ACCELERATION AND BUNCHING IN A 6 MV X BAND LINAC

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Abstract

We present detailed beam dynamic simulations in a compact X band accelerator. The accelerator must be capable of delivering an electron beam of 0.5 MW peak at 6 MeV, in order ot produce an X ray dose of 10 Gy/mn at 80 cm for medical applications. The use of a PARMELA like code (DYPAL [1]) allowed us to investigate radial and longitudinal beam dynamics. Important aspects of the calculation were to optimize the bunching, while controlling the radial behavior of the beam. This lead to reduced X ray leakage along the section and high transmitted current ratio from gun to target.

1 INTRODUCTION

A new concept for the delivery of dynamic conformal radiotherapy has been recently proposed, under the name of "tomotherapy" [2]. The basic idea is to put a linear accelerator into a CT-like ring gantry configuration and deliver a rotating modulated therapeutic radiation, while the patient moves through the gantry in the longitudinal direction. To limit the outer radius of such a machine, the embarked linac must be as short as possible; it also has to be light enough so that the mechanical assembly of the CT ring gantry can support it. Both these requirements have driven the choice of X band (9.3 GHz) for the operating frequency of the linac. This choice also reduces the electrical power that has to be transfered through circular contacts (compared to the power required in S band for the same photon energy).

2 ACCELERATOR PARAMETERS

2.1 Shunt impedance

The accelerating section is of the standing wave, tri-periodic, on axis coupled type. The standard accelerating cavity shape is shown on figure 1. It was optimized for high shunt impedance. The iris diameter is 2.3 mm, giving a theoretical (SUPERFISH) shunt impedance of 189 MΩ/m. The lower shunt impedance of the bunching cavities lead to an average shunt impedance for the accelerator of 167 MΩ/m. An alternative, more conservative design with an iris diameter of 3.5 mm gives a theoretical shunt impedance of 160 MΩ/m.

2.2 Energy, length, dose rate

Table 1 summarizes the main Linac parameters. The peak current required to obtain a dose rate of 10 Gy/mn at 80 cm is 90 mA, for an energy of 6 MeV. Assuming a magnetron peak power of 1.5 MW, the required accelerating length is 30 cm (taking into account an insertion loss of 10 % in the RF network and 30 % loss on the quality factor, mainly due to coupling between cells). The maximum on axis electric field in the section is 41 MV/m, corresponding to a peak field on copper of 95 MV/m, which should be far from the breakdown limit at X band.

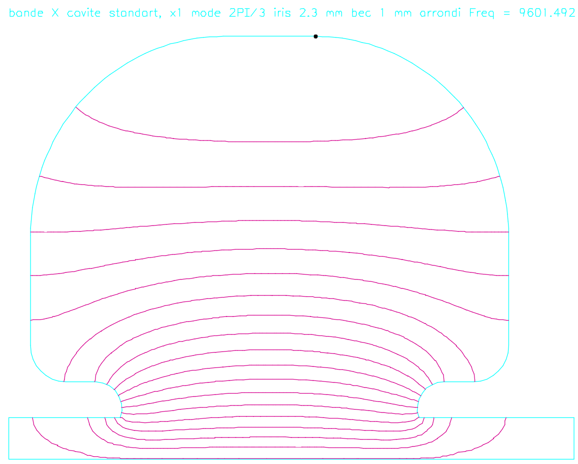

Figure 1 : standard cavity shape

Table 1 : Main linac parameters

Photon megavoltage	MV	6
Electron energy	MeV	5.6
Total length[1]	cm	38
Electrical length	cm	30.2
Magnetron RF peak power	MW	1.5
Magnetron RF mean power	kW	1.5
Peak RF power at accelerator input	MW	1.35
Theoretical Shunt impedance	MΩ/m	167
Practical Shunt impedance	MΩ/m	117
RF power dissipated in section	MW	0.85
Maximum beam power	MW	0.5
Efficiency	%	37
Pulse repetition rate	Hz	250
RF pulse length	µs	4
Max peak current on target	mA	89
Max mean current on target	µA	82
Max on axis rate at 1 m	Gy/mn	6.4
Max on axis dose rate at 80 cm	Gy/mn	10

[1] Including X ray convertion target, electron gun, and shielding.

3 BEAM DYNAMICS

3.1 Electron gun

The triode electron gun will operate between 10 and 20 kV. Beam dynamics have been studied for 12 kV and 17 kV. An EGUN simulation is presented on figure 2 for 17 kV. The cathode diameter is 6 mm. For a current of 480 mA, the beam at the exit of the gun has a radius of 0.5 mm, an emittance of 7 π mm mrad, and a convergence of 86 mrad (the grid is not simulated). The perveance is 0.23 µPerv and the beam optics is very similar for 12 kV.

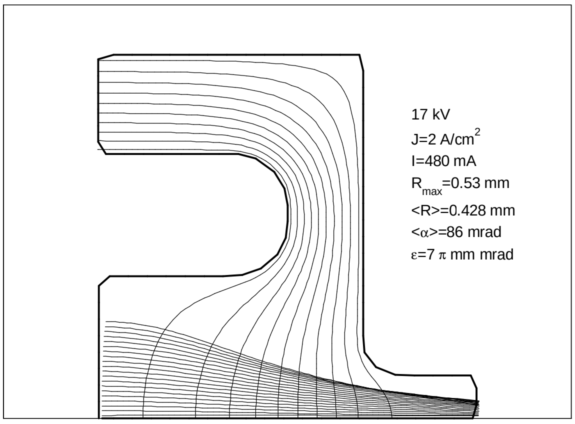

Figure 2 : EGUN simulation for 17 kV

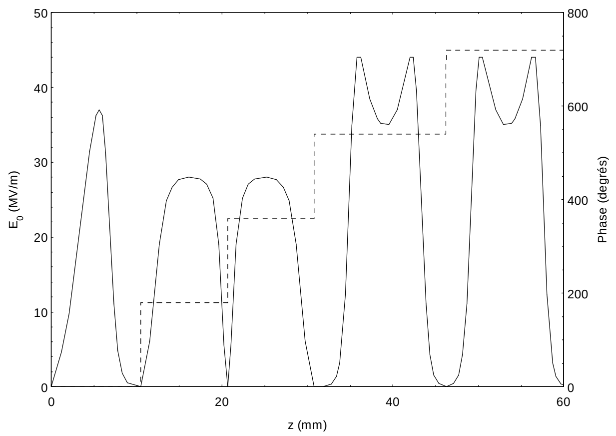

Figure 3 : $E_0(z)$ calculated by SUPERFISH

3.2 Accelerating section

The section is made of 20 accelerating cavities, with a phase difference of 120 degrees between each cavities (2π/3 mode). The resulting phase shift for the standing wave field between each accelerating cavities is 180 degrees. The field shape calculated by SUPERFISH for the five first cavities is shown on figure 3. This field shape was used for the beam dynamics simulations with the code DYPAL. The bunching cavities do not have noses due to their short length, and the first cavity has a special shape optimized for good capture with good radial control.

The aim of the simulations is to accelerate as much current as possible from the gun to the target, with a good energy spectrum, while minimizing the losses along the section that give parasitic leakage of X-rays. The difficulty is to maintain the beam to a very small diameter so that it can pass through the irises, without the help of external focusing (no solenoid). One then has to rely on RF self focusing which is incompatible with longitudinal bunching since radial focusing occurs in the longitudinally unstable region. The solution is a compromise between longitudinal focusing and radial focusing, obtained by alternatively placing the bunch behind and ahead of the crest of the wave. The dynamics is very complex, especially in the first few cells, since the bunch is not yet formed, and particles with different initial phases undergo very different histories. The approach adopted was to systematically vary the length (and then the phase of the electrons relative to the RF fields) of the bunching cavities, and of the cavities making the first five wavelengths, in order to find an operating point for wich the transmitted current was maximum. This lead to several hundreds of simulations with 300 particles, including space charge effects.

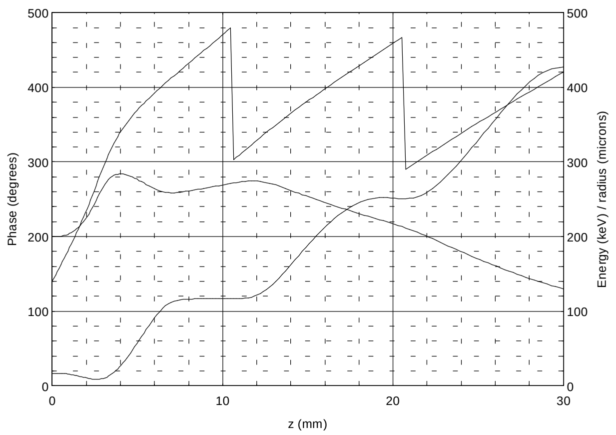

Figure 4 : Behaviour of the central particle in the first few cells

Figure 4 shows the behaviour of the central particle in the capture cavity and the two bunching cavities. At the entrance of the cavity, the particle is slightly decelerated and radially defocused, then the field becomes accelerating and the particle is focused. At the exit of the cavity, the particle is slightly defocused, as the field is still accelerating but defocusing. The phase at the entrance of the two bunching cavities is late, corresponding to a radial focusing (particle behind the crest of the wave).

Figure 5 and 6 represent the radial behaviour and the energy gain along the section for 100 particles uniformly distributed in initial phase, and for an emittance of 70 π mm mrad (accounting for the effect of the control grid).

One can see that most of the losses occur in the bunching section, where the energy is low, minimizing X-ray leakage. The beam enveloppe is contained in less than 0.8 mm and 33 % of the gun current reaches the end of the section.

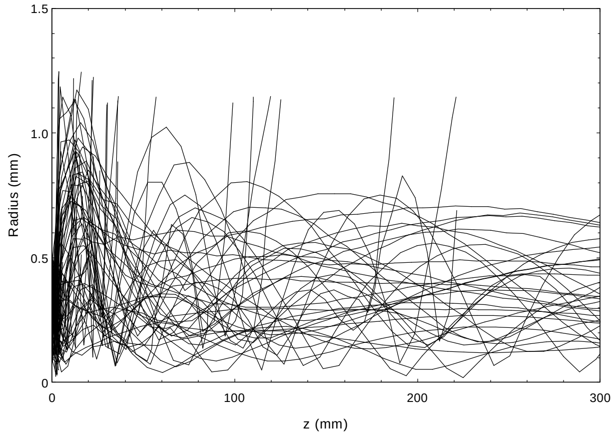

Figure 5 : Radius along z for 100 particles

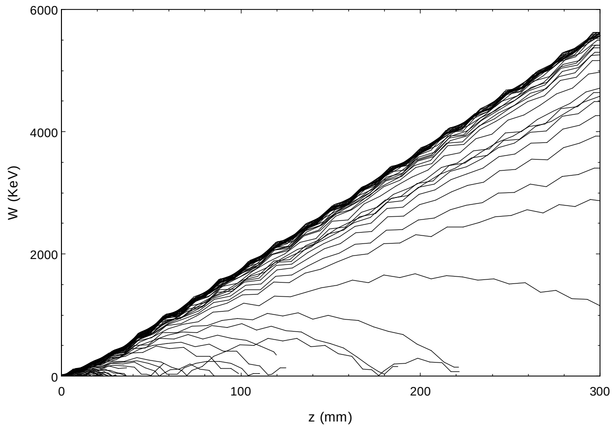

Figure 6 : Energy gain along z for 100 particles

Two histograms giving the radius and the energy at the end of the section are presented in figure 7 and 8. The mean radius is 0.37 mm. 80 % of the particles have an energy higher than 5 MeV.

We also studied the sensitivity of this operating point to a variation of the RF power (field) and of the gun voltage (injection voltage). The results are presented in table 2. When the gun voltage or when the accelerating field are too high, the bunch is too early in phase and many particles are lost due to radial defocusing. When the gun voltage and the accelerating field are too low, the particles are radially focused but lost longitudinally. One can see that a variation of + 10 % for the electric field (+ 20 % for the RF power) is drastic since the target current is lowered by half. On the other hand, the gun voltage is more flexible and the section optimized for 17 kV can still work with a gun voltage from 14 kV to 20 kV, if one can afford a loss in the accelerated current of one third.

Table 2 : sensitivity to a variation of the gun voltage and the accelerating field.

	I_{target}/I_{gun}	W (MeV)
Nominal	33 %	5.6
ΔE = + 10 %	16 %	6.2
ΔE = - 10 %	24 %	4.3
V_{gun} = 14 kV	21 %	4.8
V_{gun} = 20 kV	19 %	5.6

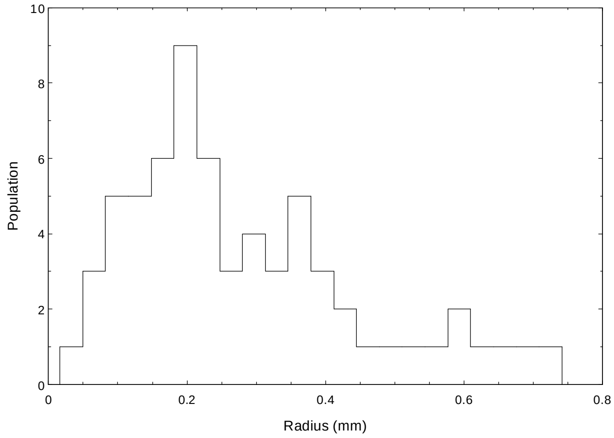

Figure 7 : Histogram for the radius at the end of the section

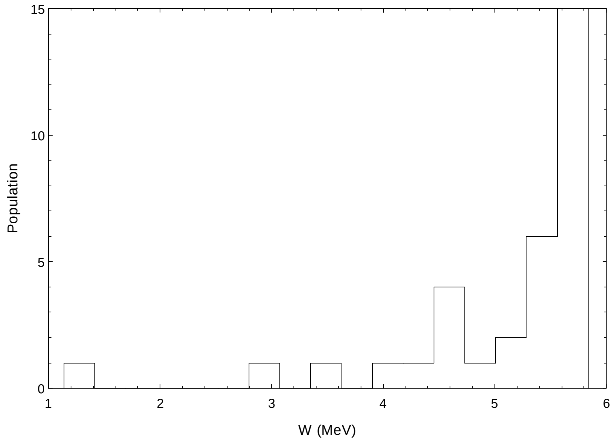

Figure 8 : Histogram for the energy at the end of the section.

4 CONCLUSIONS

Extensive beam dynamics simulations have shown that it should be possible to accelerate a current of 90 mA to 5.6 MeV in about 30 cm at X band. Good radial control achieved by RF self focusing allowed one third of the gun current to be accelerated with reduced X ray leakage along the accelerator.

REFERENCES

[1] C. Bourat, unpublished.

[2] T. Rock Mackie and al., Tomotherapy : A new concept for the delivery of dynamic conformal radiotherapy, Med. Phys. 20(6), 1993, 1709.