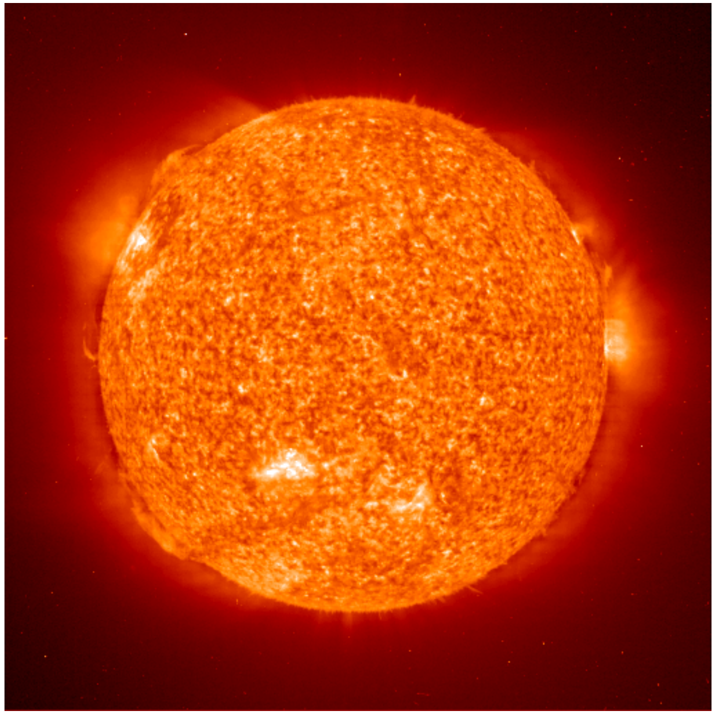
From ITER to DEMO



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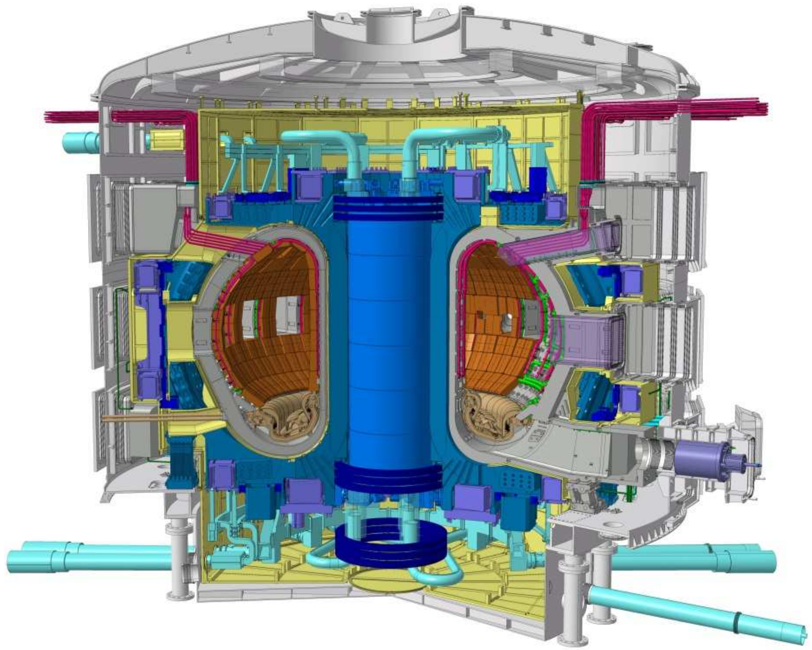

DPG Advanced Physics School
‚The Physics of ITER‘
Bad Honnef, 25.09.2014

- Introduction: what is DEMO?
- DEMO technology challenges
- DEMO physics challenges
- Risk mitigation strategies

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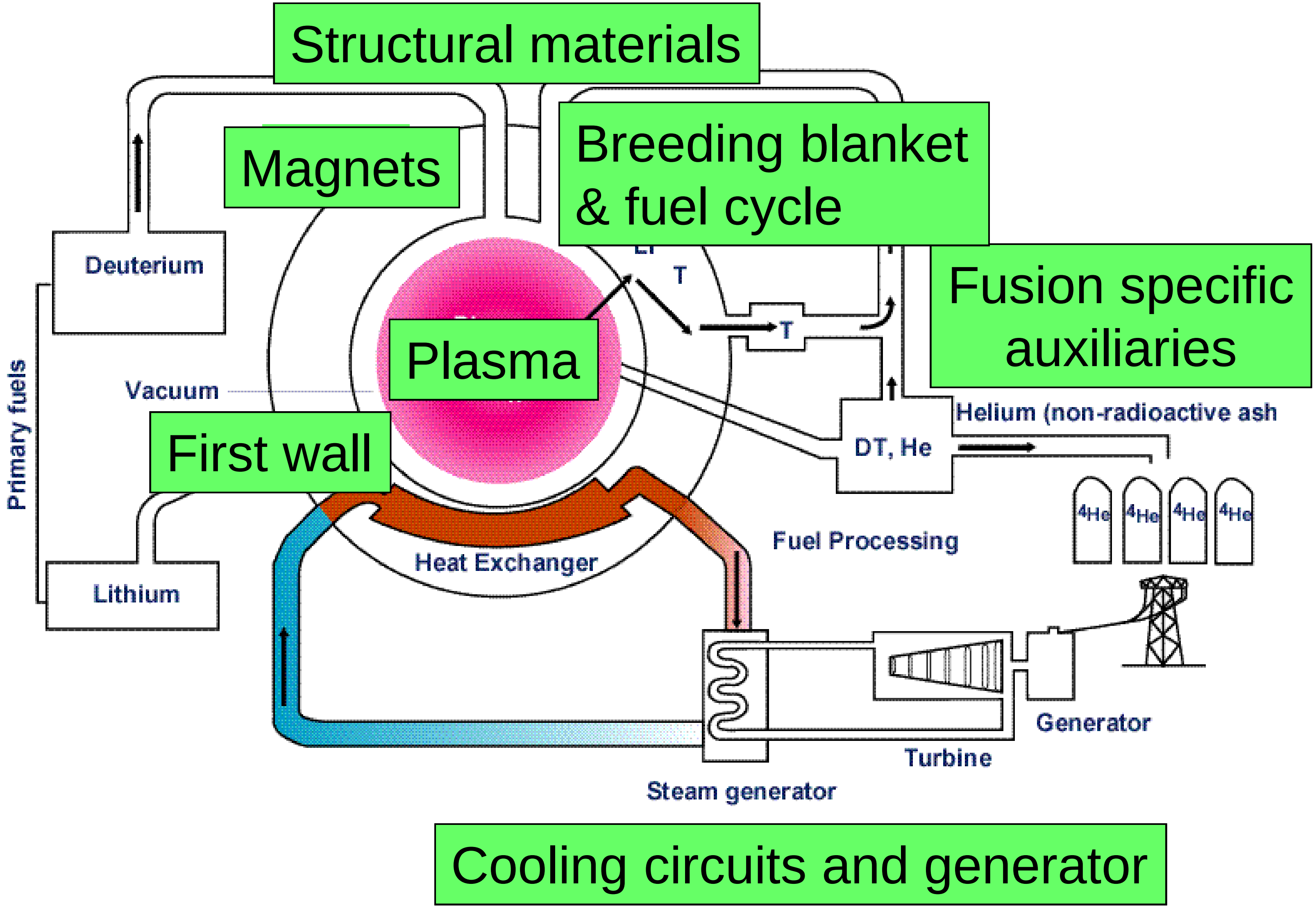
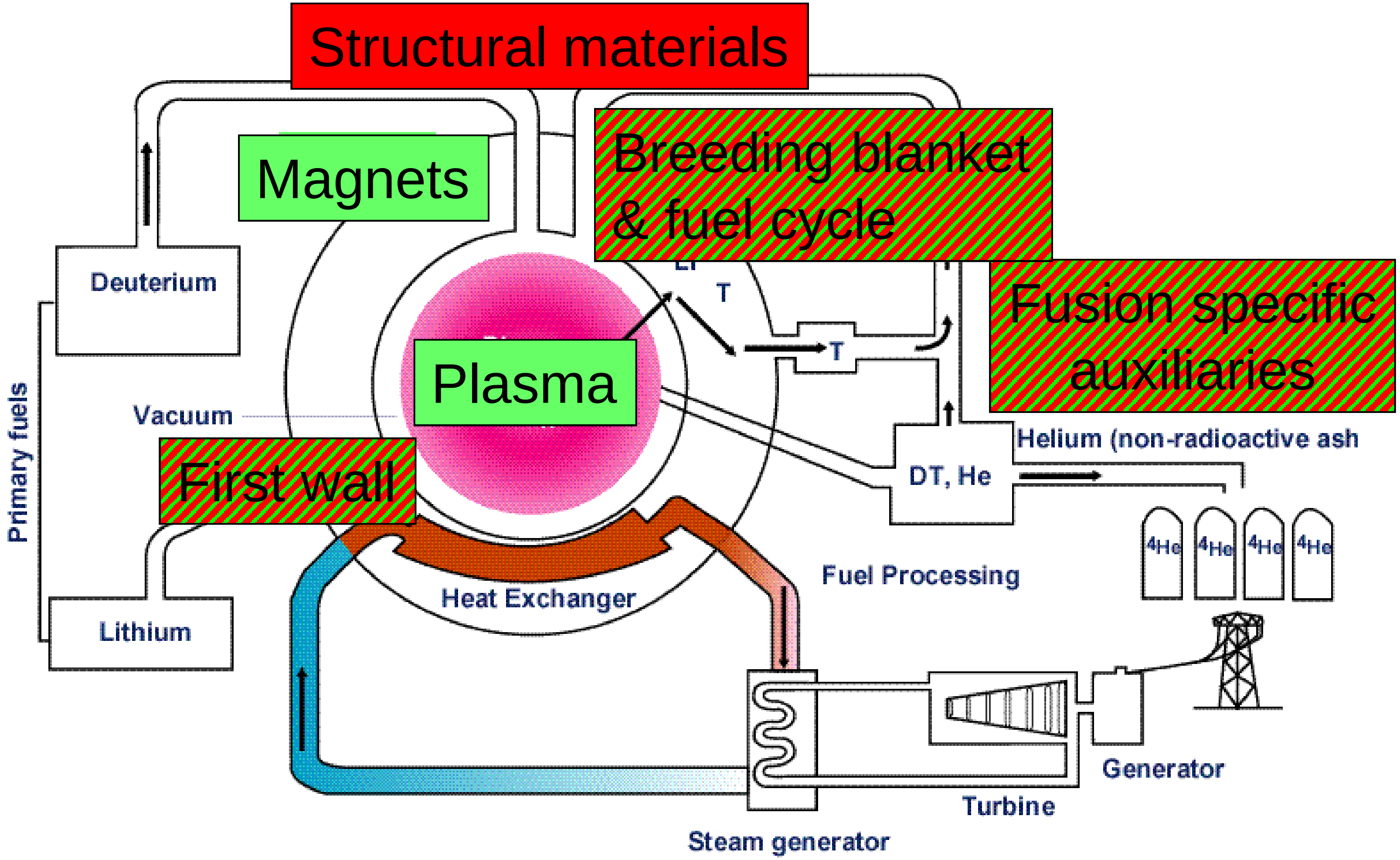
Fusion Power Plant - Challenges

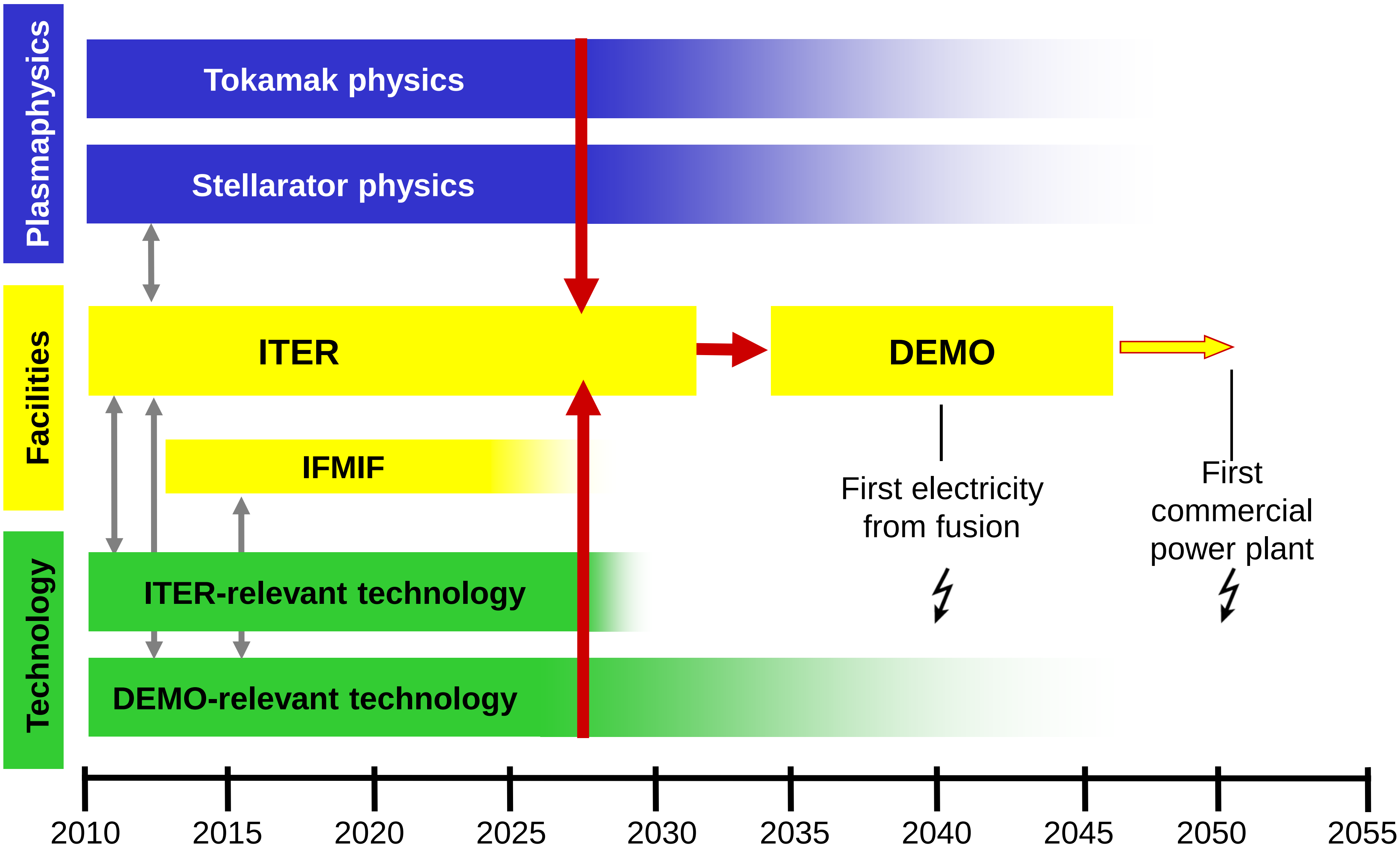




ITER contribution

Cooling circuits and generator

A Road Map to Fusion Energy



What is DEMO?

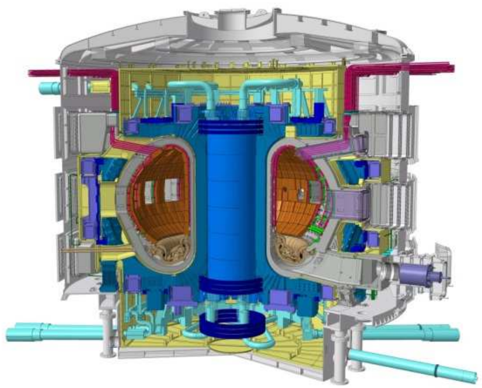
DEMO is the step between ITER and a Fusion Power Plant (FPP)

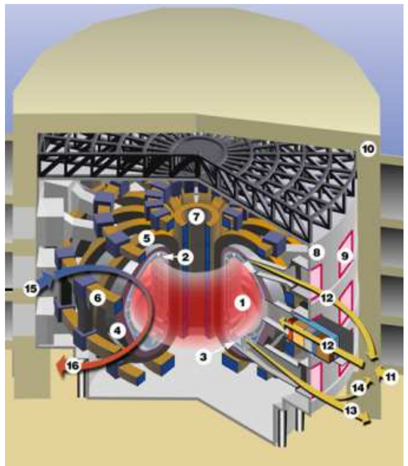
There is no unique definition, but the goals are to demonstrate…

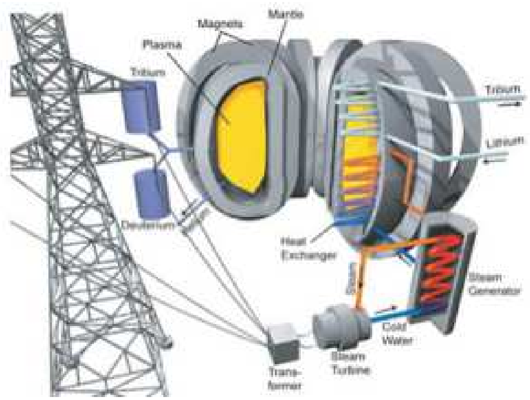
- a workable solution for all physics and technology questions
- large scale (100s of MW) net electricity production
- self-sufficient fuel cycle
- high reliability and availability over a reasonable time span

and allow an assessment of the economic prospects of an FPP

In the EU Roadmap, DEMO is a single step between ITER and an FPP







Introduction: DEMO designs

There is also no generally accepted DEMO design

Study	Ward 06	Ward 06	Garcia 08	Garcia 08	Pereverzev 06	Pacher 07	Kolbasov 08 (DEMO-S)	Tobita 08 (Slim CS)	Hiwatari 05 (DEMO-CREST)	Najmabadi 06 (ARIES-AT)
Operation mode	Pulsed	Steady state	Pulsed	Steady state	Steady state	Pulsed	Steady state	Steady state	Steady state	Steady state
P_{th} (GW)	2.4	3.3	3	3	2.5	3	2.4	3.6	3.3	1.9
$P_{el,net}$ (GW)	1	1	1	1	—	—	0.65	1	0.5	1
R_e (m)	9.5	6.9	7.5	7.5	7.5	8.1	7.8	5.5	7.25	5.2
A	4	3	3	3	3	2.9	5.2	2.6	3.4	4
B_t (T)	7.4	5.8	6	6	6	5.7	7.7	6	7.8	5.9
I_P (MA)	15.5	19	19	19	16	18	11.2	16.6	14.7	12.8
f_{bs}	0.43	0.44	0.53	0.53	0.56	0.61	0.59	0.77	0.5	0.91
γ_{CD} (A/(W 10^{20} m^{-2}))	—	0.44	0.52	0.52	0.56	0.7	0.47	0.41	0.3	0.4
P_{CD} (MW)	—	237	98	128	95	50	117	60	191	35
H	1.3	1.05	—	—	—		1	1.3	1.2	−1
β_N	2.4	3	—	—	—	3.1	4.7	4.3	3.4	5.4
Reference	3	3	4	4	5	6	7	8	9	10

Designs cluster around $R \approx 7.5$ m, $P_{el,net} \approx 1$ GW (P_{th} 2-3 GW)

- major radius basically determined by energy confinement (ignition)
- fusion power basically determined by internal electrical power needed to run the plant (He pumping, current drive systems)

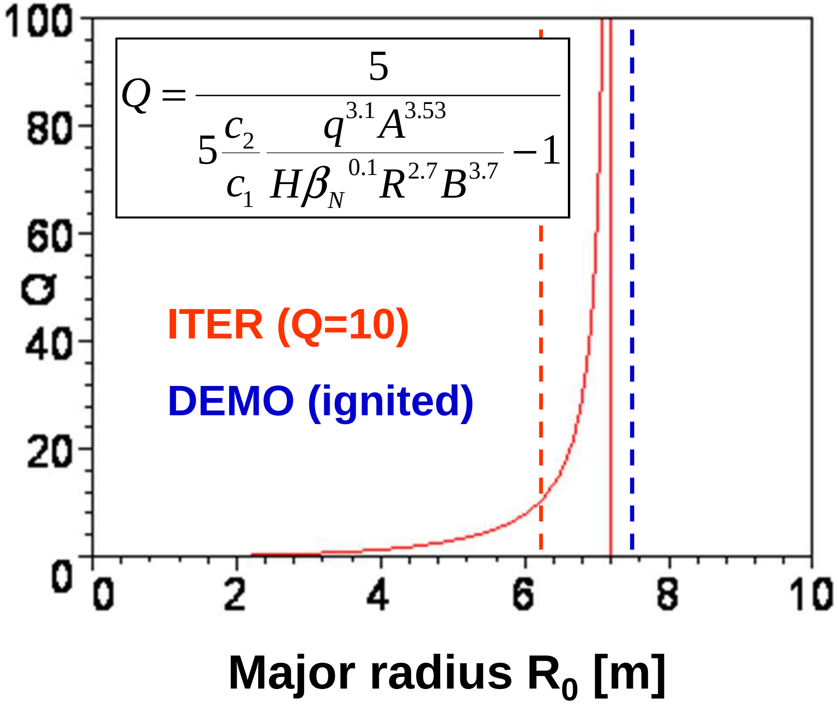
Introduction: DEMO designs

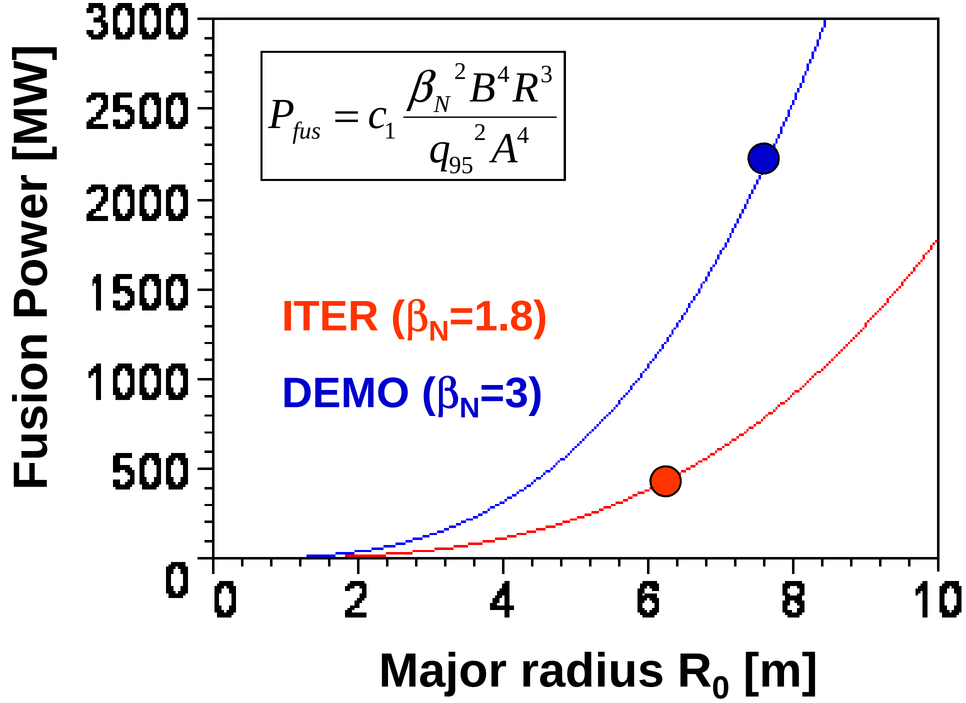
Study		Hiwatari 05 (DEMO-CREST)	Najmabadi 06 (ARIES-AT)
Operation mode		Steady state	Steady state
P_{th} (GW)		3.3	1.9
$P_{el,net}$ (GW)		0.5	1
R_e (m)		7.25	5.2
A		3.4	4
B_t (T)		7.8	5.9
I_P (MA)		14.7	12.8
f_{bs}		0.5	0.91
γ_{CD} (A/(W 10^{20} m^{-2}))		0.3	0.4
P_{CD} (MW)		191	35
H		1.2	−1
β_N		3.4	5.4
Reference		9	10

However, there is quite a spread in optimism of assumptions

- DEMO-CREST: very moderate assumptions, building on ITER Q=10
- ARIES-AT: operation at '99% of all physics and technology limits'

τ_E and β_N determine machine size





- high τ_E helps to achieve ignition, but does not enter in fusion power
- β_N does almost not enter into Q, but strongly into fusion power

- Introduction: what is DEMO?
- DEMO technology challenges
- DEMO physics challenges
- Risk mitigation strategies

DEMO technology challenges

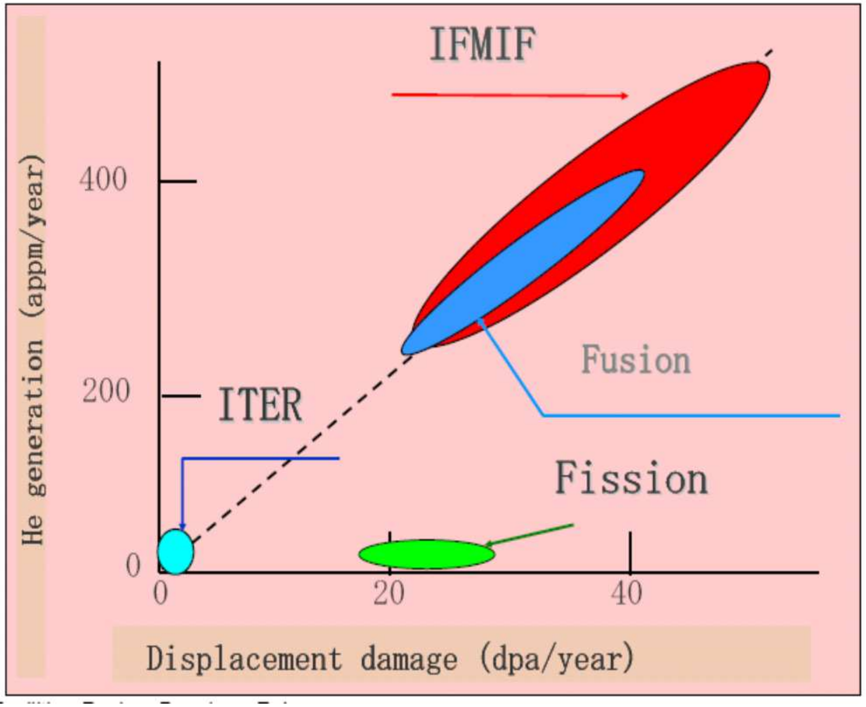
Many solutions can be adopted from ITER – these will not be treated here

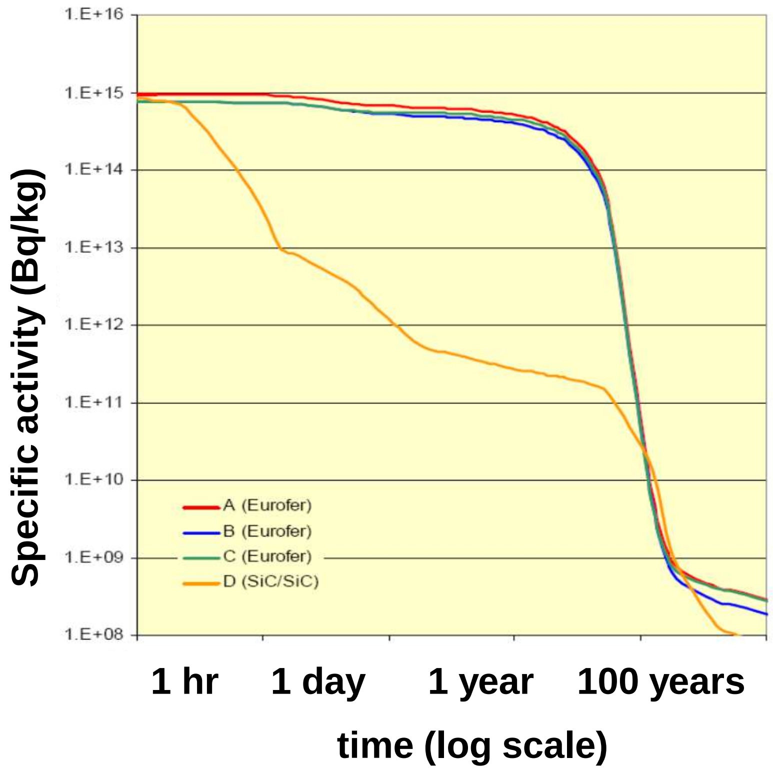
The EU programme has identified the following DEMO technology challenges, i.e. items that will qualitatively go beyond ITER

- Enabling technologies (H&CD, Diagnostics and control, T processing etc.) have to have highest **availability, reliability** and **efficiency**
- **Materials** have to cope with much higher n-fluences at adequate lifetime and, at the same time, low radiological burden
- **T-self sufficiency** has to be guaranteed

‚DEMO is no longer an experiment' – industry should be involved early on!

DEMO Technology Challenges: Structural Materials



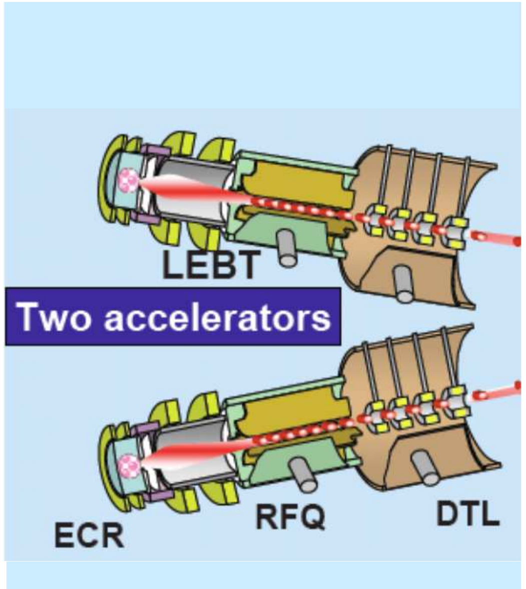


Progress in materials development needed to fully use fusion advantages

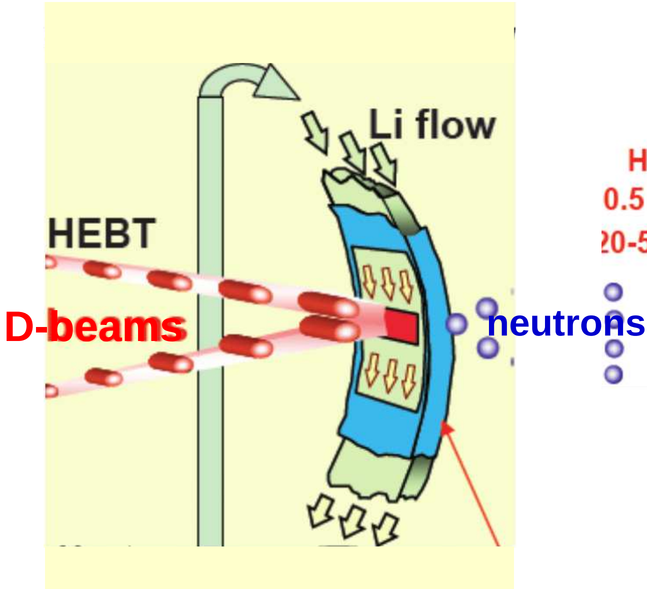
- issues: structural stability at high temperature (Carnot efficiency) and under 14 MeV n-bombardment (rise of Ductile-Brittle Transition Temperature)
- EUROFER steels up to 550^{o} C, better: Oxide Dispersion strengthened Steel
- also reduce waste issues (fuel/burn products itself have short $\tau_{1/2} \leq 12$ yrs)

Fusion Material Development – IFMIF

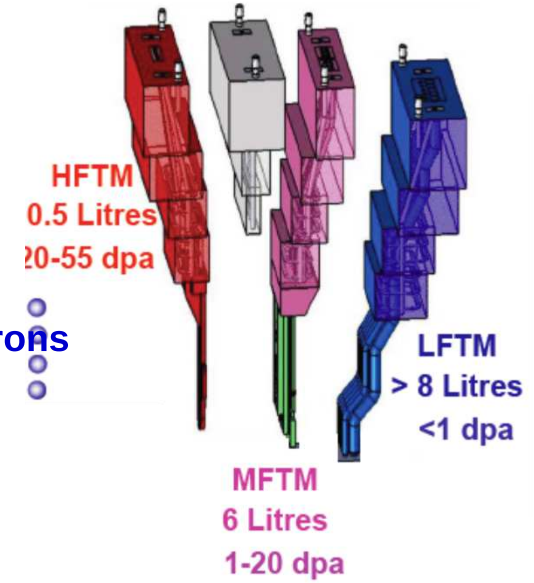
D-Accelerator



Liquid-Li Target



Test cell



Construction of DEMO as first of a kind requires qualification of materials

- need dedicated facility with high n-fluence of fusion-specific spectrum

IFMIF can address this and should run several years before DEMO licensing

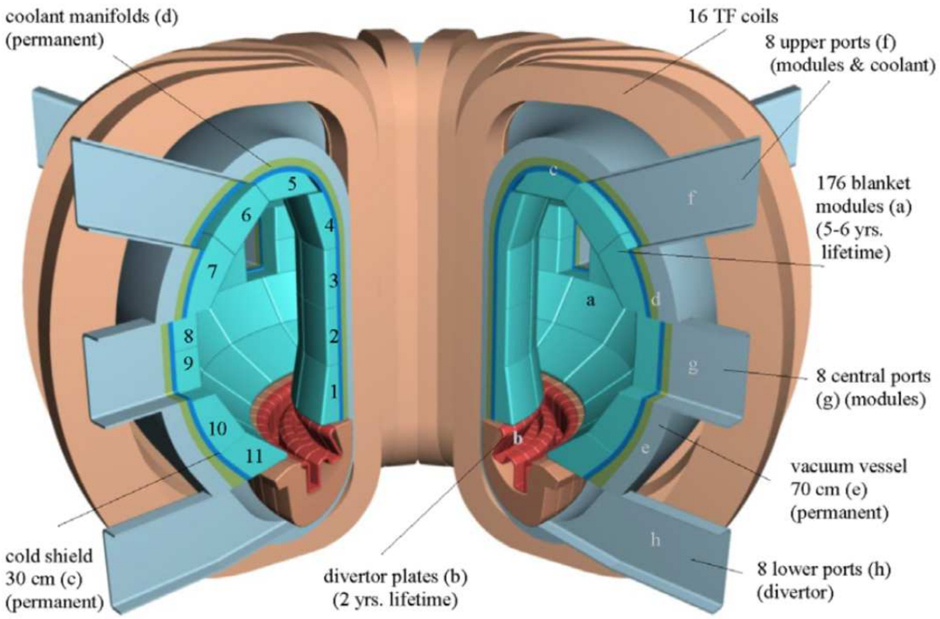
- important to get IFMIF going if ‚fast track‘ option should be kept
- present status: 5 years ‚EVEDA‘ (Japan/EU), then ready to build

Technology sets strict limits for exhaust in DEMO

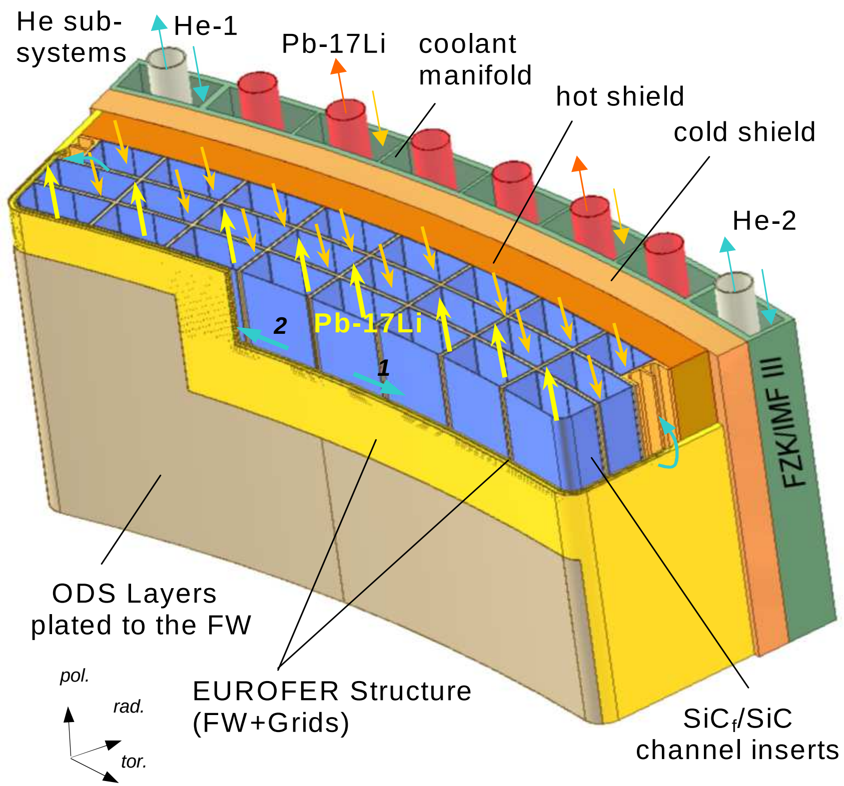
- Water cooling: (safety, small T_{op}-range (DBTT), < 5 dpa): ≤ 5-**10** MW/m^2
- He cooling: (higher T_{op}-range, but development needed): ≤ **5**-10 MW/m^2
- in addition, $T_{e,div}$ ≤ 4 eV to limit erosion (consistent lifetime estimate)

Karlsruher Institut für Technologie

DEMO Technology Challenges: Blanket



EU Power Plant Conceptual Design Study (PPCS)



"Dual Coolant" He-PbLi LM Blanket Design
$T_{max} \geq 650°$ C, 80-150 dpa in DEMO

Breeding blanket must provide self-sufficient T-supply for fuel cycle

- breeding ratio > 1 needed (1 neutron per fusion reaction)

Blanket also crucial for providing high grade heat (the hotter the better)

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- Risk mitigation strategies

The DEMO physics challenges

ITER will address key issues for DEMO beyond present day experiments, the most prominent example being α-heating

The EU programme has identified 'DEMO physics challenges' (items not needed for ITER Q=10, but absolutely vital for DEMO and an FPP)

- Steady state tokamak operation at high Q
- High density operation
- Power exhaust (R_{DEMO}/R_{ITER} = 1.2, but P_{DEMO}/P_{ITER} = 4!)
- Disruptions (W_{DEMO}/W_{ITER} > 5!)
- Reliable control with minimum sensors and actuators

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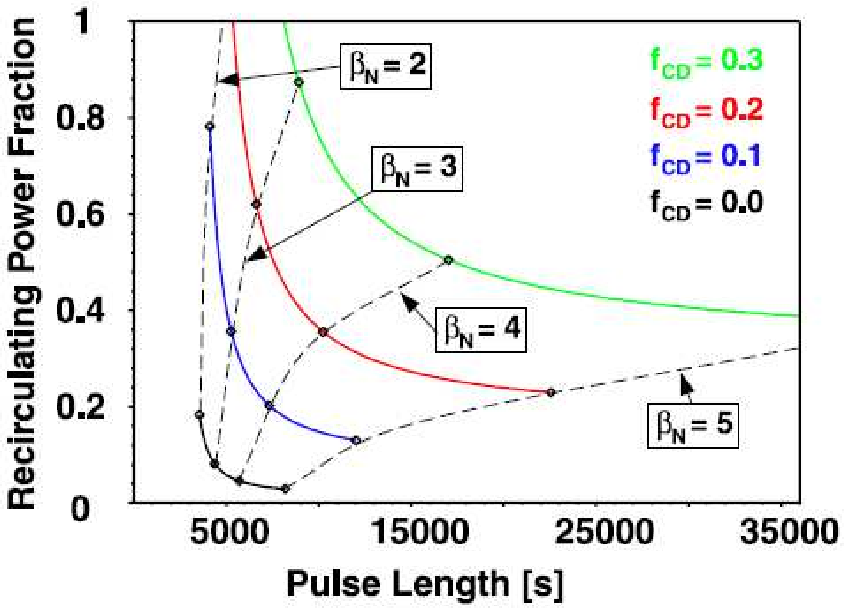
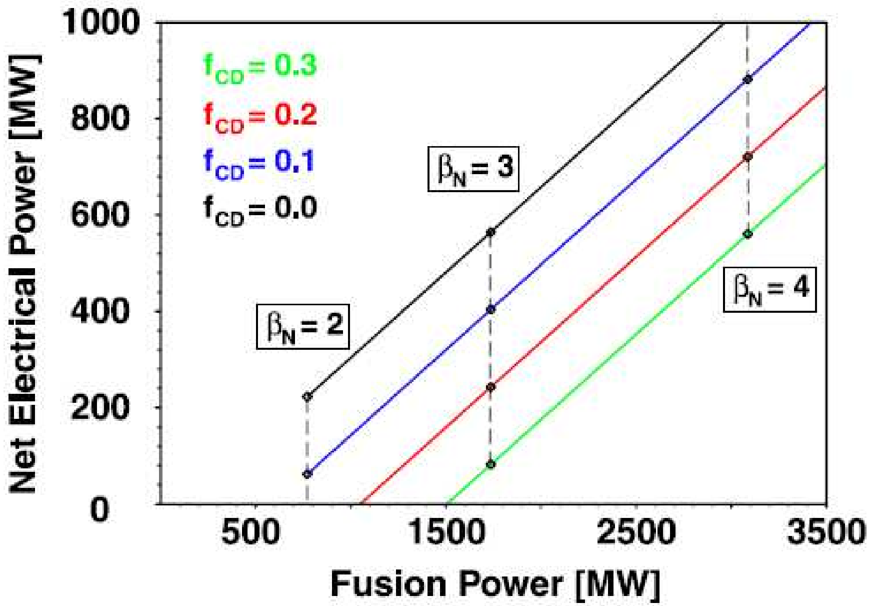
The ‘ITER’ case: R_0=7.5 m, B_t=5.2 T, A=3.1

Vary β_N = 2...5 and f_{CD} = 0 (ohmic)…0.3, assume conventional technology

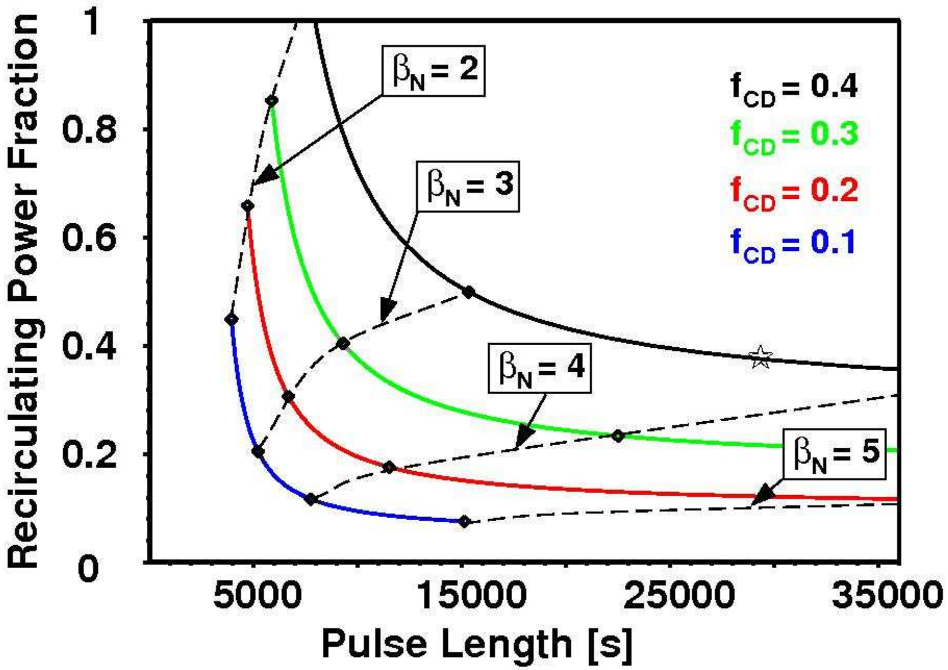




Objectives of acceptable f_{rec} and significant $P_{el,net}$ can be fulfilled, but sufficient pulse length requires high $\beta_N > 5$ (‘advanced tokamak’)!

The ‘ITER’ case: R_0=7.5 m, B_t=5.2 T, A=3.1

Assuming improved technology and physics (η_{CD}=0.5, γ_{CD}=0.4,H=1.2), the situation is relaxed w.r.t. power…



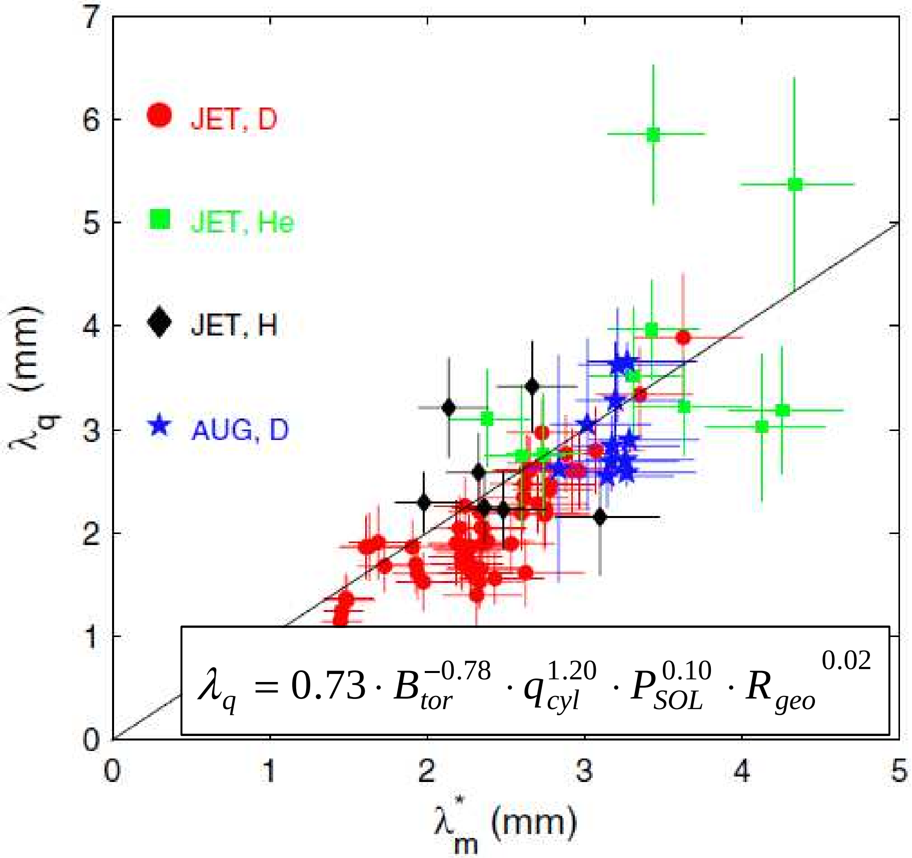
* β_N = 3.5
τ_{pulse} = 8 hrs
f_{rec} = 37%
$P_{el,net}$ = 500 MW

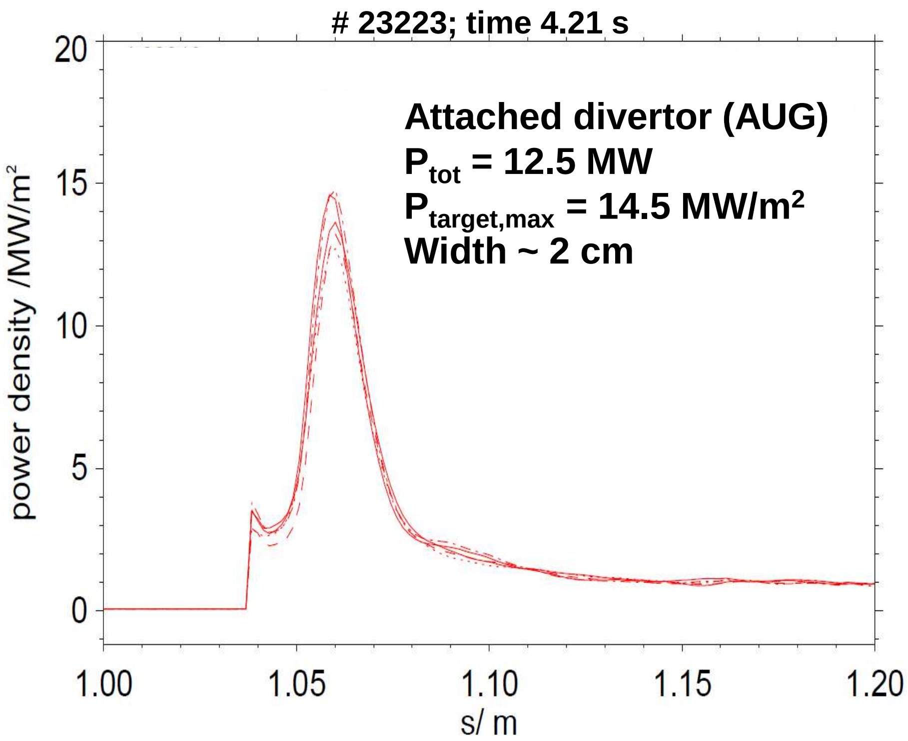
…but achieving steady state is still challenging the stability limits…

⇒ pulsed and steady state options to be studied in parallel (different A!)!

⇒ high efficiency of H&CD systems becomes crucial!

Exhaust: no R-scaling of power deposition width

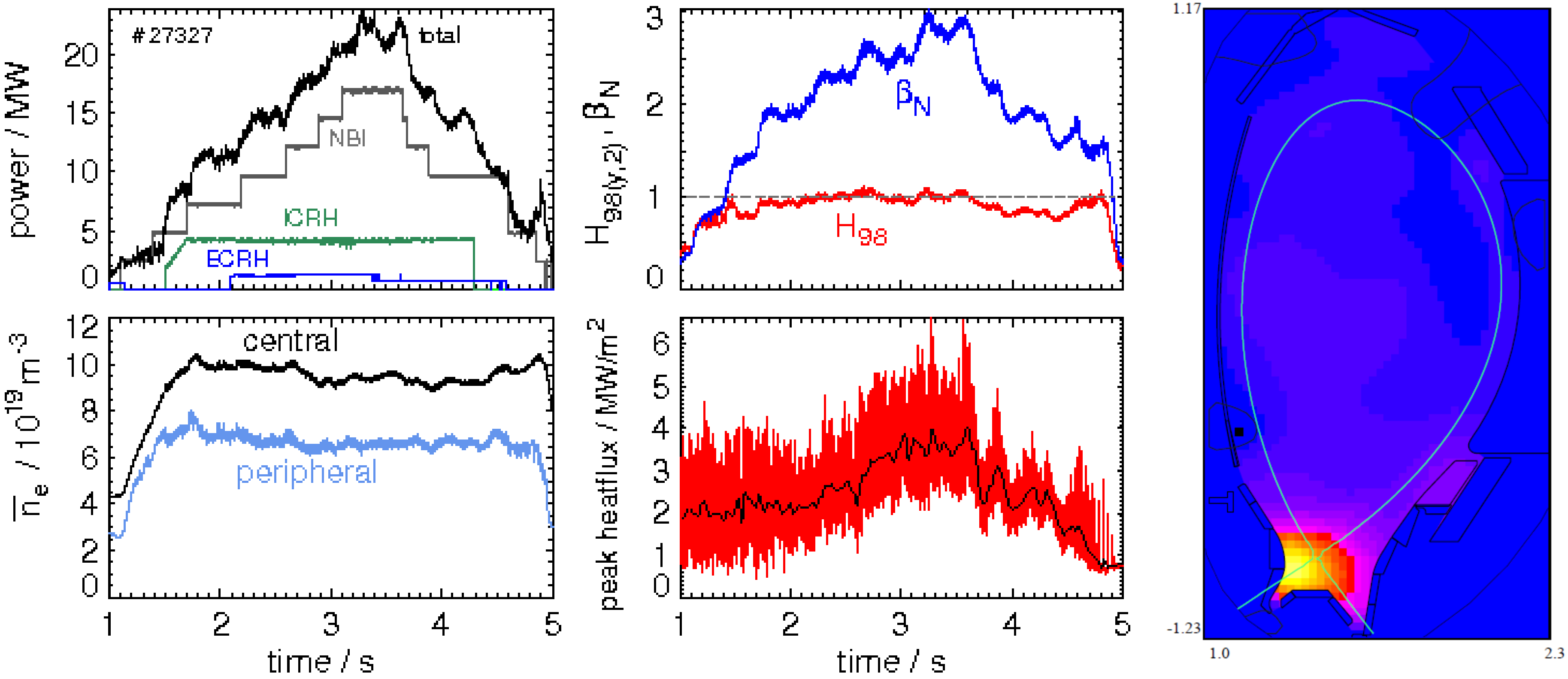




Under attached divertor conditions scaling yields 2 mm in the midplane (2 cm at the divertor target) in DEMO and ITER

figure of merit is P_{sep}/R since wetted area only increaes linearly with R

Experiments at high P/R (ASDEX Upgrade)



Feedback controlled N- seeding: q_{div} < 5 MW/m^2 at P_{heat} = 23 MW

- good core plasma performance ($\tau_E/\tau_{E,iter\ scaling}$ ~ 1, β_N ~ 2.8)
- present values of P_{sep}/R up to 10 MW/m (ITER: 15 MW/m)

Exhaust problem in DEMO different from ITER

Simple P/R divertor scaling argument:

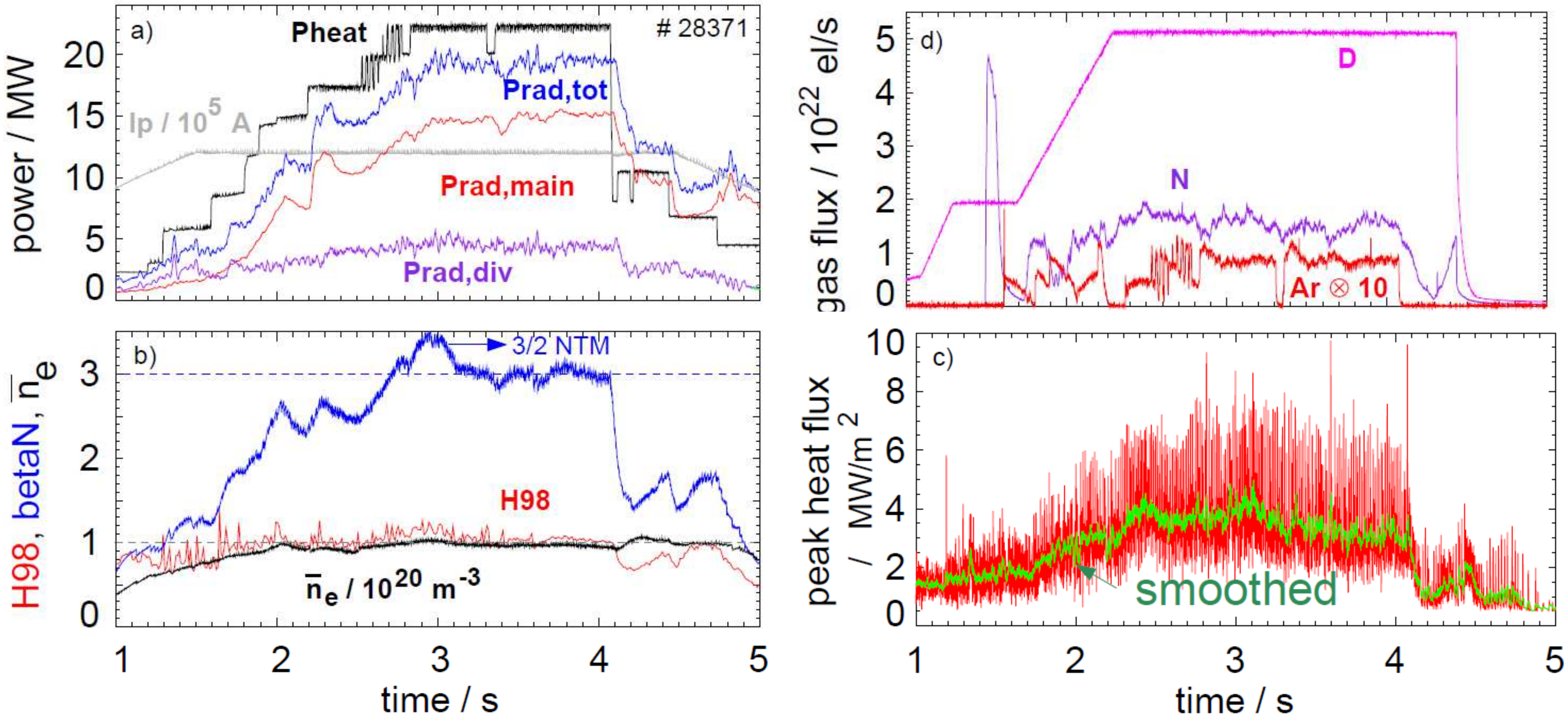
- Lower bound: ASDEX Upgrade result: P_{sep} / R = 7 MW/m
- Upper bound: ITER assumption: P_{sep} /R = 15 MW/m

	ITER (R=6.2 m, P_{tot}=120 MW)			DEMO (R=8.5 m, P_{tot}=400 MW)		
	P_{sep} [MW]	P_{LH} [MW]	$P_{rad,core}$ [MW]	P_{sep} [MW]	P_{LH} [MW]	$P_{rad,core}$ [MW]
lower bound	43	~ 70	77 (64%)	60	~100	340 (85%)
upper bound	93	~ 70	27 (22%)	125	~100	275 (70%)

An unprecedented ‚core‘ radiation level will be needed in DEMO!

- $P_{rad}(r)$ must be tailored consistent with confinement needs

Double Radiation Feedback (ASDEX Upgrade)



Now, $P_{rad,main}$ controlled by Ar-seeding (more radiation inside separatrix)

- still $P_{heat,tot}$ = 23 MW and q_{div} < 5 MW/m^2, but now $P_{rad,core}$ = 15 MW (67%)
- close to P_{LH}, but still $\tau_E/\tau_{E,\text{iter scaling}}$ =1 and β_N = 3!

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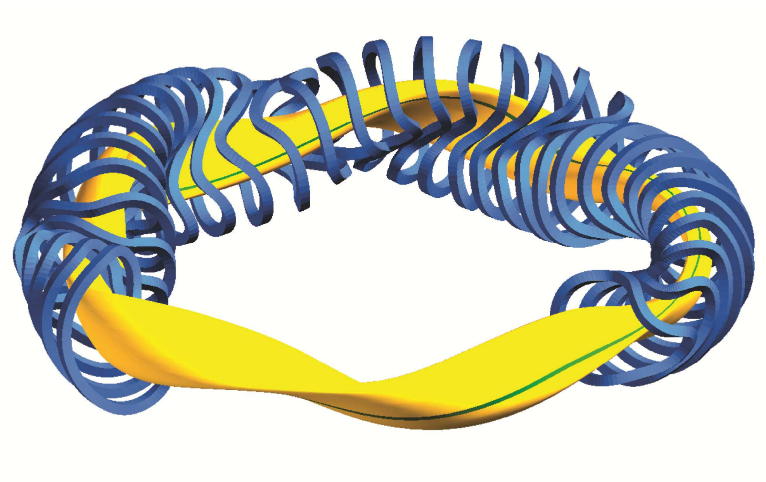
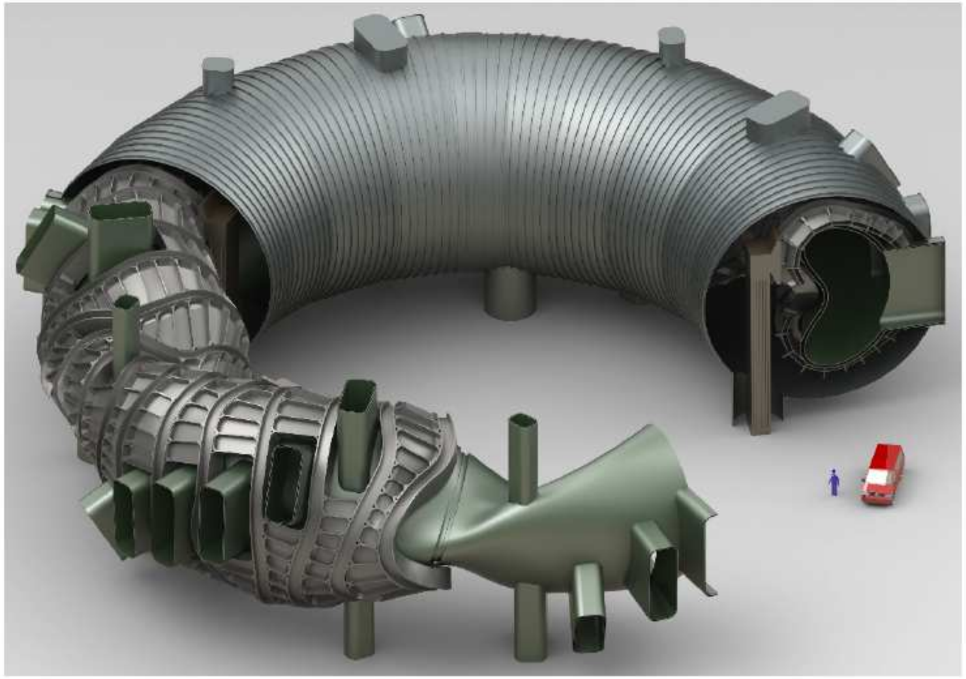
- **Risk mitigation strategies**

Stellarators are intrinsically steady state devices



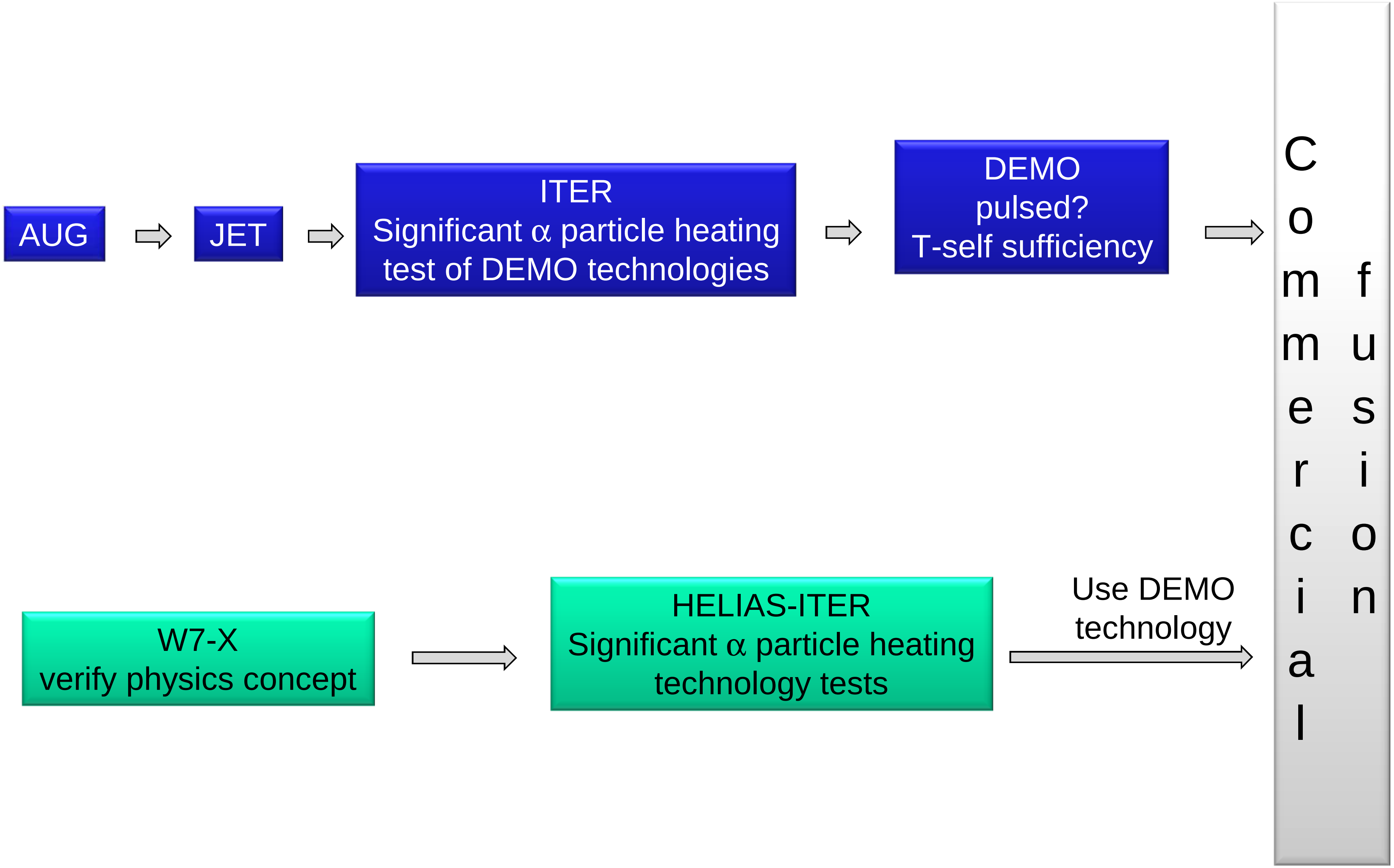
F. Schauer et al.
24th SOFE (2011)



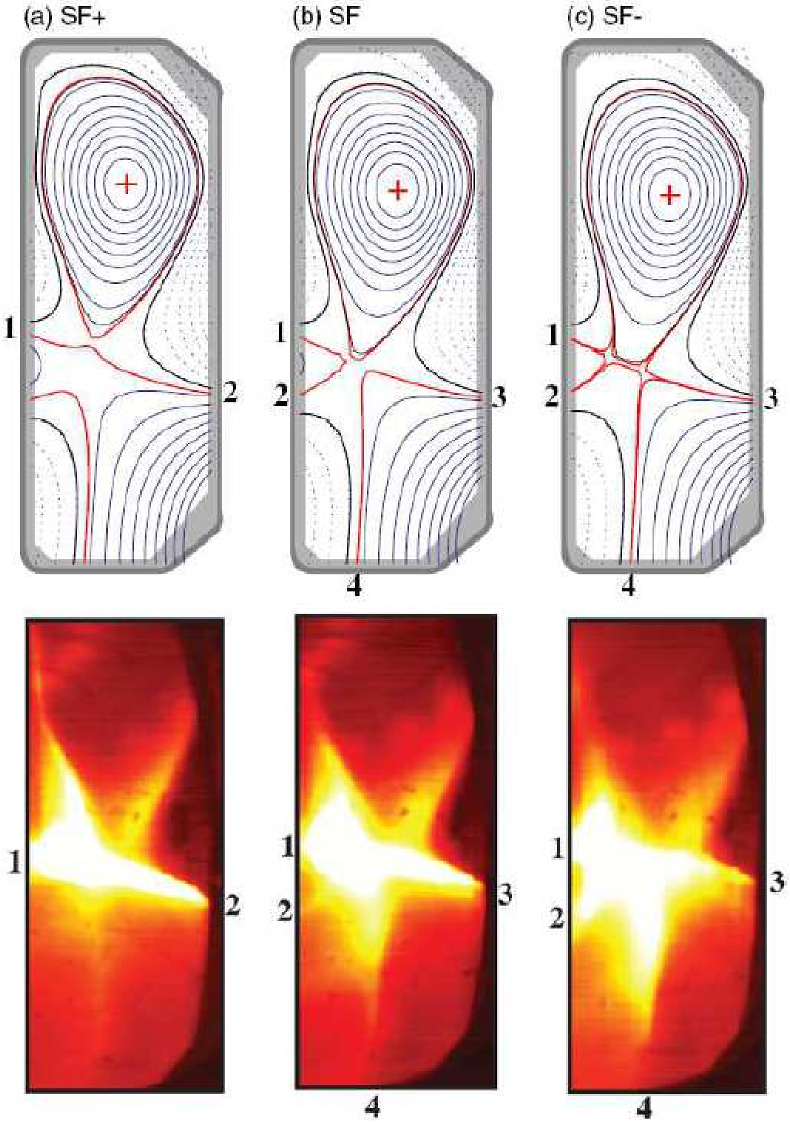
EU programme studies stellarator line as alternative to tokamak

- no internal plasma current – no limitation to steady state plasma operation
- no disruptions since no intrinsic current
- engineering feasibility of stellarator power plant must be assessed early on

Stellarator in a roadmap to a fusion reactor



Optimisation of divertor geometry



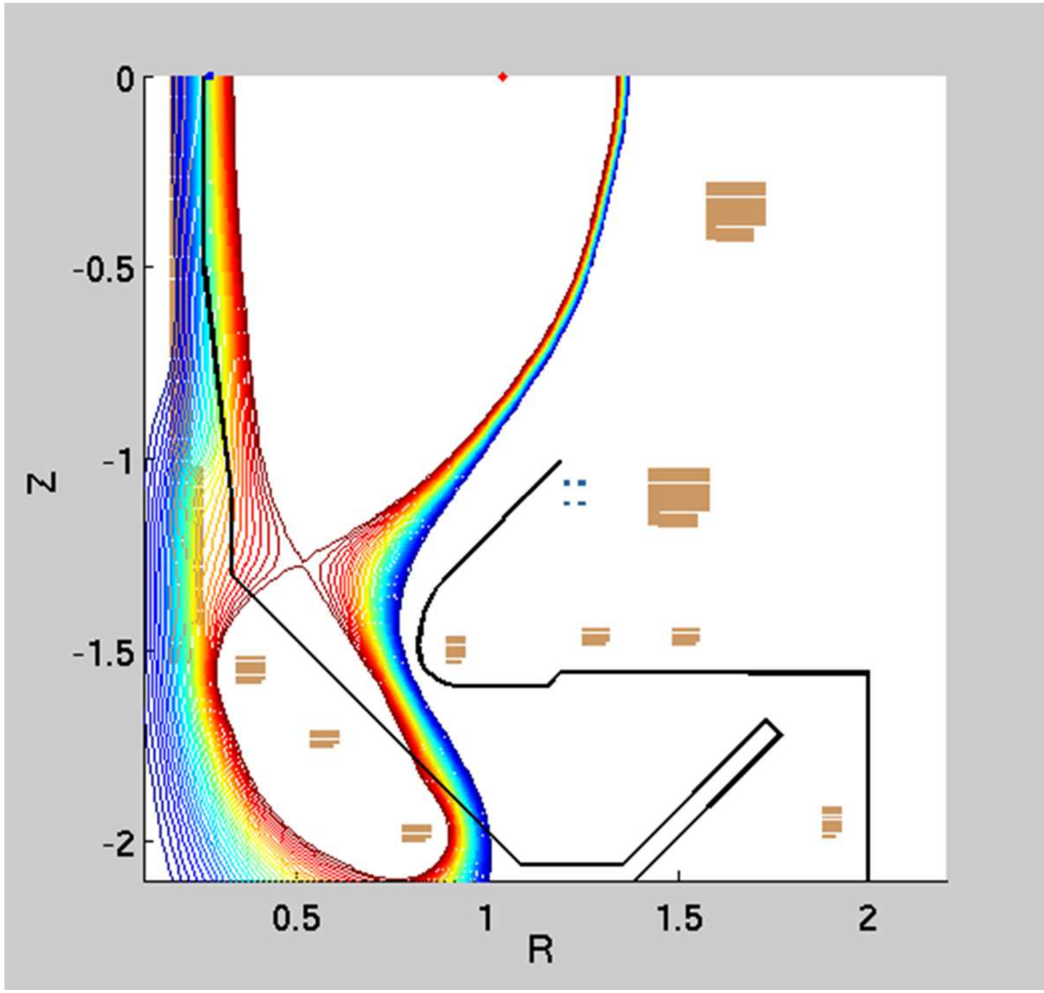
The ‘snowflake divertor’ has a higher order magnetic field null

- ‘snowflake’ promises large expansion of magnetic flux and concomitant broadening of wetted area

Technological questions to be studied:

- integration into reactor (higher multipole requires closer coils)
- controllability of configuration

Optimisation of divertor geometry



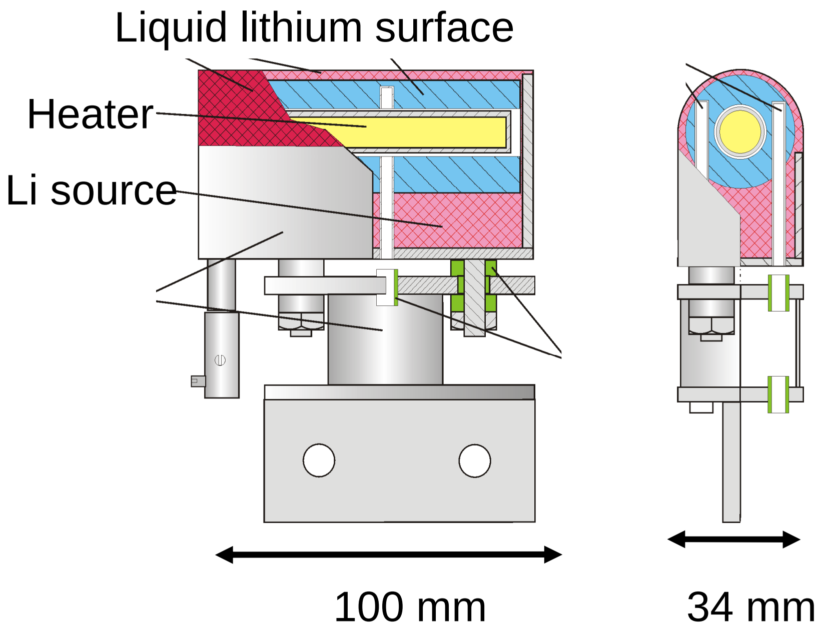
'Super-X divertor' has very long outer divertor leg

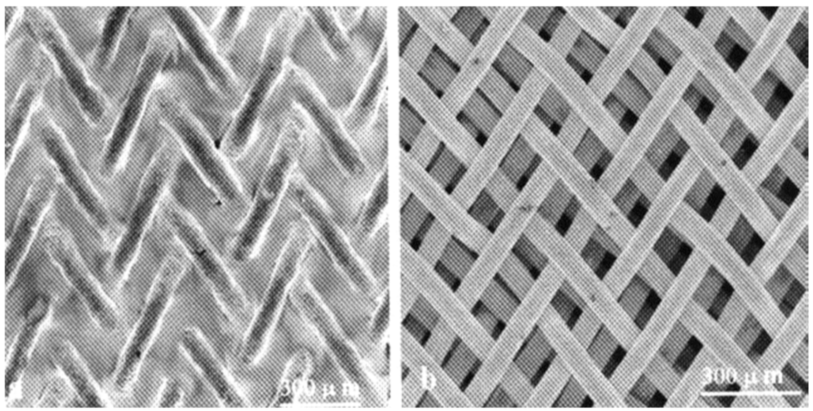
- maximises toroidal magnetic flux expansion
- promises large divertor volume and wetted area

Technological questions:

- integration into a reactor (long divertor leg $\rightarrow$ coils need to be close to plasma)
- controllability of configuration

‚New‘ materials: liquid metals





Experiments with liquid Li show

- good plasma compatibility
- capillary porous system – no droplets

However, technological questions have to be solved before this can be considered a viable candidate

- T retention will be high (use Ga?)
- heat removal concept that does not rely on evaporation heat needed (jxB forces on flowing metal!)
- concept for a closed metal cycle under steady conditions needed

Concluding Remark: Physics & Technology

Technology and physics challenges are strongly interlinked

- traditionally, physics assumptions have led to requirements for technology (example: divertor target has to stand 20^{+} MW/m^2)
- not always possible to match (see above), which calls for an iteration

Technology and physics should be treated in an integrated way, applying the same level of optimism in the assumptions!

This requires engineers and physicists to sit together at one table!

- ideally, a hierarchy of design decisions is worked out

First steps to bring the two communities closer together have proven to be very fruitful ☺