A 600 MHz CHOPPER SYSTEM FOR AN ELECTRON LINAC

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Abstract: - The 1983 ALSII project (Saclay, France) of a 100% duty cycle accelerator with a linac and a pulse stretcher ring, led to conceive and study a subharmonic chopper-prebuncher beam line to produce electron bunches at 600 MHz.The chopping system - a TM110 rectangular cavity associated with collimator and focusing - has been built and tested with a 40 kev beam at low current. The bunches lengths have been measured by spectral analysis, with an adapted coaxial cup (bandwidth 7 Ghz). Numerical simulations with a 3D space charge model, showed that the same chopping lay-out can be used with a 2 A, 150 kev beam.

INTRODUCTION

The need for a 100 % duty cycle electron accelerator to be used in nuclear physics, has led the CEN Saclay Linear Accelerator Group, to study a machine using the existing linac associated with a pulse stretcher ring [1]. The production of electron bunches at the ring RF frequency (600 MHz or fifth subharmonic of the linac frequency) requires the design of a new injector including a chopping beam system [2].
Indeed,with the strong beam power expected (280 mA peak at 1.3 Gev ,after a two turns injection), the necessity to avoid current loss in the ring leads to reduce electrons injected out of the ring acceptance, and to eliminate them at the beginning of the linac, and so to avoid "satellites". The injector schematic diagram with its chopping principle is presented on figure 1.

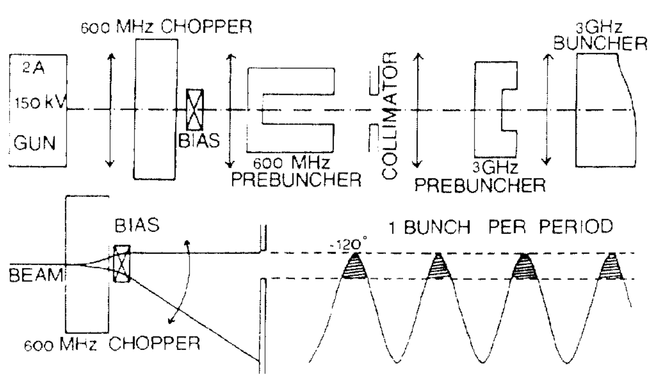

Fig. 1. - 1983 ALSII project injector and chopping principle.

We choose to transmit a bunch with around 120° of phase extension per 600 MHz period, (that is to say 30% of gun current) and to collect them at best in one period of the fundamental frequency, with a subharmonic prebuncher. Harmonic bunching is then realized by a 3 GHz prebuncher followed by a buncher section to obtain about 5° bunch lengths at 20 Mev with a 140 mA peak current. The expected total efficiency is 15% and so the gun must produce at least a 940 mA current . A safety margin requires actually that the system could operate with a 2 A beam gun.

CHOPPER CAVITY

The deflecting performances analysis with different types of modes and cavities (cylindrical, rectangular, unipolar or dipolar modes) [3], shows that the TM110 mode in parallelepipedic cavity is the most favourable, in particular to minimize power injected in the cavity. In addition, its quality factor is the lowest. This is interesting to reduce temperature sensitivity, and to lower the RF rising time. The cavity drawing, as also the field lines, are shown in figure 2. In the middle plan x=d/2, the deflecting magnetic field is :

$$Hx = \left[\frac{8\ P\ Qo\ d^2}{\pi\ Zo\ h\ (\ a^2\ +\ d^2\ )^{3/2}}\right]^{1/2} .\cos(\pi\ y/a) \quad (1)$$

where P is the power loss , Qo the unloaded quality factor and Zo ≅ 120.π the vacuum impedance.

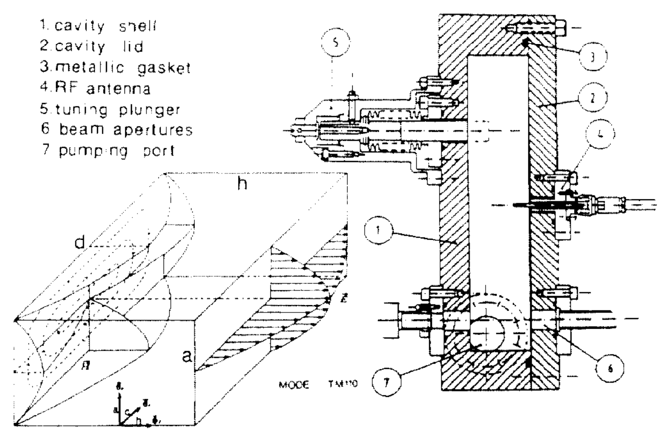

Fig. 2. - Chopper cavity.

The cavity was built of an aluminium alloy Duralumin AU-4G(2017A) with two parts and air-tightness is assured by means of a metallic gasket.Internal dimensions are a = 29,41 cm ; d = 46,93 cm ; and h = 6 cm. RF coupling is achieved by an antenna located where electrical field is maximum (x = a/2 ; y = d/2), and beam crosses the cavity where magnetic field is near to its maximum (95%). A tuning plunger allows an about 1 MHz resonance frequency variation. Such a cavity has been built and mounted on a beam test line and showed the following features :
- coupling factor β = 3,3
- unloaded quality factor Qo = 3130
- loaded " " Qc = 730
- RF rising time (10% to 90%) τ = 0,857 µs
- temperature/freq. sensitivity: - 14 khz/°C
- temperature/power sensitivity: 0,1% for 1°C or 10% for 10 °C .

For example, to have a 1 cm deflection, 40 cm from the cavity with a 40 kev beam, we must dissipate about 154 W. In fact, this power should be modified to take into account the focusing system (see following section).

BEAM LINE DESIGN AND NUMERICAL SIMULATIONS

Figure 3. shows the beam line schematic diagram. The initial beam parameters at z=0 are assumed to be known, and defined by a short transition beam line between gun and chopper system (see for example [4]). With a 40 keV beam, we have chosen: initial radius Ro=4 mm, emittance = 30π mm.mrd and divergence 18 mrd.

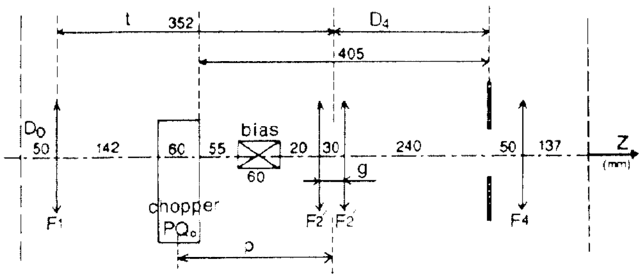

Fig. 3. - 40 keV beam line parameters.

The first lens f1 is designed to control the beam radius before chopping. The two lenses f'2, with opposite fields, allow to focus the beam on the collimator,to prevent the beam rotation and thus to have a fixed collimator independant of lenses focal lengths. The bias coils set the sweep center and determine the desired chopping. In order to optimize the chopping, the ratio ,sweep amplitude over beam radius, must be maximum.
The beam dynamics without space charge is studied with the "classical" transport matrix method, which allows to analytically determine the emittance ellipsis changes, and so the beam radius and its divergence. The focusing system can be optimized to minimize the beam radius on the collimator. We have:

$$f_2 = \frac{D_4\left[g_1^2 + (g_1\alpha_1 - g_2\beta_1)^2\right]}{g_1^2 + (g_1\alpha_1 - g_2\beta_1)^2 + g_1 g_3 + (\alpha_1 g_1 - \beta_1 g_2)(\alpha_1 g_3 - \beta_1 g_4)} \quad (2)$$

where

$$g_2 = 1 - \frac{t}{f_1} \qquad g_4 = -D_4/f_1$$

$$g_1 = t + D_0 g_2 \qquad g_3 = D_4 + D_0 g_4$$

f2 is the equivalent focal length of double-lens, which individual focal lengths are:

$$f'2 = f2 + [\ f2\ (f2 - g)\ ]^{1/2} \quad (3)$$

and α_1 , β_1 are initial parameters of the beam emittance.
The beam radius on collimator is given then by:

$$R = R1.D4\ /\ [\ g1^2 + (g1.\alpha_1 - g2.\beta_1)^2\ ]^{1/2} \quad (4)$$

with R1 initial radius.

On the other hand, the focusing system modifies the sweep amplitude. It can be shown that the cavity power losses ratio, with and without focusing, is :

$$\frac{\text{Pwithout foc.}}{\text{Pwith foc.}} = \left[\frac{D4 + p - D4.\ p\ /f2}{D4 + p}\right]^2 \quad (5)$$

With a 40 keV beam, deflected by 1 cm at 40 cm from the chopper, it is now necessary to dissipate 533 W in the cavity, with the adequate focusing system (f2 = 22,8 cm ; D4 = 25,5 cm ; p = 18 cm). In that case, the beam radius is 1,5 mm on collimator.
Because of the beam entry out of the maximum magnetic field, we must take into account an energy modulation linked with the electrical field seen by the beam. At first approximation, the sweep amplitude does not depend on this energy dispersion, but on the other hand the chopping quality and transmitted current are connected to.

As shown in figure 4. one get a debunching or bunching effect according to the sweep portion which is transmitted. It can be shown that, for example, in the nominal foregoing case, for a 120° chopping, 10 to 12% of initial current are transmitted with debunching, when it is 30 to 34% with bunching (near to the theoretical maximum current with a 120° perfect pulse). The bunching effect is also favourable to compensate longitudinal space charge.

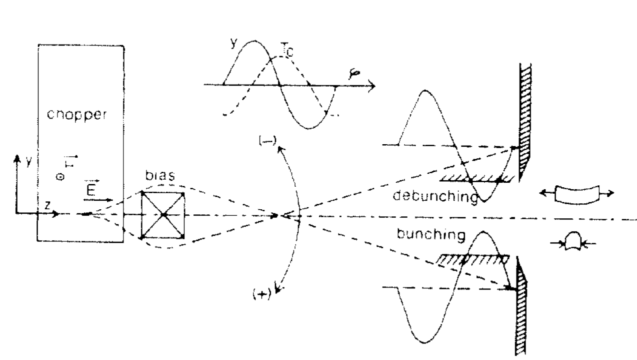

Fig 4. - Bunching and debunching processes.

Figure 5 shows a 3D typical outline of the sweeping beam and the 600 MHz bunch production (with a 40 keV beam).

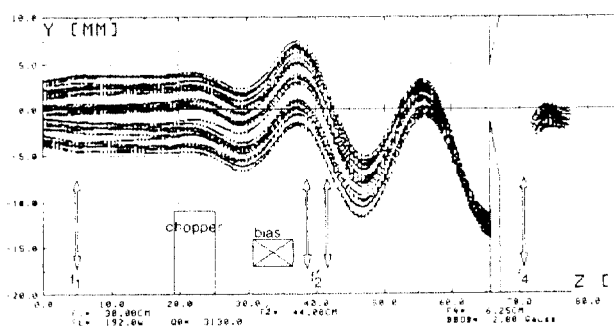

Fig. 5. - 40 keV deflecting beam enveloppe.

With the design of a 2A, 150 keV beam line, and a similar lay-out, we use a slightly more compact line to make the focusing easier.
6 kW are now needed in the cavity to deflect the beam in the same way. Beam dynamics is studied with the PARMELA program [5], with a 3D particle-particle space charge model added as a new subroutine. The electron j impulse change, in the space charge field created by electrons i, is : (6)

$$\frac{d(\gamma_j\vec{\beta}_j)}{dt} = \sum_{\{i \neq j\}}^{N} \frac{q_j}{m_0 c}\,\gamma_i \left\{ \vec{E}'_i(1 - \vec{\beta}_j.\vec{\beta}_i) + \vec{\beta}_i[\vec{\beta}_j.\vec{E}'_i - \frac{\gamma_i}{\gamma_i + 1}\vec{\beta}_i.\vec{E}'_i] \right\}$$

with :

$$\vec{E}'_i = \frac{q_i}{4\pi\varepsilon_0}\frac{\vec{r}'_{ij}}{\|\vec{r}'_{ij}\|^3} \quad \text{and} \quad \vec{r}'_{ij} = \vec{r}_{ij} + \vec{\beta}_i.\frac{\gamma_i^2}{\gamma_i + 1}(\vec{r}_{ij}.\vec{\beta}_i) \quad (7)$$

Figures 6. and 7. show an example of the undeflected beam enveloppe in the focusing system, and the 3D outline with deflection.

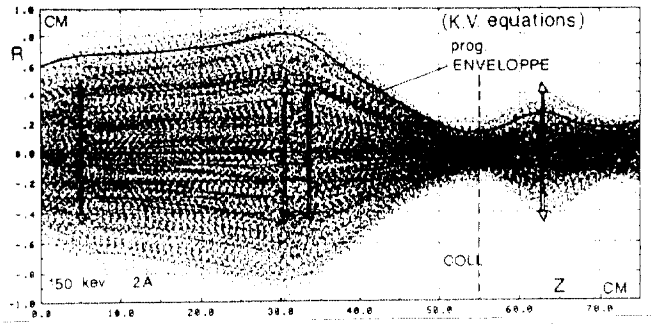

Fig. 6. - 150 keV, 2A beam enveloppe in the focusing system.

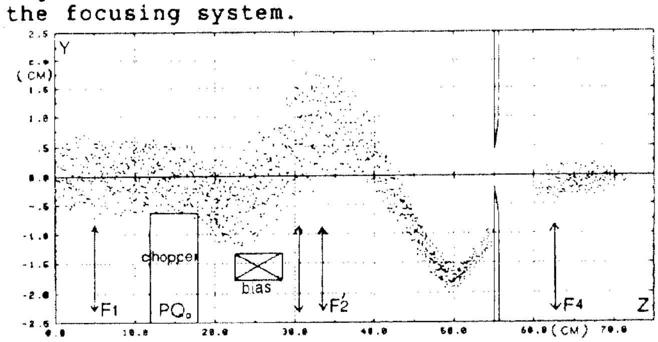

Fig. 7. - 150 keV, 2A deflecting beam enveloppe.

MEASUREMENTS

A 40 keV beam test line has been mounted to study the chopping system (figure 8.). The bunches are collected on a 50Ω adapted coaxial cup (figure 9.).The target is made of aluminium, to minimize secondary emission.The total measurement system presents a 7 Ghz bandwidth (3 dB).

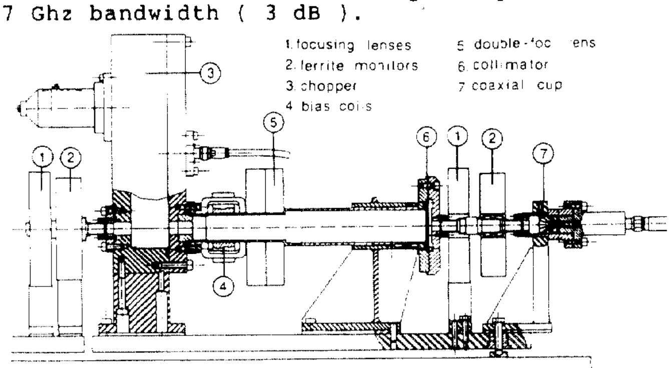

Fig. 8. - 40 keV beam test line.

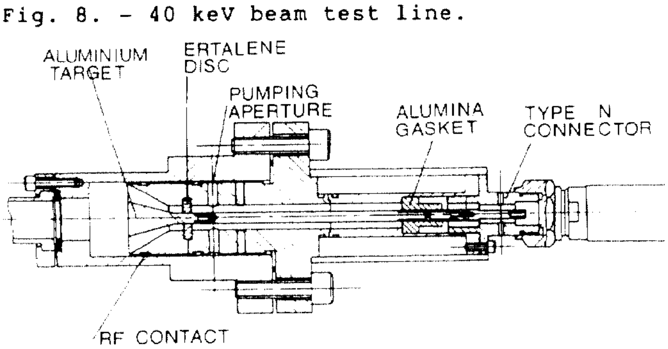

Fig. 9. - 50Ω coaxial cup.

Initial pressure without RF in the cavity, was at best about 10^{-8} Torr. RF power feeding (about 180 W peak), shows a fast rising pressure, event which has been attributed to a "multipactor effect". However, it was possible to process out multipactoring by RF conditionning during twenty hours [6].

First measurements are realized with a fluorescent screen to visualize the beam, to adjust and calibrate the system parameters such focusing and bias coils current. To measure the bunch lengths, the coaxial cup is connected to, either a spectral analyser (HP 141T - IF 8552B - RF 8555A), or a sampling oscilloscope (Tektronix 7603 - 7T11 /7S11 - HF S6/ 30 ps). With the first method, the spectral lines amplitudes are registered, corrected by the system response, and the time signal is then computed by inverse Fourier transform (figure 10). With the time sampling method, the bunch shape is directly seen on the oscilloscope screen (figure 11.).

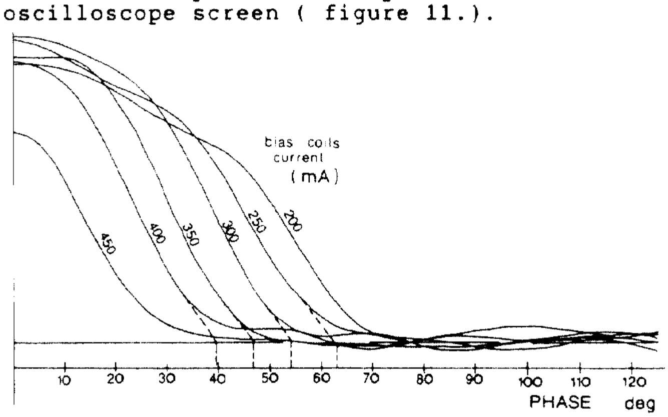

Fig. 10. - Bunches shapes by Fourier analysis

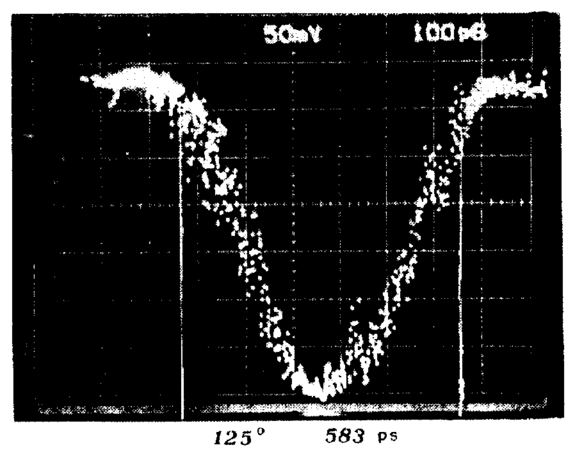

Fig. 11. - Bunch shape on sampling oscilloscope.(Chopping : 140° / Measured on cup : 125° / bunching effect)

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