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# PARMELA SIMULATIONS FOR PITZ: FIRST MACHINE STUDIES AND INTERPRETATION OF MEASUREMENTS

M. BOSCOLO, M.FERRARIO
*INFN-LNF, Via E. Fermi 40, 00044 Frascati (Roma), Italy*

S. CIALDI
*INFN-Milano, Via Celoria 16, 20133 Milano, Italy*

M. KRASILNIKOV, A. OPPELT
*DESY, 15738 Zeuthen, Germany*

First comparisons between measurements and simulations are discussed for the PITZ1.5 facility. In particular, dedicated PARMELA simulations performed using the realistic laser pulse hitting the cathode are compared to first emittance measurements performed with the SPARC e-meter and with the EMSY system. Measured energy spectra are compared to simulations, as well. It is discussed the overall good agreement between calculations and measurements.

## 1. Introduction

In summer 2005 the PITZ1.5 test facility at DESY in Zeuthen has started its commissioning phase and it is used essentially for beam dynamics studies. It consists of an intermediate setup (see figure 1) between phase 1 and phase 2 [1].

Phase 1 of PITZ has successfully concluded in November 2003 with the full characterization of a gun that has been installed and is currently in operation at the VUV-FEL. The gun was then replaced and PITZ1 run for the whole 2004 [2]. Since December 2004 the photo injector has been upgraded. The diagnostics beamline has been significantly modified, together with the installation of a normal conducting booster cavity and an extended water cooling system.

As the new 10 MW klystron has been installed in June-July 2005, PITZ1.5 has started its operations. The gun is being conditioned towards higher peak and average power with the goal of 60MV/m. The booster cavity is a normal conducting Tesla prototype cavity that accelerates the beam up to about 13MeV. Commissioning of new diagnostic components has been done at this first stage of operations. One of these new features is the SPARC emittance meter device [3], temporarily installed at PITZ.

First emittance measurements have been done with and without booster, i.e. at high and low energy for different bunch charge configurations. The measurements based on the slit mask techniques (e-meter) have been compared to the data taken with the PITZ emittance measurement system (EMSY) [1].

In this paper emittance measurements are compared to dedicated beam dynamics simulations performed with the PARMELA [4] code. Energy spectra are also measured and compared to simulations, as well.

An overall good agreement is found between measurements and simulations, as discussed in sections 3 and 4.

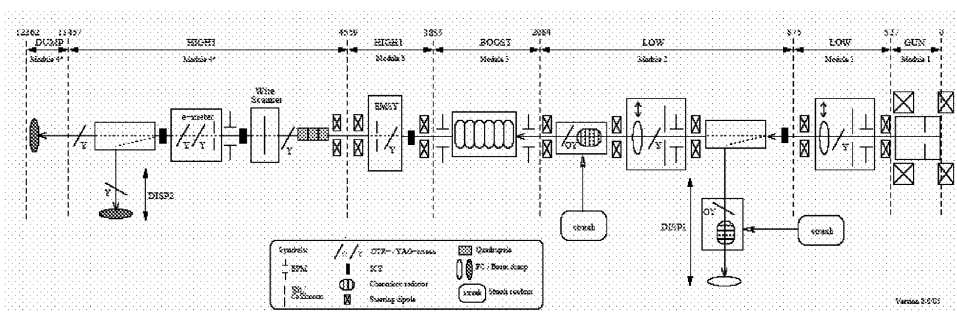


Figure 1. Scheme of the PITZ1.5 facility.

## 2. Simulations in Nominal Machine Conditions

Table 1. Beam parameters for the PITZ1.5 injector.

| | |
|---|---|
| Bunch charge [nC] | Up to 1 |
| Temporal bunch length [ps] | 20 |
| Laser pulse rise/decay time [ps] | 2 |
| Rms transverse size [mm] | 0.5 |
| Thermal emittance [µm] | 0.6 |
| Energy @gun exit [MeV] | 5.1 |
| Energy @booster exit [MeV] | 13 |

PARMELA simulations with a nominal 20 ps flat-top laser pulse length have been performed as a first step. Parameters used for these sets of simulations are listed in table 1. The gun and booster 2-D RF field maps for the PARMELA simulations have been calculated [5] from the electromagnetic code SUPERFISH [6].

Gun solenoid scans have been performed without accelerating cavity to find the best theoretical magnetic value $B_{gun}$ for the emittance compensation scheme

[7] in a low charge configuration. A bunch charge of 0.23 nC has been considered for these studies.

The best beam behavior according to the theory [7] is found for a $B_{gun}$ of 0.18 T. In fact, for this magnetic value transverse projected emittance shows two relative minima and the longitudinal position of the accelerating structure corresponds to the relative emittance maximum, as it should be from theory. Horizontal emittance and beam envelope along the beamline without and with booster are plotted in figure 2: pink and red curves are for emittance, blue and light blue curves for envelope without and with booster, respectively. A horizontal projected emittance of 1 mm mrad is calculated at the end of the beamline for the low charge configuration with these nominal parameters.

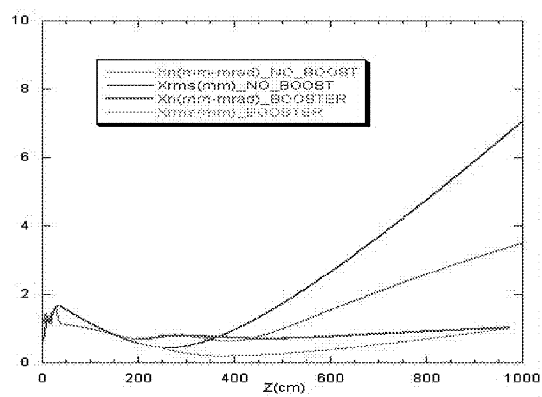


Figure 2. PARMELA simulations for a pulse length of 20ps flat-top, Q=0.23nC, transverse rms spot size of 0.5mm and B=0.18T with (red and light blue curves) and without acceleration (pink and blue curves).

## 3. Transverse Emittance and Beam Size

Two sets of measurements have been selected for a comparison between data and simulations, one at low current (Q=0.5 nC) the other at high current (Q=1 nC). In both machine configurations transverse emittance and beam envelope have been evaluated for different values of the solenoid magnetic strength. Realistic beam pulses have been used for simulations.

### 3.1. *High bunch charge configuration*

Horizontal and vertical emittance and rms beam sizes have been measured at the EMSY position, at about 4.3 m from the cathode, for different gun solenoid magnetic strengths. The magnetic strength is determined from the measurement of the current powering the coil $I_{gun}$[A] , knowing the scaling factor between the current and magnetic strength. The agreement between PARMELA simulations and measurements is quite good, as discussed below.

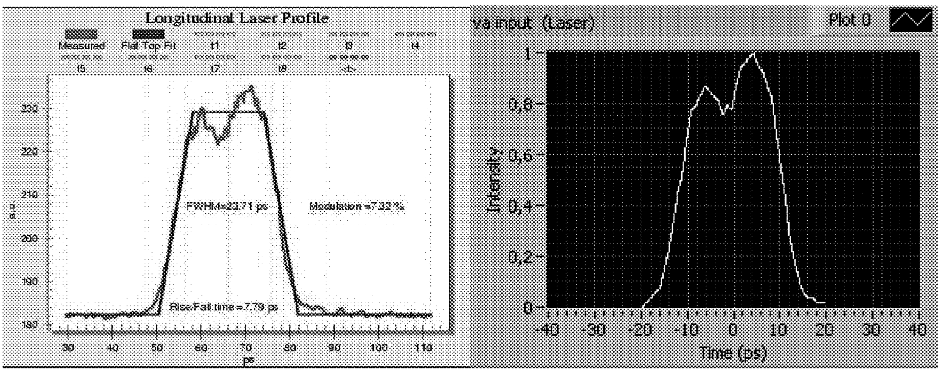


Figure 3. Left plot: Laser longitudinal profile during emittance measurements at EMSY , with the 1nC configuration. Right plot: Realistic beam pulse used for simulations.

The chosen measurements have been taken on 28-29/09/2005. During this data taking the laser temporal profile hitting the cathode was the one reported in left plot of figure 3. Its characteristics are: FWHM=23.71 ps, rise time (r.t.) of 7.79 ps with a ripple modulation on the flat top of 7.3%, but essentially two peaks can be clearly observed from the plot.

The initial longitudinal bunch shape for PARMELA simulations is taken identical to the real laser longitudinal profile (see right plot of figure 3); laser and beam pulse are assumed to be transversely uniform.

Measurements compared to simulations are reported in figure 4. Upper plot shows the horizontal and vertical beam sizes, lower plot the transverse emittance versus the gun solenoid current. Red and blue curves are the horizontal and vertical simulated values, respectively; black and green curves are the corresponding measured values. Increasing by 10% the scaling factor between $I_{gun}$[A] and the magnetic strength the agreement with simulations becomes quite good, as it appears from figure 4. The same effect has been observed in other analysis. The source of this mismatch is still under investigation.

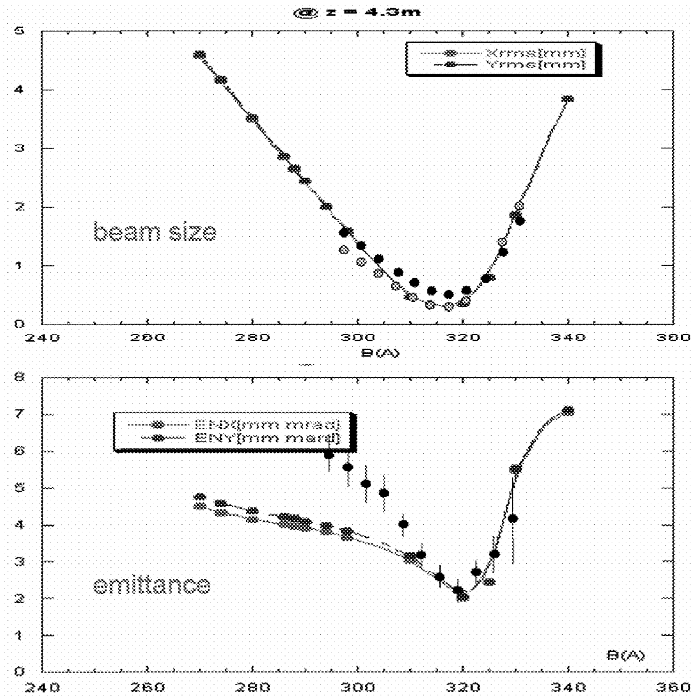


Figure 4. Beam size (upper plot) and transverse emittance (lower plot) measurements compared to simulations. Red and blue curves represent simulations for horizontal and vertical planes, respectively. Black and green dots represent measurements for horizontal and vertical planes, respectively. A 10% mismatch between the solenoid current and its magnetic strength is considered.

## 3.2. *Low bunch charge configuration*

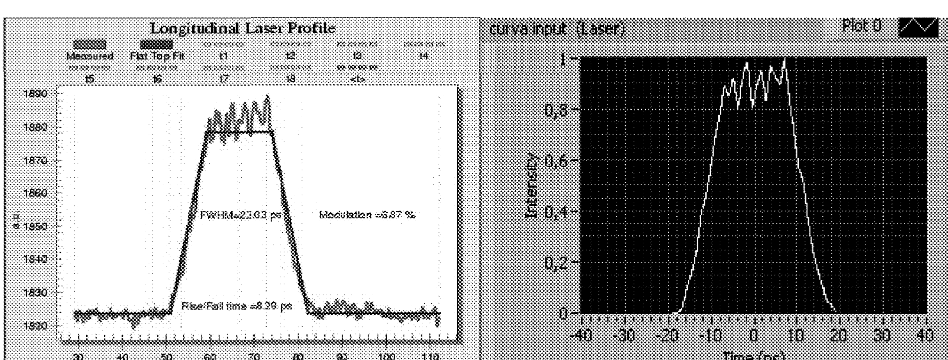


Figure 5. Left plot: Laser longitudinal profile during measurements at the e-meter with the 0.5nC machine setup. Right plot: corresponding realistic beam pulse used for simulations.

A second set of measurements taken on 29/09/2005 has been analyzed and compared to simulations. The machine was tuned for a bunch current of

Q=0.5nC and beam envelope and emittance were measured at the e-meter, at about ~7.7 m from the cathode.

The laser profile corresponding to these measurements is reported in left plot of figure 5: FWHM is 23.03 ps, r.t. is 8.29 ps and there are some high frequency ripples in the flat top with amplitude of 6.9%. This is the temporal distribution taken for the electron beam at the cathode used for simulations (right plot figure 5).

Comparison between simulations and measurements are reported in figure 6, where a 10% mismatch between solenoid current and magnetic value is taken into account, as for the studies performed at high current. Agreement with simulations is in this case not as good as for the previous one. Anyhow, especially emittance behavior is reproduced by calculations. More details on these measurements are discussed in [8].

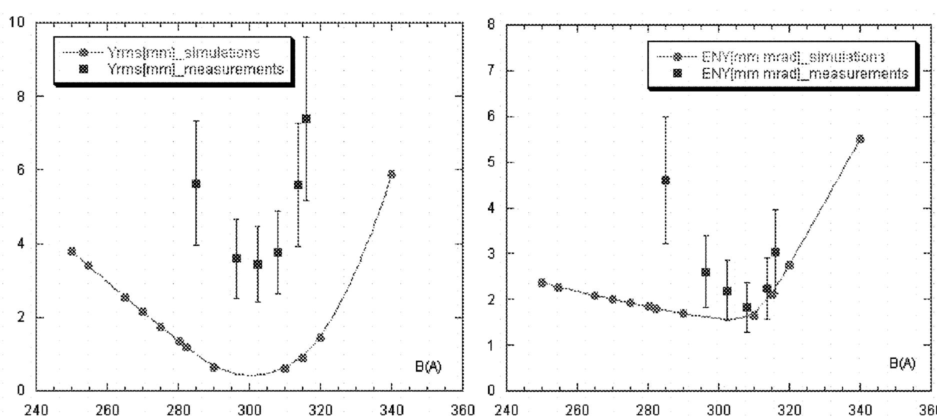


Figure 6. Vertical beam size (left plot) and projected emittance (right plot) at e-meter. Red and blue curves are simulated and measured values, respectively. A 10% mismatch between the solenoid current and magnetic strength is taken into account.

## 4. Energy Spectrum

The energy distributions are routinely measured at PITZ1.5 to tune the machine both after the gun and at the end of the beamline. Injection phase $\varphi_{inj}$, as well as booster RF phase $\varphi_{booster}$, are set to give the highest beam energy and the lowest energy spread, for a fixed accelerating voltage. This corresponds to $\varphi_{inj}$=40° and $\varphi_{booster}$=78°.

We discuss in the following the measurement of the longitudinal momentum distribution performed together with the emittance measurements already analyzed in section 3.1. Left plot of figure 7 shows the measured longitudinal momentum distribution at the two optimized phases; with average and rms values $P_{mean}$=13.0488 MeV, and $P_{rms}$=0.03183 MeV, respectively.

A double peak structure can be clearly observed. Decreasing by 3° the injection phase the two peaks structure disappear (right plot of figure 7). The results obtained using PARMELA are shown in left plot of figure 8 for the simulated energy distribution at optimal $\varphi_{inj}$ =40° and in the right plot for a shift of $\varphi_{inj}$ by -3°. We found the same effect observed in the measurements.

In addition, there is a good agreement between simulations and measurements on the energy spread, as well as on the distance between the two peaks and on their dependence on $\varphi_{inj}$.

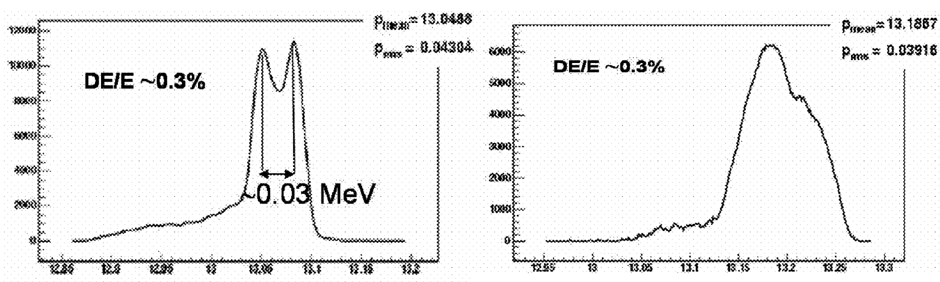


Figure 7. Measured longitudinal momentum distribution at the end of the injector, for optimized $\varphi_{inj}$ and $\varphi_{booster}$ on left plot and for $\varphi_{inj}$ = -3° on right plot.

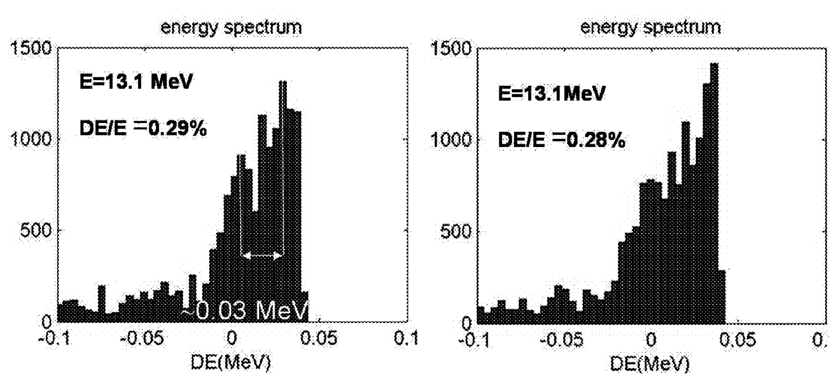


Figure 8. Simulated energy distribution at the end of beamline, for optimal $\varphi_{inj}$=40° and $\varphi_{booster}$=78°on left plot and for $\varphi_{inj}$ = -3° on right plot.

The qualitative interpretation of this measurement is in agreement with the simulation studies carried on for SPARC and briefly summarized in the following.

The two peaks in the energy distribution reported in left plot of figures 7 and 8 can be explained by the argument that temporal oscillations transform into energy oscillations [9]. In fact, in this particular measurement the initial longitudinal distribution shows a double peak behavior (figure 3). As the beam goes through the gun and drifts the two longitudinal peaks transform into energy distribution peaks, as found for the SPARC injector [10].

PARMELA simulation studies have been carried on for SPARC taking into account an amplitude modulation in the longitudinal profile. They indicate that at the entrance of the first acceleration structure the beam has lost temporal ripples which have converted into energy ripples through a fractional plasma oscillation, as long as the modulation is within 30% of the total distribution. It is a space-charge induced compensation process. These energy ripples are then suppressed in the first traveling wave cavity during the acceleration process, so that energy spread at the end of the linac is not affected by the initial pulse shape.

More detailed studies on laser pulse shaping effects [11] in SPARC have shown that the value of the emittance remains substantially constant increasing the amplitude of the oscillations, as long as the frequency is sufficiently high. The slope of the emittance-amplitude line decreases with the increase of the frequency.

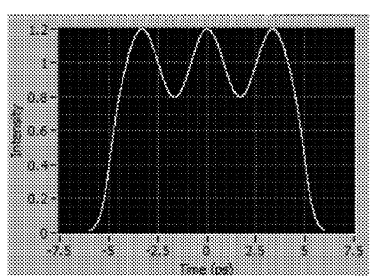

Figure 9. Initial beam pulse for a simulation for a SPARC case: FWHM=10ps, r.t.=1ps, low frequency modulation in the flat-top with 30% amplitude.

Moreover, the measurement performed at PITZ1.5 has been simulated for the SPARC case with a longitudinal profile of the initial beam pulse having a peaked structure. The dependence of energy spectrum on phase injection and on initial pulse shaping has been analyzed.

If we consider an initial pulse as the one in figure 9: FWHM=10ps, r.t.=1ps and a low frequency modulation in the flat-top with an amplitude of 30% we observe also in this case that the energy spectrum is very sensitive to the injection phase. Upper and lower plots of figure 10 show the energy distribution at the exit of the second accelerating cavity at z=4.6m from the cathode and for a beam energy of E=80.8 MeV for the optimal $\varphi_{inj}=32°$ and for a -3° shift from this value. Different spectra are observed, but energy spread is not affected by the initial pulse shape. Energy spread is 0.21% in the first case, as for the nominal profile, and 0.37% with the -3° shift.

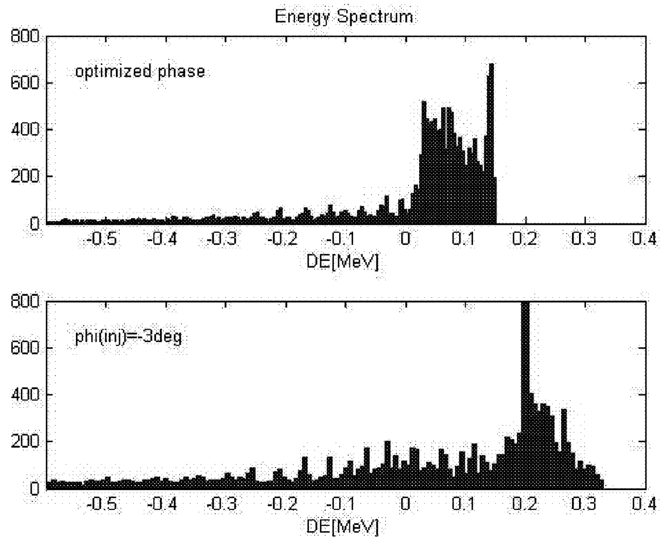


Figure 10. Simulated energy spectrum at the exit of the second cavity at ~80 MeV for a beam pulse as in figure 9. Upper plot: for optimal $\varphi_{inj}$=32° and $\varphi_{booster}$ on crest; lower plot: $\varphi_{inj}$ = -3°.

## 5. Conclusions

First PARMELA simulations have been performed for the PITZ1.5 facility and been compared to first beam measurements, like transverse emittance, envelope and energy.

There are still some problems due to the limited knowledge of machine parameters, as the gun solenoid magnetic strength versus its current. However, an overall good agreement between simulations and measurements of energy, beam size and emittance has been found.

## Acknowledgments

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