Implications of increased gas throughputs at ITER on the torus exhaust pumping system

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Abstract. The reference design of the ITER torus exhaust pumping system is based on 8 cryopumps, connected via 4 ducts to the torus. The exhaust gas flows will pass through the divertor into the pumping slots, at divertor pressures between 1 and 10 Pa. The pumping port and divertor geometry has limited conductance which reduces the available pumping speed for the whole machine. This effect together with the recycle flows at the divertor have been studied with the transitional flow code ITERVAC; this paper reports the first results of this study. ITER is also considering to increase the reference fuelling rate. As the pumping system is operated in transitional flow regime, increased flows will change the overall conductance and directly re-influence the available divertor pressures. Massive gas injection is the proposed concept to safely terminate a disrupting plasma discharge. Higher gas flows will have implications in terms of pressures inside the cryopump volume and heat loads on the 4.5 K and 80 K cooling circuits of the cryopumps, and consequently on the full pump operating envelope. The different effects and mutual influences and consequences are discussed in this paper. It is concluded that the fuel rate increase associated with ELM pellet pacing has significant consequences on the torus cryopumping system, which can currently not be predicted quantitatively. It is further shown that disruption mitigation will lead to the torus cryopumps going into regeneration.

1. Introduction and description of the present situation

The torus exhaust pumping system required to provide the needed vacuum conditions during burn and dwell of ITER operation is a powerful, high-speed cryopumping system.
Firstly, a pressure under the divertor dome of between 1 and 10 Pa has to be maintained in order to detach the plasma. This pressure results from a balance between the incoming gas flux, the effective pumping speed at the divertor and the recycling gas paths. Especially the impurities have to be kept at a minimum level to avoid large radiation and thereby allow for a repeatable machine operation. As the burn-up fraction is limited, very high gas throughputs have to be processed. This duty is fulfilled via a powerful, high-speed cryopumping system, which also provides for the necessary base vacuum in the dwell time in between the pulses.
Secondly, a base vacuum in the order of 10^{-4} Pa has to be prepared in the (limited) dwell time in between the plasma shots. Additionally, it is also needed to provide high vacuum during fine leak-testing of the torus, for wall conditioning and bake-out and to provide ultimate vacuum in the torus.
The reference design of the ITER torus exhaust pumping system is based on 8 cryopumps, connected via 4 ducts to the torus, each of them containing a pump in direct line of sight and a branched pump [1]. Fig. 1 illustrates the geometry of the pumping duct. The exhaust gas will pass through the divertor pumping slots. The divertor system comprises 54 cassettes.
The cryopumps are force-cooled from a supply which provides supercritical helium at 4.5 K (at 0.4 MPa(a)) and gaseous helium at 80 K (at 1.8 MPa). The design of the torus cryopumps is very much advanced. Different regeneration patterns for the torus cryopumps will be implemented depending on the type of plasma scenario and exhaust rate, but the most severe one will occur during long pulse operation when the time allocated for the four different regeneration steps will be only 600 s; the total cycle time of each torus cryopump, equally

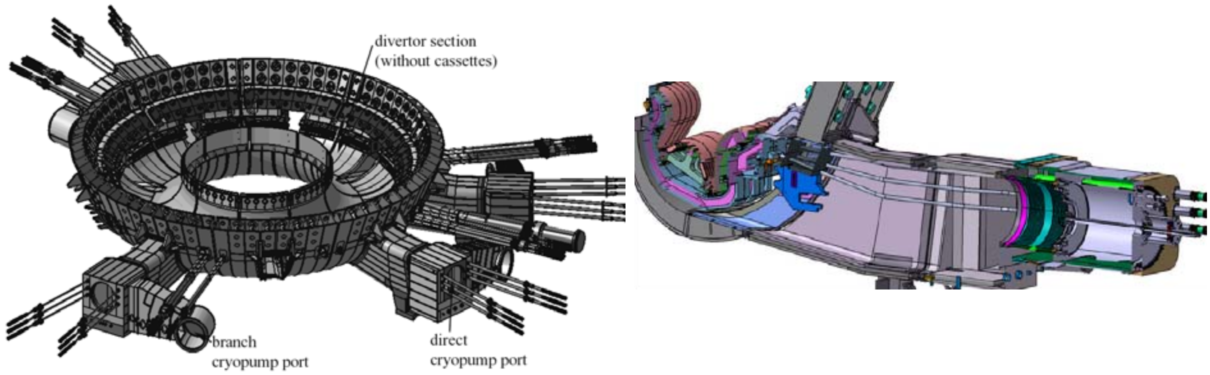

FIG. 1. Left: 3D view of the ITER lower port region, showing the torus exhaust pumping ports with branched and in-line duct. Right: Cut of the in-line torus exhaust pumping duct (ca. 10 m long).

shared between pumping and regeneration is 1200 s [2]. The limitation of the pumping time ensures to limit the complete hydrogen inventory in the complement of pumps open to the torus for explosion safety reasons. The pump sees three different regeneration levels: After each pumping period, a partial regeneration with helium gas at 100 K will be performed; less frequently, the pumps will be regenerated at ambient temperature to release the air-likes. Additionally, there is the possibility for a high temperature regeneration to take place up to 470 K to release water and hydrocarbons.

The torus exhaust pumping system is a balanced system whose performance and operation scheme are influenced by various parameters among which the exhaust gas rate is the most important. The maximum allowed hydrogenic gas accumulation per pump is limited by oxy-hydrogen deflagration safety considerations: increased gas flows will lead to more frequent regenerations. As the pumping system is operated in transitional flow regime, increased flows will change the overall conductance and directly re-influence the available divertor pressures. Here, the integral inlet valve of the torus cryopumps acts as an additional degree of freedom for exhaust control. Higher gas flows will result in higher pressures inside the cryopump volume and lead to increased heat loads on the 4.5 K and 80 K cooling circuits of the cryopumps. Depending on the heat loads, the outlet temperatures of the coolant will tend to increase which, if unmitigated, could affect the pumping speed for helium, or, alternatively, the cryogenic flows can be increased, which then has an impact on thermohydraulics and pressure losses across the pumps´ cryocircuits. To provide sufficient operating margin, ITER plans to reduce the reference cryopanel supply temperature from 4.5 K to 4.35 K [3]. If the gas flow becomes excessive, the vacuum pumps will go into regeneration, in which case the recovery time becomes a central issue for system availability [4]. In any case, no damage is allowed and all systems have to stay safe.

2. The reference design of the torus cryopumps

In a recent design effort, a detailed design of the torus cryopumps has been elaborated [5]. In this exercise, wherever possible the existing data base of experimental data with a smaller scale model pump measured in the TIMO facility at Forschungszentrum Karlsruhe (FZK) was exploited. The vacuum technological design of the full scale torus cryopump is based on a theoretical treatment by Monte Carlo calculation but the scaling laws to include transient and viscous effects which are dominating already under normal operating conditions are not known. Hence, pumping duties are not a straightforward scale-up from the model pump. Moreover, dimensional constraints from remote handling and critical mechanical components (double bellows compensator, etc.) were not investigated in the model pump and some

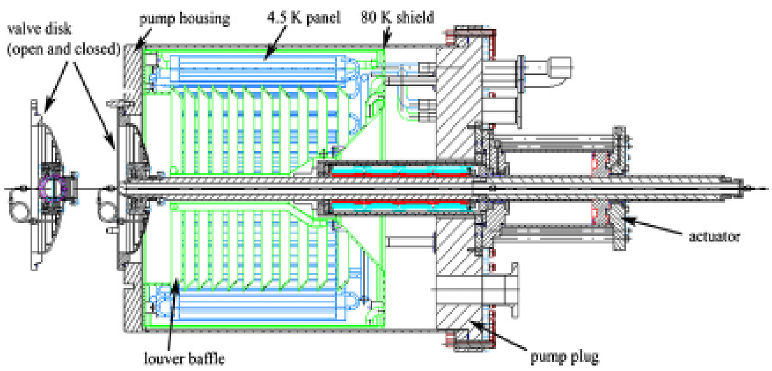

FIG. 2. Schematic design of the ITER prototype torus cryopump.

features of the model pump which were found to be problematic (water cooling and alignment springs of valve disc, shaft bearing arrangement, etc.) have been reviewed. It has therefore been decided to build a prototype torus cryopump (PTC) by industry and investigate its characteristics in the upgraded TIMO-2 testbed at FZK for validation of the design.

The reference throughput chosen for the torus cryopump design was the given maximum gas flow of 153 (Pa·m^3)/s as specified in the ITER baseline [6]. This value relates to the fuelling rate of 120 (Pa·m^3)/s and an estimated additional impurity gas load of further 33 (Pa·m^3)/s.

3. Assessment of the divertor flow pattern

The torus exhaust cryopump design was fully optimised to offer a nominal, molecular flow pumping speed of ~ 75 m^3/s per pump. However, the pumping port and divertor geometry has limited conductance which reduces the available pumping speed for the whole machine. The gas passages through the divertor cassettes incl. the asymmetries in the system and torus pumping ducts form a complex network of conductances. FZK has developed ITERVAC, a special network modelling code which is able to describe vacuum flows in the whole range of the Kn number [7], i.e. covering all flow regimes from laminar flow and transitional flow at the divertor region to molecular flow at the cryopump region. Simulations were performed to study the influential parameters of the gas flow through the divertor slots and along the pump ducts into the torus cryopumps. For this significant effort, the divertor design as of summer 2007 was used, which did not differentiate between normal and diagnostic cassettes and features an equilateral distance of 10 mm between the cassettes. Different simulation models were generated to simulate the burn and dwell phase [8].

Fig. 3 illustrates the simulations performed for the burn phase. Shown are the calculated maximum throughputs for the torus pumps and the plasma side. It must be noted that these flowrates are maximum values determined by the system geometry. It does not mean that these flows can be pumped, as the reference exhaust gas rate used for the cryogenic design of the torus pumping system is 153 (Pa·m^3)/s. However, the simulations show clearly that the integrated maximum throughputs to the plasma are at least on the same level as the ones to the cryopumps, showing a tendency to further increase at higher pressures. This is due to the fact that the pumping speed of the torus cryopumps is finite compared to the plasma, which acts as a black hole. This effect of high recycling of gas to the plasma will influence the controlling of the vacuum pumps.

At the lowest specified divertor pressures of 1 Pa (worst case for pumping), the maximum throughput is 160 (Pa·m^3)/s, which exactly meets the requirement for the reference flow rate (153 (Pa·m^3)/s). At 2 Pa there results a maximum throughput of 366 (Pa·m^3)/s.

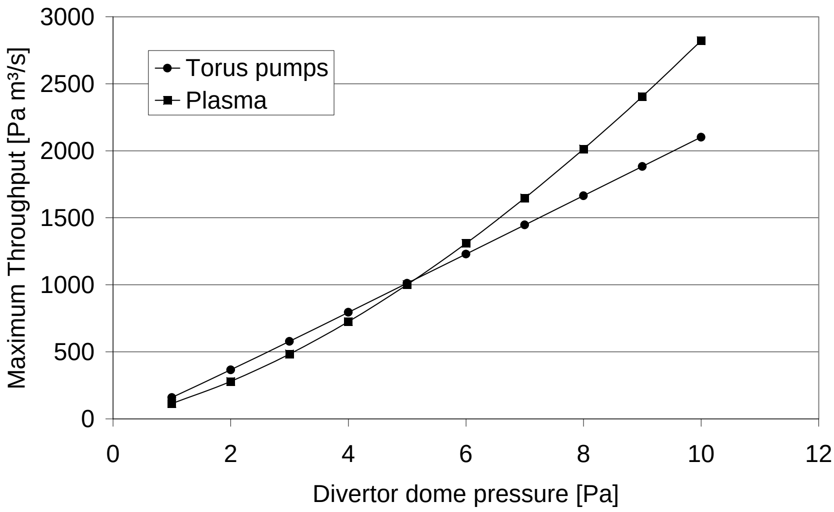

FIG. 3. Calculated maximum gas throughputs towards the plasma (recycle flow) and the torus pumps with inlet valve being fully opened (exhausted flow), calculated for D_2.

4. Increased gas throughputs at ITER

It is currently proposed to introduce ELM pellet pacing in order to manage the energy dissipation of ELMs [9]. This and other considerations has lead to a proposed increase in the reference fuelling rate of 120 (Pa·m³)/s for all pulse durations to 200 (Pa·m³)/s for 400 s pulses, and 160 (Pa·m³)/s for 1000 s pulses [3]. From the vacuum pumping system point of view, additional 33 (Pa·m³)/s impurity gas load has to be added on top of the fuelling rate. This change has some implications on the pump operating envelope and will be discussed in the following section 4.1.
Massive gas injection is the proposed concept to safely terminate a disrupting plasma discharge [10]. Many aspects of this type of disruption mitigation need more investigation to prove their suitability for ITER. Various gases or gas mixtures have been suggested (among which is helium, hydrogen, neon and argon) which would produce additional transient gas loads. The gas amount needed depends on the electron content and therefore becomes larger with lighter gases [11], the values are in the range from 500 kPa·m³ for helium to 100 kPa·m³ for argon. This impact is discussed in section 4.2.

4.1 Implications of the increased fuelling rate

The throughput per pump defines the pressure during pumping inside the torus cryopump. This is a very important property as it determines the available pumping speed which may be different from the nominal pumping speed of a cryopump given for molecular flow conditions. Under molecular conditions, the density is so low that the mean free path of the particles is significantly larger than the pump diameter. In this regime, the pumping speed is constant and independent of pressure. If the throughput will be increased so that higher densities and transitional flow regime is resulting, the pumping speed is also increasing. Fig. 4 is illustrating this effect for the ITER model pump, which was very well characterised experimentally in the TIMO facility at FZK [1]. The curve for highest throughput refers to the ITER reference exhaust gas flow rate of 153 (Pa·m³)/s. At further increase of the throughput and the pumping speed, correspondingly, the heat load due to the gas being pumped becomes more and more dominant, so that the cryogenic temperature of the pumping panels cannot be maintained any longer. This has a negative influence on the sticking coefficient of the gas particle on the charcoal [12] and, thus, on the pumping speed. However, the consequence of that depends on the type of gas being pumped. Helium shows a very strong dependence of the sticking coefficient on temperature, whereas hydrogen is rather independent as long as the temperature stays below 15 K.

The problem lies in the fact that the qualitative description above can not be given in quantitative terms, as the pumping speed evolution with increased throughput is not a priori known and very difficult to predict. Only the limit value for molecular flow conditions can be predicted by means of detailed Test Particle Monte Carlo simulation, see Fig. 4. The figure also reveals that, already under nominal operation conditions, the torus cryopumps are operated under transitional flow conditions. The pumping speed evolution behaviour can only be measured. As in the step from the model pump to the 1:1 scale pump, the pumping surface could be almost tripled, whereas the inlet cross-section could only be weakly increased (the ITER pumping port size did not change), the operation point at peak load is given by comparable surface related fluxes as was investigated in TIMO, but significantly higher pump pressures than was the case for the model pump. The proposed peak exhaust gas flow rate corresponds to 4.5 (Pa·m³)/(s·m²) related to the coated surface area, and 26.0 (Pa·m³)/(s·m²) related to the inlet area.

The ITER torus cryopump operational point is therefore out of the measured envelope with the model pump, and the scaling law is not known. Moreover, the PTC design is in many aspects different due to a rigorous system optimisation so that it is essential for ITER to develop a predictive pumping speed tool for the torus cryopumps, see section 5 below.

The transitional mode has the advantage to provide higher pumping speeds, but, on the other side, is associated with higher heat loads on the cryopanel and thermal shields as well. Table 1 lists the heat load values for the torus cryopump under nominal pumping conditions. The heat load due to the enthalpy difference of the sorbed fuel gas amount (enthalpy change between 80 K and 4.5 K plus phase change enthalpy due to sorption plus tritium decay heat) is proportional to the part of the exhaust gas, which is sorbed at the 4.5 K system; this corresponds to the fuelling rate. Under the proposed peak rate of 200 (Pa·m³)/s, there results an overall heat load on the 4.5 K system of 220 W, which is a ~ 50% increase of the overall heat load. At unchanged coolant flow, this leads to approximately 50% increase in the resulting temperature difference.

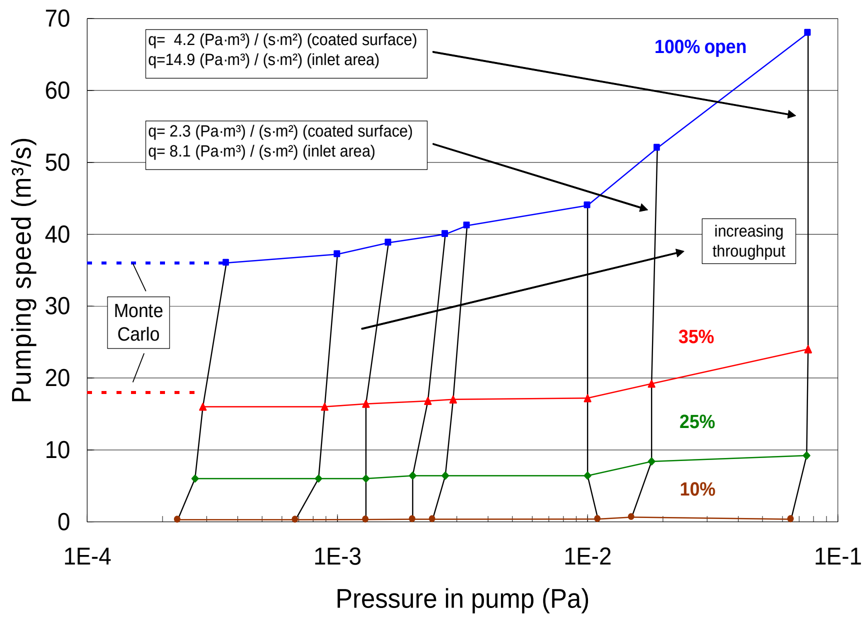

FIG. 4. Pumping speeds for the ITER model cryopump at varied throughputs and valve position, measured in TIMO. The model gas composition was 86.6% D_2 , 10% He, 1.3% CO, 1,1% CH_4, 0.6% CO_2, 0.4% O_2.

TABLE I: HEAT LOADS OF THE TORUS CRYOPUMP UNDER NOMINAL PUMPING

	4.5 K cryopanel system	**80 K thermal shield system**
Thermal radiation [W]	25	1000 (housing at 300 K, valve fully open)
Solid heat conduction [W]	12	125
Pumped gas load enthalpy [W]	110	200

This is an interesting result, as the inlet temperature of the coolant supply has been reduced recently, especially in order to meet the requirement to have the outlet temperature at 4.7 K. It is known that helium pumping at 5 K and under the high gas loads to be encountered in ITER will be associated with thermal oscillations. To avoid this risk, the cryogen mass flow would have to be increased by a factor 1.5, which, on the negative side is associated with more than doubled pressure losses through the cryopanel system resulting in distribution non-uniformities of the coolant between the various parallel cryopanel circuits. Detailed investigations on these effects are in preparation in a dedicated test facility at FZK. To change the panel geometry (larger flow cross-sections) is considered to be impossible due to limitations mainly coming from the high operation pressures and requested test pressures. In summary, this increase in the reference fuelling rate has to be matched with adaptations in cryogen mass flows or pressure drops.

The final aspect which shall be discussed is the hydrogen accumulation. The nominal 600 s pumping interval at the nominal 120 (Pa·m^3)/s fuelling rate leads to an accumulated inventory of 8 mol (the available volume for regeneration is 8.5 m^3). This still leaves some safety margins against the 1.5 mole/m^3 inventory limitation which limits the deflagration end pressure in case of a LOVA initiated oxy-hydrogen explosion to values below the design pressure of the duct (0.2 MPa) [13]. Under the new reference fuelling scheme, assuming a constant operation at the maximum value, the accumulated inventory after 400 s at 200 (Pa·m^3)/s is 7.2 mol and uncritical. The 160 (Pa·m^3)/s case, which is being introduced for the 1000 s pulse, leads to an inventory of 10.7 mol after 600 s pumping, which is still below the limit but does not provide much contingeny any more. Hence, it is planned to pump the first half of the pulse length with the first 4 pumps, and to use the second set of four pumps for the second half of the 1000 s pulse.

4.2 Implications of disruption mitigation

The central issue is to clarify if the torus cryopump goes into regeneration under the large gas loads discussed. This means we have to assess the flow rate which results to the cryopumps, if we have a pressure jump in the vacuum vessel, and the resulting pressure that we have in front of the (torus) cryopumps. Then we have to clarify the flow regime and for that to derive the pressure inside the pump corresponding to the pressure in front of the pump. Based on the torus volume (~ 1350 m^3), we arrive at typical torus fill pressures between 370 Pa (corresponding to the 500 kPa·m^3 amount case, helium) and 74 Pa (100 kPa·m^3, argon).

The first part of this task can be tackled using the ITERVAC model described in section 3, which shows clearly that we have in any case laminar flow in the pumping duct, resulting in almost identical pressures in front of the pump. Even under the limited extrapolability of the situation illustrated in Fig. 4, at resulting expected pressures it seems obvious that the torus cryopumps will go into regeneration for the helium case. In case of heavier gases such as neon, which will result in smaller injected gas amounts, it may be possible for the torus cryopump to cope with the incoming gas load. This depends on the position of the pump inlet valve at the moment of the massive gas injection event. The travel time of the valve is in the order of some seconds, so that it cannot be used for active control. However, if the valve is already in a relatively closed position, chocked flow will limit the gas inflow, which, together with the thermal inertia of the cryopump inner installations, might prevent the pump from going into regeneration. A detailed analysis based on flow and FEM modeling is recommended to study this effect in more detail.

The limit acceptable throughput for the torus cryopump is one of the issues which are planned to be measured within the tests of the PTC in TIMO-2, once the prototype pump is manufactured.

In safety investigations with the model cryopump, principle tests on a LOVA accident have been performed within which the cryopump was subjected to sudden pressurization up to very high rates of 60 kPa/s [14]. It was found that the gas release is not kinetically limited and demonstrated that the pump design is sufficiently robust to withstand this sudden venting processes.

It shall also be emphasized that the pump mechanisms are different and changing for the species helium/hydrogen, neon and argon. In the helium/hydrogen case, if the pump goes into regeneration, they will be desorbed. Under normal pumping condition, Argon is passing the 80 K shields and pumped by re-sublimation on the charcoal. During regeneration, it will be sublimed, re-adsorbed and finally released at temperatures above the partial regeneration temperature of 100 K. Finally, neon is pumped by sorption and also released below 100 K. This affects the resulting recovery time until the torus vacuum pumping system becomes available again after a disruption mitigation event. In pumping speed tests with the model pump performed at FZK, no significant poisoning effect of accumulated neon and argon has been found.

5. Development of a predictive tool for the cryopump performance under non molecular flow conditions

As outlined above, the assessment of the cryopump under non molecular flow conditions which is the case already under nominal flow conditions, but definitely under increased gas inflow conditions, is a key question. A calculation tool for pumping speeds and heat loads under these conditions is essential, also on a longer perspective to support the operation of ITER. Consequently, FZK has started to assess two options for the development of a suitable code, namely Direct Simulation Monte Carlo and Particle-in-cell Monte Carlo [16]. Both approaches are Monte Carlo calculation techniques, which include collision kernels between particles. The latter one is in principle leading to shorter calculation times and therefore it has given first priority.

FZK has developed ProVac3D, a Test Particle Monte Carlo code without molecule-molecule interaction, but directed to describe cryogenic systems with large temperature and density gradients. It has been successfully applied to the design of the ITER NBI systems [16]. This code is being used as a platform to develop the collisional kernel. To consider collision we will use the simulated density and bulk velocity in case of neglected collision cross section as starting assumption and include the non-zero cross-section in an approaching iteration process step by step. This is done in a statistical random variation of the mean free path. The question if the probe molecule will collide with another molecule or not is judged by comparing the calculated hitting time to the next wall with the calculated travelling time between the particles. Currently, this algorithm is under implementation and to achieve numerical convergence is one of the central aims.

5. Conclusion and Outlook

This paper illustrates the basic considerations and aspects to be taken into account for the design of the torus vacuum pumping system. It is clearly shown that the envisaged increase of fuelling rate is possible but adds to the operational complexity of the cryopump system. For disruption mitigation with helium, the pumps are expected to go into regeneration. In case of neon, the pump regeneration may become avoidable. But further analysis is required to investigate this effect in more detail. Experimental assessment of the limit flowrates in the prototype torus cryopump is essential.
A lack of predictive capabilities of the cryopump performance was identified. Once available, it would allow to quantitatively calculate the heat loads and the pumping speeds under transitional flow regime conditions which result in the torus cryopumps from both pellet pacing and disruption mitigation events.

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