Arc surface damage in fusion reactors

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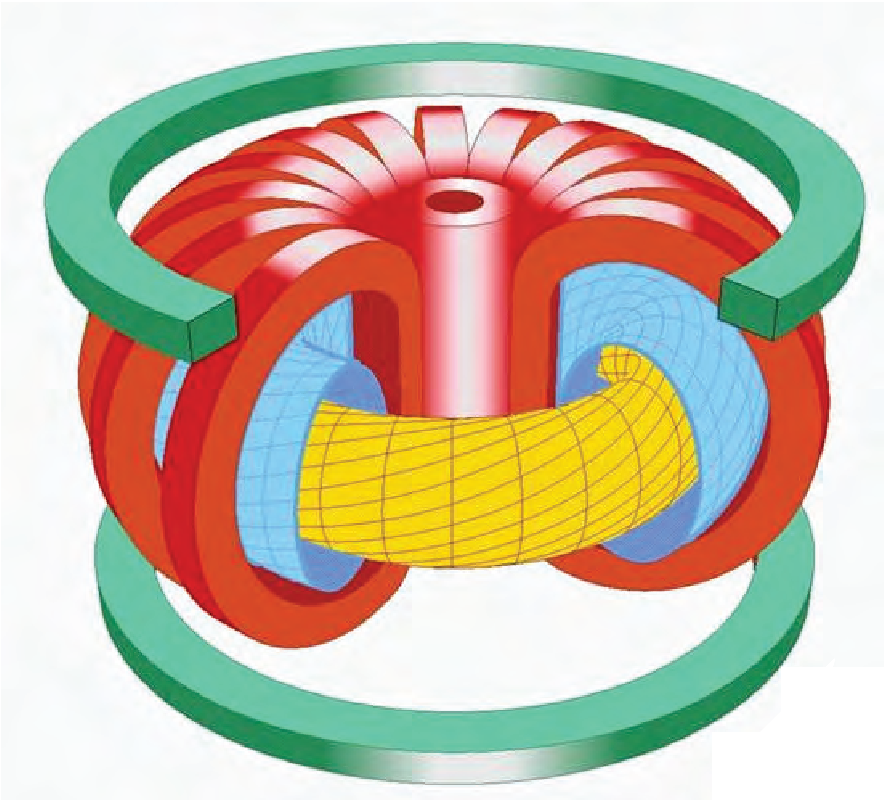
- ASDEX-Upgrade a typical fusion device
- Laboratory investigations
- Arcing events
- Erosion by arc during normal operation

Tokamak ASDEX Upgrade

magnetic confinement



Fusion: $D + T = {}^4He$ (3.6 MeV) + n (14 MeV)

high temperature plasma (25 keV)

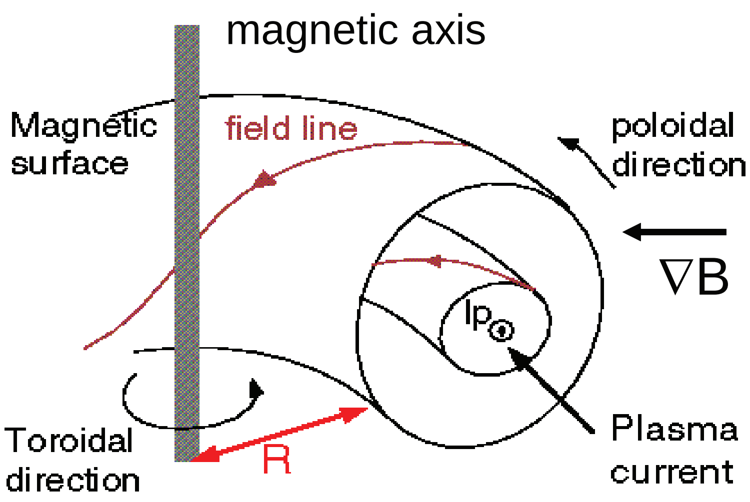
Lawson criterion $n_e T \tau > 6{*}10^{21}$ keV s/m^3

Magnetic fusion:

Ions confined by magnetic fields

toroidal geometry to avoid end losses

∇ B causes drifts, confinement reduced



ions follow field lines

same field lines at low and high B side

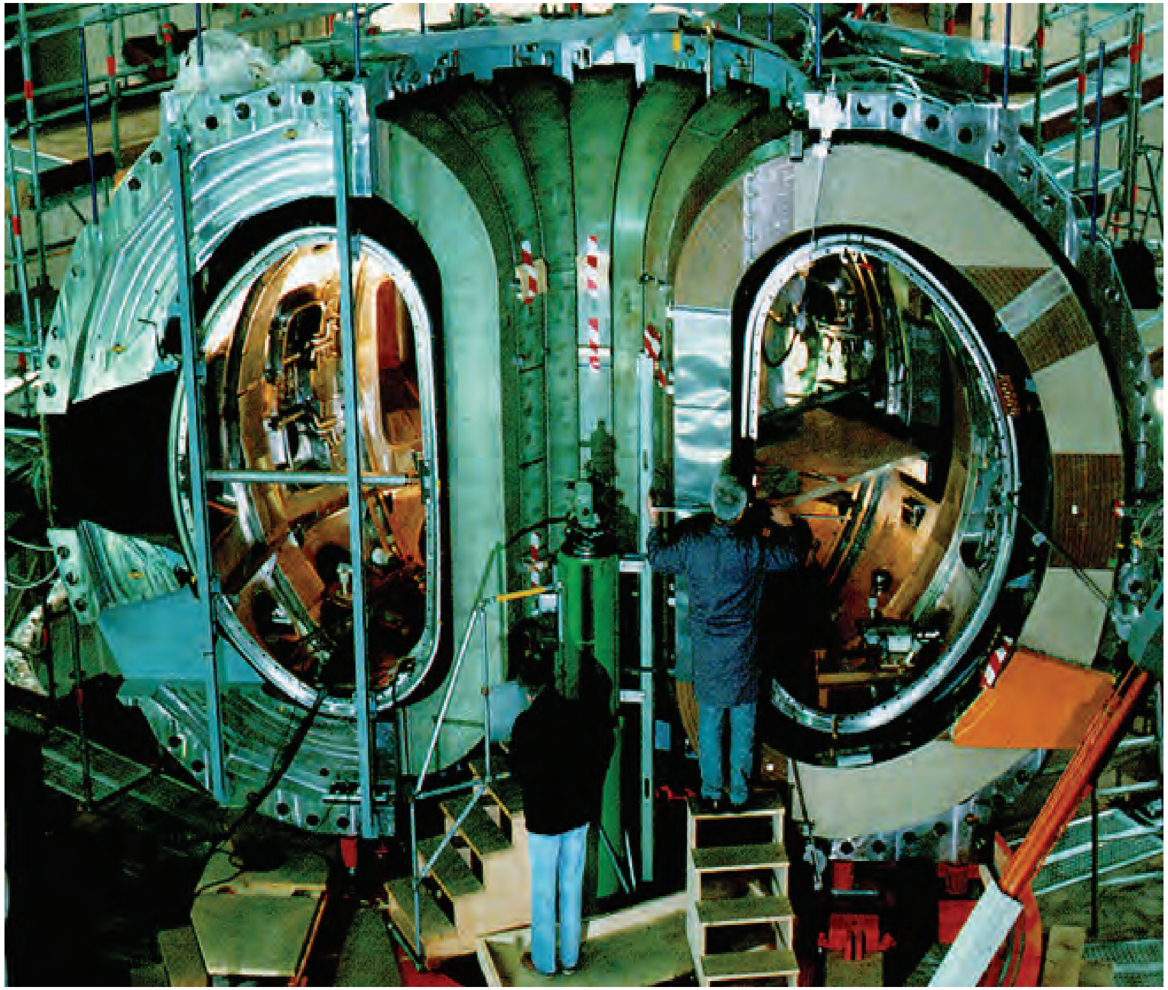
compensates drifts

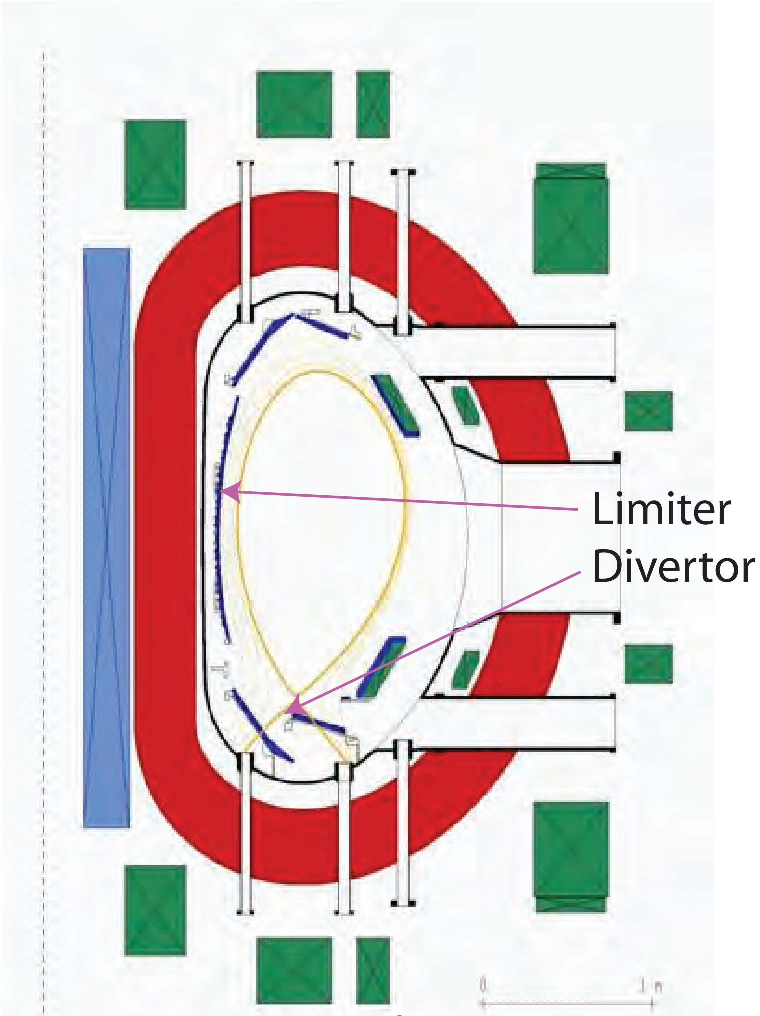
Stellarator: compensation by field structure

Tokamak : compensation by plasma current

Tokamak ASDEX Upgrade

magnetic confinement

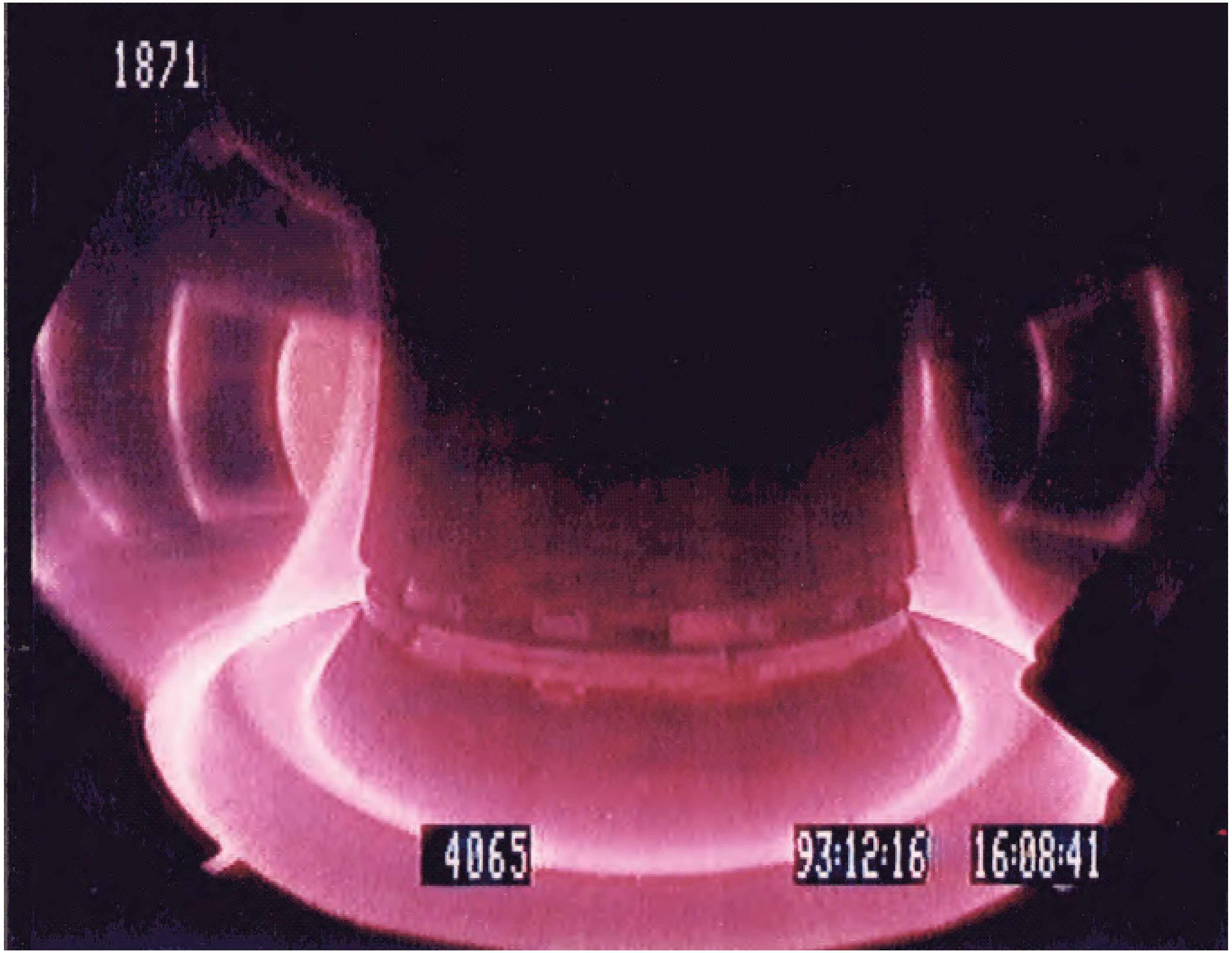




ASDEX Upgrade: a typical mid size divertor tokamak built up 1991 at IPP Garching
non supra conducting, but control coils out side, additional Passive Stabilisation Loop (PSL)
Permanent optimisaton and rebuilt (Divertor, Heating systems, Diagnostics...)
Biggest german, one of the three most important fusion devices world wide.

Tokamak ASDEX Upgrade

Plasma Discharge



Typical H-mode discharge, radiation only inside divertor

Plasmacurrent : 1 MA
Magnetic field : 2.5 T
ion density : 1e20 m^3
ion temperature : 10 keV
discharge lenght: 10 s

heating systems :

20 MW	NBI	(90 kV)
6 MW	ICRH	(37 MHz)
8 MW	ECRH	(100 GHz)

base vacuum <1e-7 mbar
gaspuff during discharge
Gas D2 3l/s

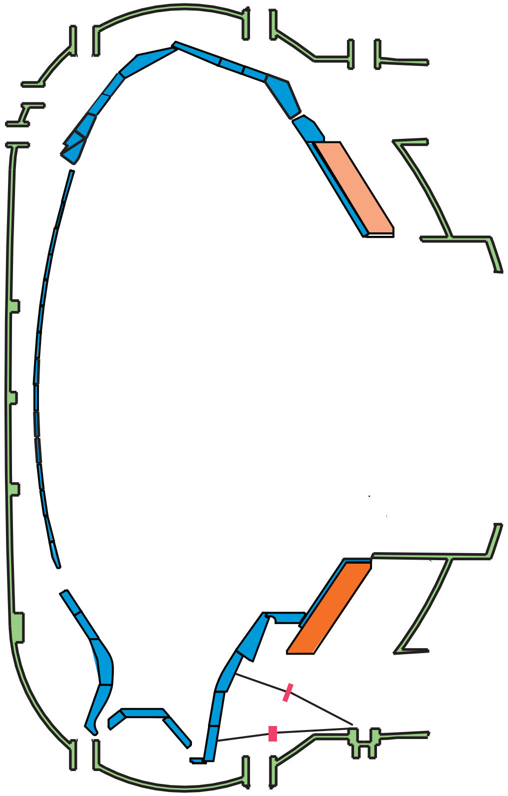
14 TMPs a 2000 l/s
cryo pump 150 000l/s

edge plasma
ne = 1e19 m^3
Te = 1 - 10 eV

Tokamak ASDEX Upgrade

Plasma Facing Components

In vessel view 2008 Plasma facing material: W coating on C tiles



Plasma Facing Components

Fusion devices long experience with Carbon

AUG: W coatings to investigate high-Z PFCs

wall conditioning by Boronisation,....

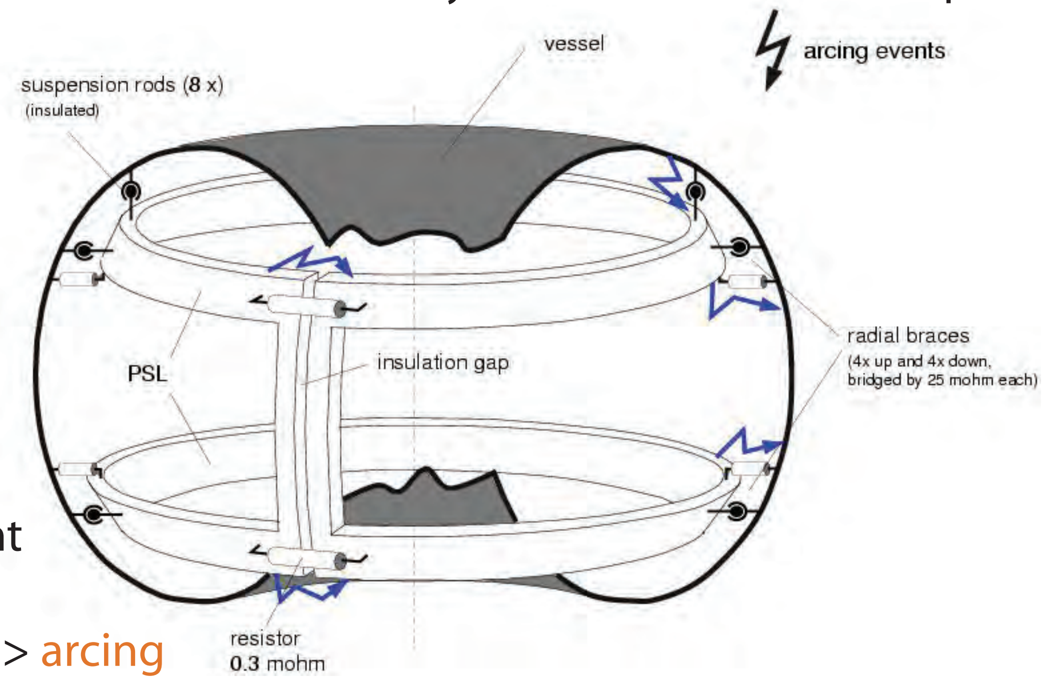
mounted on water cooled SS

structure: stainless steel

PSL Cu

Diagnostics SS

Isolations needed to avoid eddy currents ceramics, Vespel, PEEK



Passive Stabilisation Loop (PSL)
in vessel structure to slow down
plasma movements by Lenz rule.
Current induced by plasma movement
and current changes (disruptions),
higher voltage to vessel components > arcing

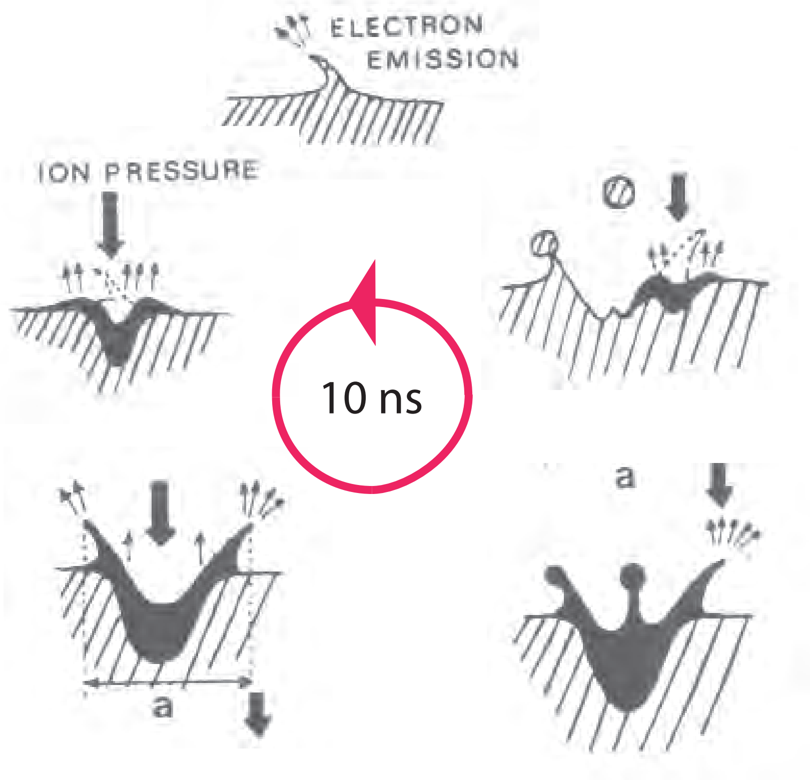
Arc Theory

Laboratory investigations

Publications on arcs are mostly 1970-1985, but they are not completely understood

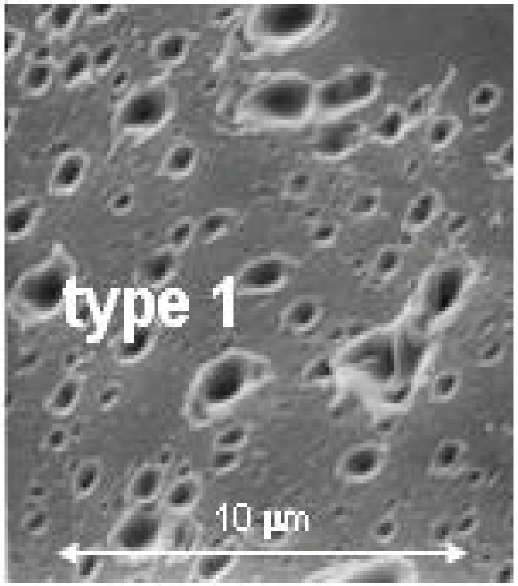
Arc cycle:

(Juettner ,Beitr. Plasma Phys. 19 (1979))

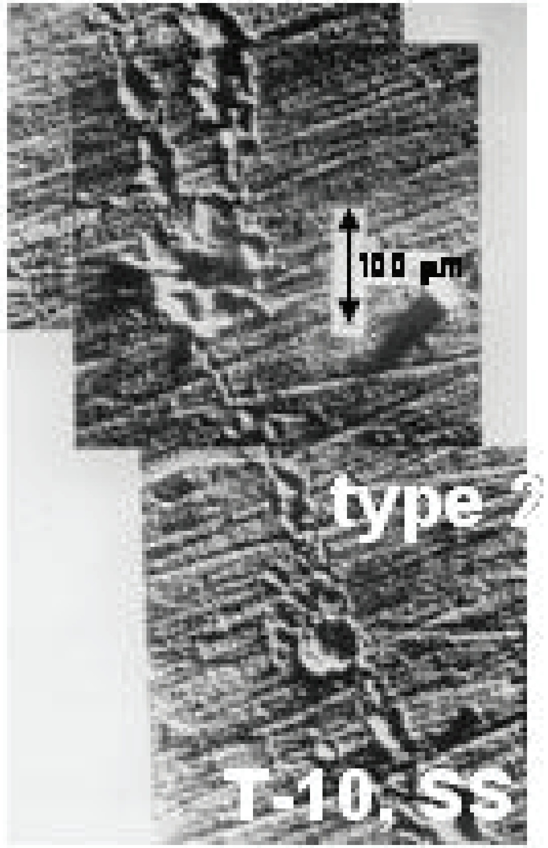


Plasma produced by arc:
$n_e \sim 1 * 10^{26}$ m^3
Te ~ 1-5 eV

Type	I	II
lifetime (μs)	0.01	0.1
current (A)	< 10	5-50
erosion (mg/C)	10	10-100



Arcs produce an dense plasma autonomous from environment



Arc Theory

with magnetic fields

without B field:

random walk

with B field:

in B direction: stable arc

other directions:

arcs move perdendicular

B field: j x B direction

but retrograd movement

different models exists

arc spot releases jets

streamer ignite next arc

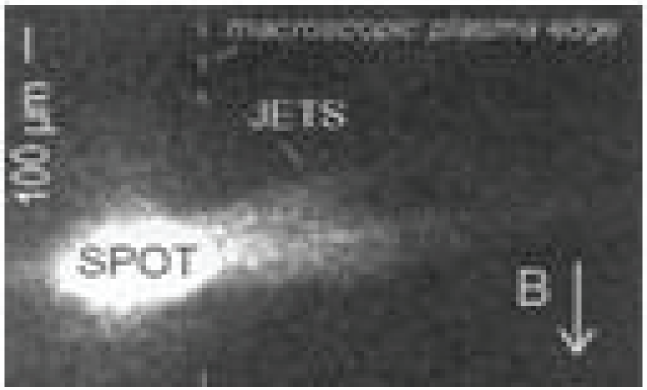
explains small scale zic-zac

Laboratory investigations

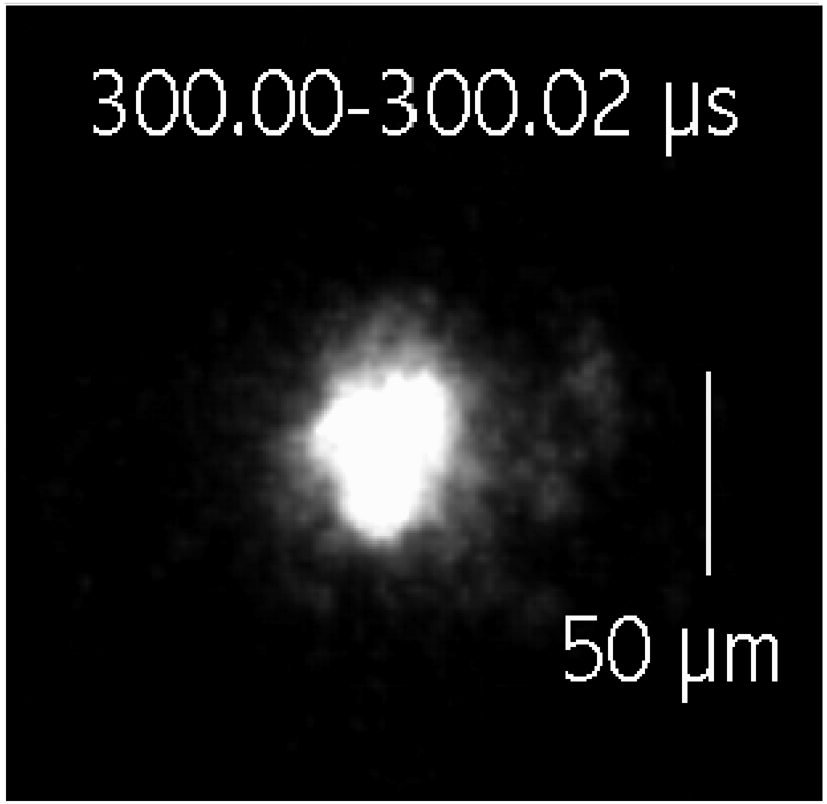
very fast camera: 7 frames

time resolution: 20 ns

arcs are stochastic



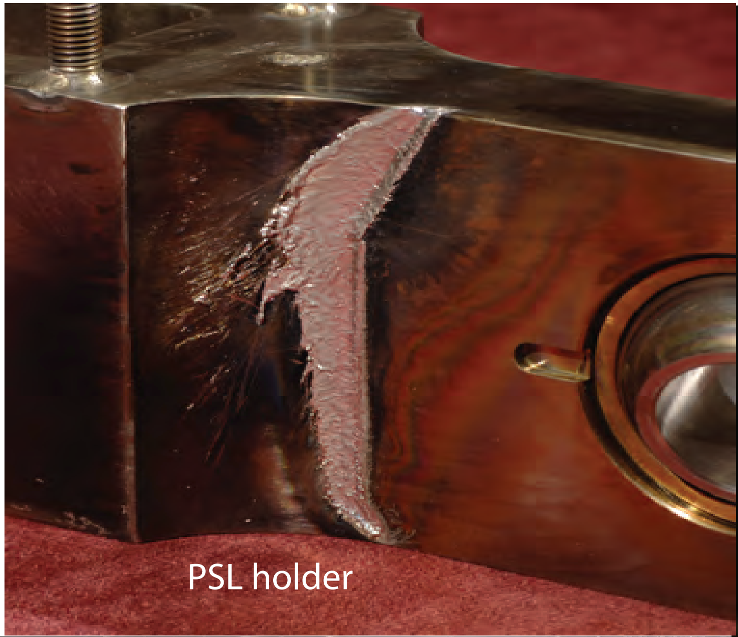
Juettner, J.Phys.D. 34 (2001) R103



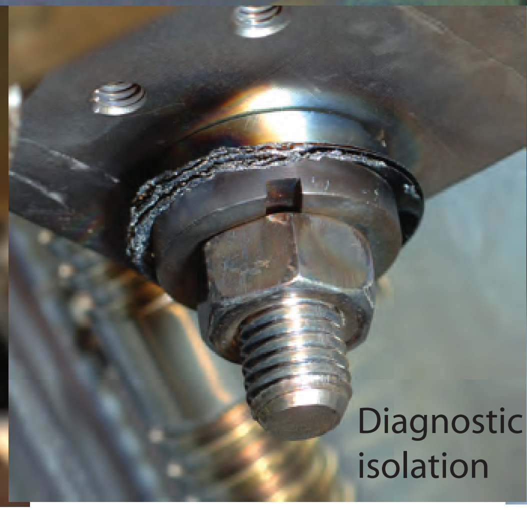
Juettner, J.Phys.D. 34 (2001) R103

Demages by Arcing

Vessel inspection



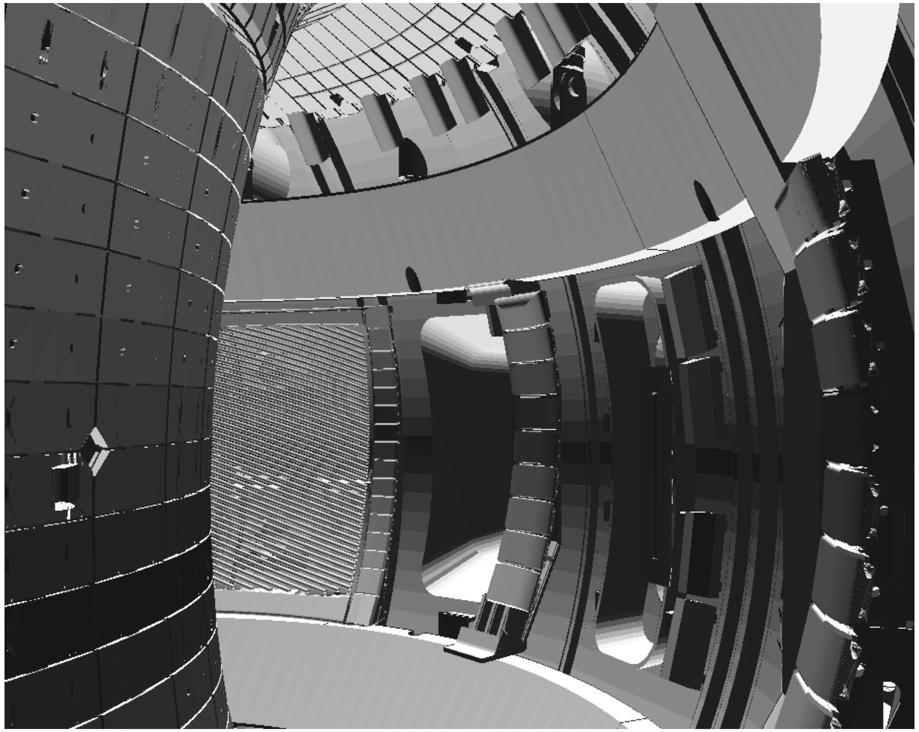
Two kinds of tracs
A: connection in B direction
B: arc traces, perpendicular B



Arcing events

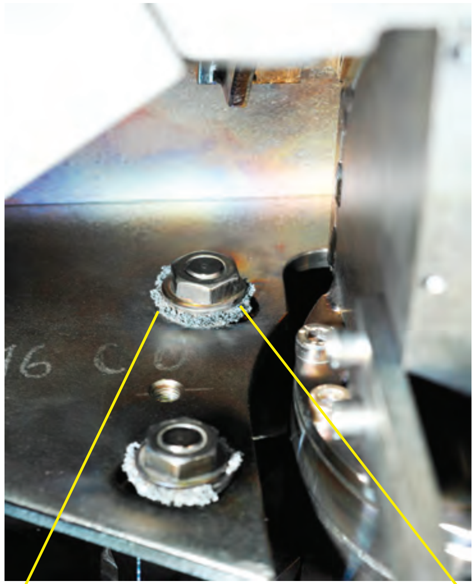
Standard video diagnostic

During plasma operation, impurity events are sometimes observed (~ 1 % of discharges)
events are mostly at the PSL region. Appearance of arcing ist not predictable
1994 many impurity events at the PSL bridge:
PSL voltage reduced by resistors now V ~ > no arcing during normal operation
Arc event observed by video diagnostic
Plasma movement induces currents at PSL > higher voltage > may trigger arcing
Arcing is mostly during instable plasma discharges and may kill an almost dead discharge
Arcing has no significant influence on the plasma operation of ASDEX Upgrade



Arc damages 2009 campaign

avoidance of arcing



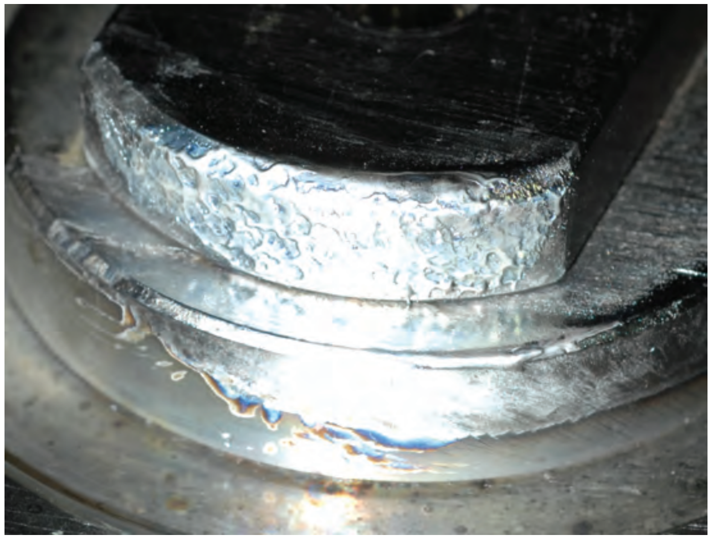
ICRH / PSL corner

Rules to deal with arcs in AUG:

- vessel conditioning (baking, HeGD)
- PSL: 30 mm distance in B direction
  toward all structures
- reduce voltage at PSL below 100 V
  (shunts 250 $\mu\Omega$)
- shield UV radiation from plasma
  (pre-ionisation reduces paschen voltage)
- use carbon, same arcing, but only
  "harmless" impurities released

Isolation S8 Co

Left-over of PSL shunts →



Plasma facing components

material selection

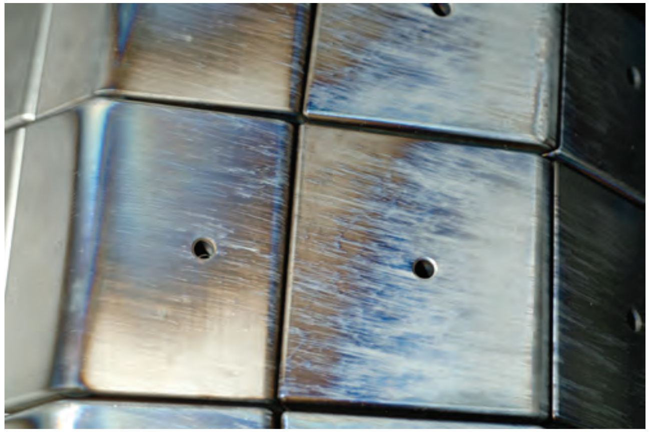
Selection of PFCs of a future fusion device is still under discussion

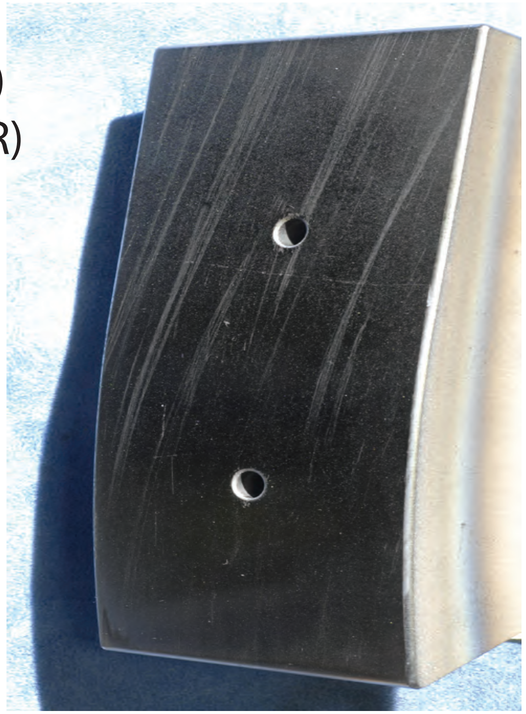
carbon :	low-Z	high erosion	/	low central radiation
tungsten	high-Z	low erosion	/	high central radiation

carbon divertor devices work presently perfect,
but C has to be avoided in ITER due to T codeposition of eroded C

1970: metal PFCs , limiter
1980: graphite PFCs , limiter
1990: graphite , divertor
2000: tungsten , divertor (AUG)
future: Be/W mix , divertor (ITER)

Erosion by arcs neglected for C PFCs
arcs observed for W, is erosion relevant ?

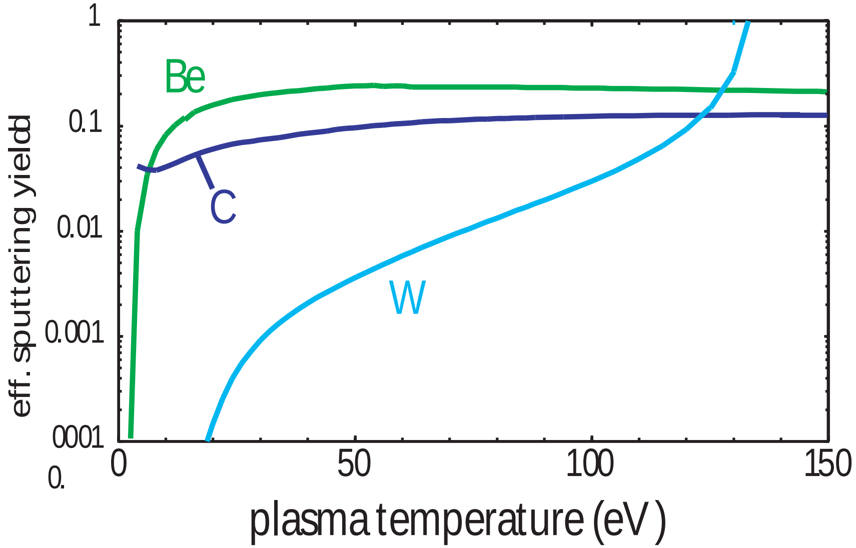




Erosion Processes

sputtering / arcing

Sputtering by D ions

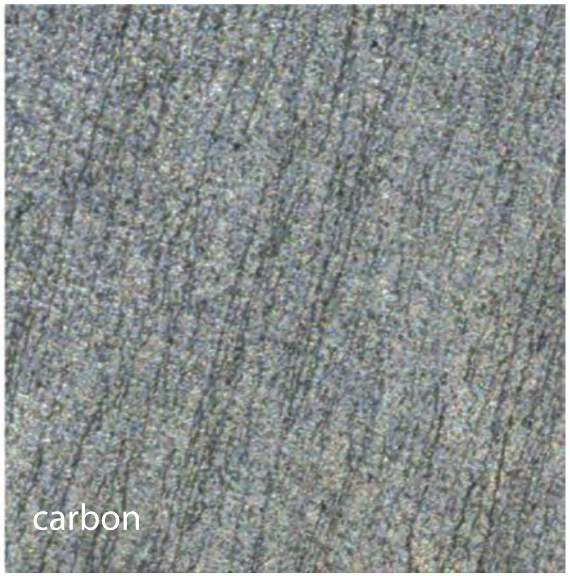


Divertor Tokamak: < 10 eV ions
C PFCs : physical sputtering dominates
W PFCs: sputtering only by impurity ions

Arc erosion depends only on material properties

	T_{melt}	λ	E_r	E_r
	C	W/mK	µg/C	at/C
C	3650	75	13.5	$68.0*10^{16}$
W	3380	130	27.1	$8.8*10^{16}$


tungsten coating


carbon

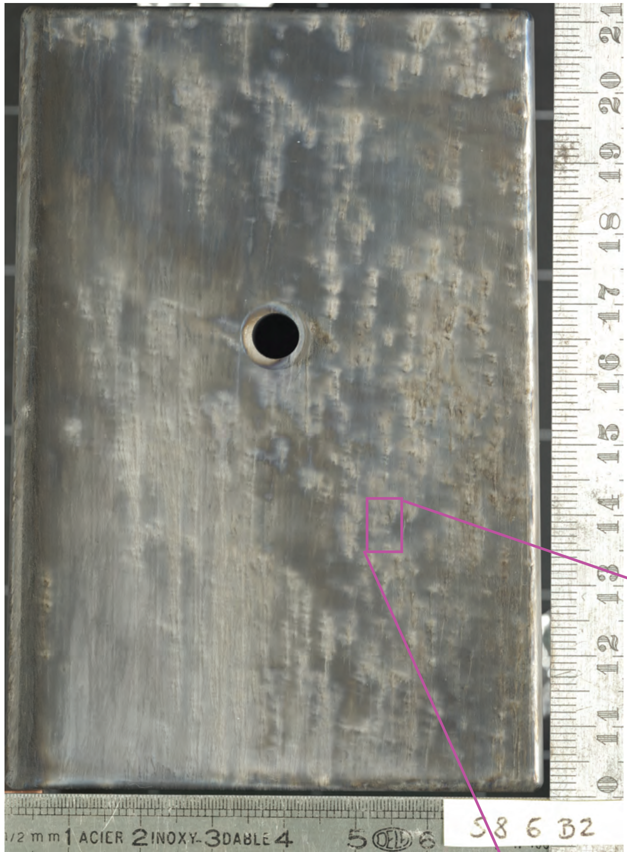
arcing : C releases only
7 times more atoms than W
sputtering : 3 orders of magnitude

same amount of traces on C and W

For carbon PFCs
arcing is negligible
For W PFCs
under investigation

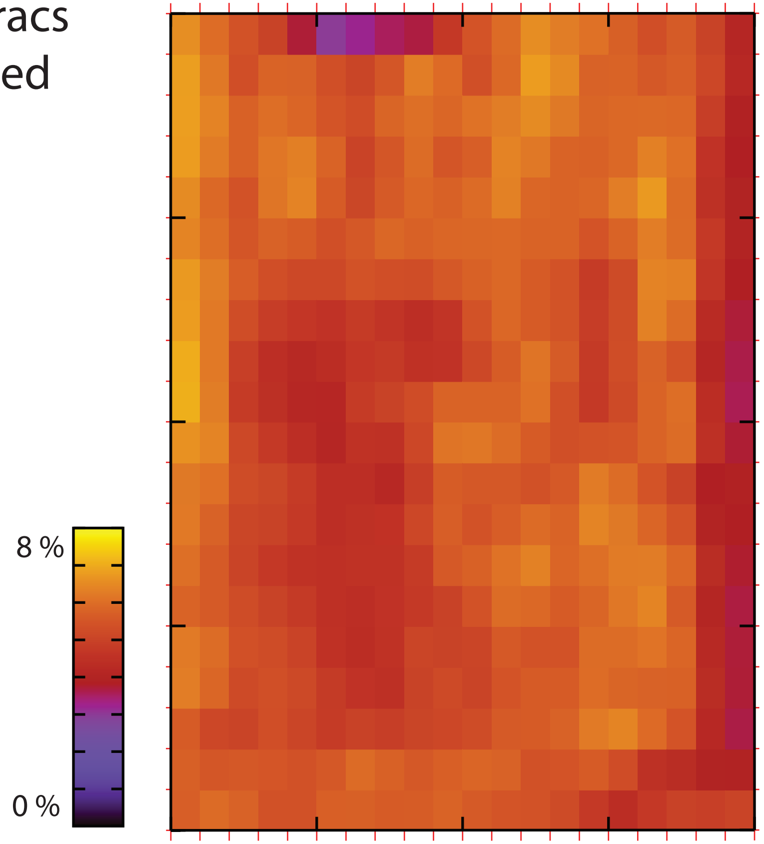
Arc Erosion

analysis of tracs



~ 4000 tiles mounted as PFCs
96 tiles removed and scanned
automatic trace identification
- 20 * 20 subpictures / scan
- identification of arcs by contrast/intensity /direction
- reliable criterion > independent from observer
- arcs only as long tracs

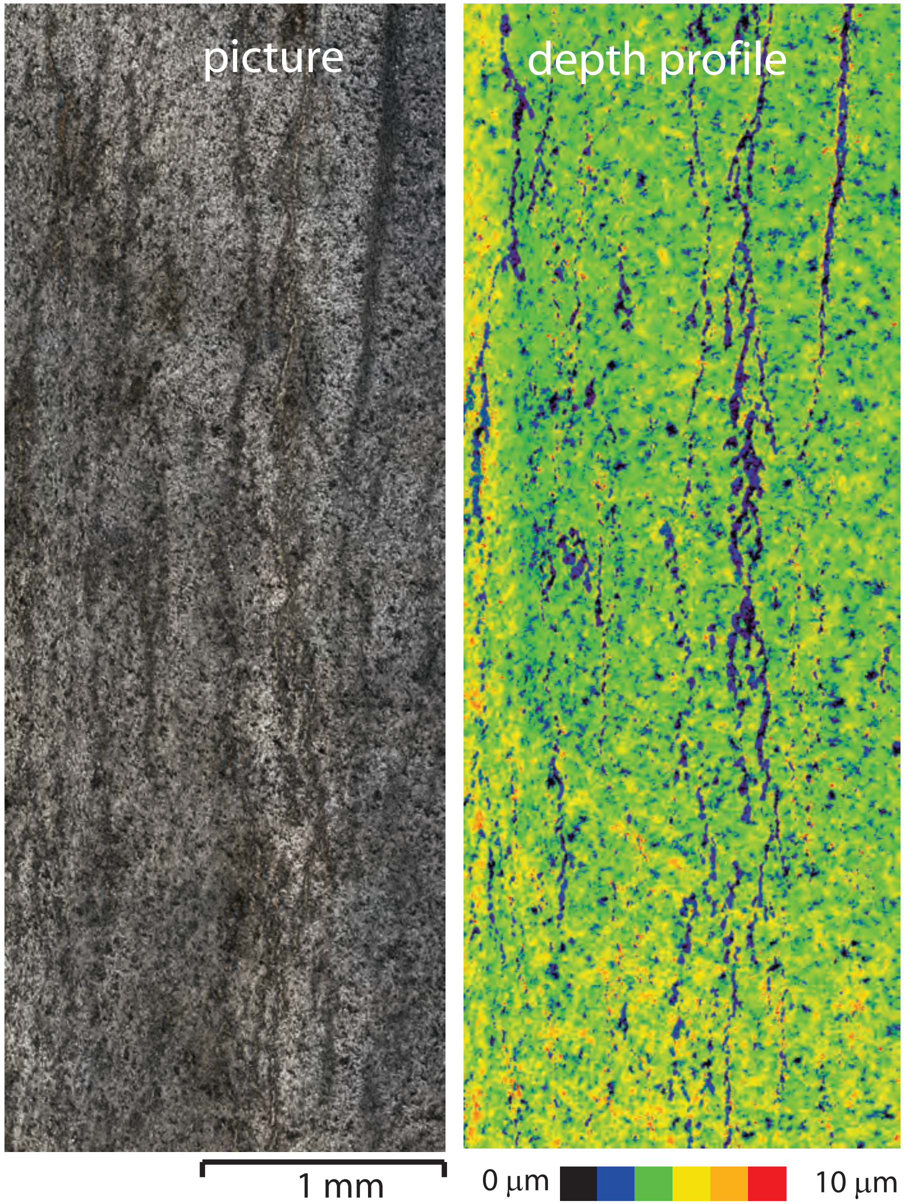
5.3 % of surface eroded
almost homogenous
erosion on this tile



tiles scaned
273 MPixel
3 *16 bit color
resolution 6 μm
(1.5 GB/tile)

Arc Erosion

erosion by arcing is localy dominant



Tiles analyzed by confocal scanning microscope

arc tracs observed in picture
depth measured
two kinds: classical arc trace 50 µm * 5 mm
orientated perpendicular B
spots 10 µm *10 µm

threshold for depth yields eroded area
tile Bgr 6 B2: 5.8 % of surface effected

total volumen (2 σ below surface)
> amount of W eroded: 0.2 mgr / cm^2
extrapolated to vessel: 1.6 gr W eroded

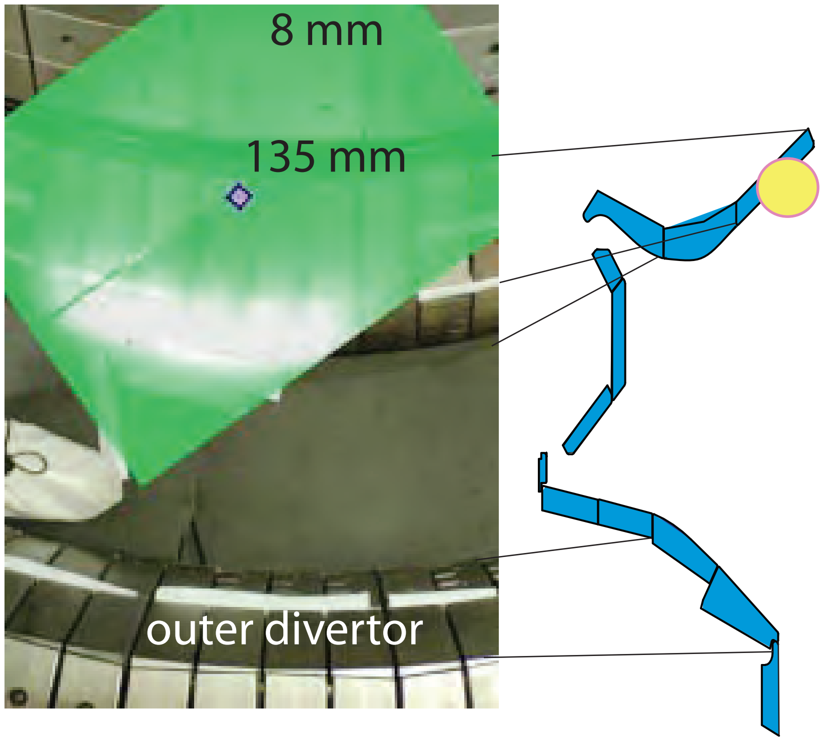
physical sputtering: marker stripes
measured by Ion Beam Techniques
inner divertor baffle gross deposition area
W erosion: < 0.2 gr
W deposition at whole divertor: 20 gr

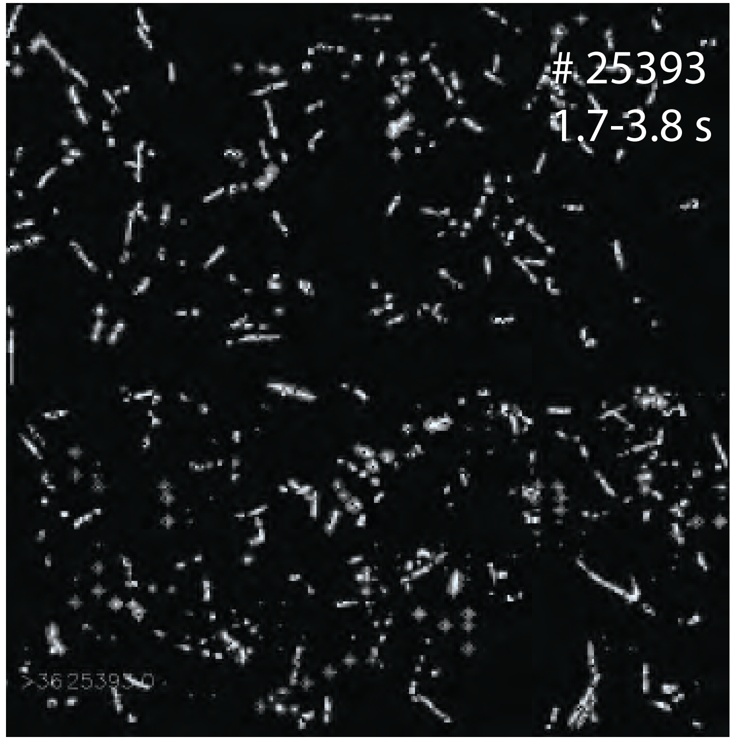
Arcing events

fast camera observation

time resolved measurements needed
  to identify arcing conditions
fast CMOS camera observing inner baffle
spatial resolution 150*150 μm2/pix
time resolution 26845 fps (256*256 pix)
exposition time 3 - 900 μs

view of camera





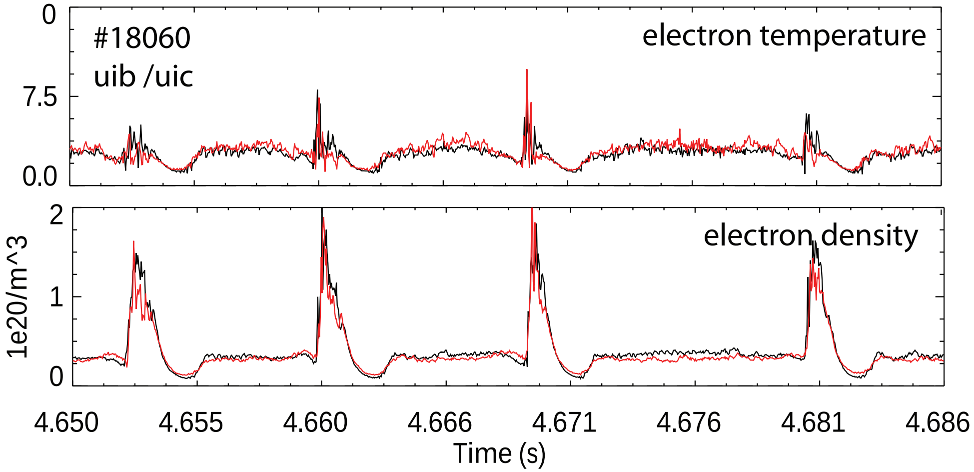
camera produces 8 GB data/shot
local events identified and marked
quantity of events strongly varieties

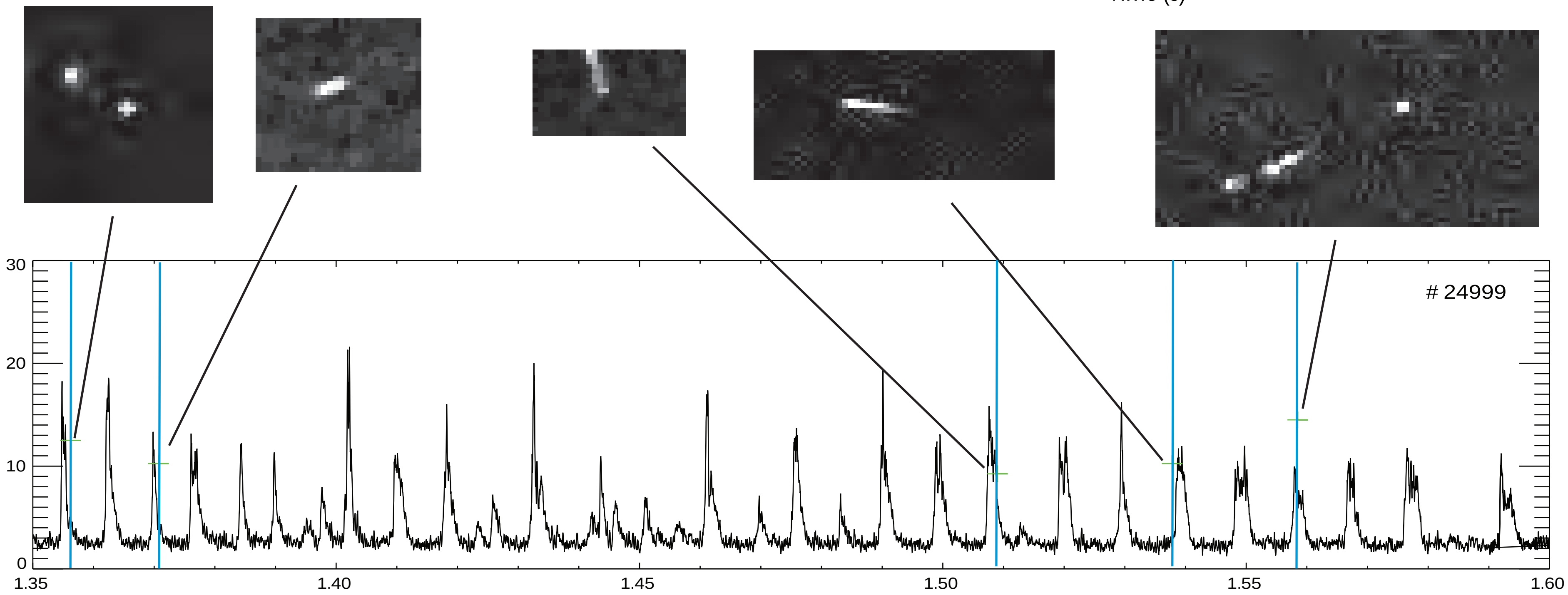
sum of all events during a discharge
- neutrons at image guide
- problems of camera
- arcs

Arcing events

arc are correlated with ELM's

Evaluation not fully automatic
example of high power discharge
5 events observed
correlation with Edge Localised Modes
(ELM: plasma instabilty typical for
ITER relevant plasma discharges)
ELM at inner baffle: strong density rise
can trigger arcing





Summary

Two kinds of arcs are usual in ASDEX Upgrade

Arcing events

- mostly at PSL
- powered by potential differences
- no significant influence on plasma operation
- may affect / destroy parts or diagnostics
- recipe to deal with

Arcs on PFCs

- observed at some tiles
- powered by plasma sheath
- triggered by edge instabilities as ELMs
- dominates locally erosion
- local variation require high resolution diagnostic
- investigations just started

Arcing is no problem in present fusion devices
Future fusion reactors (ITER) will operate with ELMs and metal PFCs
Role of arcs on PFC erosion and dust production is not yet clear -but might not negligible