INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Advanced methods for tokamak heat load studies

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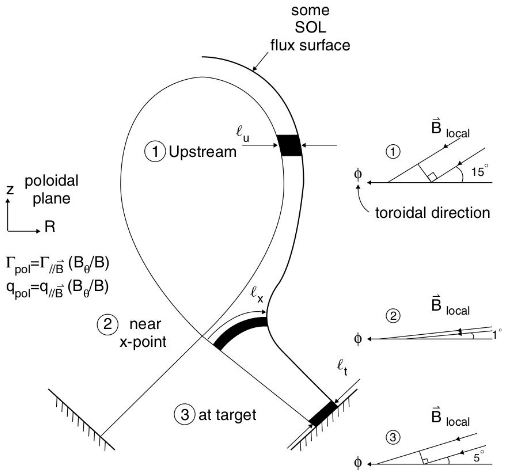
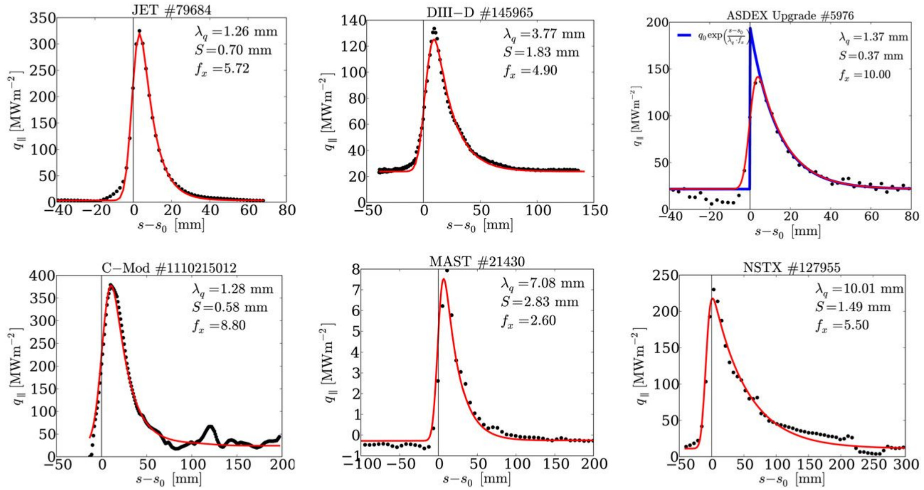
Tokamak first wall heat loads

- First wall of tokamak will be exposed to extreme heat loads - one of the unsolved challenges for fusion reactors
- Stationary plasma heat loads (q):
  - Directed at small area on the divertor
  - q ~ 10 MW/m^2 in ITER - limited by material parameters
- Transient heat loads:
  - ELMs: q ~ 1 GW/m^2, t < 1 ms
  - Disruptions: q ~ 10 GW/m^2, t = 1 - 10 ms
  - Runaway electrons: q < 1 GW/m^2
- Transient thermal loads can lead to irreversible material degradation and tokamak damage
- Heat load measurements are important for safe tokamak operation and development of heat load mitigation techniques



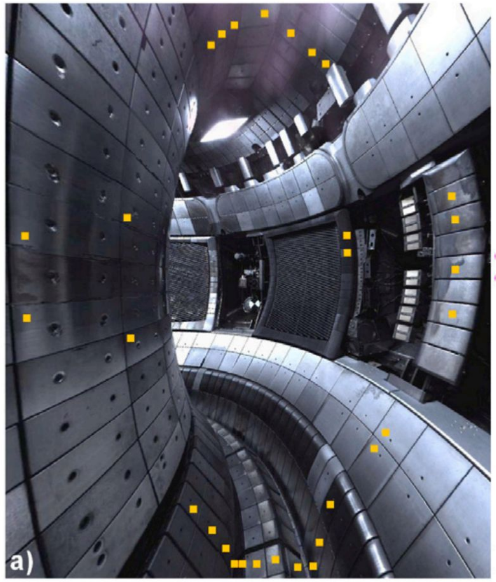
P C Stangeby et al.: The plasma boundary of magnetic fusion devices



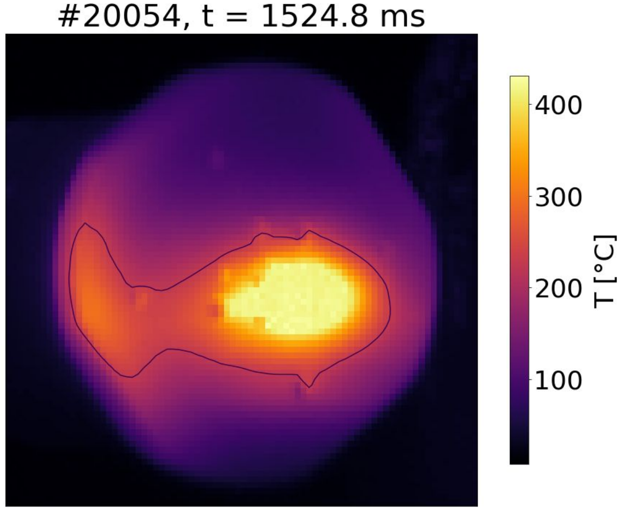
T Eich et al.: Nucl. fus. 53(9):093031, 2013

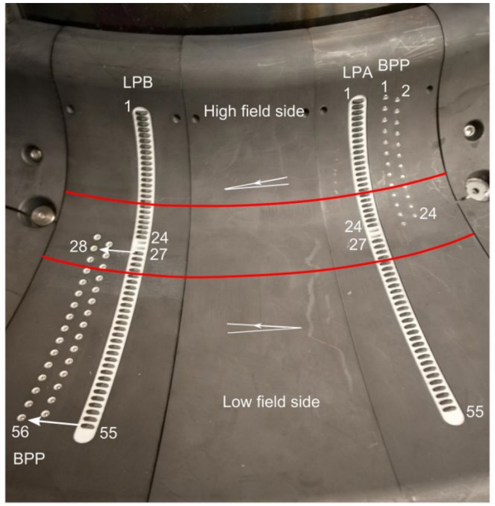
Plasma heat flux diagnostics

- PFC calorimetry
    - Deposited energy estimated from temperature change of the PFC tiles measured by temperature sensors
    - Heat flux profile estimated from multiple sensors
- IR thermography
    - Heat flux estimated IR camera measurements of surface temperature - heat diffusion equation
- Electrostatic probes
    - Heat flux determined from edge plasma parameters T_e, n_e measured by probes



T Hohmann et al.: Fus. Eng. Des. 187 (2023): 113365





J Adamek et al.: Nucl. Fus. 57.11 (2017), p. 116017

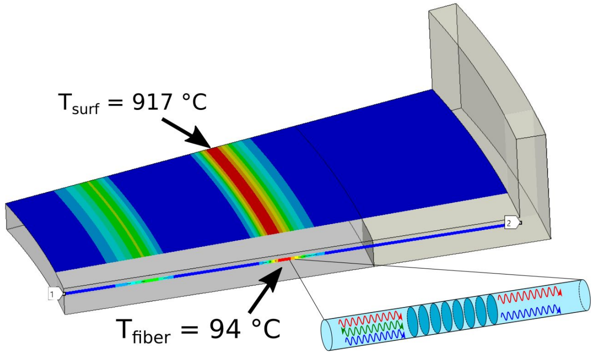
Calorimetry diagnostics for COMPASS-U

- FBG thermal diagnostics
    - Based on Fiber Bragg Grating temperature sensors
    - Heat load estimation and profile measurements
    - Conceptual design in progress
    - Inner limiter and initial divertor for plasma heat loads
    - Outer limiter considered for transient and RE heat load measurements

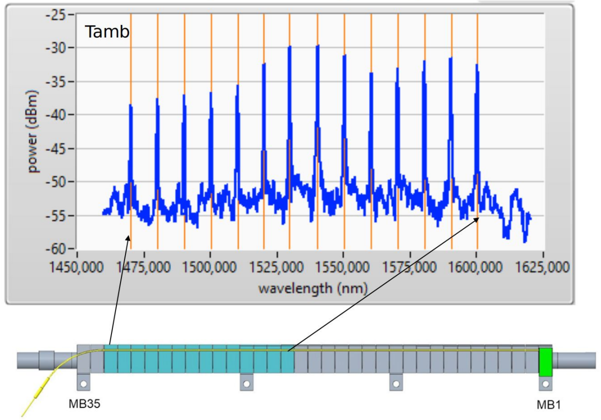
- Surface thermocouples proposed for later phases
    - Self-renewing thermocouple junction on the surface
    - Heat flux measurements from surface temperature changes

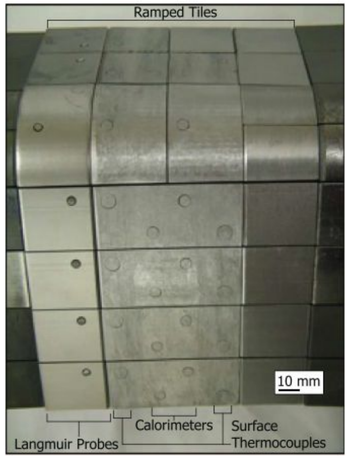
$$\lambda_B = 2 n_{\text{eff}} \Lambda$$

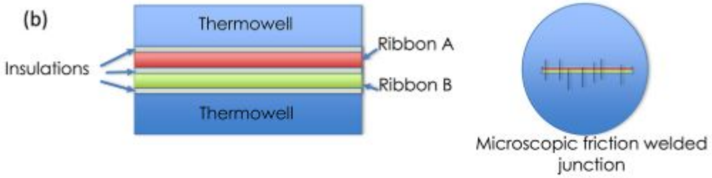
$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n}{\partial l} + n_{\text{eff}}\frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n}{\partial T} + n_{\text{eff}}\frac{\partial \Lambda}{\partial T}\right)\Delta T$$



FBG spectrum WEST (phase 2) – 14 FBGs





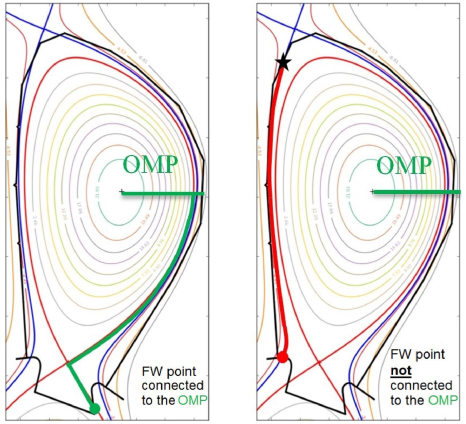


Brunner, D., and LaBombard B., Rev. Sci. Instrum. 83.3 (2012): 033501

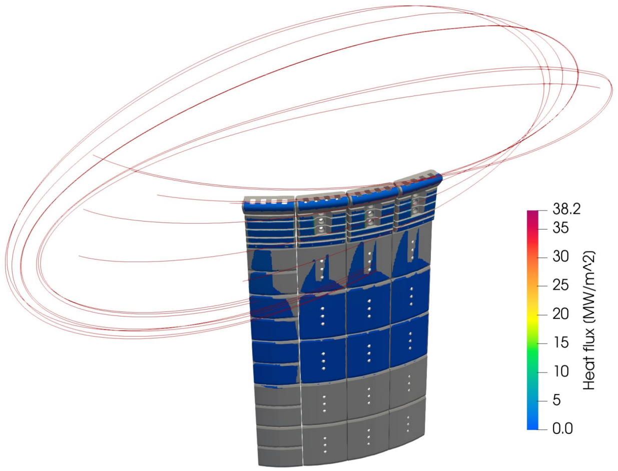
HEAT LOAD SIMULATIONS

PFCFlux heat load simulations

- 3D heat flux and shadowing simulations by field line tracing
- Optimization of PFC shape, scenario development and diagnostics design

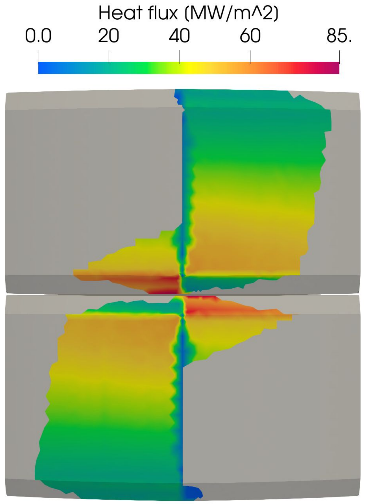


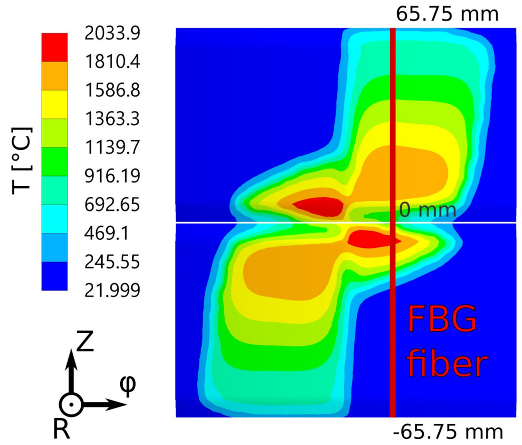
J Gerardin et al.: Nucl. Mater. Energy 20:100568, 2019



ANSYS FEA thermal analysis

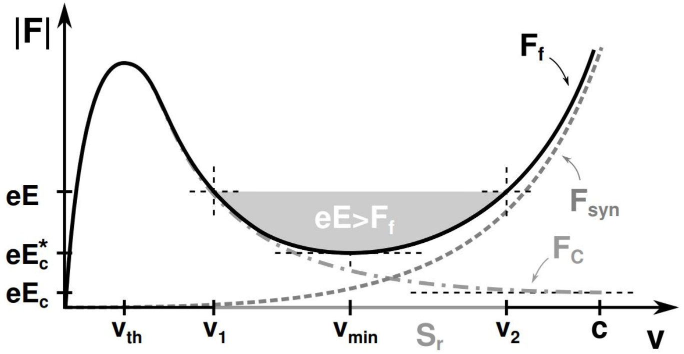
- Finite element analysis (FEA) of temperature evolution
- Solving 3D transient heat conduction equation
- Inputs:
  - PFCFlux - surface heat flux from plasma
  - FLUKA - volumetric RE heat loads



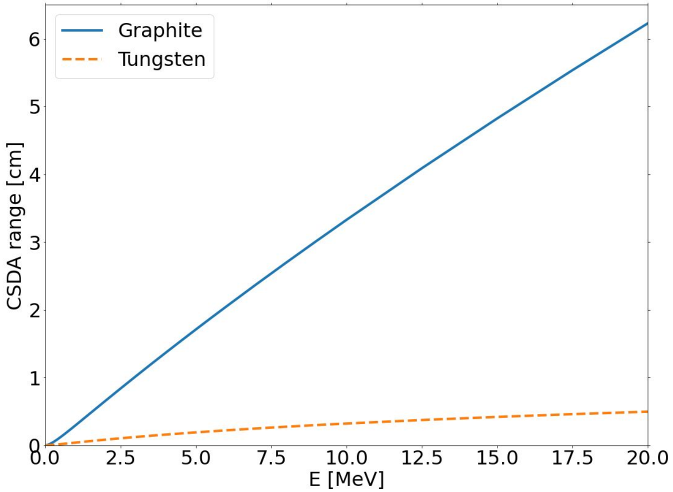


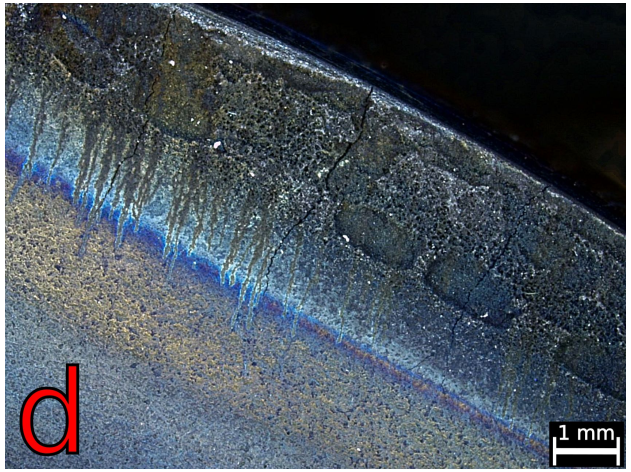
Runaway electron heat loads

- Runaway electrons (RE) - electrons accelerated to relativistic velocities by electric field
- Kinetic energy up to tens of MeV (> 90% c)
- Possible damage to tokamak
  - heat loads in tens of MW/m^2 (at COMPASS)
- Development of mitigation techniques necessary
- RE kinetic energy lost by collisions and bremsstrahlung -> energy deposition up to several cm in PFC material



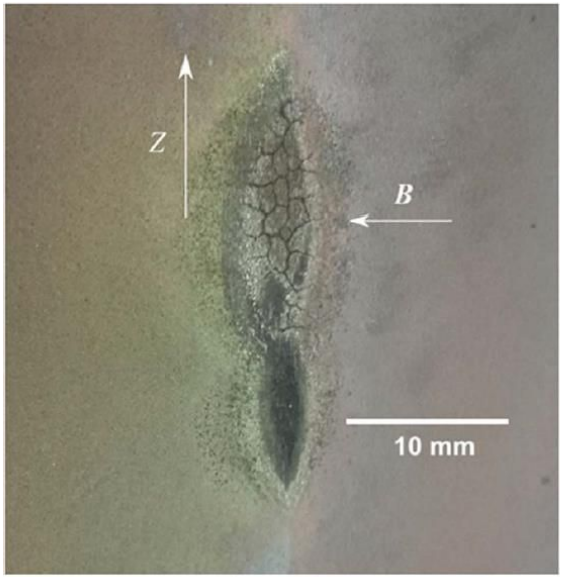
A. Stahl, PhD thesis, 2017





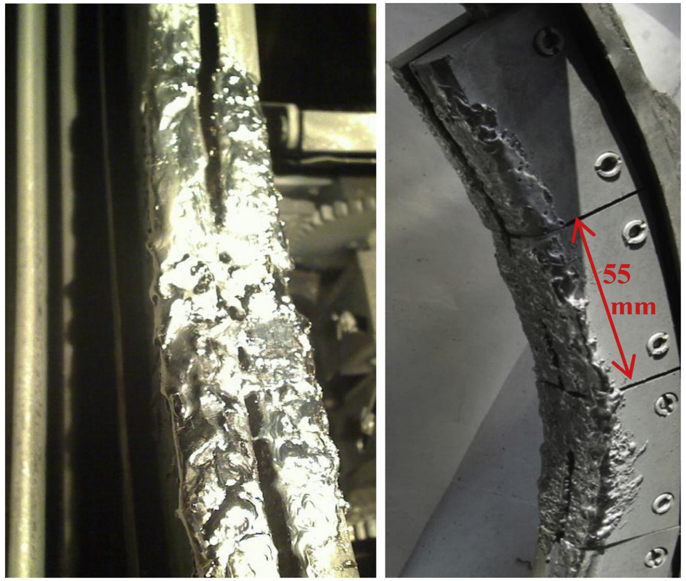
RUNAWAY ELECTRONS - PFC DAMAGE

COMPASS



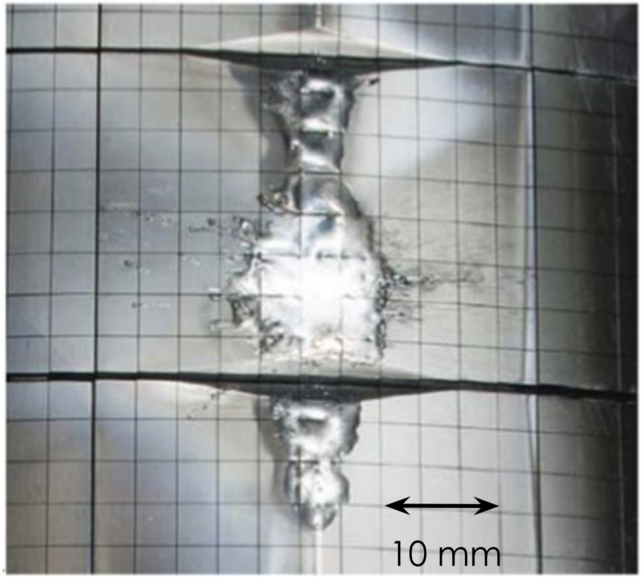
$E_{RE} < 10$ MeV
$I_{RE} = 100$ kA
$E_{max} = 15$ kJ
$q_{max} = 30$ MW/m^2

T-10



$E_{RE} < 2$ MeV
$I_{RE} < 200$ kA
$q_{max} = 1$ GW/m^2
Damage after 500 disruptions

JET



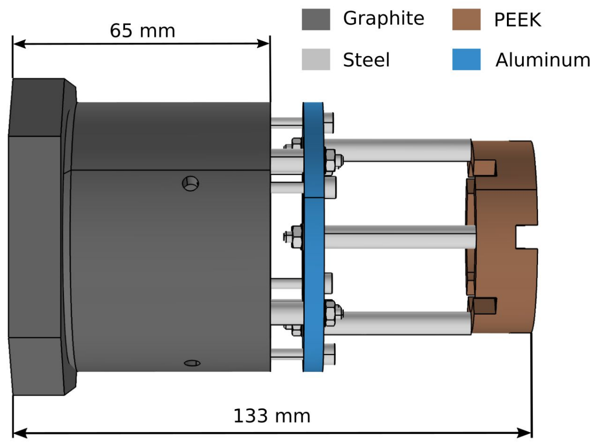
$E_{RE} < 20$ MeV
$I_{RE} < 2$ MA
$E_{max} = 1.5$ MJ
$q_{max} = 400$ MW/m^2

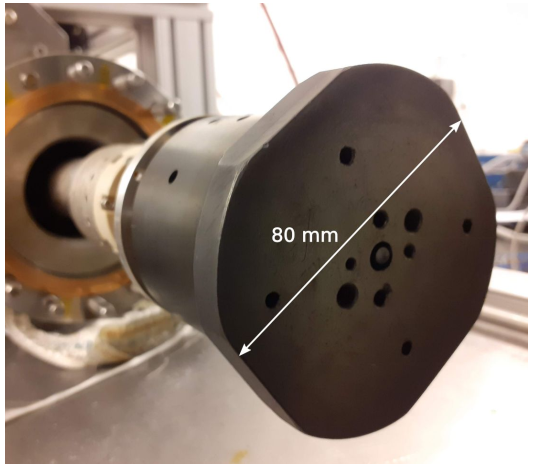
COMPASS-U estimated: $I_{RE} > 100$ kA, $E_{RE} < 20 - 25$ MeV
ITER estimated: $E_{max} = 300$ MJ, $q_{max} < 1$ GW/m^2

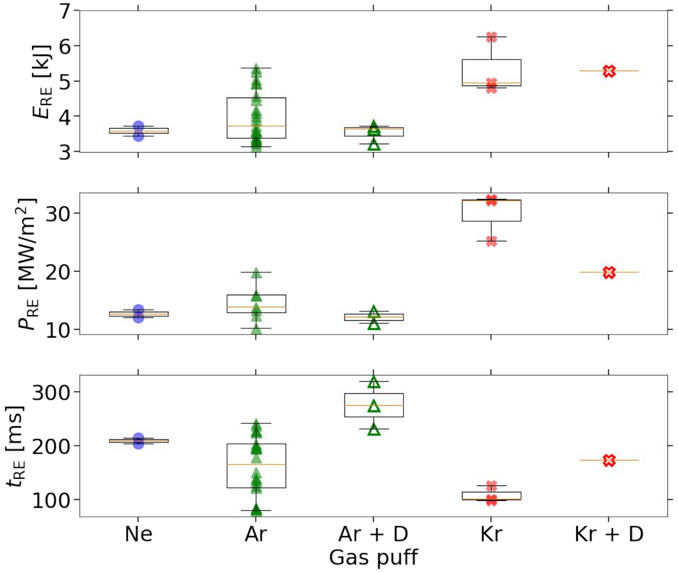
J Mlynar et al.: Plasma Phys. Control. Fusion 61.1 (2018): 014010
S Grashin et al.: Fus. Eng. Des. 146 (2019): 2100-2104
G Matthews et al.: Phys. Scr. 2016.T167 (2016): 014070

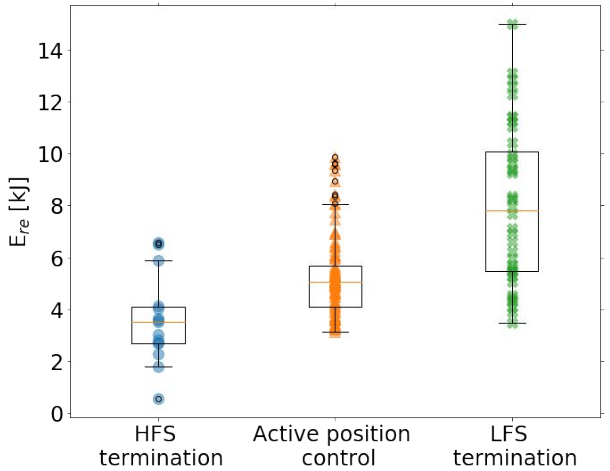
Runaway electron calorimetry at COMPASS

- RE calorimetry probe - master thesis project
- COMPASS LFS protection limiter equipped with temperature sensors for RE heat load measurements
- RE heat loads estimated from temperature sensors and IR measurements
- Measured effects:
  - Impurity injection (gas and pellets)
  - RE beam termination position
  - Additional RE drive



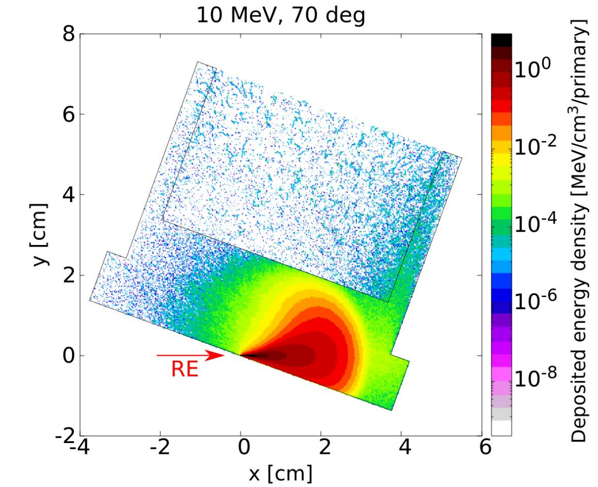


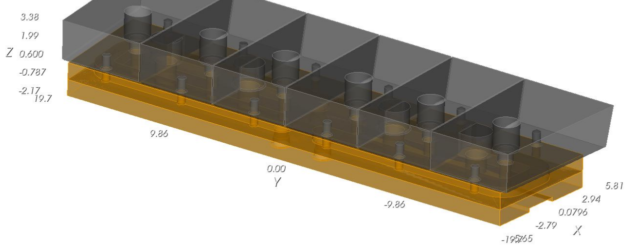


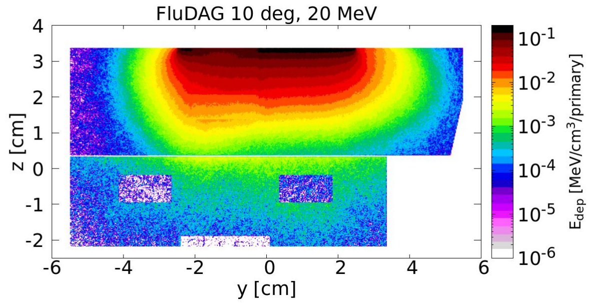


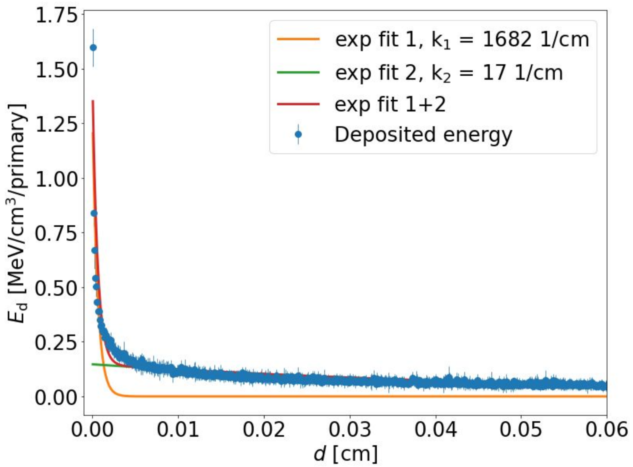
FLUKA Monte Carlo simulations

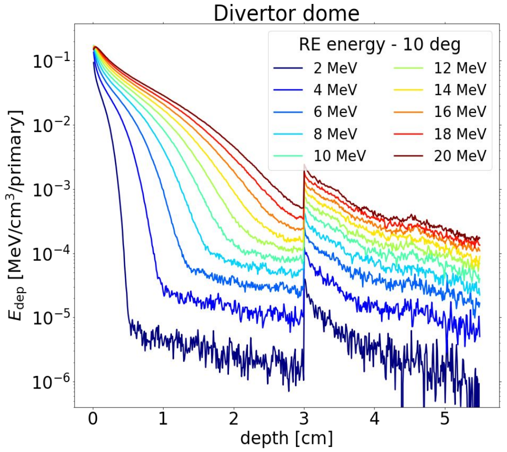
- Monte Carlo code for interaction and transport of high energy particles
- Modelling of energy deposition by runaway electrons in the PFC material
- Results can be exported to ANSYS for thermal analysis
- RE impact simulated for:
  - COMPASS RE calorimeter
  - COMPASS-U outer limiters
  - JT-60SA limiters and divertor
  - Planned: WEST calorimetry divertor tiles damaged by RE impact











Summary

- First wall thermal measurements important for safe tokamak operation and development of heat load mitigation techniques
- Predictive modelling needed for scenario development, optimization of plasma-facing components and diagnostics development
- Commonly used plasma heat flux diagnostics:
  - PFC calorimetry
  - IR thermography
  - Electrostatic probes
- Plasma heat flux simulations:
  - Field line tracing - heat flux distribution
  - Heat conduction - temperature change
- Runaway electron heat loads can damage plasma-facing components
- Calorimetry diagnostics and predictive modelling can be used for development of mitigation strategies