High-$\beta_N$ Experiments and Corresponding MHD Activities in the HL-2A Tokamak

W. Chen$^1$, L. M. Yu$^1$, M. Xu$^1$, X. Q. Ji$^1$, Z. B. Shi$^1$, X. X. He$^1$, Z. J. Li$^1$, Y. G. Li$^1$, T. B. Wang$^1$, M. Jiang$^1$, J. Wen$^1$, S. B. Gong$^1$, Z. C. Yang$^1$, J. Li$^2$, W. L. Zhong$^1$, A. P. Sun$^1$, J. Y. Cao$^1$, X. Y. Bai$^1$, J. Q. Li$^1$, X. T. Ding$^1$, J. Q. Dong$^1$, Q. W. Yang$^1$, Yi. Liu$^1$, L. W. Yan$^1$ and X. R. Duan$^1$

$^1$Southwestern Institute of Physics, P.O. Box 432 Chengdu 610041, China
$^2$School of Physics, Dalian University of Technology, Dalian 116024, China

Corresponding Author: chenw@swip.ac.cn

Abstract:
High-$\beta_N$ experiments have been carried out on HL-2A in recent several years. The high-$\beta_N$ is realized by double transport barriers (DTBs) under the circumstance of hybrid scenarios. A stationary high-$\beta_N$ ($> 2$) scenario is obtained by the pure NBI heating. The transient high performance is also achieved, and corresponding $\beta_N \geq 3$, $ne/ne_G \sim 0.6$, $H_{98} \sim 1.5$, $f_{bs} \sim 30\%$, $q_{95} \sim 4.0$ and $G \sim 0.4$. The high-$\beta_N$ scenario has been successfully modeled using integrated simulation codes, i.e. OMFIT. In high-$\beta_N$ plasmas, there are abundant MHD instabilities, including low-frequency global MHD oscillation with $n=1$ and high-frequency coherent mode (HCM) in the edge, and neoclassical tearing mode (NTM) and Alfvénic modes in the core. In some high-$\beta_N$ discharges, it is observed that the NTMs with $m/n = 3/2$ limit the growth of the plasma energy and decrease $\beta_N$. The low-n global MHD oscillation consistent with the coupling of destabilized internal ($m/n=1/1$) and external ($m/n=3/1$ or $4/1$) modes, and it plays a crucial role in the triggering onset of ELMs. Achieving high-$\beta_N$ on HL-2A suggests the core-edge interplay is key important for the plasma confinement enhancement mechanism. The experiments of enhancing-$\beta_N$ can contribute to the future plasma operation, such as ITER.

Introduction–Achieving high-$\beta_N$ for current and future tokamaks is a challenging and important issue, where $\beta_N = aB_T/B_T$ is the normalized toroidal plasma beta. High-$\beta_N$ is beneficial for the ignition and fusion reaction, as well as the ratio of bootstrap current is proportional to $\beta_N$ ($f_{bs} \propto \varepsilon^{-1/2} \beta_N q_{95} \propto \varepsilon^{1/2} \beta_p$)[1]. It also favors steady-state performance, and thus represents a key metric to enhance tokamak concept[2]. There are two major contributions to enhancements of the plasma pressure and beta: internal and edge transport barriers. For simplicity they are often treated independently. However, some experimental and theoretical studies showed that they can be strongly coupled in tokamak plasmas[3][4][5][6][7]. This core-edge couplings between the ITB and ETB are crucial important for the $\beta_N$ improvement. The high-$\beta_N$ experiments had been carried out in many tokamaks based on hybrid scenarios, such as ASDEX-U[8], DIII-D[9], JET[10], JT-60U[11], NSTX[12], EAST[13] and KSTAR[14], etc. The hybrid scenario is potentially an interesting scenario for the future fusion devices, since it can afford the high confinement factor ($H_{98} > 1$) and high MHD stability ($\beta_N > 2.5$) in stationary discharges which are longer than several energy confinement or current diffusion times. In the hybrid scenario, the q-profile is with low central magnetic shear and $q(0) \sim 1$, and it is thought to
suppress or reduce large amplitude sawtooth oscillations, thus eliminating the seed-island for the detrimental neoclassical tearing mode (NTM) with \( m/n = 2/1 \). In the present paper, we represent high-\( \beta_N \) experiment results based on hybrid scenarios and related MHD stability on HL-2A.

**Experimental setup**—The experiments discussed here are performed in single null divertor configuration deuterium plasmas with the current \( I_p \simeq 140 - 160 \) kA and NBI heating, toroidal field \( B_t \simeq 1.2 - 1.5 \) T on HL-2A, which has the major/minor radius \( R_0/a = 1.65 \) m/0.4 m, and its poloidal cross section is almost circular. The acceleration voltage and power \( P_{\text{NBI}} \) of the neutral beam are typically 45 kV and 1.5 MW, respectively. The LHCD power coupling is optimized using passive active multi-junction (PAM) antenna, by which the coupled power reaches up to 1.34 MW. The line-averaged electron density was detected using a multi-channel HCOOH laser interferometer. The electron temperature was obtained from measurement of optically thick, second harmonic (X-mode) multi-channel ECE radiometer. The ion temperature and toroidal rotation were measured by a charge exchange recombination spectroscopy (CXRS). The edge density fluctuation was detected by the microwave Doppler backscattering (DBS) and phase contrast imaging (PCI). The magnetic fluctuations and mode-numbers of instabilities were measured by toroidal and poloidal Mirnov coils.

![Typical high-\( \beta_N \) performance discharge on HL-2A](image)

**FIG. 1:** Typical high-\( \beta_N \) performance discharge on HL-2A (\#36865). Plasma current \( (I_p) \), Heating powers \( (P) \) including two beam NBI and LHCD, line-average density \( (n_e) \), stored energy \( (W_E) \), normalized toroidal beta \( (\beta_N) \), \( H_{98} \) factor and \( D_\alpha \) signal in the divertor. \( B_t = 1.3T \).

**High-\( \beta_N \) realization**—Fig.1 gives a typical experimental results about high-\( \beta_N \) performance discharge on HL-2A. The stored energy \( (W_E) \), normalized toroidal beta \( (\beta_N) \), \( H_{98} \equiv \tau_E/\tau_{98(y,2)} \) (where \( \tau_E = W_E/(P - dW_E/dt) \)) factor start to increase while the two beam NBIs are switched on. The L-H transitions occurs around \( t \sim 835 ms \), and entrance into ELM-free phase. The ELM-free H-mode sustains around several tens of milliseconds. Accompany with the density ascending, the type-I ELM emerges and \( \beta_N \) reaches maximum at the moment. In this scenario, \( W_E, n_e/n_e_G, \beta_N \) and \( H_{98} \) are up to 40kJ, 0.8, 2.5 and 1.25, respectively. Subsequently, they decrease continually due to the type-I ELM appearing, namely the plasma performance degrades. It means that the pedestal height and large ELM do not favor the high confinement and high-\( \beta_N \) maintenances.

During the \( \beta_N \) increasing, the evolutions of ion temperature and toroidal rotation are
shown in the fig.2(a), it is found that they increase and then decrease. From the fig.2(b-c), it suggests that the internal transport barrier (ITB) becomes strong and weak, but external transport barrier (ETB) enhances continuously. Apparently, the double transport barriers (DTBs) are crucial to acquire the high-$\beta_N$ scenario.

A stationary high-$\beta_N$ ($\beta_N > 2$ with $\Delta t > 500\,\text{ms}, t \sim 15\tau_E$) scenario is obtained by the pure NBI, shown in the fig.2. The transient high performance is also realized, and corresponding $\beta_N \geq 3$, $n_e/n_{eG} \sim 0.6$, $H_{98} \sim 1.5$, $f_{\phi 8} \sim 30\%$, $q_{95} \sim 4.0$ and $G \sim 0.48$ at $t \sim 590\,\text{ms}$. However, the high-$\beta_N$ scenario is obtained during the ELMly H-mode in this discharge. The ion temperature and toroidal rotation profiles corresponding fig.3 at different phases are present in the fig.4. It is found that the most highest $\beta_N$ had still been achieved by DTBs. Fig.4(a,e) gives the formation process of DTBs. During the synergy between the ITB and ETB in the fig.4(b,f), the higher $\beta_N$ is realized. The ITB and ETB both become weaker during the LHCD in the fig.4(c,g), but $\beta_N$ hardly changes due to the density decreasing. $\beta_N$ drops while the ITB and ETB become stronger and weaker due to the density decreasing at $t > 870\,\text{ms}$, respectively.

It is found from the fig.1(a) and fig.4. that the high-$\beta_N$ and high confinement depend on the ion temperature and plasma rotation. Fig.5 presents the specific dependencies. The $H_{98}$ factor increases with the increasing of core/edge temperatures/rotation-frequencies. In the core the relationship is linear seemingly, but in the edge nonlinear. $H_{98}$ depends on $\beta_N$ linearly, which is similar with measured results from several devices[8][15].

The HL-2A high-$\beta_N$ scenario has been successfully modeled using integrated simulation codes, i.e. OMFIT. A typical simulated result is shown in the Fig.6. The ion and electron temperature profiles are measured by the CXRS and ECE diagnostics, and density profile are synthetic by the laser interferometer and edge Microwave reflectometer, shown in the fig.6(a). The safe factor profile in the fig.6(b) is determined by the kinetic
FIG. 3: Most highest $\beta_N$ discharge on HL-2A. Plasma current ($I_p$), Heating powers ($P$) including one beam NBI and LHCD, line-average density ($n_e$), stored energy ($W_E$), normalized toroidal beta ($\beta_N$), and $D_\alpha$ signal in the divertor. $B_t = 1.36T$.

FIG. 4: Ion temperature ($T_i$) and toroidal rotation frequency $f_\phi$ profiles corresponding fig.3 at different phases. $\beta_N$ increasing phase(a, c), most highest $\beta_N$ phase (b, f), with LHCD (c, g) and $\beta_N$ deceasing phase(d, h). The downward vertical arrow in subplot (a-d) denotes time increasing direction.
EFIT with the pressure constraint. It is found that this scenario is a hybrid configuration. The Ohmic, bootstrap and NBI drive currents are present in the fig.6(c). The table presents the comparison results between the experiment and modeling about several key plasma parameters. Obviously, they are almost consistent. In the scenario, $f_{bs} \sim 30\%$ and $G \equiv H_{98}\beta_N/q_{95}^2 \sim 0.37$. Under the same $q_{95}$ and while $\beta_N \sim 3$ and $H_{98} \sim 1.5$, $G \sim 0.4$.

![Graphs showing dependencies](image)

**FIG. 5:** Dependence between $H_{98}$ and ion temperature ($T_i$) (a-b), $H_{98}$ and toroidal rotation frequency $f_\phi$ (c-d), as well $H_{98}$ and $\beta_N$ (e).

![Graphs showing profiles](image)

**FIG. 6:** Modeling of high-$\beta_N$ scenario for a typical discharge. Ion temperature ($T_i$), electron temperature ($T_e$) and density ($n_e$) profiles (a); pressure ($P$) and safe factor ($q$) profiles (b); Ohmic heating ($j_{ohm}$), NBI drive ($j_{NBI}$), bootstrap ($j_b$) and total current ($j_{tot}$) profiles (c); comparison between experimental and modeling results (d).

**Table**

<table>
<thead>
<tr>
<th></th>
<th>$ne$</th>
<th>$W_F$</th>
<th>$\beta_N$</th>
<th>$l_i$</th>
<th>$H_{98}$</th>
<th>$f_{bs}$</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex.</td>
<td>2.4</td>
<td>35</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod.</td>
<td>2.4</td>
<td>36</td>
<td>2.6</td>
<td>0.84</td>
<td>1.25</td>
<td></td>
<td>29%</td>
</tr>
</tbody>
</table>

**MHD stability in high-$\beta_N$ plasmas**—In high-$\beta_N$ plasmas, there are abundant MHD instabilities, including low-frequency global MHD oscillation with $n=1$ and high-frequency
coherent mode (HCM) in the edge, and neoclassical tearing mode (NTM) and Alfvénic modes in the core. In some high-$\beta_N$ scenarios, the NTM activities are measured by magnetic pickup probes and soft X-ray arrays. A typical discharge with NTM instabilities has been present in the fig.7. The mode-number and frequency of NTMs are $m/n = 3/2$ and $f \sim 25\text{kHz}$ respectively in the Lab framework, and it is observed that the $\beta_N$ deceases during the NTM oscillation. The small amplitude NTMs with $m/n = 4/3$ and $5/4$ have also been observed occasionally in HL-2A high-$\beta_N$ plasmas, but their destructive effects are inapparent for the plasma confinement.

**FIG. 7:** NTM activities in the HL-2A high-$\beta_N$ plasma (#36848, $P_{\text{NBI}} \sim 1.2\text{MW}$, $P_{\text{LHW}} \sim 0.4\text{MW}$, $B_t = 1.31\text{T}$). $\beta_N$, filtered Mirnov signal (dB$\theta$/dt) and spectrogram of Mirnov signal (Left col.); Low-frequency global MHD oscillation and high-frequency coherent mode (HCM) in the HL-2A high-$\beta_N$ plasma with NBI+LHCD (#36865). $\beta_N$, D-alpha signal, spectrograms of PCI and Mirnov signals from top to bottom (Right col.).

A low-frequency MHD oscillation with $f \sim 10\text{kHz}$ has been detected frequently by magnetic probes during ELM-free H-mode and $\beta_N$ ramping up, and it has a second harmonics, as well as the MHD mode is different from the ion fishbone instability on HL-2A, which are shown in the fig.7. Its mode-numbers are $m/n = 3/1$, which are determined by magnetic probes, present in the fig.8, and it and propagates in ion diamagnetic direction. The tomography of soft X-ray signals suggests the poloidal mode-numbers are $m = 1$ and
m = 3, which are shown in the fig.8. Apparently, this MHD oscillation is a global coupling mode. Namely, the low frequency mode is consistent with the coupling of destabilized internal and external modes with \( m/n = 1/1 \) and \( m/n = 3/1 \), respectively. Similar global low-n mode had also found in the DIII-D and JET high-\( \beta_N \) plasmas\([5,24]\). The mode occurs commonly in ELM-free or Type-I ELMy H-mode plasmas, and is observed hardly in the case of \( \beta_N < 2.1 \). It is found from the fig.7 and fig.9 that the mode plays a crucial role in the triggering onset of ELMs.

Meanwhile, a high frequency coherent mode (HCM) with \( f \sim 40 - 60 \text{kHz} \) has been observed before the first ELM crash, shown in the fig.7. The HCM is induced by the LHCD which is switched on at \( t \sim 850 \text{ms} \) (fig.1). The measurement results from the DBS and PCI diagnostics that the HCM localizes in the pedestal region, and it exhibits only strong electrostatic fluctuation components. The poloidal wave-number is \( k_\theta \sim 1.4 \text{cm}^{-1} \), so that the inferred mode-numbers are \( m \sim 40 - 50 \) and \( n \sim 10 - 13 \), and propagates in electron diamagnetic direction. The radial wave-number of the HCM is \( k_r \sim 0.8 \text{cm}^{-1} \), and it radially propagates outward. The HCM may regulates particle and energy transport\([23]\).

In the case of pure NBI heating, the HCM is not detected. In the high-\( \beta_N \) H-mode plasmas, sometime Alfvénic modes, e.g. toroidicity-induced Alfvén eigenmodes (TAEs) with \( f \sim 95 - 120 \text{kHz} \) and \( n \sim 3 - 5 \), have been measured by many diagnostics before the ELM-crash, shown in the fig.9, and it implies that the Alfvénic modes and energetic-ion redistribution may have an important influence on the pedestal evolution\([25]\).

Discussion and conclusion—A stationary high-\( \beta_N \) scenario (\( t \sim 15\tau_E \)) is obtained on HL-2A. The transient high performance is also realized, and corresponding \( \beta_N \geq 3, ne/ne_G \sim 0.6, H_{98} \sim 1.5, f_{bs} \sim 30\%, q_{95} \sim 4.0 \) and \( G \sim 0.4 \). The high-\( \beta_N \) scenario has been successfully modeled using the OMFIT. In high-\( \beta_N \) H-mode plasmas, there are many kind MHD instabilities, including global n=1 MHD oscillation, HCM, NTM and Alfvénic modes. In some high-\( \beta_N \) discharges, the NTMs degrade the plasma confinement and decrease \( \beta_N \). The low-n global MHD mode plays a crucial role in the triggering onset of ELMs.
onset of ELMs. The Alfvénic modes and energetic-ion transport may affect the pedestal evolution. Some crucial physics problems need to be resolved on HL-2A, namely how control MHD instabilities and sustain transport barrier to achieve higher steady-state $\beta_N$. The study of improving-$\beta_N$, by expanding ITB foot outward, controlling MHD activities and enhancing synergic effects between ITB and ETB, would be important for the future plasma operation, such as ITER and CFETR.

References

[14] Na, Yong-Su et al., Nucl. Fusion 60, 086006 (2020).