Loss of Coolant Accident Scenario in ITER and a Possible Solution

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Boundary Science Focus Group Meeting

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- LOCA scenario in ITER (8 VG)
- A possible solution ? (16 VG)

thanks to: C. Skinner, L. Zakharov, D. Johnson, J. Strachan

LOCA Scenarios in ITER

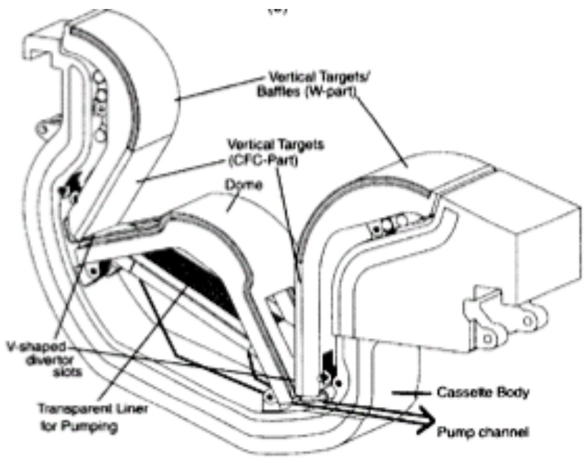
- Main problem is possible cooling water leak into hot vessel
- Could be caused by abnormal plasma termination due to:
    - Loss of electrical power, water pumping, or vacuum
    - Transient events, e.g. disruptions, ELMs, or AEs
    - Unexpected wall erosion during normal operation
    - Defective welds or accumulated metal fatigue
- Extensive documentation and references, e.g. ITER GSSR

General Sequence of Events

- Break in high pressure water cooling lines inside vessel
- Water influx into hot vessel causes a "steam explosion", chemical explosion (e.g. steam + Be), and/or a dust explosion (with any oxygen)
- "While the in-vessel coolant leak events could cause substantial damage to components of the vacuum vessel, off-site [radiation] releases remain small" (GSSR VII ES)
- Recovery from a severe LOCA may be difficult (can not find any information on how this would be done)

Possible Sources of Water Leak

- Divertor plates cooling lines only ~ 2 cm below surface
- Expect tile surfaces to erode and need to be replaced
- Similar cooling lines in first wall and blanket modules



Janeschitz NF 2002

cooling lines

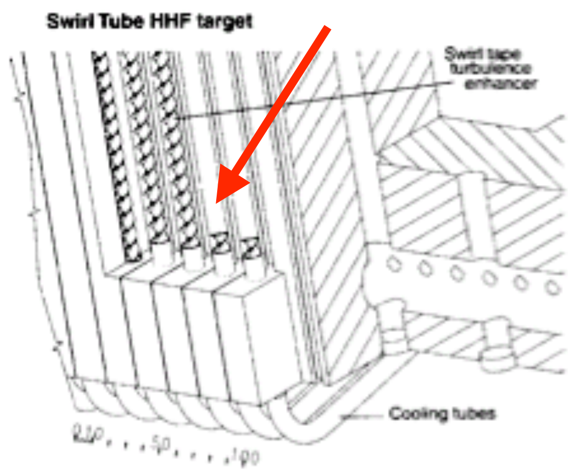


Figure 2. Detail of the reference CFC monoblock swirl tube design (scale in millimetres). The expansion pipes on the bottom and the swirl tape turbulence enhancer inside the tube can be seen.

cassette

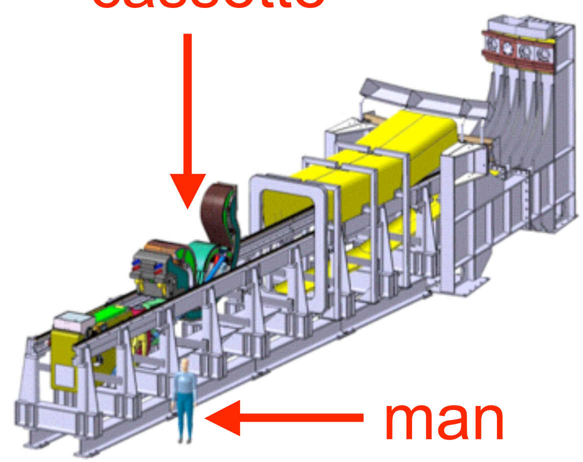


Fig. 2. Global view of the DTP2 facility.

Palmer FED 2007

Available Energy Sources

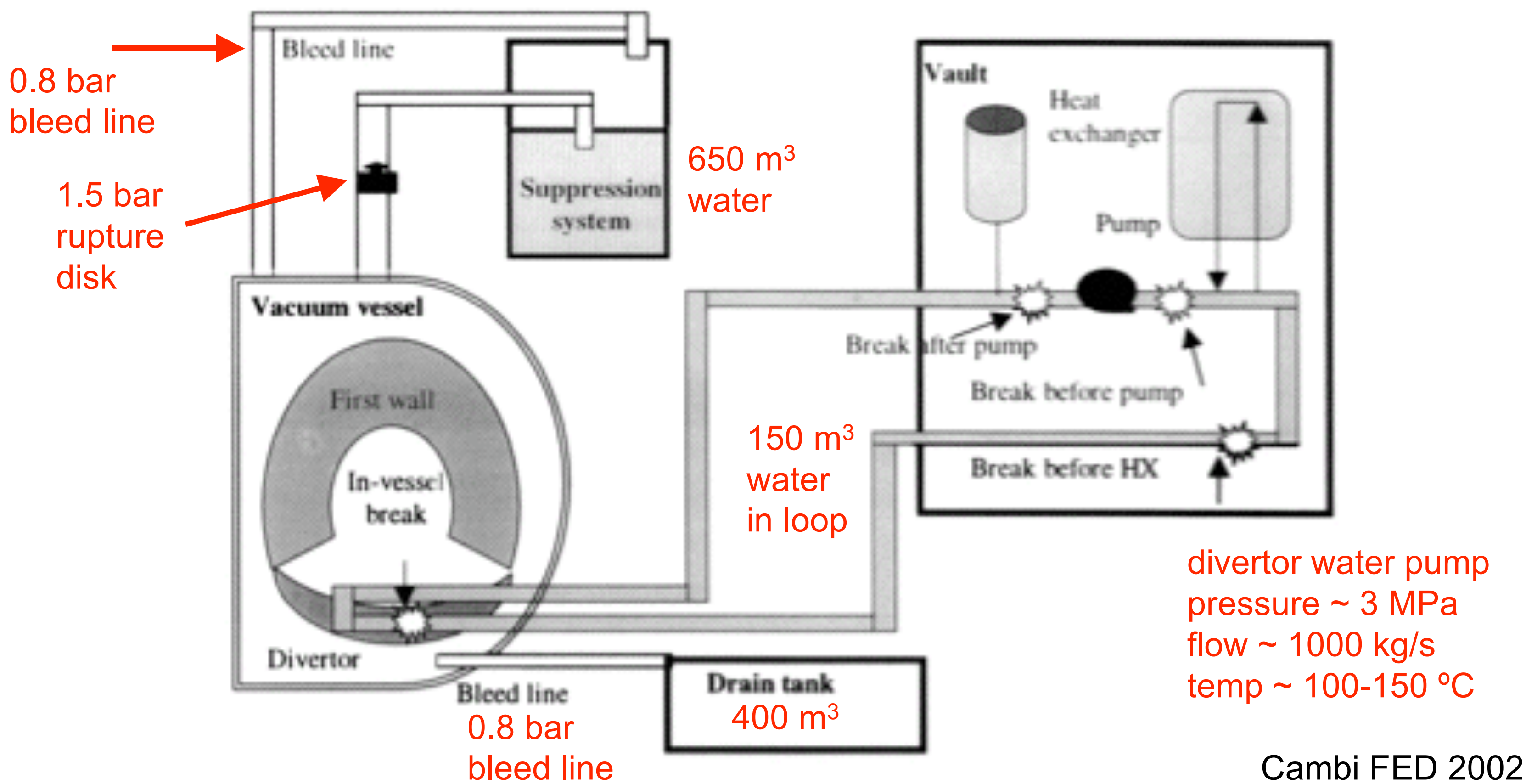
- Stored plasma energy ~ 0.5 GJ (~ 4 gallons of gasoline)
  can vaporize ~ 100 kG of tungsten (~2 cm x 2000 cm^2)
  can vaporize ~ 20 kG of carbon (~2 cm x 5000 cm^2)

- Be-steam chemical energy ~ 500 GJ (maximum available)
  $Be + H_2O \rightarrow BeO + H_2$ + 41 GJ/ton x 13 tons of Be
  H + O explosion in suppression tank is possible
  self-sustained reaction is possible in dust or wall

- Dust explosions ~ ? GJ
  expect 100's of kG of tungsten, carbon and Be dust
  could ignite if there is an air leak into hot vessel
  important source of potential radiation release

ITER LOCA Protection Strategy

- steam pressure in vessel ruptures disk to suppression tank
- water + tritium + dust left in vessel goes into drain tank



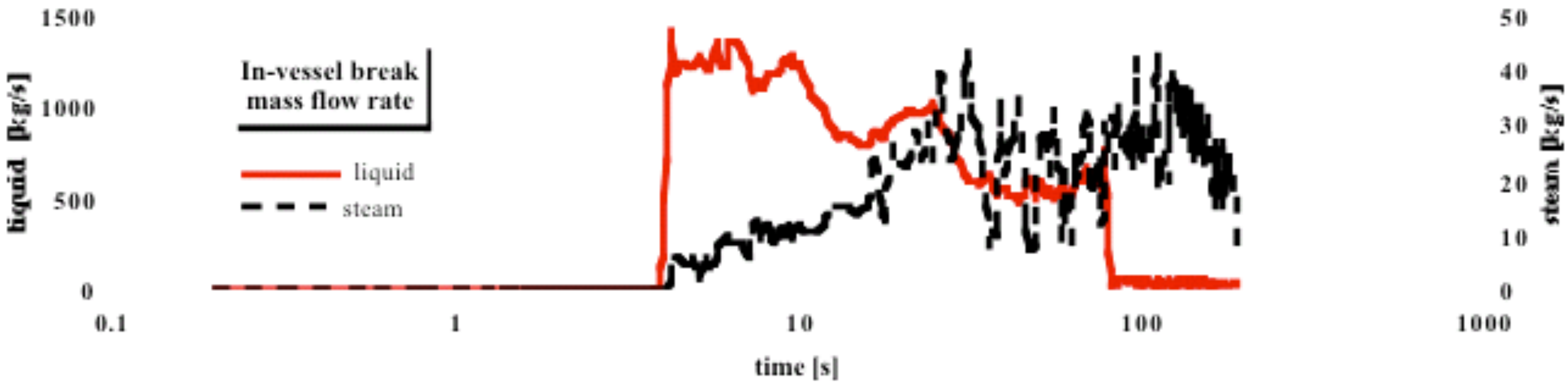
Cambi FED 2002

Fig. 1. Plant scheme and breaks' locations.

Modeling of ITER LOCA

- Various codes used for thermal / hydraulic / aerosol transport + chemical reactions for assumed 'reference events'

- Worst case: ex-vessel divertor coolant leak => starts FPTS => disruption => 0.4 GJ on divertor in 1 sec => in-vessel water leak from 0.3 m^2 break of carbon tiles of divertor => 70 tons of water and 7 tons of steam into vessel



GSSR Vol. VII.3.4.4, Fig. VII.3.4.4-3

Recovery from a LOCA ?

- Investigation of the cause(s)
  - what is the chance of this happening again ?
  - is this really a viable energy technology ?

- Repair / replacement with remote handling
  - one cassette can be replaced in ~ 2 months
  - can vessel and LOCA systems be cleaned ?

- Redesign to avoid repeating the same LOCA
  - might be possible during hydrogen phase
  - very difficult during DD or DT phases

- Possible termination of project
  - may be viewed like TMI or Superphoenix

LOCA Prevention Methods

- Mitigation and/or avoidance of disruptions, ELMs, etc.
  - need to monitor of wall thickness to mm accuracy
  - reduce damage with gas jets, pellet pacing, RMP

- In situ repair of eroded or damaged tiles or walls
  - some work on Be plasma spray (not in plan)
  - possible analogies to space shuttle tile repair

- Redesign of plasma-surface interaction region
  - Use another coolant (e.g. He, liquid metal walls)
  - entirely remove coolant from vicinity of plasma

Moving Divertor Plates ?

Goals:

- avoid LOCA by removing cooling water from vessel
- spread divertor heat load over a larger plate area
- remove dust, tritium, and maybe helium ash

- General ideas (qualitative)
- Estimates of plate parameters
- Additional options and problems
- Comparison with other similar ideas

  (moving belts, cascading pebbles)

Moving Divertor Plates

- Plasma contacts divertor on a set of removable plates
- Plates remain cool for a time due to thermal inertia
- Plates removed for processing and returned like new

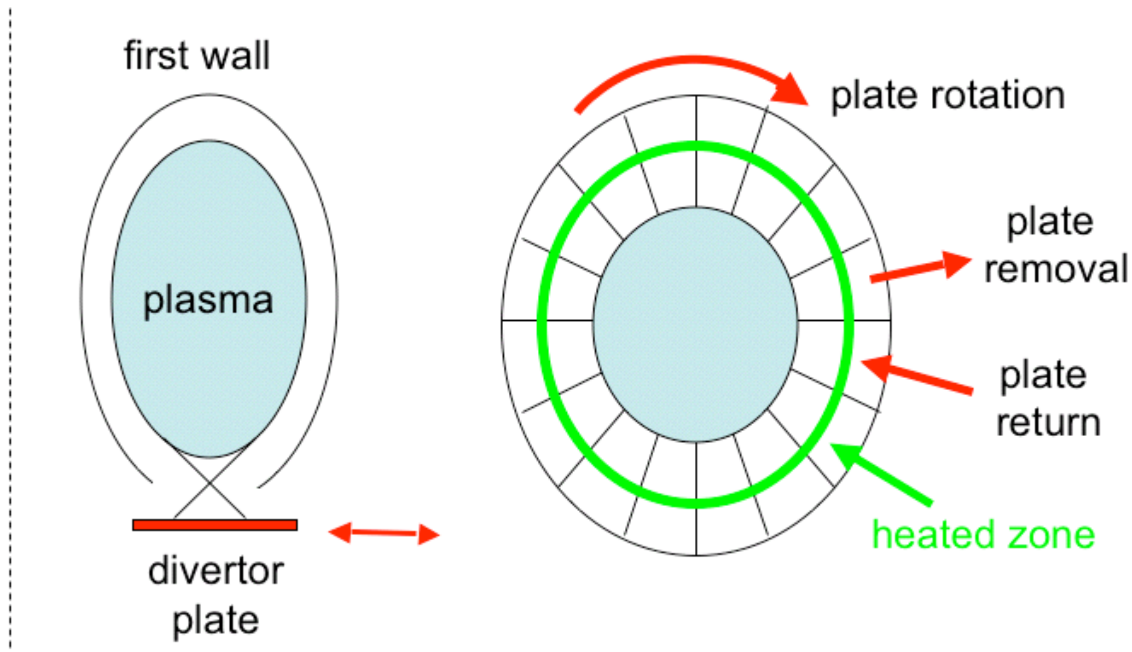


Plate Sweeping in Radial Direction

- Sweep plates in radial direction to use full radial width of plates as thermal sink
- Potentially eliminates high heat flux problem (can sweep fast multiple times if necessary)

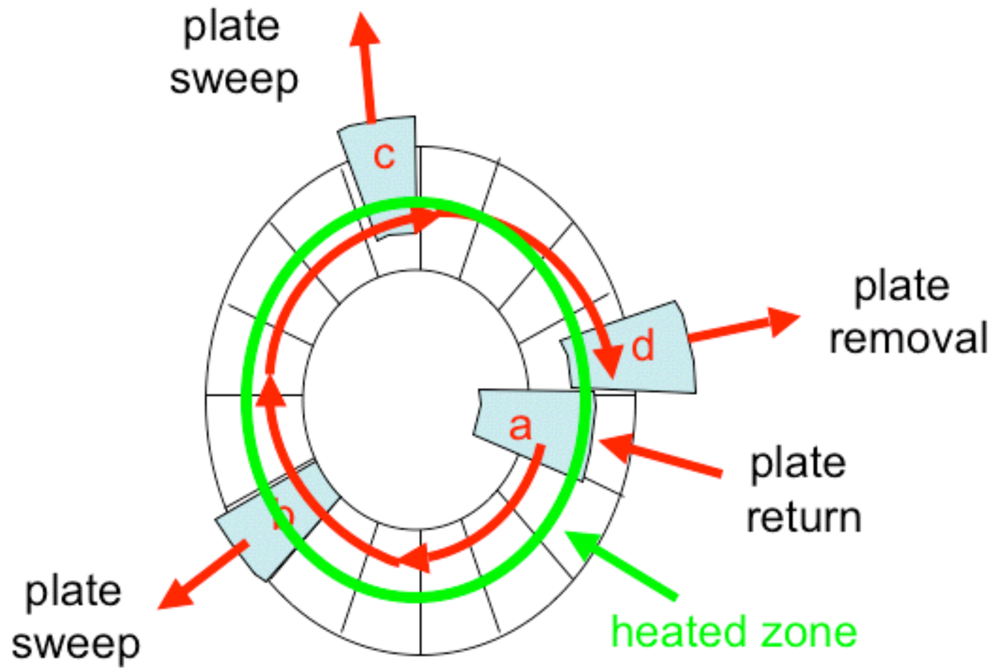
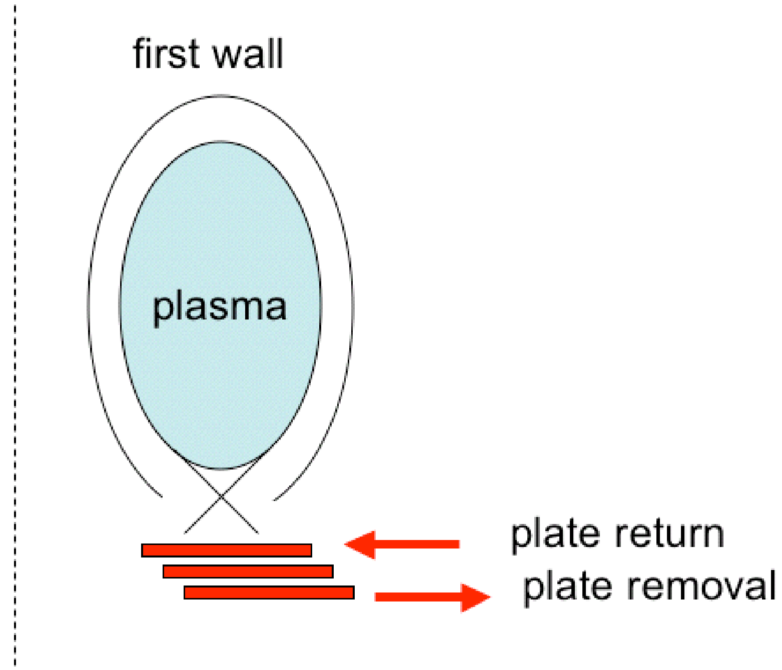
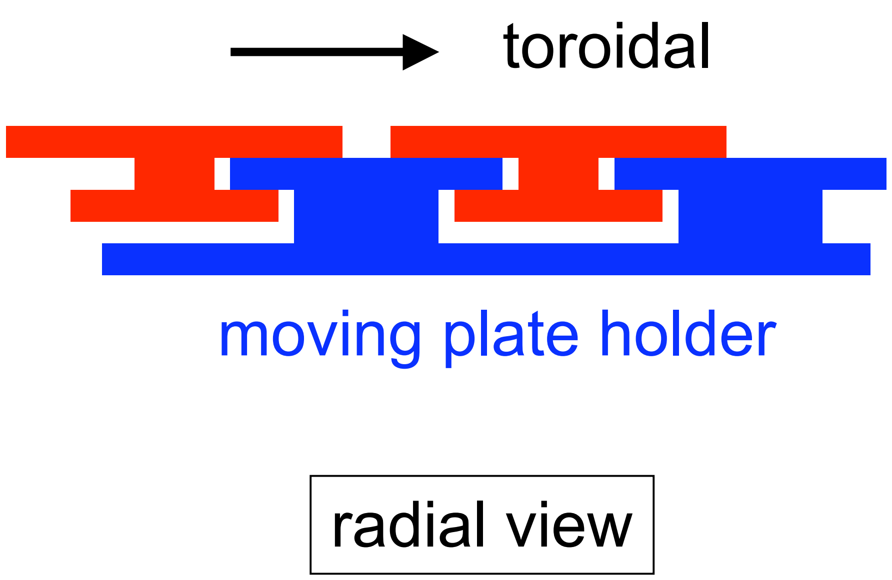


Plate Stacking and Insertion

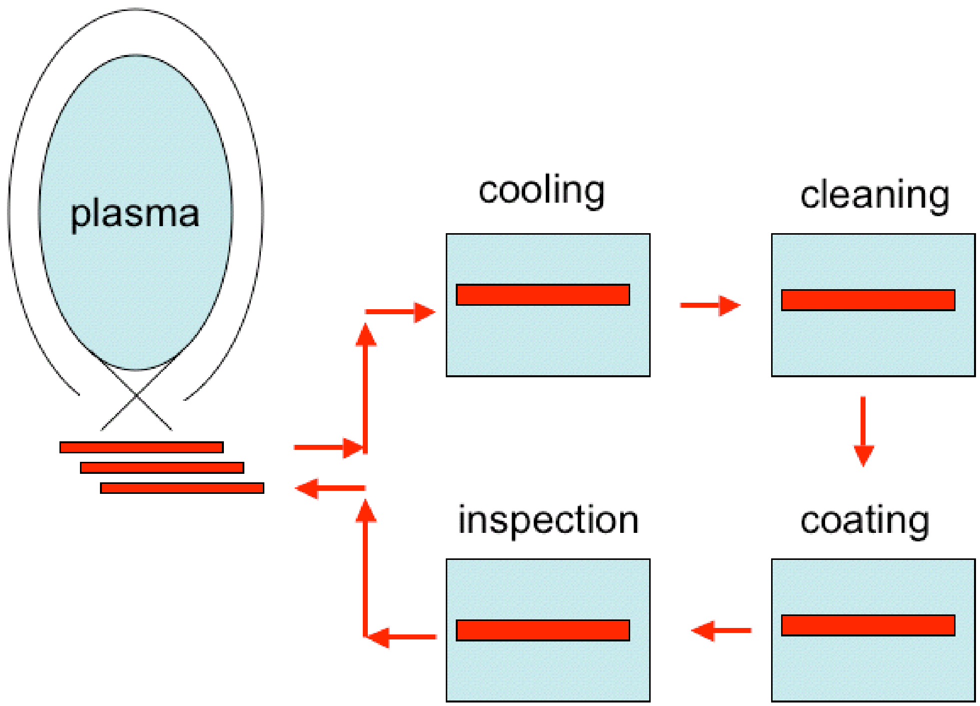
- Plates can be stacked so while one is removed the plasma contact temporarily shifts to the plate below
- Plates can be held in movable carousel or moved on rails





Ex-vessel Plate Processing

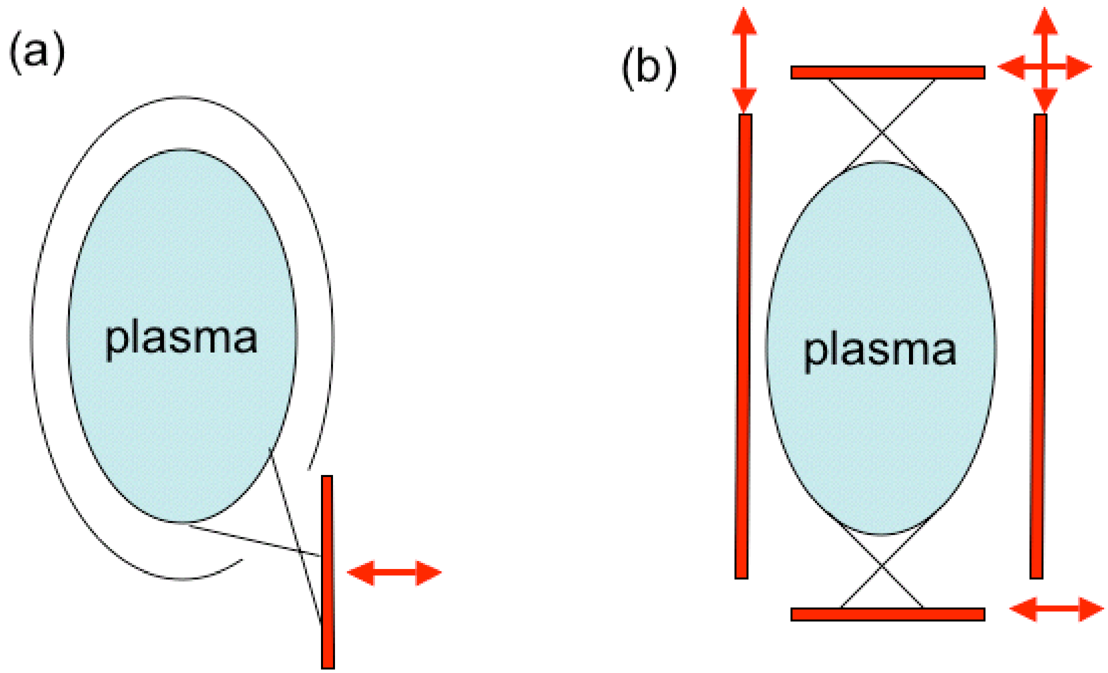
- Plates can be cooled by conduction to a big heat sink
- Plates can be dusted, cleaned and recoated
- New plates types can be substituted



all this
under
vacuum

Alternative Geometries

- Plates can be removed at multiple toroidal locations or at every toroidal location, with no toroidal rotation
- Plate angle, length, or shape could be varied
- Larger coverage of first wall is possible



Simple Model for Plate Heating

- Time τ to heat plate of thickness d with diffusivity χ (cm^2/sec)

  $\chi \sim d^2/3\tau$ [$\chi = \kappa$(W/cm ºC) / c(J/g ºC) ρ(g/cm^3)]

- Average temperature T_{ave} after time τ for heat Q(Watts)

  $T_{ave} \sim Q\tau/c\rho V$ [$V=2\pi Rwd$, w=width]

- Therefore time to reach T_{ave} and thickness for a given T_{ave}

  $\tau \sim T_{ave} c\rho V/Q \sim T_{ave} c\rho(2\pi Rwd)/Q$

  $d \sim 6\pi\chi T_{ave} c\rho Rw/Q \propto$ 1/(power per unit area)

Surface vs. Average Temperature

- For infinite plate with heat flux $Q(W/cm^2)$ for time τ

$$T_{surf} = 2\, Q(W/cm^2)\, [\tau/\pi\kappa\rho c]^{1/2}$$ [Herrmann, EPS '01]

- For this model with $\chi \sim d^2/3\tau$, $T_{surf} \sim 2\, T_{ave}$, independent of heat flux or material properties !

Some Numerical Values

Material properties

material	heat capacity c (J/g °C)	density ρ (g/cm³)	heat conductivity κ (W/cm °C)	heat diffusivity χ (cm²/sec)
tungsten	0.13	19.3	1.74	0.7
carbon fiber	~ 0.7	~ 2	~ 2	1.4
beryllium	1.82	1.85	2.01	0.6

Machine properties

machine	major radius R (cm)	exhaust power P (MW)	P/R (MW/m)
ITER	620	130	21
ARIES-AT	520	370	71
NHCX	100	50	50

Typical Plate Thickness and Lifetime

machine	material	d (cm)	τ (sec)
ITER	tungsten	1.8	1.6
ITER	CFC	2.0	1.0
ITER	Beryllium	2.1	2.5
ARIES-AT	tungsten	0.56	0.15
ARIES-AT	CFC	0.62	0.10
ARIES-AT	Beryllium	0.65	0.23
NHTX	tungsten	0.8	0.3
NHTX	CFC	0.9	0.18
NHTX	Beryllium	0.9	0.5

Assumes for all cases:

$w = 20$ cm

$T_{ave} = 300$ °C

$Q = P/2$

For ITER CFC case:

$\tau \sim 1$ sec
$d \sim 2$ cm

Example for ITER case

- Assume CFC, T_{ave} = 300ºC, w = 20 cm, Q = 65 MW
- If radial sweep ~ 20 cm/sec over ~ 200 cm radial length

=> plate residence time in vessel ~ 10 sec

Parameter	ITER CFC plate
plate thickness	2 cm
plate diffusion time	1 sec
plate radial length	300 cm
plate toroidal length	200 cm
plate mass	750 kG
plate residence time	10 sec
plate speed	1-4 m/sec

For 360º toroidal rotation
toroidal speed ~ 4 m/sec

For 90º toroidal rotation
toroidal speed ~ 1 m/sec

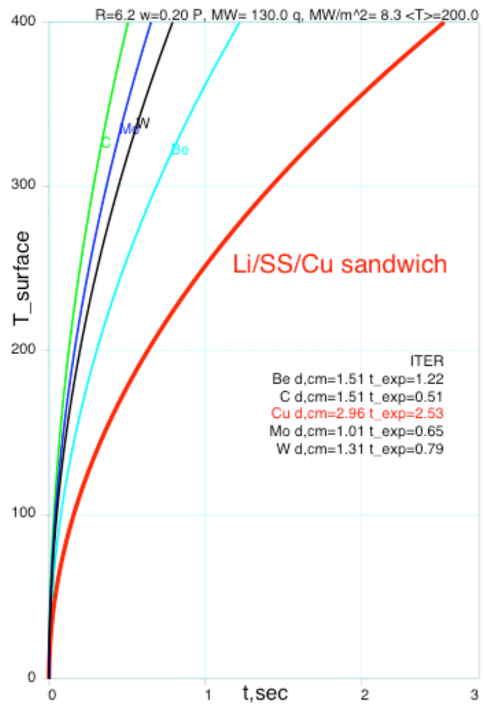
Variation in SOL thickness

- If w=2 cm instead of 20 cm, d ~ 0.2 cm and τ ~ 0.01 sec
- Can handle with radial sweep ~ 2 m/sec over ~ 1 sec
- Over 1 sec sweep, heat will diffuse ~ 2 cm into a plate
- Do ~ 10 radial sweeps to fill 2 cm plate over ~ 10 sec
- Possibly could use a thicker plate for a longer time

=> Ideally, both radial and toroidal plate speed could be controlled independently based on plate temperatures

Additional Options

- Plates can be 'sub-cooled' to increase thermal capacity
- Plates can carry a surface designed to melt, e.g. lithium
- Plates with composite structure to improve properties



Surface temperature vs. time for Li/SS/Cu sandwich for ITER case (Zakharov)

Potential Problems

- Thermal stresses
- Transient heat loads
- Multiple divertor strike points
- MHD forces - normal and disruptive
- Plate mechanically stuck in vessel or processing plant
- Vacuum incompatibility of vessel and processing plant

Comparison with Similar Ideas

moving belt divertor

belt ~ 1 mm thick @ ~ 5 m/sec

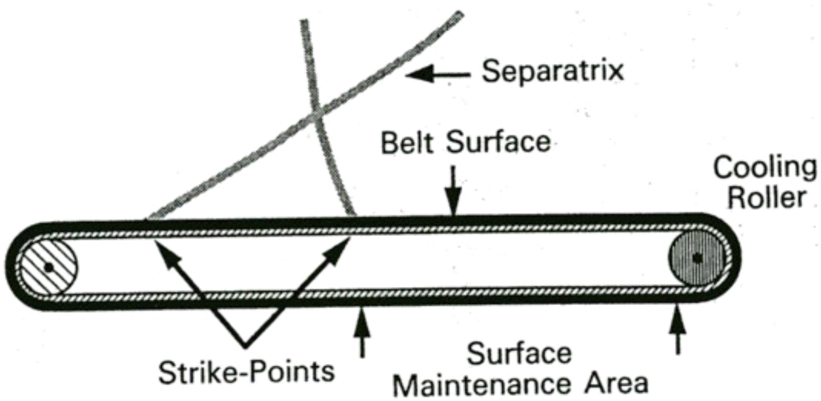
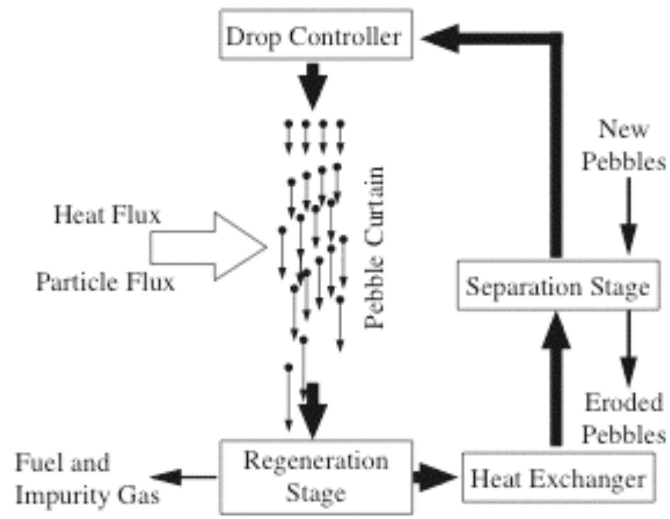


Fig. 2. Divertor belt.

Snead Vesey, Fus. Tech. 24, 83 (1993)
Hirooka et al, Fus. Eng. Design 65, 413 (2003)
Hirooka et al, J. Nucl. Mat. 363-365 (2007)

pebble drop divertor

pebbles ~ 1 mm thick @ ~ 5 m/sec



Isolbe et al Nucl. Fusion 40, 647 (2000)
Matsuhiro et al, Nucl. Fusion 41, 827 (2001)
Voss et al, Fus.Eng. Design 81 327 (2006)

Kazakhstan Tokamak (KTM)

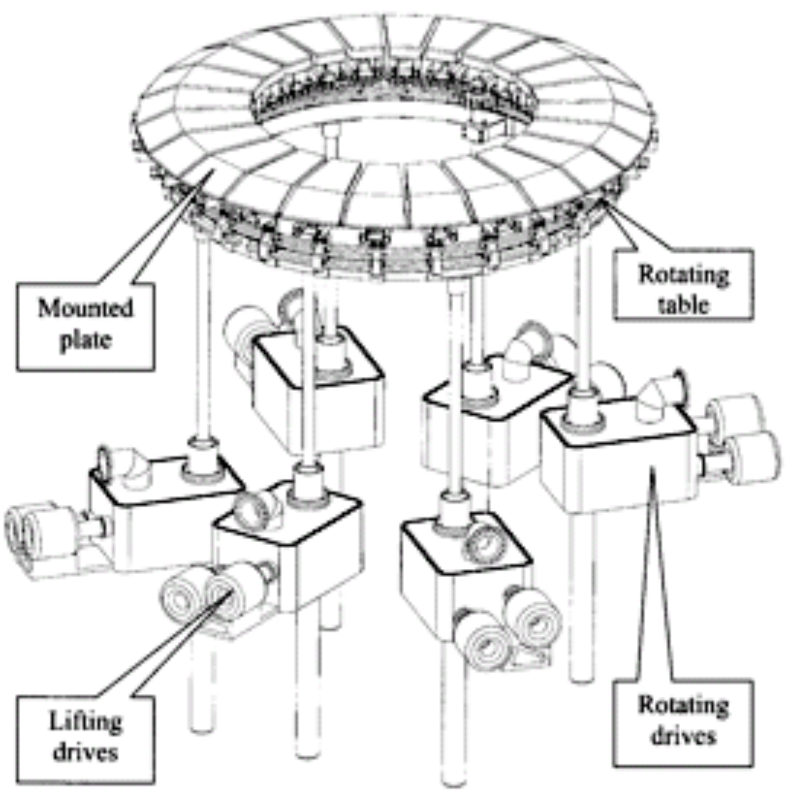


FIGURE 13 Divertor of the KTM tokamak

Azizov Plasma Devices Operations 2003
Tazhibayeva Fus. Sci. Tech. 2005

- Similar to NSTX and MAST
- Focused on testing materials and structures for divertor
- Removable divertor plates on rotating internal table
- External "transport sluice device" for replacement divertor plates without a vacuum break