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DESIGN STUDY OF A 1 MV, 4 A, D- TEST BED IN EUROPEAN COMMUNITY

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ABSTRACT:

The design study of a 1 MV, 4 A, D^-, > 30 seconds, test bed is being conducted by the EURATOM-CEA association (Cadarache) with support from the EURATOM-UKAEA association (Culham) and from FOM-Amsterdam. A proposal for the construction of this test bed at Cadarache will be made by the middle of next year. The options chosen for the beamline are derived from the conceptual design originally proposed one year ago by A.Holmes et al. for the ITER neutral beam systems: pure volume negative ion production, electrostatic multi-stage accelerator, vertically subdivided beamline, electrostatic deflection of the ions at the neutraliser exit, HV vacuum insulation with voltage grading screens. This design has been reviewed in detail and in particular three basic topics have been carefully examined: beam acceleration, gas flow and beam transmission. This review resulted in various changes with respect to the original design, the major change being the decision to put the ion source at high voltage. In parallel to this test bed design study, the conceptual study of a 1 MV, 15 A power supply and of its protection system is conducted by european industrial companies under the supervision of Cadarache.

1) INTRODUCTION:

In view of NET/ITER, the European Community (EC) is supporting a development programme in the field of negative ions for neutral beam injection[1]. In the framework of this program, three tasks have to be performed during the 1990-1992 period by two EURATOM Associations (EURATOM-CEA at Cadarache and EURATOM-UKAEA at Culham):

(i) improvement of source performances and demonstration of the feasibility of a multi-ampère D^- beam from a pure volume source with relevant characteristics, i.e. optics, pressure and electron suppression (DRAGON experiment at Culham);

(ii) industrial study of the feasibility of a 1 MV, 15 A power supply and of its protection system, conducted under the supervision of Cadarache;

(iii) complete design of a mega-volt test bed (1 MV, 4 A D^-, 2 A D^0, > 30 second pulses), for scalable model developments of NET/ITER neutral beam injectors; this design is conducted at Cadarache, with support from Culham.

The present aim of this integrated programme is to prepare a proposal for a 1 MV, 4 A, deuterium test bed to be presented to the EC authorities during the summer of 1992.

We present below the status of the tasks (ii) and (iii), mostly conducted by Cadarache. The DRAGON experiment at Culham is described in a separate paper by A.Holmes[2].

2) STATUS OF THE TEST BED DESIGN

2.1) THE ORIGINAL EC DESIGN:

The design study of the 1 MV, 4 A D^-, 2 A D^0, > 30 seconds, test bed is based on the options originally chosen by A.Holmes et al. in their conceptual design for the ITER neutral beam injectors[3]:

(i) grounded source;
(ii) pure volume negative ion production;
(iii) electrostatic multi-stage accelerator;
(iv) vertically subdivided beamline;
(v) electrostatic deflection of the ions at the neutraliser exit;
(vi) inline dump of residual ions;
(vii) high voltage vacuum insulation with voltage grading screens.

A scheme of this design is given on Figure 1.

A first originality in this design, was the source placed at ground potential and the neutraliser at high voltage (GS option), as in the Tore Supra lines[4]. This scheme was presented to have many advantages with respect to the other possibility of the high-voltage source and grounded neutraliser (HVS option):

(i) easy differential pumping in the accelerator;
(ii) no need for a high-voltage platform for the source auxiliary supplies (reduction of the stray capacitance);
(iii) possibility of easily deceleration the residual negative ions.

Another novel feature of the design by Holmes et al is the subdivided beamline, which allows:

(i) reduction of the neutraliser gas flow;
(ii) inline dumping of the residual D^+ and D^- ions, with a simple electrostatic deflection.

Holmes et al also proposed to have a special commissioning mode, in which the beam would be unneutralized. The full beam, constituted of D^- ions, would then be dumped on the residual ion dump. With this option, it would not be necessary to have a separate dump for the neutral beam.

This design has been reviewed in detail at Cadarache, with support from Culham. We present below our main conclusions, concerning source polarity, beam acceleration, gas flow and beam transmission.

2.2) SOURCE POLARITY:

Both the GS and the HVS options have been examined in details and a comparison has been made, based on as many quantitative parameters as possible. The results are summarized in Table 1; they have been obtained in the following case:

- ITER NB module following EC proposal by A.Holmes et al.[3] ;
- 8.3 MW/module, 1.3 MeV;
- two sources per module, filament sources;
- gas neutraliser;

The beamline schemes used are those presented on Figures 2 and 3.

Table 1 has served as a basis of discussion for the Coordinating Committee of the integrated EC program on negative ions. This committee has decided that it would be more realistic to chose the high-voltage source option (HVS), since:

(i) most of the arguments originally presented in favor of the GS option (see section 2.1 above) are invalidated by the quantitave evaluation (in particular, section 2.4 below adresses the question of stripping and pumping),

(ii) the neutraliser gas pumping would be very delicate in the case of a high-voltage neutraliser

2.3) ACCELERATOR:

In view of designing the electrostatic accelerator, a particle trajectory code has been developed at Cadarache in 1990 and validated by comparison to existing experimental data[5]. This code uses a specific 2-Dimensionnal treatment of the electron contribution to the sheath build-up described by diffusion processes; it also takes into account the extracted electron space charge and the negative ion stripping. These physical effects have been found, in most cases, to play a significant role on beamlet optical characteristics.

Beamlet acceleration studies at the MV level have been performed with this code and showed that the effect of space charge is important, even at the level of 10 to 20 mA/cm^2 of accelerated D^-,at which we propose to operate. In order to compensate for this diverging space-charge effect, one has to use electrostatic focusing in the accelerator, by increasing the electric field in each accelerator stage. The calculations show also that it will be difficult, with a pure linear electrostatic accelerator, to increase the accelerating length far beyond the Child-Langmuir limit[6]: typical accelerating length will be around 50 cm at 1/1.3 MV. These conclusions have been confirmed by calculations performed independently at Culham with another particle trajectory code (AXCEL). Therefore, the constant electric field acceleration that was originally proposed[3,7] has now been changed. An example of beamlet calculation is given on figure 4.

The Cadarache code has also been used to specify the ripple characteristics on the various extraction and acceleration power supplies (e.g. a +- 10% ripple is tolerable on the main power supply).

2.4) BEAM TRANSMISSION AND BEAMLET DIVERGENCE:

The subdivided beamline option, was originally proposed with the following parameters:

(i) beamlet clusters of two beamlets in width (N_b = 2) at a pitch, P_b, of 18 mm;
(ii) width of the beam dump slots, W_{bd} = 52 mm
(iii) distance from source to beam dump exit, L = 7.5 m

This demands a very low beamlet divergence, $\theta < 2$ mrad in order to ensure a transmission higher than 90%. This constraint on beamlet optics is considered to be too severe, in particular if one thinks of a possible influence between beamlets inside the same cluster, of grid misalignements and/or thermal dilatation, and of the effects of the various magnetic fields used to deflect the electrons inside the accelerator. Therefore, it has been decided to revise the design with an equivalent beamlet divergence $\theta' = 3.5$ mrad ('equivalent' means that all effects of misalignement, etc. are included). Figure 5 presents the results on beam transmission, calculated with $\theta' = 3.5$ mrad, a variable beamline length and three different cases:

(i) original design, as defined above;

(ii) modified design: $N_b = 4$, $P_b = 18$ mm, $W_{bd} = 120$ mm

(iii) modified design: $N_b = 4$, $P_b = 18$ mm, $W_{bd} = 110$ mm

On the basis of these calculations, it has been decided to change the original design as follows:

(i) beamlet clusters of $N_b = 4$ beamlets in width at a pitch $P_b = 18$ mm;

(ii) width of the neutraliser slots: $W_n = 110$ mm; distance from source to neutraliser exit: approximately 7 m;

(iii) width of the beam dump slots: $W_n = 120$ mm; distance from source to beam dump exit: about 10.5 m;

This should ensure a beam transmission larger than 90%. The longer neutraliser has been chosen in order to reduce the required gas flow. These changes also allow the width of the water cooled dumped plates to be increased from 9 mm originally (which is considered to be rather narrow) to 12 mm.

2.5) STRIPPING LOSSES AND GAS PUMPING:

Gas flow and pumping requirements have been calculated for a full ITER module, on the basis of the EC proposal[3] (i.e. two sources/module).

Gas flow has been calculated using an equivalent resistor network solved with a computer code. The gas pressure distribution has been used to calculate the stripping losses inside the accelerator. Various cases have been studied:

(i) HV source with SF6 insulation (no differential pumping in the accelerator);

(ii) HV source with vacuum insulation, differential accelerator pumping and semi-transparent voltage grading screens (as shown on figure 2);

(iii) same as (ii), but with grounded source (see figure 3).

For a source pressure of 0.66 Pa (5 mTorr), it has been found that, at best, one could expect stripping losses of 60%, 33% and 33%, for cases (i), (ii) and (iii) respectively. Therefore option (i) has ben rejected, unless the source operating pressure can be considerably reduced. It also appears that the GS option presents no advantage for stripping reduction, contrarily to what was originally stated[3,7].

Pumping speed requirements have also been calculated.

For the accelerator differential pumps, the effective speed has to be around 10^3 m^3/s, assuming a gas pressure at the pump lower than $6.6\ 10^{-3}$ Pa (gas flow 6 $Pa.m^3/s$).

For the calculation of the neutraliser gas pumping, it was decided than one would tolerate only one percent of additionnal stripping loss, which corresponds to a pressure increase of $6.6\ 10^{-3}$ Pa in the gap between the accelerator and the neutraliser entrance. For a neutraliser gas target of $2.5\ 10^{20}$ mol/m^2, and with the revised neutraliser geometry (see above, section 2.4), one expects a neutraliser gas flow of 12 $Pa.m^3/s$ and an effective pumping speed of $1.8\ 10^3$ m^3/s. In the GS case, it is difficult to achieve this effective pumping speed because of the voltage grading screens.

2.6) SUMMARY:

We have summarized in Table 2 the design modifications with respect to the original proposal by Holmes et al[4]. Other changes have ben made, in addition to those described in sections 2.2 to 2.5: the beam dump has been simplified (no separate deflection plates, but polarised beam dump plates, for both deflection and dumping) and a neutral beam calorimeter has been added, at least for the test bed (the commisioning mode originally proposed[3,7] has been appreciated to complicate the dump design, to limit the operation during conditionning and no neutral beam diagnostics could have been available). A scheme of the new beamline design is also shown on figure 6, which can be compared to the original, figure 1.

We are now at the stage where the engineering studies and the engineering design can start. We are confident that, on the basis of our studies, a proposal for a 1 MV, 4 A D^-, 2 A D^0, 30 s, test bed can be made to the EC authorities in due time, i.e. in July 1992.

3) 1 MV, 15 A POWER SUPPLY CONCEPTUAL STUDY:

An essential component of a megavolt neutral beam injector will be the high voltage power supply and its protection system. For this reason, the EC has decided to finance, through the EURATOM-CEA Association at Cadarache, industrial studies of a 1 MV, 15 A power supply and of its protection system.

After a call for tender, three european companies, Siemens in Germany, Vivirad and Irelec in France, have been chosen for making this conceptual study independantly. The work has started beginning of 1991 and reports are expected by early 1992. This work is supervised by C.Jacquot and R.Hemsworth from Cadarache.

The studies are well advanced, all problems have been clearly identified, and the three companies are proposing very different solutions, which are summarized in Table 3. One can note that the question of the auxiliary power is treated in two of the three cases.

We expect that a general layout will be ready by the end of 1991, followed by a careful analysis of the costs and an assesment of the outstanding problems. A choice will then be made with the intention of ordering a 4 A module for the Cadarache megavolt testbed.

REFERENCES:

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3 A.J.T.Holmes, R.S.Hemsworth, H.Hopman, C.Jacquot, L.Lea, K.Martle and R.Parker, 'Conceptual study for a neutral beam injector for ITER', ITER report 1990.

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TABLE 1: Comparison of grounded source and HV source

	GROUNDED SOURCE	HV SOURCE	COMMENTS
HIGH VOLTAGE:			
HV auxiliaries : Source Power	None	350 kW, (additional isolation transf.)	HV platform: additional stored energy
G2/G3 Power	None	1160 kW (auxiliary winding on HVPS)	
Steering, profile control	100 kW, HV platform	none	
HV transmission line	5 cables	8 cables	
Total area to be conditioned	770 m^2	450 m^2	Breakdown frequency
Beamline stored energy (Power systems at HV excluded)	670 Joule (max./stage: 160 J)	450 Joule (max./stage: 120 J)	Deconditioning breakdowns
Insulators	same		
Water: thermal power at HV	8 MW	1.5 MW	HV water choke pipe diameter
HV control and instrumentation	Profile controller, steering system and deflector	Source, extractor	
HV diagnostics	Neutraliser, ion dump	Extractor	
GAS AND PUMPING			
Stripping in the accelerator	33 %	33 %	
Pumping speed for the accelerator	1.5 10^5 l/s	3.0 10^5 l/s	
Pumping speed for the neutraliser	1.8 10^6 l/s	8.0 10^5 l/s	
Tritium containment	same		
MISCELLANEOUS			
Dowstream electron control	Screens + magnets at beamline exit	None	
Problematic remote maintenance	Neutraliser, ion dump, profile controller, ...	Source, accelerator	
Flexibility and upgrading	Easy on source side only (RF source)	Easy on neutraliser side (plasma neutr.)	
Commisionning and operation	Danger of double acceleration of D^+		

TABLE 2: Changes in the beamline design

	Original EC Design	Present Design
Source: - type	Pure volume	Pure volume
- potential	Ground	High voltage
Accelerator	Electrostatic, constant accelerating field	Electrostatic, increasing electric field
Neutraliser	Gas, subdivided 6 * 50 mm channels 4.8 m long	Gas, subdivided 3 * 110 mm channels 6.0 m long
Residual Ions: - deflection:	Separate deflector	No separate deflector Plates of the residual ion dump biased
- dump	In line 6 * 52 mm channels 9 mm thick plates 1.5 m long	In line, insulated plates 3 *120 mm channels 12 mm thick plates 2.5 m long
Neutral Beam Power handling and diagnostics	No full power neutral beam dump Special mode of commisioning	Neutral beam dump capable of accepting the full beam (ions + neutrals)
HV insulation	Vacuum, around HV neutraliser	Vacuum around HV source
Beam transmiss.	< 80 % for 3.5 mrad beamlet divergence	> 90 % for 3.5 mrad beamlet divergence

TABLE 3: Status of 1 MV, 15 A power supply studies

Company:	Siemens	Vivirad	Irelec
PS type	Cascade transformer Primary switch-off Passive protection	Insulated Core Transformer (ICT) Short transm. line Passive protection	Cockcroft-Walton, 5 stages, 38 units in parallel
Stored energy	4 kJ	300-500 J	none
Switch off time	50-100 µs	10 µs	1 µs
Inverter	400 Hz	10-20 kHz	0.5-1 MHz
Transitor type	GTO 10^6 VA each	IGBT 10^5 VA each	MOSFET 10^4 VA each
Development	Low	Medium	High
Size/integration	Large size (>100 m^3) Long transm. line	Small size (5-10 m^3) PS near the injector	Integration of PS in the injector
Intermediate pot	Fixed	Large choice	Fixed
Auxiliary Power	Solved	Solved	Not solved

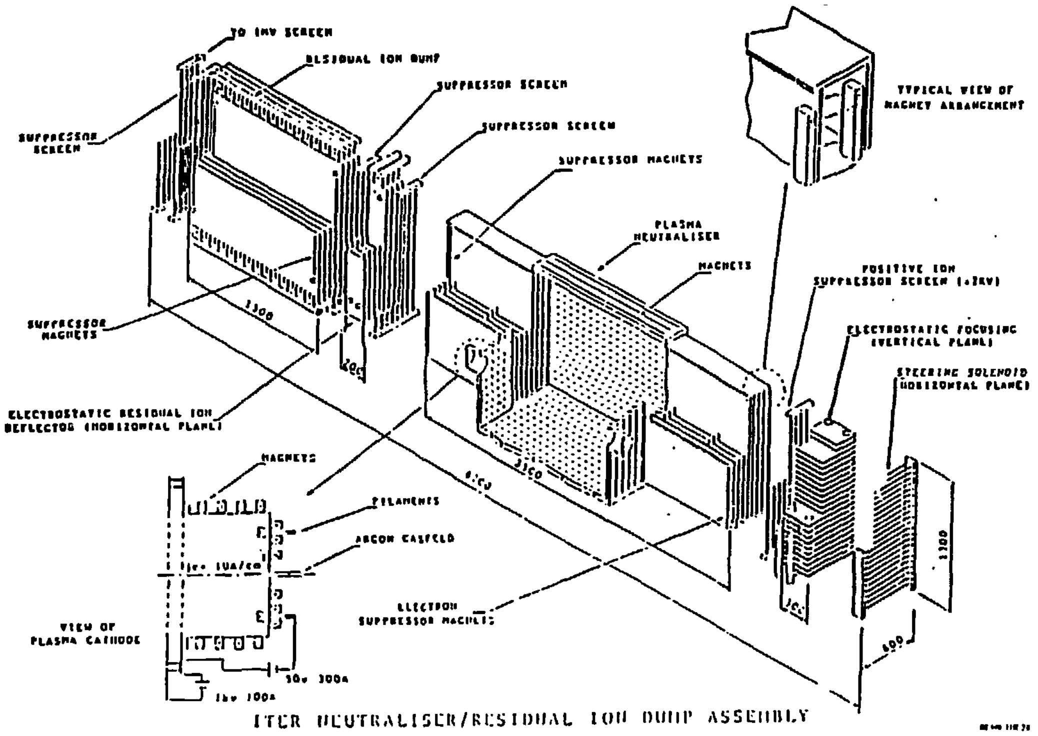

FIGURE 1: THE ORIGINAL EC DESIGN BY HOLMES et al[3].

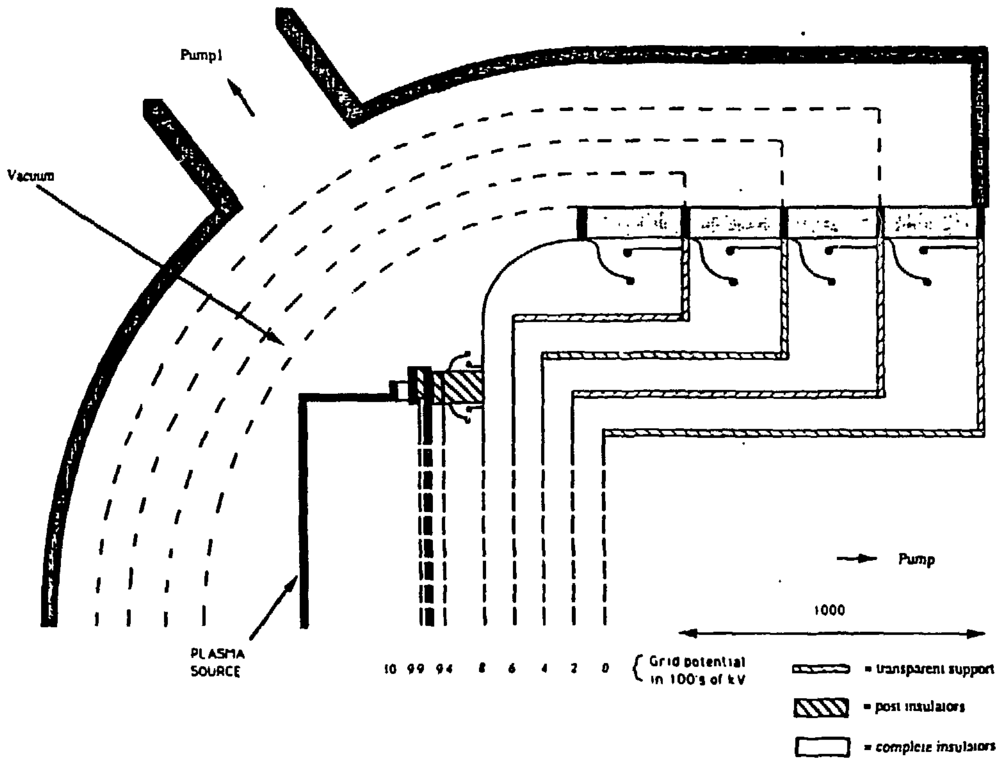

FIGURE 2: SCHEMATIC VIEW OF HIGH-VOLTAGE SOURCE BEAMLINE WITH VACUUM HIGH-VOLTAGE INSULATION

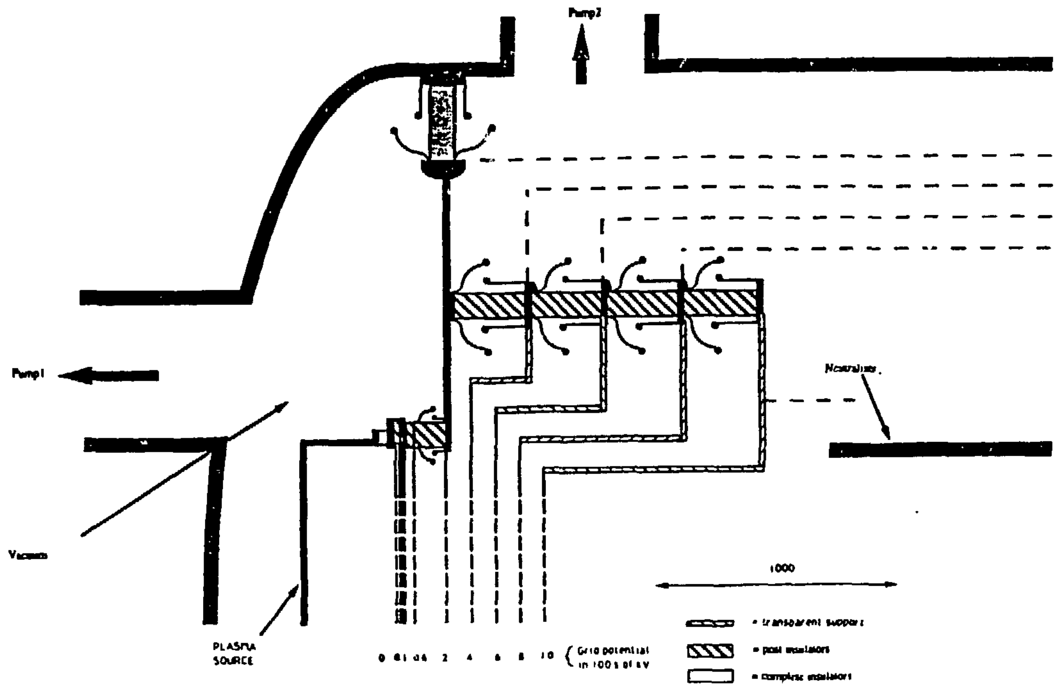

FIGURE 3: SCHEMATIC VIEW OF GROUNDED SOURCE BEAMLINE WITH VACUUM HIGH-VOLTAGE INSULATION

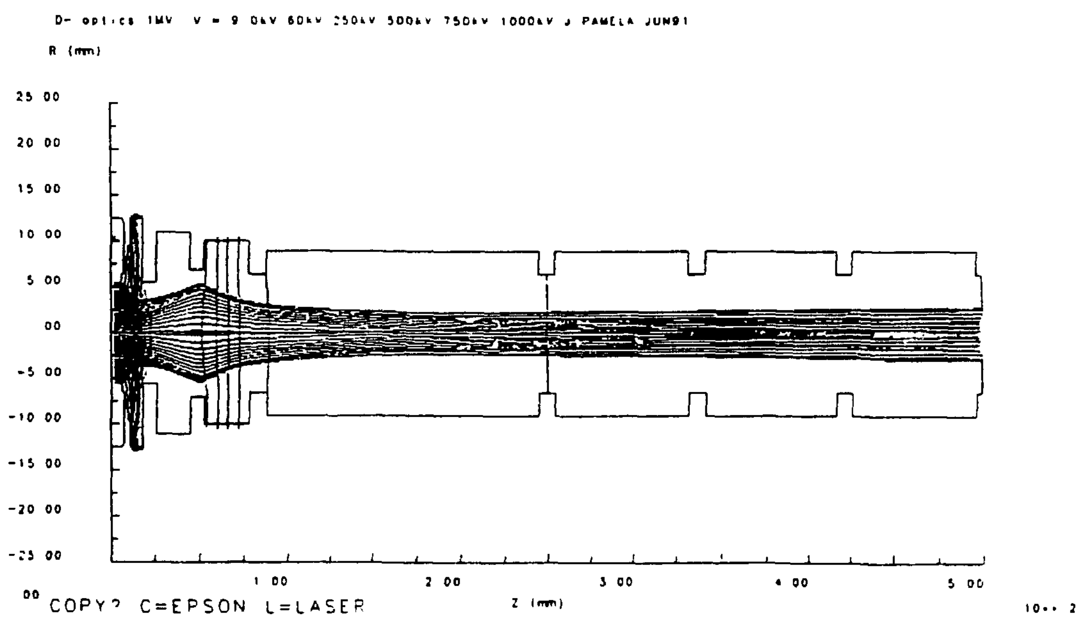

FIGURE 4: 1.3 MV, 16 mA/cm² (ACCELERATED) D⁻ BEAMLET OPTICS CALCULATION

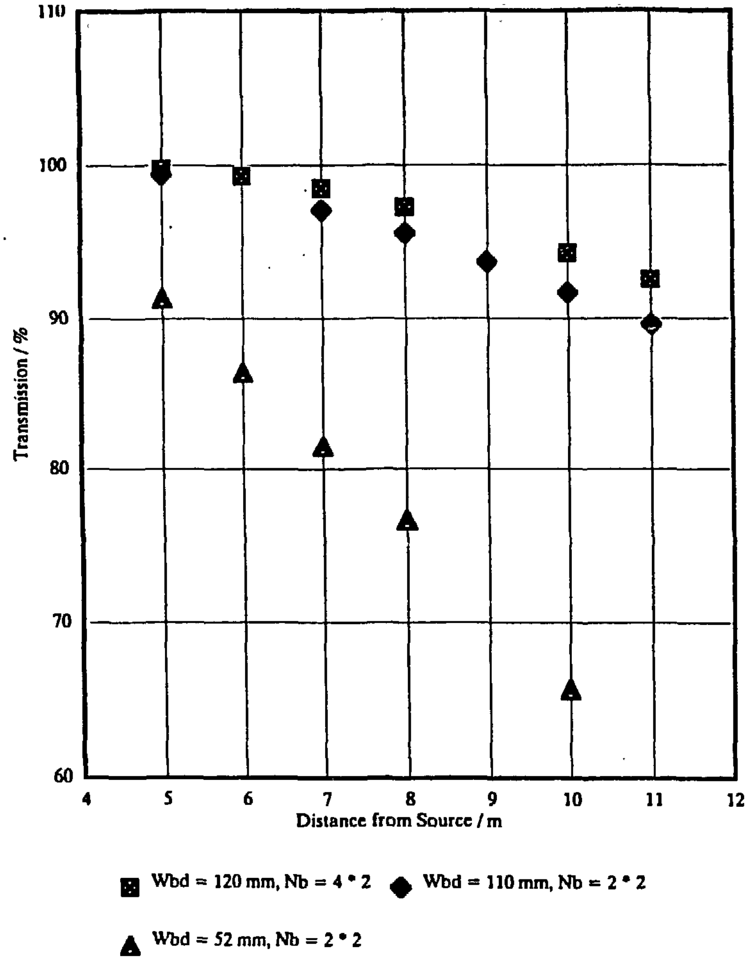

FIGURE 5: TRANSMISSION CALCULATIONS

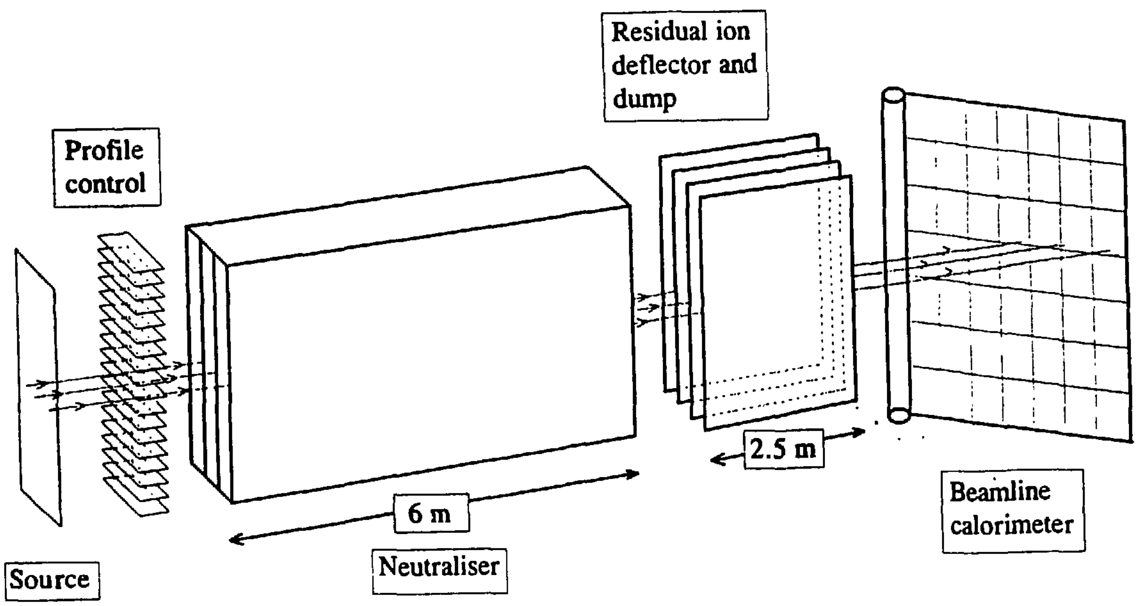

FIGURE 6: SCHEME OF THE NEW BEAMLINE DESIGN