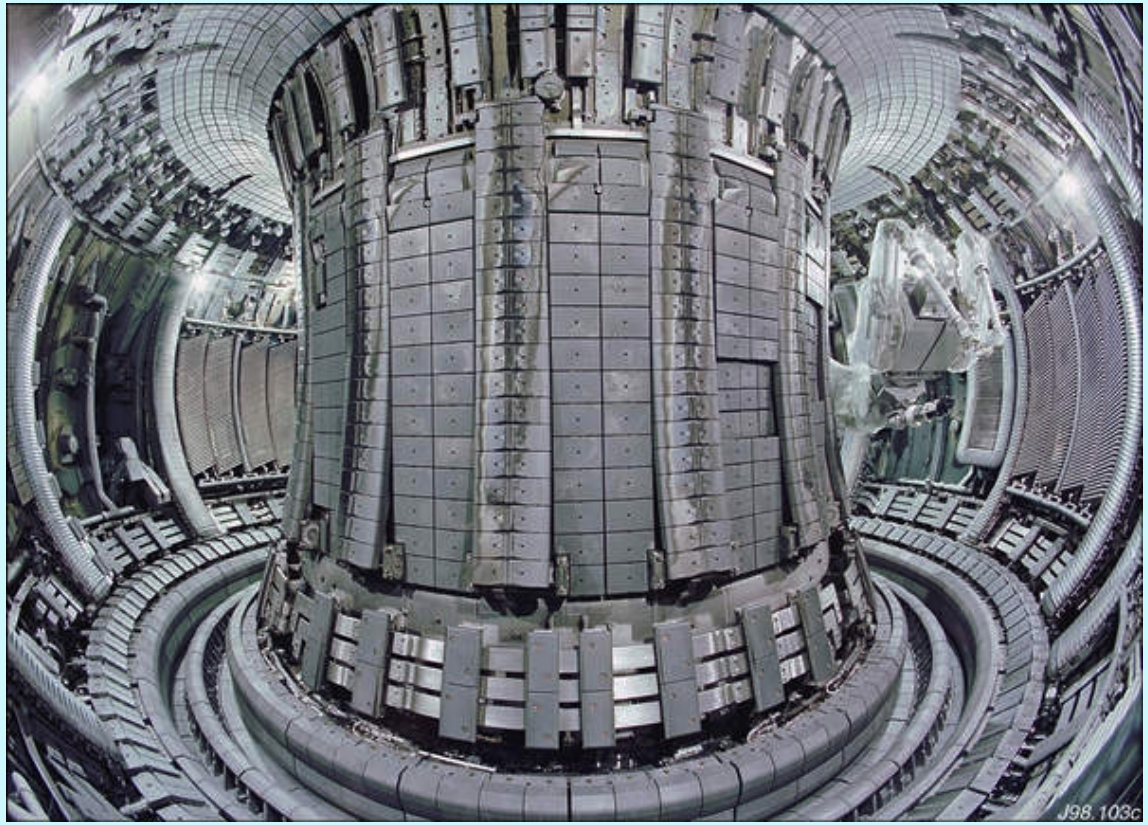
# Investigation of Tritium Pathways in the JET Tokamak




A view inside the JET Vacuum Vessel

# Tritium Pathways in JET

- **In addition to record fusion power, JET D-T experiments have provided an opportunity to study the link between core, edge, and wall plasmas**

- **The D-T inventory in the graphite walls of a tokamak ultimately determines the isotopic composition found in the core plasma**
  - **"Dynamic" inventory : controls the fueling behavior within a discharge, and determines the isotopic composition**
  - **continually growing inventory - usually found in co-deposited layers**

- **If the continually growing T inventory proceeds, this can have profound consequences for the safety and environmental acceptability of future fusion reactors**

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# Tritium Retention Issues

- **Tritium uptake and retention by tokamak wall materials requires a detailed understanding of tritium processes which take place:**

| | |
|---|---|
| **1. during a shot:** | **implantation** |
| **(dynamic inventory)** | **trapping/detrapping** |
| | **recombination** |
| **2. between shots:** | **outgassing** |
| | **pumping** |
| | **diffusion into bulk** |
| **3. over many shots:** | **diffusion into the bulk** |
| | **tritium accumulation in co-deposited material (continually growing inventory)** |

- **This presentation will primarily address topics 1 and 3**

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# Outline

- **Address the dynamics of Tritium retention/loading by the graphite walls of JET -**
- **Utilize new JET diagnostics which provide tritium concentration measurements in the divertor and sub-divertor regions**
- **Analysis and modeling with Eirene and W-Diffuse(wall model)**
  - **- Combining divertor and sub-divertor T concentrations with Eirene modeling provides T recycling coefficients at wall surface**
  - **- various wall models can be tested to evaluate fundamental rate coefficients for:**

    **Recombination, trapping, thermal detrapping,**

    **and particle induced detrapping**
- **As an example of plasma core- wall interaction: Apply inferred T recycling coefficients to H-mode Trace T Transport Experiments**
- ***Long term tritium storage in co-deposited material***
  - **- over many shots**

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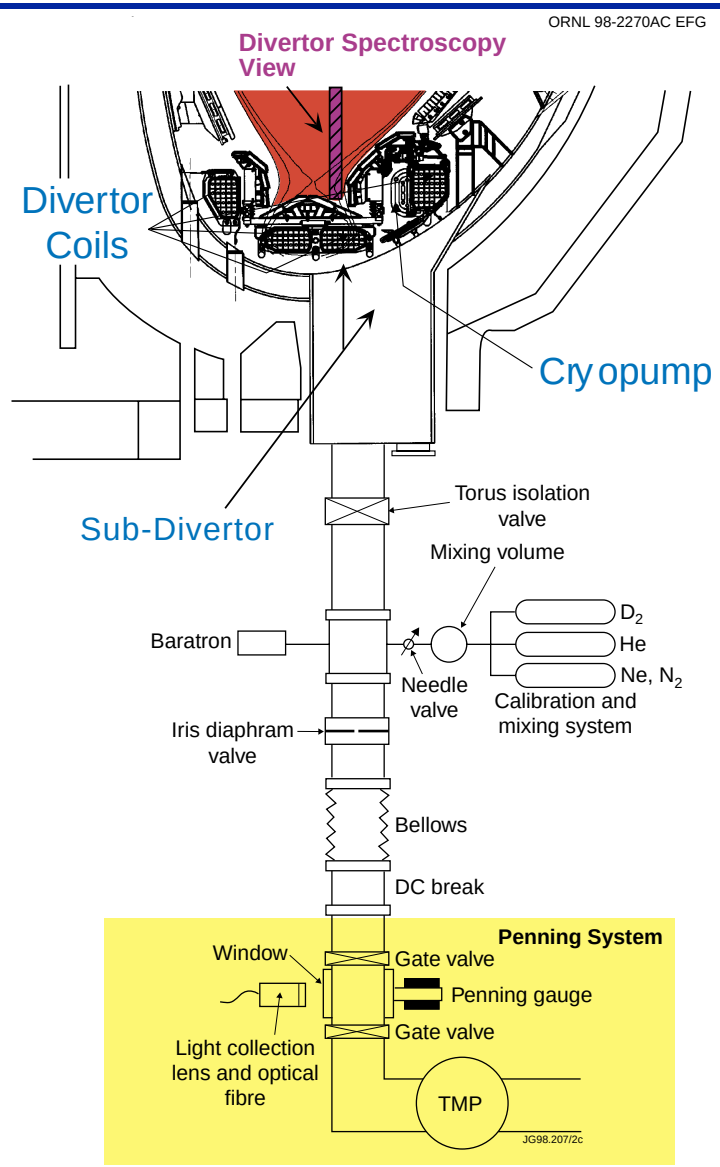
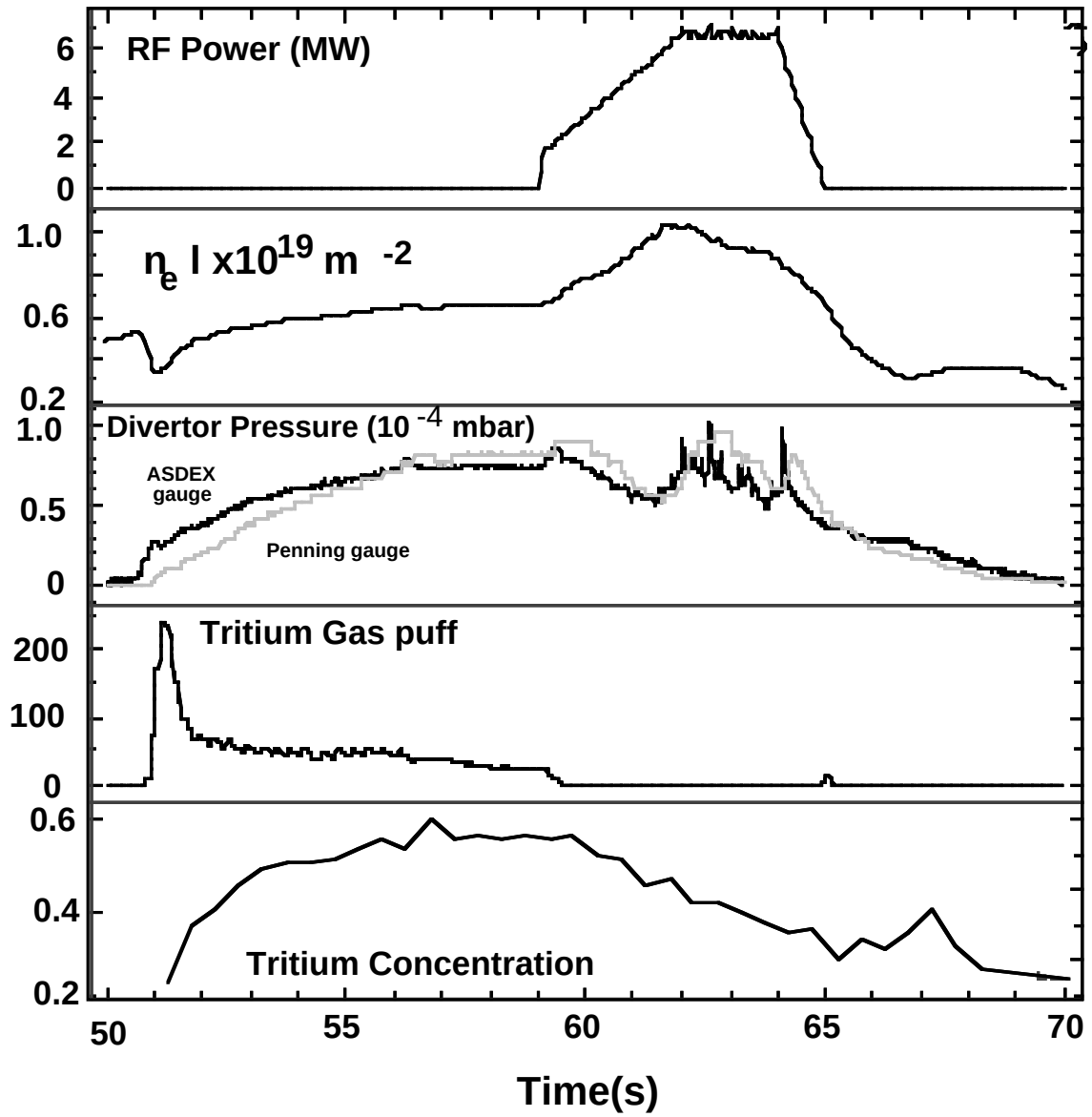
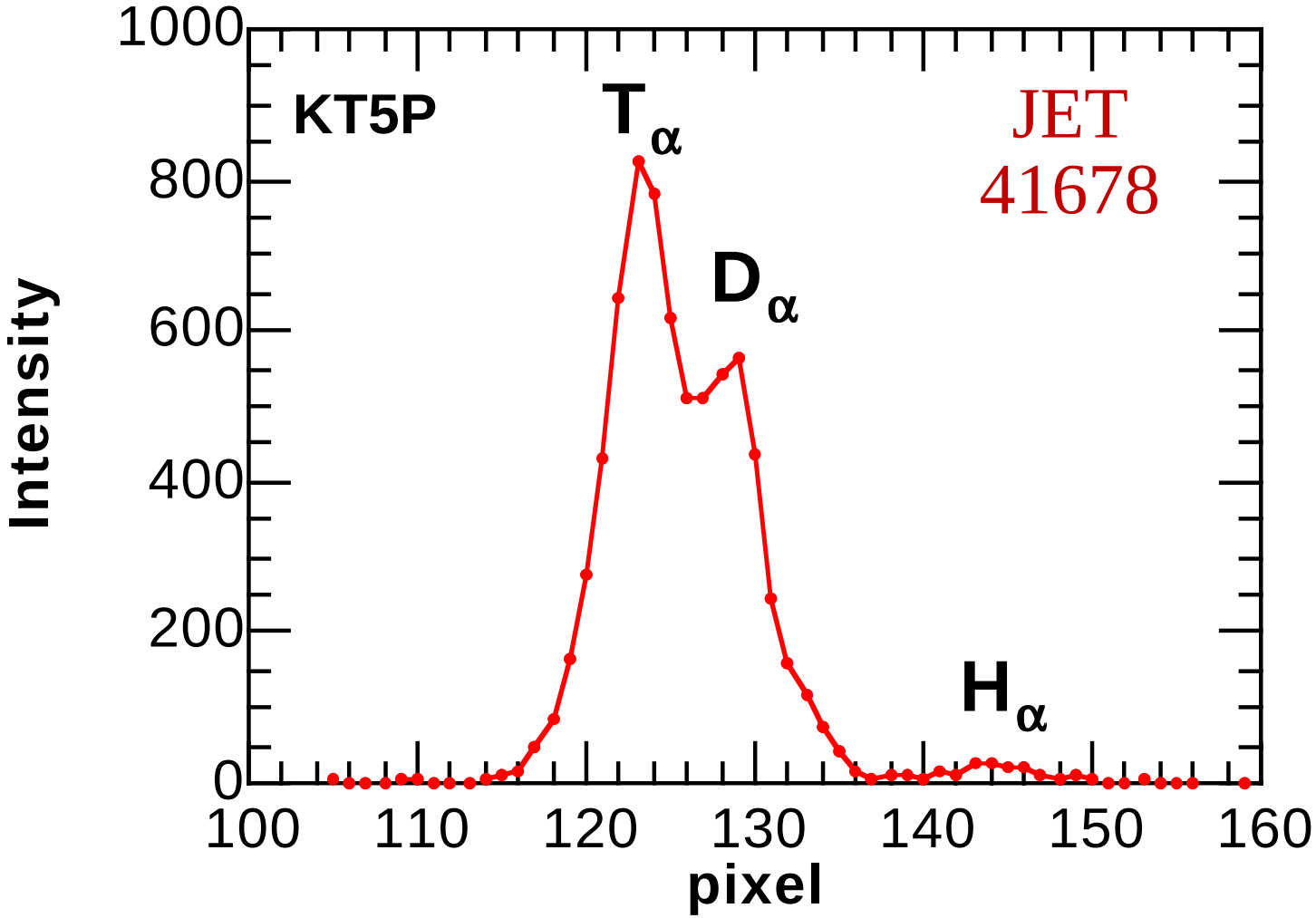
# Spectroscopy and Penning Gauge Provide Tritium Concentrations in the Divertor



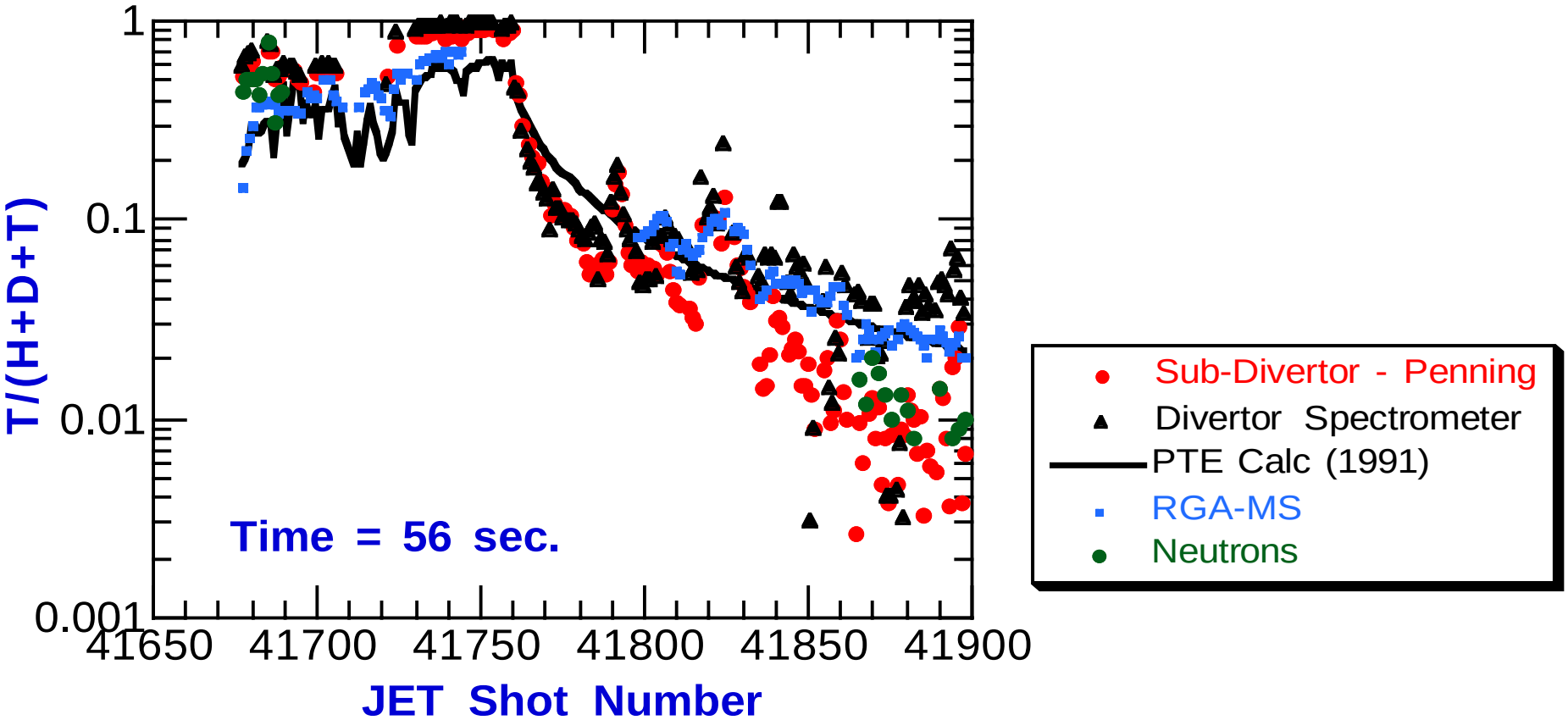
# Tritium Concentration in the Divertor of JET via ORNL Designed Penning Gauge



# Hydrogenic Isotope Mix Measured with Penning Gauge during JET DT Experiments



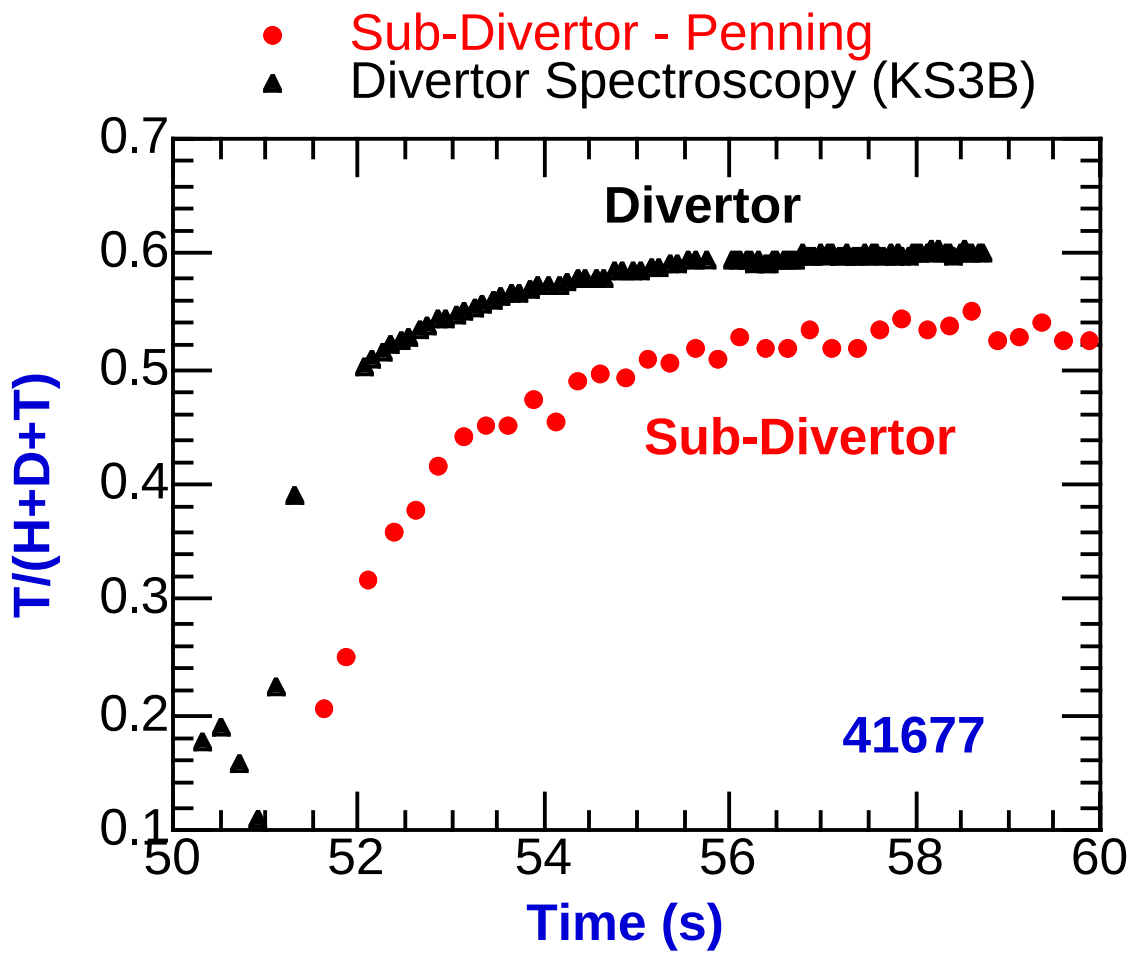
# Tritium Concentration Measurements in JET during DT Operation




- Penning gauge provided T Concentration Measurements throughout the JET DT campaign

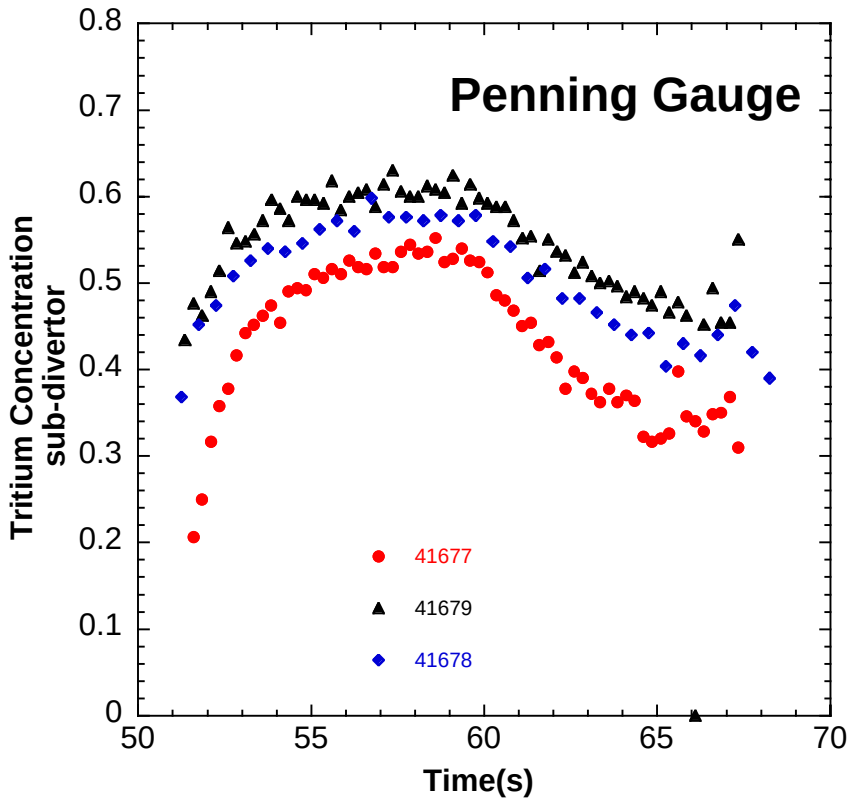
# Comparison of T Concentration in the Divertor and Sub-Divertor

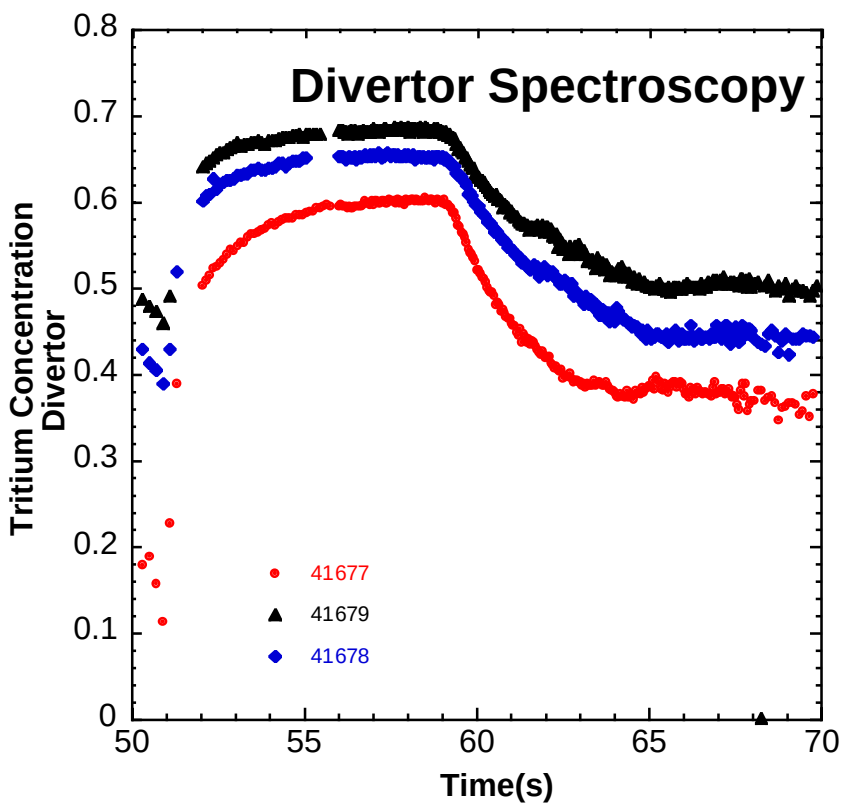
## First Tritium fueled Discharge with 100% D Loaded Walls



# Tritium Wall Loading during first 3 shots

## Changes in T concentration in Divertor and sub-Divertor sensitive to the wall saturation and uptake of T



# Tritium Uptake Processes

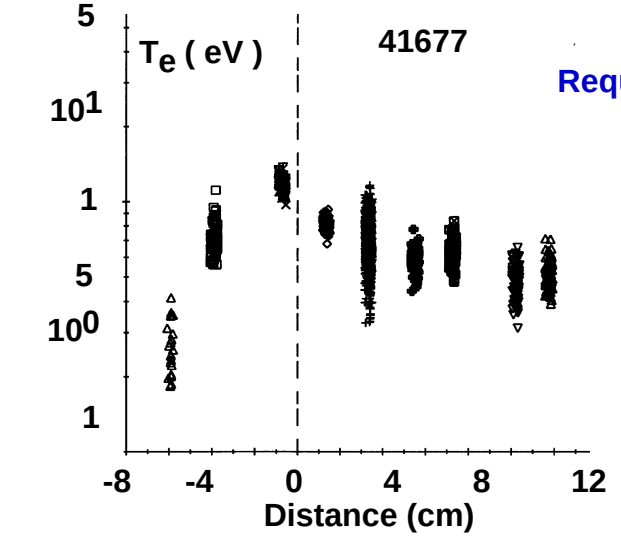
- Difference between divertor, sub-divertor T concentration indicates wall status, as the wall evolves from D-rich to T-rich
- EIRENE neutrals transport code relates sub-divertor D/T concentrations to measured divertor concentrations and Langmuir probe measurements by varying local wall D/T recycling
  - simulation includes D, T, $D_2$, $T_2$, DT and impurities
- Utilize wall model (W-Diffuse) to test fundamental rate coefficients for:
  - recombination, trapping, thermal detrapping, and particle induced detrapping
- Basis for current wall parameter choice are those determined by JET-PTE post shot decay (no plasma), and by Ehrenberg for plasma-induced detrapping (DTE1)

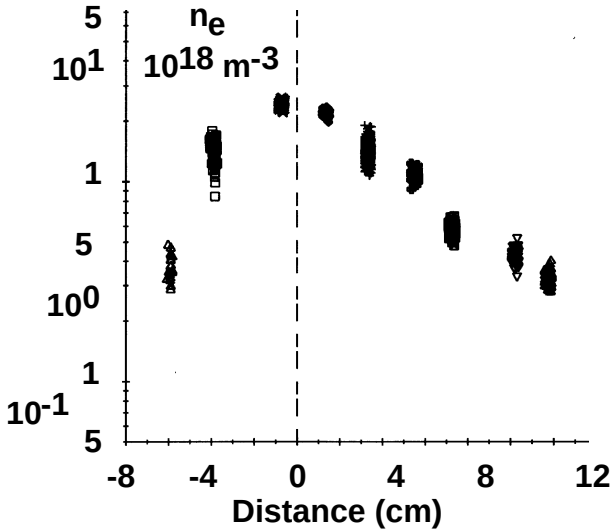
# EIRENE database: sub-divertor T concentration vs $R_T$

**EIRENE incorporates**
- detailed JET geometry
- TRIM database (reflection, recycling)
- species D, T, $D_2$, DT, $T_2$

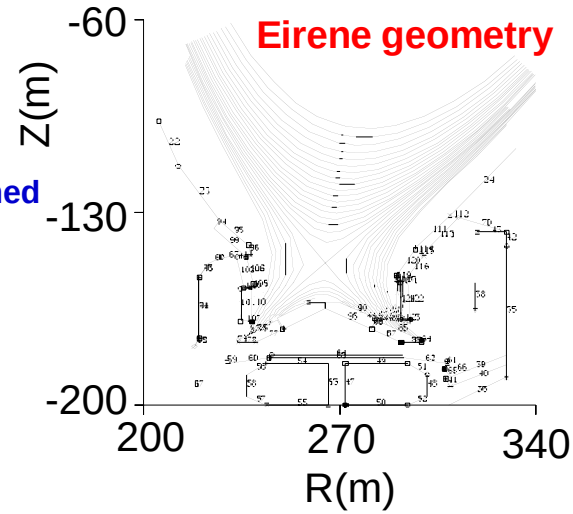
**Requires plasma background:**
- L.P. profiles constrain B2-Eirene solution
- Vary strikepoint D and T ion concentrations with constrained total ion density

## Langmuir probe profiles

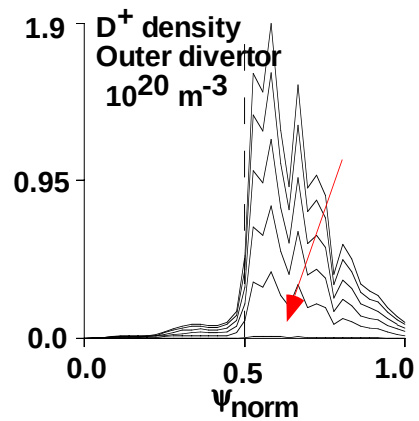


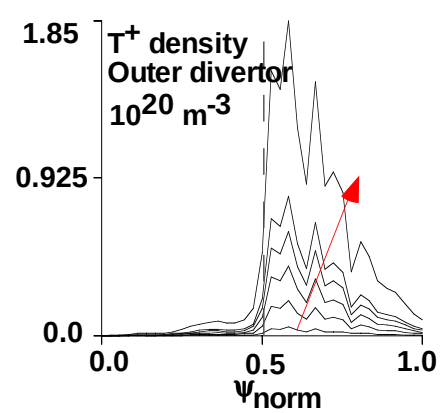




## Eirene geometry



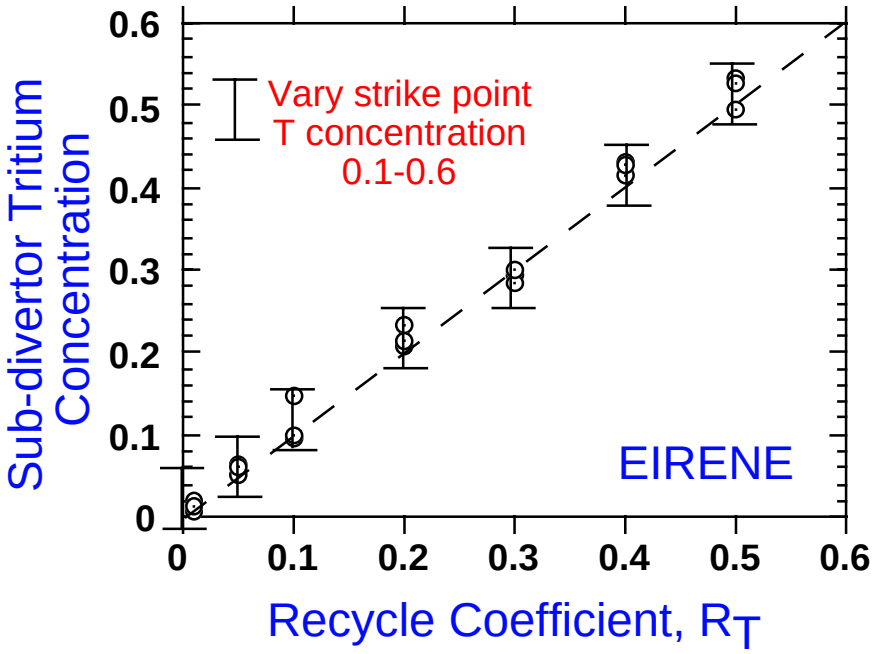

## Eirene $D^+$, $T^+$ strike point profiles



# Eirene data base results

- **Calculated sub-divertor T concentration depends ~linearly on assumed wall T recycle coefficient**
  - **very weakly on strike point concentration**
- **because sub-divertor T measurement samples particles after many surface interactions:**
  - **energetic atom reflection**
  - **thermal molecular re-emission**
- **The latter is dominated by the saturation status of the wall**



# Hydrogenic Inventory in Graphite

**solute concentrations**

$$\frac{dc_s^D}{dt} = -k_0 (c_s^D)^2 - k_0 c_s^D c_s^T - \frac{dc^D}{dt} + \Sigma^D$$

$$\frac{dc_s^T}{dt} = -k_0 (c_s^T)^2 - k_0 c_s^D c_s^T) - \frac{dc_t^T}{dt} + \Sigma^T$$

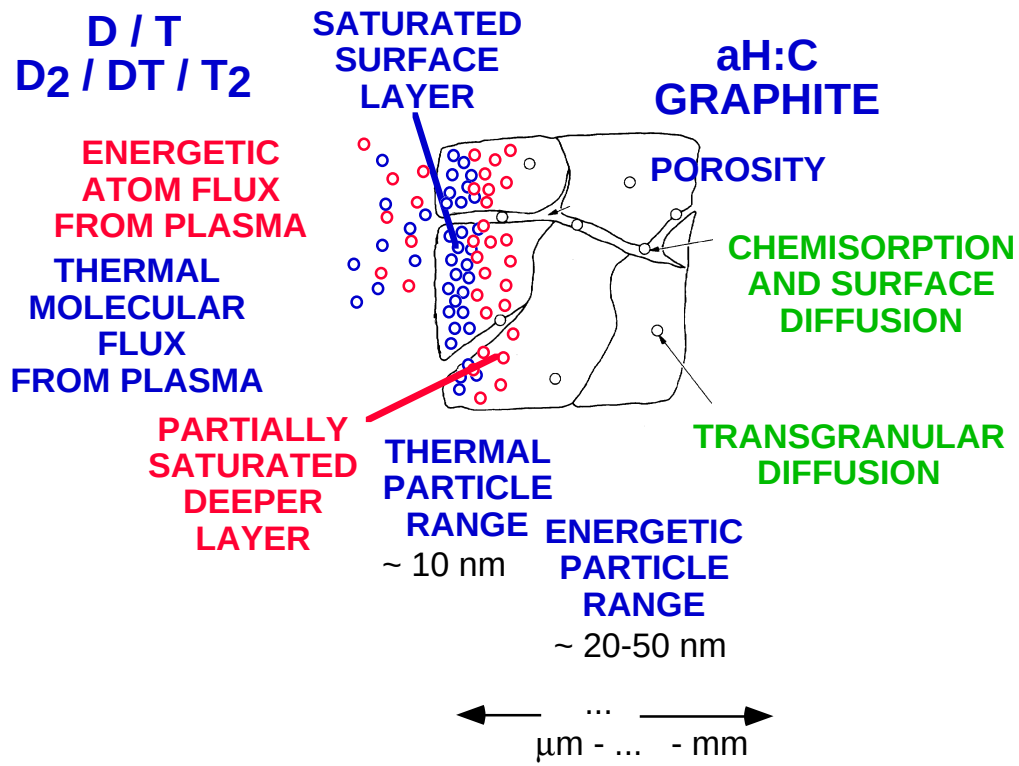
**trapped concentrations**

$$\frac{d}{dt} c_t^D = k_{s,t} c_s^D \left(1 - \frac{(c_t^D + c_t^T)}{c_{t,s}}\right) - k_{t,s}\, c_t^D$$

$$- k_d\, c_t^D (\Sigma^D + \Sigma^T)^{1/2} - \sigma_{dt}\, c_t^D (\Sigma^D + \Sigma^T)$$

$$\frac{d}{dt} c_t^T = k_{s,t}\, c_s^T \left(1 - \frac{(c_t^T + c_t^D)}{c_{t,s}}\right) - k_{t,s}\, c_t^T$$

$$- k_d\, c_t^T (\Sigma^D + \Sigma^T)^{1/2} - \sigma_{dt}\, c_t^T (\Sigma^D + \Sigma^T)$$

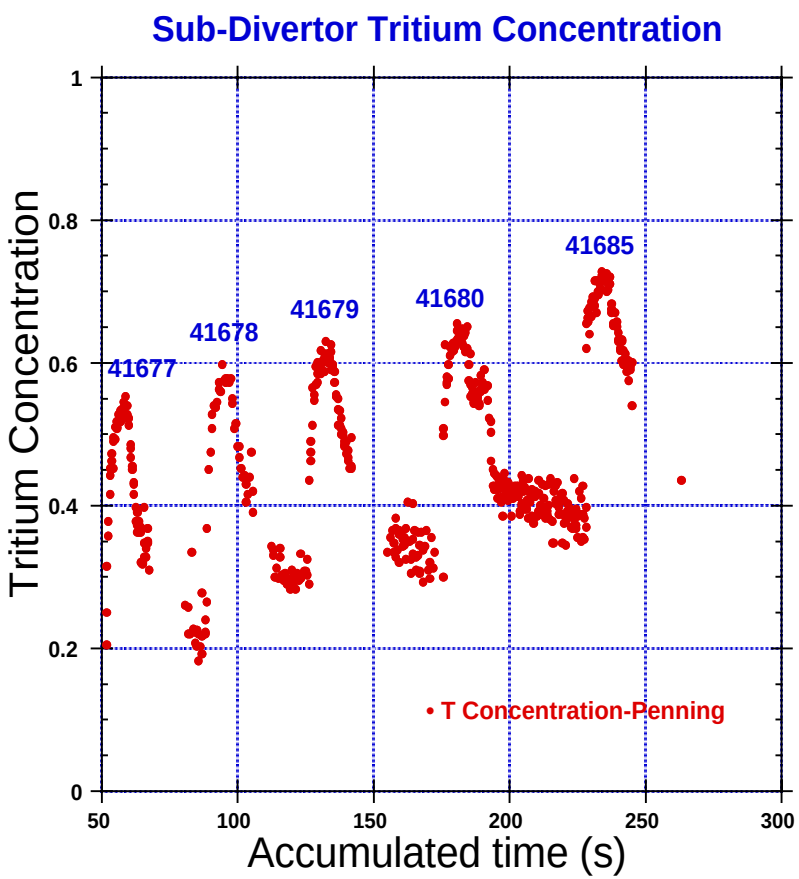


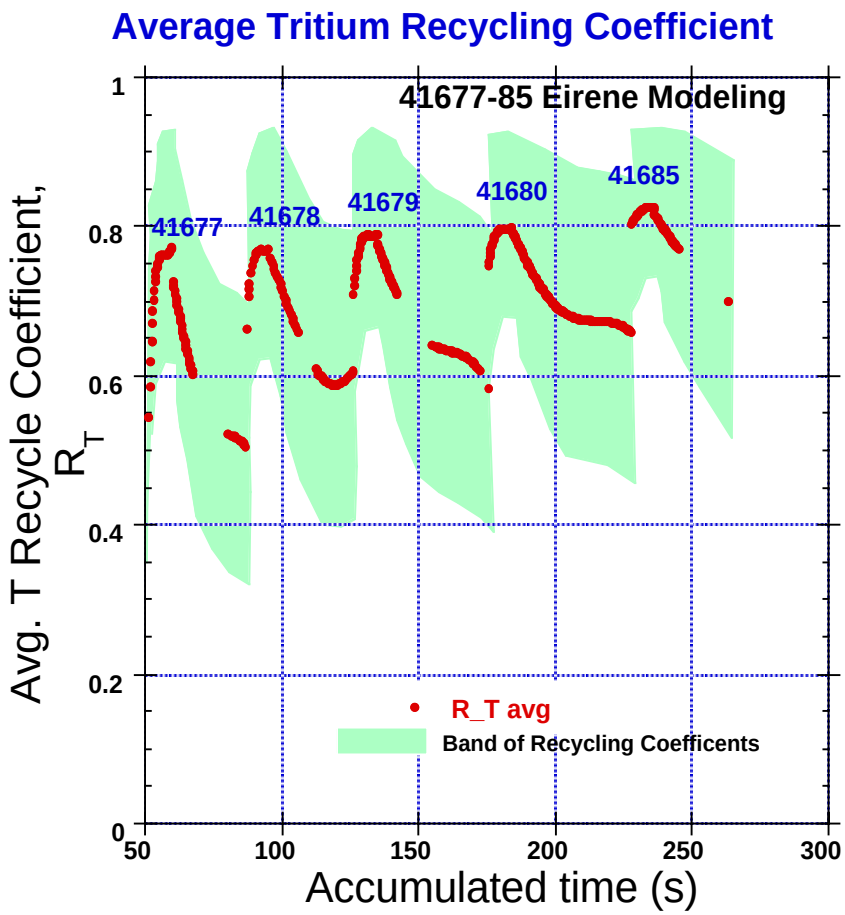

Main mechanisms for formation of hydrogen inventory in graphite
[from. K.Wilson, W. Hsu, J. Nucl. Mater, 1987]

| MODEL | Recombination | Trapping | Thermal detrapping | Particle-induced detrapping | |
|---|---|---|---|---|---|
| | $k_0$ ($cm^3/s$) | $k_{st}$ ($s^{-1}$) | $k_{t,s}$ ($s^{-1}$) | $k_d$ ($cm^{3/2}\, s^{-1/2}$) | $\sigma_{dt}$ ($cm^2$) |
| Ehrenberg | $2.5\ 10^{-21}$ | $10^4$ | 0. | $6\ 10^{-13}$ | - |
| Moeller-Scherzer | $1.2\ 10^{-18}$ | $10^{-4}$ | $1.9\ 10^{-12}$ | - | $5\ 10^{-17}$ |
| Grisolia | $1.0\ 10^{-20}$ | $10^2$ | $5\ 10^{-2}$ | - | $8\ 10^{-17}$ |

# Tritium Recycling in JET Divertor

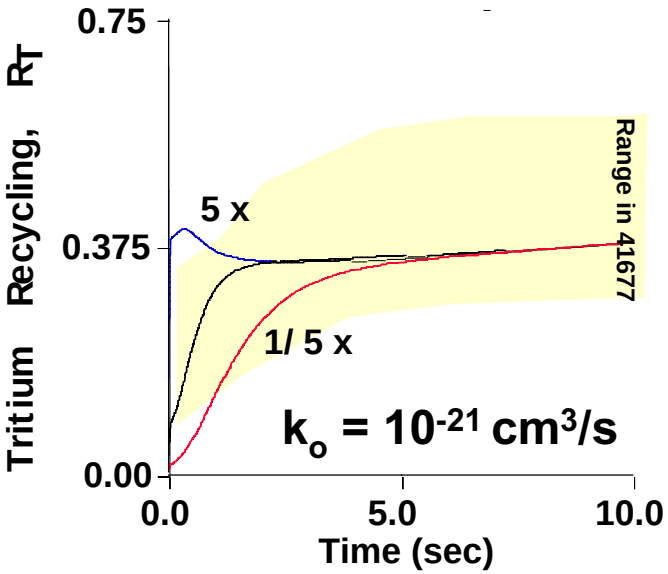
¥ Beginning T Concentration of subsequent shot is determined by T Concentration at end of last shot



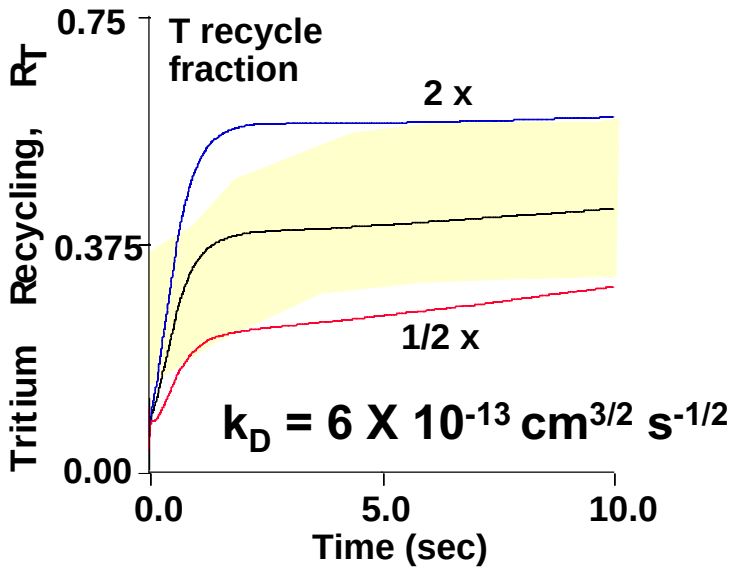



# Comparison of Ehrenberg Semi-empirical Wall Model with $R_T$

## Vary volume recombination rate



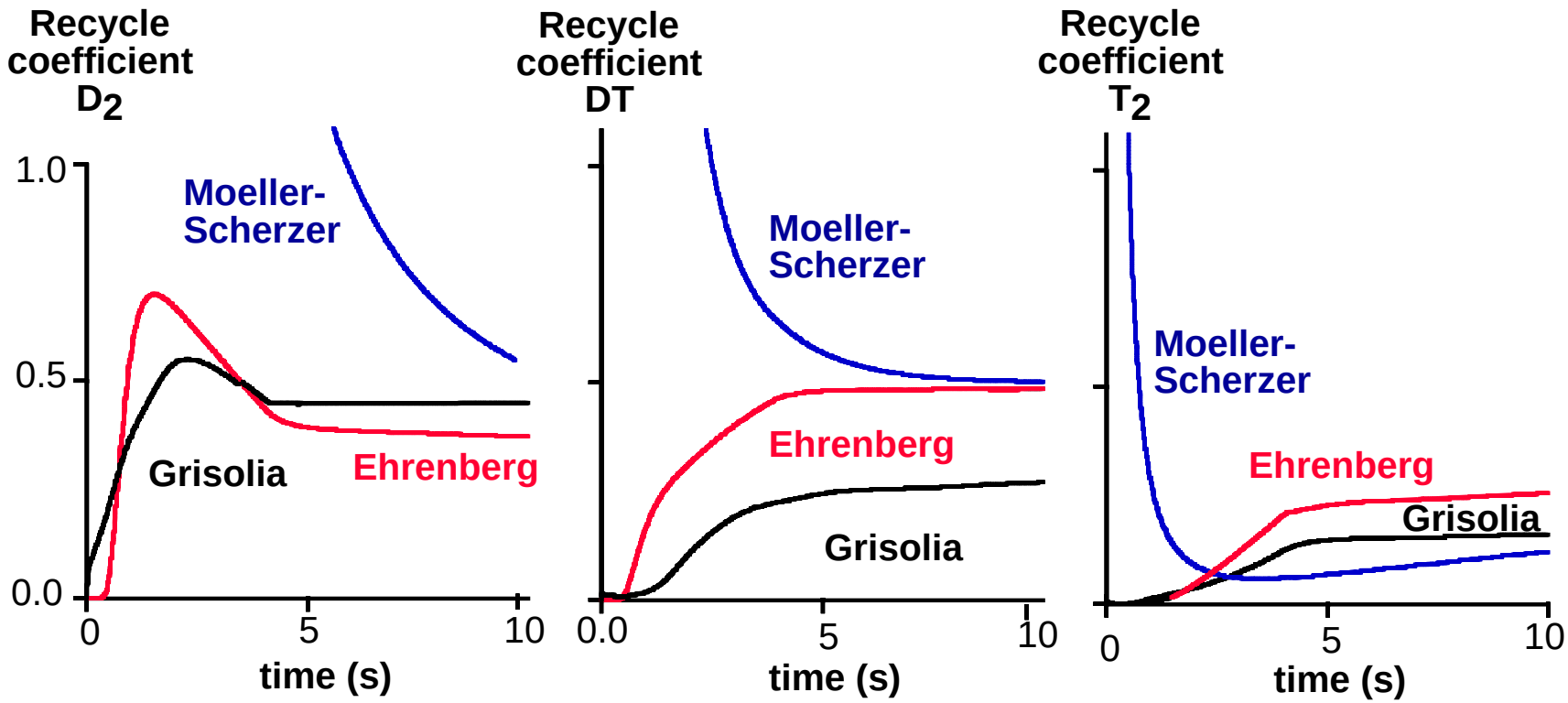

## Vary particle-induced detrapping rate




- **Wall rate coefficients from Ehrenberg Semi-empirical model**

  - **particle-induced detrapping rate governs magnitude of plasma-induced isotope exchange**
  - **recombination coefficient governs time scale**

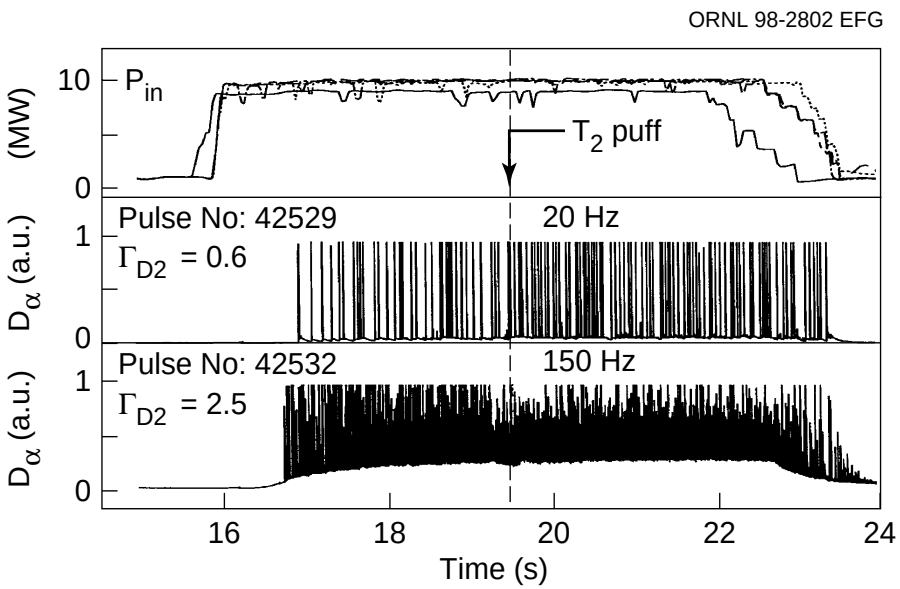
# Wall model comparison:
# T uptake experiment 41677



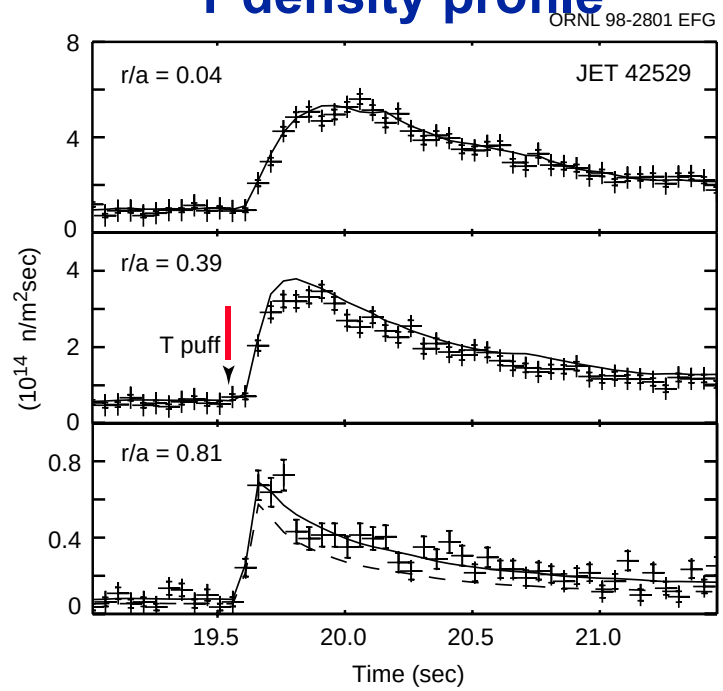

**- Models lead to similar final T concentration, but the time dependence is very different**

# Tritium Transport
## - by Trace T injection -

### ELM frequency varied




### neutron brightness measurements provide T density profile




- 1 - 2% trace amounts of T were injected into D plasmas via short 40 ms puffs to study Tritium transport

# Connection between wall recycling and transport

**Examine JET pulses with trace T injection into D plasmas**

- **Neutron brightness profiles were analyzed to find "kinematic" fit[1]:**

  **i.e., the $D_A$, $V_A$ which reproduce these signals when the Ehrenberg semi-empirical tritium recycling model is used:**

  $$R_T(t) = R_{T0} + [\, R_{T\infty} - R_{T0} \,] \; ( t / t_T )^{\alpha}$$

  **[ $R_{T0} = 0.2$, $R_\infty = 0.98$, $t_T = 0.75$ s, $\alpha = 1.0$]**

- **Connect T evolution with fundamental transport**
- **Issues:**
  - **ELM effects on inferred radial transport**
  - **Effect of wall diffusion models (recycling)**
  - **Relation of residual transport to neo-classical (NCLASS code)**

[1]K-D. Zastrow et al, EPS Prague, 1998

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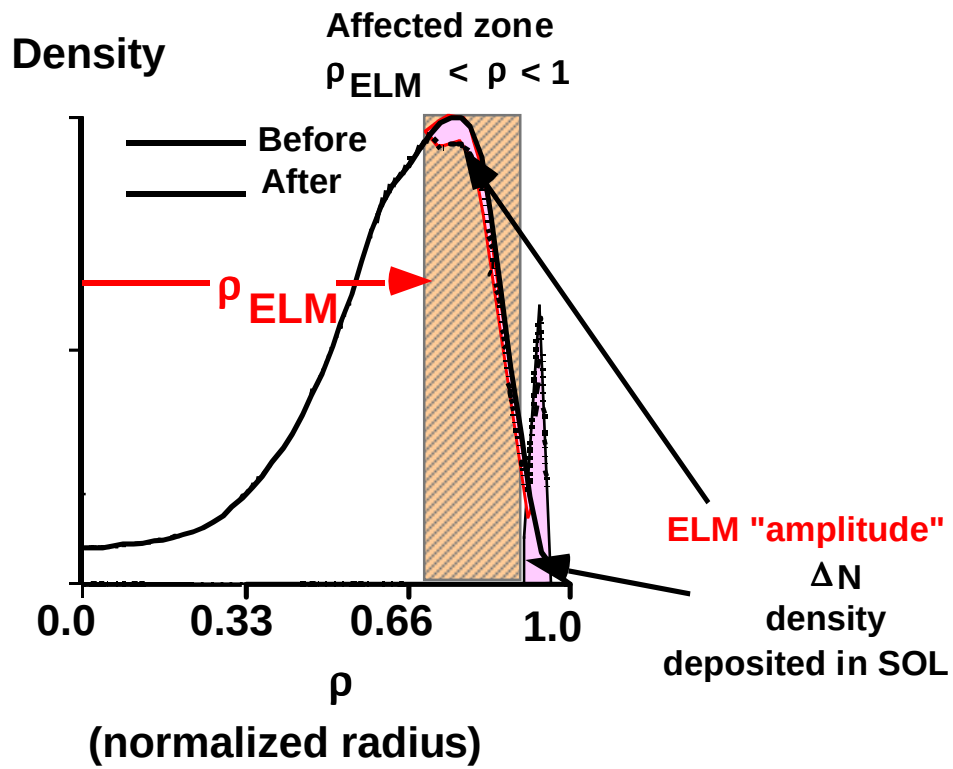
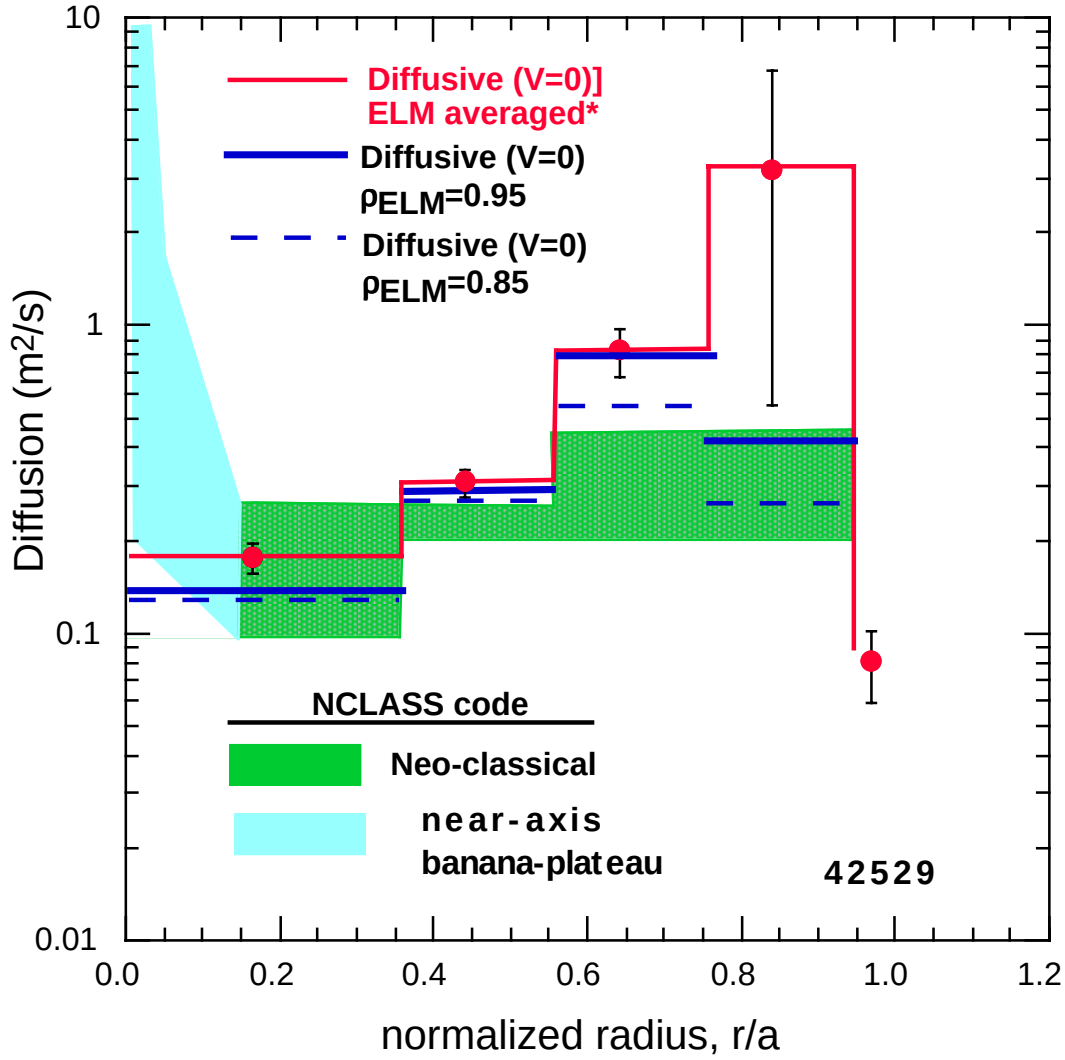
# MIST ELM Model

## Expulsion of Core Density by ELMs




**Determine $D_A$ and V from fit to T density profiles**

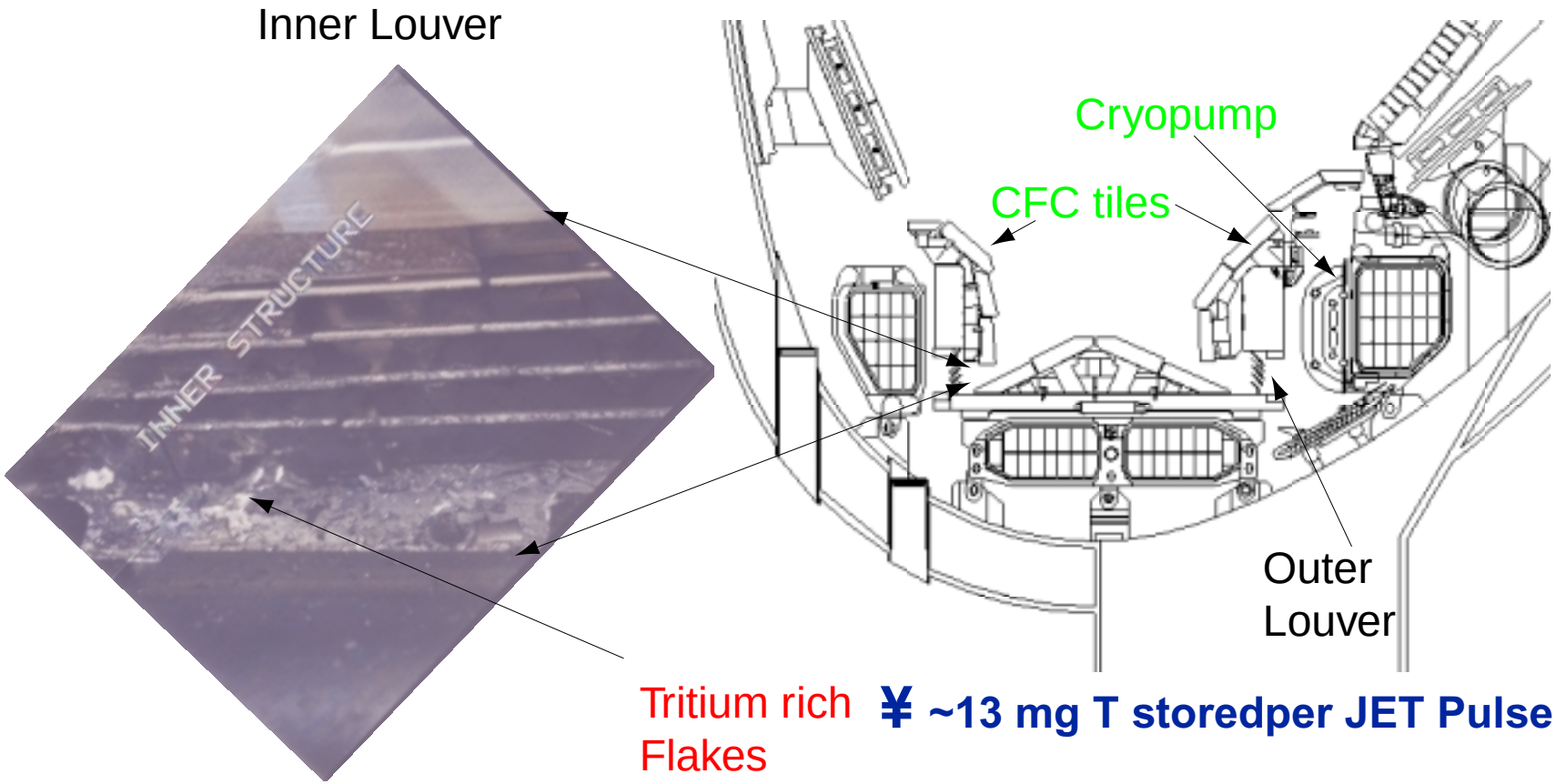
# When ELMs are explicitly included $D_A$ approaches neo-classical values




*K-D. Zastrow et al, EPS Prague, 1998

# A large unrecoverable tritium inventory is found near the cold surfaces of the divertor louvers

JET MKIIa Divertor




**¥ ~13 mg T storedper JET Pulse**

**- Troubling when scaled to ITER,**
**may limit ITER to < 100 pulses before the T site limit is reached**

# Summary

- Analyzed the first T shots with D saturated walls to determine the rate of tritium uptake by JET walls.
- Utilizing divertor measurements of T combined with Eirene modeling the relation between the dynamic evolution of the T recycling and wall status was determined within a shot.
- Utilizing the deduced Tritium Recycling - various wall models were tested to determine fundamental rate coefficients for:
  - recombination, trapping, thermal detrapping, and particle induced trapping.
- Wall Rate coefficients from the Ehrenberg Semi-empirical model were found to give good agreement with observed T recycling.
- Trace tritium experiments with ELMs demonstrate the wall-edge-core linkage.

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# *This research is a collaborative work performed by:*

**[1]Oak Ridge National Laboratory-** ornl

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

## Contributors

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