0-D modeling of W7-X reactor scenarios in OP2

Can we access high-β and low-ν_i^* simultaneously?

Arturo Alonso

Discussions with : A. Dinklage, S. Bozehnkov, G. Fuchert, M. Beurskens

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By way of motivation...

- Wendelstein 7-X is Europe's main tool to assess the prospects of a fusion reactor based on the HELIAS line.
- To learn about this, identify potential problems, necessary concept improvements, etc. one needs to operate as close to reactor conditions as possible.
- In Physics terms, "close to reactor conditions" means to approach reactor-relevant dimensionless parameters, most prominently, $\beta, \nu*$ and $\rho*$, which are the relevant parameters in a kinetic/MHD description of the thermal plasma[1]
- Operating at reactor-relevant parameters in W7-X would be a kind of "wind-tunnel" experiment for a HELIAS reactor.

[1] Not all reactor-relevant physics depend solely on these parameters. Particular problems (i.e. models) are characterised by different sets of dimensionless parameters.

Methodology I

- We consider P and n our independent variables and start from the ISS04 scaling for the τ_E

$$\tau_E^{\text{ISS04}} = f_{\text{ISS04}} \times 0.134 a^{2.28} R^{0.64} P^{-0.61} \overline{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41} \tag{1}$$

where variables have their usual meaning.

- The total plasma energy content is then:

$$W = \frac{3}{2} \sum_{s=i,e} \int dV n_s T_s = 3 \langle nT \rangle_V V \ , \qquad (n_i = n_e = n, T_e = T_i = T) \ . \tag{2}$$

and the plasma beta

$$\langle \beta \rangle_V = \frac{p}{B_0^2/2\mu_0} = \frac{2 \langle nT \rangle_V}{B_0^2/2\mu_0} \ . \tag{3}$$

Methodology II

- One can further define a characteristic temperature as

$$T = \frac{\langle nT \rangle_V}{\overline{n}_e} \tag{4}$$

which we assume to be close to the volume-averaged temperature.

- With these variables we obtain the collisionality and normalised gyroradius

$$\nu_i^* = 5.18 \times 10^{-4} \frac{n[10^{19}\mathrm{m}^{-3}]}{T[\mathrm{keV}]^2} R[\mathrm{m}] \ , \quad \rho_i^* = 4.6 \times 10^{-3} \frac{T[\mathrm{keV}]^{1/2} A[\mathrm{amu}]^{1/2}}{B[\mathrm{T}] R[\mathrm{m}]} \tag{5}$$

Typical parameters of stellarator reactors

	HSR4/18	HSR5/22	ARIES-CS
R(m)	18	22	7.75
B(T)	5.0	4.75	5.7
T(keV)	4.96	4.96	6.6
$n(10^{19}\text{m}^{-3})$	26	21	40
$\langle\beta\rangle$(%)	4.2	4.2	6.4
$\nu_i^*(10^{-2})$	0.99	0.98	0.37
$\rho^*_{2.5\text{amu}}(10^{-4})$	1.8	1.5	4.1

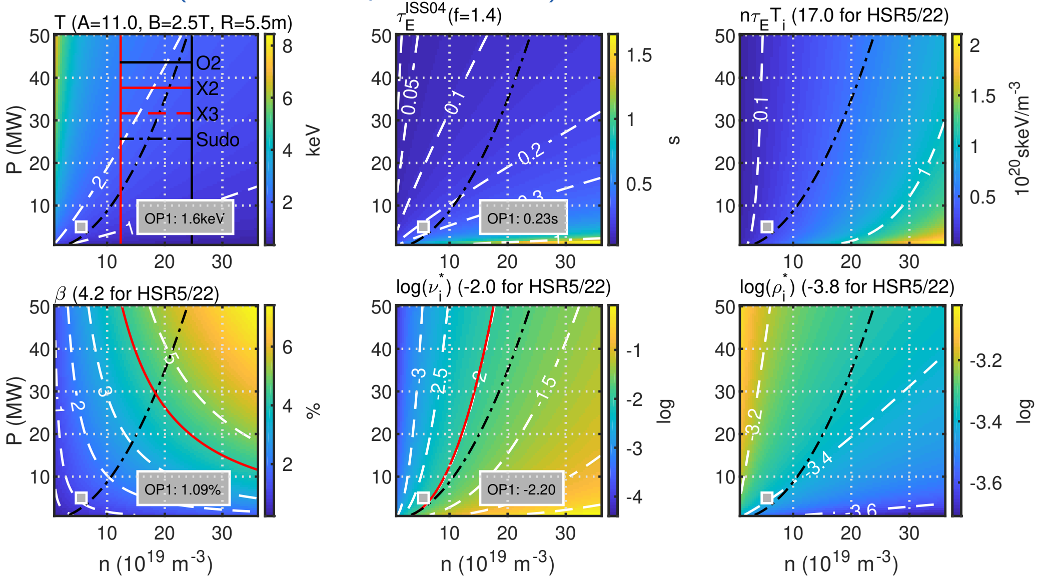
Table: Design values of fusion reactors

Design values of fusion reactors based on the HELIAS line[2] and the compact quasi-axisymmetric concept[3].

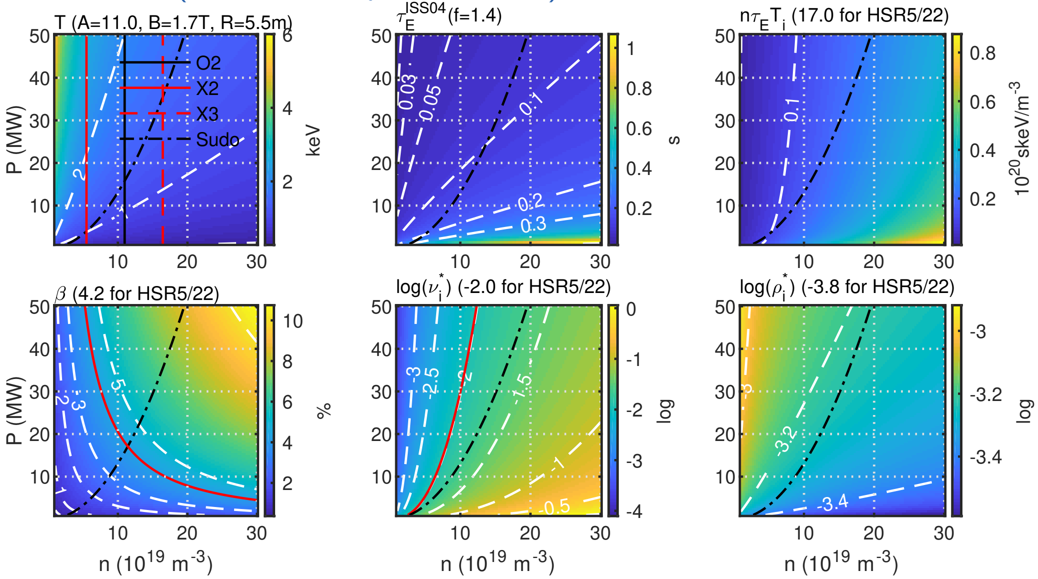
[2] Beidler et al. 2001.

[3] Najmabadi et al. 2008.

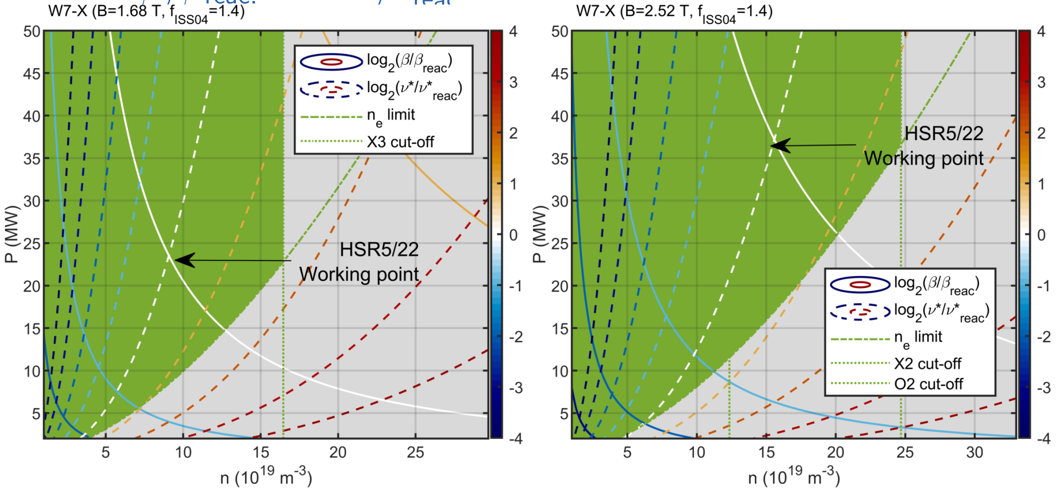
OP2 scenarios ($B = 2.5$T, $f_{\mathrm{ISS04}} = 1.4$)



OP2 scenarios ($B = 1.7$T, $f_{\mathrm{ISS04}} = 1.4$)



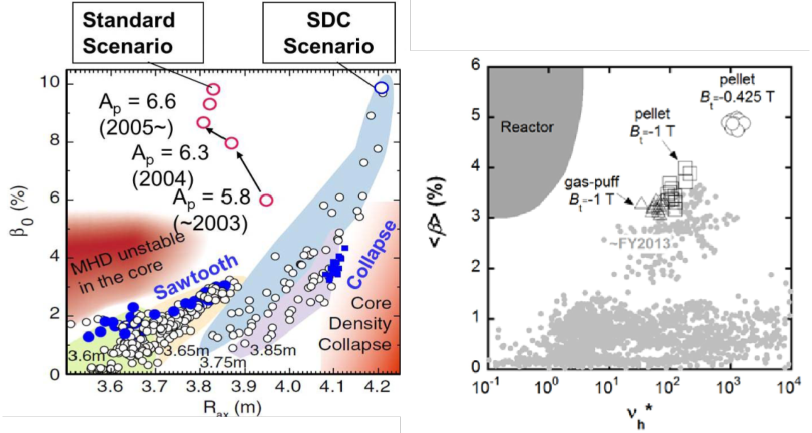
Contours of $\beta/\beta_{reac.}$ and $\nu^*/\nu^*_{reac.}$ for 1.7 and 2.5T



The intersection of the two white curves marks the simultaneous matching of $\beta_{reac.}$ and $\nu^*_{reac.}$. The other red (blue) countour lines represent $\times 2$ increments (decrements) with respect to the reactor value.

What has been done in LHD?

High-β operation (above ideal limit!) has been achieved in LHD[4], but at low field or very dense NBI plasmas (i.e. high ν_i*).



[4] Sakakibara et al. 2017; Takeiri 2018.

Conclusions

We assume that the high-performance operation observed in OP1 can be stabilized in OP2 and that we can operate with an enhancement factor $f_{\text{ISS04}} = 1.4$. Then:

- Reactor scenarios ($\langle\beta\rangle \sim 4.2\%$ and $\nu_i^* \sim 10^{-2}$) in W7-X appear possible with a (heating power / plasma density) of
  - ($\sim 35 - 40$ MW / 1.5$\times 10^{20}$ m^{-3}) at $B = 2.5$T
  - ($\sim 20 - 25$ MW / 1.0$\times 10^{20}$ m^{-3}) at $B = 1.7$T

  compatible with density and cut-off limits as well as EC absorption ($\langle T\rangle > 1$ keV).
- The stability limit $\langle\beta\rangle = 5\%$ can be accessed with this confinement at 1.7T with $25 - 30$ MW heating power and densities (1.0-1.5)$\times 10^{20}$ m^{-3}.

W7-X operation in reactor-relevant conditions is within reach in the coming years!

It could be the first stellarator operation at high-β, low-ν_i*

What next

- From the operational side, stabilising high performance should be a priority. According to our present understanding this requires to sustain density gradients ($\rightarrow$ we need to improve our understanding of particle transport!!).
- NTSS simulations of these scenarios would help refine the statements and provide estimates of central values.
- In particular, heating schemes (X3) in plasmas with increasing beta need to be devised (diamagnetic resonance shift).

References I

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