ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

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CERN/MPS/SR 72-4
21.7.1972

DEVELOPMENT OF AN ELECTROSTATIC SEPTUM AT CERN

FOR HIGH ENERGY PROTON SYNCHROTRONS

J. Bleeker, C. Germain, M. Thivent and R. Tinguely

This report will be presented at
the V International Symposium on Discharges
and Electrical Insulation in Vacuum
Poznan, Poland, August 28 - September 1, 1972

DEVELOPMENT OF AN ELECTROSTATIC SEPTUM AT CERN FOR HIGH ENERGY PROTON SYNCHROTRONS

J. Bleeker, C. Germain, M. Thivent and R. Tinguely
CERN, MPS-Division, 1211 Geneva 23, Switzerland

1. Introduction

The slow ejection of protons from synchrotrons, to produce smooth bursts of protons lasting several hundreds of milliseconds, has until now been achieved by using a magnetic septum as the first element of the ejection system. This is a C-shaped magnet with a thin current-carrying barrier (the septum) which restricts the deflecting field to the aperture of the magnet. When the protons are swept across the aperture of the magnet in the ejection process, a fraction of the beam is lost on the septum. With increasing beam intensities it becomes necessary to reduce the proton losses and an electrostatic deflector which can have a very thin septum since no current is flowing in it, therefore appears to be preferable for the first element of the slow ejection system.

An electrostatic septum (ES) consists essentially of a pair of plane parallel electrodes in a vacuum tank. One of the electrodes is very thin and separates the region of the circulating beam, without field, from the region where a field is applied to the ejected beam (Fig. 1 and 2). In the present case the thin electrode has to be the anode and can be at ground potential. The other electrode, at a high potential, is therefore the cathode. The position of the electrodes is adjustable with great accuracy. A gap of 1 to 2 cm is needed with a field in the range of 100 to 150 kV/cm to achieve the required deflection of the proton beam.

The project was based on the technology developed for electrostatic separators (Ref. 1,2,3) but some new problems, specific to the ES, had to be studied in vacuum test chambers. The septum should ideally be vanishingly thin and perfectly flat and remain so in the presence of an electric stress. Besides, it should not be damaged by sparks. It can be made of parallel wires or a thin foil stretched on a frame. In contrast with separators operating in secondary beams, the ES is part of the synchrotron vacuum system which runs at a pressure of 10^{-7} to 10^{-6} torr and therefore cannot take advantage of the better conditions prevailing in a semi-vacuum of 10^{-4} to 10^{-3} torr when a controlled flow of gas is introduced into the vacuum tank (Ref. 1).

A prototype ES, accomodated in a 1 m long free section of the CERN 25 GeV synchrotron, has been tested since 1970 in the synchrotron during a series of "machine development" periods devoted to the project of the future slow ejection system. New problems arose in the presence of the proton beam, namely effects of the protons on the electrodes and of the ions created by the protons in the residual gas of the vacuum chamber. Finally the ES has been used in the normal operation of the slow ejection and now becomes a standard element of the 25 GeV synchrotron. An ES will also be used in the 300 GeV synchrotron which is under construction at CERN.

2. Experimental programme in the laboratory

2.1 Cathode problems

The experience gained with electrostatic separators can be used directly. The best results in the gaps of 1 to 3 cm have been obtained with a cathode made of a light alloy PRE30 (97% Al + 3% Mg), coated with a 6 to 10 µm aluminia layer by anodization in a chromic acid bath. This oxide layer is then sealed in boiling distilled water.

Titanium, which can also give good results, has been tested but not retained since it appeared to be more delicate to use: ~~t~~itanium laminations did not yield reproducible and as good results as our oxide-coated PRE30 alloy (Table 1) The electrode should be made from solid material and the skin layer carefully removed (Ref. 4). A possible advantage of titanium is that it can stand higher energy in the sparks across small gaps but this is irrelevant in the present case since a much lower energy limitation is set on the thin anode by damages. Yet, it is possible that, under other conditions, (higher temperature or proton losses for instance) the choice might have been different.

2.2 Thin anode problems

Stainless steel is the best material for thick separator anodes but its low thermal conductivity precludes its use for the 0.1 mm septum either as wires, which break easily under sparking when the energy available in the discharge exceeds, say, 100 millijoules, or even as foil which becomes wavy or punctured for slightly higher energies.

Copper gives fairly good results, especially from the standpoint of geometrical stability but it is nevertheless preferable to use refractory metals having a low thermal expansion and a high mechanical strength and thermal conductivity such as molybdenum and tungsten. Less brittle than tungsten, molybdenum is to be preferred for the foil which has to be stretched to 10^8 P (about 10 kg/mm^2) on its frame, but tungsten can be used for the wires.

Some results obtained with small electrodes (30 cm^2), spaced by 15 mm in a vacuum of 10^{-6} torr, are presented in Table 1. The electrodes were first conditionned to the maximum possible voltage U_c and then tested for successive periods of 20 hours starting at 70% of the U_c and increasing each time the voltage by 10 kV until the sparking rate stabilized at 10 sparks/hour with the corresponding voltage U_{W10}. The available energy in the discharge was limited by a resistor to a few hundreds of millijoules. These results pertain to 0.1 mm foils of different materials, with the exception of the last line obtained with an array of parallel 0.12 mm tungsten wires (the spacing was set successively at 0.5, 1 and 2 mm without significant variations in the resulting voltages).

0.1 mm foil anode	cathode	fully condit. voltage U_c (kV)	max. working voltage U_{W10} (kV)
stainless steel	titanium sheet	310	300
stainless steel	oxide-coated PRE30	400	340
copper	id	330	270
Be-copper	id	370	280
tungsten	id	370	330
molybdenum	id	410	350
0.12 mm tungsten wire array	id	400	290

Table 1 : Voltage across a 15 mm gap at 10^{-6} torr

W.A. Smith has shown that using somewhat transparent electrodes, such as the ones made of an array of thin parallel rods, can improve the performance of separators both by the higher field, which they can sustain, and by making them much less sensitive to the state of cleanliness of the vacuum system (Ref.5). This improvement seems to apply only in relatively unclean systems where the performance is limited by some particle exchange process, and does not appear to be relevant in our case either for separators or for ES.

There are other arguments in favour of wires. It is easier to build and maintain a perfect plane with an array of wires than with a foil since in the former case the stresses which can develop (in case of local heating for instance) are only one-dimensional. Another argument is that the mean Coulomb scattering angle of the protons hitting the septum is smaller in the case of wires and therefore the proton losses are smaller.

On the other hand the field integrated along the ES is only a few percents smaller in the case of wires which implies that the deflection of the wires under the electric stress is roughly multiplied by d/ϕ with respect to a foil where ϕ is the wire diameter and d the wire spacing. Furthermore, and even worse, the wires are broken by sparks as soon as the available energy reaches a critical value of less than one joule for 0.05 mm tungsten wires. This critical energy scales up as ϕ when applying Utsumi and Dalman's analysis for sparks of short duration in the relevant range of wire diameters, gaps and critical voltages (Ref. 6).

A compromise solution between foil and wire array septum, gathering some of the advantages of both types, could be to use an array of narrow strips retaining the better geometry of wires without being so sensitive to spark damages or electric stress.

3. Performance of the prototype ES

The dimensions of the ES are shown in Figs. 1 and 2. The anode has an aperture of 150 x 70 mm^2 for the circulating beam and the active area of the electrodes is about 600 cm^2, i.e. 20 times larger than the test electrodes. Different screens, whose functions are discussed in section 3.2.1, are mounted at both ends of the anode so that the circulating beam cannot see the cathode. The ejected beam goes once through the thin parts of the screens which limit the gap longitudinally. The capacity between the electrodes, which determines the energy available in the sparks, is about 50 pF. The external energy is absorbed in the resistor connecting the anode to the ground.

3.1 Conditionning and maximum performance in the laboratory

With the gap set at 4 cm the voltage is progressively increased while keeping the current constant at 10 µA. The maximum voltage of 300 kV is usually reached in a dozen hours. The gap is then reduced to 1 cm and the conditionning at 10 µA is resumed until a practical limit U_c is reached, which is accomplished in less than a few hours. In Table 2 is shown the performance achieved with different types of septa facing our standard oxide-coated PRE30 cathode, where U_{W10} is the working voltage, corresponding to a sparking rate of less than 10 sparks/hour, which was applied during the stated length of time.

Type of septum	U_c (kV)	U_{W10} (kV)	Duration	could last longer
0.1 mm stainless steel foil	245	190	110 hours	no
0.1 mm molybdenum foil	245	160	60 hours	yes
0.1 mm Mo or W wire array	200	130	76 hours	yes

Table 2 : voltage across a 10 mm gap at 10^{-6} torr in prototype ES

For the given sparking rate and gap the ES can withstand a voltage of about 20 kV higher for stainless steel than for molybdenum but the flatness of the stainless steel foil is spoiled by the sparks, the energy of which is less than 1 J . Before a HT test the foil is stretched on its frame to within ± 25 µm of an ideal plane; after 3000 sparks in 550 hours the stainless steel foil was within ± 600 µm whereas the molybdenum foil after 10.000 sparks in 350 hours remained within ± 30 µm.

From 30 cm^2 to 600 cm^2 the maximum voltage U_c across a 10 mm gap scales up as A^{α}, where A is the electrode area and $\alpha \simeq - 0.11$. This exponent is about twice what is found for thick anodes (ref. 3).

3.2 Performance during short tests in the 25 GeV synchrotron

As soon as the ES was installed in the synchrotron at the beginning of 1970, it became apparent that the high voltage behaviour was strongly perturbed by the circulating proton beam. The perturbations could be caused by protons hitting the electrodes or by secondary ions falling onto the cathode. Furthermore, the anode in the vacuum tank behaved like an RF cavity coupled to the proton beam and could be tuned on some harmonic of the beam structure at well defined positions, thereby spoiling it and increasing the proton losses which then triggered sparks in the ES.

3.2.1 Effect of secondary ions

When the ES was first installed in the synchrotron there were no screens at the ends of the anode and the ES behaved just as well as in the laboratory when the beam was off, withstanding 160 kV across 1 cm without current (< 1 µA). When the beam was accelerated, sparks appeared, eventually tripping out the generator, when the beam intensity was not very much reduced. Several possible parameters, including the pressure, were varied in order to find the cause of this behaviour and it seemed likely that the origin of the troubles was the ionization of the residual gas by the proton beam.

With a vacuum around 10^{-6} torr and a beam 1.4 x 10^{12} proton/pulse the ion current created by this 110 mA proton beam is bout 2 x 10^{12} ions/s per metre of vacuum chamber. These ions have a very small energy (< 0.1 V) and are driven in a short time (a few tens of µs) to the chamber walls by the potential of a few volts generated by the proton beam. Under these conditions the negative potential of the ES cathode can only drain ions over a short distance, so that perhaps only a few times 10^{11} ions/s fall onto the cathode. The assumption that these ions can trigger sparks in the ES seems valid since we could drastically improve the situation by carefully screening the cathode against them.

The screening has been designed so that the ions in the synchrotron chamber cannot see the cathode and furthermore so that there exists a significant impedance for the flow of gas from the synchrotron chamber and anode beam passage to the inside of the ES tank itself, which has its own pumping station. This is obtained, as shown in Figs. 1 and 2, by using tubular screens positionned close to the plane screens. Out of the way of the ejected beam the plane screens are thick and in the way they are thin and made of 0.02 mm aluminium foil streched on a frame. It is essential that the thin Al screen be placed almost in contact with the septum foil to prevent ions from leaking through the small passage to the cathode. With this screening it became possible to withstand the same voltage with and without the proton beam (about 2 x 10^{12} protons per pulse) in the case of no beam losses in the ES.

There is another way of reducing the influence of the secondary ions: instead of screens one can use clearing electric fields at both ends of the ES to prevent the secondary ions from falling onto the cathode.

A pair of electrodes shaped to fit the synchrotron chamber aperture has been installed at both ends of the ES close to the anode and their efficiency was tested in the absence of all the screens just described. The two pairs of electrodes are connected in such a way as to provide fields of opposite directions in order not to perturb the proton beam ~~and~~ they can be supplied by a DC voltage up to 10 kV. Under these conditions several parameters have a strong influence on the behaviour of the ES: the voltages of both electrodes, the radial position of the anode, the pressure in the chamber and the intensity of the beam. To make a long story short, we give only the main result from a practical standpoint: in normal operating conditions it is also possible to withstand the full voltage on the ES in the absence of all the screens with one of the clearing electrodes at a negative voltage of a few kilovolts and the other at ground in each pair, whereas without this clearing field the voltage on the ES cannot exceed 30 kV. This is still true with a value of pressure times beam intensity increased up to 4×10^{-7} A·torr when the clearing voltage is - 7 kV.

3.2.2 Effect of beam losses on the ES

If the protons hit only the septum foil, i.e. the anode and not the cathode, the effect on the voltage behaviour is negligible at our present maximum beam intensity of 2×10^{12} protons/pulse. On the other hand, when too many protons are sent onto the cathode at grazing incidence, during the setting-up periods for instance, sparks are triggered by intense secondary electron emission. This effect is also observed at injection, when the chamber is filled most widely with low energy protons, if the orbit has not the right shape to miss the ES, but this can easily be corrected. It seems that at least 10^{11} protons are necessary for this effect to be observable in our conditions.

When the ejection operation is correctly adjusted, the total proton losses on the ES are only a few percents of the beam intensity and since a very small fraction of these protons are lost onto the cathode, the ES sparking rate is not appreciably increased by this process.

3.2.3 ES-beam electromagnetic coupling

When the ES is installed in the synchrotron it is electromagnetically coupled to the proton beam and attention has to be paid not to spoil the structure of the beam by this coupling. The anode is not directly connected to the earth potential but through a protection resistor of 200 to 300 ohms which is needed to avoid damaging of the electrodes by sparks. The harmful self-oscillations which could be excited by the beam circulating through the anode are strongly damped by using a properly matched coupling loop placed in the ES tank and connected to an external dissipative circuit. Strong oscillations occur at discrete positions of the anode which tune the ES on some harmonic of the beam RF structure (about 10 MHz); in the absence of the dissipative circuit, beam oscillations are induced and sparks can be triggered in the worst cases by the resulting proton losses.

As an alternative to the design just described the protection resistor, instead of being placed between the anode and the ground, can be located between the bushing and the cathode. In this case the anode is well earthed but the ET behaviour is slightly more delicate because the resistor is always at a high negative potential, and also it requires more space on this side of the ES. This solution will eventually be used in future.

4. Operation of the ES in the 25 GeV synchrotron

The experience of operation in the synchrotron is still limited. We have used one or the other ES altogether during about fifty periods of slow ejection tests lasting in general six hours each. A voltage of 150 to 170 kV was required and provided during these tests across a 1 cm gap. Sometimes the voltage could be pushed up to 200 kV but these tests lasted only for a few hours each time.

We have not yet any long-term operational experience with an ES except for a trial high energy physics run of 245 hours which was carried out in October 1971 without any major troubles. The sparking rate averaged one per 37 PS cycles, which was acceptable in a first test but will have to be reduced, while maintaining the working field at 140 to 150 kV/cm across a 10 to 12 mm gap. The pair of electrodes which was used withstood altogether ten thousand sparks before the ES was opened for inspection while it still operated satisfactorily: the flatness of the anode was not deteriorated and the surface of the cathode did not show appreciable damages.

5. Conclusion

In the present status of the project there seems to be no fundamental difficulty ahead and we are therefore confident that reliable working conditions will be found when the ES is used in the standard operation of the 25 GeV synchrotron. Some development is still required to further reduce the septum app ent thickness and to accomodate the future higher beam intensity of this machine The length of the ES in the future 300 GeV synchrotron is scaled up by an order of magnitude and the radiation field will be much higher so that some problems have still to be dealt with in this new project.

Acknowledgement

We are pleased to thank G. Plass for his continuous support and to acknowledge the contribution of the whole "Special Project" section in this work.

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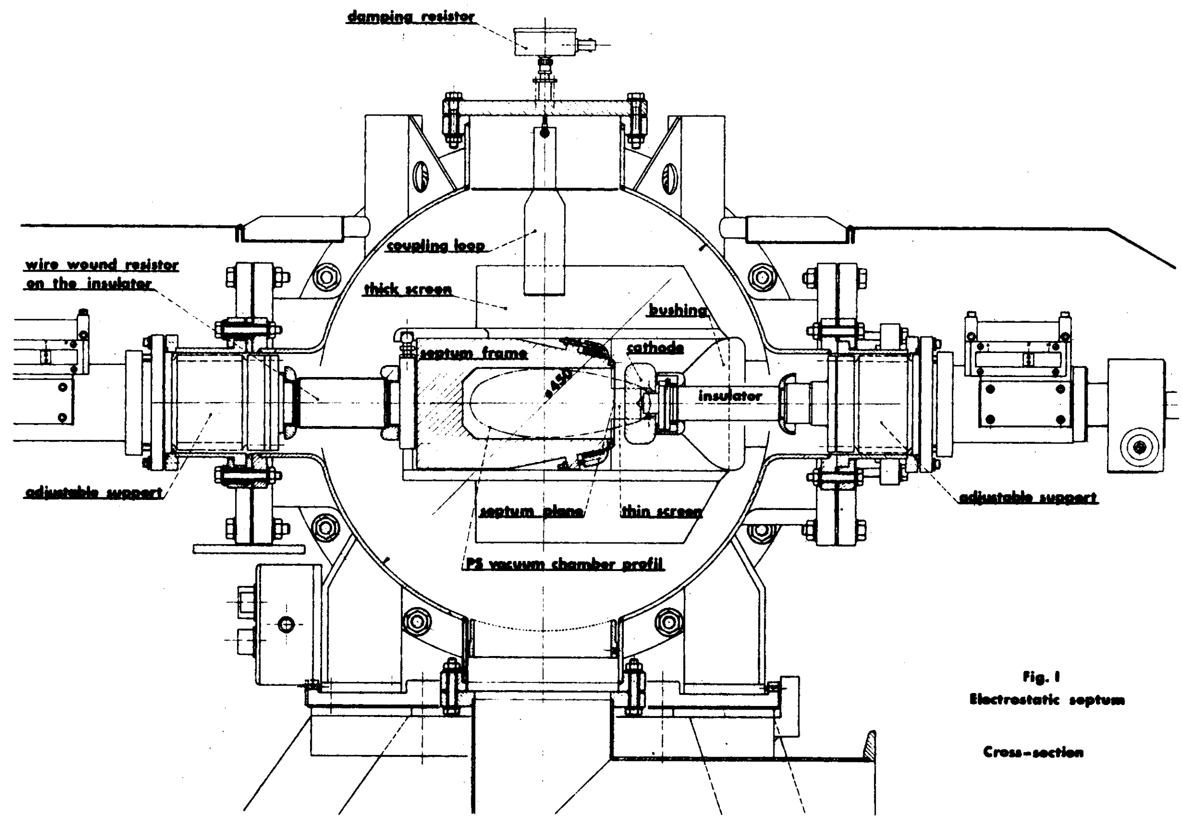

Fig. 1
Electrostatic septum

Cross-section

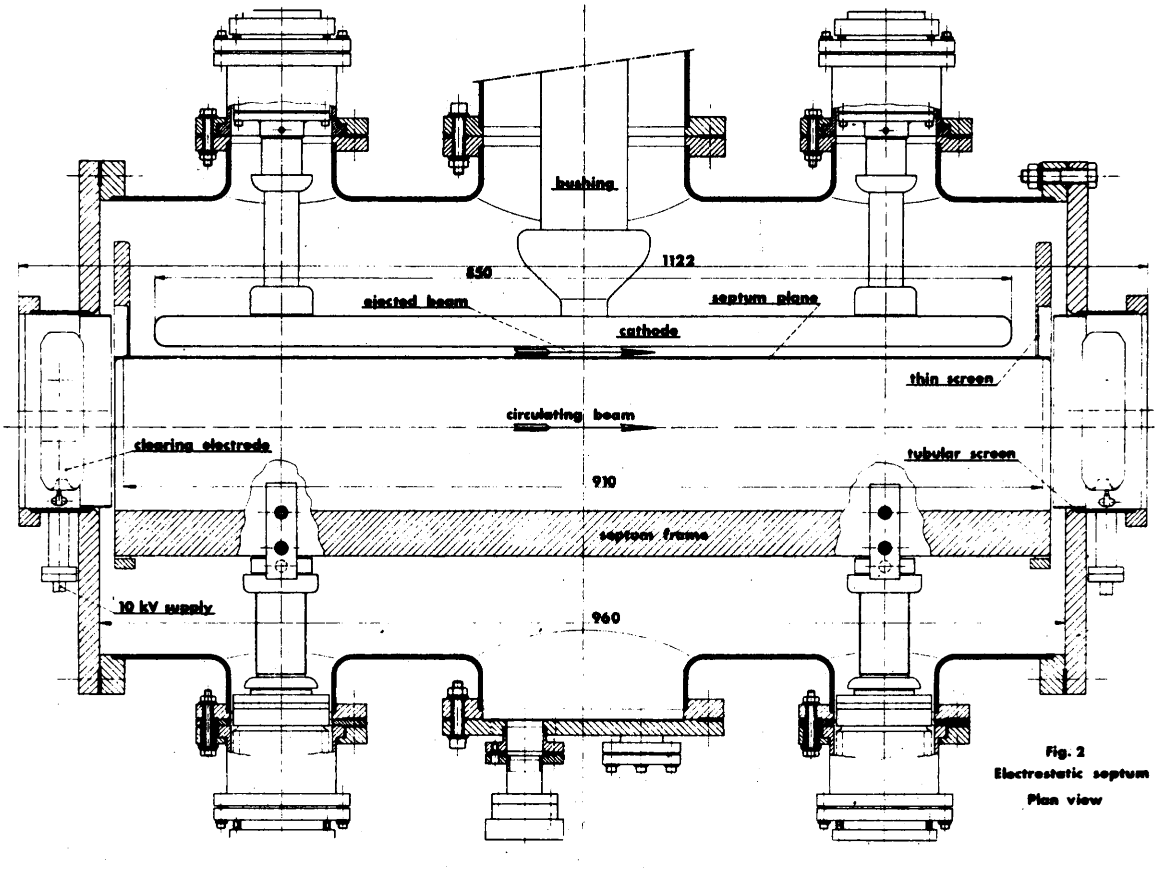

Fig. 2
Electrostatic septum
Plan view