ITER RF Systems and Microwave Diagnostics

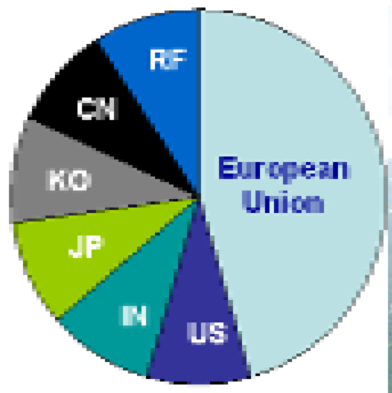
Stefan Simrock, ITER

Outline

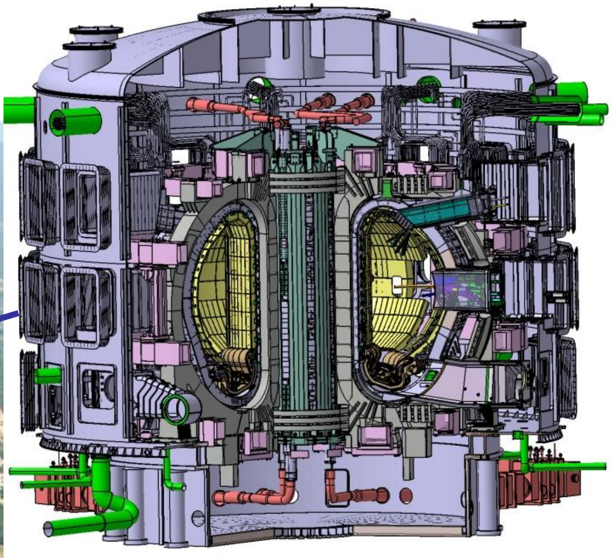
- ITER Project
- Heating Systems
- Diagnostics
- Plasma Control System

ITER Project

ITER - A Unique Scientific, Technological and Industrial Project

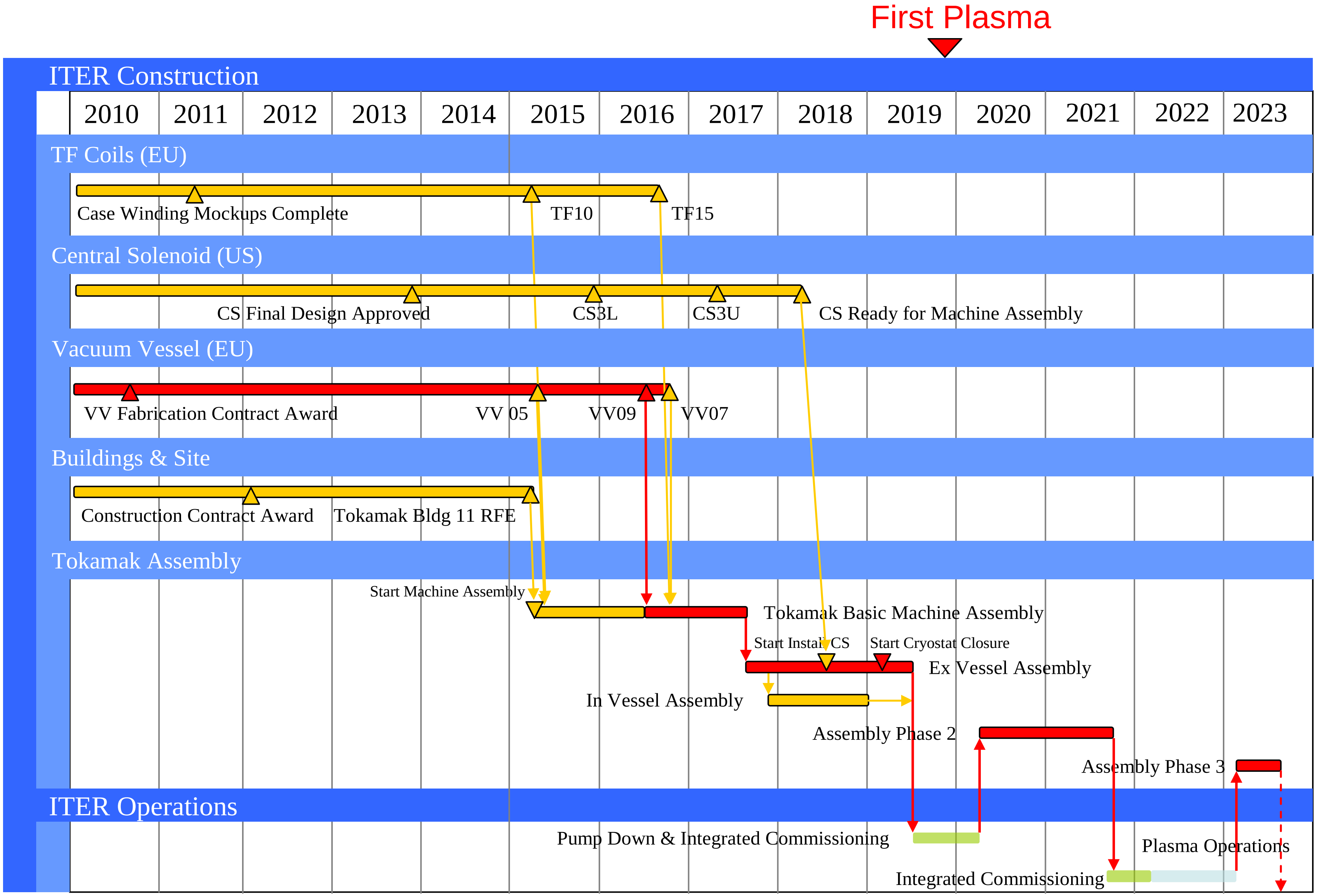


Seven Party Sharing

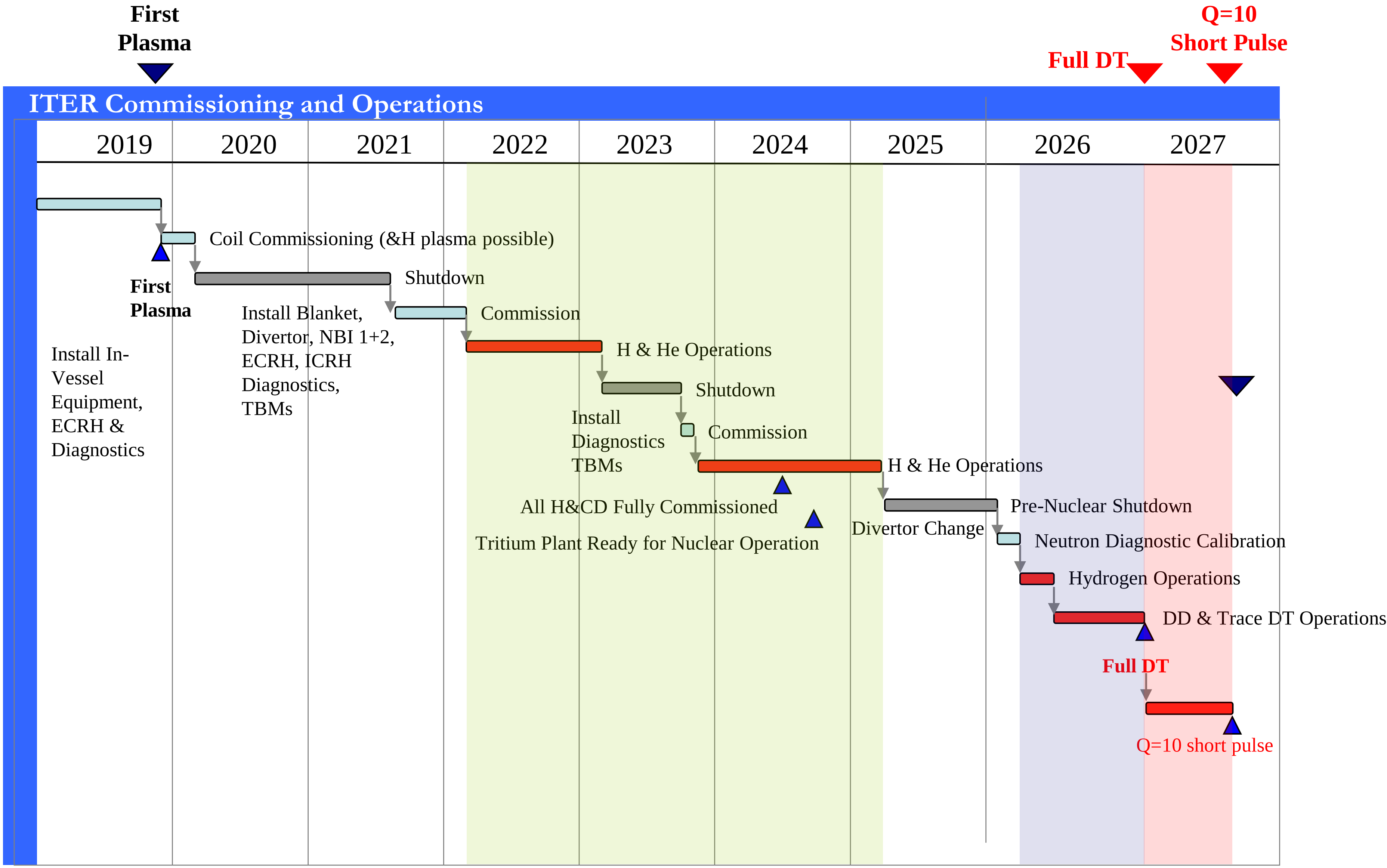


- **Objective -** Demonstrate the scientific and technological feasibility of fusion energy
- **Goal -** produce significant fusion power amplification (10x the power input):**output 500 MW**

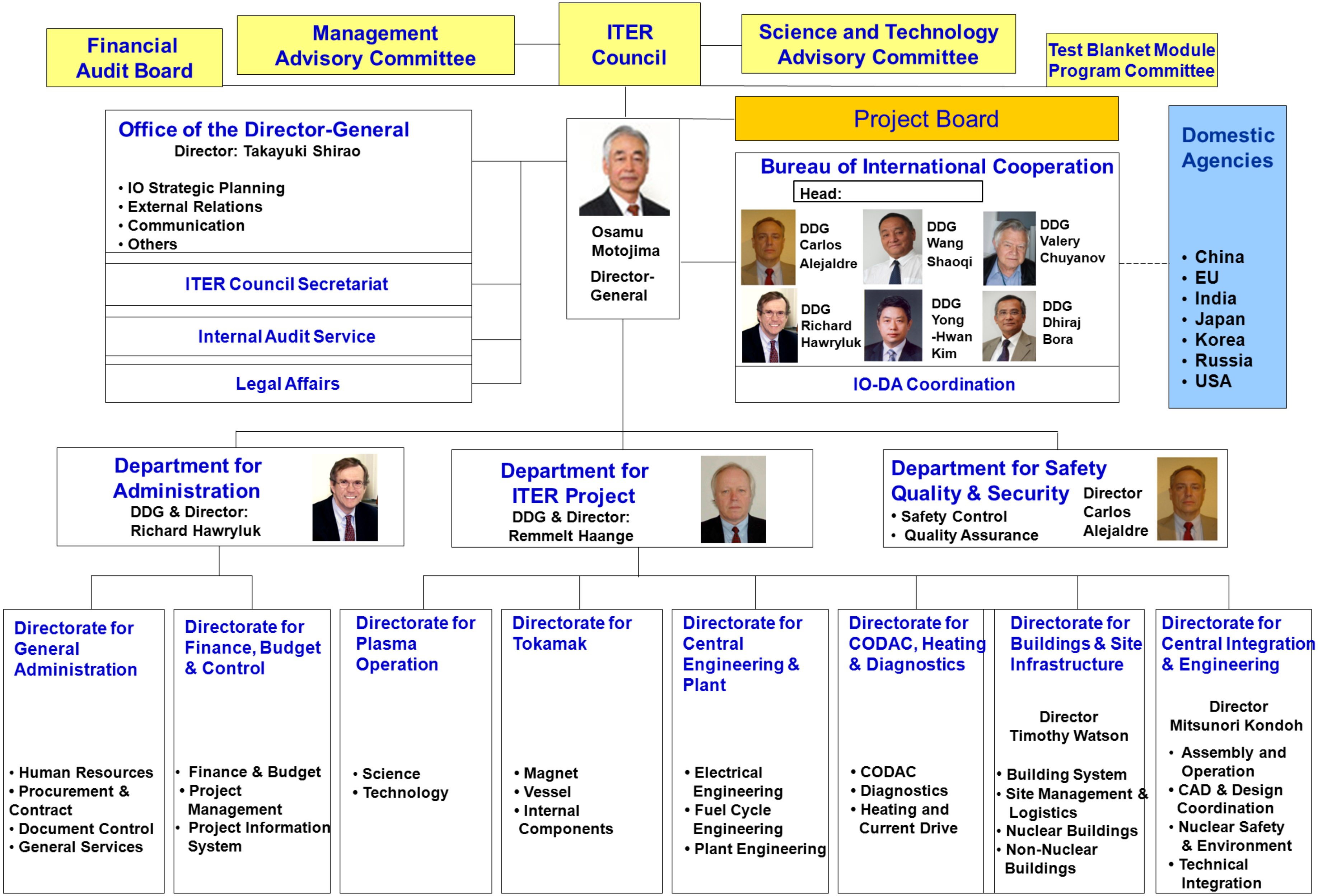
ITER Construction Schedule



ITER Experimental Schedule to DT



ITER New Organization Structure



Financial Audit Board

Management Advisory Committee

ITER Council

Science and Technology Advisory Committee

Test Blanket Module Program Committee

Project Board

Office of the Director-General
Director: Takayuki Shirao

- IO Strategic Planning
- External Relations
- Communication
- Others

ITER Council Secretariat

Internal Audit Service

Legal Affairs

Osamu Motojima
Director-General

Bureau of International Cooperation
Head:

DDG Carlos Alejaldre
DDG Wang Shaoqi
DDG Valery Chuyanov
DDG Richard Hawryluk
DDG Yong-Hwan Kim
DDG Dhiraj Bora

IO-DA Coordination

Domestic Agencies

- China
- EU
- India
- Japan
- Korea
- Russia
- USA

Department for Administration
DDG & Director:
Richard Hawryluk

Department for ITER Project
DDG & Director:
Remmelt Haange

Department for Safety Quality & Security
- Safety Control
- Quality Assurance

Director
Carlos Alejaldre

Directorate for General Administration
- Human Resources
- Procurement & Contract
- Document Control
- General Services

Directorate for Finance, Budget & Control
- Finance & Budget
- Project Management
- Project Information System

Directorate for Plasma Operation
- Science
- Technology

Directorate for Tokamak
- Magnet
- Vessel
- Internal Components

Directorate for Central Engineering & Plant
- Electrical Engineering
- Fuel Cycle Engineering
- Plant Engineering

Directorate for CODAC, Heating & Diagnostics
- CODAC
- Diagnostics
- Heating and Current Drive

Directorate for Buildings & Site Infrastructure
Director
Timothy Watson
- Building System
- Site Management & Logistics
- Nuclear Buildings
- Non-Nuclear Buildings

Directorate for Central Integration & Engineering
Director
Mitsunori Kondoh
- Assembly and Operation
- CAD & Design Coordination
- Nuclear Safety & Environment
- Technical Integration

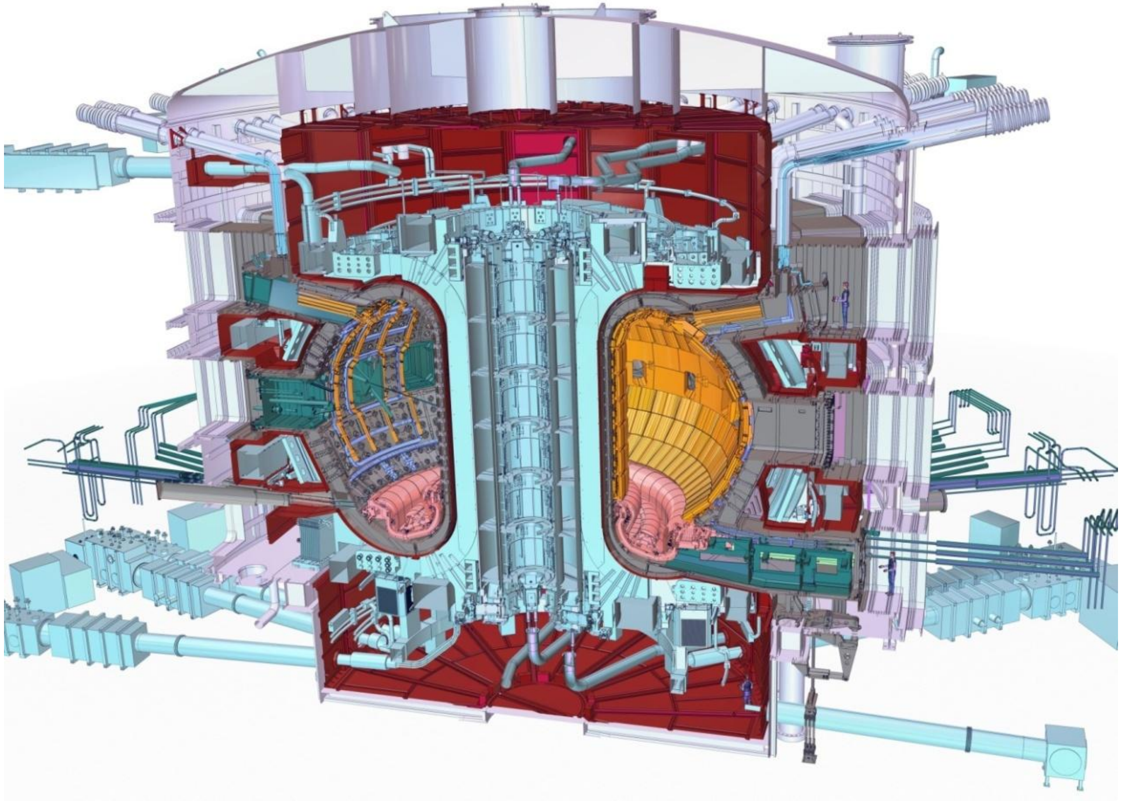
Version of 6 May 2011

ITER Platform – September 2011

ITER Project

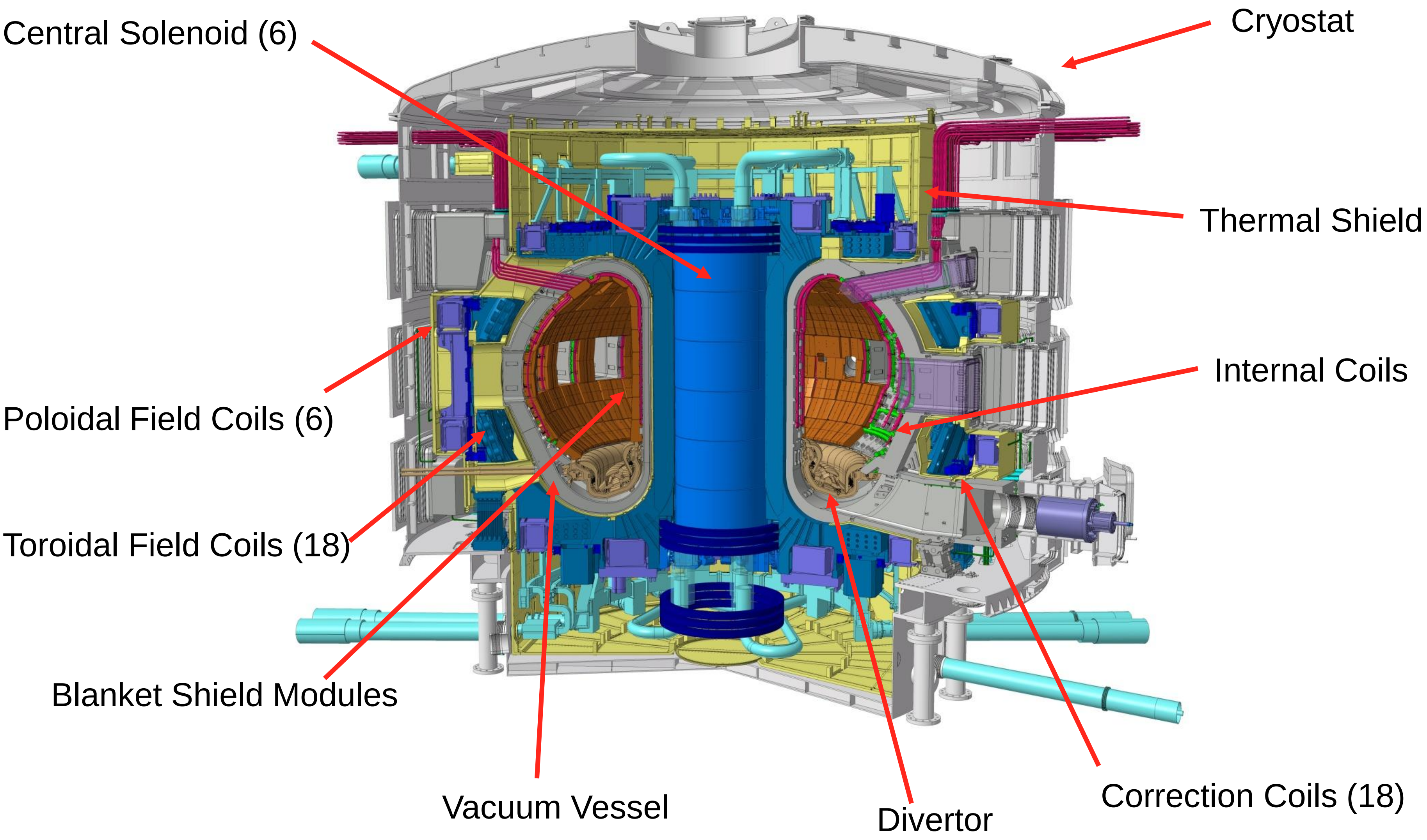
Principal fusion goals for ITER:

- demonstrate Q=10 for 400 seconds
- demonstrate Q=5 for 1000 seconds



Plasma Current	15 MA
Toroidal Field	5.3 T
Major Radius	6.2 m
Minor Radius	2.0 m
Elongation κ_{96}	1.7
Triangularity δ_{96}	0.33
Fusion Power	500 MW
Q	10
Burn Time	~400 s

ITER Tokomak – Major Components



Central Solenoid (6)

Cryostat

Thermal Shield

Internal Coils

Poloidal Field Coils (6)

Toroidal Field Coils (18)

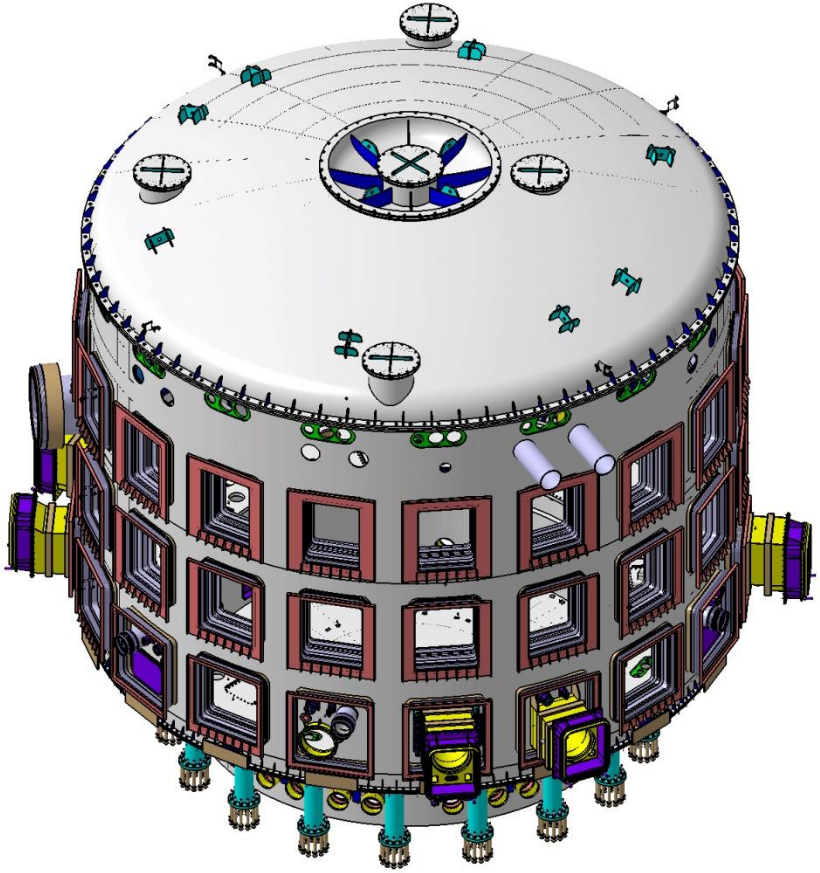
Blanket Shield Modules

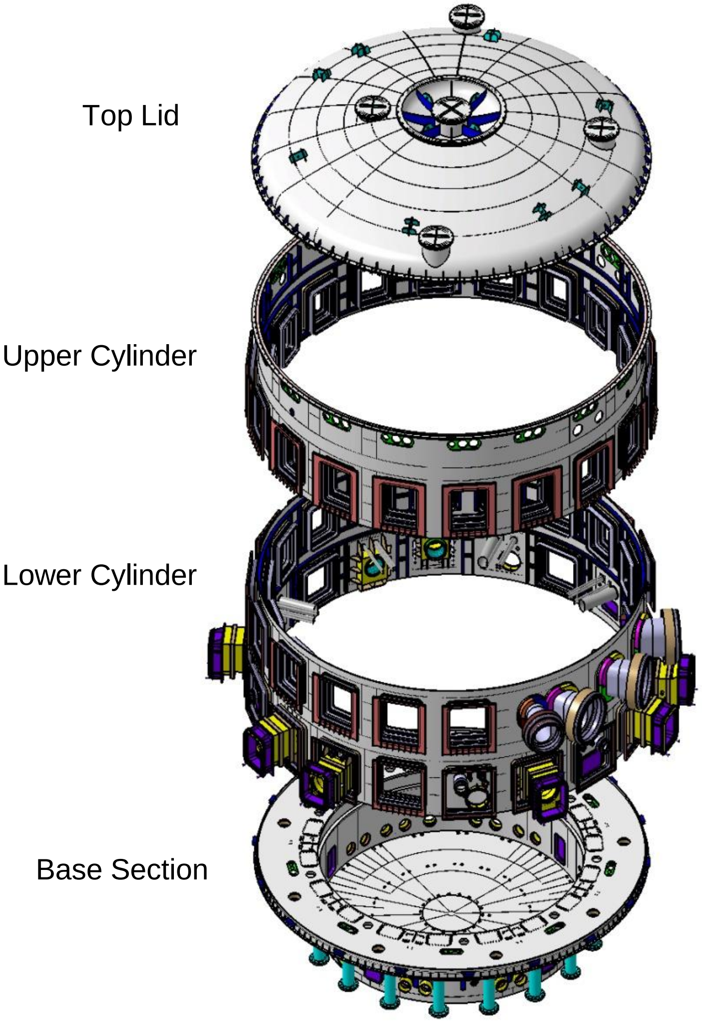
Vacuum Vessel

Divertor

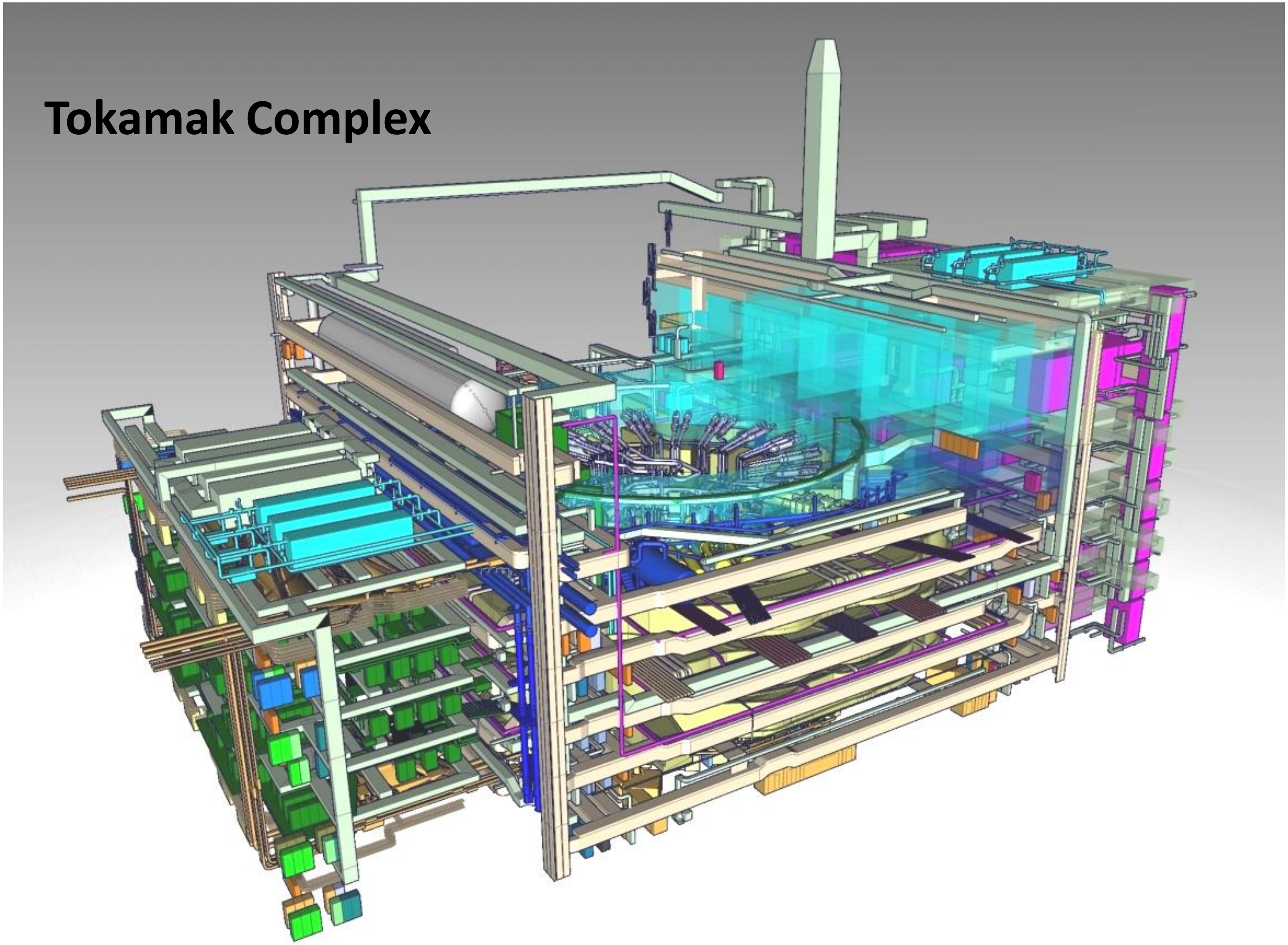
Correction Coils (18)

Cryostat with



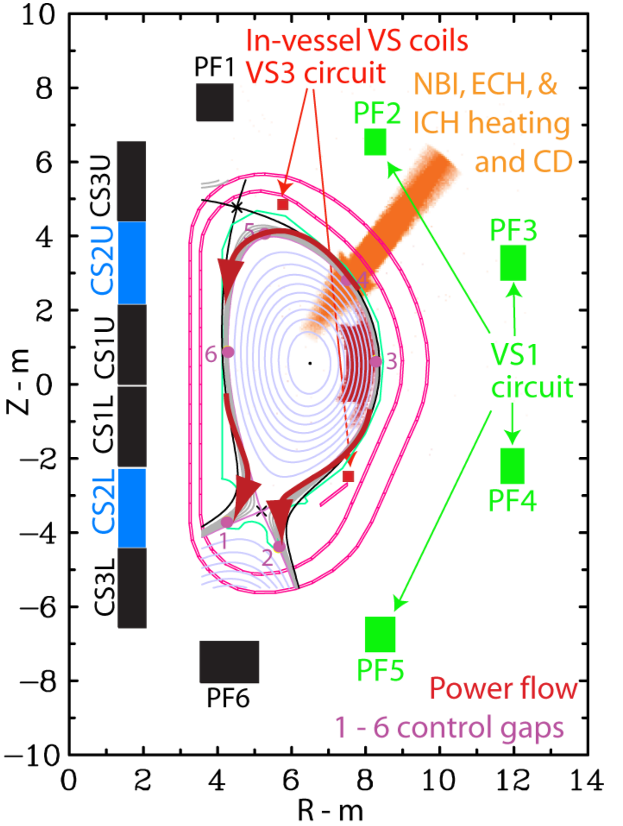


Plant Systems Configuration Models



Plasma Control System

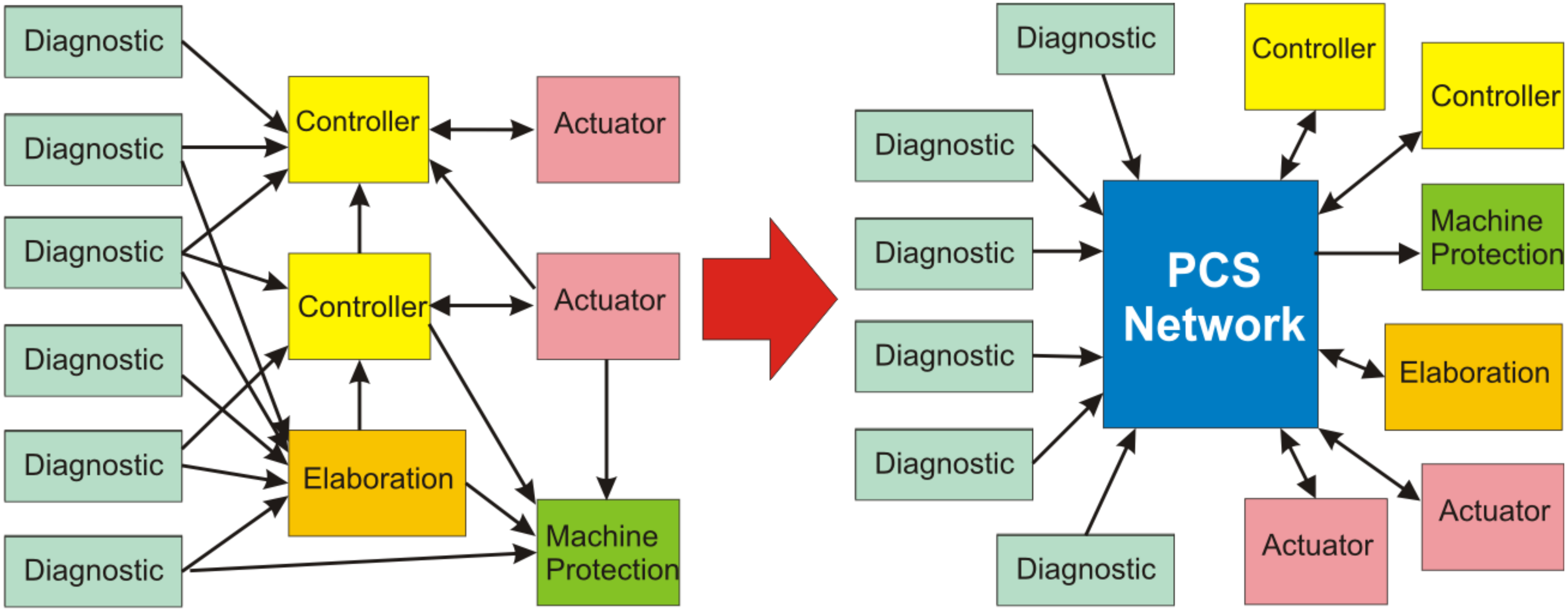
Requirements for the ITER PCS (basic and advanced control)



- Plasma equilibrium and basic control
  - Plasma shape, position, density, current
  - Routine and robust
- Plasma kinetic control
  - Fuel mixture, fusion power, radiated power…
  - Exploratory to robust
- Control for advanced operation
  - current profile, temperature profile
  - Exploratory
- Active MHD stability control
  - Error field modes, edge localized modes, neoclassical tearing modes, resistive wall modes
  - Exploratory to established
- Disruption/vertical displacement avoidance and mitigation
  - Exploratory to robust

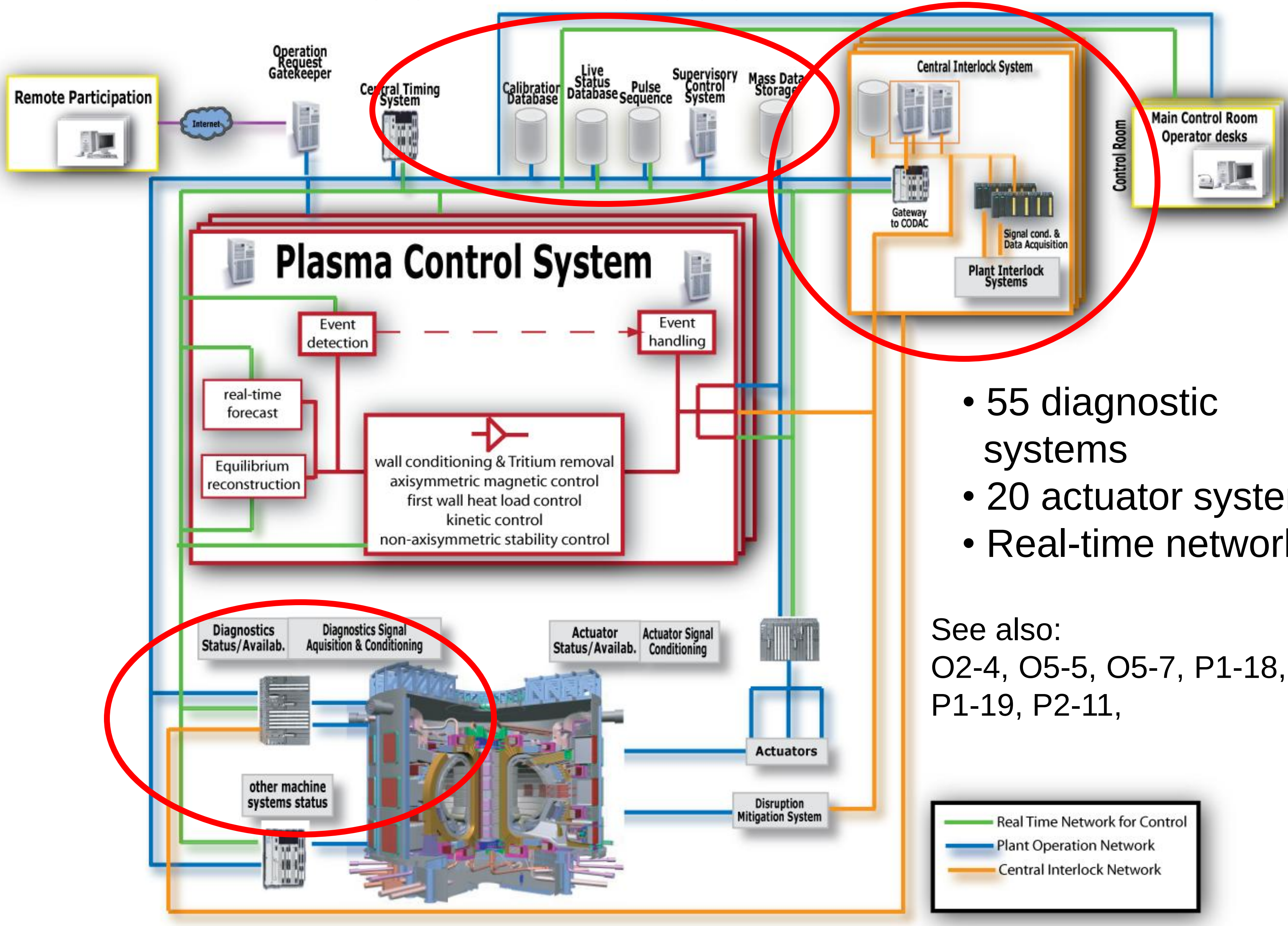
Plasma Control System

Since a large number of Module outputs need to be shared **a PCS network becomes necessary**.



The network should allow **efficient management of PCS,** and at the same time **satisfy the technical requirements. ➔**

PCS Interfaces in ITER



- 55 diagnostic systems
- 20 actuator systems
- Real-time networks

See also:
O2-4, O5-5, O5-7, P1-18, P1-19, P2-11,

ITER Plasma Control requires multiple actuators

Wall conditioning and tritium removal requires ion cyclotron (IC), electron cyclotron (EC), & high frequency glow discharge cleaning (HFGDC))

Plasma axisymmetric magnetic control requires Central Solenoid (CS), Poloidal Field (PF), and internal Vertical Stability (VS) coils & power supplies

Plasma kinetic control requires heating and current drive H&CD (IC, EC, & neutral beam injection (NBI)), H, ^{4}He, ^{3}He, D, T, Ar, Ne, and N gas and H, D, T, Ar, Ne, and N pellet injection, real-time pumping & strike point control

Non-axisymmetric stability control requires H&CD systems, ELM coils and pellet pacing, gas and pellet fuelling, shape control, & external correction coils

Event handling requires also disruption and runaway mitigation

RF Heating Systems

Plasma Auxiliary Systems

They are absolutely necessary for a Tokamak to operate in high performance regime

- Heating and current drive systems

  The Auxiliary Heating Systems are the tools to make the plasma perform : Heating to thermonuclear temperatures, current drive for long pulses, mode stabilization, plasma breakdown and current rise.

- Diagnostics

  Diagnostics are key part of tokamak research

  They provide the reality-check for our physics understanding

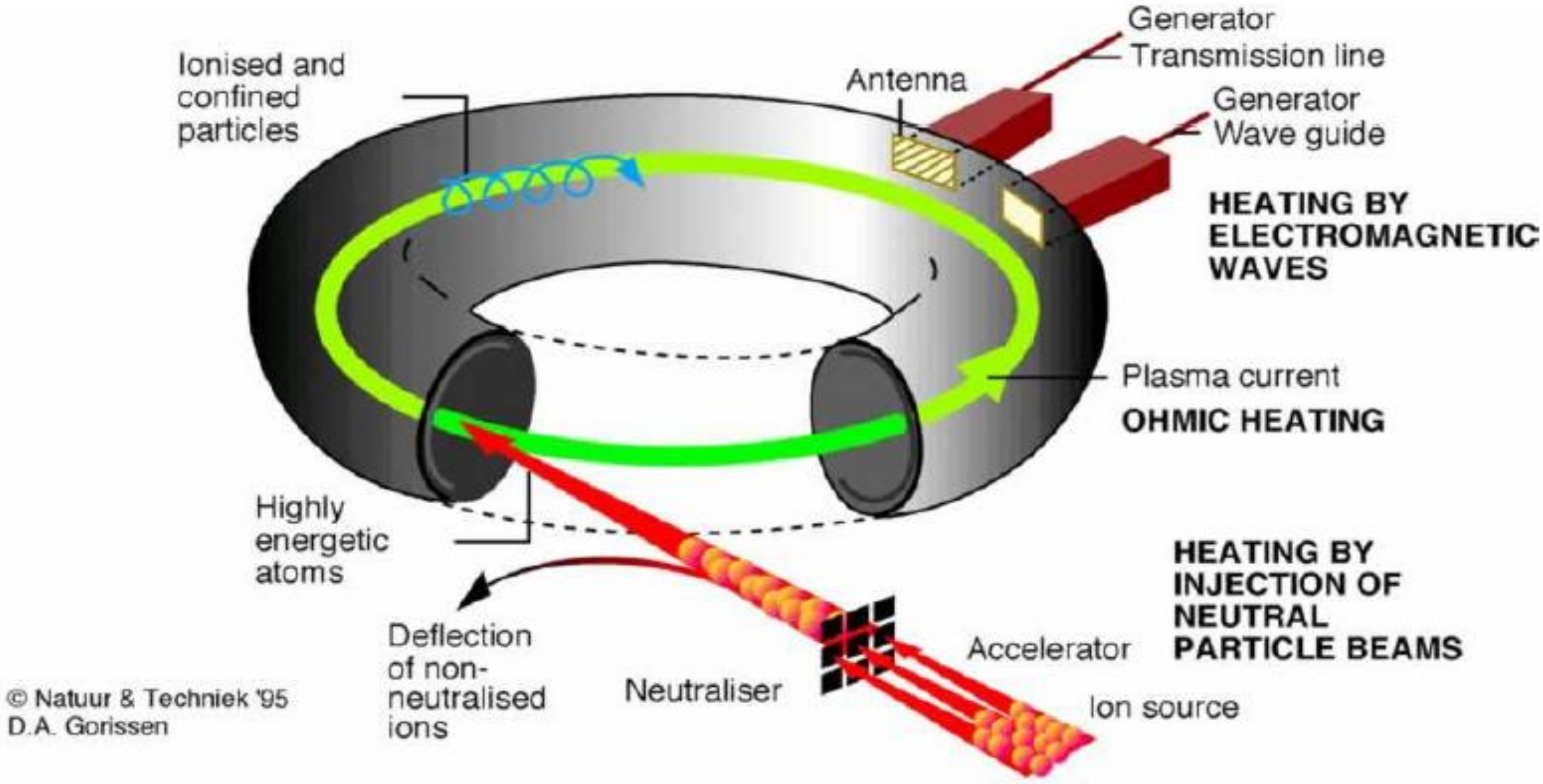
- Instrumentation and Control System

  All hardware and software required to control and operate the ITER machine. Comprises Plant System I&C and Central I&C Systems.

Heating and Current Drive Systems

How to obtain the ultra high temperatures needed ?

Ohmic heating: $\eta \propto T^{-3/2}$ => limited to T~1keV, additional heating needed



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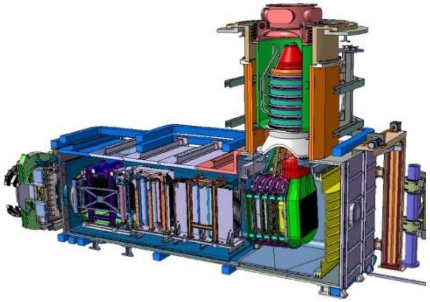
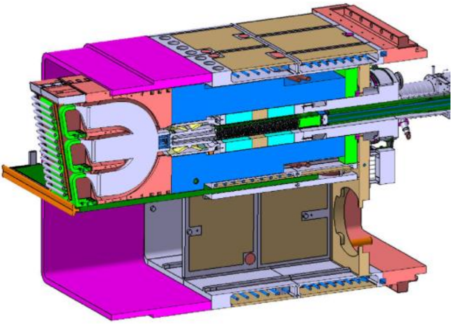
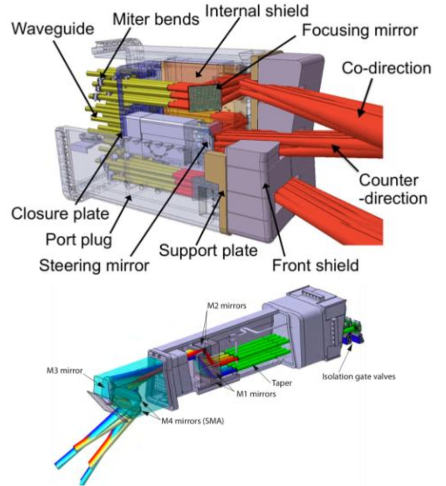
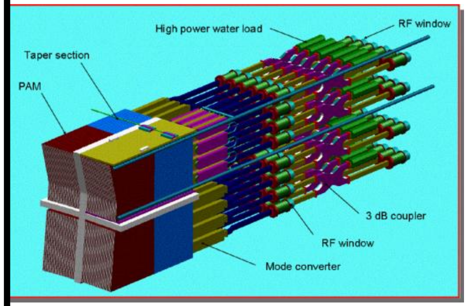
RF Heating and Current Drive Systems

NB	IC	EC	LH
Neutral Beam - 1 MeV	Ion Cyclotron 40-55MHz	Electron Cyclotron 170GHz	Lower Hybrid ~5 GHz
			
33MW* +16.5MW#	20MW* +20MW#	20MW* +20MW#	0MW* +40MW#
Bulk current drive limited modulation	Sawtooth control modulation < 1 kHz	NTM/sawtooth control modulation up to 5 kHz	Off-axis bulk current drive

*Baseline Power
#Possible Upgrade

P_{aux} for Q=10 nominal scenario: 50MW

130 MW (max installed)
(110 MW simultaneous)

Heating and Current Drive Systems

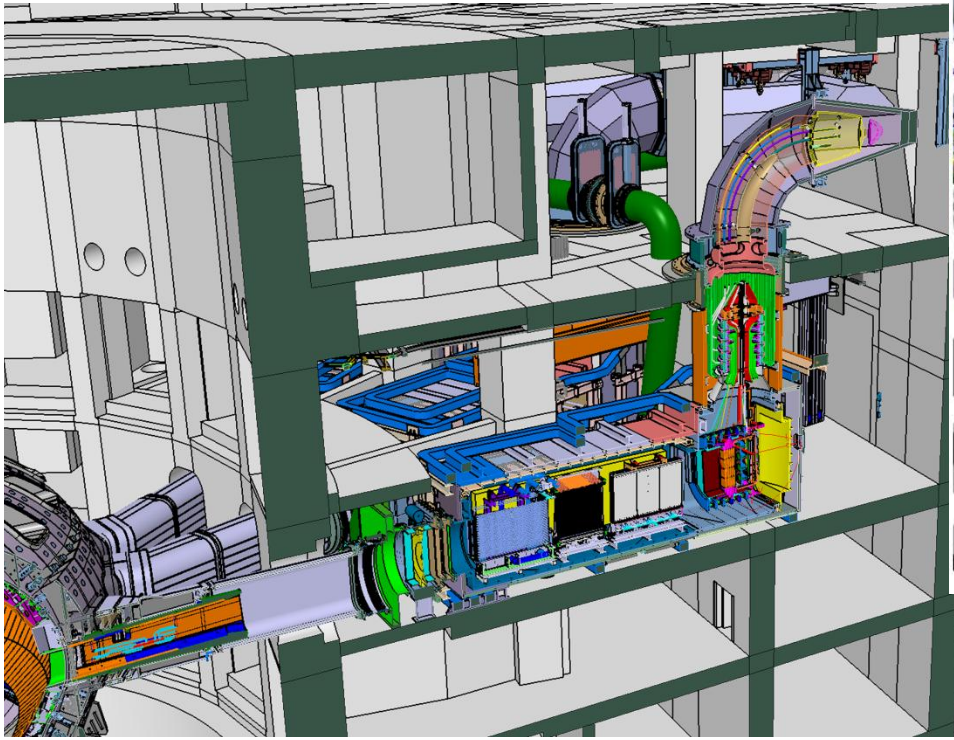
Provide a total auxiliary heating power of 73 MW to achieve H mode and Q=10

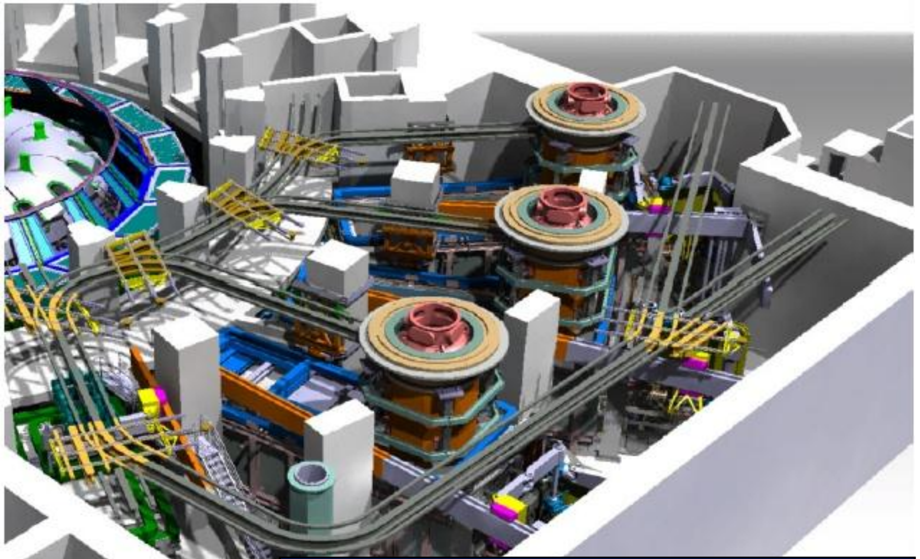
- 2 Heating (HNB) neutral Beams at 1 MV (2X16.5 MW) and Diagnostics (DNB) neutral Beam at 100 kV
- Electron Cyclotron System (EC) (20 MW at 170 GHz)
- Ion Cyclotron System (IC) (20 MW at 40-55 MHz)

Neutral Beam Injector

First of its kind; hence a Neutral Beam Test Facility in Padua:

- 100kV ion source test bed (beg. 2014)
- full size HNB injector test bed (end 2016)





- **2 N-NBIs**
- **P_{beam} = 16.5 MW**
- **I = 40 A**
- **V = 1 MV**
- **T_{pulse} = 3600 s**

60 GJ to be delivered to the plasma by each beam

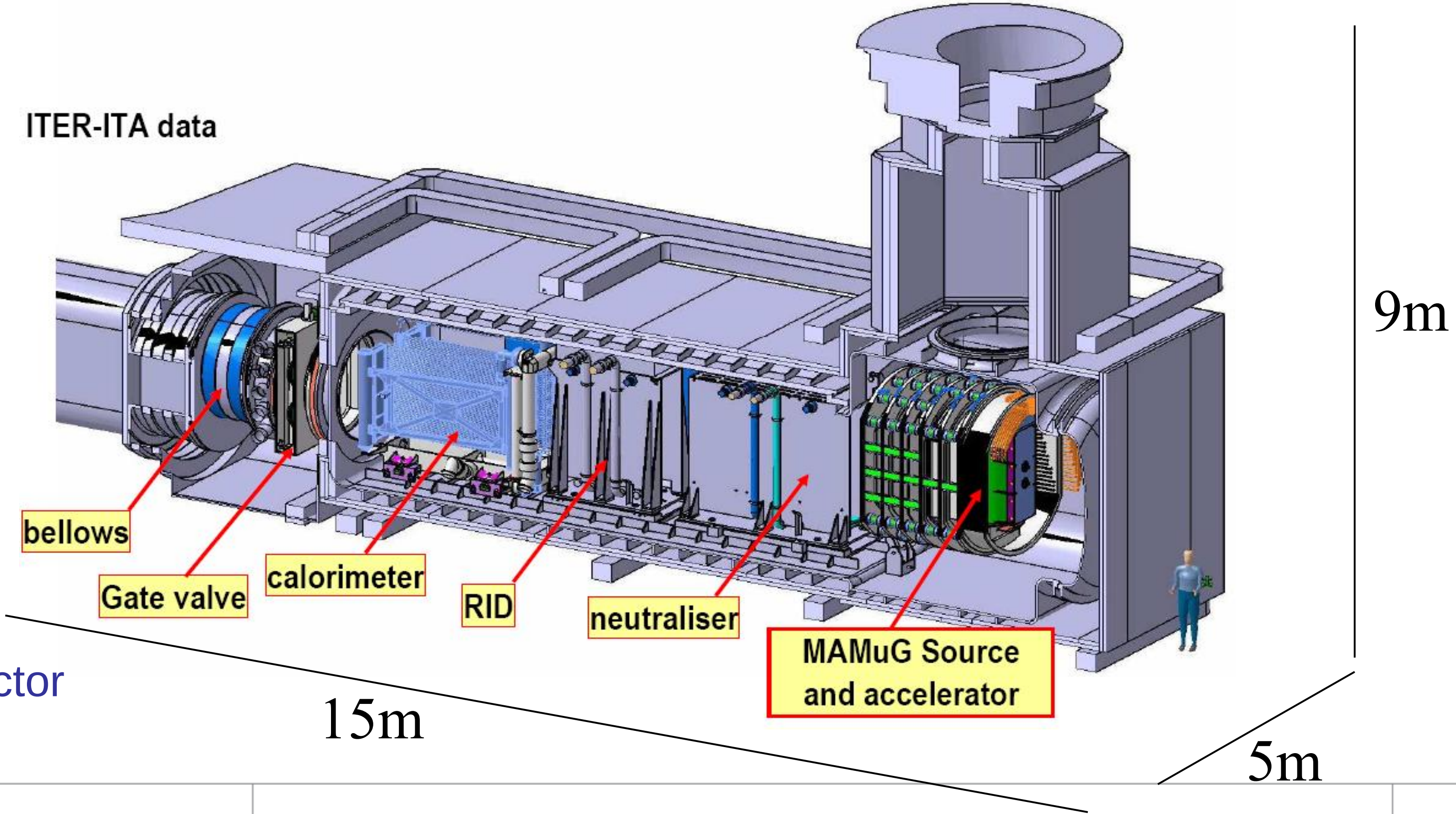
- 1MeV neutrals implies negative ions for efficient neutralisation (60%)

Neutral Beam Injector

The Injector can be separated in

beam components (**Ion Source, Accelerator, Neutralizer, Residual Ion Dump** and Calorimeter)

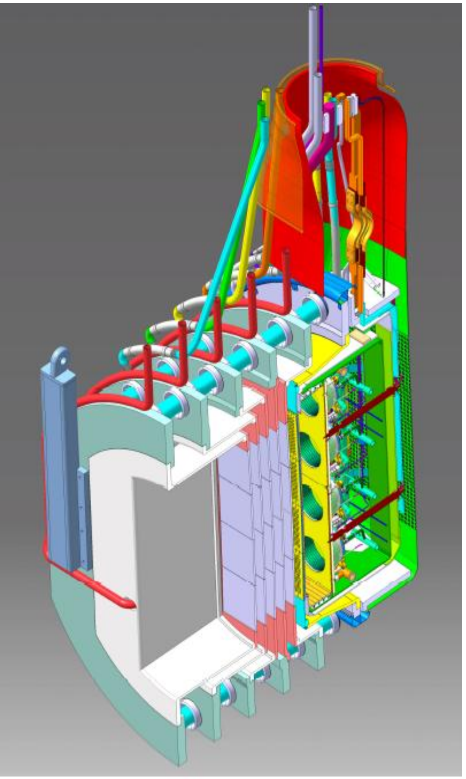
other components (cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils)



HNB Injector
~1000t

Challenges for Neutral Beam Injector

Large scale negative ion source

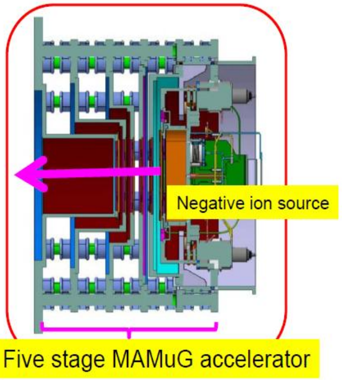


Challenges:

- High current density 200A/m^2 in D$^-$ / 300A/m^2 in H$^-$
- High reliability / low maintenance frequency , 2years
- Stable long pulse operation (for 1hour ITER pulse)
- Spatial and temporal uniformity ± 10%

5 stage Multi Aperture Multi Grid accelerator

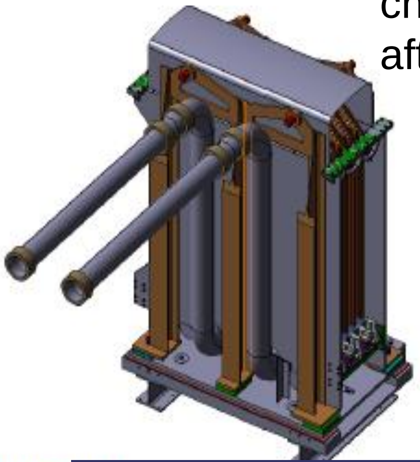
- 200kV per stage
- 1280 apertures in 4 x 4 matrix

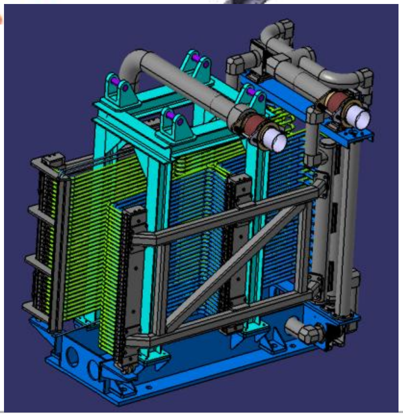


High heat-flux components, like calorimeter or Residual Ion Dump

- Hypervapotron or Swirl-tube technology
- Actively cooled
- CuCrZr

RID: Remove remaining charged ions in the beam after neutralisation

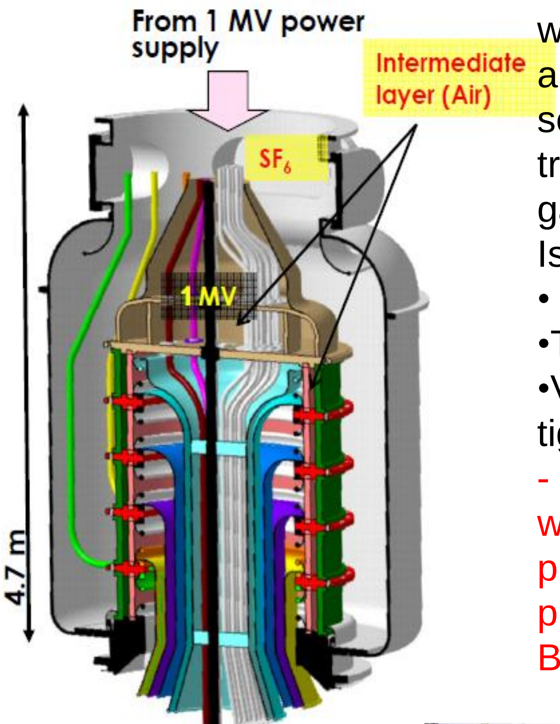




Calorimeter: Used to measure beam power and profile

Challenges for Neutral Beam Injector

1MV HV Bushing for the Heating Neutral Beam Injector



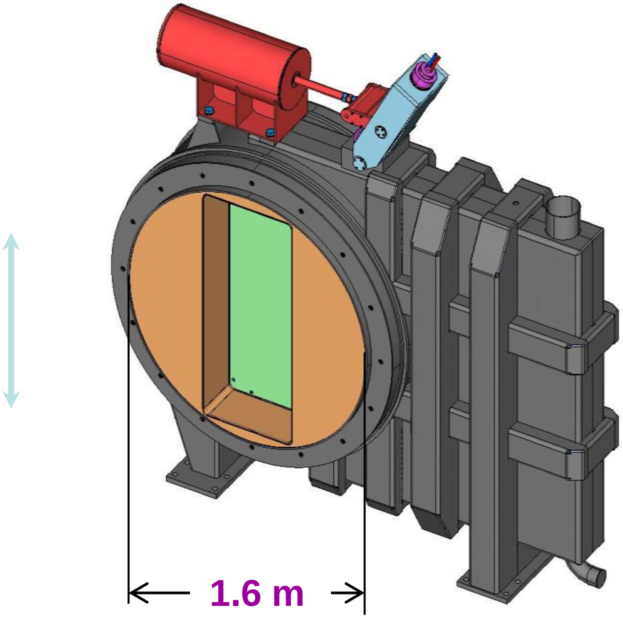
High voltage, cooling water and H_2/D_2 gas are fed to the beam source through HV transmission line (SF6 gas insulation):

Issues:
- HV Holding (1MV)
- Tritium confinement
- Vacuum leak tightness
  - Largest ceramic ring with brazed Kovar plate in the world produced for HV Bushing

Development of an all-metal seal isolation valve of ~ 1.6m diameter

Used to isolate the injectors from the ITER vacuum vessel for interventions:

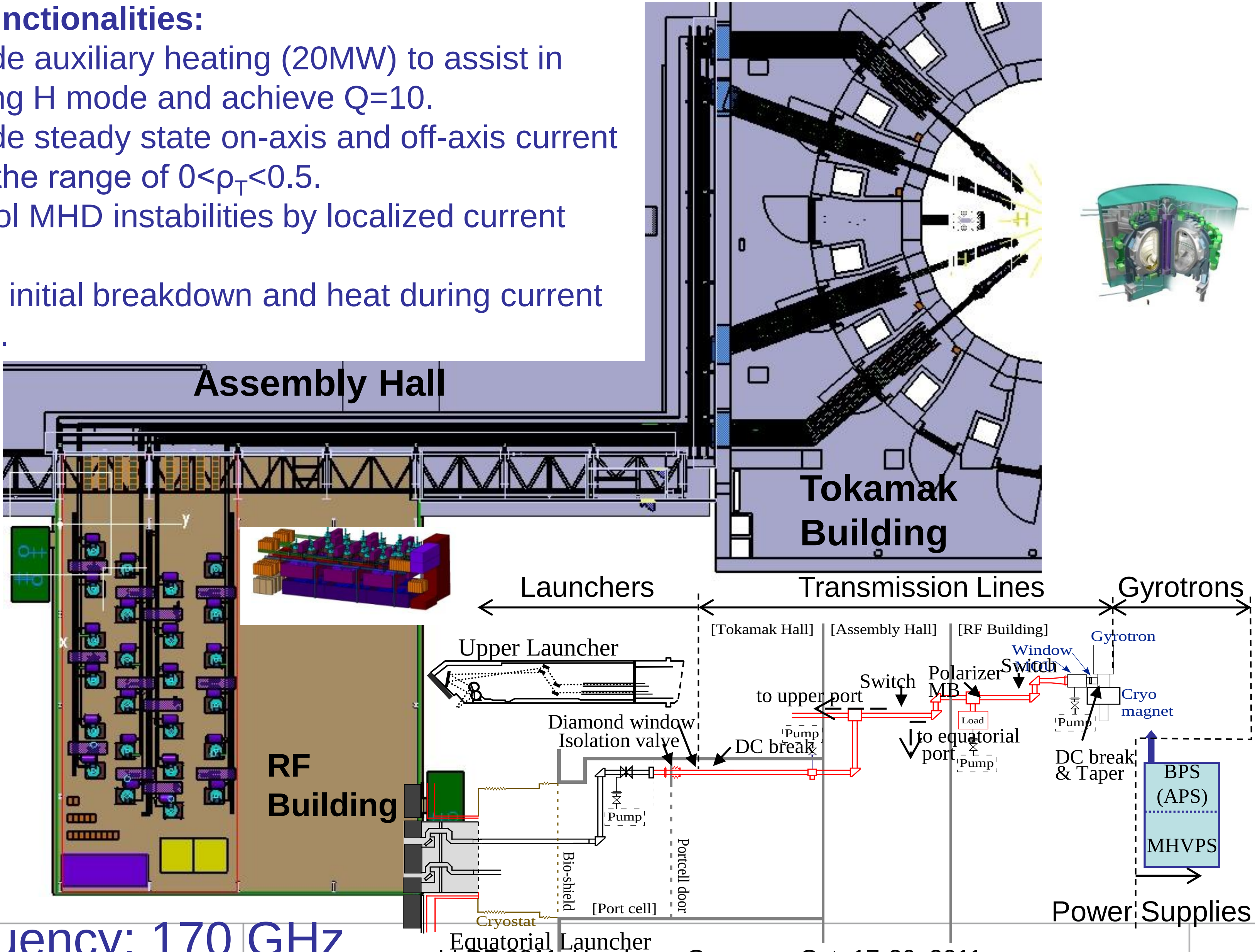
- Weight more than 14.5 tons
- Maximum permissible leak rate 1 x 10^{-10} Pa m^3 /s
- Has to withstand 20MPa in injector, vacuum in ITER vacuum vessel



Electron Cyclotron H & CD System

Main Functionalities:

- Provide auxiliary heating (20MW) to assist in accessing H mode and achieve Q=10.
- Provide steady state on-axis and off-axis current drive in the range of $0<\rho_T<0.5$.
- Control MHD instabilities by localized current drive.
- Assist initial breakdown and heat during current ramp-up.

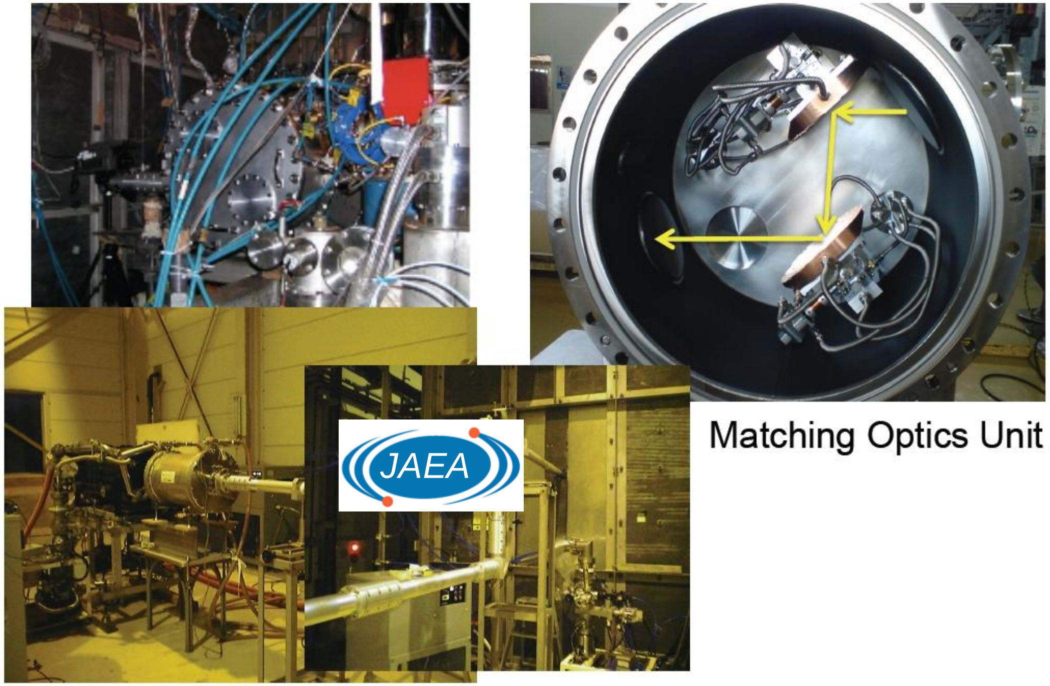


Frequency: 170 GHz

Electron Cyclotron H & CD System

5 Parties provide in-kind procurement of the 4 subsystems

IAP RAS **GYCOM** **INF**



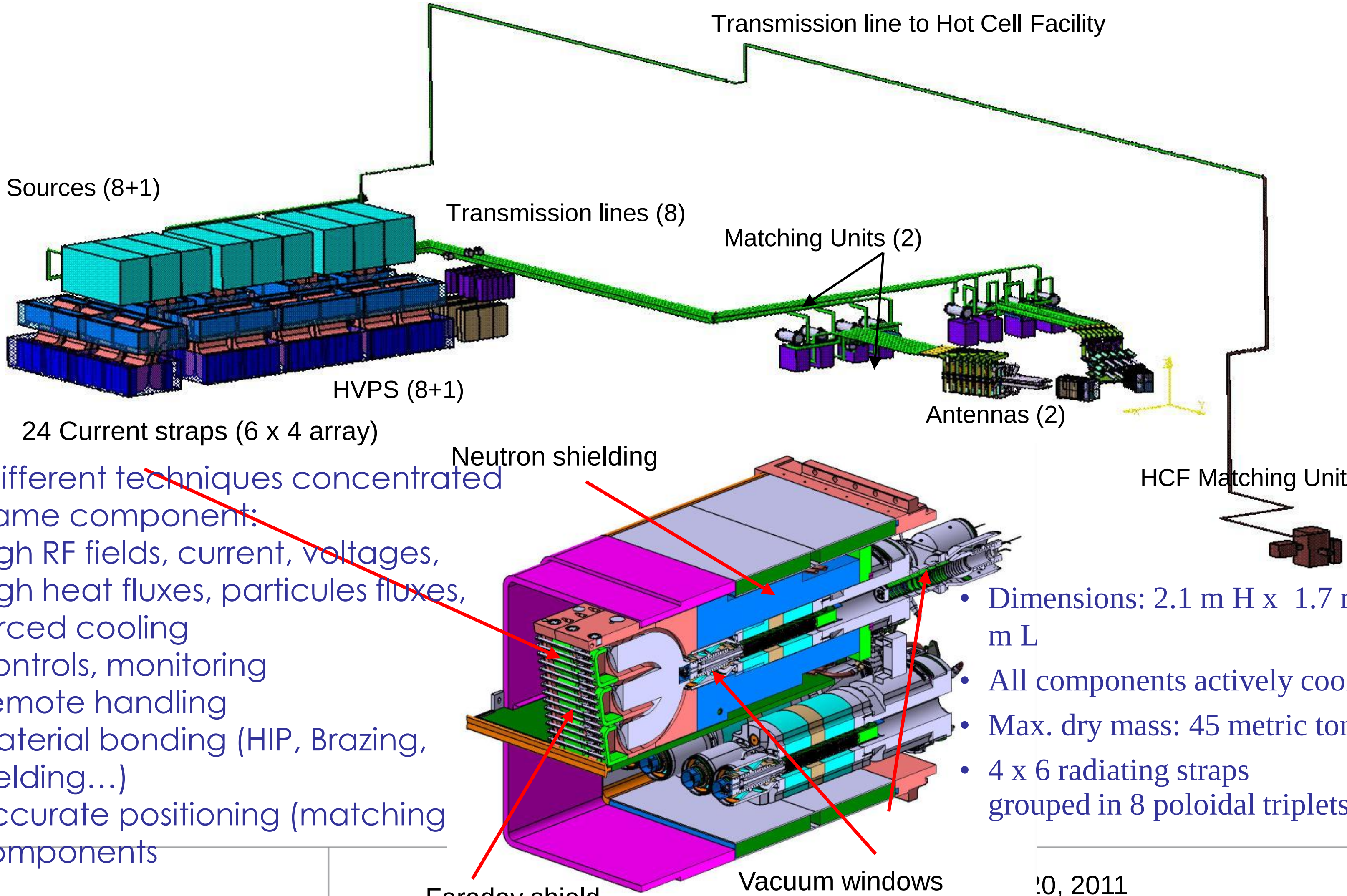
Matching Optics Unit

Cryogen free magnet for 1MW gyrotron (Cryomagnetics, Inc.)

- Cryo-magnets and condensors for gyrotrons (EU, JA, RF, IN)
- HV power supplies (60kV, 100A) and (50kV, <1A) (EU, IN)
- Evacuated waveguide components (US, EU, JA)
- Cooling manifold systems (JA, EU, RF, IN, US)
- Control systems (JA, EU, RF, IN, US)

Ion Cyclotron H & CD System

- Two antennas (equatorial port plugs) (EU)
- Transmission and matching systems (US)
- RF sources (8x3MW + 1 spare, 40-55MHz, for 20MW in plasma) (IN)
- High Voltage power supplies (IN)

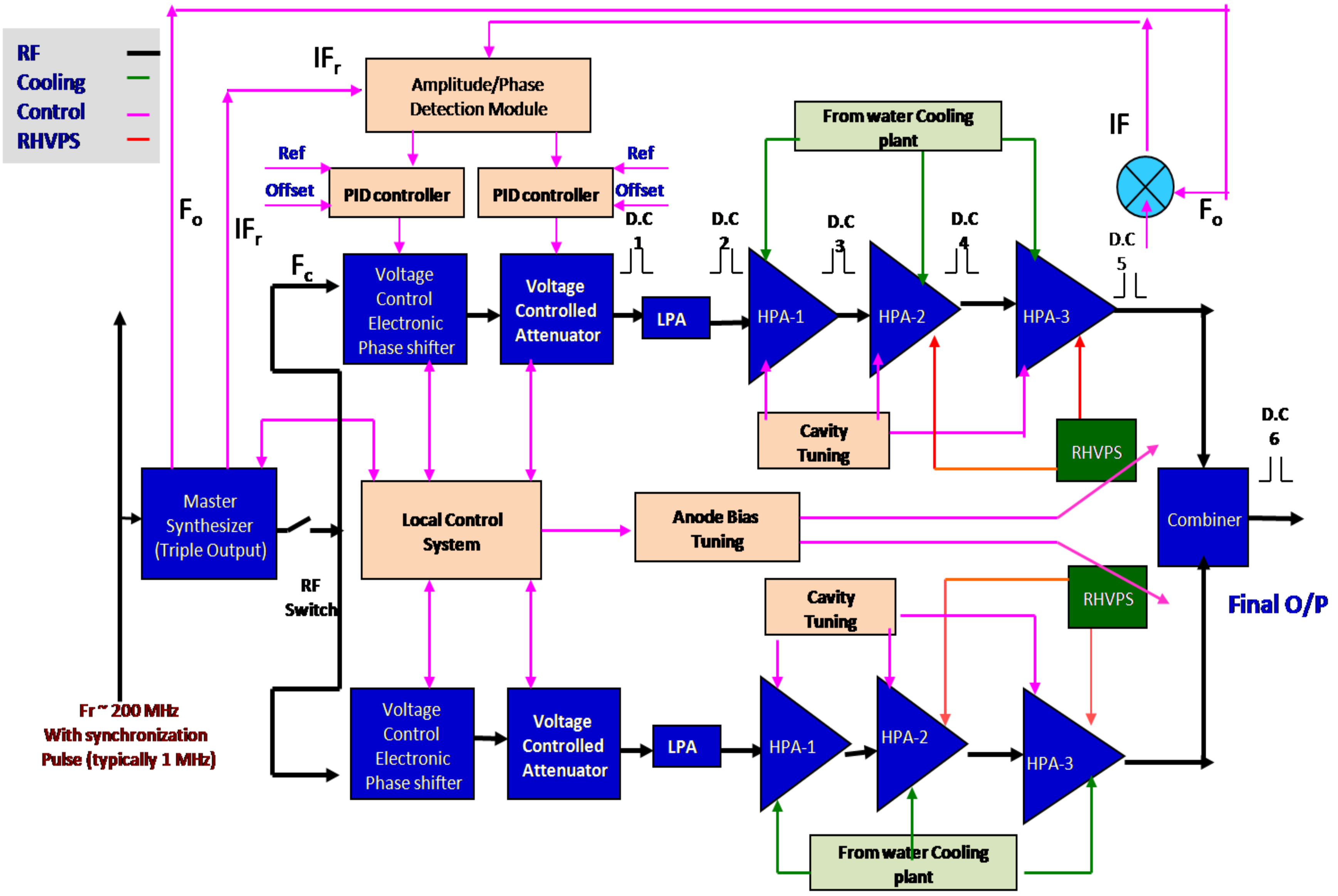


Many different techniques concentrated in the same component:

- High RF fields, current, voltages,
- High heat fluxes, particules fluxes, forced cooling
- Controls, monitoring
- Remote handling
- Material bonding (HIP, Brazing, welding…)
- Accurate positioning (matching components

- Dimensions: 2.1 m H x 1.7 m W x 3.6 m L
- All components actively cooled
- Max. dry mass: 45 metric tons
- 4 x 6 radiating straps grouped in 8 poloidal triplets

ICH RF Power Source Diagram



Diagnostic Systems

Requirements for Diagnostics Measurements

- In order to prevent the plasma and auxiliary heating systems from damaging the internal components, especially the divertor and first wall, measurements of key parameters will be needed in real time at very high reliability, for example: separatrix/wall gap, first wall temperature, fusion power, etc. **Machine Protection**

- Many other measurements are needed to control the plasma in real time so that the required operating regime and plasma performance is achieved, for example: plasma shape and position, plasma current, electron density, impurities, etc **Plasma Control**

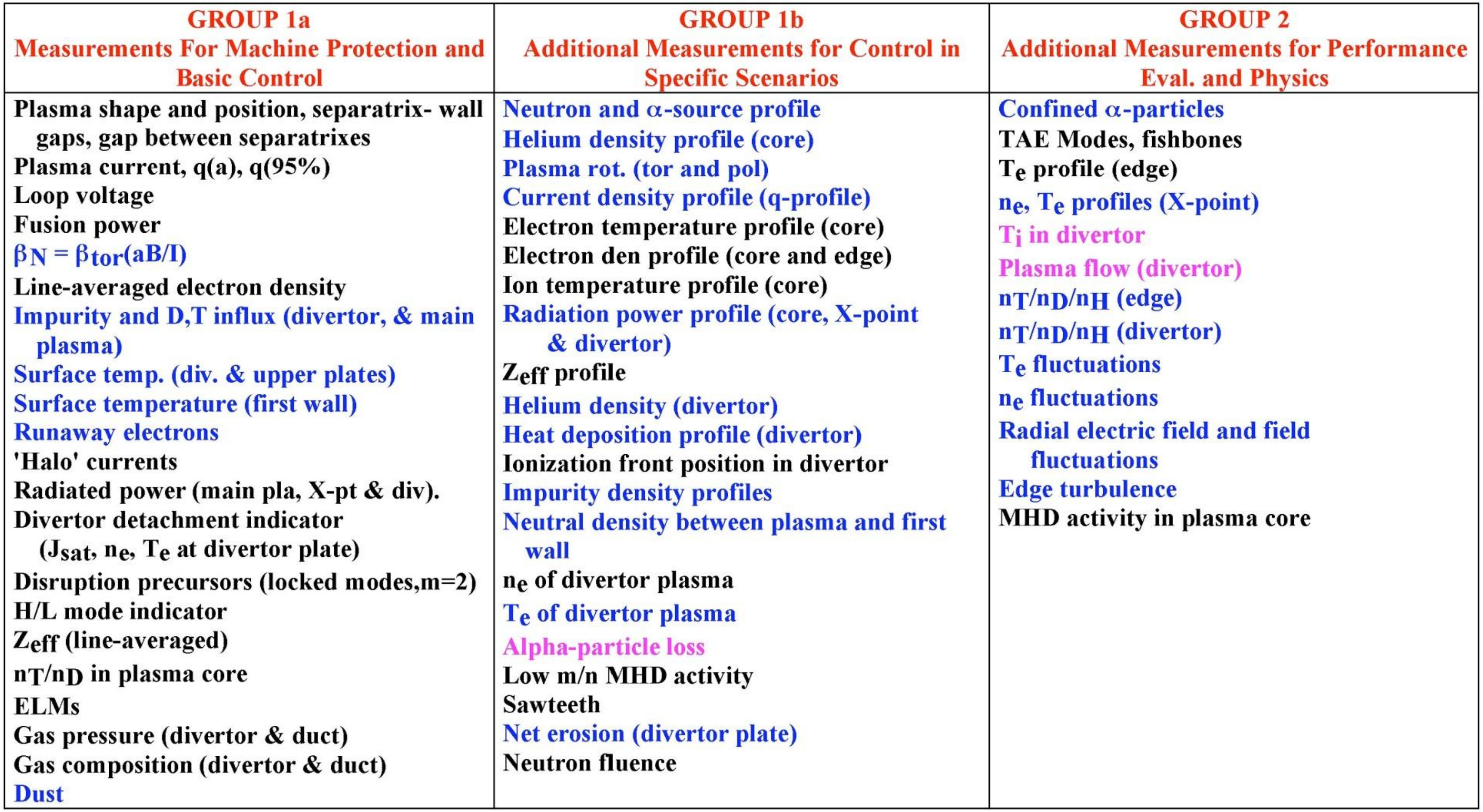
- Additional measurements are needed for specific physics studies, for example: confined and escaping alpha particles, turbulence, n_e and T_e fluctuations, etc **Physics Studies**

Environment for ITER Diagnostics

Relative to existing machines, on ITER some of the diagnostic components will be subject to (relative to JET)

- **Neutron and gamma fluxes (0.1 – 1) x10^{18} n / m^2s (x 5–50)**
- **Nuclear heating 0.3 - 3 MW / m^3 (x 5 – 50)**
- **High fluxes of energetic neutral particles from charge exchange processes (to x5)**
- **Pulse length of 3600s (to x 100)**
- **High neutron fluence (0.2 – 2) x 10^{25} n / m^2 (> x 10^4 !)**
- **For Instrumentation and Controls relevant are:**
  - ➢ **High magnetic field and radiation levels in port cell**
  - ➢ **Long cables to diagnostic building**

Selected Measurements



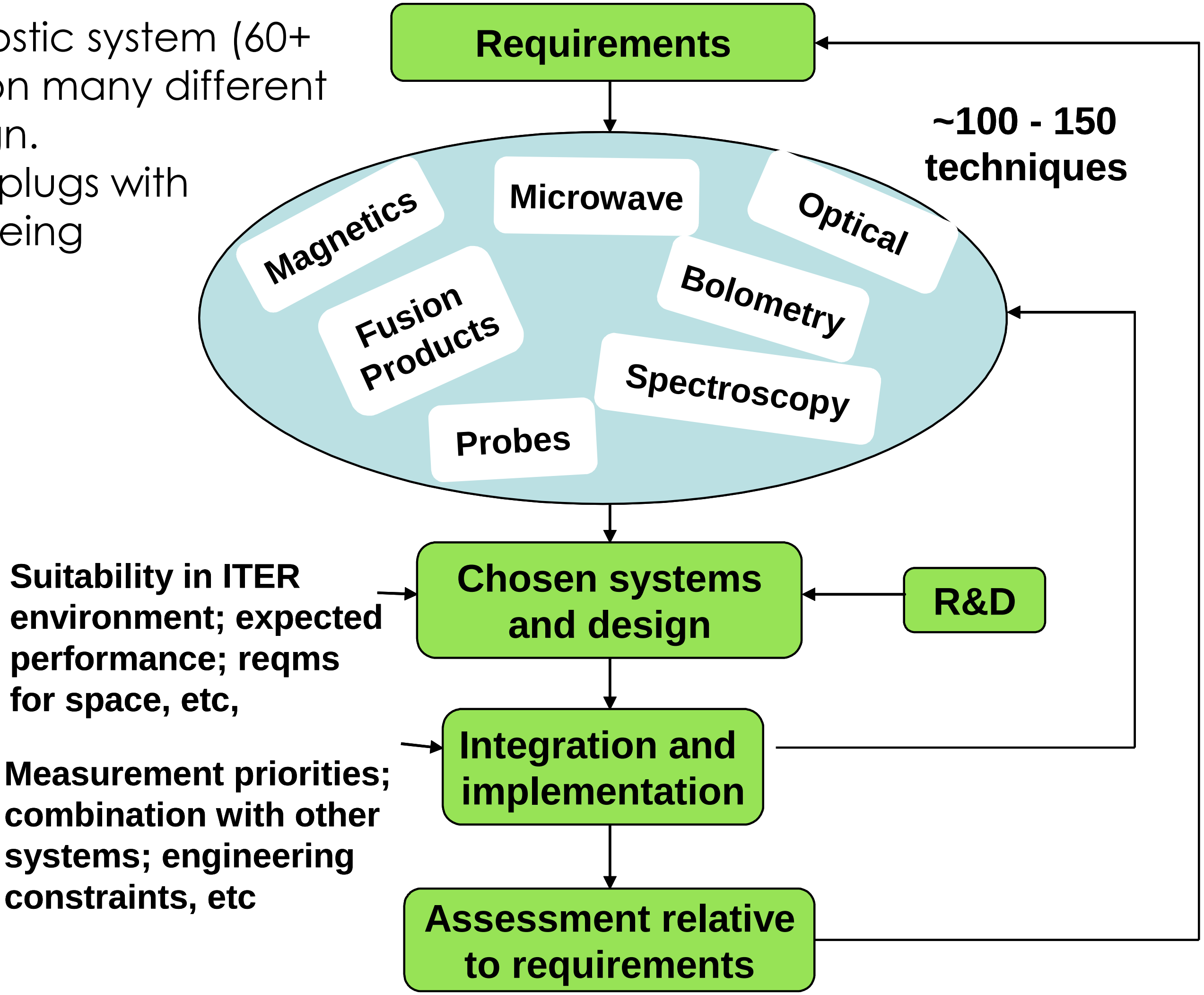
GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Additional Measurements for Control in Specific Scenarios	GROUP 2 Additional Measurements for Performance Eval. and Physics
Plasma shape and position, separatrix- wall gaps, gap between separatrixes Plasma current, q(a), q(95%) Loop voltage Fusion power $\beta_N = \beta_{tor}(aB/I)$ Line-averaged electron density Impurity and D,T influx (divertor, & main plasma) Surface temp. (div. & upper plates) Surface temperature (first wall) Runaway electrons 'Halo' currents Radiated power (main pla, X-pt & div). Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate) Disruption precursors (locked modes,m=2) H/L mode indicator Z_{eff} (line-averaged) n_T/n_D in plasma core ELMs Gas pressure (divertor & duct) Gas composition (divertor & duct) Dust	Neutron and α-source profile Helium density profile (core) Plasma rot. (tor and pol) Current density profile (q-profile) Electron temperature profile (core) Electron den profile (core and edge) Ion temperature profile (core) Radiation power profile (core, X-point & divertor) Z_{eff} profile Helium density (divertor) Heat deposition profile (divertor) Ionization front position in divertor Impurity density profiles Neutral density between plasma and first wall n_e of divertor plasma T_e of divertor plasma Alpha-particle loss Low m/n MHD activity Sawteeth Net erosion (divertor plate) Neutron fluence	Confined α-particles TAE Modes, fishbones T_e profile (edge) n_e, T_e profiles (X-point) T_i in divertor Plasma flow (divertor) $n_T/n_D/n_H$ (edge) $n_T/n_D/n_H$ (divertor) T_e fluctuations n_e fluctuations Radial electric field and field fluctuations Edge turbulence MHD activity in plasma core

Expect to meet measurement requirements; performance not yet known; expect not to meet requirements

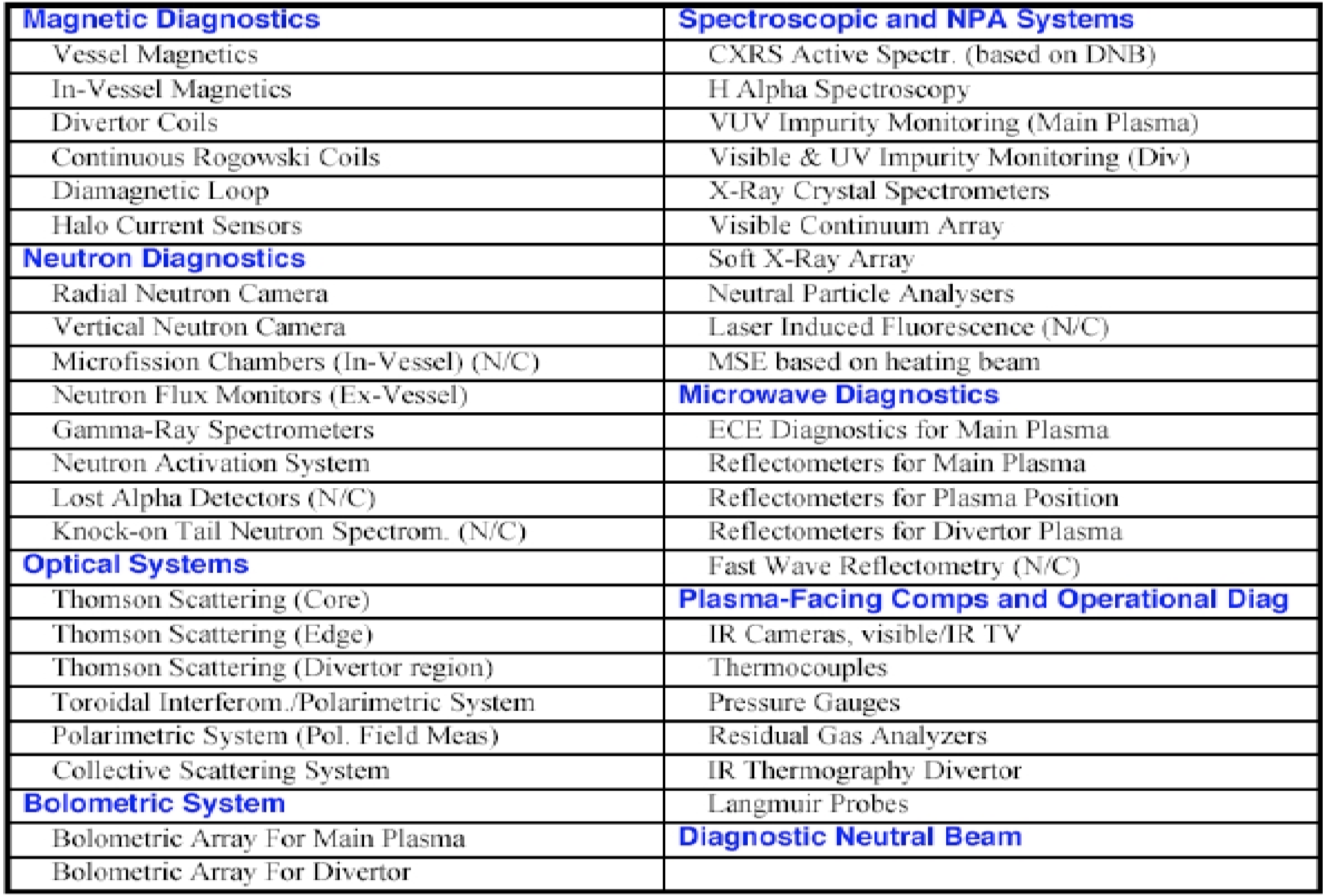
ITER Diagnostics Technologies

- A comprehensive diagnostic system (60+ individual systems) based on many different technologies is under design. Engineering design of port plugs with complicated structures is being progressed.

- A number of R&D projects including irradiation effects on diagnostic components, and innovative diagnostics has been carried out



Selected Diagnostics for ITER



Magnetic Diagnostics	**Spectroscopic and NPA Systems**
Vessel Magnetics	CXRS Active Spectr. (based on DNB)
In-Vessel Magnetics	H Alpha Spectroscopy
Divertor Coils	VUV Impurity Monitoring (Main Plasma)
Continuous Rogowski Coils	Visible & UV Impurity Monitoring (Div)
Diamagnetic Loop	X-Ray Crystal Spectrometers
Halo Current Sensors	Visible Continuum Array
Neutron Diagnostics	Soft X-Ray Array
Radial Neutron Camera	Neutral Particle Analysers
Vertical Neutron Camera	Laser Induced Fluorescence (N/C)
Microfission Chambers (In-Vessel) (N/C)	MSE based on heating beam
Neutron Flux Monitors (Ex-Vessel)	**Microwave Diagnostics**
Gamma-Ray Spectrometers	ECE Diagnostics for Main Plasma
Neutron Activation System	Reflectometers for Main Plasma
Lost Alpha Detectors (N/C)	Reflectometers for Plasma Position
Knock-on Tail Neutron Spectrom. (N/C)	Reflectometers for Divertor Plasma
Optical Systems	Fast Wave Reflectometry (N/C)
Thomson Scattering (Core)	**Plasma-Facing Comps and Operational Diag**
Thomson Scattering (Edge)	IR Cameras, visible/IR TV
Thomson Scattering (Divertor region)	Thermocouples
Toroidal Interferom./Polarimetric System	Pressure Gauges
Polarimetric System (Pol. Field Meas)	Residual Gas Analyzers
Collective Scattering System	IR Thermography Divertor
Bolometric System	Langmuir Probes
Bolometric Array For Main Plasma	**Diagnostic Neutral Beam**
Bolometric Array For Divertor	

Diagnostics by Type (1)

Selected Diagnostic System	Parameters Measured
Magnetic Diagnostics	
Coils and loops mounted on the interior surface of the vacuum vessel. Halo current sensors mounted on the blanket shield module supports. *Coils mounted between the vacuum vessel skins.* Rogowski coils and *loops* mounted on the exterior surface of the vacuum vessel. Coils mounted in the divertor.	Plasma Current, Plasma Position and Shape, Loop Voltage, Plasma Energy, Locked-modes Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Halo Currents, Toroidal Magnetic Field, Static error field of PF and TF, High Frequency macro instabilities (Fishbones, TAE Modes)
Fusion Product Diagnostics	
Radial Neutron Camera, *Vertical Neutron Camera*, Micro-fission Chambers (N/C) Neutron Flux Monitors (Ex-Vessel) Gamma-Ray Spectrometer Activation System, *Lost Alpha Detectors (N/C)* *Knock-on Tail Neutron Spectrometer (N/C)*	Total Neutron source strength, *Neutron/Alpha source profile*, Fusion Power, Fusion power density, Ion temperature profile, Neutron fluence on the first wall, nT/nD in plasma core, *Confined alpha particles*, *Energy and Density of escaping alphas*

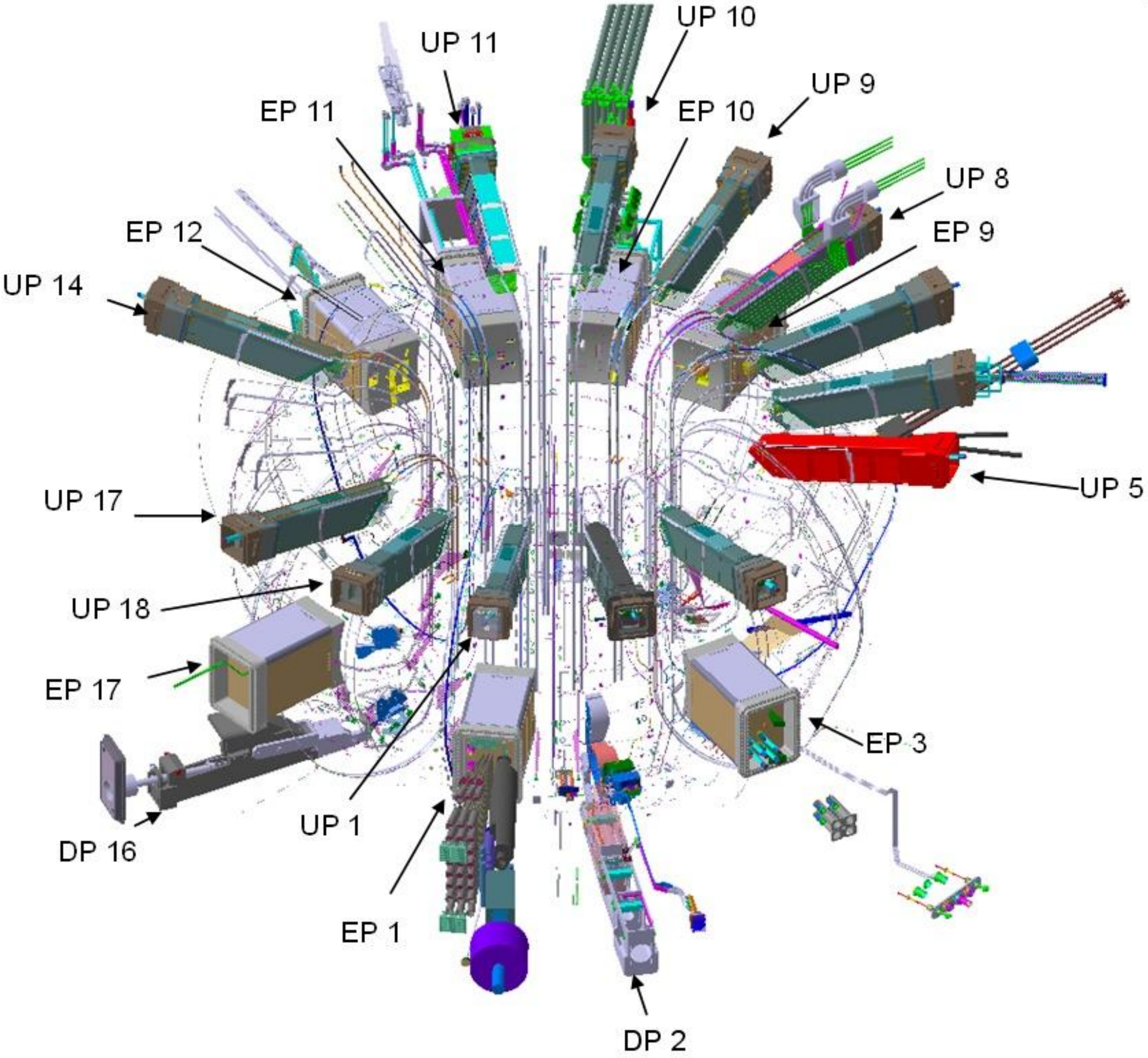
Diagnostics by Type (2)

<table>
<tr><th colspan="2">Optical/IR(Infra-Red) Systems</th></tr>
<tr><td>Core Thomson Scattering
Edge Thomson Scattering , X-Point Thomson Scattering, <i>Divertor Thomson Scattering</i>
Toroidal Interferometer/ Polarimeter, <i>Polarimeter (Poloidal Field Measurement)</i>
<i>Collective Scattering System</i></td><td>Line-Averaged Electron Density
Electron Temperature Profile (Core and Edge)
Electron Density Profile (Core and Edge)
<i>Current profile</i>
<i>Divertor Electron Parameters</i>
<i>Confined alpha particles.</i></td></tr>
<tr><th colspan="2">Bolometric Systems</th></tr>
<tr><td>Bolometer arrays mounted in the ports, in the divertor and <i>in the vacuum vessel.</i></td><td>Total Radiated power, Divertor radiated power
<i>Radiation profile (core and divertor)</i></td></tr>
<tr><th colspan="2">Spectroscopic and Neutral Particle Analyser Systems</th></tr>
<tr><td>H Alpha Spectroscopy, Visible Continuum Array Main Plasma and <i>Divertor Impurity Monitors</i>, X-Ray Crystal Spectrometers,
Charge eXchange Recombination Spectroscopy (CXRS) based on DNB, <i>Motional Stark Effect (MSE) based on heating beam, Soft X-Ray Array (N/C)</i>, Neutral Particle Analysers (NPA), <i>Laser Induced Fluorescence (N/C)</i></td><td>Ion temperature profile, Core He density, Impurity density profile, Plasma rotation, ELMs, L/H mode indicator, nT/nD & nH/nD in the core, edge and divertor, Impurity species identification, Impurity influx, <i>Divertor He density</i>, Ionisation front position, Zeff profile, Line averaged electron density, <i>Confined alphas</i>, <i>Current density profile.</i></td></tr>
</table>

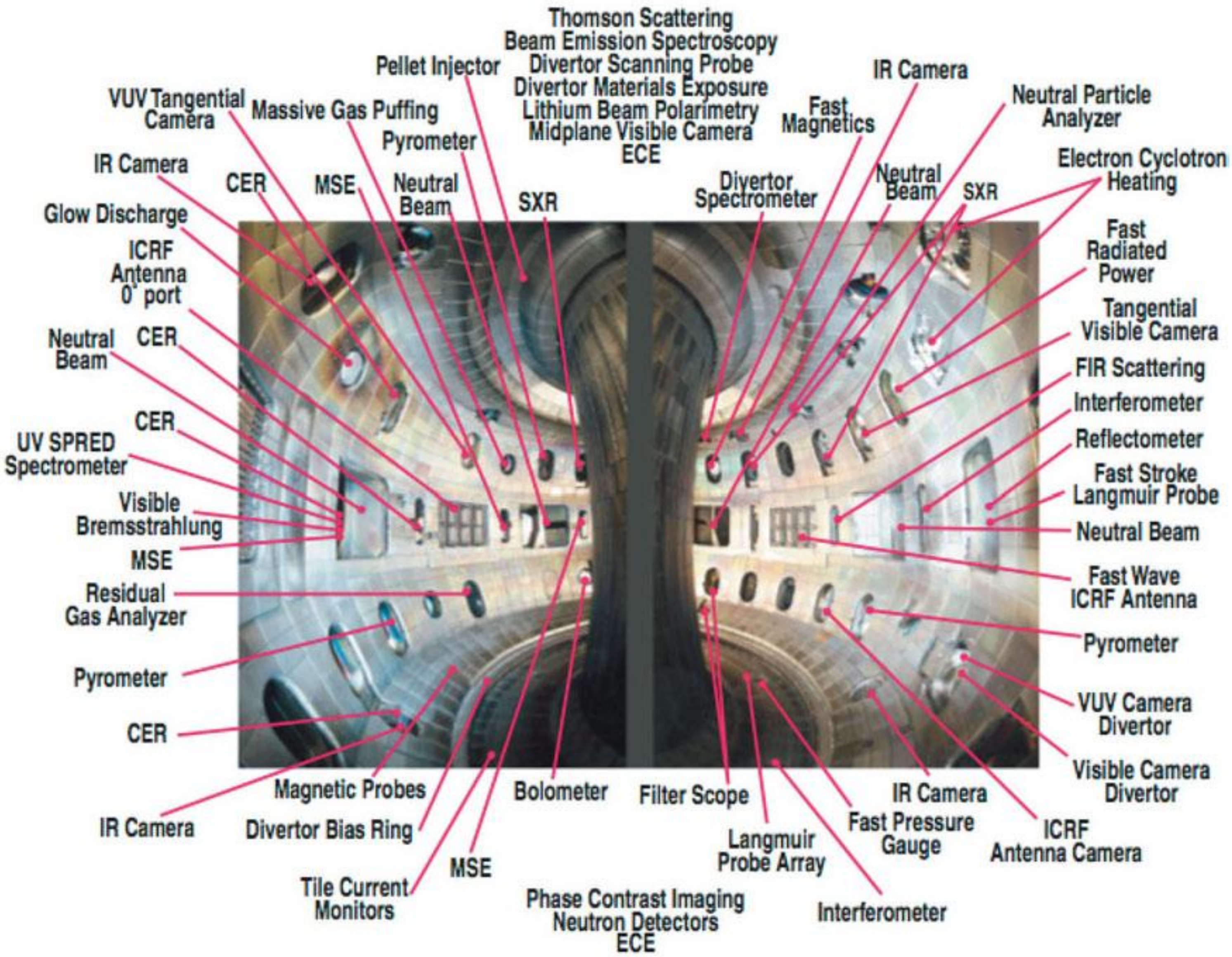
Diagnostics by Type (3)

Microwave Diagnostics	
Electron Cyclotron Emission (ECE) Main Plasma Reflectometer Plasma Position Reflectometer, Divertor Interferometer / *Reflectometer, Divertor EC absorption (ECA)*, Main Wave Plasma Microwave Scattering, *Fast Wave Reflectometry (N/C)*	Plasma position and shape, Locked Modes, Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Plasma Rotation, H-mode indicator, Runaway electrons, Electron Temperature Profile, Electron Density Profile, High Frequency microwave instabilities, *Divertor electron parameters*
Plasma-Facing Components and Operational Diagnostics	
IR/Visible Cameras, Thermocouples, Pressure Gauges, Residual Gas Analysers, *IR Thermography (Divertor), Langmuir Probes*	Runaway electrons: energy and current Gas pressure and composition in divertor Image and temperature of first wall Gas pressure and composition in main chamber and duct, *Escaping alphas*, Ion flux, ne and Te at divertors plates, *Surface temperature and power load in divertor.*

Diagnostic Locations



DIII-D Example for Installed Diagnostics



Basic Diagnostic Needs for I&C

- Data Acquisition
  - 100 kS/s ADCs (16+ bit resolution, 32 ch.)
  - 1 MS/s ADCs (16+ bit resolution, 8 ch.)
  - 100 MS/s ADCs (14+ bit resolution, 8 ch.)
  - 1 GS/s (12 bit resolution, 4 ch.)
  - (Digital) Frame Grabber for Cameras (GbE / CameraLink)
- Signal Processing
  - FPGA
  - DSP
  - CPU
  - GPU
- Communication Links
  - PCI express (PCIe)
  - Gigabit Ethernet (GbE)

Note: Covers most diagnostics fast controller needs

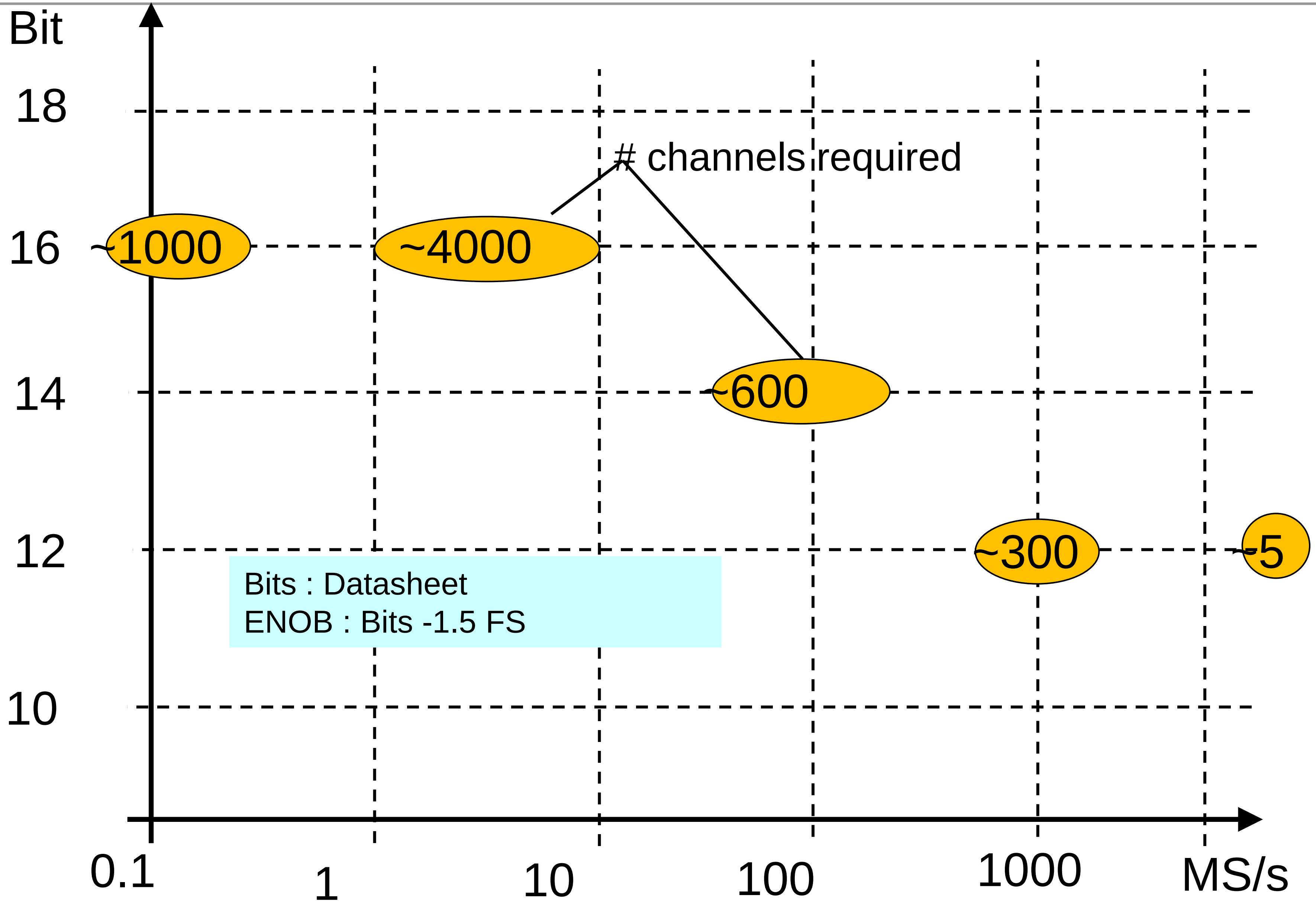
Diagnostics IO Needs

Measurement Group	Signal Conditioning	Data IO	Signal Processing in Plant	Signal Processing in PCS
Magnetics	Chopper Amplifier (low offset)	1400 ADC (1 MS/s) 240 ADC (10 MS/s)	FPGA / GPU / CPU	GPU/CPU
Dosimetry and Fusion Products	Custom	50 ADC (100 MS/s)	FPGA / CPU	GPU/CPU
VIS/IR Cameras	Built-in Camera Functions	24 cameras (1 kHz frame rate)	FPGA / CPU	NA
Optical (ex. LIDAR)	Custom	150 ADC (20 GS/s)	FPGA/GPU	NA
Imaging Spectroscopy	NA	~ 200 cameras / Detector arrays	FPGA / CPU	GPU/CPU
Other spectroscopy and neutral particle analyzer	COTS Spectrometers	Custom	FPGA / CPU	GPU/CPU
Bolometers	Bias + Amplifier	~500 ADC (1 MS/s)		GPU/CPU
Microwave	RF/Microwave Back End	~100 ADC(1 GS/s) ~100 ADC (10 MS/s)	FPGA / CPU (Teraflop computing)	GPU/CPU
(Langmuir) Probes	Preamplifier	~300 ADC (1 MS/s)	CPU	GPU/CPU
Integration System (Port Plugs)	Amplifier/Filter	~100 ADC (1 MS/s)	CPU	NA
Engineering Systems	Amplifier/Filter	~100 ADC (1 MS/s)	CPU	NA

Diagnostics Data Rates (Archiving)

Measurement Group	Data IO	Raw Data Rate (Gbyte/sec)	Processed Data Rate (Gbyte/sec)	Storage/Pulse (GB in 1000s)
Magnetics	1400 ADC (1 MS/s) 240 ADC (10 MS/s)	2.8 4.8	0.056* 0.48*	56 480
Dosimetry and Fusion Products	50 ADC (100 MS/s)	10*	< 0.001	10000 (?)
VIS/IR Cameras	24 cameras (1 kHz frame rate)	50 (uncompressed)	0.5/5* (normal / event)	500+
Optical (ex. LIDAR)	150 ADC (20 GS/s)	0.015*	< 0.001	15
Imaging Spectroscopy	~ 200 cameras / Detector arrays	20*	< 1	20000
Other spectroscopy and neutral particle analyzer	~300 ADC (100MS/s)	60*	< 1	60000 (?)
Bolometers	~500 ADC (1 MS/s)	1	0.05*	50
Microwave	~200 ADC(1 GS/s) ~200 ADC (10 MS/s)	0.2*	0.2*	400
(Langmuir) Probes	~300 ADC (1 MS/s)	0.6	0.6*	600
Integration System (Port Plugs)	~100 ADC (1 MS/s)	0.2	0.2*	200
Engineering Systems	~100 ADC (1 MS/s)	0.2	0.2*	200

First Estimate of ADC needs for Diagnostics



Bits : Datasheet
ENOB : Bits -1.5 FS

Fast Controller R&D Programs (Prototyping)

PXIe (RF-DA)

PXIe (KSTAR)

Existing Installations (IO delivery)

PXIe (Ciemat)

ATCA (IST)
PCIe

ATCA (DMCS)
GbE, PCIe
ADC + Camera

uTCA (ATOS)
ADC

PXIe (CN-DA)
ADC, DAC dig. IO

cRIO (Procon)
ADC, DAC dig. IO

PXIe (NI)
Analog Integrator
(Eagleharbortech)

uTCA(DMCS)
PCIe
ADC + Camera
uRTM Int. (Hytec)

On-going (finish 2011)

PXIe (Ciemat)
+FPGA
+FlexRIO

ATCA (IST)
PCIe
+PCIe Hub +4xAMC
+Timing +4xAMC
+ User Node +4xAMC

Planned (2012)

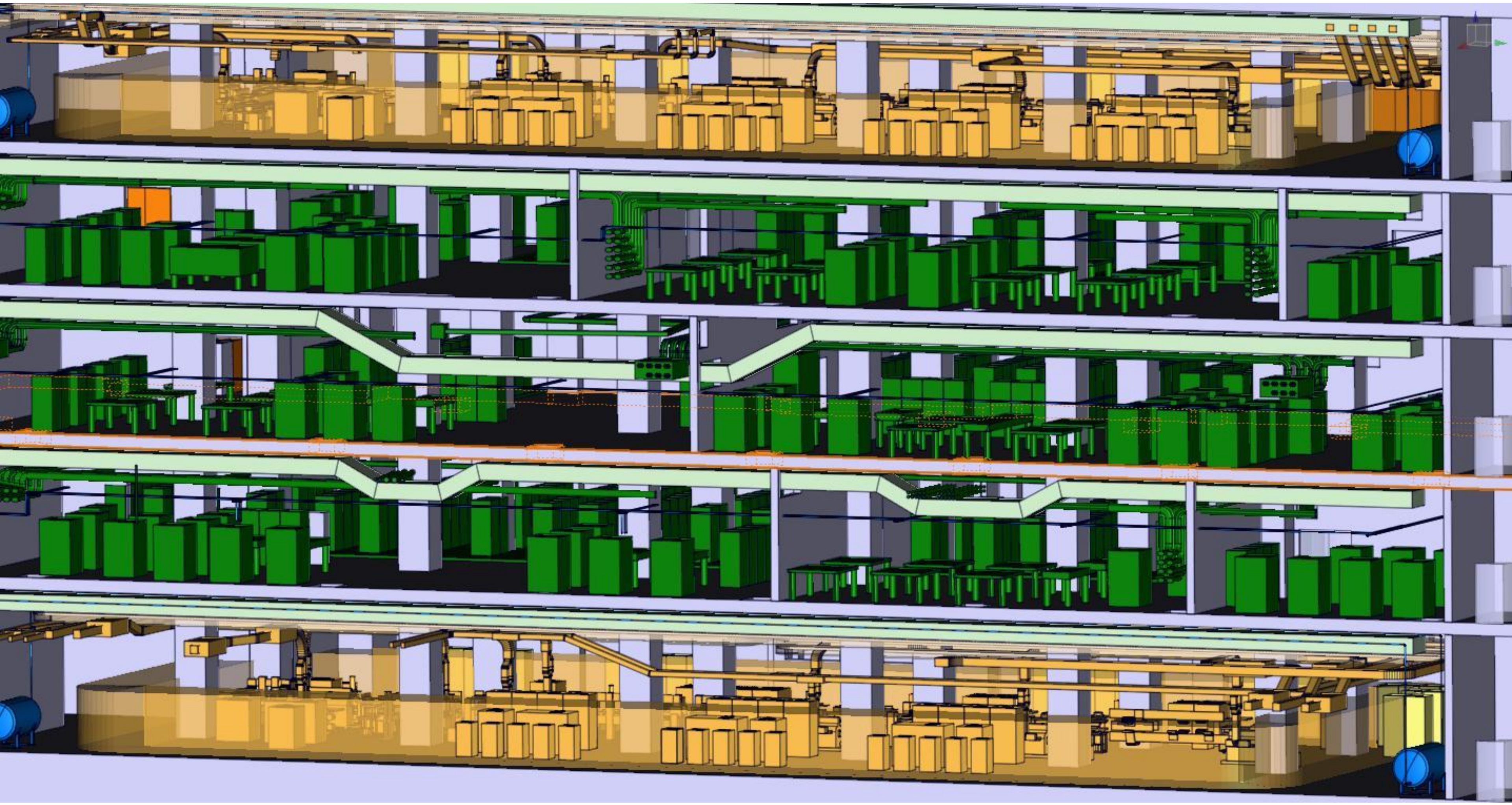
Fast Controller Selection Criteria (in progress)

Fast Controller Formfactor →	PCIe/PXIe	μTCA/μRTM	ATCA
General features / functionality :			
Timing (timing receiver (clock and trigger) / distribution / hardware time stamping)			
Applicable to instrumentation			
Signal conditioning support			
High Availability (up to 99.99 %)			
Magnetic field environment (5 mT and up to 150 mT)			
Radiation (up to 10e5 n / cm**2 / sec)			
EMI shielding / EMC compatibility			
Shelf management			
Health management support (complete system)			
Scalability (IO channels and processing power)			
Modularity (IO, signal processing, comm. links etc.)			
Hardware:			
Analog IO : fast / medium / slow ADCs			
Camera Interface: Camera Link / GbE			
Signal Processing: FPGA / GPU / CPU			
Network : PON / SDN / TCN			
Software:			
EPICS driver (library)			
Linux system driver			
Application programming tools			
FPGA (Virtex 5 and 6)			
GPU (TESLA)			
IOC (CPU)			
Other:			
Cost			
Commercial availability (short / long-term)			

Product Expected from Prototyping

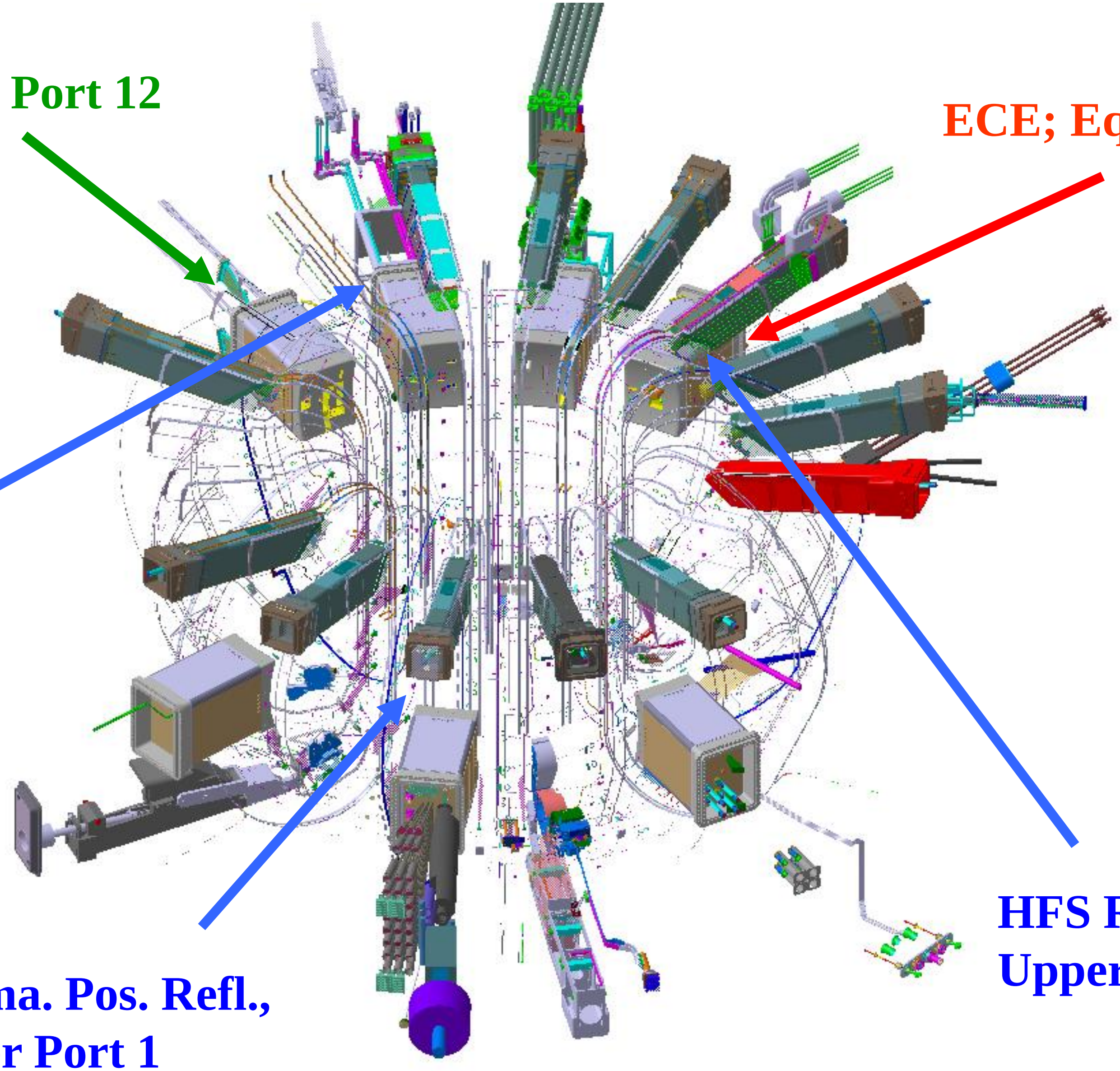
- **Complete example systems close to plant system needs**
  - To be included in CODAC core system
- **Hardware in fast controller catalog**
  - Chassis/shelf (including health monitoring)
  - Boards (ADC, Camera Interface, Timing receiver, Carrier boards)
  - Network Interfaces
- **Software**
  - Linux drivers for boards in fast controller catalog
  - EPICS device support for boards in fast controller catalog
  - Prototype examples included in CODAC core system (Application software, configuration data (SDD), HMI (Boys screens)
  - Source code in SVN
- **Documention in IDM**
  - Cubicle installation and wiring, thermal and fire load studies
  - User and developer manuals
  - Other design documents
  - FAT and SAT reports

Diagnostic Hall for Instrumentation (700 Cubicles)



Microwave Diagnostics

Microwave Diagnostics on ITER: an Overview



CTS (LFS); Eq. Port 12

ECE; Eq. Port 09

LFS Refl.,
Eq. Port 11

HFS Refl.,
Upper Port 8

Plasma. Pos. Refl.,
Upper Port 1

Introduction: Microwave Diagnostics on ITER - responsibilities

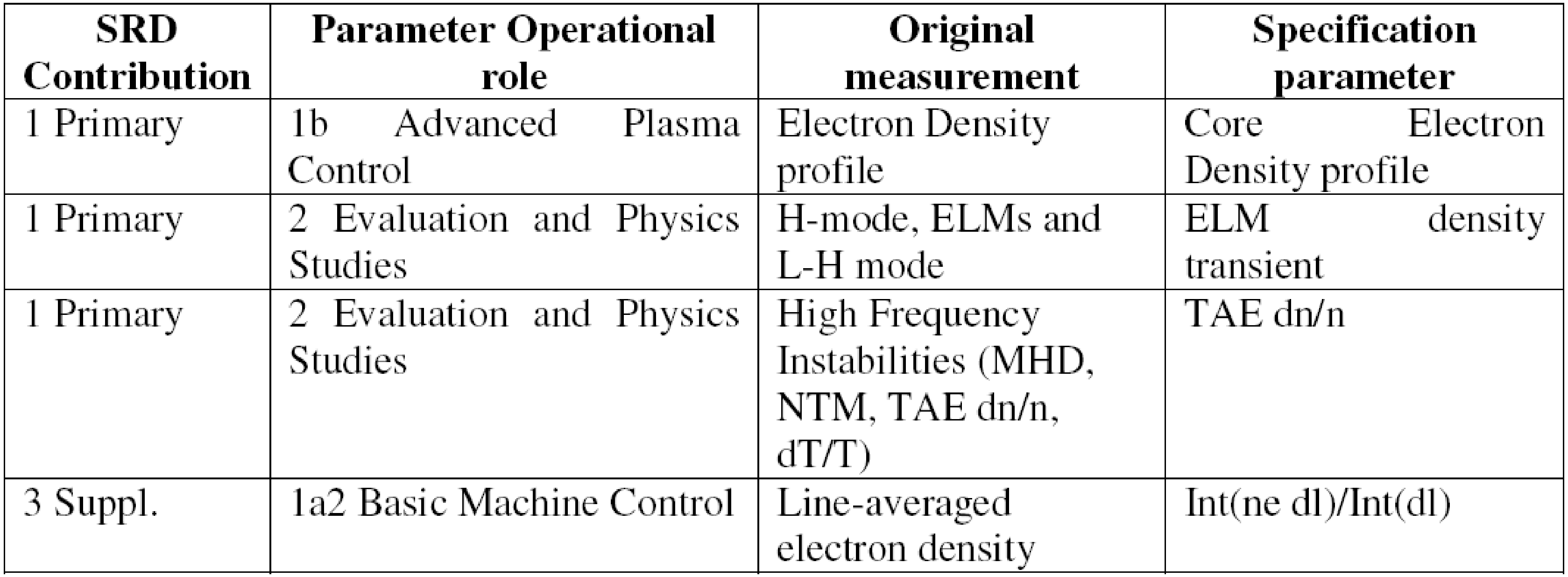
- ECE: Equatorial port 09, Front end: US; Transmission: IN; Receivers: IN and US
- Reflectometers: HFS, in-vessel and Upper Ports 08, 09 and 17: RF

  LFS, EP11: US

  Plasma Position, in-vessel and UP01, 14 and EP09: EU
- Collective Thomson scattering: LFS front end: EU

Integration of all these diagnostics into ITER, taking into account all necessary interfaces, is a challenge

HFS Reflectometry Role



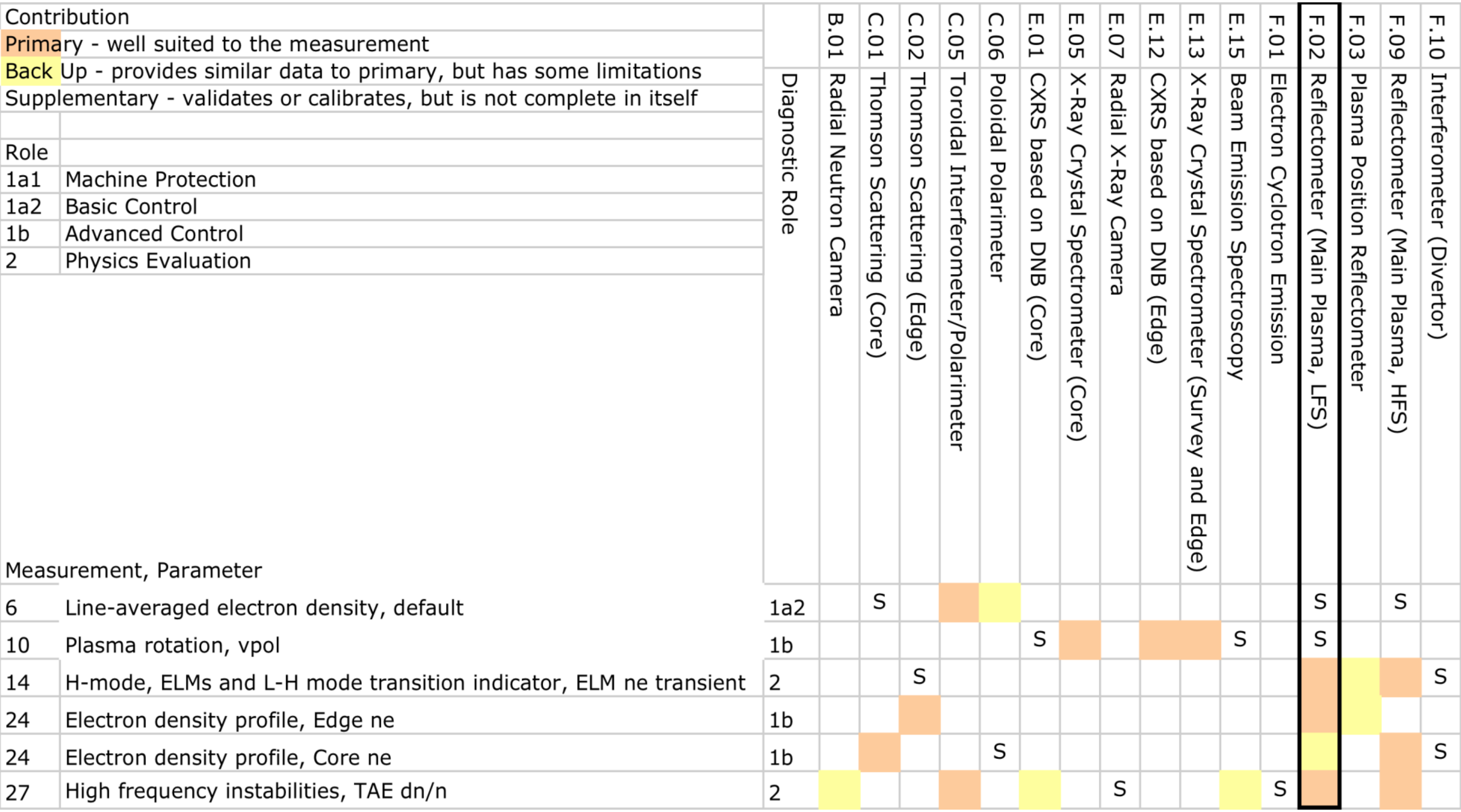
SRD Contribution	Parameter Operational role	Original measurement	Specification parameter
1 Primary	1b Advanced Plasma Control	Electron Density profile	Core Electron Density profile
1 Primary	2 Evaluation and Physics Studies	H-mode, ELMs and L-H mode	ELM density transient
1 Primary	2 Evaluation and Physics Studies	High Frequency Instabilities (MHD, NTM, TAE dn/n, dT/T)	TAE dn/n
3 Suppl.	1a2 Basic Machine Control	Line-averaged electron density	Int(ne dl)/Int(dl)

The locations of the HFS Reflectometry antennas must be capable of monitoring the plasma core to fulfil the measurement requirements.

It is planned to use the same waveguides for X-mode observation in frequency band 10-98 GHz and O-mode observations in the band of 15-155 GHz.

Low-Field-Side Reflectometer

Contributions and Measurement Roles



Contribution
🟧 Primary - well suited to the measurement
🟨 Back Up - provides similar data to primary, but has some limitations
Supplementary - validates or calibrates, but is not complete in itself

Role	
1a1	Machine Protection
1a2	Basic Control
1b	Advanced Control
2	Physics Evaluation

Measurement, Parameter		Diagnostic Role	B.01 Radial Neutron Camera	C.01 Thomson Scattering (Core)	C.02 Thomson Scattering (Edge)	C.05 Toroidal Interferometer/Polarimeter	C.06 Poloidal Polarimeter	E.01 CXRS based on DNB (Core)	E.05 X-Ray Crystal Spectrometer (Core)	E.07 Radial X-Ray Camera	E.12 CXRS based on DNB (Edge)	E.13 X-Ray Crystal Spectrometer (Survey and Edge)	E.15 Beam Emission Spectroscopy	F.01 Electron Cyclotron Emission	F.02 Reflectometer (Main Plasma, LFS)	F.03 Plasma Position Reflectometer	F.09 Reflectometer (Main Plasma, HFS)	F.10 Interferometer (Divertor)
6	Line-averaged electron density, default	1a2		S		🟧	🟨								S		S	
10	Plasma rotation, vpol	1b						S	🟧		🟧	🟧	S		S			
14	H-mode, ELMs and L-H mode transition indicator, ELM ne transient	2			S										🟧	🟨	🟧	S
24	Electron density profile, Edge ne	1b			🟧										🟧	🟨		
24	Electron density profile, Core ne	1b		🟧			S								🟨		🟧	S
27	High frequency instabilities, TAE dn/n	2	🟨			🟧		🟨		S			🟨	S	🟧		🟧	

PCS Needs for Reflectometer Measurements

- **ELM control (MP, BC)**: As a backup measurement of the amplitude and timing of ELMs and pellet perturbations
- **Event handling (BC)**: Together with other measurements, as a backup measurement to distinguish L- and H-mode
- **Plasma position and shape control (BC)**: Additional measurement of the plasma position to verify or correct drift in the magnetic measurements of the plasma boundary
- **Error field control (AC)**: Additional measurement of n=0, 1, 2 boundary perturbations for disruption avoidance
- **Density profile control (AC)**: Primary measurement of n_{eped}, dn_{eped}/dr, and their radial locations
- **Alfvén eigenmode control (AC)**: Measurement of AE amplitude, γ, and radial eigenfunction

Principles and advantages of reflectometry for reactor grade tokamaks

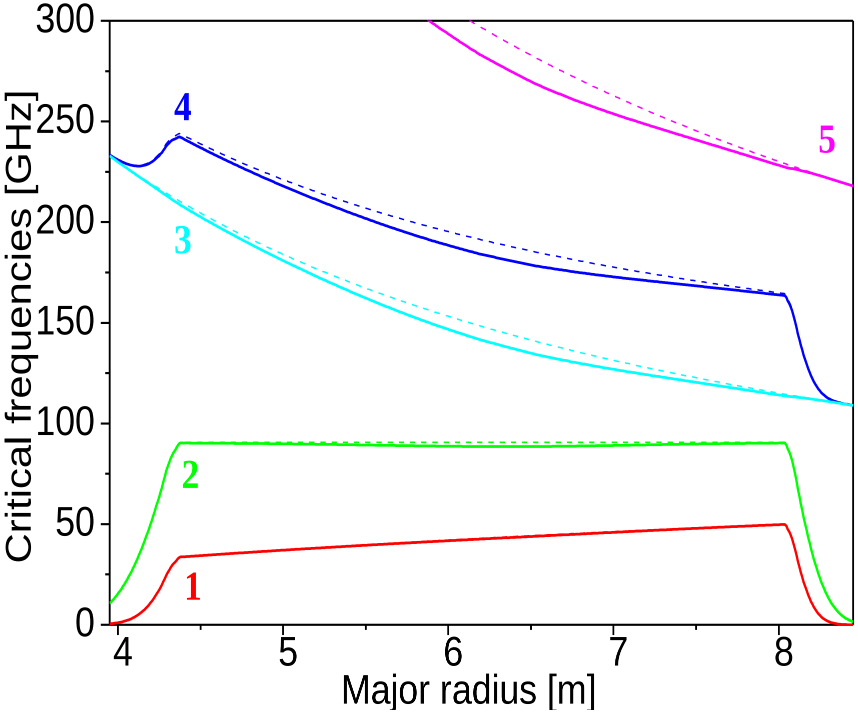
Reflectometry based on the analysis of the characteristics of reflected from critical layer mm-wave. So the phase of the received wave is determined by the integral along the wave pass.

Thus it is possible to reconstruct the density profile from the phase or time delay of the waves reflected from plasma with a set of frequencies.
It is important to note that as the waves propagate along the same line the procedure of density profile recovering from the integral equation does not need any assumptions about the symmetry as in interferometry.

The fluctuations of the reflected wave gives important information about plasma density fluctuations. As the typical wavelength is in mm range, reflectometry is very sensitive to small density fluctuations.

As reflectometry measures the plasma properties at given poloidal and toroidal angles, it enables to investigate poloidal and toroidal characteristics of turbulence and plasma position by means of probing at a number of angles.

Principle of ITER HFS Reflectometry

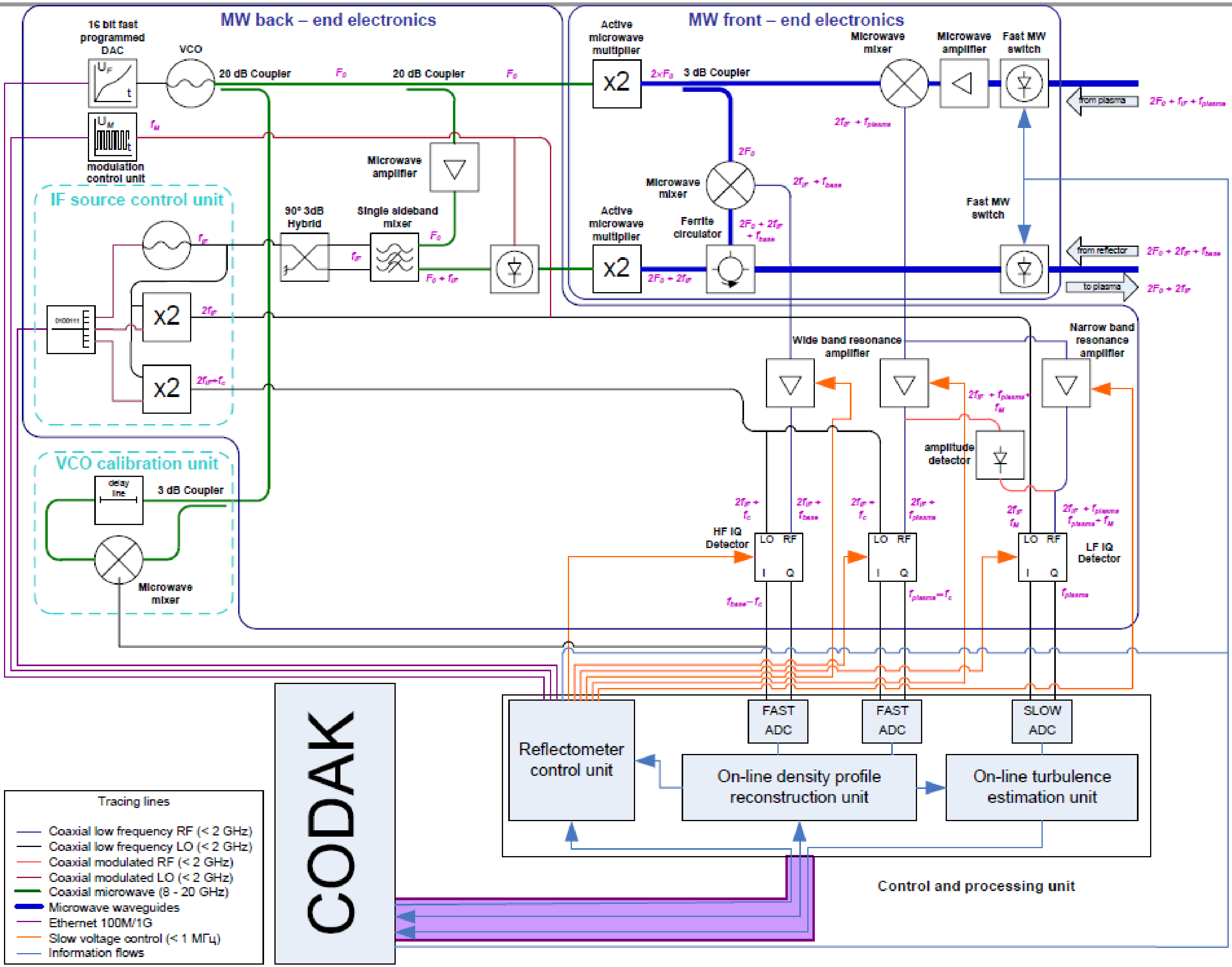


Two branches exist for electromagnetic wave propagation in plasma with magnetic field. - Ordinary (O) wave with electric field parallel to the magnetic field line direction. Extraordinary (X), wave with electric field perpendicular to the magnetic field line has two waves Xu and Xl with cut off frequencies: Waves permittivities at high temperature should be corrected to account relativistic effect.

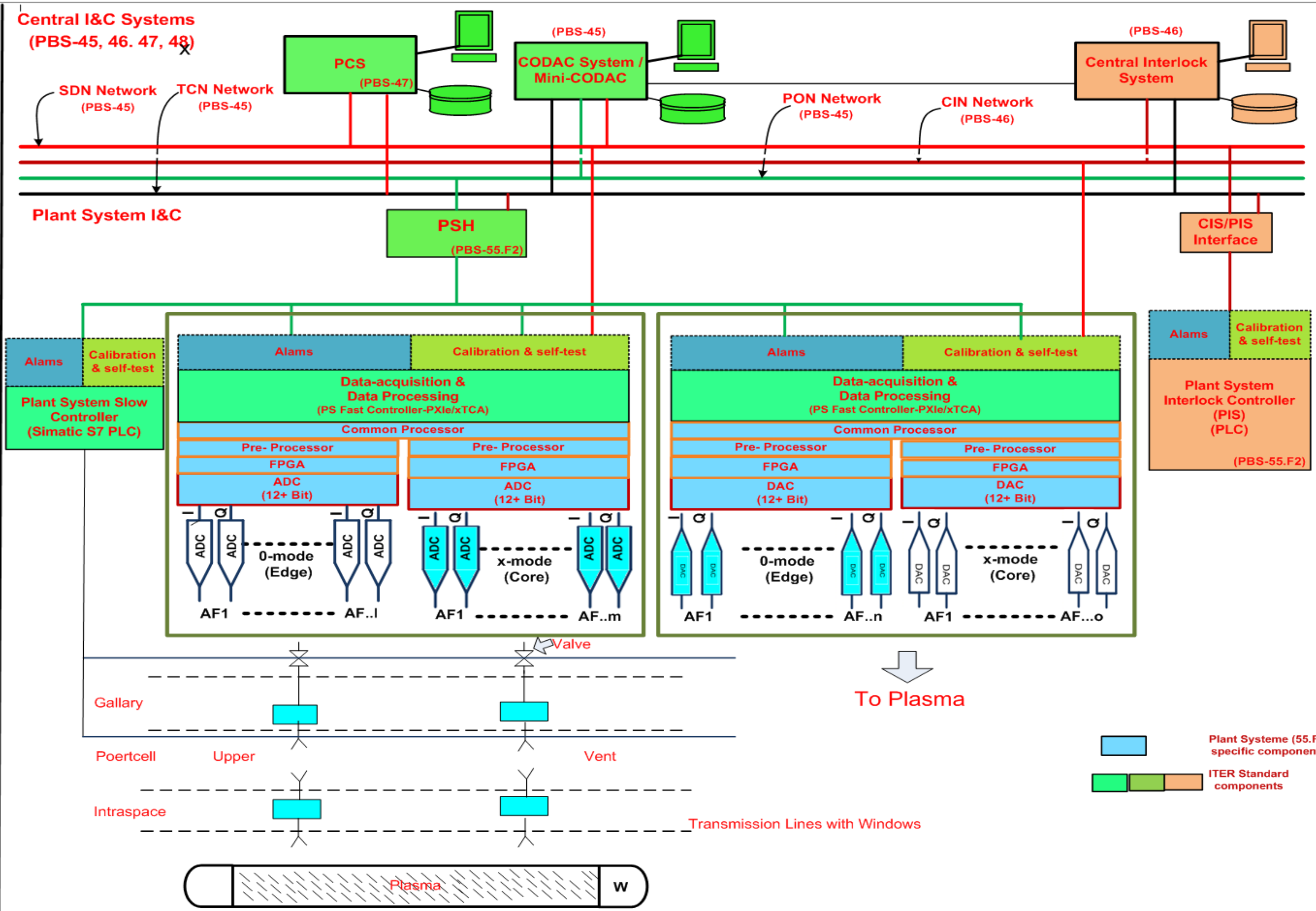
HFS reflectometry probes plasma from inner equator circumference of the torus in order to access to the core plasma with flat density profile and uses O and X-waves. For densities up to 3 10^{20} m^{-3} O and X-modes should use frequencies from 15 to 155 GHz and 10 – 98 GHz respectively.

Advantages of HFS reflectometry: ability to access core plasma at flat density profile; relatively low frequencies (higher launched power-higher Signal/Noise, less influence of turbulence); lower turbulence level at HFS (higher measurement accuracy); small relativistic corrections; low plasma emissivity at the used frequencies (higher S/N).

Front-end Electronics for HFS



I&C Functional Breakdown for LFS Reflectometry

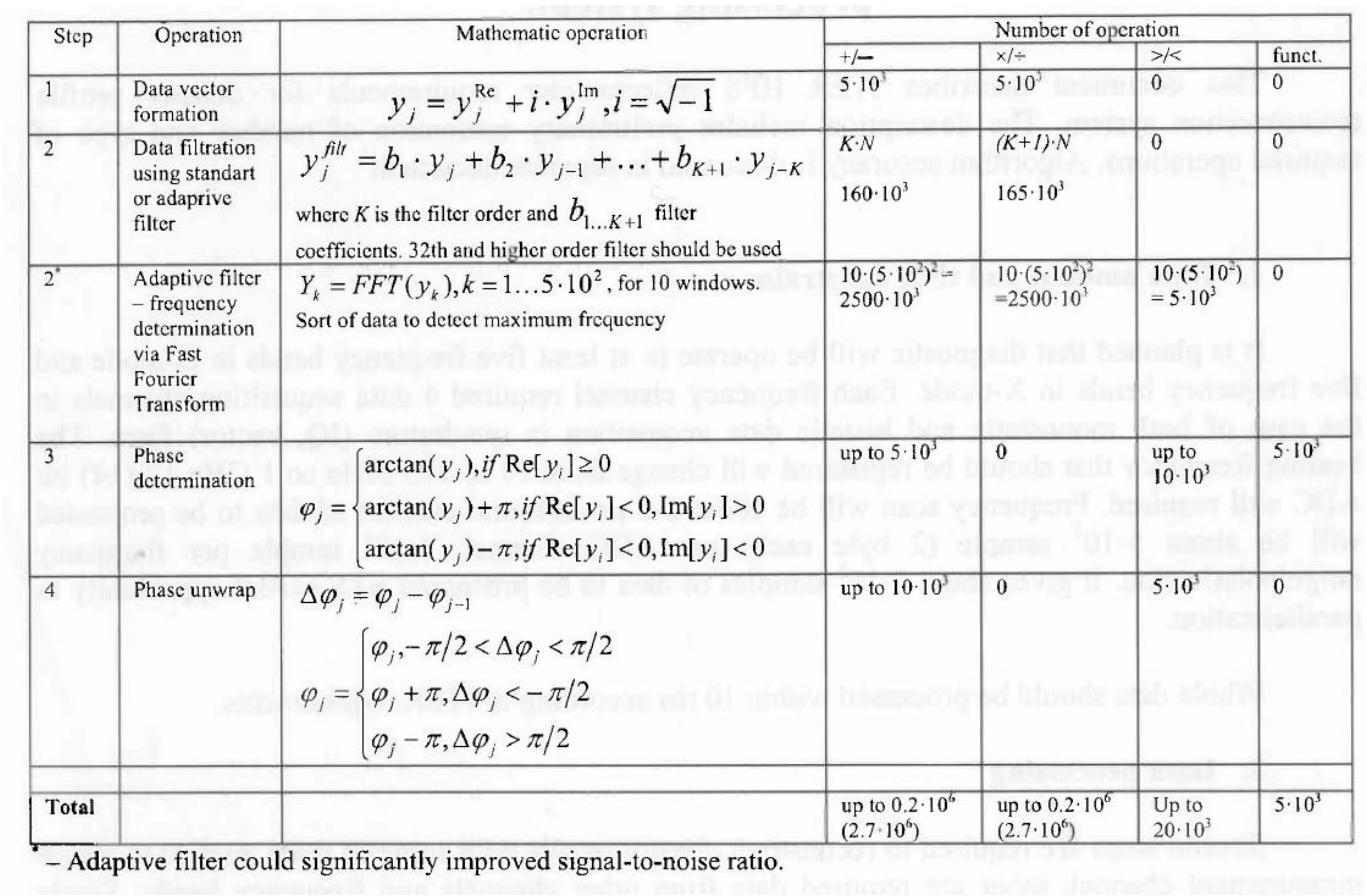


55.F2 (LFS) I&C Functional Breakdown

DAQ and Signal processing Requirements for LFS Reflectometry

	ADC / other I/O / comm	**Processing**	**Comm**
Profile Reflectometer 1. Data acquisition (IF) 2. Real time measurement 3. Microwave source ctrl. 4. Monitor data	30 x 500 MS/s (12+bit) Commlink (DAQ → PROC) few DAC / dig. I/O 30 x 250 MS/s (12+bit)	FPGA, CPU (~1 GF/1ms ?) 1.25 kS/ch.	PCIe
Doppler Reflectometer 1. Data acquisition (IF) 2. Real time measurement 3. Microwave source ctrl. 4. Monitor data	8 x 50 MS/s (12+bit) Commlink (DAQ → PROC) Few DAC/ dig. I/O 8 x 10 MS/s (12+ bit)	FPGA, CPU	PCIe
Turbulence / MHD Reflect. 1. Data acquisition (IF) 2. Real time measurement 3. Monitor data	60 x 50 MS/s (12+bit) Commlink (DAQ → PROC) 30 x 0.1 MS/s (12+bit)	FPGA, CPU	PCIe
Power Transmission / ECH 1. Monitoring 2. ECH Protection	120 x 0.1 MS/s (12+bit) 12 x 10 MS/s (12+bit)		

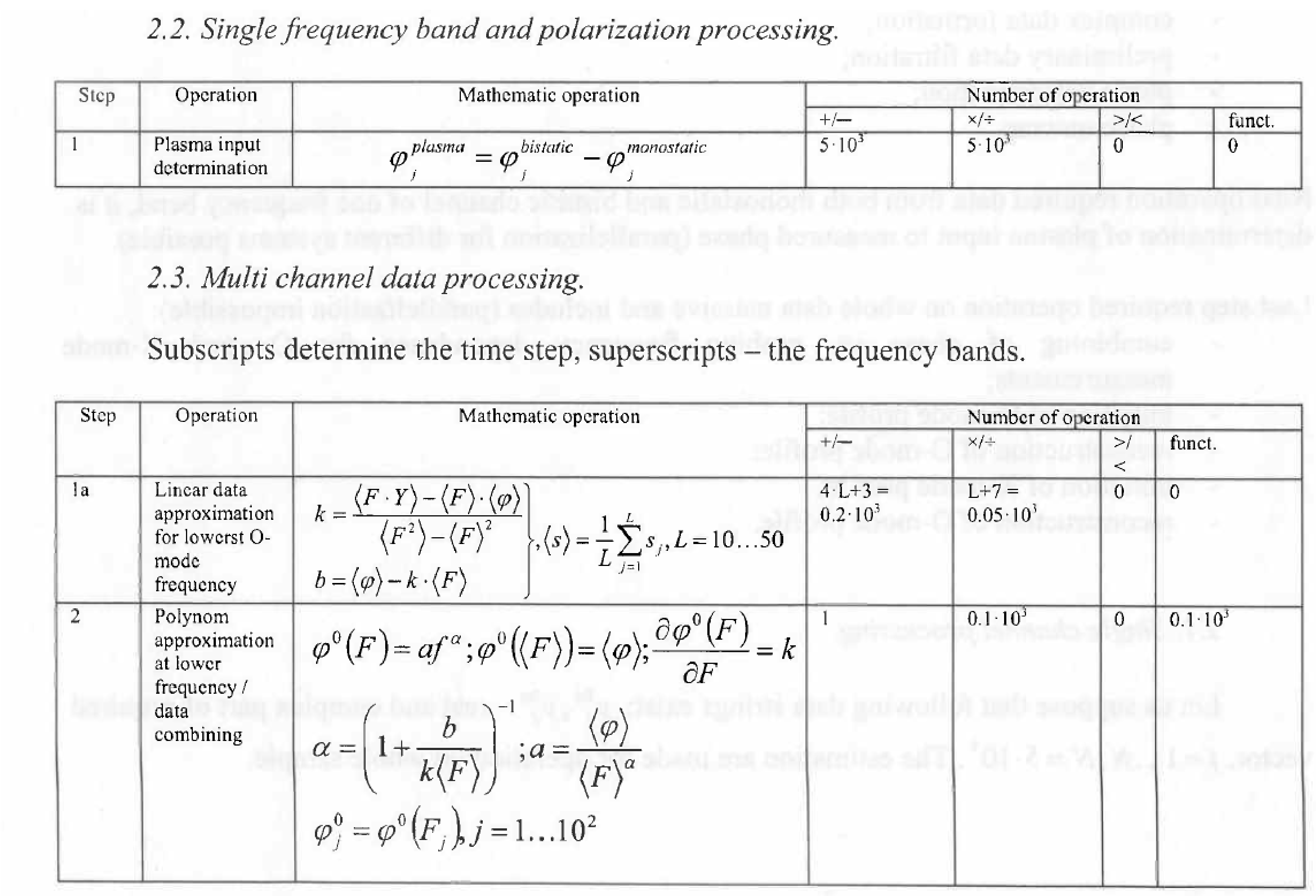
Algorithms for HFS



Step	Operation	Mathematic operation	Number of operation			
			+/–	×/÷	>/<	funct.
1	Data vector formation	$y_j = y_j^{\mathrm{Re}} + i \cdot y_j^{\mathrm{Im}}, i = \sqrt{-1}$	$5 \cdot 10^3$	$5 \cdot 10^3$	0	0
2	Data filtration using standart or adaprive filter	$y_j^{filt} = b_1 \cdot y_j + b_2 \cdot y_{j-1} + \ldots + b_{K+1} \cdot y_{j-K}$ where K is the filter order and $b_{1 \ldots K+1}$ filter coefficients. 32th and higher order filter should be used	$K \cdot N$ $160 \cdot 10^3$	$(K+1) \cdot N$ $165 \cdot 10^3$	0	0
2*	Adaptive filter – frequency determination via Fast Fourier Transform	$Y_k = FFT(y_k), k = 1 \ldots 5 \cdot 10^2$, for 10 windows. Sort of data to detect maximum frequency	$10 \cdot (5 \cdot 10^2)^2 = 2500 \cdot 10^3$	$10 \cdot (5 \cdot 10^2)^2 = 2500 \cdot 10^3$	$10 \cdot (5 \cdot 10^2) = 5 \cdot 10^3$	0
3	Phase determination	$\varphi_j = \begin{cases} \arctan(y_j), if\ \mathrm{Re}[y_i] \geq 0 \\ \arctan(y_j) + \pi, if\ \mathrm{Re}[y_i] < 0, \mathrm{Im}[y_i] > 0 \\ \arctan(y_j) - \pi, if\ \mathrm{Re}[y_i] < 0, \mathrm{Im}[y_i] < 0 \end{cases}$	up to $5 \cdot 10^3$	0	up to $10 \cdot 10^3$	$5 \cdot 10^3$
4	Phase unwrap	$\Delta\varphi_j = \varphi_j - \varphi_{j-1}$ $\varphi_j = \begin{cases} \varphi_j, -\pi/2 < \Delta\varphi_j < \pi/2 \\ \varphi_j + \pi, \Delta\varphi_j < -\pi/2 \\ \varphi_j - \pi, \Delta\varphi_j > \pi/2 \end{cases}$	up to $10 \cdot 10^3$	0	$5 \cdot 10^3$	0
Total			up to $0.2 \cdot 10^6$ $(2.7 \cdot 10^6)$	up to $0.2 \cdot 10^6$ $(2.7 \cdot 10^6)$	Up to $20 \cdot 10^3$	$5 \cdot 10^3$

* – Adaptive filter could significantly improved signal-to-noise ratio.

Algorithms for HFS



2.2. Single frequency band and polarization processing.

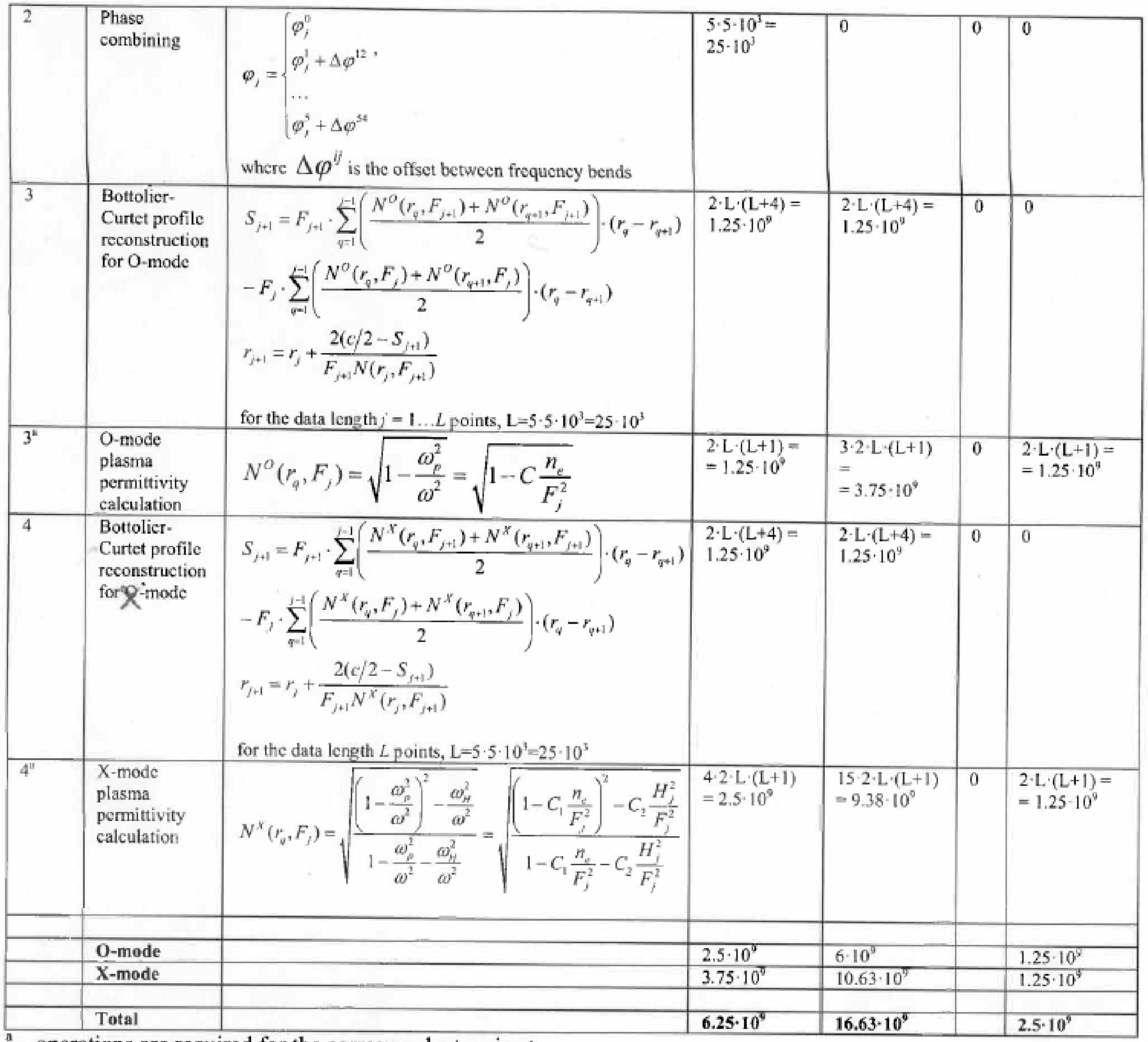
Step	Operation	Mathematic operation	Number of operation			
			+/–	×/÷	>/<	funct.
1	Plasma input determination	$\varphi_j^{plasma} = \varphi_j^{bistatic} - \varphi_j^{monostatic}$	$5 \cdot 10^3$	$5 \cdot 10^3$	0	0

2.3. Multi channel data processing.

Subscripts determine the time step, superscripts – the frequency bands.

Step	Operation	Mathematic operation	Number of operation			
			+/–	×/÷	>/<	funct.
1a	Linear data approximation for lowerst O-mode frequency	$\left.\begin{aligned} k &= \frac{\langle F \cdot Y\rangle - \langle F\rangle \cdot \langle \varphi\rangle}{\langle F^2\rangle - \langle F\rangle^2} \\ b &= \langle\varphi\rangle - k \cdot \langle F\rangle \end{aligned}\right\}, \langle s\rangle = \frac{1}{L}\sum_{j=1}^{L} s_j, L = 10\ldots50$	$4 \cdot L+3 = 0.2 \cdot 10^3$	$L+7 = 0.05 \cdot 10^3$	0	0
2	Polynom approximation at lower frequency / data combining	$\varphi^0(F) = af^{\alpha}; \varphi^0(\langle F\rangle) = \langle\varphi\rangle; \frac{\partial\varphi^0(F)}{\partial F} = k$ $\alpha = \left(1 + \frac{b}{k\langle F\rangle}\right)^{-1}; a = \frac{\langle\varphi\rangle}{\langle F\rangle^{\alpha}}$ $\varphi_j^0 = \varphi^0(F_j), j = 1\ldots10^2$	1	$0.1 \cdot 10^3$	0	$0.1 \cdot 10^3$

Algorithms for HFS



2	Phase combining	$\varphi_j = \begin{cases} \varphi_j^0 \\ \varphi_j^1 + \Delta\varphi^{12}, \\ \dots \\ \varphi_j^5 + \Delta\varphi^{54} \end{cases}$ where $\Delta\varphi^{ij}$ is the offset between frequency bends	$5 \cdot 5 \cdot 10^3 = 25 \cdot 10^3$	0	0	0
3	Bottolier-Curtet profile reconstruction for O-mode	$S_{j+1} = F_{j+1} \cdot \sum_{q=1}^{j-1} \left(\frac{N^O(r_q, F_{j+1}) + N^O(r_{q+1}, F_{j+1})}{2} \right) \cdot (r_q - r_{q+1})$ $- F_j \cdot \sum_{q=1}^{j-1} \left(\frac{N^O(r_q, F_j) + N^O(r_{q+1}, F_j)}{2} \right) \cdot (r_q - r_{q+1})$ $r_{j+1} = r_j + \frac{2(c/2 - S_{j+1})}{F_{j+1} N(r_j, F_{j+1})}$ for the data length $j = 1 \dots L$ points, $L = 5 \cdot 5 \cdot 10^3 = 25 \cdot 10^3$	$2 \cdot L \cdot (L+4) = 1.25 \cdot 10^9$	$2 \cdot L \cdot (L+4) = 1.25 \cdot 10^9$	0	0
3[a]	O-mode plasma permittivity calculation	$N^O(r_q, F_j) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} = \sqrt{1 - C \frac{n_e}{F_j^2}}$	$2 \cdot L \cdot (L+1) = 1.25 \cdot 10^9$	$3 \cdot 2 \cdot L \cdot (L+1) = 3.75 \cdot 10^9$	0	$2 \cdot L \cdot (L+1) = 1.25 \cdot 10^9$
4	Bottolier-Curtet profile reconstruction for ~~O~~X-mode	$S_{j+1} = F_{j+1} \cdot \sum_{q=1}^{j-1} \left(\frac{N^X(r_q, F_{j+1}) + N^X(r_{q+1}, F_{j+1})}{2} \right) \cdot (r_q - r_{q+1})$ $- F_j \cdot \sum_{q=1}^{j-1} \left(\frac{N^X(r_q, F_j) + N^X(r_{q+1}, F_j)}{2} \right) \cdot (r_q - r_{q+1})$ $r_{j+1} = r_j + \frac{2(c/2 - S_{j+1})}{F_{j+1} N^X(r_j, F_{j+1})}$ for the data length L points, $L = 5 \cdot 5 \cdot 10^3 = 25 \cdot 10^3$	$2 \cdot L \cdot (L+4) = 1.25 \cdot 10^9$	$2 \cdot L \cdot (L+4) = 1.25 \cdot 10^9$	0	0
4[a]	X-mode plasma permittivity calculation	$N^X(r_q, F_j) = \sqrt{\frac{\left(1 - \frac{\omega_p^2}{\omega^2}\right)^2 - \frac{\omega_H^2}{\omega^2}}{1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_H^2}{\omega^2}}} = \sqrt{\frac{\left(1 - C_1 \frac{n_e}{F_j^2}\right)^2 - C_2 \frac{H_j^2}{F_j^2}}{1 - C_1 \frac{n_e}{F_j^2} - C_2 \frac{H_j^2}{F_j^2}}}$	$4 \cdot 2 \cdot L \cdot (L+1) = 2.5 \cdot 10^9$	$15 \cdot 2 \cdot L \cdot (L+1) = 9.38 \cdot 10^9$	0	$2 \cdot L \cdot (L+1) = 1.25 \cdot 10^9$
	O-mode		$2.5 \cdot 10^9$	$6 \cdot 10^9$		$1.25 \cdot 10^9$
	X-mode		$3.75 \cdot 10^9$	$10.63 \cdot 10^9$		$1.25 \cdot 10^9$
	Total		$\mathbf{6.25 \cdot 10^9}$	$\mathbf{16.63 \cdot 10^9}$		$\mathbf{2.5 \cdot 10^9}$

[a] – operations are required for the correspondent main step.

Plasma Position Control Using Microwave Reflectometry

Magnetic measurements are usually the prime diagnostic for inferring the position and shape of tokamak plasmas; indeed all present devices base their position feedback control on this information.

In a new approach, the microwave reflectometry is used to track the position of the plasma boundary in real time using dedicated algorithms and the a priori knowledge about typical edge density profile shapes. The estimation of the boundary density is obtained from a combination of local and line integrated density measurement (the latter coming from interferometry as well as O-mode reflectometry) which does not require any information on the magnetic equilibrium.

It has been possible to measure the position of the separatrix of the plasma in real time at a rate of 1 ms and with an accuracy of better than 1 cm.

Plasma Position Control Using Microwave Reflectometry