PHYSICS DESIGN OF CHS-QA BASED ON CHS EXPERIMENTS

K. Matsuoka [1], S. Okamura [1], S. Nishimura [1], M. Isobe [1], C. Suzuki [1], A. Shimizu [2], A. Fujisawa [1], K. Ida [1], T. Minami [1], H. Iguchi [1], Y. Yoshimura [1], M. Osakabe [1], I. Nomura [1], S. Murakami [1], M. Yokoyama [1], N. Nakajima [1], T. Hayashi [1], K. Itoh [1], P. Merkel [3], M. Drevlak [3], C. Nührenberg [3], S. Gori [3], R. Zille [3], J. Nührenberg [3]

[1] *National Institute for Fusion Science, Toki, Japan*
[2] *Nagoya University, Nagoya, Japan*
[3] *Max-Planck-Institute für Plasmaphysik, Greifswald, Germany*

CHS-qa, a quasi-axisymmetric helical device, has been designed as a post-CHS device in NIFS, the main purpose being to improve the neoclassical and anomalous transports of a helical plasma. In CHS, a variety of improved modes have been observed. On the basis of these improved modes further improvement of transports is to be pursued in CHS-qa by taking into consideration methods verified in other toroidal magnetic configurations, e.g. large velocity / radial electric field shear, and maximum J criterion. The toroidal viscosity is shown to be smaller by two orders than that of CHS and the poloidal viscosity, which is mainly determined by the aspect ratio with additional contribution from residual ripples, is also smaller by roughly 1 order than that of conventional helical system. The maximum J criterion is satisfied at the edge region in the vacuum configuration by the presence of small residual ripples and the region where the criterion is satisfied is extended to the core region due to the stellarator shear produced by the bootstrap current in a finite beta plasma. Design priority is put on the low aspect ratio ($A_p = 3.2$) because of a large plasma volume: R = 1.5 m, a = 47 cm, B = 1.5 T, toroidal period number N = 2, 10 modular coils per period, 8 additional modular toroidal coils, 3 pairs of poloidal coils. Residual ripples can be controlled with these coils to keep flexibility in the experiments.

1. Introduction

Helical systems have advantages of being free from difficulties resulting from the plasma current: by way of example, low disruptivity, low recirculating power and no need of elaborate current profile control. However, it has been claimed that conventional helical systems have an inherent helical ripple that leads to the enhancement of neoclassical transport in the low collisionality regime. Now it can be said that the above problems have been mitigated essentially. This owes to the sequence of advances of stellarator theory, where not only drift orbits but also other physics quantities can be optimized. Realizing quasi-symmetry in helical systems is one method for the drift optimization: QHS (quasi-helical symmetric system) [1] and QAS (quasi-axisymmetric system) [2, 3]. The other method relies on QOS (quasi-omnigenous or quasi-isodynamic system) like W7-X [4]. Along with the theoretical advance, experiments in stellarators have made a significant progress and the scaling law on the energy confinement time is now available for the prediction of future helical reactors. Although a variety of improved modes have been observed in stellarators including CHS, the improvement of energy confinement time is not remarkable in comparison with tokamaks. CHS-qa has been designed putting the top priority on the transport improvement by adopting the methods that have been verified to be useful in other toroidal plasma confinement devices.

2. Summary of improved modes in CHS

The transport improvement is one of most important subjects in the study of toroidal plasma confinement. The improvement is closely related to the radial electric field and its shear. The radial electric field is determined by the ambipolar condition between electron and ion fluxes caused by bulk viscosity, orbit loss, charge exchange loss, non-ambipolar diffusion and so on. The plasma potential is in the ion root or electron root being determined by the ambipolar condition. Usually improved modes of tokamaks are in the ion root in a stellarator sense (negative radial electric field), where there is a positive feedback relation between the radial electric field and the ion pressure gradient. In CHS, trials for transport improvement following tokamaks have been made and a variety of improved modes have been observed since its start of operation in 1988 [5]. The H-mode like discharge was obtained by controlling the edge transform (adjusted to be nearly 1 just inside LCFS) through inducing the OH current in an NBI heated plasma [6]. Here, the simultaneous increases in the line averaged electron density and the decrease in the Hα signal were observed in spite of a constant gas puffing, which is usually seen in H-modes of tokamaks. The electron density profile at the LCFS measured with a lithium beam probing shows that the density profile becomes steepened at the onset of the H-mode like behavior. However, the jump in the poloidal rotation velocity, which is seen in W7-AS [7], has not been observed in CHS and the improvement factor is at most up to 15%.

High ion temperature (high T_i) mode in an NB plasma was realized by making the electron density peaked [8]. Here, the density was fuelled primarily with neutral beam without gas puffing under intensive titanium gettering, while the fuelling with gas puff results in an L-mode. There is a big difference, about factor of two, in the central ion temperature between high T_i mode and L-mode at the same line-averaged electron density. The ion thermal diffusivity in high T_i mode is lower by factor of two than that in the L-mode, reflecting the steeper T_i profile. The calculation is done based on the PROCTR-mod code under an approximation of a single helicity. However, the central electron temperature in L-mode is higher than that in the high T_i mode, of which reason has still been unresolved. The radial electric field is derived from the poloidal rotation velocity measured with CXS, and it is shown that the improvement of ion energy confinement is not due to the rotation shear of bulk ions but to the radial electric field shear. Again, the improvement factor is not large in the high T_i mode, although the maximum ion temperature of 1 keV was reached in the high T_i mode.

Recently the neoclassical internal transport barrier (ITB) on the electron temperature has been observed in an ECH plasma [9]. Here, the electric potential is in the electron root. The application of ECH to an NB heated plasma, i.e. the increase in the electron temperature, results in the potential bifurcation, and the potential pulsation was found for the first time in the toroidal plasma [10]. In ECH plasmas several types of potential profiles have been observed depending on the ECH power or on the electron density. As the ECH power is increased the potential becomes more of electron root, and the neoclassical ITB was observed in the profile with the dome structure [11]. At the barrier the radial electric field shear reaches $40V/cm^2$ and density fluctuations measured with HIBP in the frequency range of a few tens of kHz are reduced. The central electron temperature of about 2.5 keV is attained in the improved mode with the ITB. The electron thermal diffusivity of the ITB mode is almost same as the neoclassical value at the barrier and is lower by factor of two than that of L-mode.

As was shown in the W7-AS experiment [7], the H-mode is obtained in the magnetic field configuration where the neoclassical parallel viscosity is low. In CHS the toroidal rotation velocity was measured as a function of the vacuum magnetic axis (R_{axis}) position to investigate the parallel viscosity [12]. The profile of helical ripple depends on the R_{axis} position (R_{axis} is scanned for three cases of R_{axis} of 97.4 cm, 94.9 cm and 89.9 cm in this experiment). The modulation of magnetic field strength for three cases is estimated by taking account of the Shafranov shift due to the parallel beam pressure; the modulation is lowest for R_{axis} of 89.9 cm and largest for 97.4 cm. Following this tendency the measured toroidal rotation velocity is maximum and minimum for 89.9cm and 97.4cm, respectively. To explain the absolute value of the toroidal rotation velocity it is necessary to take account not only of neoclassical parallel viscosity but also of perpendicular anomalous viscosity. It is shown that the neoclassical viscosity should at least be lowered to make the rotation velocity high and, in another word, not to damp the rotation velocity induced.

3. Physics design of CHS-qa

The top priority has been put on the transport improvement in designing CHS-qa , as mentioned before. Among options of advanced stellarators, QAS has been selected because of its low parallel viscosity both in the toroidal and poloidal directions. Furthermore, the maximum J criterion is applied to the magnetic field configuration of CHS-qa for the suppression of turbulence. Besides these, QAS is suitable for low aspect ratio (A_p) and CHS-qa surpasses low A_p aspect of CHS that has the lowest A_p of 5 among existing helical devices. Low A_p is practically important for an experimental device because it gives large plasma volume, which leads to longer confinement time and relatively low contribution of edge phenomena to physics in the core region. The aspect ratio lower than that of CHS is possible, i.e. about 3-4 in QAS, which results in the toroidal period number N of 2 in CHS-qa. The major radius and the magnetic field strength of CHS-qa are determined to be 1.5 m and 1.5 Tesla, respectively, primarily from facility constraints. Design studies have been done from physics and engineering viewpoints [13 - 16]. The rotational transform ι, QA-ness, magnetic well, local ballooning stability criterion and α particle confinement are taken into account in the optimization process. Up to now the configuration called 2b32, where the priority is put more on the local ballooning stability and the aspect ratio is 3.2, is considered to be most preferable from the purpose of CHS-qa experiment because the configuration can satisfy the max. J criterion. Fourier components of its magnetic field strength as a function of the normalized minor radius r/a show that the B_{00} component, the measure of vacuum magnetic well, is several % at the boundary, and B_{10} showing the toroidicity is the dominant one. The toroidicity is about 15%, which means that the effective aspect ratio is about 6. Effective high aspect ratio is favorable for obtaining low poloidal viscosity. Cross-sections of the magnetic surfaces of CHS-qa are similar to those of QHS and QOS; roughly speaking, bean shape at the vertically elongated cross-section and tear drop shape at the horizontally elongated corss-section. When the cross-sections are decomposed into the axisymmetric one and 3D shaping, the axisymmetric shape looks like a typical advanced tokamak cross-section with moderate elongation and triangularity, which are favorable for magnetic well and max. J criterion [17].

The neoclassical viscosity is discussed here in more detail. The velocity shear is known to be one of the stabilizing mechanisms of micro-instabilities. The QA concept is originally motivated to obtain a strong toroidal rotation velocity, as was mentioned before. The modulation of magnetic field strength in the toroidal direction is compared between CHS-qa and CHS and it is shown that the parallel viscosity in CHS-qa is lower by two orders than that in CHS, as is expected [18]. Actually in CHS-qa the toroidal velocity will be determined primarily by the anomalous perpendicular viscosity as in a tokamak and will be up to the level where VH-mode and H-mode are observed in DIII-D [19] and JFT-2M [20], respectively. The poloidal viscosity is also shown to be smaller by one order than that in CHS and is determined primarily by its high effective A_p, i.e. relatively small B_{10} component and additionally by small residual Fourier components. The low toroidal and poloidal viscosities in CHS-qa will be helpful for achieving high rotation shear for the transport improvement.

In the famous FM-1 spherator experiment [21], where trapped particles were shifted from the bad to the good curvature region by controlling its magnetic field structure with the vertical field, the particle confinement time was remarkably improved and was close to the classical confinement time. This is because the max. J criterion was satisfied. The criterion is effective to reduce the growth rate of micro-instabilities, i.e. collisionless trapped particle instabilities, η_i modes and so on. Collisionless trapped particle instabilities are stabilized when the toroidal drift velocity of ion (electron) banana is anti-parallel to the toroidal component of ion (electron) diamagnetic drift velocity, which is called the drift reversal. The criterion is satisfied more for barely trapped bananas than for deeply trapped ones, because the former particles experience the good curvature region more than the latter ones. This means that the magnetic well is effective for the criterion. The η_i mode can be stabilized when the ion diamagnetic drift velocity is anti-parallel to the gradient B and curvature drift, i.e. again when the magnetic well is formed. The confinement improvement in the reversed shear tokamak configuration may result from the max. J criterion. The max. J criterion is satisfied in the magnetic configuration with the magnetic well and the stellarator shear of $d\iota / d\Psi > 0$ (Ψ : the normalized toroidal flux) [17]. In usual tokamak configurations, the tokamak shear of $d\iota / d\Psi < 0$ enhances the instability. On the contrary, CHS-qa has the favorable magnetic field configuration with the average magnetic well in vacuum and the stellarator shear of $d\iota / d\Psi > 0$ due to the bootstrap current that will be discussed later. Application of this criterion to helical plasmas was once discussed in the design study of LHD [22], however, it was not successful for the criterion to be incorporated in its design. Because it could be said that this criterion has been shown to be effective for the confinement improvement in real experiments, the design effort incorporating the criterion in CHS-qa is one of key elements in its design. Recent detailed calculation shows that because of small non-axisymmetric Fourier components growing outwards the parallel velocity for J calculation gets reduced near the boundary, which results in the max. J configuration in the edge region [23]. The extent of the region where the criterion is satisfied can be extended into the core region because of the stellarator shear resulting from the bootstrap current and also can be changed, for example, by controlling R_{axis} [23].

To keep the flexibility to realize ITB found in CHS it is necessary to be able to increase residual ripples to enhance non-ambipolar diffusion; the ripples can be controlled by changing the current ratio not only of 3 pairs of poloidal field coils (for R_{axis} shift, quadrupole magnetic field, OH current) but also of main and additional modular coils (for mirror ripple and ι controls, respectively) in CHS-qa. Although only electron energy transport is improved in ITB of CHS, the increase in the ion energy content should be investigated with high power ion heating in the near future CHS experiment. The particle flux determining the radial electric field is approximately estimated as a function of the helical ripple [16]. The radial electric field is uniquely determined by the neoclassical non-ambipolar diffusions when the ripple is about 10%, under which situation the bifurcation with positive radial electric field is expected as in CHS. The mirror ripple is to be controlled by changing the current ratio of two groups of main modular coils [24]. When the residual ripple is reduced to about 1%, the fluxes due to such as bulk viscosity, loss-cone loss and charge exchange loss that determine the radial electric field in tokamaks become comparable to the reduced neoclassical one. There the bifurcation with negative radial electric field seen in tokamaks is expected.

The neoclassical transport in CHS-qa should be much better than that in conventional stellarators and its calculation on CHS-qa was done without the radial electric fields. The results show tokamak-like behavior in the low collisionality regime [15, 25], which is even much better than that of the drift-optimized configuration of CHS where the bottom of helical ripple has the same value by shifting the position Raxis inward, so-called σ=1 configuration [26]. The α particle confinement is estimated in the reactor-relevant CHS-qa configuration (5 Tesla, plasma volume of 1000 m^3) and the ripple diffusion of banana particles can be overcome [27], although the configuration is different from that of 2b32. There, the residual ripples are shifted into the high field side, by which optimization the banana tip has less possibility to encounter the residual ripples. This might be the reason why the α particle confinement is improved. Compatibility with the optimization made in the 2b32 configuration awaits a future work.

In QA configuration, the bootstrap current flows in the direction to augment the external rotational transform like in a tokamak. The increase in ι brings about a favorable effect on MHD properties, however care should be taken for ι not to cross the dangerous low order rational surface. The bootstrap current is estimated with the NIFS bootstrap code under the temperature and density profiles realized in the CHS high-β experiment. The resultant ι profile for $\langle\beta\rangle$ of 1.3 % is shown in Fig. 3 of reference 16. In the calculation, β is increased by increasing the temperature under the electron density kept constant, which is not the case in CHS and LHD experiments [28 - 30] where the increase in the electron density primarily contributes to the β increase. At present the calculation with NIFS bootstrap code is reliable up to $\langle\beta\rangle$ of about 1.5 %. When the rotational transform has the stellarator shear $d\iota / d\Psi > 0$ in QAS or tokamaks, the bootstrap current, which is supposed to preferentially flow at the node of island, creates the radial magnetic field of which direction is to cancel the perturbing radial magnetic field producing the island; it stabilizes the neoclassical tearing mode.

MHD calculation on the Mercier criterion gives stability $<\beta>$ of about 5% under the pressure profile of $(1-\Psi)^{1.5}$. In CHS and LHD, $<\beta>$ values obtained in the real experiments are higher than those predicted by the Mercier criterion [28 - 30]. However, in the more inward shifted configuration, where the magnetic hill is even enhanced, than the standard adopted in the high β experiment ($<\beta>$ of 2.1%), MHD instabilities limiting $<\beta>$ to 1% have been observed, which shows that the Mercier criterion is valid as a rough guideline of the achievable $<\beta>$ prediction. Because the average minimum B is satisfied in vacuum in CHS-qa, the interchange instability of the flute type is stabilized but the local ballooning modes should be examined. It is estimated by the TERPSICHORE code. The local ballooning mode stability, which should be more pessimistic than real experimental plasmas, gives $<\beta>$ stable up to 3 %, which gives a sufficient value of β for investigating the main objective of CHS-qa. Ideal kink modes are also estimated by TERPSICHORE under the plasma current of which value is 100 kA and of which profile is elaborately tailored, and it is shown that 3D shaping of CHS-qa stabilizes the modes although the modes are unstable for the averaged cross-section without the 3D shaping; 100% of 3D shaping means the real CHS-qa configuration and more than 70% of shaping is enough for the stabilization. Ideal kink modes are examined by using the CAS3D code, too. Here is assumed the current profile to be the one resulting from the bootstrap current obtained from the pressure profile giving $<\beta>$ of 1.3 %. At a current of around 150 kA corresponding to $<\beta>$ of about 4 %, ι crosses over 0.5 and the m/n=2/1 external kink mode gets unstable. In the experiments in JIPP T-II and W7-A, no current disruption was observed when the external ι is larger than 0.14 [31, 32]. The external ι is shown to enlarge the stability window [33] and it produces the restoring force against the displacement of the current-carrying plasma column, irrespective of the displacement direction. These have been considered to be the reason of no disruption, however, it should be noted that the β value was low in the experiments. Recent W7-AS experiments [34] have shown that major disruptions occur occasionally. The situation, where the disruption is avoided even when the total ι crosses over 0.5, has been also studied in W7-AS, and it gives us the clue to operate CHS-qa by controlling ι profile with Ohkawa and OH currents when the total ι exceeds 0.5 because of the bootstrap current as $<\beta>$ increases up to 4 or 5 %, although more calculation studies on external kink and tearing modes are needed.

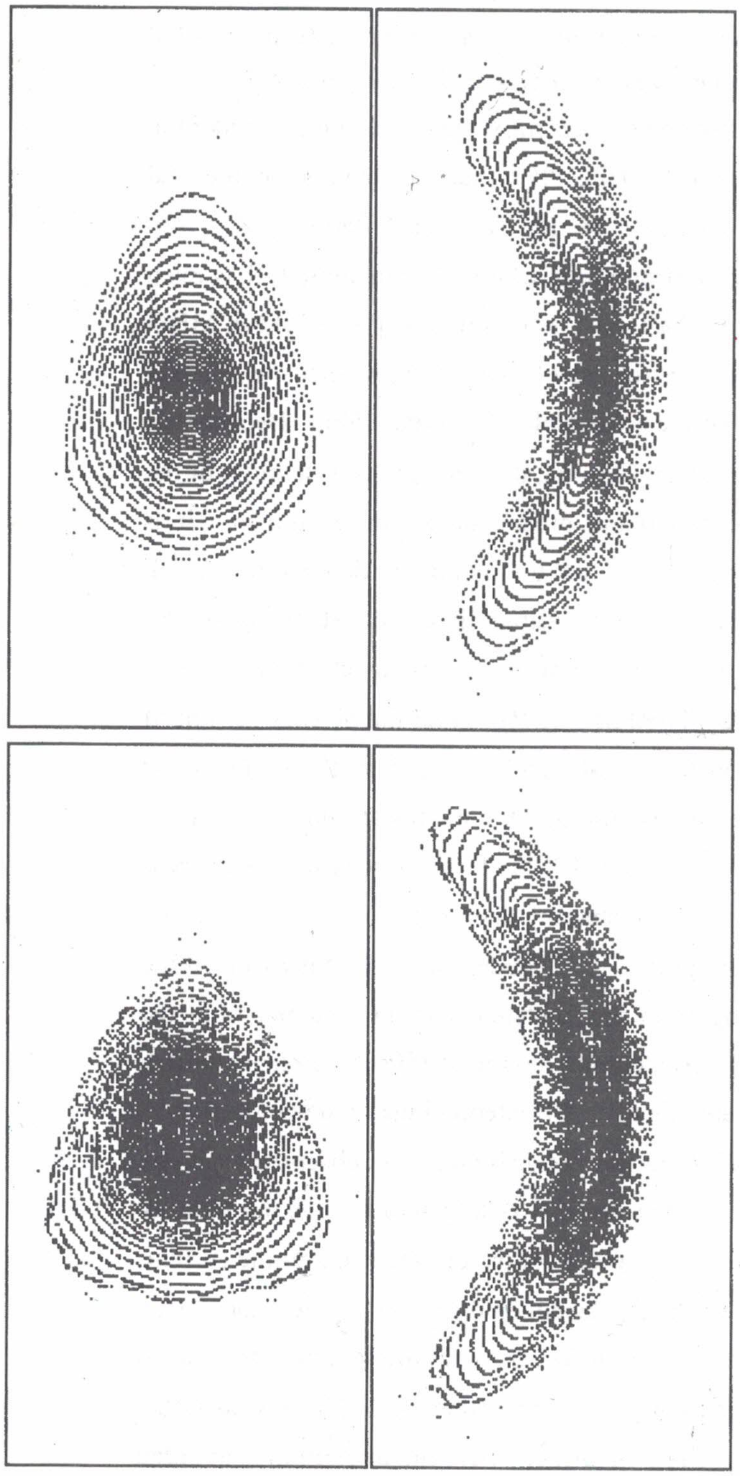

Fig. 1. Magnetic furfaces from the HINT code in the vacuum (top) and at <b> of 3.3% (bottom). The finite β calculation is with rather flattended pressure profile and with no net current.

The Pfirsch-Schlueter current can not be eliminated in QA configurations. The strong reduction in the parallel viscosity in the toroidal and poloidal directions is selected at the expense of P.S. current in CHS-qa. However, it should be noted that the associated Shafranov shift is substantially reduced in the configuration 2b32 in comparison with other CHS-qa configurations. The reason of the reduced Shafranov shift is under investigation. By using 3D MHD equilibrium code HINT [35] where the existence of magnetic surfaces is not assumed a priori, the fragility of magnetic surfaces has been examined. It is shown in Fig. 1 that up to the volume averaged beta $<\beta>$ of about 3.3% clean magnetic surfaces are kept under the condition of no net current and rather flattened pressure profile. The calculation taking account of net current due to the bootstrap and Ohkawa currents is under way. Again, this β value might be enough for the mission of CHS-qa.

4. Discussion and Conclusion

As has been shown above, the consistent physics design of CHS-qa has been almost completed for fulfilling its main objectives, i.e. the transport improvement in helical plasmas. The engineering design, which is not mentioned here, has also been completed. QAS configurations enjoy advantages of compactness, low disruptivity, low recirculationg power, which are thought to be the disadvantages of tokamaks. However, when the QAS reactor is envisaged in the future there still remain several problems to be solved: compatibility between optimizations toward good α particle confinement and stability of ballooning mode, the amount of residual ripples that satisfies max. J criterion and ripple diffusion of bananas, and the effect of bootstrap current at high electron temperature on current driven MHD instabilities.

In conclusion, by keeping advantages inherent in the helical system CHS-qa places itself in a unique position, incorporating magnetic configuration features of advanced tokamaks, to study the confinement improvement among a variety of toroidal plasma confinement devices. This experiment will elucidate the role of basic quantities of magnetic field structures on the plasma confinement.

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ФІЗИЧНИЙ ПРОЕКТ CHS-QA, ЩО БАЗУЄТЬСЯ НА ЕКСПЕРИМЕНТАХ НА CHS

К. Мацуока, С. Окамура, С. Нішімура, М. Ізобе, К. Сузукі, А. Шімізу,
А. Фуджісава, К. Іда, Т. Мінамі, Х. Ігучі, Й. Йошімура, М. Осакабе, І. Номура,
С. Муракамі, М. Йокояма, Н. Накаджіма, К. Іто, П. Меркел, М. Древлак,
К. Нюренберг, С. Горі, Р. Зілле, Ю. Нюренберг

CHS-qa, квазі-осесиметричний гвинтовий пристрій, було розроблено як наступник CHS у Національному Інституті фізики ядерного синтезу. Головною метою було покращення неокласичних і аномальних переносів гвинтової плазми. У CHS спостережено ряд покращених режимів. На базі цих режимів планується здійснити подальше покращення транспорту в CHS-qa, приймаючи до уваги методи, перевірені в інших тороїдальних магнітних конфігураціях, наприклад, великі швидкості обертання плазми та радіальний шир електричного поля, а також критерій максимального J. Показано, що тороїдальна швидкість буде меншою на два порядки, ніж у CHS, а полоїдальна швидкість, що головним чином визначається аспектним відношенням із додатковим внеском від залишкової гофровки є також меншою приблизно на один порядок, ніж у відповідній гвинтовій системі. Критерій максимального J задовольняється в граничній області у вакуумній конфігурації за присутності малої залишкової гофровки, а область виконання критерію розширяється до центру завдяки стелараторному ширу, що створюється бутстреп-струмом у плазмі зі скінченим бета. В основу проекту покладено мале аспектне відношення (A_p = 3.2) та великий об'єм плазми. Проектні параметри такі: R = 1.5 м, a = 47 см, B = 1.5 Тл, число тороїдальних періодів N = 2, 10 модульних котушок на період, 8 додаткових модульних тороїдальних котушок, 3 пари полоїдальних котушок. Залишкова гофровка може контролюватися цими котушками для забезпечення гнучкості експерименту.