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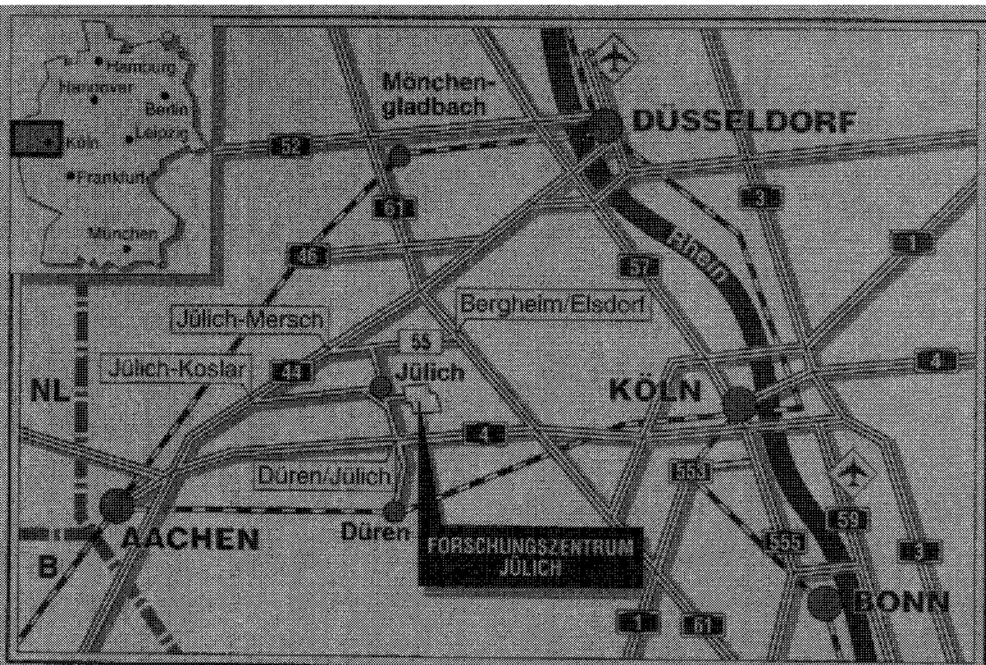

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Abstract

Determination of the vertical stray field in the plasma centre produced by poloidal field coils is essential for the control of breakdown and of the horizontal plasma position in tokamaks. Measurement by magnetic probes does not provide satisfactory results since the toroidal field perpendicular to the poloidal one is 30 ... 3000 times higher and thus induces error signals.
Electron beam technique has been chosen to solve this problem. Therefore an electron gun has been specially designed for TEXTOR and implemented for measurements.
Magnetic field lines „became visible“ using the effect of electron movement in magnetic fields and light emission in a gas. Vertical fields were determined from the measured toroidal field and vertical electron beam displacements.
In addition to the measured efficiencies of poloidal field coils, exact values for the field compensation during premagnetization have been defined.
Results have been verified by field calculations and compared with plasma breakdown experiments.

Contents

1 Why Field Measurements ?

One main operating principle of a tokamak like TEXTOR is the confinement of charged particles in plasma by means of a magnetic field. Electrons and ions in TEXTOR move along magnetic field lines with a toroidal component (up to 2.8 T) and a poloidal component (up to some 100 mT).

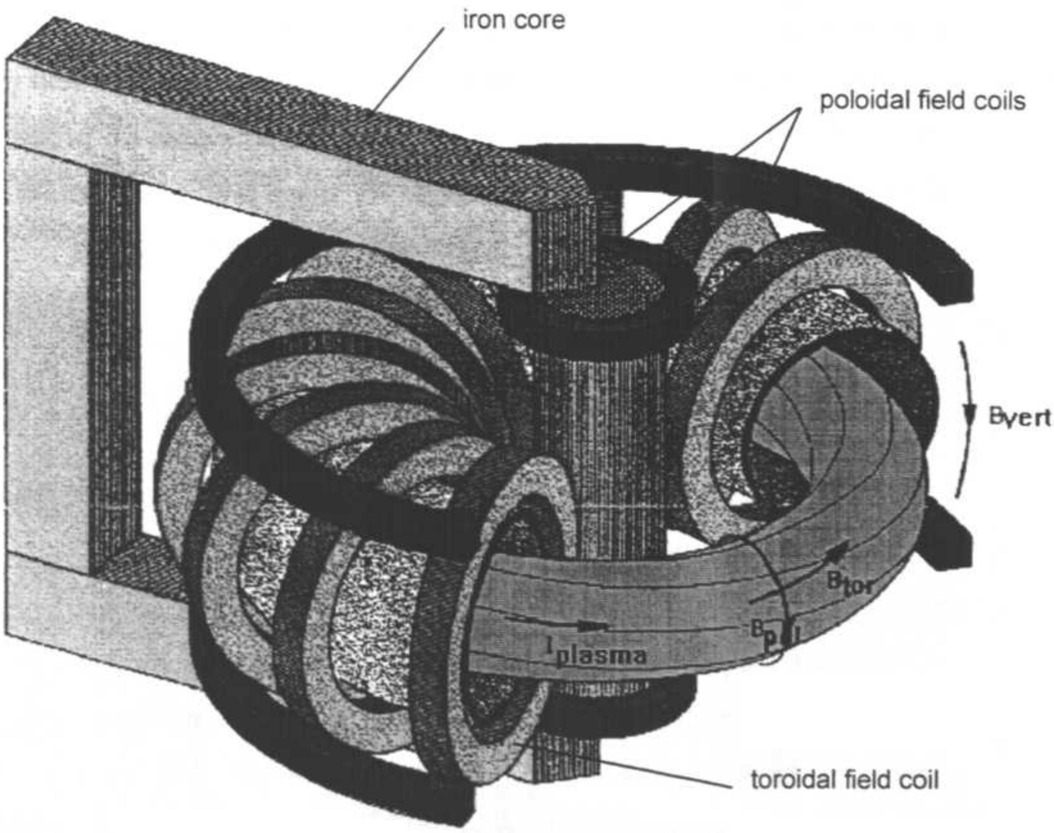


Fig. 1. Tokamak principle.

The latter is produced by a set of poloidal field coils for ohmic heating, shaping and position control of the plasma, all with currents variable in time, and by the plasma itself whereas the main magnetic field (toroidal) is generated by 16 specially arranged toroidal field coils carrying a constant current during the whole plasma discharge.

Regarding the poloidal field, there are two aspects of interest:

(1) For optimal control of plasma position and shape the poloidal field produced by each coil in the plasma volume during discharge (coil efficiency) has to be determined.

(2) For plasma breakdown the vertical field has to be as low as possible (by compensation) thus particles remain in the plasma volume as long as possible and giving better conditions for ionization.

During plasma operation the TEXTOR diagnostic system already provides some vertical field measurements with magnetic probes outside the vessel. Due to the large ratio between the toroidal and poloidal field (order of 30 ... 3000) and the influence of horizontal components on probe coils their precision is limited. For that reason for more precise measurements even in the plasma centre an electron beam method was chosen.

2 The Method of Field Measurement

2.1 Physics Background

Charged particles with an initial velocity are „captured“ by a magnetic field. The velocity component parallel to the field remains unaffected by the field whereas the component perpendicular to the field produces a rotation round the field line caused by the Lorenz force. The radius of the electron's rotation is less than 1 cm in case of our experiment.

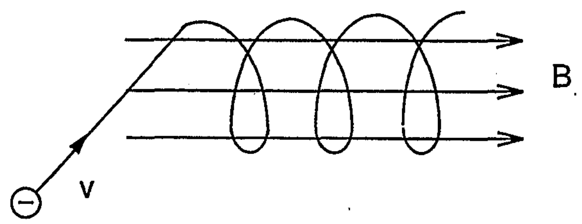


Fig. 2. Movement of electrons in a magnetic field.

Electrons are brought into the TEXTOR vacuum vessel and accelerated. By making the electron's way visible in an appropriate gas, which is excited for radiation by collisions with electrons, one can directly „observe" magnetic field lines as light beam. In this case the gas atmosphere has to be highly diluted.

2.2 Technical Description

The method described above was realised in TEXTOR by an electron gun /1/. A special introduction device which allows arbitrary vertical positioning without disturbing the vacuum was designed. It places an ordinary vacuum diode without a glass tube emitting electrons in the vacuum chamber filled either with argon or hydrogen at about 10^{-3} Torr.

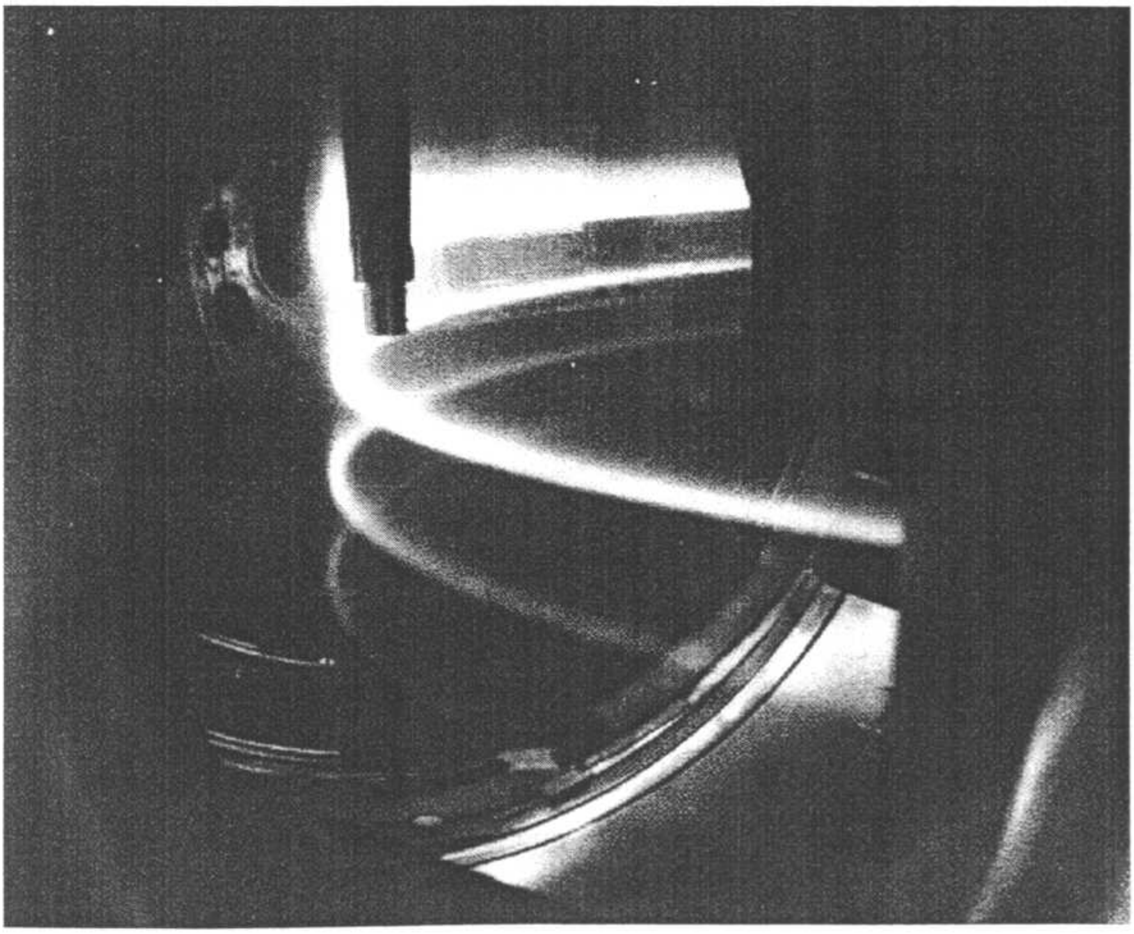
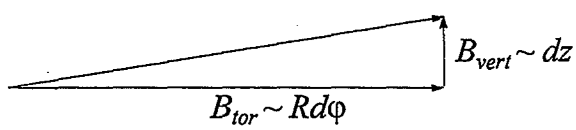


Fig. 3. View into vacuum vessel with electron beam.

The electrons were accelerated by an anode voltage. A constant toroidal field held the electrons in a circular orbit. Additional small vertical fields produced deflection forces which resulted in helical orbits. The value of the vertical field was determined by the vertical displacement per turn of the electron beam.

2.3 Determination of the Field from the Beam Displacement

The pass of the electron beam can be described by figure 4,



$$\frac{dz}{Rd\varphi} = \frac{B_{vert}(\varphi)}{B_{tor}(\varphi)}$$

Fig. 4. Field components.

where z and φ are the vertical and toroidal coordinates, B_{vert} and B_{tor} the vertical and toroidal field densities and R the radial position of the electron gun.

The vertical displacement after n revolutions is

$$\Delta z = \int_0^{n2\pi} \frac{Bvert(\varphi)}{Btor(\varphi)} Rd\varphi .$$

Assuming a constant toroidal field, we find

$$\Delta z \approx \frac{\overline{B_{vert}}}{B_{tor}} n2\pi R .$$

The accuracy of determining absolute vertical field values mainly depends on the measurement of displacement and is estimated to be about 10%. The more revolutions of the beam are visible the less the error is.

However, the method allows very exact measurements of the field compensation. After one revolution at a vertical displacement of *1 cm* and a major radius of *1.75 m* the vertical field is

$$\overline{B_{vert}} \approx \frac{\Delta z}{2\pi R_0} \overline{B_{tor}} \approx 10^{-3} \overline{B_{tor}} .$$

That means the vertical stray field may be compensated to *1 mT* at $\overline{B_{tor}}=1\ T$ and at lower toroidal fields even lower.

2.4 Experimental Parameters

The parameters of the experiments were adjusted according to /2/. The electron gun was placed at the centre of the vacuum vessel.

The emission current was about 5 mA.

Electrons were accelerated by an anode voltage of about 80 V.

During operation with hydrogen the pressure was 1.05 10^{-3} mbar. For toroidal fields above 20 mT argon had to be used because the beam was no longer visible in hydrogen. The pressure in argon was chosen at 2.7 10^{-3} mbar.

An usual CCD video camera with an image intensifier (sensitivity: 1 μLx) and an exposure of 20 ms was installed to observe the electron beam through a window of the TEXTOR vessel. The camera provided safety in observation of the beam and more reliability of displacement data. The beam displacement was determined directly from the monitor. However, digitally processing is also possible by applying image processing methods on the video pictures.

3 Results of Vertical Field Measurements

During electron beam experiments, all poloidal field coils of TEXTOR were fed separately, covering the typical range of operation. In addition a wide range of stray fields produced by currents in the inductor coils was compensated by either the plasma shaping coils or the position control coils to obtain current values for the stray field compensation during the premagnetization phase.

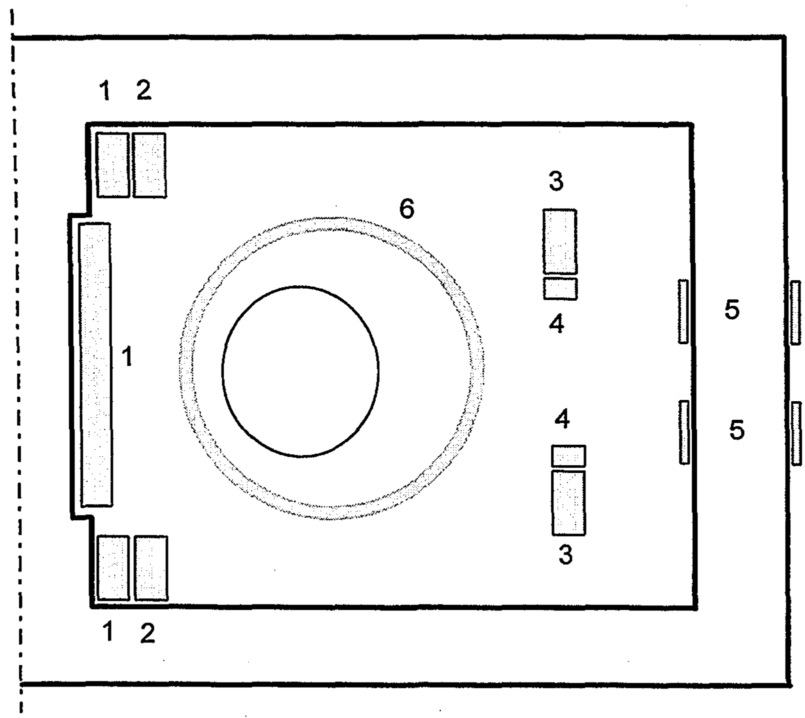


Fig. 5. Arrangement of the TEXTOR coils. Vertical cut through the yoke plane.
1 Inductor coils (BM),
2 Shaping coils (BF),
3 Position control coils (BV),
4 Position control coils (KV) in series with 5,
6 Toroidal field coils.

3.1 Efficiency of BM Coils - Inductor Coils

Shot No.	I_{BM} [kA]	I_{tor} [kA]	B_{tor} [mT]	Δz [m]	B_{vert} at R_0 [mT]	Efficiency [mT/kA]
BM3	0.250	0.20	7.4	0.35	0.236	0.942
BM2	0.330	0.40	14.8	0.35	0.471	1.428
57400	0.392	0.70	25.9	0.29	0.671	1.713
57401	0.392	0.70	25.9	0.25	0.589	1.502
BM1	0.420	0.60	22.2	0.35	0.707	1.683
57398	0.624	0.70	25.9	0.46	1.084	1.736
57399	0.624	0.70	25.9	0.46	1.084	1.736
57533	1.900	11.50	428	0.16	6.033	3.176
57521	3.380	11.50	428	0.22	8.564	2.534
57534	4.360	11.50	428	0.23	8.953	2.053
57509	5.800	16.40	609	0.16	8.862	1.528
57510	7.760	16.40	609	0.15	8.308	1.071
57520	10.70	16.40	609	0.17	9.416	0.880
57511	14.58	16.40	609	0.15	8.308	0.570

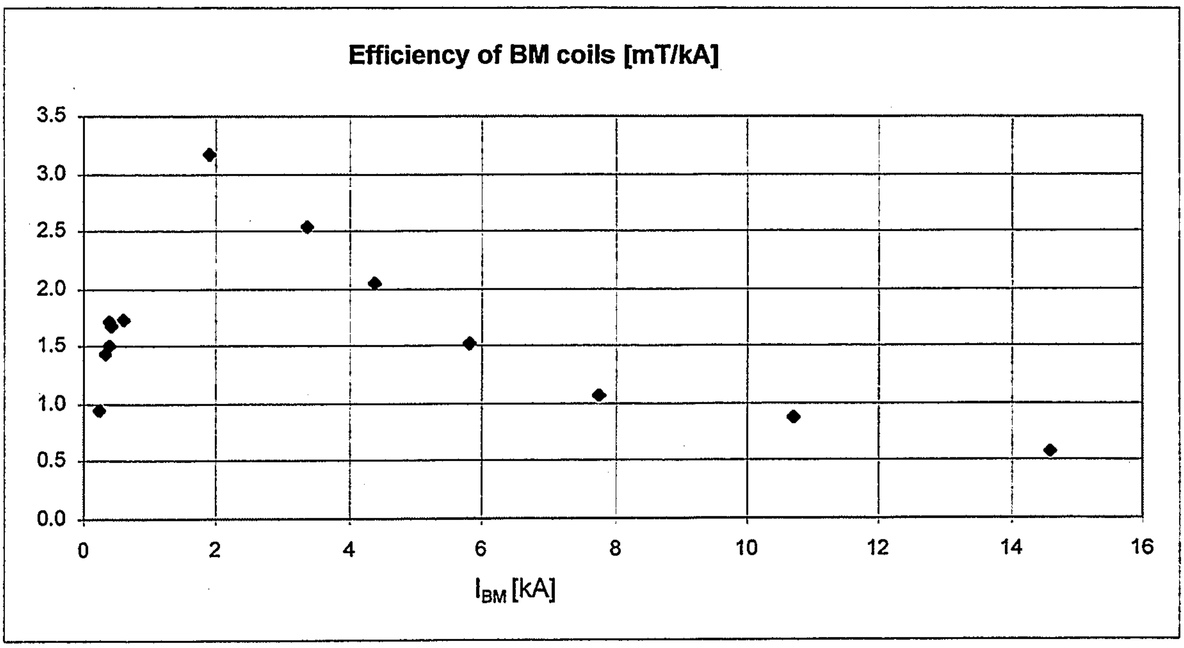


Fig. 6.

Being close to the iron core, the inductor coils show saturation of their efficiency.

3.2 Efficiency of BV Coils - Position Control Coils

Shot No.	I_{BV} [kA]	I_{tor} [kA]	B_{tor} [mT]	Δz [m]	B_{vert} at R_0 [mT]	Efficiency [mT/kA]
57406	0.029	0.7	25.9	0.20	0.471	16.25
57408	0.066	0.7	25.9	0.44	1.036	15.70
57407	0.067	0.7	25.9	0.44	1.036	15.47
57537	0.386	11.5	426	0.15	5.805	15.04
57536	0.900	16.4	607	0.25	13.631	15.15
57514	1.380	16.4	607	0.37	20.419	14.80
57525	1.900	35.7	1,321	0.26	31.235	16.44
57526	1.900	45.1	1,669	0.22	33.388	17.57
57538	2.870	45.1	1,669	0.31	47.047	16.39

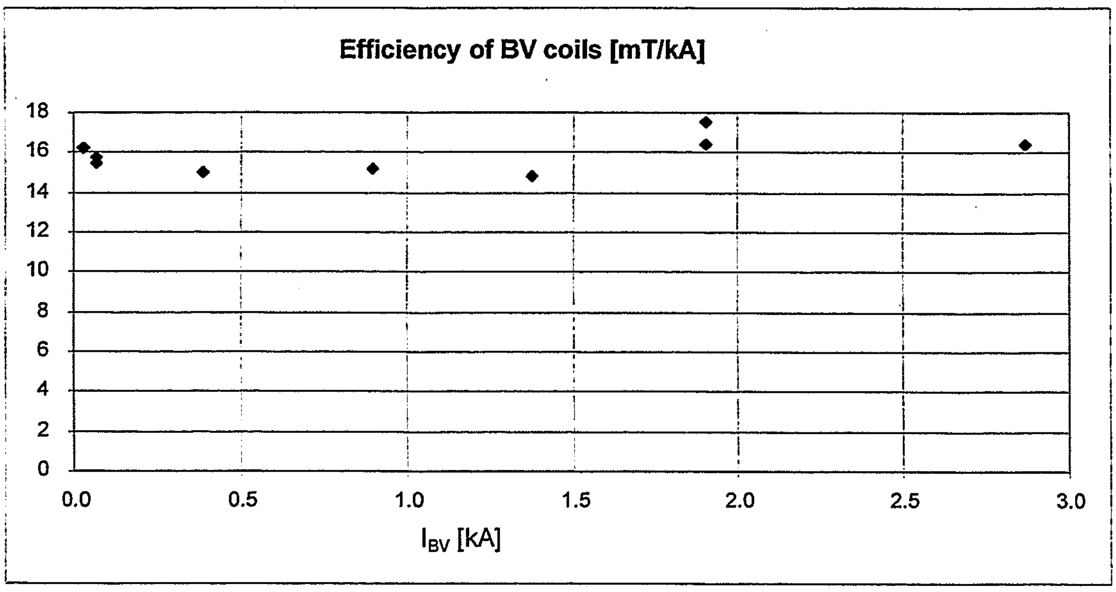


Fig. 7.

Position control coils have a considerable distance to the iron core thus like an air coil showing almost constant efficiency.

3.3 Efficiency of BF Coils - Shaping Coils

Shot No.	I_{BF} [kA]	I_{tor} [kA]	B_{tor} [mT]	Δz [m]	B_{vert} at R_0 [mT]	Efficiency [mT/kA]
BF3	0.14	0.2	7.4	0.350	0.236	1.68
BF2	0.23	0.4	14.8	0.350	0.471	2.05
BF1	0.32	0.6	22.2	0.350	0.707	2.21
57527	1.97	11.5	425.5	0.170	6.579	3.34
57518	4.76	16.4	606.8	0.230	12.693	2.67
57517	9.70	16.4	606.8	0.345	19.040	1.96
57515	14.60	16.4	606.8	0.440	24.282	1.66

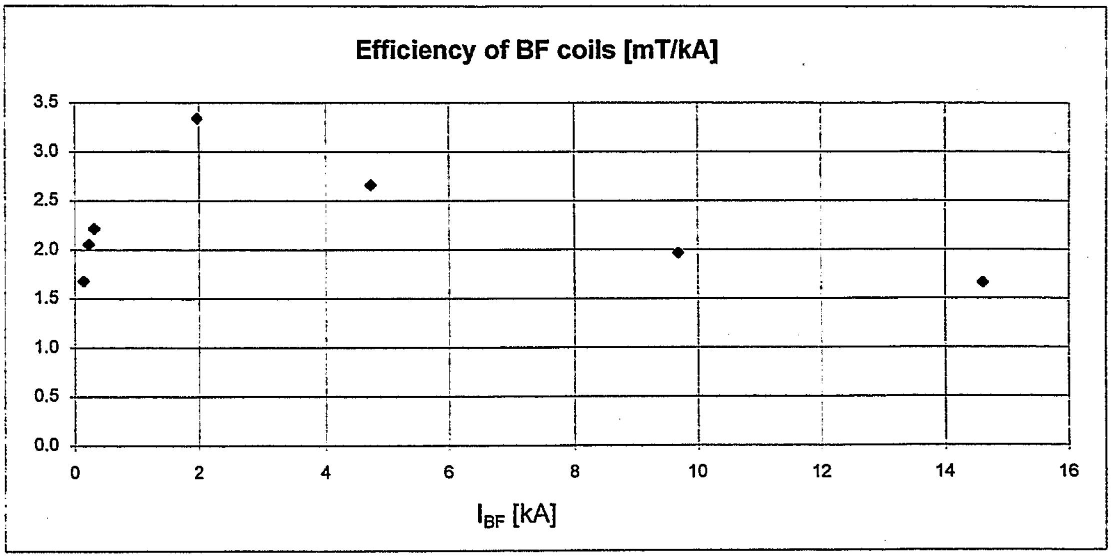


Fig. 8.

Shaping coils close to inductor coils have similar characteristics (apart from the total value depending on the number of turns).

3.4 Efficiency of KV Coils - Position Control Coils

Shot No.	I_{KV} [kA]	I_{tor} [kA]	B_{tor} [mT]	Δz [m]	B_{vert} at R_0 [mT]	Efficiency [mT/kA]
57413	0.313	0.70	25.9	0.180	0.424	1.355
57414	0.609	0.70	25.9	0.300	0.707	1.160
57415	0.917	0.70	25.9	0.400	0.942	1.028
57416	1.150	0.70	25.9	0.440	1.036	0.901
57531	1.190	6.77	250.5	0.050	1.139	0.957
57544	2.160	3.78	139.9	0.132	1.679	0.777
57543	2.930	6.77	250.5	0.111	2.529	0.863
57532	2.980	6.77	250.5	0.126	2.870	0.963

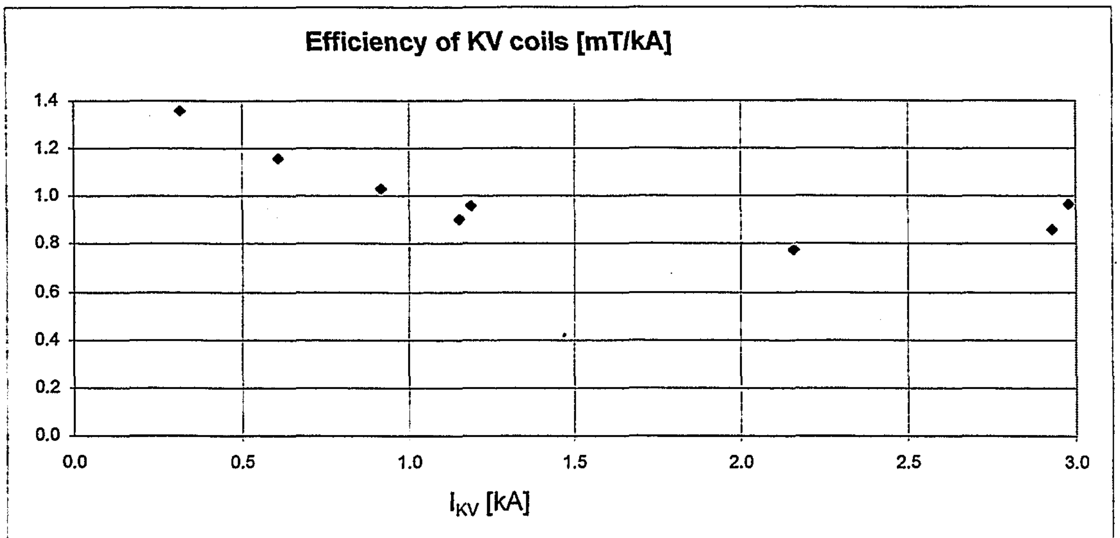


Fig. 9

The KV position control coils act differently to the BV coils since their effect on the iron core and additionally a fraction of the stray field is compensated by the yoke coils (see fig. 5, position 5) connected in series with KV coils.

3.5 Compensation of BM Field

B_{tor} = 26 mT, Δz < 3 cm, B_{vert} < 0.1 mT

Shot No.	I_{BM} [kA]	I_{BV} [kA]
57433	1.07	0.140
57434	1.07	0.150
57438	4.95	0.450
57449	9.90	0.490
57455	14.67	0.494
57459	19.45	0.415
57462	23.97	0.333

Shot No.	I_{BM} [kA]	I_{BF} [kA]
57468	14.70	5.20
57469	14.70	5.38
57471	13.68	5.40
57473	9.80	5.31
57475	4.94	4.01
57479	19.06	5.13
57480	23.96	3.87

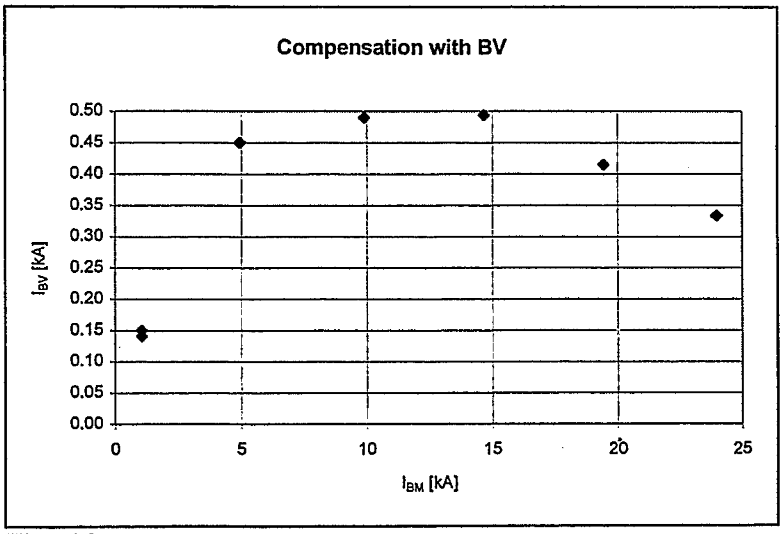


Fig. 10

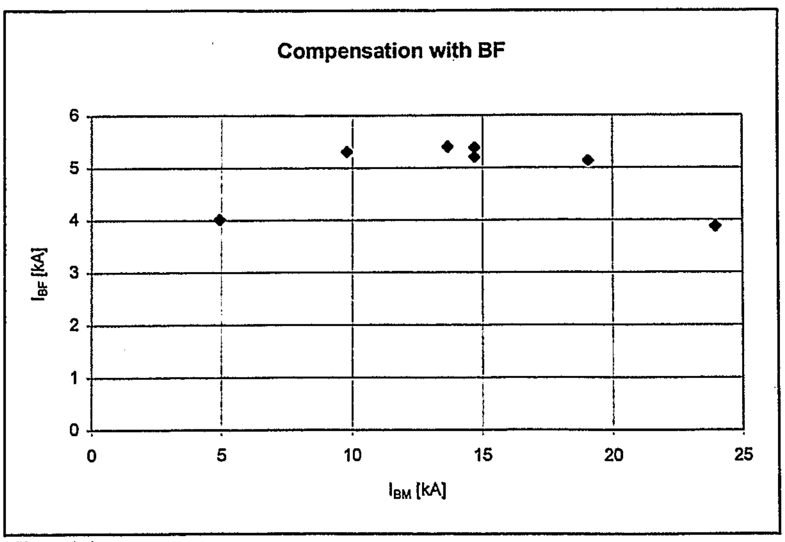


Fig. 11.

The efficiencies of poloidal field coils strongly depend on the saturation of the iron core. Thus the results of stray field compensation are not a simple superposition of single efficiencies

4 Evaluation of Results

4.1 Comparison with Calculated Efficiencies

Due to the principle to measure magnetic fields by the electron beam method, the results are an excellent verification of calculations. Calculations are necessary because electron beam measurements do not work during tokamak operation. Calculations provide information about spatial distribution of stray fields as well.

In the TEXTOR case several 2 dimensional and 3 dimensional models were developed to calculate magnetic fields /3/, /4/.

In /3/ a 3 dimensional model is described. Taking into account the symmetry of TEXTOR, only half of the height and 30 ° of the circumference had to be modelled. Among others this model is used to calculate the stray field in the plasma region. As small changes or inaccuracies in the model have considerable influence even on the calculated field outside the iron core, designing an adequate model requires experience and verification by experiments.

In order to check the results of the model described above the results of the electron beam measurements provided an appropriate basis. A comparison between measurements and calculations proved the suitability of the 3 dimensional model.

4.2 Results of Stray Field Compensation during Premagnetization

During plasma operation with premagnetization of the iron core leading to disturbing stray fields, the results of electron beam measurements were helpful to find improved conditions for plasma breakdown. The values given in figure 10 and figure 11 provide the necessary compensation currents either in position control coil or in shaping coil for the whole range of premagnetization currents in the inductor coil.

The accuracy of the electron beam measurements was confirmed by comparison of the results with one set of operating conditions found in experiments at I_{BM} = 14 kA and I_{BF} = 5.4 kA. In addition, the results of magnetic probes for stray field measurements confirmed the field compensation under the conditions described above

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