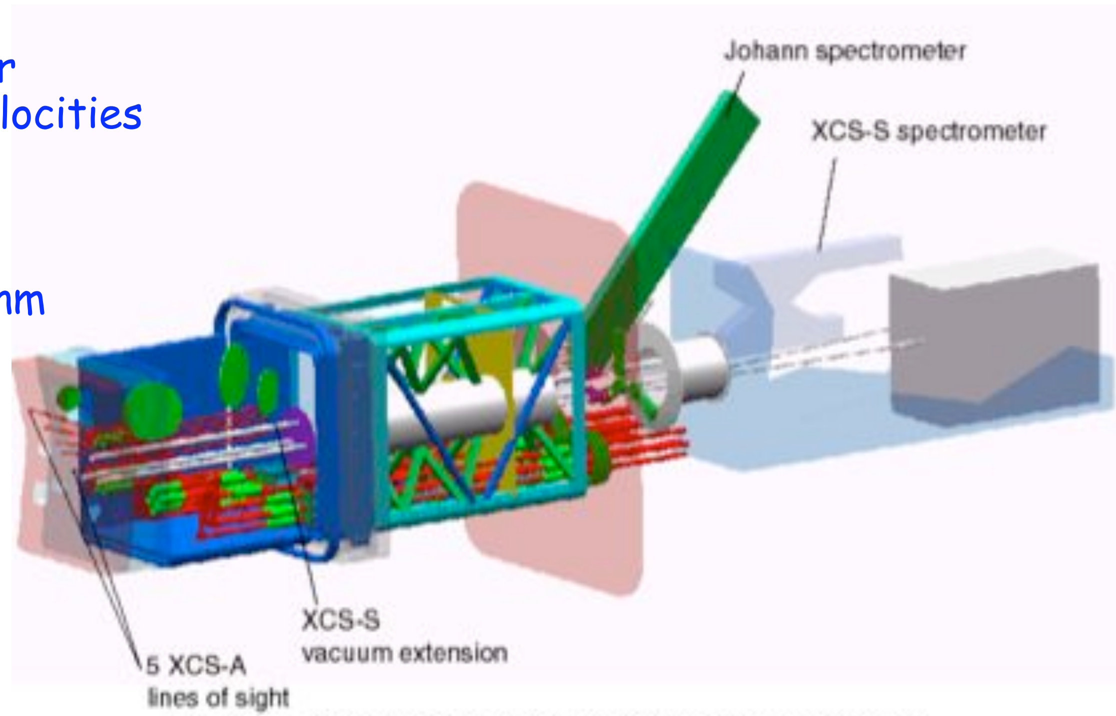


Fig. 6.1–2 Isomeric view of the XCS diagnostics arrangement

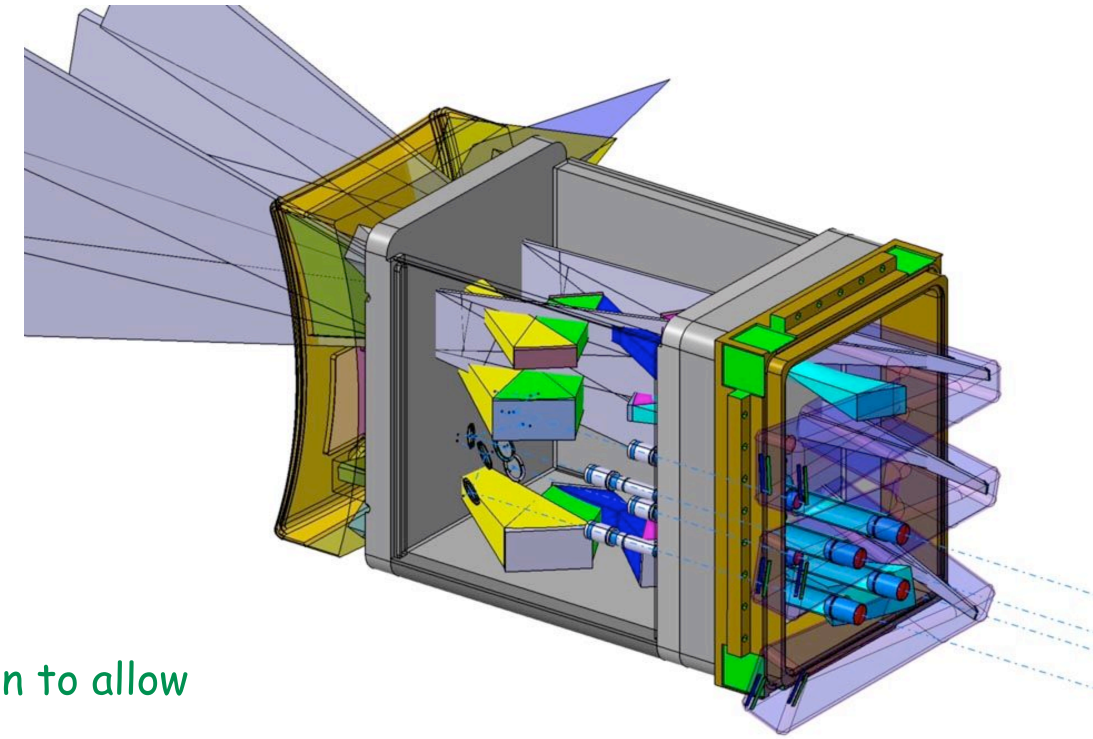
Measurement Requirements:

- Nw/ne range 1e-6 to 4e-4
- W influx 4e14 - 2e17 /s
- Ne,Ar,Kr /ne 1e-4 to 2e-2
- Ne, Ar, Kr influx 4e16 - 8e18 /s
- Ti 0.05 - 40 keV
  Accuracy 10%

PROCUREMENT PACKAGE # 55.PE
SPECTROSCOPIC DIAGNOSTICS ANNEX 1:
TECHNICAL SPECIFICATION

Responsible Party: US/India tbd.

Imaging Crystal Spectrometer



R Barnsley, IPR, India. 8th Feb 2006.

Design options for spectrometer location:

- Ex-port: Better access, Better shielding

- In-port: Wider view of plasma

Choice will be based on:

- Neutronics modelling

- **Detector radiation hardness**

- **Detector background rejection**

Design improvements ongoing:

2-D detectors, better spatial resolution to allow tomographic reconstruction.

Well resolved Ti, Te, Vpol in H-mode pedastal region.

Better spectral resolution, especially for tungsten.

Trend reported by Barnsley at Sendai ITPA mtg. :

- Visible measurements complicated by high continuum and mirror issues
- VUV, x-ray detectors becoming better, less expensive
  - e.g. Pilatus II Bitter talk.

Time to develop new energy sources is short….

J.Comiso

- The Arctic perennial ice cover has been decreasing at 9 to 10% per decade.
- Polar bears may be extinct by end of 21st century.
- Many Carribean reefs have seen a 80 % decline in coral reef cover partly due to global warming

Summary of areas where EBIT data could help:

1. Search for W emission lines > 450 nm
2. Identifying emissions of charge states for ionization states below about W^{26+}
3. Corresponding photon efficiency (S/XB) measurements

   -> measure of influx without recycling.
4. Identification of emission lines from neon-like tungsten for ITER temperatures 10-30 keV.
   – Use data for JET in 2009 with W PFC and 35 MW NBI.
5. Improve ADAS - energy dependence of ionization equilibria and excitation rates for W (Putterich). Look at spectral lines, where strong discrepancies between codes and experimental spectra appeared (such as 0.793 nm of Ni-like W^{46+}).
6. More identified lines always desirable to measure W density gradients and transport barriers.
7. Ne, Ar, Kr, Cu lines also…
8. Measurements of charge exchange spectra ?