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Abstract

The Alcator C-Mod divertor bypass has for the first time allowed *in situ* variations to the mechanical baffle design in a tokamak. The design utilizes small coils which interact with the ambient magnetic field inside the vessel to provide the torque required to control small flaps of a Venetian blind geometry. Plasma physics experiments with the bypass have revealed the importance of the divertor baffling to maintain high divertor gas pressures. These experiments have also indicated that the divertor baffling has only a limited effect on the main chamber pressure in C-Mod.

1. Introduction

Over the last two decades of research on controlled thermonuclear fusion in tokamaks, one of the principal areas of investigation has been the effect of the "divertor" on reactor performance [1,2]. The divertor takes magnetic field lines around the periphery of the fusion plasma and "diverts" them into a separate chamber. Heat and, to a lesser degree, particles originating in the main plasma are then exhausted in the divertor. The original purpose of the divertor was to locate the primary plasma-wall interaction, and hence impurity production, at a location remote from the confined plasma, where plasma purity is of critical importance. It was later realized that the divertor also aided in the compression of the fuel and the helium "ash" gases, forming an ideal place for extraction via vacuum pumps. In addition, it was in a divertor tokamak that high modes of plasma confinement (i.e. the H-mode) were first discovered [3] and it was subsequently concluded that the exclusion of gas from the main chamber was a key feature of the divertor and its accompanying baffle structure [4].

Since that time, the early 1980's, virtually all divertor tokamaks have been designed with increasing levels of divertor baffling, or "closedness", specifically to restrict the leakage of gas out of the region. However, the level of required closedness has never been established in a controlled experiment, mainly because baffle changes usually involve significant in-vessel modifications, and thus comparisons are usually made across several years, under varying machines conditions, magnetic geometry and diagnostic calibrations. In the present paper, we address this problem with a divertor baffle design that can be altered *in situ*, between discharges and even during discharges. Comparisons are thus made under identical conditions. We called this baffle the divertor "bypass", since it allows gas to escape the divertor, returning to the main chamber, and thus effectively simulates varying levels of divertor "closedness".

2. Alcator C-Mod

Alcator C-Mod is a relatively small, high-field tokamak, with a single-null (bottom) divertor and molybdenum first-walls [5]. A poloidal cross-section of the machine appears in Fig. 1. Under normal operating conditions, gas leakage from the divertor to the main chamber is either through the divertor plasma fan and X-point regions via charge-exchange diffusion of atoms, or occurs through gaps behind the mechanical structure that supports the outer divertor plate. The exact magnitude of this latter, intrinsic leakage "conductance" is estimated to be of order ~ 20 m^3/s (free-molecular), which is comparable to the "bypass" leakage discussed in the next section.

C-Mod has a large number of edge and divertor plasma diagnostics. In this study we focus on gas pressure gauges, indicated by "G" in Fig. 1. These include a capacitance manometer connected to the divertor and plenum by a long duct (~ 1.7 m), and an ionization gauge at the outside wall in the main chamber. Both pressure gauges have time responses fast enough to follow the variation in pressures during discharges.

2. Divertor Bypass

The conductance between the divertor plenum and the main chamber is altered using the Alcator C-Mod divertor bypass, Fig. 1. The bypass consists of 10 discrete stainless steel structures equi-spaced in the toroidal direction. A single unit consists of 7 louvered inconel flaps, arranged in a Venetian blind geometry, Fig. 2. Each flap has dimensions 2 cm by 5.5 cm, approximately, therefore giving a total area of, 10 units × 7 flaps x 11 cm^2 ~ 0.08 m^2, and a free-molecular conductance of ~ 23 m^3/s. At the high gas pressures of the C-Mod divertor (up to 300 mTorr), these conductances can be enhanced by factors as large as ~ 2 due to viscous effects (i.e. neutral-neutral collisions in the gas phase).

The bypass is controlled using a small coil, Fig. 2. When energized with approximately 1 A of current, the resulting interaction with the ambient toroidal magnetic field produces a torque which rotates all 7 flaps of the bypass (since they are mechanically tied together by the louver arm). The bypass can open or close in a time as short as ~ 20 ms, although ~ 40 ms is the typical opening time.

3. Materials, Construction, Electrical

The flap assembly shown in Fig. 2 can be subjected to rather severe conditions, including operation in vacuum at elevated temperatures (~ 400 C) and strong electrical eddy currents associated with abrupt disruptions in the central plasma current. The eddy currents arise from the rapidly changing poloidal magnetic field, which in C-Mod can be as high as ~ 1 T in 1 ms. The eddy currents can produce strong forces on conductors since they interact with the strong toroidal magnetic field, which is in the range of ~ 5 T. Such forces can and have permanently deformed stainless steel structures in C-Mod and indeed calculations indicate that stainless steel flaps could potentially be damaged by the disruption eddy current forces. For this reason, the flaps are constructed from heated treated inconel 718 AMS 5596, which gives a yield strength ~ 3 times higher than stainless steel and a resistivity ~ 2 larger, combining to give a factor ~ 6 improved safety margin over stainless steel.

To ensure that neighboring flaps are not weld together, either from cold vacuum welding or arcs associated with eddy or plasma-induced currents, one edge of each flap is flame-sprayed with a thin (~ 0.1 mm) alumina coating (see Fig. 3). Graphite (POCO AXF-5Q) bearings for each flap ensure a relatively frictionless operation even at 400 C. Each unit, consisting of 7 flaps, incorporate 4 return torsion springs (inconel X750) that keep the flaps closed in the presence of various magnetic forces when not being operated.

Each unit contains a single race-track shaped coil consisting of ~ 60 windings of 27 AWG (diameter ~ 0.3 mm) wire. The high temperature magnet wire, consisting of copper with a nickel cladding, is coated with a thin layer of ceramic (~ 0.02 mm). Although the nickel cladding makes the wire magnetic, the strong fields in C-Mod (which essentially saturate the nickel) and the small size of the coil, ensure a negligible perturbation to the magnetic fields in the plasma. The electrical leads for the coil, necessarily moving during operation, are made from fine copper braid to prevent fatigue damage from repeated use. All 10 bypass coils are powered in parallel with a single fast bipolar programmable power supply (±20 V, ±20 A).

During plasma disruptions the changing poloidal field can induce a voltage up to100 V across the coil, potentially causing arcing. To protect against this breakdown diodes are place across each coil (outside the vessel) which limit the voltage to ~ 40 V. The coil power supply is programmed with a CAMAC controlled function generator. All currents and voltages are recorded and stored with standard CAMAC. During operation the power applied to each coil is in the range of ~ 10 W, which in vacuum can overheat the coil in several seconds. For this reason, the coil power supply line runs through a “time-out” circuit, which allows operation for only a few seconds, once every few minutes. This eliminates the possibility of damaging the coils through hardware or software errors.

Although not shown in Fig. 2, an electrical limit switch constructed from MACOR indicates when the flaps are in the closed position. Care is taken in its design to ensure no line of sight into the switch from the plasma environment, since even a very diffuse plasma can interfere with the operation of bare electrical contacts.

In off-line testing in a magnet with a field of ~ 4 T, a single bypass was subjected to greater than 10,000 operations with no failure. A model of the flap motion was developed during the design of the bypass, the basic elements of which are presented in the next section

3. Model

The balance equation for the total torque T_{total} on the flaps/louver assembly is given by,

$$T_{total} = T_{coil} + T_{spring} + T_{eddy} = I_m \frac{d^2\theta}{dt^2} \quad [1]$$

$$T_{coil} = A\ I\ B \cos\theta \quad [2]$$

$$T_{spring} = -k\left(\theta - \theta_0\right) \quad [3]$$

$$T_{eddy} = -\kappa B^2 \cos^2\theta \frac{d\theta}{dt} \quad [4]$$

where T_{coil} is the torque produced by the energized coil interacting with the toroidal magnetic field, T_{spring} is the torque due to the return spring, T_{eddy} is the torque generated by the eddy currents induced in the inconel flaps as they rotate through the toroidal magnetic field (during normal discharges, not disruptions), I_m is the effective moment of inertial of the assembly, θ is the angle of the flaps with respect to the horizontal (0° when closed, 70° fully open, see Fig. 2), A is the effective area of the coil, I is the electrical current in the coil circuit, B is the magnetic field strength, k is the effective spring constant of the 4 springs and θ_0 is the equilibrium angle for the springs. κ is a constant dependent on the properties of the flaps (see Fig. 3), i.e.

$$\kappa \equiv \frac{f^2 d^3 eg}{4\rho} \quad [5]$$

where d ~ 2 cm is the width of the flap, fd is the effect moment arm of the eddy current path (f ~ 0.75), e ~ 5.5 cm is the flap length, g ~ 0.25 mm is thickness of the flap and ρ is the resistivity of the inconel material.

The voltage V in the coil circuit is given by,

$$V = R\ I + A\ B \cos\theta \frac{d\theta}{dt} \quad [6]$$

where R is the electrical resistance of the circuit (including the coil and leads). The second term on the right-hand side of Eqn. 6 is the back EMF voltage generated by the coil as it rotates in the magnetic field. Combining the above equations one arrives at a 2nd order non-linear differential equation,

$$\frac{d^2\theta}{dt} = F\left(\theta, \frac{d\theta}{dt}\right) \qquad [7]$$

which can be solved by standard numerical techniques.

Fig. 4 gives an example of model results for a case where the assumed magnetic field is B = 4.7 T (corresponding to the typical magnetic field strength at the position of the bypass in C-Mod), a voltage of V = 7 V (applied at t = 0.0 s), a coil resistance of ~ 1.3 Ohms and lead resistance of 5.5 Ohms. The lead resistance includes approximately 4 Ohms resistance purposely added to measure and limit the current. Figs. 4a and 4b give the current through the circuit and the angle of the flaps. While the applied voltage is a “square-wave” (not shown), the induced current is not. Instead, during the rotation of the flaps the current is depressed from the motionless or fully-open value of ~ 1 A. This is due to the aforementioned EMF voltage generated across the coil during its rotation in the magnetic field. The coil opens completely in approximately 40 ms, and at this point the current abruptly rises to its purely resistive value as rotation ceases.

Fig. 4c gives the three components of torque acting on the flap/louver assembly, including the torques from the coil, the return spring and the induced eddy currents. The system ensures that the net torque (not shown) is virtually zero through most of the motion, so that the angular velocity is nearly constant during the opening. The main resistance to opening is the eddy current induced in the flap as it rotates through the strong toroidal magnetic field.

4. Observed Performance during Discharges

Fig. 5 gives results from an experiment during plasma operation in Alcator C-Mod, including the applied voltage, circuit current, limit switch indicator, flap angle and divertor gas pressure. In the case of the divertor pressure, a comparison discharge is shown where the bypass was kept closed. At t = 0.9 s, voltage is abruptly applied to the circuit. The applied voltage is in the range of 7 V (Fig. 5a), which droops slightly as the current increases. This is due to resistive loss in the distribution electronics. The current (Fig. 5b), as in the model calculation in Fig. 4, is at first low during the flap rotation and then abruptly increases to the fully-opened value. The limit switch (Fig. 5c) indicates rotation away from the fully-closed position within a few milliseconds of the application of voltage to the coil. The angle of the flap (Fig. 5d) as a function of time is deduced from experiment by integrating Eqn. 6 along with knowledge of the applied voltage V, the resistance R, the effective area of the coil A and the magnetic field at the coil B. As expected, the flap angle increases linearly with time, indicating zero net torque on the flap assembly due to the damping effect of the induced eddy currents. Finally, Fig. 5e gives the evolution of the divertor gas pressure, which drops by a factor of ~ 2 in a time of ~ 0.1 s following the opening of the bypass.

4. Effect on Gas Pressures

The above factor of two decrease in divertor pressure with the bypass open is found in most types of discharges in C-Mod. Fig. 6 gives a compilation of results for a large number of discharges at different line-average plasma densities $\bar{n}_e$. Included in the figure is the pressure in the divertor, at the mid-plane in the main chamber and the ratio of the two, which we call the "compression ratio". Generally, pressures in C-Mod increase rapidly with discharge density, whilst the compression ratio rises to a maximum of ~ 200/100 with the bypass open/closed and then decreases at high density. As above, the bypass reduces the divertor pressure by a factor of ~ 2 at moderate or high density, although the effect is less at low plasma density. In the case of the main chamber pressure, no effect of the bypass can be discerned in the data within the experimental scatter of the data. This is believed to be due to a combination of recycling of plasma from limiters and walls in the main chamber [6], which generates a relatively large amount of gas, and a nearly constant level of leakage flux from the divertor plenum to the main chamber through the intrinsic leaks in the outer divertor structure and/or bypass [7,8]. The latter is consistent with a factor ~ 2 increase in conductance when the bypass opens, and the factor of ~ 2 decrease in gas pressure.

4. Conclusions

The Alcator C-Mod divertor bypass has allowed for the first time *in situ* variations to the mechanical baffle design in a tokamak. The design utilizes small coils which interact with the ambient magnetic field inside the vessel to provide the torque required to control small flaps of a Venetian blind geometry. The bypass design successfully operates in a challenging environment which includes operation in vacuum, at high temperature (designed for < 400 C), high magnetic field (up to 8 T) and repeated use (> 10,000 cycles). After one year of operation, all ten bypass units are still fully operational.

Plasma physics experiments with the bypass have revealed the importance of the divertor baffling to maintain high divertor gas pressures. These experiments have also indicated that the divertor baffling has only a limited effect on the main chamber pressure in C-Mod. The first results of these physics studies are presently being published [7,8] and experiments are continuing in the tokamak.

Acknowledgements

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Figure Captions

1. Poloidal cross-section of the lower half of Alcator C-Mod showing the location of the divertor bypass and pressure gauges, denoted by “G”. The circulation of gas through the bypass is illustrated.
2. A top view (photograph) and side view of the flap/louver assembly, showing the Venetian blind geometry.
3. Top schematic view of a single flap.
4. Model results, using parameters given in the text, for the current in the coil, the angle of the flaps and the various torque components for a single bypass unit consisting of 7 flaps, 4 return springs and a single coil.
5. Results during a discharge in Alcator C-Mod.
6. Compilation of results from a series of discharges in Alcator C-Mod, including the main chamber or mid-plane gas pressure, the divertor gas pressure and the ratio of the two.

Fig. 1

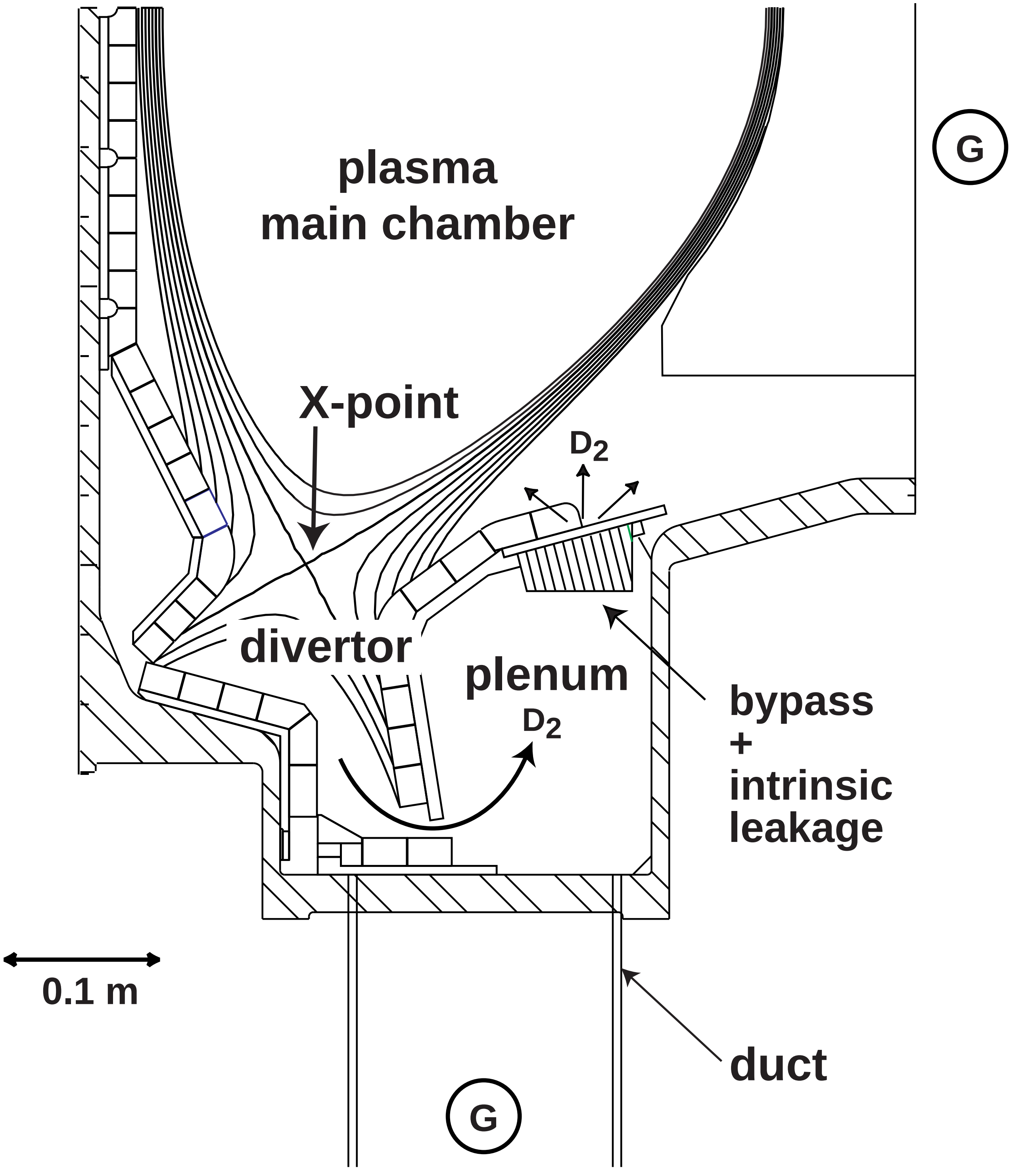

G
plasma
main chamber
X-point
D2
divertor
plenum
D2
bypass
+
intrinsic
leakage
0.1 m
duct
G

Fig. 2

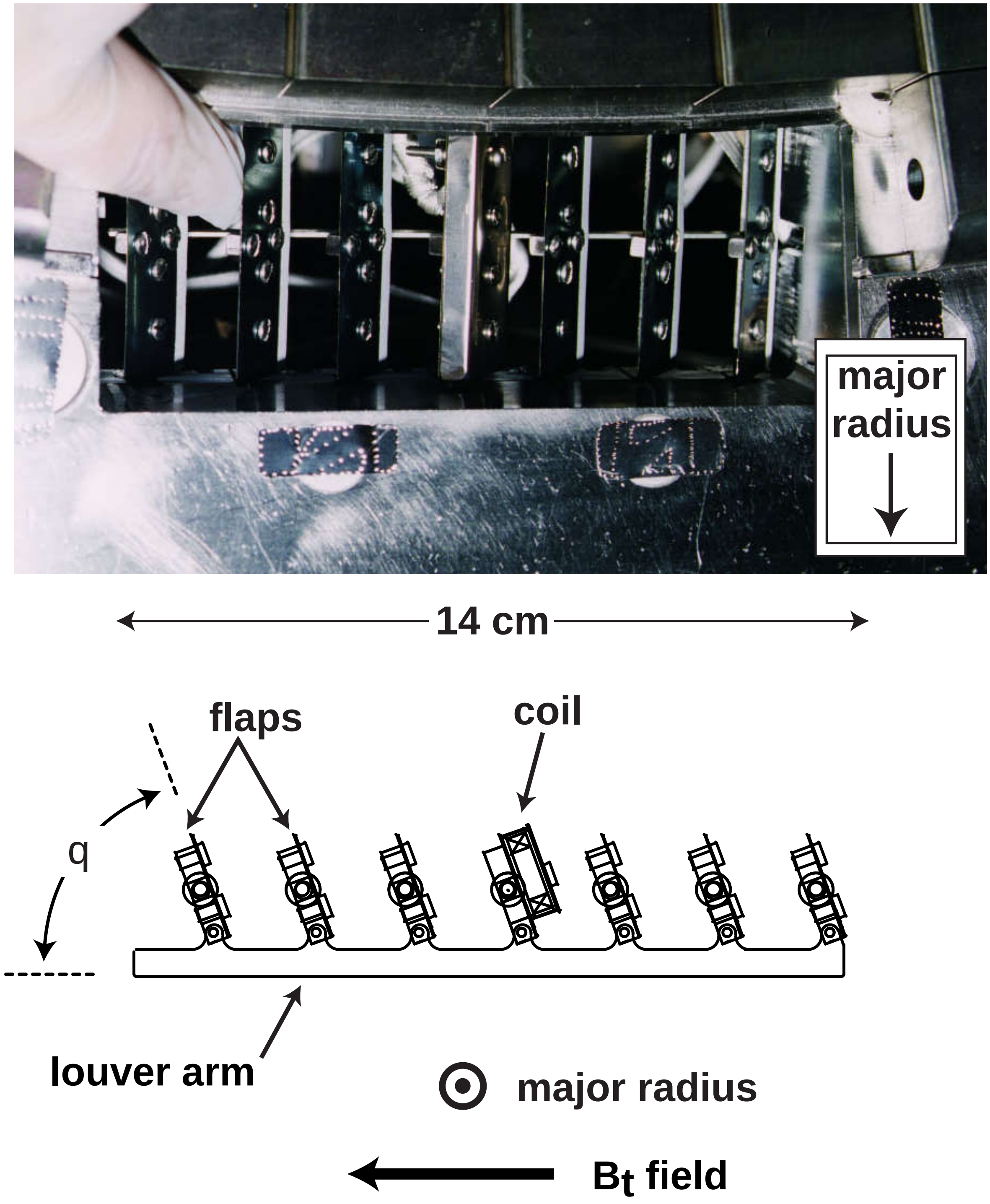

major radius
14 cm
flaps
coil
q
louver arm
major radius
B_t field

Fig. 3

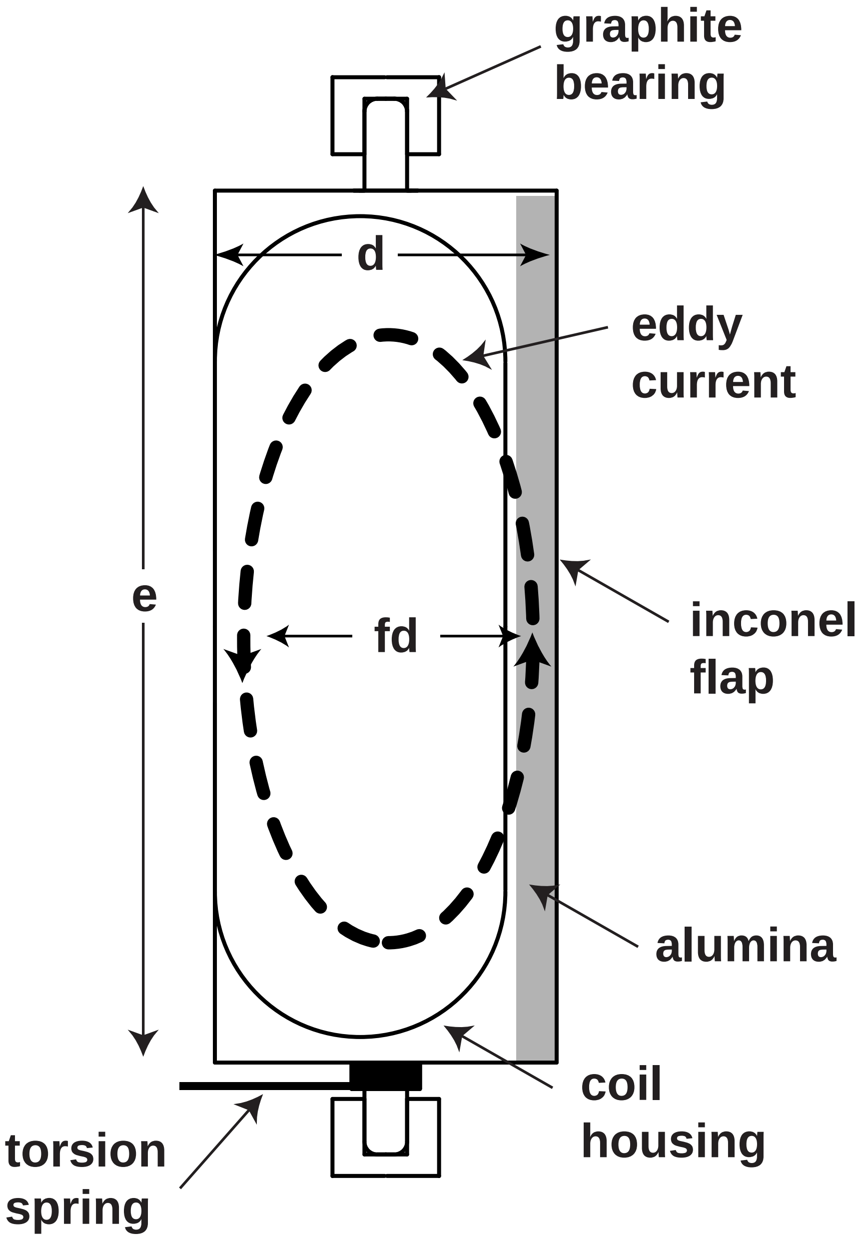

graphite
bearing
d
eddy
current
e
fd
inconel
flap
alumina
coil
housing
torsion
spring

Fig. 4

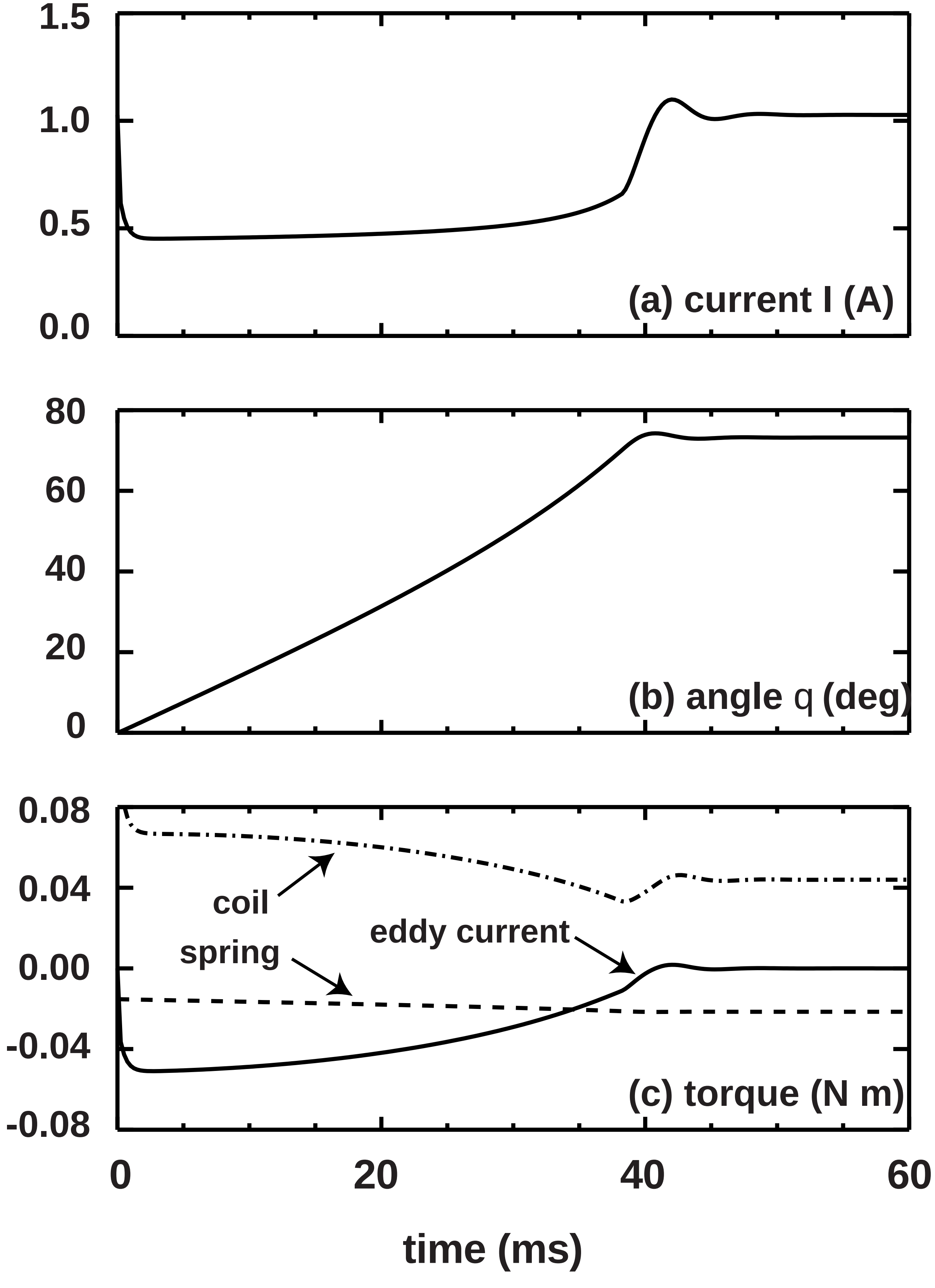

1.5
1.0
0.5
0.0
(a) current I (A)
80
60
40
20
0
(b) angle q (deg)
0.08
0.04
0.00
-0.04
-0.08
coil
spring
eddy current
(c) torque (N m)
0
20
40
60
time (ms)

Fig. 5

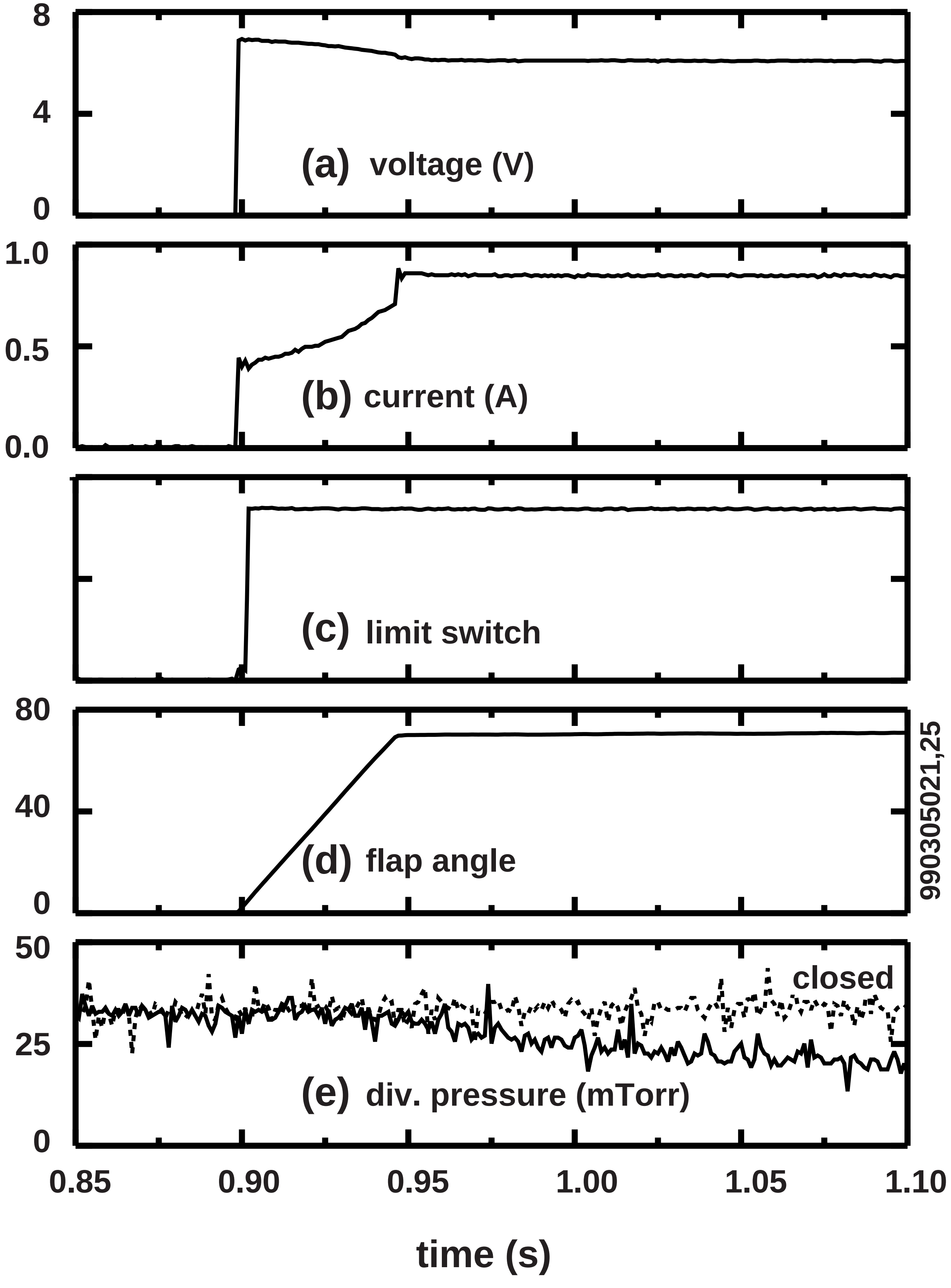
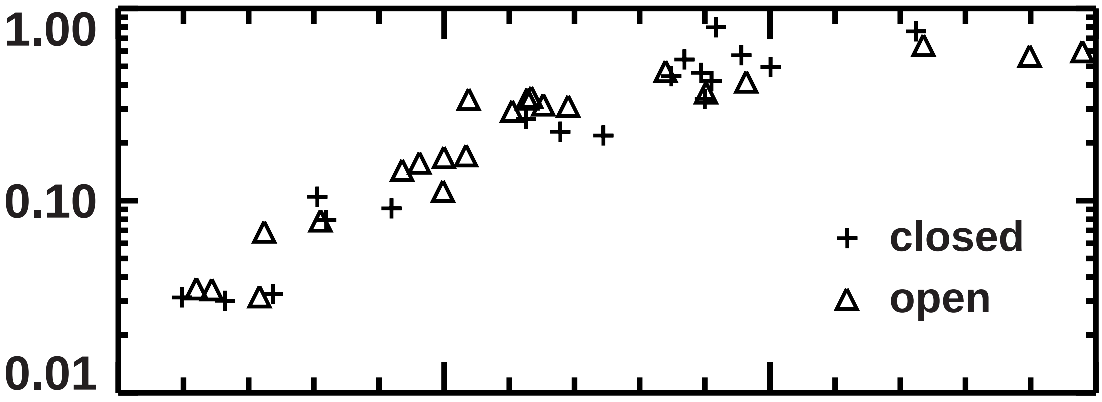
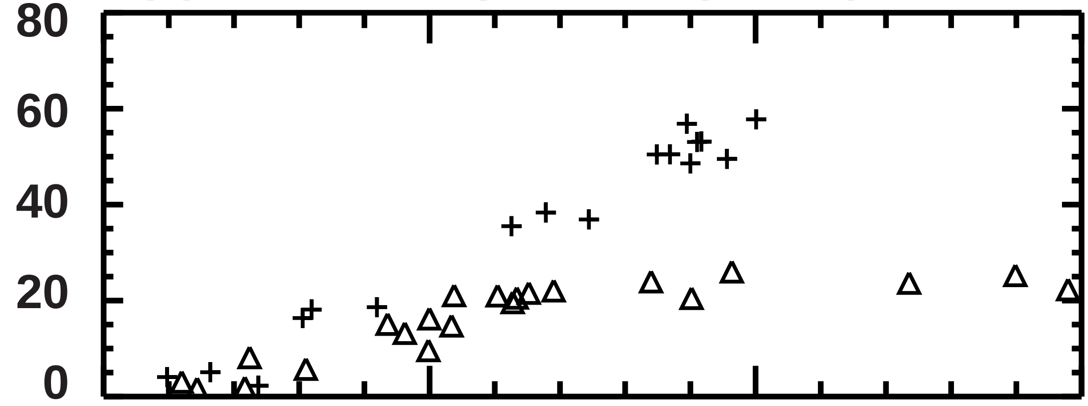

8
4
0
(a) voltage (V)
1.0
0.5
0.0
(b) current (A)
(c) limit switch
80
40
0
(d) flap angle
990305021,25
50
25
0
closed
(e) div. pressure (mTorr)
0.85
0.90
0.95
1.00
1.05
1.10
time (s)

Fig. 6

(a) D_2 main chamber pressure (mTorr)



(b) D_2 divertor pressure (mTorr)



(c) D_2 compression ratio