Moving Divertor Plates in a Tokamak

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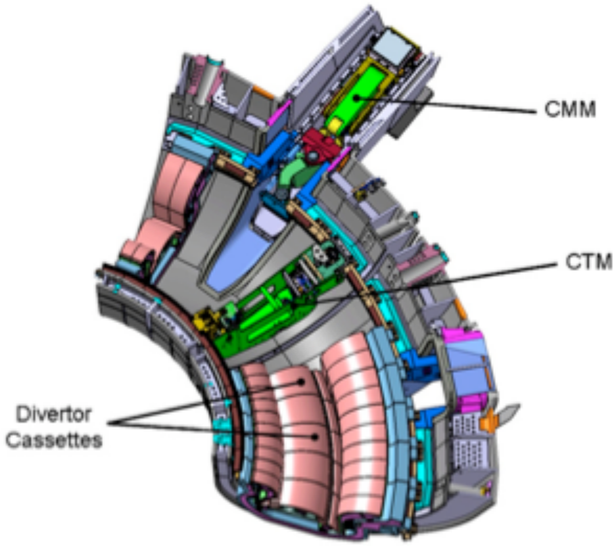
- Moving parts in ITER divertor
- Other moving divertors ideas
- Moving divertor plate idea
- Some potential problems

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

Divertor Cassette Movement in ITER

- Divertor cassettes will be replaced every ~ 3-4 years (?)
- Each of 54 cassettes is 8-9 tons (3.5 m x 2 m x 1 m)
- All remotely handled, e.g. cutting/welding water lines

removal



transfer

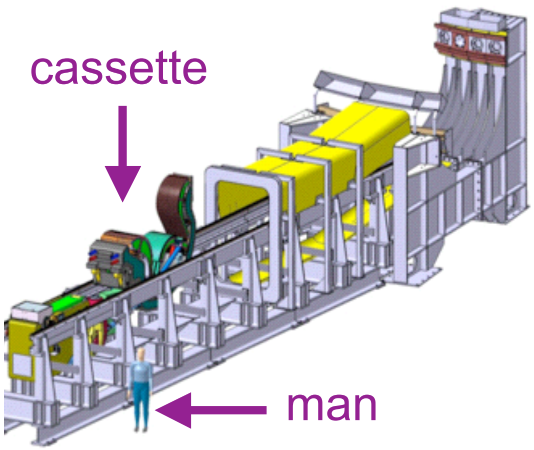
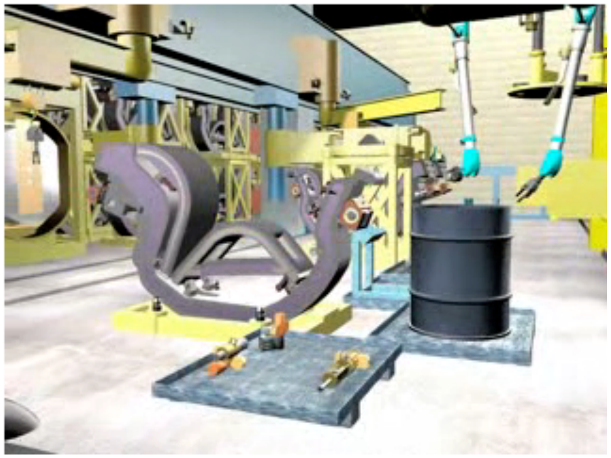


Fig. 2. Global view of the DTP2 facility.

refurbishment



Palmer FED 2007

http://www.iter.org/a/index_nav_5.htm

Divertor Water Cooling in ITER

- 150 m^3 water @ ~1 ton/sec, 3 MPa, 100-150 ºC, 3.7 MW
- Needs major systems to mitigate damage due to LOCA

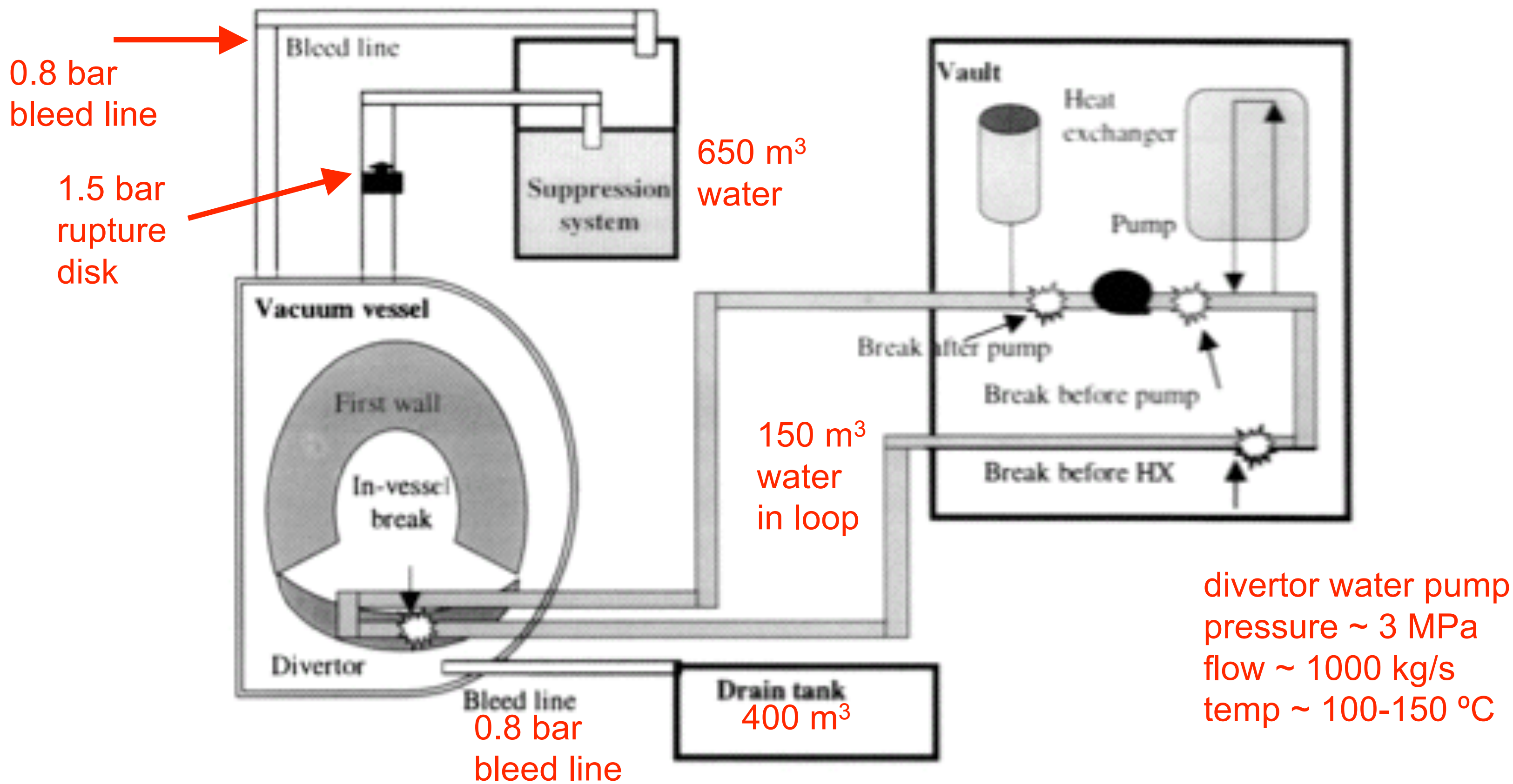


Fig. 1. Plant scheme and breaks' locations.

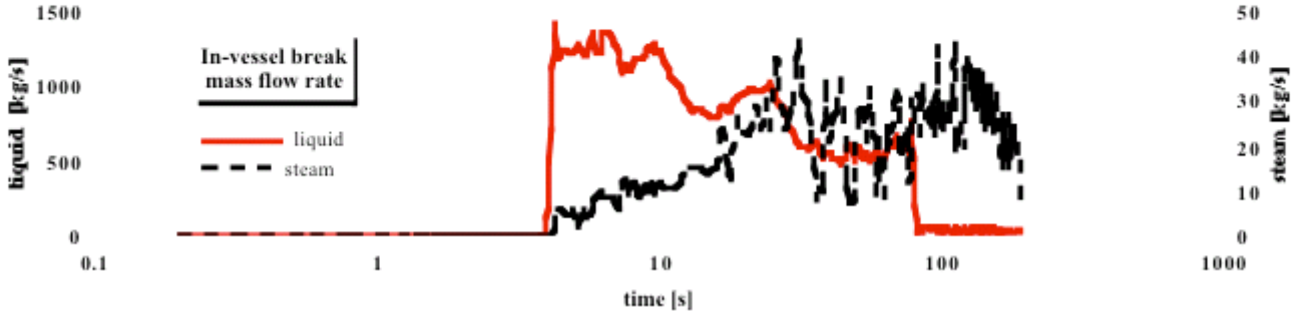
Cambi FED 2002

Modeling of ITER Divertor 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 plus 7 tons of steam into vessel + tritium + Be and W dust => "mixed waste"



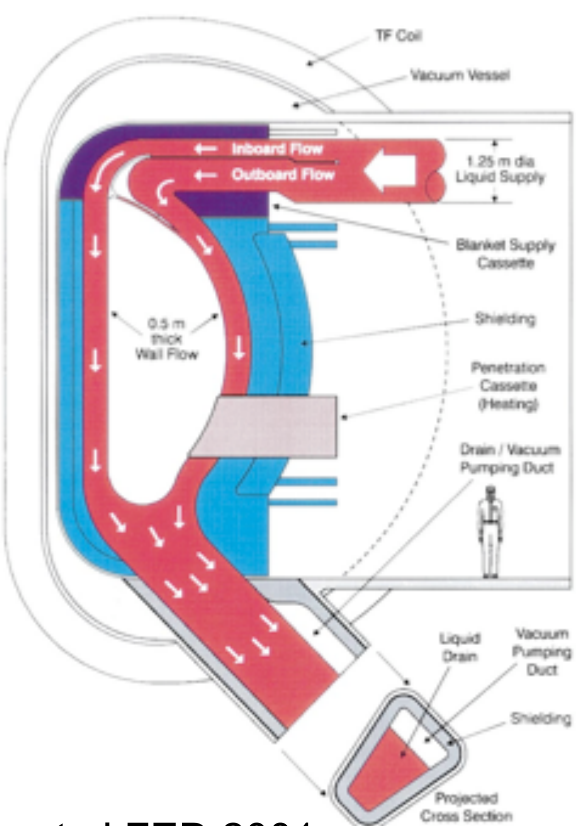
GSSR Vol. VII.3.4.4, Fig. VII.3.4.4-3

Moving Liquid Walls (ALPS and APEX)

thick ~ 0.5 m
@ 10 m/sec

thin ~ 1 cm
@ 10 m/sec

divertor jets
@ 10 m/sec



Abdou et al FED 2001

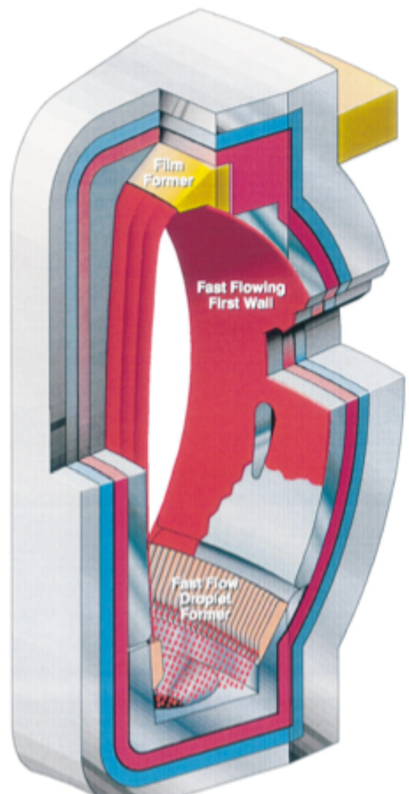


Fig. 24

Table 1
Possible materials, configuration, and confinement options

Liquid species	Li, Flibe, SnLi, Ga
Surface configuration	Fast film, droplets, waterfall, stagnant film, pool, backside impinging jet
Confinement options	Tokamak, advanced tokamak, spherical torus, field reversed configuration, stellerator

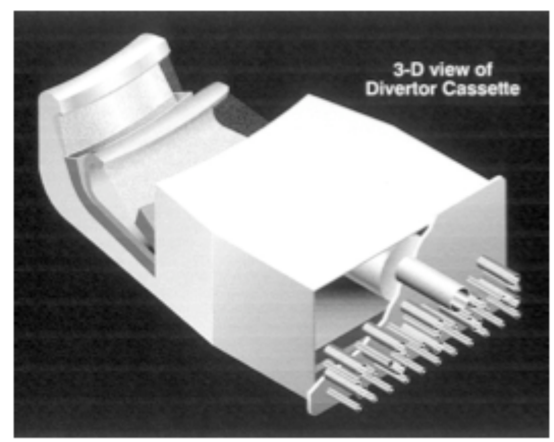


Fig. 1. Example of an advanced liquid surface divertor module.

Mattas et al FED 2000

Moving Belt Limiter and Pebble Drop

moving belt divertor

belt ~ 1 mm thick @ ~ 5 m/sec

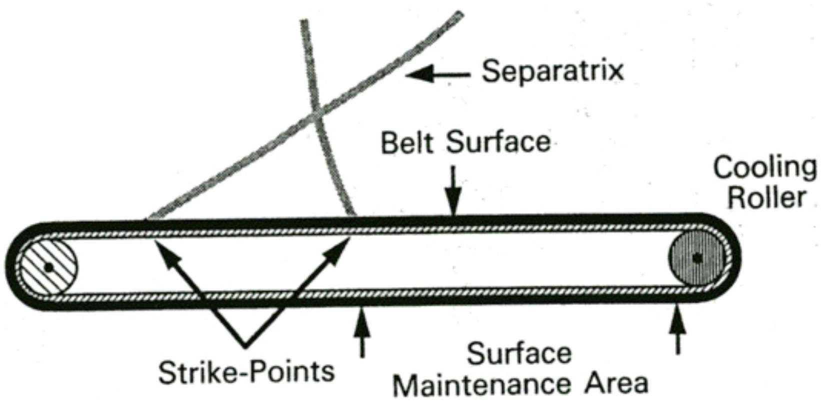
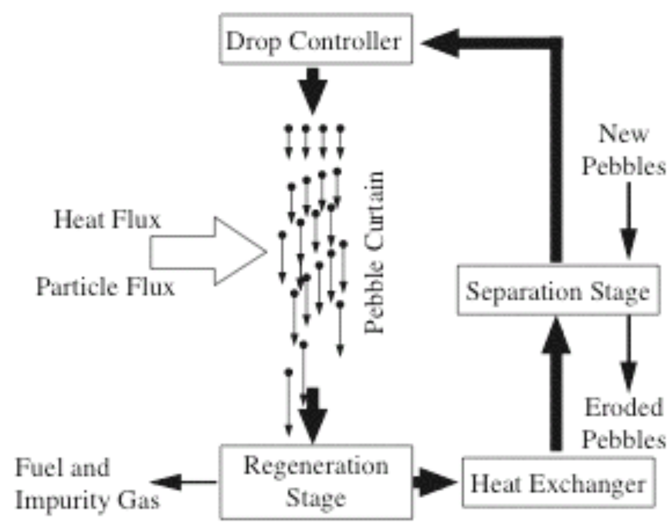


Fig. 2. Divertor belt.

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



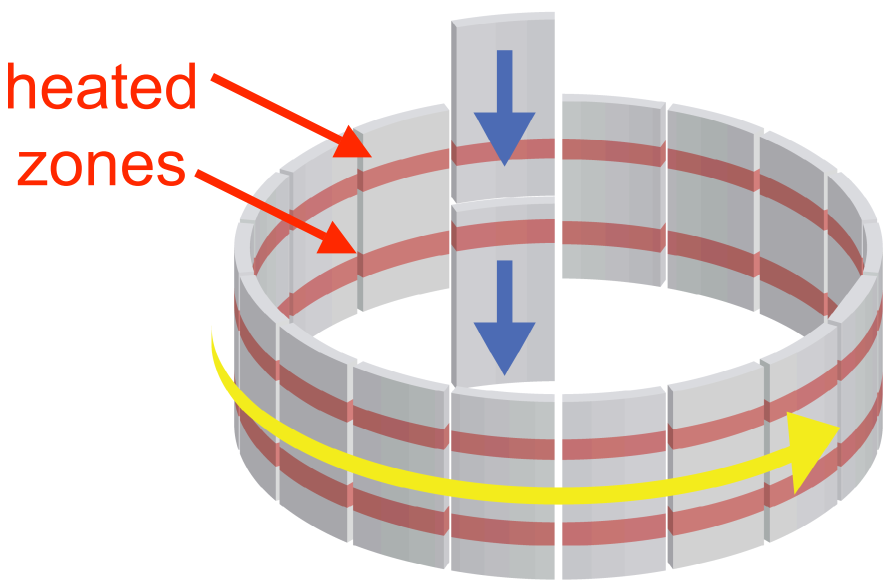
Isolbe et al Nucl. Fusion 40, 647 (2000)
Matsuhiro et al, Nucl. Fusion 41, 827 (2001)
Voss et al, Fus.Eng. Design 81 327 (2006)

Moving Divertor Plates

- Basic idea (pictures)
- Plate parameters (#'s)
- Alternate geometries
- Degrees of Freedom
- Potential Problems

Simple Moving Divertor Geometry

- Plasma contacts divertor on a set of removable plates
- Plates heated locally over thermal diffusion time
- Plates removed for processing and returned



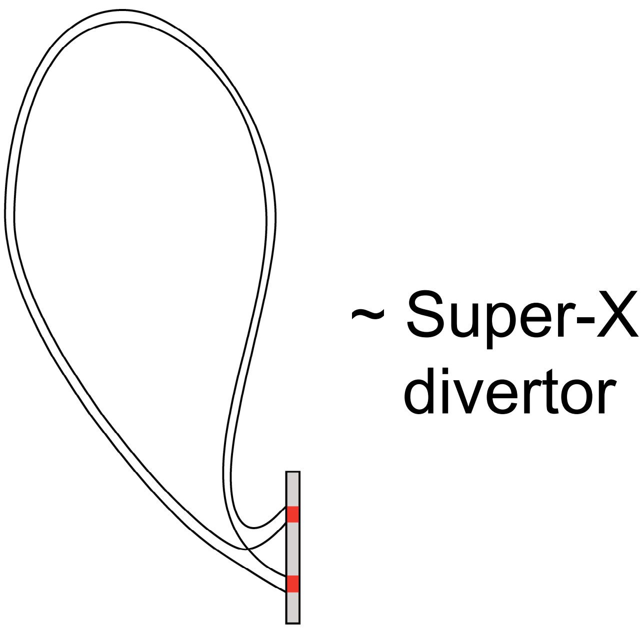
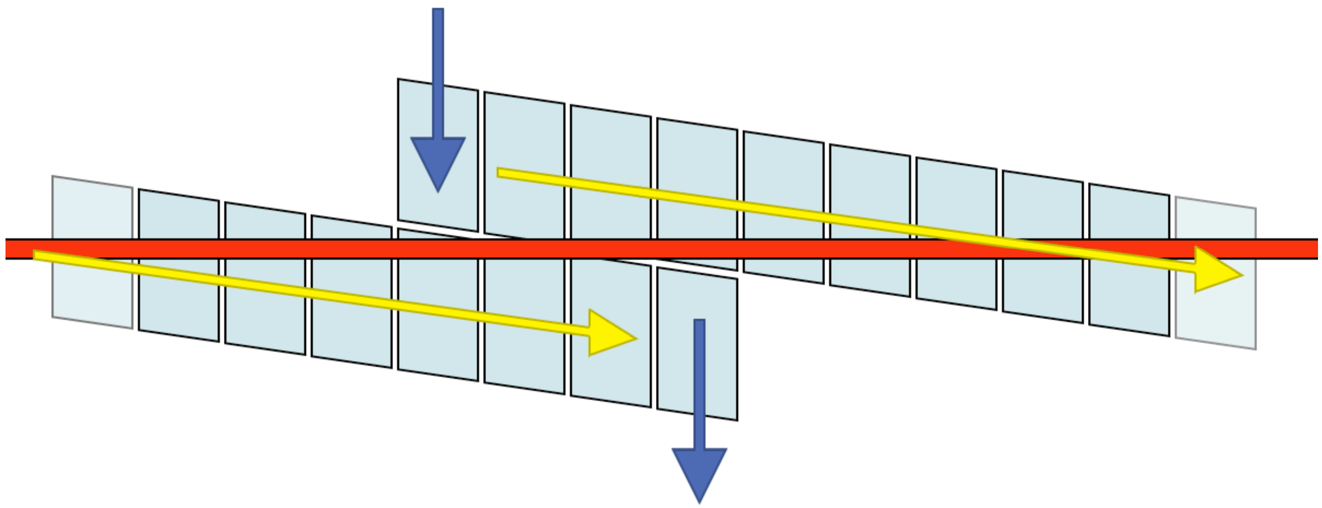


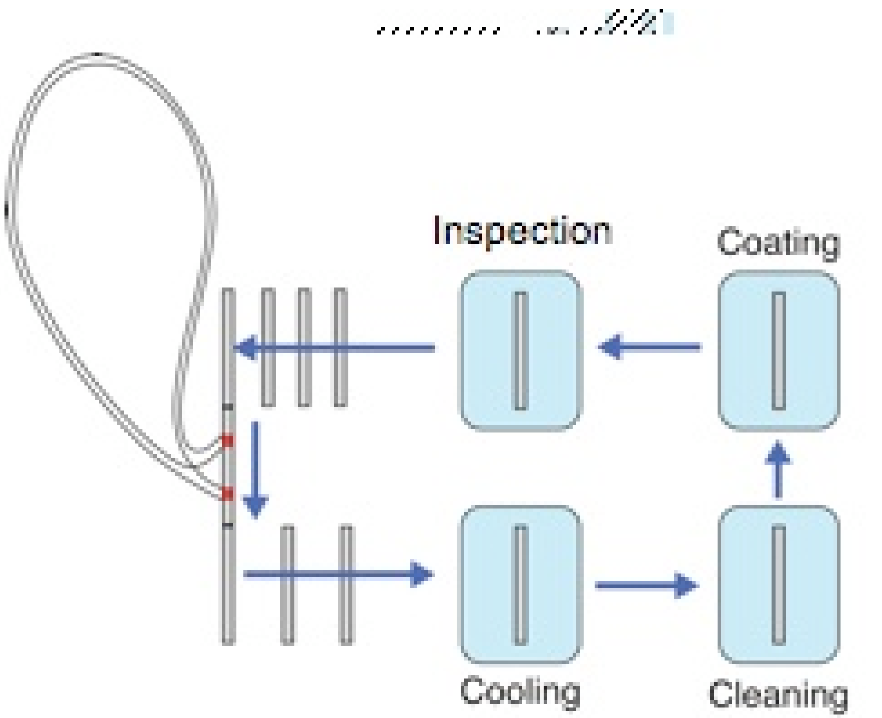
Plate Motion Vertical and Toroidal

- Sweep plates in vertical and toroidal directions to use full height of plates as thermal heat sink
- Sweep speed can be adjusted to keep plate temperature within desired range



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 easily



all this done under vacuum and remotely handled

Simple Model for Plate Heating

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

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

- 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}

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

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

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 Estimates

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

Plate Thickness and Diffusion Time

		T_{ave} = 300 ºC		T_{ave} = 600 ºC	
machine	material	d (cm)	τ (sec)	d (cm)	τ (sec)
ITER	tungsten	1.8	1.6	3.6	6.4
ITER	CFC	2.0	1.0	4.0	4.0
ITER	Beryllium	2.1	2.5	4.2	10.0
ARIES-AT	tungsten	0.56	0.15	1.1	0.6
ARIES-AT	CFC	0.62	0.10	1.2	0.4
ARIES-AT	Beryllium	0.65	0.23	1.5	0.9
NHTX	tungsten	0.8	0.3	1.6	1.2
NHTX	CFC	0.9	0.18	1.8	0.7
NHTX	Beryllium	0.9	0.5	1.8	2.0

Assumes for all cases:

w =20 cm
Q = P/2

For ITER CFC case:

300 ºC	600 ºC
τ ~ 1 sec	4 sec
d ~ 2 cm	4 cm

Plate Parameters and Speeds

Parameter	T_{ave} = 300 ºC	T_{ave} = 600 ºC
plate thickness	2 cm	4 cm
plate diffusion time	1 sec	4 sec
plate width	250 cm	250 cm
plate height	200 cm	200 cm
# of plates in vessel	18	18
plate mass (each)	200 kG	400 kG
plate energy (each)	40 MJ	160 MJ
plate residence time	10 sec	40 sec
vertical plate speed	20 cm/sec	5 cm/sec
horizontal plate speed (360º rotation)	500 cm/sec	100 cm/sec

Assumes for all cases:

ITER power flux
CFC plates
w =20 cm

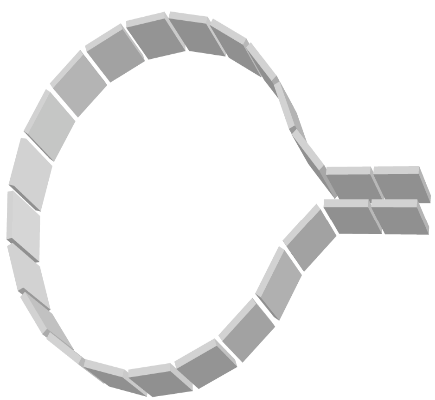
For 360º toroidal sweep:

	300 ºC	600 ºC
T	~10 sec	40 sec
v	~ 5 m/sec	1 m/sec

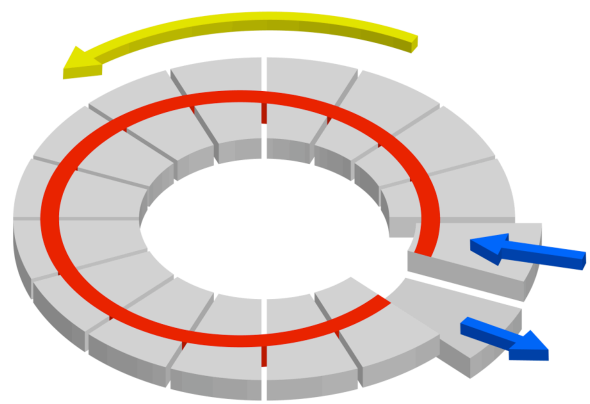
Alternate Geometries

- Could allow gaps in toroidal coverage of strike zone
- Could used curved plates to reduce edge heating
- Other options using shaping, tilting, rotation etc

loop



offset sweep/swap



Other Degrees of Freedom

- Plates can be inserted at multiple toroidal locations to reduce plate speed (but with added machinery)
- Wide variety of plate sizes and/or structures can be tried with the same rails (if designed cleverly)
- Plates surface can be optimized, e.g. with slots or grooves to reduce impurity influx or increase helium pumping
- Could install gas puffing or biasing on plates, recharged every cycle through processing

Some Potential Problems

- Tokamak operation with flat plates
- Mechanical motion in vacuum
- Plate cooling outside vessel
- Thermal and transient stress
- Plate processing

Tokamak Operation with Plates

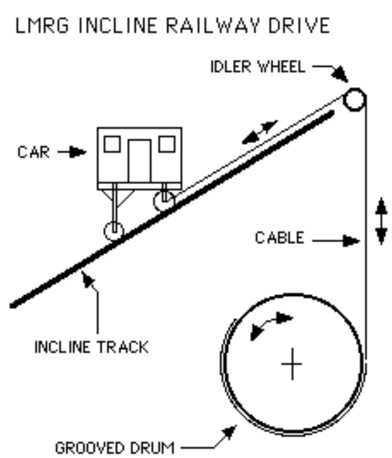
- Magnetic geometry of divertor needs to be modified but this needs to be done anyway (e.g. “Super-X”)
- Effects of “open’ geometry on impurity influx, helium pumping, etc. needs to be tested experimentally
- Possible to use plates as moving “pumped limiters”

Mechanical Motion in Vacuum

- Plates can be mounted on wheels and moved by cables
- Plates can be cleaned and lubricated every ~60 seconds
- Wheels could be motorized as in lunar rover (ca. 1971)

roller coaster

cable car



lunar rover

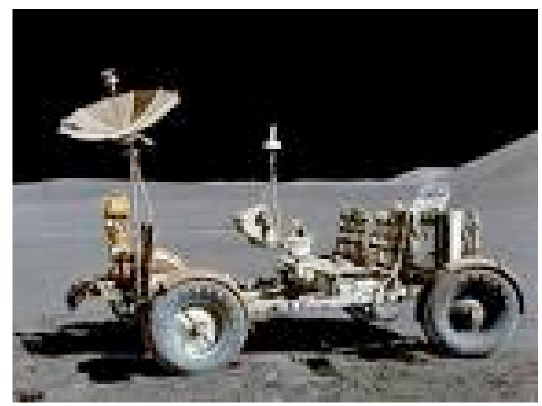


Plate Cooling Outside Vessel

- Plates can be cooled by conduction to cold copper plates
- Cooling times ~10-40 sec, comparable to in-vessel times

time to cool the divertor (divertor final temperature)				
material and initial temperature	one-side cooling		double-side cooling	
	cooling plate temperature		cooling plate temperature	
	80K	273K	80K	273K
tungsten (873K/600°C)	23.5 s (77°C)	39 s (127°C)	12 (27°C)	16 s (127°C) 24.75 (77°C)
tungsten (573K/300°C)	16.5 s (27°C)	32.35 s (77°C)	6.6 s (27°C)	13 s (77°C)
CFC (873K/600°C)	26.5 s (77°C)	39 s (127°C)	11 (27°C)	14 s (127°C) 19.5 s (77°C)
CFC (573K/300°C)	20 s (27°C)	33.5 s (77°C)	6.4 (27°C)	11 s (77°C)
Beryllium (873K/600°C)	30 s (97°C)	39.25 s (177°C)	17 (27°C)	23 s (127°C)
Beryllium (573K/300°C)	22.75 s (27°C)	40 s (87°C)	9.2 (27°C)	18.2 s (77°C)

ANSYS results

1 MPa pressure

0.14 mm Grafoil
for better contact

Thermal and Transient Stress

- ANSYS analysis of maximum thermal strain during cooling gives ~1e9 cycles to failure (tungsten)
- Since plates will be inspected every ~60 sec, any gradual damage should not be a problem
- Disruption loads will be a problem as usual, but any damaged plates can be replaced immediately

$\Rightarrow$ Only damage which would prevent plates from being removed would be a problem

Plate Processing

- More complex RH process are being developed for ITER
- Plates can be dusted and tritium removed every cycle
- Plate coating/structure can be changed easily and often
- Tokamak vacuum isolation from processing can be done with differential pumping chamber or ‘plasma window’
- New plates can be stored in processing chamber to replace worn or damaged plates (plate cost should be low)

Summary of Advantages

- No down time to replace divertor cassettes
- No divertor loss-of-coolant accidents scenario
- Divertor surfaces ‘refreshed’ every minute
- Plate structure design can be changed easily
- Plates more rugged than belts, drops, liquids
- Plate-plasma contact similar to existing divertors

Things to Do ?

- Test options for mechanical motion in vacuum, e.g. lubrication and motors
- Engineering design for large-scale tokamak, e.g. access and remote handling issues
- Limited test on existing tokamak (e.g. one plate sweeping radially during a shot)
- Design small tokamak test facility with moving divertor plates, like Kazakhstan Tokamak

Kazakhstan Tokamak (KTM)

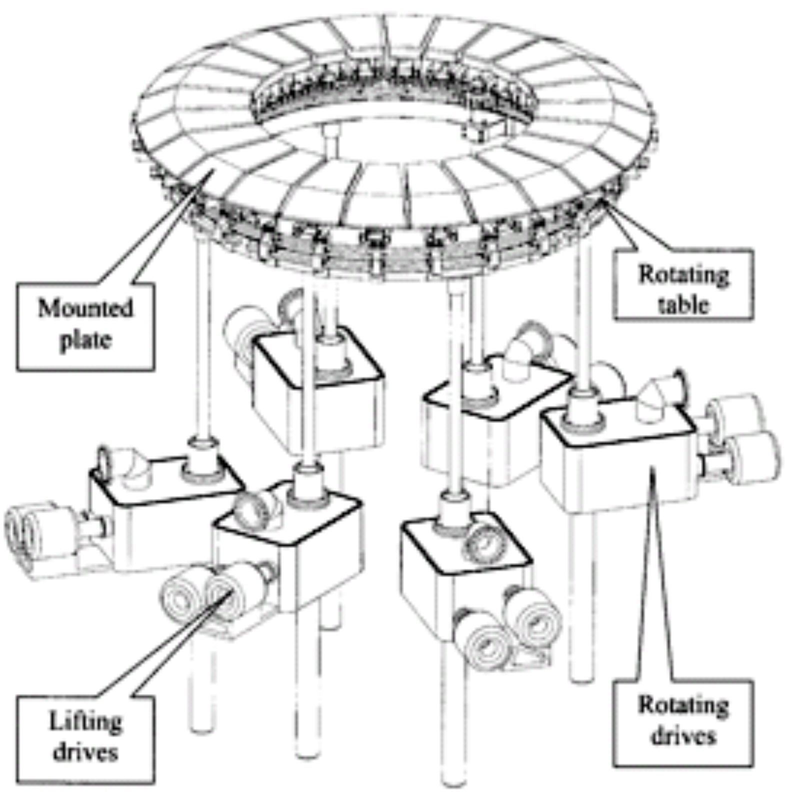


FIGURE 13 Divertor of the KTM tokamak

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