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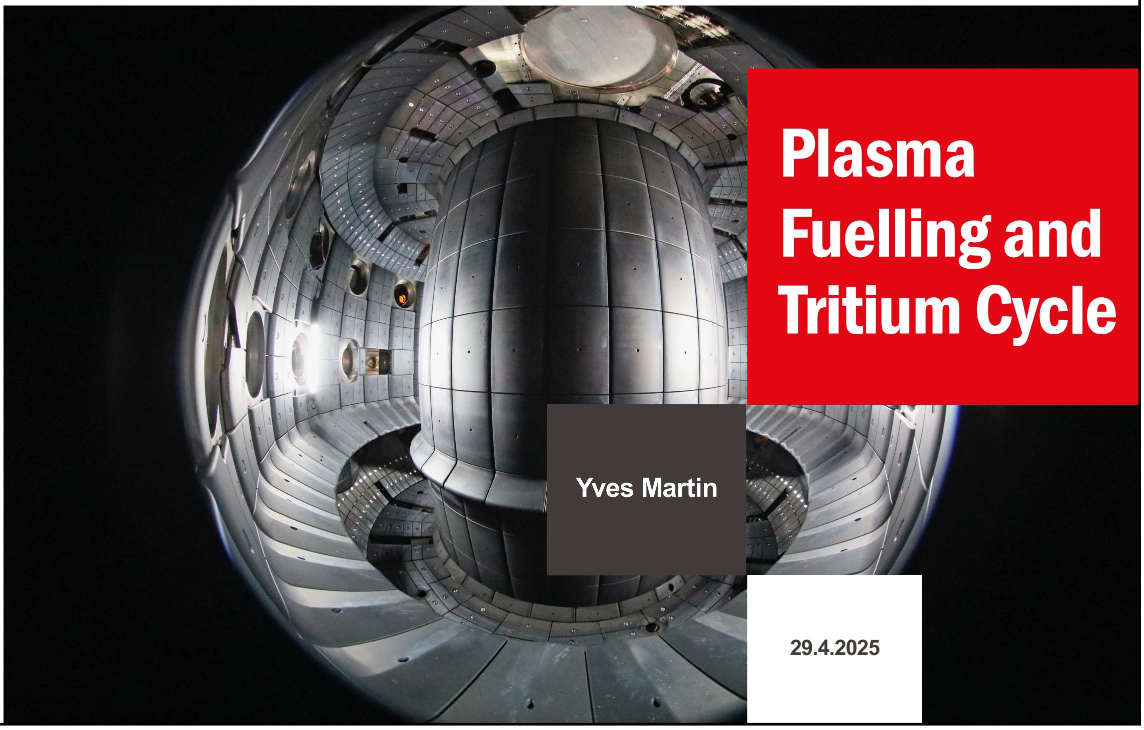

Plasma Fuelling and Tritium Cycle

Yves Martin

29.4.2025

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Plasma Fuelling and Tritium Cycle - Introduction

- Man-made plasmas are usually operated
  - At low densities
  - With selected elements (H, D, T, He, …, SiH_4, …)
  - Sometimes highly reactive and/or toxic

➔ Plasmas are usually contained in vacuum vessels

➔ Fuelling has to be controlled to reach the desired density

➔ Fuelling must be safe and efficient (T handling)

- Fusion plasmas may benefit from localised or particular fuelling
  - Low field side vs high field side (ELMs)
  - Main plasma vs divertor (radiative divertor)
  - Strong gas puffing or pellets (central fuelling, disruption mitigation)

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Plasma Fuelling and Tritium Cycle – Introduction II

- Variety of fuelling schemes
  - Gas valves, including Massive Gas Injection systems (MGI)
  - Supersonic gas injection
  - Pellet injection
  - *Neutral beam injection*

- Tritium cycle
  - Fusion reaction produces one neutron
  - Neutron colliding with Lithium produces one Tritium
  - Losses (openings in the walls, Tritium decays, …)
  - Reserve for future plants

➔ Multiplication factor must be greater than one

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Plasma Fuelling and Tritium Cycle - Plan

- Fuelling: units, efficiency
- Gas injection: generalities, examples
- Supersonic gas injection
- Pellet injection: principles, development, examples
- Tritium cycle: Tritium Breeding Ratio

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Basic units

- Pressure P
  - 1 atm = 760mm Hg = 760 Torr = 1.013 10^5 Pa
  - 1 bar = 10^5 Pa; 1mbar = 100 Pa
- Volume flow rate q_v
  - liter / second
  - m^3 / s
- Mass flow rate q_m
  - Torr . liter / second
  - Pa . m^3 / s
- Relation between volume and mass flow rates
  - $q_m = q_v . P$
- Particle flow rate
  - part / s

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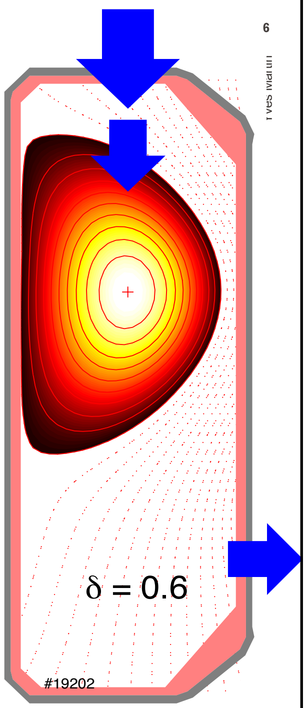
Fuelling efficiency

- Fuel
  - Injected from an aperture in the vessel wall
  - Transits through an 'empty' volume
  - A fraction enters the plasma
- Efficiency
  - $\eta = dN_e/dt / \Gamma_s$ (gas)
  - $\eta = \Delta N_e / N_s$ (pellet)
- where
  - N_e is the total electron number in plasma. Δ denotes its variation
  - Γ_s is the particle flow
  - N_s is the particle content (of the pellet)



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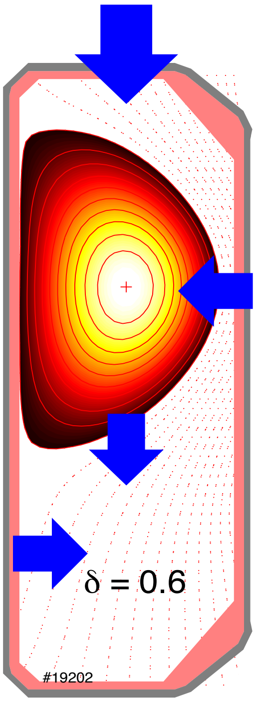
Particle confinement time

- Particle confinement time - τ_p
  - $dN_e/dt = \eta_G S_G + \eta_B S_B + S_I - N_e/\tau_p$

where G, B and I denote gas, beam and recycling , resp.

- Effective particle confinement time - τ_p^*
  - $N_e = N_e(0)\exp(-t / \tau_p^*)$
  - Does not exactly corresponds to τ_p because of recycling
  - $dN_e/dt = \eta_G S_G + \eta_B S_B - N_e/\tau_{p*}$
  - $\tau_p^* = \tau_p / (1\text{-}R)$ where R is a recycling coefficient



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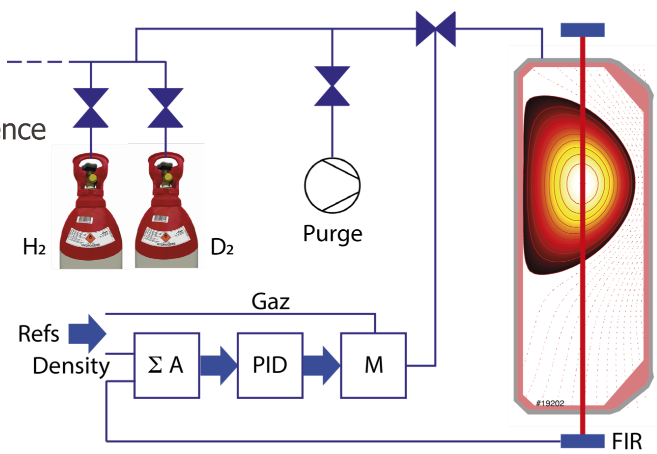
Gas fuelling - Principles

- A gas valve on the torus
  - Fed via gas lines
    - choice of gas
    - gas lines purging system
  - Controlled via feedforward reference
- A feedback loop
  - Density measurement
  - Comparison with reference
  - PID controller
  - Correction to ff reference



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Gas valve - example

- Basic systems
  - Electromagnetic valve
    - Non-linear, sensitive to magnetic fields
- Advanced systems
  - Piezzoelectric valve
    - not sensitive to magnetic fields
  - Flow measured by pressure sensor
    - feedback loop
- GA valves
  - Piezzoelectric
  - up to 500 torr L / s
  - opening time 2ms after voltage
  - Controller: for 4 valves

[General Atomics (GA) web site]

- GA / TCV valves & controller

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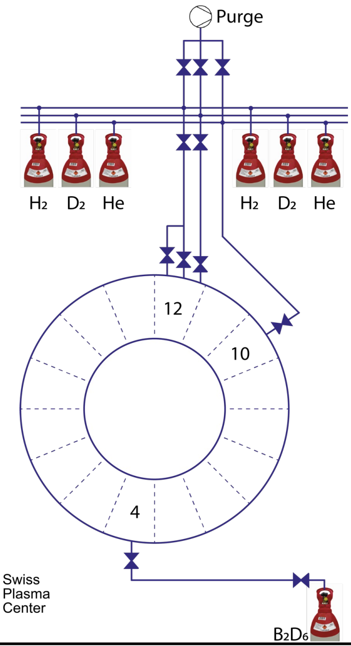
Gas fuelling at TCV



- TCV -1 level
  - Gas storage: bottles of H_2, D_2, He
  - Lines & valves to connect gases to TCV lines
  - Purging system
- TCV 0 level
  - Lines and valves on the tokamak
  - Discharge fuelling Sect. 12 top and bottom
    - bottom: private region of the divertor
  - Glow fuelling: Sect. 12 bottom
  - Reserve line: Sect. 10 bottom
- TCV 0 level outside
  - Diborane (B_2D_6) storage
- TCV 0 level
  - Line and valve
  - Boronisation: Sect. 4 bottom and 12 top

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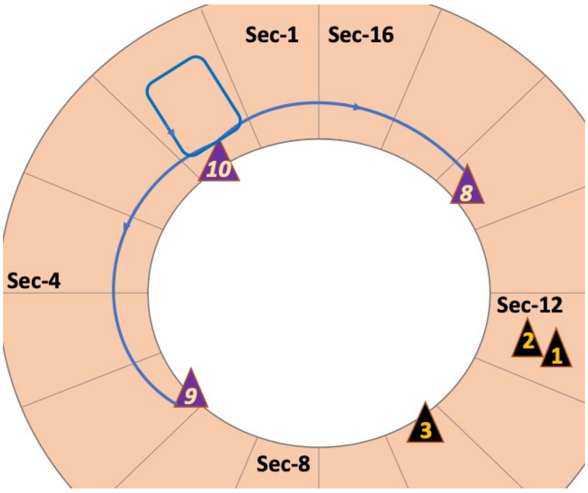
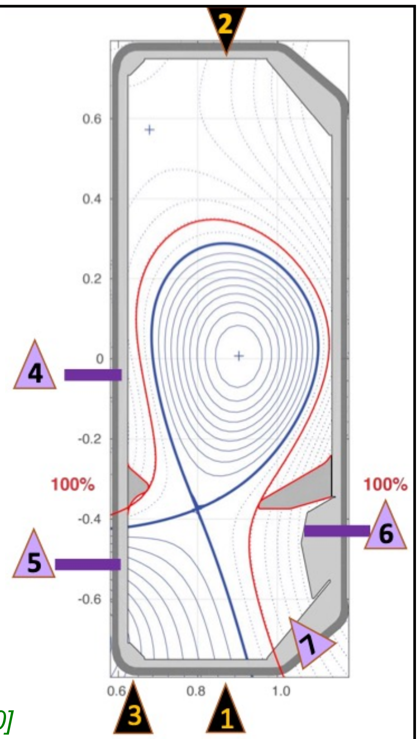
Gas fuelling in upgraded TCV

- Additionnal valves are installed
  - To feed the divertor chamber with heavier particles





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[Raj, TCV, 2020]

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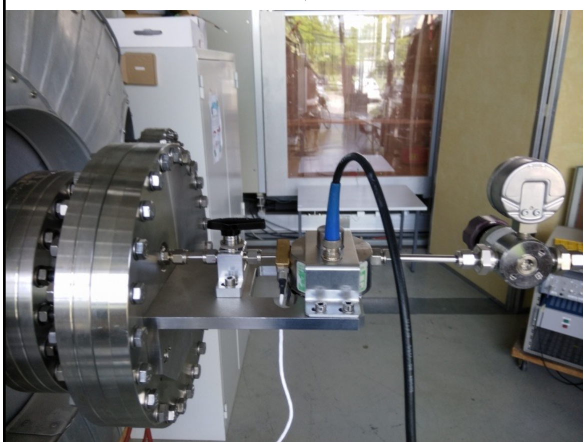
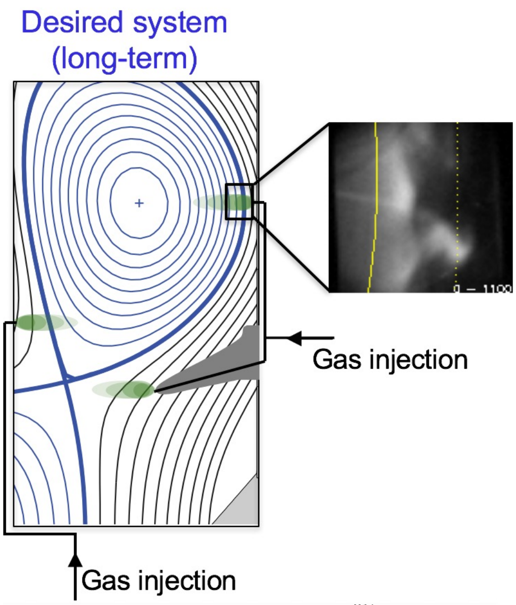
Gas Puff Imaging

- Gas puff to measure the turbulence
- ~100ms, 3-12 10^{19} at/s





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[Offeddu, SPC wiki]

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Gas Injection System (GIS) in ITER

Yves Martin

- Scope
  - Gas fuelling for the glow discharge cleaning
  - Gas fuelling for the plasma operation
  - Impurity injection for the radiative divertor
  - Massive gas injection for discharge termination
  - Gas supply for NBI
  - Gas supply for pellet injectors
- Glow discharge cleaning
  - H, D, He
  - Before and after venting
    - Before: in D to decrease T retention
    - After: H first and then He to clean walls
  - Max throughput: 50 Pa m^3 / s
  - Response time: a few seconds
  - Will share the same system as the main plasma fuelling

[Yang, Fus Eng & Des 2010, 2292]

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Gas Fuelling System (GFS) in ITER

Yves Martin

- Prefil
  - Initial pressure: 8-40 10^{-3} Pa ~ 0.8-4 10^{-4} mb (same as in TCV)
  - Throughput: 260 Pa m^3 / s (in excess to pumping speed)
- Ramp-up
  - Density ramp-up proportional to plasma current ramp-up
  - Gas injection in the first phase; pellet injection later
  - Gas injection used to control the D-T mixture
- Flattop
  - Efficiency of GFS for core fuelling
    - η < 10% for hydrogen isotopes (~1% in *[Baylor, PoP 2005, 12 56103]*)
    - η < 20% for helium
    - Pellet injection: η~100%
    - Pellet injection more suitable for core fuelling, but for H, D and T only !
  - GFS for core fuelling of He
    - 1st operational phase of ITER (previous timeline)

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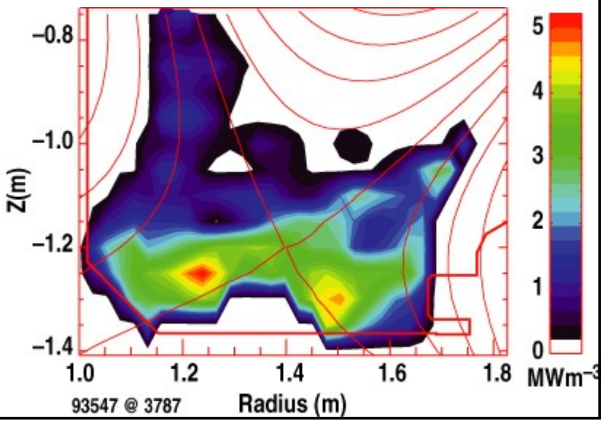
GIS for Divertor Control

- In ITER, heat flow onto divertor tiles is too large. Actions required.
  - Tiles orientation, flux expansion, ELM control, …
- Radiative divertor
  - Escaping particles flow along field lines towards divertor plates
  - Collisions with neutrals in the divertor slow down ions and create radiation
  - Less energetic ions reach divertor plates
- DIII-D example
  - Divertor 2D radiation profile inverted from the bolometer arrays (only gas puffing)

➔ High neutral pressure in the divertor will produce a 'radiative divertor' and decrease the impact on the divertor tiles



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[Leonard, NF, 2012, 63015]

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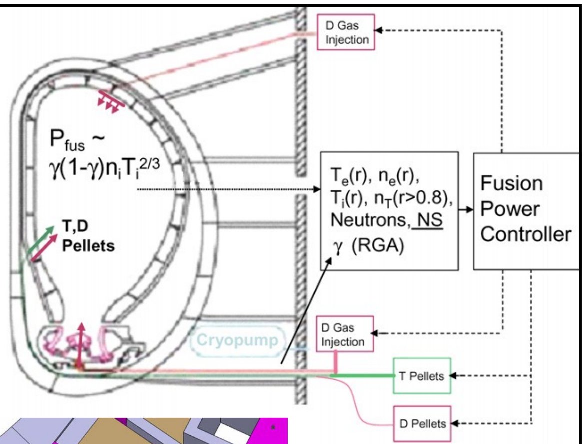
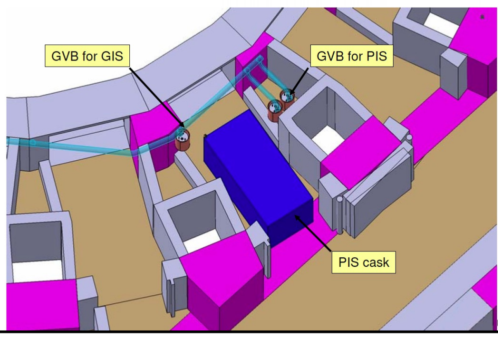
GIS – Technical aspects

- Core fuelling
  - 4 independent Gas Valve Boxes (GVB)
  - Located at the top of vessel
  - 50-100 Pa m³/s each
- Divertor fuelling
  - 6 independent Gas Valve Boxes (GVB)
  - Located in the divertor
- Mixture control
  - D_2 gas injection





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[Baylor, NF, 2007, 443]

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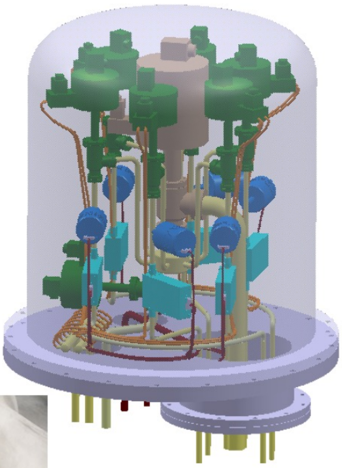
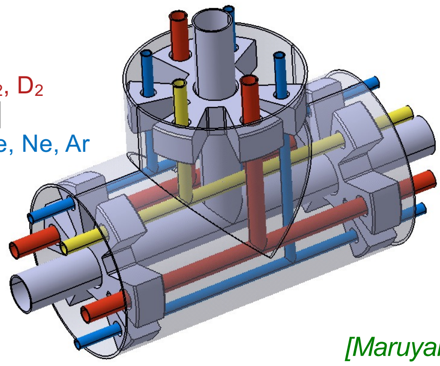
ITER Gas Valve Box

- Design
  - Valves
  - Flowmeters
  - Temperature measurement
  - Exhaust



H_2, D_2
T_2
He, Ne, Ar



[Maruyama, 2008, Seminar in Hefei]

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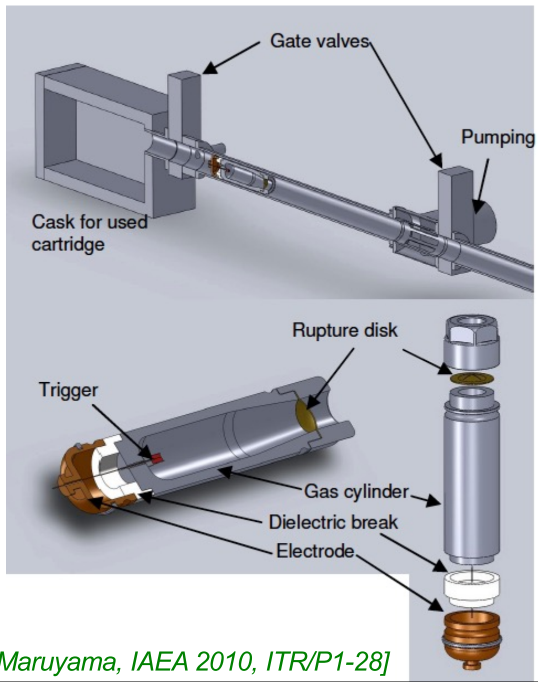
Massive Gas Injection in ITER

- Massive gas injection needed to
  - mitigate disruptions
  - suppress runaway electrons
  - …
  - Loss of coolant
- Requirements
  - Swift action
    - Disruption prediction
    - Mitigation initiation
    - Gas in the plasma
- Example: Fast gas injector
  - Small high pressure gas cylinders
  - Rupture disk
  - 1 kPa m^3; 100 atm
  - Discharge time 1-2 ms
  - Cartridge must be replaced

[Putvinski, IAEA 2010]



[Maruyama, IAEA 2010, ITR/P1-28]

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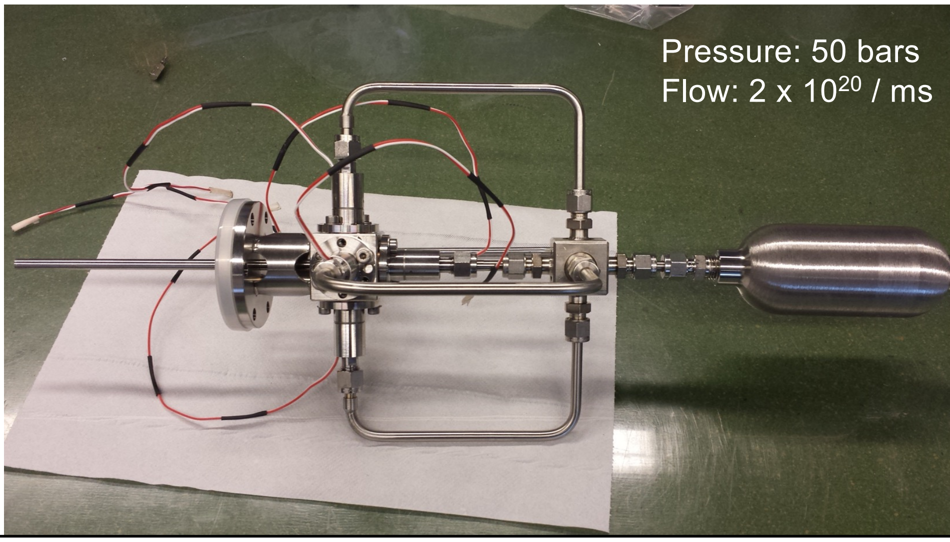
Massive gas injection in TCV

- Used for disruption mitigation



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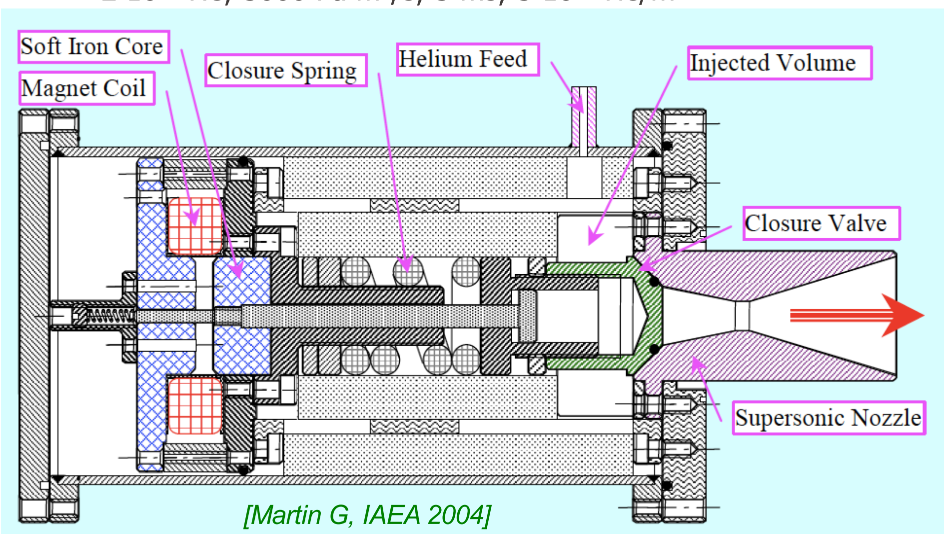
Tore Supra / WEST Massive Gas Injection

- Aimed at disruption mitigation
  - 2 10^{23} He; 5000 Pa m³/s; 3 ms; 5 10^{21} He/m³



[Martin G, IAEA 2004]

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Supersonic Gas Injection

- Idea
  - A supersonic particle beam would penetrate deeper in the plasma core than gas puffing
- Aim
  - Plasma core fuelling
  - Disruption mitigation
  - ELM control
  - *Transport studies*
- Advantages
  - Higher efficiency than gas puffing
  - Simpler implementation than pellet injection

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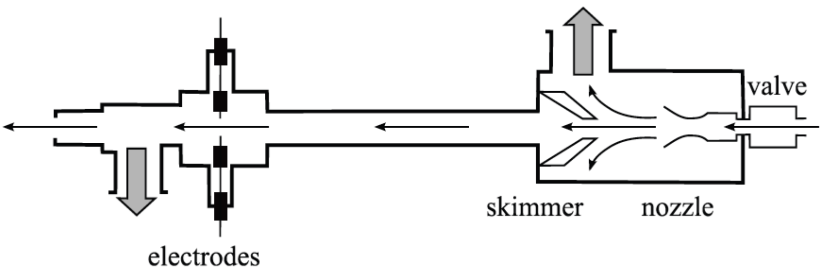
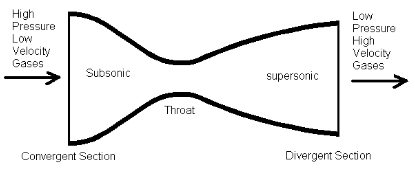
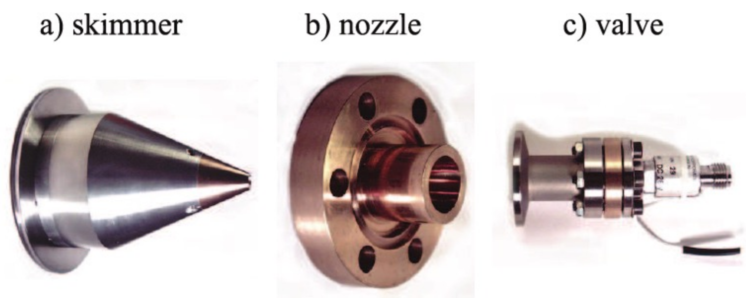
Supersonic Gas Injection in TCV



- Principle
  - High pressure tank
  - Fast valve
  - Laval Nozzle
  - Skimmer
  - Diagnostic





[Wagner, thesis, 2013]

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Supersonic Gas Injection in TCV

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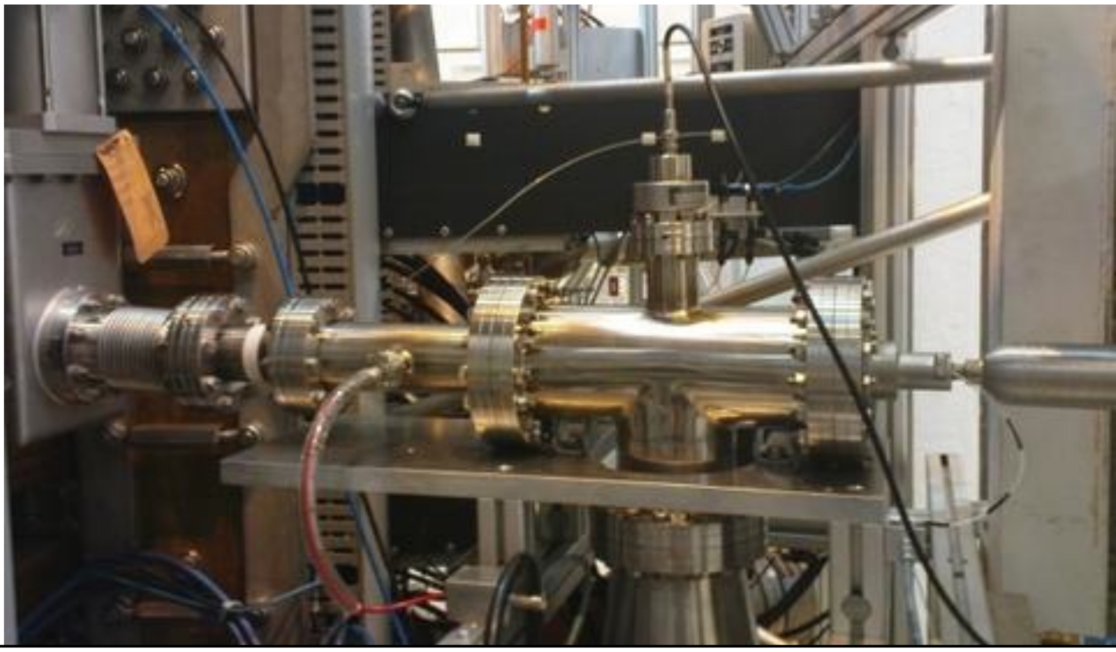

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NSTX Supersonic Gas Jet

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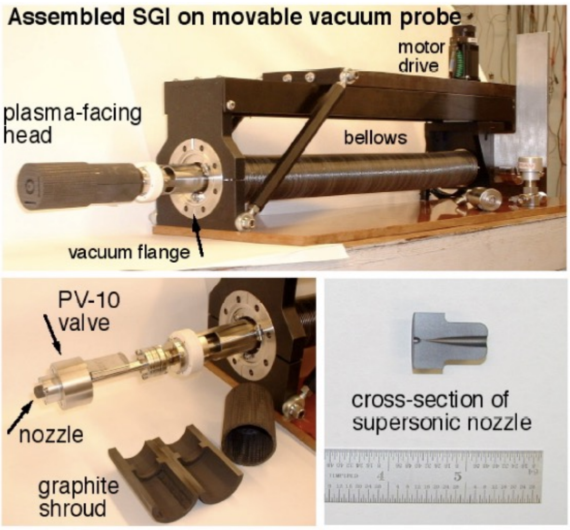
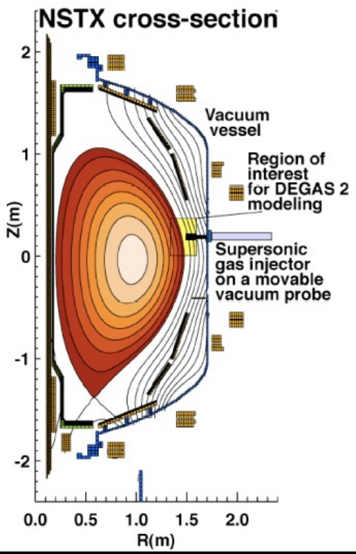
- Movable vacuum probe – Head/nozzle very close to the plasma





logy, 29.4.25

[Soukhanovskii, EPS, 2004]

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Pellet Injection

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- Idea
  - Produce small H, D or T 'ice cubes'
  - Shoot them into the plasma
  - Should not 'feel' the cold neutral gas surrounding the plasma
  - Should be able to penetrate deep into the plasma
  - More efficiency than other techniques

- More than 40 years of development
  - Technology
    - High pressure gas acceleration or centrifugal acceleration
    - In situ or in extruders pellet preparation
  - Modeling
    - Neutral gas shielding model

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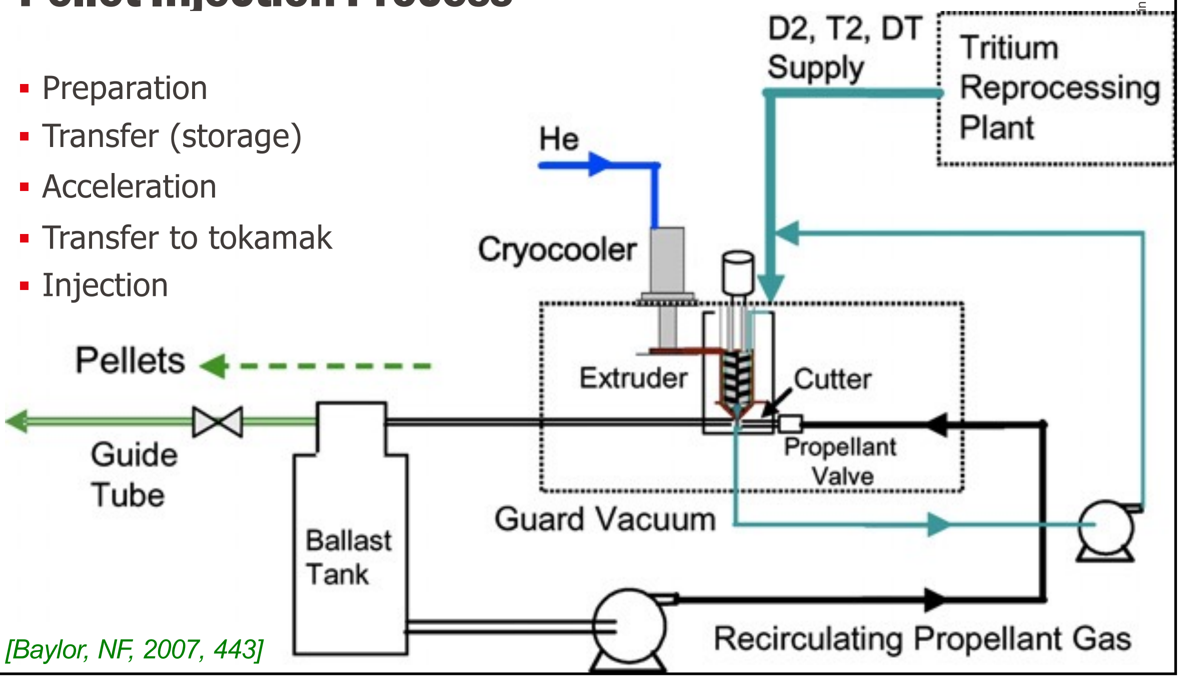
Pellet Injection Process

- Preparation
- Transfer (storage)
- Acceleration
- Transfer to tokamak
- Injection



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[Baylor, NF, 2007, 443]

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Pellet Injection and Ablation Studies in TCA

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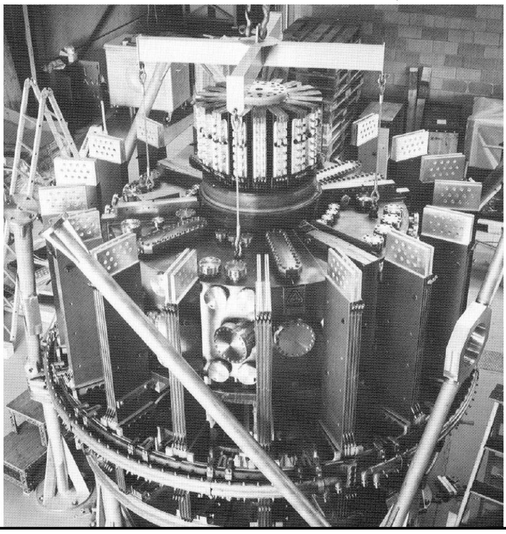
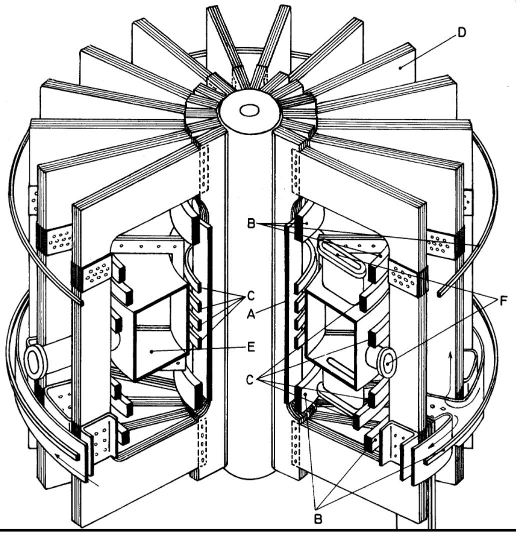
- TCA – Tokamak à chauffage par ondes d'Alfvén
  - $R=0.61m$; $a=0.18m$; $B_{\varphi}<1.5T$; $I_P<130kA$; circular, limited configuration, $t_p<200ms$





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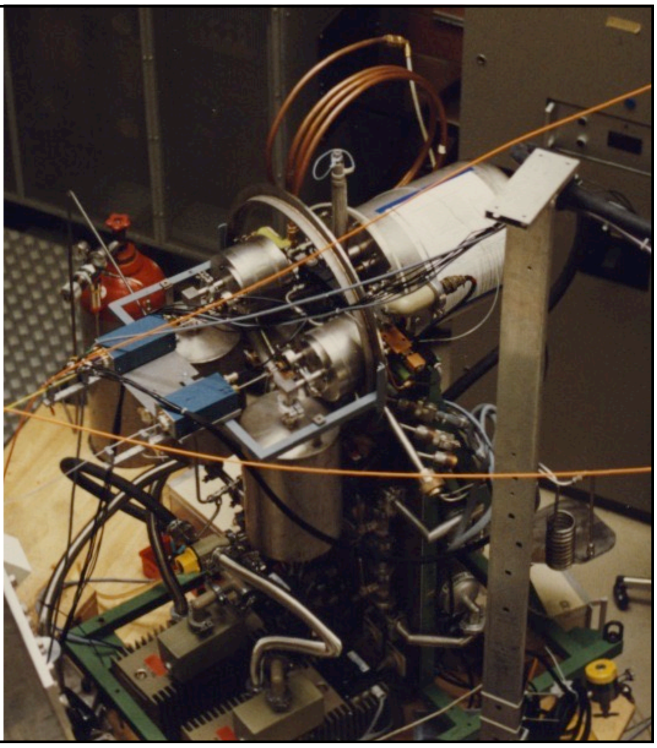
TCA Pellet Injector

- Pellet preparation
  - Cryostat + D_2 bottle
- Pellet acceleration
  - He bottle
  - Expansion volumes
- Pellet transfer
  - Nylon tubes (extruded)
- Diagnostics
  - Velocity measurement



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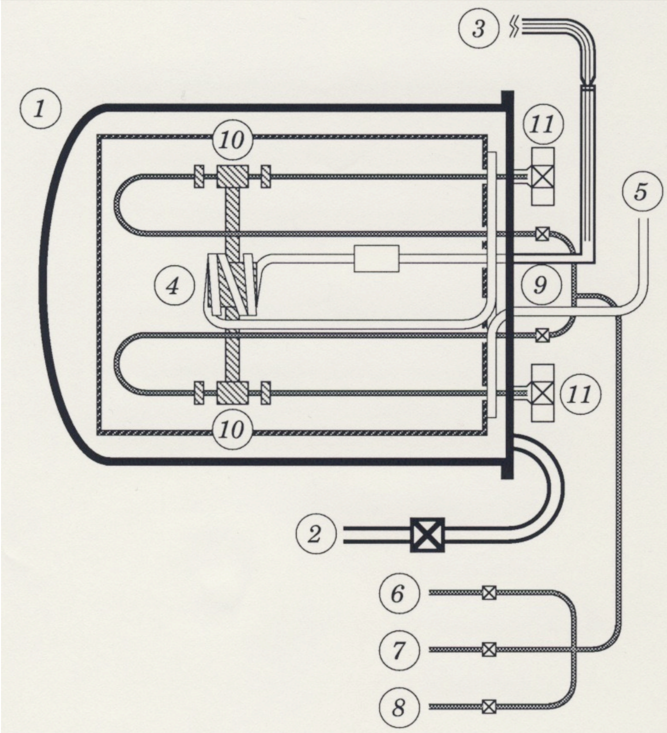
Pellet Injector Cryostat

1. Cryostat
2. To the pump
3. LHe inlet
4. Heat exchanger
5. He exhaust
6. Pumping
7. Production
8. Propulsion
9. Fast valves
10. Cells
11. Exit valves



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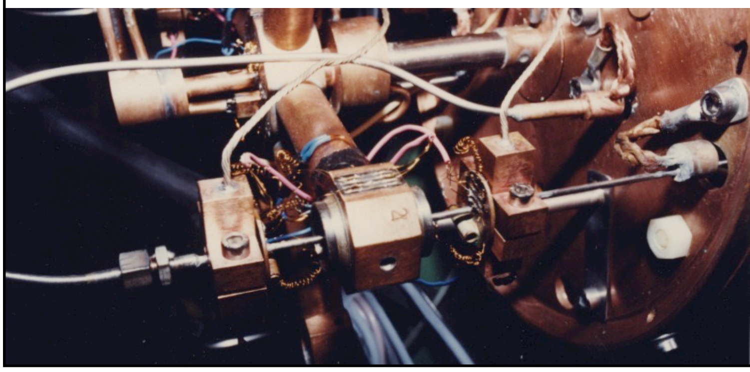
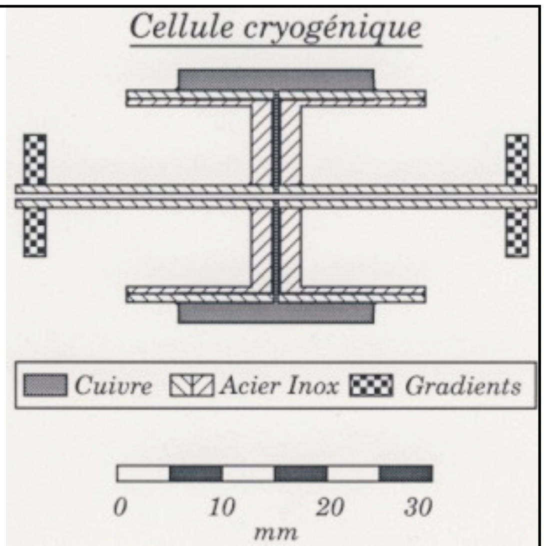
Cells for pellet growth

- In situ formation
  - Cell, directly in the 'blowpipe'
  - Brazed copper section of the SS blowpipe
  - Cooled to 8-9ºK
  - H_2 or D_2 inlet
  - Heaters to unstick the pellet
  - ø = l =~0.5mm





Course on Fusion & PP Technology, 29.4.25

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Acceleration and Transfer to TCA

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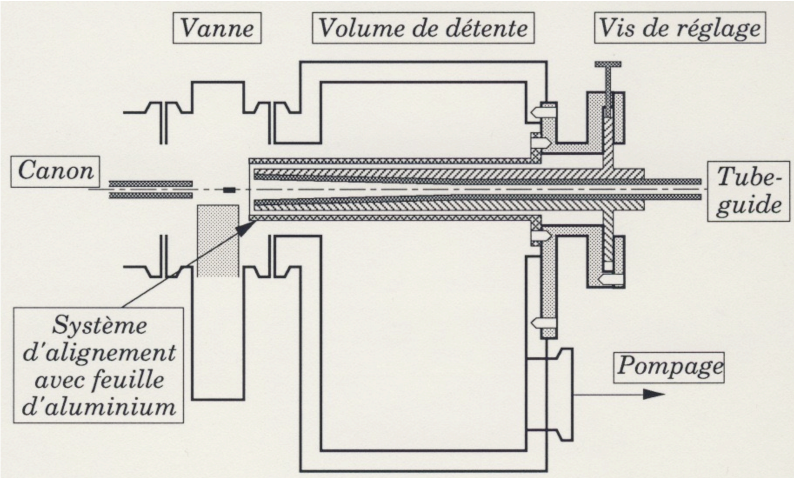
- Acceleration
  - 30 bars He
  - Fast valves (over powered)
  - 150 – 800 m/s
- Transfer
  - Exit valve
  - Expansion volumes
  - Guiding tubes



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Pellet Injection Control

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- LHe circuit control
- Pressure in cells and cryostat
- Temperature in cryostat
- Programmable controller
- Commands
- Cell temperature (x 6 cells)
- Heat pulse control (x 6 cells)
- Fast valves pulse shaping (x 6 cells)

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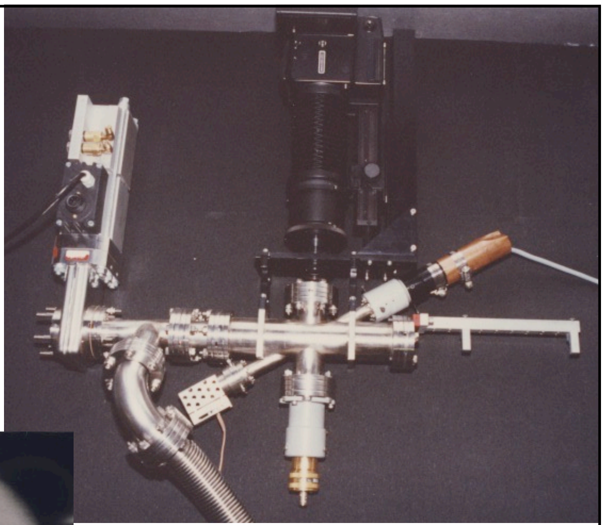
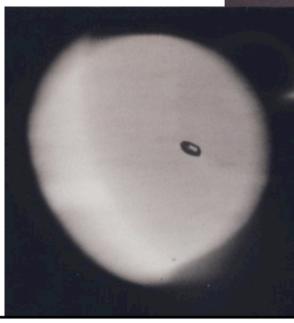
Pellet Diagnostics

- Pellet velocity
  - 2 photoelectric barriers ~10cm apart
  - Across nylon tube
  - Measure of the delay
- Pellet integrity and mass
  - macro-photo of the pellet
  - Photoelectric barrier
  - Fast flash





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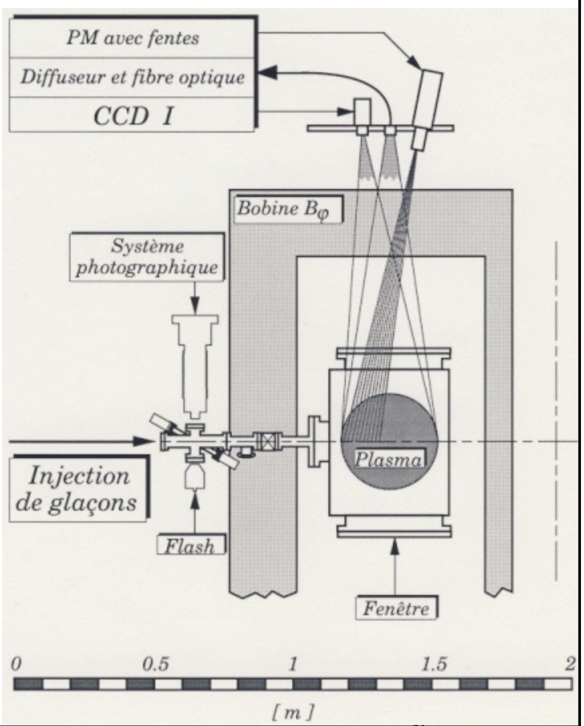
Pellet Ablation Diagnostics

- Photomultiplier (PM)
  - Time resolution
- CCD camera
  - Spacial resolution
- Slits + PM
  - Combination of spatial and temporal resolution



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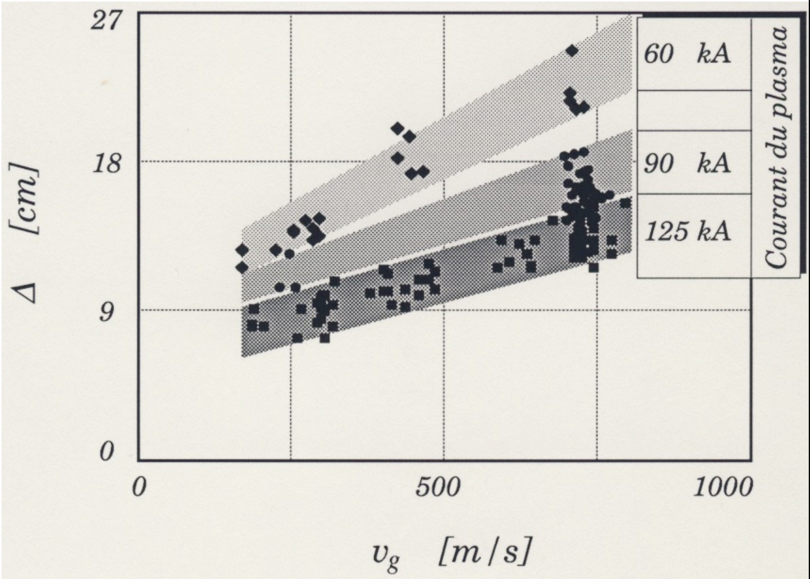
TCA Pellet Injection - Results

- Penetration depth measurement
  - Pellet size and velocity scan
  - Plasma density and current scan
  - Comparison to models



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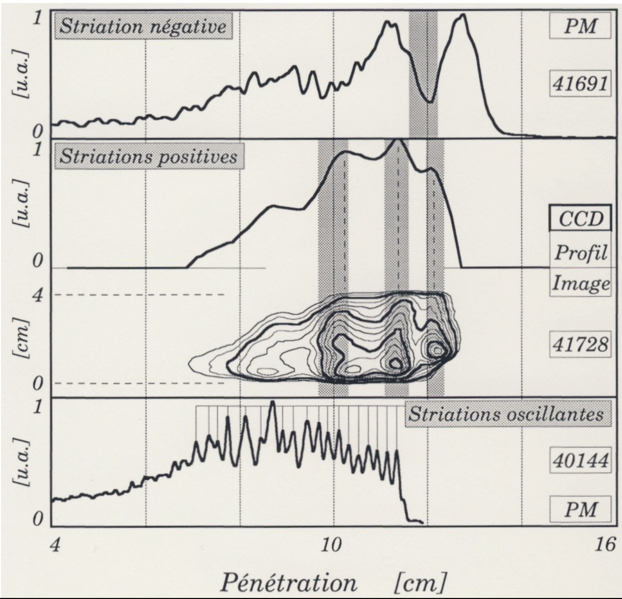
TCA Pellet Injection - Results

- Ablation process qualification
  - Differences between PM and CCD
    - ➢ Change in velocity
  - 2D CCD images
    - ➢ non-straight trajectories
    - ➢ Asymmetries in ablation
  - Striations
    - ➢ Oscillations in ablation
    - ➢ rational q surfaces



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Pellet Injection in ASDEX Upgrade – JT-60SA

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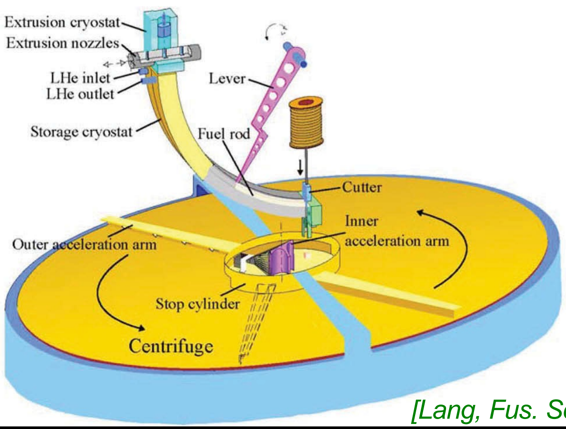
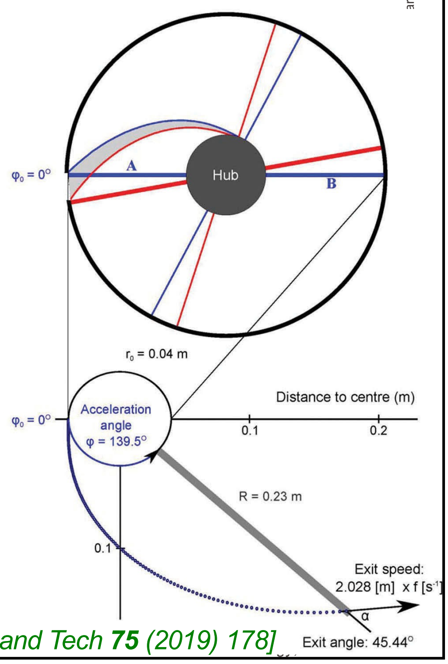
- Design
  - Ice rod extrusion, piston, storage
  - Pellet cut on demand
  - First arm, stop cylinder
  - Centrifuge-accelerated





*[Lang, Fus. Science and Tech **75** (2019) 178]*

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Pellet Injection in ASDEX Upgrade

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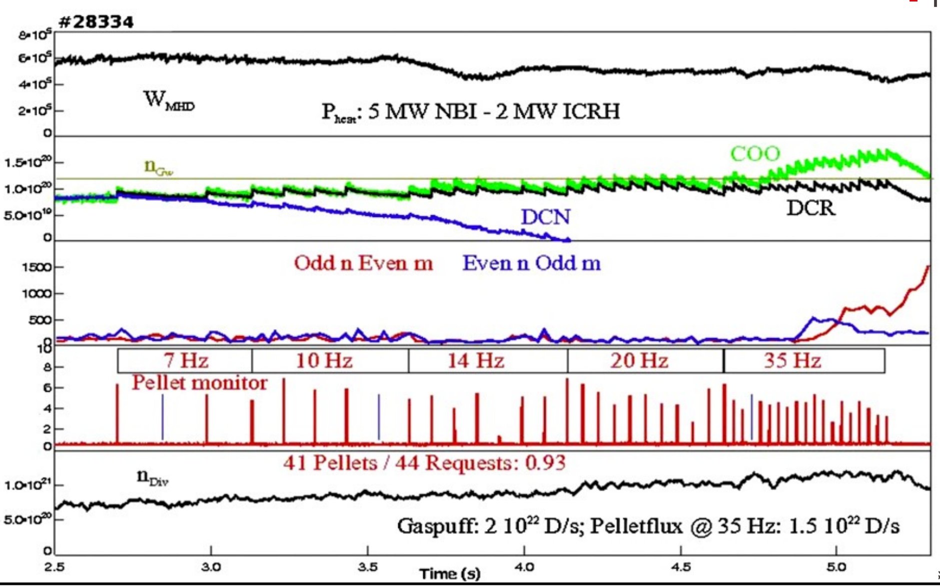

- Parameters
  - Ice rod: 1.4, 1.65, 1.9mm^2
  - Pellet mass: 1.6, 2.7, 4.1 10^{20} D atoms
  - Velocity: 240 – 1000 m/s
  - Repetition rate: integer fraction of rotation frequency

[Plöckl, Fus En & Des, 2013]

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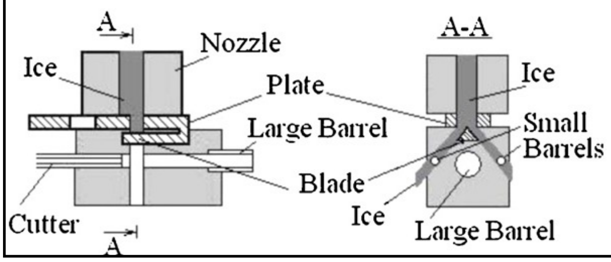
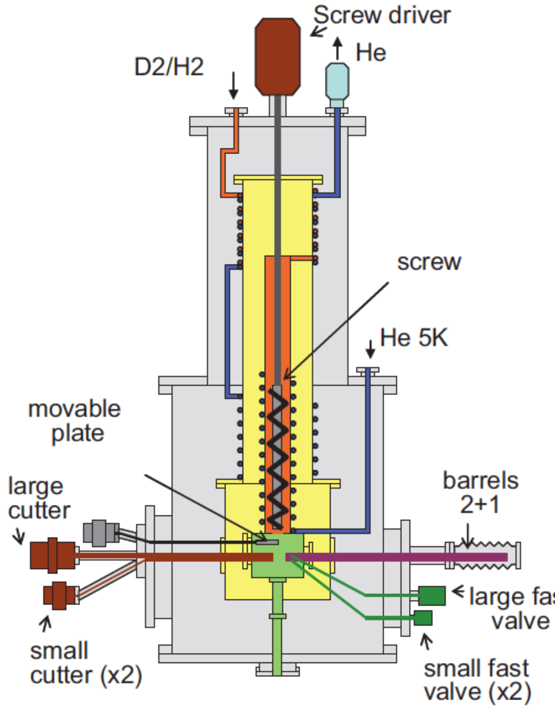
Pellet Injection in JET

- Design
  - Screw extruder
    - Gas ➔ liquid ➔ solid
  - Movable plate
    - 1 large filament
    - 2 thin filaments
  - Cutters
  - Fast valves / high pressure
  - 1400mm³/s, 15Hz for large pellets





[Géraud, Fus En & Des, 2013]

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Pellet Injection in JET – Diagnostics and Transfer

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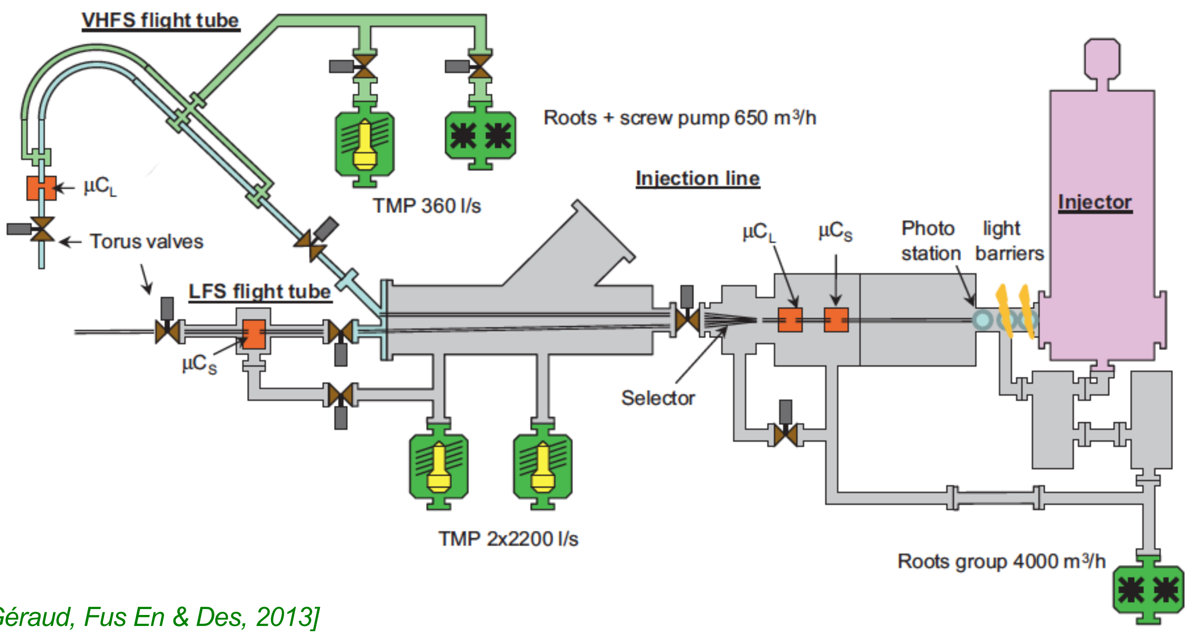

[Géraud, Fus En & Des, 2013]

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Pellet Injection in ITER

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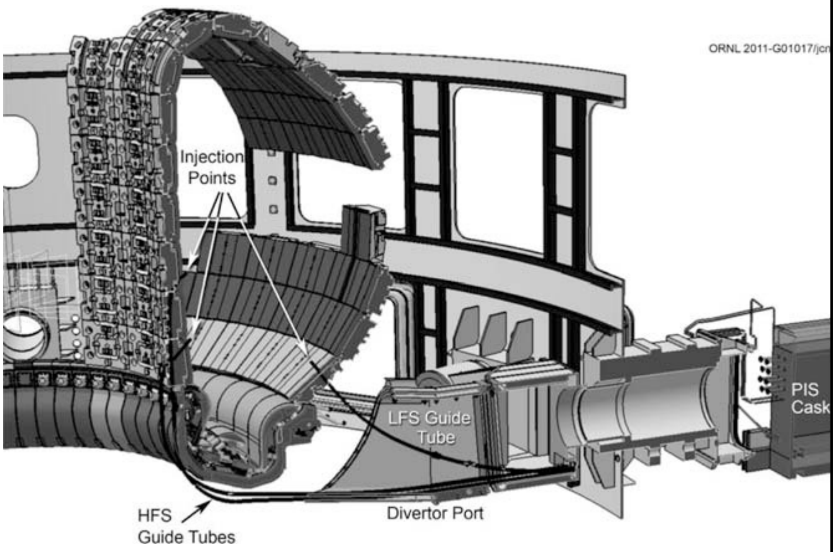
- Aim
  - Core fuelling
  - ELM mitigation
- Requirements
  - Large flow
    - 1500mm^3/s
  - Moderate speed
    - 300m/s
- Solution
  - continuous extrusion
  - cutter
  - guide line selector
  - HFS efficiency
  - 2 injectors
    - up to 6



[Combs, Fus Eng & Des, 2012]

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Pellet Injection in ITER

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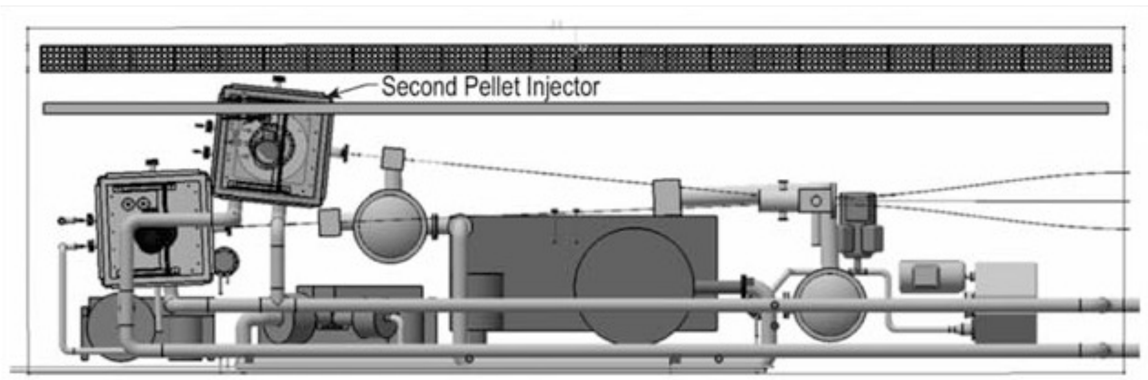
- Plan view: 6.5m x 2.5m x 3.5m



[Combs, Fus Eng & Des, 2012]

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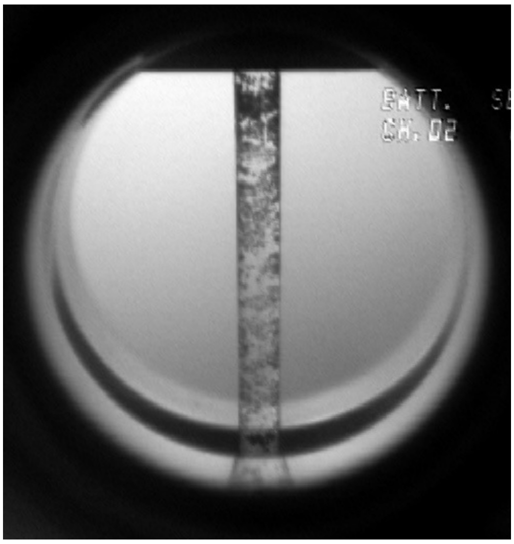
Double Extruder for ITER Pellet Injector

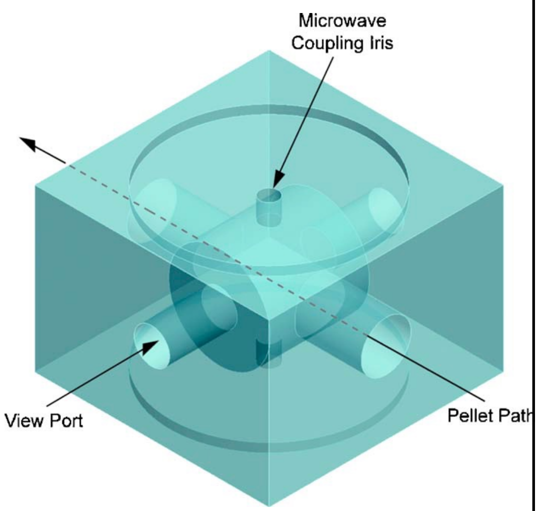
- 3mm Ø ice rod



[Maruyama, IAEA 2010, ITR/P1-28
Meitner, Fus Sci & Tech, 2009, 52]

Pellet Mass Measurement – Microwave Cavity

- Principle
  - Resonant microwave cavitiy installed on the pellet path
  - Change in resonance frequency due to the pellet volume
  - Application: detune the cavity to 70%, pellet will shift frequency downwards, signal will increase. Linear range
- Set-up
  - Cavity dimensions: Ø=7.16cm, L=6.98cm
  - Cavity frequency: ~3.2GHz
  - Calibration of cavities
- Advantage
  - More precise than photography or pressure rise in a volume



[Combs, RSI, 2006]

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Tests of Curved Guide Lines

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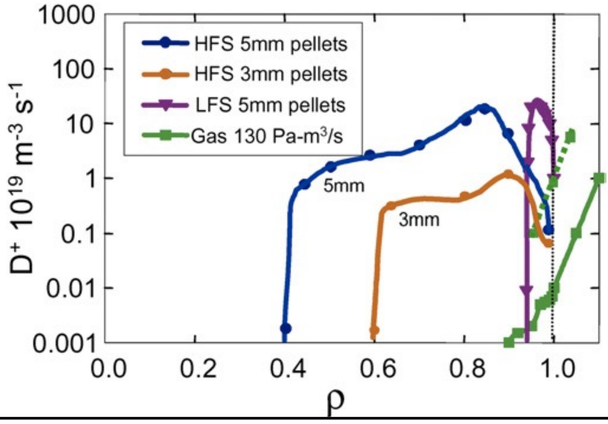
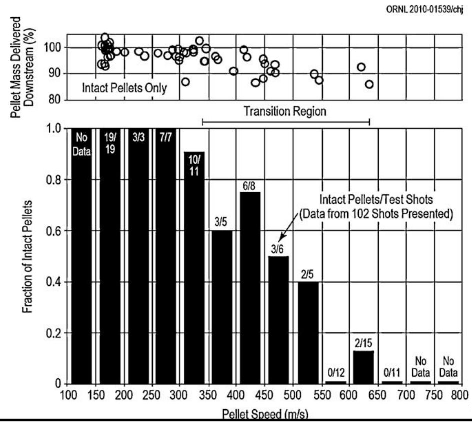
- HFS injection is more efficient
  - Major radius mass drift, due to ExB drift

➔ more curved guide lines

- Tests with ITER guide lines geometry ➔ OK with 300 m/s





[Combs, Fus Eng & Des, 2012]

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Massive Pellet Injection for ITER

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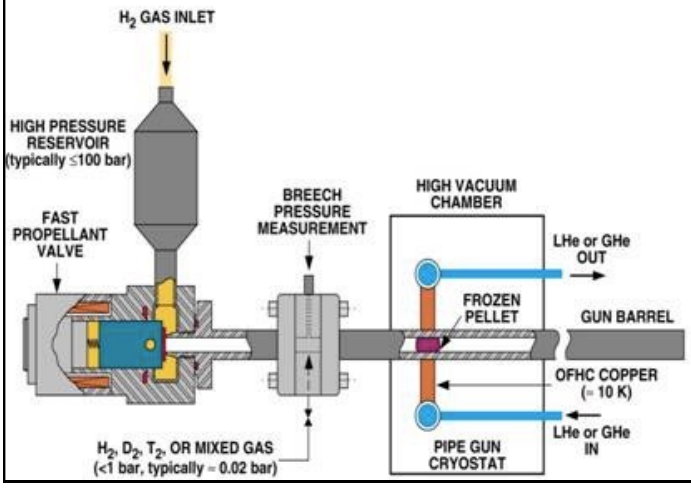
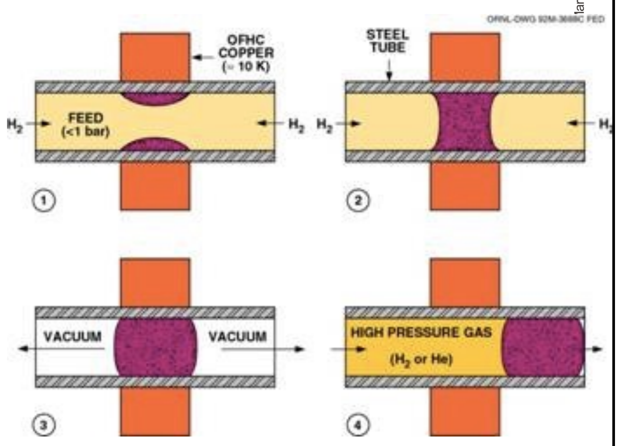
- Aim
  - Mitigate disruptions
  - 40 kPa m³





[Maruyama, IAEA 2010, ITR/P1-28]

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Pellet Ablation Physics and Models

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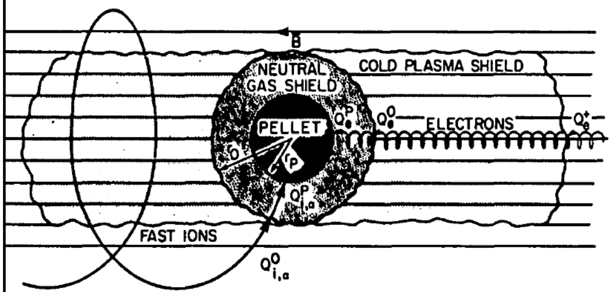

- Ablation process
- A neutral gas cloud forms around the pellet
  - due to incoming hot electrons and evaporation of pellet material
  - ~10^{25}-10^{26} m^{-3}, close to pellet surface
  - protects the pellet
  - self-regulated process
  - ionisation process lead to a cigar shaped cloud
- Models
  - Neutral Gas Shielding model (NGS)
    - Calculates the ablation rate dr_p/dt of a pellet (r_p) in a plasma with given n_e and T_e
    - Includes several assumptions: spherical pellet, heat flux➔ablation only, spherical expansion of ablation cloud
  - Neutral Gas and Plasma Shielding model (NGPS)
    - Adds a cold dense plasma flowing along field lines that increases the shielding factor
  - Hydrogen Pellet Injection (HPI2)
    - Takes into account the effect of fast ions / electrons from heating or current drive

[Houlberg, NF, 1988; Pégourié, PPCF **47**, 2005; Pégourié, PPCF, 2007]

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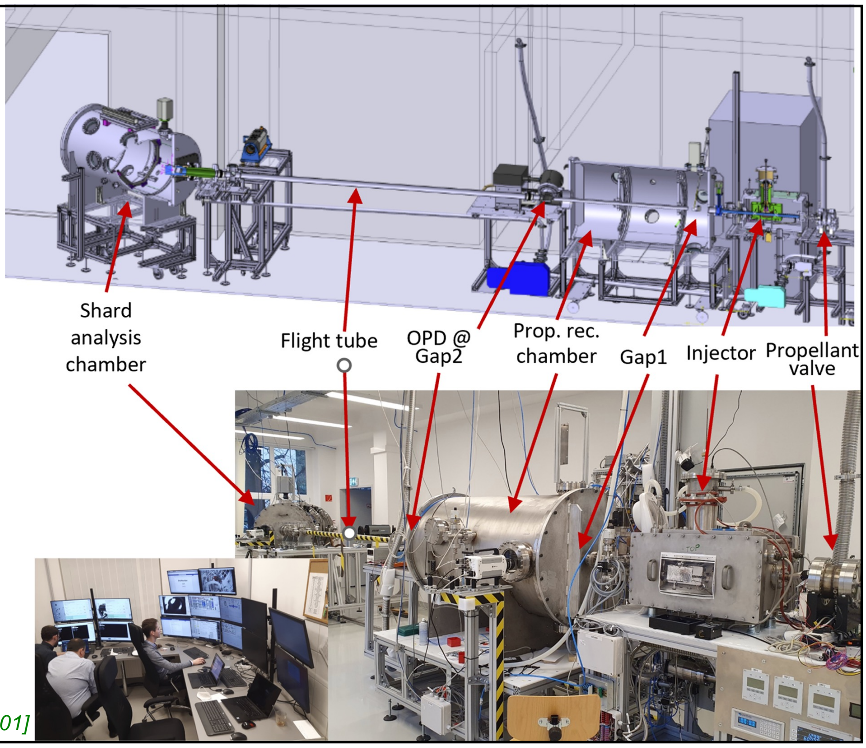
Shattered pellet

- ITER disruption mitigation system
- Pellet injector
  - 19 x 38mm
  - 28.5 x 55mm
  - 30-100bars
  - 400-800m/s
- Shattering head
  - Inclined SS plate (20-30°)
- Diagnostics
  - Laser curtain & fast cam

[Zoletnik S., FED, 2023, 113701]



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Tritium Cycle - Introduction

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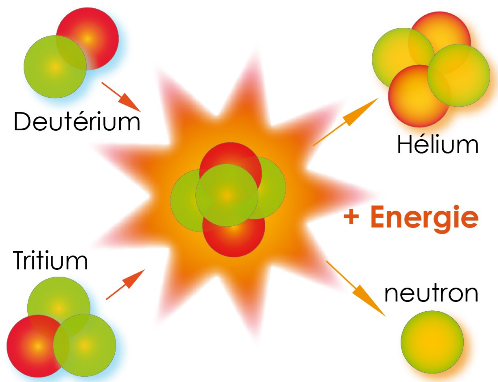
Yves Martin

- Fusion reaction
  - D + T ➔ He + n
- Fuel abundancy
  - D: for >100'000 years
  - T: ~none; radioactive;

➔ T must be provided / produced

➔ T must be handled with care



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Tritium Availability and Requirements

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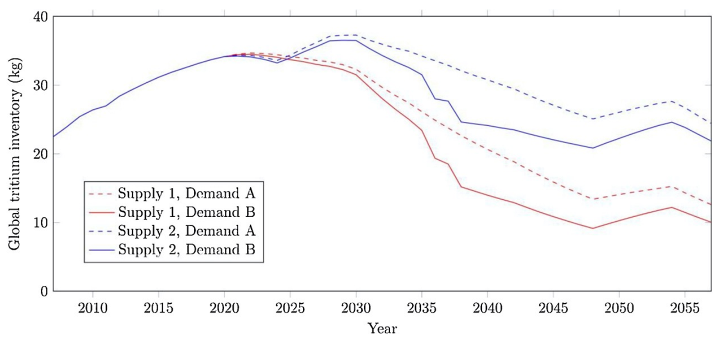

- Properties
  - Half life time: 12.3y
  - Decay mode: β decay
    - T ➔ $^3He^{1+}$ + e^- + ν_{-e} + 18.6keV
    - Activity = 3.6 x 10^{14} Bq/g
- Availability
  - Natural inventory: 3.6kg (stationary)
  - Man-made T production (CANDU)
    - 1.7kg/y until 2025
  - T consumption: 0.1kg/y
  - T decay: 5.47%/y
- Requirements
  - 1 year at 1GW fusion power: 55.6kg

➔ Need self-sufficiency + increase for new plants

➔ May not fullfill ITER requirements

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[Pearson, Fus Eng & Des, 2018]

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Tritium Fuel Cycle

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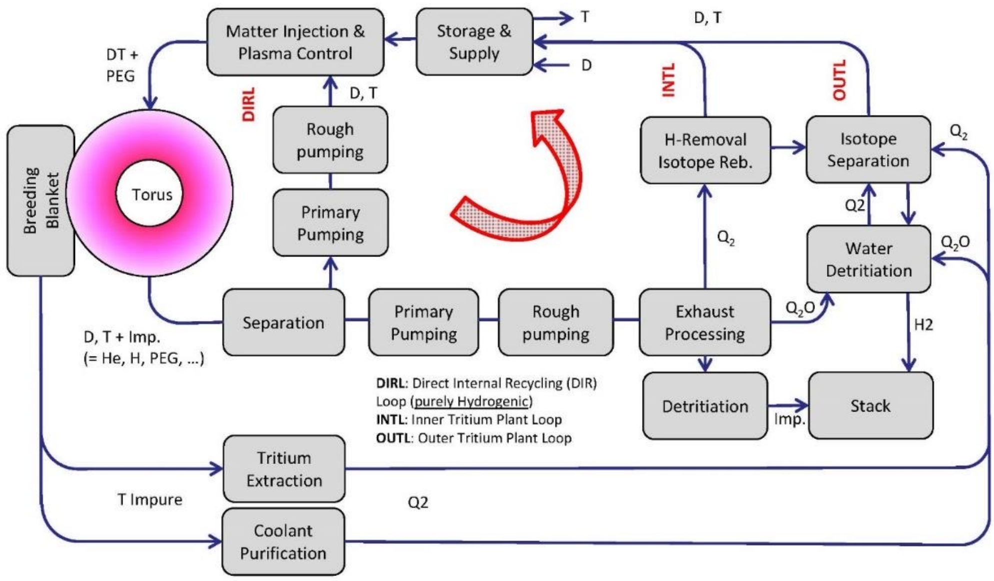

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Tritium Generation – Tritium Breeding Ratio

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- Use of fusion neutron and Lithium
  - ^{6}Li + n ➔ T + ^{4}He + 4.8 MeV
  - Tritium Breeding Ratio (TBR) = 1.000
- Required TBR must be larger than 1.000
  - Neutron losses
  - Tritium natural radioactive decay
  - Supply inventory for starting new reactors
  - Provide a reserve for safe continuous operation
- Important parameters for assessing the TBR
  - Tritium burn-up fraction
  - Fuelling efficiency
  - Tritium inventories
  - Time dependent processes
    - Impurity and isotope separation
    - Storage
  - Tritium 'losses'
    - Retention

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Tritium Burn-Up Fraction

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- Definition
  - Probability that T injected into the plasma fuses before escaping
  - f_b = fusion reaction rate / T fuelling rate
- Details
  - fusion reaction rate: $f_f = n_D\, n_T <\sigma v>_{DT}$ (and $n_D = n_T$)
  - T fuelling rate: S_T
  - T balance: $dn_T/dt = S_T - f_f - n_T/\tau_T$
    - τ_T = Tritium (particle) confinement time
  - In steady-state: $S_T = f_f + n_T/\tau_T$
  - $f_b = f_f / S_T = f_f / (f_f + n_T/\tau_T) = 1 / (1 + 1 / \tau_T n_T <\sigma v>_{DT})$

➔ Tritium burn-up fraction only depends on density and particle confinement time

- … but:
- T fuelling rate = T injection rate x fuelling efficiency (η)

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Achievable Tritium Breeding Ratio (TBR)

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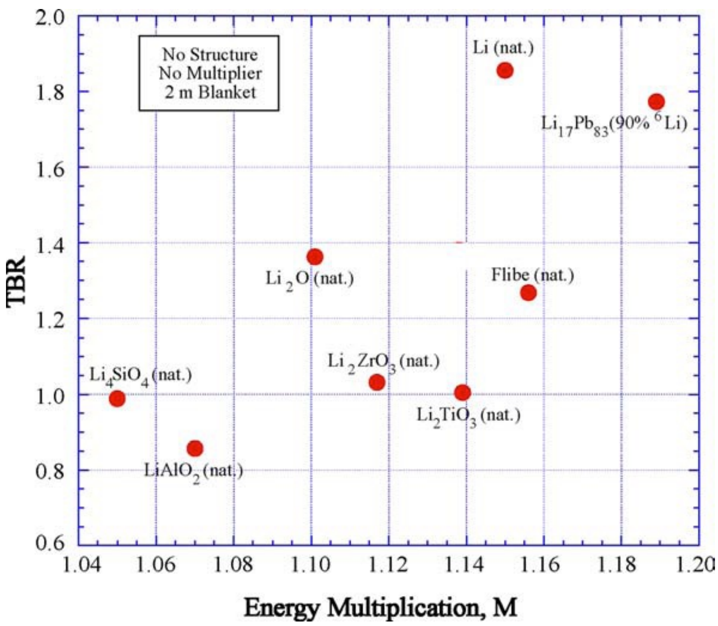

- TBR depends on
  - Breeding material
  - Design of FW
- Breeding material
  - Beryllium:
    - $^{9}Be + n + 3$ MeV ➔ $2\alpha + 2n$
  - Lead:
    - Pb + n + 10 MeV ➔ Pb + 2n
  - Other material also available

[Sawan, Fus Eng & Des, 2006]

- Tritium breeding potential in a 2m-thick blanket without structure

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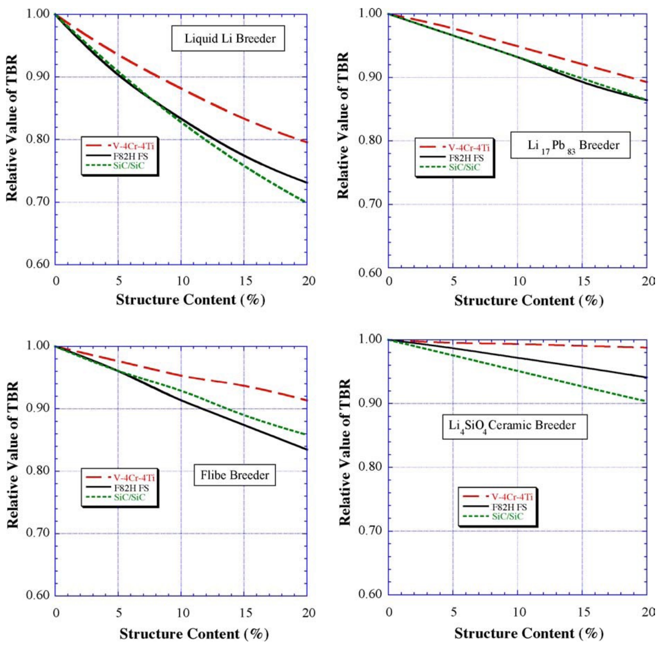
Parameters impacting TBR



- First wall
  - structural material
    - ferritic steels / SiC/SiC / V /…
  - structure content
    - % volume
  - coolant
    - He
  - neutron multiplier
    - Be vs Pb
  - 3D configuration of reactor
    - holes, gaps, …
- Including all constraint / compromises:

➔ max TBR < 1.15

[Sawan, Fus Eng & Des, 2006]

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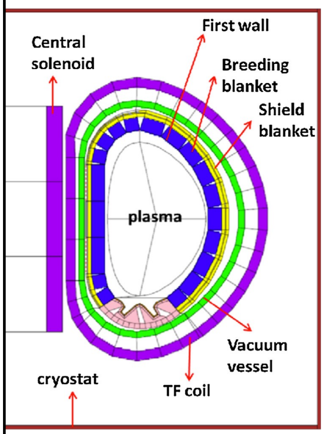
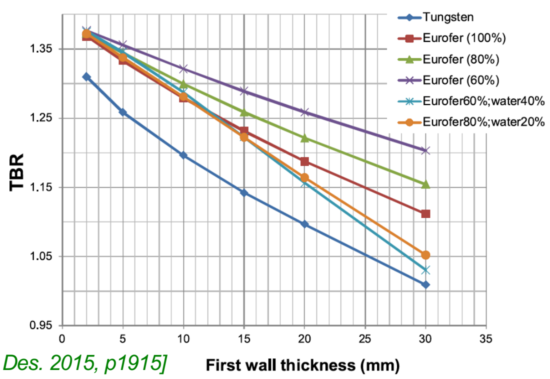
ITER First Wall Design



- Simulations of TBR (HCPB) with
  - First wall thickness (2-30mm)
    - -13% (Eurofer); -16% (Tungsten)
  - Number of equatorial ports
    - Empty ports: -0.5% / port
    - Port with 50% structure: -0.35%
    - Many small ports is better than few large ports
  - Divertor
    - 1 divertor: -11%



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[Zheng, Todd, Fus Eng & Des. 2015, p1915]

European breeding blanket concepts

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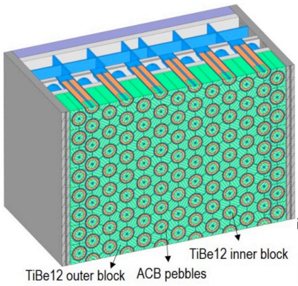
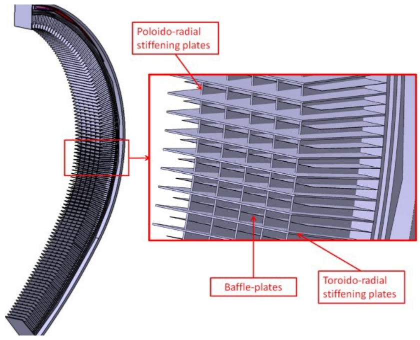
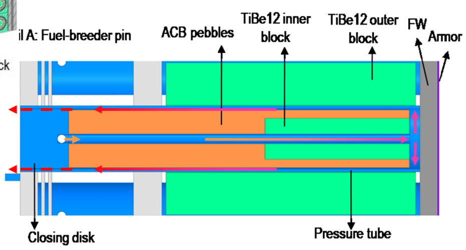
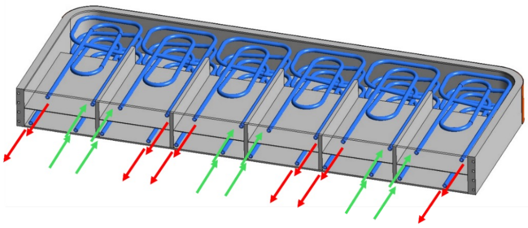
- Helium Cooled Pebble Bed Concept (HCPB)
  - Neutron multiplier: Beryllide ($TiBe_{12}$)
- Water Cooled Lead Lithium Concept (WCLL)
  - Neutron multiplier: Lead (PbLi)









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[EFPW, 2025]

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Tritium Blanket Modules (TBM)

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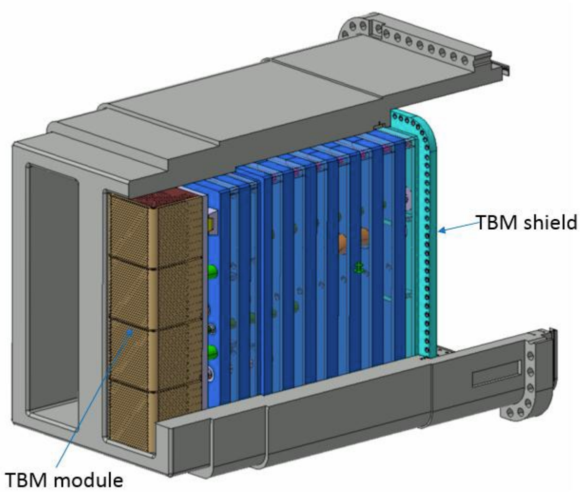
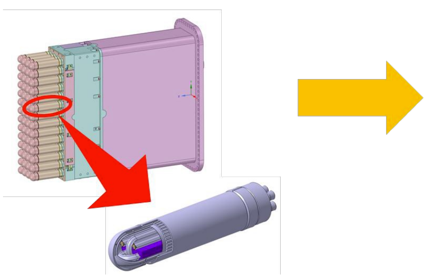
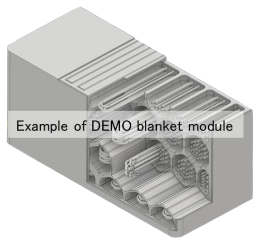
- TBM will be tested in ITER
- Two equatorial ports, each with two TBM







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Comparison Required / Achievable TBR

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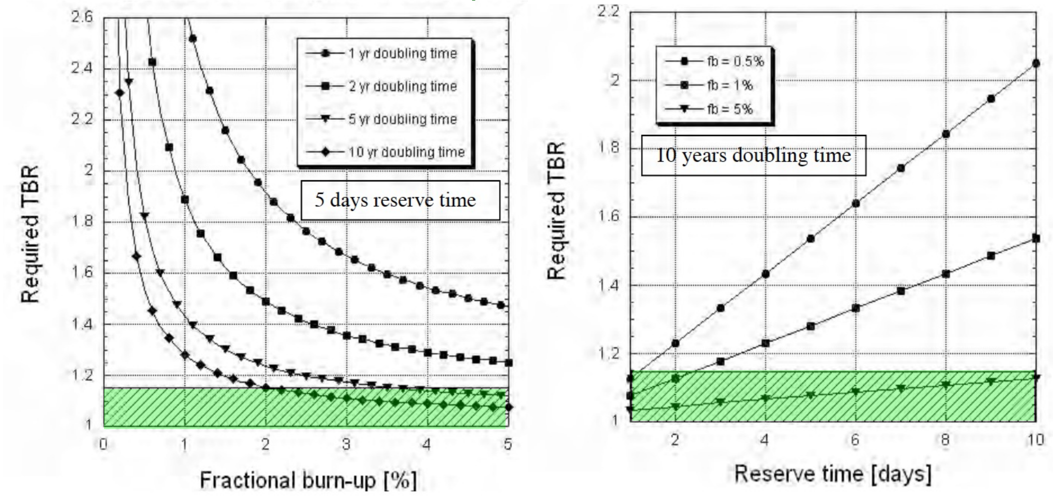
- Dynamics analysis including all discussed parameters
- 'Window' for T self sufficiency



[Sawan, Fus Eng & Des, 2006]

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Comparison Required / Achievable TBR

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- Required: high TBR for T self-sufficiency
  - Depends on burn-up fraction, fuelling efficiency, and fusion reactor doubling time.
- Achievable: maximum of TBR ≤ 1.15

➔ Small window for T self-sufficiency

➔ R&D needs …

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