BEAM DYNAMICS TOOLS FOR LINACS DESIGN

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Abstract

In the last 25 years, we have been using our in house 3D code PRODYN [1] for electron beam simulations. We have also been using our in house code SECTION for the design of the travelling wave accelerating structures and the beam loading compensation. PRODYN follows in time, the most complicated electron trajectories with relativistic space-charge effects. This code includes backward as well as forwards movements. This paper will describe those two codes and will give some simulations and measurements results.

INTRODUCTION

The electron dynamics are complicated. Their energies varies from zero to more than one MeV in a length comparable to the prebucket dimension. Velocities are different at the same abscissa. On-axis oscillations occur. RF field phase and amplitude laws must be shaped precisely. Radial behaviour can be analyzed by noting optical effects at the input and output regions of the cells. The equivalent lenses have either a convergent, a divergent or a null effect. It depends on the electron beam to RF electrical field dephasing. Their positions can be modified as long as overall longitudinal acceleration occurs.

BEAM DYNAMICS TOOLS

For the design of a linac we use 5 principal codes:

- Our in house code SECTION, for the design of the travelling wave accelerating structures and the beam loading compensation.
- Our in house code PRODYN, for the beam dynamics simulations.
- The well-known EGUN [2] code written by Dr. Hermannsfeldt from SLAC, for the gun design.
- The also well-known SUPERFISH code written by Ron. F. Holsinger and Klaus Halbach from LOS ALAMOS for the design of cavities and electric field in accelerating structures.
- The also well-known POISSON code written by the same authors from LOS ALAMOS, for the shielded lenses and solenoids.

SECTION code

SECTION code provides along a travelling wave structure the filling time, the group velocity, the circulating power, the shunt impedance, the electric field and the energy gain.

This code uses the beam loading theory, based upon diffusion equation (Beam loading and transient behavior in travelling wave electron linear accelerators", J.E Leiss page 151, linear accelerators edited by P. Lapostolle and A. Septier, 1970 North-Holland publishing company-Amsterdam) and the S band measurements mainly the ALS structures ("Les sections accélératrices" page 1194 D. Tronc et Al, L'onde électrique Vol 49, Fasc 11-n°: 513 Dec 1969).

This code was used recently for the design of the ALBA and BESSY accelerating structures, in particular the beam loading effects.

The accelerating structures met the calculated values at ALBA, 53 MeV for 18.8 MW in the first accelerating structure (16 MeV in the buncher) July 2008 Spain.

PRODYN code

PRODYN code tackles particle dynamics, electrons in our case, according to time and in the presence of an electromagnetic field. The code includes backward as well as forward movements and relativistic space-charge effects. The space to be simulated is divided into several elementary cells. Each cell changes the input beam into an output beam that can then be injected into the next cell. If the simulation covers a large number of cells, one can test a change by taking the beam at the output of the cell that precedes the change, and injecting it into the sequence of new cells.

The particle beam is either generated by the code using the entered settings, or read from the particle file supplied by the user.

An elementary particle is represented by its position, its energy, and its phase. To solve differential equations, one uses the Runge-Kutta method with x, y, z, Vx, Vy and Vz as variables, and time as the integration variable.

The provided elements are: RF accelerating cell, drift, magnetic lens, quadripole, dipole and bending magnet. The accelerating cell may include a magnetic lens and a dipole. Subharmonic frequencies can be used.

Space charge module

When calculating dynamics at low beam currents, we can neglect the space charge effects. But with nominal beam currents, as soon as we want to properly define an accelerating section that is self-focused or provided with external focus, we must take the space charge forces into account.

In particular, in the first cavities of a buncher where the beam energy is low, the charge density becomes significant when modulating the beam. This results in significant radial de-focussing.

To elaborate the space charge calculation, we proceed as follows:

Initially, we change the Coulomb law for macro-particles that are close to each other. In order to eliminate

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the calculation artefacts due to repulsive forces in the particle field in $1/R^2$ that had nothing in common with physical reality.

We replace the macro-particle with the product of a charge density and the interaction volume, which produced a field in R. However, the whole difficulty lies in the determination of the threshold radius from which the interactive law is modified.

Then, we express the fields applied to particle P at point j by a charge q placed at point i.

This module was validated using drift spaces that are appropriate for the analytical calculation of space charge for continuous beams. We placed ourselves in very unfavorable conditions. In particular, we handled the behavior of a parallel beam with energy equal to 16 keV, current of 1 Ampere and an initial diameter equal to 1 mm. The radius is doubled after 9 mm. We observe a gap of a few % due to the longitudinal limitation of the packet and the finite number of macro charges.

Our 3D modeling of the particle dynamics enabled us to replace the analytical feasibility study with a more detailed step-by-step approach to the behavior and evolution of each beam particle along an accelerating line.

Validation on operating machines

The PRODYN dynamics code enabled us to simulate the beam line of the following accelerators:

- Helios I injection at 200 MeV (IBM - USA).
- ESRF synchrotron accelerator at 200 MeV.
- ELETTRA synchrotron accelerator at 1200 MeV.
- SOLEIL synchrotron at 100 MeV.
- ALBA synchrotron at 100 MeV.
- BESSY II synchrotron at 50 MeV.

This code also enabled us, using adjustment settings only, to improve the ARTEMIS accelerator (Moronvilliers AEC) by reconstructing the computer model of the accelerator, conducting a setting optimization survey, and recovering the corresponding performance results at the experimental level.

SIMULATION RESULTS

Turnkey linacs were manufactured by Thales Communications and Security in order to inject electrons into boosters of SOLEIL [3], ALBA and BESSY II synchrotrons. The figures hereafter represent the beam dynamics simulations for the SOLEIL linac.

Fig. 1 shows the energy histogram at the buncher exit for the 120 mA mode.

Figures 2 and 3 show the phase-energy diagram and the Y-Y' plane emittance at the linac end for the 120 mA mode.

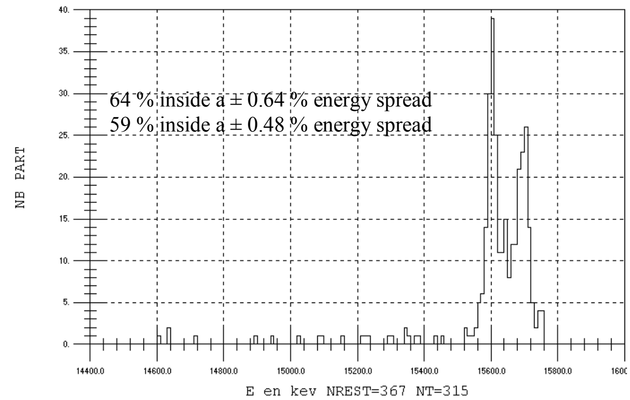

Figure 1: Energy histogram at the buncher exit for the 120 mA mode.

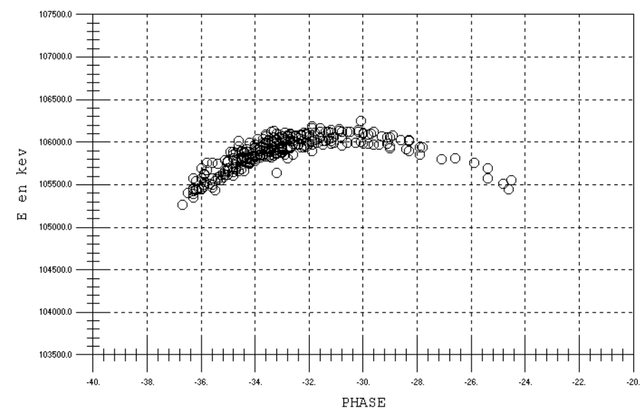

Figure 2: Phase-energy diagram at the linac exit for the 120 mA mode.

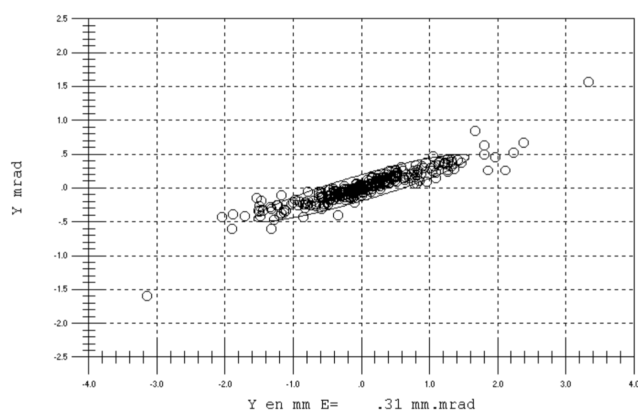

Figure 3: Emittance at the linac end for the 120 mA mode.

BEAM LOADING COMPENSATION

Generally, the first electrons of a long pulse have the greatest energy gain while crossing an accelerating section as the stored energy left for the last electrons is reduced. This is what we call the beam loading effect.

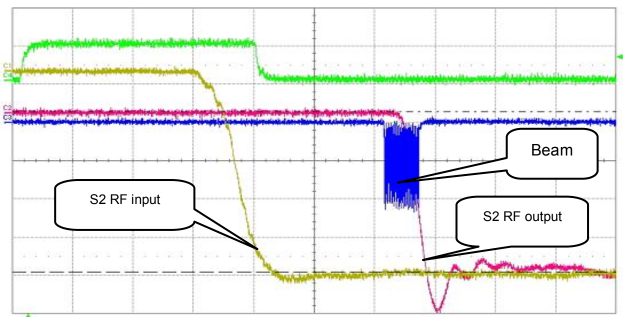

Figure 4: Beam loading compensation

The beam loading compensation is achieved by sending the beam during the filling time of the second accelerating structure. In fact, the first electrons cross the last part of the section without the nominal stored energy in it. The last electrons cross a full stored energy section. In certain conditions of power, charge and pulse length, the beam loading effect can be considerably reduced [3].

Fig. 4 shows the RF input and output signals of the second section of SOLEIL together with the beam pulse.

Fig. 5 shows, for SOLEIL, the 2 measured curves without and with beam loading compensation. The FWHM energy spread has been reduced from 3.75 MeV to 0.77 MeV for the 9.3 nC behind the slit.

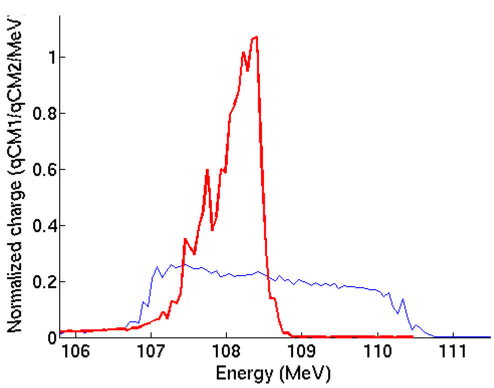

Figure 5: Energy spread for both cases

SIMULATIONS AND MEASUREMENTS

For ALBA, measurements of the beam at 70 MeV were done with and without the prebunching cavities for the Multi Bunch Mode [4]. The measured values met the simulated ones. The results are summarized in table 1.

Table 1: Simulations and measurements (%)

	Buncher exit		AS1 exit	
Beam mode	Simul.	Meas.	Simul.	Meas.
0.5 & 3 GHz	98	96	68	66
3 GHz	84	83	67	58*
0.5 GHz	77-87**	80	47	47
No cavities	59***	64	-	37

* Measurement was done without the phase adjustment of the 3 GHZ prebuncher.
** Simulations show oscillations of some electrons being apart from the main bunch. The main bunch and the first satellite, being 333 picoseconds apart, contain 77% and 5% of the gun current.
*** Simulation has been done without space charge and without magnetic field.

The 500 MHz prebunching cavity allows for only one pulse at 3 GHz, instead of three, from the 1 ns pulse. The energy spread is then reduced. Table 2 gives the summarized results at 70 MeV.

Table 2: Charge and energy spread measurements

	BCM1(nC)	ΔE/E%
Without cavities	0.25	0.6
500 MHz	0.30	0.6
3 GHz	0.45	**0.9**
500 MHz & 3 GHz	0.55	0.6

CONCLUSION

In the last decade, turnkey linacs were manufactured by Thales Communications and Security in order to inject electrons into boosters of SOLEIL, ALBA and BESSY II [5] synchrotrons. The measured linacs parameters fitted well with the beam dynamic simulations.

Our in house codes, SECTION for the design of the travelling wave accelerating structures and the beam loading compensation with PRODYN for the beam dynamics simulations, helped us to obtain those performances.

REFERENCES

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