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A COLLIMATOR FOR HIGH INTENSITY OPERATION OF THE CERN NARROW BAND NEUTRINO BEAM

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Abstract

Downstream of the narrow band neutrino production target, a collimator with a small fixed aperture hole absorbs those pions and kaons which fall outside the acceptance of the beam transport channel which selects the momentum of the neutrino parents. The design of this collimator is described in this report.

The 3 m long collimator has an aluminium core with a conical aperture hole with a diameter of 20 mm and 30 mm at the upstream and downstream end respectively. The aluminium core is embedded in a massive cast iron shield. Both are water-cooled for the disposal of the energy of the absorbed secondaries.

The performance of the collimator during six months of operation with short proton bursts of up to 10^{13} ppp indicate that intensities of up to 3×10^{13} ppp on the target may be tolerated.

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1. Introduction

For the SPS narrow band neutrino beam, the contamination of $\bar{\nu}$ in ν - beams or vice-versa and the muon background represent major problems. To suppress the parent particles of this background as much as possible, a collimator is placed immediately downstream of the production target. This collimator has a fixed aperture which approaches as near as possible the acceptance of the secondary beam transport channel which selects the momentum of the neutrino parents. In this way, nearly all of those particles which anyway are not accepted by the secondary beam, are absorbed in the collimator material immediately downstream of the target before their decay.

In the first instance, it is desirable that the collimator be made of a heavy material with a short absorption length which reduces further the probability of a decay in flight of the "background parents" inside the collimator.

It is however, difficult to avoid that the primary proton beam misses occasionally the target and hits directly the front face of the collimator, when the aperture of the latter is very small. In particular, the adiabatic heating of a heavy collimator material by the coherent fast resonant extracted proton beam[*)] may become problematic. In fact, such thermal problems have been experienced with collimators in CERN as well as in FERMI-LAB. Therefore, a special collimator was constructed with an aluminium core which is placed as close as possible to the production target and which offers good resistance against thermal shock and over-heating, even when irradiated accidentally with 10^{13} protons/pulse (ppp) at 400 GeV/c.

2. General Layout of the collimator

2.1 Basic requirements

To study the thermal problems created by strongly focused high intensity proton beams, measurements of the instantaneous temperature rise due to each fast extracted proton pulse have beem made in copper and aluminium[1)]. These experiments showed that copper is severely damaged when irradiated by a 400 GeV/c-beam of 5×10^{12} protons/pulse and of a focus of 5 mm diameter.

[*)] Two or more proton bursts extracted on alternate turns, each of about 23 μs duration.

In aluminium, however, the temperature rises per pulse under identical conditions were well below 100 °C.

For higher proton intensities of 10^{13} ppp and for smaller beams of 2 mm diameter, however, the temperature rises in aluminium after each pulse may still lead to material failures due to excessive thermal stresses. Nevertheless, with the help of an appropriate beam observation system, the collimator can be protected against repetitive direct irradiation which reduces substantially the risk of material failures due to fatigue. At least the central collimator core should therefore be made of aluminium in order to provide sufficient safety against thermal destruction of the collimator. The small increase of the background, due to the larger pion mean free path in aluminium (~ 50 cm) as compared to that in copper (~ 20 cm) has to be tolerated.

Under proper operational conditions, when the beam is well focused onto the target, the collimator is heated only by the emerging secondary particles. Since these are rather widely spread over the front face of the collimator, the resulting temperature rise after each pulse is of no concern.

Nevertheless, a substantial part of the average beam power, which is about 67 kW in the case of 10^{13} ppp at 400 GeV/c and a repetition time of 9.6 s, is deposited via the secondary particles in the collimator. The latter must therefore be cooled in order to avoid the build-up of excessive average steady state temperatures.

Furthermore, the actual aluminium core of the collimator must be embedded in massive cast iron blocks of at least 50 cm thickness. The latter protect other components which are installed beside the collimator, against excessive irradiation. Moreover, the thick cast iron blocks provide sufficient self-shielding against the remanent activity from the ensemble of the collimator in order to permit limited access.

The collimator length must be sufficient, firstly to absorb efficiently all "background parents", and secondly to protect the downstream beam transport elements from excessive irradiation. Therefore a collimator length in aluminium of well above 2 m is desirable.

Since future narrow band neutrino experiments will certainly require different collimator apertures, it must be possible to remove at least the aluminium core from the collimator ensemble in order to replace it by another one.

2.2 Basic design

The principal design of the narrow band neutrino collimator is shown in Fig. 1. The collimator aperture is located along the axis of a beam in aluminium alloy Aℓ Mg Si 1 of 3150 mm length and with a square cross-section of 110 mm x 110 mm. This aluminium core is assembled from a top and a bottom half piece.

Along each of the mating surfaces a groove of semi-circular shape is machined which forms, after assembly, the required circular aperture. This technique permits to provide extremely small apertures over considerable lengths.

The presently installed core carries a conical aperture with an upstream and downstream diameter of 20 mm and 30 mm respectively, which was shaped on a computer controlled machine. Since each aluminium beam was machined in longitudinal direction, small facets appear along the inner surface of the aperture hole. Details can be seen in Fig. 2, which shows a rear view of the aluminium core with its top half already mounted on the central cast iron support. Fig. 3 shows a side view of this ensemble.

As shown in Fig. 1, the ensemble of the aluminium core and its cast iron support is inserted vertically into a corresponding gap between two massive cast iron shields. In this way, the aluminium core is completely enclosed in the centre of a shielding ensemble, which has an overall width and height of 800 mm. Due to, on the one hand, the restricted longitudinal space between the target and the collimator, and on the other hand, the need to minimize the target-collimator distance, the front face of the cast iron could not be made flush with the front face of the aluminium core which protrudes by 500 mm into the shield of the neutrino target station. This upstream part of the aluminium core is supported by an aluminium structure of triangular shape, as shown in Fig. 3.

The two cast iron half shields, each 2650 mm in length and 5.5 t in weight were both placed by crane onto a prealigned support table carrying a key for the precise positioning of the two blocks. The positioning was facilitated by the tightening of two lateral tie bolts at either end of the cast iron blocks.

Thereafter the central core with a total weight of 0.8 t was lowered into the gap between the two cast iron blocks onto self centering V-shaped supports which are mounted on each shoulder of the shield. In this way, a sufficient and a reproducible lateral alignment of better than ± 0.5 mm is achieved.

By loosening the two aforementioned lateral tie bolts, the two halves of the side shield can be displaced horizontally in opposite direction. This might be of help in the event that the central core would be blocked between the two side shields and could not be lifted out.

A layout drawing of the installed collimator is shown in Fig. 4. It shows details of the narrow band neutrino target station on the left, the collimator and the target monitor on the right. The latter measures the particle flux downstream of the collimator aperture.

2.3 The cooling of the collimator

The heat deposited by the beam in the aluminium core as well as in the cast iron shield has been computed with the Monte-Carlo-cascade programmes MAGKA and FLUKA2). For the dimensioning of the cooling system it has been assumed pessimistically that a full primary proton beam of an average power of 67 kW is incident directly on the front face of the aluminium core. As a consequence, about 10% of the beam power would be deposited in the aluminium core proper while about 50% would be dissipated in the surrounding cast iron shield. The remainder of the beam power escapes mainly through the end face of the collimator. To confine more than 90% of the beam power, a cast iron shield of about 4 m length would have been necessary which is excluded due to space limitations of the present layout of the narrow band neutrino beam.

In the case of proper operation with the beam centered onto the upstream 50 cm long beryllium target, about 30% of the incident protons traverse the target as well as the collimator aperture. Therefore, the power dissipated in the different parts of the collimator is reduced accordingly. To dispose of the heat deposited in the collimator, the aluminium core as well as the cast iron shield are water-cooled. This cooling system is also indicated in the layout drawing 4. Further details are shown in perspective at various cuts along the collimator axis in Fig. 5.

The stationary cast iron shield and the cast iron part of the central insert are cooled via 5 stainless steel tubes with an inside and an outside diameter of 16 mm and 36 mm respectively. These have been placed into the mould prior to the casting of the iron. They are arranged symmetrically around the collimator axis on a radius of 180 mm.

Good adherence for the thermal contact between the stainless steel tubes and the cast iron is achieved by careful cleaning of the tubes and coating their outer surface with a thin zinc layer. The latter diffuses off the tubes during casting so that the liquid iron meets a clean stainless steel surface free of oxide. During and after casting, the stainless steel tubes were cooled by flushing with argon. Thus, deformations or a collapse of the stainless steel tubes at elevated temperatures under the hydrostatic pressure of the liquid iron are prevented.

Each tube runs from the rear of the collimator towards the front and returns through a bend of 115 mm radius towards the end face. As shown in Fig. 5, all inlets and outlets of these tubes are connected in parallel through stainless steel tubes to the main inlet and outlet water manifolds of each half shield. These are finally linked by metallic flexible hoses to the easily accessible main water manifold. All tube connections are made by welding in order to avoid water leaks.

A water flow of 1 ℓ/s through each of both side shields has been measured at a pressure drop of 6 bars between the inlet and the outlet.

Particular attention has been paid to prevent the thermal deformation or bending of the shielding blocks due to thermal gradients which may occur over the cross-section of the blocks. That relatively small lateral gradients in long structures can cause considerable deformations is shown in the following example: a linear temperature variation of 50 °C over the width of 400 mm and maintained over the total length of the block, would give rise to a horizontal sagitta of about 1.5 mm.

The major amount of the beam energy is deposited in the cast iron shield inside a central region with a radius of about 180 mm. Since the cooling pipes of the shield are located on this radius, the temperature of the cast iron beyond that circle does hardly rise. As this volume represents the part of the shield with the largest moment of inertia, the risk of thermal deformations or bending of the shield is decreased to a large extent.

The maximum steady state temperature of the cast iron shield is reached at the inside surface adjacent to the aluminium core. It has been estimated to remain well below 125 °C, even when the primary proton beam would be directly incident on the collimator face. This estimate was made under the assumption of a water temperature of 25 °C at the inlet and a perfect thermal contact between the stainless steel cooling tubes and the adjacent cast iron. It is difficult to control or to measure the quality of the above mentioned thermal contact. However, even when for example, 30% of the surface of the cooling pipes would not be in thermal contact with the surrounding iron, the maximum steady state temperature would increase by only about 10 °C.

To control nevertheless the efficiency of the cooling system and to protect the collimator against over-heating, two thermo-resistors were mounted on the top and one on the front face of the cast iron at a radial distance of 130 mm from the aluminium core. On the front face a temperature of 64 °C was registered with 10^{13} ppp of 400 GeV/c incident on the target. The temperatures at the outside surfaces of the shield remained always below 32 °C.

Particular attention has been paid to the cooling of the 3150 mm long aluminium core. The average temperature of this delicate structure must be kept as low as possible to avoid any thermal deformation of the aperture.

Aluminium tubes of a square outside cross-section of 12 mm x 12 mm and an inside diameter of 8 mm are used as cooling tubes. Each cooling pipe is electron beam welded at two side faces into a groove which is machined along each of the four corners of the aluminium beam. Fig. 6 shows the rear of the lower part of the aluminium beam. The cooling pipe of each part leads from the rear towards the front and returns through a 180° bend back to the rear of the aluminium core.

The inlets and outlets of the aluminium pipes are connected in parallel with the corresponding inlet and outlet of the stainless steel tube in the attached cast iron support to manifolds which are linked via welded metallic flexible hoses to the main water station. A water flow of 0.24 ℓ/s through the aluminium core and 0.6 ℓ/s through the cast iron support has been measured with a pressure drop of 6 bars between the inlet and the outlet. Details of this part of the cooling circuit are also shown in Fig. 5.

Average steady state temperatures at the front face of the aluminium core of 40 °C for 10^{13} ppp at 400 GeV/c on the target and a repetition time of 9.6 s have been registered. Assuming that this temperature is reached over the total length of the core, the elongation of the latter will be about 1.1 mm assuming an average water temperature of 25 °C. Therefore, the aluminium core is suspended from its cast iron support in such a way that the core is free to expand in longitudinal direction in order to avoid buckling of the aluminium beam.

Deformations of the aluminium core could also result from an asymmetric temperature field over the cross-section of the aluminium beam. A temperature difference of 10 °C between two opposite side faces over the total length of the aluminium core would for example provoke a sagitta of about 2.7 mm. Therefore, the two pipe fittings at the rear of the core which are located diagonally to each other are used as inlets and vice-versa for the outlets. This arrangement assures the maximum symmetry of the transverse temperature distribution along the aluminium core and thus an optimum geometrical stability even when the temperatures at the two outlets are systematically above those at the inlets.

An asymmetric transverse temperature field can also occur when the proton beam falls directly onto the collimator front face due to a missteering of the beam or when the target, onto which the beam is focused, is not perfectly aligned with the collimator. To reduce further the risk of buckling or deformation of the aperture due to the above effects, half circular grooves with a radius of 45 mm and a width of 3 mm have been machined by electro-erosion transversally into the mating surfaces of the aluminium half beams. The distance between adjacent grooves is 300 mm. Two of these can clearly be seen in Fig. 6. These grooves facilitate the longitudinal expansion of the hot central part of the aluminium core with respect to its cooler peripheral region which is closer to the cooling pipes. Thus, the longitudinal thermal stresses and thermal bending moments in the centre of the core are reduced. Therefore, the overall stability of the aluminium beam is dominated by its relatively cool peripheral region, which in addition has the largest moment of inertia.

3. Conclusion

The collimator downstream of the narrow band neutrino production target has now been in operation for about six months. The proton intensities incident on the 500 mm long upstream beryllium target were in average 6 - 7 x 10^{12} ppp at 400 GeV/c and a repetition time of 9.6 s. On several occasions an intensity of 10^{13} ppp was reached, during which the temperatures in the aluminium core and the cast iron of the collimator rose to 40 ^{o}C and 64 ^{o}C respectively.

These rather low temperatures maintained by the efficient water cooling system show that proton beams of about 3 x 10^{13} ppp can safely be used, provided the beam does not hit accidentally the collimator face. When the latter cannot be excluded, the proton intensity of the fast or fast resonant extracted beam must not exceed 10^{13} ppp.

Particular attention has been paid to the proper design of the aluminium core in order to avoid thermal deformation of the 3150 mm long collimator aperture. After six months of operation, the aluminium core and its aperture were visually inspected. No thermal damage or deformations of the core were found.

The basic design of the described collimator is equally valid for other beams where collimation is necessary. In particular, for slow extracted beams where the thermal shock caused by the proton burst is of no concern, the collimator core can be made of copper, which improves its stopping power. Such a collimator could be operated at intensities of up to 3×10^{13} ppp, provided the proton burst has a duration of at least 1 s.

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2) MAGKA: Lab II-RA/71-4
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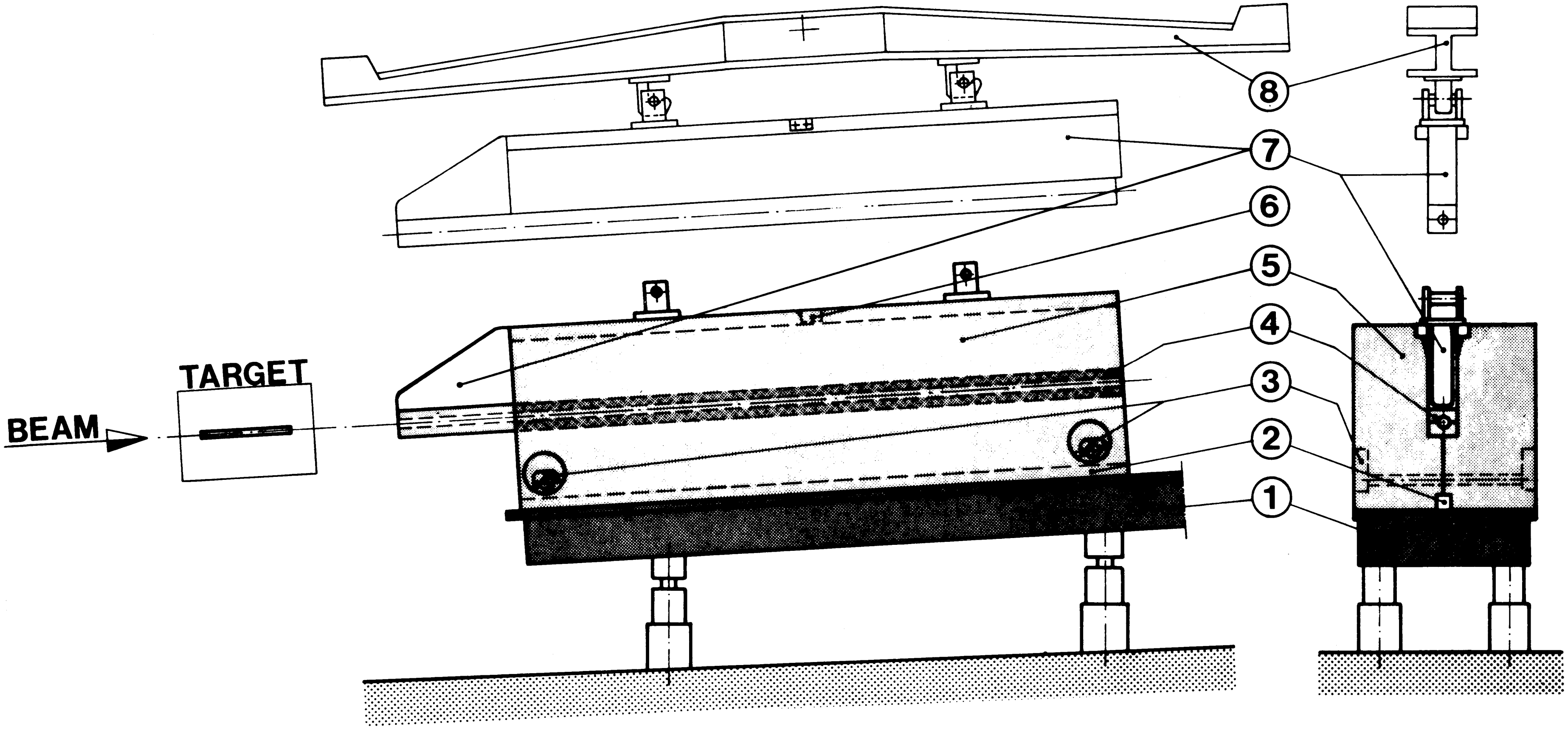

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Fig. 1 - Side and front view of the collimator with its central mobile core which is embedded inside a massive cast iron shield

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① SUPPORT TABLE
② CENTRING KEY
③ TIE BOLTS
④ AL CORE
⑤ CAST IRON SHIELD
⑥ SELF CENTRING V SUPPORT
⑦ MOBILE CENTRAL ENSEMBLE
⑧ OVERHEAD CRANE

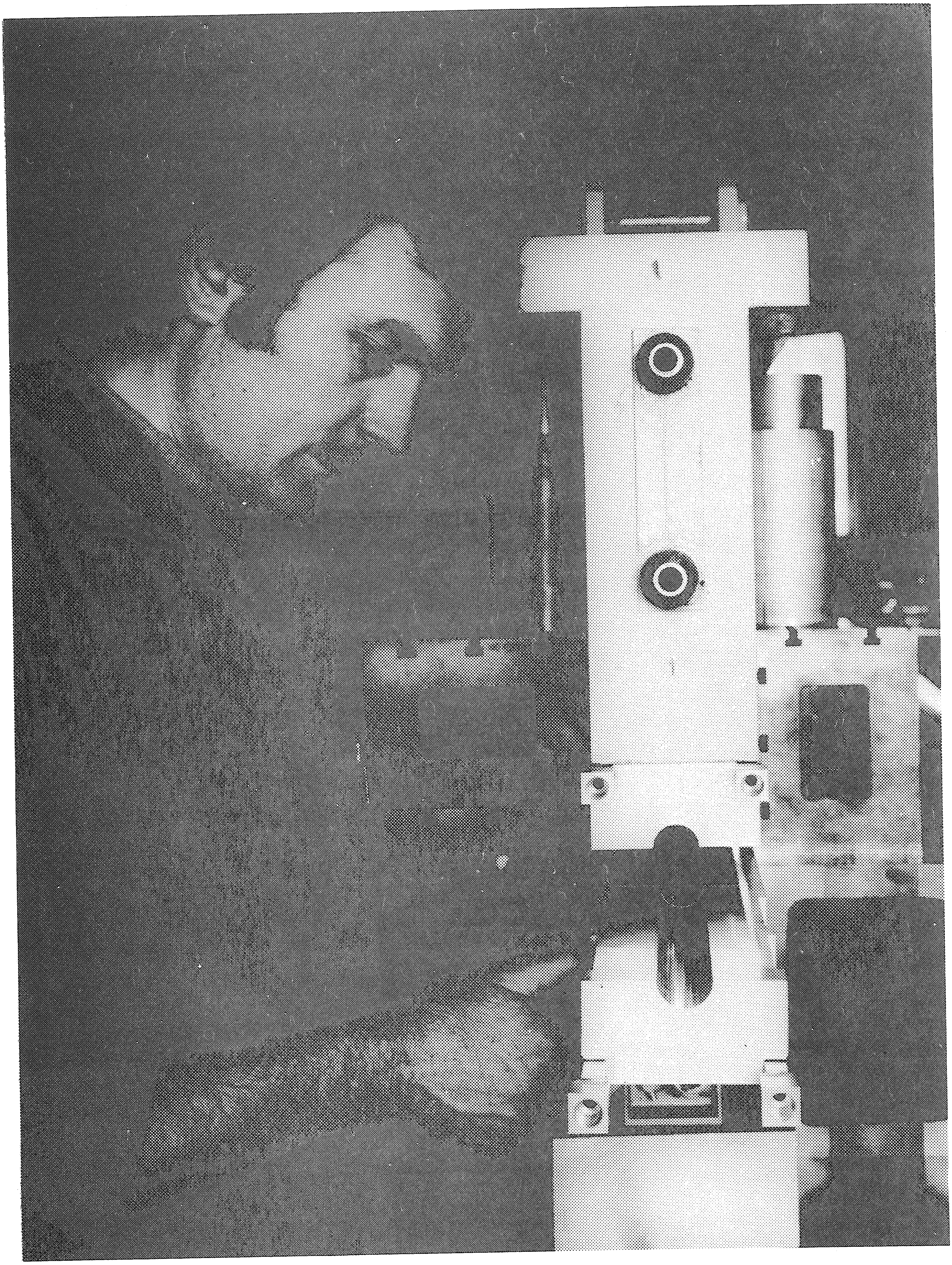

Fig. 2 - Rear view of the central collimator ensemble. It shows the assembly of the bottom half of the aluminium core and its top half which is already attached to the cast iron support.

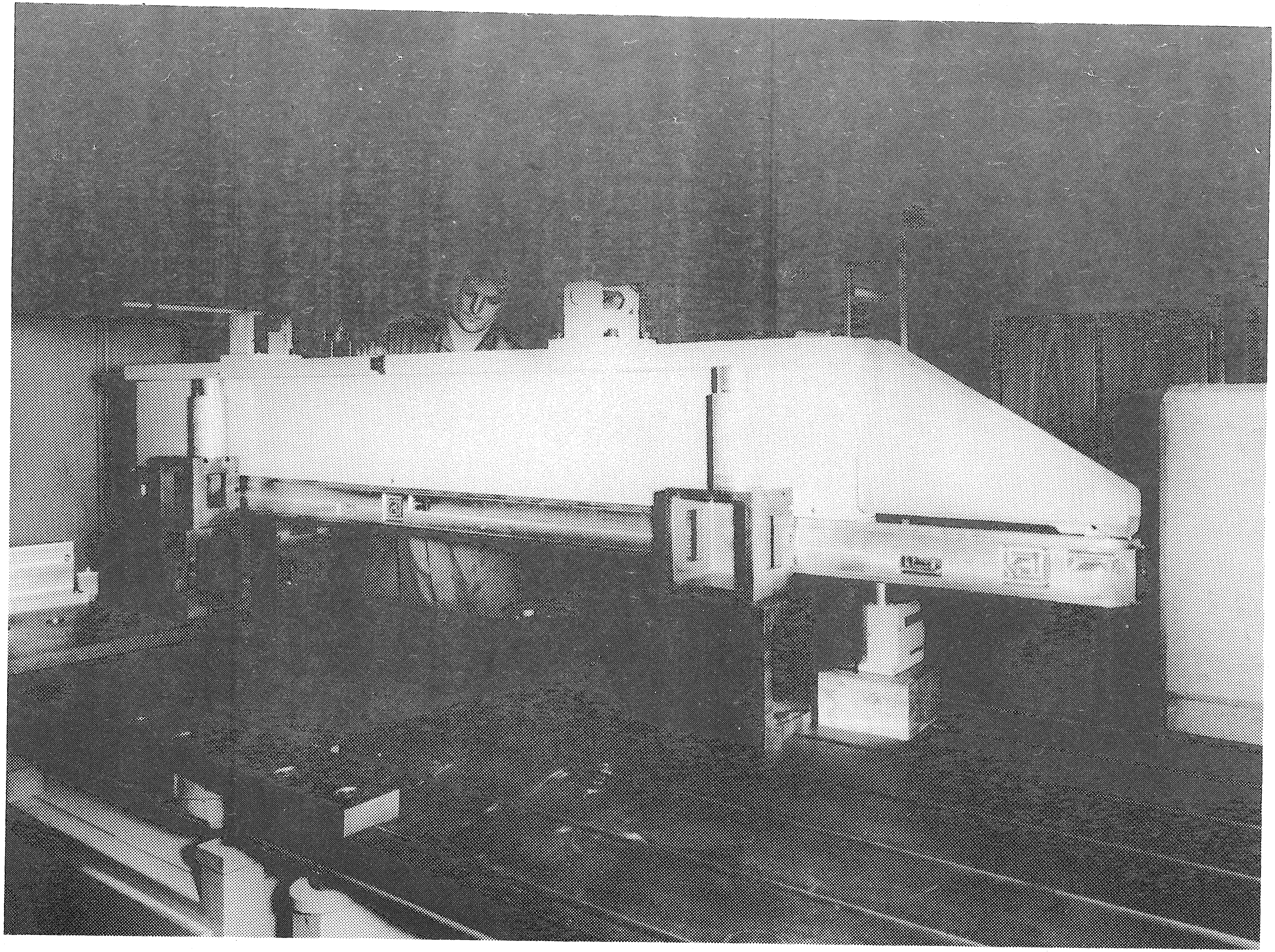

Fig. 3 - Overall view of the central collimator ensemble with its aluminium core fitted underneath its cast iron support.

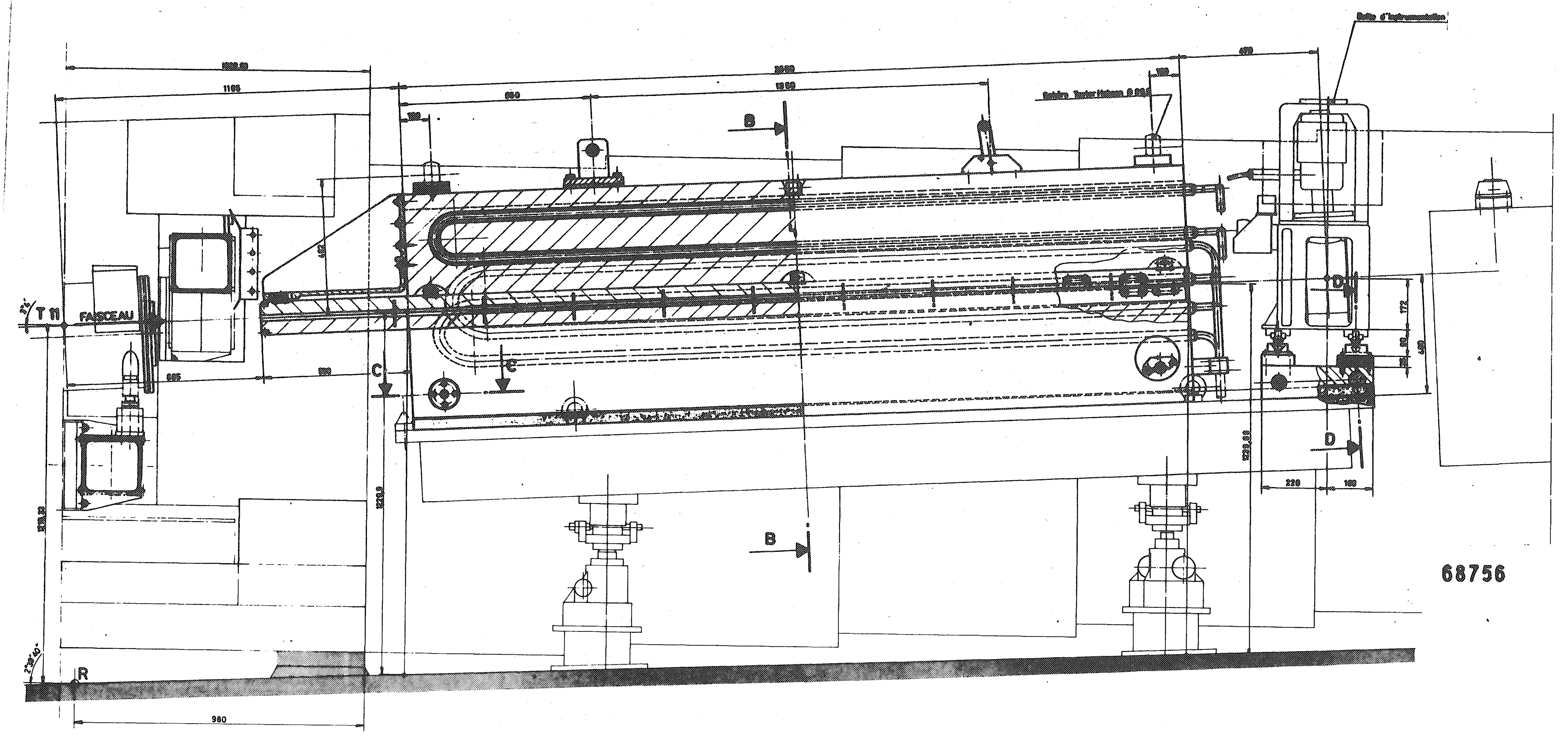

Fig. 4 - General layout of the collimator installed downstream of the narrow band neutrino target T11. The beam monitor downstream of the collimator is also indicated.

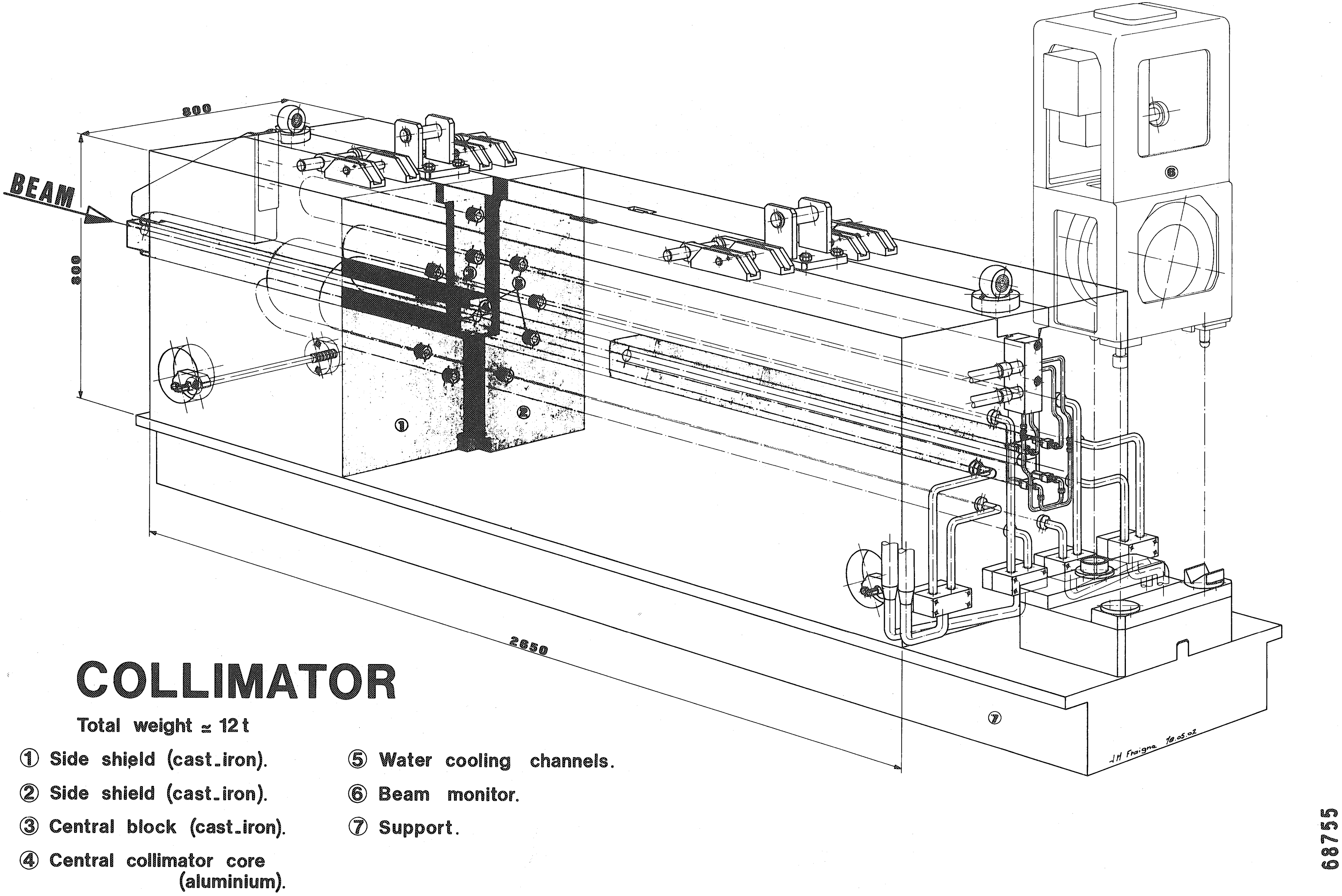

Fig. 5 – Various lateral cuts along the collimator, shown in perspective. The water cooling circuits of the central aluminium core and the surrounding cast iron are indicated. Details of the pipes connecting the various water circuits at the collimator rear are also shown.

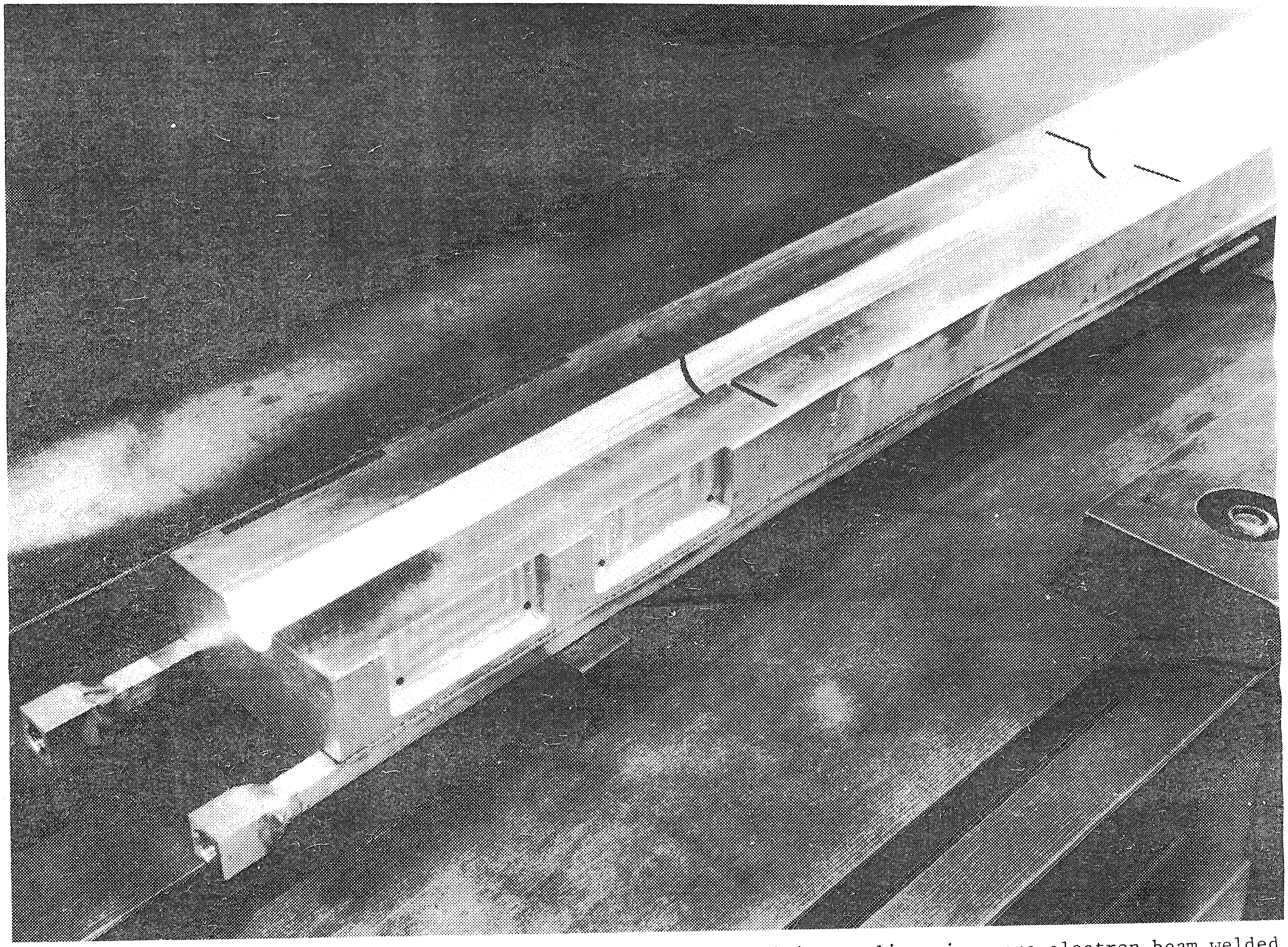

Fig. 6 - The lower half of the central aluminium core. The aluminium cooling pipes are electron beam welded into two of the corners. Several half circular grooves of which two can be seen in this photo, are machined by electro erosion transversally along the inside surface of the aluminium beam. They serve to unload longitudinal thermal stresses and bending moments in the proximity of the collimator aperture.