Plasma shielding during ITER disruptions

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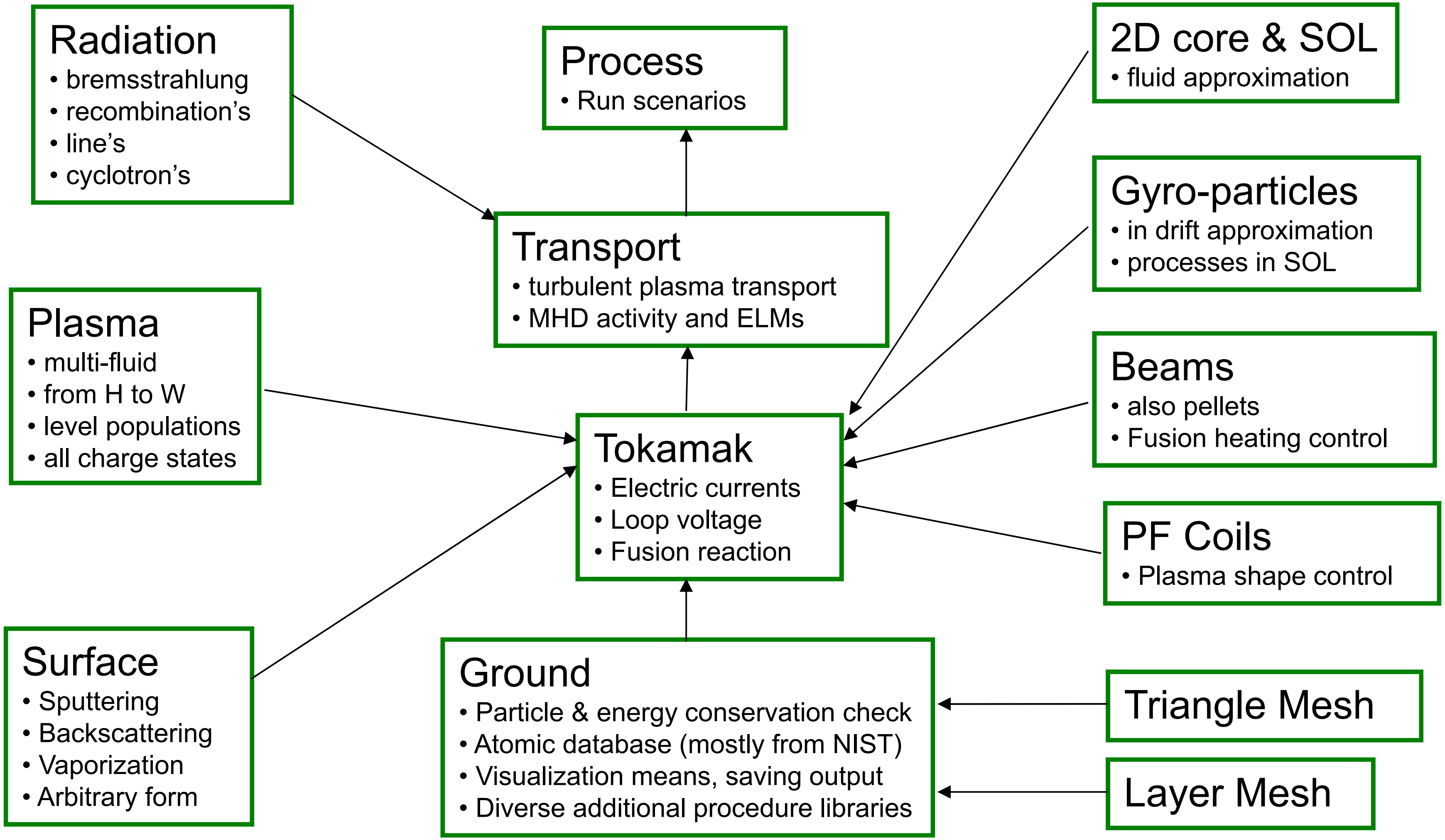
Integrated tokamak code TOKES is a workshop with various ‘tools’ – objects



Radiation
- bremsstrahlung
- recombination’s
- line’s
- cyclotron’s

Process
- Run scenarios

2D core & SOL
- fluid approximation

Transport
- turbulent plasma transport
- MHD activity and ELMs

Gyro-particles
- in drift approximation
- processes in SOL

Plasma
- multi-fluid
- from H to W
- level populations
- all charge states

Tokamak
- Electric currents
- Loop voltage
- Fusion reaction

Beams
- also pellets
- Fusion heating control

PF Coils
- Plasma shape control

Surface
- Sputtering
- Backscattering
- Vaporization
- Arbitrary form

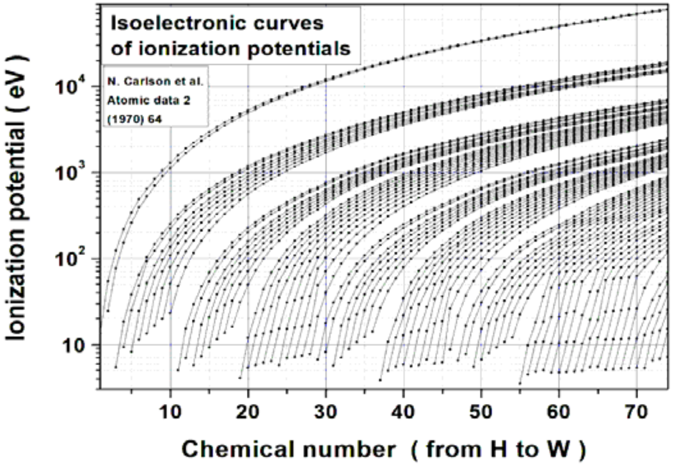
Ground
- Particle & energy conservation check
- Atomic database (mostly from NIST)
- Visualization means, saving output
- Diverse additional procedure libraries

Triangle Mesh

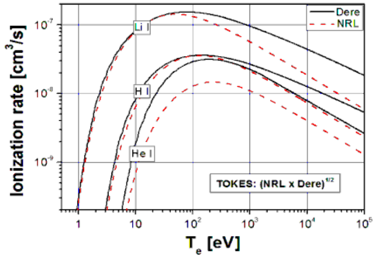
Layer Mesh

TOKES is written in DELPHI: object oriented language based on Pascal (Embarcadero Technologies)

Atomic database of TOKES



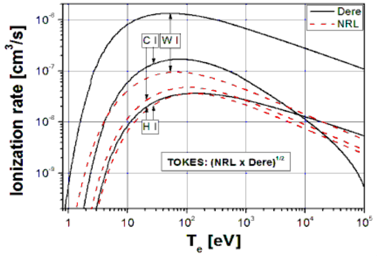
Isoelectronic sequences on z: (e.g. $W_{z=1}$ '=' $Ta_{z=0}$).
Level energies E_{mzk} and transition energies E_{mzl} are interpolated proportionally to I_{mz} from lower m.
The Lotz scaling works.
The Bethe scaling works.
Collisional excitation: van Regemorter formula
Those symmetries are used in TOKES.



Dere: tables
NRL: a formula:

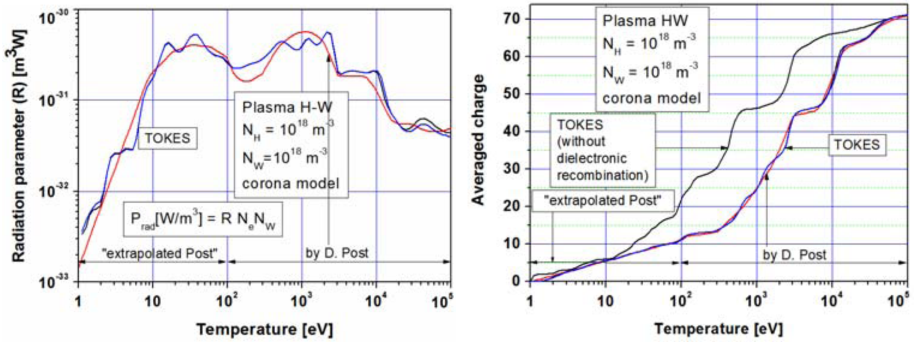
$$k_{zk}^{\mathrm{Ei}}\left[\frac{\mathrm{cm}^3}{s}\right]=f\sqrt{\frac{T_e}{I_{zk}}}\exp\left(-\frac{I_{zk}}{T_e}\right)$$

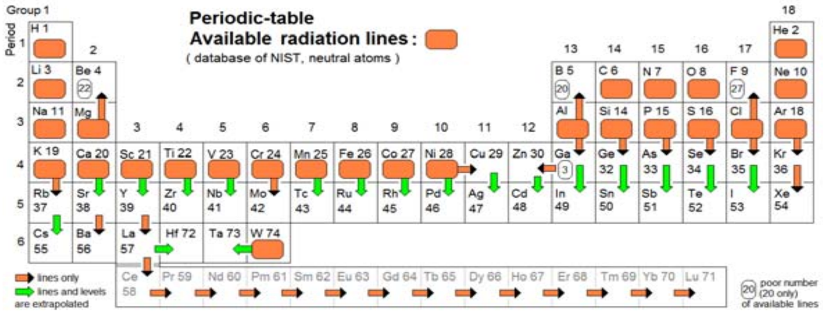
$$f=\frac{10^{-5}}{6+T_e/I_{zk}}\left(\frac{\mathrm{eV}}{I_{zk}}\right)^{3/2}$$



Many atomic data are from free Internet access NIST database (Ralchenko et al.). But many chemical elements are lacking. Then available data of other elements are assumed according to the periodical table.

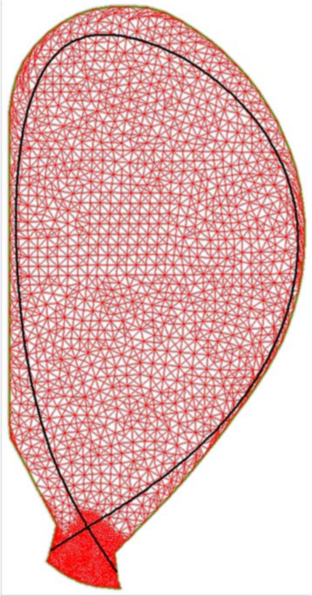
fitting of W data with DR coefficient in Burgess formula



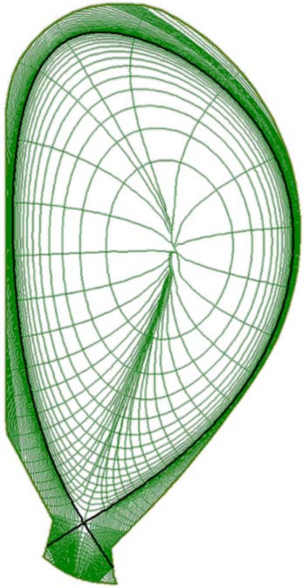


TOKES grids, magnetic flux coordinates

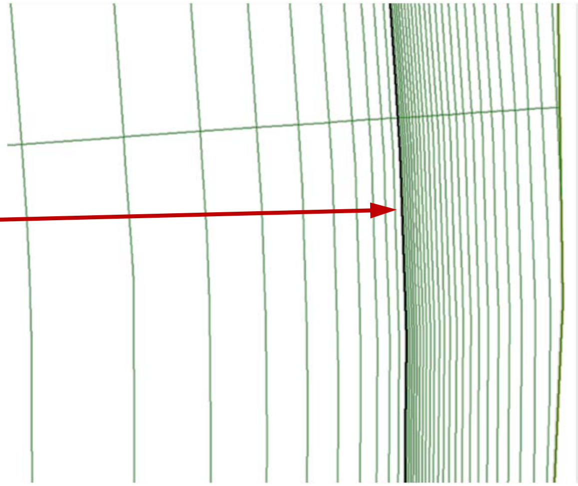
Triangular grid for neutrals and radiation

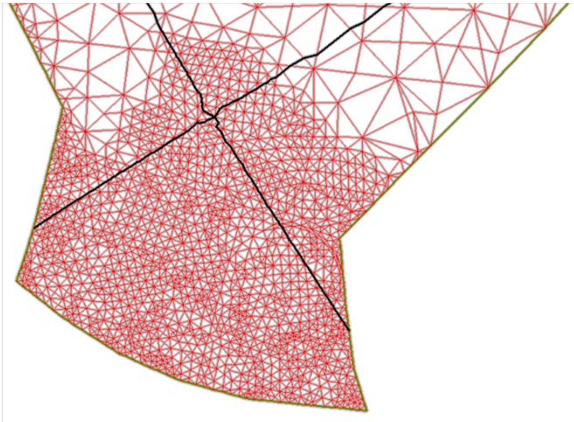


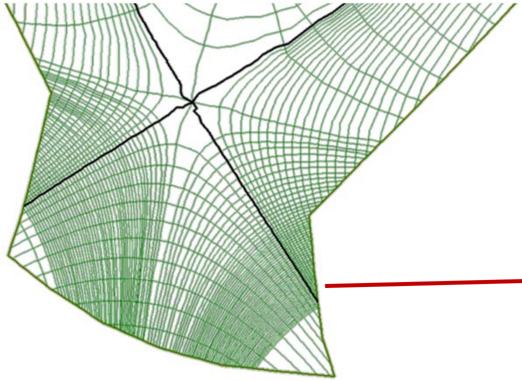
MFC grid for plasma aligned with magnetic field



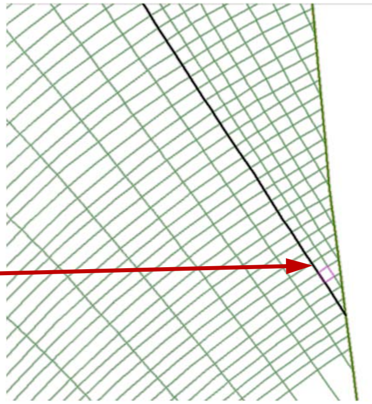
Mimimum radial size at separatrix ~1.5 mm







Mimimum sizes ~5 mm

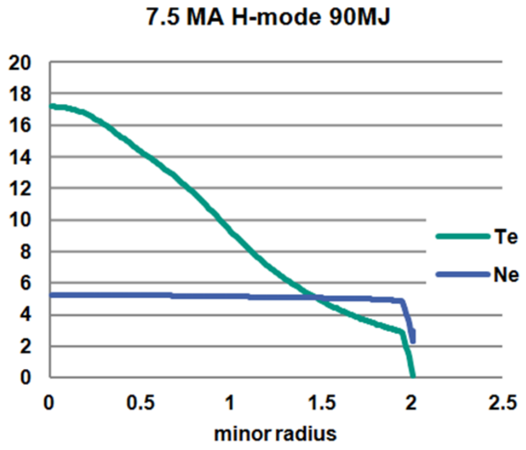


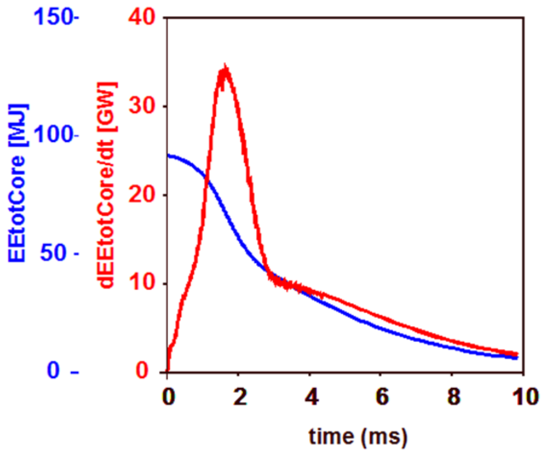
Shielding treatment in TOKES

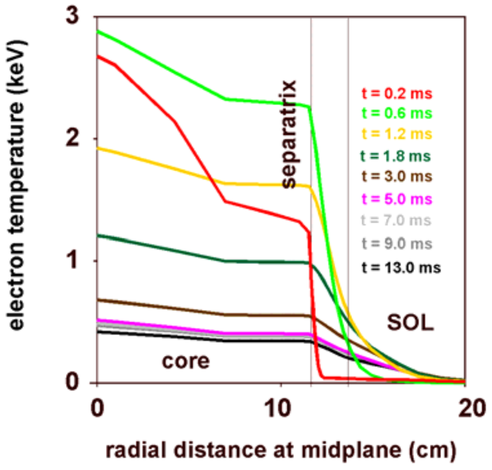
- There are no special model for plasma shielding treatment in TOKES
- All the physical processes necessary for shielding simulation are routinely implemented in TOKES. These are:
  - Plasma-wall interaction: DT plasma heats and evaporates the wall
  - The vapor is deposited in the plasma adjacent to the vaporization point
  - The plasma treated as mixture of fluids, each ionization state with unique levels populations is treated as a separate fluid.
  - Each ion species is described by temperature, density and velocity
  - All ionization-recombination, excitation and radiation processes are taken into account as well as convection, diffusion and thermoconductivities.
- Plasma shield is characterized by sharp density and temperature gradients → fine enough mesh is necessary.

Simulation of the disruption in TOKES

- Disruptions are simulated in TOKES by drastic increase of cross-transport coefficients (thermoconductivity and diffusion)
- Cross-transport coefficients in the core are determined to fit time duration of the disruption
- Cross-transport coefficients in SOL are determined to fit the predefined broadening of heat flux width at the midplane.

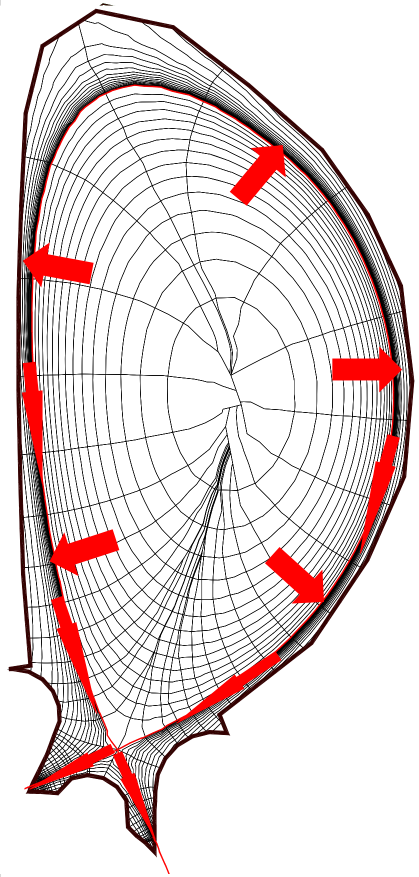


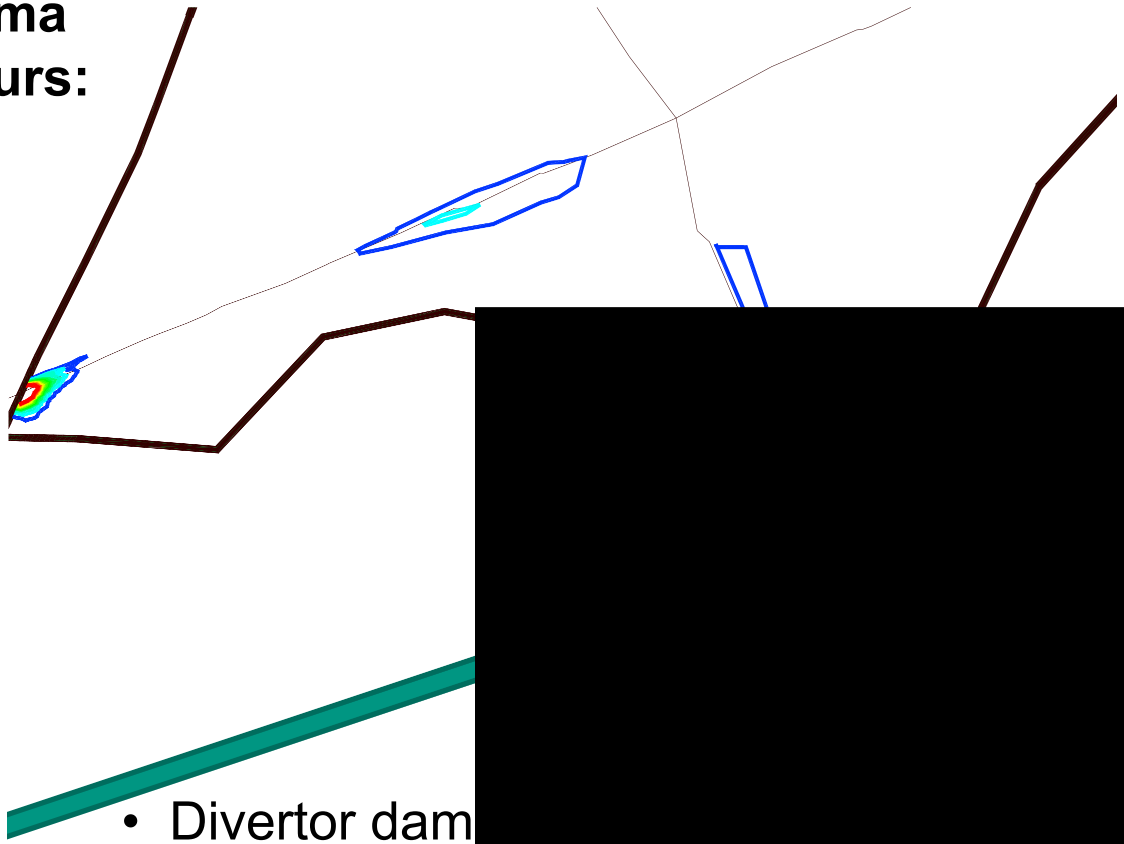




Simulation of W plasma shield during unmitigated disruption (ITER)

tungsten plasma density contours:

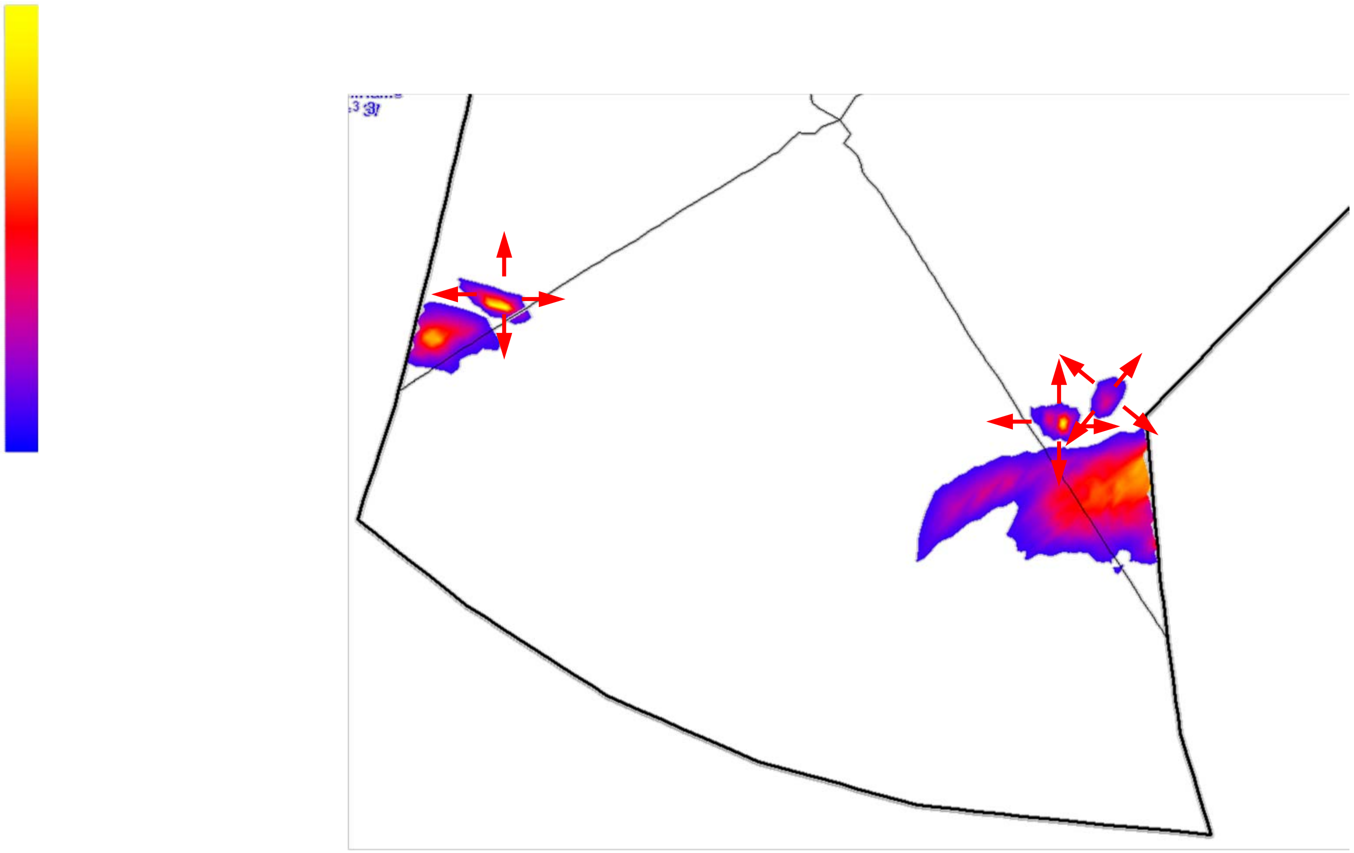




[redacted]

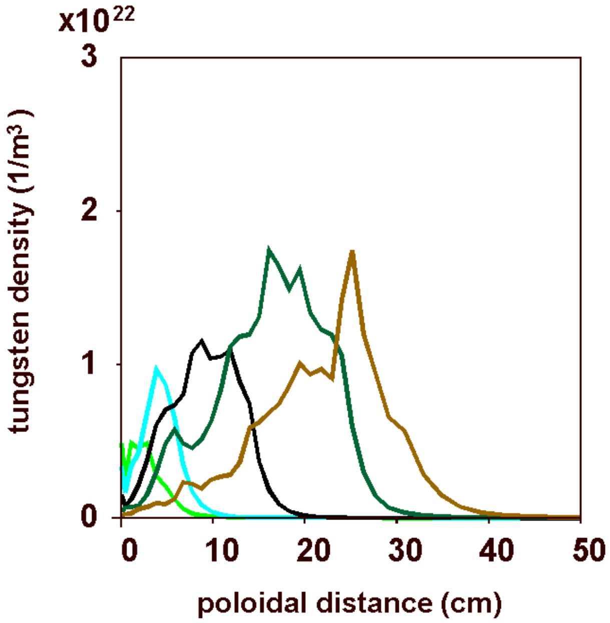
- Divertor dam[redacted] to shielding:
  - ✓ Melt pool [redacted]
  - ✓ Melt pool [redacted] (ISFNT12)

Radiation power density distribution in W plasma shield (DEMO)

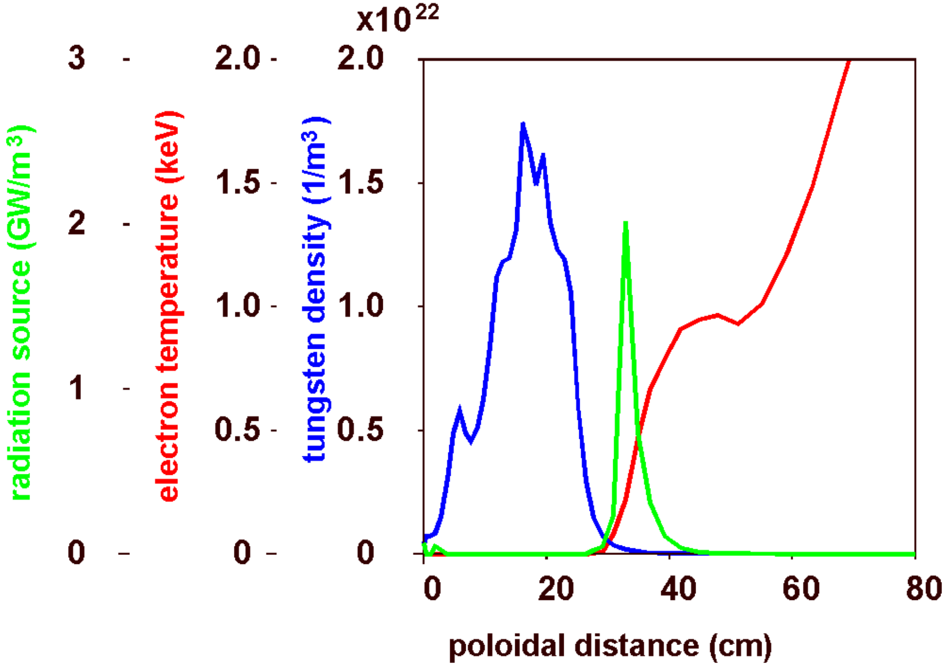


W plasma expansion along the magnetic field (DEMO)

W plasma expansion along the magnetic field

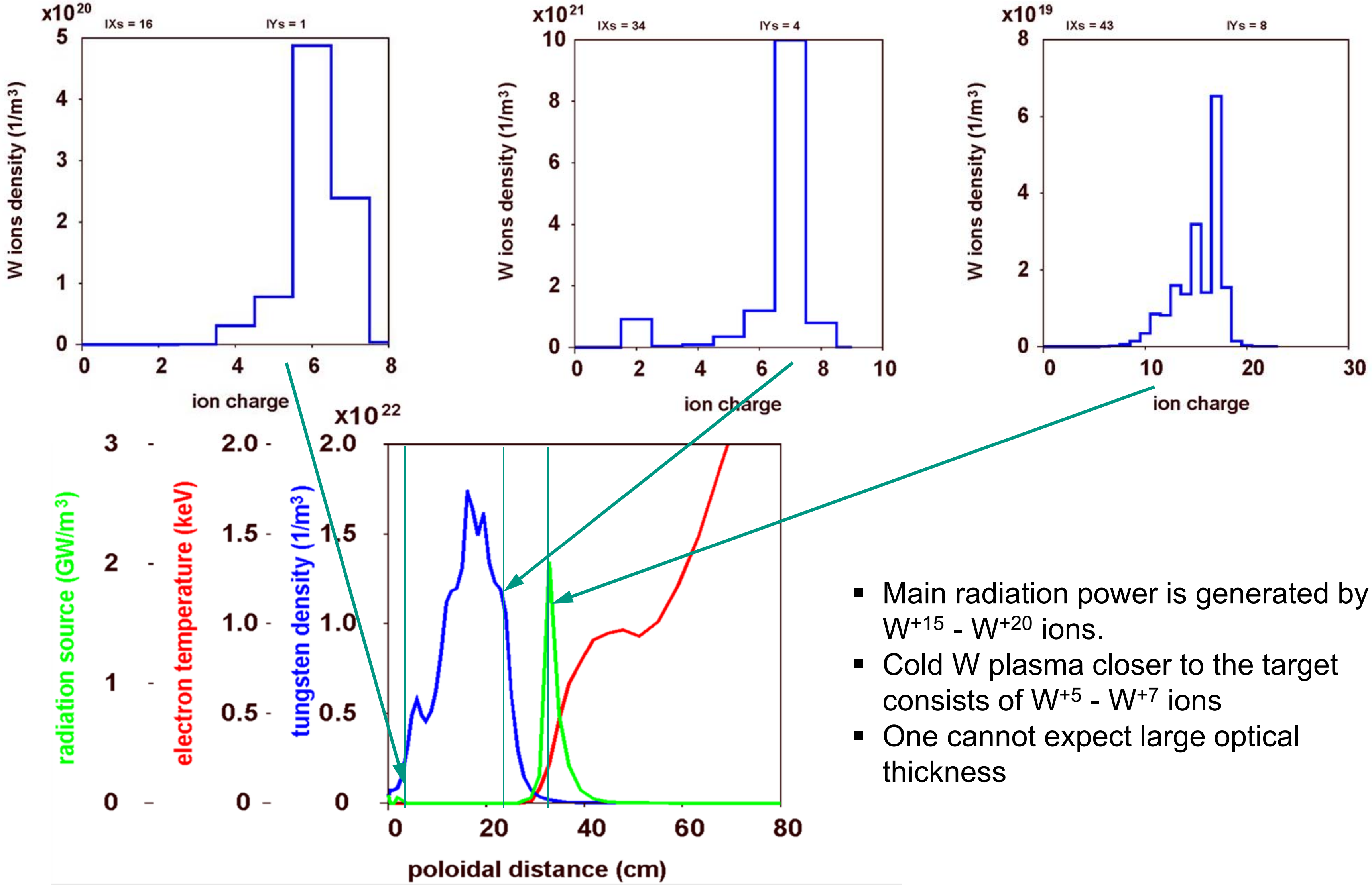


Maximum radiative power is in the intermediate region with T_e~100-200eV



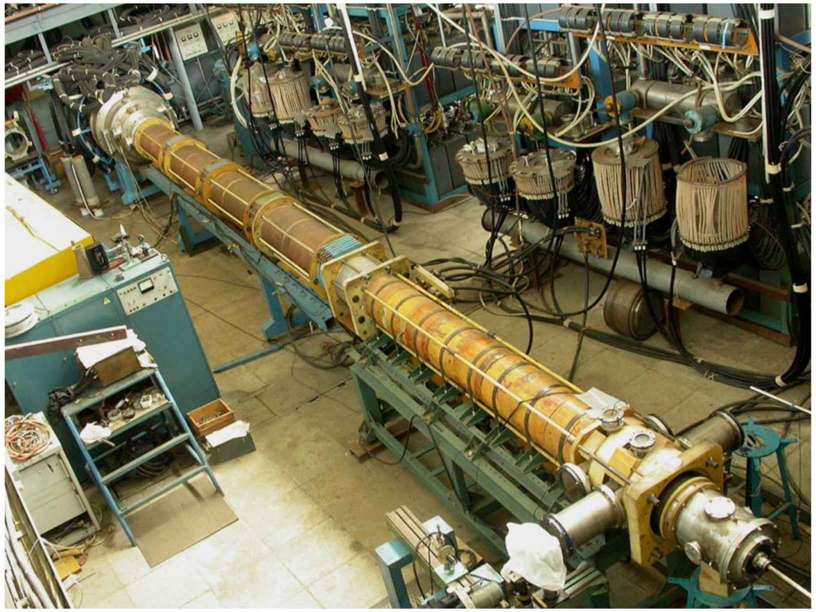
- The plasma shield expands along the field
  - cold ions fly into the hot electrons, ionized and radiate
- The process is dynamic, no LTE

Ion composition of W plasma in the shield

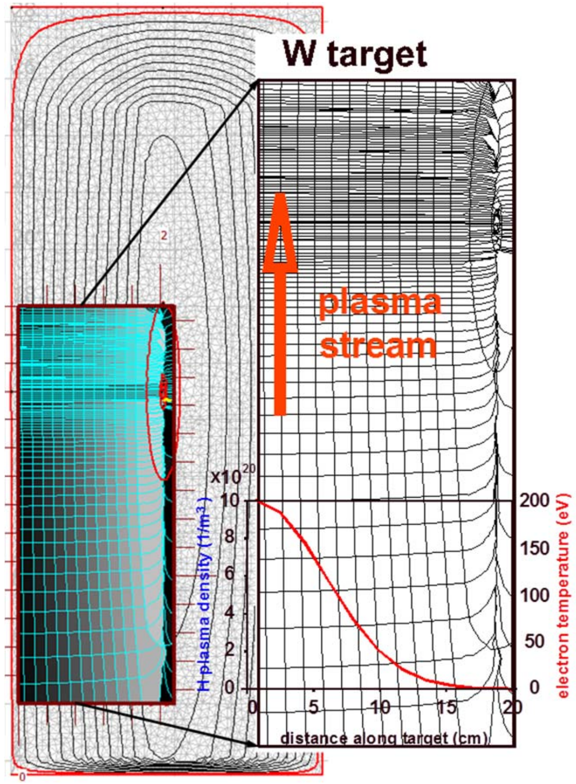


- Main radiation power is generated by W^{+15} - W^{+20} ions.
- Cold W plasma closer to the target consists of W^{+5} - W^{+7} ions
- One cannot expect large optical thickness

TOKES validation against MK200UG experiment



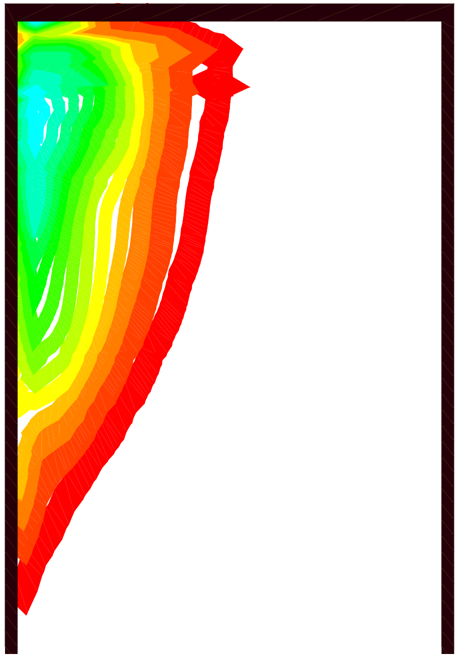
MK-200UG plasma gun



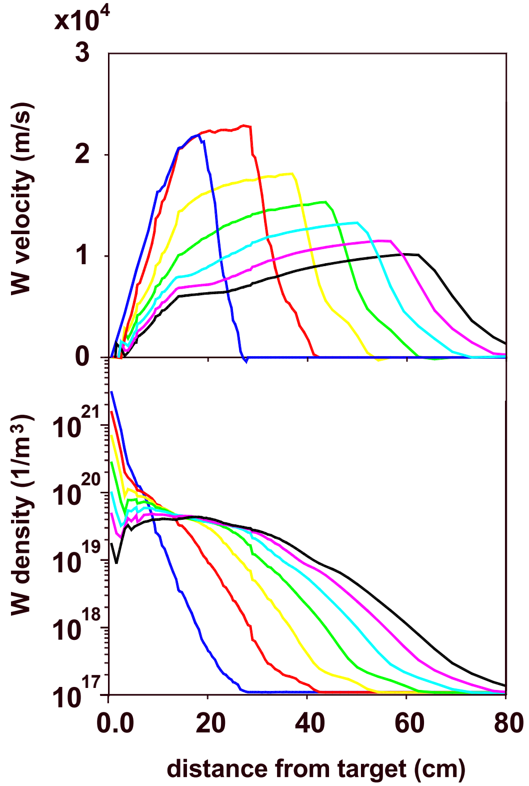
TOKES modification for MK-200UG plasma gun simulation

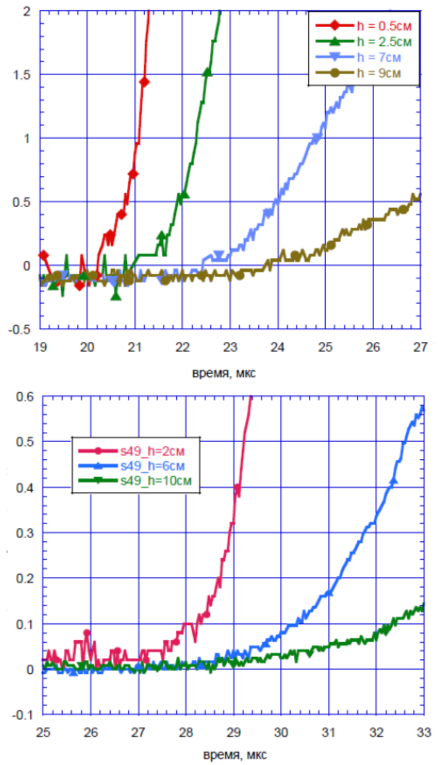
TOKES validation against MK200UG experiment

- The velocities of the W plasma have been estimated for the first time using the time delays for the sharp increase of radiation in the AXUV diodes situated at the distances of 2, 4.5, 6, 8.5 and 10 cm from the target
- Radiating plasma front propagation measured in the experiment does not depend on the energy load and estimated as 2×10^4 m/s, in a good agreement with the simulations.

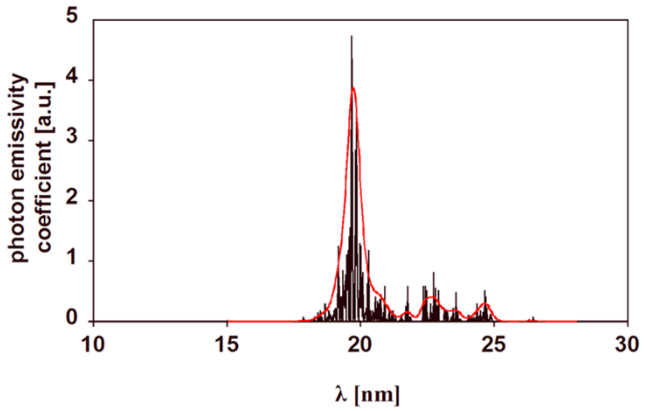


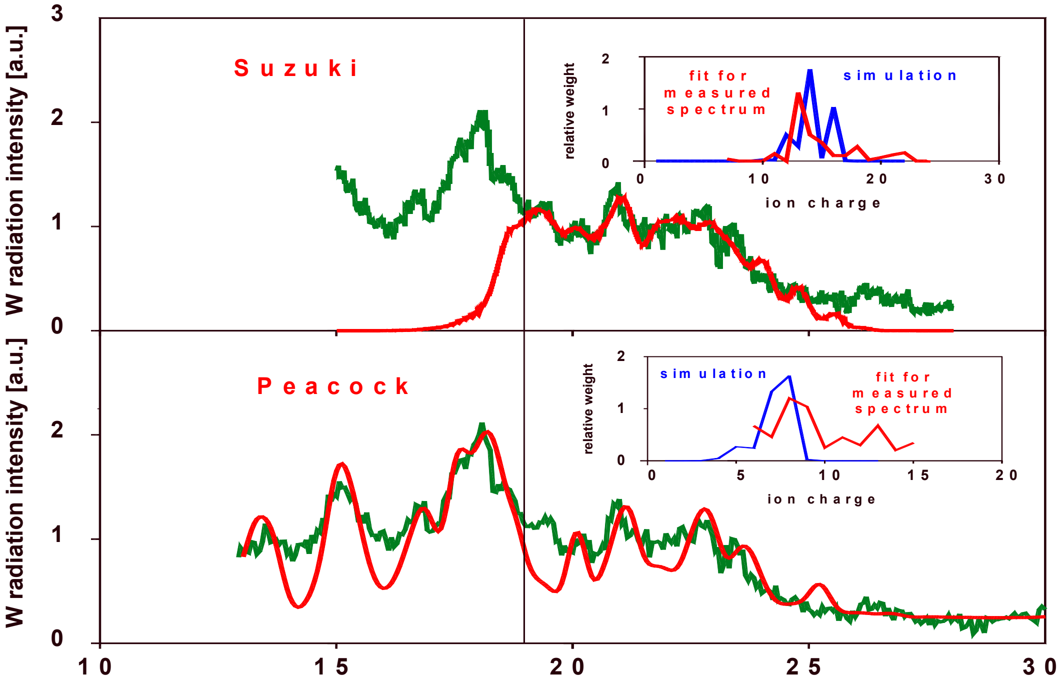
W plasma density contours





TOKES validation against MK200UG experiment. Ion composition comparison

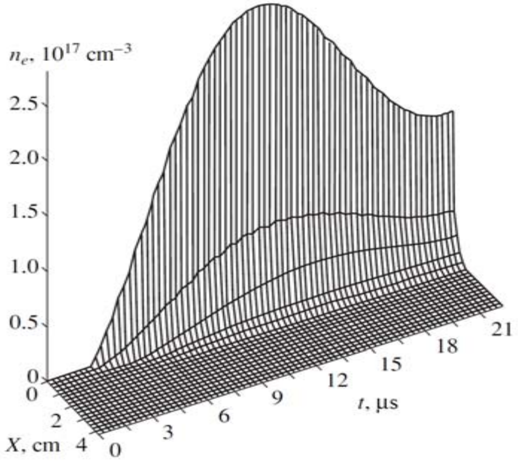




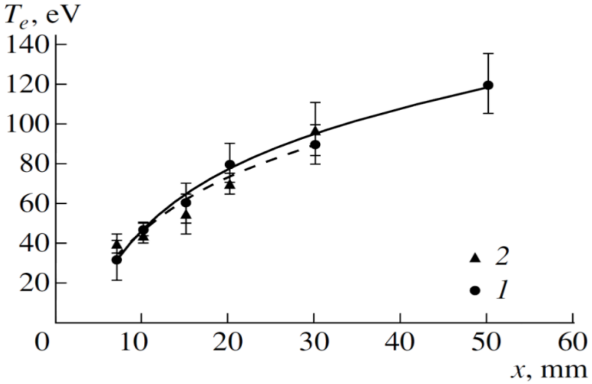
- Resolution of the spectrum measured in MK-200UG is much lower than the W line widths
- But one can distinguish radiation from each ion species by decomposing the measured spectrum using the ion spectra as an eigenfunctions.

- Comparison of the measured W plasma radiation spectrum at 3 cm from the target with the fitted spectra.
- Two groups of ions were found which correspond to the hot central plasma and the cold edge

TOKES code verification against 2MK200 facility



Dynamics of the electron density in the shielding layer of the tungsten target



T_e (*1*) t = 8 μs and (*2*) t = 15 μs measured by Thomson Scattering

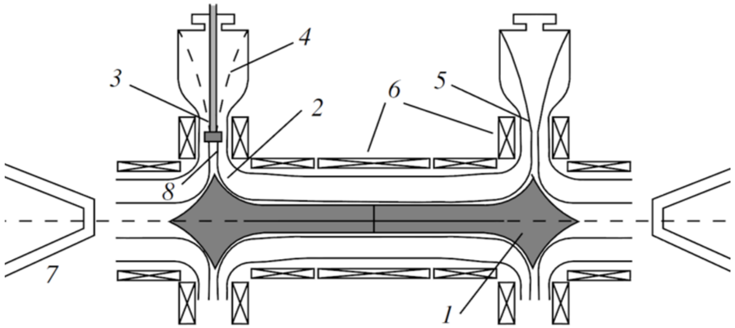
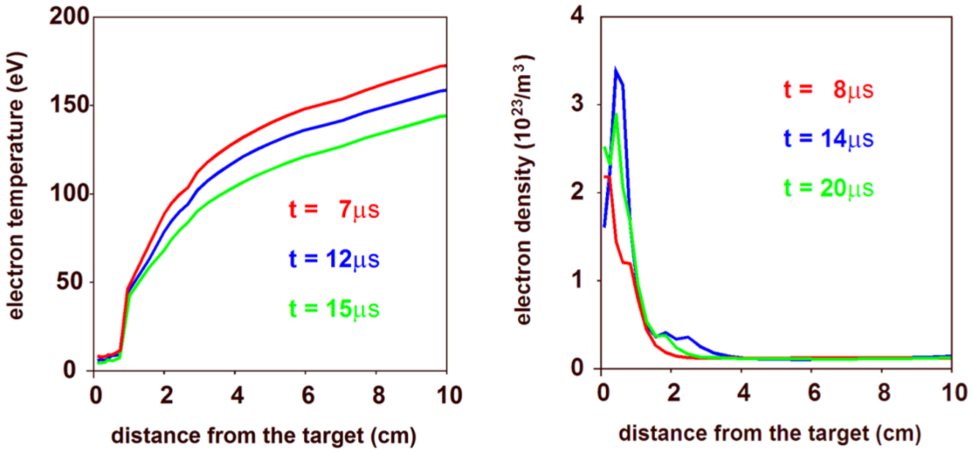


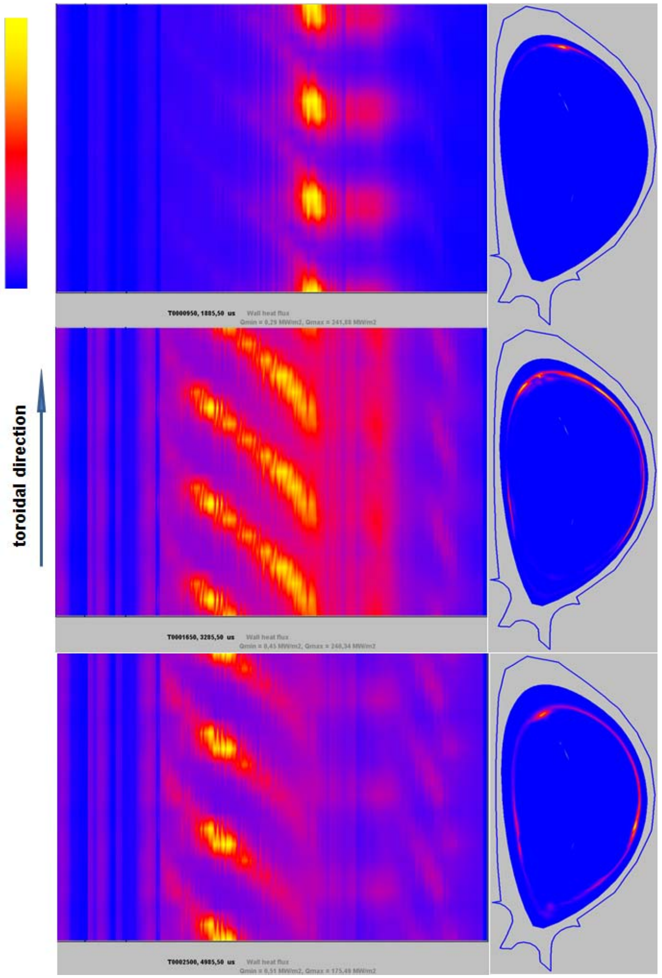
Fig. 1. Schematic of the device: (*1*) high-temperature plasma, (*2*) magnetized skin-layer plasma, (*3*) target on the mount, (*4*) expander, (*5*) annular slit of the cusp, (*6*) solenoids, (*7*) plasma accelerators, and (*8*) measurement point.

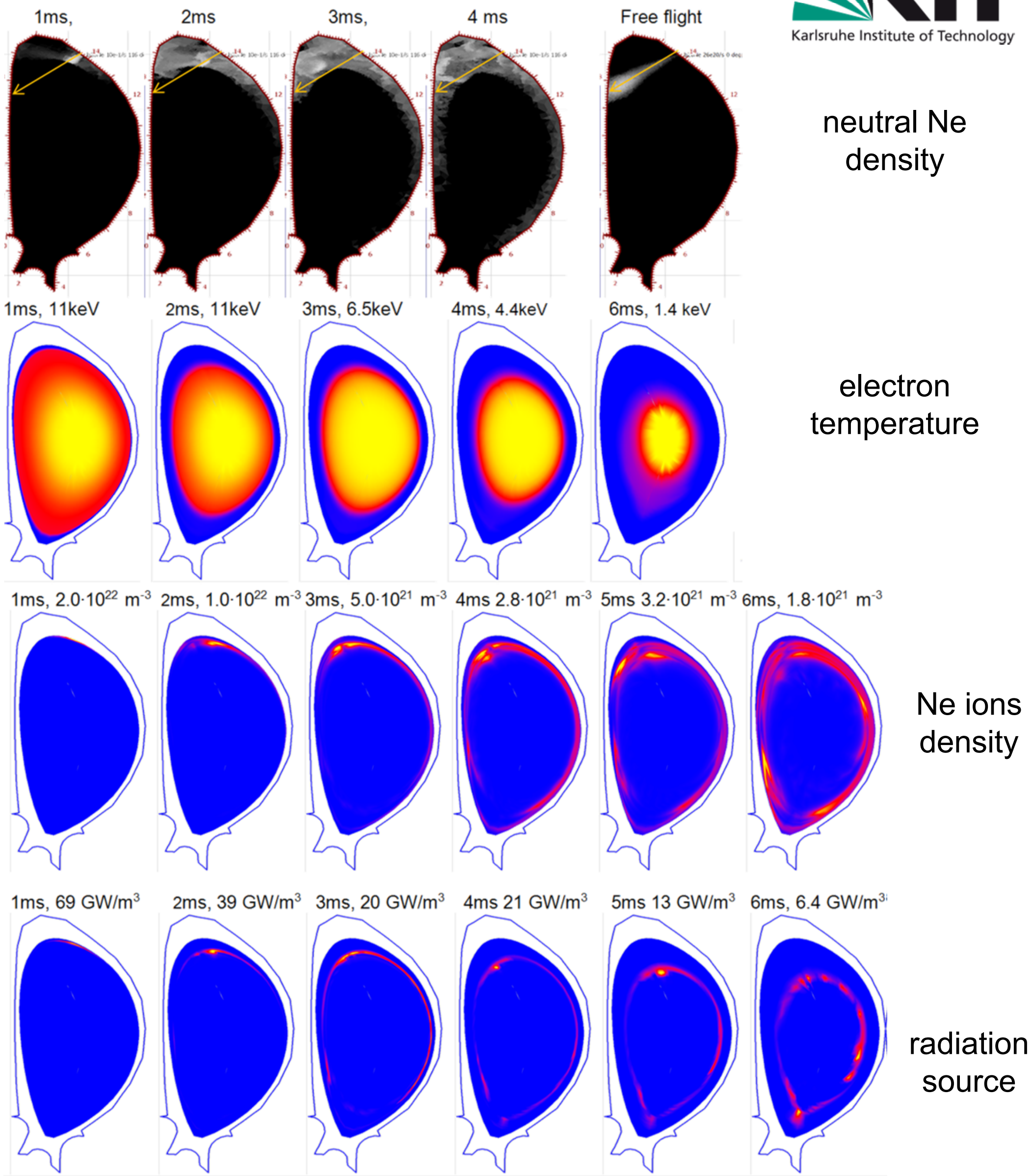


sharp drop in T_e very close to the target was not found as a result of unacceptably low signal/noise ratio there

Ne pellet injection into ITER discharge

Radiation source in poloidal plane (right) and heat flux along the first wall (left)





Discussion (1)

- Plasma shield expansion is fast dynamic process
  - Thermal equilibrium is unlikely
- Atomic kinetics data needed for simulations with W, Ar, Ne, Sn
  - Ionization and recombination rates (available in ADAS)
  - Dielectronic recombination (incomplete in ADAS)
  - Excitation rates as well as lines for W^{+1} - W^{+20} ions (available in ADAS)
  - Resonant charge exchange cross sections (available in ADAS)
- We intend to switch TOKES to ADAS data, but this needs personnel to assist in implementation (!)
- In ADAS all above mentioned data are available except of:
  - some neutral and first few ionization stages
- Experimental validation of calculated atomic data! (even indirect)

Discussion (2)

- In ITER radiation from plasma shield is mainly optically thin (to be verified)
- Optical thickness of the shielding plasma may (?) play a role in determining the amount of vaporized material
- Opacities and emissivities may be important for simplified models
- Very precise atomic data plays minor role in estimation of wall damage
  - because all the incoming energy should be irradiated from the shield
  - even large error in the atomic data compensated by additional vaporization
  - vaporization wall erosion is small: of a few μm
  - main wall damage is due to melting and melt splashing: ~200 μm
- Precise atomic data is important for estimation of amount of vaporized material (pellets ablation)

Discussion (3)

- The atomic data for W is huge: ~2GB → need for simplification:
  - choosing the correct set of contributing configurations
  - configuration-average reduces level number.
  - data reduction by assuming that the population of each ionization stage primarily resides in the ground state and that excitation - decay is rapid
  - new ideas for the simplification (?)
- Experimental validation of the simulation results is very important
  - Some preliminary comparisons of the TOKES results with measurements in the plasma gun has been already done
    - http://dx.doi.org/10.1016/j.jnucmat.2013.01.093,
    - http://dx.doi.org/10.1016/j.fusengdes.2017.02.048
  - New series of plasma gun experiments with W are planned for 2018-2019