TRANSVERSE EMITTANCE MEASUREMENT AT HIGH ENERGY USING LONG PEPPER-POT

N. Delerue*,
John Adams Institute, University of Oxford

Abstract

Although the pepper-pot method has been used for decades to measure the transverse emittance of particles sources at low energy, it has only been extended to high energy very recently. We report on some of the recent measurements done at high energy (several hundred MeVs) and discuss the practical consideration of such measurements. We demonstrate that a long pepper-pot does not significantly affect the phase space of the beam and thus provides a valid transverse emittance measurement.

INTRODUCTION

In the past few years several experiments have reported the generation of high energy (several hundred MeVs) beams of electrons over very short distances [1, 2, 3], achieving gradients as high as 10-100 GeV/m. At present such beams suffer from large shot to shot fluctuations of their pointing stability requiring the use of single shot measurements to measure their properties. So far there has been no direct measurement of the emittance of such beams but simulations indicate that at the source the beam is a few tens of micrometres wide with a divergence of the order of a milliradian. To confirm these prediction experimentally single shot transverse emittance measurement techniques have been developped such as the use of a "long pepper-pot".

PEPPER-POT MEASUREMENT AT LOW ENERGY

The pepper-pot method is often used at low energy to measure the transverse emittance of particle beams [4, 5, 6]. In this method an array of holes in a sheet of material is used to separate a large beam into several beamlets (see figure 1). After a short drift length the width of each beamlet can be measured. This width gives a measure of the beam divergence at the position where the beam was sampled by the pepper-pot. Hence pepper-pots can be used to measure simultaneously the transverse size and the divergence of each beamlet thus providing a direct measurement of the beam transverse emittance.

* nicolas.delerue@adams-institute.ac.uk; Work supported by the John Fell Fund, University of Oxford

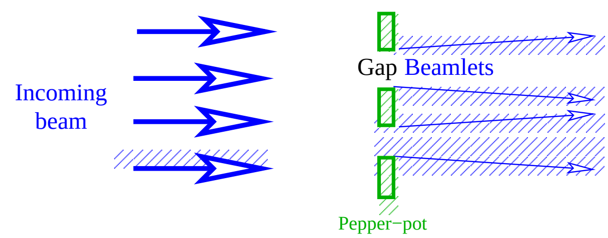


Figure 1: Pepper-pot sampling a beam into several beamlets.

PENETRATION OF PARTICLES IN MATTER

The use of a standard pepper-pot with a high-energy beam is unlikely to lead to the expected result. In fact as shown on figure 2 a thin pepper-pot plate exposed to a high energy beam may induce a shower containing more particles than the initial beam.

This can be overcome by using a pepper-pot long enough to absorb most of the shower induced by the electrons when they hit the absorber. However this requires the beam to travel for a long distance in the holes of the pepper-pot and one may be concerned by the effect that this has on the measured phase space.

ACCEPTANCE OF A LONG PEPPER-POT

The acceptance of long pepper-pot can be estimated by looking at the propagation of the beam from the waist to the exit of the pepper-pot as shown on figure 3. At the entrance of the pepper-pot only a slice of the phase space is accepted by the hole. This slice will shear will travelling toward the exit of the pepper-pot. This means that some electrons that were within the acceptance of the pepper-pot at the entrance willbe intercepted before the exit of the hole. Reciprocally some electrons that would be in the acceptance of the hole will be rejected at the entrance of the hole. Hence the phase space measured after the pepper-pot will be clipped due to the length of the pepper-pot.

This clipping of the phase space can be estimated by comparing the area accepted by both the entry and the exit of the hole ($\mathcal{A}_s$) to the total area accepted by either the entry or the exit or both($\mathcal{A}_o$). In the case of a cenral slit this ratio can be derived as [7]:

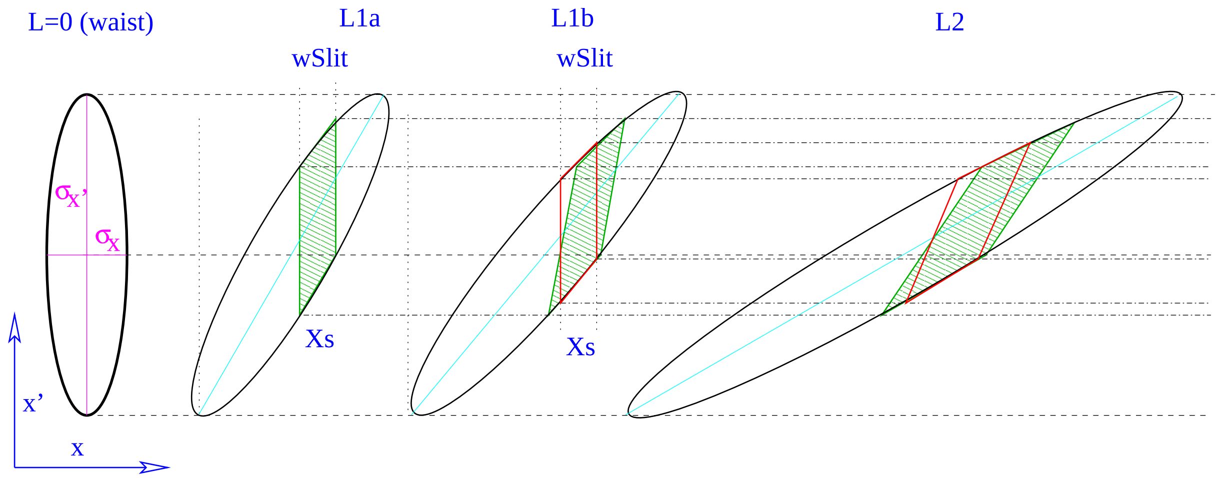


Figure 3: Long pepper-pot: Evolution of the phase-space as the beam drifts. At the source or at a wait ($L = 0$) the phase space of the beam is first represented by an upright ellipse. As the beam drifts the ellipse gets sheared. At L_{1a} the beam enters a slit and thus only the particles in the green area pass the slit. While the beam travels in the slit the ellipse is further sheared, hence at L_{1b}, the exit of the slit, the area of phase space within the slit acceptance (red box) is different from that occupied by the particles sampled at the entrance of the slit. Hence the full acceptance of the slit correspond to the overlap between the green and the red areas.

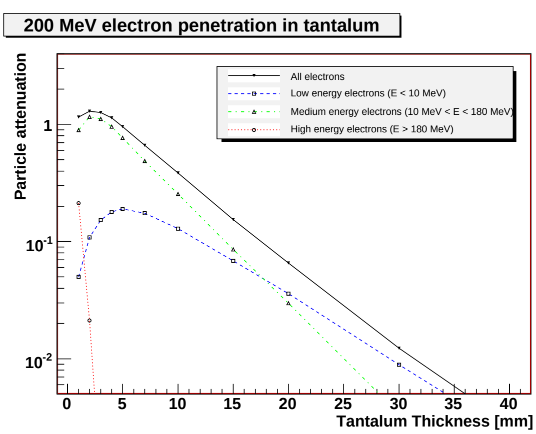


Figure 2: GEANT4 [8] simulations of the penetration of high energy electrons in a block of Tantalum. The horizontal axis gives the penetration depth and the vertical axis gives the number of electrons remaining at that depth for one initial electron. The red lines (round markers) correspond to high energy electrons whereas the blue lines (square markers) and the green lines (up-pointing triangular markers) correspond to lower energy particles emitted by the initial particle. The black lines (down-pointing triangular markers) show the total number of electrons remaining. These simulations were performed for 200 MeV electrons.

$$\frac{\mathcal{A}_s - \mathcal{A}_o}{\mathcal{A}_o} \simeq \frac{2(w_{\text{slit}}^2 + 2\sigma_x^2)\Delta L_{ba}}{2\sigma_x w_{\text{slit}} L_{1b} + \Delta L_{ba}\left[\sigma_x^2 + (w_{\text{slit}} - \sigma_x)^2\right]} \quad (1)$$

where ΔL_{ba} is the length of the pepper-pot, σ_x is the size of the beam at the waist, w_{slit} is the aperture of the hole, L_{1b} is the position of the exit of the hole.

SIMULATIONS

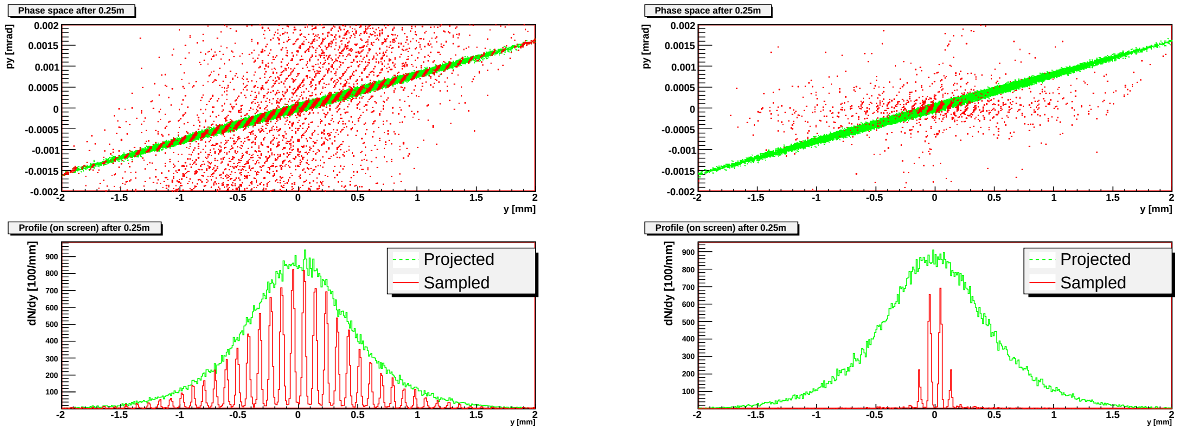
GEANT4 [8] has been performed to simulate the effect of a long pepper-pot on the phase space of a 200 MeV electron beam (see figure 4). These simulations agree with equation 1.

HIGH ENERGY PEPPER-POT EXPERIMENTS

A single shot transverse emittance measurement has been performed at the DAFNE Beam Test Facility (see figure 5) [9] and similar measurements are on-going in the Booster To Storage ring line at DIAMOND and at a laser-driven plasma accelerator.

CONCLUSION

We have shown that the pepper-pot method can be used to measure the emittance of beams of several hundred MeV provided that the dimensions and location of the pepper-pot is carefully chosen. Hence such carefully chosen pepper-pot could be used to measure in a single shot the transverse



$\Delta L_{ba} = 10\,\text{mm};\ \frac{\mathcal{A}_s - \mathcal{A}_o}{\mathcal{A}_o} = 4.5\%$ $\Delta L_{ba} = 200\,\text{mm};\ \frac{\mathcal{A}_s - \mathcal{A}_o}{\mathcal{A}_o} = 90\%$

$w_{\text{slit}} = 25\mu m$; $\sigma_x = 50\,\mu\text{m}$;$\sigma_{x'} = 0.5mrad$; $L_{1a} = 1m$; $L_2 = 1.25m$; 200 MeV; 100 000 electrons

Figure 4: Reconstruction of the transverse phase space of a beam sampled by a long pepper-pot. In each pair of plots the top plot shows in green the original phase space of the electrons and in red the phase space of the electrons after the pepper-pot. In each pair the bottom plot shows the projection along the spatial component of the transverse phase space. In all these plots the beam energy is 200 MeV. The slit width is 25 μm, the beam size at the waist is 50 μm with an emittance of 0.5mrad and the pepper-pot are located 1 m away from the beam waist. The screen is located 250 mm after the pepper-pot. For each plot 100 000 electrons were simulated with GEANT4. The left pair of plots corresponds to a pepper-pot length of 10 mm and the right pair of plots correspond to a pepper-pot length of 200 mm. For each plot the value of $\frac{\mathcal{A}_s - \mathcal{A}_o}{\mathcal{A}_o}$ as defined in [7] is given. High energy photons (X-rays) are not shown on this figure.

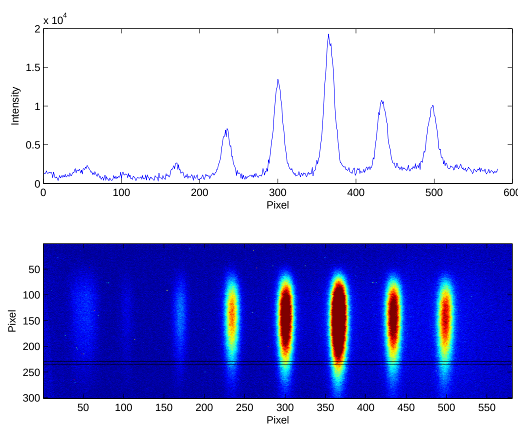


Figure 5: Long pepper-pot measurement of a 500 MeV electron beam taken at the DAFNE BTF [9].

emittance of beams produced by laser-driven plasma accelerators.

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