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PULSED HIGH CURRENT OPTICS FOR THE FERMILAB ANTIPROTON SOURCE

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ABSTRACT

The production parameters for the Fermilab antiproton source are p=5.4 GeV/c, $\varepsilon=5\pi\mathrm{x}10^{-6}$ m, $\Delta p/p=\pm 2\%$. The optimum conditions of $\overline{p}$ production may be provided only by using a short focus optical device with high magnetic field as is shown in /1/. These pulsed devices with B>100 kG are lithium lenses, parabolic lenses and special high gradient pulsed quadrupoles.

The dependence of $\overline{p}$ collection efficiency on the angular acceptance for different focusing devices in comparison with an ideal lens is shown in Fig. 1. This dependence is taken from /2/ and has been obtained as result of the computer simulation of the capture efficiency into acceptance $\varepsilon=5\cdot10^{-6}$ m, $\Delta p/p=\pm 2\%$ taking into account chromatic aberrations, nuclear absorption, and multiple scattering in lithium and beryllium lenses.

1. Lithium lenses /3/

The lithium lens to focus 80 GeV proton beam onto the production target is described in /4/ in detail and is shown in Figs. 2,3. The lens for collecting $\overline{p}$ within the angle α=50 m has the parameters aperture $2R_a$=1.2 cm., length ℓ=6 cm., B_{max}=140 kG, I=420 kA with a pulse duration τ=400 μsec. The stored energy of the power supply system is W~15 kJ. The structure of the lens is clear from Figs. 4,5. The current supply of the lens is provided by a matching transformer with turns ratio N=10. Its design is very like the one shown in Fig. 2. We use air insulation between primary and secondary turns here also, but in this case the laminated iron core makes a complete circuit for better flux linkage. Reliable current connection between the lens and transformer is obtained by means of twenty levers as shown in Figs. 4,5. In later development the levers will be remotely movable for easy replacement of the top part of the lens.

2. Parabolic lens (Figs. 6,7)

The shape of the current envelope is chosen for insuring the linear dependence of a particle's exit trajectory on its entrance angle (so called "linear lens" /5/). It provides the minimum of geometric aberrations. The lens has the following parameters: F=25 cm., I=180 kA at p=5.4 GeV/c, inductance L$\simeq$20 nH, neck diameter $2r_0$=0.5 cm., and B_{max}=144 kG. The collection angle is α=50 mrad. The particle loss on the neck is $\lesssim$4%. The wall thickness is varied along lens as $\Delta=\Delta_0 r_0/r$, where Δ_0=0.5 mm. The lenses can be fabricated of either Al or Be. The collecting efficiency of the beryllium lens is quite satisfactory (by Fig. 1). The current connection structure is clear from Fig. 6. Cylindrical conductors (2,4) insure axially symmetric current input. The cylinder (2) is cut diametrically in half and can move along the oxide coated aluminum insulator (3), avoiding mechanical stress on the lens body when tightening the contact at the lens ends. The lens is placed onto exactly the same secondary as the proton beam lithium lens and has exactly the same pulsed current supply system. The pulse duration is τ=50 μsec. In the event of failure, we need only replace one lens with another. A simple air cooling system can be used for cooling this lens for one pulse per five second operation. The optical and mechanical properties and test results for such lenses are described in detail in /5,6/. The fabrication technology of beryllium lenses of similar geometrical size has been developed at INP /6/.

3. Pulsed quadrupole triplet

The possibility of the creation of quads with magnetic fields of more than 100 kG has been studied at INP as far back as 1975, viz., a pulsed single turn device without iron in which the magnetic field is determined by means of the special form of the current conductors. To obtain linear field within the aperture to specified accuracy, the experimental and numerical investigation of the dependence of the field nonlinearity on the current pulse duration (skin depth) and the point and angle of the cut of the current conductors (α and d in Fig. 8a) has been pursued with different conductor geometries. The angle of cut of the conductors α and the values R_c/R_a, R_o/R_a, d/R_a and δ/R_a have been chosen as adjustable parameters where R_a is the aperture radius, R_c is the conductor surface radius, d is the conductor height (Fig. 8a), and δ is the effective skin depth. The results given in Fig. 8b, c,d demonstrate the dependence of the field nonlinearity on δ/R_a and R_c/R_a and the ratio of the stored energy in the aperture to full stored energy, W_a/W_o. These dependences show that from the point of view minimum stored energy, heat dissipation, and absolute value of the magnetic field it seems advantageous to take $1.3 \leq R_c/R_a \leq 1.6$ and $0.1 \leq \delta/R_a \leq 0.2$. Trapezoidal shape of the conductors is simpler to fabricate and has slightly more effective W_a/W_o but worse gradient uniformity within the aperture. For experimental test and investigation of the mechanical properties, some quads with fields >100 kG, length 23 cm., and $2R_a$=1.6 cm. aperture have been fabricated. The quad (Fig. 9) has been machined from a single block of copper and has a laminated iron core guiding magnetic flux where the magnetic field does not exceed 20 kG. Magnetic flux guides have been formed by means of iron rings 0.5 mm thick cut in half so that they may be placed over the insulated cylindrical surfaces of the conductors (9). In assembly each plate is turned relative to the next one by 90°. By means of the magnetic flux guide radial strength is insured and the lens efficiency (W_a/W_o) is increased by 15 to 20%. The magnetic field pressure on the conductor surface creates a radial force of more than 10 T on each conductor. This force is transmitted to the iron through the thin insulation (9) located where the conductor's supported surface is increased considerably. To contain the radial force the entire structure is held very tightly by means of a binding of thin steel wire (1mmϕ)(4) wound over a second thin insulation (3) under great tension. Glass fiber insulators (5) are fit tightly between the conductors. By means of the wire binding, pre-compression of the structure exceeding the magnetic field pressure is insured. After winding, all structures are impregnated with epoxy resin under high pressure. After impregnation the conductor surface (6) is carefully machined to obtain a precise profile by a special tool. In the axial direction the structure is tightened between two cuplike iron flanges (7) by six longitudinal rods (8). Each of the conductors have been extended at its end by wide, flat conductors (10) to insure reliable current input for pulses of up to 400 kA amplitude. The lens is supplied by unipolar current pulses of duration τ=300 μsec and amplitude I_o=330 kA from a stepdown matching transformer. The magnetic field gradient is 150 kG/cm. The stored energy is W~10 kJ. Tests were carried out with these parameters and the lens has survived for 10^6 pulses without failure.

We have considered the possibility of the creation on the basis of such quads a triplet for $\overline{p}$ collection for the FNAL project. The triplet would have the parameters L_1=9 cm., L_2=11 cm., L_3=5.6 cm., drifts d_1=4 cm. and d_2=5 cm., magnetic field gradient G=150 kG/cm and focal lengths F_x=28 cm., F_z=35.7 cm.. All lenses would be supplied in series with current I_o=330 kA. The full stored energy of the power supply system is W≈20 kJ.

We can see that a quadrupole triplet with even so great a gradient as 100 kG/cm has collection efficiency less than the short focus lithium lens. In this case the collection efficiency reduction is only due to chromatic aberration, because of the value of the β function in the middle quadrupole is large.

FIGURE CAPTIONS

Figure

1 Capture efficiency versus angular acceptance at the target for antiproton collection: 1 - ideal lens. 2 - lithium lens with F=10 cm., ℓ=7.5 cm., $2R_a$=1.2 cm. 3 - quadrupole triplet with field gradient 150 kG/cm., aperture $2R_a$=1.6 cm. and F_x=28 cm., F_z=35.7 cm. The beam's losses due to aperture restriction have been taken into account by the computer simulation of the capture efficiency. 4 and 5 - linear parabolic lenses with F=25 cm. made of beryllium and aluminum, respectively.

2,3 Li-lenses described in Ref. /4/

4 The antiproton lithium lens cross-section: 1 - flat current input, 2 - current connection cups, 3 - beryllium windows, 4 - titanium envelope of the lens, 5 - lithium axi-symmetric current input, 6 - water cooling system.

5 The antiproton lithium lens on a test transformer.

6 The parabolic lens cross-section: 1 - the lens current envelopes, 2,4 - cylindrical current input, 3 - cylindrical oxide coated aluminum insulator, 5 - current-connection, 6 - the secondary turns of the transformer.

7 The parabolic beryllium lens.

8 a) The current conductor shape: trapezoidal shape of the surface (left) and cylindrical shape of the surface (right).

b,c,d) The dependence of the magnetic field non-linearity $\Delta H/H$ at the point $x=0.8R_a$ for various R_o/R_a, δ/R_a, and d/R_a versus R_o/R_a.

b) dashed lines W_a/W_o

c) dashed lines - trapezoidal shape
solid lines - cylindrical shape

d) trapezoidal shape of the current conductors

9 The pulsed quadrupole cross-section: 1 - copper conductors, 2 - laminated iron core, 3,9 - thin glass fiber insulators, 4 - steel wire binding, 5 - glass fiber insulators, 6 - precise conductor surface, 7 - iron flanges, 8 - longitudinal tension rods, 10 - wide, flat current input.

10 The quadrupole lens at the test transformer.

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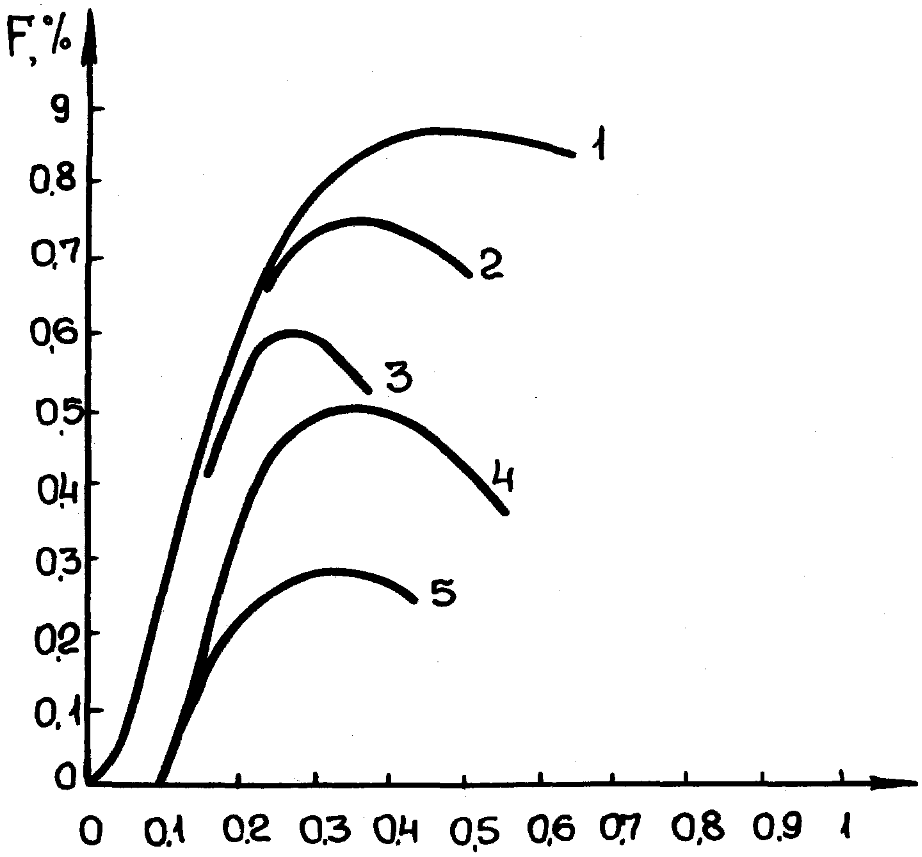
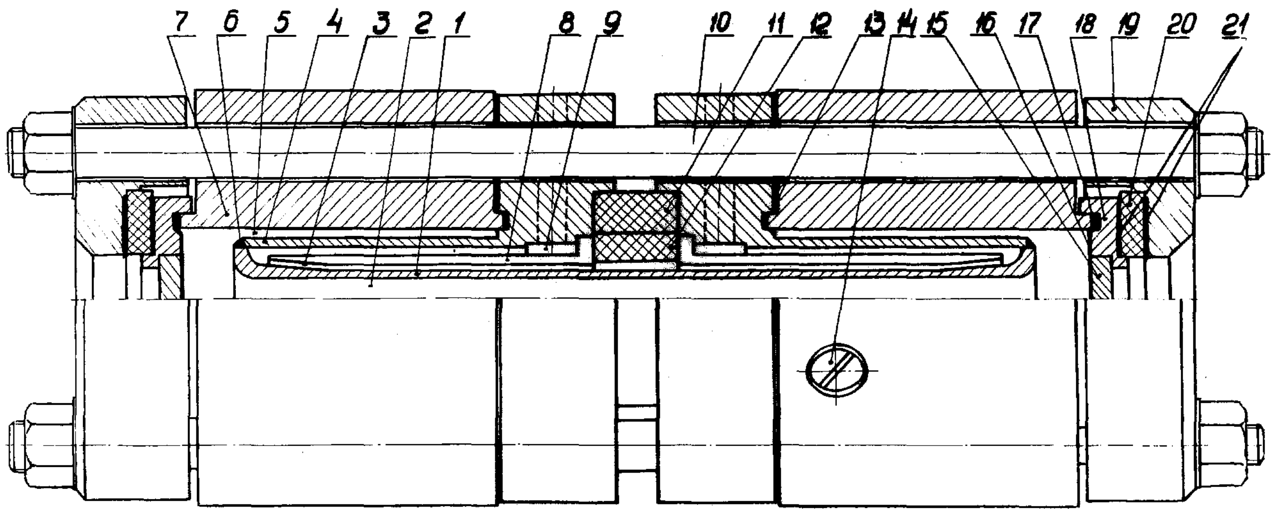


Figure 1



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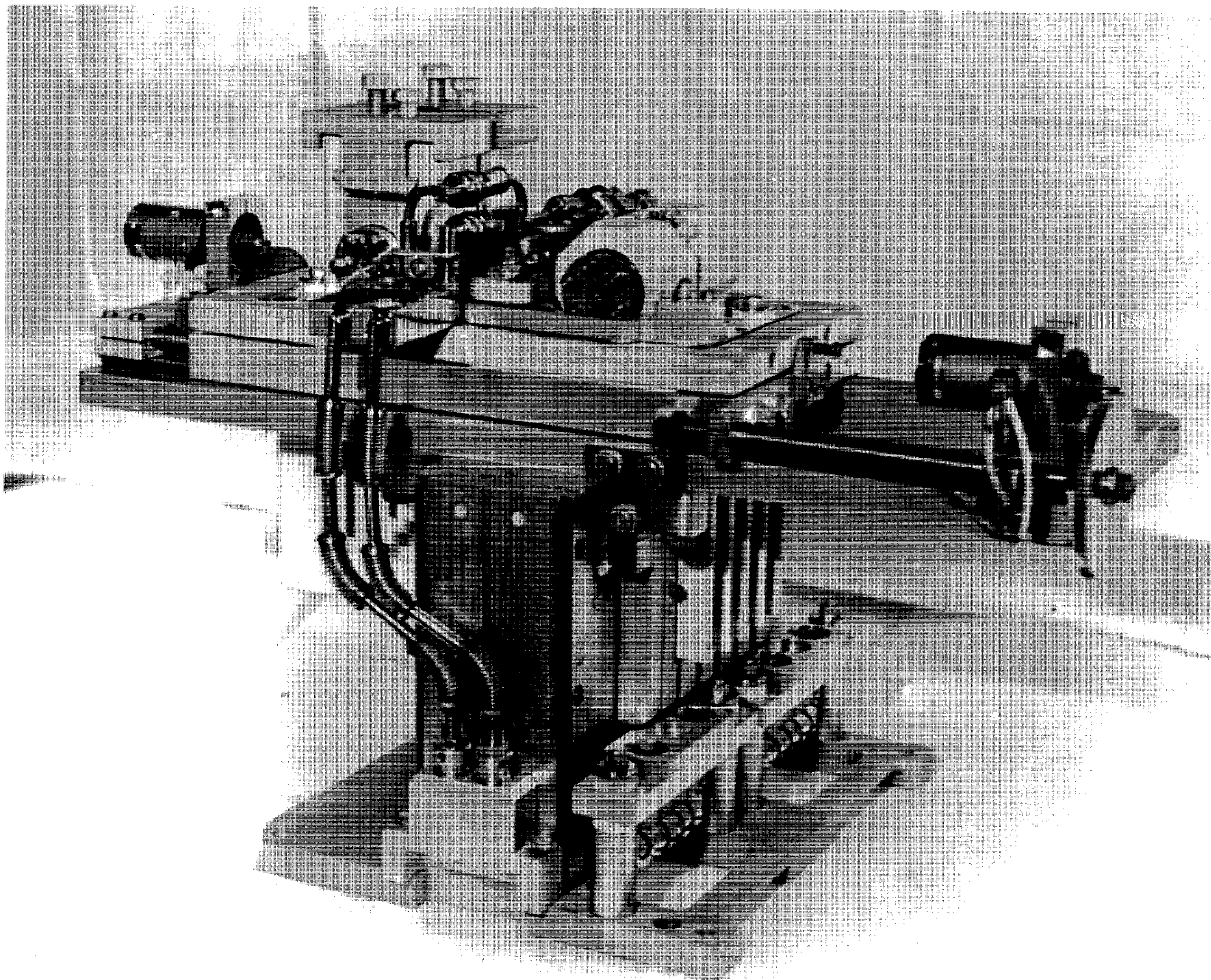
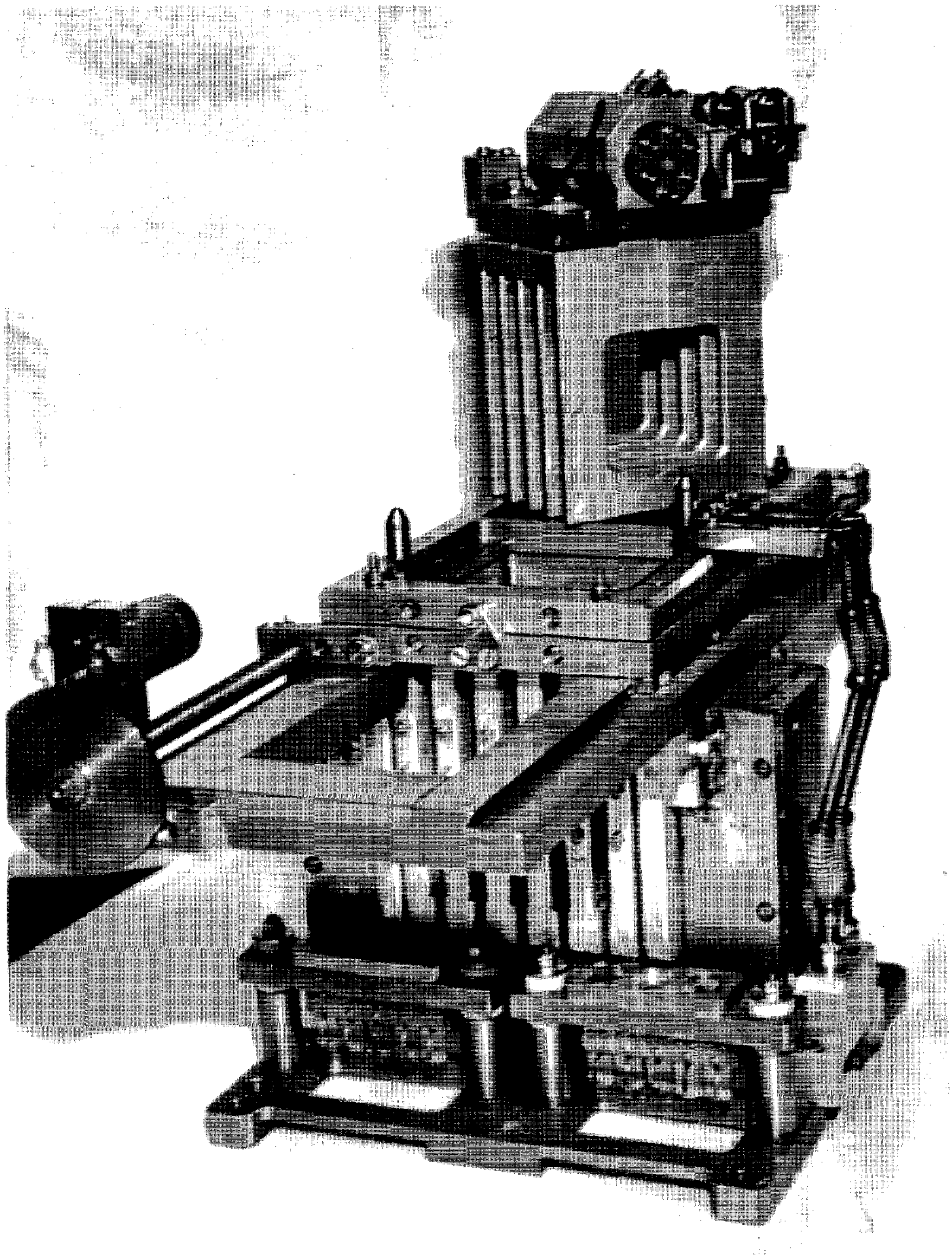


Figure 3A



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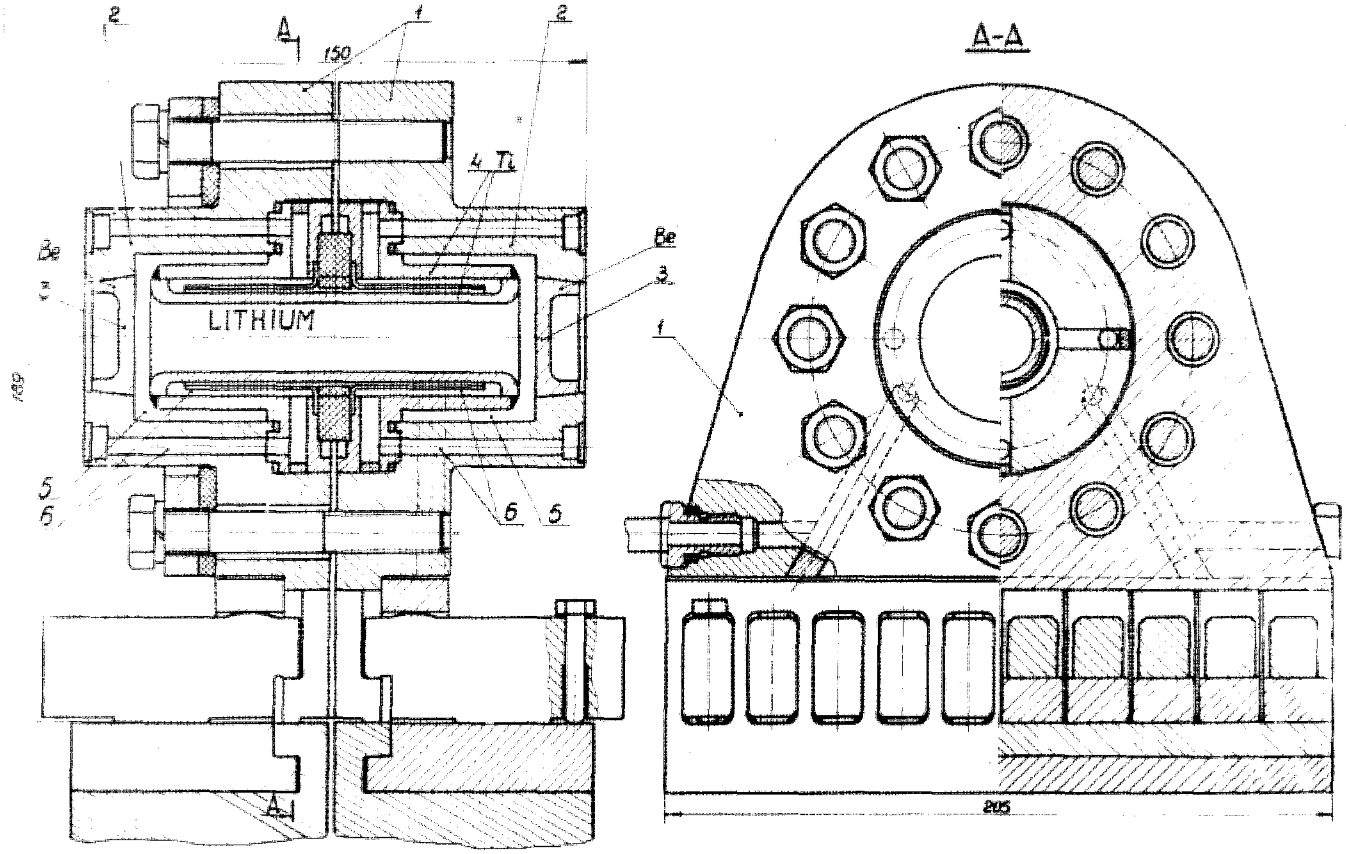

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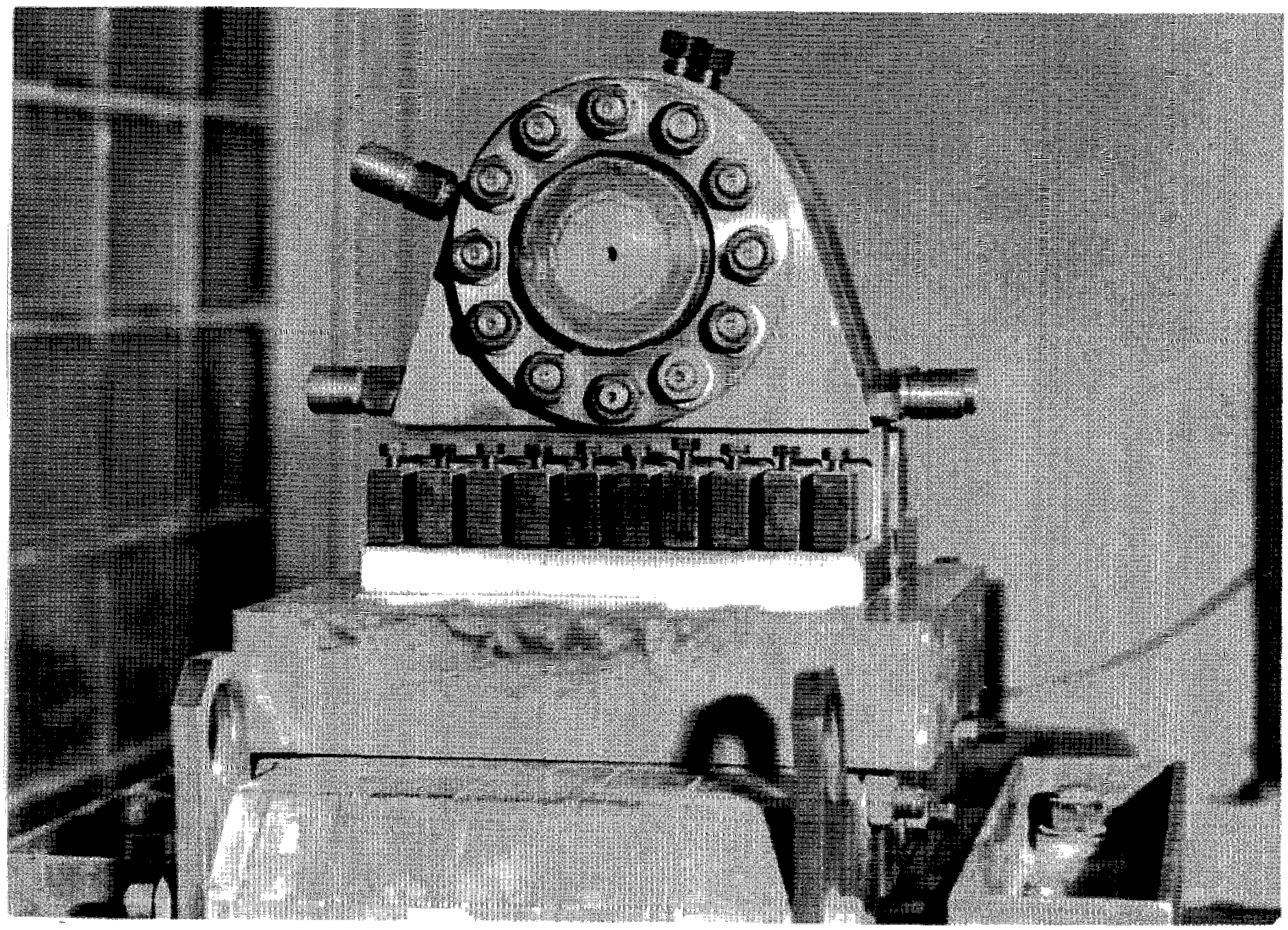

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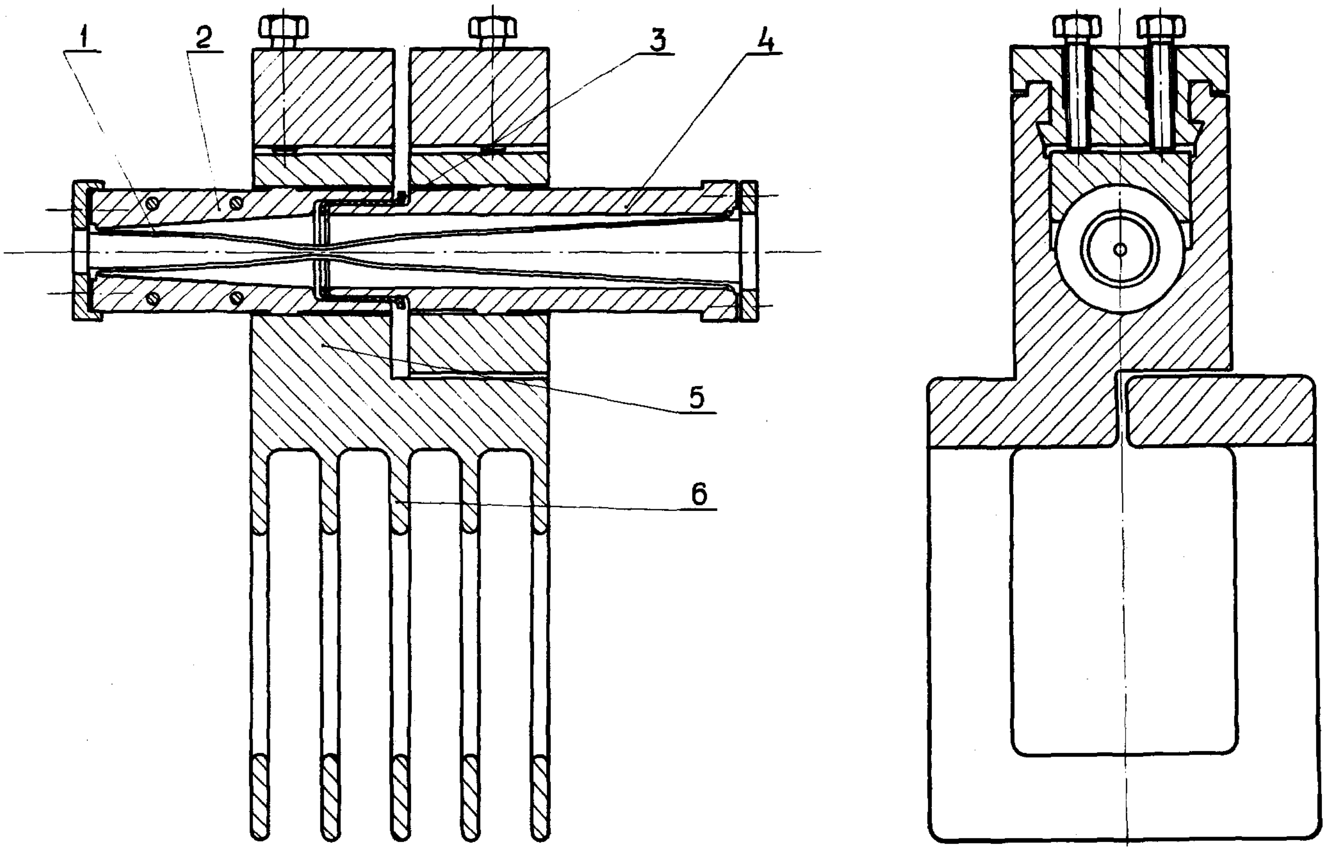

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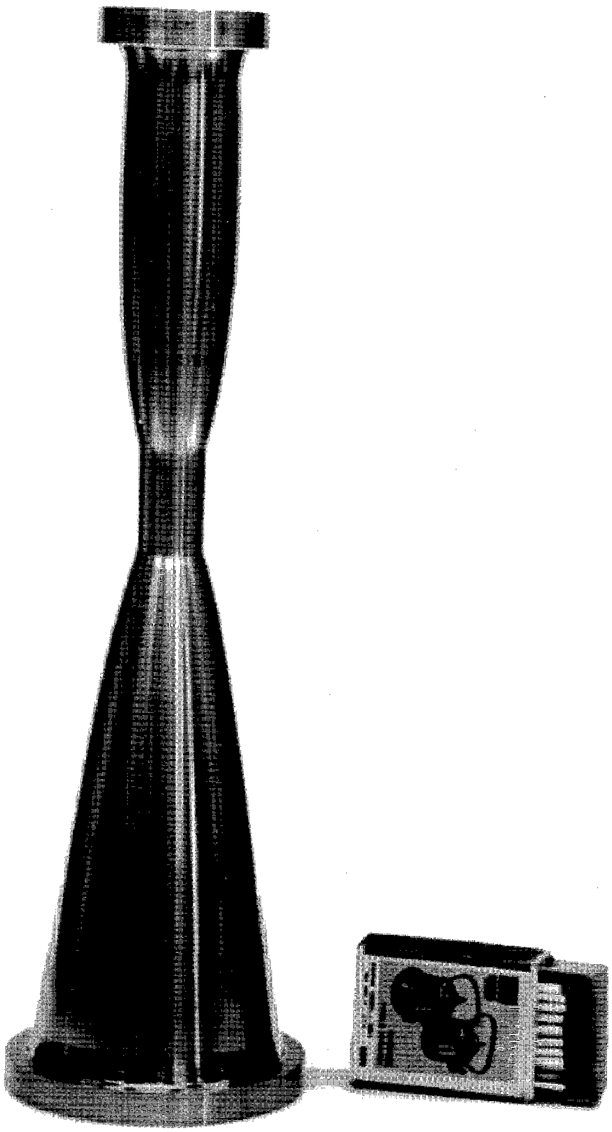

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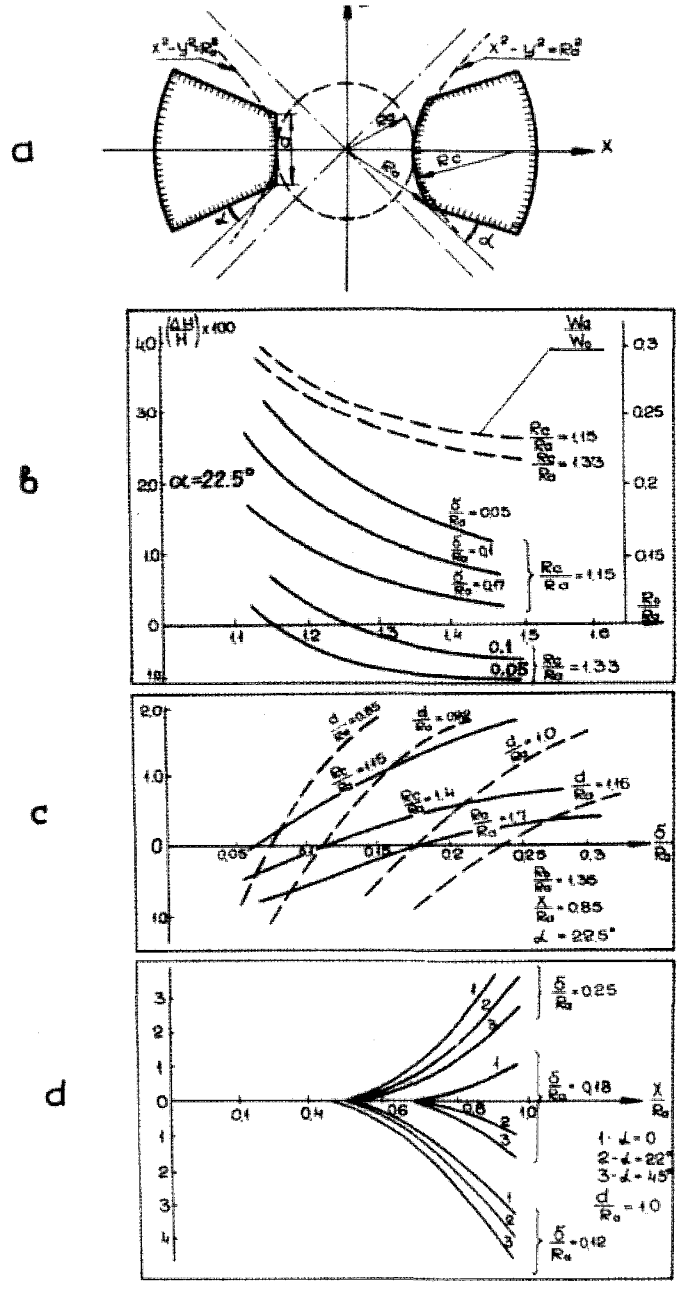

Figure 8a,b,c,d

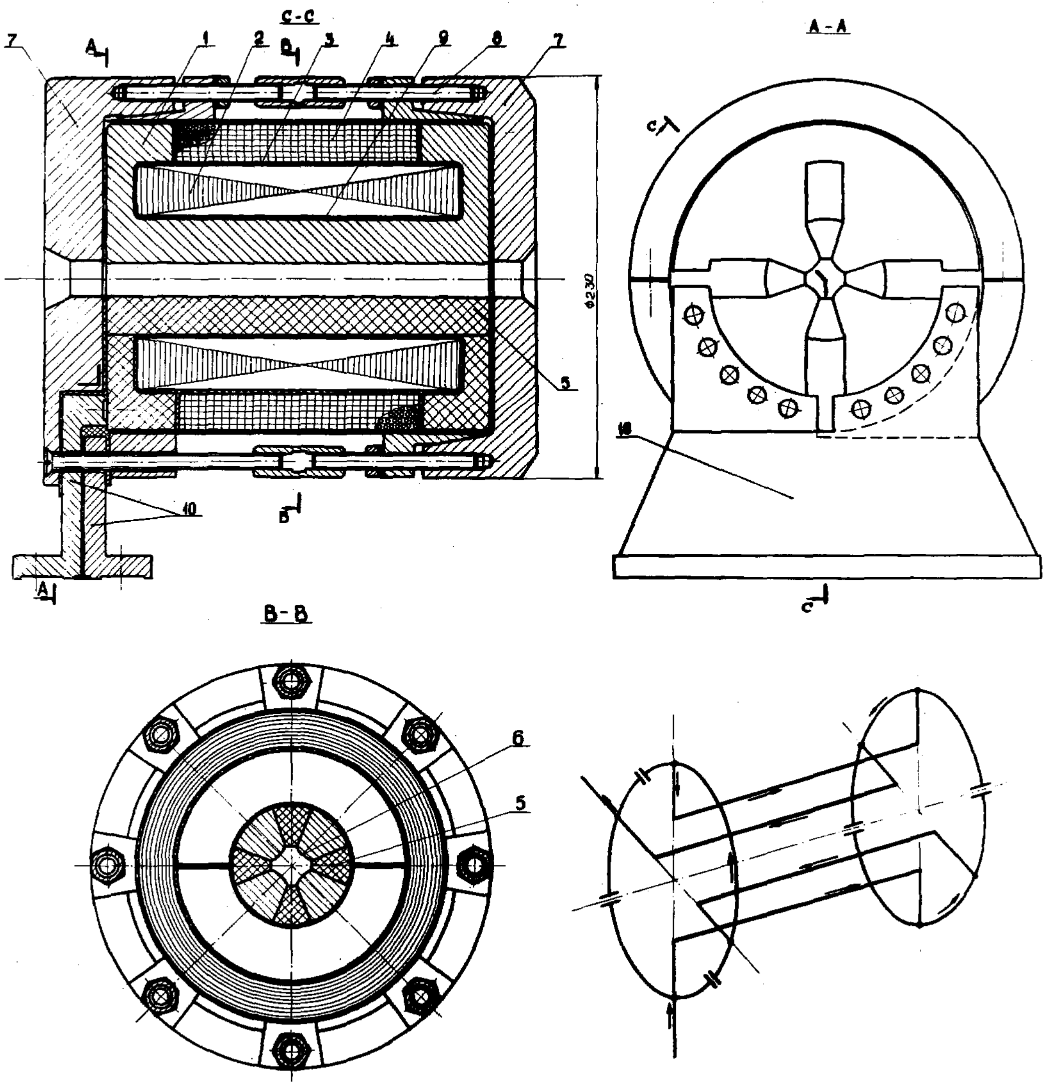

Figure 9

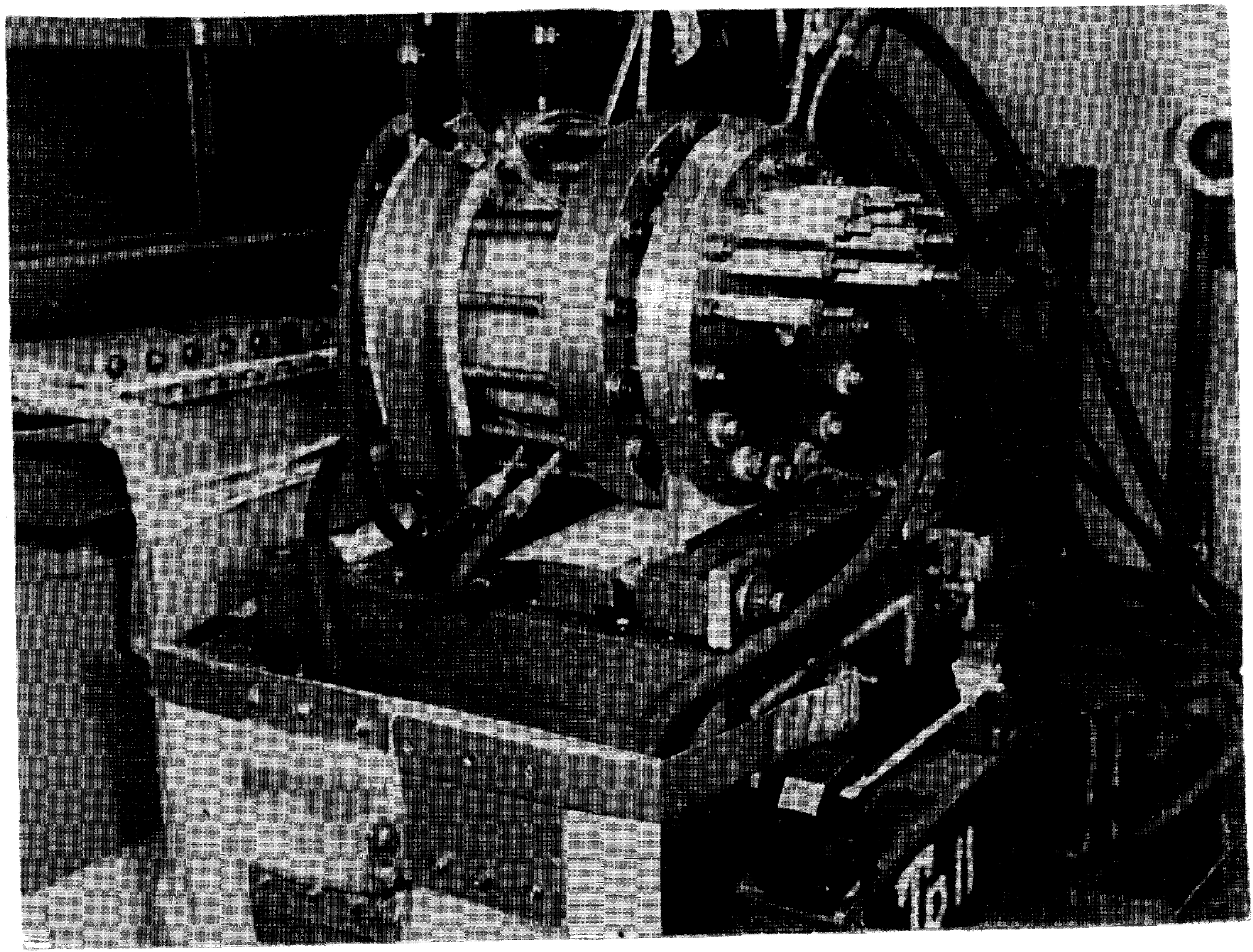

Figure 10