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Thesis aiming at the Research Professor (DSc.) degree

Heat transport in tokamak plasma boundary

název disertace

Komise pro obhajoby doktorských disertací v oboru
Fyzika vysokoteplotního plazmatu

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ABSTRACT

With the goal to obtain the title of Research Professor (DSc.), here I summarize all my peer-reviewed publications (mostly in the field of the edge plasma physics (mainly its turbulence) on various European tokamaks), all inter-linked with common *goal to contribute to a successful design of tokamaks ITER*[1] *and later DEMO*[2]*, paving the way to sustainable thermonuclear fusion production of electric (and heat) power for the benefit of humankind sustainable development.* **This research lead me to the decision to work on the principal Res. Prof. thesis topic in chapter 3:** ***heat flux predictions for future tokamaks*** **(by scalings and simulations) but mainly** ***engineering solutions sustaining intense heat fluxes.***

[1] ITER = international thermonuclear experimental reactor
[2] DEMO = demonstration thermonuclear fusion power plant

1. GENERAL MOTIVATION: URGENT NEED FOR EMISSION-FREE AND SAFE ENERGY

Climate change urgently pushes for zero-carbon energy

Energy consumption is the principal driver of the world economy (and so the human civilization development), however, it's extremely strongly correlated with the carbon dioxide emissions (and CH_4), see Fig. 1.1 , because still 85% of primary energy is produced by burning fossil fuels (oil, gas, coal). As this anthropogenic CO_2 is a greenhouse gas, it warmed the Earth surface already by 1^oC and the implied climate changes already started to have significant socio-economic impact. Among many, let's mention one example of soon perturbation of planetary scale to come: the volume of Arctic sea ice already dropped by factor of 4 during the last 40 years [41], suggesting an "ice-free summer Arctic" may arrive by 2030. In Czechia today, this impacts mainly forestry and agriculture through the increased intensity of floods and droughts, monitored by project https://www.intersucho.cz.

Mitigating the climate changes has been progressively recognized as one of the greatest challenges for humanity according to Pope Francis [1], NASA.org [3] and mainly the United Nations IPCC [2], overwhelming the problem of future fossil fuels depletion because "2/3 of current fossil fuel reserves must remain underground to stay below 2^oC" [7]. That's why the European Commission released a strategic vision for a climate-neutral Europe by 2050 [4]. As shown in Fig. 1.2 , last 40 years the emissions continued to rise by +1.5%/year whilst in order to stabilize the Earth temperature below 1.5^oC (above the pre-industrial level), it's necessary [2] to decrease it by −7%/year from the actual 42 billion tons CO_2^{eq}/year down to zero net emissions by 2050 when some remaining really unavoidable emissions (e.g. from air traffic or cement production) should be compensated by carbon capture and storage technologies (so far yet under scientific development). This somehow controversial and political statement I presented many times publicly (TV, radio, public seminars) since 2014.

This implies very challenging changes in most human activities, among those

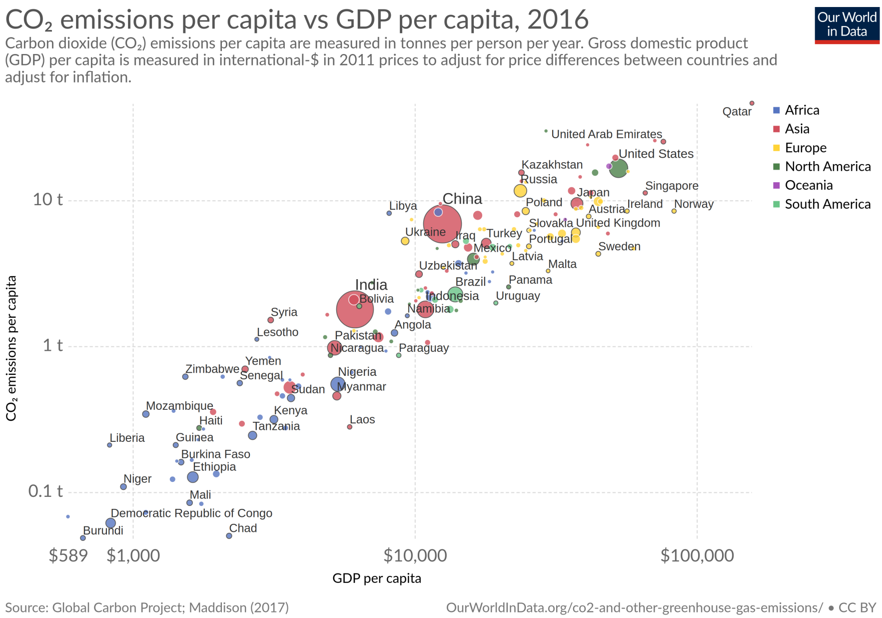


Fig. 1.1 *:* Historic pathways of world countries: CO_2 emissions strongly correlate with the gross domestic product. Czechia is between Poland and Japan. The *carbon emission intensity* CO_2/HDP=0.35 kg/€ is nearly constant across countries and time (weakly drops by -1.5%/year). Since global GDP grows, emissions rise by +1.5%/year [9].

e.g. increase in installed nuclear power stations by a factor of 2-5 until 2050 according to complex and reasonable scenarios on [2, page 19], whilst the last 20 years the nuclear power-generation industry stagnates [WNA IAEA 2017] due to lack of public support given its safety. This would require constructing 30-80 GW_e nuclear power plants per year worldwide, thus investments 150-400 billion € per year (requiring immediate order of magnitude increase in manpower in the nuclear industry) plus much more for others (wind + solar + biomass + electromobility + agriculture + ...) accounting for more than 1% of the world *gross domestic product* (GDP_{2018}=88'000 billion €). Paying this price seems reasonable in view of the actual *social cost of carbon, SCC* which has been estimated at \$31/tonCO_2 (which accounts now for 1% GDP) and rising up another 3%/year [8][1] for the "climate-economy optimal" scenario reaching 3.5^{o}C by year 2100, however, it should be \$230/tonCO_2 if aiming for less than 2^{o}C. In the EU, the price of the *emission allowance* in 2019 increased upto \$30/tonCO_2. According to the respected economic OECD report [10], projections "of the climate changes cost" by the year 2100 are somewhat less alarming (upto 2-10% GDP), which is still way above the growth rate, therefore suggest climate-change-induced economic recession of most countries. The pressure to realize *zero-carbon economy* will thus most likely dominate throughout the 21st century and it will be an extremely challenging endeavour.

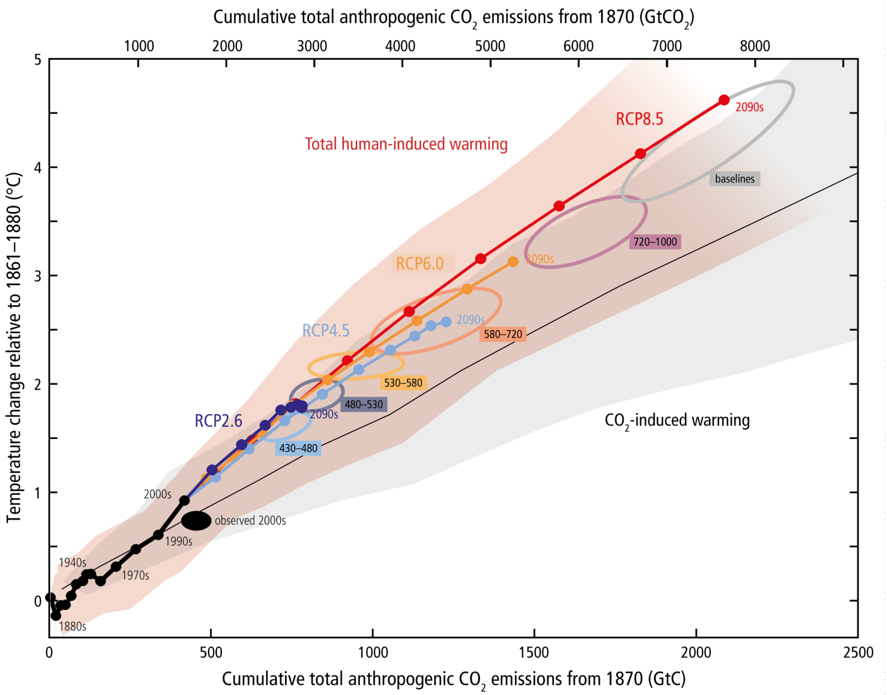
Fusion is a safe, zero-emission and inexhaustible energy source

Fusion offers a much longer-term, safer and cleaner option for energy production than nuclear fission. **Fusion is as renewable** as water, wind and photovoltaics power sources are [12]:

- **no greenhouse gas** emissions
- **no highly radioactive long-term waste**. There's only fast decaying waste from construction materials (ten thousand tons of mainly steel) which becomes radioactive during the operation, however, it doesn't burn nor it dissolves in water thus cannot be released into environment. Decay time of the steel radioactivity is decades-long instead of millenia for fission products.
- **no risk of serious nuclear accidents (meltdown)**: due to the extremely difficult conditions required for fusion, it's **inherently safe**. Any accident (or attack) leads to immediate stop of the nuclear reactions. The

[1] the author received the Nobel prize for the economy of the climate change in 2018

a)



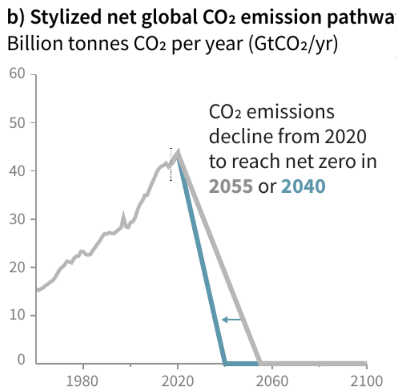


Fig. 1.2 *:* **a)** The Earth mean surface temperature rise nearly equals to cumulative integral as $\delta T[^{o}\mathrm{C}] = \int_t \text{emissions} \cdot dt \;/\; 2\times10^{15}\ \mathrm{kgCO_2}$. **b)** Historic $CO_2^{\text{equivalent}}$ emissions and its required pathway to stabilize the Earth temperature at 1.5^{o}C above the pre-industrial level [2]. Such scenario is extremely challenging for technical, economic, social and political reasons.

amount of radioactive fuel (energy) stored inside fusion reactor is 10 million times lower than in a fission reactor. If any disturbance (accident) occurs, the plasma (weighing only grams) cools down within a millisecond and so the nuclear reaction stops. In the three main nuclear fission accidents which ever happened (Three mile island, Chernobyl, Fukushima) it was dangerous principally because of the large amount of the radioactive fuel released into environment. Accidental release of fuel (3/4 kg Tritium) is principally possible in a fusion reactor. It may produce at maximum 4 litres of weakly-radioactive water (it's a β-radiator).

- the fusion fuel is **inexhaustible**: Lithium and Deuterium sources are sufficient for million years of worldwide consumption
- **limited nuclear military proliferation**. Fusion doesn't employ fissile materials like uranium and plutonium - there's no link to nuclear weapons.
- **its economy is comparable to photovoltaics** or better if externalities were included [Entler 17, Entler 18]. Taking all possible uncertainties in this century-long and expensive R&D project, the expected future economic value of fusion energy is significantly positive [11].
- **the fuel** (Lithium and Deuterium) **is present everywhere** in the world, thus mitigating possible geo-political conflicts

Additional advantages with respect to renewables (wind, photovoltaics and water energy) is the **weather independence**. There is simply no need for:

- **backup power plants** (usually fossil-fuelled)
- **huge energy storages** (pumped storage hydroelectric power stations or batteries)
- **enlargement of power grids capacities**

Around half of the worldwide fusion research happens in Europe. It is coordinated by the EUROfusion organization (previously EFDA), part of the Euratom organization with the reasonable R&D path towards fusion power plant specified in the political-administrative document [13] with the goal to provide fusion electricity around 2055 in a tokamak reactor called EU DEMO. Its most recent design strategy is overviewed in [23], with issues concerning critical material qualification for high plasma and neutron loads in [22].

History and future: how far is fusion R&D now?

Within half a century of this goal-oriented research there have been dozens of concepts (cold fusion, muon fusion, magnetic mirrors, magnetic traps, etc.) which were later wisely abandoned after critical experimental evaluations. At the best of my understanding the most promising concept remains magnetic fusion, especially tokamaks, backed-up by stellarators (which are better than tokamaks in confinement physics and machine safety but worse in engineering complexity), both marching far in front of any alternatives including the inertial fusion concept [5].

Refering Fig. 1.2 b, the challenging effort to achieve zero-carbon economy by 2050, it's becoming more and more likely that fusion will become mature too late: assuming optimistically that DEMO starts around 2060 (20 years [13] after the first DT fusion in ITER), 10% of world electricity could be supplied by fusion in 2090 [6], likely not earlier. Will the energy market still need it so late? Frankly speaking, I believe the scenario Fig. 1.2 b is (hardly) achievable within EU (as officially stated in its 2018 strategy document [4]), however, it would be very challenging even for EU and impossible without strong boom of nuclear (fission) energy new installations. Since EU (as clearly the worldwide most climate-oriented leader) is responsible for only 11% of CO_2 world emissions, it's very difficult to imagine zero-carbon world by 2050. According to [9], the economy-climate optimum strategy is to accept yearly-emissions to rise until 2050 ... which implies global warming by 3.5^oC in year 2100 (and stabilizes at 4^oC). Such warming would have, however, strongly devastating consequences on most global ecosystems, food production worldwide, droughts and flooding and overall global economy, as clearly stated in [2, page 13]. That's probably why fusion is well financially supported: ITER is the second most expensive civil experiment. With $18 billions budget it's after the International Space Station worth $150 billions. However, the worldwide fusion program lacks resources for additional (much cheaper but necessary) parallel experiments (especially the neutron-irradiation facility IFMIF for new material development and testing).

Principles of thermonuclear fusion in tokamaks, basic plasma concepts, the tokamak geometry and especially the remaining physics/engineering challenges are well explained in our 2019 Czech-language book [Entler 19b] for general public or in a more detailed English book [12], both available free on-line.

2. PATH THROUGH 1999-2009 TOWARDS RES. PROF. THESIS

2.1 Master's Thesis on small tokamak plasma turbulence

During my Master thesis, 1996-2000, Charles University, Prague [Horacek 00] I participated on experiments with arrays of probes on small tokamak CASTOR on understanding the turbulent energy transport [Stockel 99,Hron 99,Duran 00, Dyabilin 01, Gunn 01b, Gunn 01a] from the edge of the magnetically-confined plasma core onto the plasma-facing components.

2.2 PhD thesis on medium-size tokamak turbulence: experiment & simulation

During my PhD thesis, 2001-2006, EPFL, Lausanne, Switzerland, I continued research on turbulent transport on the medium-size tokamak TCV by means of Langmuir probes reciprocating into the edge plasma (returning back within 0.1 second before overheating). Those experimental data with relatively unique quality [Graves 05, Horacek 05, Labit 07] and interesting fractal properties we cross-checked later with a 2D fluid turbulence plasma model ESEL ran by research group from Denmark RISØ. It describes plasma turbulence (split into blobs) driven by fundamental interchange instability through gradients of the magnetic field and plasma pressure. This collaboration yielded many highly cited publications [Garcia 06,Pitts 07,Garcia 07a,Garcia 07c,Garcia 07b, Fundamenski 07,Chankin 07] since especially the plasma density spatial profiles and its fluctuations were found very well described by this relatively simple model.

In parallel, I studied also the physics of divertor (detachment) by means of probes embedded to the wall published in many papers [Pitts 01, Pitts 03, Pitts 05]. We tried to develop a model [Horacek 03] explaining why divertor probes don't measure correctly low temperatures. Even though the model could not explain it successfully, later [Duran 15] we attempted it again on data from the tokamak JET, finding again that the physics mechanism (non-local effects of plasma electrons) cannot explain this misbehaviour. Combination of probes with newly installed infrared cameras allowed studies of the plasma-wall interaction [Marki 07, Veres 07, Marki 09]. We interpreted these experiments by means of 2D transport code SOLPS [Wischmeier 04, Gulejova 07].

Some alongside collaborations on tokamak TCV yielded another interesting publications on various topics not covered by the PhD thesis [Moret 02, Henderson 03, Mlynar 03, Goodman 03, Martin 03, Goodman 05].

2.3 Collaboration on various topics

2.3.1 CASTOR turbulence and improved confinement mode

After having finished the PhD thesis, I moved back from Switzerland to Prague, where I became again part of the small tokamak CASTOR team. I focused on edge plasma turbulence [Van Oost 07, Brotankova 09, Fuchs 09] where we tried to improve plasma confinement by external electrode biasing: inducing poloidal velocity shear indeed destroyed the outwards-moving plasma blobs and so improved the plasma confinement [Stockel 07]. This technique, however, cannot be extrapolated to bigger tokamaks with much much longer plasma duration as it requires immersing a big electrode into the hot plasma, resulting in release of huge amount of impurities and destruction of the electrode.

2.3.2 Development of novel tokamak probes

A modification of Langmuir probe, the so-called *ball-pen probe (BPP)* was invented [16] and tested [Adamek 09, Adamek 10] within our team, even though theoretical understanding of its functionality was modeled in PIC code [30] with partial success and only much later successfully verified by another PIC team [33]. It uniquely directly measures plasma potential and combined with a floating Langmuir probe it provides extremely fast (and local) plasma temperature measurement. Adding another negatively-biased Langmuir probe (measuring J_s) yields fast (on turbulent 1 μs time-scale) and local (2 mm) measurement of most of the important plasma parameters: *plasma potential* ϕ, *electron temperature* T_e, *plasma density* n_e. Since the so-called ion saturation current density J_s/e equals to the ion flow along magnetic field lines, the *plasma heat flux* is evaluated as $q_{||} = \gamma J_\mathrm{s} T_\mathrm{e}$ where theoretically [40, page 92] the *sheath heat transmission coefficient* $\gamma > 7$ we found experimentally [Vondracek 19] $\gamma = 11$. The (turbulence-driven) *cross-field flux* (perpendicular to the magnetic flux surfaces) of both particles and heat is also derived from the combination of those probes.

We cross-checked ball-pen probes data many times with classical (slow) Langmuir probes [Mueller 10, Mueller 11, Kocan 13, Loureiro 14], concluding that it measures most reliably in simple L-modes especially in the limiter shadow [Horacek 10] (much closer to the modelling-based expectation than swept Langmuir probes). Cross-checking with self-emissive probe showed excellent match in [Adamek 14], later also verified with fast (but non-local) triple probes and laser Thomson scattering [Adamek 16]. Infrared camera allowed verification of the derived heat flux even suprisingly during very fast H-mode ELM events [Vondracek 19].

We also experimentally tested another probe technique [Popov 14,Popov 15] on COMPASS divertor demonstrating a double-temperature character of the edge plasma, however, its reliability seems very limited.

2.3.3 Reinstalling tokamak COMPASS, probe diagnostics and its control system

In 2008, we replaced the old small CASTOR for a medium-size tokamak COMPASS [Panek 15], which required building new diagnostics [Weinzettl 11,Weinzettl 17]. With my student I reinstalled reciprocating probe (built by the University of California in San Diego and used for my PhD thesis [Horacek 06] in Switzerland). We fit its vacuum-mechanical design for COMPASS vertical orientation [Vondracek 10] and made the control system fully digital [Vondracek 12].

Since a new digital control system of the tokamak plasma position, current and density was required, we built it from scratch [Valcarcel 11,Janky 11] and I was leading PhD thesis on this topic [Janky 16]. We developed a physics-based numerical model of the plasma vertical instability control system based on the coil and plasma geometry. However, as being too simplistic it's never been published, even though it helped to tune the PI controller.

2.3.4 EUROfusion collaboration

Our collaboration on EU tokamaks (TCV, MAST, JET and ASDEX-Upgrade) is regularly broadly overviewed at annual papers [Romanelli 13, Meyer 13, Romanelli 15, Chapman 15, Coda 17, Litaudon 17, Kirk 17, Meyer 17, Kazakov 17, Coda 19]. My direct contribution to those papers with a hundred of co-authors is very limited. In principle, those papers rather reference other publications and put them into broader mutual context.

2.3.5 Tokamak JET divertor physics

I analysed divertor probes on tokamak JET, which yield surprisingly low electron temperature during the ELM events. The analysis [Guillemaut 15] was based on the so-called *conditional-averaging (CAV)* method: this yields fast enough time-resolution based on slowly-swept Langmuir probe, assuming all the ELMs (averaged together) are identical. This yields time-resolved ELM plasma electron temperature, which shows suprisingly low values: order of magnitude lower than the *pedestal temperature* from where the plasma is expelled. Even though the method cannot resolve fine ELM structure (filaments), we concluded that indeed the electrons are strongly cooled down. Such a result was expected according to the free-streaming model [24], implying that their energy is transfered into ions. So indirectly estimated high ion temperature yields to so-implied tungsten sputtering [Guillemaut 16] which is (due to non-linear temperature dependency) therefore much higher than usually expected. Since the ELM-induced ion sputtering of tungsten thus seems to be the dominant impurity source into the plasma of big tokamaks, those two papers already yielded 27 citations per 4 years. Comparable CAV ion temperature from the tokamak Asdex Upgrade we published [Kocan 13] already in 2013, directly measured using the slow retarding-field analyser.

This conditional-average method has a risk of "not seeing ELM fine structure - filaments" which may thus significantly overestimate the ELM-typical ion temperature, thus its sputtering. In order to verify it, in 2019 on COMPASS we used the uniquely fast BPP-LP divertor array. Direct verification of this method, based on a limited number of suitable data, demonstrated that indeed the CAV method was not too far from true, calling for another COMPASS experiment with higher voltage span to really prove it.

2.3.6 Tungsten divertor melting by ELMs

We studied the undesired divertor tungsten melting by regular expells of plasma (ELMs) [Coenen 15a, Coenen 15b, Arnoux 15] on JET, see Fig. 2.1 . We observed that indeed each ELM melts shallow surface of tungsten. The melt then flows away along the surface and re-solidifies, as properly interpreted by the MEMOS 3D numerical model [18] where the dominant forces include the melt friction and viscosity and mainly the $J \times B_{\mathrm{toroidal}}$ force where J is the *thermo-emissive current*[1]. Its exponential rise with surface temperature (and the implied $J \times B$-force induced melt motion) we studied on ASDEX Upgrade [Krieger 17].

[1] it's the current of electrons emitted from hot surface by thermal (evaporation) emission

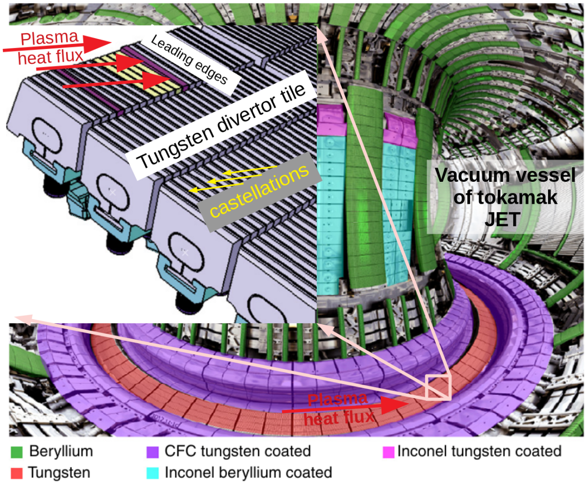


Fig. 2.1 *:* View inside the vacuum vessel of tokamak JET. The insert shows details of a tungsten divertor tile with its leading edges of the lamellas exposed at shallow angle ($\approx 3^o$) to the plasma heat flux. Here the yellow lamellas were, however, deliberately recessed to let the violet lamella be exposed to full perpendicular heat flux (which was therefore melted by ELMs).

PFCs on powerful tokamaks must be castellated. This means a surface with notches allowing for thermal expansion. If absent, intense heat pulse cracks the surface (to release the thermal expansion stress) which is sometimes called "self-castellation" ;-). Leading edges of those castellations are prone to melt since its surface is perpendicular to the plasma heat flux, especially prone are if misaligned (surface of neighbouring tiles shifted by more than a fraction of a millimetre). Heat loads on edges of *castellated PFCs* we studied in COMPASS [Dejarnac 18], concluding that the classical optical approximation well describes the observed heat loads (therefore electrons dominate the heat channel) with minor modification by ions which (due to large Larmor radius) heat regions in magnetic shadow). In the preceding well-diagnosed and modelled experiment [Dejarnac 17] we realized that indeed no mysterious mitigation factor needs to be applied, which was indeed suggested in [Coenen 15a] to explain the IR observation of the JET leading edges. finally concluded for ITER divertor design in [Pitts 17].

3. CONTENTS OF THIS RES. PROF. THESIS: 2010-2019

The previous research lead to the decision to work on **my principal Res. Prof. thesis topic** : *heat flux predictions for future tokamaks* (by characterising turbulent transport, empirical scalings and turbulence simulations) but mainly *engineering solutions sustaining intense heat fluxes.* Here it's very briefly overviewed. In more details it's in the main Res. Prof. thesis [Horacek 20b]. In Czech, successes of the COMPASS team are overview in [Entler 19a].

Watch 75 minutes video summarizing this chapter in popular form in Czech language

3.1 Turbulence simulation (ESEL) compared with probe measurements

Good correspondence between the model ESEL and both the edge plasma density spatial profiles and fluctuations we found [Horacek 10] also on the large tokamak ASDEX Upgrade. This time we started to measure also the plasma potential and temperature with uniquely high time resolution by means of ball-pen probes, resulting in a quite bad model description of both the potential and temperature [Horacek 10, Ondac 15], described in more details in MSc thesis [Ondac 14]. Therefore we stopped using the 2D ESEL as it's too simplistic, even though we attempted joining it with another 1D model [Havlickova 11b,Havlickova 11a] but rather later used a follow-up 3D model [Halpern 13, Halpern 16] used for the Near-SOL physics (see later). Extremely high statistics allowed scaling of blob velocities [Tsui 18] in four established edge plasma regimes.

Using extremely long probe time-series of edge plasma turbulence, we later argued [Garcia 15, Theodorsen 16] that the established paradigm of the "long-range correlations" is false: the observed correlations and statistical properties measured (among many others) in [Labit 07, Horacek 05, Garcia 06, Garcia 07a, Garcia 07b, Garcia 07c] are a pure statistical coincidence of uncorrelated blobs passing by the probe. This simple stochastic model strongly simplifies the edge plasma physics understanding: it explains many statistical features, published in a hundred of papers worldwide, as a simple consequence of uncorrelated blobs with Poisson distribution passing by a probe.

We also studied physics of the Geodesic Acoustic Modes [Seidl 17] which have an indirect link to the transition into the tokamak high confinement H-mode.

Likely the most advanced EU edge plasma turbulent model is the 3D version of the model GBS [36] where also the blob velocity scaling is compared with the analytical formulas [Tsui 18]. Running this code requires, however, several millions of CPU hours even for a medium tokamak like TCV.

Passing through all those modeling efforts I realized, however, that developing a predictable model for a big tokamak is still far far away from nowadays computer capabilities: simulations either must be strongly simplified (with very limited practical applicability) or its CPU run-time is just too long. Successful examples of model-experimental comparisons are mentioned in [Horacek 20a, Halpern 16, Garcia 06], however, none of them is capable of credible simulation predictions for ITER. The principal reason is the large amount of blobs in the edge plasma: the typical blob size is around $10\rho_s$ (the hybrid Larmor radius) which drops with magnetic field, whilst the edge plasma volume is very large in ITER, thus the 3D GBS model may require some hundreds of millions CPU hours.

That's why in the next section we refocused on much more simple *scaling* techniques which require a lot of experimental time, however, no simulations and only a bit of physics understanding.

3.2 Optimization of ITER plasma-facing components

Each plasma in tokamaks starts and ends up in a limiter shape (c.f. the the time-evolution in Fig. 3.1). Within the ITER Div/SOL ITPA activity, we experimentally predicted the thickness of the plasma edge. The motivation was that the inboard heat shield tiles surprisingly melted on the world-largest tokamak JET [Silva 13, Arnoux 13], it's result of an unexpected steep heat flux gradient in the plasma edge called "Near SOL region". COMPASS was quite a suitable tokamak fur such study due to its flexibility, easy diagnostics access, and a still relevant plasma conditions. At first we had to install and calibrate three new infrared camera systems [Ulicny 13, Vondracek 19]. We tried to explain it by the non-ambipolar plasma behavior [Dejarnac 15] (even though we found it's too weak to explain the effect), but mainly we quantified it [Horacek 15] in accordance with the heuristic drift-based model [27]. Since the heat flux profile is indeed double-exponential, the 2nd part called "the Main SOL" I scaled in [Horacek 16] based on experiments on 10 tokamaks, followed by physics understanding and simulations [Halpern 13, Halpern 16, Tsui 17, Nespoli 17]. All this led to a change of the optimum design shape of the plasma-facing components in both future ITER [Kocan 15] and DEMO [Wenninger 17] tokamaks, later indeed accepted by the ITER organization for its engineering construction plan [14, pages 111-112].

Standard operation shape of plasma is diverted as shown by the green curve in Fig. 3.1 . While already in divertor shape, the so-called *L-mode* is used on all tokamak discharges startup phase before switching into higher confinement H-mode. I measured and collected data from five tokamaks, deriving 13 new scalings based on well-known parameters, all yielding roughly similar and credible prediction for future ITER and COMPASS-Upgrade plasmas [Horacek 20a].

We also contributed to the scaling of ELM heat pulses, starting at mid-plane [Adamek 17b] and mainly divertor [Adamek 17a] which again allowed to predict its (devastating) impact in those future tokamak divertors.

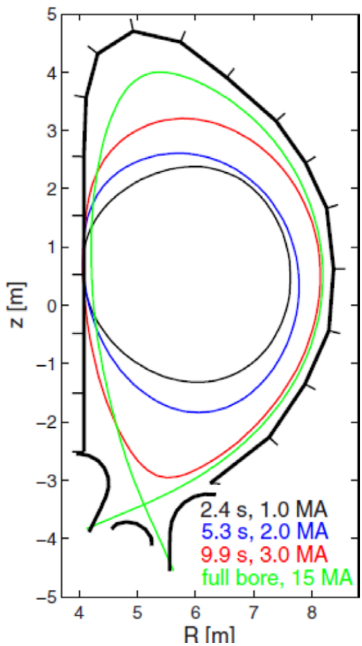


Fig. 3.1 *:* Plasma current ramp-up 10 seconds long sequence of magnetic configuration LCFS of the ITER start-up scenario (from [Kocan 15]).

3.3 Solutions for DEMO divertor and future plans

Those experimental predictions of unacceptably high ELM pulses shed light on the still remaining big problem for a divertor in DEMO. This pushed me to invent a novel engineering technique suppressing ELM heat pulses. Based on a model of 3D heat diffusion (developed within the Bc. thesis [Wolff 11]) and thermovision data from JET rescaled for DEMO, we designed within the Master thesis [Duban 17] a set of special coils and its power electronics, concluding that it's a feasible technique for DEMO with reasonable cost. After having published it in [Horacek 17], we changed significantly the C-coil design in [Sedmidubsky 17] because the published design would likely suffer from induced currents, as explained in [Horacek 20b, Section 6]. We're now waiting for a feedback from the international community to decide whether its first experimental test (on COMPASS-Upgrade) shall be planned or not.

Since 2018 we refocuse on the testing of a *liquid metal divertor (LMD)* test target as a *plasma-facing component (PFC)* exposed to extreme heat flux ($q_\perp < 40$ MW/m^2). Published in [Horacek 18b, Horacek 18a] we modified the 3D heat diffusion simulation for direct interpretation with the expected experimental observation on COMPASS in Autumn 2019. Within Bachelor's thesis [Cecrdle 19] we add an additional module of the liquid metal cooling by the Lithium *vapour shielding* of the LMD surface. Based on this experience on COMPASS, we hope to design a full toroidal liquid metal divertor on the new tokamak COMPASS-Upgrade for which I estimated the heat fluxes also reaching values [Weinzettl 19] above damage limits.

The conceptual design [Panek 17] of the COMPASS-Upgrade tokamak represents a compact, medium-size, high-magnetic-field and high-density device with a flexible set of poloidal field coils used for generation of single, double null and snowflake configurations. In addition, it will be equipped with a closed divertor, which will be operated at high plasma and neutral density and with high optical opacity similar to future reactors. COMPASS-U is capable of addressing some of the key challenges in the field of plasma exhaust physics, reactor-relevant edge plasma physics, advanced confinement regimes, advanced magnetic configurations and materials for next-step devices.

4. PERSONAL RESUMÉ AND FUTURE PLANS

Looking back at the 10 years of research described in my Master and Phd theses, followed by another 10 years described in this Res. Prof. thesis [Horacek 20b], it's clear that the thermonuclear research made huge progress especially in Czechia, based principally on upgrading from the 60 years(!) old small tokamak CASTOR (still in operation under the name GOLEM at FNSPE Czech Technical University in Prague) towards the reinstallation of the medium-size tokamak COMPASS in 2008 (now 25 years old, ran at our IPP institute in Prague) with just starting construction of the modern COMPASS-Upgrade, based on our long-term team experience also on European tokamaks (TCV, JET, ASDEX Upgrade, etc.) within intensive EUROfusion collaboration. The table shows the big stepladder which those devices represent towards realization of the thermonuclear fusion reactors ITER (experimental) and finally DEMO (generating heat and electricity). All the thesis chapters naturally follow each other, demonstrating necessity of those steps without which DEMO could never be constructed, and I'm happy to be part of this challenging endeavour.

Tokamak	CASTOR	COMPASS	COMPASS	TCV	JET	ITER	EU DEMO
Fus.Power	0	0	Upgrade	0	15 MW	1/2 GW	4 GW
Reference	[Stockel 99]	[Panek 15]	[Panek 17]	[Coda 17]	[Litaudon 17]	[Pitts 17]	[Entler 18]
Country	CZ	CZ	CZ	Swiss	EU	1/2 world	EU
discharge cost	10 €	200 €	1 k€	1 k€	50 k€	500 k€	generate 6 TWh/y
vol./m^3	0.05	0.7	2	2	70	700	2400
pl.energy	15 J	10 kJ	1 MJ	50 kJ	8 MJ	350 MJ	1 GJ
Plas.surf. heat flux $q_\perp$ MW/m^2	≈ 0.2	2	100	1–3	20	10–20	100
duration[s]	0.02	0.15	1.5	1.5	10	1000	10^8
Triple product $m^{-3} eVs$	10^{15}	2×10^{18}	10^{20}	10^{19}	3×10^{20}	5×10^{21}	10^{22}
temperat.	100 eV	1.5 keV	3 keV	3 keV	20 keV	15 keV	15 keV
operation	1960+	1990-2020	2023+	1990+	1974-2020	2036+	2055+

Tab. 4.1: Czech tokamaks in world perspective with approximate maximum parameters. One discharge cost estimate includes all $\frac{investment + yearly\ budget}{discharge\ total}$

My personal opinion is that our turbulence studies at the small CASTOR (my Master thesis) used to be worldwide relevant only until the ninetieth. It was wise to concentrate only on edge plasma as relevant to bigger tokamaks, since other CASTOR parameters (size, discharge length, energy) were already off scale. 2D turbulence simulations of my PhD thesis enabled explanation of turbulence measurements performed on modern divertor tokamaks, however, with very limited predictability towards ITER/DEMO which we hoped for. This activity we therefore nearly stopped in 2012, even though later (2016) we've found much better predictability for the TCV tokamak with more advanced (3D) model GBS.

Reinstallation of COMPASS since 2008 allowed us to significantly contribute especially to predictions (mainly by experimental scalings) of key parameters necessary for the construction of ITER, which is the principal part of this Res. Prof. thesis. Empirical scaling of lots of experimental data allowed us to change the design shape of the ITER inboard high heat flux panels, specified in the ITER engineering research plan. The most advanced predictions, however, show quite high risk that the ITER divertor will be easily damaged (melted) during weakly abnormal operation and that for the subsequent DEMO reactor it's even worse. This led me to refocus on possible solutions for DEMO: a new concept of fast swept divertor target spreading the ELM heat pulses across a larger area, but mainly the use of liquid metals as plasma-facing components. Liquid metal experiments on our Prague tokamak start in 2019 and will hopefully continue on COMPASS-Upgrade - a new tokamak currently under construction with expected worldwide record magnetic field and power density. In the meantime we'd like to construct a much smaller facility: an interaction chamber of our existing neutral beam injector with liquid metal targets, all this without magnetic field and plasma. It should deliver power density up to 80 MW/m^2 for a couple of seconds - enough to test (liquid metal) divertor target concepts for the future EU DEMO reactor.

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Authors orders = relative contributions (first = main author) but some use (after few main authors) alphabetical order

Publons H-index = 28 Google Scholar H-index=33	**Part of this Res. Prof. thesis**	**Total sum**
Publications	6	96
Citations	80+	2450
Citations w/o autocitations	77+	2100+

Tab. 4.2: **Jan Horacek publications (ResearcherID G-8301-2014) and online self-citations.**

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