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Tests of Pressure Gauges in High-Magnetic Fields at Forschungszentrum Karlsruhe (FZK), Institute for Technical Physics (ITP) and Department for Highest-Magnetic Fields

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Preamble

This report describes investigations on ASDEX Pressure Gauges (APG) which have been done 1996 in a super conducting magnet at FZ Karlsruhe (FZK, now KIT). 1995 several APG's installed at JET had failed due to deformation of the filaments. The deformation was strange and unexpected. The central parts of the filaments moved parallel to the gauge axis, i.e. roughly parallel to the magnetic field, towards the next electrode (control electrode). The direction was independent of the sign of magnetic field and heating current. But it was generally accepted, that only the Lorentz force (heating current vs toroidal field of JET) could be the reason.

Until that time no such deformation was observed at the APG's in other fusion devices and in the Neutralgaslabor at IPP, Garching. The suspicion was, that the longer pulses of JET, which lead in sum to a longer operation time of the gauges under the load of the Lorentz force, could be crucial. To test this assumption FZK allowed the company PTS, Freiburg, at that time the licensee for the APG, to perform tests using their superconducting magnet JUMBO. The deformation could be reproduced and the mechanism cleared. As consequence of the non-planar geometry of the filaments exclusively used at that time any vertical force may result in distortions of the filament wire such that the central part moves parallel to the magnetic field independent of the direction of the Lorentz force.

Günter Haas June 2019

REPORT

Tests of Pressure Gauges in High-Magnetic Fields

at

Forschungszentrum Karlsruhe (FZK)
Institute for Technical Physics (ITP)
Department for Highest-Magnetic Fields

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ABSTRACT

In 1995 filaments of ASDEX gauges installed in the JET divertor became deformed obviously by JxB forces. This problem not yet seen to such an extend on gauges of similar type on other tokamaks calls for an intensive investigation. At the superconducting magnet JUMBO of FZ Karlsruhe ideal conditions for studying the behaviour of these gauges in DC magnetic fields up to 9 Tesla especially the effects of JxB forces onto filaments were found. In the course of the deformation tests performed on 0.4 and 0.6 mm filaments problems appeared to reach high emission currents in high magnetic fields.

I. INTRODUCTION

For total pressure measurements in high magnetic fields of magnetic fusion machines like tokamaks and stellarators, a special type of ionisation gauge, the so called ASDEX gauge[1], is commonly used[2].
The gauge was developed by G.Haas at IPP-Garching and is covered by an exclusive licence given to PTS.
It is foreseen to use a large number of these gauges in ITER as a reliable and fast neutral gas diagnostic mandatory for high performance machines.

During a shutdown of JET in summer 1995 pressure gauges were exchanged after several of them had failed. An investigation showed, that the filaments of some of the failed pressure gauges were deformed, most likely by JxB forces[3].
Subsequently, intensive studies were performed at PTS[4] in order to simulate the Lorentz force by weights fixed with thin tungsten wires on the filament. They resulted in similar bending patterns for loads corresponding to combinations of magnetic field strength and filament current which may have occurred at JET.
Such bending could be deleterious for the planned use of the gauges in ITER due to
* the much longer pulse duration (1000 sec instead of < 100 sec on JET)
* the higher field strength (9 Tesla instead of < 4 Tesla on JET)
* and the need to start the gauges within the strong magnetic field.
This underlines the urgent need of a search for means to avoid these deformations.

It became also evident, that such effects could hardly be seen in the high magnetic field/vacuum facility at IPP-Garching due to the short pulse duration (1 to 3 seconds) possible in the old Cu coil.
Nevertheless, one reference to possible bending behaviour could already be verified in Garching during tests[5] of a JET gauge proto type with the highest possible value of field x pulse duration and switched off emission current feedback before first installation in early ‘93.

In the Forschungszentrum Karlsruhe (Institute for Technical Physics, Department for Highest Magnetic Fields) good conditions exist for testing the pressure gauges in high, DC magnetic fields, i.e. up to 9 Tesla for hours, which are necessary to identify operation conditions especially for ITER at which filament deformations are likely.

II. AIM OF THE STUDY

Intensive tests were carried out during the period 19-23 August 1996 in the magnetic field of the superconducting JUMBO facility at ITP-Karlsruhe.
The original aims of the tests were:

* investigation of the deformation of filaments in magnetic fields up to 9T.
* comparison of the deformation of standard W/Th-filaments (0.6mm$^{\varnothing}$)and of new etched W/Th filaments (0.4mm$^{\varnothing}$).
* comparison with results of Lorentz simulations at PTS.
* attainable range of emission current $\mathbf{I_e}$ in high magnetic field **B** for both filament types.
* dependence of ion current $\mathbf{I_i}$ on **B**, $\mathbf{I_e}$ and the pressure **p**.

In addition there are other interesting points to be investigated like

* new filament material W/Lanthanum
* comparison of different etched filaments in order to find the optimum geometry
* AC filament heating

However, these points had to be postponed to future measuring campaigns due to lake of time during the one week.

III. TEST SET-UP

A. JUMBO magnet test facility

The superconducting JUMBO Magnet produces magnetic fields up to 10 T. The centre of the magnetic field is 1507 mm below the access flange as shown in Figure1. The region of the field maximum is accessed by an anticryostat with a warm bore of 72.9 mm. The magnetic field is homogeneous within 5% over an axial length of 100 mm.

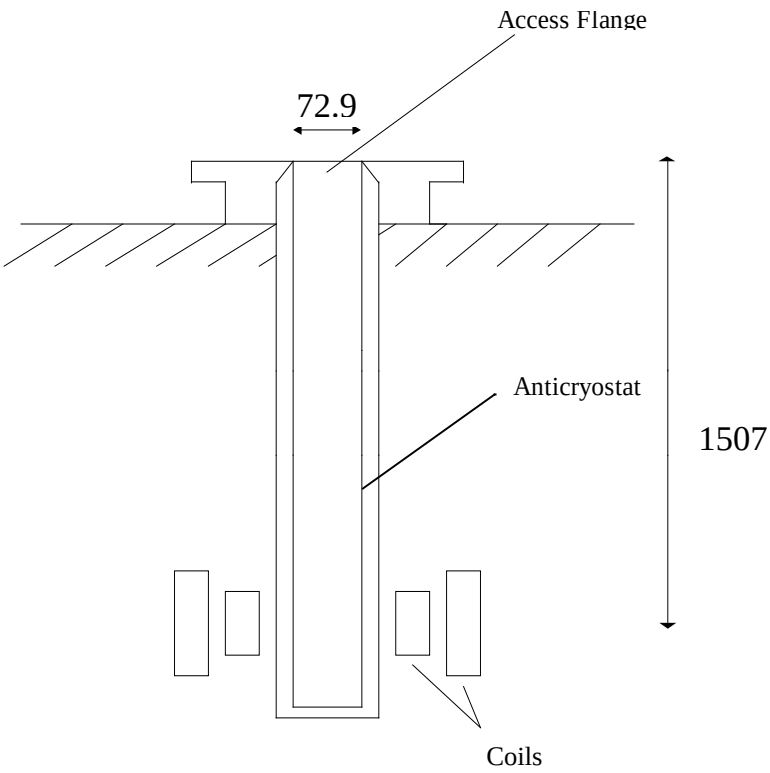

Figure 1. Schematic Assembly of JUMBO Magnet

B. Vacuum housing and support for pressure gauge

A 5 way cross (NW 100) is mounted on top of the access flange. The cross is equipped with:
* turbomolecular pump (connected by a metal bellow to a roughing pump)
* electrical feedthroughs for gauge operation and thermo couples
* throttle valve for N_2 inlet
* HP pressure gauge (Balzers)
* window for filament observation

The pressure gauge is mounted on an AISI-tube (diameter 10, length: 1.5m) fixed onto the 5-way-cross. The orientation of the pressure gauge can be widely changed with respect to the tube. A centralizing disc (∅=72.0 mm) keeps the tube and the pressure gauge in place and avoids movements due to the Lorentz force during operation and damage during inserting or removing the system.

The cables for the gauge head (PTFE-insulated) and two NiCrNi-thermocouples are routed in the AISI tube. Temperatures were measured at the base plate of the pressure gauge (cable side) and in the AISI-tube in order to monitor the cable temperature. A second short AISI tube surrounds the

first one in the region of the gauge head as an additional radiation shield to reduce the heat load to the cables from the radiation of the filament.
As the experiments showed, a reflector on the outer side of the equipment is recommended to protect the super isolation of the anticryostat.

The pressure gauge was operated by a complete laptop controlled PTS-electronic unit. The filament was observed through a mirror inside the 5 way cross with a video camera and a monitor on which the deformation could be measured.

To investigate the influence of the gas pressure on emission and ion collector current N_2 was used. The experimental program called for frequent venting of the vacuum system. Due to the restricted overall duration of the campaign only short periods for pump down were available. The geometry of the whole arrangement allowed, however, only a small pumping speed at the position of the gauge resulting in generally poor vacuum conditions. All results reported here where pressure and composition of the gas at the gauge head may play a role have to be considered as preliminary and need further investigation with better control of vacuum conditions.

C. Definitions and explanations:

p_{HP}: pressure measured with High Pressure Gauge (Balzers)
p_{N2}: N_2 partial pressure
υ_{gauge}: pressure gauge temperature, measured at the base plate (opposite side of filament)
υ_{tube}: cable temperature, measured in the AISI-tube
I_F: filament current
I_e: electron emission current
I_i: ion current

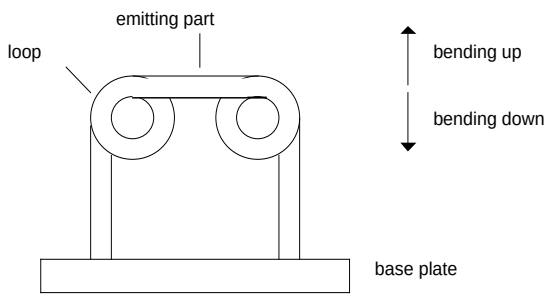

Figure 2. Schematic sketch of the hot cathode (filament)

IV. TESTS

A. Tests in chronological order

Following is a short chronological description of the tests performed in order to give an idea of the test execution.

Legends:

(1): Emission without magnetic field.

(2): Emission in magnetic field.

(3): Lorentz force upwards
B = const.
I_F = const.
t = maximum 30min or until bending

(4): Lorentz force upwards
B = const.
I_F = increased in steps
t = 5min.

(5): Lorentz force downwards
B = const.
I_F = const.
t = maximum 30min or until bending

(6): Restoring original shape

(7): Dependence of ion current

Monday 19.08.96

Filament W/Th 0,6mm in gauge with metal base plate.

(1): Emission without magnetic field.
Result: --I_F = 18A at start
13A after conditioning

Tuesday 20.08.

First task was to define the correct setup of the I_F connection for a given direction of the Lorentz force.

(4): L-force upwards
B = 6T
I_F = 14A 22A
t = 5min at fixed I_F
Result: --at 20A first indication of bending by anomalous behaviour of I_e
--at 22A distinct bending

W/Th 0,6mm in ceramic base plate without electrodes.
Aim: Verification of Lorentz simulation

Wednesday 21.08.

(5): L-force downwards B = 3,5T
I_F = 17,9A
t = 33min
Result: --after 30min bent by about 45°
--after 33min short circuit in one filament loop

(6): Restoring original shape
B = 3,5T
I_F = 17,9A
t = 11min
Result: --after 8min filament bent back to the original height.

W/Th 0,4mm in gauge with ceramic base plate

(1): Emission without magnetic field
Result: --$I_F \approx 12A$, no conditioning effect.

(2): Emission in magnetic field. B = 6T
Result: --emission current limit $I_e \approx 300\mu A$.
--emitting part bent at $I_F \approx 16A$ after about 1min.
--bending does not influence emission current, emitting part still in aperture area of control grid.
--no bending at loops.

(6): Restoring original shape. B = 9T.
Result: --by changing current polarity and I_F = 15,7A, filament bent in original shape.
(3):: L-force upwards B = 9T
Ie = 200µA
I_F = 11A
t = 30min
Result: --no bending.

(5):L-force downwards B = 9T
Ie = 200µA
I_F = 11A
t = 30min
Result: --no bending.

(1): Emission without magnetic field
Result: -- $I_F \approx 9A$.

Thursday 22.08.

(1): Emission without magnetic field
Result: -- $I_F \approx 9A$

(2): Emission in magnetic field. B = 3,5T
Result: -- max. Ie = 340µA

(4): L-force upwards. B = 9T
I_F = 9A....15,7A
t = 5min at fixed I_F
Result: --clear bending upwards (≈1mm)
--max. Ie = 150µA

W/Th 0,6mm in ceramic base plate without electrodes.
Aim: Gauge operation at 9T in comparison with 0,4mm filament.

(5): L-force downwards. B = 9T
I_F = 14,71A
t = 30min.
Result: --no bending.

(5): L-force downwards. B = 9T
I_F = 16,1A
t = 30min.
Result: --first deformation after about 15min.
--clear deformation after about 20min.
--short circuit in one winding after 24min.

W/Th 0,4mm in ceramic base plate without electrodes.

(5): L-force downwards. B = 3,5T
I_F = 14,06A
t = 30min.
Result: --no bending.

(5): L-force downwards. B = 3,5T
I_F = 16,14A
t = 30min
Result: --first deformation after 4min.
--clear deformation after 12min.

(6): Restoring original shape B = 3,5T
I_F = 16,11A
t = 30min
Result: --original shape after about 9min.

(4): L-force upwards. B = 6T
I_F = 12A.....16,7A
t = 5min at fixed I_F
Result: --clear bending at 16,7A within 5min.

W/Th 0,4mm in gauge with ceramic base plate
Aim: Ion current I_I in dependence of pressure (N_2) and B-field.

(1): Emission without magnetic field.
Result: --I_F = 11,5A.

Friday 23.08.

(1): Emission without magnetic field.
Result: --I_F = 11,5A.

(2): Emission in magnetic field. B = 3,5T, 2,5T, 2T, 1T, 0,5T, 0T
Result: --measurement of maximum I_e in dependence from B-field.
-- $I_F \approx 12A$

(7): Dependence of ion current. B = 3,5T, 5T, 2T, 6T, 0T
p = 5E-4, 1E-3, 5E-3
Result: --no proportionality of I_e and I_I at high B and high p.

B. Test Overview

As clearly indicated in the legend above, there were 7 different tests executed and labelled herein with reference numbers.
For the sake of clarity, the following table lists the tests in a more analytical order.

Table 1.

Ref.-No.	***Test description***	***W/Th ∅0,6mm typical values***	***W/Th ∅0,4mm typical values***
(1)	Emission without magnetic field	$I_F \approx$ 18A non conditioned $I_F \approx$ 13A conditioned	$I_F \approx$ 12A non conditioned $I_F \approx$ 9A conditioned
(2)	Emission in magnetic field B = I_e = I_F =	 6T 500µA 14,4A (no systematic measurement)	 6T 300µA (max. obtained emission current) 11A
	B = I_e = I_F =		3,5T 340µA (max. obtained emission current) 10A
	B = I_e =		0- 0,5- 1- 2- 2,5- 3,5T systematic investigation
(3)	Lorentz force upwards (directed opposite to base plate) B = I_e = I_F = t = t_{max} = 30min or until bending is observed.		 9T 200µA 11A 30min, no bending
(4)	Lorentz force upwards (directed opposite to base plate) B = I_F = [min., max.] = t = t_{max} = 5min or until bending is observed	 6T 14,4- 16,7- 17,7- 18,8- 19,8- 21- 23A 5min bending starts probably at 19,8A	 6T 12- 14,7- 15,7- 16,7A 5min bending starts probably at 16,7A
	B = I_F = [min., max.] = t = t_{max} = 5min or until bending is observed		9T 9,1- 12,6- 13,6- 14,7- 15,7A 5min bending starts at 14,7A

(5)	Lorentz force downwards (directed to base plate) B = I_e = I_F = t = t_{max} = 30min or until bending is observed	 3,5T -- 17,9A 30min, bending about 45° 33min, short circuit in winding	 3,5T -- 14,1A 30min , no bending
	B = I_e = I_F = t = t_{max} = 30min or until bending is observed		3,5T -- 16,1A 4min, bending starts 12min, substantial bending
	B = I_e = I_F = t = t_{max} = 30min or until bending is observed	9T -- 14,7A 30 min, no bending	9T 200µA 11A 30min, no bending
	B = I_e = I_F = t = t_{max} = 30min or until bending is observed	9T -- 16,1A 15min, bending starts 20min, substantial bending 24min, short circuit in winding	
(6)	Restoring original shape B = I_F = t =	 3,5T 17,9A 8min	 3,5T 16,1A 9min
	B = I_F = t =		9T 15,7A not measured
(7)	Dependence of Ion current B = p_{N2} =		 0- 2- 3,5- 5- 6T 5E-4, 1E-3, 5E-3 torr

C. Measurements and Results

The chopping frequency of the controller was set to 3kHz throughout the test campaign.

(1): Emission without magnetic field.
Filament W/Th 0,6mm in gauge with metal base plate.

First stable emission: $\mathbf{I_e}$ = 100µA with $\mathbf{I_F}$ = 17,9A
υ_{gauge} = 270°C
υ_{tube} = 50°C
p_{HP} = 3,8E-5Torr

Emission characteristic: υ_{gauge} = 280°C
υ_{tube} = 80°C
p_{HP} = 3,5E-5Torr
$\mathbf{I_{Fmax}}$ = 20A

Table 2.

I_e [µA] =	100	200	300	400	500	600	700	800	900	1000
I_F [A] =	17,61	17,96	18,16	18,3	18,42	18,52	18,6	18,5		

↑
At this point starts a dramatic decrease of the filament current.

1. Repetition of Emission characteristic: υ_{gauge} = 285°C
υ_{tube} = 104°C
p_{HP} = 3,3E-5Torr
$\mathbf{I_{Fmax}}$ = 20A

Table 3.

I_e [µA] =	100	200	300	400	500	600	700	800	900	1000
I_F [A] =	12,79	13,10	13,31	13,46	13,59	13,69	13,77	13,84	13,92	14,00

2. Repetition of Emission characteristic: υ_{gauge} = 193°C
υ_{tube} = 98°C
p_{HP} = 2,7E-5Torr
$\mathbf{I_{Fmax}}$ = 20A

Table 4.

I_e [µA] =	100	200	300	400	500	600	700	800	900	1000
I_F [A] =	12,85	13,04	13,30	13,39	13,48	13,60	13,69	13,75	13,80	13,81

Stability test: I_e = 500µA
$I_{F\,max}$ = 20A

Table 5.

t [min]	υ_{gauge} [°C]	υ_{tube} [°C]	I_F [A]	p [*E-5Torr]
0	117	89	0	1,9
1	117	89	13,42	1,9
2	136	91	13,49	2,1
3	154	92	13,48	2,1
4	171	94	13,46	2,1
5	185	95	13,45	2,1
6	198	97	13,43	2,15
7	208	98	13,42	2,2
8	217	100	13,41	2,2
9	223	102	13,39	2,25
10	229	103	13,38	2,3
12	239	106	13,35	2,35
14	246	108	13,32	2,45
16	251	111	13,3	2,5
18	255	113	13,3	2,55
20				
22	261	117	13,3	2,7
24	263	119	13,32	2,75
26				
29	267	124	13,37	2,8
30	268	125	13,41	2,8

Emission at higher pressure:

p_{N2} = 2E-4Torr
υ_{gauge} = 126°C
υ_{tube} = 108°C
$I_{F\,max}$ = 20A
I_e = 500µA at I_F = 14,12A degreasing to 13,35A by closing N_2-valve.

Conclusion:

The above data confirm very well the typical emission characteristic of the filament with 0,6mm diameter[5].
It was interesting to see the sudden conditioning as shown in Table 2 and 3 where the filament current dropped from 18,5A to about 13A at constant emission current within minutes. It was never observed at this comparable high pressure but only at much lower pressures.

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1. Filament W/Th 0,4mm in gauge with ceramic base plate

Emission characteristic: υ_{gauge} = 285°C.....310°C
υ_{tube} = 146°C.....155°C
p_{HP} = 1,9....1,1E-5Torr
$\mathbf{I_{Fmax}}$ = 12,8A

Table 6.

	I_e [µA] =	200	400	600	800	1000
1. Emission	I_F [A] =	11,80	12,07	12,20	12,29	12,37
2. Emission	I_F [A] =	11,77	12,01	12,15	12,25	
3. Emission	I_F [A] =	11,30	11,40	11,80	11,95	12,10
4. Emission	I_F [A] =	11,60	11,80	11,91	12,01	12,10
5. Emission	I_F [A] =	11,53	11,80	12,02	12,15	12,25
6. Emission	I_F [A] =	11,55	11,84	11,02	12,15	12,25

Here between is a longer time with measurements with B-field.

7. Emission	I_F [A] =	8,94	9,2	9,36	9,5	9,61
8. Emission	I_F [A] =	8,97				

Emission with better vacuum and cold gauge
υ_{gauge} = 67°C
υ_{tube} = 68°C
p_{HP} = 3,7E-6Torr
$\mathbf{I_{Fmax}}$ = 12,8A

9. Emission	I_F [A] =	8,98	9,24	9,40	9,54	9,65
10. Emission	I_F [A] =	8,86	9,16	9,36	9,51	9,65

2.Filament W/Th 0,4mm in gauge with ceramic base plate

Emission characteristic: υ_{gauge} = no value
υ_{tube} = no value
p_{HP} = no value
$\mathbf{I_{Fmax}}$ = 12,8A

Table 7.

	I_e [µA] =	200	400	600	800	1000
1. Emission	I_F [A] =	11,80	12,08	12,25	12,36	12,43
2. Emission	I_F [A] =	11,49	11,82	12,03	12,19	12,43

Emission after heating filament with 14,7A for 4min.

3. Emission	I_F [A] =	11,28	12,66	11,91	12,07	12,22
4. Emission	I_F [A] =	11,34	11,70	11,91	12,08	12,22

Emission with better vacuum and cold gauge
υ_{gauge} = 34°C
υ_{tube} = 31°C
p_{HP} = 3,9E-6Torr
$\mathbf{I_{Fmax}}$ = 12,8A

5. Emission	**I_F [A] =**	11,12	11,35	11,65	11,90	12,10
6. Emission	**I_F [A] =**	11,88	12,10	12,20	12,27	

Conclusion:

The conditioning of the first filament could not be monitored despite the fact that the attention was focused to conditioning.
After a certain time of measurements the filament current dropped from 12A to about 9A (=25%) which is not as much as the drop of the 0,6mm filament which reduced the filament current after conditioning by about 30%. However, in view of the poor vacuum conditions, this effect is not significant.
There was no effect of conditioning with the second filament, even after about 2 hours working in magnetic field!

(2): Emission in magnetic field.
Filament W/Th 0,6mm in gauge with metal base plate.

There are no systematic measurements to this point.
The only definite values are: B = 6T
I_e = 500µA
I_F = 14,4A

Conclusion:

There were no indications during all the test series, that the maximum emission current could not be reached.

Filament W/Th 0,4mm in gauge with ceramic base plate

In the course of the test campaign it became evident, that the electron emission current was significantly influenced by the magnetic field. This is a generally known effect, also observed with 0,6mm filaments at IPP and JET and also mentioned in [5]. The nature of this effect is not well understood and thus being object to closer investigation.

All tested 0,4mm filaments showed a limitation of the emission current decreasing with increasing magnetic field. (s.Tab.9)

Table 8. No systematic measurements

B =	3,5T	6T	
I_e [µA] =	340	300	Maximum attainable current
I_F [A] =	10,7	14,7	Filament current limit

Table 9. Systematic measurements

B = 0T	**I_{Fmax} =** 13,7A						
I_e [µA] =	200	400	600	800	1000		
I_F [A] =	11,12	11,35	11,65	11,90	12,10		
I_F [A] =	11,88	12,10	12,20	12,27			
B = 3,5T	**I_{Fmax} =** 14,7A						
I_e [µA] =	100	200	300	340	360	380	
I_F [A] =	12,04	12,32	12,73	13,0	13,15	not reached	
B = 2,5T	**I_{Fmax} =** 14,7A						
I_e [µA] =	100	200	300	400	420	440	
I_F [A] =	12,0	12,3	12,7	13,4	13,7	not reached	
B = 2T	**I_{Fmax} =** 14,7A						
I_e [µA] =	100	200	300	400	440	460	480
I_F [A] =	12,0	12,28	12,61	13,13	13,5	13,85	not reached
B = 1T	**I_{Fmax} =** 14,7A						
I_e [µA] =	100	200	300	400	500	600	620
I_F [A] =	11,9	12,16	12,34	12,62	13,0	13,5	not reached
B = 0,5T +/-0,25T	**I_{Fmax} =** 14,7A						
I_e [µA] =	200	400	600	800	900		
I_F [A] =	11,92	12,31	12,75	13,6	not reached		
B = 0T	**I_{Fmax} =** 14,7A						
I_e [µA] =	200	400	600	800	1000		
I_F [A] =	11,75	12,05	12,24	12,38	12,48		

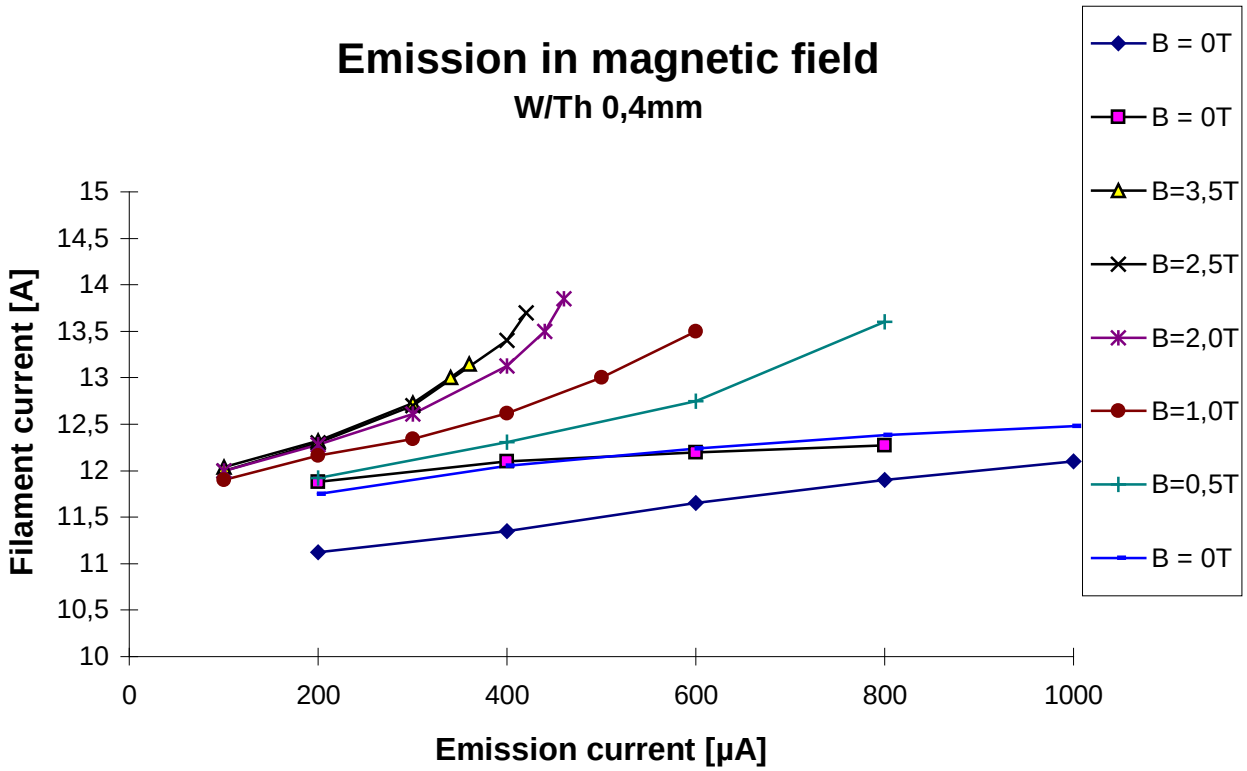

Figure 3. Emission characteristics in different magnetic fields.

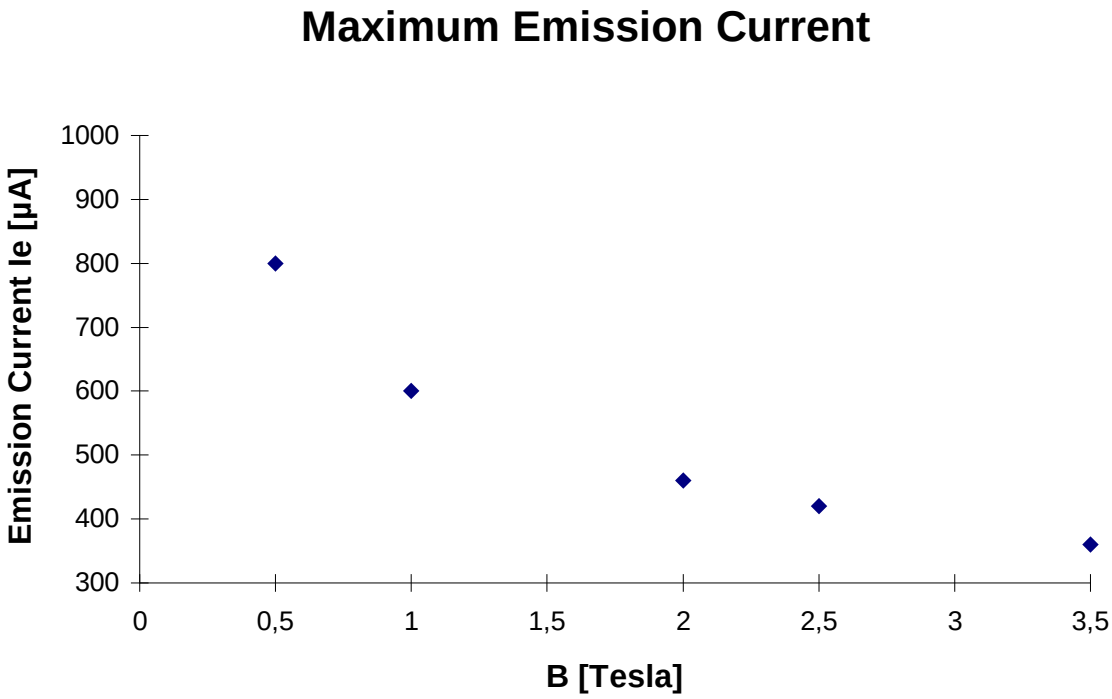

Figure 4. Maximum reached emission currents as a function of B

Conclusion:

Contrary to the behaviour of the 0.6mm filaments, the emission current from a 0.4mm filament was limited with magnetic field as shown in Tab. 8 and 9 and Fig. 1.
The limitation of the emission current drops with increasing magnetic field. Without magnetic field an emission current of 1000 µA represents no problem.

(3): Lorentz force upwards B = const.
I_F = const.
t = maximum 30min or until bending

The aim of this test was to investigate the behaviour of the gauge and the filament in normal operation for a period as long as 30 minutes.
Since the deformation by a Lorentz force upwards is less dangerous than downwards and the filaments proved to be more stable against it, the majority of tests were done with Lorentz force downwards under ***(5).***

Filament W/Th 0,6mm

No tests done.

Filament W/Th 0,4mm in gauge with ceramic base plate

The gauge worked properly with a programmed emission current I_e = 200µA in a magnetic field of B = 9T. The filament current necessary for this emission current was I_F = 11A.

No bending could be observed.

(4): Lorentz force upwards B = const.
I_F = [min., max.]
t = 5min.

To determine the threshold for bending in a high magnetic field the filament current was increased stepwise after time intervals of 5 minutes, respectively.

Filament W/Th 0,6mm

B = 6T
Bending starts within the 5 minute interval at filament current I_F = 19,8A.

Filament W/Th 0,4mm

B = 6T
Bending starts within the 5 minute time interval at filament current I_F = 16,7A.

B = 9T
Bending starts within the 5 minute time interval at filament current I_F = 14,7A.

(5): Lorentz force downwards B = const.
I_F = const.
t = maximum 30min or until bending

As mentioned above and learned by examination of deformed filaments of failed JET gauges and by the Lorentz force simulations at PTS, the most critical situation for the filament occurs with Lorentz force directed towards the base plate (downwards). Therefore, special attention was given to the study of this situation.

Filament W/Th 0,6mm

B = 3,5T and I_F = 17,9A
This can be a normal situation for a gauge with badly conditioned filament.

After 30 minutes, the emitting part of the filament was bend down by 45°. This deformation would definitively destroy the gauge due to contact between the filament and the control grid.
After 33 minutes additionally a short in one of the loops appeared.

B = 9T and I_F = 14,7A
This is a normal situation for a well conditioned filament in a high field tokomak, e.g. ITER.

No hint for deformation was found after 30 minutes.

B = 9T and I_F = 16,1A
Bending starts after 15 minutes. A short circuit appeared after 24 minutes.

Filament W/Th 0,4mm

B = 3,5T and I_F = 14,1A
This situation is much worse than the operation of a 0.6 mm filament with a filament current I_F = 17.9 A. The filament current is about 15% above the one necessary for emission from a non conditioned 0.4mm filament.
No bending was observed during 30 minutes.

B = 3,5T and I_F = 16,1A
Bending starts after about 4 minutes.

B = 9T and I_e = 200µA with I_F = 11A
This is a normal emission status for an unconditioned filament in a high field tokomak.

No hint for deformation was observed during 30 minutes.

Conclusion:

Both filaments are able to work properly without deformation by Lorentz forces even in as high magnetic fields as 9T.
It is evident however, that the 0,6mm filament has to be well conditioned. Otherwise the inevitably increased filament current will destroy the gauge.
In comparison to this, the 0,4mm filament is more stable. Even an unconditioned filament works with a comfortable safety margin.

(6): Bending back to starting point

It is important to know, if the shape of a bent filament can be restored to reactivate gauges with deformed filaments.
Some investigations were done to bend filaments back to the original geometry.

Conclusion:

Filaments can be bent back with the same combination of magnetic field and filament current which caused the deformation. The time is even shorter than the time needed for the original deformation.

There are considerable differences between the two filaments:

1. The 0.6 mm filaments are bent only in the loops. The electron emitting part remains straight, but moves vertically up- or downwards, depending on direction of force, and horizontally towards the control grid.
The bending is illustrated in figure 5.

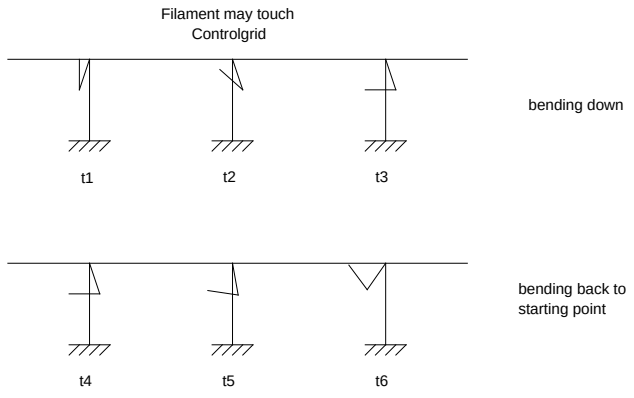

Figure 5. Illustration to bending of a 0,6mm filament.

In fact this bending is not reversible, i.e. the original geometry can not be restored. The emitting part of the filament can only be brought back to its original vertical position, but not to its original horizontal position. Additionally bending downwards can destroy the gauge, if the incandescent filament touches the control grid becomes welded to it. These were typical failures observed at the investigated JET gauges and confirmed herewith.

2. The 0.4mm filaments show a different behaviour.
Only the electron emitting part is bent and the loops remain unchanged. The filament does not move horizontally. Fig. 6 illustrates a typical bending pattern.

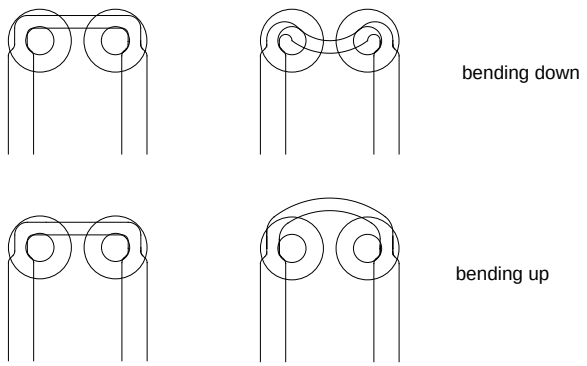

Figure 6. Illustration to bending of 0,4mm filament.

The geometry can be restored so far, that the gauge can be used again despite the fact, that the emitting part becomes not as straight as it was originally. There is no danger of touching the control grid. It may be advisable to change the polarity of the filament current periodically between pulses to compensate any deformation from the beginning

(7): Dependence of ion current

For hot cathode pressure gauges it is usually assumed

$$I_i << I_e$$

Under this condition the ion current is according to the Barkhausen equation proportional to the emission current measured at the acceleration grid and to the pressure.

$$I_i = C*p*I_e$$

The above mentioned assumption is equivalent to a negligible contribution to the electron current from the ionisation and is valid for low sensitivity C and/or pressure. It is not fulfilled for ASDEX gauges or other special hot cathode pressure gauges operated in high magnetic field and high neutral pressure[6]. The sensitivity rises steeply already at low magnetic fields by more than an order of magnitude due to the better confinement of the electrons. The D_2 or H_2 pressure can exceed the range, in which commercial hot cathode pressure gauges are usually operated, nearly by an order of magnitude as well. In this case I_e has to be corrected for the contribution by ionisation:

$$I_i = C*p*(I_e-a*I_i)$$

One gets a rather linear dependence on the pressure p with a close to 1.

Despite the poor vacuum condition, the lack of a calibrated reference pressure gauge, the long distance between the external Balzers HP gauge and the ASDEX gauge and the fact, that only N_2 instead of H_2 or D_2 was available, in a last test we attempted to investigate qualitatively the mutual dependences of ion current, emission current, pressure and magnetic field.
The pressure was adjusted with a micro-flow valve.
The used filament was a W/Th 0,4mm in ceramic base plate.

Table 10. Measured data
Electronic settings: si= 3, f=3kHz fixed

a)

B = 3,5T	p = 5E-4torr		gi = 1		
I_e [µA] =	300	200	100	200	300
I_F [A] =	12,95	12,43	12,15	12,44	12,91
I_+ [V] =	1,57	1,2	0,86	1,13	1,51

b)

B = 5T	**p =** 5E-4torr		gi = 1		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,23	12,48	12,11	12,49	13,25
I_+ [V] =	1,48	1,05	0,87	1,05	1,43

c)

B = 2T	**p =** 5E-4torr		gi = 1			
I_e [µA] =	300	200	100	200	300	400
I_F [A] =	12,47	12,28	12,04	12,30	12,48	12,85
I_+ [V] =	1,59	1,23	0,80	1,29	1,59	2,00

d)

B = 6T	p = 5E-4torr		gi = 1		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,58	12,47	12,04	12,50	13,59
I_+ [V] =	1,48	1,14	0,87	1,14	1,48

e)

B = 6T	p = 9,8E-4torr		gi = 1		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,52	12,54	12,14	12,56	13,41
I_+ [V] =	2,56	1,75	1,54	1,76	2,49

f)

B = 6T	p = 5E-3torr		gi = 1		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,00	12,63	12,35	12,66	13,00
I_+ [V] =	13,1	14,9	11,5	14,4	13,1

g) Repetition of f) with reduced gain

B = 6T	p = 5E-3torr		gi= 2		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,00	12,65	12,36		
I_+ [V] =	6,54	7,10	5,52		

h)

B = 6T	p = 2E-3torr		gi= 2		
I_e [µA] =	300	200	100	200	300
I_F [A] =		12,66	12,23	12,66	13,43
I_+ [V] =		1,72	1,74	1,71	2,2

i)

B = 6T	p = 5E-4torr		gi= 2		
I_e [µA] =	300	200	100	200	300
I_F [A] =	13,6	12,45	11,97	12,47	13,59
I_+ [V] =	0,73	0,51	0,35	0,53	0,74

j)

B = 2T	p = 5E-3torr		gi= 2		
I_e [µA] =	300	200	100	200	300
I_F [A] =	12,80	12,61	12,34	12,63	12,80
I_+ [V] =	12,56	9,63	5,51	9,65	12,59

k)

B = 0T	p = 5E-4torr		gi= 2			
I_e [µA] =	300	200	100	200	300	0
I_F [A] =	12,56	12,37	12,10	12,37	12,54	0
I_+ [V] =	0,702	0,451	0,217	0,453	0,707	-0,016

l)

B = 0T	p = 1,1E-5torr	gi= 2

I_e [µA] =	300
I_F [A] =	11,36
I_+ [V] =	-0,011

On the following pages the data are printed in diagrams of figures 7 to 16.

Conclusion:

At a pressure of 5E-4 torr we could verify a good linearity between emission current and ion current in the measurement range from 100µA to 300µA which seems to be only slightly dependent from the magnetic field in the range of 2 to 6Tesla (fig.7,8,9,10). A very good linearity was found at 0Tesla (fig.14). The sensitivity however is reduced in comparison with magnetic field.
These results are qualitatively in conformity with[6].

Strange effects occur at high magnetic fields and high pressure.
Starting at a pressure of 9,8E-4torr (figure 11), the linearity gets lost. At the highest measured pressure of 5E-3torr (figure 12), the relation between emission- and ion current is completely non linear but reproducible.

At reduced magnetic field (2T) and the same high pressure, the linearity is given again (figure 15).

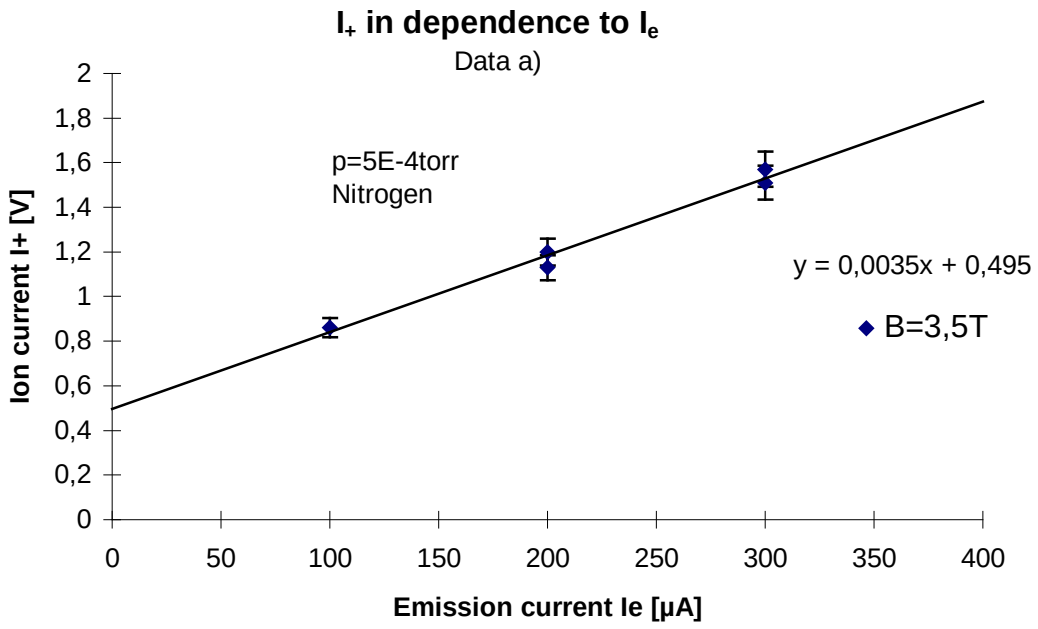

Figure 7. Data a) gi=1, B=3,5T, p=5E-4torr

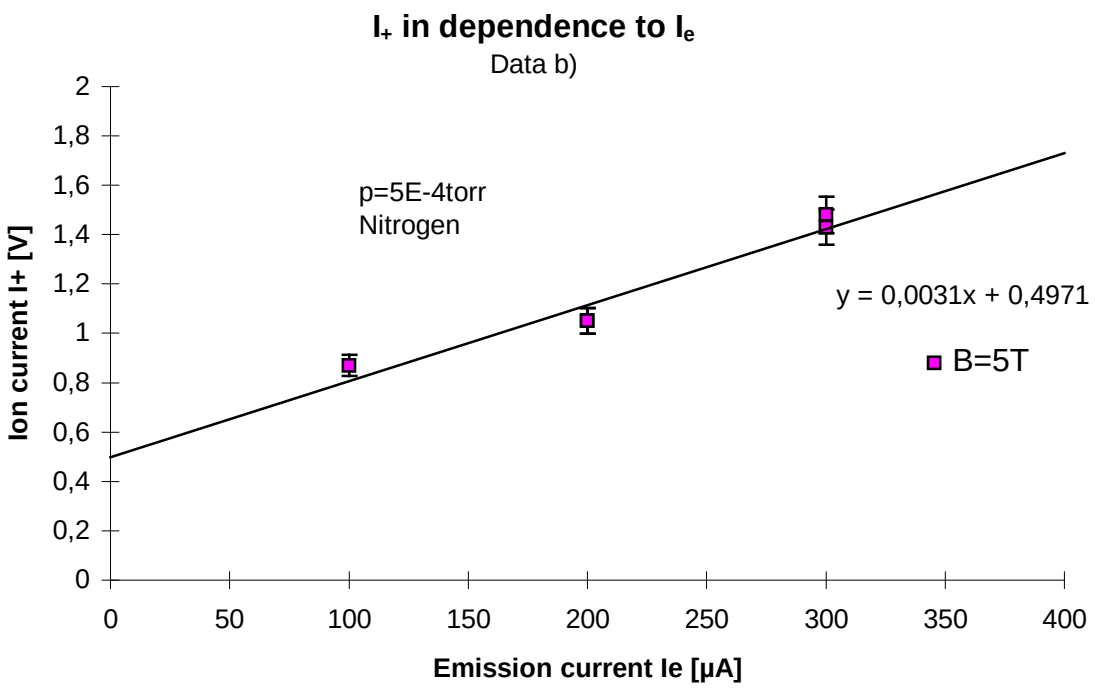

Figure 8. Data b) gi=1, B=5T, p=5E-4torr

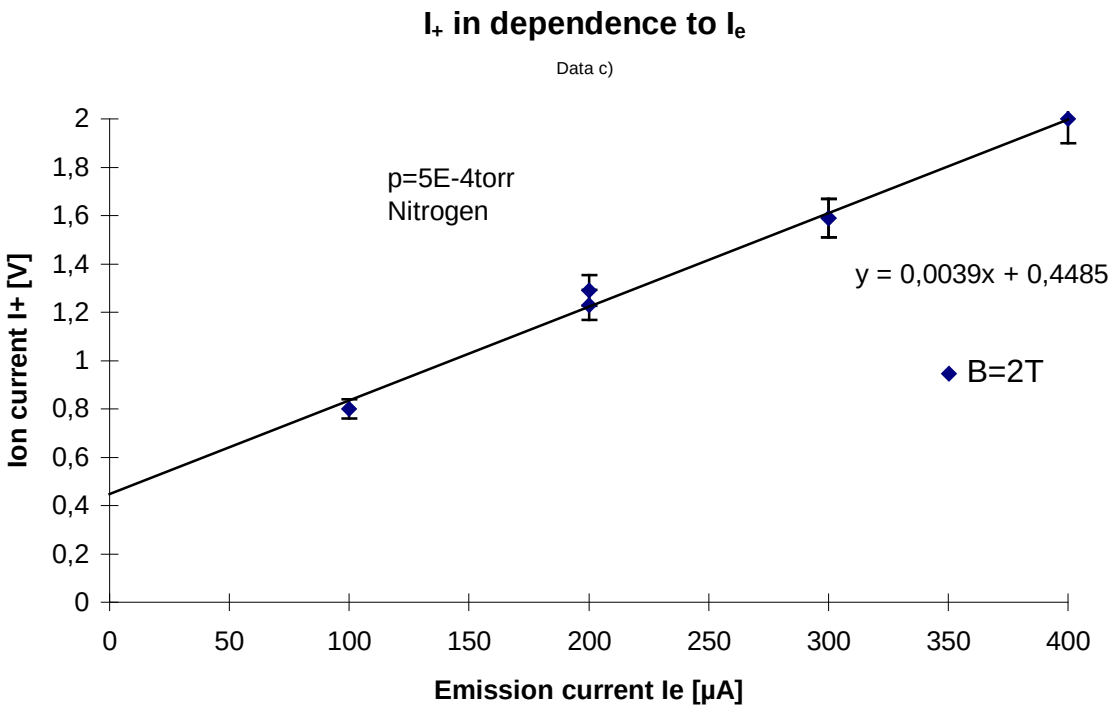

Figure 9. Data c) gi=1, B=2T, p=5E-4torr

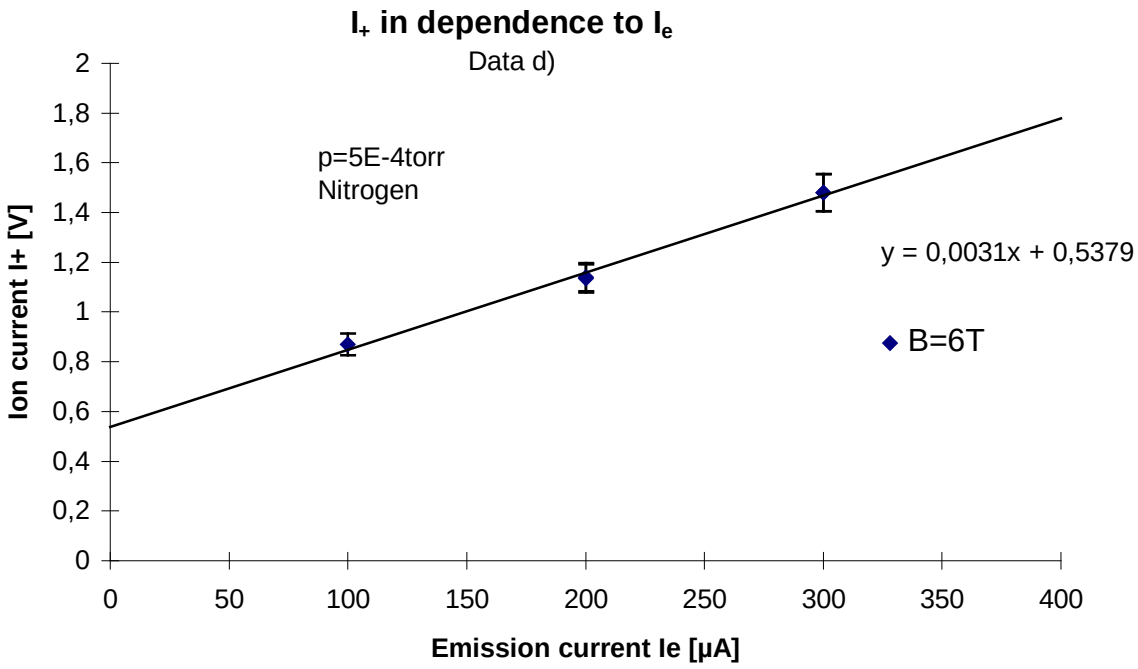

Figure 10. Data d) gi=1, B=6T, p=5E-4torr

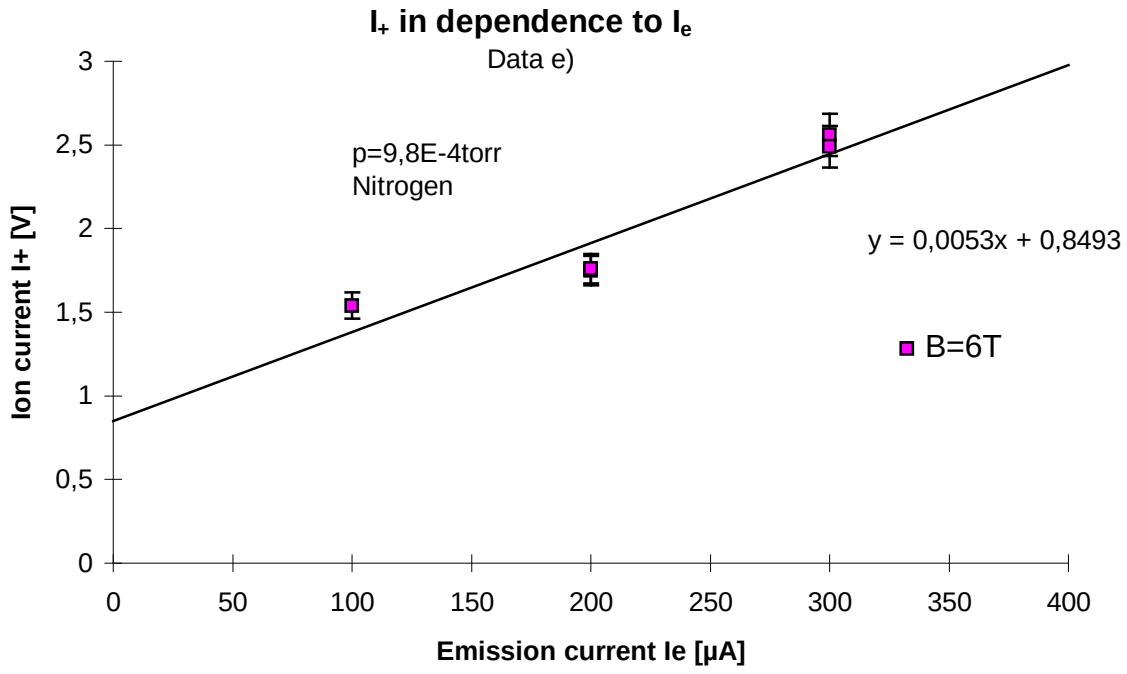

Figure 11. Data e) gi=1, B=6T, p=9,8E-4torr

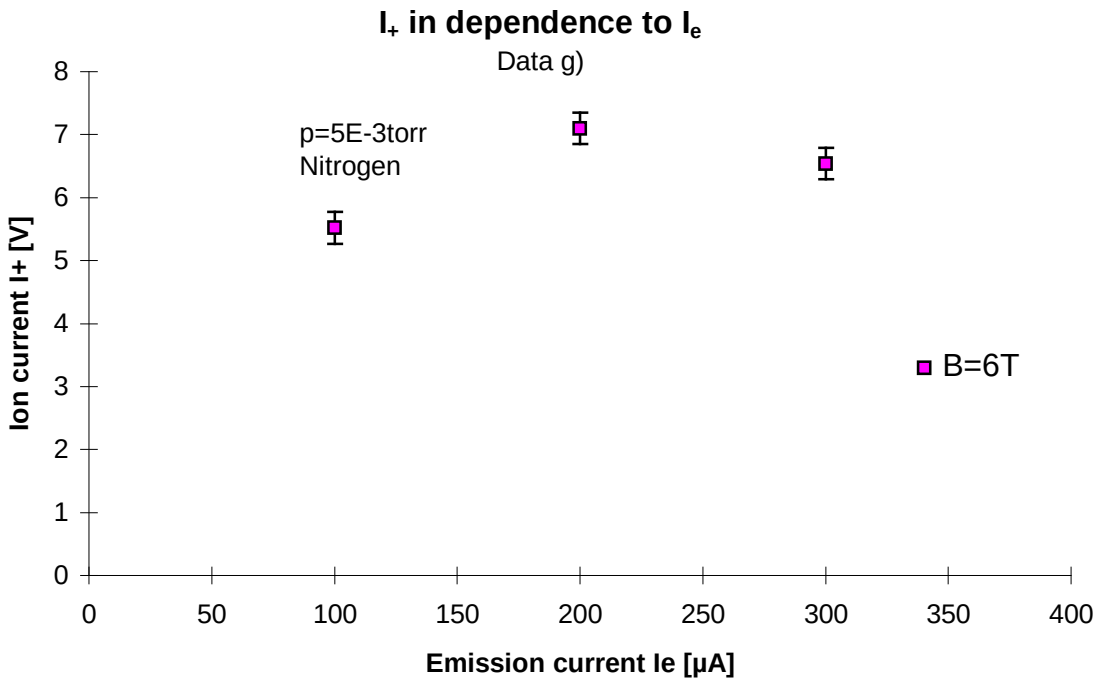

Figure 12. Data g) gi=2, B=6T, p=5E-3torr

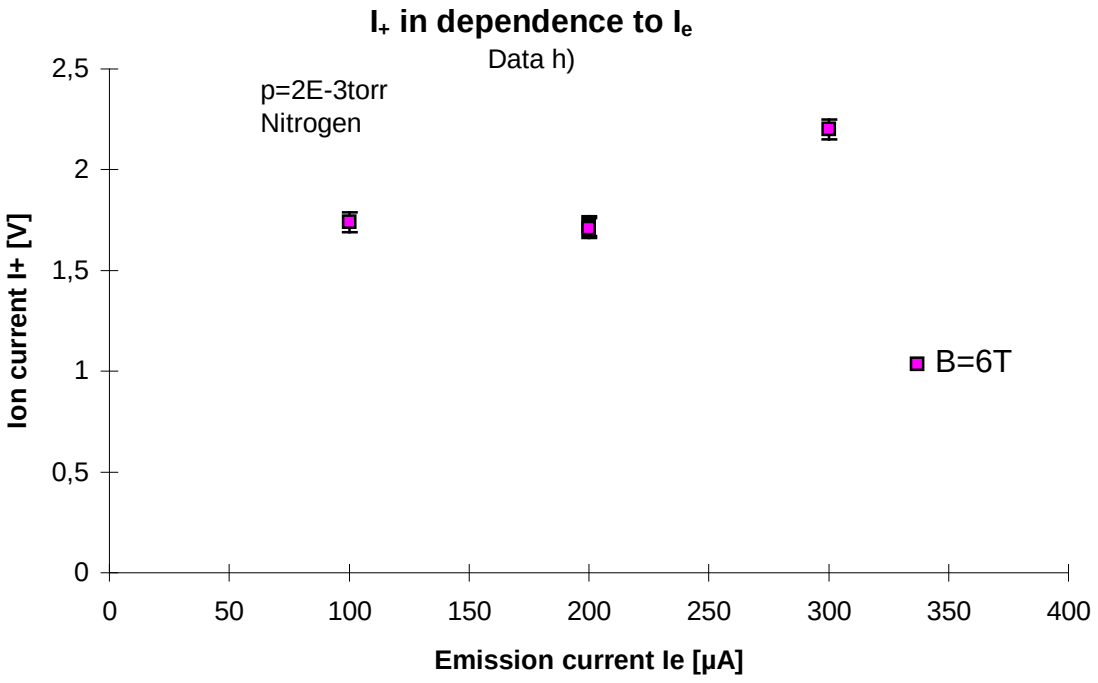

Figure 13. Data h) gi=2, B=6T, p=2E-3torr

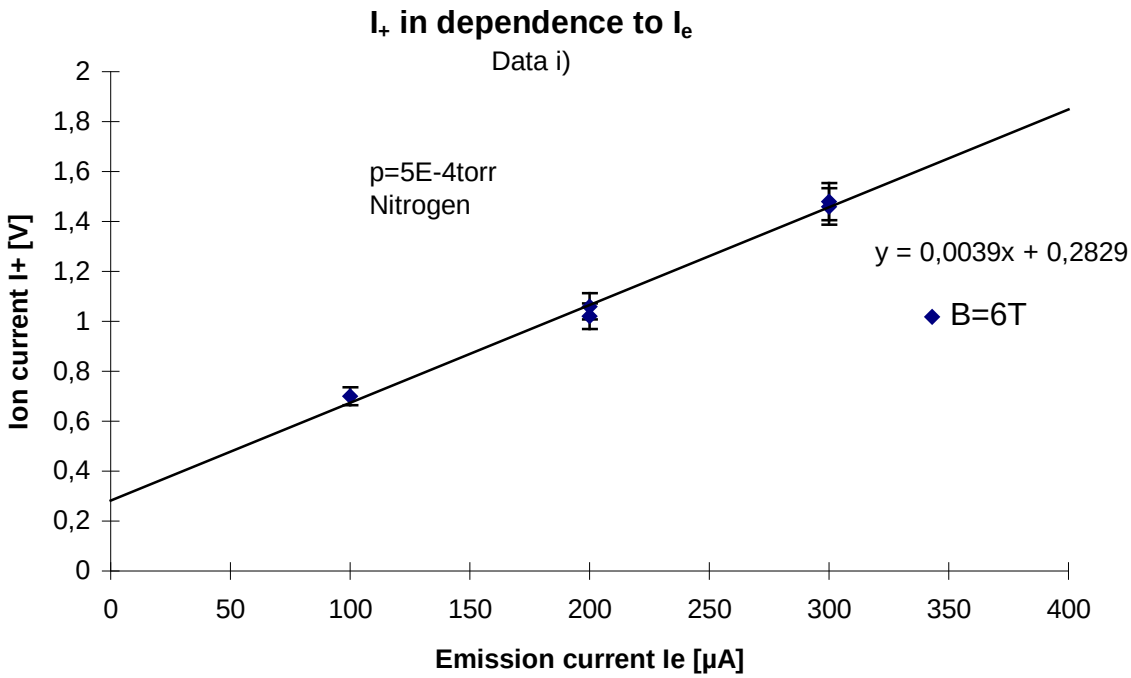

Figure 14. Data i) gi=2, B=6T, p=5E-4torr. Data are multiplied by 2 in this diagram.

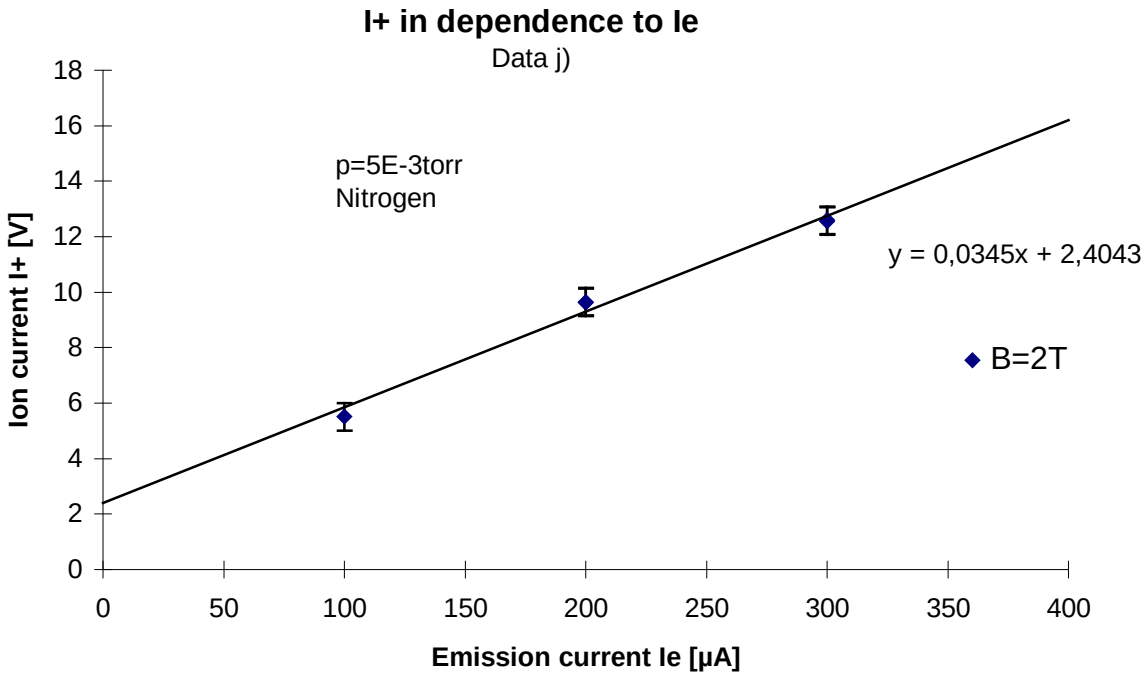

Figure 15. Data j) gi=2, B=2T, p=5E-3torr.

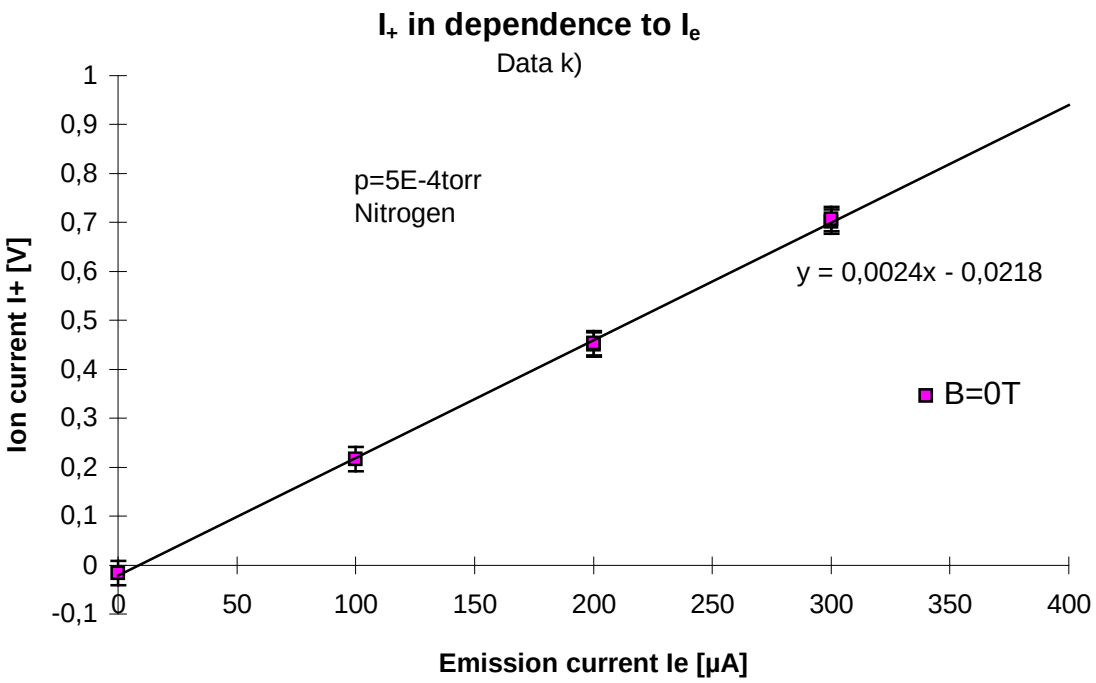

Figure 16. Data k) gi=2, B=0T, p=5E-4torr.

V. CONCLUSION

The superconducting magnet JUMBO offers good conditions to investigate the behaviour of ASDEX pressure gauges in high magnetic fields.

Some important effects arose which are not yet fully understood. They must be investigated in further tests for a better understanding of the behaviour of the pressure gauges.

With good conditioning both filaments -the 0,6mm and the etched 0,4mm- are able to work satisfactory in high magnetic fields without risk to be bent. With the increased filament current necessary, e.g. for bad conditioning the 0,6mm filament will be bent. The figures 17 and 18 below illustrate the ranges for safe and critical performance.

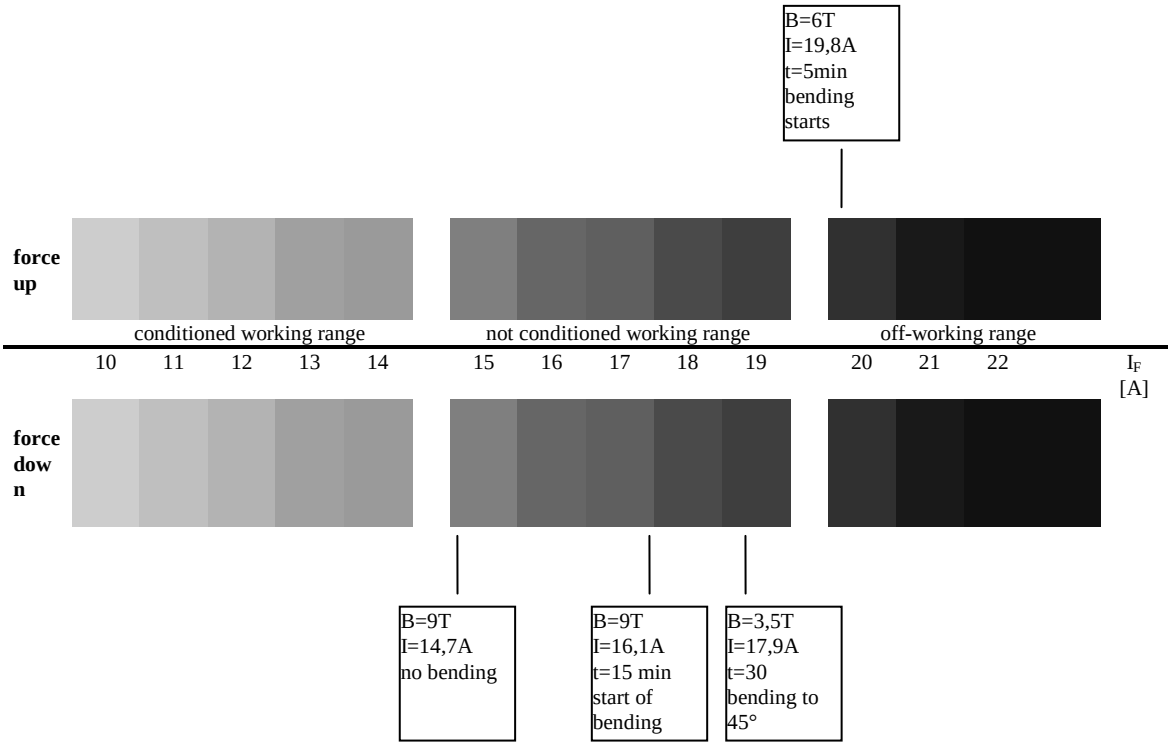

Figure 17. Working and critical range of performance for 0,6mm filaments.

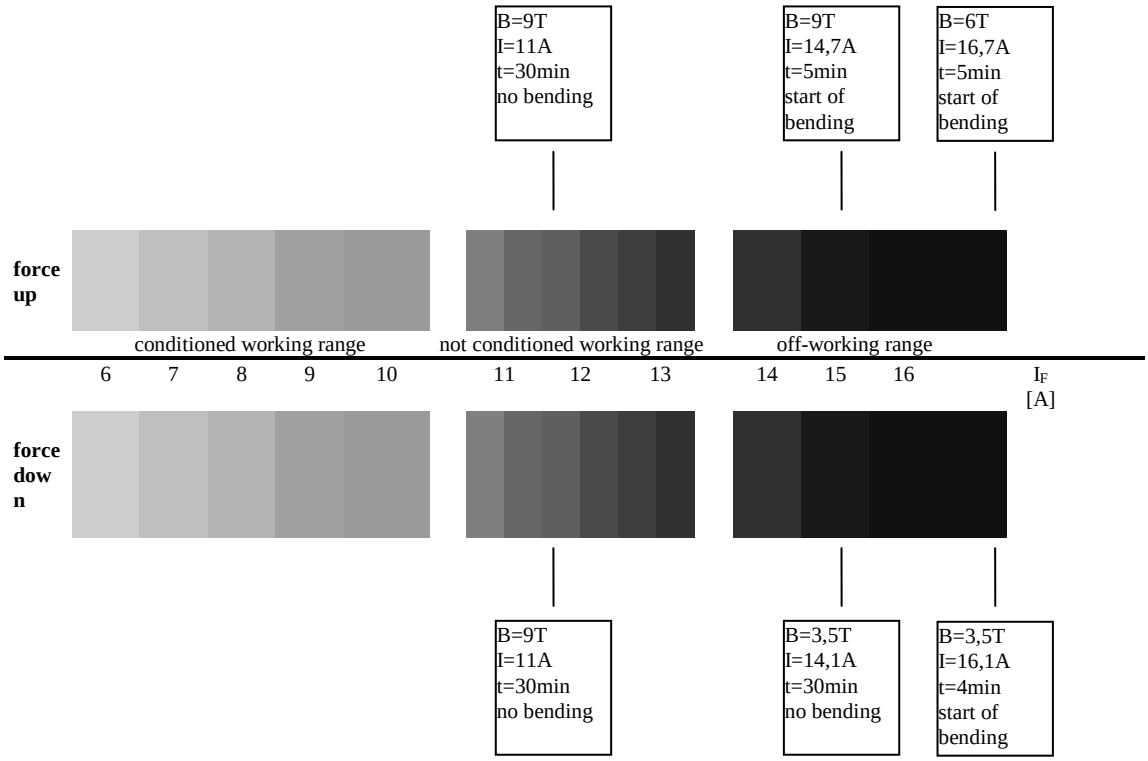

Figure 18 Working and critical range of performance for 0,6mm filaments

It was very helpful not only to learn when filaments start to be bent, but also the way they will be bent. There is less risk damaging the gauge with a 0,4mm filament than with a 0,6mm filament, because the typical bending pattern of a 0.6mm filament can lead to a contact with the control grid.

Using the results summarised in figure 17, it becomes evident, that the deformations seen at the JET filaments may not occur at normal gauge operation.

Not the increase of the Lorentz force by high magnetic fields or extreme filament currents are dangerous but the overheating caused by the high filament currents by which the tungsten looses its strength.
To avoid dangerous situations arising by any malfunction of the emission current feedback the filament current has to be limited to a safe value which can not overheat the filament.

There was no time left to study different diameters. From these results it is doubtless, that a diameter of 0.4mm is below the optimum, but closer to it than 0.6mm.

Choosing a 0,4mm filament has in addition several advantages:
* less thermal stress of the gauge by reduced heating power
* thinner and more flexible cables for the filament current
* reduction of dimension at feedthroughs and connectors
* reduction of price for electronics by reduced power supply

VI. REFERENCES

[1]G.Haas and F.Schneider, Vortragsversanstaltung der Deutsche Physikalische Gesellschaft e.V. vom 16.-20.März 1987, Göttingen.
„Ein neuartiges Ionisationsmanometer zur Neutraldichtemessung in Fusionsexperimenten.“

[2]C.C.Klepper, T.E.Evans, G.Haas, G.L.Jackson and R.Maingi, J. of Vac. Sci. and Technol. A 11(2), Mar/Apr 1993.
„Neutral pressure studies with a fast ionisation gauge in the divertor region of the DIII-D tokamak.“

[3]J.Ehrenberg, Telefax 12.9.1995.

[4]H.Albrecht and R.Wirth, Internal PTS Report 7.3.1996 „Test von Kathoden für Ionisationsmeßkopf“.

[5]R.Wirth and G.Haas, PTS Report January 1993 „ Tests of the pressure gauge in high magnetic field at IPP-Garching for JET Joint Undertaking“.

[6]G.Haas, H.-S. Bosch, L. de Kock, Workshop on Diagnostics for ITER, Varenna, 28th Aug. to 1st Sept. 1995 „Neutral Gas Diagnostic for ITER“.

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APPENDIX: Photographs