Areas of research needed for Demo and how U.S. and international collaboration might play a role

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A. General – An enormous step to Demo is the demonstration of understanding of the processes/physics at high Plasma Facing Component (PFC) temperature (600-800 C) w/He cooling and under high heat and particle fluxes. This work is not being done anywhere at the moment.

The level of current understanding for most knowledge gaps between where we are now and Demo is such that longer pulses are not the limiting factor for the near future (5-10 years). In the near term, whether here or abroad, we need to develop better diagnostics and utilize them in appropriate experiments. However, as both diagnostic measurements and our understanding of the issues get better, then going to longer pulses, ***with similar or better diagnostics***, could lead to additional understanding. One must note that on a spectrum of conditions from today's tokamaks to a Demo the Asian tokamaks are in the range of existing tokamaks in not utilizing high temperature PFCs and not having high flux/fluences of heat and particles. In fact heat and particle fluxes to PFCs will likely be lower than for existing tokamaks to achieve long pulses. One has to be careful that to achieve longer pulses the parameters associated with plasma wall interactions are not so low (heat/particle fluxes) that longer pulses do not gain much (e.g. TRIAM). Also note that in some gap areas (e.g. development of better PFC materials) the initial work is primarily on linear facilities, not toroidal devices. In others (e.g. better magnetic divertor configurations) the effort is centered in the US (not planned for Asian or EU machines) and not much is to be gained by longer pulses.

Serious thought should also be given to what composes a useful US – overseas collaboration. The paradigm of successful collaborations with the EU machines has been partly due to the structure of ITPA which gave a platform for exchange of ideas, and partly that the partners involved are usually of equal capability in terms of diagnosis and physics knowledge. If there are unequal partners then the flow is one way – and can be the wrong way for US interests.

Lastly, we (nor the Asians) are not really devoting enough effort to removing disruptions (the magnetic instability part) and finding alternative scenarios for confinement (no ELMs) and power handling.

B. Specifics goals – ordered into three subsections by level of importance
Ia Development of PFC materials, cooling and attachment methods for reactor-like high temperature steady state operation

a) Issues - The tungsten we use now has nuclear damage problems (e.g. vacancies associated with He created in lattice cannot all be annealed out) and brittleness in general and possibly degradation even due to T and He fluxes into surfaces. Loss of T through permeation through the PFC into cooling channels; How to really cool with He in steady state (water cooling is not possible at reactor temperatures). In any case new versions of W must be developed to address these limitations and tested at steady state, high heat and neutron loads. This all

has to be done in reactor like steady state temperatures (600-800C) as opposed to up and down temperatures associated with pulses as that is bad for materials. He cooling, neutron and high hydrogenic implantation fluences are needed.
b) measurements/research – work is needed in materials development and with plasmas. The measurements would ideally include real-time measurements of the T in the material and the material properties. Proper atomic/molecular modeling should be coupled to the measurements.
c) What can be done in the US – We have a materials development and modeling community. We also have linear plasma facilities (primary facility as opposed to a tokamaks) for testing as well as a range of tokamak heat/particle fluxes (C-Mod, DIII-D, NSTX).
d) What can be done in Asian machines – Mostly need linear machines and modeling which, for the Asian labs, is not at US level but could be over some period. Longer tokaaamak pulses would not be as interesting if not at heat/particle fluxes more Demo-like than U.S. (primary step beyond linear facilities and US tokamaks).
e) What is not being done – need detailed studies of what is going on inside the material under nuclear damage (need IFMIF or equivalent that works faster). Need linear and tokamak facilities to test materials under high particle and heat fluxes – steady state.

Ib Physics solutions to reactor heat loads and transients
a) Issues – Steady state reactor heat loads to divertor and first wall with be 4-5x that of ITER which are already too high. Need solutions to transients such as ELMs and disruptions which, if they exist will also do much more damage than in ITER. Example - one cannot predict/prevent a droplet of tungsten from going in the plasma core -> radiate all energy and magnetic instability -> fast deposition of heat loads - > damage -> reactor down for years. Need to remove magnetic instability from sequence as stellarators have leaving a relatively slow shutdown.
b) Measurements/research - Experiments aimed at evaluating new divertor topologies (e.g. snowflake, 'super-x'), disruption elimination (as far as magnetic instability) as well as alternate operating modes without ELMs. Understand power heat load width in SOL with better diagnostics/modeling. Need dedicated facilities aimed at removing magnetic instabilities from occurring after a thermal collapse of plasma.
c) What can be done in US – Beginning experiments with advanced divertor configurations. Already a robust research program developing diagnostics and modeling for understanding pedestal and heat flux widths. Work ongoing on disruption physics. Some modeling work on removing magnetic instability in disruptions.
d) What can be done in Asia – Similar to US. The development of such alternative magnetic solutions does not require long pulse. In fact, the next step after initial development would probably be to completely replace the divertor in an existing machine or build a new machine. That step would serve to optimize the configuration beyond what can be created in today's tokamaks.
e) What is not being done anywhere – new facility aimed at taming disruptions.

IIa. Fuel retention

a) Issues – Curently fuel retention as a percentage of flux/fluence to surfaces is of order .1 – 1% for the few measurements made. A reactor needs this percentage to be of order .001% or too much T will be stored in PFCs (site limit issues) as opposed to being burned.
b) Measurement/experiments – direct measurement of the fuel in a surface. Experiments examining that retention as a function of fluxes, surface temperature, fluence.
c) What can be done in the US – Continued development of surface interrogation technique (being developed using ion beam by D. Whyte, Laser technique being pursued at Juelich). Use simultaneous with variations in surface temperature (e.g. heated divertor in C-Mod).
d) What can be done in Asian machines – Dependent on available diagnostics and physics knowledge longer pulses will allow more detailed studies if the measurement can be done during a discharge – not currently available.
e) What cannot be done anywhere – need to do the above studies at high heat and particle fluxes, high PFC temperatures and along with the measurements.

IIb. Material erosion/transport/deposition

a) Issues - Material from PFCs will erode, transport and re-deposit. We cannot predict the rate of net erosion not to mention its transport and where it goes. So we cannot predict how long a surface will last before it needs to be replaced, where the material will go (and its properties) and how much dust might be generated. One of the biggest problems with modeling impurity transport is that we do not yet properly model the background plasma transport – generally in the SOL as well as specifically in shadowed regions.
b) Measurements/experiments - The real time determination of surface makeup is being developed (see #5 above) but it needs to be proven and implemented at many places in a device.
c) What can be done in the US – Ongoing development of diagnostics for surfaces as well as impurity and plasma transport.
d) What new things can be done in Asia (or EU) – Dependent on the development and implementation of diagnostics for real time determination of surfaces concentrations of impurities (not presently available) then longer pulses could bring more information (statistics) on material movement. Of course, if such longer pulses are at reduced parameters, than the length of the pulses need to compensate for reduced erosion. Reduced fluxes will also affect the penetration and transport of impurities into the plasma.
e) What cannot be done anywhere – the above experiments under the high heat and particle flux conditions and at high temperature and steady state.

IIc RF compatibility for steady state

a) Issues – A reactor needs efficient heating & current drive with low impurity levels, compatibility with PFCs (e.g. not leading to hot spots), compatibility with

SOL – steady state which means water cooling, high SOL heat/particle loads and nuclear environment compatibility.
b) measurement requirements –basic physics of how the waves travel through the SOL and are absorbed in the core – making sure to benchmark models in detail. The same is true for understanding effects ON the SOL – we need measurements of the wave fields in the SOL and relate them to other effects (e.g. sheath rectification, absorption of power….) and the physics underlying those processes. These efforts are minimal now in the field.
c) What can be done in the US - Currently only being addressed at C-Mod (ICRF, LH). EU work at Tore Supra (ICRF, LH) and AUG (ICRF) to some extent. Better plasma potential measurements needed in the SOL and measurements of wave fields.
d) What could be addressed at Asian machines – The addition of diagnostics would bring them to a level equivalent to the US. The development of cooled components can be done in a test stand anywhere but the final testing in a long pulse tokamak could be done in Asian machines to the level of heat/particle fluxes/fluences allowed .
d) What cannot be addressed anywhere –steady state high heat fluxes at the same time as launching waves. Need experience at high heat loads with reactor temperatures and He cooling.

III. Dust
a) Issues – Dust is potentially a show stopper for reactors in terms of buildup (getting in the way of the plasma), being pulled into the plasma (impurity injection) and T retention (fuel can be stored in huge amount of surface area).
b) Measurements/experiments - We need means to understand the physics of dust creation (what events lead to it and how much is generated per event), dust movement and accumulation, and some means of removing dust.
c) What can be done in the US – The research is addressing dust movement but not dust generation. Better diagnostics are needed.
d) What can be done in Asian machines (or EU) – Dependent of what is the primary mechanism of dust creation (e.g. disruptions vs deposition) longer pulses would help here somewhat through better statistics. Again, this is dependent on new diagnostics being developed (work which will probably occur elsewhere) and whether the fluxes/fluences of heat and particles are significantly reduced in order to achieve longer pulses.
e) What cannot be done anywhere at the moment – full diagnostic coverage of vessel following and identifying dust creation under high heat and particle loads and high surface temperatures.

IV. Interaction/feedback between surface reservoir of fuel and the SOL and the core plasma
a) Issues – The core – SOL – material surface – material bulk is a coupled system with a large range of time scales from ms up to thousands of seconds. We need experience with understanding this system under reactor conditions.

b) Measurements/experiments – real-time measurement of the fuel in the PFCs as well as in other reservoirs (SOL, core). Vary the PFC temperature up to reactor temperatures and determine how the coupling changes. Validate understanding with models.
c) What can be done in the US – continue with fuel retention studies in C, Li and Mo/W. Plans for higher PFC temperatures (C-Mod) and direct measurement of fuel in material.
d) What can be done in Asian machines. Measurements need to be brought up to same level as US and EU. Long pulse would require measurements during plasma discharge.
e) What cannot be done anywhere – reactor temperatures and high heat/particle fluxes.