WENDELSTEIN VII-A IN TORSATRON MODE

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IPP 2/275 March 1985

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiet der Plasmaphysik durchgeführt.

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Introduction

Recent experiments in the Wendelstein VII-A Stellarator demonstrated an appreciable degradation of the plasma confinement in correlation with rational values of the rotational transform ι near the plasma edge. It is well known that magnetic islands are introduced at rational values of ι by some perturbation in the magnetic fields which breaks the helical symmetry. The size of these islands depends on the magnitude of *shear* in the system. Therefore it is of interest to investigate by computation of vacuum fields, up to which value the *shear* can be increased in the Wendelstein VII-A Stellarator device above its comparatively low /1/ value of about 1 % . Out of scope of this paper are engineering questions correlated with such an extension of the parameter range of the experiment.

Since in the Wendelstein VII-A Stellarator the current connection of the helix is equipped with a center tap which is designed up to the full helix current, one pair of the helical winding can be switched off, thus generating a 'torsatron' magnetic field which has larger *shear* than the pure stellarator field. Because of the coupling of the helix with the OH-transformer, which is balanced only in pure stellarator mode, such experiments with a torsatron field have not been done in ohmically heated plasmas. By means of electron cyclotron resonance (ECR), plasma built-up and heating was demonstrated /2/ without the help of the OH-transformer. In these ECR-plasmas, deep minima of the stored plasma energy are seen in correlation with rational values of ι, which could be (at least partly) removed by some ($\approx 2\,kA$) current parallel to the magnetic field. This influence of a residual plasma current on the confinement can be discussed /3/ in terms of a modified *shear* present in the system. Similar results were obtained with 'currentless' plasmas heated by neutral injection. These results stimulated a more detailed investigation of how to operate the Wendelstein VII-A device with more externally produced *shear*. As is well known, the *shear* in an $\ell = 2$-torsatron device is due to the $\ell = 4$ components of the helical field, which are small in a standard $\ell = 2$-stellartor.

The present investigation is done by numerical computation of vacuum fields. Two cases are considered : a 'pure' torsatron mode where only one set of the helical conductors is energized, and a 'mixed' mode where the two helices of Wendelstein VII-A carry different and opposite currents. In both cases, the major part of the toroidal field is produced by the toroidal field coil system.

Geometry of the System and Polarities

The following computations are done in a right-handed frame of reference : R, Φ, Z denote the major radius, the toroidal angle and the vertical dimension, resp. The value $\Phi = 0$ corresponds to the toroidal angle $\varphi = 18^o$ in the convention used at Wendelstein VII-A with $\varphi = 0$ corresponding to the position of the limiter.

In the computation, the magnetic field of the TF–coils of Wendelstein VII-A is represented by a toroidal field B_Φ in the direction of positive Φ and proportional to $1/R$. This approximation is fully sufficient because of the large number of 40 TF–coils and their comparatively large bore. The field of the vertical field coils of Wendelstein VII-A is represented by a homogeneous field B_Z . This simplification can easily be improved by entering the concrete positions and currents of the various vertical field coils into the computation.

The helical system of Wendelstein VII-A is of the $\ell = 2, \mathrm{m} = 5$ - type . The twist of the helix conductors is counter-clockwise when looking in the positive φ - direction. The whole helix of Wendelstein VII-A comprises one single current path with the current leads at $\varphi = 9^o$ and some negative Z - value. Four windings in each of the two 'positive' helix segments are made up by following the helix conductors twice the long way around the machine, with three 'minor' and one 'major' interturn connections , which are called a 'helix step' in /1/ . This helix step is positioned at $\varphi = 18^o$. At the position of the current leads, and in a type of bi-filar arrangement, the connection to the 'negative' helix segments is made. Their helix step is at $\varphi = -18^o$. Both helix steps are placed at $Z = 0$ towards the outside of the torus. There the magnetic forces are minimum due to the $1/R$–dependance of the toroidal field. As mentioned above, the current leads are equipped with a third conductor designed up to the full helix current.

In the computation of the stellarator fields, a helix segment is modelled by four polygones with 200 points each, i.e. 100 points once the long way around the machine. The center of the polygones of the 'positive' helix segments is positioned at $\Phi = Z = 0$ and carries a positive current, whereas that of the 'negative' segments is centred at $\Phi = 180^o, Z = 0$. These conventions apply for a radial position of $R = R_o + r_{HX}$, where $R_o = 2m$ and $r_{HX} = 22.5cm$ are the major torus radius and the minor helix radius, respectively.

In the computations of unperturbed configurations, the fields of the helix steps and of the current leads are omitted. The system thus is toroidally fivefold symmetric. For studies of perturbed configurations, we model the shapes of the helix steps and of the current leads by appropriate spatial polygones and superpose the fields of their actual currents.

The system now is of m = 1 –symmetry. Only at rational values of $\iota = i/k$, with i, k being not too large integers , magnetic islands of appreciable size are produced by these perturbations.

Reference Case of Stellarator Field

As a reference configuration for the following part of this paper we choose in FFR840 a system of magnetic vacuum fields of the Wendelstein VII-A Stellarator with an irrational value of ι slightly above 1/2 . In an overlay of two toroidal positions, several nested magnetic surfaces are shown in the top half of *Fig.*1 . A helix current of $I_{HX} = +/-36\,kA$ is required for this value of ι at a magnetic field set to $B = 2.5\,T$ at $R = 2\,m$. Note that this radial position is just a few *mm* outside of the magnetic axis.

The major axes of the nearly elliptical magnetic surfaces are in the horizontal direction at a toroidal position of $\Phi = 0$. There, the external toroidal field is weekened by the local toroidal field components of the helical conductors. The system of magnetic surfaces at a toroidal distance of 1/2 field period is also shown in the figure. The long sides of the surfaces are vertical and the inherent radial offset of the center magnetic surfaces with respect to the outer ones is clearly visible in the vacuum fields.

The lower half of *Fig.*1 shows a perturbed configuration. In FFR932, by a slight reduction of 1% of the helix current, the resonance of $\iota = 1/2$ is established and the perturbation currents of the two helix steps and of the current leads are included into the computation. Between the closed magnetic surfaces, two large magnetic islands are present. They are slightly tilted with respect to the midplane of the system. This is caused by the toroidal offset of the effective perturbation field.

A small variation of the toroidal field changes the radial position of the islands. Since the perturbation fields used in this computation decrease rapidly from the outside of the system towards the magnetic axis, the size of the islands increases with the minor radius. For the example shown in the figure, the *shear* present in the configuration is low enough so that only the main resonance at $\iota = 1/2 = 5/10$ is effective. On the other hand, this low value of *shear* determines the actual size of the islands. It amounts to several *cm* in the radial direction near the so-called *O-points*. If the islands or the separatrix around them touch the limiter of Wendelstein VII-A one expects a poor confinement resulting already from the drastic reduction of the plasma radius.

The neighbouring main resonances in the m = 5 – system would be at $\iota = 5/11$ or $5/9$ and require different values of either the helix currents or the toroidal field.

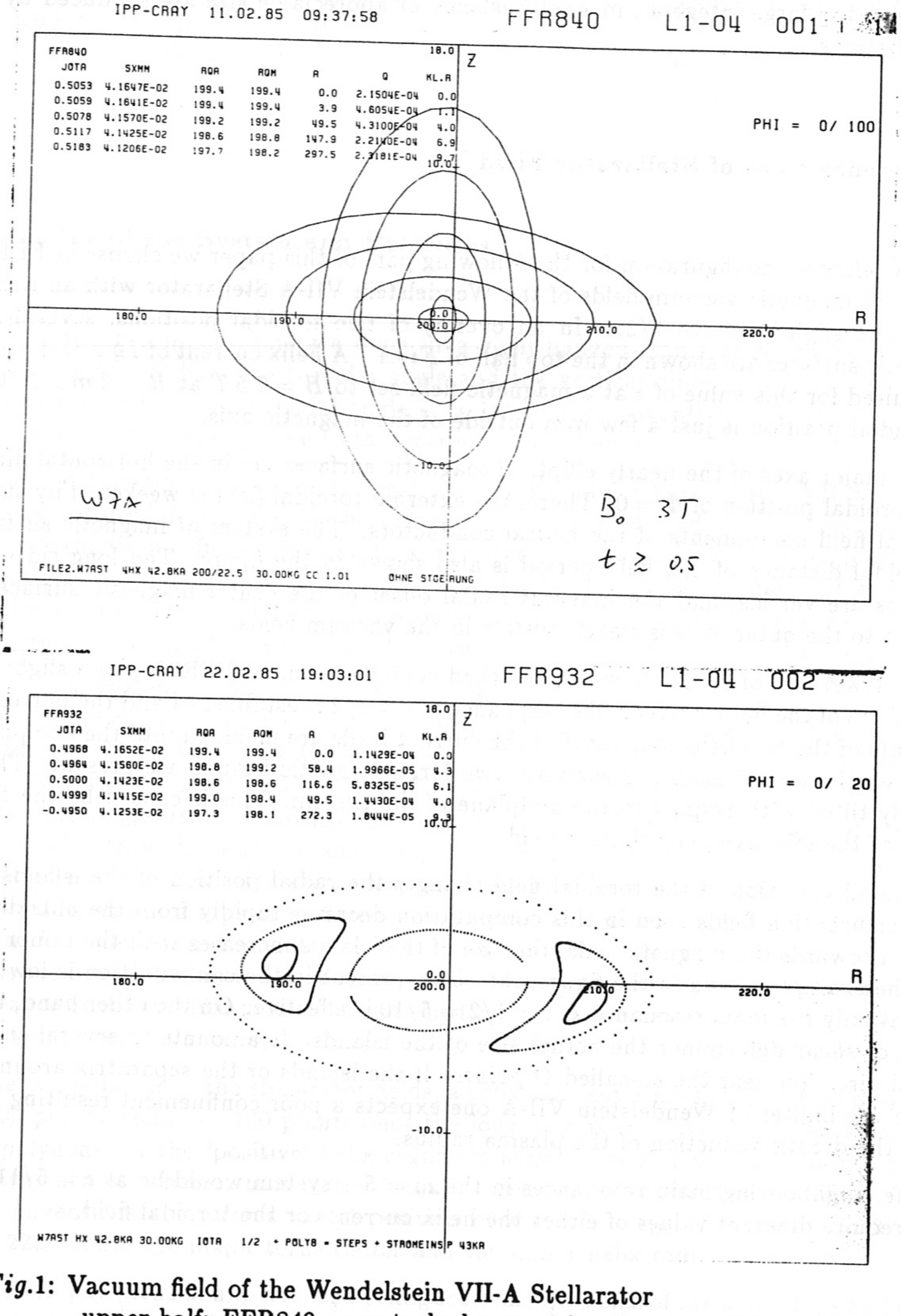


***Fig.1*: Vacuum field of the Wendelstein VII-A Stellarator**
upper half: FFR840 unperturbed case at irrational $\iota \approx 0.5$.
$R = 200\,cm$: $B_\Phi = 2.5\,T$; $TF - coils = 2.5\,T$; $I_{HX} = 36\,kA$; $B_Z = 0.00\,T$
lower half: FFR932 perturbed configuration at $\iota = 1/2$
helix current slightly different.

Torsatron Mode in Wendelstein VII-A

In contrast to stellarators the standard torsatron configurations /4/ are produced by a set of helical windings which carry their current in identical directions, thus producing the toroidal and poloidal field components as well. An appropriate vertical field is required in order to get centred magnetic surfaces. In the so-called *ultimate torsatron* this vertical field is introduced by a special winding law of the helical conductors /4/.

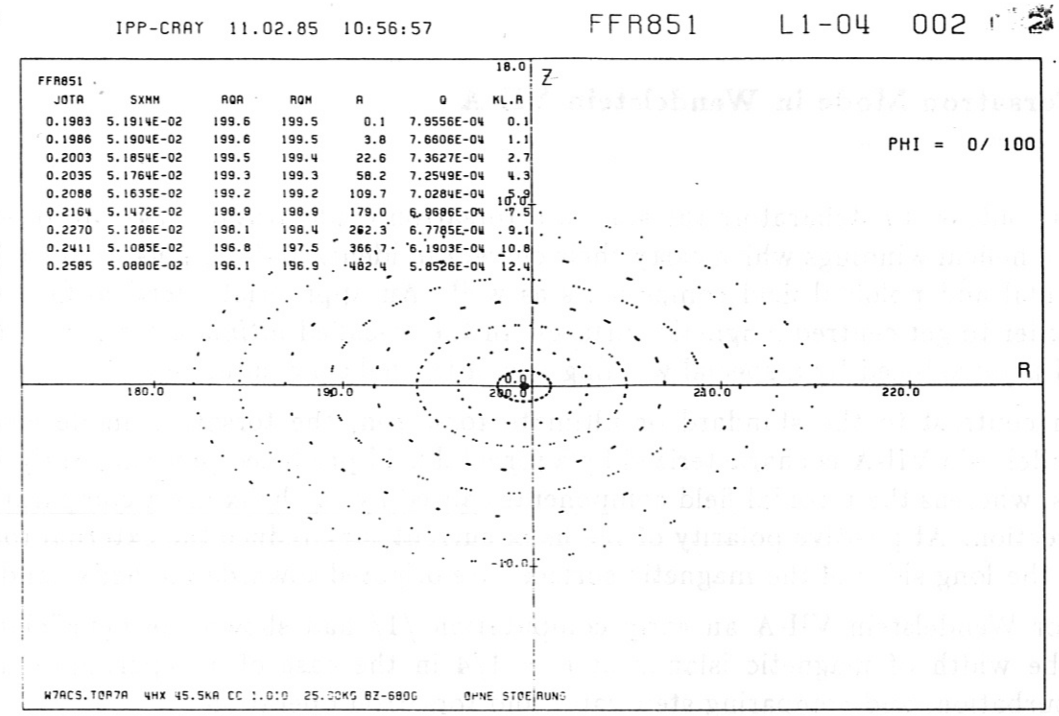
In contrast to the standard or ultimate torsatron, the torsatron mode envisaged for Wendelstein VII-A is characterized by a toroidal field produced predominantly by the TF-coils, whereas the toroidal field components caused by the helix are a comparatively small correction. At positive polarity of the helix current they reduce the external toroidal field and the long sides of the magnetic surfaces are oriented towards the helix conductors.

For Wendelstein VII-A an early computation /1/ had shown the beneficial reduction of the width of magnetic islands at $\iota = 1/4$ in the case of a superimposed m = 1 – perturbation, and comparing stellarator and torsatron operation.

In order to refresh this former computation the unperturbed system of magnetic surfaces is shown in *Fig.* 2 under similar conditions. The current in the $TF-coils$ is set to produce a toroidal field of $B_\Phi = 2.5\,T$ at $R = 2\,m$. The helix segment starting at $\Phi = 0$ is energized by a current $I_{HX} = 44.9\,kA$. With a homogeneous vertical field $B_Z = -0.068\,T$ a value of $\iota(0) \approx 0.2$ is obtained at the magnetic axis. The last magnetic surface shown in the figure is at $\iota \approx 0.26$, at a minor radius $r = 12.4\,cm$. Note that this surface is outside of the limiter radius of the Wendelstein VII-A device. If we restrict our attention to surfaces within the limiter aperture we have to discard the two outermost surfaces, and arrive at a value of $\iota(r_L) \approx 0.23$. The upper half of *Fig.* 2 is calculated for a toroidal position of $\Phi = 0$. The lower half of the figure is at $\Phi = 18^o$, corresponding to a value of $\varphi = 36^o$. This is the position of the first plane of the experimental ports. For an actual application of the torsatron mode in Wendelstein VII-A, attention is to be paid at which toroidal positions objects inside of the torus require the orientation of the long sides of the magnetic surfaces to be vertical and in agreement with the presently used orientation in stellarator mode.

The *shear* $= \delta\iota/\iota = \big(\iota(r_L) - \iota(0)\big)/\iota(0) = 15\%$ for the conditions of *Fig.* 2 , between the magnetic axis and the limiter. This value is about an order of magnitude larger than the *shear* present in the pure stellarator mode of Wendelstein VII-A.

The magnetic forces acting onto the helix are different in the pure stellarator and the torsatron modes. In the stellarator mode, the major contribution is the force resulting from the toroidal field. One pair of the helix segments is compressed towards the torus, the other envisages a force in the minor radius direction. In the torsatron mode as discussed in this chapter, the force density $I_{HX} \times B_\Phi$ is compressive. This results from the combination of the left-handed pitch of the helix, its positive current, and the direction of $B_{+\Phi}$. In torsatron mode, another force results from the interaction of the helix current with the vertical field. This force is in the $-R$ -direction. The force between the two helix segments is attractive. The magnitude of these forces and engineering considerations regarding operation limits of the Wendelstein VII-A experiment are not treated in this report.



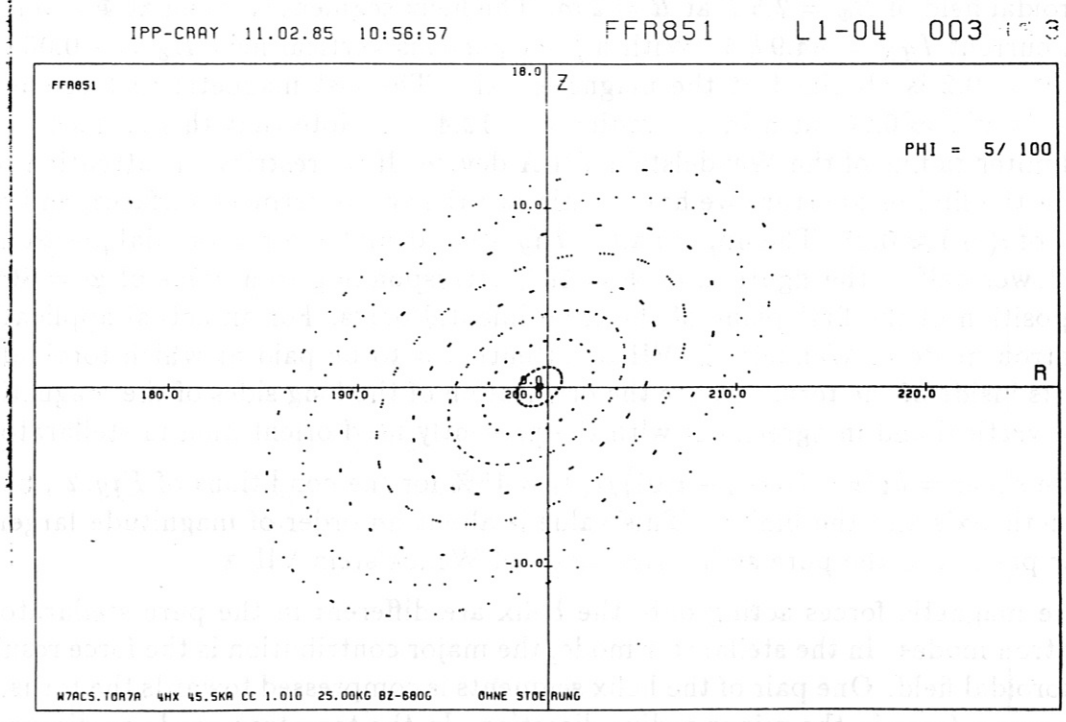


***Fig.2*: Vacuum field of Wendelstein VII-A in torsatron mode**

FFR851: unperturbed case at irrational $\iota(0) \approx 0.2$.

$R = 199.6\,cm$: $B_\Phi = 2.415\,T$

$TF - coils = 2.5\,T$; $I_{HX} = 44.9\,kA$; $B_Z = -0.068\,T$

upper half : toroidal position $\Phi = 0$

lower half : as above , $\Phi = 18^o$

In the configuration shown in the previous figure the edge value of the rotational transform is close to the value $\iota = 0.23$ as obtained in the 'standard case' of the Wendelstein VII-A Stellarator when applying equal currents to the TF-coils and to the helix. As it is to be expected, a considerably larger helix current is required in the torsatron mode of *Fig.* 2, in comparison to the stellarator case. In order to increase the rotational transform to a value comparable to that of the stellarator reference configuration of Wendelstein VII-A as given in *Fig.* 1, the helix current and the vertical field are to be increased further.

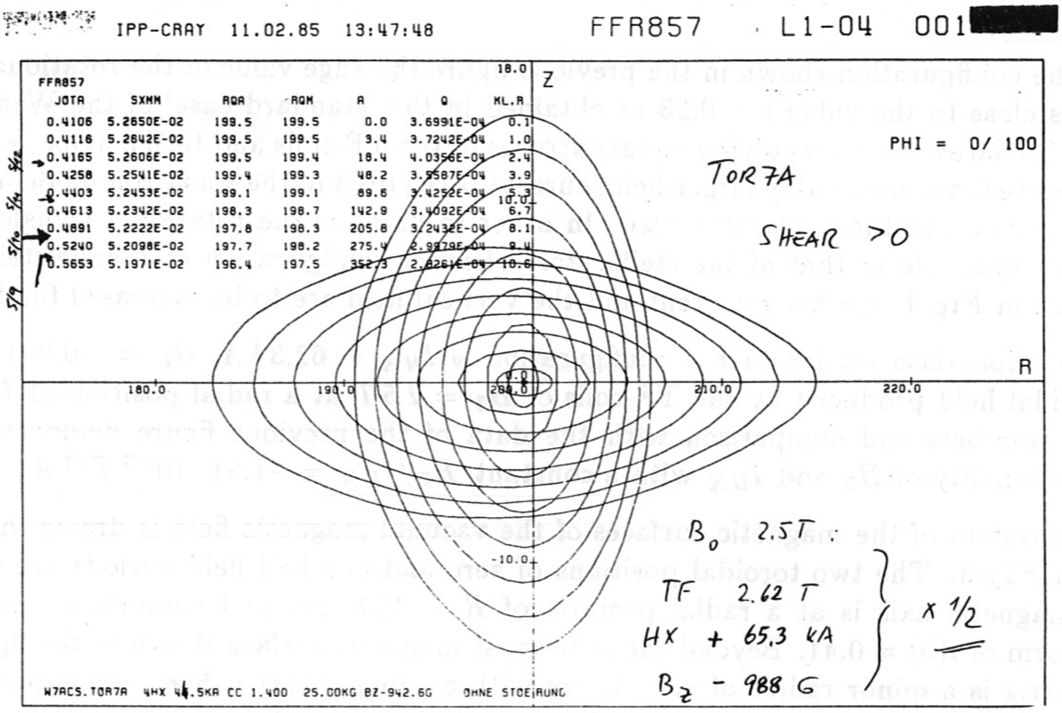
A possible data set for such a configuration is $I_{HX} = 62.3\,kA$, $B_Z = -0.0943\,T$, and a toroidal field produced by the TF-coils of $B_\Phi = 2.5\,T$ at a radial position of $R = 2\,m$. These numbers and comparison with the data of the previous figure demonstrate the proportionality of B_Z and I_{HX} with a constant $B_Z/I_{HX} = -1.51 \cdot 10^{-3}\,T/kA$.

The system of the magnetic surfaces of the vacuum magnetic field is drawn in the top half of *Fig.* 3. The two toroidal positions of zero and one half field periods are overlaid. The magnetic axis is at a radial position of $R = 199.5\,cm$ and comprises a rotational transform of $\iota(0) \approx 0.41$. Beyond the outermost magnetic surface shown in the figure, the separatrix is a minor radius of $r_s = 12\,cm$ with a value of $\iota(s) = 5/8$. Consequently, the whole series of rational values of $\iota = 5/12 \ldots 5/9$ is contained within the separatrix , and the main resonance at $\iota = 1/2$ is found at $r \approx 8.5\,cm$.

A magnetic surface touching the limiter is obtained by discarding the two outermost surfaces of *Fig.* 3. Thus we obtain a minor radius at the limiter $r_L = 8.1\,cm$ with a value of the rotational transform of $\iota(L) = 0.49$. Between this magnetic surface and the axis the *shear* amounts to 19 %, according to the definition as given above. The increase of *shear* with ι is a common feature of stellarators.

Normalizing the input data of *Fig.* 3 to a value of $B_{axis} = 2.5\,T$ requires a factor of ≈ 1.05. This normalization factor is obtained from the plot of the magnitude of the magnetic field *vs* the length of the field line.

As shown in the lower half of *Fig.* 3 , before the normalization the axis value is at $B_{axis} = 2.38\,T$. The magnetic axis is nearly circular, and there is practically no ripple. For the trace B_{213} of an outer field line starting at $R = 213\,cm$ outside of the limiter position and at an absolute minimum of $|B_{min}| = 2.2\,T$, an absolute maximum $|B_{max}| > 2.5\,T$ is obtained at a radial position of $R \approx 185.4\,cm$. This point is reached after 4 1/2 field periods, as can easily be seen by following the undulating trace of the curve of $|B|$. The toroidal ripple exceeds the helical one by a factor of about three. Inspection of the trace of $|B|$ shows that the helical ripple itself is modulated by approximately 50% of its average value, the deepest minima being at the radial outside of the system. In conventional and ultimate torsatrons the helical ripple usually exceeds the toroidal one. A modulation of the helical ripple is typical for toroidal stellarators.



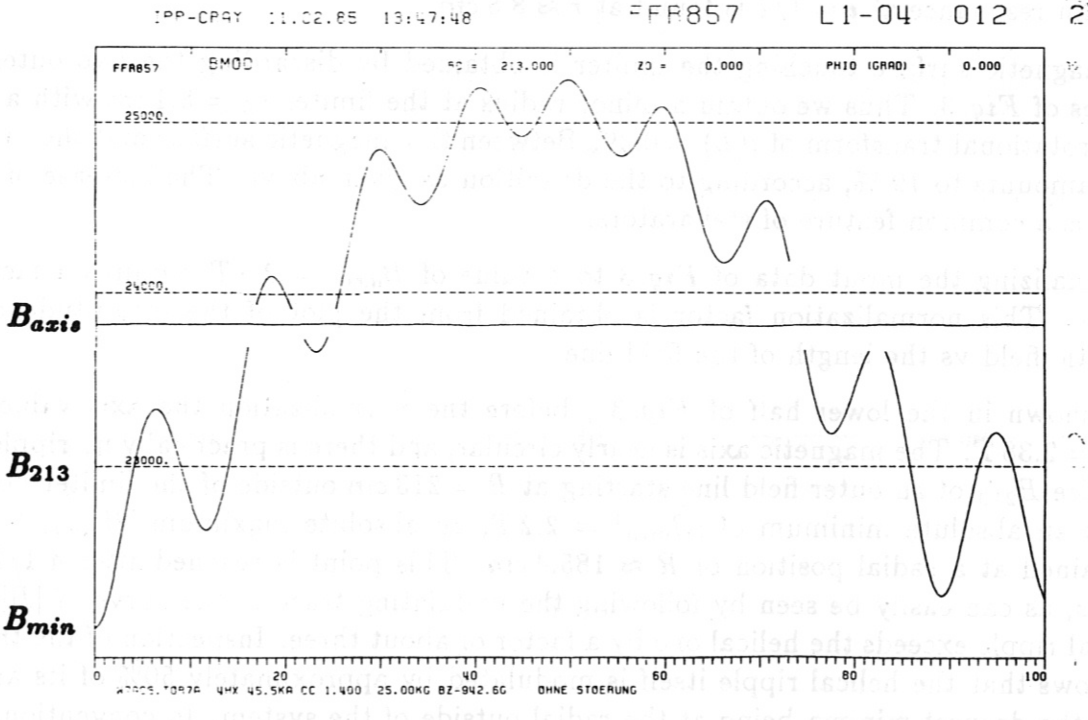


Fig.3*: Vacuum field of Wendelstein VII-A in torsatron mode with positive *shear

FFR857: unperturbed case at irrational $\iota(0) \approx 0.41$ and $\iota(L) \approx 0.49$.

upper half: magnetic surfaces at toroidal positions $\Phi = 0$ and $\Phi = 36^o$

lower half: magnitude of the magnetic field

at the magnetic axis and at a starting point $R = 213\,cm$

two toroidal transits , input data not yet normalized.

Normalized input data :

$R = 199.5\,cm$: $B_\Phi = 2.50\,T$

$TF - coils = 2.624\,T$; $I_{HX} = 65.26\,kA$; $B_Z = -0.0988\,T$

Increasing the current in the toroidal field coils only and keeping the other input data constant reduces the rotational transform. As example, an intermediate configuration between *Fig.* 2 and *Fig.* 3 is produced with $\iota(0) \approx 0.37$, $\iota(L) \approx 0.44$. In contrast to the input data of *Fig.* 3 and instead of a normalization of all parameters, the toroidal field of the $TF - coils$ is increased by $0.12\,T$ in order to attain $|B_{axis}| = 2.5T$. Thus, the input data for this case are : $TF - coils = 2.62\,T$; $I_{HX} = 62.3\,kA$; $B_Z = -0.0943\,T$.

The effect of a perturbation of the vacuum field is studied for the same configuration as that of *Fig.* 3. The input data is as given in the text, i.e. the normalization factor of 1.05 is not yet applied. This factor had been used to obtain $|B_{axis}| = 2.5\,T$.

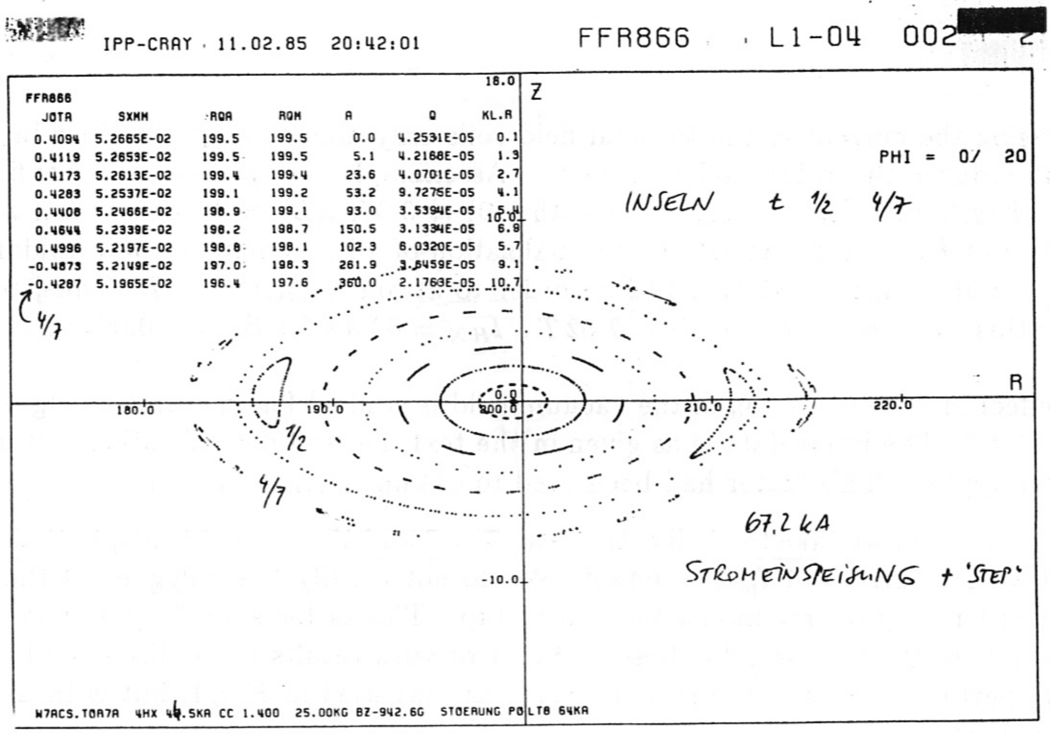
As perturbation we take the helix step near $\Phi = 0$ and the current leads, both polygones charged with a current of $I_{pert} = 64\,kA$. We do not modify the polygone of the current leads in order to properly model the center tap. This is for simplicity and in order to better compare the results with those of *Fig.* 1 or with results to be discussed later. The resulting perturbation is of the $m = 1$ - type, as that used in *Fig.* 1, but with a different phase angle Φ_{pert}.

In the top half of *Fig.* 4 we show the nested magnetic surfaces as obtained in the toroidal position $\Phi = 0$. Two systems of magnetic islands are present : the inner one at the main resonance $\iota = 1/2$, and the outer one at $\iota = 4/7$. The inner system comprises $n_i = m_{pert}/\iota = 2$ islands in each toroidal plane. The islands are connected after one toroidal transit. For the outer system of $n_i = 7$ islands the following relation can be stated: $n_i = (m - m_{pert})/\iota$, and the islands close after 7 toroidal transits. Although the outer system of islands is closer to the perturbation polygones and larger local fields are present, their radial dimension is smaller than that of the inner islands. This contrasting feature is caused by both, the increased *shear* near the outside of the topology and the increased number of islands.

The resonance at $\iota = 4/10$ is not within the configuration, but the resonance at $\iota = 4/9 = 0.4444$ could possibly be seen between the fifth and the sixth magnetic surface. Its radial extent is expected to be small because of the large number of 9 islands.

A different example could be conjectured near the fourth field line counted from the magnetic axis. Here $\iota = 0.428 \approx 3/7$ would require the second sideband of $m - 2 \cdot m_{pert}$ being active. Such a combination has not yet been seen so far. The same holds for resonances of the type $n_i = (m + m_{pert})/\iota = 6/\iota$.

The lower half of *Fig.* 4 shows two traces of $|B|$ *vs* the length of the field line in the perturbed configuration. Two toroidal transits are computed. For the magnetic axis, the small undulations at the ends and in the middle of the trace are caused by the local fields of the perturbation polygones. They amount to $B_{pert} \approx +/- 2.5\,mT$. At the trace of the outer magnetic field line starting at $R = 213\,cm$ the local perturbation field, being larger because of the closer distance to the perturbation polygones, can be seen only near the beginning and at the end of the trace. In the middle of the figure, the magnetic field line is far from the perturbation at a position of $R \approx 185\,cm$.



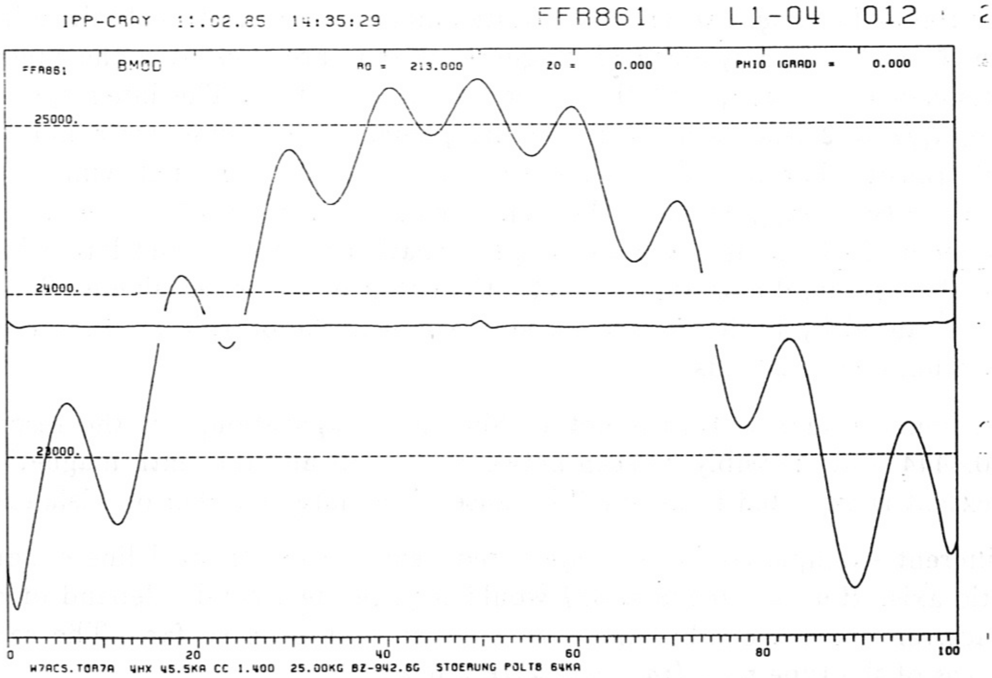


Fig.4: **Vacuum field of Wendelstein VII-A in torsatron mode with positive *shear***
perturbed case at irrational $\iota(0) \approx 0.41$.
$R = 199.5\,cm$: $B_\Phi = 2.38\,T$
$TF - coils = 2.5\,T$; $I_{HX} = 62.3\,kA$; $B_Z = -0.0943\,T$
perturbation : one helix step + current leads
upper half: FFR 866 magnetic surfaces at $\Phi = 0$
with two systems of magnetic islands
lower half: FFR 861 magnitude of the magnetic field
at the magnetic axis and at a starting point $R = 213\,cm$
two toroidal transits, perturbation field at axis $\approx 2.5\,mT$.

Torsatron Mode with Negative Shear

In the previous section, vacuum magnetic field systems are derived for operation of Wendelstein VII-A in torsatron mode with positive *shear*. In this mode, the toroidal field components produced by a positive current in the helix at $\Phi = 0$ reduces the toroidal field B_Φ of the TF-coils which is in the $+\Phi$-direction in the present computations. Centred magnetic surfaces are obtained by a vertical field $-B_Z$ with a value proportional to the helix current. The magnetic surfaces have a magnetic well of about 1 % at $\iota \approx 1/2$.

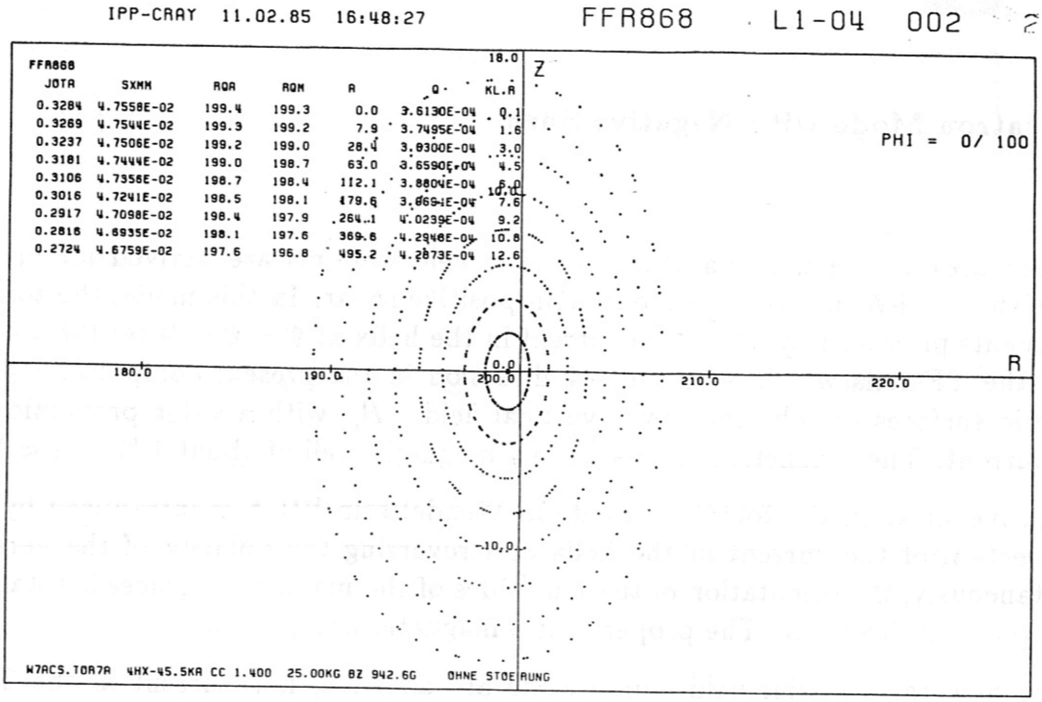
Negative *shear* in the torsatron mode in Wendelstein VII-A is introduced by changing the direction of the current in the helix and reversing the polarity of the vertical field. Simultaneously, the orientation of the long sides of the magnetic surfaces is rotated by 90^o in the poloidal direction. The property of a magnetic well is maintained.

Since now the toroidal field components are additive, less current in the TF-coils is needed in order to obtain a desired value of $|B|$. If one is interested in a certain value of the rotational transform near the plasma edge, because of negative *shear* a larger transform is present at the magnetic axis which is to be produced by a larger helix current, when comparing both types of torsatron mode at comparable ι at the edge.

The same general result is obtained by the following argument: in stellarators, the value of ι is proportional to the ratio of poloidal to toroidal flux. At a given helix current with additive toroidal field components the toroidal flux is increased and the rotational transform is decreased, in comparison to the case at reversed polarity.

These general results are applied when construction several vacuum field configurations for operation of Wendelstein VII-A in torsatron mode with negative *shear*. Using the same and unnormalized input data as in ***Fig.*** 3 and reversing the polarity of the helix current and of the vertical field, yields in FFR868 a topology as shown in ***Fig.*** 5 for the two toroidal positions of $\Phi = 0$ and 36^o. The values of the rotational transform are $\iota(0) = 0.328$ at the magnetic axis and $\iota(L) \approx 0.29$ near the limiter, respectively. The latter value applies for a magnetic surface sligthly outwards and close to the third flux surface, as counted from the largest one shown in the figure. A minor radius of $r \approx 10\,cm$ can be envisaged, when measuring, in the lower half of the ***Fig.*** 5, a distance of about $12.5\,cm$ along the major axis of the magnetic surfaces towards the upper inside of the topology. The separatrix is at a considerably larger minor radius and is not shown in the figure.

In comparison to ***Fig.*** 2, the orientation of the major axes of the magnetic surfaces is rotated by 90^o in the poloidal direction.



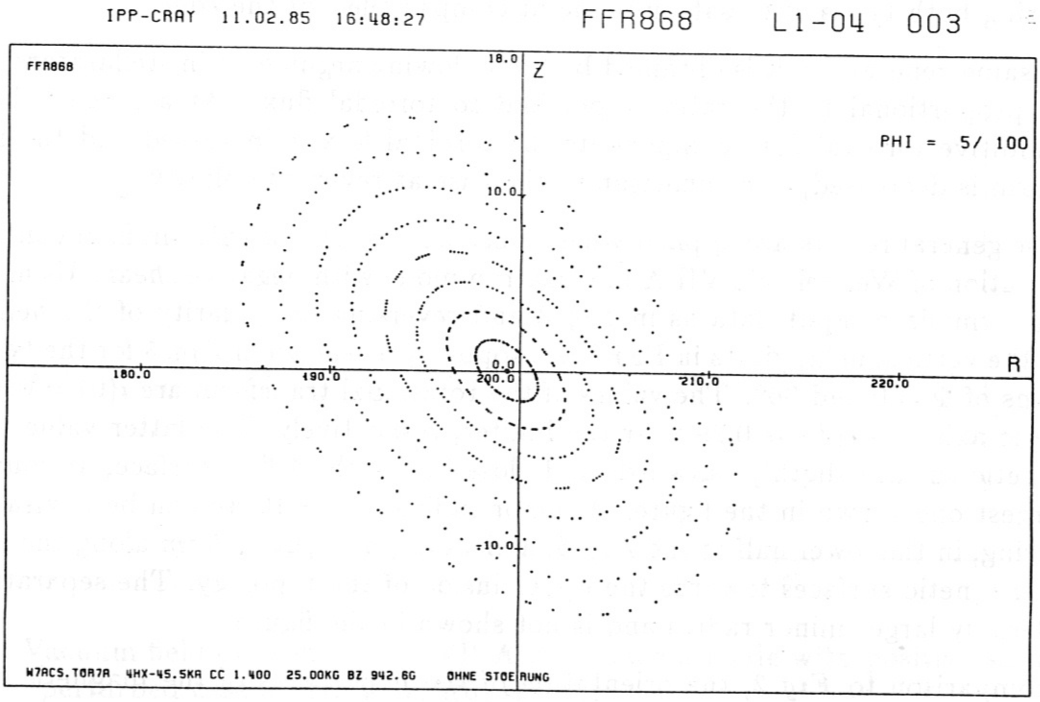


Fig.5 **FFR868: Wendelstein VII-A in torsatron mode with negative *shear***
unperturbed case at irrational $\iota(0) \approx 0.33$ and $\iota(L) = 0.29$ at $r_L \approx 10\,cm$.
upper half : magnetic surfaces at a toroidal position $\Phi = 0$
lower half : magnetic surfaces at a toroidal position $\Phi = 36^o$
input data not normalized.
$R = 199.4\,cm$: $B_\Phi = 2.634\,T$
$TF - coils = 2.5\,T$; $I_{HX} = -62.3\,kA$; $B_Z = 0.0943\,T$

In oder to increase the rotational transform near the plasma edge to a value comparable to that used in many of the experiments at Wendelstein VII-A, and in order to compare with the numerical results of *Fig.* 3, the following data set is chosen for FFR883.

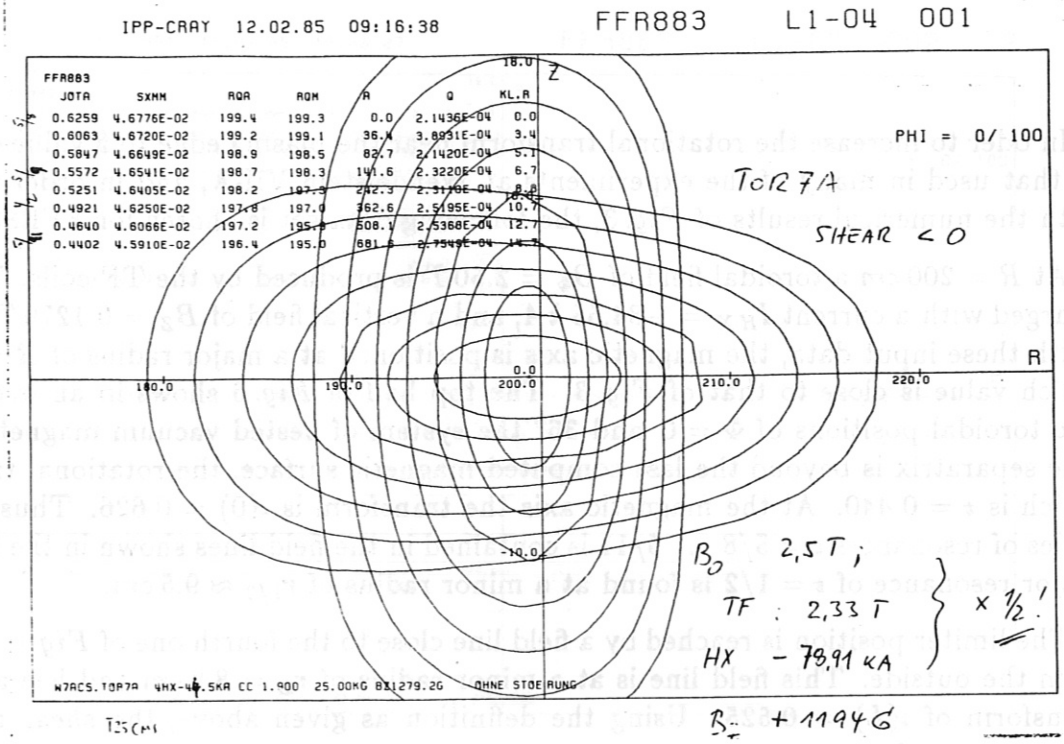
At $R = 200\,cm$ a toroidal field of $B_\Phi = 2.50\,T$ is produced by the TF-coils. The helix is charged with a current $I_{HX} = -84.55\,kA$, and a vertical field of $B_Z = 0.1279\,T$ is applied. With these input data, the magnetic axis is positioned at a major radius of $R = 199.4\,cm$, which value is close to that of *Fig.* 3. The top half of *Fig.* 6 shows in an overlay of the two toroidal positions of $\Phi = 0$ and 36^o the system of nested vacuum magnetic surfaces. The separatrix is beyond the last computed magnetic surface, the rotational transform of which is $\iota = 0.440$. At the magnetic axis the transform is $\iota(0) = 0.626$. Thus, the whole series of resonances $\iota = 5/8 \ldots 5/11$ is contained in the field lines shown in the figure. The major resonance of $\iota = 1/2$ is found at a minor radius of $r_{1/2} \approx 9.5\,cm$.

The limiter position is reached by a field line close to the fourth one of *Fig.* 6, as counted from the outside. This field line is at a minor radius of $r_L = 8.8\,cm$ and has a rotational transform of $\iota(L) = 0.525$. Using the definition as given above, the *shear* amounts to $\delta\iota/\iota(0) = -16\%$.

The magnitude of the magnetic field at the axis amounts to $|B_{axis}| = 2.678\,T$, due to the additive toroidal field of the helix. The normalization to a value of $|B_{axis}| = 2.5\,T$ yields the data entered in the last two lines of the figure caption.

The bottom half of *Fig.* 6 gives, with input data not yet normalized, the perturbed configuration. Again, the perturbation polygones of one helix step and of the whole current leads are used, charged with a current of $I_{pert} = 87\,kA$. The magnetic surfaces are shown at the toroidal position $\Phi = 0$. The two island systems are at the resonances $\iota = 1/2$ (two islands), and $\iota = 4/9 = (m - m_{pert})/n_i$. Two of the $n_i = 9$ islands are outside of the plot frame at the toroidal position shown in the figure.

Considering the limiter position in Wendelstein VII-A, the islands at $\iota = 1/2$ are just in the limiter shadow. The limiter is touched approximately by the fourth flux surface counted from the outside of the topology drawn in the lower half of *Fig.* 6. It has a value of $\iota = 0.523$ and an effective minor radius of $r_L = 8.8\,cm$. Within this magnetic surface, no magnetic islands of appreciable size had been found by further computations. The resonance at $\iota = 5/9$ occurs near $r \approx 7\,cm$; that at $\iota = 4/7$ at $r \approx 6\,cm$. The axis value of $\iota = 0.624$ is just below 5/8, and this resonance does not occur in this perturbed configuration.



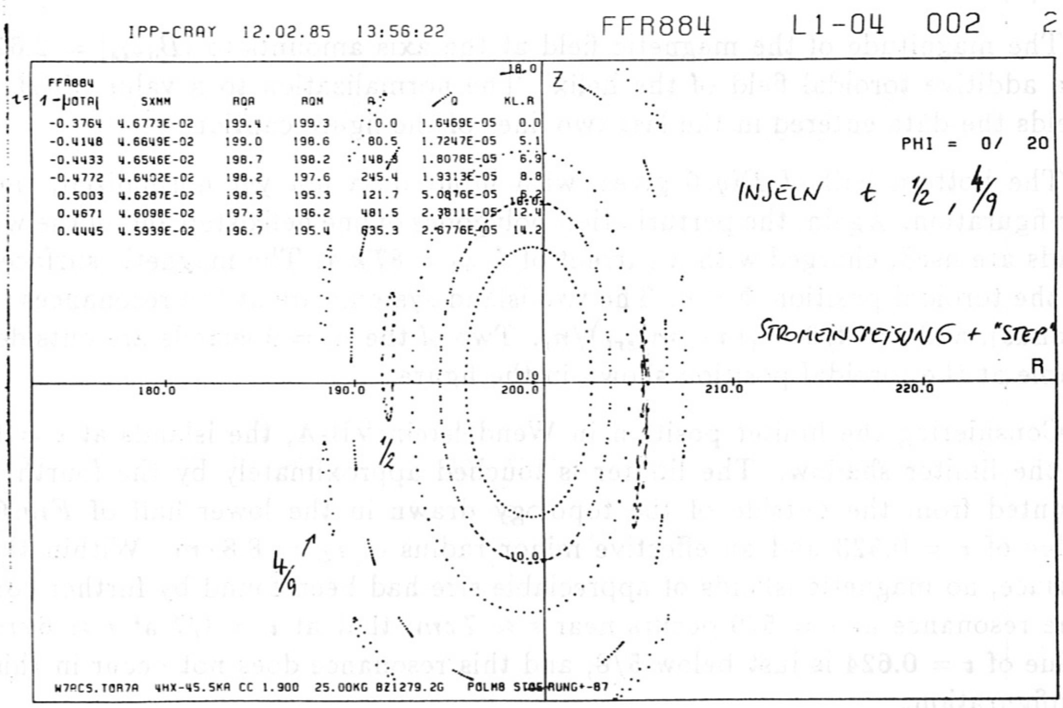


Fig.6: **Vacuum field of Wendelstein VII-A in torsatron mode with negative *shear***
irrational $\iota(0) \approx 0.63$ and $\iota(L) \approx 0.52$ at $r_L = 8.8\,cm$
input data not yet normalized.
upper half : FFR883, unperturbed magnetic surfaces at $\Phi = 0$ and $\Phi = 36^o$
lower half : FFR884, configuration as above perturbed by $I_{pert} = 87\,kA$
in one helix step + current leads
Normalized input data :
$R = 199.4\,cm$: $B_\Phi = 2.50\,T$
$TF - coils = 2.333\,T$; $I_{HX} = -78.91\,kA$; $B_Z = 0.1194\,T$

Comparatively large values of the rotational transform at the magnetic axis are possible by further increasing both, the helix current and the vertical field.[1] As an example, the following data set is obtained in FFR881: In this computation, at $R = 200\,cm$ a toroidal field of $B_\Phi = 2.50\,T$ is produced by the TF-coils. The helix is charged with a current $I_{HX} = -97.9\,kA$, and a vertical field of $B_Z = 0.1481\,T$ is applied. With these input data, the magnetic axis is positioned at a major radius of $R = 199.4\,cm$ and the rotational transform is $\iota(0) = 0.873$. Measuring the distance to the limiter at $\Phi = 18^o$ towards the upper inside of the magnetic surfaces we arrive at an effective minor radius of $r_L = 7.7\,cm$ where the rotational transform is calculated as $\iota(L) = 0.72$. This value of the minor radius is comparatively large at such an elevated rotational transform. On the other hand, the product of $B_\Phi \cdot I_{HX} = 250\,T \cdot kA$ exceeds the technical limits of Wendelstein VII-A, but operation at a total magnetic field normalized to $|B| = 1.25\,T$ could be reasonable.

[1]In this paper, engineering constraints are not treated, e.g. regarding limits in helix current, the effects of magnetic forces , the associated stresses (also due to the temperature increase) or any limits caused by the stray vertical fields, etc.

Mixed Mode with Positive or Negative Shear

In this section, vacuum magnetic field systems are derived for operation of Wendelstein VII-A in a mixed mode of stellarator and torsatron with, alternatively, positive or negative *shear*. In the computations for this mode, both helices of Wendelstein VII-A are energized by different currents, typically below $60\,kA$ at a magnetic field of $|B| \approx 2.5\,T$. Centred magnetic surfaces are obtained by a vertical field with a value proportional to the mismatch in the helix currents and a polarity opposing that of the current in the helix at $\Phi = 0$. The magnetic surfaces are found to have a magnetic well of about 1 % at $\iota \approx 1/2$.

Positive *shear* in the mixed mode in Wendelstein VII-A is introduced by increasing the current in the 'positive' helix at $\Phi = 0$ above the value used in the 'negative' helix. The polarity of the vertical field is negative. At $\Phi = 0$, the orientation of the long sides of the magnetic surfaces is horizontal. The toroidal field components of the excess current in the 'positive' helix are subtractive, more current in the TF-coils is needed in order to obtain a desired value of $|B|$, e.g. at the magnetic axis, as compared to the pure stellarator mode. The value of *shear* is reduced in the mixed mode, as compared to the torsatron mode at comparable ι at the axis.

The advantage of the mixed mode is threefold: a value of $|B_{axis}| = 2.5\,T$, which is desirable for operation of Wendelstein VII-A with electron cyclotron resonance, can be established without an excessively large current in the helix, and the amount of *shear* can be controlled easily. Furthermore, the magnitude of the vertical field is reduced in comparison to the torsatron mode, which reduces the torque acting on the TF-coils and eases possible problems with the stray vertical fields, e.g. regarding certain diagnostics and the vacuum pumps of Wendelstein VII-A.

Using the input data as entered in the caption of ***Fig.*** 7 the unperturbed and the perturbed vacuum fields are shown in the upper and lower halves, respectively, at the position $\Phi = 0$. For both cases, FFR929 and FFR942, the values of the rotational transform are $\iota(0) = 0.44$ at the magnetic axis and $\iota(L) < 1/2$ near the limiter. The latter value applies for field lines starting at a major radius $R = 211\,cm$. In the top half of the figure, this is the second field line from the outside. In the perturbed configuration it is the first field line shown inside of the two islands. The effective minor radius for both cases is $r_L \approx 8.7\,cm$. Between this field line and the magnetic axis, the *shear* $\delta\iota/\iota$ amounts to approximalely 10%. The separatrix is not shown in the figure.

As perturbation we take both helix steps charged with the two different currents and the current leads charged with the difference of them, i.e. $I_{pert} = 31.85\,kA$.

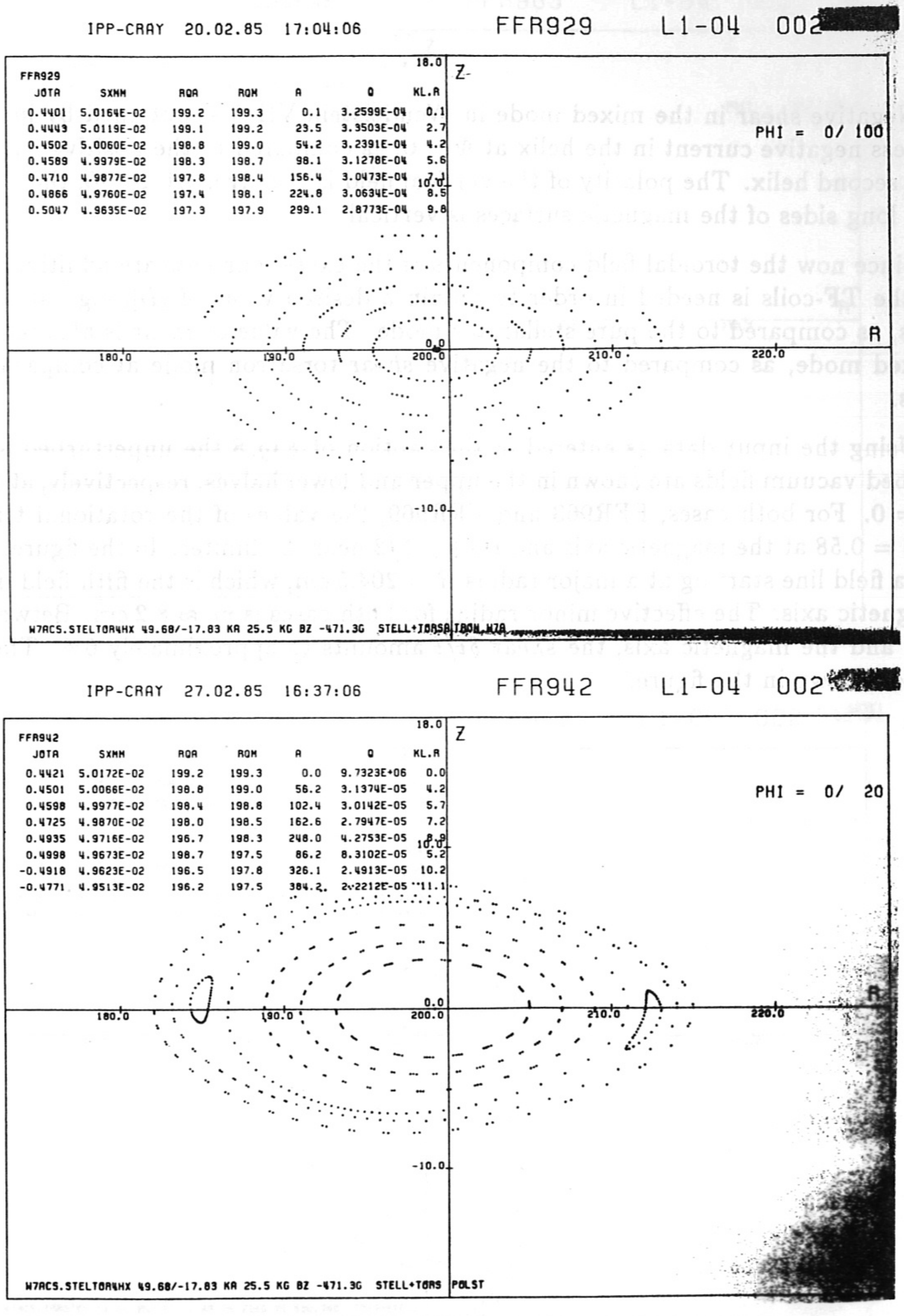
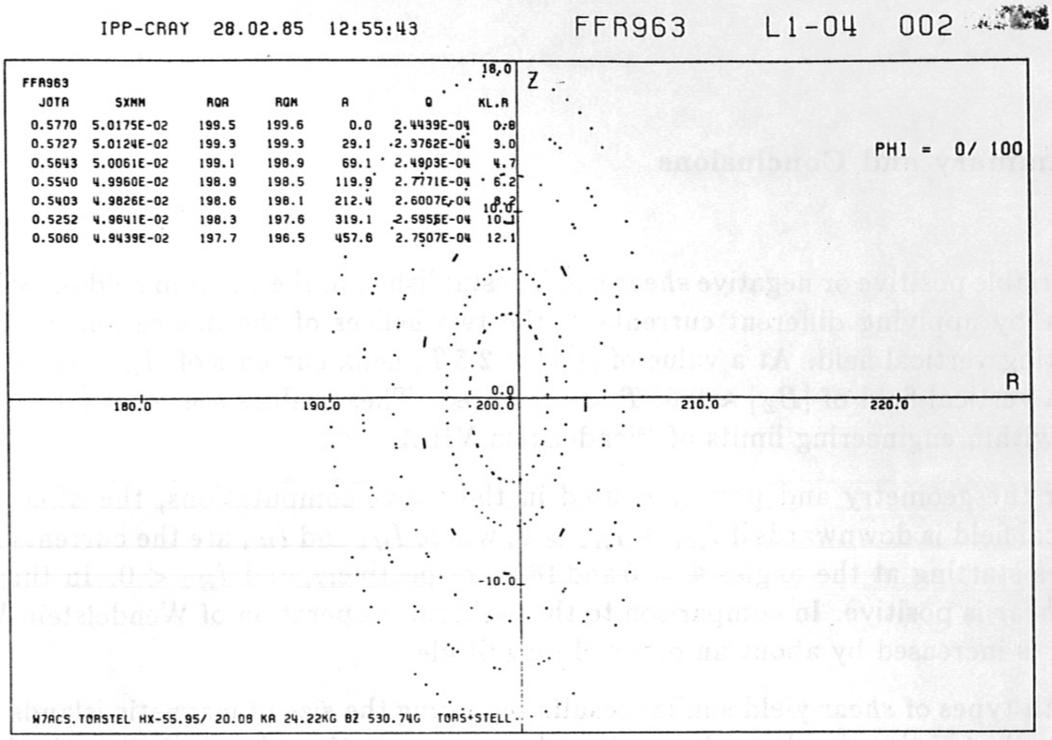


Fig.7*: Vacuum field of Wendelstein VII-A in mixed mode with positive *shear
irrational $\iota(0) \approx 0.44$ and $\iota(L) \approx 0.49$ at $r_L \approx 8.7\,cm$
input data approximately normalized to a value of $|B_{axis}| = 2.5\,T$
upper half: FFR929 unperturbed magnetic surfaces at $\Phi = 0$
lower half: FFR942 configuration perturbed by $I_{pert} \approx 32\,kA$
Normalized input data :
$R = 199.2\,cm$: $B_\Phi = 2.50\,T$
$TF - coils = 2.55\,T$; $B_Z = -0.0471\,T$
$I_{HX} = 49.68$; $-17.83\,kA$;

Negative *shear* in the mixed mode in Wendelstein VII-A is obtained by introducing an excess negative current in the helix at $\Phi = 0$, as compared to the positive current used in the second helix. The polarity of the vertical field is positive. At $\Phi = 0$, the orientation of the long sides of the magnetic surfaces is vertical.

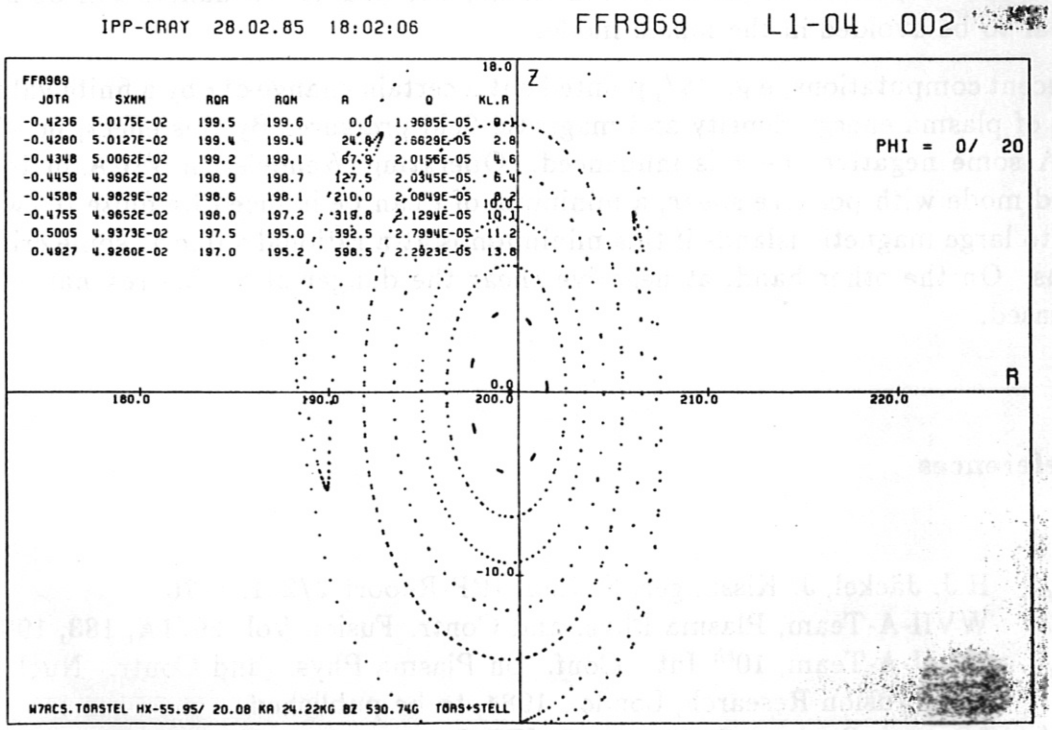
Since now the toroidal field components of the excess currents are additive, less current in the TF-coils is needed in order to obtain a desired value of $|B|$, e.g. at the magnetic axis, as compared to the pure stellarator mode. The value of *shear* is also reduced in this mixed mode, as compared to the negative *shear* torsatron mode at comparable ι at the axis.

Using the input data as entered in the caption of ***Fig.*** **8** the unperturbed and the perturbed vacuum fields are shown in the upper and lower halves, respectively, at the position $\Phi = 0$. For both cases, FFR963 and FFR969, the values of the rotational transform are $\iota(0) = 0.58$ at the magnetic axis and $\iota(L) > 1/2$ near the limiter. In the figure, this applies for a field line starting at a major radius $R = 204.5\,cm$, which is the fifth field line from the magnetic axis. The effective minor radius for both cases is $r_L \approx 8.2\,cm$. Between this field line and the magnetic axis, the *shear* $\delta\iota/\iota$ amounts to approximalely 6%. The separatrix is not shown in the figure.



FFR963

JOTA	SXMM	RQA	RQM	A	Q	KL.R
0.5770	5.0175E-02	199.5	199.6	0.0	2.4439E-04	0.8
0.5727	5.0124E-02	199.3	199.3	29.1	2.3762E-04	3.0
0.5643	5.0061E-02	199.1	198.9	69.1	2.4903E-04	4.7
0.5540	4.9960E-02	198.9	198.5	119.9	2.7771E-04	6.2
0.5403	4.9826E-02	198.6	198.1	212.4	2.6007E-04	8.2
0.5252	4.9641E-02	198.3	197.6	319.1	2.5955E-04	10.[illegible]
0.5060	4.9439E-02	197.7	196.5	457.6	2.7507E-04	12.1



FFR969

JOTA	SXMM	RQA	RQM	A	Q	KL.R
-0.4236	5.0175E-02	199.5	199.6	0.0	1.9685E-05	[illegible]
-0.4280	5.0127E-02	199.4	199.4	24.8	2.6629E-05	2.8
-0.4348	5.0062E-02	199.2	199.1	67.9	2.0156E-05	4.6
-0.4458	4.9962E-02	198.9	198.7	127.5	2.0345E-05	6.4
-0.4588	4.9829E-02	198.6	198.1	210.0	2.0849E-05	8.2
-0.4755	4.9652E-02	198.0	197.2	319.8	2.1294E-05	10.1
0.5005	4.9373E-02	197.5	195.0	392.5	2.7994E-05	11.2
0.4927	4.9260E-02	197.0	195.2	598.5	2.2923E-05	13.8

Fig*.8: Vacuum field of Wendelstein VII-A in mixed mode with negative *shear
irrational $\iota(0) \approx 0.58$ and $\iota(L) \approx 0.54$ at $r_L \approx 8.2\,cm$
input data normalized to a value of $|B_{axis}| = 2.5\,T$
upper half: FFR963 unperturbed magnetic surfaces at $\Phi = 0$
lower half: FFR969 configuration perturbed by $I_{pert} \approx 36\,kA$
Normalized input data :
$R = 199.5\,cm : B_\Phi = 2.50\,T$
$TF - coils = 2.422\,T\ ;\ B_Z = 0.0531\,T$
$I_{HX} = -55.95\ ;\ 20.08\,kA$

Summary and Conclusions

Variable positive or negative *shear* can be established in the vacuum fields of Wendelstein VII-A by applying different currents in the two helices of the device and balancing the resulting vertical field. At a value of $|B_\Phi| = 2.5\,T$, helix currents of $|I_{HX}| \approx$ 50 and 20 kA and a vertical field of $|B_Z| \approx 0.05\,T$ are required. These values are reasonable in order to stay within engineering limits of Wendelstein VII-A.

For the geometry and polarities used in the above computations, the direction of the vertical field is downwards if $I_{H1} + I_{H2} > 0$, where I_{H1} and I_{H2} are the currents in the two helices starting at the angles $\Phi = 0$ and 180^o, respectively, and $I_{H2} < 0$. In this situation the *shear* is positive. In comparison to the stellarator operation of Wendelstein VII-A, the *shear* is increased by about an order of magnitude.

Both types of *shear* yield similar results regarding the size of magnetic islands which are obtained at rational values of ι, in the above computations by modelling the helix steps and the current leads of the helix by appropriate spatial polygones. The size of the islands at $\iota = 1/2$ is smallest in the torsatron mode, but double resonances can be seen. They appear to be avoided in the mixed mode.

Recent computations, e.g. /5/, pointed out a certain change of ι by a finite value of β, the ratio of plasma energy density and magnetic field pressure. By this effect, in Wendelstein VII-A some negative *shear* is influenced. Operating Wendelstein VII-A in torsatron or mixed mode with positive *shear*, a minimum of ι can be induced by finite β , which could lead to large magnetic islands if this minimum is at a rational value at some critical minor radius. On the other hand, at negative *shear* the danger of double resonances might be increased.

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