Extended Consolidation of Scaling Laws of Potentials Covering Over the Representative Tandem-Mirror Operations in GAMMA 10

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Abstract. Scaling laws of potential formation and associated effects are constructed in the GAMMA 10 tandem mirror. *A novel proposal* of extended consolidation and generalization of the two major theories of (i) *Cohen's strong electron cyclotron heating (ECH) theory* for the formation physics of plasma confining potentials, and (ii) *the generalized Pastukhov theory* for the effectiveness of the produced potentials on plasma confinement is made through the use of the energy-balance equation. This proposal is then followed by the verification from experimental data in two representative operational modes, characterized in terms of (i) a high-potential mode having kV-order plasma-confining potentials, and (ii) a hot-ion mode yielding fusion neutrons with 10-20 keV bulk-ion temperatures. The importance of the validity of the proposed consolidated physics-based scaling is highlighted by a possibility of extended capability inherent in Pastukhov's prediction of requiring ion-confining potential (ϕ_c) of 30 kV for a fusion Q value of unity on the basis of an application of Cohen's potential formation method. In addition to the above potential physics scaling, *an externally controllable parameter scaling* including both plug and barrier ECH powers for potential formation is investigated. The combination of (i) the physics scaling of the above-proposed consolidation over potential formation and effects with (ii) the externally controllable practical ECH power scaling provides a scalable way for the future tandem-mirror researches. Under the assumption of the validity of the extension of the present theoretically well interpreted scaling, the formation of Pastukhov's predicted ϕ_c for confining Q=1 plasmas is scaled to require total plug with barrier ECH powers of 3 MW.

1. Introduction

Following the Sorrento IAEA Fusion Energy Conference [1], intensive investigations are carried out for constructing generalized and consolidated scaling laws of potential formation and associated effects [2] covering over representative tandem-mirror operational modes. These modes are characterized in terms of (i) *a high-potential mode* having kV-order plasma-confining potentials [3], and (ii) *a hot-ion mode* yielding fusion neutrons with 10-20 keV bulk-ion temperatures [4]. On the other hand, theoretical investigations for finding the physics bases on the constructed generalized scalings are made so as to explore the future upgraded operational modes with plasma-parameter improvements under the extension of these physically clarified theoretical bases.

A novel proposal [2] of extended consolidation and generalization of the two major theories of (i) *Cohen's* strong electron cyclotron heating (ECH) theory for the *formation physics* of plasma confining potentials [5], and (ii) the generalized *Pastukhov* theory for the *effectiveness* of the produced potentials on plasma confinement [6] has been made through the use of the energy-balance equation. This proposal is then verified by experimental data from the above two representative modes in GAMMA 10 [2]. The importance of the validity of this proposed consolidation is highlighted by a possibility of extended capability inherent in Pastukhov's prediction of requiring ion-confining potential (ϕ_c) of 30 kV for a fusion Q value of unity [6] through an application of Cohen's potential formation method.

Accordingly, the present paper is prepared for summarizing these updated experimental and theoretical progresses for constructing and exploring the future roadmap in tandem-mirror researches, which is supported by a large number of experimental databases obtained through 1979-2002 with the proposed consolidated and generalized theoretical physics bases.

2. Experimental Apparatus

GAMMA 10 is a minimum-B anchored tandem mirror with outboard axisymmetric plug and barrier cells [1-4]. It has an axial length of 27 m, and the total volume of the vacuum vessel is 150 m^3 (Fig. 1). The central cell has a length of 6 m and a fixed limiter with a diameter of 0.36 m, and the magnetic-field intensity at the midplane B_m is 0.405 T with a mirror ratio R_m of 5.2. Ion-cyclotron heatings (ICH) (200 kW at 4.47 or 6.36 MHz, as well as 100 kW at 9.9 or 10.3 MHz) are employed for the central-cell hot-ion production and the anchor stabilization, respectively. The plug and barrier cells are axisymmetric mirrors; they have an axial length of 2.5 m (B_m=0.497 T, and R_m=6.2). Microwaves (200 kW at 28 GHz) are injected in the extraordinary mode into the plug and the barrier regions to produce an ion-confining potential ϕ_c, and a thermal-barrier potential ϕ_b, respectively. A preliminary application of microwaves (50 kW at 28 GHz) into the central cell is made for verifying the extended capability of the consolidated scaling predictions (see Section 3). Plug potentials Φ_P are measured with originally developed electrostatic spectrometer arrays for end-loss-ion energy analyses (ELA). Central-cell potentials Φ_C and barrier potentials Φ_B are directly measured with heavy-ion (Au^0) beam probes (HIBP). Therefore, one can obtain ϕ_c and ϕ_b, as Φ_P-Φ_C and Φ_C-Φ_B, respectively (see Fig. 1(c)). X-ray diagnostics give profiles of electron temperatures T_e along with detailed electron-energy spectra in each region [2].

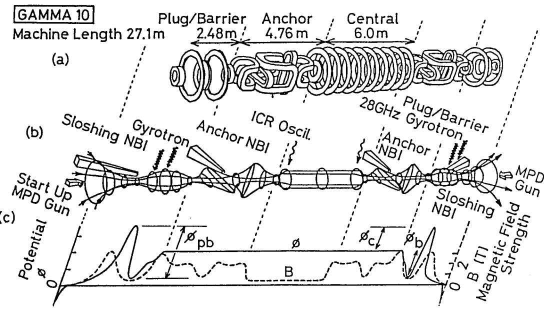

FIG. 1. Schematic view of the GAMMA 10 tandem-mirror; (a) magnetic coil set, (b) magnetic-flux tube with heating systems, as well as (c) axial magnetic-field (dashed curve) and potential profiles (solid curve).

3. Proposed Theoretical Bases and Experimental Verification of the Relation between the Thermal-Barrier and the Ion-Confining Potential Formation

In Fig. 2, an original finding of a good data fit to the consolidated theoretical surfaces of (a) and (b) for representing the high-potential and hot-ion modes, respectively, is shown. The surfaces are calculated from the strong ECH theory with a combination of the Pastukhov confinement in the electron energy balance equation (see Ref. 2). This consolidation procedure gives a novel general formula of ϕ_c [kV]:

$$\phi_c = T_e\left[0.665\left(n_p/n_c\right)\exp\left(1.19\,\phi_b/T_e\right)\right]^{2/3} - \phi_b$$

with

$$x = \phi_b/T_e = f^{-1}\left(2.01\times10^4\, n_c{}^2\, \ln\Lambda\, T_e{}^{-1/2}\, P_e{}^{-1}\right). \qquad (1)$$

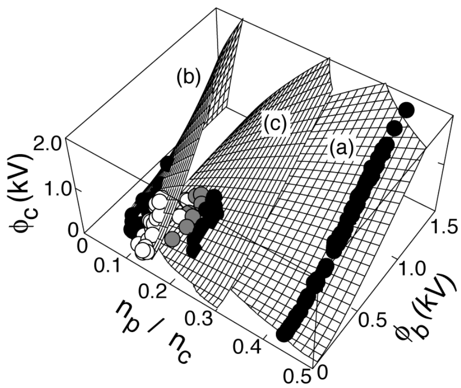

FIG. 2. Proposed theoretical surfaces [2] consolidated over Pastukhov's and Cohen's theories with energy balance for data fit in the representative modes for the future extension.

Here, $f(x)=[x\exp(x)]/[(2/3)x+I(x^{-1})]$ with $I(x)\approx(1+x/2)/(1+x^2/4)$ (see Section 5), the Coulomb logarithm ln Λ, and total electron heating powers P_e [W m^{-3}] [2] are employed for plotting the surfaces in Fig. 2.

For further scaling extension, *the physics bases of the proposed consolidation* should be reminded (i.e. the dominant "electron loss" being along lines of magnetic force compared to transverse losses as employed in both theories [5,6]); that is, central-cell electrons having a temperature T_e [keV] and a density n_c [10^{18} m^{-3}] flow partially beyond a thermal-barrier potential ϕ_b [kV], and then into a plug region, where *they contribute to an electron source term in the strong ECH theory* [5]. *The amount of these electrons overcoming ϕ_b is described in terms of the generalized Pastukhov theory*. Therefore, the amount of source (target) electrons of plug ECH for plug potential formation is anticipated to closely relate to the electron energy (or particle) confinement time τ_{Ee} (i.e. the ratio of stored electrons to those lost beyond ϕ_b) estimated from the generalized Pastukhov theory with ϕ_b and T_e (i.e. *the use of the energy balance equation for the consolidation* [2] of the two major theories).

These physics bases in turn bring an idea of the use of central-cell ECH for bridging the "separated" surfaces (a) and (b) in Fig. 2; that is, the central-cell electron heating increases the electron flow into the plug over ϕ_b. An increase in the ratio of the plug to central electron densities, n_p/n_c, (see Fig. 2) results in an approach from the surface (b) to (a) (i.e. a possibility of a high-potential with hot-ion temperature mode). Further, it is noteworthy that our formula originated from the surfaces (a) and (b) is verified by the good data fit to the third novel theoretical surface (c). *Such good agreement between the data and the extension of our proposed consolidation* [2] encourages the validity and future further extension of this scalable generalization.

4. Scaling Law of the Ion-Confining Potential Formation with Plug and Barrier ECH Powers

Following the construction of the ϕ_c formation scaling at the IAEA 2000 with plug ECH alone [1], plug-power saving experiments with barrier ECH auxiliary applications are carried out for finding a consolidated general scaling of the plasma-confining potential formation covering over the high-potential and hot-ion modes simultaneously along with the consistency with the IAEA 2000 scalability. In Fig. 3, data on ϕ_c [kV] (or equivalently ϕ_b with n_p/n_c (see Fig. 2)) as a function of externally controllable plug and barrier ECH powers, (P_{PECH} [kW] and P_{BECH} [kW], respectively), and n_c [10^{18} m^{-3}] are plotted in the hot-ion mode along with the scaling surfaces labeled with n_c from a novel extended scaling with both ECH powers:

$$\phi_c = 1.0\times10^{-4}\ \left(1+5.0\times10^{-3}P_{BECH}{}^{1.04\pm0.02}\right)P_{PECH}{}^{1.73\pm0.02}$$
$$\times\left[c\left(n_p/n_c\right)^{2/3}-1\right]\ \exp\left[-(0.33\pm0.05)n_c\right]. \qquad (2)$$

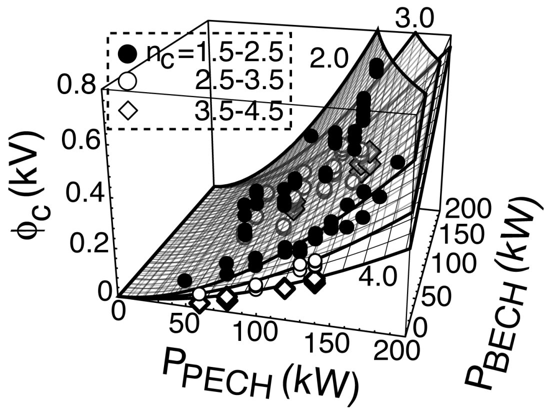

FIG. 3. Scaling of potential formation with plug and barrier ECH powers. Three scaling surfaces described by Eq. (2) are plotted as a function of n_c[10^{18} m^{-3}] along with the corresponding experimental data points.

Here, the same functional dependence is obtained over the hot-ion and high-potential modes along with the values of c=9-11 and 7-9, respectively. For obtaining this formula, ϕ_b (or ϕ_c from Fig. 2) in our consolidated relation [2] is replaced by the scaling data on ϕ_b (or equivalently ϕ_c in Fig. 3; see Fig. 2) with P_{PECH} and P_{BECH} [1]. *According to the scaling relation, further favorable increase in ϕ_c is anticipated with installing more powerful ECH power sources* beyond the present device power limit of 200 kW. Experiments beyond 200-kW ECH injections into tandem-mirror plasmas have never been carried out all through the tandem-mirror history. This favorable scaling of ϕ_c with P_{PECH} and P_{BECH} may provide a possibility of a remarkable performance of potential capabilities with increasing ECH powers.

It is also noted that the relation between ϕ_c and ϕ_b (Fig. 2) is interpreted in terms of the efficient ϕ_c formation in association with efficient plug-electron heatings due to the thermal isolation effect of ϕ_b on localized plug electrons from large-volume central-cell electrons. In turn, from the viewpoint of a contribution of P_{PECH} to the ϕ_b formation, such a close relation between ϕ_c and ϕ_b is partially based on a source-term contribution of plug-originated warm electrons heated by P_{PECH} to P_{BECH} because of the increase of the grad B drift in the plug.

In Fig. 4, under the assumption of the validity of the extension of the consolidated relation of Eq. (1) on the basis of Pastukhov's and Cohen's theories with the power-balance equation, scaling surfaces of the formation of ϕ_c are mapped onto a parameter surface in Fig. 4 as a function of P_{PECH} and P_{BECH}, for instance, with n_p/n_c=0.3 and n_c=10^{19} m^{-3} for the convenience of a comparison to the IAEA 2000 scaling with P_{PECH} alone [1].

From the plot in Fig. 4, minimized power sharing of ECH is found; required ECH powers of 5 MW for ϕ_c=30 kV (providing a scaled possibility for Q=1 with T_i=16 keV, and $n_c\tau_E$~2×10^{19} m^{-3}s, for instance, along with a direct-converter efficiency of 0.8 with n_p/n_c=0.3 in the case of P_{PECH} alone at the IAEA 2000 presentation [1]) are reduced totally to 54% with both P_{PECH} and P_{BECH} applications. This power saving is interpreted in terms of the thermal-isolation effect due to the ϕ_b transport-barrier formation.

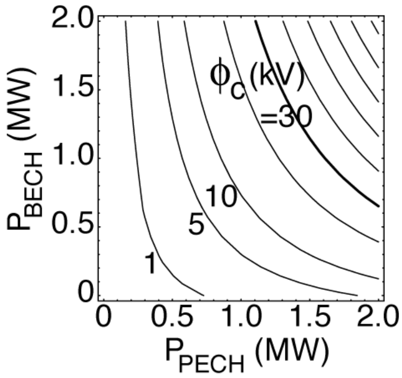

FIG. 4. Extended plots of the formation of the ion-confining potential ϕ_c as a function of externally controllable plug and barrier ECH powers. Reduced total ECH powers [1] due to plug with barrier ECH for ϕ_c are found on the basis of the scaling formula of Eq. (2).

This favorable scaling of ϕ_c may provide a possibility of a remarkable performance of potential capabilities with increasing ECH powers. In Fig. 4, minimized power sharing of ECH is found from this scaling; required ECH powers of 5 MW for ϕ_c=30 kV with P_{PECH} alone (e.g. n_p/n_c=0.3) presented at the IAEA 2000 [1] are reduced totally to 54% with P_{BECH}.

5. Effects of Thermal-Barrier Potentials on the Central-Cell Electron Confinement along with the Physics Interpretations for the Future Scalable Extension

The scaling of T_e has been remained as an unsolved important issue in tandem-mirror plasmas for a long time. Recently, *the scalings of T_e increase with increasing ϕ_b* are shown for both high-potential and hot-ion modes [2]. In particular, for finding out the common physics interpretations covering over both modes, theoretical generalized analyses are carried out by the use of an energy balance equation for the bulk-electron energy density of $3/2n_cT_e$. It is found [2] that the data on T_e with ϕ_b are well fitted by the substitution of Pastukhov's energy-confinement time [6] into τ_E in the energy balance equation. Such good agreement between the data and the calculated results in the individual different parameter regime with the different dominant-heating source in each mode (i.e. plug ECH produced warm electrons flowing from the plug region, and ICH produced hot ions for the high-potential and the hot-ion modes, respectively [1-4]) provides *a finding of the validity of the generalized Pastukhov theory on the central-cell electron energy confinement*. The scaling validation confirms *the importance and efficacy of the formation of ϕ_b to confine and heat up tandem-mirror central bulk electrons* in addition to the similar effects of ϕ_c on ions.

The result of the consolidation of the Pastukhov theory and the energy balance equation under the assumption of the predominant loss in the axial direction compared to losses including the radial direction *leads to a finding of the generalized equation for the relation of T_e with ϕ_b* (see the second equation of Eq. (1)). A good approximation of $f^{-1}(x) \approx 0.04 + 0.97 \ln[f(x)]$ along with the substitution of standard formula for slowing down powers into P_e in Eq. (1) allows us to derive the previously reported experimentally obtained scaling relation for the high-potential mode (Fig. 2(a)), for instance: $T_e \approx 0.23\phi_b + 0.03$, where the units of T_e and ϕ_b are in keV and kV, respectively. Here, the Taylor expansion in the above-described parameter regime is employed. Similarly, the previous empirically reported formula of $T_e \approx 0.16\phi_b + 0.01$ in the hot-ion mode (Fig. 2(b)) is also reproduced. As one can remind of the consolidation essentials over the Pastukhov and the Cohen theories, the above-derived generalization between T_e and ϕ_b provides an important physics "glue" for these two major theories (see again Eq. (1)). The experimental verification of the above-described assumption of the predominant axial losses encourages the availability of potential control in tandem-mirror plasma performance. Also, it is conveniently estimated from this relation for extending the required auxiliary central ECH powers of the order of one MW to provide the consistency with the 30-kV ϕ_c achievement (Fig. 4) having $T_i = T_e = 15$ keV (i.e. $\phi_c/T_i = 2$).

6. Summary

In summary, (i) a verification of *our novel proposal for the physics generalization of potential formation and effects* [2] is carried out for consolidating two major theories (i.e. *Pastukhov's* potential confinement and *Cohen's* potential formation theories [5,6]) by the use of updated total data sets in GAMMA 10. The validity of the theory provides a roadmap of bridging and combining present representative modes for upgrading to hot-ion plasmas with high potentials. (ii) *A novel efficient scaling of ϕ_c formation with both barrier and plug ECH* is summarized as the extension over the IAEA 2000 scaling with plug ECH alone [1] (i.e. thermal-barrier essentials). *The combination* of *the physics scaling of (i)* [2] with the externally controllable *power scaling of (ii)* provides a scalable way (Fig. 4) for the future tandem-mirror researches.

[1] CHO, T., et al., in Fusion Energy (Proc. 18th Int. Conf. Sorrento, 2000) IAEA-CN-77-EXP5/10.
[2] CHO, T., et al., Phys. Rev. Lett. **86** (2001) 4310.
[3] MIYOSHI, S., et al., in Plasma Phys. and Controlled Nucl. Fusion Research (Proc. 13th Int. Conf. Washington D.C., 1990) **2**, IAEA, Vienna (1991) 539; CHO, T., et al., Phys. Rev. Lett. **64** (1990) 1373.
[4] TAMANO, T., et al., in Plasma Phys. and Controlled Nucl. Fusion Research (Proc. 15th Int. Conf. Seville, 1994) **2**, IAEA, Vienna (1995) 399.
[5] COHEN, R. H., Phys. Fluids **26** (1983) 2774.
[6] PASTUKHOV, V. P., Nucl. Fusion **14** (1974) 3; COHEN, R. H., et al., Nucl. Fusion **18** (1978) 1229; COHEN, R. H., *ibid.* **19** (1979) 1295; *ibid.* **19** (1979) 1693.