# Enivsaged X3-scenario in OP2.1 and its startup commissioning

Torsten Stange on behalf of the W7-X team

# Outline

1. **Motivation: Why third harmonic X-mode heating (X3)?**
2. **Heating scenarios using X3**
3. **Startup Scenarios for X3-operation**
4. **Proposal for first startup tests**
5. **Summary & Outlook**

# 1. Motivation

- Lower field allows probably higher beta (even though $\tau_E$ is reduced) *… see talk by G. Fuchert @ X3-Workshop 03/2021*

⇒ Investigation of scaling laws in dependence on B ($\tau_E$, radiative density limit, transport coefficients $\chi$ …)

- Several magnetic configurations (e.g. low-iota very high mirror UFM) maybe possible @ $B_{axis,0°} < 2$ T

⇒ Predicted unstable against e.g. global free-boundary perturbations, allowing investigation + understanding of MHD stability *… see related talks by C. Nührenberg*

- Interesting ECRH physics + further validation of TRAVIS-code (even though X3-heating is already used at TCV)

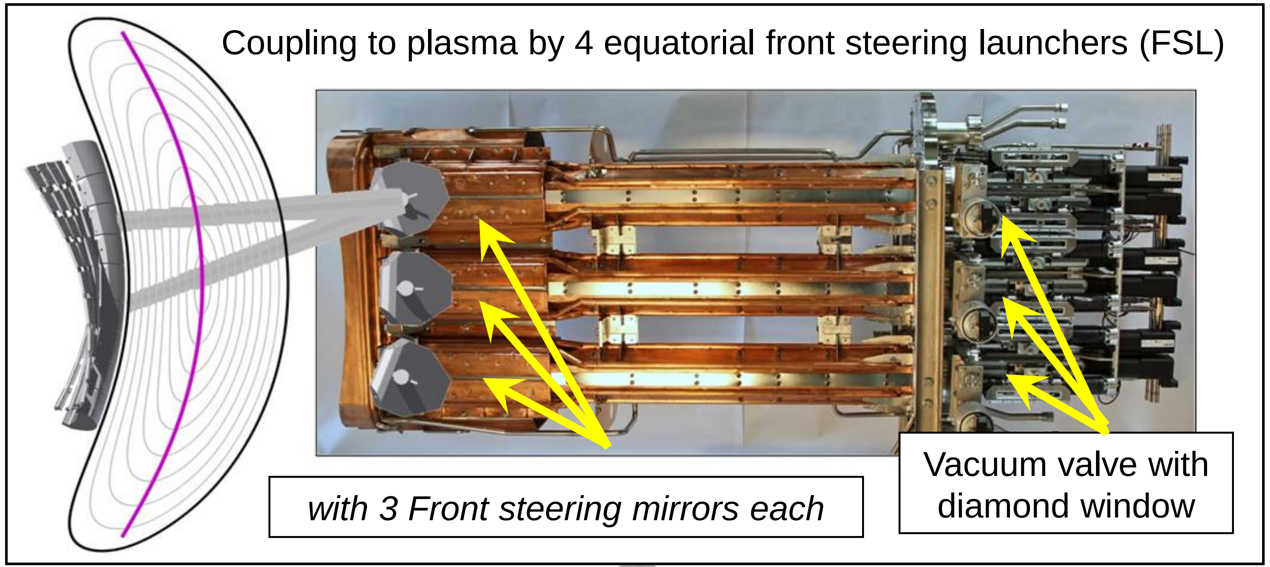
Operation regimes at W7-X with 140 GHz - ECRH around 2.5T:

- X2-heating $10^{19}$ m$^{-3}$ < $n_e \le 10^{20}$ m$^{-3}$, $T_e > 0.2$ keV
- O2-heating $5 \cdot 10^{19}$ m$^{-3}$ < $n_e \le 1.8 \cdot 10^{20}$ m$^{-3}$, $T_e \ge 3$ keV (cutoff @ $2.4 \cdot 10^{20}$ m$^{-3}$ but refraction and reduction of absorption)

Further operation regime with 140 GHz around 1.7 T

- X3-heating $n_e \le 1.2 \cdot 10^{20}$ m$^{-3}$ with similar behavior as O2-heating (cutoff @ $1.6 \cdot 10^{20}$ m$^{-3}$ but refraction difficult to handle)

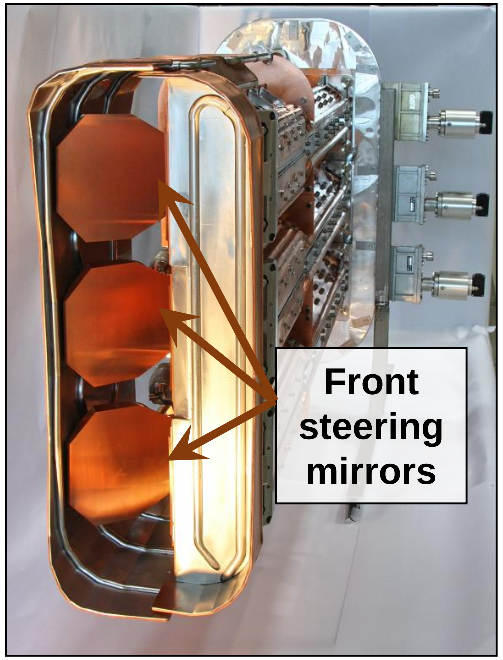
# 2. Heating scenarios: ECRH-system



Coupling to plasma by 4 equatorial front steering launchers (FSL)

*with 3 Front steering mirrors each*

Vacuum valve with diamond window

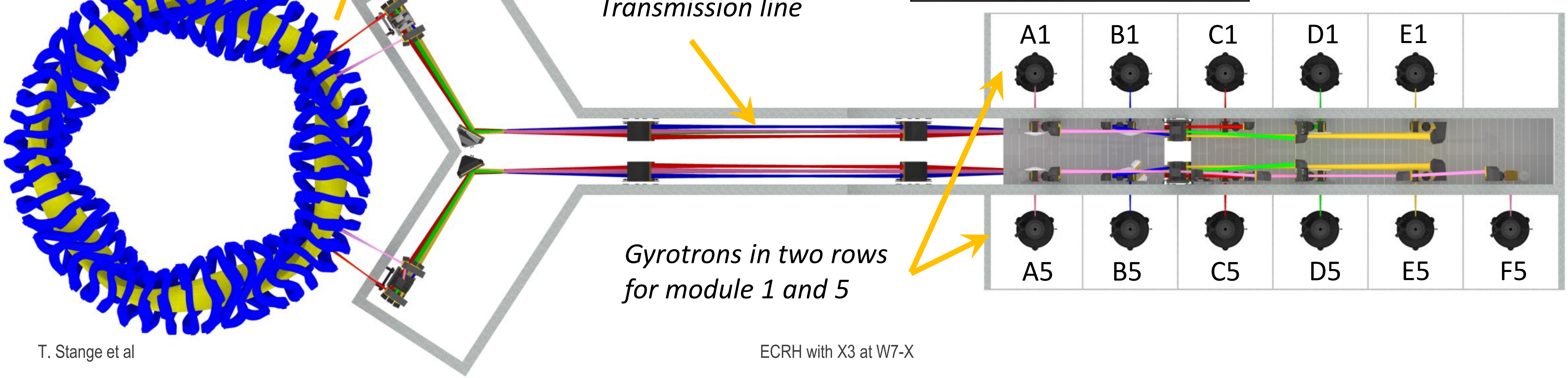


**Front steering mirrors**

- Currently 10 Gyrotrons with up to 0.9MW each @ 140GHz

⇒ overall input power of up to 7.5 MW steady state

- Further upgrade: with 11 gyrotrons ≈ 8.5MW in 2022



*Transmission line*

*Gyrotrons in two rows for module 1 and 5*

# 2. Heating scenarios: comparison of O2- & X3-absorption

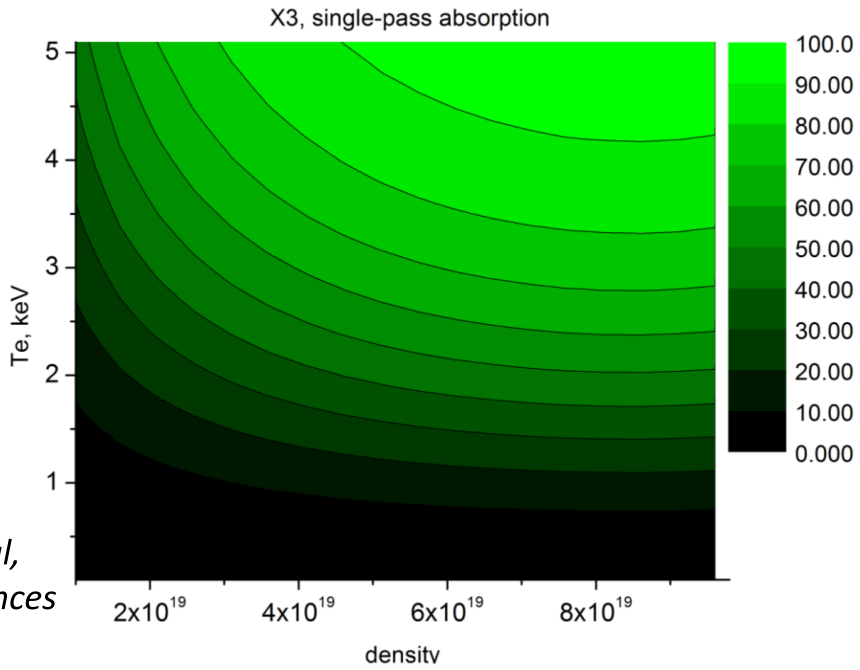
- X3-absorption with similar characteristics compared to O2-absorption (with regard to $n_e$ and $T_e$ – scales with $nT^2$)

⇒ Use of multipass scenario (for several seconds with central temperatures of the order $T_e \geq 3$ keV)

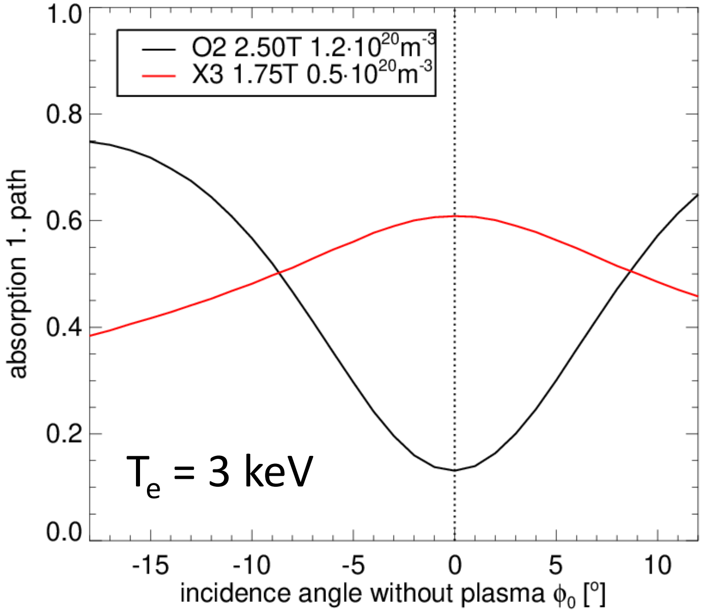
⇒ Plasma startup only possible by other heating scenario
(in case of O2-heating by switch from X2 to O2 during the discharge) *… detailed discussion later in the talk*

- Different angle dependence of absorption + X-mode polarized beam undergoes much stronger refraction

⇒ Same multipass scenario only useable for low densities around 3 - 7 $\cdot 10^{19}$ $m^{-3}$



*[Marushchenko et al, EPJ Web of Conferences 203, 01006 (2019)]*

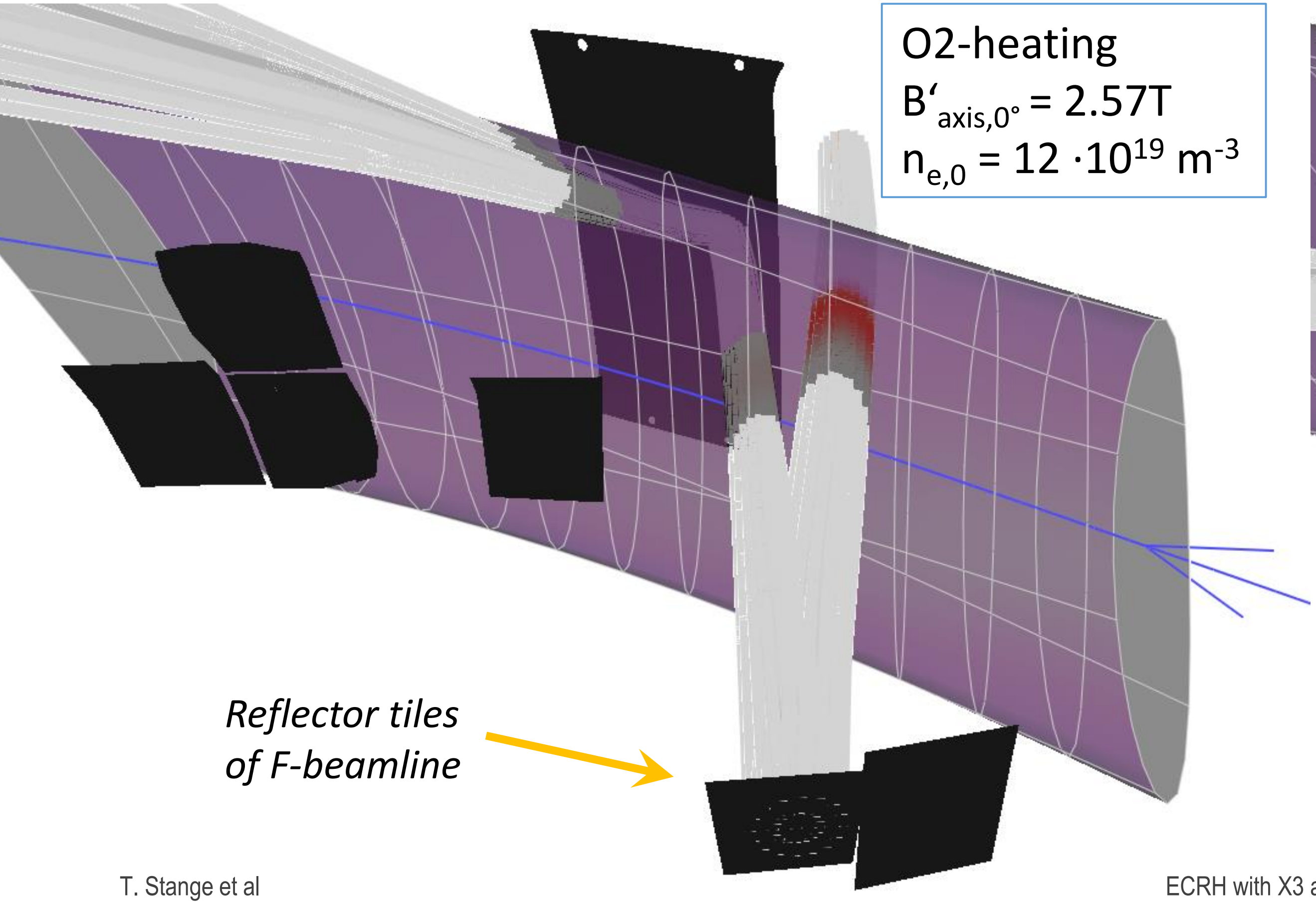


# 2. Heating scenarios: comparison of O2- & X3-refraction …

- O2-heating scenario was redesigned for OP2 to reduce stray radiation by about 50%

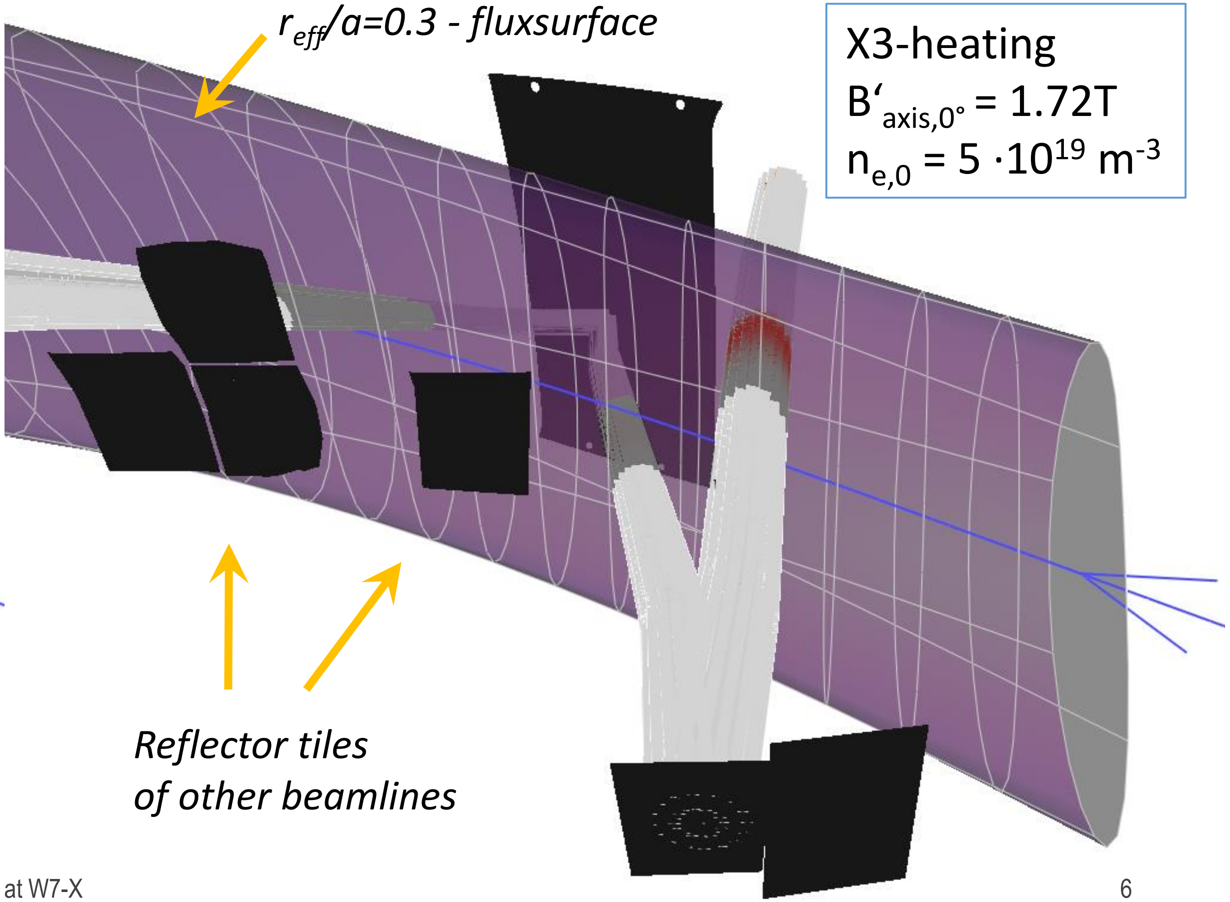
⇒ Higher incidence angles with regard to plasma for better absorption + polarization gratings for 2nd pass matching

- X3-heating with $n_e > 8 \cdot 10^{19}\ \mathrm{m}^{-3}$ and fast density variation: 2nd pass can enter into the other ECRH-launcher



O2-heating
$B'_{\mathrm{axis},0^\circ} = 2.57\mathrm{T}$
$n_{e,0} = 12 \cdot 10^{19}\ \mathrm{m}^{-3}$

*Reflector tiles of F-beamline*



*$r_{eff}/a=0.3$ - fluxsurface*

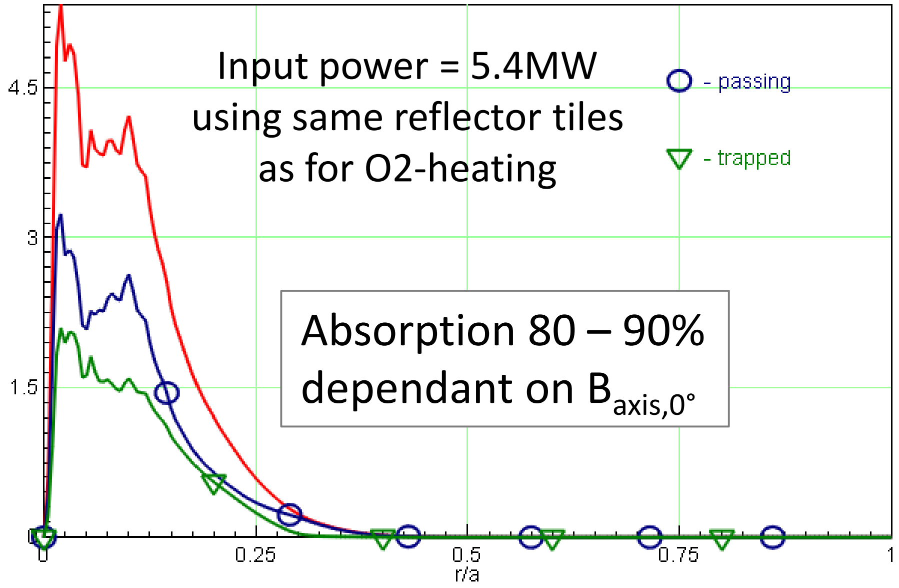
X3-heating
$B'_{\mathrm{axis},0^\circ} = 1.72\mathrm{T}$
$n_{e,0} = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$

*Reflector tiles of other beamlines*

# 2. Heating scenarios: X3 at low density

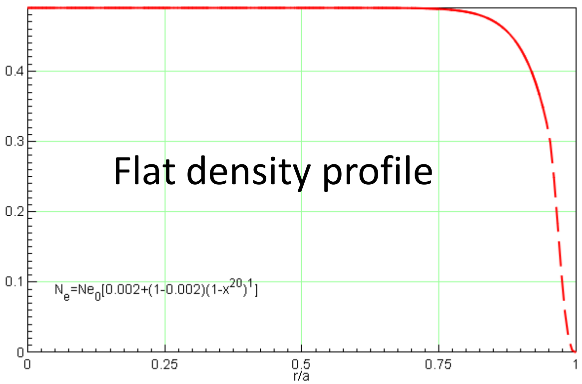
⇒ Multipass via O2-tiles only useable for low densities up to 7 $\cdot 10^{19}$ $m^{-3}$

⇒ However, these tiles allow cw operation and polarization matching of 2nd pass and



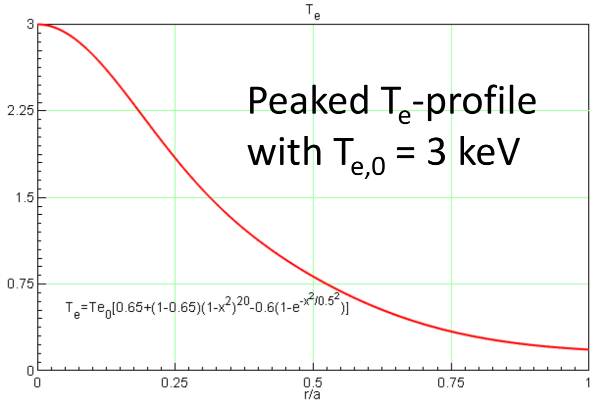
Input power = 5.4MW
using same reflector tiles
as for O2-heating

Absorption 80 – 90%
dependant on $B_{axis,0°}$



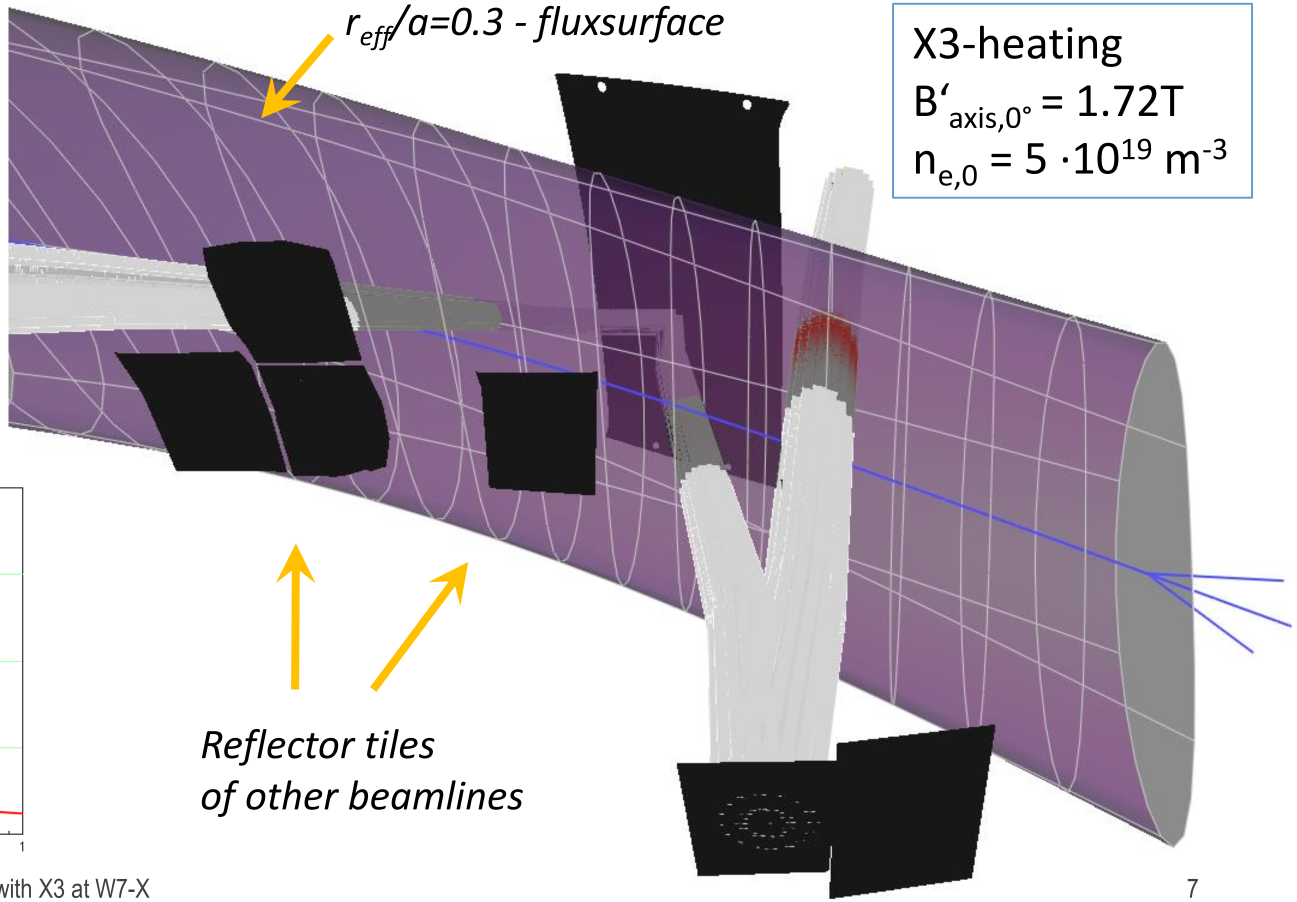
Flat density profile

$N_e = Ne_0[0.002+(1-0.002)(1-x^{20})^1]$



Peaked $T_e$-profile
with $T_{e,0}$ = 3 keV

$T_e = Te_0[0.65+(1-0.65)(1-x^2)^{20}-0.6(1-e^{-x^2/0.5^2})]$



*$r_{eff}/a$=0.3 - fluxsurface*

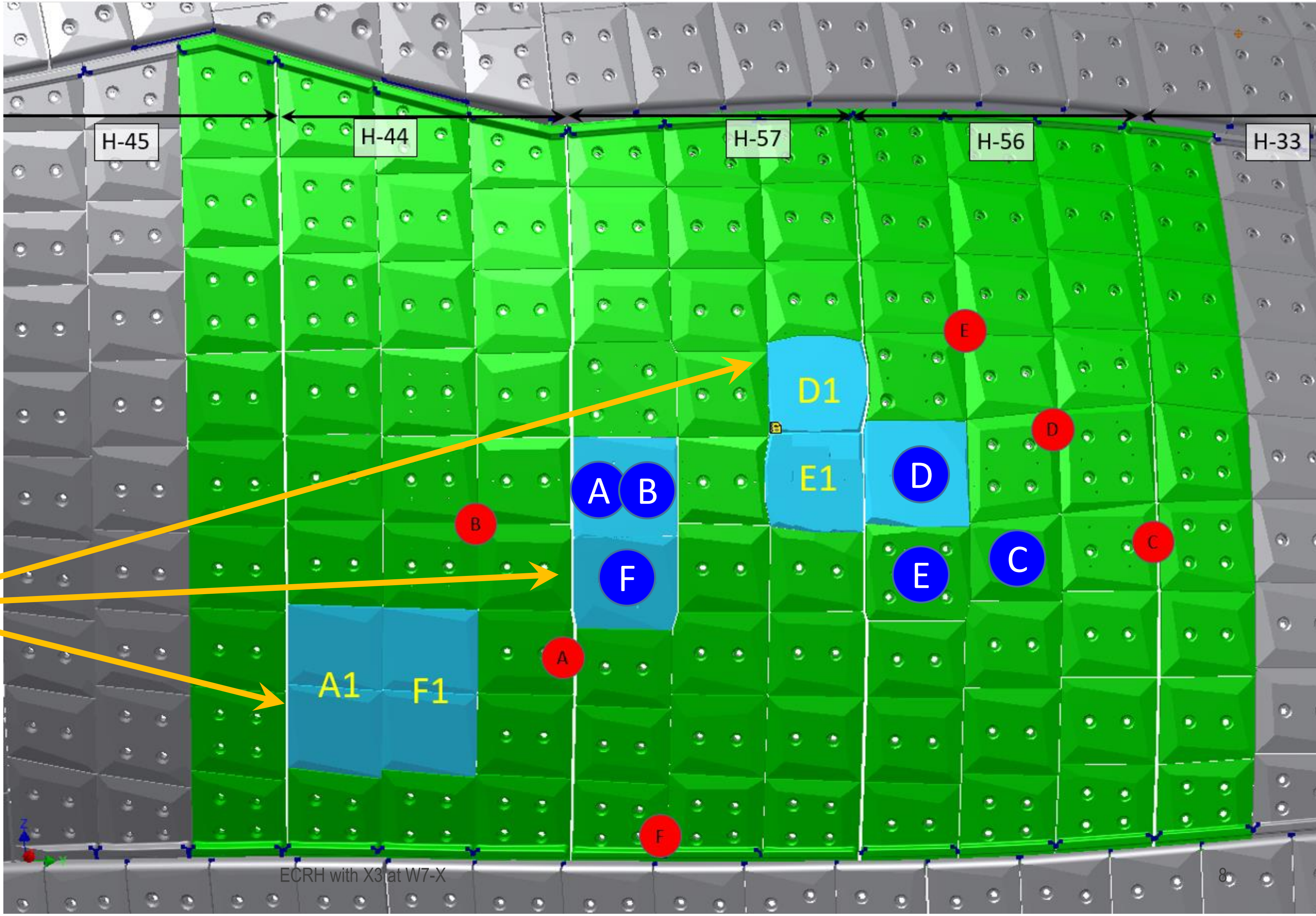
X3-heating
$B'_{axis,0°}$ = 1.72T
$n_{e,0}$ = 5 $\cdot 10^{19}$ $m^{-3}$

*Reflector tiles*
*of other beamlines*

# 2. Heating scenarios: X3 at high density

- broad area of heat shield opposite to ECRH-Launchers is W-coated in OP2 (green)
- same low absorption of direct ECRH-beam compared to dedicated reflector-tiles

⇒ possibility to use W-coated graphite tiles for several seconds as non-optimized reflector during X3 (take care of arcing)

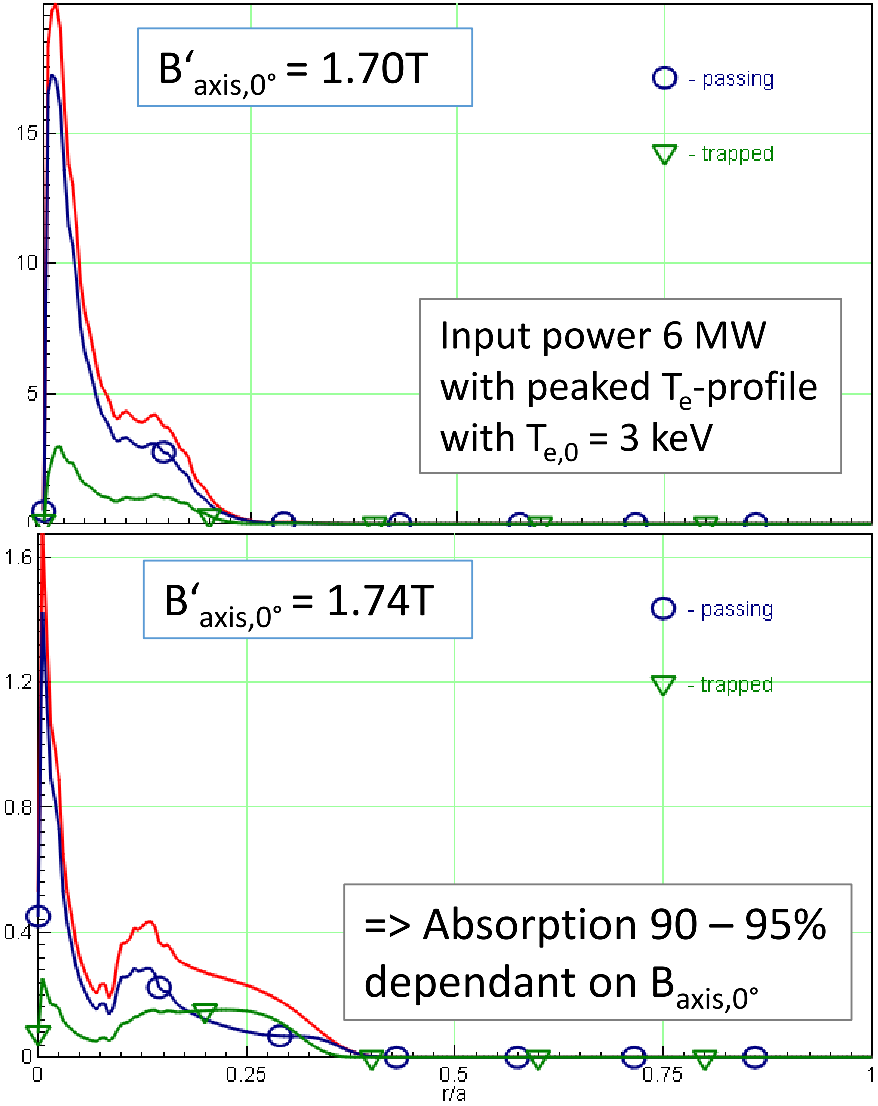


*TZM-reflector tile dedicated to O2 (also W-coated)*

**Red dots:** *perpendicular incidence during X2*

**Blue dots:** *possible reflectors for high density X3*

# 2. Heating scenarios: X3 at $n_{e,0} = 10^{20}\ m^{-3}$



$B'_{axis,0°} = 1.70T$

Input power 6 MW
with peaked $T_e$-profile
with $T_{e,0}$ = 3 keV

$B'_{axis,0°} = 1.74T$

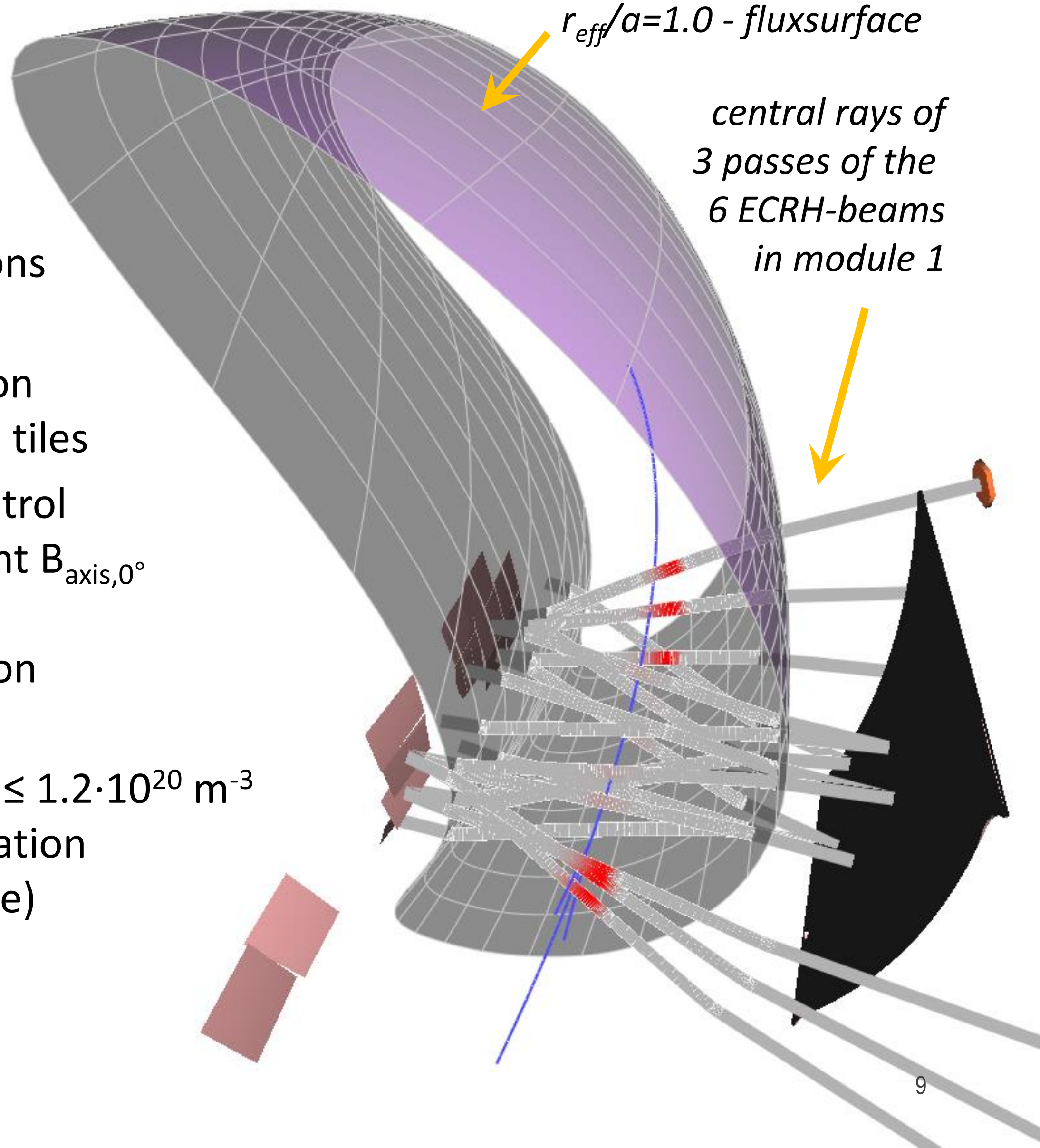
=> Absorption 90 – 95%
dependant on $B_{axis,0°}$

- single pass absorption of the order 80%

⇒ more relaxed conditions for reflector tiles

⇒ at least 95% absorption with future optimized tiles

- power deposition control by variation of setpoint $B_{axis,0°}$ without noteworthy reduction of absorption
- up to now:
  density limit set to $n_e \leq 1.2{\cdot}10^{20}\ m^{-3}$
  (after further optimization hopefully slightly more)



*$r_{eff}/a$=1.0 - fluxsurface*

*central rays of*
*3 passes of the*
*6 ECRH-beams*
*in module 1*

# 3. Startup scenarios – ICRH + NBI @ $B_{axis,0°} > 1.76$ T

- simulations for NBI-startup (by D. Gradic) with NBI-power of 3.4 MW (55 kV acceleration) and $T_e > 15$ eV

⇒ Use of helium (lower ionization energy) seems to be beneficial to broaden the window of optimal neutral gas pressure

⇒ $n_e > 10^{17}$ $m^{-3}$ enough for increasing $T_e > 1$ keV within 1-2s

- Takeover by 140 GHz – gyrotrons after 1 - 3 seconds

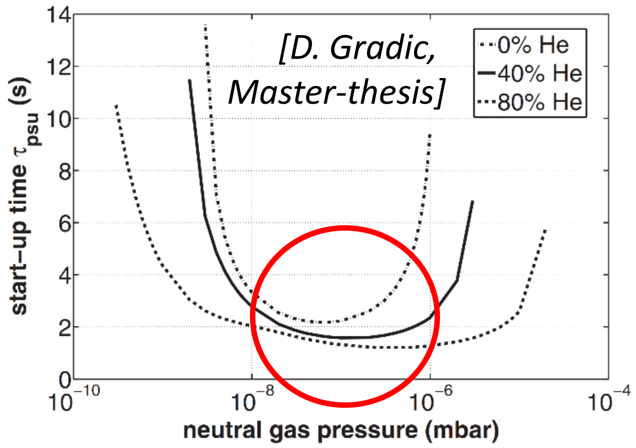
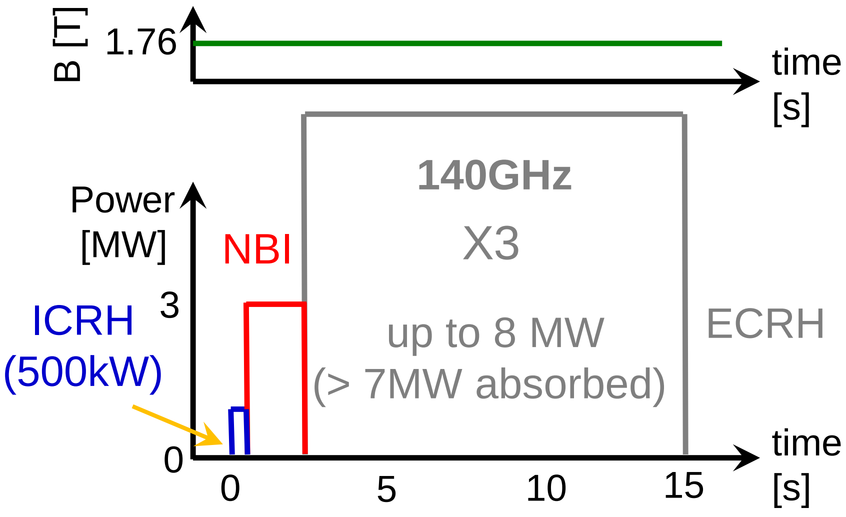
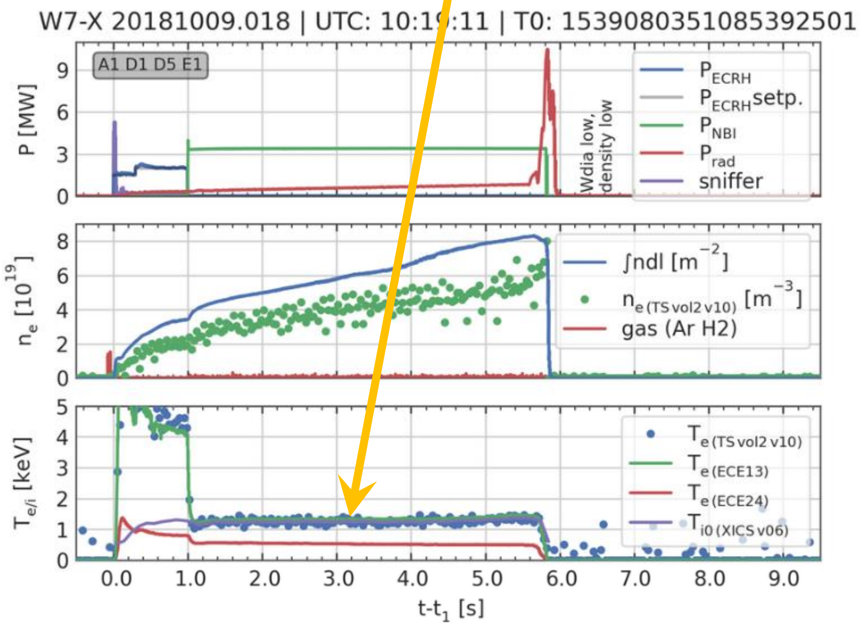
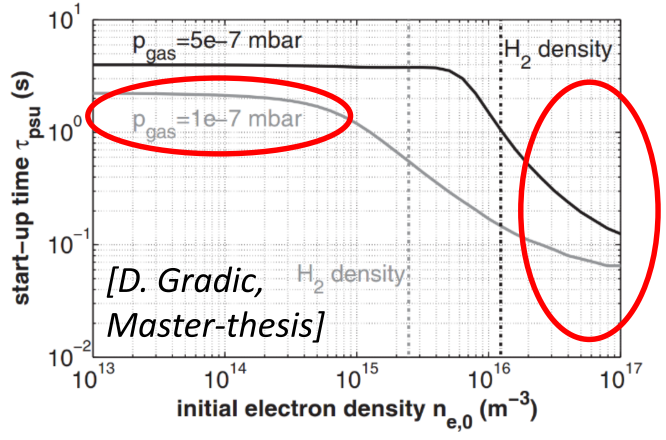


**Figure 9.** Plasma start-up time (criterion: $T_e > 15$ eV) in a pure hydrogen gas target and in helium–hydrogen admixtures for different neutral gas pressures $p_{gas}$.



*Envisaged optimal scenario*
*(ECRH maybe stepwise – dependent on density)*



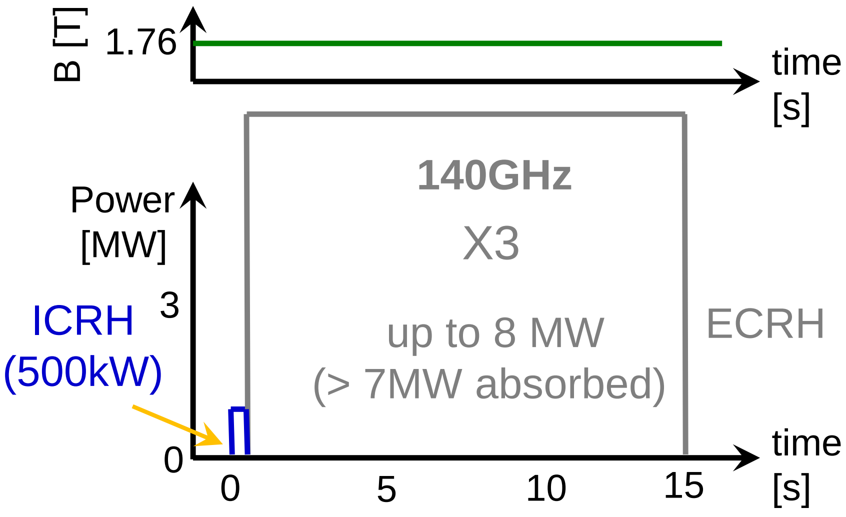


igure 10. Start-up time (criterion: $T_e > 15$ eV) in dependence on he initial electron density, $n_{e,0}$, (the initial ion density was set equal o the electron density). The vertical lines indicate the initial neutral gas density during the simulation.

# 3. Startup scenarios – ICRH only @ $B_{\mathrm{axis},0°} > 1.76$ T

- Even though absorption @ $T_e < 100$eV is tiny a direct takeover should be tested @ maximum possible $T_e$
- use of helium or argon probably is beneficial, too
- Takeover by 140 GHz – gyrotrons after <1 seconds *(dependent on maximum $T_e$)*
- time dependent NTSS-calculations coupled with Travis-code for 5 MW by N. Marushchenko (dt until 50% absorption for different $n_e$ and $T_e$)

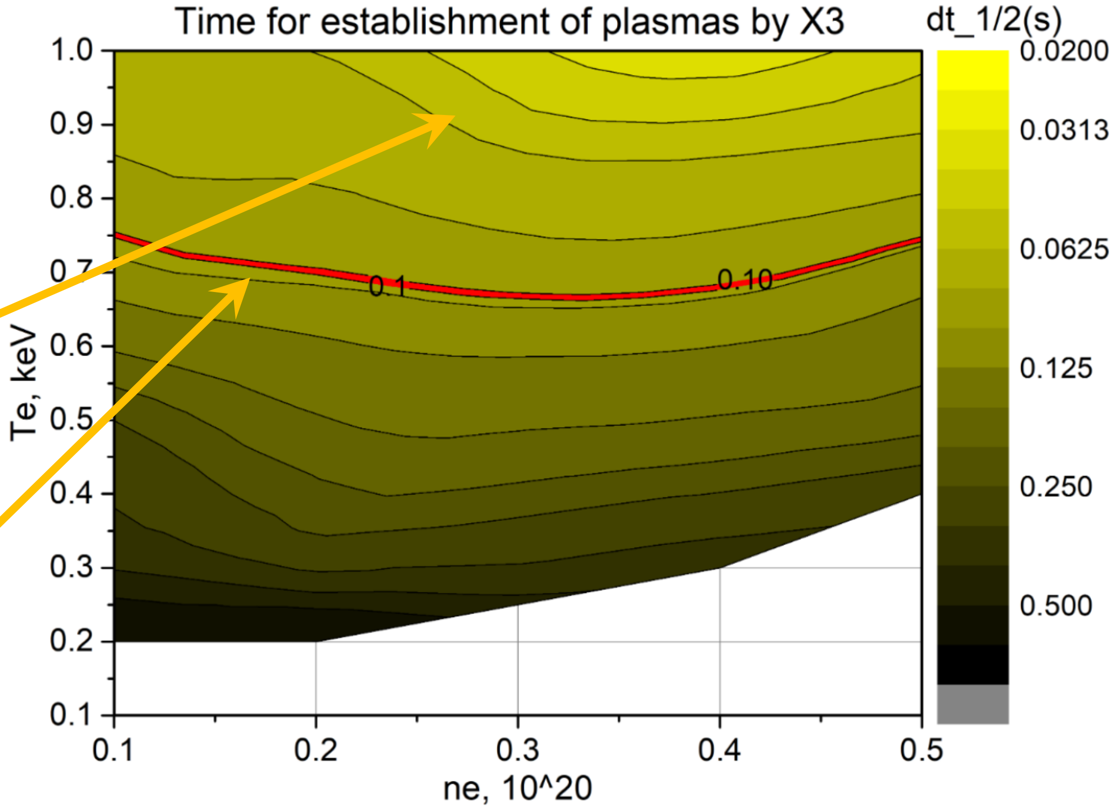
⇒ Direct takeover doubtful, but ICRH+NBI+X3 will work!



*Envisaged optimal scenario*
*(ECRH maybe stepwise – dependent on density)*

dt < 50ms
for $T_e > 1$ keV

dt = 100ms
for $T_e > 0.7$ keV



*[Marushchenko et al, EPJ Web of Conferences 203, 01006 (2019)]*

# 3. Startup scenarios – Experience with ICRH breakdown

- Theoretical studies and several experiments conducted by V. Moiseenko + Collaborators

⇒ Hydrogen minority heating

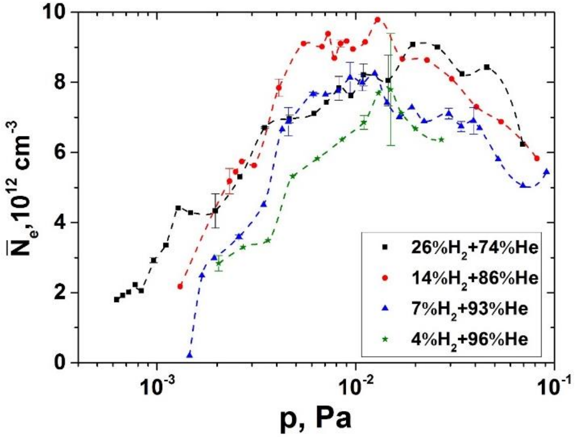
*… here only short teaser to following talk by V. Moiseenko*

*[S. Kamio et al 2021 Nucl. Fusion 61 114004]*

<u>Experiments at Uragan 2-M</u>

- Experiments with different gas mixtures show maximum achievable density for 14% $H_2$ + 86% He
- Neutral gas pressure can be < 10e$^{-4}$ mbar

*[Kovtun, Moiseenko et al, ITC30]*



<u>Experiments at LHD (similar volume as W7-X)</u>

- similar gas mixture with 19% $H_2$ + 81% He
- Breakdown with < 5 $10^{-7}$mbar and increase to sufficient densites < 0.5 s
- Achieved density $10^{18}$ m$^{-3}$ with 200 kW @ final pressure < $10^{-7}$ mbar

⇒ Startup time by NBI to 15 eV < 0.1s

⇒ Overall time to 1keV assumed to be < 0.5s

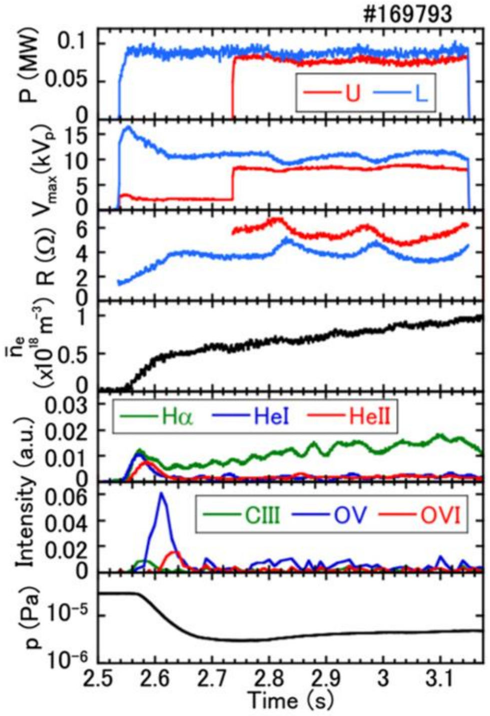


**Figure 4.** Time evolutions of ICRF power $P_{ICRF}$, (antennas FAIT U and L), maximum voltage at the coaxial line $V_{max}$, loading resistances (including vacuum loading resistance) $R$, average electron density $\bar{n}_e$, optical emission intensities of $H_\alpha$ (656.3 nm), HeI (587.6 nm), HeII (468.6 nm), CIII (97.7 nm), OV (63 nm) and OVI (103.4 nm), and neutral gas pressure $p$. Working gas content is ~81% He + 19% $H_2$.

# 4. Strategy - commissioning phase

- ICRH project team presented commissioning plan of ICRH-system

*… see talk by D. Hartmann 25/01/2022*

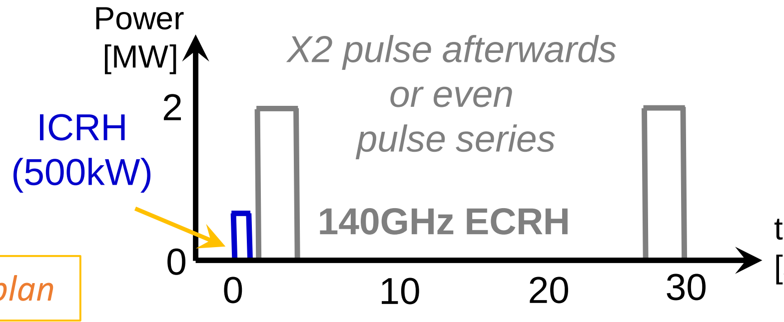
- First ICRH breakdown tests in session 5 @ 2.5 T with 38 MHz
  *(resonance layer at same position as for 1.8 T)*

⇒ can be supported by ECRH-target plasma (X2)

⇒ ECRH cleaning discharge afterwards to guarantee same conditions for next breakdown test
*(within the same experiment program!)*

⇒ combination with takeover by NBI
*(Later tests with direct takeover by X3 only reasonable, if the optimum parameters with maximum $T_e$ are found in session 5! Therefore, takeover by NBI not too early!)*

- Ideally, first try in session 7 with 25 MHz @ 1.8 T leads to same results
- Search for absorption scheme in hydrogen only should be first tried with 38 MHz @ 2.5 T, too!
  *(ECRH cleaning pulses available)*



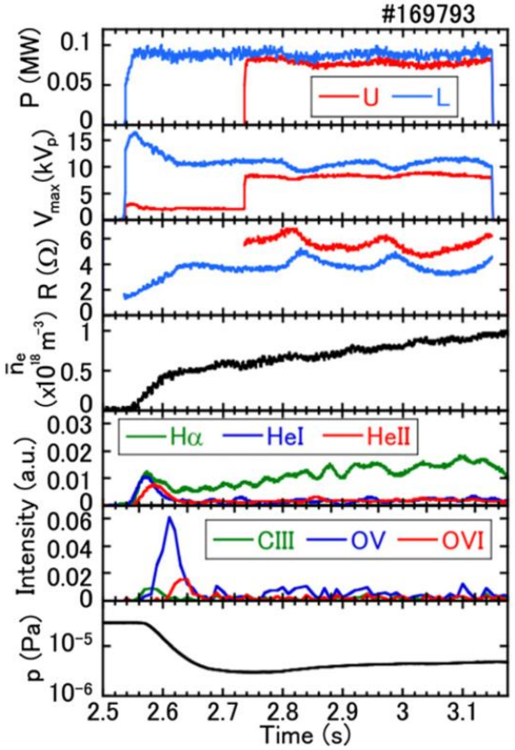
*Extract of ICRH commissioning plan*

| # | Purpose | ICRH System Modification | Mgn. Conf. | B36 [T] | Freq [MHz] | Phasing | working gas | Absorption | max. RF power [kW] | target plasma |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | antenna position | | std. | 2,5 | 38 | pi | He | He (H) | 0 | ECRH |
| 2 | **plasma operation** | | std. | 2,5 | 38 | pi | He | He (H) | 500 | ECRH |
| 3 | antenna position and operation | | **high mirror** | 2,5 | 38 | pi | He | He (H) | 500 | ECRH |
| 4 | **antenna gas inlet** | | high mirror | 2,5 | 38 | pi | He | He (H) | 500 | ECRH |
| 5 | **plasma startup** | | tbd, but known | 2,5 | 38 | pi | He | He (H) | 500 | ECRH |
| | | pi phasing, 25 MHz | | | 25 | | | | | |
| 6 | plasma operation | | tbd, but known | 2,5 | 25 | pi | He | **none** | 100 | ECRH |
| 7 | plasma startup | | tbd, but known | **1,8** | 25 | pi | He | He (H) | 500 | none |
| 8 | plasma startup | | tbd, but known | 1,8 | 25 | pi | **Hydrogen** | **none** | 100 | none |
| | | 0 phasing, 25 MHz | | | | | | | | |
| 9 | plasma startup | | tbd, but known | 1,8 | 25 | 0 | He | He (H) | 500 | none |
| 10 | plasma startup | | tbd, but known | 1,8 | 25 | 0 | Hydrogen | none | 100 | none |

# 4. Strategy – commissioning phase – session 5

Assumption: minority heating works (session 2+3) and antenna gas inlet works (session 4)

Goal:
- ICRH breakdown scenario with $n_e > 10^{17} – 10^{18}$ $m^{-3}$
- use of minimum gas inlet and/or maximum hydrogen content
  to allow a fast gas exchange to hydrogen in the later NBI + X3-phase
- demonstrate usability without ECRH cleaning discharge afterwards



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⇒ All experiment programs with 2 MW ECRH discharge (length > 3s)
or pulse series afterwards (interval between ECRH pulses 30s)

1. Establish scenario similar to LHD with pulses up to 1s by use of main gas inlet
   (≈ 80% He + 20% $H_2$, vary initial gas pressure between $5 \cdot 10^{-7}$ mbar to $10^{-8}$ mbar)
2. If in step 1 not already done, try to realize breakdown with antenna gas inlet
   (needs eventually less gas volume compared to main gas inlet system)
3. Combine optimal ICRH discharge (about 0.5s) with 2 NBI sources for 250 ms
   (technical maximum without absorption – interlock must be prevented!,
   no overlap of ICRH & NBI due to disturbance of ICRH coupling by NBI)
4. If success, repeat with only 1 NBI source and without ECRH afterwards
5. Repeat step 4 to demonstrate reliable operation

*… details on ICRH parameters planned by V. Moiseenko + ICRH-team*

# 4. Strategy – commissioning of ICRH+NBI+X3

Assumption: startup scenario with NBI works @ 2.5 T

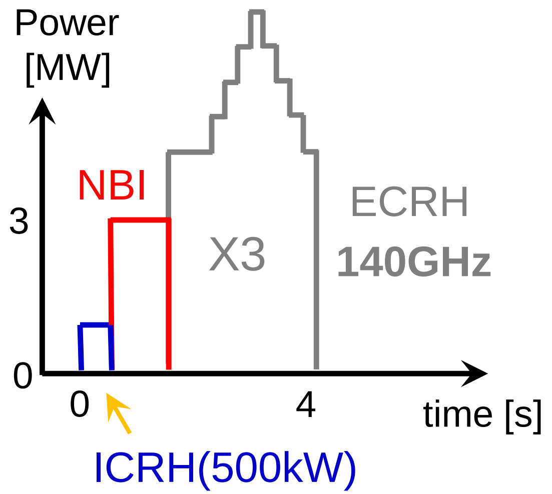
Goal:
- Repeat/demonstrate the 2.5T ICRH+NBI scenario @ 1.8T with 25 MHz
- demonstrate takeover of ICRH+NBI by ECRH with X3 multipass scenario
- Eventually test of direct takeover of ICRH plasma by X3

1. ICRH breakdown without NBI
2. ICRH+NBI
3. ICRH+NBI + takeover by X3 (100ms)
   with 6 beams which are not affected by refraction

*Should be tested as early as possible to identify unexpected problems (e.g. control systems, interlocks etc.)*

4. With knowledge of density repeat point 3 with
   all beams for > 0.5s in different combinations
5. Eventually test direct X3-takeover with all ECRH-beams
   (technical limit 50ms without ECRH absorption)
6. At session end further adjust parameters of
   ICRH and NBI with safe X3-scenario
   (session finished anyway if wall conditions become too bad)

*Shall give a feeling of necessary X3-Scenario „commissioning“ and goes far beyond the commissioning of ICRH breakdown*



# 5. Summary & Outlook

- X3-operation with similar absorption and conditions as O2-heating (85% to 95% for $T_e$ > 3 keV)

⇒ all O2-reflector tiles usable up to 7 $\cdot 10^{19}$ $m^{-3}$

⇒ for 7 - 12 $\cdot 10^{19}$ $m^{-3}$ partly use of W-coated graphite tiles as reflector for shinethrough power of up to 200kW (time limitation of the order seconds and slight tile damage by arcing at the tile screws)

⇒ after this high density tests further upgrade by TZM-reflector tiles optimized for X3-operation (maybe densities up to 1.4 $\cdot 10^{20}$ $m^{-3}$ possible)

- ICRH+NBI+X3 most probable candidate for first tests/operation of X3-heating scenario (however, nothing is guaranteed)