Studies of Requirements for ITER Disruption Mitigation Systems

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Abstract. Recent work conducted under the aegis of the US Burning Plasma Organization related to establishing recommendations for requirements for ITER disruption mitigation systems is described. The recommendations and assessments of the resulting plasma and tokamak operations impacts of a massive-gas-injection disruption mitigation system have been developed in concert with the ITER Fusion Science and Technology Department. Several recommendations are made for the system: high reliability, large flexibility in the choice, mixture and quantity of gases, and its installation in at least two toroidal locations to provide redundancy. The large quantity of deuterium or helium neutral gas, ~500 kPa-m^3 estimated to provide unequivocal collisional mitigation of runaway electron conversion is found to have significant after-injection impacts on the ITER torus vacuum pumping and exhaust processing systems. These impacts are reduced but not eliminated by employing neon injection. The impact assessments have highlighted needs to limit injected gas quantity to the minimum necessary for adequate runaway mitigation and to optimize the plasma uptake of injected gas or particles delivered to the torus. A variety of alternate or optimized gas, liquid and solid injection mitigation schemes and/or consideration of enhanced stochastic losses that may offer mitigation efficacy relative to presently-conceived basic, single MGI options have been identified.

1. Introduction

ITER in-vessel components are designed to withstand the electromagnetic and thermal loading stress and erosion caused by disruptions. However, there are clear incentives in ITER to both avoid the occurrence of disruptions whenever possible and to reduce the deleterious effects of such disruptions that do occur. Disruption damage may limit the usable lifetime of the affected internal components, and time consuming reconditioning of plasma facing surfaces after disruptions will likely be required for subsequent discharges. Requirements for mitigation of disruption effects fall into three categories: (1) reduction of thermal loading on divertor and first-wall plasma facing component surfaces, and in particular avoiding material thermal limits (melting/ablation), (2) reduction of electromagnetic forces associated with halo currents, and (3) mitigation of runaway electron conversion in the current quench phase of the disruption. Methods and actions that accomplish these categories of mitigation have been tested and demonstrated with a large degree of success and ITER relevancy in present tokamaks [1-3].

This paper summarizes recent work, conducted under the aegis of the US Burning Plasma Organization and in concert with the ITER Fusion Science and Technology Department, related to establishing recommendations for requirements and design concepts for ITER systems. The initial focus of the work has been on establishing requirements for a single massive gas injection (MGI) system sized to accomplish simultaneously, if possible, all three mitigation objectives. The goals of this work are: a) to quantify the MGI requirements to the best of our present knowledge, b) identify critical gaps in science and technology and c) discuss strategies for the deployment and testing of disruption mitigation in ITER.

2. Physics Basis and Specifications for an ITER MGI System

Mitigation of thermal loading and electromagnetic forces from halo currents is relatively well established empirically [1-2]. More recent studies combining empirical observations [4,5] and numerical modeling [6,7] have provided better understanding of the mitigation phenomena of MGI in present devices. Injected impurities strongly cool the boundary plasma, in the vicinity of the pedestal. Progressive cooling produces unstable current profile with evolving and growing islands. Of particular importance is the cooling and island growth at q=2, which finally invokes a rapid cooling of the entire plasma through both convection and impurity mixing. The core energy is effectively dissipated by impurity radiation, and the cold, dense poorly conducting outer region results in a significant reduction of wall heating. Poloidal halo currents are reduced by forcing a high resistivity, and therefore rapid resistive decay, of the core plasma which prevents the plasma [3,8] from strongly limiting on the wall, such as is the case in unmitigated vertical displacement induced disruptions. While it is encouraging that very high global radiation fractions can be obtained, an open research question is the exact toroidal and poloidal distribution of the radiated energy, since the Be wall of ITER may melt if the radiation pattern is too asymmetric. Empirical observation [2,3,5] is that this thermal/electromagnetic (T/E) mitigation can be achieved with impurity density injection $n_{imp} \sim 5 \times 10^{21}$ m^{-3} (gas particles / plasma volume) introduced on a several millisecond timescale. Further injection does not clearly improve mitigation because a) radiated dissipation is close to 100% [3,5] and b) halo forces cannot be lowered because the plasma resistivity reaches its maximum value [9] when the temperature becomes pinned at its lowest possible value at fixed current density and ohmic power density. Fast particle delivery is desired since this minimizes the response time of the mitigation to a disruption detection trigger, and therefore the gas(es) sound speed and the distance of the injecting volume to the plasma come into design optimization. Further optimization is possible by mixing high-Z noble gases at low percentage with lighter (faster) carrier gases [10]. For ITER, with a volume $\sim 10^3$ m^3, the requirements for T/E mitigation are then: $N_{inject} \sim n_{imp} V_{ITER} \sim 5 \times 10^{24}$ particles or 20 kPa-m^3, at least two toroidally dispersed injection locations for both operational redundancy and impurity/radiation spreading, and a MGI system which allows for various noble and hydrogenic gases and mixtures thereof. We also note that this n_{imp}, in contrast to much smaller impurity injections when "killer" pellets are used for disruption mitigation, is generally successful on present devices at suppressing runaway electrons [2,3].

The third mitigation concern is runaway electrons (RE), i.e. relativistic electron beams that can be produced and sustained in the high electric fields, E (V/m), of the current quench. If a substantial RE beam (> MA) is produced and then eventually lost into the material structures due to its n=0 movement, the localized heating and relatively deep penetration of relativistic electrons could substantially damage first wall components. The specific concern in extrapolation of runaway generation to ITER is the effect of "knock-on' avalanche amplification [11]. The rate equation of RE current, I_{RE}, in the current quench can be generally expressed by

$$\frac{dI_{RE}}{dt} = \delta(t=0)(I_{seed}) + \gamma_{RA} I_{RE} - \gamma_{loss} I_{RE} \qquad \text{Eq. 1}$$

where I_{seed} is the seed RE population produced by the Dreicer or hot-tail [12] mechanism in the rapidly cooling plasma of the thermal quench, γ_{RA} is the avalanche growth–rate, and γ_{loss} is a generic loss rate due to RE transport out of the plasma. Rosenbluth established a general formula for γ_{RA} as a function of collisional slowing rate, normalized electric field E/E_c and impurity nuclear charge Z (see Eq. 18 in [11]). Connor and Hastie [13] showed that if E falls below the critical electric field, E_c (V/m) ~ $1.2\text{x}10^{-21}$ n_e, where n_e is electron density (m^{-3}), runaway electrons are not possible; a limit which was which was modified by Rosenbluth [11] such that n_e includes all electrons (free + bound) that may be present during disruption mitigation. Therefore if the total electron density in the plasma volume can be raised to this Connor-Hastie-Rosenbluth (CHR) limit, $E_c \geq E$, then collisional suppression of RE is guaranteed. Fig. 1 shows how γ_{RA} decreases with n_e, with the CHR limit being reached at n_e~$5\text{x}10^{22}$ m^{-3} for E=65 V/m. If $E \geq E_c$ then γ_{RA} is positive and exponential growth of the I_{seed} can occur. Integrating Eq. 1 through the duration of the current quench, τ_{CQ} (s), the final RE current can exponentially increase, i.e. $I \sim I_{seed} \exp\{(\gamma_{RA} - \gamma_{loss}) \tau_{CQ}\} \equiv I_{seed} \exp(G)$, where G is the exponential gain factor. At fixed resistivity, which we roughly expect for mitigated disruptions, τ_{CQ} is proportional to the cross-sectional area of the plasma S. The difficulty in extrapolating MGI RE suppression from present devices, is that G is significantly larger for ITER due to its size, such that exp(G) becomes so large (G > 20) that extremely small seed currents can lead to nearly full conversion of plasma current to RE [11], even though γ_{RA} is of similar magnitude to present devices. If one assumes γ_{loss}=0, then the solution to the RE problem is to force the CHR limit by increasing total electron density in the plasma, an option we explore quantitatively with two methods: 1) Empirical extrapolation and 2) a 0-D numerical radiation model of the impurity injection.

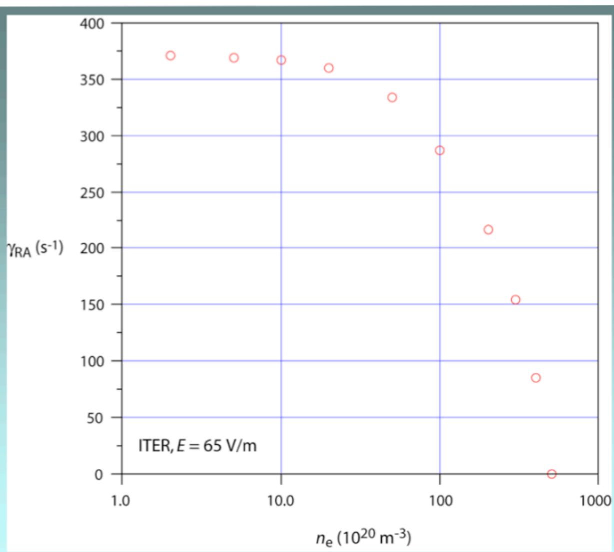

Fig. 1 Avalanche growth rate, γ_{RA} vs. total electron density (free+bound) in ITER when E=65 V/m.

The empirical extrapolation uses a disruption database [14] to project likely electric field values in ITER disruptions. It finds that the shortest normalized current quench (CQ), and hence highest E, is τ_{CQ}/S ~ 1.7 ms/m^2. Taking the ITER cross-sectional surface area, S~21 m^2, this corresponds to a linear CQ decay time ~ 40 ms and E ~ 60 V/m ($\propto S/\tau_{CQ}$). Applying the CHR limit, we obtain a simple relationship for the required total electron density n_{CHR} (m^{-3}) ~

Species	M (amu)	Z	N_{CHR} 10^{25} particles	m_{CHR} (g)	N_{CHR} kPa-m^3
H_2	2	2	2.8	94	104
D_2	4	2	2.8	186	104
He	4	2	2.8	186	104
Ne	20	10	0.56	186	20
Ar	40	18	0.31	206	12

Table 1. Gas quantities to achieve N_{CHR} for ITER (830 m^3), for the maximum current quench rate of τ_{CQ}/S = 1.7 ms/m^2 using the empirical extrapolation method.

$8x10^{22}$ (S/ τ_{CQ}). Therefore for the minimum τ_{CQ}/S ~ 1.7 ms/m^2, the required density is n_{CHR} ~$4.7x10^{22}$ m^{-3}, corresponding to a total electron number in the 830 m^3 plasma of N_{CHR} ~ 4 x 10^{25}. Table 1 summarizes the neutral gas injection requirements for τ_{CQ}/S ~ 1.7 ms/m^2 in terms of gas quantity and mass. Note that higher-Z gases require smaller injections due to the higher number of electrons per gas atom, and that the required gas inventory decreases linearly with (S/ τ_{CQ}) ~ E, indicating that longer normalized current quench durations are desirable. The injected mass is approximately 200 g, which is roughly species independent, and applies for all forms of material injection (gas, solid, liquid, particulate), since it is the number of electrons in the plasma volume that provides RE suppression. Importantly, n_{CHR} is about 5-10 times larger than the density (~$5x10^{21}$ m^{-3}) required for T/E mitigation; if RE suppression is met we expect T/E mitigation requirements to be met also. This also highlights the fact that present MGI experiments suppress RE but do not reach the CHR limit; since the n_{CHR} density depends on *normalized* CQ decay, n_{CHR} is essentially the same in present devices as in ITER.

Case	$c_{s,eff}$ m/s	τ_{CQ} (ms)	N_{CHR} kPa m^3
100% He	1019	45	126
100% Ne	456	43	26
25% Ne, 75% H_2	676	40	73
10% Ne, 90% H_2	797	40	368
5% Ne, 95% H_2	857	36	100
100% Ar	322	22	26
10% Ar, 90% H_2	684	24	78
5% Ar, 95% H_2	780	24	90

Table 2. Gas quantities to achieve N_{CHR} for ITER (830 m^3) using the 0-D KPRAD model, which also calculates τ_{CQ}. Sound speeds for pure and mixed gases are also shown.

KPRAD is used to perform numerical 0-D radiation-balance modeling of the plasma thermal equilibrium at the beginning of the current quench [3,9]. Because the model self-consistently calculates the electric field with an arbitrarily imposed impurity density, it allows us to examine the tradeoffs in the selection of impurity species. For pure noble gases, there is very good quantitative agreement on N_{CHR} between KPRAD (Table 2) and the empirical method (Table 1), generally validating the calculations. Impurity mixtures of Ar or Ne with H_2 are also shown in Table 2 with effective sound speeds, indicating possible tradeoffs between gas delivery time and RE suppression. Fig. 2 shows E/E_c and G versus impurity density for Ne/H_2 mixtures. It is important to note that RE amplification becomes less dominant (G < 4-5 such as found on present devices) at densities even a factor of 2-3 times below n_{CHR}; this suggests it may not be required to exactly reach n_{CHR} in ITER, but rather obtain G < 5. Therefore, overall we assign a factor of two uncertainty to the predictions, but error on the conservative side and

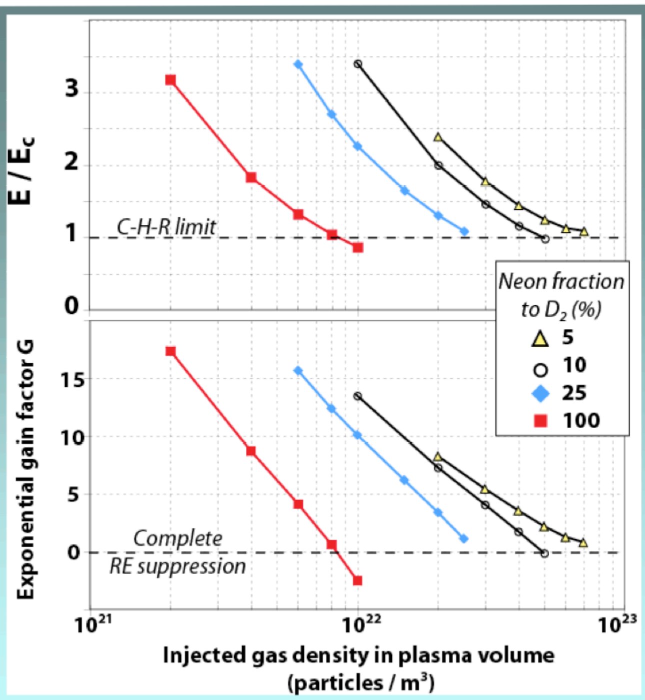

Fig. 2 Example 0-D model predictions of E/E_c and exponential RE gain factor, G, for varying total gas particle injections (in plasma volume) and neon-deuterium mixtures.

assign n_{CHR} as the design goal for MGI. Another key point for the MGI specification and implementation is to avoid possible deleterious effects, for example a current quench that is too fast (electromagnetic loading concerns) or excessive local radiation energy loading.

Table 3 summarizes key specifications for an ITER MGI disruption mitigation system sized to deliver sufficient in-plasma total electron content to suppress runaway avalanche. The design basis is injection of noble and/or hydrogenic gases. The maximum gas injection quantity N_{gas} is ~500 kPa-m^3 for He injection. This arises from requiring the N_{CHR} ~100 kPa-m^3 CHR limit (Tables 1-2) and assuming a 20% assimilation of the impurity species into the core plasma. The 20% assimilation is based on average experimental measurements of free-electron increase in DIII-D MGI experiments [4] although there is evidence that different species may have higher assimilation factors. This recommendation adopts a "worst-case scenario" for N_{gas} such that: a) runaways are assumed to have perfect confinement (γ_{loss}=0, Eq. 1), b) the most pessimistic particle assimilation is taken, and c) pure low-Z gases are used for collisional suppression even though high-Z gases require lower N_{gas} (Tables 1-2). Section 4 examines the operation consequences of this gas load and Section 5 explores ways in which N_{gas} required for RE suppression could be decreased. Other design features recommended in Table 3 are also discussed and justified.

Parameter	Value	Comment
Gases	H_2,D_2, He, Ne, Ar	Mixing available
N_{gas}, kPa-m^3	≤ 500	Assumes 20% assimilation
N_{gas} variability %	1 - 100	Adapt to reduced RE suppression requirements
Duration, ms	10	FWHM, ~1/4 τ_{CQ}
Rise time, ms	< 3	Depends on gas mix
Action time, ms	< 10	Determines "look-ahead" requirement for detection
Exit ram pressure, MPa	3-6	Facilitate direct gas penetration in CQ
Injector Locations	≥ 2	Redundancy and radiation energy dispersal
Injector reliability	> 99%	

Table 3. Recommended parameters for ITER MGI system

3. Impact of Injected Gas or Particles

The operational impacts of ~500 kPa-m^3 of gas injected into the ITER torus vessel are examined. The after-injection torus pressure rises to ~300 Pa. For He injection, the torus and neutral beam cryo-pumps are likely to regenerate. In this case, vacuum recovery time is presently estimated at ~3-4 hours with some system optimization, which is marginally acceptable for device operations. Hydrogenic injection would surpass the current deflagration pressure limits for cryo-pump enclosures; design modifications necessary to safely handle a full hydrogenic injection are too large. Significantly lower levels (~ factor of 10) of hydrogenic injection could be acceptable. Argon is not preferred due to activation issues. For vacuum recovery, neon gas is considered to be the optimal choice. Further validation of the cryopump performance is required but it is considered that the recommended ≤ 100 kPa-m^3 injection (assuming 20% assimilation) of neon could be recovered with minimal impact to the ITER operational duty cycle. A possible concern with pure high-Z injection is more seed electrons at the thermal quench and a slower response time due to its lower sound speed. Overall, we find that there is substantial variability in the recovery consequences as gas species is varied. At the same time, the disruption mitigation also depends on the gas species. Hence we suggest that the choice of the optimal gas species, or mixture of species, for ITER MGI should remain open, and that pure or mixed gas injection with significant low-Z (H, He) gases be anticipated.

4. Optimization, Runaway Physics, and Alternate Injection Concepts

In general, the operational impact for recovery (Section 3) will be minimized if N_{gas} can also be minimized for a given gas species or mix. It should be noted that reducing N_{gas} may not necessarily reduce recovery time by the same proportion since in some cases there is a minimum time associated with vacuum recovery (e.g. regeneration). In other cases, such as deflagration, there are threshold values in gas loading which are important. Yet overall, we are strongly motivated to examine our assumptions behind the recommendations given in Table 3, and to note where reductions in N_{gas} could be achieved.

An important factor is obviously the assumed 20% assimilation. We note that this measurement in present devices is based on the increase in free electron density near the beginning of the current quench [4], while for RE suppression all electrons, including those in neutral atoms, should be accounted; therefore 20% is the minimum assimilation value. Given that 0-D models predict sufficiently low core temperature that neutrals could reside there [3], further research on improving diagnosis of assimilation is needed. Improvement in early current quench gas assimilation would also have obvious merits. Configuring the gas exit stream such that the at-plasma kinetic (ρv^2) neutral ram pressure is comparable to the toroidal field magnetic displacement pressure, $B\Delta B/\mu_0$, may enhance assimilation. Here $\Delta B = \delta R \cdot dB/dR$ is the toroidal field increment corresponding to 'direct' gas jet penetration a distance δR beyond the plasma surface. Although practical experience and diagnostic capability is lacking, close-coupled injection tubes could in principle provide sufficient kinetic pressure to achieve appreciable penetration (~0.2 m) in ITER, and motivates our ram pressure recommendation in Table 3. This would be particularly attractive for high-Z gases injected only in the CQ since they would reach n_{CHR} with small gas loads (Tables 1-2).

Alternately, liquid jet and/or solid pellet injection can, in principle, provide equivalent particle injection capability, with improved penetration, although in these cases assimilation may ultimately be limited by the cold plasma's ability to stop the pellets or liquids in the CQ, such as was found for multiple (20) D_2 pellet injections for disruption mitigation on Alcator C-Mod [15]. The use of condensable materials, for example, lithium or beryllium, could also be considered. Like liquid or pellets, stopping efficiency by the CQ plasma is a concern. If an appreciable fraction of CHR limit mass delivery is required, the amount of condensed material is equivalent to ~100 atomic monolayers per injection distributed on the wall. Hence non-condensable injection of any non-intrinsic material will modify the following plasma-wall interactions of the following pulse. Beryllium injection may be an exception, although it is not clear whether the surface conditions obtained with massive material injection will necessarily be the same as an otherwise previously plasma-conditioned wall. In general, experimental tests of liquid, solid and condensable material injection in quantity regimes applicable to collisional mitigation of runaway avalanching in ITER are presently lacking. If the experience with gas injection applies, interaction of the injected materials may be significantly different than present 'small-quantity' injection examples.

Our other key assumption is that runaways are perfectly confined (γ_{loss}=0). Since the effective RE exponential gain factor is $G \sim \tau_{CQ} (\gamma_{RA}-\gamma_{loss})$, if intrinsic transport losses are $\gamma_{loss} \sim \gamma_{RA} \sim 100\ s^{-1}$ (Fig. 1) this has the effect of effectively suppressing RE ($\gamma_{loss} \geq \gamma_{RA}$) and/or substantially decreasing the density at which RE suppression will be obtained even if $\gamma_{loss} < \gamma_{RA}$. It was previously calculated by Harvey et al [12] that stochastic transport losses set by ~ $\delta B/B$ ~ 0.1% were sufficient to effectively suppress RE amplification, and that such magnetic fluctuation levels were roughly consistent with DIII-D MGI experiments, partially explaining the RE suppression below n_{CHR}. Recent MHD modeling suggests stochastic field development during MGI [7], while external application of stochastic fields using coils was found to suppress RE on JT-60U [16] and recently on TEXTOR [17]. Therefore there is a strong probability that a combination of intrinsic and extrinsic stochastic RE losses will substantially reduce the N_{gas} requirements. Unfortunately, predictive extrapolation to ITER is presently lacking in this area, and is called out as a critical research topic.

Overall we note that by assuming worse case scenarios for both assimilation and RE transport we have applied a "double-layer" of conservatism such that our N_{gas} estimates are in fact up to 25 times larger than simple empirical extrapolations of $n_{impurity}$ as used in present successful MGI experiments for both T/E mitigation and RE suppression. We believe this conservatism is justified by the extraordinary capacity for RE amplification gain in ITER (~exp(25)!) as compared to present experiments. While we have outlined various reasons to believe that this approach is perhaps over-conservative for ITER, the actual RE suppression limits can only be directly tested in ITER itself. Fortunately, this will be possible in the hydrogen phase of ITER with a gradual increase of plasma current, with final confirmation done at full plasma current ~ 15 MA, since the RE physics is set by current density and size, rather than achieving high performance H-mod plasmas. Therefore a strong recommendation is to allow for a large variability (1-100%) in the injected gas quantity (Table 3) such that N_{gas} and gas species can be adjusted based on ITER experimental observations. Fortunately, such flexibility is relatively easy to implement in an MGI system by designing in various capabilities such as variable reservoir gas pressure, valve opening time and diameter, etc. It will also be important to extend capabilities of the gas exhaust and processing system to realize these recommended operational flexibilities; as much as possible trying to achieve an acceptable recovery time within constraints of cost increase and schedule delay.

Furthermore, we note that the physics requirements of RE detection and suppression are fundamentally quite different than for the T/E mitigation, owing in part to the vastly different natures of the target plasma and the cold CQ plasma. Therefore, we also recommend that ITER examine a dedicated injection system solely for RE suppression. Such a system may allow optimization (reduction) of N_{gas}, improved vacuum recovery, and redundancy in protection against RE-caused damages.

5. Summary and Future Research Needs

A set of specifications has been developed for massive gas injection disruption mitigation in ITER. A preliminary assessment of the operational impacts of MGI mitigation has been carried out. It is expected that while thermal and electromagnetic loading mitigation will be achieved, when finite in-plasma uptake of the injected species is taken into account, the large quantity of gas required to provide unequivocal collisional suppression of runaway electrons could lead to a significant impact on the torus vacuum pumping and exhaust processing systems. This would have the possible undesired consequence of slowing plasma operations, with our present worst-case estimate being 3-4 hour delay for recovery with some system optimization. Differences in the ability of the present ITER systems to rapidly exhaust hydrogenic and various noble gas species will affect the recovery of the vacuum systems after a mitigated disruption, and must be considered in making a selection of the optimal mitigation system concept and species, along with mitigation effectiveness. These calculations have lead to preliminary set of design requirements for the MGI system in ITER. Key recommendations are: the ability to inject ~500 kPa-m^3 of He gas with an allowance to reduce this by a factor of 100 to account for different operational scenarios, flexibility in

MGI operating parameters such as gas species and mixture, and the installation of MGI at minimum two toroidal locations for redundancy and radiation spreading. Benefits from a closed-coupled injector exit orifice are also anticipated.

We have identified several key areas for further research. The quantity of injected gas required in ITER may be less if appreciable intrinsic runaway losses, for example from stochastic fields or magnetic fluctuations, occur. Better predictive capability in this area is required, both in understanding intrinsic magnetic fluctuations and how external fluctuations could be applied. Particle assimilation into the core plasma during the current quench should be better diagnosed. The gas quantity could be reduced by optimizing the plasma uptake of injected particles (possibly by use of solids, liquids or particulates) or by separate injection of a high-pressure gas in the current quench solely dedicated to runaway suppression, but experimental trials are required.

Finally, since mitigation of disruption effects may enter in reducing the likelihood of certain classes of off-normal event chains that have consequences for maintaining ITER in-vessel system integrity, the reliability and efficiency of the disruption detection and mitigation methods become important design considerations. These considerations motivate an overall better understanding of disruption and runaway physics, and mandate exploring a range of design concepts beyond the presently-conceived single MGI option. Also, due to its unique features of runaway amplification, it will likely be necessary to finally explore mitigation options in ITER itself. Therefore, integration of disruption mitigation physics and technology with the overall research plan of ITER seems critical.

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