Preliminary Design of the ITER Diagnostic Residual Gas Analyzer System

Presented at the

ITPA 2013: Diagnostics Topical Group Meeting

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General Atomics, San Diego, CA, USA

June 4th - 7th, 2013

U.S. DEPARTMENT OF ENERGY

Brooks

PECOS Precision Engineering Contracting Services, Inc.

DeNuke

irfm cea cadarache

US iter

PPPL

iter china eu india japan korea russia usa

Oak Ridge National Laboratory
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Thanks to ITER DRGA team

- ITER International Organization
  - Philip Andrew (Technical Responsible Officer)
- US ITER (Domestic Agency of the US)
  - Dave Johnson (WBS manager), Bill DeVan, Emil Nassar
- ORNL FMNS Division (subcontract to US ITER)
  - Ted Biewer, Chris Klepper (project managers); Van Graves, Chris Marcus, Tim Younkin
- PECOS Inc. (subcontract to ORNL, engineering)
  - David Prieto, James Owens
- DeNuke Inc. (subcontract to ORNL, scheduling)
  - Mike Morris

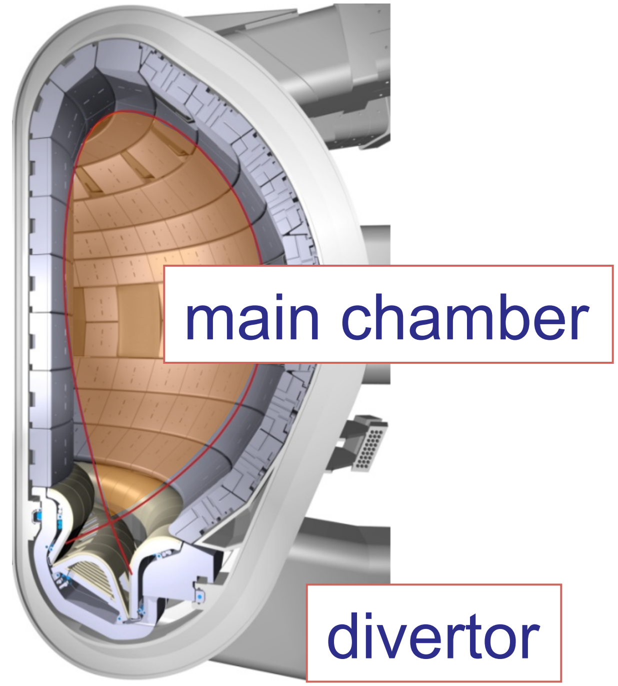
Outline

- Introduction: PDR and Diagnostic Goals
- DRGA System Overview
  - Equitorial Port 11 Concept
  - Divertor Port 12 Design
- Harsh environment: Magnetic Field and Radiation
  - Shielding and separation of sensitive electronics
- 3 Sensor DRGA Design: QMS, OPG, ITMS
- Project evolution towards FDR and Installation

Introduction

- The ITER Diagnostic Residual Gas Analyzer system (PA 5.5.P1.US.01) was defended at a Preliminary Design Review on April 9-10, 2013 at the "new" ITER building in France.
- This was the "first US-credited diagnostic to reach PDR."
- Provisionally passed; Cat. 1 Chits currently being resolved.
- The DRGA is expected to be installed for "first plasma".

Diagnostic Objectives



- **Physics understanding**
  - **Divertor impurity compression**
  - **Particle balance (fuel, helium)**
  - **Wall retention**
- **Assistance to T inventory measurement**
  - **Back-up**
  - **This system is NOT responsible for T inventory measurement**
- **Not responsible for measurement at Massive Gas Injection**
- **ITER vacuum pumping section (PBS 31) also provide RGA to monitor vacuum condition (operational aspects)**
  - **Detection of air leak**
  - **Wall condition monitor**
  - **Readiness for operation**
  - **Breakdown**

Measurement Requirements for DRGA

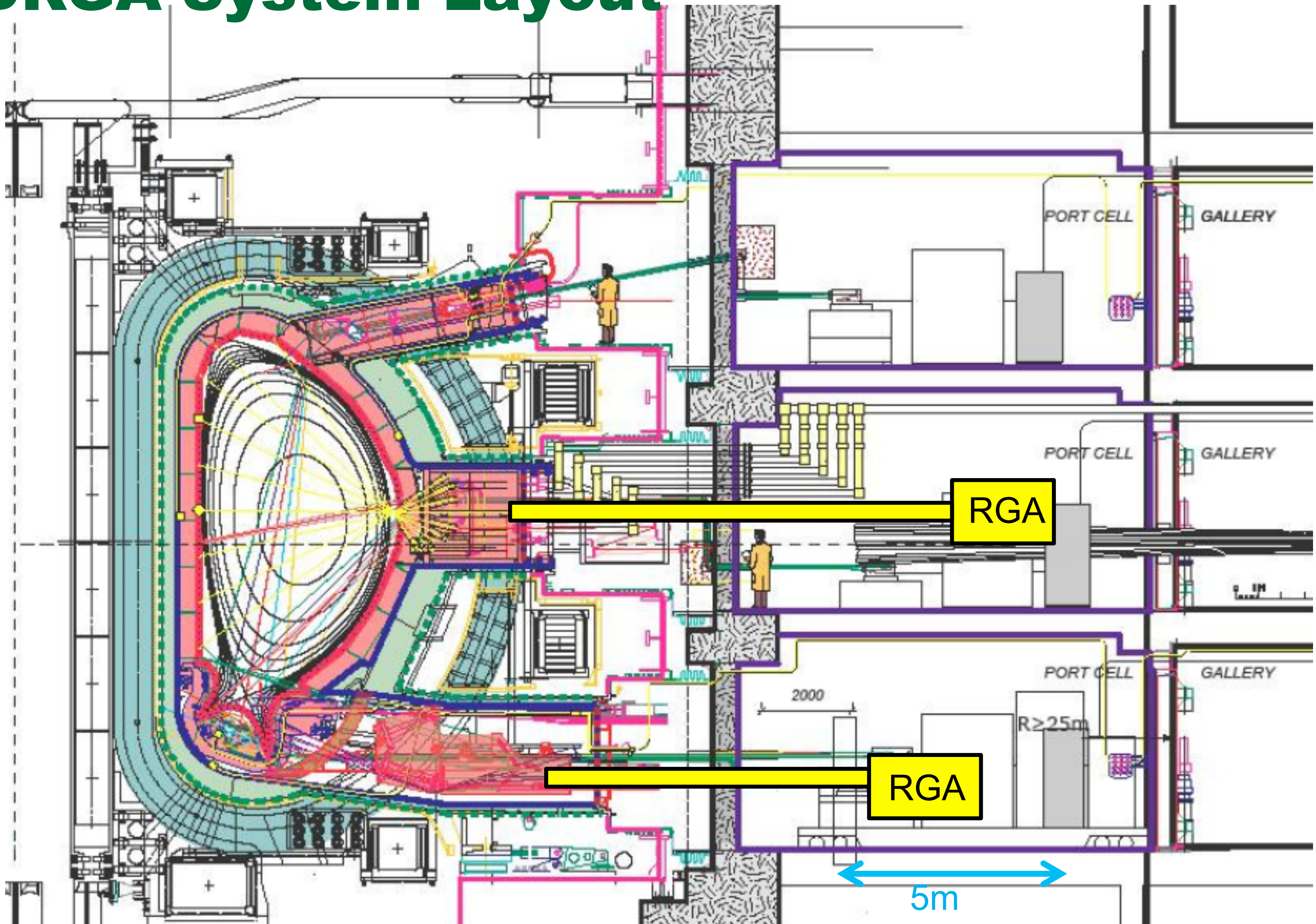
G.04 **Residual Gas Analyser**	Measurement role:	1a1: Machine Protection 1a2: Basic Control 1b: Advanced Control 2: Physics	Diagnostic role:	Primary Backup Supplementary

Measurement	**Parameter**	**Condition**	**Range**	**Meas. role**	**Resolution** time or freq	**Resolution** spatial or wave number	**accuracy**
16. Divertor operational parameters	Gas composition. Fuel, He, impurities	A = 1 - 100, DA = 0.5Fuel vs. He & H20 vs. CxHy discrimination	(10-4 - 1) ·Pdiv	1a.2	1 s	several points	20% during pulse
18. Gas pressure and composition in main chamber	Gas composition. Fuel, He, impurities	A = 1-100, ΔA=0.5 Fuel vs. He & H20 vs. CxHy discrimination	(1E-4 - 1) ·Pmain	1a.2	10 s	several points	50% during pulse
19. Gas pressure and composition in vacuum ducts	Gas composition. Fuel, He, impurities	A = 1-100, ΔA=0.5. Fuel vs. He & H20 vs. CxHy discrimination	(10-4 - 1) ·Pduct	1a.2	1 s	several points	20% during pulse
39. Divertor Helium density	nHe		1E17 - 1E21 m-3	1a.2	1ms	-	20%
40. Fuel ratio in divertor	nH/nD		0.01 - 100	2	100ms	integral	20%
	nT/nD		0.01 - 10	2	100ms	integral	20%
18. Gas pressure and composition in main chamber	Gas pressure		1E-4 - 1 Pa	1a.2	1 s	several points	20% during pulse
19. Gas pressure and composition in vacuum ducts	Gas pressure		1·10-4 - 20 Pa	1a.2	100 ms	several points	20% during pulse
16. Divertor operational parameters	Gas pressure		1E-4 - 20 Pa	1a.2	50 ms	several points	20% during pulse

Measurement Requirement Summary

- DRGA measurement requirements
  - Group 1a2 measurements needed for basic machine control.
  - Goal: measure fuel ratios, He, and impurity concentrations
  - 1-100 amu range, with 0.5 amu or better
  - Time response: <1 s in divertor, <10 s at midplane
  - Accuracy (better than): 20% in divertor, 50% in main chamber
- Mass difference D_2 (4.0271 amu) - He (4.0026 amu) = 0.0245 amu
  - Not resolvable by conventional QMS (1-100 amu scan)
  - Utilize OPG (as on JET DT) to optically separated He, D
- Conjecture: "new" ITMS technology can scan 1-150 amu and resolve He/D_2

DRGA System Layout



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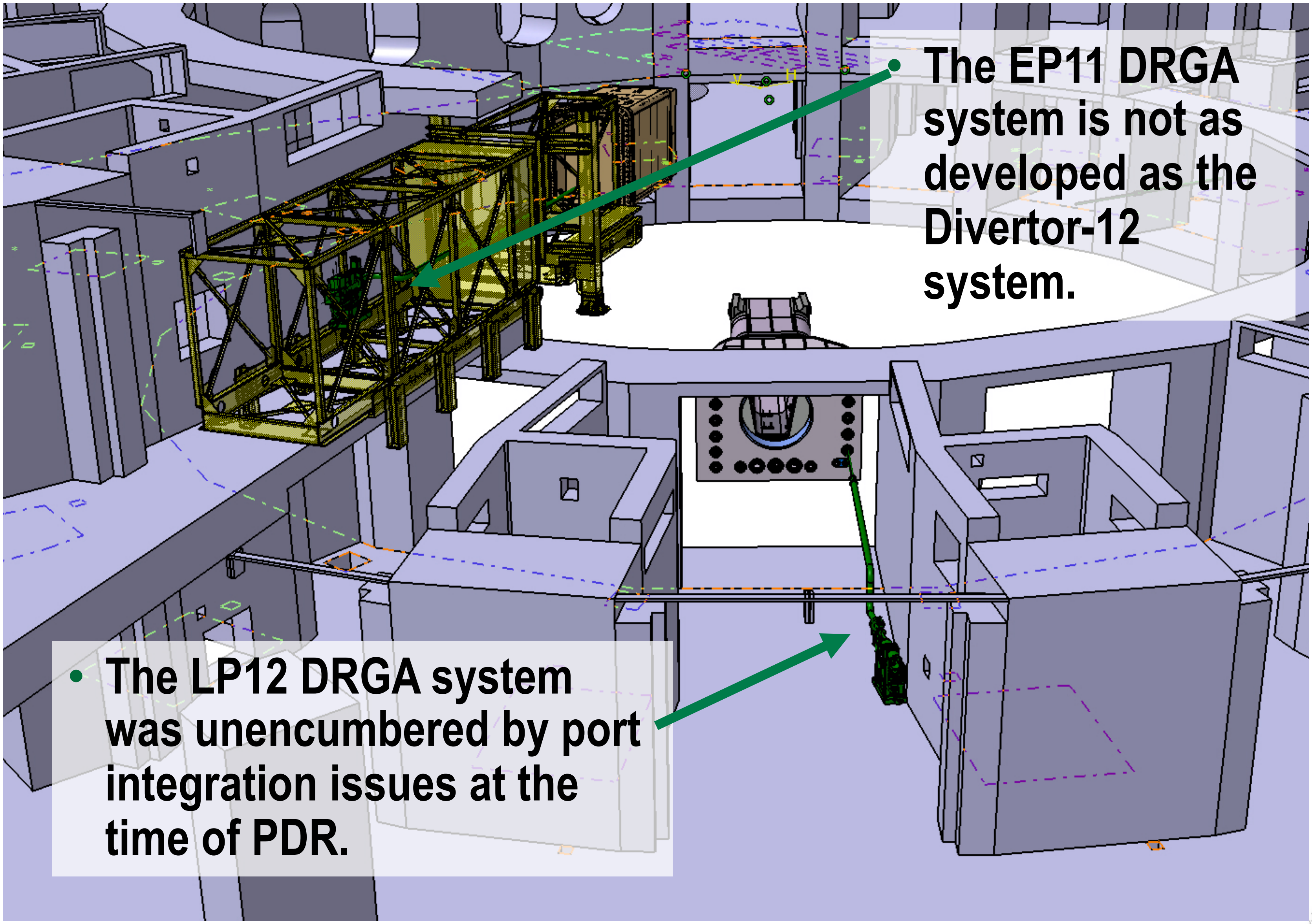
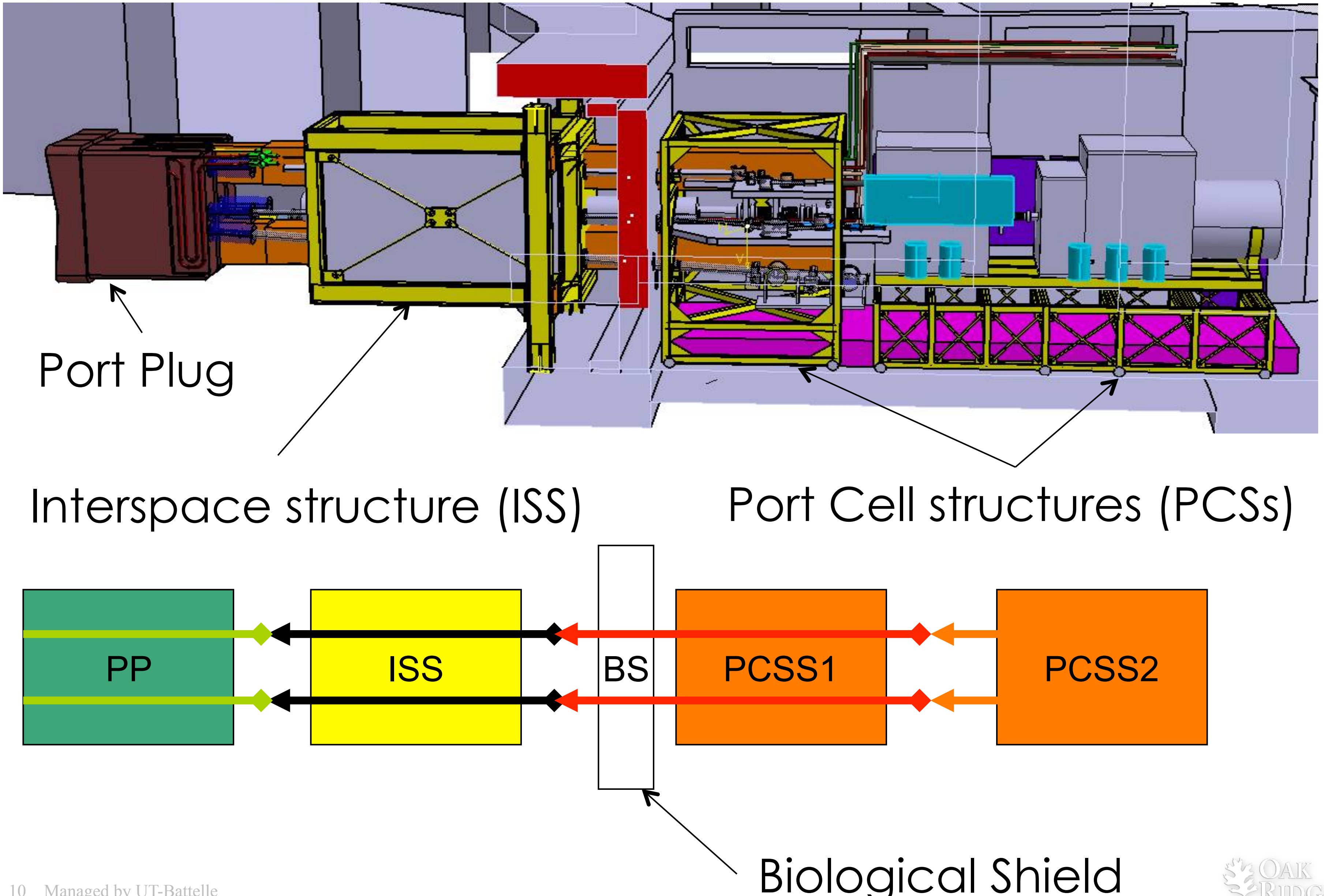
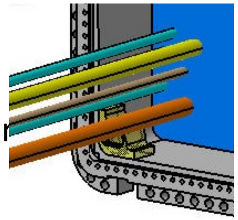
PDR baseline DRGA configuration

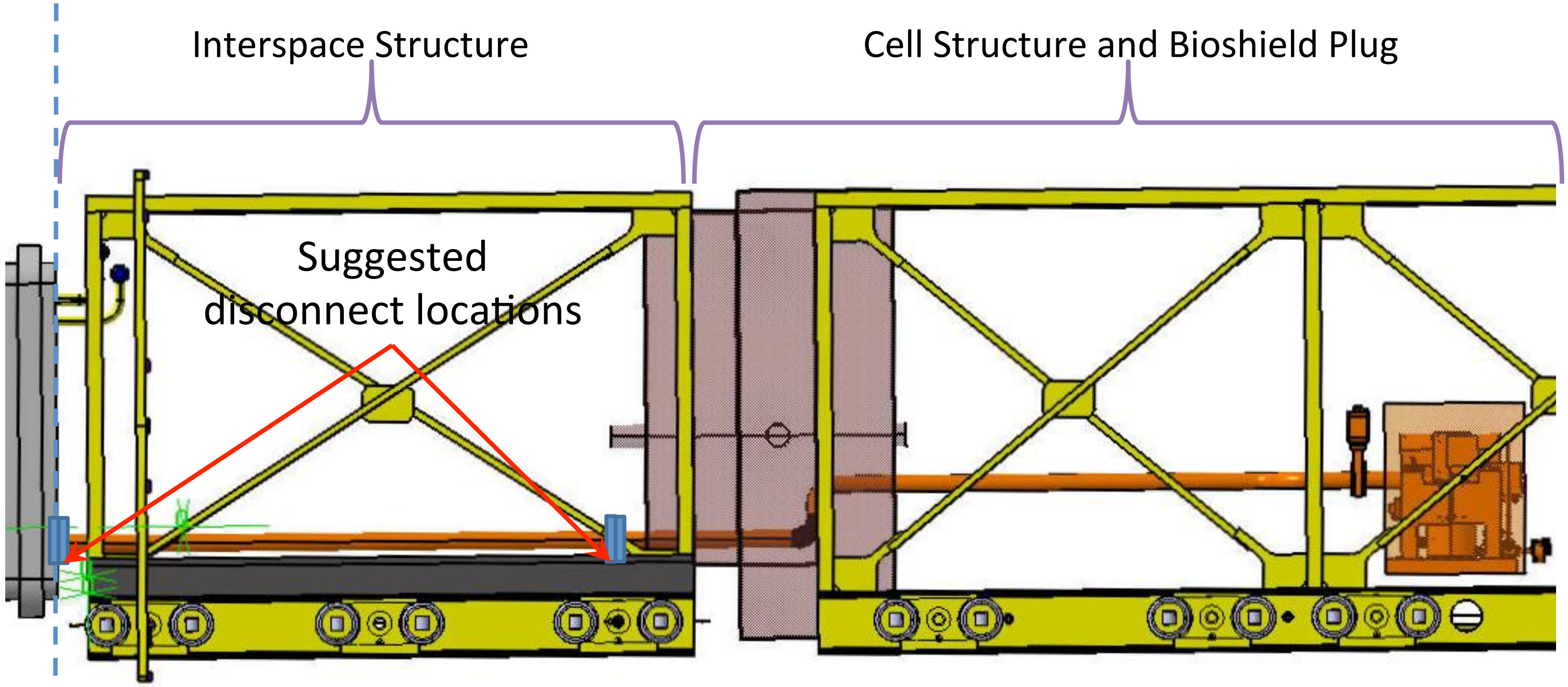


Equatorial Port 11 integration is ongoing



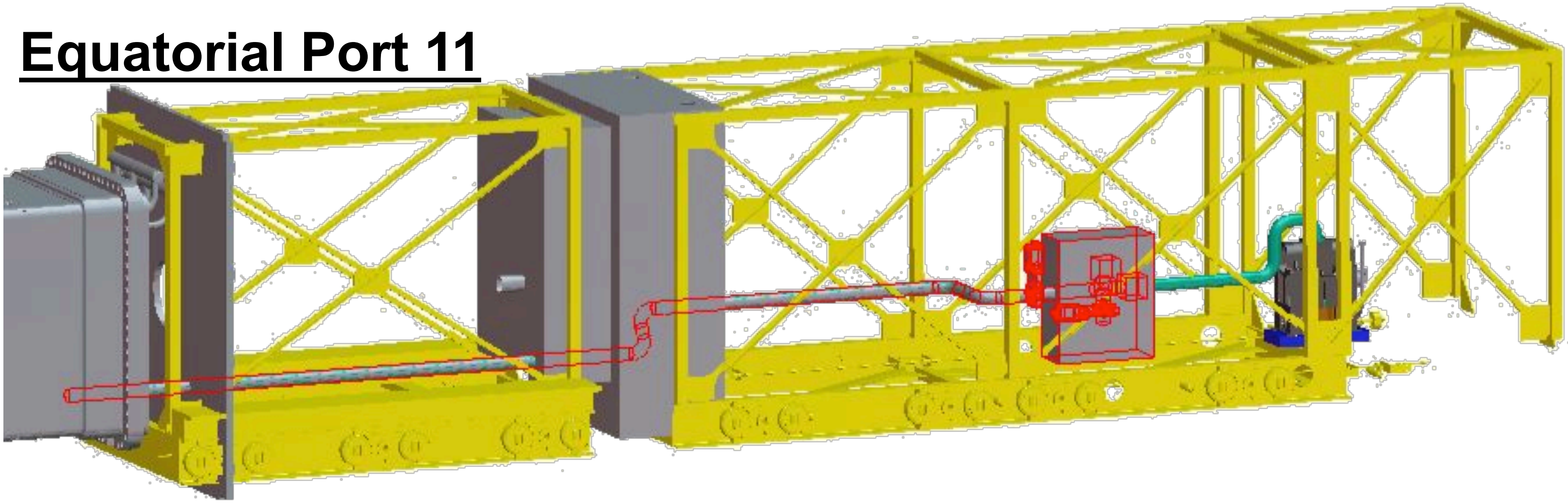
Equatorial Port DRGA

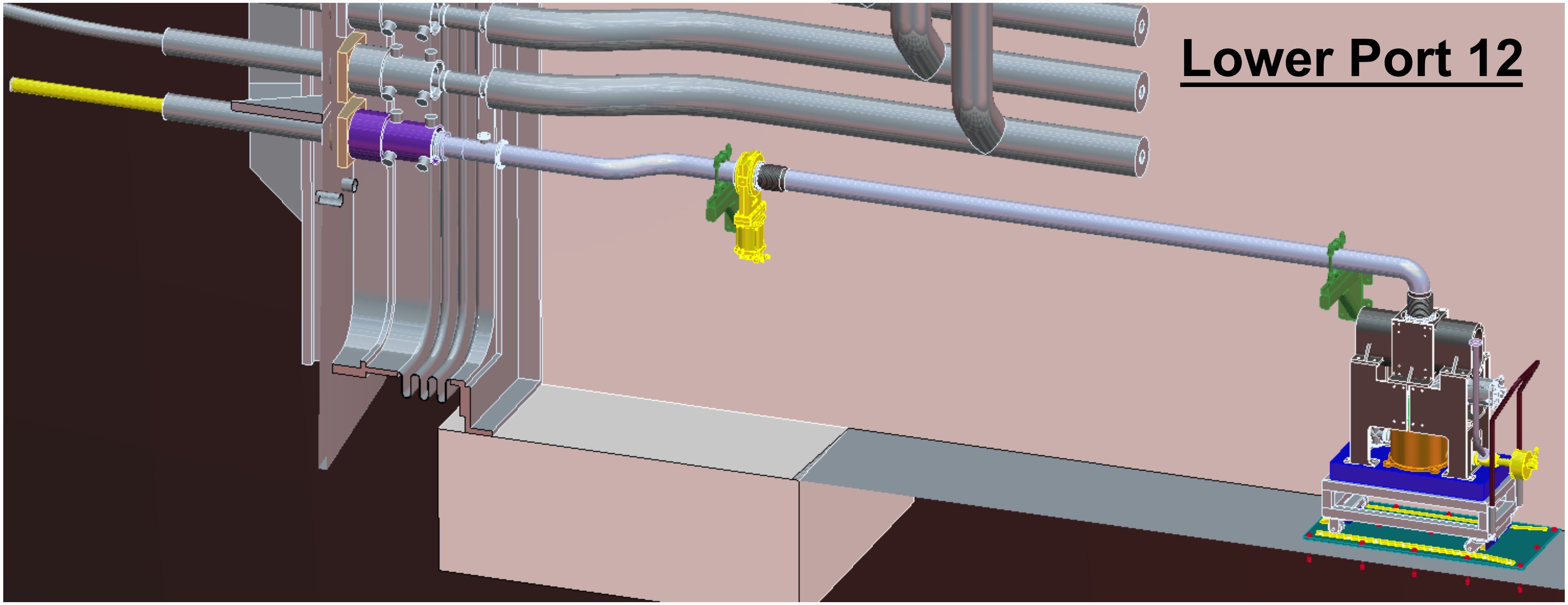




- **The EP11 DRGA system is not as developed as the Divertor-12 system**
  - **EP11 environment evolved substantially during the PD phase, as a result of EP11 Integration Process & PCSS CD activity.**
- **Preliminary Design includes a <u>concept</u> for DRGA in EP11.**

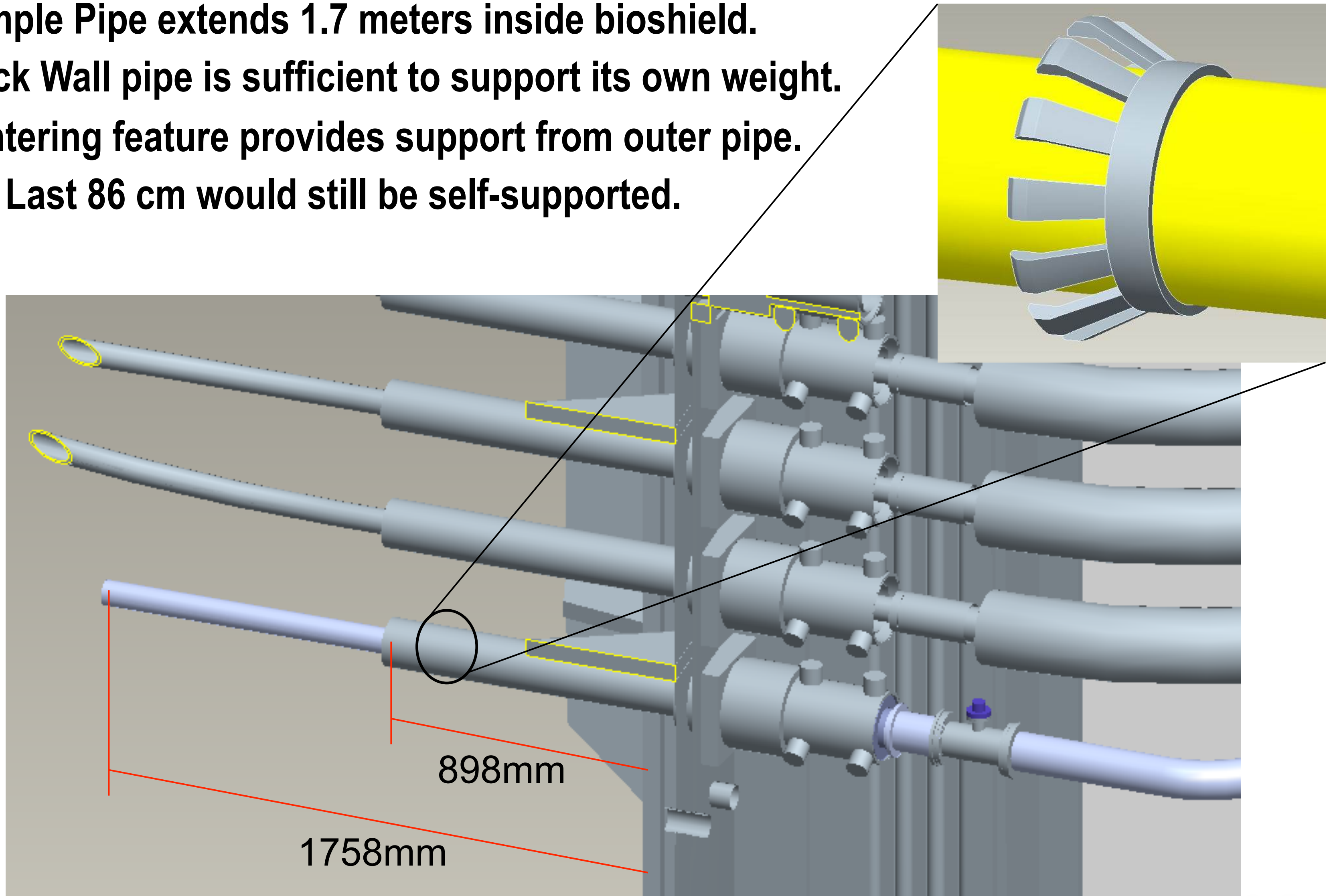
PDR design focused on LP12 DRGA system



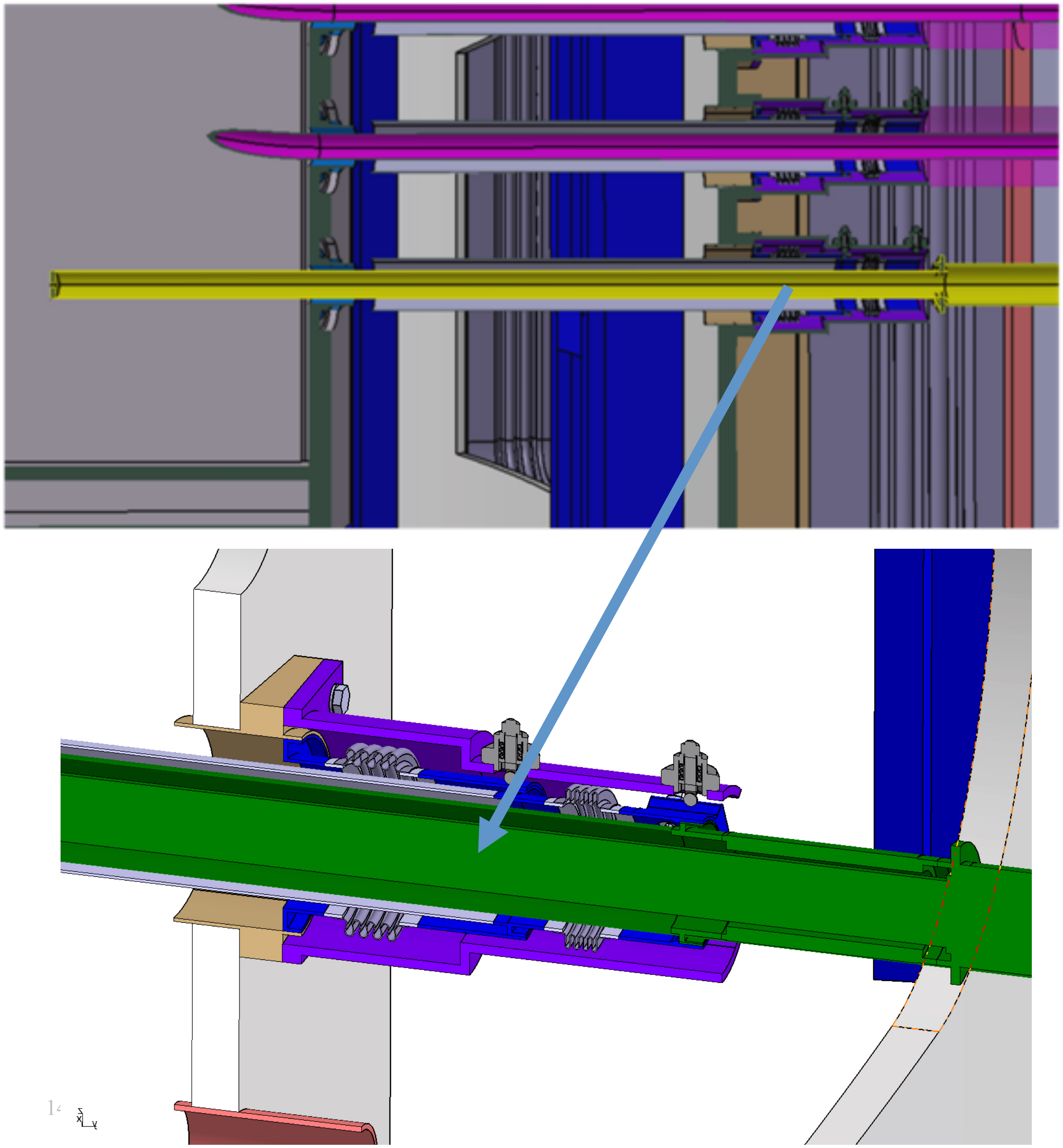


Gas sample tube inside crystat

- Sample Pipe extends 1.7 meters inside bioshield.
- Thick Wall pipe is sufficient to support its own weight.
- Centering feature provides support from outer pipe.
  - Last 86 cm would still be self-supported.

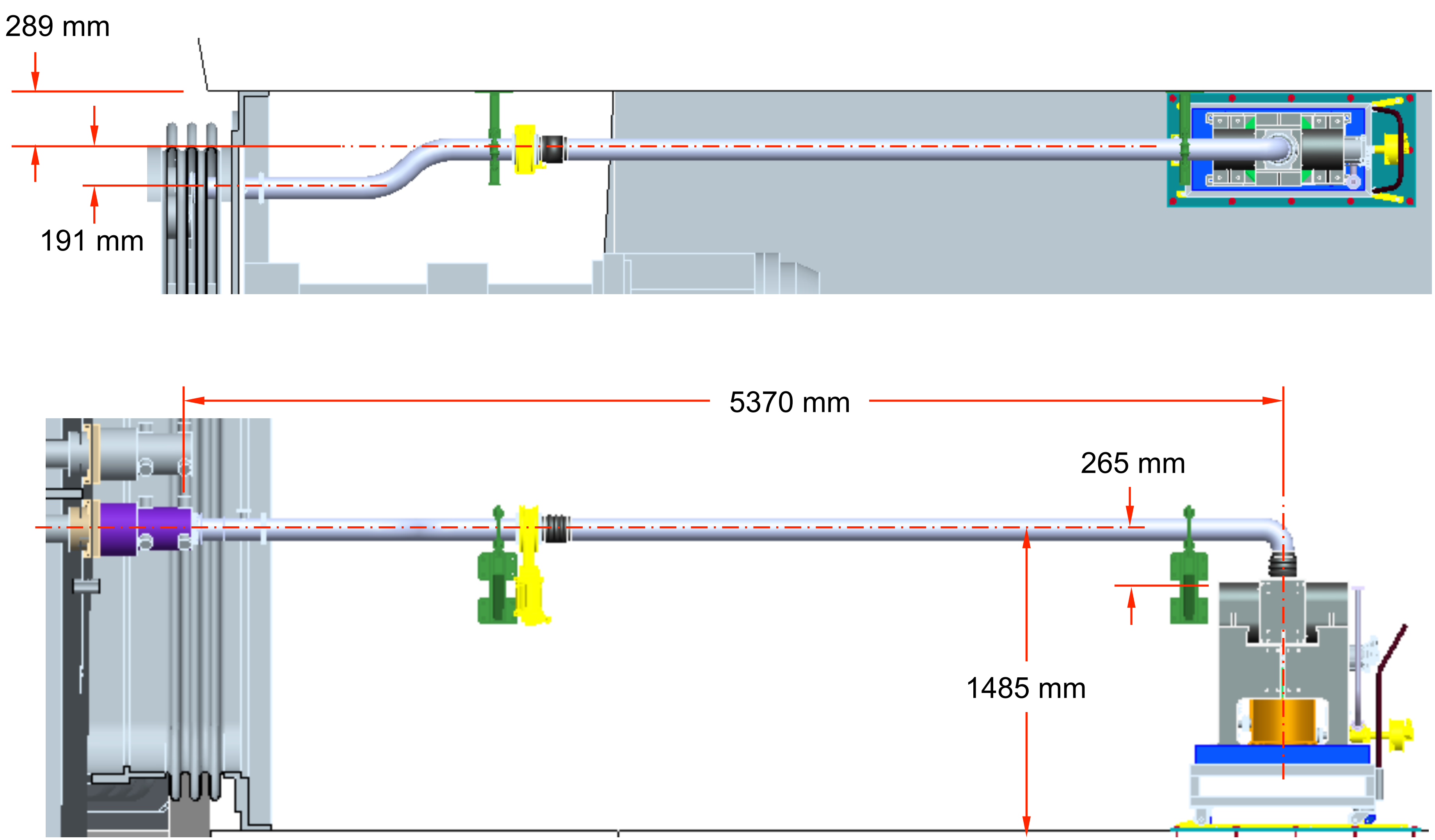


Cryostat Pass-through

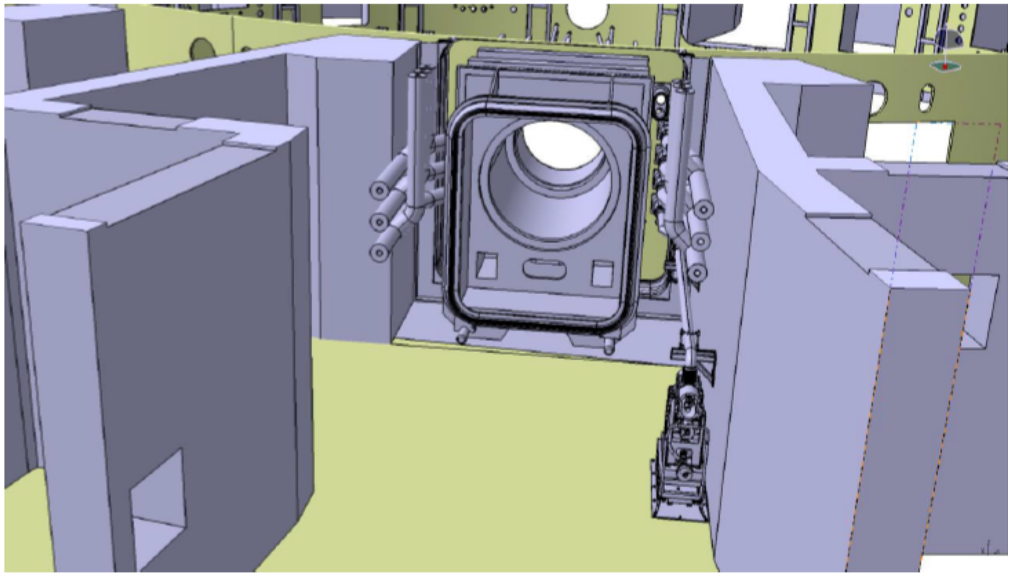


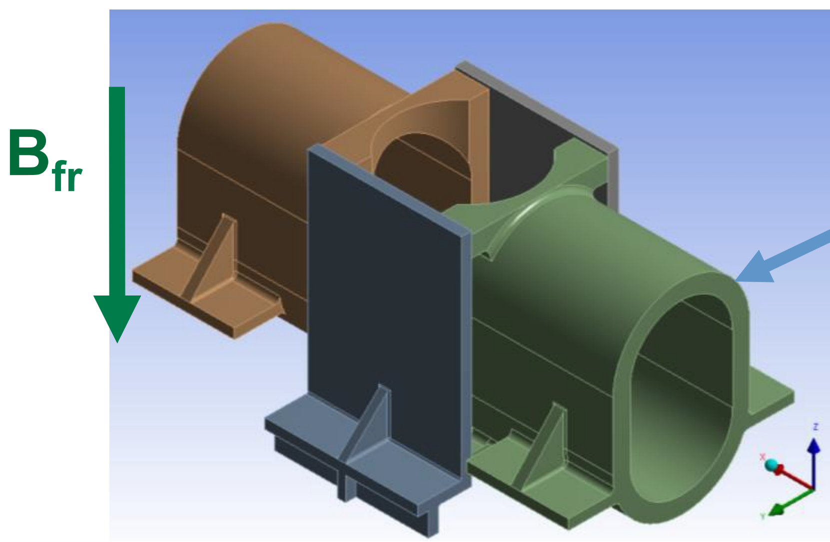
- One of the PD challenges, for the Divertor DRGA, was the cryostat pass-through
  - Essential to access the divertor region
- Preliminary Design includes a CONCEPT for
  - Aperture Replacement
  - External heating of the pass-through section of the sampling pipe.

Gas sample pipework in port cell LP12



Harsh Environment: Fringing B-fields





- During operation, instruments in the port-cell are also exposed to fringing magnetic
  - Estimated ~100mT; designing for 150mT
- Most RGA sensors will only tolerate up to 5mT
  - ➔Magnetic Shielding is essential
  - Good news: Substantial experience already (Tore Supra, JET)
  - See Magnetic Effects R&D Report for validation of present concept

Loughlin model estimates for the port-cell radiation dose

- Assuming then ~5,000 hours of operation for ITER, one can estimate a total, accumulated dose in the range of 0.5MGy or 5×10^5 Gy for the lifetime of the machine
- **Main impact for DRGA is lifetime of electronics:**
- Commercial electronics can only take up to 30 Gy (cumulative dose) before showing measurable deterioration.
  - **This still means that in the port-cell environment, we need ~10^5 attenuation or 28cm of lead (assuming N-16 γ' s).**
- **But RGA sensors need to be in the port-cell to meet measurement requirements!**

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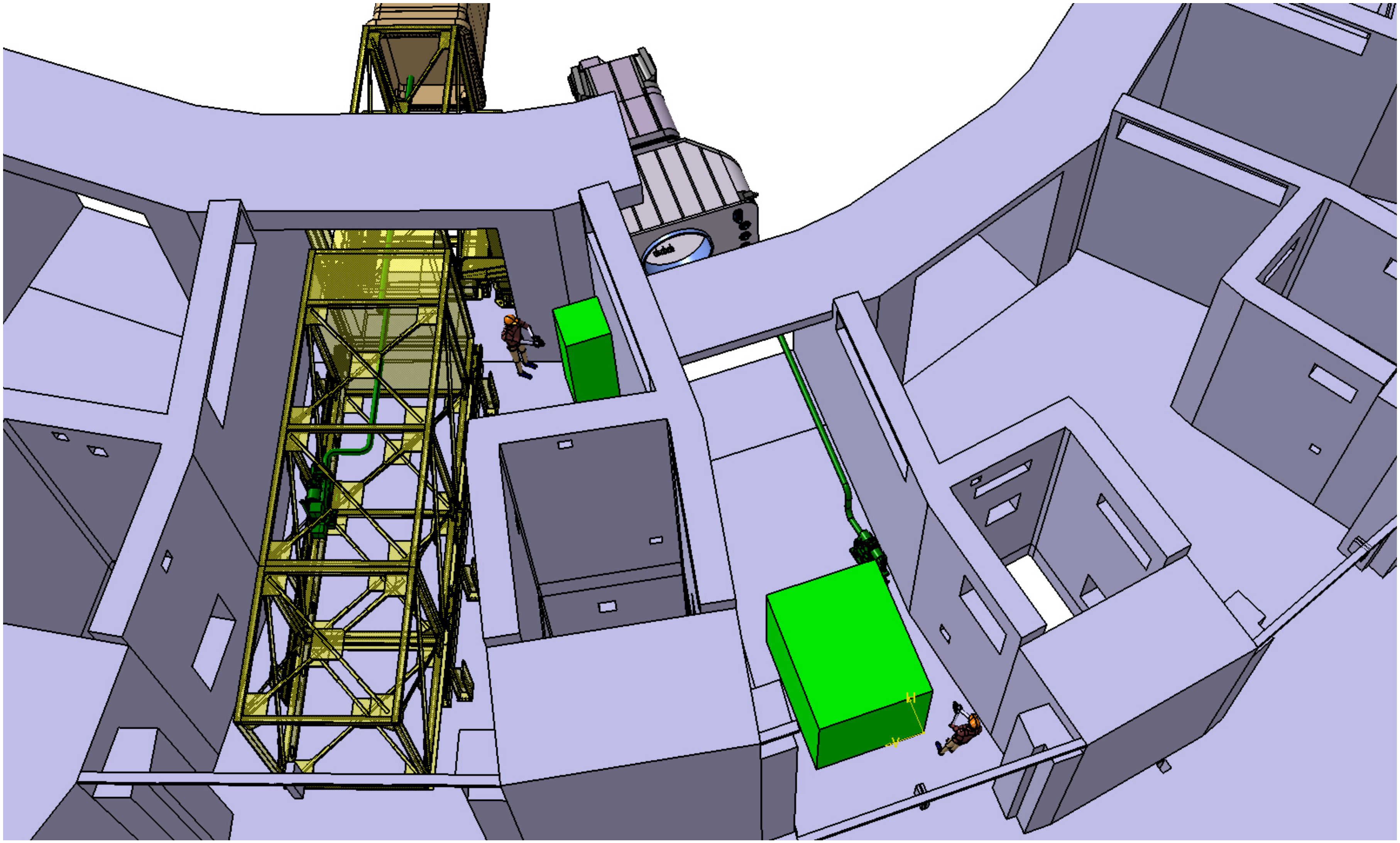
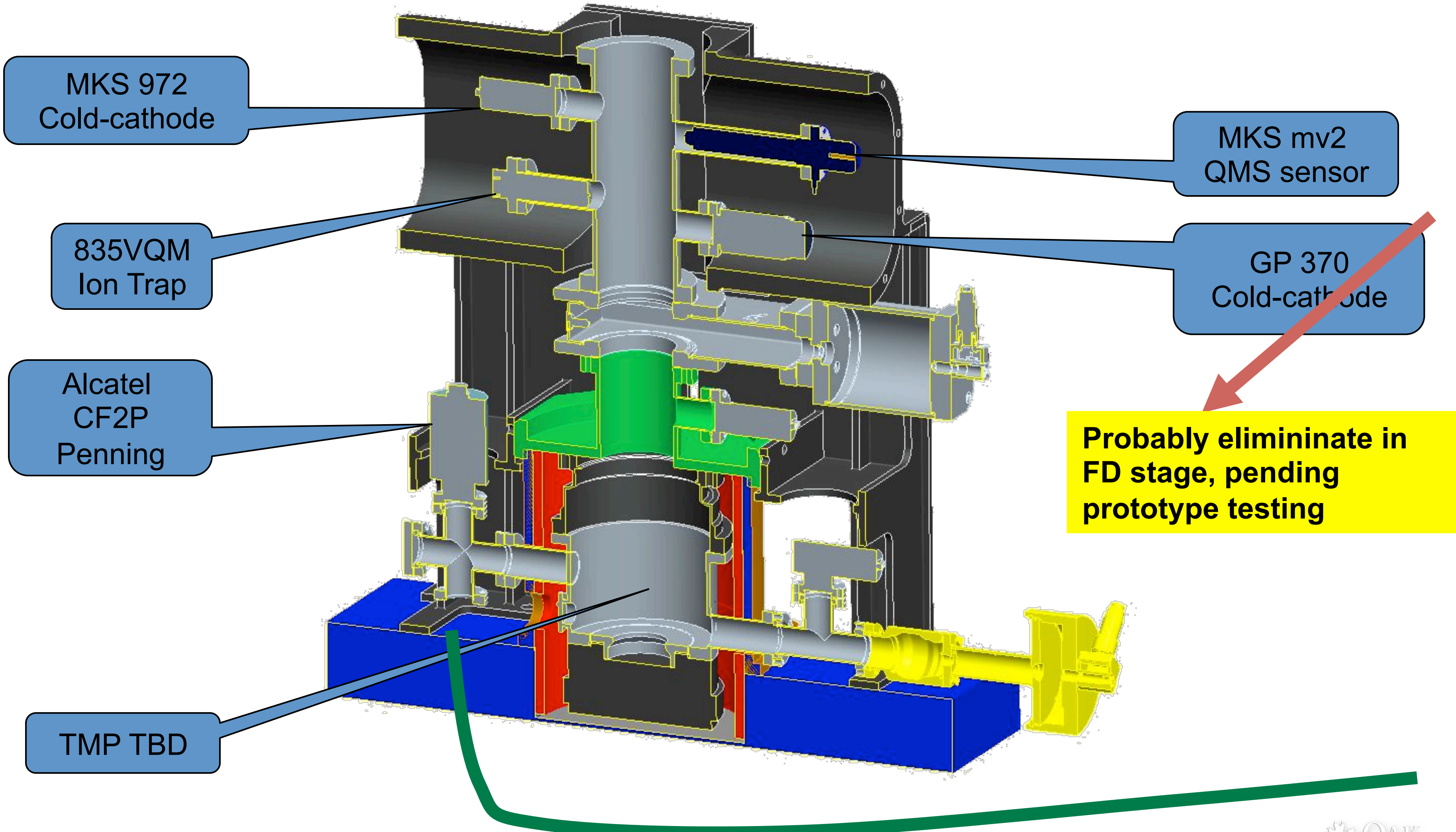
Current cubicle allocation unacceptable



Sensor selection will be further validated by prototype testing



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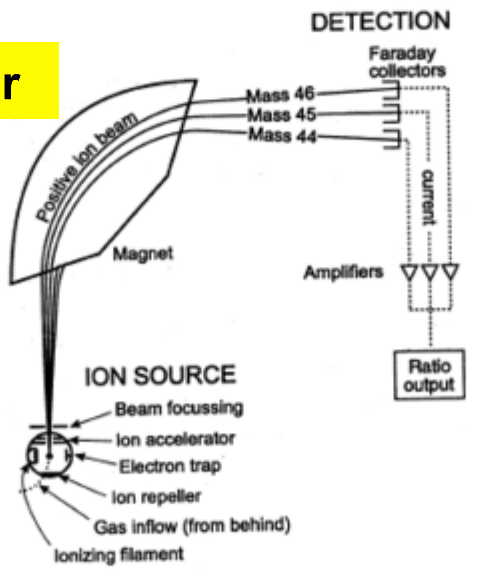
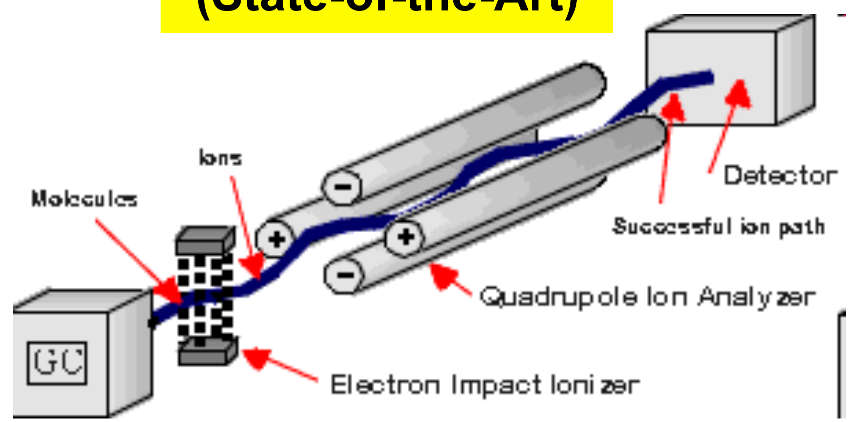
Mass Spec Analyzers

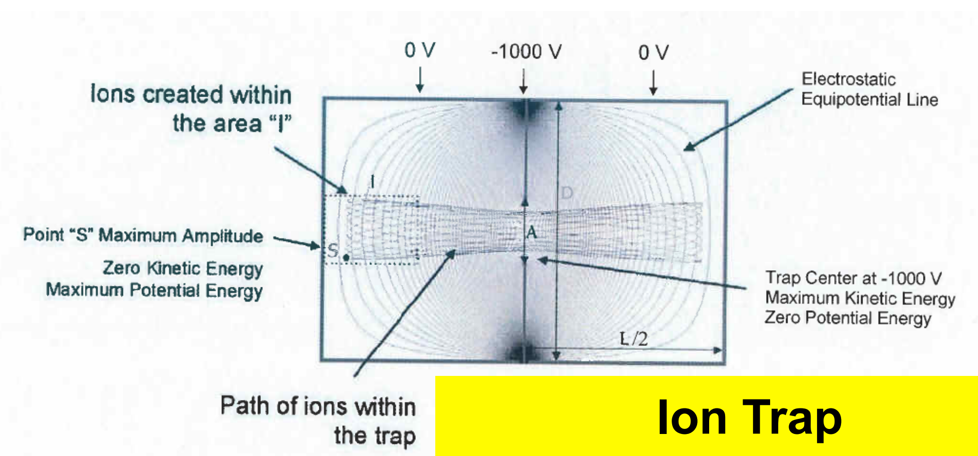
Sector



QMS

(State-of-the-Art)



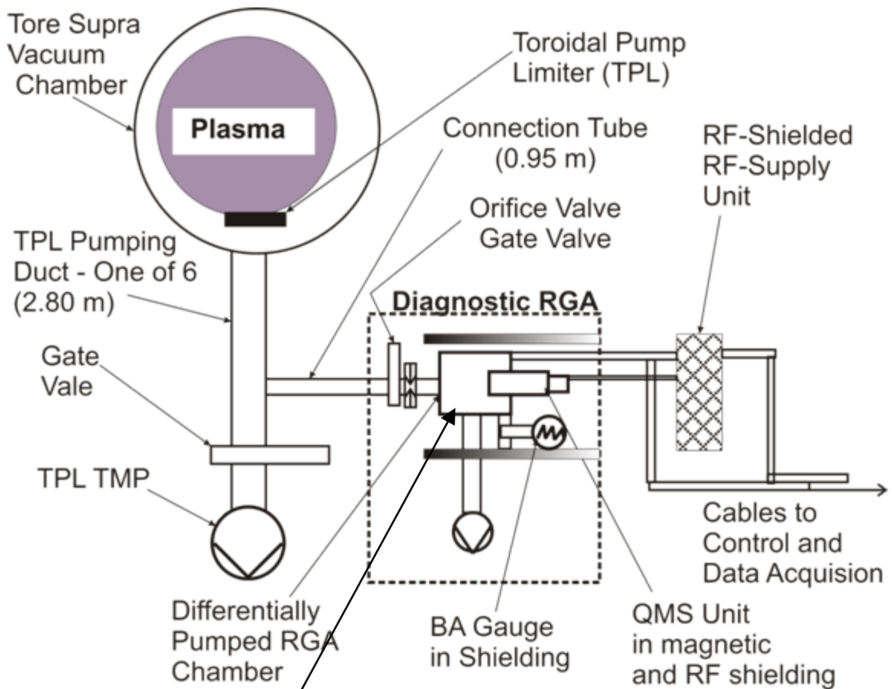


Ion Trap

(Emerging Technology)

See Ted Biewer's R&D Report and presentation on Ion Trap qualification study for ITER

Precedent on Continuous Mass-Spec DRGA on a Tokamak

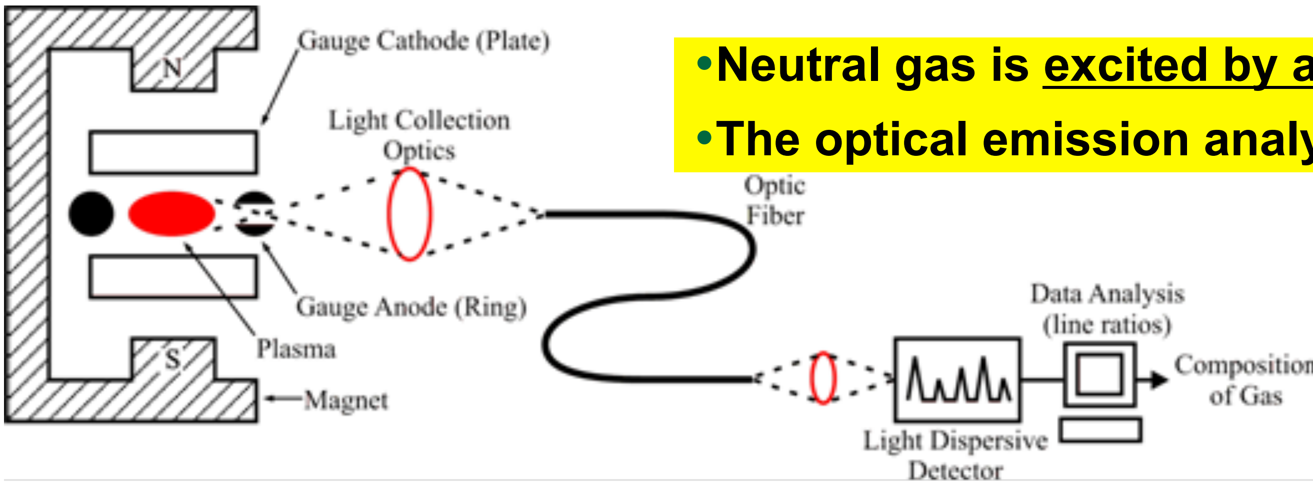


Used commercial Balzers QMG-421 Mass-Spec

****Klepper et al., *REVIEW OF SCIENTIFIC INSTRUMENTS* 81, 10E104 (2010)**

- **Tore Supra used a QMS DRGA (magnetically + EMI) shielded for operation during plasma operation****
  - **Continuous data acquisition and data transfer (15 channels/ 32ms)**
  - **Successfully used with shots up to 6 min**
- **Similar system currently on JET**

OGA Concept and Current Use



•Neutral gas is excited by a local plasma discharge

•The optical emission analysis → gas composition.

- A Optical Gas Analyzer based on the Penning gauge discharge (« Penning Optical Gas Analyser » or Penning-OGA) is already in use on DIII-D, JET and Tore Supra.
  - Originally developped to distinguish He from D_2 (both M = 4)
  - On DIII-D it also measures Ne/D_2 and Ar/D_2
  - On JET it measures H_2/D_2 and T_2/D_2
  - On Tore Supra it measures He/D_2

Penning-OGA at JET with T runs*

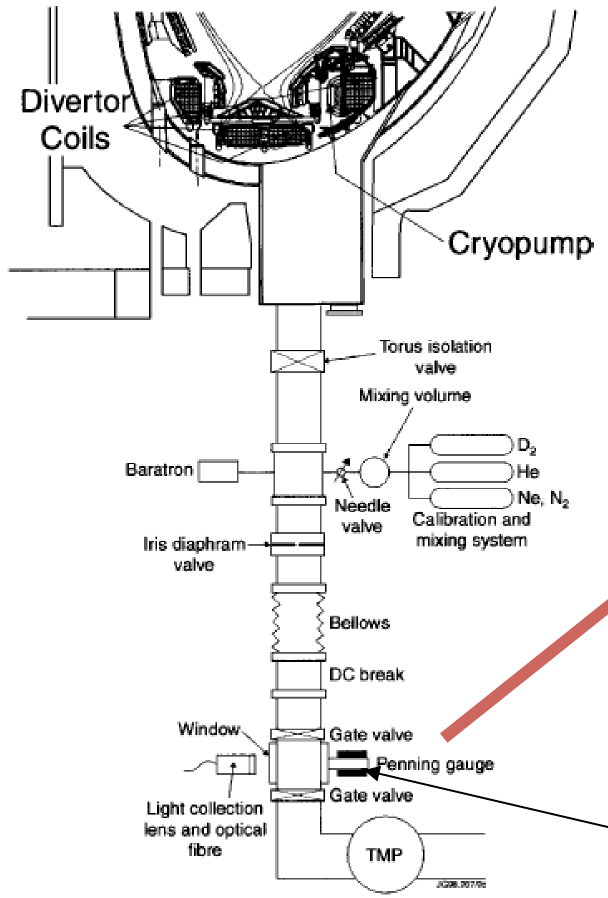
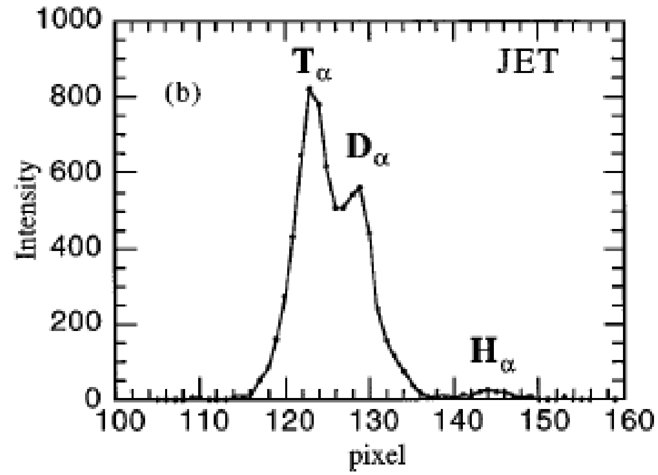


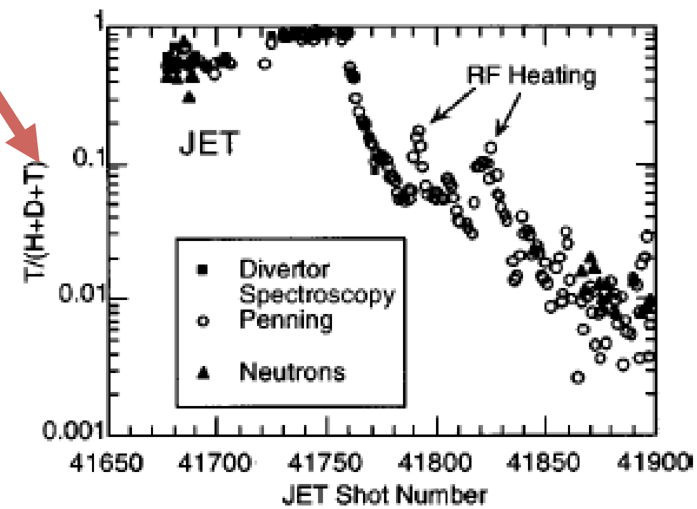
FIG. 1. Penning gauge diagnostic system for the measurement of the tritium concentration in the divertor of JET.

* Hillis, et al., Rev. Sci. Instrum., Vol. 70, No. 1, January 1999

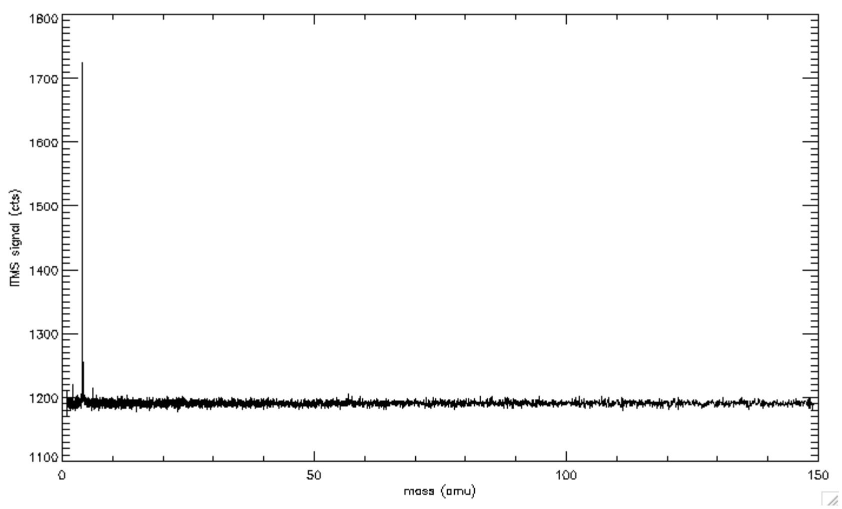


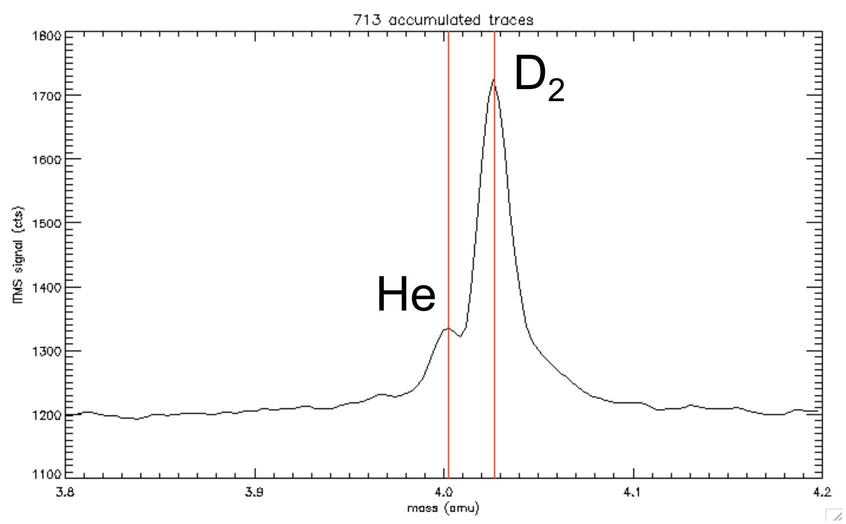
- OGA T_2/D_2 measurement is "self-calibrating"!
- JET study is best proof-of-principle for OGA on ITER

OGA: Uses commercial** Alcatel CF2P Penning Gauge Tube



Sample mass spectra from ITMS





- ITMS mass scan covers a full range from 1-150 amu
  - Exceeds ITER measurement requirement
- Single scan achieved in 85 ms
  - Noise reduced by ensembling multiple scans
  - Data shown is ~1 minute avg.
- Zoom in on "mass 4" region shows that He and D_2 mass peaks are resolved (50/50 mixture at P~8x10^{-6} Torr)

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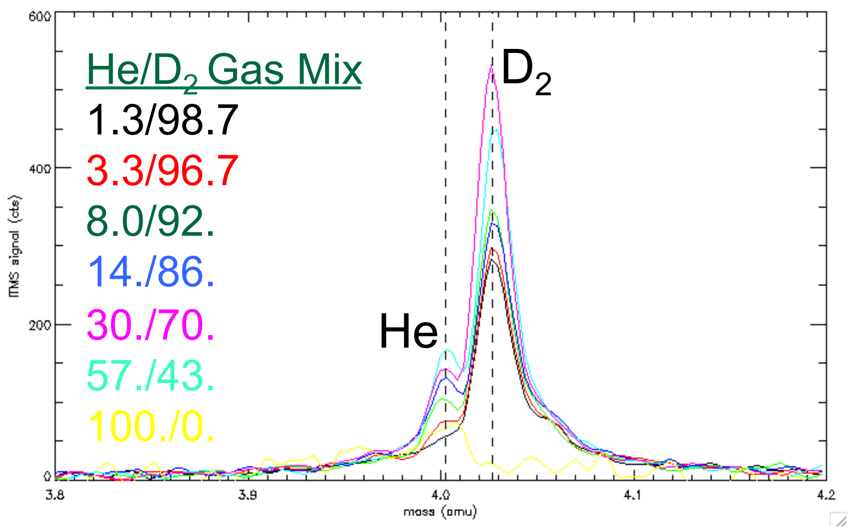
He/D_2 discrimination possible at 1% He



- Percentage of He gas in D_2 gas stream was varied in CVC:
  - Target: 0, 1, 2, 5, 10, 20, 50, 100%
- If a SNR~1 can be tolerated, then even a ~1% concentration of He in D_2 can be measured within the 10 s measurement requirement for E11 DRGA.

Desire: ITMS to perform as well as OPG, and as well as conventional QMS

OPG & ITMS

- Previous slide is example of OPG monitoring of relative concentration of He and D_2
- OPG was not calibrated for these tests
- OPG was not operated simultaneously with ITMS

QMS & ITMS

- Conventional QMS cannot resolve He/D_2 at full (1-100 amu) mass scan rates.
- ITMS also scans > 1-100 amu range
- Claim by MKS that MV-2 QMS can resolve He/D_2

- Cross-comparison tests of OPG & ITMS & QMS to be performed on fully calibrated prototype DRGA

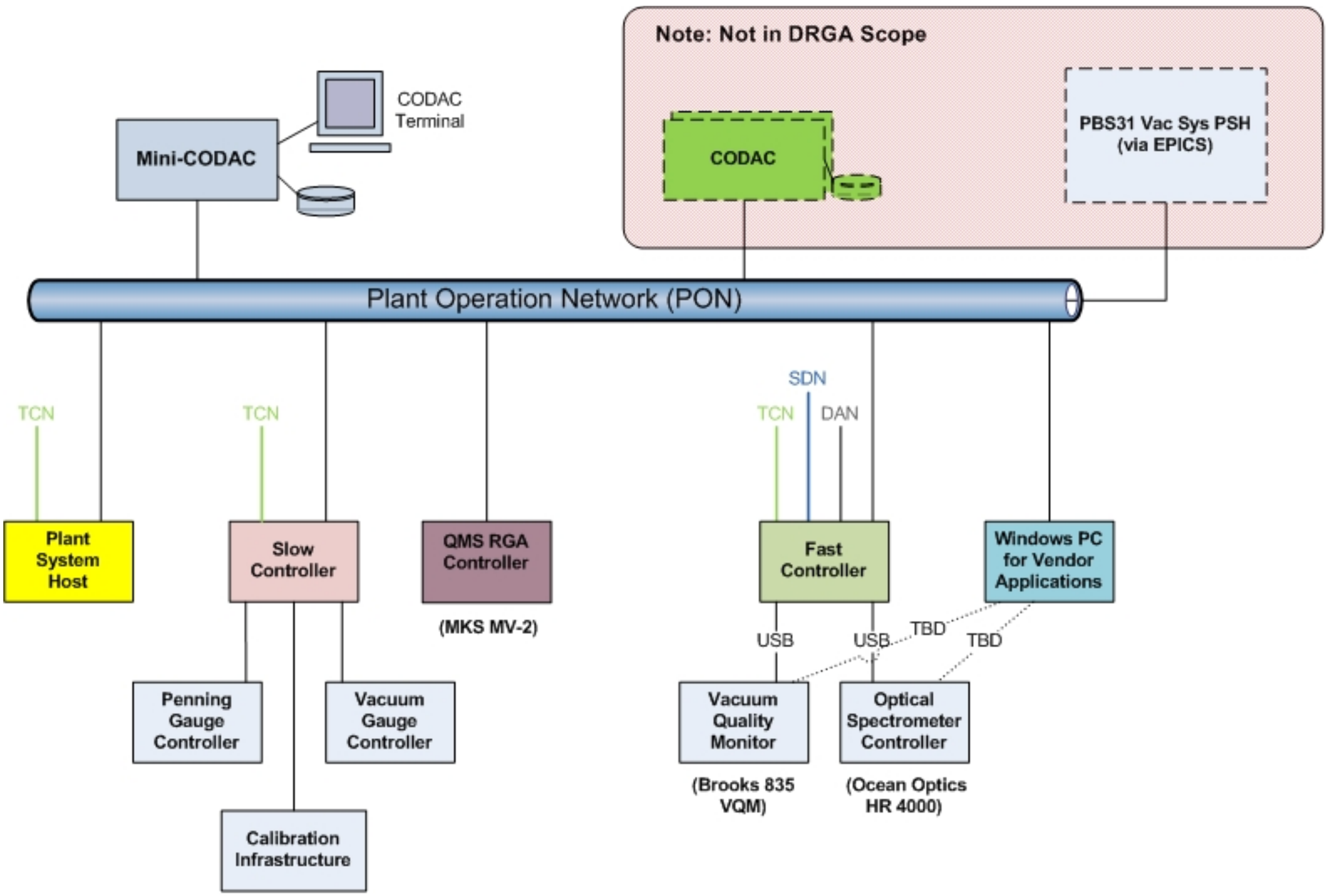
Documents Delivered

/ 55.G4 - RGA / Incoming Documentation (DA > IO) / Planned Documentation / PDR related documentation

	date	Date
2012.04_PA_R&D_Plan_5.5.P1.US.01_55.G4_RGA *(ITER_D_7GH226 v1.0)*	29 Mar 2013 17:43	23 Apr 2012
2013.03_PA_Risk and Mitigation Plan_5.5.P1.US.01.55.G4_RGA *(ITER_D_DVVK6X v1.0)*	02 Apr 2013 11:04	29 Mar 2013
Aperture Replacement Strategy Report *(ITER_D_D3ZT7C v1.0)*	01 Apr 2013 16:51	01 Apr 2013
Assessment of Penning OGA operation with the Penning tube mounted between stages of Turbo Pump *(ITER_D_DW3FGU v1.0)*	29 Mar 2013 09:52	28 Mar 2013
Chit_tracking_table_5.5.P1.US.01_55.G4_RGA *(ITER_D_CUMGSG v0.0)*	29 Mar 2013 11:42	29 Nov 2012
DDD for PD stage of diagnostic RGA *(ITER_D_EH6N29 v1.0)*	03 Apr 2013 20:44	28 Mar 2013
Design Compliance Matrix *(ITER_D_F92TXM v1.0)*	29 Mar 2013 11:08	29 Mar 2013
Diagrams and Drawings	19 Dec 2012 21:32	
DRGA I&C Integration Plan (FAT and SAT Scenarios) *(ITER_D_FZTHXJ v1.0)*	28 Mar 2013 22:27	28 Mar 2013
DRGA I&C Software Design Description *(ITER_D_F933J9 v1.0)*	28 Mar 2013 22:17	28 Mar 2013
DRGA Software Requirement Specification *(ITER_D_F84LHC v1.0)*	28 Mar 2013 22:10	28 Mar 2013
Electrical Power and Grounding Requirements *(ITER_D_DWYMQY v1.0)*	03 Apr 2013 20:36	28 Mar 2013
Electromagnetic Forces Analysis Report *(ITER_D_EAUDY4 v1.0)*	03 Apr 2013 20:25	28 Mar 2013
Interface documents	19 Dec 2012 21:35	
Ion-trap mass spectrometer testing for the ITER DRGA *(ITER_D_DCNXTY v1.0)*	01 Apr 2013 16:11	01 Apr 2013
ITER DRGA Calibration Procedure *(ITER_D_DX8JZM v1.0)*	03 Apr 2013 20:41	28 Mar 2013
Load Specification for PDR *(ITER_D_EAYTDW v1.0)*	03 Apr 2013 20:38	28 Mar 2013
Report on Magnetic Shielding Calculation for the ITER DRGA *(ITER_D_DWYUUL v1.0)*	29 Mar 2013 12:20	29 Mar 2013
Report on Radiation Shielding Calculation for the ITER DRGA *(ITER_D_DHXJDM v1.0)*	29 Mar 2013 12:25	29 Mar 2013
Seismic Response Analysis *(ITER_D_EAWR34 v1.0)*	03 Apr 2013 20:34	28 Mar 2013
Structural Integrity Report *(ITER_D_EAXVST v1.0)*	03 Apr 2013 20:39	28 Mar 2013

No. of Records : 21

DRGA I&C Architecture



History of DRGA project

- 2007: Diagnostic Systems design review
- July 2010: CDR for DRGA (W. Gardner, *et al*.; ORNL)
- September 2011: PA signed (5.5.P1.US.01) between ITER IO and US DA (IDM: D2G28K)
  - Official begin to PD phase
- November 2011: ORNL QP established as supplier to US DA (ITER_D_57384X)
- December 2011: MOA signed between ORNL-PPPL
- R&D, Preliminary Design, etc.
- April 2013: PDR
  - Documentation (IDM: D2G28K), Presentations (IDM: ENR3XF)

CAS Milestones for DRGA

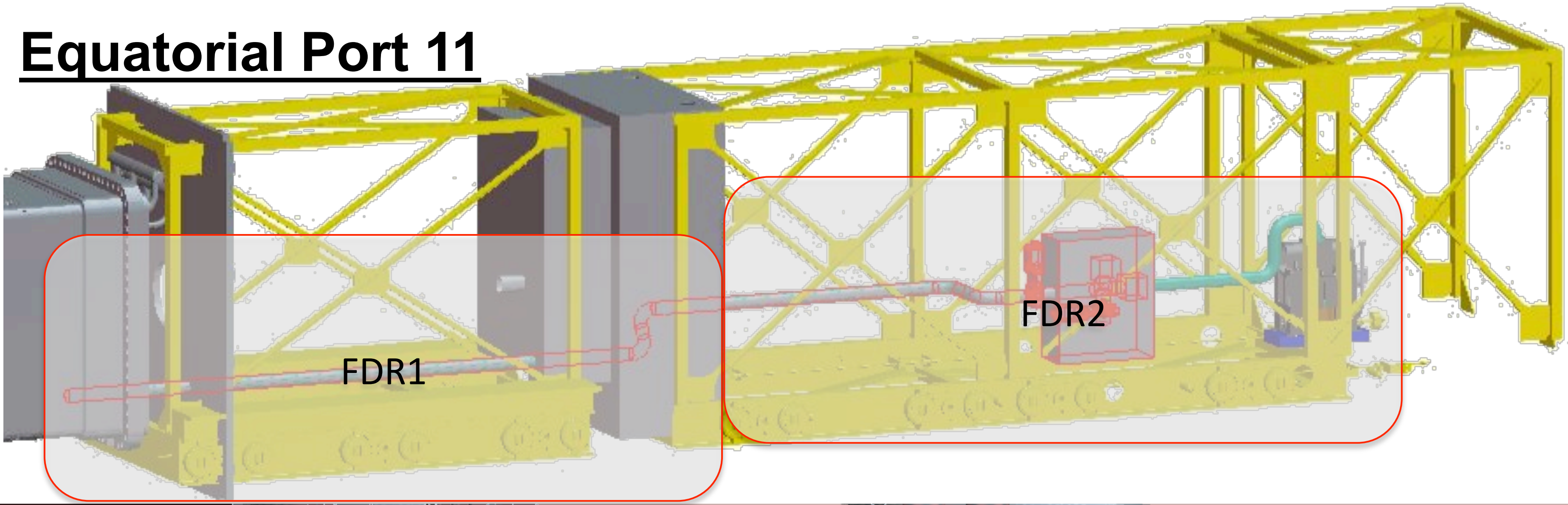
ActivityID	Activity Name	Finish
USDA0604001400	IO - RGA CAS - Preliminary Design G4 Residual Gas Analyzers Approved by IO	10-May-13
USDA0604002400	IO - RGA CAS - Final Design Review G4 REsidual Gas Analyzers Approved by IO	13-Jan-14
USDA0606002944	IO - RGA CAS - Manufacturing Readiness Review and MIP Approved by IO	21-Aug-14
USDA0607016730	IO - RGA CAS - Delivery of Vacum Interface G4 Residual Gas Analyzers EQ11 to Integration Site	2-Mar-15
USDA0607020030	IO - RGA CAS - Delivery of G4 Residual Gas Analyzers EQ11 to Integration Site	7-Dec-16
USDA0607023530	IO - RGA CAS - Delivery of G4 Residual Gas Analyzers LP12 to Integration Site	31-Jul-17
USDA060702750	IO - RGA CAS - Manufacture G4 Residual Gas Analyzers EQ11 Complete	2-Sep-15
USDA060703200	IO - RGA CAS - Factory Acceptance Testing G4 Residual Gas Analyzers EQ11 Approved by IO	25-Aug-16
USDA060704050	IO - RGA CAS - Manufacture G4 Residual Gas Analyzers LP12 Complete	31-Aug-15
USDA060704700	IO - RGA CAS - Factory Acceptance Testing G4 Residual Gas Analyzers LP12 Approved by IO	21-Jun-16
USDA060L011500	IO - RGA CAS - Successful Agreement of Commissioning Work Plan	13-Jan-14

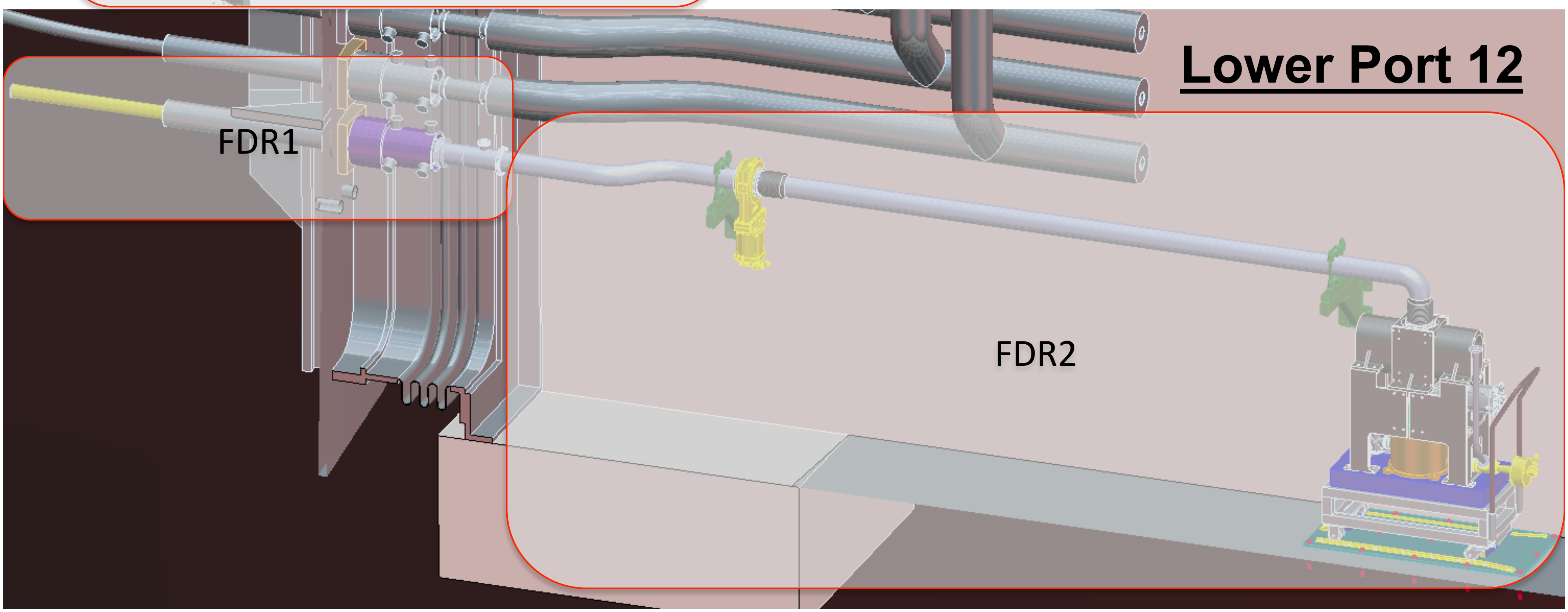
- **PDR – Apr. 2013**
- **FDR – by Jan. 2014**
- **MRR – by Aug. 2014**
- **FAT – by Aug. 2016**
- **Delivery to site – by July 2017**

Strategy for Final Design phase

- FDR date between Nov. 2013 and Apr. 2014
- ITER design issues impacting DRGA design
  - Approved double-seal flange designs (~1 month)
  - Finalized TMP selection (~Summer 2014)
  - EP11 port integration baseline (???)
  - LP12 port integration: glove box/pipe extractor & PCR 502 (???)
  - Outstanding DRGA R&D (~Summer 2013)
- Conjecture: Split DRGA FDR (with PCR)
  - FDR1: Nov. (Sep.?) 2013; "front end" design needed for port plug integration, driving schedule
  - FDR2: ~Fall 2014; DRGA analysis chamber in port cell can be delivered "later", allowing time for port cell design to stabilize

Visual representation of FDR1/FDR2 boundary

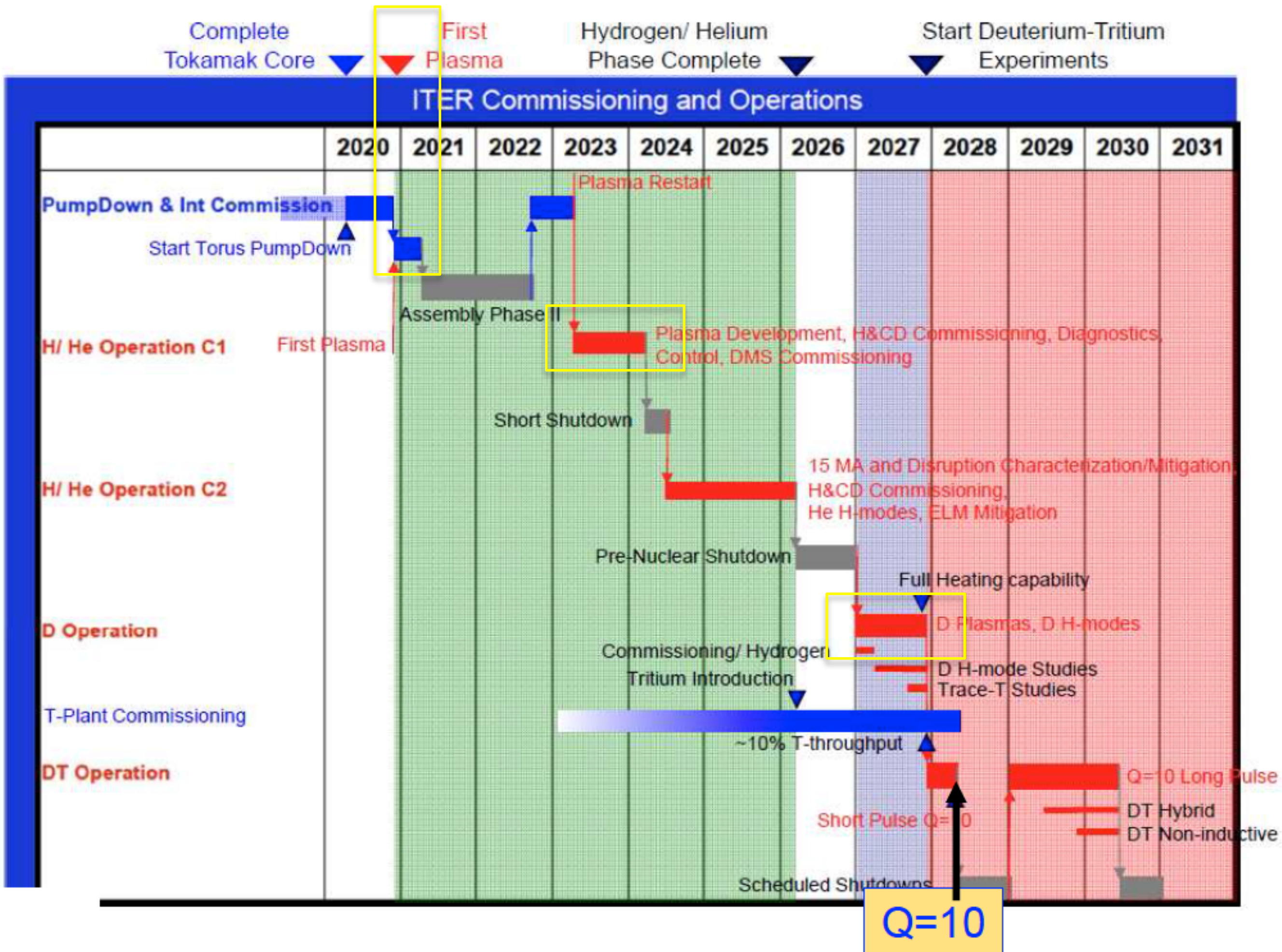




ITER schedule from G. Sips, JET GPM5

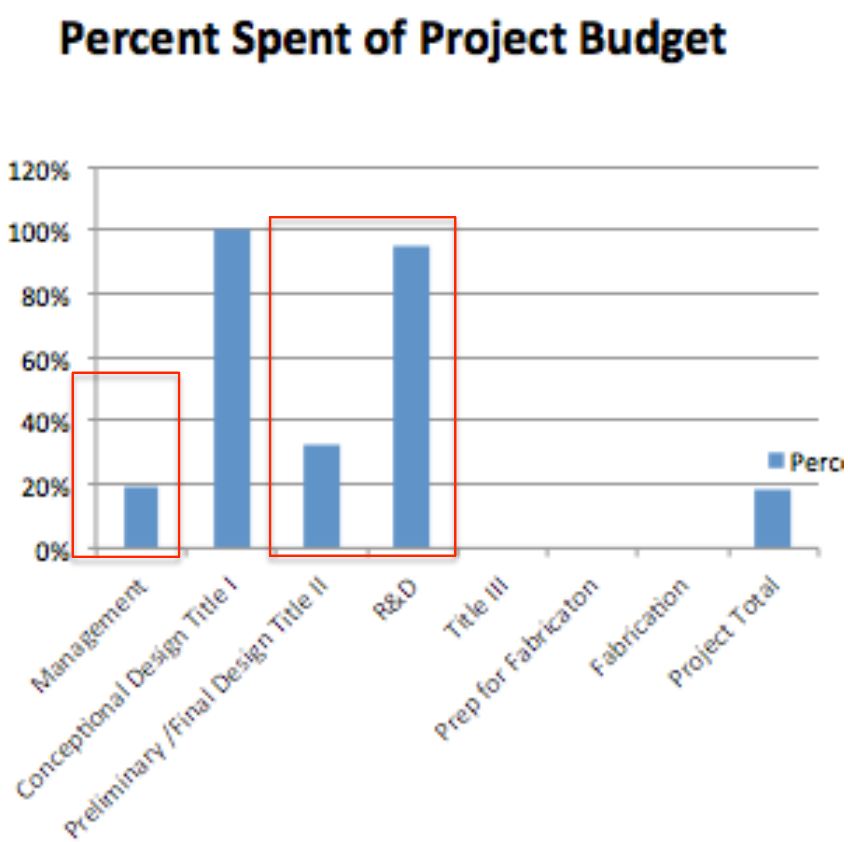
Motivation – The ITER Research Plan

The ITER Research Plan: Allows less than two years to go from first deuterium operation, to Q=10 in DT by early 2028.



ITER-IO, 2012

Project is "on budget", inc. Feb 2013



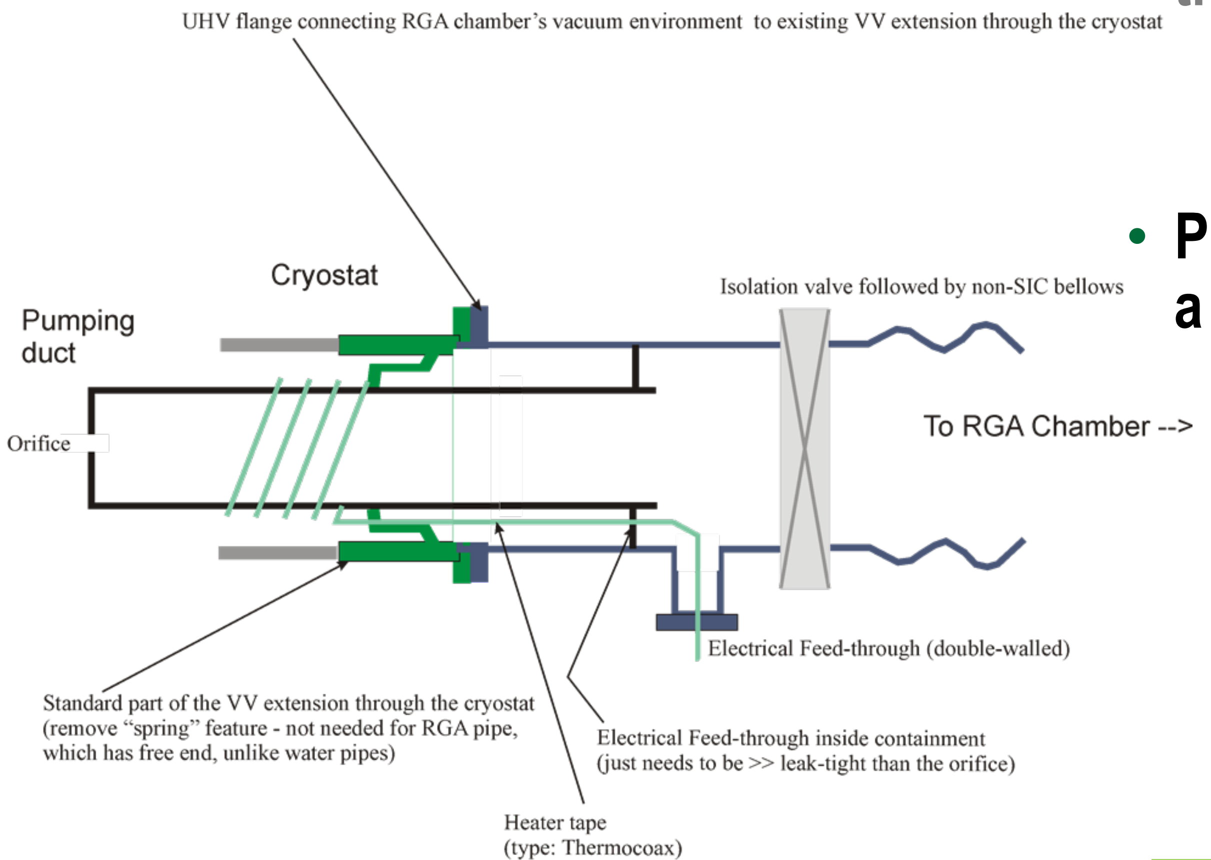
- CDR is complete, defining 100% spend point.
- Title III Engineering, pre-Fabrication, and Fabrication haven't begun, defining 0% spend points.
- Management covers ~FY11-FY17: 2/7~28%
- PD budget is ½ FD budget: should be ~33% spent
- R&D is wrapping up.

Summary and Conclusions

- To first order, the project is "on schedule and on budget", assuming a timely completion PDR Cat 1 Chits.
- Some R&D tasks have been delayed.
  – Those R&D tasks will be completed in the Final Design phase.
- ITER port cell design is impacting ability of DRGA system to meet FDR milestone.
  – We propose splitting the FDR (with PCR) so that "front end" components reach FDR earlier, allowing port cell design to formalize, enabling FD of DRGA analysis chamber & mounts.
- Three sensor design allows for measurement redundancy if any 1 gauge fails.
- Two complete DRGA systems are expected to be delivered to ITER in Summer 2017.

Supplemental Material

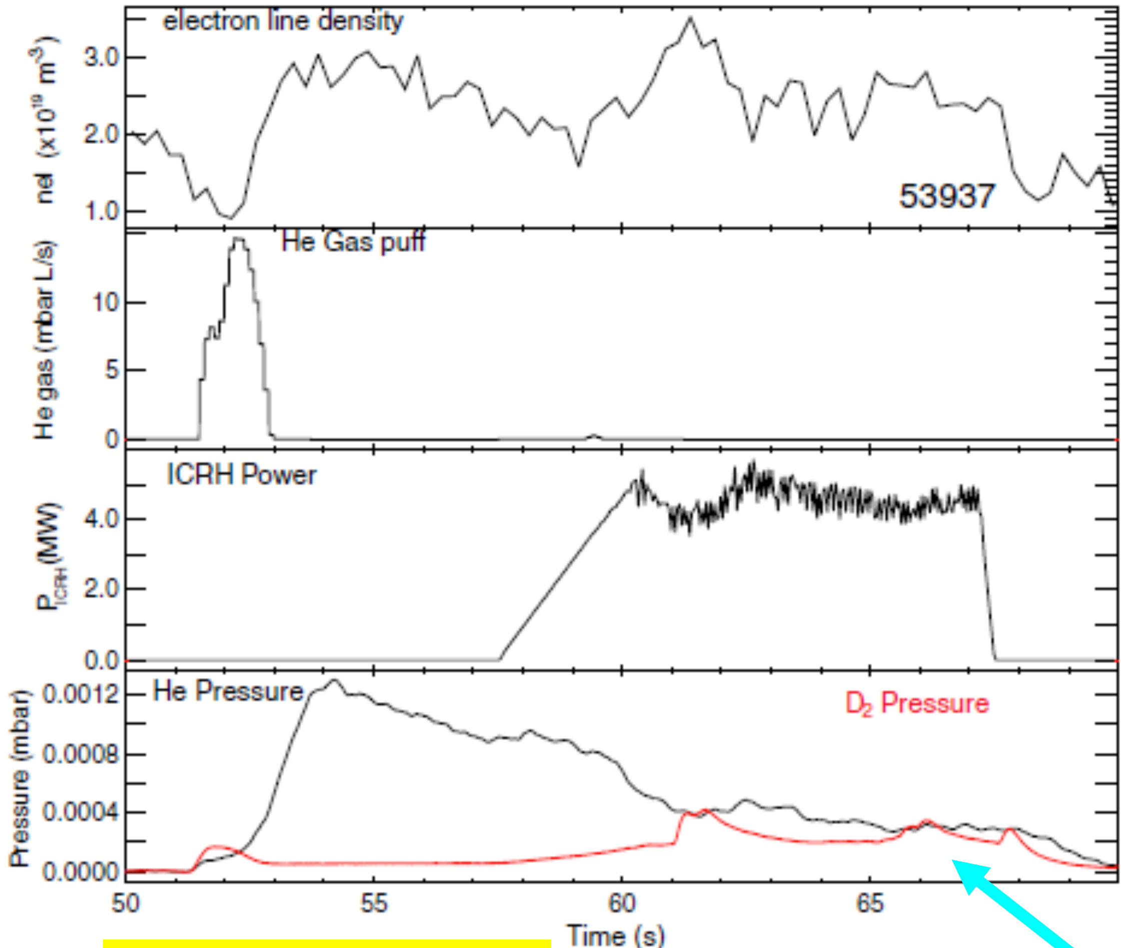
Aperture Replacement and Local Pipe Heater Concept



- One of the PD challenges, for the Divertor DRGA, was the cryostat pass-through
  - Essential to access the divertor region
- **Preliminary Design includes a CONCEPT for**
  - **Aperture Replacement**
  - **External heating of the pass-through section of the sampling pipe.**
  - See corresponding R&D Report for details (also related talks)

Moved to Ted Biewer's RH/Mantainance Talk

He/D_2 even more critical for ITER's OGA

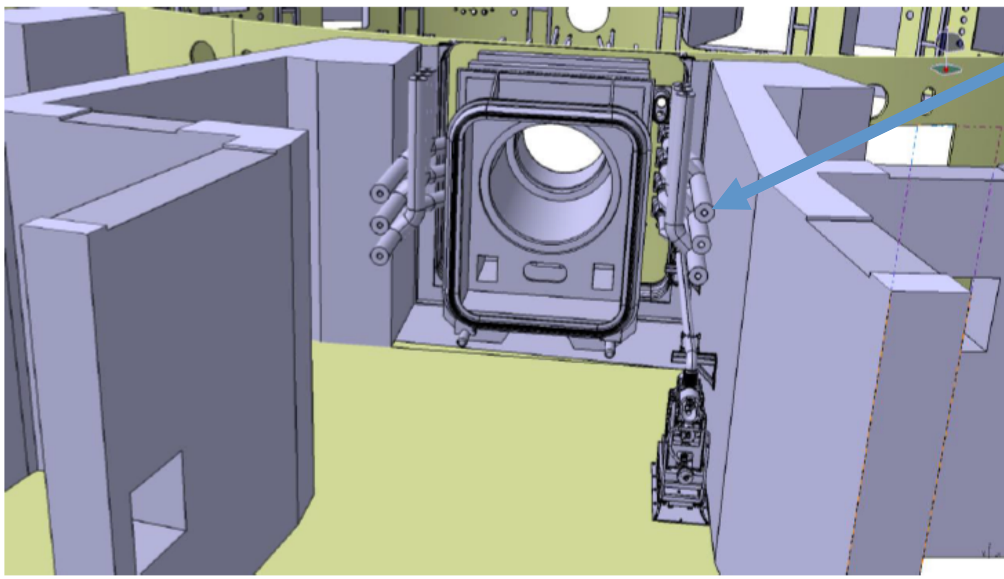


[**]D.L. Hillis et al. / *Journal of Nuclear Materials* 313–316 (2003) 1061–1065

Penning-OGA Data

- **This also from JET Divertor Penning-OGA**
  - **Earlier results with the Penning emission sampled with Dα and He I filtered detectors.**
  - **Change-over experiments with the the MkII-GB (gas box divertor configuration)[**]**
- **This measurement is not possible with present QMS sensors**

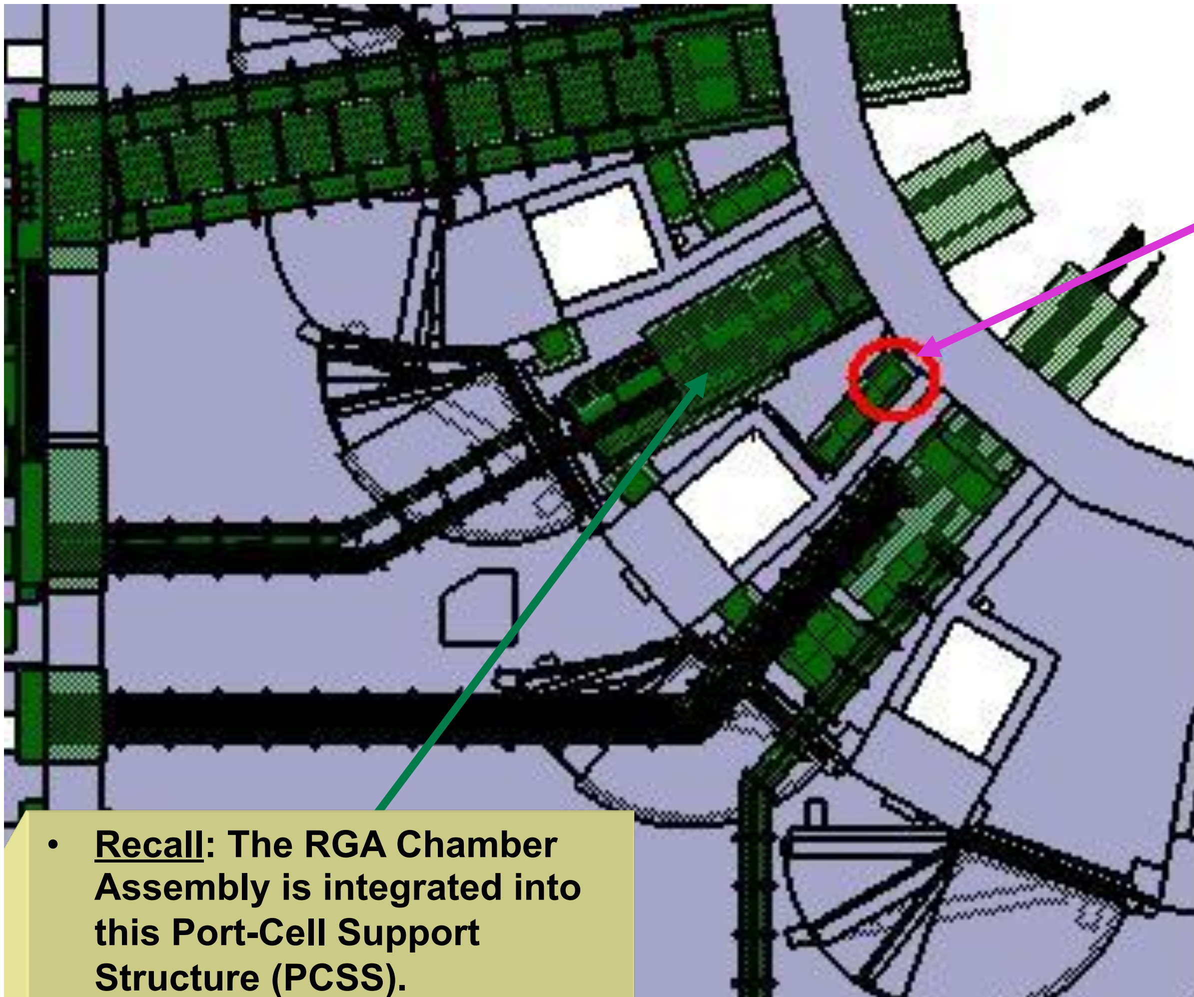
Cooling pipes bring high radiation dose into the Divertor port-cell



- Cooling pipes from the divertor come through the bio-shield and run just above the RGA chamber assembly.
- They constitute the main source of γ radiation in this region.
- Surrounding every sensor in the RGA *sensor tree* with 28" thick lead is clearly impractical!

- Impractical to rad-shield sensors
- ➔ Need to separate out the electronics
- ➔ Used radiation-hardened sensors only (to the extent possible) at the sensor tree.

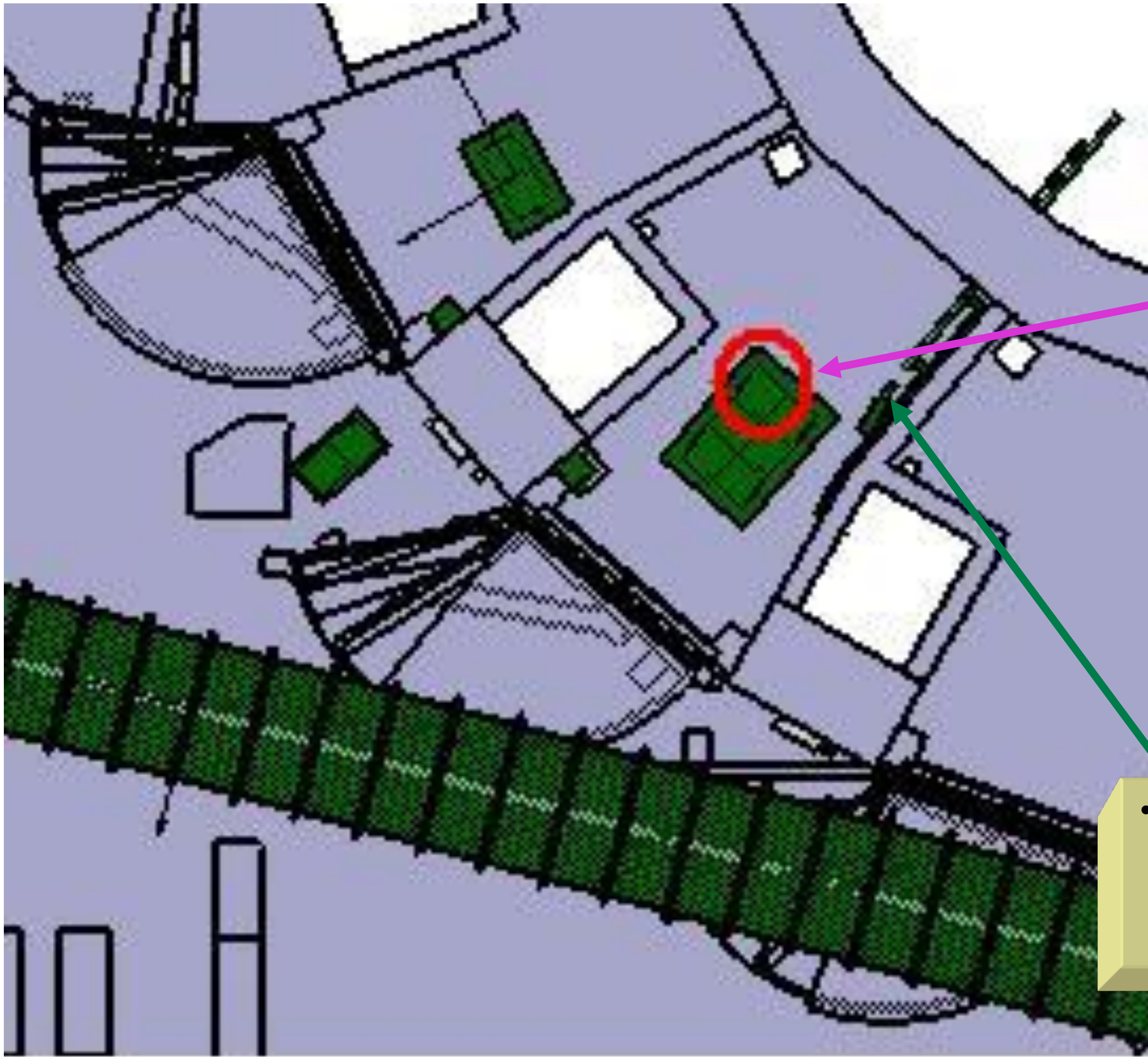
Alternative placement and shielding of electronics – Equatorial Port Level



- **<u>Recall</u>: The RGA Chamber Assembly is integrated into this Port-Cell Support Structure (PCSS).**

- Top view of Eq.11 port cell showing the alternative place for a DRGA LCC cubicle & its radiation shielding.
- The cubicle size is 800x800x2200 mm (Height).
- The shielding space is 200mm in front and top.

Alternative placement and shielding of electronics -- Divertor Level

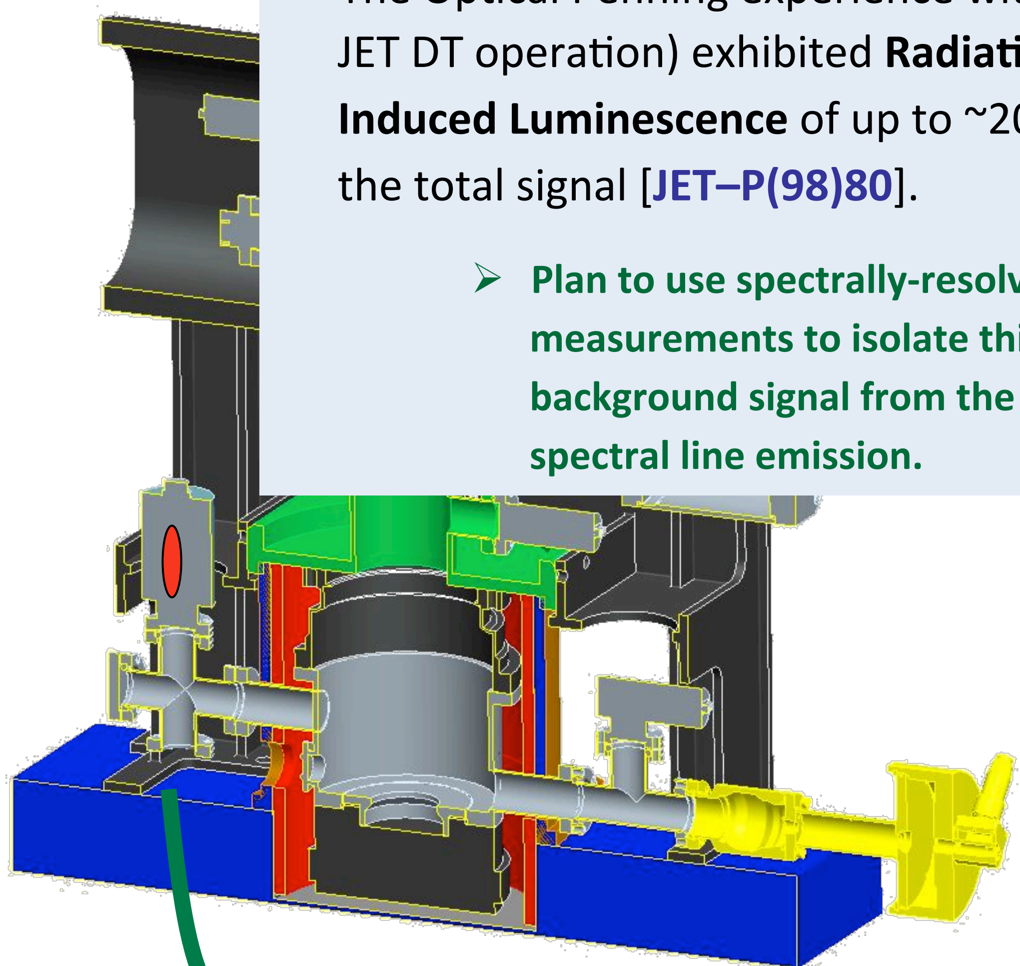


- In Lower port 12, the IO has also made provisions to have cubicles with shielding on a trolley.
- This provides for an alternative place for the Divertor DRGA LCC cubicle & its radiation shielding.

- **Recall**: The RGA Chamber Assembly is on a cart, anchored to the floor and right next to the wall

The ITER Optical Penning will use spectrally resolved detection

- The Optical Penning experience with the JET DT operation) exhibited **Radiation Induced Luminescence** of up to ~20% of the total signal [JET–P(98)80].
  - ➢ **Plan to use spectrally-resolved measurements to isolate this background signal from the spectral line emission.**

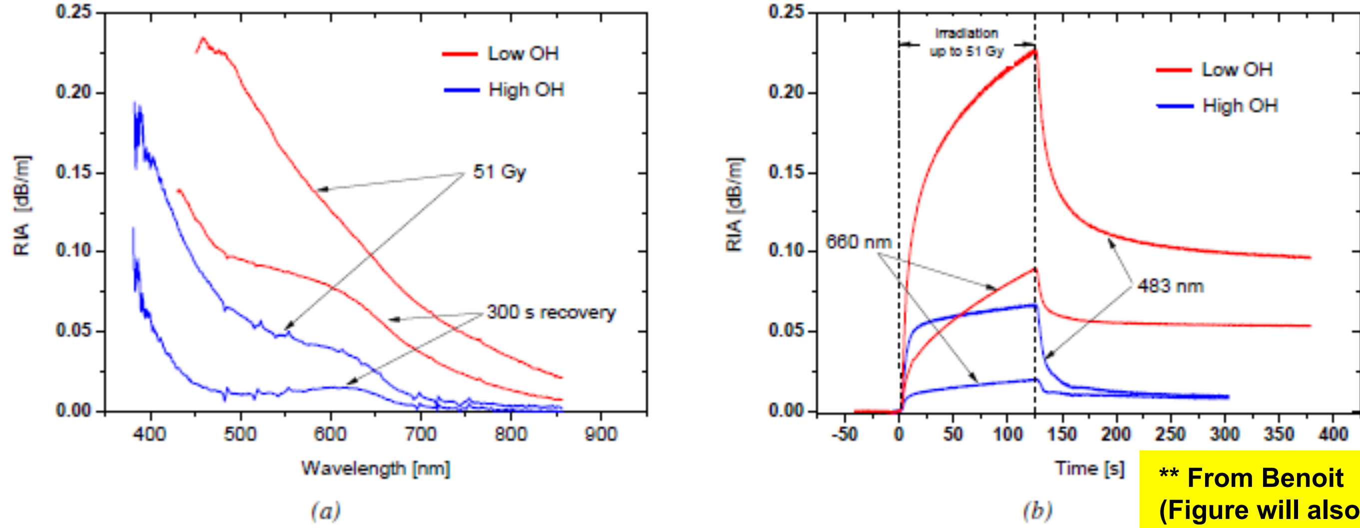


Compact Spectrometer

Recall: Optical Penning is currently aimed only for the He/D_2 measurement (not H_2/D_2/T_2)

Pure silica optical fibers

Penning-OGA Optical Fiber Concerns

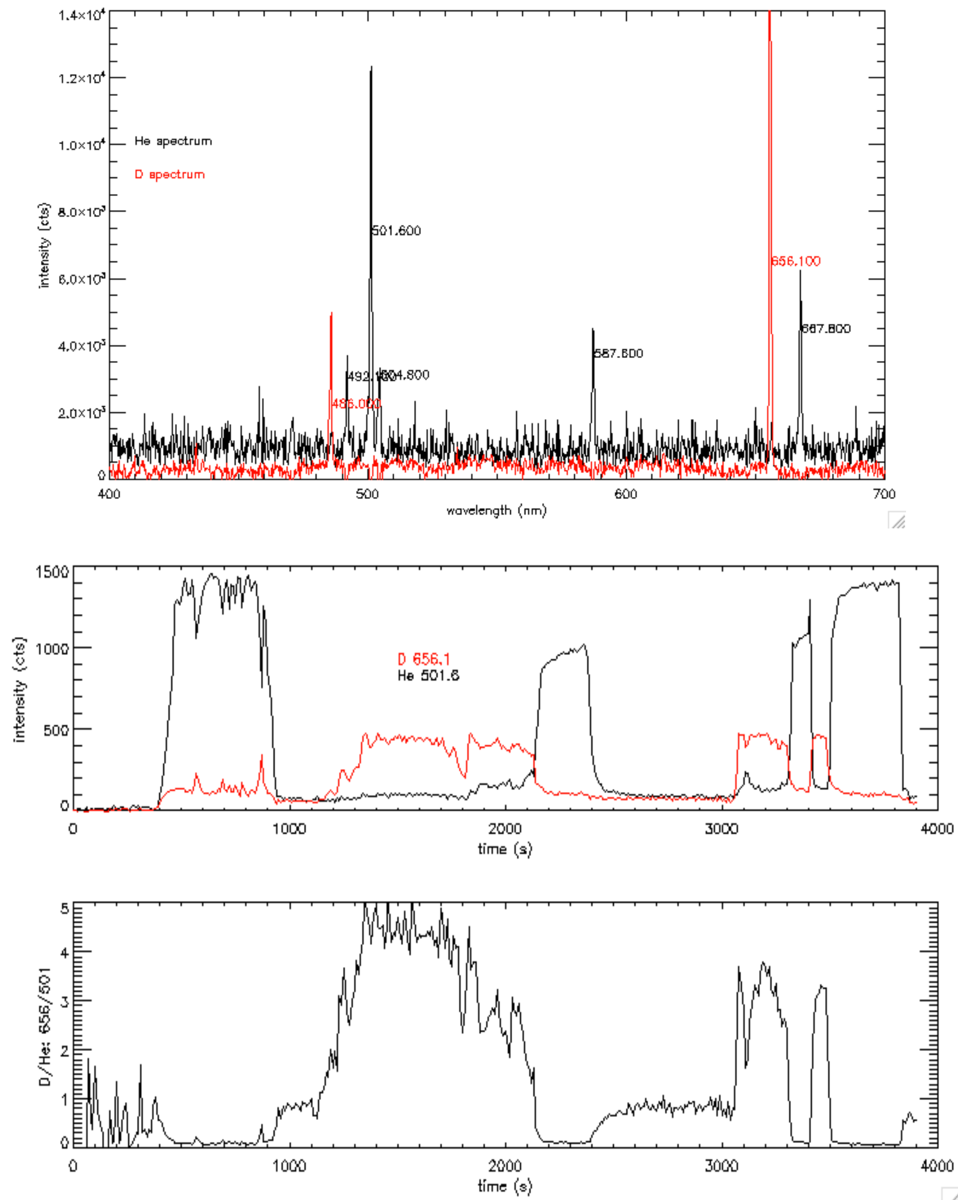


** From Benoit Brichard, Priv. Comm., Mar-2013 (Figure will also appear in Chapter 7 of his dissertation).

Figure 7.1: RIA behaviour in low OH (STU) and high OH (SSU) pure silica fibres (100 μm core diameter) irradiated at 1.5 kGy/h (25 °C) as a function of *(a)* wavelengths *(b)* irradiation time.

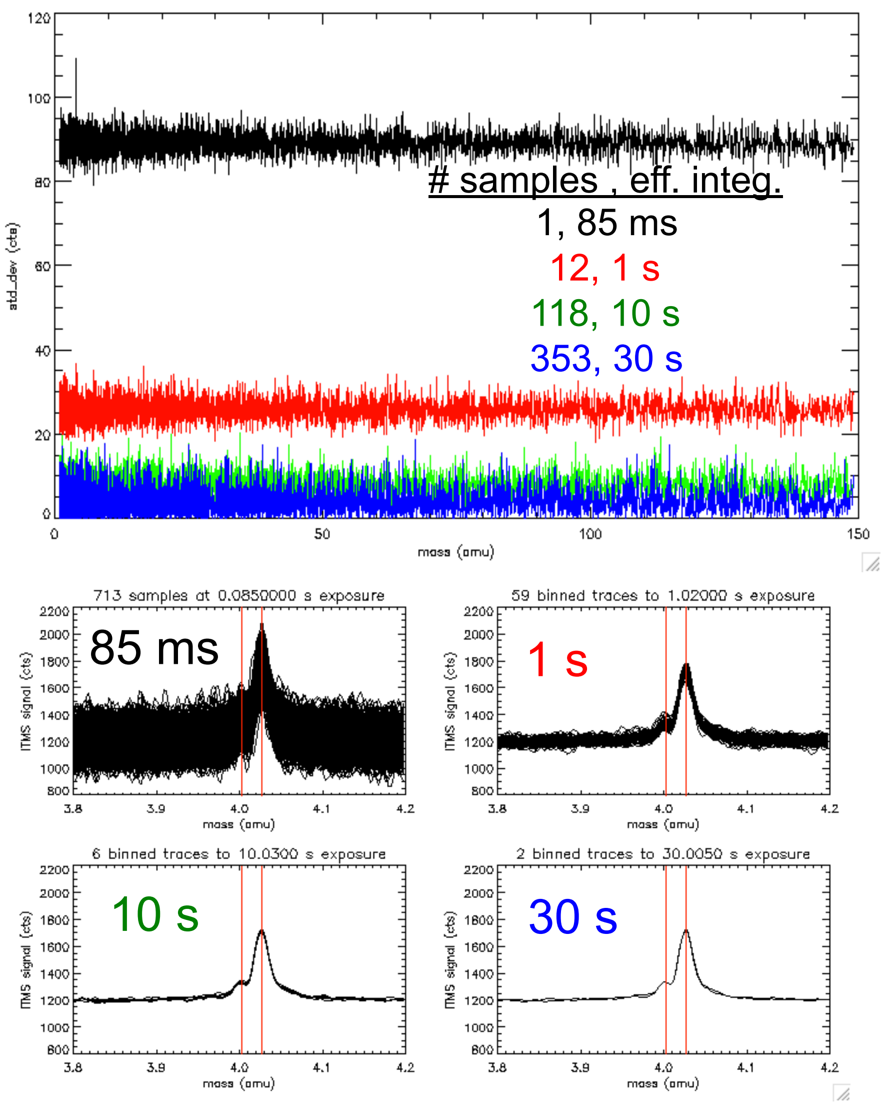
- **Radiation-Induced Attenuation (RIA) can impact transmission → S/N.**
  - **Produces a "transient" response as a function of total γ radiation dose.**
  - **Potentially problematic for the "standard" Penning-OGA mode of operation is that RIA bands appears around both preferred He I lines and $H_\alpha/D_\alpha/T_\alpha$!**
- **Also cumulative damage**
  - **➔ curing by heating the fibers and/or regular replacement**
- **However, most RIA data are from much higher radiation rates that we anticipate in ITER**
  - **Favorable experience with pure, high-OH SiO_2 core/clad fibers on JET and TFTR with DT operation**

Optical Penning Gauge Spectra on CVC



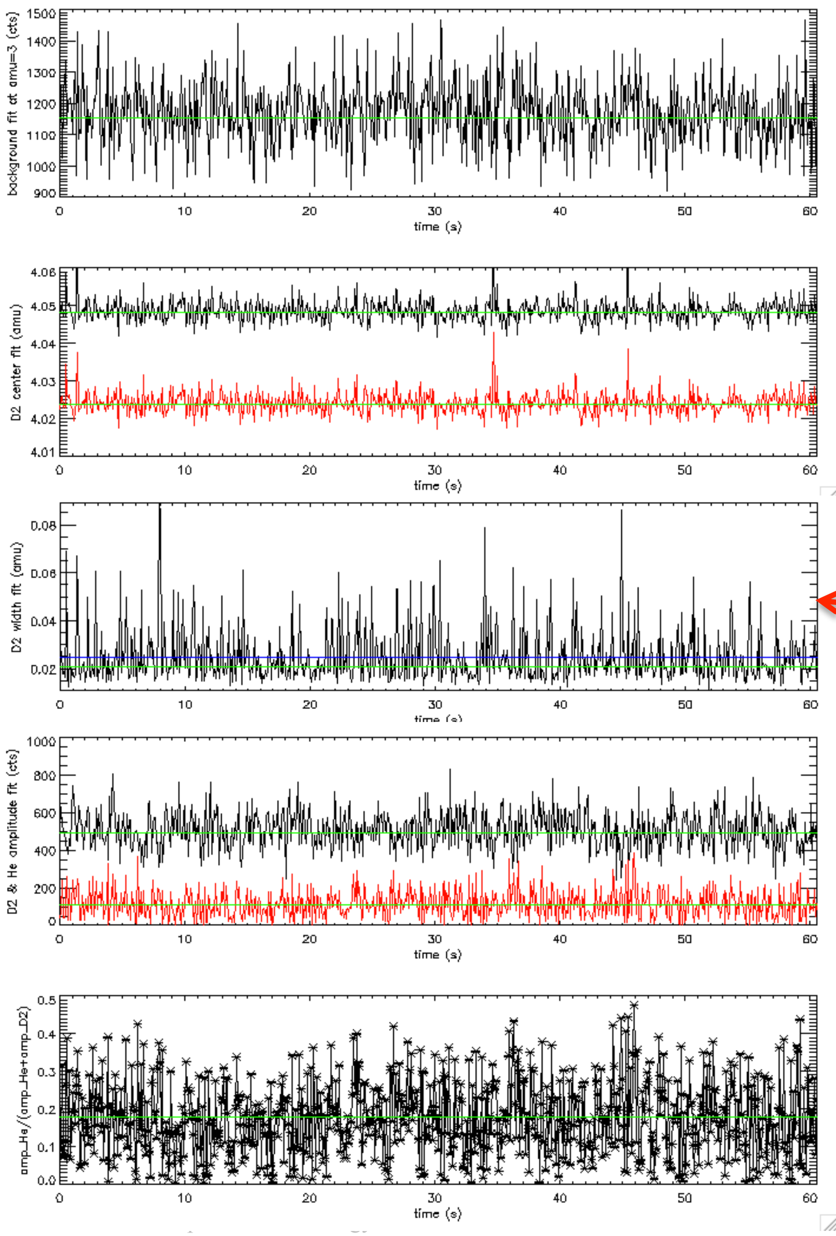
- Optical emission spectra of He and D are distinct, and emission lines are easily resolved and monitored.
- Ocean Optics HR4000CG-UV-VIS spectrometer
  - 200-1100 nm coverage
  - 4 ms to 10 s integration periods
- To resolve H/D/T will require higher resolution
- Example of ~1 hour of CVC operation

Ensembling improves read noise



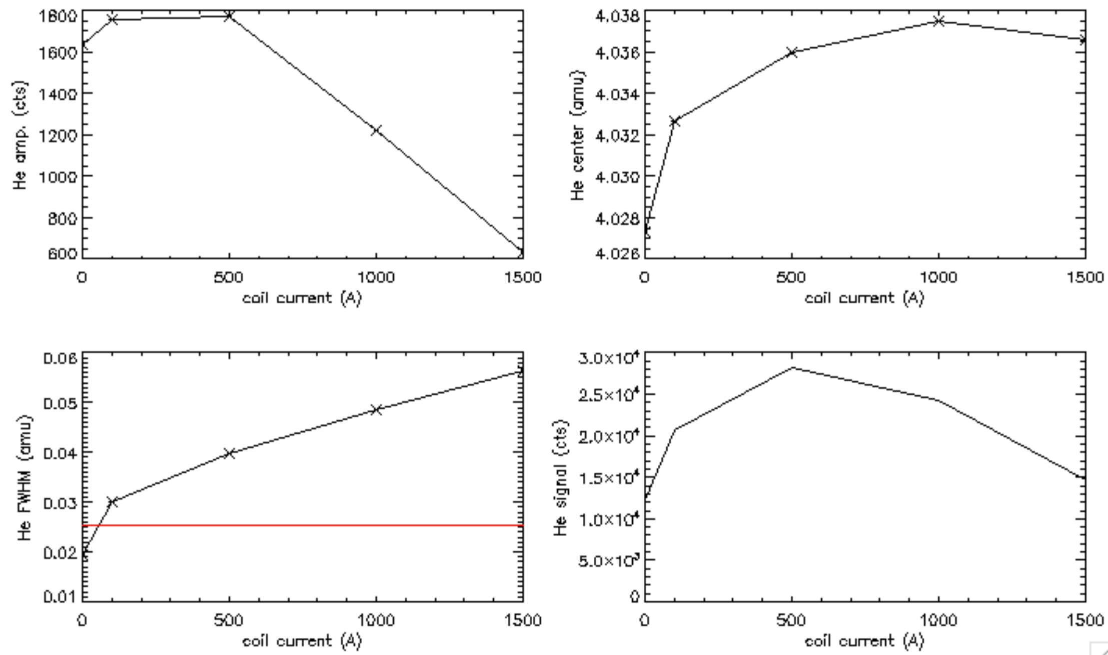
- Unlike QMS (dwell time/mass determines count total & total scan period), ITMS scan rate and resolution is fixed (85 ms)
- Standard deviation of sample-to-sample count variation (at constant pressure) for various ensembles
  - ~same at all masses as expected
- Ensembling "reduces" noise level and improves signal quality
- Desired SNR determines effective integration time

ITMS sufficient for He/D_2 resolution



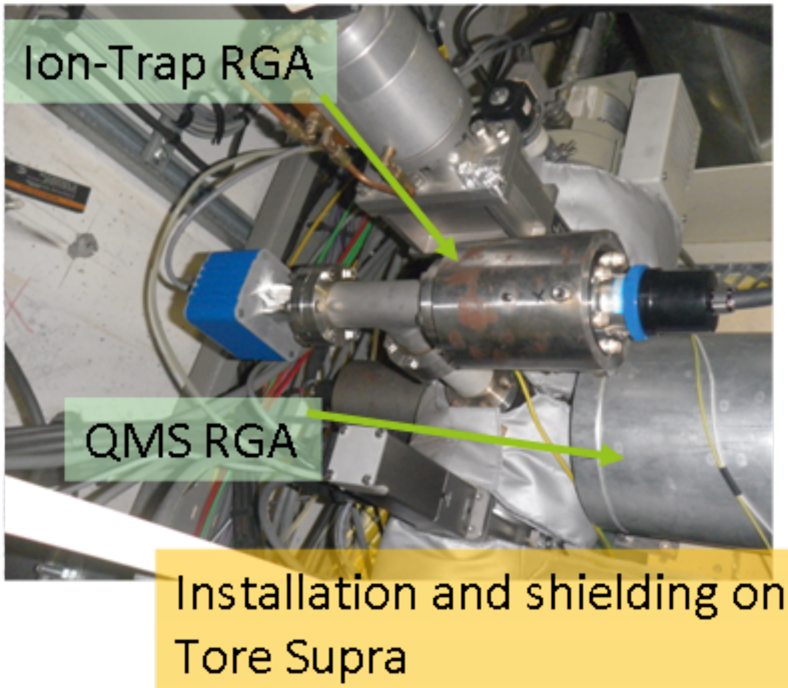
- Gaussian line shapes fit to raw ITMS output logged at constant pressure
- Shown are the fit results for each 85 ms sample (D_2, black and He, red) compared to the ~1 minute ensemble fit values (green)
- Resolution is inherent to the ITMS gauge:
  - R=(mass)/(FWHM)
  - R~195 measured, i.e. >R~164 needed
- The ITMS can resolve He/D_2, provided there is sufficient signal to discriminate the peaks above the noise floor.

Unsheilded ITMS is sensitive to B



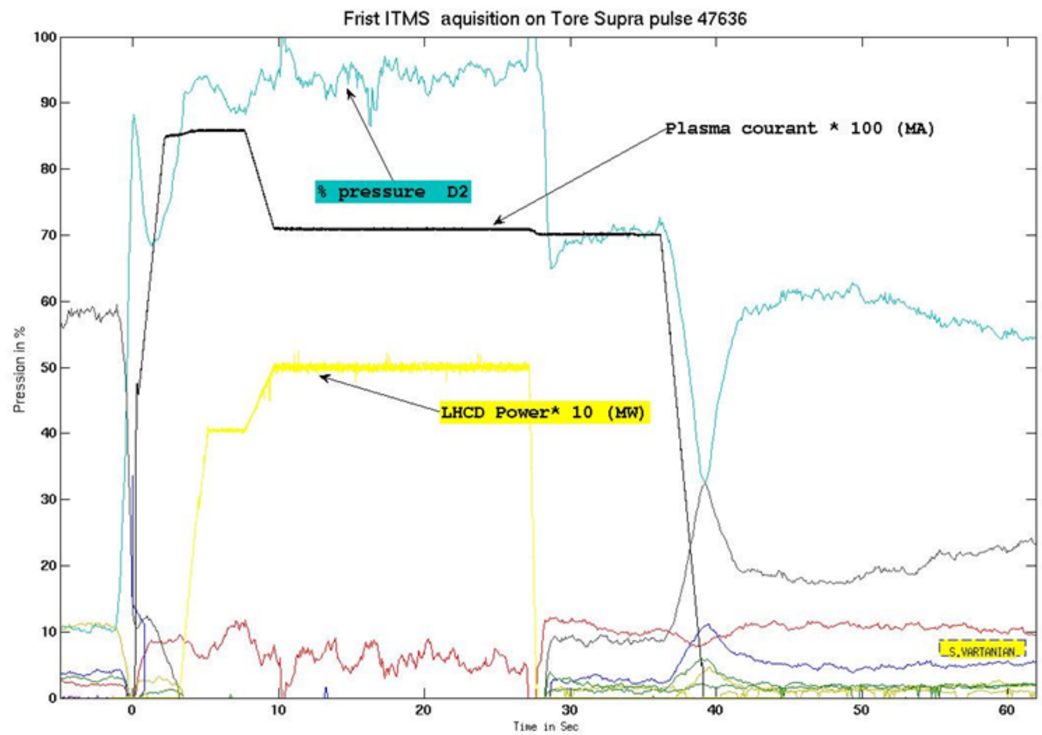
- Magnet coil current varied at constant fill pressure.
- Raw mass peak becomes increasingly distorted as coil current ramped up.
- Resolution degraded and accuracy compromised.

ITMS testing on Tore Supra



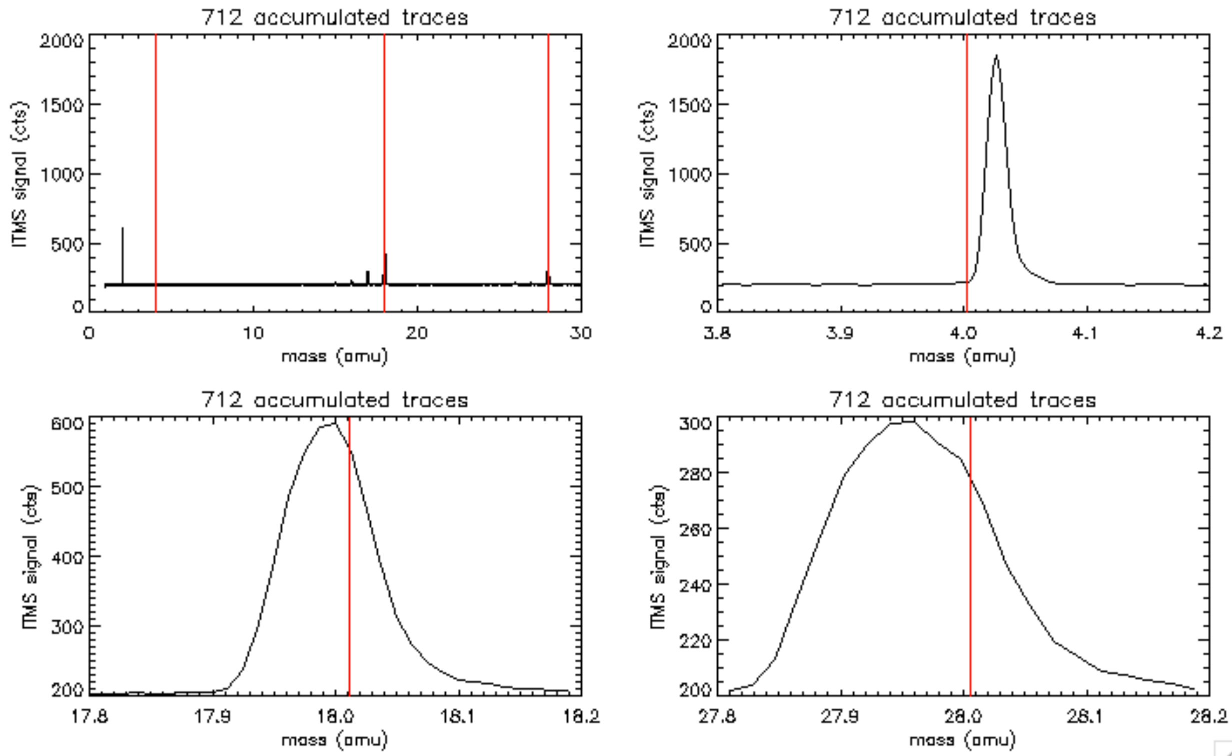
- ITMS was installed on Tore Supra, physically adjacent to QMS.
- Similar magnetic shielding on both.

- Shielded ITMS successfully operates in rf-noise, B-field, etc. of Tore Supra for long pulse.



T.M. Biewer, ITPA 2013 Diagnostics Topical Group Mtg., San Diego, CA, USA, Jun. 4-7th, 2013

Mass variation of ITMS resolution



- R=(mass)/(FWHM) is mass dependent, generically
- Measured FWHM of ITMS follows ~1/(mass) relation, such that R_{ITMS}~190, independent of mass
- ITMS has insufficient resolution for N- compound discrimination

T.M. Biewer, ITPA 2013 Diagnostics Topical Group Mtg., San Diego, CA, USA, Jun. 4-7th, 2013

Cost Performance Report (inc. Feb. 2013)

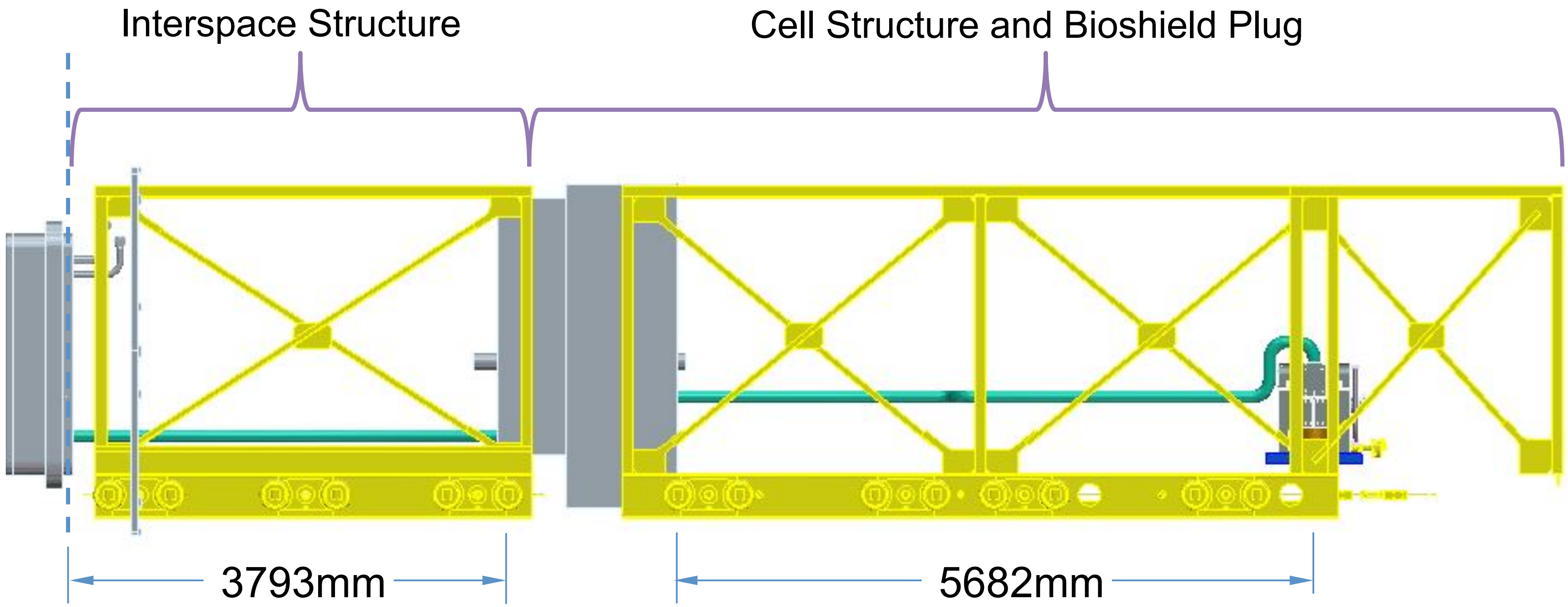
- **Most recent numbers from US DA (WBS managers) indicate:**
- **Cumulative Project Metrics:**
  - **Cost/Performance Index (CPI): 0.98**
  - **Cost Variance (CV%): -2%**
  - **Schedule/Performance Index (SPI): 0.82**
  - **Schedule Variance (SV%): -18%**
- **Since we are currently at PDR, schedule variance was recovered by work performed in March (not reflected here).**

CONTRACT PERFORMANCE REPORT
FORMAT 1 - WORK BREAKDOWN STRUCTURE

PERFORMANCE DATA

February 2013	CURRENT PERIOD							CUMULATIVE TO DATE								
	BUDGETED COST		ACTUAL	VARIANCE				BUDGETED COST		ACTUAL	VARIANCE					
ITEM	WORK SCHEDULED	WORK PERFORMED	COST WORK PERFORMED	SCHEDULE	SV%	COST	CV%	WORK SCHEDULED	WORK PERFORMED	COST WORK PERFORMED	SCHEDULE	SV%	SPI	COST	CV%	CPI
1.05.03.06 Residual Gas Analyzer	*180*	*62*	*71*	*-118*	*-66%*	*-9*	*-15%*	*1,230*	*1,014*	*1,031*	*-216*	*-18%*	*0.82*	*-17*	*-2%*	*0.98*
1.05.03.06.01 Management Support	9	9	3	0	0%	6	68%	145	145	135	0	0%	1.00	10	7%	1.07
1.05.03.06.02 R&D	61	11	34	-50	-82%	-23	-206%	291	231	258	-60	-21%	0.79	-27	-12%	0.89
1.05.03.06.03 Conceptual Design	0	0	0	0	0%	0	0%	220	220	220	0	0%	1.00	0	0%	1.00
1.05.03.06.04 Preliminary/Final Design	109	41	34	-68	-62%	7	17%	575	419	419	-156	-27%	0.73	0	0%	1.00
1.05.03.06.05 Title III	0	0	0	0	0%	0	0%	0	0	0	0	0%		0	0%	
1.05.03.06.06 Preparation for Fabrication	0	0	0	0	0%	0	0%	0	0	0	0	0%		0	0%	
1.05.03.06.07 Fabrication	0	0	0	0	0%	0	0%	0	0	0	0	0%		0	0%	

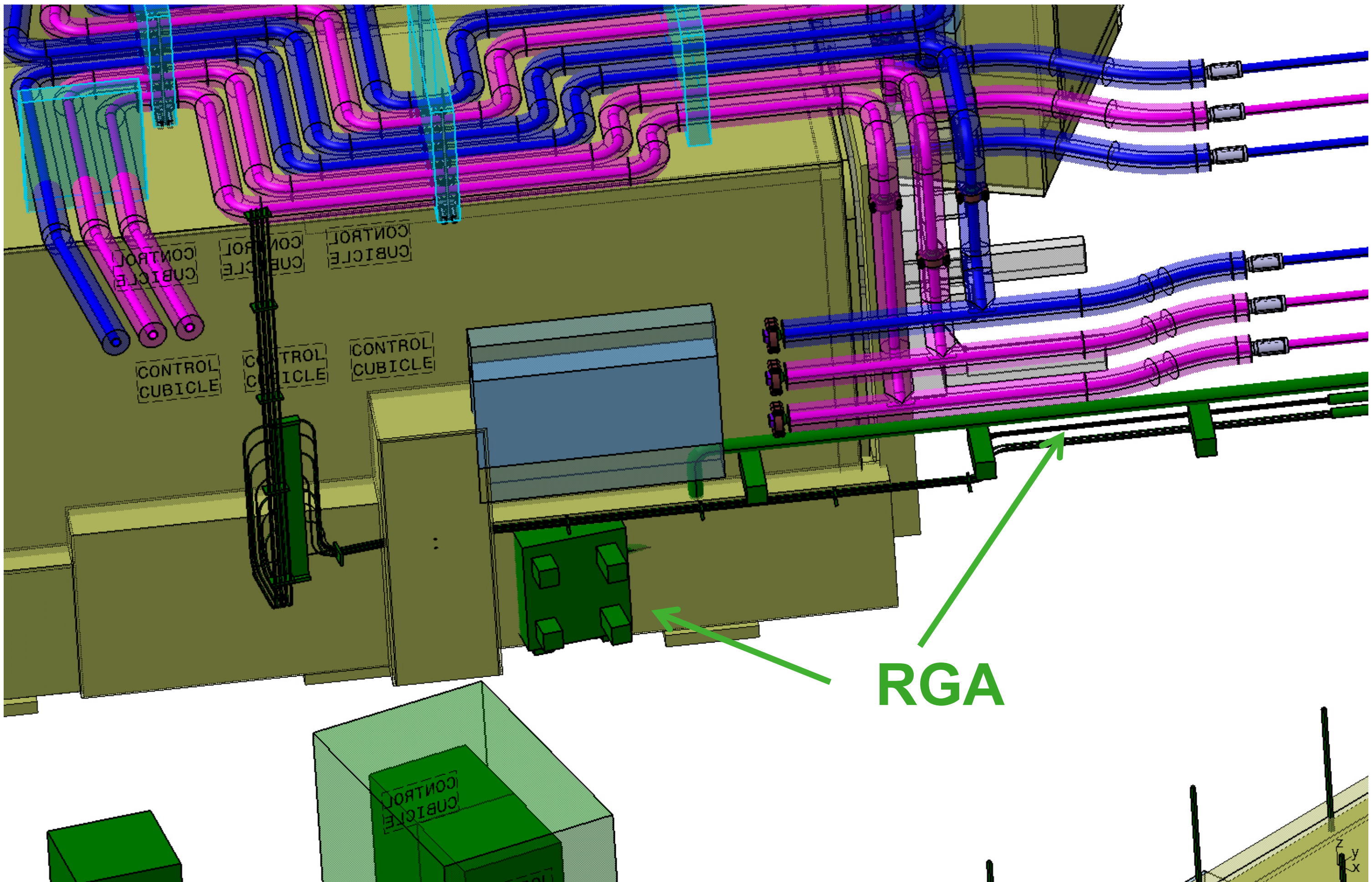
PIPE THERMAL EXPANSION



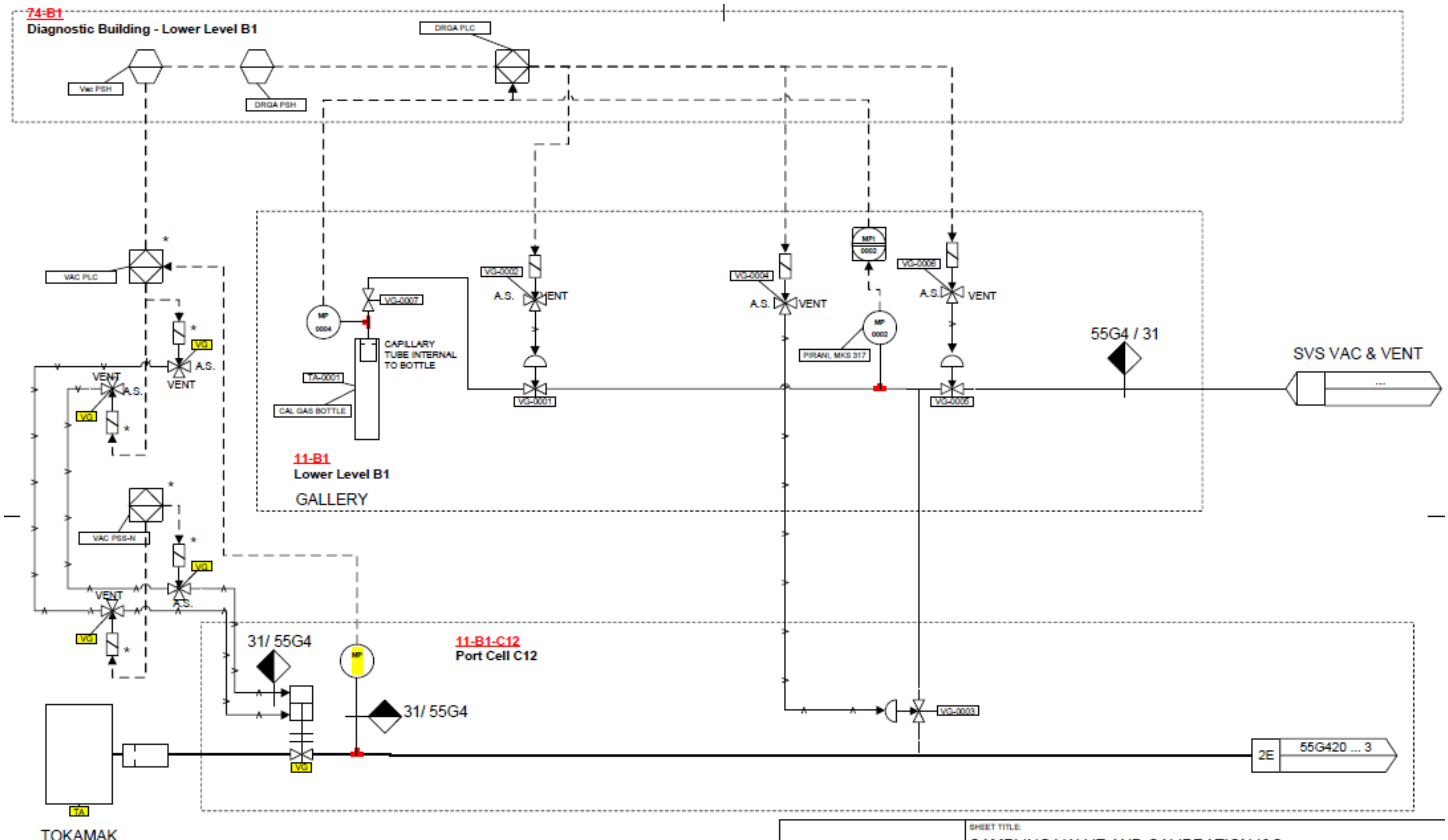
- **Sample Pipe is fixed at bioshield & port plug; pipe sections figured separately**
- **Linear expansion = $C_{EXP} L \Delta T$**
- **ΔT = 200 °C (for bake-out)**
- **Coefficient of Linear Thermal Expansion for 304 SS pipe**

$$C_{EXP} = \frac{17.3 \times 10^{-6}\, m}{m\, ^{\circ}\mathrm{C}}$$

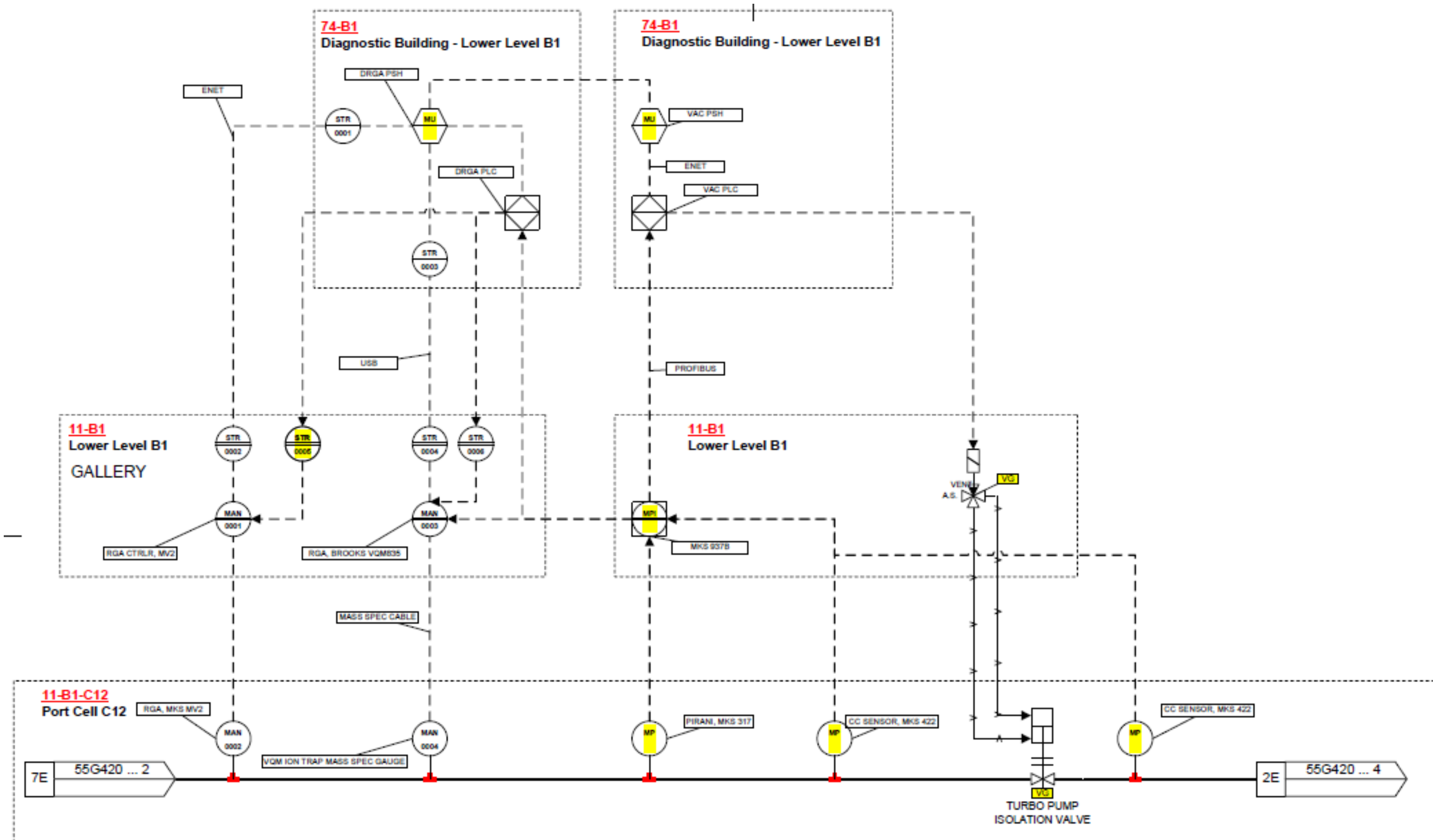
Clash with standardized RH rail (PCR 502) in lower port cell



DRGA P&ID p.1: Sample Line & Cal. Infrastructure



DRGA P&ID p.2: High-Vacuum Section



DRGA P&ID p.3: Foreline Section