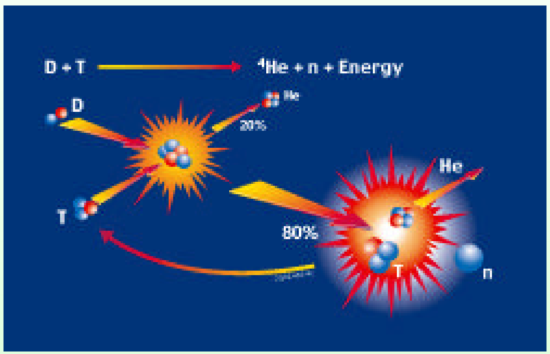
The need to model the ITER high vacuum systems in transitional flow regime – An engineering perspective

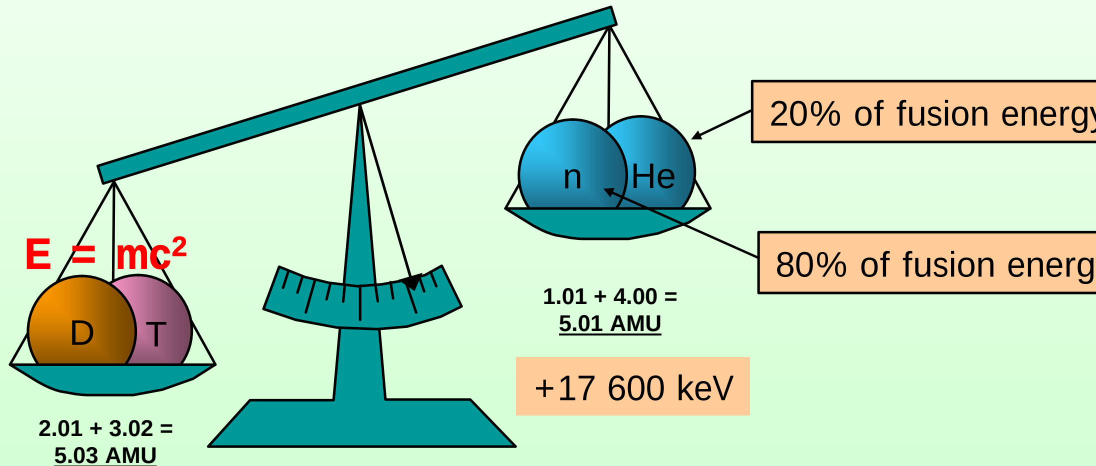
Christian Day

For the Vacuum Pumping Task Force
Institute for Technical Physics,
Forschungszentrum Karlsruhe, Germany,

Thermonuclear fusion of deuterium and tritium



Plasma state



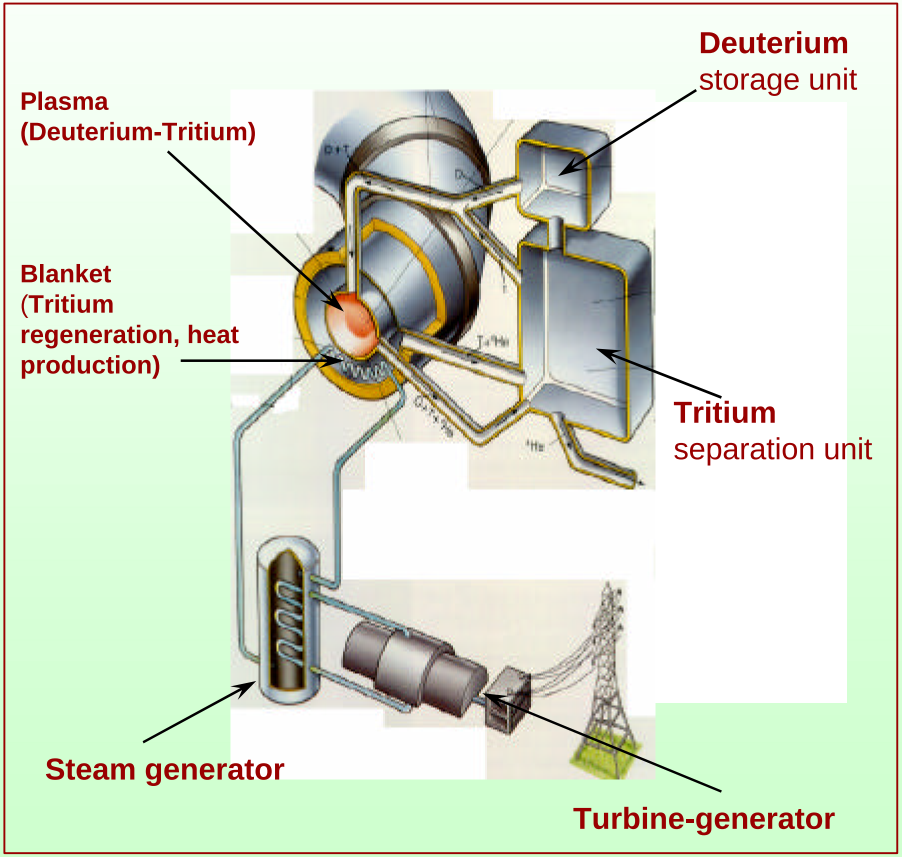
First main challenge for ITER vacuum systems:

- ➢ Processing of tritium → availability, safety, accountancy, control → *cryopumps*

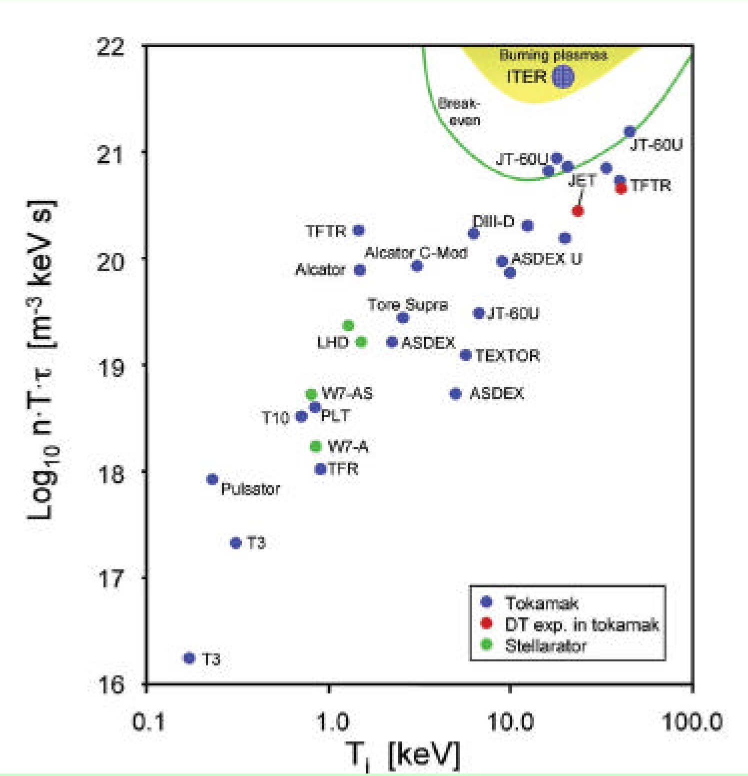
The scheme of a commercial fusion reactor

- The energy of the neutrons is converted into heat in the structures (blanket) lining the torus walls
- A circulating coolant removes the heat and, in the heat exchangers, steam will be generated to drive turbines for electricity production

- In ITER, the fuel tritium will be supplied from external
- In ITER, the fusion energy will be ´wasted´ (not taken out)

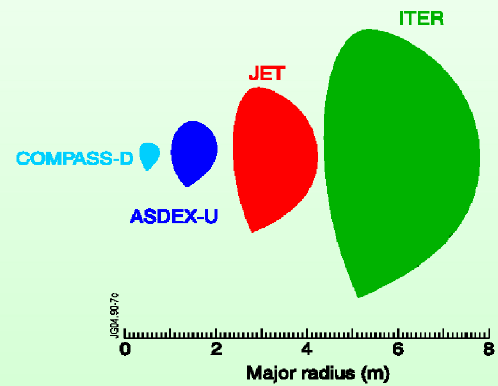


Current fusion status and the role of ITER



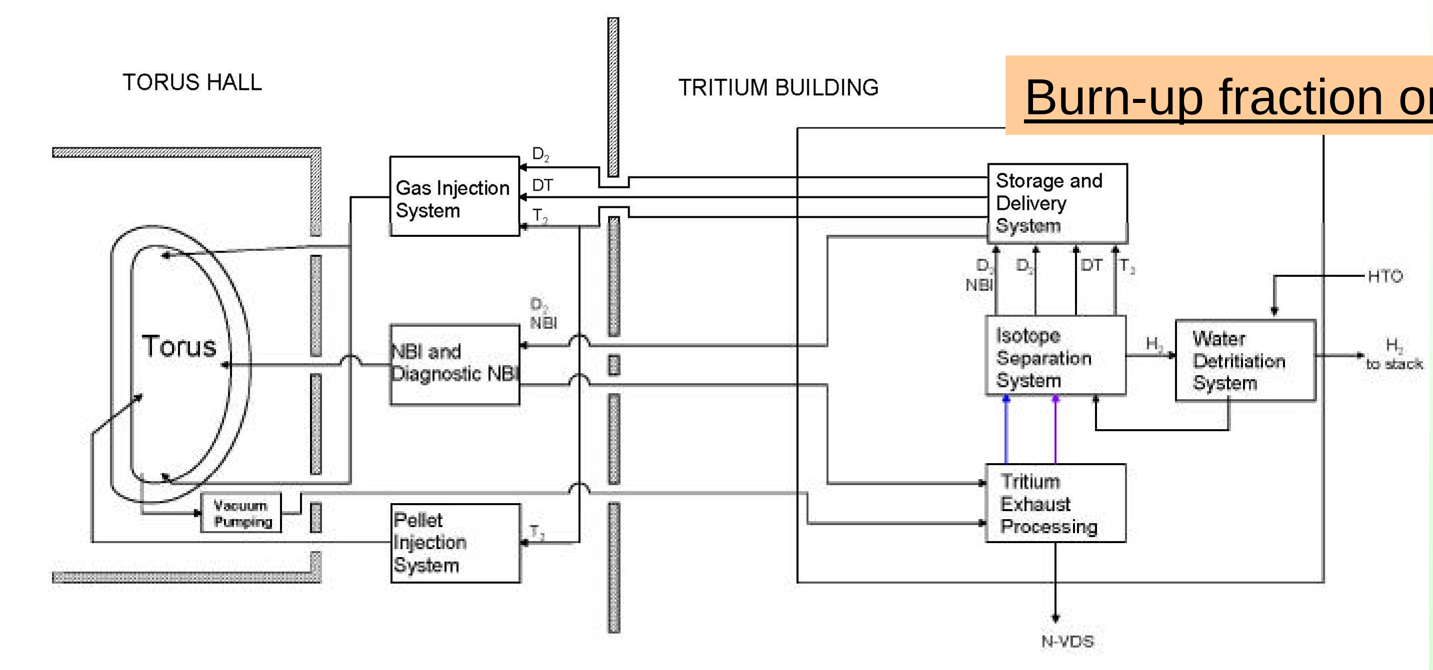
Confinement time τ :

$$t_{\mathrm{E,\,th}}^{\mathrm{ELMy}} = 0.0562 \times I^{0.93} B^{0.15} P^{-0.69} n_{e,19}^{0.41} M^{0.19} R^{1.97} e^{0.58} k^{0.}$$



Second main challenge for ITER vacuum systems
➢ Very big in size → highest pumping speeds !
→ *cryopumps*

ITER fuelling



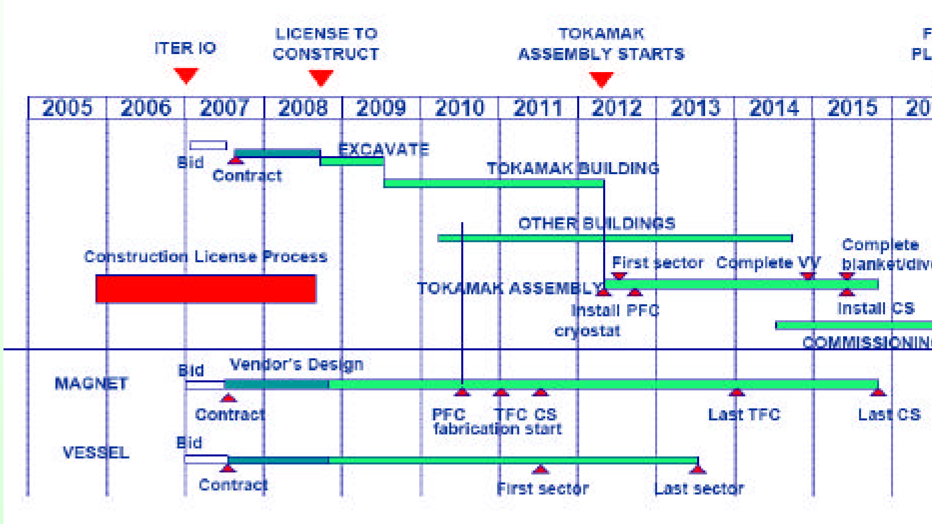
Burn-up fraction only 2%

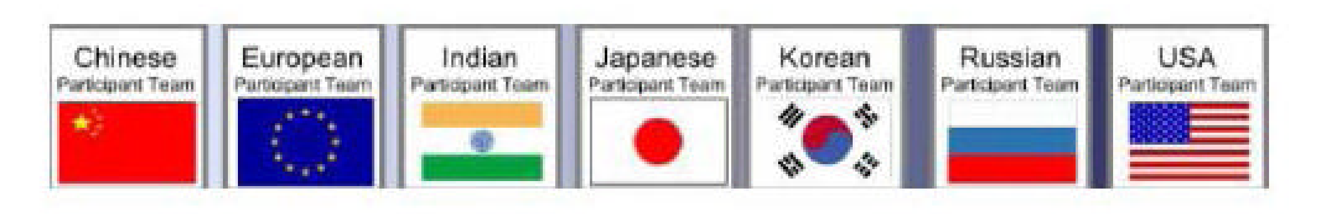
Third main challenge for ITER vacuum systems

- Very high throughputs →
- Comparatively high pressures (in spite of the high pumping speeds we have) →
- Transitional flow conditions inside the cryopumps and in the associated pumping ducts

The ITER mission

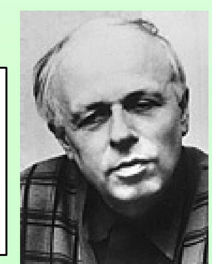
- *Role of ITER (=still a R&D project)*
  - Burning plasma physics
  - Integration of physics and technology
  - Demonstrate and test fusion power plant technologies and safety features (tritium)
  - Demonstrate the technological feasibility of fusion (availability)





ITER is being built in Cadarache, South of France

Andrei Sacharov



Tokamak: ?? ?????????? ?????? ? ? ???????? ? ? ????? ???? ?

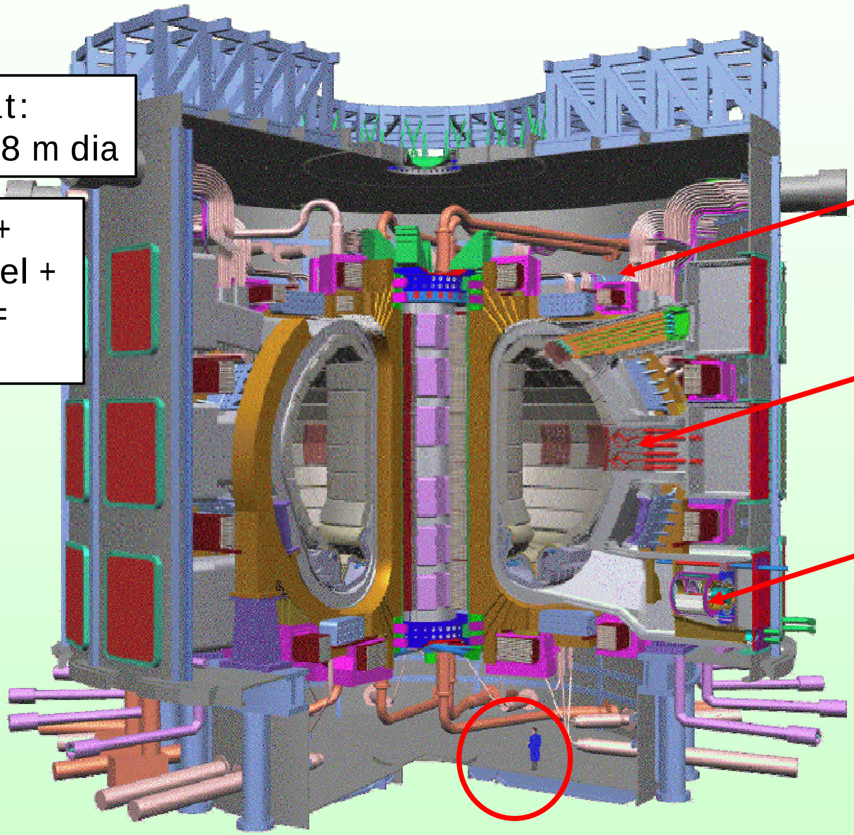
(to**roidalnaya** ka**mera,** ma**gnitnymi** k**atushkami)**

Lev Artsimo

ITER and its main vacuum systems

Cryostat:
4m high x 28 m dia

Cryostat +
Vacuum vessel +
magnets=
23 350 t



3 Large Cryopump system

Cryostat HV pumping system

Neutral Beam HV pumping system

Torus exhaust HV pumping system

+ *Mechanical forepump trains*
(identical for each of the three high vacuum systems)

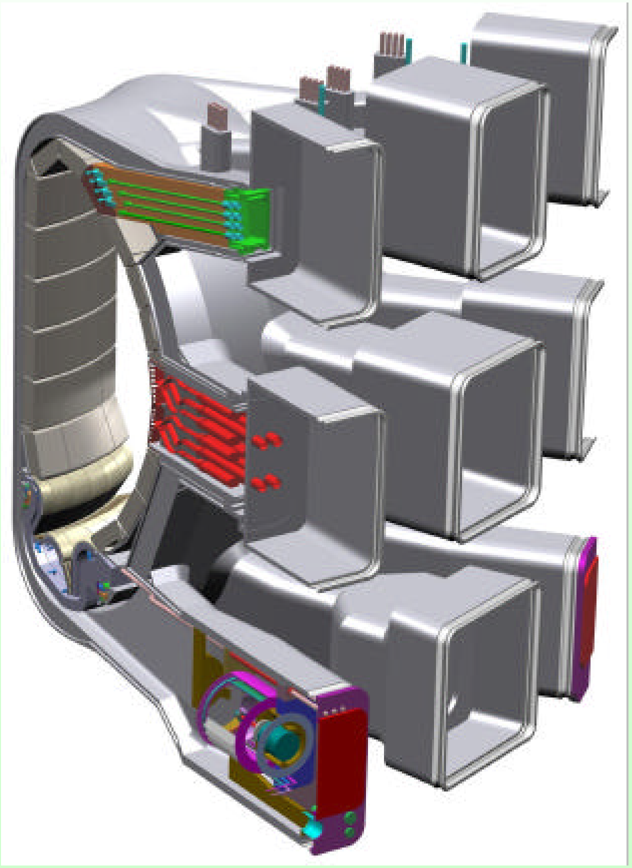
Major plasma radius 6.2 m
Plasma Current: 15 MA
Typical Temperature: 20 keV
Plasma Volume: 840 m^3
Typical Density: 10^{20} m^{-3}
Fusion Power: 500 MW

Cryo-mech cross-over pressure is 10

ITER large high vacuum cryopump systems - overview

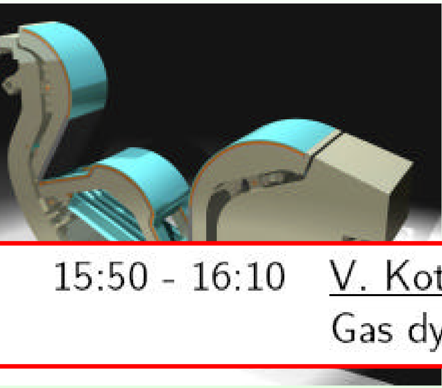
	Torus	NBI	Cryostat
# Pumps	8	2 (3) +1	2
Pumping mode	Dynamic = maintain the pressure inside the VV volume (1350 m^3) at a total gas throughput of (120 Pa·m^3/s (fuelling rate) or 60 Pa·m^3/s (He case))+ (33 Pa·m^3/s (impurities)); Base pressure for hydrogens: 10^{-5} Pa.	Dynamic = maintain the pressure inside the NBI volume (150 m^3/H-NBI) at a throughput of 36 Pa·m^3/s/H-NBI (protium operation)	Transient pump-down (closed cryostat volume of 8400 m^3) to 10^{-4} Pa and steady-state pumping of magnet coolant leak helium and outgassing species
Gases	Hydrogen (all six isotopes), helium, impurities Depending strongly on the operation mode (burn& dwell, conditioning, leak detection..)	Hydrogen (H_2, D_2)	Nitrogen, outgassing and leaking gas,
Sorbent coating	**Yes**	**Yes**	**Yes**

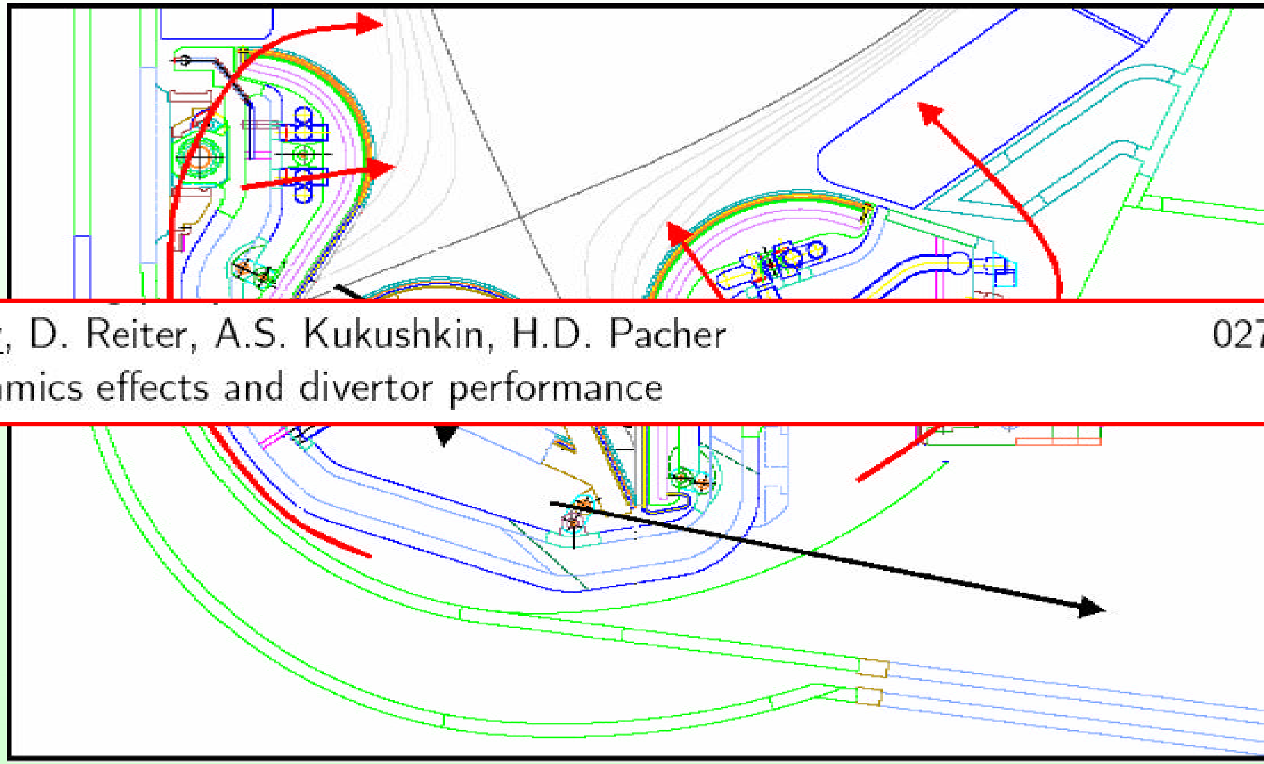
Some ITER areas of concern for transitional flow modelling



1. The divertor system.
2. The torus exhaust pumping duct system
3. The torus cryopump itself.
4. The neutral beam injector system.
5. The forepumping system.
6. ...

1. Flow modelling of divertor





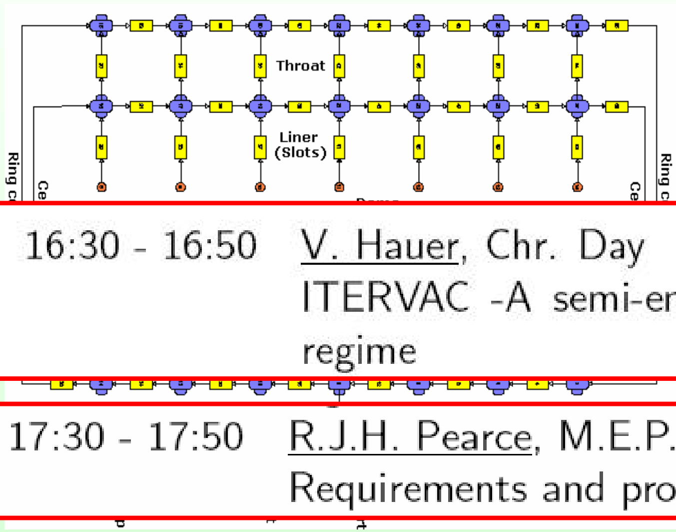
15:50 - 16:10 V. Kotov, D. Reiter, A.S. Kukushkin, H.D. Pacher 027
Gas dynamics effects and divertor performance

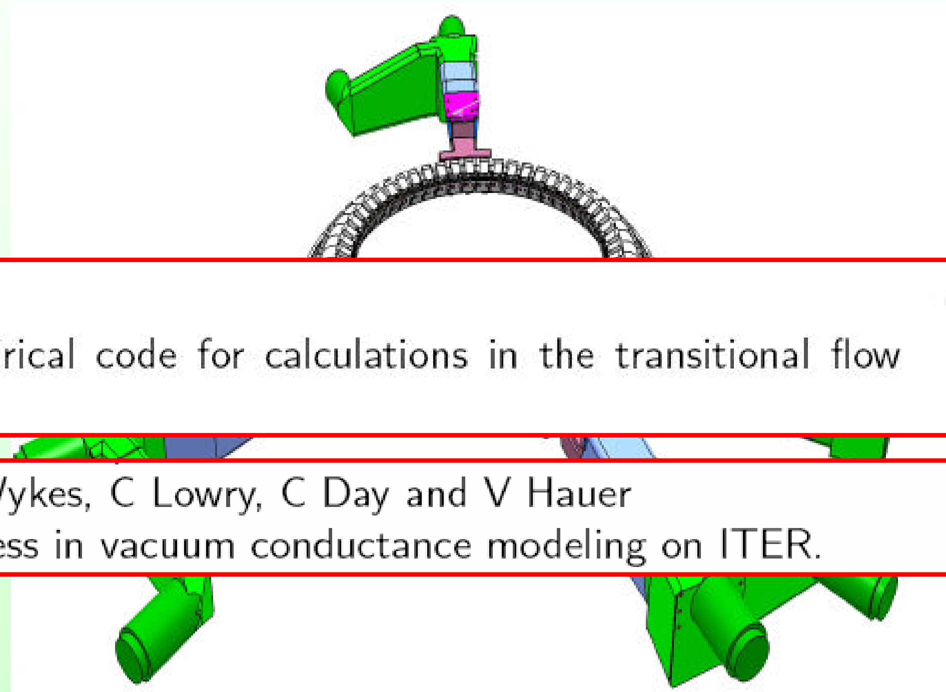
For correlation of the divertor performance vs. geometry, the
B2-EIRENE code is used, which describes the interaction of the plasma and neutral ga

2. Torus vacuum pumping system – Technical data

Ultimate Pump Down		
Vacuum Vessel free volume	m^3	~1300
Total surface area for outgassing	m^2	~ 2600
Base pressure for hydrogen isotopes	Pa	$< 10^{-5}$
Dwell Pump-down (in between the	***pulses)***	
Base pressure	Pa	$< 5 \cdot 10^{-4}$
Plasma Operations (pulsewise 400 to 3000 s)		
Typical divertor pressure during plasma operations		
Maximum throughput during plasma operations		

Conductance modelling of divertor and duct system



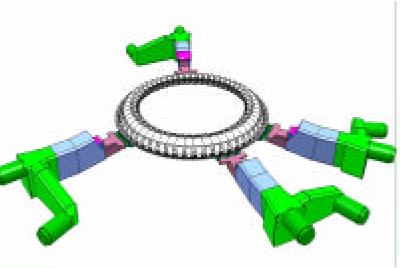


16:30 - 16:50 V. Hauer, Chr. Day 031
ITERVAC -A semi-empirical code for calculations in the transitional flow regime

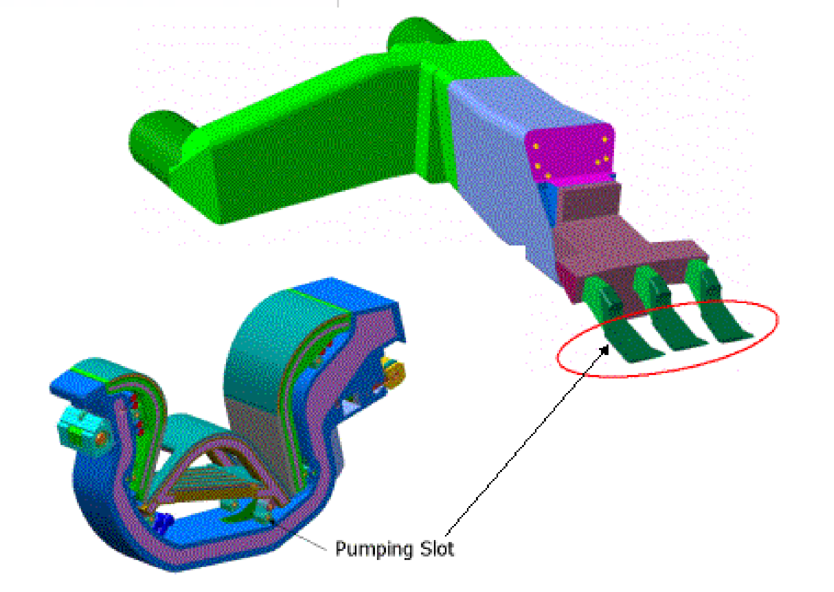
17:30 - 17:50 R.J.H. Pearce, M.E.P. Wykes, C Lowry, C Day and V Hauer 051
Requirements and progress in vacuum conductance modeling on ITER.

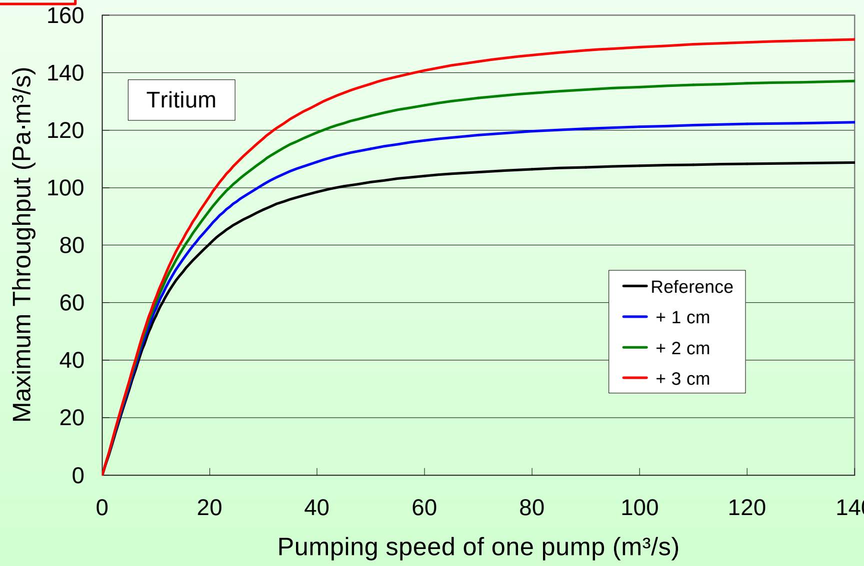
Very complex geometry (varying cross-sections, short ducts) →
For design purposes, we have developed a quick, semi-empirical code for flow calculations and a system for network modelling.

Target pumping speed per pump



Requirement:
150 Pa·m³/s @ 1-10 Pa divertor pressure,
Requires slot increase

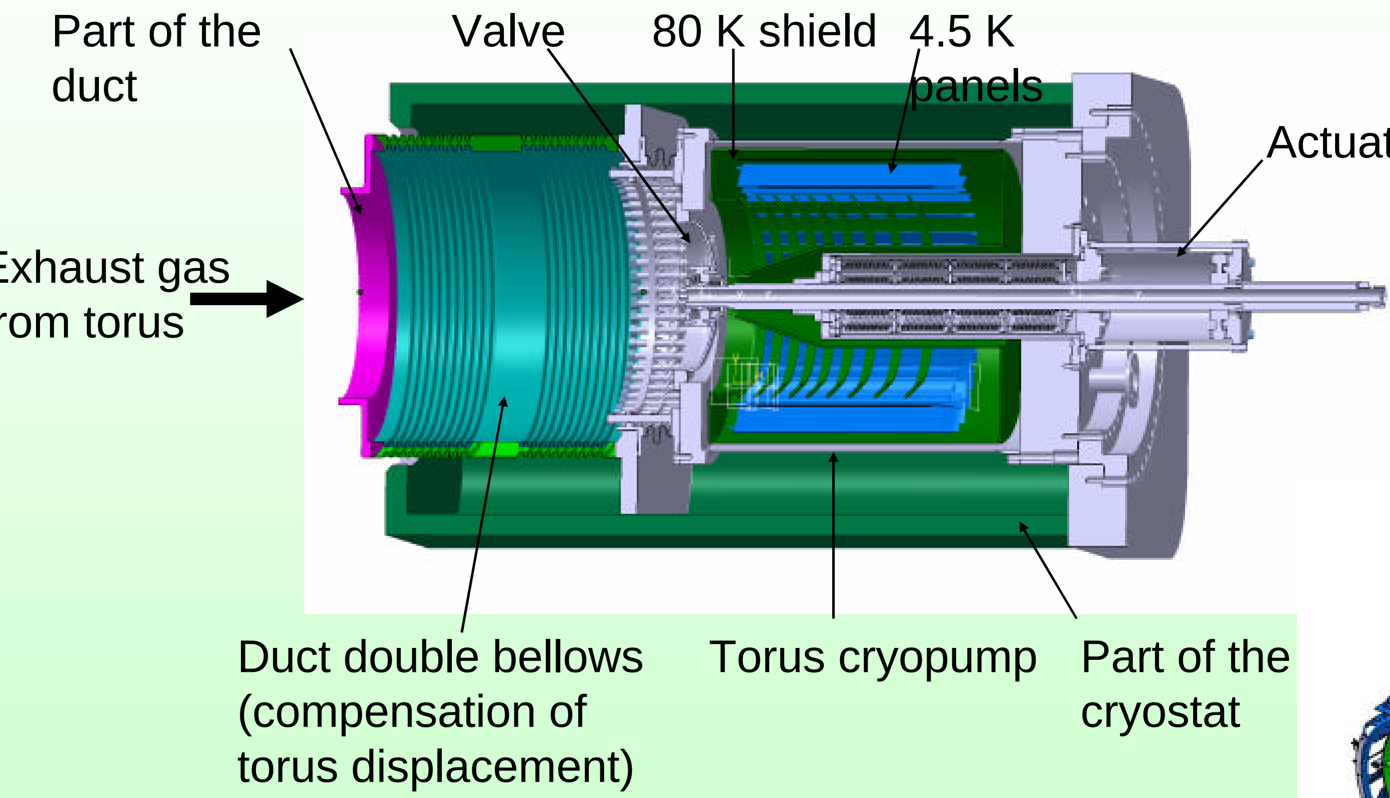


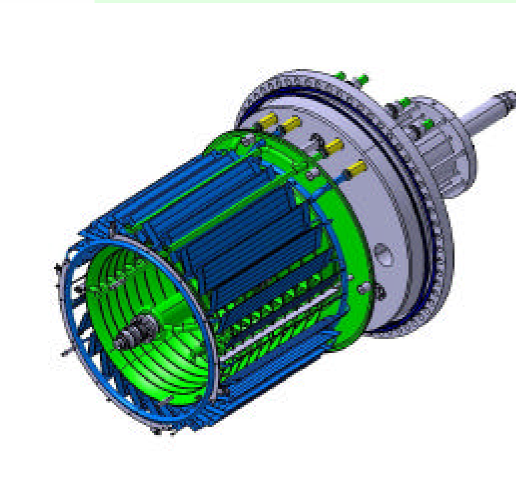


@ 2 Pa divertor pressure

Result → The design pumping speed of the individual pump shall be 80 m³/s

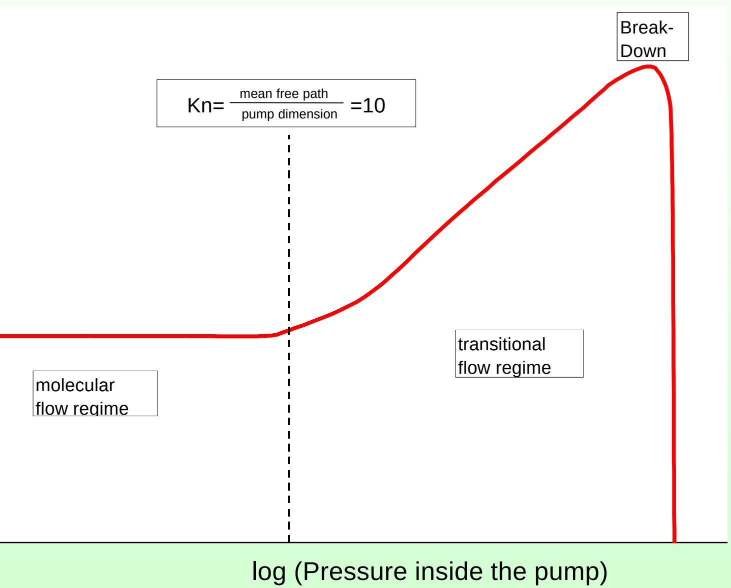
3. The set-up of the torus cryopump

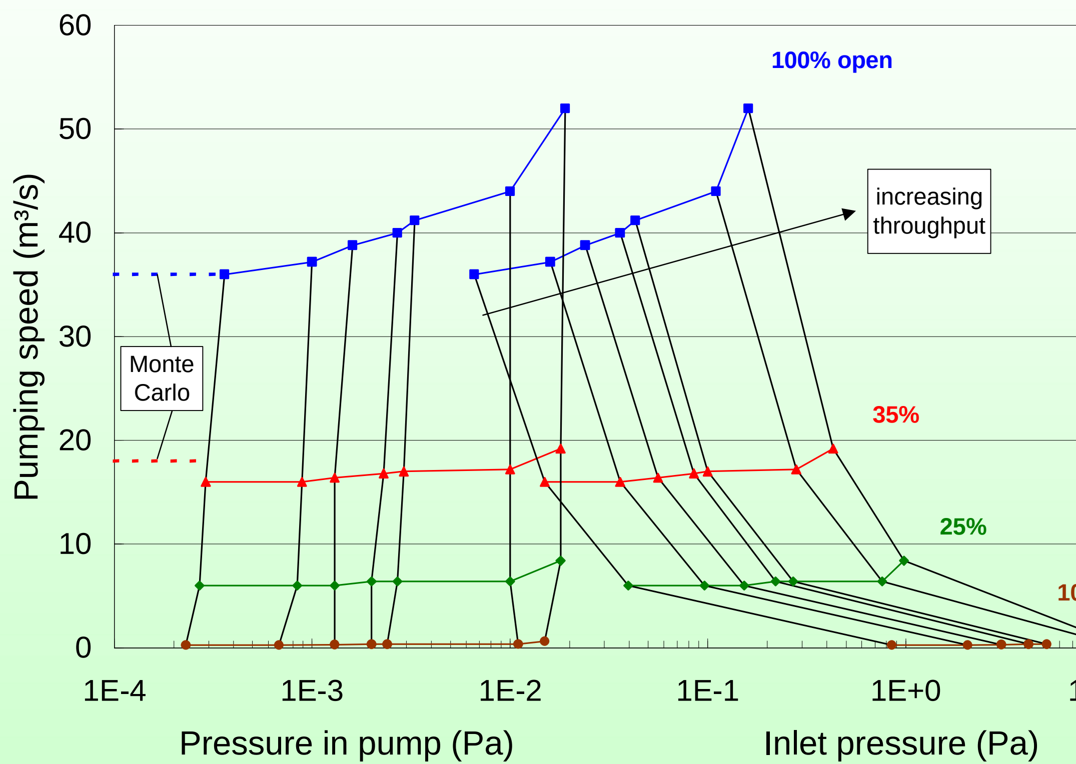




Molecular nominal pumping speeds:
Pump + bellows : ~ 55 m^3/s
Pump:~ 75 m^3/s

Transitional flow conditions inside the torus cryopump

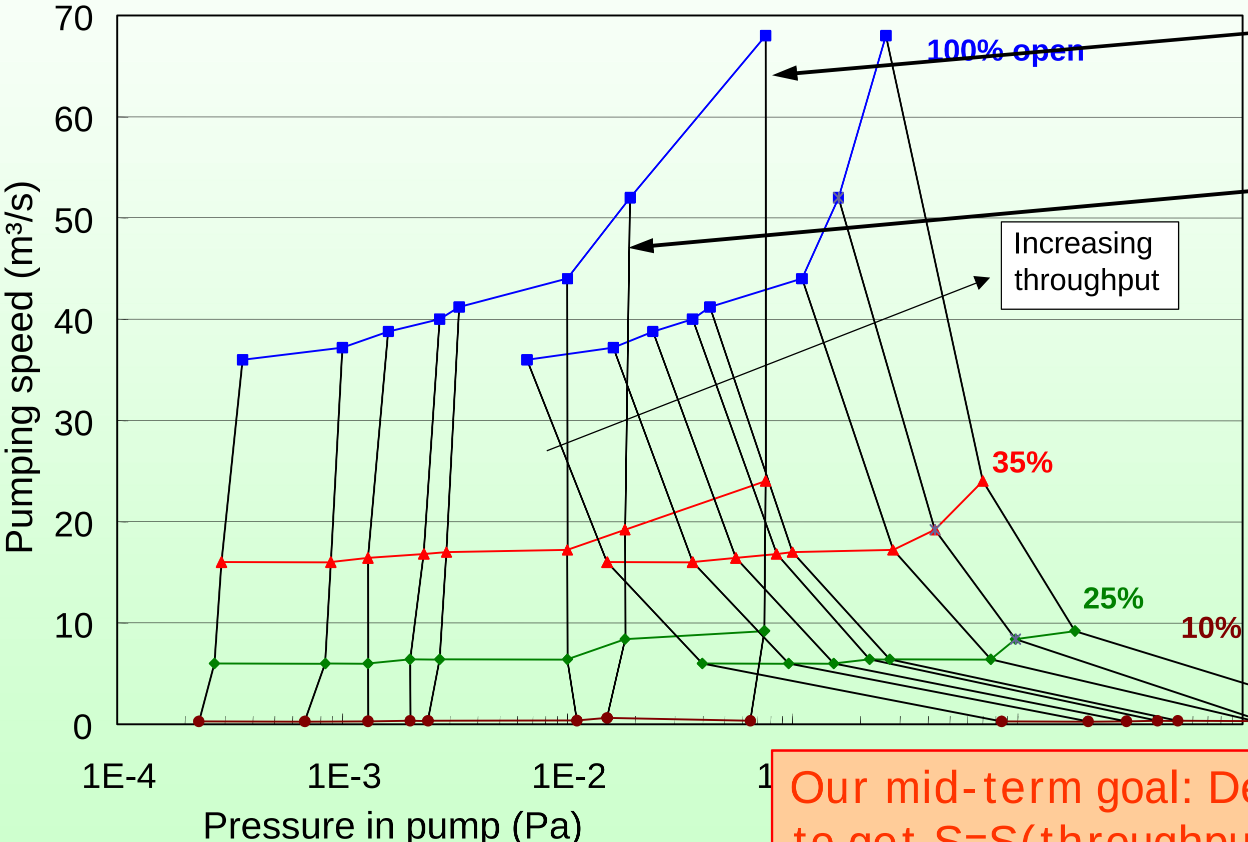




Generic dependence
S=S(Kn(p))

Experimental results for a 1:2 scale
ITER model pump

Extrapolation of pumping speeds?



q=42 mbarl/sm² (coated surfac
q=149 mbarl/sm² (inlet area)

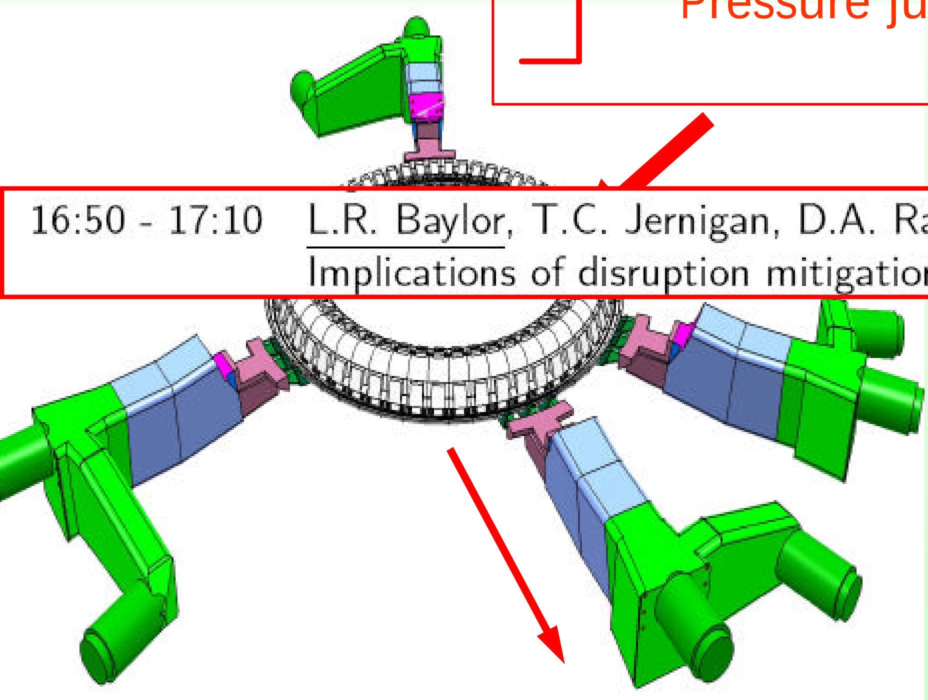
q=23 mbarl/sm² (coated surfac
q=81.4 mbarl/sm² (inlet area)

<u>New requirements</u>
(200 Pam³/s total ELM pellet pa
q=45 mbarl/sm² (coated surface
q=260 mbarl/sm² (inlet area)

Our mid-term goal: Develop a predictive tool to get S=S(throughput), via DSMC?.

4. Instantaneous massive gas injection (for disruption mitigation)

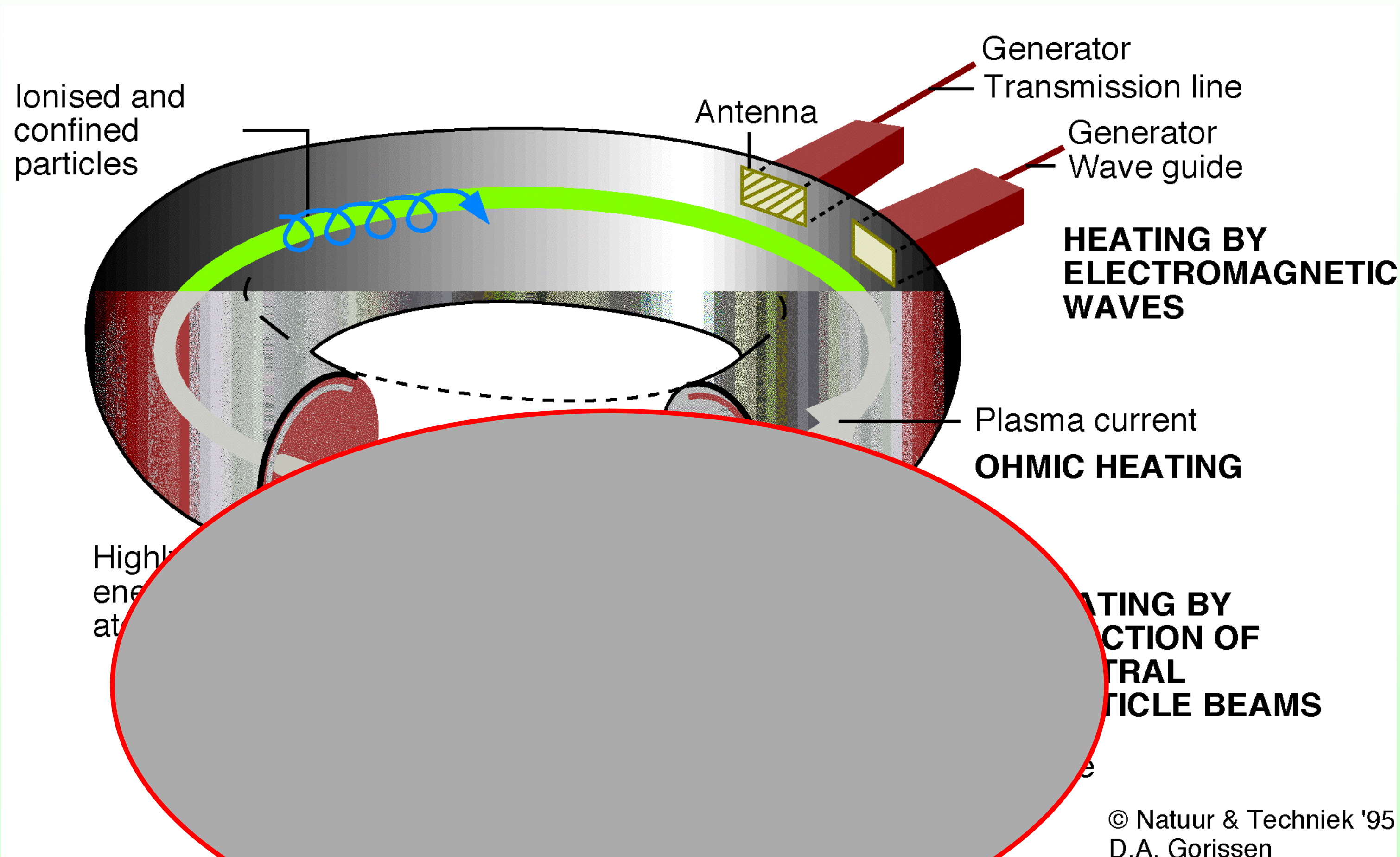
Pressure jumps from ~ zero to 100 Pa



16:50 - 17:10 L.R. Baylor, T.C. Jernigan, D.A. Rasmussen 038
Implications of disruption mitigation for the ITER vacuum system

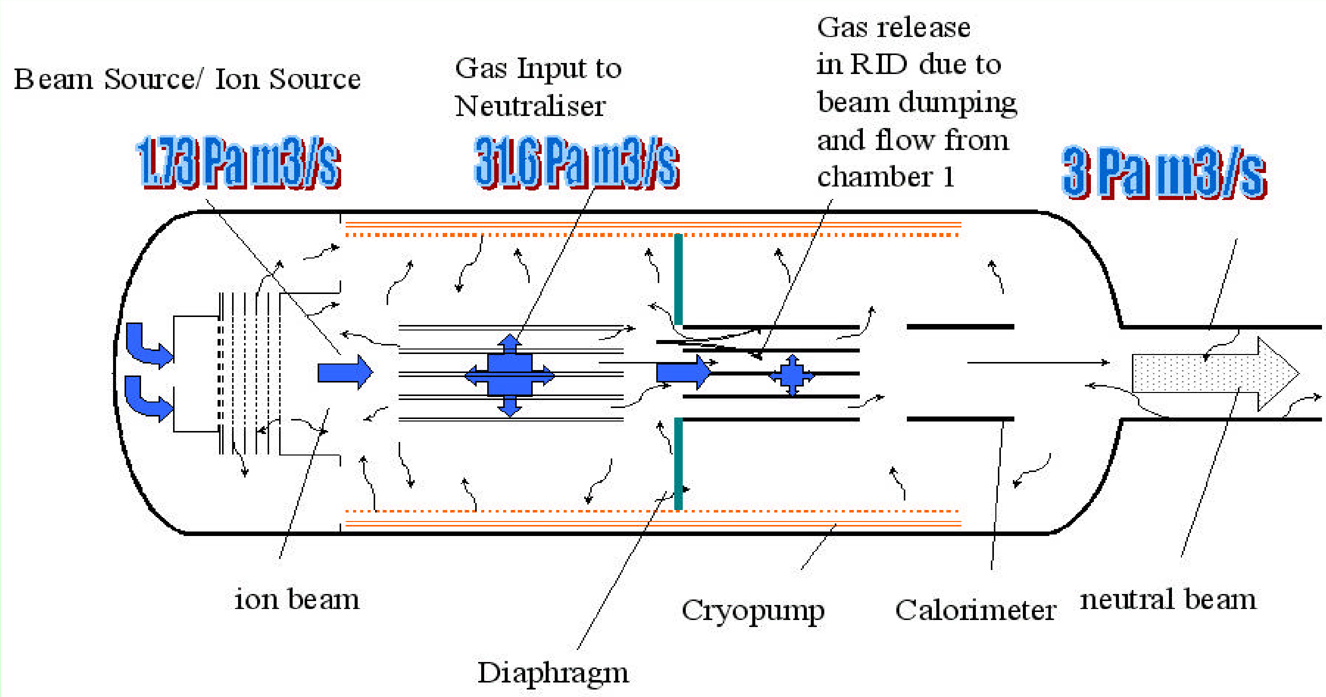
How does the pressure (and the speed) evolve in the cryopump?

5. Plasma heating at ITER



The NBI cryopumping task

Design case :
→ H2 (higher flows, more difficult to pump)

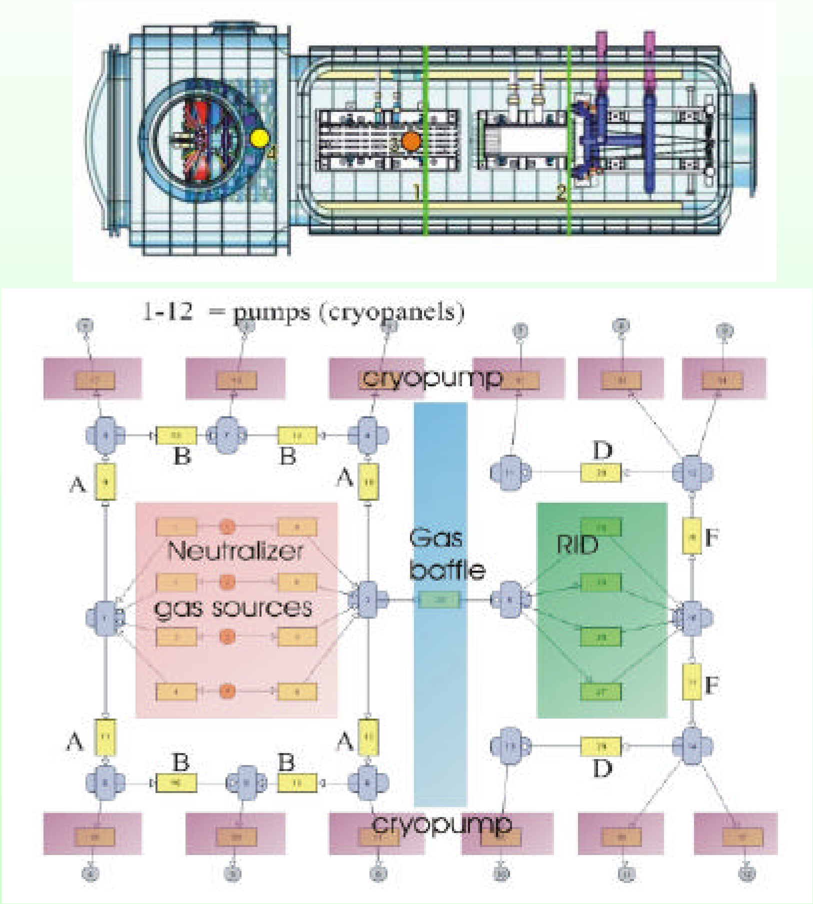


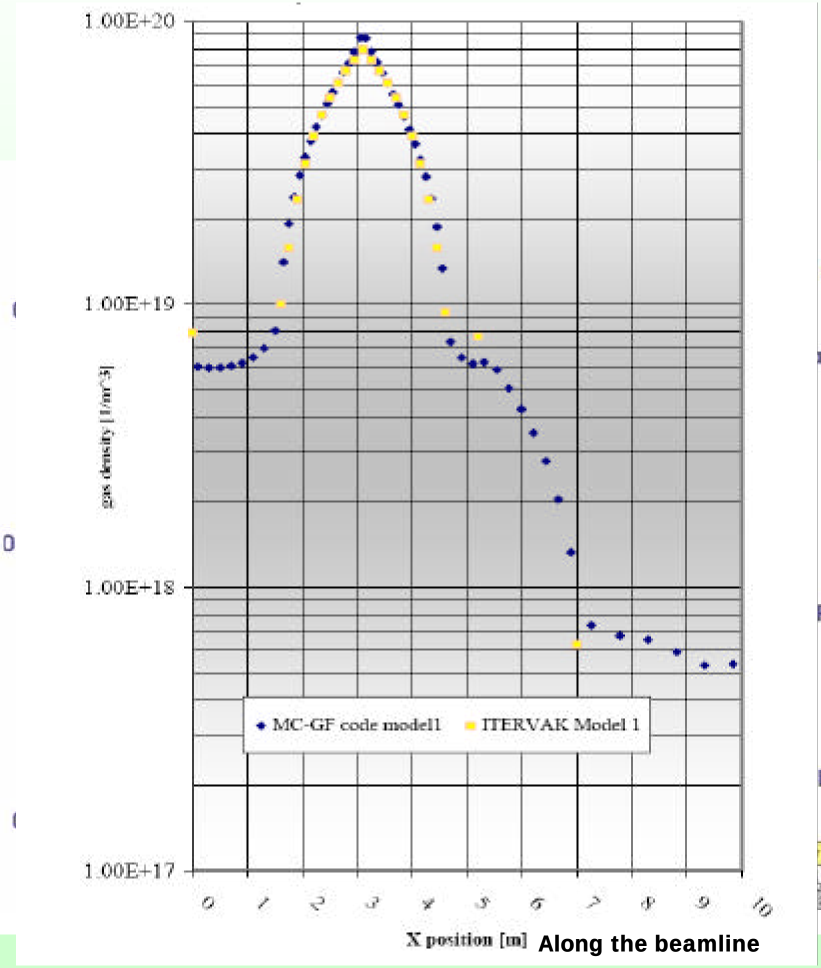
P_1=0.3 Pa (filling pressure)

$P_2/P_1 \approx 0.1$

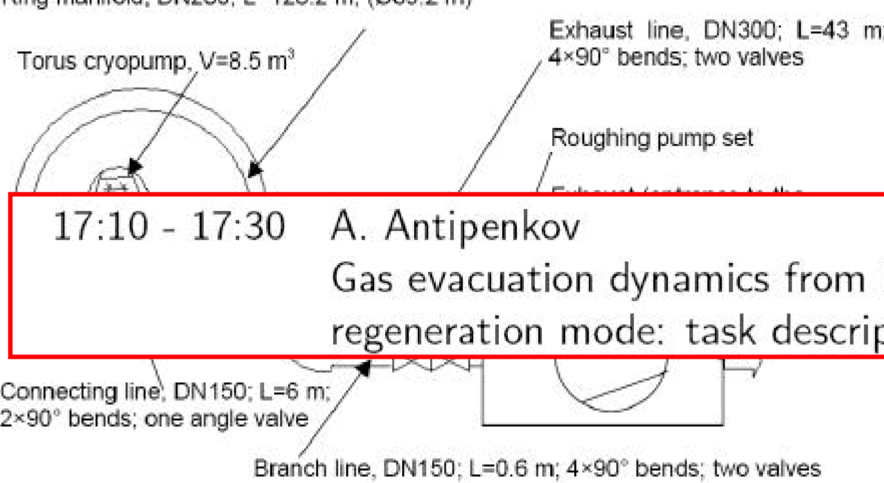
S(av, 1+2)=3800 m^3/s

Flow and pressure distribution (ITERVAC)





6. Gas dynamics during cryopump regeneration



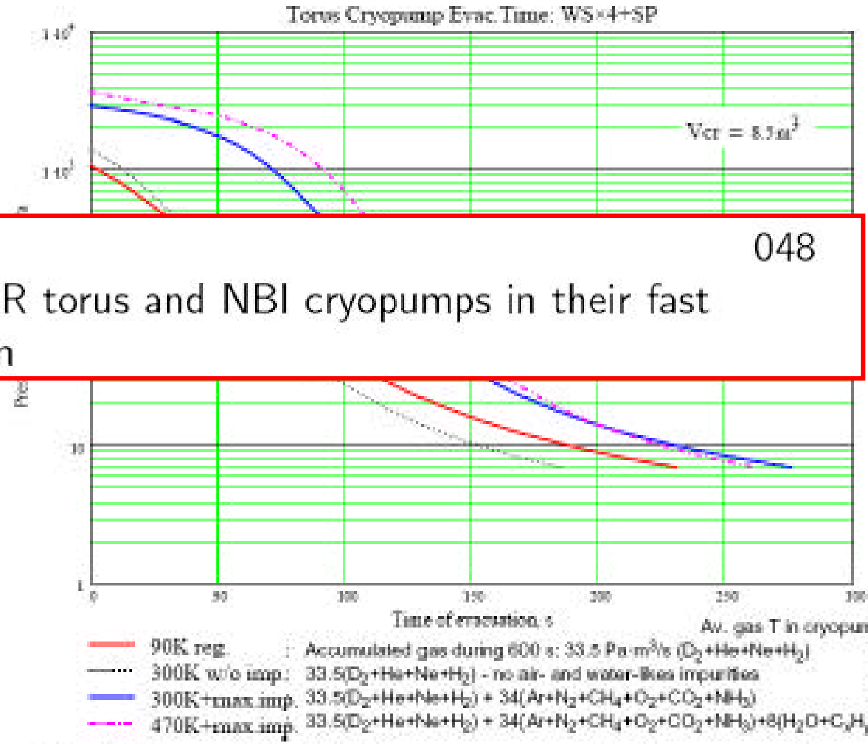


Fig. 37. Evacuation of the torus cryopump during regeneration: 120 Pa·m³/s fuelling rate; V=8.5m³

17:10 - 17:30 A. Antipenkov 048
Gas evacuation dynamics from ITER torus and NBI cryopumps in their fast regeneration mode: task description

3 regeneration levels:
At 100K, 300K, 470 K.
Evacuation from a few kPa to 10 Pa over long lines and varying temperature

Conclusions

- ✓ ITER is a very complex, technologically first of its kind device.
- ✓ In many areas, the vacuum systems are operated under transitional flow conditio
- ✓ ITER is alive and must be built now:
  There will rarely be the situation that the design is frozen and you get the time to do ´nice, accurate and parametric´ calculations.
- ✓ The calculations will in most cases have a design support function to show that operational goals can be met.
- ✓ It must reflect aspects such as: manufacturability, versatility, design robustness.
- ✓ So: From an academic point of view, this means difficult boundary conditions.

- ✓ But everybody who can imagine working under these conditions is encouraged to come up and do so!