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ELECTROSTATIC SEPTUM IN A HIGH INTENSITY ELECTRON ACCELERATOR

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### Abstract

Calculations of beam power losses and equilibrium temperatures of the wires of an electrostatic septum have been carried out. The occurence of an electromagnetic shower has been examined in the case of a metal foil septum and the longitudinal profile of the beam power losses is given.

#### Introduction

A 100% duty cycle, high intensity, 100 $\mu$ A, and 2 GeV electron accelerator has been studied at Saclay<sup>1,2</sup>. The well-known scheme using a pulsed high peak intensity electron linac and a stretcher ring was first chosen. The maximum energy can reach 3 GeV without changing the ring lattice.

Avoiding particle losses in the accelerator structures becomes a very important goal when high average intensity and higher energy beams must be handled. Indeed, such losses produce  $\gamma$  rays radiation, ( $\gamma$ ,n) reactions, activation of the structures and may eventually destroy accelerator components. A part from energy selection slits, the major sources of losses are the injection and extraction channels into and from the stretcher ring. This work is devoted to minimizing the beam losses in the extracting septa, and to studying the feasibility of an electrostatic septum as the first deflecting element in the extraction channel.

In the case of negative charged particles, the electric field of an electrostatic deflector can accelerate low energy electrons from the surface of the septum wires or foil towards the bulk electrode. These could induce a gas discharge which would destroy the electric field configuration. Thermo-electronic emission then must be avoided, mainly by reducing the beam energy losses in the septum.

### Extraction channel

A resonant extraction in the horizontal plane (x,s) is used, either with a half integer or with a third integer resonance. In figure 1 is shown the extracted beam emittance, assuming that the septum is at 15 mm from the closed orbit and at the end plane of a



Fig.1 - Typical extracted beam in horizontal phase space at the entry of the septum (septum abscissa d = 15 mm)

focusing quadrupole, near a maximum of  $\beta_x(s)$ . The histogram of 10.000 particles passing through the same plane with x > 14.8 mm is shown in figure 2. It can be seen that 3% of the extracted current falls in a 0.1 mm thick "slit" in the vicinity of the septum position.



Fig.2 - Histogram of electron amplitudes  $x_0$  in horizontal plane at the septum entry ( $x_0 < 14.8$  mm not plotted)

If a magnetic septum was used, the thickness would be at least 0.5 mm and up to 15% of the average current, that is 15  $\mu$ A, would be intercepted. This is not tolerable. On the contrary, an electrostatic septum can be as thin as 0.1 mm or even less<sup>3,4</sup>. Our extraction channel could begin with such a septum, 2 meters long, with an electric field E ~ 25 kV/m.GeV, giving a deflection angle of 5 mrd. The channel then includes drift spaces and two septum magnets which will not be described here.

## Minimisation of losses

As can be seen in figure 1, and due to the location chosen in the ring lattice, the beam has a negative slope in the horizontal plane (x' = dx/ds<0). The losses can be reduced by giving to the septum an angle X' with respect to the closed orbit. This is shown in figure 3, which is the horizontal phase plane  $(x_0, x_0')$  at the entrance of the septum. The ellipse ① is the extracted beam (as in fig.1), line ② is the way followed by the resonant particles every second turn, ③ is the region occupied by the circulating beam. The upper shaded area is the location of eventual circulating particles which will hit the septum downstream.

The lower shaded area is the location of electrons which enter the active part of the septum with a too large negative slope  $x_0$ ' and which the electric field cannot deflect enough to avoid hitting the septum somewhere.

The beam must be adjusted as well as possible between these two areas, and it is evident that in this case there is a class of electrons which cannot avoid hitting the edge of the septum foil (or the first septum wire), those with  $x_0' = X'$  and  $d-e/2 < x_0 < d+e/2$ , where e is the septum thickness. Of course, in real

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Fig.3 - Horizontal phase space at the septum entry. Shaded areas are unallowed regions. The septum makes an angle X' with the equilibrium orbit. () is the extracted beam ellipse.

life, a few electrons following in the line  $\bigcirc$  -  $\bigcirc$  will fall in either of the two shaded areas.

# Heating of the septum

Electrons impinging to a thin material are scattered by Coulomb interaction and loose energy locally by ionisation, if the thickness is smaller than the radiation length. In the case of a wire septum, it was first assumed that the first few wires were independently heated by ionisation loss. A computer calculation of the wire equilibrium temperature was performed for various metals, taking into account cooling by radiation and by thermal conduction to the septum frame. The following equation was solved by a RKGS method :

 $K(\pi D^2/4)d^2T/dy^2 - \pi D\varepsilon\sigma T^4 + (\pi D^2/4)k\rho j(y) = 0$  $j(y) = (I/Db/\pi) \exp(-y^2/b^2)$ 

D is the wire diameter, y the coordinate along the wire, b the vertical beam width, T the temperature, K the heat conduction coefficient,  $\epsilon$  the metal emissivi-

ty,  $\sigma$  the Stephan constant,  $\rho$  the specific gravity, k the ionisation loss coefficient, j the current density, I the total current impinging to the wire. The results for D = 50 µm, I = 1 µA, E = 2 GeV, a wire total length = 40 mm and the values of  $\varepsilon$  and K found in current literature are given in table 1.

The materials whose equilibrium temperature  $T_{r+c}$  is sufficiently low with respect to the melting point are tungsten, molybdenum and carbon, and eventually iron. Carbon is the only one to keep a very low temperature where electron emission would be insignificant. However, the use of carbon fibers as electrodes is questionnable. A metal stress study is necessary to know how much the yield strengths are lowered at the quoted temperatures  $T_{r+c}$ .

# Electromagnetic shower

In the previous calculations, the energy deposited in the septum was assumed to be due to ionisation only. Actually, the  $\gamma$  rays produced by bremsstrahlung can produce pairs of e<sup>+</sup>, e<sup>-</sup>, and these interact again with material, provided that the target thickness is of the order of the radiation length. This is the well known electromagnetic shower. It can be shown by 1D theoretical calculations<sup>5</sup> (infinite transverse dimensions) that the deposited energy in such a shower passes through a maximum at a depth  $T_{max}$ ; the value of heating power at maximum is  $\pi_{max}$  times the ionisation power "psg". For tungsten, at E = 2 GeV,  $\pi_{max} \approx 25$ .

In the case of a wire septum it is possible that the effect of the shower be small, due to angular scattering, although the photons produced in the first wire have a rms angle ( $\theta \simeq mc^2/E$ ) much smaller than the angular width of the next wire. A discussion of the various effects in a wire septum can be found in refs.6 and 7.

In the case of a thin foil septum, an electromagnetic shower can  $\text{grow}^8$ , provided the electrons impinge to the edge with a direction identical to the foil direction z. However, due to the very small transverse dimension of the foil, parts of the shower will be scattered out of it, and the theoretical model no

Table 1

Material		Au	17	₩+Rh(26%)	শত	Cu anneal.	Cu poli.	Cu+Be(2%)	Fe oxyded	Tİ	Al oxyded	Al poli.	C fiber
Z		79	74	74/75	42	29	29	28.5	26	22	13	13	6
ρ	(g/cm <sup>2</sup> )	19.3	19.2	19.2	10.2	8.9	8.9	8.25	7.8	4.5	2.7	2.7	1.88
k	(MeV.cm <sup>2</sup> /g)	1.7	1.6	1.6	1.8	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.1
ε	(emissivity)	0.03	0.29/0.23	0.29/0.23	0.21/0.14	0.26	0.03	0.2(?)	0.75	0.2(?)	0.19/0.15	0.06	0.8
ĸ	(cal/s.cm <sup>2</sup> .deg)	0.62	0.25	0.15	0.20	0.82	0.82	0.35	0.11	0.045	0.54	0.54	0.13
Pbeam	(Wm)	129	120	120	72	66	66	62	58	34	21	21	15
T <sub>ray</sub> (0)	(K)	4060	2266	2266	2160	2005	3440	2105	1490	1805	1630	2175	1055
$T_{r+c}(0)$	(K)	2060	1710	1844	1620	980	1190	1270	1155	1427	700	720	690
$T_{r+c}(0)$	(°C)	1787	1437	1571	1347	707	917	997	882	1154	427	447	417
T <sub>melt</sub>	(°C)	1065	3400	3000	2620	1100	1100	880	1500	1660	6 <b>6</b> 0	660	3500
Fraction	(%)	66	15	7.5	21	65	91	36	3.2	2.9	79	90	11
Elasticity modulus	$(daN/mm^2)$ ×10 <sup>-3</sup>	9	34		29	12		12.7	20	10	7	7	40

Equilibrium temperatures of wires (50 $\mu$ m o.d.) made of various metals, hitten by a 2 GeV, 1  $\mu$ A electron beam. T<sub>r+c</sub> is obtained by taking into account radiation and heat conduction.

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longer applies. Numerical calculations of the electromagnetic shower were performed with the EGS code (version 3) $^9$  which uses a Monte Carlo method.

First, the e.m. shower growth and maximum were studied as a function of the foil thickness e, the 2 GeV electron beam impinging to a e/10 width at the edge center. The results for molybdenum foils are shown in figure 4 ( $X_0$  is the radiation length, psg is the power deposited by excitation and ionisation only). The electron flux is 1 µA, the foil height is 40 mm. The theoretical point  $T_{max}$ ,  $\pi_{max}$  is plotted. Decreasing the thickness results in shifting the shower maximum and decreasing it. Also, the total power deposited decreases from 98% to 2.2% of the incident beam power. This is due to an increase of the scattering of secondary particles out of the foil. However, for a 0.1 mm thick foil, the heating is still larger than the psg level (by a factor ~ 1.4) at maximum (depth  $z/X_0 \sim 0.6$ ).

Then, runs with up to 4000 primary electrons and different initial conditions were performed to obtain a smooth and reliable profile of the deposited power, with incident electrons spread over the full edge of the foil. The results for three energies and the same 0.1 mm thick foil are summarized in table 2. More information is available in reference 7.

#### Table 2

Results of EGS calculations (molybdenum foil 0.1 mm thick)

Incident energy	(GeV)	0.6	2	3
Incident power	(kW)	0.6	2	3
Total deposited power	(W)	20	44	60
Maximum power density	(W/mm)	2.22.8	2.5±0.2	2.53.0
Ionisation power density	(W/mm)	1.83	1.84	1.85
Depth of maximum	(mm)	4	6	11

In this energy range, the value of the maximum power density is approximately a constant, although the total power deposited along the foil increases with energy (as  $E^{2/3}$  in the range).

These calculations indicate that a power density higher that the ionisation power (psg) is deposited in a region of the foil located a few mm from the edge. The results can be extended to other metals by using the ionisation power density (psg) and the radiation length as a scaling. The calculation of the equilibrium temperature of the foil has to be carried out by solving the 2D heat diffusion equation. In the case of a wire septum it is doubtful that the present results be applicable, saying only that a 6 mm depth corresponds to 60 wires of 0.1 mm diameter. Runs of EGS with the actual geometry must also be carried out. However, as an indication, the temperature attained by a tungsten wire in the conditions of table 1, but with a heating power equal to 1.5 times the ionisation power loss, was calculated. The result is  $T_{r+c} = 1840$  °C unstead of 1440°C. Such a difference is important as concerns thermo-electronic emission. As a result, more work has to be done to assert the feasibility of an electrostatic septum in the case of high average intensity electron beams.

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Fig.4 - Profiles of the deposited power density by 2 GeV,  $\mu$ A electrons impinging foil edges of various thickness (0.1 mm  $\leq e \leq 100$  mm).  $X_0$  is the radiation length. psg is the power loss due to ionisation. Computation makes use of the EGS code.

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