ELECTRON BEAM COOLING - PROSPECTS OF RIBBON-TYPE E-BEAMS

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Some time ago we made an exercise to find out how an electron beam cooling device would look if you had to cool antiprotons with very large momentum bite. In the device described below the 100 MeV antiprotons will concentrate at the lower end of its momentum range. The spot size will of course depend on the electron temperature.

I. General Description

The beam profile of the antiprotons in the cooling straight sections is 700 mm wide and 136 mm high. The electron beam will cover the antiproton beam in the width, i.e., 700 mm, whereas the height will be 80 mm. This profile will be maintained all the way from cathode to collector in order to keep the transverse temperature of the electrons as low as possible. The momentum spread in the antiproton beam requires the corresponding momentum spread in the electrons, i.e., ±6%. This can be achieved by surrounding the electron beam with a wire cage, in which the wires are parallel with the electrons. Each wire is kept at the appropriate potential, creating inside the cage a potential distribution so that the electrons entering the cage are post-accelerated.

The total potential difference across the cage is 15 kV; the higher potential is at the outside of the cooling ring. The magnetic guiding field in the straight sections is uniform and parallel to the electron velocity; its value is 600 G. The solenoid creating this field has a circular section with a bore of 1 m, so that there is ample space to stiffen the flat vacuum tank and to accommodate high-voltage feedthroughs and other diagnostic means. The electron beam must bypass the lattice elements of the storage ring. Hence the electron beam is bent in at the upstream end of the cooling straight section and bent out at the downstream end of the cooling straight section. The bending is achieved by a toroidal magnetic field on which is superimposed a weak dipole field of about 2.6 G which has actually a small gradient in order to minimize the transverse temperature.

The torus is a substantial piece of equipment, for it has to accept the antiproton beam as well. The bending radius of the torus is 3.15 m at the center of the electron beam. The bore of the torus is 2.75 m, the angle of bending is 45°. The electron beam in one upstream bypass is actually in line with the electron beam in the preceding downstream bypass. Hence it is possible to daisy-chain the electron beams of the four cooling sections so that we need only one electron gun and one collector. The acceleration of the electrons to the final energy will be in magnetically confined flow. The cathode of the gun will be of the dispenser type and will be built up of rectangular slabs to obtain the required cathode emitting area of 700 × 80 mm.

The cathode has the conventional Pierce-type focusing electrodes ensuring uniform current density of 0.2 A cm^{-2}, and a set of four focusing slits of the resonant type. The electrons leaving the last slit will be post accelerated to assume the potential in the wire cage. Upon entering the collector region they will be decelerated by the same amount so that they pass the magnetic shunt with approximately equal energy. The magnetic shunt exerts an outward force on the electrons so that the collector is appreciably wider than the original electron beam. This facilitates collection of electrons at a potential only a few kilovolts above the cathode potential and minimizes the electron backstream.

Considerable attention has been given to the problem of space charge neutralizing the electron beam. Partial space-charge neutralization, to the amount of $(1 - \beta^2)$, would keep the electron paths parallel to the beam axis. However, the potential gradient in the cage seems to be prohibitive in achieving permanent trapping of (+ ve) ions. As the current density is relatively low, the peripheral transverse energy is about 1.2 eV and decreases with the square of the distance from the median plane. If, on the other hand, a system were devised in which the electrons moved in a field-free tank with initially the proper velocity spread across the beam, perfect space charge neutralization becomes a must, for otherwise a small resulting drift would mix the high and low velocity electrons in the long run.

Hence space-charge neutralization seems to be out of the question. The potential gradient in the cage would also produce a vertical drift coupled to appreciable transverse energy. However, this motion can be suppressed by superimposing a weak vertical magnetic field on the longitudinal guiding field, thus the resultant magnetic field is slightly tilted. The tilt field is proportional to dp/dx and amounts to about 1.4 G. This correction persists also in the torus: it is added to the field of the same sign needed for the bending proper, totalling about 4.0 G. The tilt fields are produced by a cage of current wires coaxial with the center line of the electron beam and outside the vacuum tank, which in addition allows small corrections to be made to ensure optimum parallelism of the electron beam and the antiproton beam. The circulating antiprotons receive in the toroids alternating vertical kicks of about 44 mrad. Vertical displacement of the large quadrupoles adjacent to the toroids would compensate for this. The above measures ensure that the electron beam apparatus is symmetric with respect to the (horizontal) median plane, which facilitates construction and alignment.

II. Magnetic Field

Figure 1 shows the assembled guiding magnets. There are four cooling solenoids of 11 m length, four bypass solenoids of 10.9 m length, and eight toroids of 45° bending angle and 2.47 m length as measured along the mean radius of 3.15 m. One of the bypass solenoids is interrupted to accommodate gun, collector, and vacuum pumps. The solenoidal field is 600 G. The toroidal field is matched to the same value at a radius of 3.15 m. The current density in the copper coils is conservative, 3 A mm^{-3}. The effective copper thickness is 16 mm. A return mild steel shield is foreseen. The flux density in the shield will be 10 times the internal field. The shield will effectively protect the electron beam from stray fields and from the leads powering the coils. The coil will be moulded in the shield. The coil structure is sufficiently stiff to be supported from the ground in two V blocks. Solenoids are bolted to the toriods by means of flanges.

Table 1 gives particulars about the amount of copper, steel, and power. Figure 2 shows a section of the current wire cage which provides the tilt magnetic field; maximum currents are of the order of 5 A. The idea is to have independent control in each of the solenoids or toroids.

III. Vacuum System

Figure 3 shows the assembled vacuum tanks. There are four cooling vacuum tanks of 11 m length, four bypass vacuum tanks of 18.9 m length, and eight manifolds which are located in the toroids. In the bypass tank which houses the gun and the collector are located additional vacuum ion pumps. The manifold is built to accommodate ion getter pumps plus some titanium sublimation pumps. Each vacuum tank is aligned within its corresponding solenoid or toroid. The vacuum tank flanges will be flush with the magnet flanges. There will be a simplified bellows structure on each pair of vacuum flanges in order to handle small misalignments. Each flange will have double sealing with prevacuum in between. The high vacuum side will be metal to metal, the low vacuum side will be viton. The 11 m tank would weigh about 1800 kg (stainless steel), the 19 m tank about 3000 kg, and the manifold 1500 kg. The total tank volume is 30 m^3. The total length of the metal-to-metal seal is about 60 m.

IV. Velocity Cage

Figure 4 shows some details of the cage in which the potential gradient is made to achieve a velocity spread of the electrons. The strips are supported on alumina spacers, which are screwed in the vacuum tank walls. Mini conflats assure vacuum tightness of the bolt holes. The strips are daisy-chained from tank to tank by means of spring contacts. In the first and last tank the strips are individually brought out by means of multiple feedthroughs. In this way complete control of the potential distribution inside the cage can be obtained. Figure 5 shows the equipotential plot in the cage, taking into account the space-charge electric field.

V. Gun

Figure 6 shows a section of the cathode and the resonant focusing slits. The design is based on the computer calculations of the circular beam of the ICE gun. Clearly the linear device with which we are concerned in this proposal needs reconsideration. Although the post acceleration program has still to be developed, the expectation is that this will give positive results as the electrons are already at 90% of their final velocity. The cathode is presumably one of the most delicate parts of the system. Preliminary discussions with a potential manufacturer resulted in a design in which the tungsten dispenser cathode is subdivided into rectangular slabs of 8 mm thickness, 20 mm width, and 70 mm height. Each slab has two holes in which is located a protected bifilar heater. A filament lifetime of 10,000 hours seems to be feasible. (This would be higher if oxide cathodes were utilized.) The slabs are assembled in submodules, which in turn are mounted on a molybdenum carrier. The carrier is kept at about 600°C and is mounted in its turn on a water-cooled copper base via stainless-steel studs.

The crucial part seems to be the thermal expansion which could result in bending and warping of the emitting surface. The tantalum Pierce-type focusing electrode is heat sunk so as to avoid spurious electron emission, and is mounted with heat conducting studs on the copper base. The resonant focusing slits are water-cooled to avoid damage to these electrodes in case of mal-steering of the electron beam. The flat tank being located in a round coil facilitates the high-voltage feedthrough of the various electrodes. The applied voltages are maximum of the order of -60 kV with respect to ground. Some consideration will be given to decreasing the current density, in case the tune shift of the antiproton beam is larger than can be handled. Table 2 shows some of the parameters of the gun.

VI. Collector

Figure 7 shows some details of the collector structure. The nominal current is 112A so that the power in the beam is over 6 MW. To sink this power into the collector would certainly be very difficult and wasteful. However, one can recuperate most of the power by deceleration of the electrons. To this end the collector is kept at a potential slightly higher than that of the cathode. The expectation is that between 1 and 2 kV is manageable. Secondary emission can be minimized by choosing the appropriate collector surface treatment. The magnetic field in the collector cavity is greatly reduced by means of a magnetic shunt. The so ensuring vertical component of the magnetic field would bend the electrons outwards so that the collector cavity is appreciably higher than the original height of the electron beam. The small magnetic field in the collector volume is further shaped by additional current wires in order to have the lateral velocity of the electrons reduced to a small value of the order of 100 eV at the point of impact with the collector. Table 2 shows some of the parameters of the collector.

VII. Power Supply

The power supply for the cathode potential is well stabilized to 3×10^{-5}. The rated current is 100 mA, although the cathode draws in theory no current at all. It would be advisable to make this power supply short-circuit proof. The same applies to the slit anodes; their stability is 10^{-3} and rating 10 mA. The collector power supply is rated for 150 A, 2 kV, and is stabilized to 10^{-2}. The wire cage power supply provides the appropriate potential to the wires by means of a voltage divider. Its rating is 20 kV, 100 mA, and is stabilized to 10^{-4}. The filament power supply is rated 30 V, 500 A. A separation transformer is needed to bring the collector power supply and the filament transformer on cathode potential. The rating is 380/380, 400 kVA, 50 Hz. All components at cathode potential are housed in a high-voltage Faraday cage which is surrounded by a grounded Faraday cage. The volume of the former is about 120 m^3.

VIII. Control System

It is at this stage rather difficult to specify the precision with which parameters have to be controlled. Indeed the purpose of the ICE experiment is to ascertain which parameters are critical and which are not. Consequently, some of what follows may have to be amended as the ICE experiment progresses. Clearly the relative velocity of electrons and antiprotons is the most important quantity to be controlled. This would entail precise control of the cathode potential and the cage potential. The latter could possibly be approached with a b-parameter fit. Magnetic guiding field, anode slits, and collector potentials are presumably of lesser importance. The vertical magnetic correction must be adapted to the potential gradient in the cage, and a horizontal component might be necessary to correct for misalignment and temperature effects. Diagnostic means to find out the whereabouts of the beam will have to be developed. Another part of the control would be the switching-on procedure. Apart from the interlocks, which are trivial, one should envisage adjusting the applied voltages to the magnetic field, since the latter scales with the square root of the potential to achieve minimum excursions of the electrons around their guiding centers. Without control, the electrons could hit the anode slits during the switching-on time. In this case, current protection of the anode voltages would trip the high voltage.

TABLE 1: Guiding field

	Quantity	Weight (ton) each	
11 m cooling solenoid	4	Cu 5.12	Fe 7.57
19 m bypass solenoid	4	Cu 8.84	Fe 13.07
Toroid	8	Cu 3.12	Fe 15.34

IX. Diagnostics

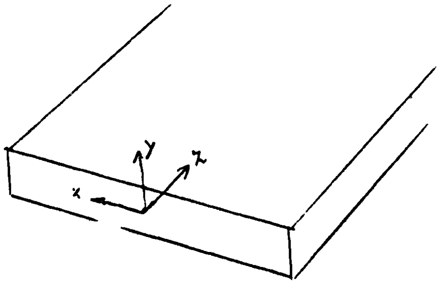
The efforts made so far in this field are mostly concerned with the effect the electron beam has on the coasting protons. Extrinsic effects as such are not within the scope of this section; rather, we discuss briefly the essential measures to ensure the correct functioning of the device. Now the power in the beam is of the order of 6 MW, although the heat content in the beam is only 6 joule. The first number tells us that permanent landing of the electron beam on some part other than the collector would damage the device. Hence fast switching-off will be in demand. Presumably, crowbarring the cathode to ground with a triggered spark gap would be possible. The spark gap would trigger on excessive current in the slit anodes, the wire cage, and in the cathode power supply. A pick-up electrode surrounded by a guard electrode is common practice in monitoring properties of an electron beam. In the present device this is only possible under pulsed conditions. Also this can be done with triggered spark gaps. A rise-time and fall-time of about 10 μsec seem within reach, and pulse lengths of up to 1 msec can be tolerated. Several movable probes would be needed to indicate the position of the electron beam. Instabilities with a time structure could be detected on the elements of the wire cage, and possibly a small but fast electric or magnetic disturbance working on the electron beam could, via the signals on the wire cage, tell the position of the beam. Intrinsic transverse temperature control has as yet not found a practical solution, but hopefully synchrotron radiation or the scattering of laser light on the spiralling electrons would some day or another show results.

TABLE 2: Gun and Collector

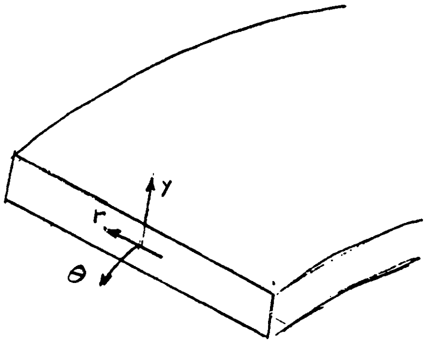
Cathode potential	-51.4	kV
Filament voltage (rated)	36	V
Filament current (rated)	500	A
1 anode slit potential	-31.4	kV
2 anode slit potential	-23.9	kV
3 anode slit potential	-12.2	kV
4 anode slit potential	-2.9	kV
perveance	7.610^{-6}	$AV^{-3/2}$
Current density	2000	$A\ m^{-2}$
Total current	112	A
Collector potential (nominal)	2	kV
Collector power (nominal)	224	kW

X. Some Pertinent Formulas

Solenoid



Toroid



Potentials	Rectangular coordinate solenoid	Cylindrical coordinate toroid
Magnetic guiding field	$A_x = B_z y$	$A_y = \mu_0 I \ln r/(2\pi)$
Self magnetic field	$A_z = -\frac{1}{2}\mu_0 j y^2$	$A_\theta = f(r,y)$ (elliptic integral)
Vertical tilt field (e.g., bending)	$A_z = -B_y x$	$A_\theta = \frac{1}{2} B_y r$
Space charge electric field	$\phi = -jZy^2/(2\beta_\parallel)$	$\phi = -jZy^2/(2\beta_\parallel)$
Cage electric field	$\phi = -E_x x$	$\phi = -E_r r$

Current density $j = 2000$ A m^{-2}

Vacuum impedance $Z = 377\ \Omega$

Relative velocity $\beta_\parallel = 0.44 \pm 6\%$

Peripheral space charge potential (with respect to the median plane) $\phi = 1370$ V

Drift angle (horizontal) $\sigma = v_x/v_z = jZy(1 - \beta_\parallel^2)/(\beta_\parallel^2 B_z c)$

Peripheral drift angle $\sigma_{max} = 5.9 \times 10^{-3}$ rad

Peripheral drift temperature $E_\perp = \frac{1}{2} mc^2 \beta_\perp^2 = 1.74$ eV

Tilt field $B_y = -(1/e)(dp/dx) = 1.41 \times 10^{-4}$ tesla (p = electron momentum)

Cage electric field $E_x = E_r = \beta c B_y = 18$ kV m^{-1}

Magnetic bending field $B_y = p/(eR) = 2.65 \times 10^{-4}$ tesla (R = 3.15 m) to be added to tilt

Budget electron cooling device in KSF

	Weight (ton)	Unit price	Quantity	Subtotal	Total
11 m cooling solenoid	12.69	214	4	856	
19 m bypass solenoid	21.91	369	4	1476	
Toroid	18.46	213	8	1704	
					4036
11 m vac. tank (cooling)	SS 1.76	70	4	280	
19 m vac. tank (bypass)	SS 3.04	114	4	456	
Toroid	SS 1.50	60	8	480	
					1216
Wire cage				280	
Gun				240	
Collector				120	
					640
Power supplies 500 kVA incl. cooling				400	
Faraday cage				100	
Manual control				100	
Remote control				200	
Cabling				100	
					900
Vacuum pumps					200
			Grand Total		6992
Power bill (in kW)					
11 m cooling solenoid		102	4	408	
19 m bypass solenoid		177	4	708	
Toroid		70	8	560	
					1676
Collector (nominal)					224
Power hut					100
			Grand total		1400

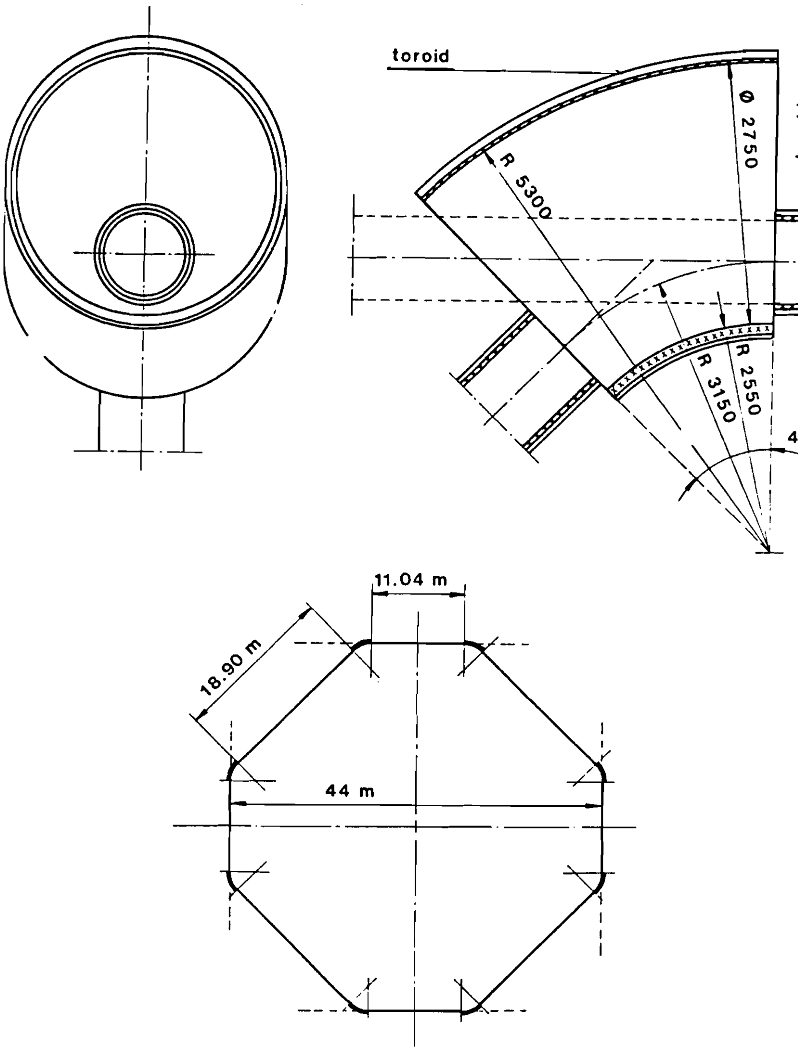


Fig. 1. Guiding magnets

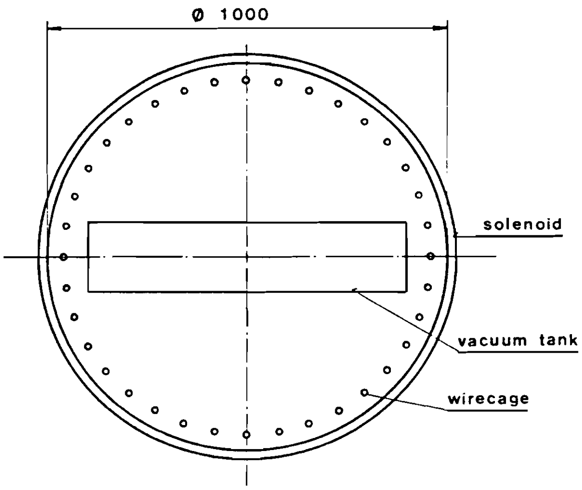


Fig. 2. Wire cage (magnetic)

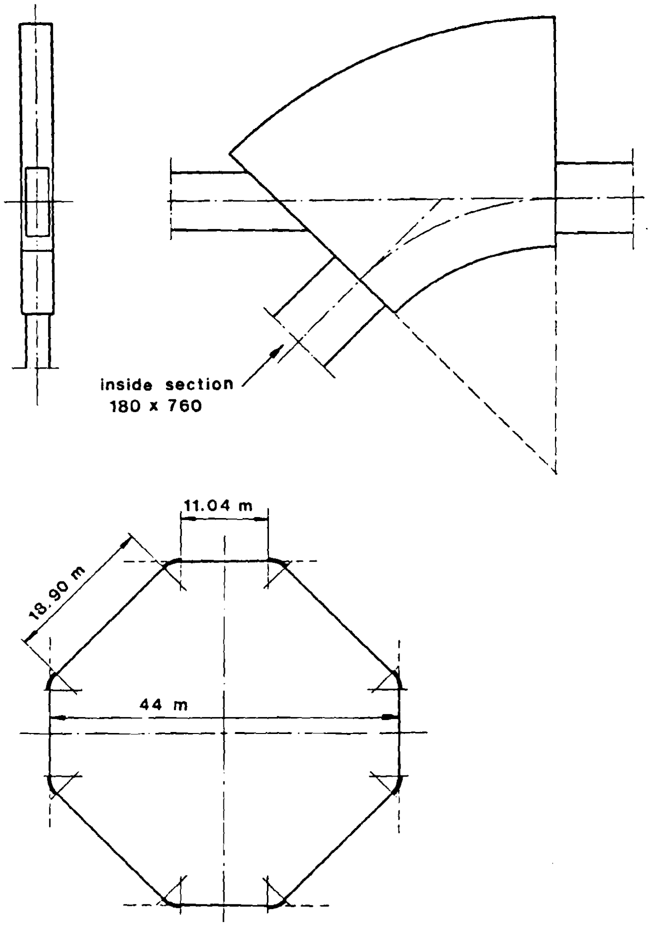


Fig. 3. Vacuum tank

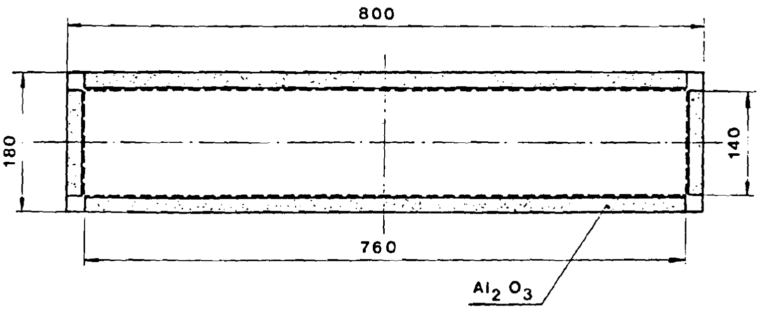


Fig. 4. Wire cage (electrostatic)

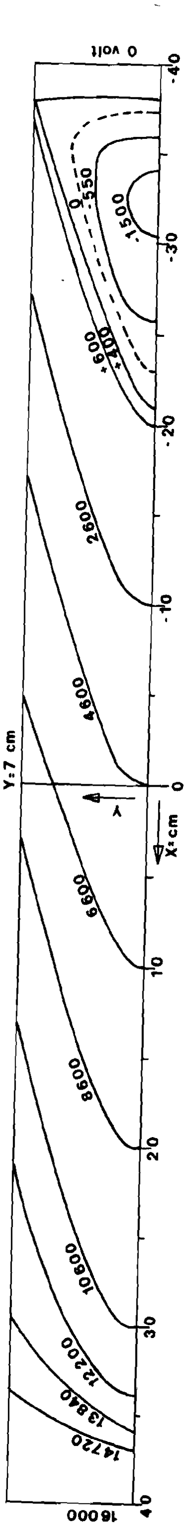


Fig. 5. Equipotential plot (including space charge)

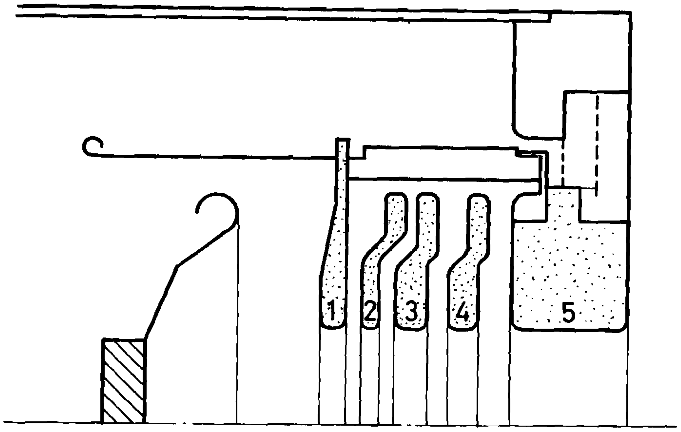


Fig. 6. Gun

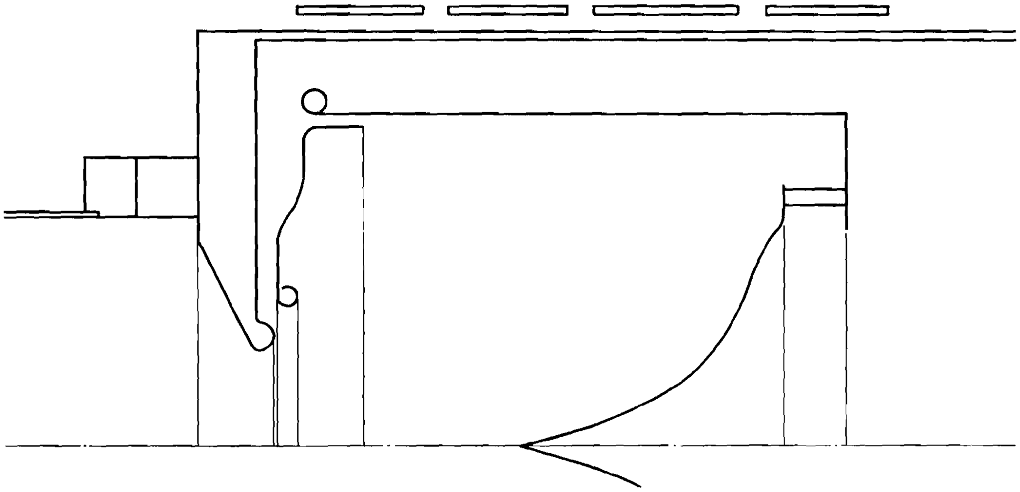


Fig. 7. Collector