RECENT PROGRESS IN LINAC PRE-ACCELERATORS*

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Introduction

Linear accelerators put out beam currents in excess of 100 mA, operating with about three times larger preinjector current (CERN, Serpukhov). Experience with these machines and recent numerical calculations by R. Chasman (BNL) suggest that efficient operation imposes specific requirements on the preinjector beams. The exact requirements being unknown the ideal preinjector should provide for adjustability of the beam characteristics, controlled at the entrance of the linac.

Recent development in preinjectors has mainly concentrated on beam currents below 200 mA with the object to pre-accelerate, transport and bunch beams without dilution and to match them to the longitudinal and transverse phase spaces of the linear accelerator.

We shall consider developments of the ion source, such as the control of the current and uniformity of the plasma emitter in the expansion chamber of the duoplasmatron and a possible relation between expansion cup geometries and the apparent source emittances. We shall summarize the results obtained with low and high gradient acceleration without significant apparent dilution up to 750 kV with and without prefocusing. Finally we shall discuss some ideas for the transport region between accelerator and linac.

Ion Source Developments

A. Cathodes and Anodes

The duoplasmatron is used in all accelerator laboratories because it is a flexible, powerful proton source. It delivers currents up to hundreds of milliamperes with a high content of protons (70-80%), low energy spread (10-100 eV) and good gas economy.

The reliability of such a source is mainly determined by the lifetimes of its cathode and anode. To my knowledge three cathodes exceed the period of 2 to 3000 hours (see Fig. 1):

a. The Brookhaven oxide coated nickel mesh cathode designed by L. Oleksiuk (BNL) and brought into operation by H. Wroe. This design is adapted in Los Alamos, Rutherford and Saclay (1966, Ref. 1).

b. The CERN oxide coated mesh cathode (1966, Ref. 2).

c. The I-2 Moscow tantalum cathode≠ (1968, Ref. 3).

Serious heating damage to the anode caused by the arc current or sometimes by backstreaming secondary electrons in high gradient accelerating tubes is avoided by proper choice of materials (copper and tungsten) and by adequate cooling arrangements.

A point of practical interest is extremely high source pressures (10-100 mmHg) with large plasma expansion cups necessary to obtain the required 400-700 mA beam intensities (CERN, Serpukhov). In general smaller expansion cups ($\phi <$ 15 mm) are operating with pressures less than 1 mmHg.

B. Source Emittances

The beam from the plasma expansion cup has to be matched to the accelerating structure. Rules concerning the geometry of the cup are based on local experience. Comparing emittances from expansion chambers measured in different laboratories, we found that the best emittance was obtained with the smallest dimensions. Figure 2 shows four expansion chambers. The apparent non-aberrant emittances are obtained in nearly Pierce shaped extraction geometries; the source plasma conditions such as arc currents and pulse lengths are comparable. The emittances have been calculated, assuming

a. an ion temperature of 10^5 °K or 10 eV.

b. a plane plasma emitter at the exit of the cup.

c. an angular distribution of ions emerging from the anode outlet as suggested by Demirkhanov and Fröhlich (1963, Ref. 4) and observed by Gautherin (1967, Ref. 5).

Figure 3 shows an example of the calculation. Comparing results, the best agreement and the smallest emittance (.007 cm-mrad) has been obtained when the extraction was closest coupled with the plasma column inside the source and where the magnetic stray field inside the cup was suppressed by use of a septum. Our attention to "close coupled" extraction arose from Bennett and Turner's (BNL) work with a P.I.G. source (1967, Ref. 6). They measured a remarkable low

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≠Oxide cathodes were replaced by tantalic ones to reduce the molecular content in the beam.

emittance value ($E\beta\gamma$ = .002 cm-mrad). The extraction takes place inside the single region where the plasma is formed, so that one cannot be "closer coupled" and the effect of space charge is the smallest (see Fig. 4).

Recently measured emittances at extraction voltage follow closely the values summarized in Fig. 6.

C. Density Distribution

A first attempt to control the density distribution at the very beginning of the accelerator has been published by the group of Vienet (1967, Ref. 7). With biased side walls in the expansion cup one can in principle adjust the electron excess originating from the source and therefore influence the ion density distribution within the cup. Reasonably uniform beams of 100 mA have thus been obtained. An additional advantage of the insulated walls seems to be that (under certain conditions) the beam output may be increased (1967, Ref. 8).

Accelerator Systems Without Significant Apparent Emittance Growth After The Extractor

Acceleration to the required linac injection energy without apparent dilution of emittance has been achieved successfully by:

a. a focusing lens in front of the accelerator tube.

b. a short acceleration without lens prefocusing.

The first method has been applied by Vienets' injector group at Saclay for a 100 mA and 200 μsec pulsed beam using an immersion lens and a 750 kV accelerating tube with a gradient of 15 kV/cm (1968, Ref. 9). The "secret" in this design is that the beam has been accelerated to 150 KeV before it entered the lens and accelerating tube in which it does not exceed 1/3 of its aperture to avoid nonlinear regions (see Fig. 5a). No dilution is observed.

Prefocusing with lower energy beams is applied in the injector of the I-2 and 100 MeV Serpukhov linac for 400 mA and 30 μsec pulsed beam; the gradient of the tube is 12 kV/cm (Fig. 5b). In this case beam dilution in phase space caused by the optics of the focusing system is observed (1967, Ref. 10).

The second type of preinjectors without lens prefocusing, pioneered by the CERN group, requires gradients of 30 kV/cm or larger in dependence on required beam transmission and imposed potential distribution. Focusing takes place <u>after</u> acceleration.

CERN reported in the previous conference (1966, Ref. 11) a double gap 500 kV tube development with a gradient 50 kV/cm and producing about 500 mA beam currents of 30 μsec pulse length (see Fig. 5c). We assume that aberrations observed at 500 keV occur in the extractor region.

Brookhaven has built a quintuple gap 750 kV Pierce tube for beam current densities of 80 mA/cm^2 with a gradient which increases gradually from 30 to 47 kV/cm. In theory it will compensate for the radial field of space charge of a uniform beam. Beam currents up to 200 mA have been accelerated. There is no apparent dilution in the acceleration tube (1967, Ref. 12). See Fig. 5d.

An elegant single gap acceleration experiment up to 350 kV mainly to demonstrate the invariance of emittance was constructed by H. Wroe (1968, Ref. 13).

Figure 6 summarizes most of the undiluted apparent emittance and brightness values as a function of beam current as measured at injection energy. This figure shows that there is an increase in emittance value (and thus a decrease of brightness) for larger beam currents as reported in 1965 by van Steenbergen (1965, Ref. 14); the absolute values* of the present generation of pre-accelerators, however, have improved by an order of magnitude. The deterioration of emittances is now limited to the extractor region of the tube, where it is still extremely difficult to obtain a plane emitter.

Are these emittances and brightnesses adequate for operational and planned linear accelerators?

As will be discussed by R. Chasman in the session hereafter and as has been observed both at CERN and at Serpukhov an increase of the preinjector brightness may cause increased dilution in the linac so that increase in brightness of the linac beam is not nearly as large as that in the preinjector beam. Consequently, increases in preinjector brightness beyond the values already achieved may not be of much practical value at least for linac output currents up to 100 mA.

Mechanical Accelerator Construction

Most high current accelerator structures are of the air insulated type in which the power supply is separate from the accelerator tube. It is mainly chosen for the accessibility of the tube. The high gradient machines (> 30 kV/cm) with re-entrant structures seem to have survived most after growing pains of childhood. The use of titanium alloys as electrode materials, the advantage of multiple gap structures and an extremely clean vacuum have all proven to be essential for reliable operation.

Strong metal ceramic bonds for ring diameters as large as ϕ 26 in. have been developed. They use either vinyl acetate (1966, Ref. 16) or epoxy (1966, Ref. 11, 1968, Ref. 17, 1968, Ref. 18) as

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* ε_a= .8 x I cm-mrad, where I is in amperes.

a bonding agent. Brazing techniques for diameters larger than 20 cm were unsuccessful so far.

A closed structure recently developed at Saclay, which has both the accelerator tube and its Cockcroft-Walton supply inside a common pressure vessel has the advantage of compactness and closely controlled environment. With this design increasing the linac injection energy up to say 2 MeV seems to be technically possible. This should reduce space charge problems in the linac. Open preinjectors seem to be limited to about 750 kV. The reduced accessibility of the closed structure is offset by the longer life expectances of modern ion sources.

The Low Energy Transport System

Apart from the buncher region (discussed by Lapostolle, Agritellis and Chasman on this conference) the low energy transport system for large beam currents is straightforward. The effective diameter of the quadrupoles has to be increased to transport larger diameter beams in order to maintain low charge density. In most triplets the effective diameter is about half the physical inner diameter which is for instance 4 in. in the 200 MeV linac injector; for these beam cross sections and currents up to 250 mA beam, i.e., for current densities up to 20 mA/cm^2, transport in this part of the system may be calculated without taking space charge into account. After the buncher short quadrupoles and smaller inner diameters have to be used in order to reduce the drift length and to provide space for beam quality detection equipment.

Beam diagnostic equipment in this part of the machine has hardly been developed mainly because of lack of space to put such equipment in. Pre-accelerators now under construction allow for this. The control of the mean energy and energy spread will be very useful especially for large beam currents and double bunchers.

The removal of the molecular content of the beam (20-30% H_2^+) will be a first logical step in beam control. This not only cleans up the beam, it also prevents radiation damage, simplifies and improves tuning of the linac and provides a non-destructive measurement of mean energy, energy spread and possibly a converted emittance of the beam actually injected.

Perry (1967, Ref. 19) constructed a 360° beam separating magnet composed of two adjacent field regions I and II (see Fig. 7a). An elegant modification of this magnet is shown by Claus (1968, Ref. 20), which is dispersion-free in the emerging beam and is less sensitive to variation in the magnetic fields (see Fig. 7b).

Another possibility is a crossed field ion separator as shown in Fig. 8 in which the unwanted particles (H_2^+) are deflected. In addition this device can be used as beam chopper by varying the electric field.

After all mentioned separators the deflected unwanted particles may be used for monitoring the preinjector (see Fig. 8). The mean energy may be measured by very sensitive non-destructive magnetic beam position sensors* before and after an analyser; the emittance pattern of the H_2^+ beam may be measured using a single pulse phase space analyser (1967, Ref. 21); the conversion ratio of the H^+ and H_2^+ emittance can be determined with the same analyser.

An additional monitor region just in front of the linac to detect phase and emittance pattern of the bunched beam should be very useful for linac tuning and improving the understanding of linac behavior. Miniaturized retractable monitors for longitudinal phase detection and a short window type magnetic sweeper (see Ref. 21) with fixed slits for the emittance measurement seem to be practical possibilities in new designs.

Conclusions

The recently built 100 to 250 mA preinjectors accelerate beams without dilution after the extractor. The beam qualities fit well within the theoretical linac acceptances. Though improvements of the beam quality such as uniformity and flat ion emitters in the plasma expansion cup have to be pursued to give the preinjectors more flexibility, this does not seem to be essential up to 100 mA linac beams.

Beam monitoring equipment in the low energy transport channel should be developed.

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*Under development by J. Claus and R. Larson (BNL) for high energy beams.

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DISCUSSION

(T. Sluyters)

VAN STEENBERGEN, BNL-NAL: The proportionality of the emittance with current, related to a set of parameters for a Linac-Booster-Storage ring injector combination was used recently at NAL. It should be pointed out that this is a rule of "thumb" and that, to my knowledge, it has not been enforced by any theoretical study. It really illustrates that the limit on density in two dimensional phase space is most likely related to space charge phenomena. It would seem desirable that more attention be paid to this from a theoretical point of view.

SLUYTERS, BNL: Yes. I think that J. Faure has just mentioned that they plan to make a beam analysis at the entrance at the ion source and try to calculate the beam behavior inside the cup. I think this is a first real start in this direction.

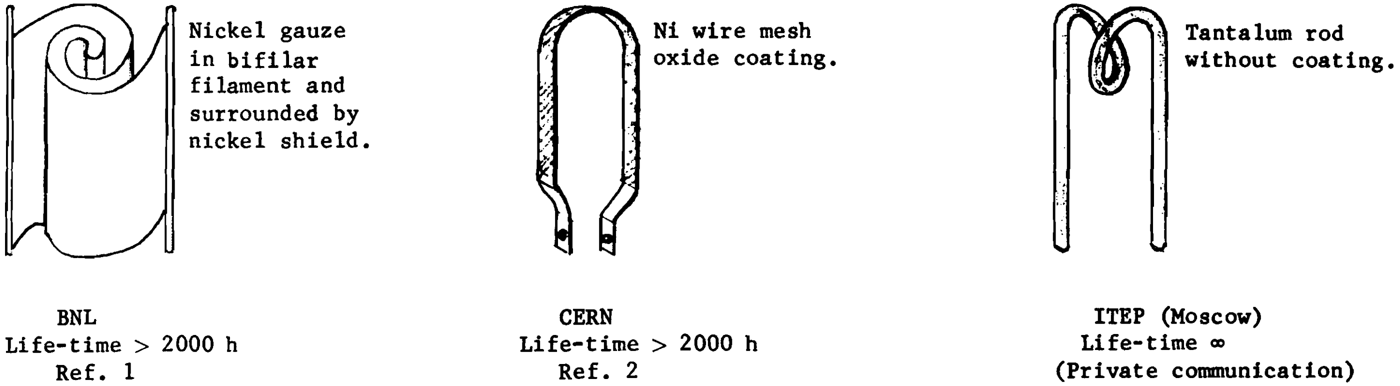
CURTIS, NAL: You showed some theoretical calculations of emittance to compare with experimental measurements. What was the basis of your temperature determinations?

SLUYTERS, BNL: Gautherin at Orsay has measured the energy of the emerging ions. It is of the order of 10 eV. This figure seems to be in reasonable agreement with other authors. These emittances were calculated in this simple way using the geometry of the plasma cup, adapting a plane emitter and assuming the beam comes out in a directional way.

PERRY, ANL: In regard to metal bonding to ceramics, we have contacted a vendor (Coors) who will supply us with metal bonded ceramic rings as large as 20 inches in diameter.

LEFEBVRE, SACLAY: Would they supply an assembly of rings or just single rings?

PERRY, ANL: They would supply single rings to which would be bonded OFHC copper. We would then join the rings together by a brazing process.



Nickel gauze in bifilar filament and surrounded by nickel shield.

BNL
Life-time > 2000 h
Ref. 1

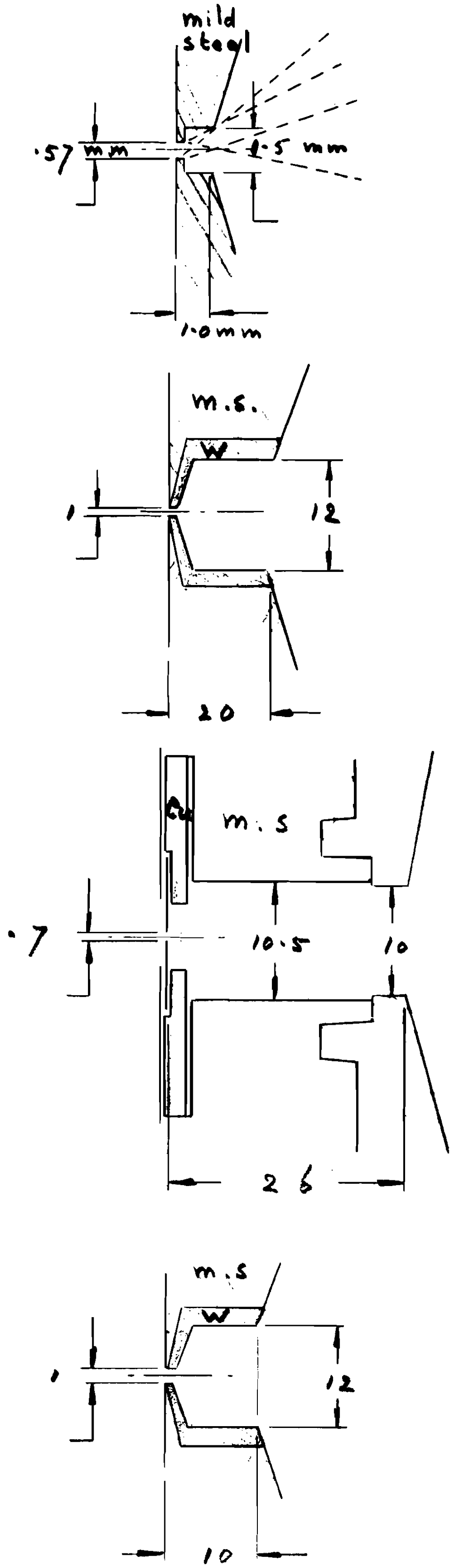
Ni wire mesh oxide coating.

CERN
Life-time > 2000 h
Ref. 2

Tantalum rod without coating.

ITEP (Moscow)
Life-time ∞
(Private communication)

Fig. 1 Cathodes Exceeding 2000 h Life-time.



I = 35 mA

$\varepsilon_2 = \beta\gamma \frac{\text{area}}{\pi}$ = .007 cm-mrad

$\varepsilon_{\text{theor}} \approx$ .007 cm-mrad

(Wroe, 1968, Ref. 13)

Photographic Measurement

I = 50 mA

ε_2 = .036 cm-mrad

$\varepsilon_{\text{theor}} \approx$ .01 cm-mrad

(Sluyters, 1967, Ref. 12)

Photographic Measurement

I = 100 mA

ε_2 = .04 cm-mrad

$\varepsilon_{\text{theor}} \approx$ .003 cm-mrad

(Bex, 1967, Ref. 8)

Electric Wire Detection

I = 100 mA

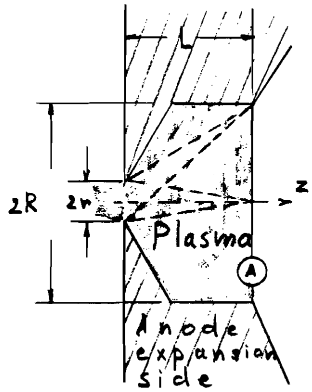
ε_2 = .038 → .062 cm-mrad

$\varepsilon_{\text{theor}} \approx$ .020 cm-mrad

(Sluyters, 1967, Ref. 12)

Photographic Measurement

Fig. 2 A Comparison of Non-Aberrant Emittances for Several Geometries.



Emittance at plasma emitter Ⓐ:

$$\mathcal{E}_2 = \beta\gamma \frac{\text{area}}{\pi} = \frac{V_0}{c} \frac{\text{area}}{\pi} (\gamma = 1)$$

$L = 10$ mm

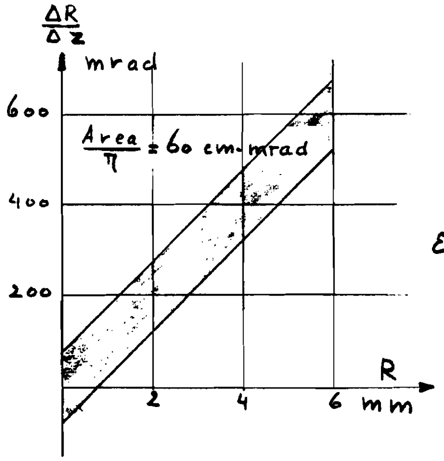
$2r = 1{\cdot}5$ mm

$2R_0 = 12$ mm

$\frac{\text{area}}{\pi} = 60$ cm·mrad

$$(V_0)_{max} = 2\sqrt{\frac{2kT_i}{m}} \approx 10^5 \text{ m/sec}$$

$T_i = 10^5$ °k



$\mathcal{E}_2 = {\cdot}020$ cm·mrad

Fig. 3 Example of Emittance Calculation.

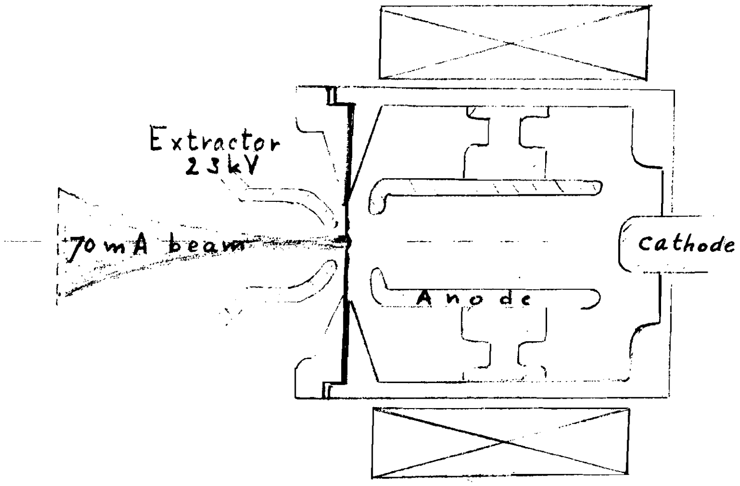
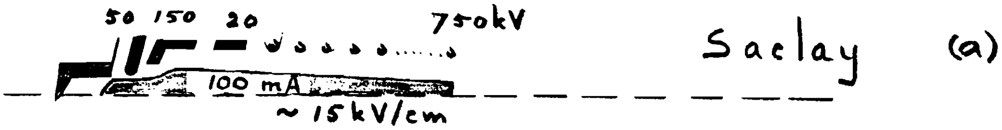
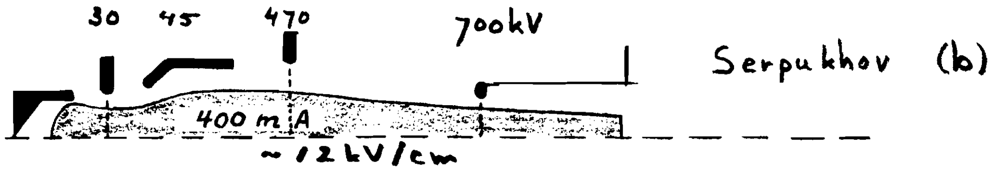
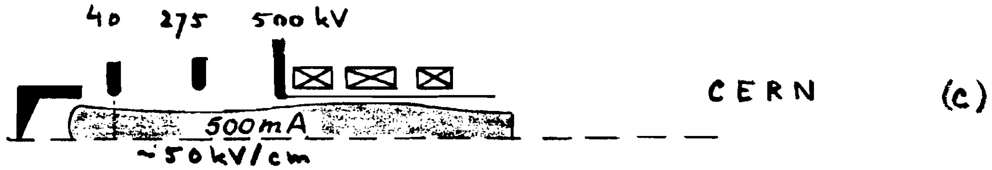


Fig. 4 "Close Coupled" Extraction in Modified PIG Source.
(Turner, 1967)







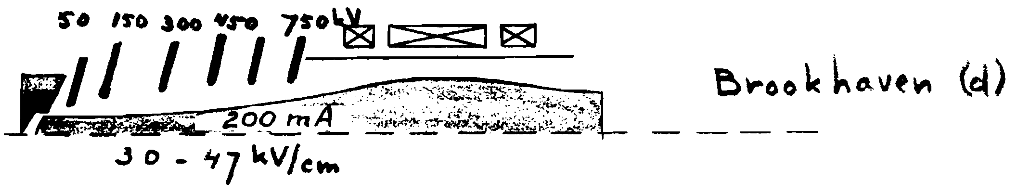


Fig. 5a The "Conventional" Non-Aberrant Preaccelerator Arrangement of Saclay (1968, Ref. 9).

Fig. 5b The "Conventional" Preaccelerator of Serpukhov (1967, Ref. 10).

Fig. 5c The High Gradient Preaccelerator of CERN (1966, Ref. 11).

Fig. 5d The High Gradient Preaccelerator of Brookhaven (1967, Ref. 12).

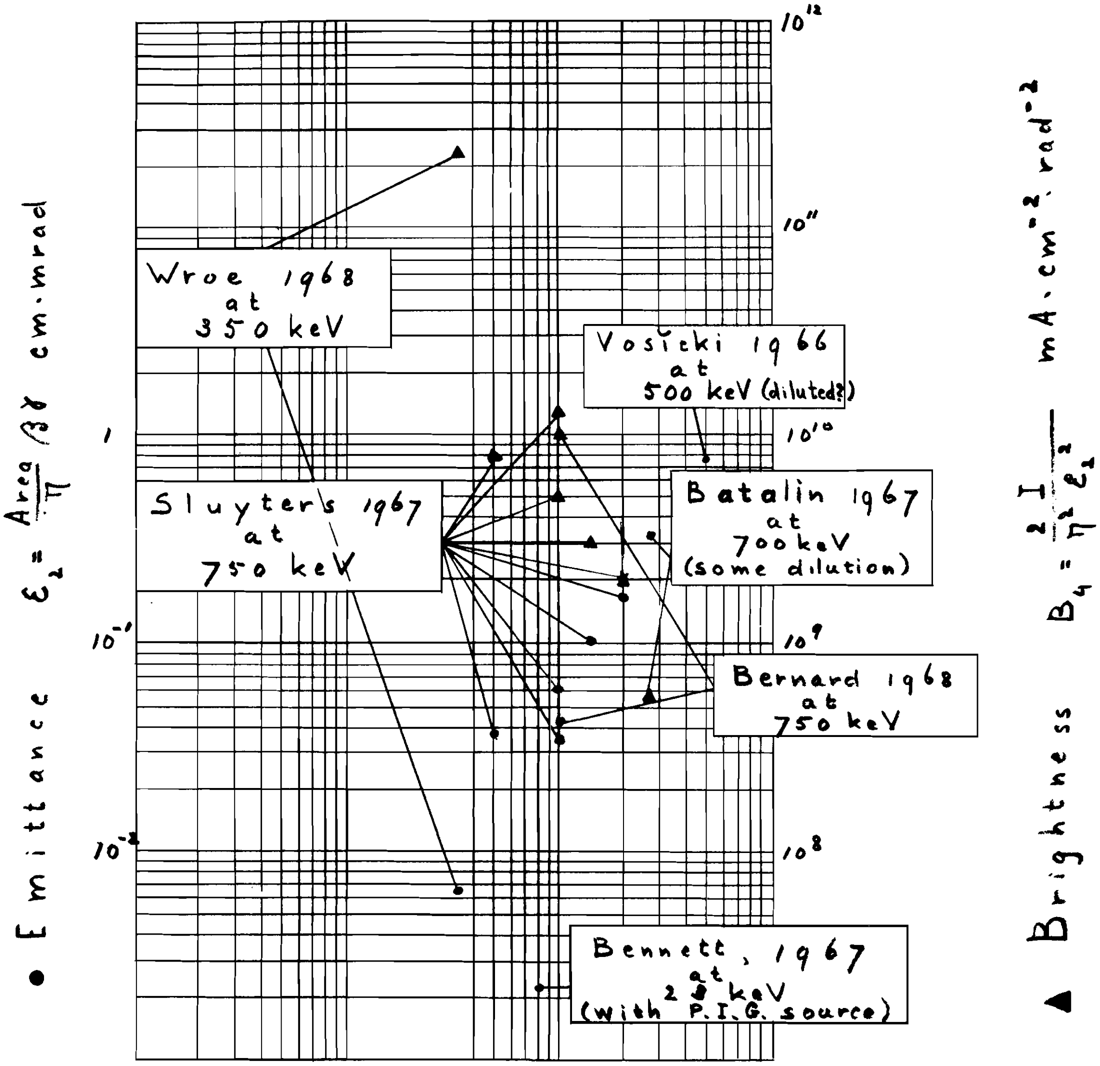


Fig. 6 Undiluted Normalized Emittance and Brightness Values.

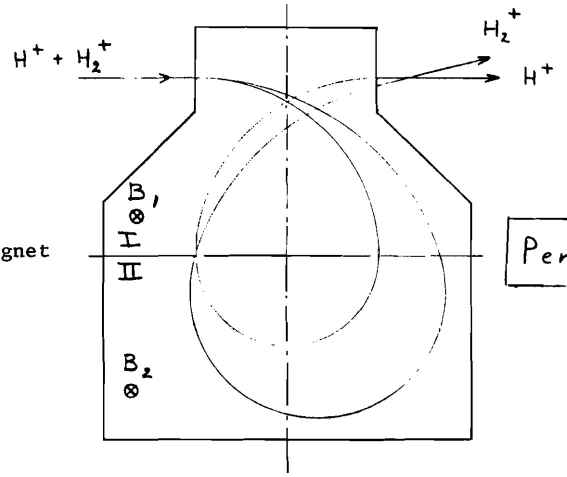


Fig. 7a A 360° Beam Separating Magnet

Perry, 1967

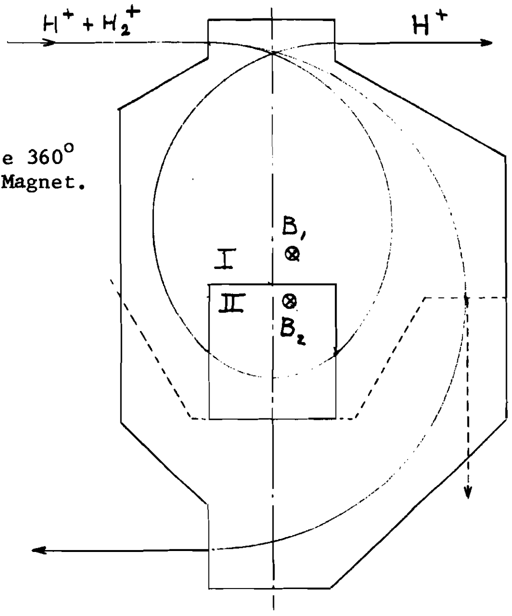


Fig. 7b A Dispersion-Free 360° Beam Separating Magnet.

Claus, 1968

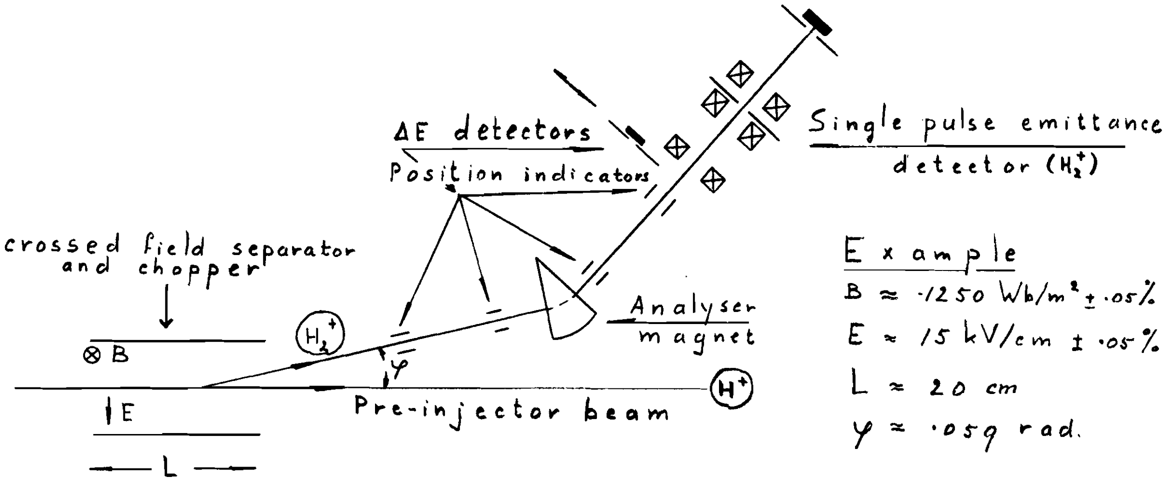


Fig. 8 Crossed Field Separator for 750 kV $\left(H^+ + H_2^+\right)$ Beams and Detector Equipment in the Monitor Channel.