Integrated exhaust for DEMO class devices

(a personal view)

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(with ideas from many people and papers)

First IAEA Technical Meeting on Divertor Concepts

29 September – 2 October 2015
IAEA Vienna

CCFE is the fusion research arm of the United Kingdom Atomic Energy Authority. This work was funded by the RCUK Energy Programme [grant number EP/I501045].
Main points

• Differences on DEMO*
  • Look from perspective of DEMO

• Integration
  – importance & elements; constraints vs. flexibility
• Margin
  – importance, ideas
• Decisions
  – what is needed, how to know if a “gap” is closed
  – How to judge if final gap is closed?

• Bring known issues and ideas together

* DEMO-class usually replaced by DEMO here, noting DEMO means different things in different parties. DEMO, Pilot Plant, CTF…
Contents

• Nature of exhaust on DEMO-class devices
• The operating point - quantitative estimates
• The wider scenario
  – r,θ,ϕ,t control, technology,
• Search for increased margin
• How to be sure for DEMO? Role of TRLs, modelling, size of final gap
• Summary

This follows on from talks at the 2013 and 2013 IAEA DEMO Programme Workshops
What’s the problem?

Much higher exhaust power at DEMO-scale
- can damage PFCs quickly: damage < control timescale?
- impact on other goals (e.g. main chamber protection can reduce tritium breeding ratio)

Thin SOL leads to high target power density at divertor target

Present plasma scenario requires large power into SOL ELMs hard to handle

If move to high $P_{\text{rad}}$, may need new scenarios
Why are DEMO-class devices different?

Exhaust power much higher, materials & technology demanding

Plasma scenario at high Q may only be achieved with DT (i.e. high neutron flux, very limited diagnostics) because installed power is low (money, TBR)

Diagnostics likely to be very limited and/or use very different approaches. How do we measure and control

- $P_{\text{rad}}$ (main plasma and divertor),
- power flux and distribution at target,
- position of detachment front
- even position of strikepoint (?)

Plasma and exhaust scenarios may have to adapt to diagnostic and control capabilities

But we are only just beginning!
Why are DEMO-class devices different?

Scale of the investment means that confidence levels have to be much higher even than for ITER. Not obvious how to prepare decisions – look from DEMO - a theme of this talk.

- what uncertainty or performance range is acceptable at DEMO scale (and when)?
- does the DEMO exhaust performance need to be precisely defined at the start of the EDA?
- what developments (plasma and plant) are possible during DEMO life?

All this, as well as the technical issues, affects the approach, especially for earlier DEMOs.
The gap

• Which type of gap? All of them!
The gap

- Perhaps the best picture: need sophisticated, well-supported approaches from both the R&D programme and from DEMO
- Build from both ends
- Need a plan

DEMOMO adapting (design, phasing/decision process etc)
Power & particle flow – issues and integration

(Not including neutrons)

Main chamber PFCs

$P_{\text{rad}}$

Burn control
Stability control
$P_{\text{SOL}}$ control?

Core Plasma

Neutron MW/m$^2$

$P_{\alpha}$

$P_{\text{electric}}, \Delta P_{\text{electric}}$

T breeding

Suitable pedestal

SOL width, seeding for radiative losses, turbulent transport, control, transients, start-up, ramp-down

Impurities $P_{\text{SOL}}$ Fuel

SOL + Divertor plasma

L-H access, ELMs, separatrix conditions (e.g. $f_{e,i}(\nu)$) etc

Impurities $P_{\text{SOL}}$ Fuel

Divertor target PFCs

MW/m$^2$, erosion, melting, fatigue

Divertor chamber PFCs

MW/m$^2$, erosion, melting, fatigue

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Many elements need to act together to get performance.
Each can have different types of solution (e.g. ELMy, ELM-less, internal transport barriers, detachment front, advanced PFCs etc)
They can lead to synergy, conflict, new paradigms
The operating point
(conventional divertor)

• Global, 0-D + bits of 1-D
Finding basic 0-D operating point

Each blob has a range. Iterate...

- Plasma scenario
- $P_{aux}$
- Solution
- $P_{rad}$
- Flux expand
- $P_{rad}$ SOL + div
- Wall max MW/m$^2$
- Div max MW/m$^2$
Consider pessimistic case, large DEMO ("low extrapolation"): 3GW (thermal), R=8-9m, Q=20: 750MW deposited in plasma
Assume ELMy H-mode
  – $P_{\text{sep}}$ set by 1.5-2xPLH for "good H-mode":
  – $P_{\text{LH}}=120-200\text{MW} \Rightarrow P_{\text{sep}}>180-400\text{MW}$
Assume $P_{\text{sep}} \sim 300\text{MW}$
60-70% to outer leg: up to 200MW to outer leg?
10MWm$^{-2}$ limit: wetted area $> 20m^2$ (no divertor losses)
Assume ITER-like flux-expansion & target angling, no divertor losses, $\lambda_{\text{mid}}=2\text{mm}$
  $\Rightarrow 180\text{MWm}^{-2}$
Can’t fix by more flux expansion (even alternative geometries)

But, this is much too pessimistic…
What else can help?

- Reduce $P_{sep}$ more – higher $P_{rad}$ (core); absolute power densities matter, not only $f_{rad}$
- Increase divertor radiation
- Move to detached divertors (remember He pumping…)
- Keep trying to increase wetted area (sweeping as well)
- Improve PFCs

All of this is being done, separately, and now starting to be put together (EU and elsewhere)
How much can be radiated in divertor?

Models of DEMO can get $P_{\text{rad, div}} \sim 400\text{MW}$, $\rightarrow 100\text{MWm}^{-3}$ locally

- 1-2% Ar
- $n_e$ up to $4 \times 10^{20}\text{m}^{-3}$
- $\sim 60\text{Wm}^{-3}$ seen on C-mod (Lipschultz et al FST 2007)

So, may be possible with short divertor. Not easy? Controllable?

Left: “short super-X”
Right: conventional
Asakura et al JNM 2015

Kallenbach et al, PPCF 2013
“Impurity seeding for tokamak power exhaust: from present devices via ITER to DEMO”
Divertor detachment

Partially detached (ITER-like, ~stable)
- Peak power reduced factor ~10 (ITER)
- Separatrix power density reduced x50
But this is about maximum factor possible at separatrix, still ~3MW/m²

➔ Go to fully detached to reduce peak
- Very low target pressure/power
- Harder to control in standard divertor*
- Very high upstream density, & 2-D effects
  - change pedestal paradigm?
- Integration!

* how much can be detached and still be ~stable?

A.S. Kukushkin et al. J Nucl Mat 2013
B Lipschultz et al, Fusion Science &Tech 2007
DEMO estimates – higher $P_{\text{rad}(\text{core})}$

Exploration – not a design point
Spot point found, $P_{\text{fus}} < 2\text{GW}$

Constraints:

a) Power to divertor targets (total) below ~30MW
b) $P_{\text{sep}} > f_{\text{LH}} P_{\text{LH}}$ ($f_{\text{LH}} > 1$)

Core radiation, Ar+Xr, to reduce $P_{\text{sep}}$.

SOL+divertor radiation fills gap (~150MW)

- Possible point with $P_{\text{rad}} / P_{\text{total}} = 64$
- ~acceptable local loads on first wall ($<0.5\text{MWm}^{-2}$) – reflections will help

- Significant achievement, even if 0.5D
- Small margin– improve by increasing size. Note $P_{\text{LH}}$ very uncertain

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Wenninger at el, Nucl Fusion 2014, 2015, EPS 2015
Operating point – summary

- Integrated solution, core to coolant, plasma + technology
- ITER point does not extrapolate comfortably
- May be a solution; margin small, confidence not high
- Push several lines – none enough alone

IDEAS LIST

- Higher core radiation
- Higher heat flux PFCs
- Higher divertor and SOL radiation
- Flux expansion
- Advanced – snowflake, X-divertor, super-X, mix
- Increase SOL cross-field transport

So far “just” use the first 4
The wider integrated exhaust solution

- Operating point – full solution
- Start-to-end scenario (plasma + technology)
- Control
- Margin!
Contributors to integrated solution

- High level goals
- Plasma scenario (core + divertor)
- Divertor configuration and engineering integration
- Materials + technology (main chamber, divertor)
- Control: diagnostics + actuators

Explore these for improvements, trade-offs, margin, resilience, but we’ll find extra constraints too
Explore these for improvements, trade-offs, margin, resilience, but we’ll find extra constraints too.
Top level goals drive/driven by exhaust

- **Fusion power**: a large and/or precise number adds constraints (higher exhaust power, possible control conflict)
- **Breeding ratio** – limits surface power to main chamber (thin armour+coolant), space for non-breeding divertor gaps
- **Tritium inventory** in PFCs, tritium throughput
- **Pulsed vs steady state** – affects $P_{\text{exhaust}}$ through $Q$, scenario
- **Blanket** materials and technology – specific temperature ranges (possible control conflict due to link to $P_{\text{fus}}$)
- **Extrapolable divertor PFC technology** (e.g. helium-cooled limits MW/m$^2$, small $\Delta T$ for ductile W and W-steel joints)
- **Availability** – PFC lifetime goals, options for in-vessel coils
- **Capital cost** – opposes large-volume divertors

Most of these are constraints of course
Balance desirable performance features vs confidence and margin
Plasma scenario (core + divertor)

JET, ASDEX Upgrade emphasise importance of integration:
- change wall material $\rightarrow$ pedestal change $\rightarrow$ core performance change

- Pedestal (link to upstream SOL and fuelling), small/no ELMs
- SOL and divertor transport – e.g. what sets turbulence level
- Detachment formation, stability, impact on SOL, pedestal, pumping
- Radiation physics (thermal instability)
- Pumping (helium, neutral pressure, tritium plant capacity)
- Ramp-up + ramp-down (detached? Does flat-top exhaust depend on path?) *
- Transients: slow, fast (L-H), v fast (ELMs, disruptions)

* ramp-up/down often forgotten
• Compliant
  – handle significant variations in input power and particle flux
  – different plasma scenarios, ramp-up, ramp-down etc
  – varies during a pulse, not a point design
• Self-regulating, self-organising (diagnostics & control limitations)

Use as guide, even if only partly achievable (carbon was quite good...)

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Configuration – lots of ideas

- **Conventional** – JET, ITER
  - try to make it work!
  - SND, DND, dome, sweep etc

- **Snowflake**
  - NSTX, TCV, DIII-D, EAST…
  - Expand the low-field region around X-point – affects turbulence?
  - Transients to different legs?
  - Needs large currents in coils close to plasma
  - radiates near core – integration!

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Configuration – lots of ideas

- **Super-X, long leg** – still theory only, being built on MAST
  - Extend outer leg reduce $B_{\text{pol}}$ (connection length, flux expansion)
  - Falling $B_t$ in flux tube* helps detachment control? Easier at low R/a
  - Partly shield PFCs?
  - Needs extra volume and probably coils inside the TF
  - Originally DND (simpler solution on HFS) - “Double decker” for SND?

- **X-divertor**
  - Local poloidal flux expansion near target plates (“local” coils?)

*Lipschultz, this meeting

**A combination?** Don’t assume best option looks like present ideas.
New configurations are for understanding & ideas as much as prototypes
• Several divertor options in proposed ADX (LaBombard et al, Nucl Fusion 2015)
Materials & Technology

• PFCs and coolants
  – power range, and time-constants (e.g. to melting)
  – divertor chamber PFCs – location(s) of radiation
  – main chamber PFCs – power limits (related to T breeding)
  – same strike-point PFCs for flat-top, start-up, ramp-down, transients?
  – new manufacturing techniques may raise MW/m²

• Materials (incl liquids)
  – operating temperature (is a minimum P_{fus} or exhaust power needed to stay in ductile regime?)
  – lifetime due to radiation embrittlement, erosion, transients
  – D, T retention, effect on properties (e.g. very high particle fluxes)
  – transmutation can limit life
  – can brittle materials be used?
  – liquids? Resilient but other issues. Sn, Sn-Li?

• Wider
  – New manufacturing; high temperature, jointed superconductors etc etc
Control – a new challenge

• Several things to control for exhaust, especially:
  – configuration and core plasma
  – mean and fluctuating power entering SOL
  – divertor state (detachment, radiated power)
• All during all phases of the plasma (e.g. low and high neutron flux)
• **Diagnostics**: some quantities hard to measure, especially:
  – $P_{\text{rad}}$ (85% → 70%: $P_{\text{sep}} \times 2!$) [many thin sightlines?]
  – detachment state [divertor currents?]
  – $P_{\text{target}}$ [thin IR sightlines?]
• **Actuators** probably slower and less direct (less precise?) than today ($P_{\text{aux}}$ a fast actuator for $P_{\text{sep}}$?)

[W Biel et al, FED 2015]
Seek passive mechanisms
- cf vertical position control: passive conductor bridges natural Alfvén-time growth and control loop timescales
- cross-field transport and dq//ds//

Include control precision (low?) in exhaust design

Seek large margins

Probably need model-based controllers, which can also integrated sparse, imprecise, coupled diagnostic data

Must be able to model (but could be ~linear excursions from operating points)

Control must be included in the design from outset – could be decisive

[There is a specific DEMO diagnostics and control work package in EUROfusion]
Integration - Control

- Parameters to control
- Allowed variations
- Limits (MWm$^{-2}$ etc)
- Disturbances
- Solution?
- Diagnostics
- Controller
- Actuators
- Models

Parameters to control:
- Allowed variations
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Solution?:
- Diagnostics
- Controller
- Actuators
- Models
Ideas for margin

Margin is really important! Most likely to come from improved plasma scenarios and configurations?

• New, easily controlled integrated scenarios (wider SOL, higher $P_{\text{rad}}$, “no” ELMs) – well-known challenge

• Advanced divertor configurations to increase
  – radiating volume and/or
  – detachment stability and/or
  – cross-field transport (also affected by edge turbulence level)

• Advanced PFCs to raise heat flux limit (20MWm$^{-2}$?): new materials (including liquids), manufacturing, cooling technology

• Integrated engineering – calculate load limits/reserve factors together not separately (unnecessarily conservative?)

• Be ready to review overall approach, traditional constraints
  – e.g. fixed $P_{\text{fus}}$, minimised TF volume
How to be sure for DEMO?

Demonstrating the gaps are closed
Approach may guide the R&D plans
Gap closing and shrinking

• Whatever exhaust solution is adopted for a DEMO, there will be remaining uncertainties
  – Gaps in knowledge and in scale of demonstration
  – Can’t test full solution at DEMO scale, parameters, environment
• Shrink the gaps:
  – Development time on DEMO and scope for modifications
  – Allow for lower DEMO fusion power (initially?)
  – Quantify and review tolerable uncertainty
• Various approaches to close:
  – Improve predictive modelling and its validation
  – Improve models with intermediate experiments, and ITER!
  – Test some components to full individual & partly combined loads
• Try to define closure – when have we done enough?
How one might make decisions – TRLs?

• High confidence needed for DEMO-scale

• Technology Readiness Level (TRL) is the established approach, with a large literature from defence, space and aeronautics

• Start to apply to fusion
  – D Meade (IAEA DEMO workshop 2013)
  – T Taylor (SOFE 2013)
  – Discussions at IAEA DEMO WS 2015
  – Work starting in EU and other parties
## TRLs (US DOE)

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<td>Actual system completed and qualified through test and demonstration</td>
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<td>Full-scale, similar (prototypical) system demonstrated in a relevant environment</td>
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<td>Basic principles observed and reported</td>
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How one might make decisions – TRLs?

• Normal TRL system relies heavily on physical tests, prototypes, and takes a conservative low-risk approach: fine for some elements, not for others:
  – integration aspects can be critical and not testable
  – prototypes and full scale tests in relevant environment very expensive, time consuming, or “impossible”
  – physical mechanisms and their mix changes
  – there may be unavoidable but significant uncertainties

So, new approaches needed to supplement TRLs?
  – Modelling, virtual engineering (often only considered at low TRL today – but not in all industries)
  – Incorporate range of performance in the goal?
Bridging the gaps – conventional exhaust

- Todays experiments
- TRL3 models
- TRL4-7 models, materials, tech R&D
- ITER Upgrades to other medium/large tokamaks
- TRL7 models, materials, technology
- “DEMO”
How can models be used?

• For integration and control – no alternative?
• For some individual elements (pedestal, detachment, materials properties…)
• For uncertainty quantification and propagation
• Theory-based models can allow for changes in mechanisms, new regimes – only option?
• Set up a modelling plan aimed at decisions?
• Can we start to imagine what a model-based decision looks like?
Modelling for decisions (plasma, materials)

Do what is needed for robust defensible decisions
- not “we know it has gaps but it is the best we can do” - stakes high

Some different approaches from today?
- Theory-based everywhere, no empirical elements(?): predictive
- Validation with a new level of rigour?
  - all relevant underlying mechanisms validated against experiment
  - check for divergent predictions due to fortuitous balancing of mechanisms that scale differently

Uncertainty Quantification & propagation key
- Confidence level, performance range

Is a high TRL model feasible – technically (ExaFLOPS), or because of theory uncertainties?
- No in-principle showstoppers, but much to do
- HPCs, new generation computing approaches

Many intriguing options, scope for imagination
Bridging the gaps – conventional exhaust

- Todays experiments
- TRL3 models
- TRL4-7 models, materials, tech R&D
- ITER Upgrades to other medium/large tokamaks
- TRL7 models, materials, technology
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Bridging the gaps – alternative exhaust

Today’s and upcoming experiments

ITER
Upgrades to other medium/large tokamaks

FNSF, ADX(?), “DTT”
Upgrades to existing medium-large tokamaks

“DEMO” with alternate exhaust

Where to position?

TRL3 models
TRL4-7 models, materials, tech R&D
TRL7 models, materials, technology
Exhaust path?

- Theory-based models of conventional and advanced SOL and divertor, and link to core
- Conventional and advanced exhaust experiments in medium-sized tokamaks, JET, JT-60SA, ITER
- Engineering & technology of PFCs, diagnostics, advanced divertors
- JET, JT-60SA, ITER: core plasma optimisation

Combining and deciding process (tbd!) → TRL~7

Are major new facilities/upgrades needed? Scope and timing?

Where?

FNSF (or CTF)

DEMO
• Integration is key – end-to-end, core to coolant; plasma scenario; control; materials + technology; overall goals.
• May be a robust solution with present knowledge and approaches (i.e. ITER-like); confidence still low
• Need to generate significant margin (confidence, uncertainties) – new ideas, challenge “rules”
• There will always be a gap in physical demonstration
• How to validate a full solution adequately?
  – Heavy reliance on validated models (no full-scale test)
• Huge scope for ideas and exploiting advances (especially theory, modelling and computing)
• Start to ask about DEMO decision process – progress!