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Status and plans for 2013, CERN NA63

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NA63

Abstract

We summarize the status and plans for the future for the CERN NA63 collaboration.
Our results for the quantum synchrotron radiation emission, measured in 2009, have been published [1]. Owing to the close relation between the strong field radiation emission in crystals and beamstrahlung emission at the interaction point of a linear collider, we have in essence tested the approach to calculating the effective luminosity decrease from radiation loss in such machines.
A systematic study of the structured target 'resonance' appearing from radiation emission by electrons passing two amorphous foils positioned with separations in the range 10 – 20000 μm was performed in september 2012. Preliminary results confirm a previously obtained result [2] that by this method, the formation length - of macroscopic dimensions up to 0.5 mm - for the generation of MeV-GeV radiation from multi-hundred GeV electrons can be *directly* measured. In fact the results obtained allow a distinction between competing theories [3, 4], showing the need for a correction-term introduced by Blankenbecler [5].
With a substantially improved setup compared to the run in 2010 (where the deconvolution of synchrotron radiation prevented results in the most interesting regime below 0.5 GeV), we investigated again the impact of the Landau-Pomeranchuk-Migdal (LPM) effect with 178 GeV electrons, in particular for low-Z targets where a discrepancy between experiment and theory might turn up. Furthermore, measurements with 20 GeV electrons in a Cu target shows no indication of the 'kink-like' structure seen in Migdal's theory (the most widely used) for photon energies around 300 MeV.
A proof-of-principle measurement of the efficiency of production for positrons originating from electrons impinging on an axially aligned diamond crystal was also performed, where the production angles and energies can be measured by means of so-called MIMOSA detectors arranged in a magnetic spectrometer configuration with a permanent-magnet-based magnetic dipole.

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1) On behalf of the collaboration.

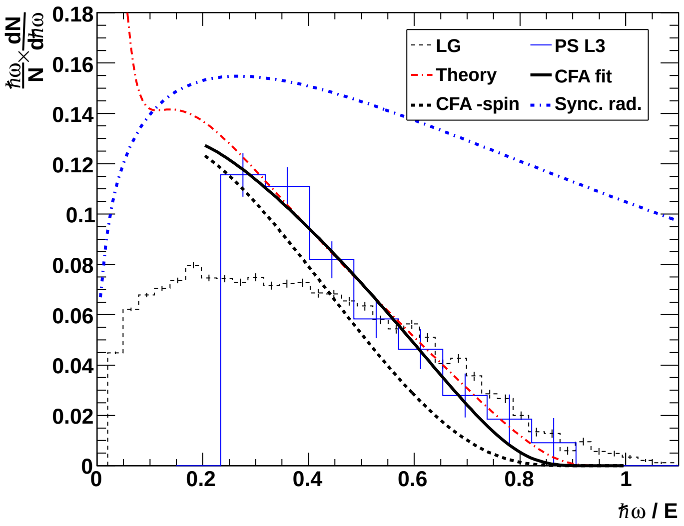

Figure 1: 100 GeV PS data with theoretical calculations. The CFA has been fitted to the data (black line) and we find $\chi = 0.68 \pm 0.16$. The CFA without the spin contribution has been plotted with the parameters found from the CFA fit (black dotted) and the classical synchroton radiation spectrum has been plotted for the same field (blue). From [1].

1 Quantum synchrotron radiation

Recently, our results obtained in the 2009 run on the quantum corrections to synchrotron radiation emission were published [1].

In the regime where $\chi \equiv \gamma B/B_0 \sim 1$, with the critical magnetic field $B_0 = m^2c^3/e\hbar = 4.414 \cdot 10^9$ T and the Lorentz factor γ, the classical formulas predict radiation that violate energy conservation, and quantum corrections become decisive, with both magnetic moment (spin-flip) and recoil corrections being important. With electrons of energies 10-150 GeV penetrating a germanium single crystal along the $\langle 110 \rangle$ axis, we have experimentally investigated the transition from the regime where classical synchrotron radiation is an adequate description, to the regime where the emission drastically changes character; not only in magnitude, but also in the spectral shape. The spectrum can only be described adequately by quantum synchrotron radiation formulas. Apart from being a test of strong-field quantum electrodynamics, the experimental results are also relevant for the design of future linear colliders where beamstrahlung - a strongly related process - may limit the achievable luminosity.

One of the central objectives of this experiment was to observe the change in radiation spectrum when quantum recoil and spin-flip transitions affect the process. In figure 1 we compare the 100 GeV pair spectrometer (PS) data to several theoretical calculations. Besides theoretical calculations based on formulas by Baier *et al.* [6], we have fitted a Constant Field Approximation (CFA) calculation to the data. The fit parameters are the strong-field parameter χ and a scaling factor. We find $\chi = 0.68 \pm 0.16$. With this field we plot the CFA theory without the spin-flip contribution and the classical radiation spectrum. Spin-flip transitions are only a small contribution at this field but the difference between the classical spectrum and the measurements is drastic and the classical formula is clearly inadequate.

Combined with earlier measurements performed with a tungsten crystal, we have now covered the parameter space from 0.05 to 7 of the associated strong-field parameter $\chi_s = \frac{V_0 E\hbar c}{a_s(mc^2)^3}$ [6], proportional to χ, in the case of radiation emission. In contrast to our measurements of the trident process [7] (performed with the same type of crystal), the radiation emission data are very well described by theory, giving confidence in the codes used for simulations of the beamstrahlung emitted at the interaction point of e.g. CLIC.

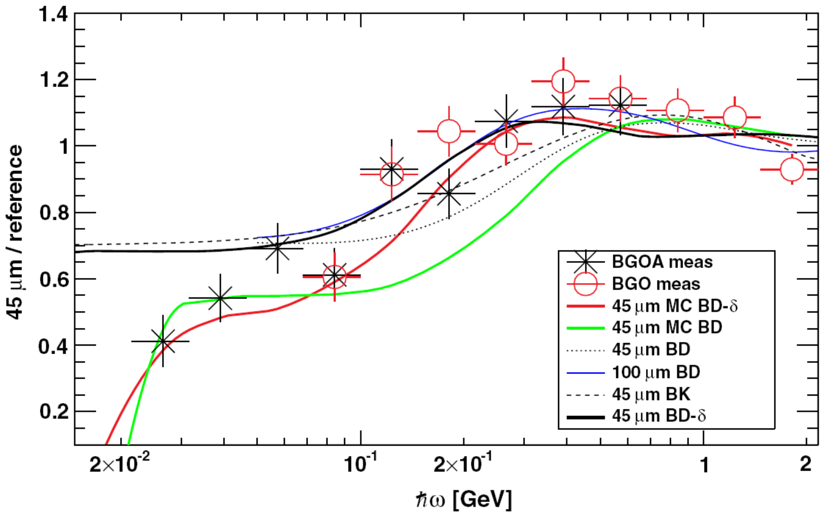

Figure 2: (Color online) The ratio between a measurement with $l_g = 45\ \mu$m and the reference measurement. Both spectra have been background subtracted. The BGOA measurements (amplified BGO signal for increased sensitivity at low energies) are shown with black stars and BGO with red circles. Monte Carlo simulations using the uncorrected theory of Blankenbecler (green) and Blankenbecler's theory including a correlation term (red) are also shown. Several theoretical curves based on Blankenbecler's and Baier/Kaktov's theories are shown for different gap sizes. The horizontal bar is the bin width and the vertical bar is the statistical errors. From [2].

We emphasize that the results obtained in 2012 and presented in the following are all of preliminary character. The experiment was finished less than one month ago at the time of the deadline for this status report. In particular the calibration of the photon energy scale is uncertain, as it relies on a measurement by means of the extracted beam from the ASTRID storage ring in Aarhus, performed 10 days ago. The data presented nevertheless give a good impression of the results within reach.

2 Structured target 'resonances'

2.1 2011 measurement

As described in [8], one of the aims of the 2011 run was to perform a dedicated experiment directed towards the detection of a so-called structured target resonance [3, 5, 4]. This gave a publishable result [2] which, however, left room for a more systematic study, based on resonances for several distances. In particular such a systematic investigation was desirable due to the lack of agreement with the unmodified theory of Blankenbecler [3] and that of Baier and Katkov [4], whereas good agreement with Blankenbecler's theory including a correction term $\bar{\delta}$ [5] was found. In fact, as previously reported [9], the discrepancy between the uncorrected theory of Blankenbecler, the theory of Baier and Katkov and experimental values initially forced a thorough check of our distance measurements. The best agreement between those theories and our experimental data was obtained for a separation of about 100 μm, whereas 3 independent measurements showed that the physical distance was about 45 μm with only a few micron uncertainty. It turned out, though, that the discrepancy was due to insufficient theories.

In figure 2 is shown the 2011 measurement of a structured target 'resonance', in that case for 45 μm separation [2].

The correction term arises due to correlations between transverse coordinate amplitudes (with respect to the scattering centers) and the phase of the eikonal wave function, and is generally small for non-structured targets but gives a significant shift in 'resonance energy' for structured targets, corresponding to about a factor 2 in distance. Structured targets are thus attractive to verify the relevance of the correlation term in multiple scattering.

2.2 2012 measurement

Although experimentally little was left open for discussion - distances e.g. measured by three independent methods, each with few micron accuracy - the element of chance of course could not be entirely ruled out, since essentially only one distance was measured in the 2011 experiment. We therefore in 2012 performed a more extensive investigation of the structured target resonances to confirm that the correlation term is significant to obtain an accurate description of radiation emission in the presence of multiple scattering.

In a naïve approach, the resonance (or, rather, the lack of destructive interference) appears when the formation length

$$l_{\mathrm{f}} = \frac{2E(E-\hbar\omega)}{m^2c^3\omega} = \frac{2\gamma^2 c}{\omega^*} \qquad \omega^* = \omega\frac{E}{E-\hbar\omega}\ , \tag{1}$$

extends across the separation gap between two closely positioned foils. Thus, when the formation length equals the target spacing or gap width δg it leads to a resonance at a photon energy

$$\hbar\omega < \hbar\omega_{\mathrm{r}} = \frac{E}{1+\dfrac{\delta g}{2\gamma\lambda\!\!\!^{-}_c}}\ , \tag{2}$$

Other effects involving the concept of formation length may be found in [10, 11].

In order to avoid the problems associated with stacks of foils, we measured with only two foils, mounted on a precisely controlled translation stage, such that the internal separation between the two foils could be controlled with an accuracy of a few microns. This sets rather severe constraints on the amount of extra material in the beam, e.g. from thin trigger scintillators, vacuum-pipe windows and beam-line diagnostics such as wire-chambers. Furthermore, the requirement of measuring photon energies down to a few tens of MeV imposes constraints on the magnetic field applicable to deflect the electron from its radiated photon, due to the emission of typically several synchrotron radiation photons. To obtain a gentle deflection, i.e. a low field, two 2 meter long magnetic dipoles were run in series at a fairly low field, 0.17 T, giving a synchrotron radiation critical energy of $\hbar\omega_c = 3\gamma^3 e\hbar B/2p \simeq 3.6$ MeV. Even with pile-up originating from several synchrotron radiation photons being emitted simultaneously, this allows detection down to ≈ 30 MeV, without the need for deconvolution.

In figure 3 is shown an example of the measurements of a structured target 'resonance', in this case for 60 μm separation. We have measured for distances 10, 60, 100, 200, 500 and 20.000 μm between the foils to determine the variation of the peak energy with foil separation, essentially a direct measurement of the formation length variation with photon energy.

A series of measurements of the surface-flatness for different kinds of foil mountings in the holders, have lead to a technique where the flatness of the foils over the entire Ø 15 mm hole in the holder through which the beam passes, shows variations of only a few microns. By means of a scintillator anti-coincidence, only the central part, Ø 9 mm, of the beam is used. A photograph of a gold foil mounted in the holder is shown in figure 4. This, combined with one of the holders being mounted in a damped spring-loaded gyro, assures that the foils after being pressed against each other are parallel and equidistant all across the measurement surface, with a tolerance of not more than 5 microns. The maximum separation is more than 50 mm, assuring that the foils, when positioned at this spacing, act completely independently.

Extensive simulations based on the formalism of Blankenbecler, have shown that the optimum choice for the target thicknesses in order to verify the existence of the effect, is 20-30 microns for each foil [12]. For the experiments in 2012, we used foils of thickness 26 microns.

As shown in figure 3, there is quite good agreement between theory and measured values for the ratio between the radiation spectra (after background subtraction) obtained with 178 GeV electrons passing 2 foils of each 26 micron thick gold, at separations of nominally 60 microns and 20 mm. Using the ratio as the observable eliminates many systematic effects, but also the spectra by themselves (not shown) are in good agreement with theory, including LPM and TSF effects (for these effects, see [13]). Clearly, there is an effect of increasing the distance between the foils, and already from these data we can

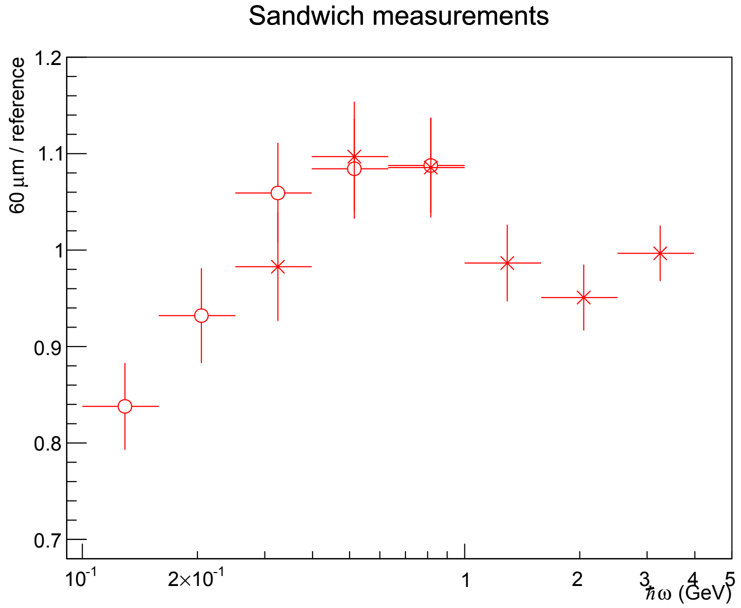

Figure 3: *Preliminary results for one of the measurements of the structured target 'resonances'. Shown with crosses is the ratio between the radiation spectra (after background subtraction) obtained with 178 GeV electrons passing 2 foils of each 26 micron thick gold, at separations of nominally 60 microns and 20 mm. Open symbols represent the amplified BGO signal. In the latter case, there should be no 'resonance', the formation length being much too short to extend across the gap between the foils, whereas for the 60 micron separation the 'resonance' appears. Thus the ratio of the two spectra shows the 'resonance' in units of a normal bremsstrahlung (including LPM and TSF effects, see [13]) reference.*

Figure 4: *A photograph of one of the gold foils, mounted in the holder. The foil is glued to the edges and subsequently the central part of the holder is tightened against it such that the central part protrudes and is kept flat.*

conclude that formation lengths for $\simeq$ 1 GeV photons emitted by multi-GeV electrons can be measured directly, in effect by means of a micrometer screw.

3 Landau-Pomeranchuk-Migdal effect for low-Z targets

The Landau-Pomeranchuk-Migdal (LPM) effect was investigated experimentally in the mid-90s with 25 GeV electrons at SLAC [15] and later with up to 287 GeV electrons at CERN [16, 17]. These investigations - combined with relevant theoretical developments - have shown that the theory of multiple scattering dominated radiation emission is describing experiment very well, at least for high-Z targets.

In his review paper on the LPM effect from 1999 [18], Spencer Klein stated among the explanations for a small, but significant discrepancy found for carbon with electrons at 25 GeV that "‘it is also possible that Migdals theory may be inadequate for lighter targets."’. Likewise, in the CERN experiments [17], where carbon was used as a calibration target, the systematic deviations from the expected values for E_{LPM} could possibly be explained by an insufficient theoretical description of carbon.

As described in [14], the most widely used theory for the LPM effect, developed by Migdal [19], potentially has at least two shortcomings: It is based on the Thomas-Fermi approximation, known to be inaccurate for atoms of low nuclear charge [19, eq. (22)], and for several combinations of electron energies and photon energies, the resulting spectra show what seems to be an unphysical 'kink' in the radiation spectrum. The aim of our measurements in 2012 was to address these questions.

Moreover, the more modern theory by Baier and Katkov which includes Coulomb corrections and other fine details, is developed mainly for high-Z targets, and therefore does not include screening adequately for low-Z targets. The accuracy of their theory is expected to be a few percent for high-Z targets, whereas for low-Z targets the error may be as much as 10-15%.

Finally, the contribution from electrons may be influenced differently by the LPM effect than the nuclear contribution, resulting in another potential difference between the true multiple scattering effects in low-Z and high-Z targets.

3.1 Measurements with electrons of 178 GeV

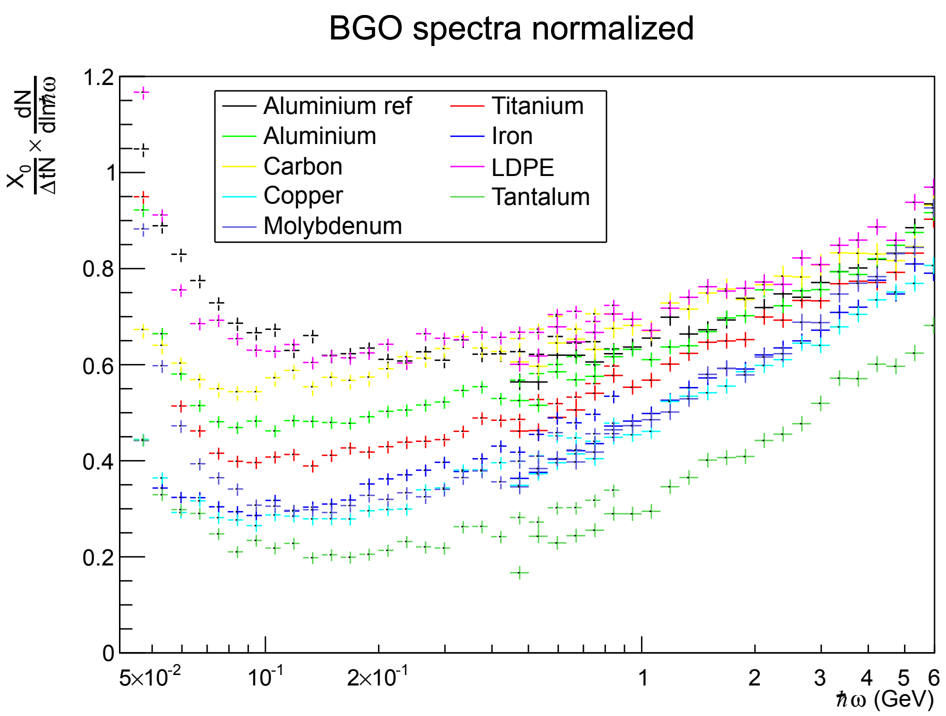

Figure 5: *Preliminary results for the low-Z LPM measurement performed with electrons of 178 GeV in* $\simeq$ *2.5%* X_0 *targets of LowDensityPolyEthylene (LDPE), Carbon, Aluminum, Titanium, Iron, Copper, Molybdenum and Tantalum. For detector efficiency calibration purposes we measured also a* $\simeq$ *2.5%* X_0 *target consisting of 80 foils of Al, each subtarget 25 microns thick, i.e. significantly thinner than* $l_\gamma = \alpha/4\pi X_0 = 52\mu m$*, thus ensuring single interaction conditions yielding a standard Bethe-Heitler spectrum.*

As shown in figure 5, the general tendency is that the higher the nuclear charge of the target, the stronger is the LPM suppression, exactly as expected. The possible presence of discrepancies with theory cannot be concluded upon yet, but analysis is in fast progress and is expected to be finished by the end of 2012.

3.2 Measurements with electrons of 20 GeV

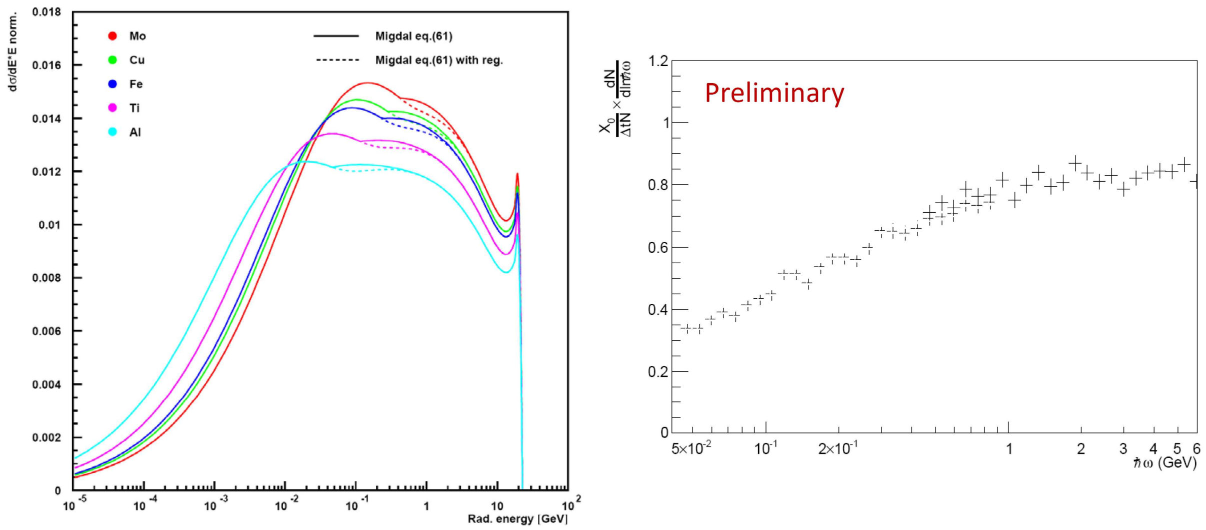

Figure 6: *Preliminary results for the low-Z LPM measurement performed with electrons of 20 GeV in a* $\simeq 2.5\%$ X_0 *target of Copper.*

In figure 6 is shown the preliminary results for the low-Z LPM measurement performed with electrons of 20 GeV in a $\simeq 2.5\%$ X_0 target of Copper. The presence of a 'kink' in the radiation spectrum - while clearly visible from the theory - is not apparent from the experimental data. A more firm conclusion awaits further analysis.

4 Positron production by electrons in a diamond

In view of recent developments in the field of efficient positron production by use of crystalline targets [21, 22, 23, 24, 25], we have on previous occasions [14, 8] shortly described a possible study using diamond crystals. The relevance of such a study is high, as e.g. CLIC and LHeC e^+-production schemes are expected to gain significantly (at least several tens of percent, perhaps even factors of 3-4) from using crystalline targets where the strong field effects - studied in detail experimentally by the NA43 and NA63 collaborations - play a decisive role. Due to the high power of the primary electron beam in such schemes, characteristics such as radiation hardness, melting point and thermal conductivity of the target are key elements. Diamond is unique in this respect, known to be superior to all other crystals, but clearly has the disadvantage of high cost, in particular for large specimens.

From prof. M. Winter, Strasbourg, we have acquired 4 of the so-called MIMOSA-26 detectors [26], CMOS-based position sensitive detectors with 1152 columns of 576 pixels, $\simeq$ 18.4 μm pitch, readout in 110 ms, $\simeq$ 3.5 μm resolution and true multi-hit capability (at least 20 charged particles per read-out). These detectors are approximately 1×2 cm^2 (two of them are 'doubles', i.e. approximately 2×2 cm^2) and represent only the material of $\simeq$ 50 μm of silicon to the beam, i.e. $\Delta t/X_0 \simeq 0.05\%$ each. Unfortunately, the remaining detectors necessary for a complete measurement could not be acquired in time, so we reduced the setup to a test of the principle of operation of the magnetic pair spectrometer configuration. The production angles and energies can be measured by means of the MIMOSA detectors arranged in a magnetic spectrometer configuration with a permanent-magnet-based magnetic dipole that through a shunting mechanism has a variable field (the dipole was kindly provided on loan from DANFYSIK). The advantage of a permanent-magnet-based magnetic dipole is naturally its lack of power consumption that makes it possible with relative ease to install the entire spectrometer configuration in vacuum - no need for water cooling nor current supply. We plan to do this in future measurements, giving a significantly improved momentum resolution at the low pair energies (few tens of MeV) which are of main interest.

A photograph of the setup is shown in figure 8. With a 1.5 mm thick single crystal diamond aligned along the $\langle 100 \rangle$ axis as target, a first measurement of the positron-production in diamond has been performed. A more firm conclusion awaits further analysis based on generating tracks between the MIMOSA detectors - a non-trivial task due to the presence of a substantial amount of noise-hits (inherent to the MIMOSA-technology, i.e. a solvable problem).

We have found that measurements using diamond have been performed, but with a somewhat different setup that only allows measurements at specifically chosen positron momenta and integrated over forward angles [27]. In those measurements the enhancement is high for diamond of small thicknesses, whereas for thicknesses large enough to yield an acceptable production rate the enhancement for diamond is smaller than for other crystals, and fairly rapidly approaches one, with increasing thickness. It must be emphasized, though, that the actual phase-space density has not been measured, the enhancement thus likely being a pessimistic number.

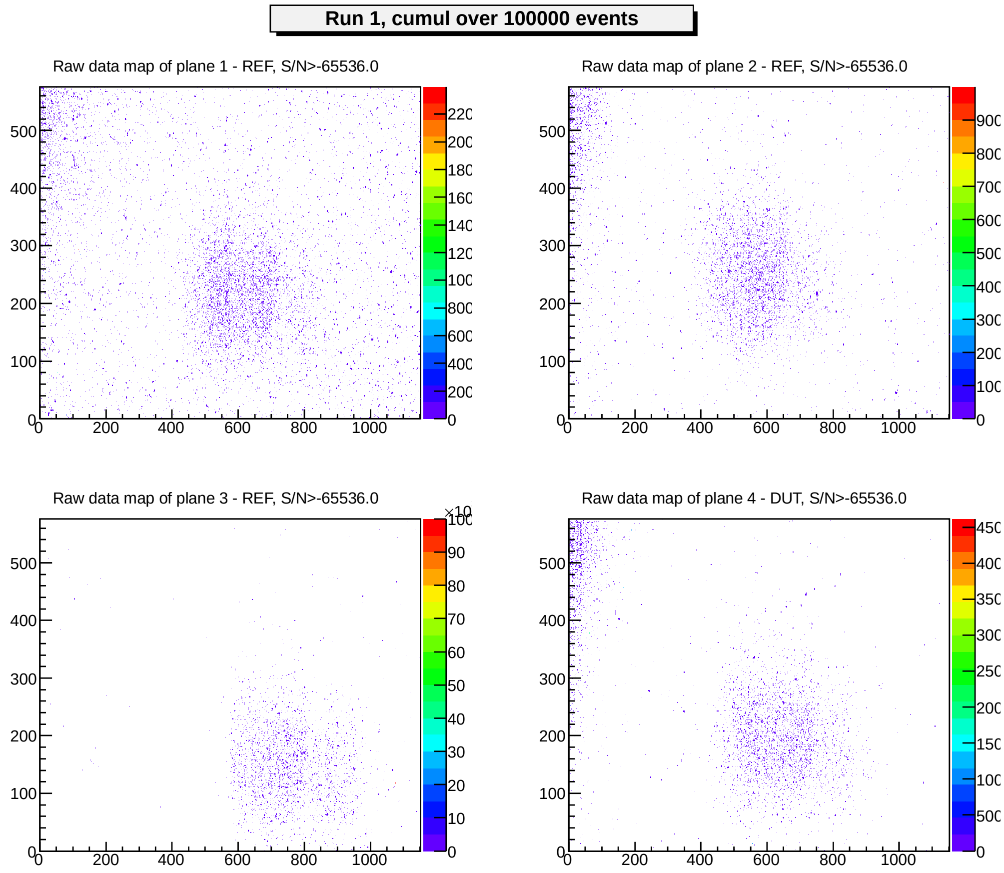

Figure 7: *A 'screen-shot' of the 4 MIMOSA detectors, showing the beam-profiles observed at the 4 locations, 2 upstream the spectrometer permanent magnet and 2 downstream.*

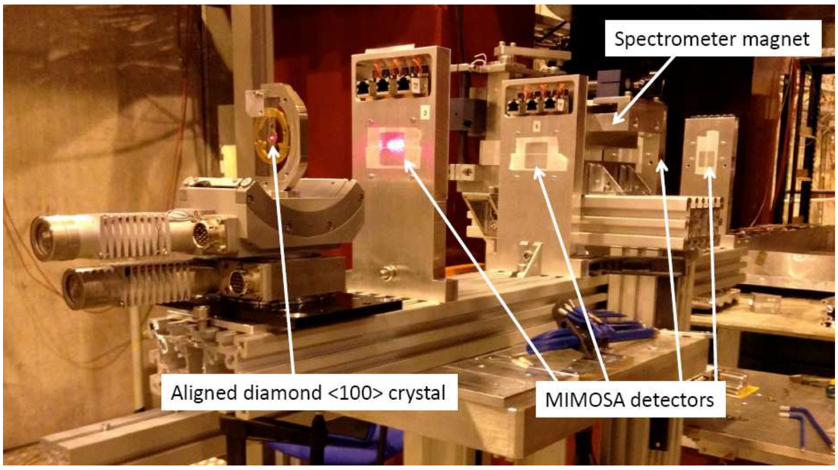

Figure 8: *MIMOSA-setup*

5 Plans for 2013

Due to the lack of beam in 2013, our main focus will be on finishing the analysis of 1) our structured target measurements and 2) our low-Z LPM measurements. Judging from the preliminary results obtained so far, we expect both of these data sets to be publishable.

Furthermore, we aim to prepare equipment and calculations/simulations such that we will be ready in the fall of 2013 to propose for 2014 a full measurement of the positron production in diamond and a measurement of the bremsstrahlung/δ-electron emission from ultrarelativistic heavy ions.

6 Status of publications

Publications related to the activities of NA63:

1. T. Virkus, U.I. Uggerhøj, H. Knudsen, S. Ballestrero, A. Mangiarotti, P. Sona, T.J. Ketel, A. Dizdar, S. Kartal and C. Pagliarone (CERN NA63): *Direct measurement of the Chudakov effect*, Phys. Rev. Lett. **100**, 164802 (2008)
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8. H.D. Thomsen and U.I. Uggerhøj: *Measurements and theories of the King-Perkins-Chudakov effect*, Nucl. Instr. Meth. B, **269**, 1919 (2011)
9. A. Mangiarotti, P. Sona, S. Ballestrero and U.I. Uggerhøj: *A general semi-analytic method to simulate discrete bremsstrahlung at very low radiated photon energies by the Monte Carlo method*, Nucl. Instr. Meth. B, **269**, 1977 (2011)
10. A. Mangiarotti, P. Sona, S. Ballestrero, K.K. Andersen and U. I. Uggerhøj: Comparison of analytical and Monte Carlo calculations of multi-photon effects in bremsstrahlung emission by high-energy electrons, Nucl. Instr. Meth. B **289** 5-17 (2012)
11. K.K. Andersen, S.L. Andersen, J. Esberg, H. Knudsen, R. Mikkelsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel and S. Ballestrero (CERN NA63): Direct measurement of the formation length of photons, Phys. Rev. Lett. **108** 071802 (2012); see also accompanying Physics Synopsis and Science Daily.
12. K.K. Andersen, J. Esberg, H. Knudsen, H.D. Thomsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero (CERN NA63): Experimental investigations of synchrotron radiation at the onset of the quantum regime, Phys. Rev. D **86**, 072001 (2012)

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