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ELECTROMAGNETIC PROCESSES IN STRONG CRYSTALLINE FIELDS

Addendum to the NA63 proposal

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NA63

Abstract

As an addendum to the NA63 proposal [1], we propose to measure 1) the Landau-Pomeranchuk-Migdal (LPM) effect in low-Z targets, 2) Magnetic suppression of incoherent bremsstrahlung resulting from exposure to an external field during the emission event, and 3) the bremsstrahlung emission from relativistic ($\gamma = 170$), fully stripped Pb nuclei penetrating various amorphous targets.

Concerning the LPM effect, both the 'traditional' Migdal approach and the modern treatment by Baier and Katkov display inaccuracies, i.e. a possible lack of applicability in low-Z targets. Moreover, the LPM effect has been shown to have a significant impact on giant air showers for energies in the EeV range - evidently processes in a low-Z material.

A measurement of magnetic suppression is demanding in terms of necessary accuracy (an expected $\lesssim$15% effect), but would prove the existence of a basic interplay between coherent and incoherent processes, also believed to be significant in beamstrahlung emission.

For bremsstrahlung from Pb^{82+}: In contrast to earlier expectations, recent investigations have shown that the bremsstrahlung emission from heavy, relativistic particles does not appear with constant power for all photon energies up to the end-point given by the energy of the incident ion, but instead the spectrum has a peaked shape, due to the finite size of the nucleus. Beyond an energy of about $2\gamma\hbar\omega_1$, where $\hbar\omega_1$ corresponds to the energy transfer above which the Z protons in the nucleus can be considered quasi-free, the power-spectrum falls off quite steeply, eventually leaving pair production as the dominant energy loss mechanism for sufficiently high values of the Lorentz-factor.

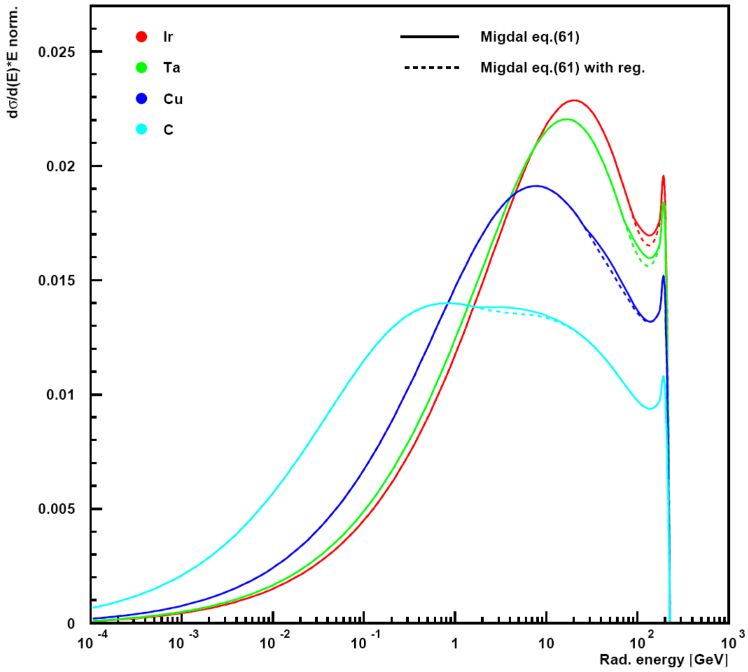


Figure 1: *Expected radiation spectra, based upon simulations using GEANT, as described in [7], but updated to extend the applicable range to lower photon energies. The full curves shown are for 207 GeV electrons in different solids, as indicated, based on the theory of Migdal [6] and the dashed curve is a 'regularization' procedure, as described in the text.*

1 LPM effect in low-Z targets

The Landau-Pomeranchuk-Migdal (LPM) effect was investigated experimentally in the mid-90s with 25 GeV electrons at SLAC [2] and later with up to 287 GeV electrons at CERN [3, 4]. 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 [5], 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 [4], where carbon was used as a calibration target, the systematic deviations from the expected values for $E_{\rm LPM}$ could possibly be explained by an insufficient theoretical description of carbon.

Furthermore, simulations using GEANT, see figure 1, show that the theory of Migdal has a discontinuous derivative at a photon energy of a few GeV from 207 GeV electrons, indicating exactly such an insufficient theoretical description. In figure 1 is also shown with the dashed line an attempt at 'regularizing' the Migdal $\xi(s)$ function by adding a small term that 'repairs' the derivative, but still has the correct asymptotic limit.

As seen from figure 2, there may very well be a theoretical problem for photon energies in the 1-100 MeV range from a 1 TeV electron in air - clearly a low-Z target. Similar results (not shown) indicate problems in the understanding of radiation emission from 1 TeV to the endpoint energy ($\hbar\omega/E_e \in [10^{-3}, 1]$) for 1 PeV electrons in air, relevant for the development of extended air showers.

We emphasize that the aim is not to do a measurement that enables a distinction between the dashed and full curves in figures 1 and 2, but that these observations indicate a potential problem in the understanding of the LPM effect in low-Z targets.

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%.

In figure 4 is shown the result of a short (≈ 1 hour datataking on Al) pilot-experiment performed

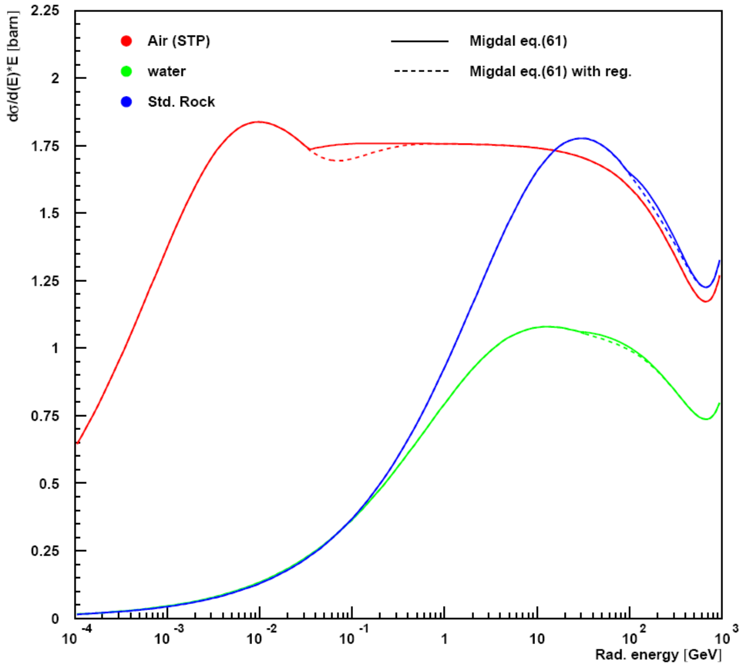


Figure 2: *As figure 1 but for 1 TeV electrons in air, water and standard rock (defined as in [5]), as indicated.*

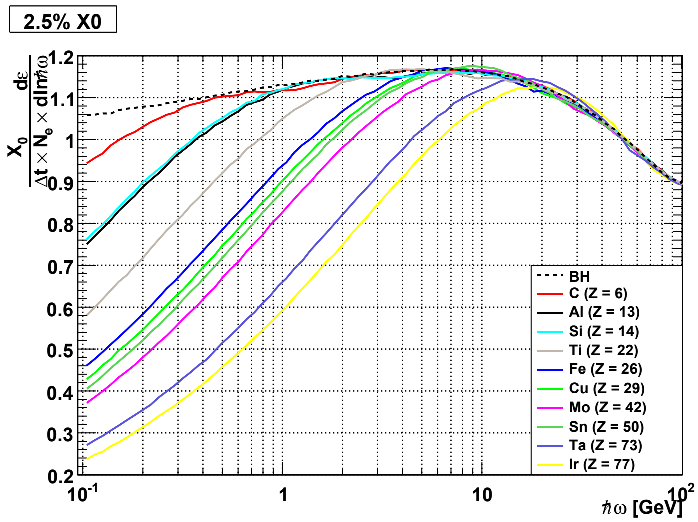


Figure 3: *Expected radiation spectra, based upon simulations using GEANT, as described in [7], but updated to extend the applicable range to lower photon energies. The curves shown are for 178 GeV electrons in different solids, as indicated and as a function of the photon energy in the realistically detectable range.*

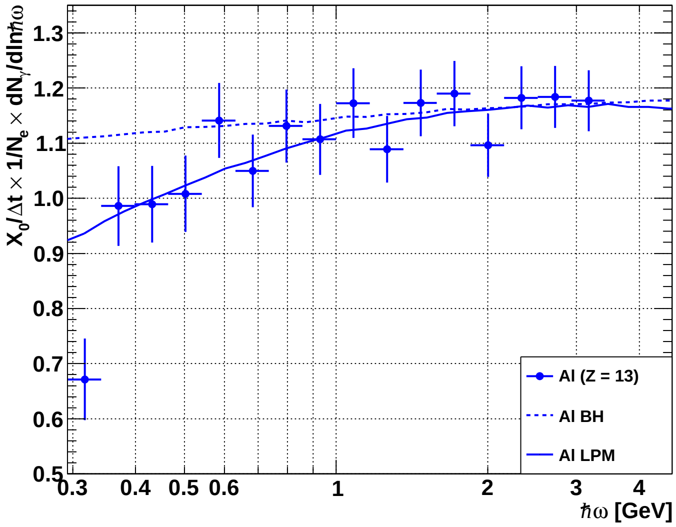


Figure 4: *Measured and expected (dashed line is the Bethe-Heitler value, full line shows LPM) radiation spectrum for* $2.3\% X_0$ *aluminum with 207 GeV electrons.*

during the June beam time of NA63 in 2009. It shows measured values for the radiation emission from aluminum, compared to expectations based upon simulations using GEANT, as described in [7].

The agreement between data and simulated values based upon LPM theory is generally good, but a firm conclusion requires more statistics, and a more careful reduction of the synchrotron radiation background (the critical frequency of which can be lowered by a factor $\simeq 3$) which is the explanation for the lowest point being far below expectations. In the same run, tantalum and carbon were tested, with good agreement between data and simulated values for the former, but inconclusive for the latter.

There is thus a motivation to measure radiation emission in low-Z targets to search for deviations from LPM theory. We therefore request 10 days of beam in the H4 beam line of the CERN SPS in 2010 to perform the measurements in targets with Z-values of 6, 13, 14, 22, 26, 29, 42, 50, 73 and 77, see figure 3, with a setup similar to that previously used by NA63, see e.g. [8].

2 Magnetic suppression

Magnetic suppression of incoherent bremsstrahlung may appear if the electron is exposed to an external field during the emission event. It is an example of an interplay between coherent and incoherent processes. The magnitude of the magnetic suppression effect as a function of photon energy was discussed in the late 90's by the SLAC E-146 group, in a transparent, but very rough approximation. In continuation of this, Klein showed [5] that the so-called magnetic suppression appears when the deflection angle of the emitting electron over half a formation length

$$\theta_B = \frac{\Delta p}{p} = \frac{eBl_\mathrm{f}}{2E} \tag{1}$$

exceeds the emission angle $1/\gamma$ (taken here with the electron trajectory perpendicular to the magnetic field) which is the case for photons of relative energy

$$\frac{\hbar\omega}{E} = \xi < \frac{\chi}{1+\chi} \simeq \chi \tag{2}$$

where $\chi = \gamma B/B_0$ is the Lorentz-invariant field parameter expressed from the critical field $B_0 = m^2c^3/e\hbar = 4.414 \cdot 10^9$ T, and the last approximation is valid when $\chi \ll 1$. This is always so for laboratory experiments since magnetic fields are limited to about 2 T if iron is used for the magnet poles, and the Lorentz factor is smaller than about 10^6, i.e. $\chi \lesssim 5 \cdot 10^{-4}$. Nevertheless, for sufficiently energetic particles and soft photons, the effect could be observable.

In the limit of strong suppression, the suppression factor S according to Klein [5] can be rewritten as

$$S = (\frac{\hbar\omega}{\chi(E-\hbar\omega)})^{2/3} \tag{3}$$

which for 20 MeV photons from 207 GeV electrons in a 2T field ($\chi = 1.8 \cdot 10^{-4}$) amounts to $S = 0.65$, a significant suppression. Nevertheless, as this is a very rough model, applied in the limit of strong suppression, the magnitude of the effect is not so reliable.

However, already in a paper from 1988, Baier, Katkov and Strakhovenko [9] discuss the influence of an external field on radiation processes in a medium, and in fact show in their introduction the same rough approximation as employed by the SLAC group. Their paper was a 'pioneering' effort in the sense that it supplied the basis for many subsequent papers of that group, discussing the interplay between coherent and incoherent effects, notably in crystals. As emphasized by the authors, their theory finds direct application in the emission of beamstrahlung where there is a strong coherent field from the opposing bunch. Another example of an external field could be a magnetic field supplied from an electromagnet across an amorphous foil. The expression of Baier, Katkov and Strakhovenko [9] is more complicated, but expected to be much more precise than eq. (3):

$$\begin{aligned}\frac{d\sigma}{d\hbar\omega} &= \frac{4Z^2\alpha^3\hbar}{15m^2c^2\omega}\ln((1+(\frac{\chi}{u})^{1/3})\frac{1}{\gamma\theta_1}) \\ &\cdot [\frac{\hbar^2\omega^2}{E^2}(x^4\Upsilon(x) - 3x^2\Upsilon'(x) - x^3) + (1+\frac{E'^2}{E^2})(x^4\Upsilon(x) - 3x\Upsilon(x) + 5x^2\Upsilon'(x) - x^3)]\end{aligned} \tag{4}$$

where $x = (u/\chi)^{2/3}$ (equal to S in eq. (3)), $u = \hbar\omega/(E-\hbar\omega)$, $E' = E - \hbar\omega$, $\theta_1 = \hbar c/Ea_s$, $a_s = 0.81a_0Z^{-1/3}$ is the screening radius and

$$\Upsilon(x) = \int_0^\infty \sin(xt + \frac{t^3}{3})dt \tag{5}$$

which - for computational purposes - can be expressed as definite integrals of modified Airy functions of the first and second kind $\mathrm{Ai}(x)$, $\mathrm{Bi}(x)$

$$\Upsilon(x) = \pi Gi(x) = \pi[\frac{1}{3}\mathrm{Bi}(x) + \int_0^x (\mathrm{Ai}(x)\mathrm{Bi}(t) - \mathrm{Ai}(t)\mathrm{Bi}(x))dt] \tag{6}$$

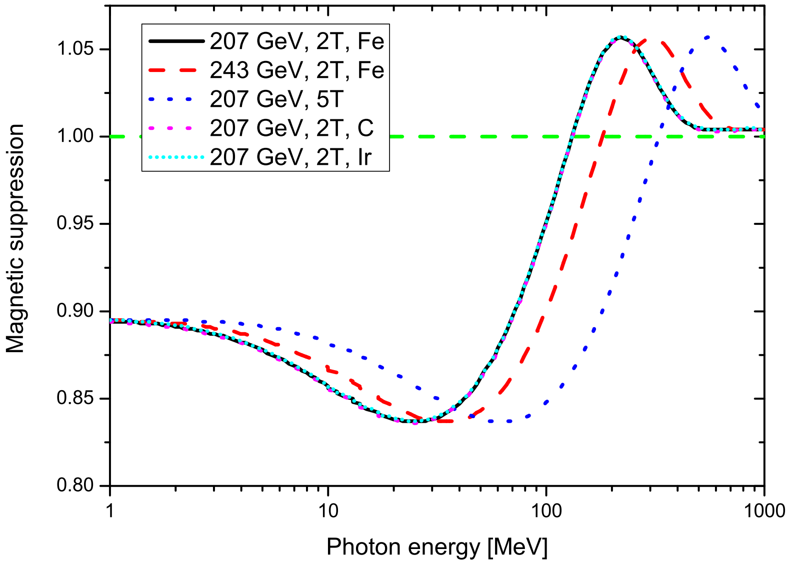


Figure 5: *The expected magnetic suppression according to* (4) *for experimentally relevant situations as indicated.*

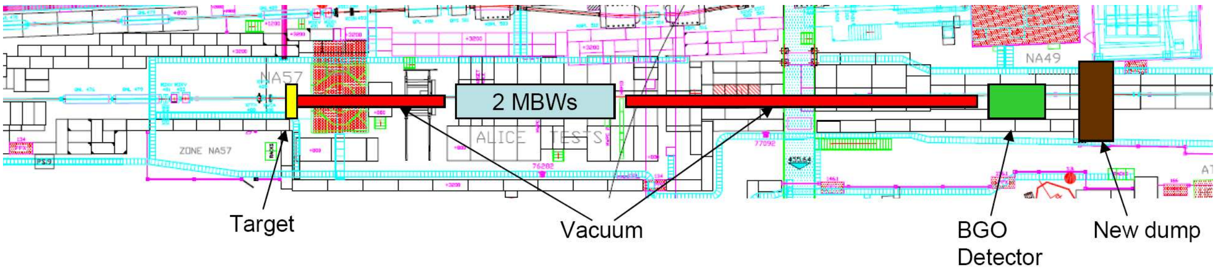


Figure 6: *A sketch of a possible layout of the H4 zone, where PPE 134 must be extended approximately 20 metres downstream.*

As shown in [9, eq. (3.29)], eq. (4) reduces to a suppression approximately given by eq. (3) in the strong field limit ($\chi/u \gg 1$).

A calculation based on the above of the expected magnetic suppression - defined here as the ratio of $d\sigma/d\hbar\omega(B \neq 0)$ and $d\sigma/d\hbar\omega(B = 0)$ - for experimentally relevant situations is shown in figure 5.

A BGO detector is capable of detecting MeV photons with high efficiency, but there is a complication arising from the emission of synchrotron radiation. Since the emitting particle and the radition must be separated at the location of the detector by at least the sum of the radii of the detector r_d and the beam r_b, either a high field is required or a long baseline. The high field option is unattractive due to the emission of synchrotron radiation. The characteristic energy $\xi_c E$, proportional to γ^2, where $\xi_c = 3\chi$ must be kept below about 5 keV in order not to influence the detection near the lower limit, meaning a maximum field of about 0.1 T. Thus, even with two 6.3 m long MBW dipoles running at 70 A, $r_b = 9$ mm and $r_d = 37.5$ mm, the resulting distance from the center of the deflecting dipole to the detector must be ≥ 26 m. This is however not excluded in the H4 beam line as shown in figure 6.

In figure 7 is shown the expected count rates per 10^4 electrons, i.e. approximately per burst in H4. As seen, the configuration discussed above is largely sufficient for synchrotron radiation to be insignificant above 25 MeV. There is, however, a slight complication arising from synchrotron radiation from the 'main bend', B7, one of the last of the elements that transport the beam from the target to the H4 beam

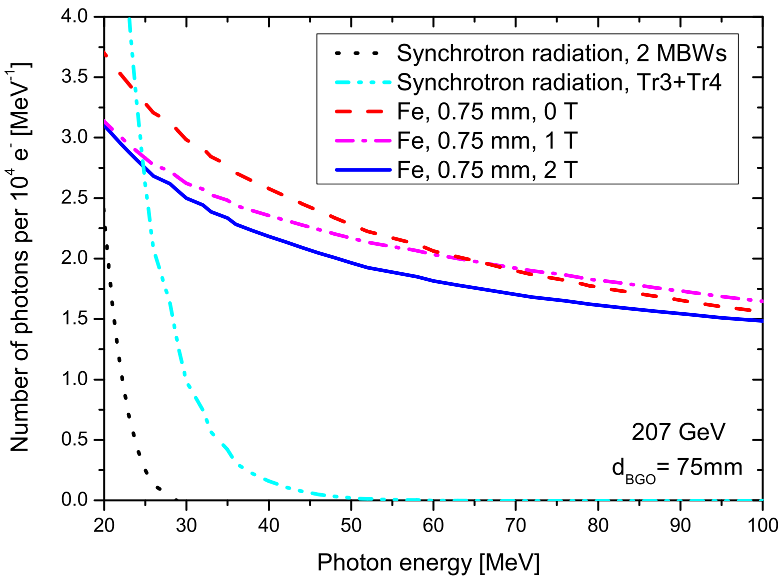


Figure 7: *The number of photons emitted by* 10^4 *electrons, per MeV for a) synchrotron radiation from two MBW magnets run at 0.1 T (70 A), b) synchrotron radiation from two Trim magnets run at 0.2 T (86 A) , c) an iron foil of thickness 0.75 mm without field, d) as c) but with* $B = 1$ *T and e) as c) but with* $B = 2$ *T.*

line. Even though the solid angle subtended by the detector is very small as seen from B7, the high field ($\simeq 0.95$ T) in B7 at 207 GeV results in a high characteristic frequency, and a number of synchrotron radiation photons that is a factor 5-10 higher than from the amorphous target. By setting the main bend slightly too low in current, i.e. the beam directed slightly upwards, this emission escapes the detector. The wrong beam direction can then be compensated by Trim 3 and Trim 4 which can run at much lower field (0.2 T at about 86 A), leading to synchrotron radiation at much lower frequencies. The resulting displacement at the BGO is tolerably small, about 4 mm.

In order not to 'mix' the observation of magnetic suppression with for instance the suppression due to the longitudinal density effect, the photon energy must fulfill $\hbar\omega > \gamma\hbar\omega_p$. There is thus a 'window of opportunity' with photon energies between 22 and $\simeq 130$ MeV for 207 GeV electrons (presently the realistic maximum energy at the CERN SPS when an intensity of 10^4 electrons per burst is required) traversing saturated iron, $B = 2$ T.

As seen from figure 7 and figure 5 the magnetic suppression effect is small, up to $\simeq 15\%$. Thus, in order to clearly be able to verify the effect, high statistics is required. Moreover, running a BGO in a high energy photon beam (where occasionally the detector is hit by 200 GeV photons), has previously proved to be quite difficult, in particular when aiming for the detection of photons in the tens of MeV range. Furthermore, since it is essential to reduce synchrotron radiation as much as possible, beam tuning is important. We therefore request 6 days of beam for the installation, commissioning and calibration. This means that, as high statistics is required with $\gtrsim 10^4$ counts per MeV (corresponding to $\simeq 20$ hrs. with beam from the SPS) for all settings (Fe at 2 T, Fe at 1 T, Fe at 0 T and empty target), and several runs with each setting is desirable, 8 days of datataking is requested. It should be emphasized, though, that a clear advantage arises from being able to switching on and off the effect, by applying a magnetic field to the iron foil and by 'degaussing' it, while all other mechanisms stay constant, eliminating to a large extent the systematic errors. Thus, in total we request 14 days of beam in H4 in 2011 to detect the magnetic suppression of radiation emission from an amorphous foil.

3 Bremsstrahlung emission from $\gamma = 170$ Pb^{82+}

A relatively straightforward approach to derive the bremsstrahlung emission from a relativistic heavy ion, is to use the Bethe-Heitler cross section for bremsstrahlung emission from an energetic lepton and simply replace the electron mass by that of the ion, and likewise for the charge. This leads directly to a $Z_1^4\gamma$ dependence of the energy loss per unit path-length, as e.g. shown in [13]. However, in the rest-frame of the penetrating ion, the impinging virtual photons (in a Weizsäcker-Williams approach) that eventually lead to emission in the laboratory system of photons with energies of the order of that of the incident ion, will have a wavelength significantly smaller than the size of the nucleus. Such photons will therefore not interact with the nucleus as a whole, but instead 'probe' its interior, interacting individually with each of the charged constituents. This leads to a significantly reduced differential cross section $d\sigma/d\hbar\omega$, and likewise a non-constant power-spectrum $\hbar\omega d\sigma/d\hbar\omega$, as opposed to claims otherwise seen in the litterature [14, 13].

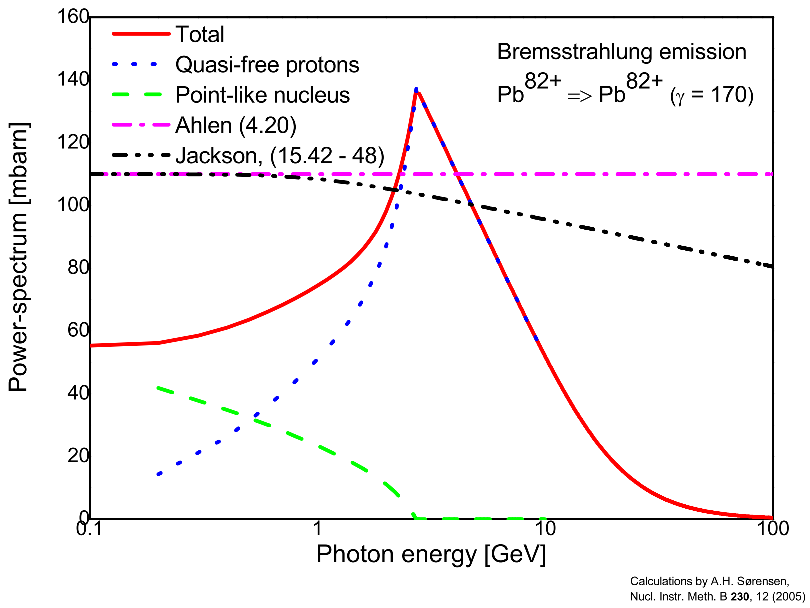


Figure 8: *The power-spectrum $\hbar\omega d\sigma/d\hbar\omega$ for bremsstrahlung emission from Pb^{82+}, with the condition that the nucleus stays intact during the emission process. The dash-dotted line shows the 'traditional' expectation excluding screening [14, 13], and including screening with dash-dot-dot [10], whereas the full-drawn line shows the values based on the finite size of the impinging ion, composed of the contribution from the nucleus being treated as point-like (dashed), and the nucleus being a collection of quasi-free protons (dotted) [11].*

In figure 8, we show the significant difference expected, compared to the 'traditional' expectation [10, 14, 13]. The location of the peak in the spectrum (full line) is given by $2\gamma\hbar\omega_1$, where $\hbar\omega_1$ corresponding to the energy transfer above which the Z protons in the nucleus can be considered quasi-free [11]. Thus, the exact location in energy as well as the width and height of the structure are not expected to be very accurate in this treatment. Nevertheless, the tendency for the spectrum to fall off very steeply compared to other calculations, is an inherent feature of the treatment of the finite nuclear size, and it is seen that already at 20 GeV emission from the 33 TeV ion, the difference between the 'traditional' and the new treatments amounts to about an order of magnitude. Moreover, the calculations have recently been refined (with an expected accuracy of about 10%) [12], showing a similar tendency, but with the resonance at a slightly higher energy and a higher cross section.

However, the cross sections are fairly small, requiring targets of not too small a thickness to generate a reasonable count-rate in a 10^4 ions/spill beam. Thus there is a slight complication arising from

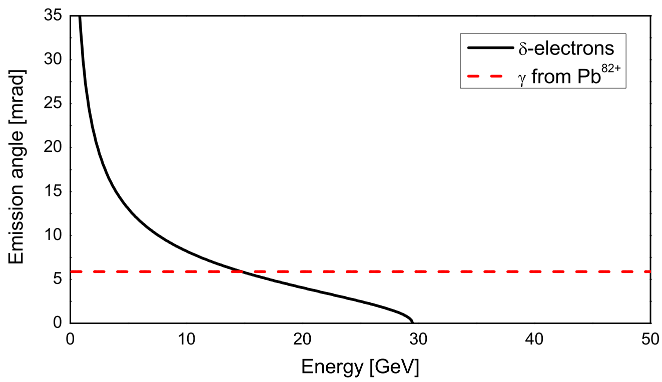


Figure 9: *The emission angle of photons from $\delta-$electrons and Pb^{82+} ions as a function of photon energy.*

the production of $\delta-$electrons by the penetrating ion. These electrons will produce bremsstrahlung with a cross section that for low energy photons is significantly higher than for the heavy ion. However, the $\mathrm{Pb}^{82+} \rightarrow \delta-$electron$\rightarrow \gamma$ process is proportional to the square of the thickness of the target, whereas the $\mathrm{Pb}^{82+} \rightarrow \gamma$ process is directly proportional to the thickness of the target. Thus, targets of approximately 0.35 X_0 thickness (2 mm for Pb) lead to an acceptable compromise between countrate and ratio of signals to false signals. Furthermore, this procedure can be checked by measuring with several thicknesses for a specific element, and by a comparison of target elements with significantly different nuclear charges, but similar areal electron densities.

In figure 9 is shown the emission angle of photons from $\delta-$electrons and Pb^{82+} ions as a function of photon energy. It is assumed that the emission angle with respect to the momentum is $1/\gamma$ (which more reasonably should be a distribution with a half-maximum angle of $1/\gamma$) and that the momentum of the emitting $\delta-$electron is directly correlated with the emission angle with respect to the incoming Pb^{82+} ion, i.e. that multiple scattering can be neglected.

Due to the difference in magnetic rigidity, $\lesssim$ 29 GeV/c per charge as opposed to 400 GeV/c per charge, the produced $\delta-$electrons can easily be deviated without disturbing the heavy ion beam significantly.

The proposed setup is shown schematically in figure 10. Since the signal in scintillators is roughly proportional to Z^2 it is not difficult to discriminate against e.g. cosmics, so two scintillators is sufficient to define the beam. The targets to be used are inserted by means of a remote-controlled rotation stage, and after the target, the Pb^{82+} ions are deflected using a 4 Tm magnetic dipole field into a MUltiple Sampling Ionization Chamber (MUSIC) where the charge state of the spent ion can be detected. Thus, reactions where one or several protons have been lost from the projectile can be investigated as well. If a $\delta-$electron is produced by the ion, it is deflected in the opposite direction by a significantly larger angle, and the event can be 'flagged' by recording the signal in a scintillator S3. The emitted photons are intercepted by a BGO (for energies 0.1-2 GeV) or lead glass (for energies 2-200 GeV) calorimeter. Since the Pb^{82+} ion beam is 400 GeV/c per charge, the deflection in a 4 Tm integrated field is only 3 mrad. However, the longitudinal distance from the MBPL to the detector can be up to 18 metres in H4, meaning a transverse separation of 54 mm, sufficient to separate the radiation from the spent ion.

Shown in figure 11 are two simulations based on the recent refinement of the theoretical treatment [12]. The simulations include the emission of bremsstrahlung from delta-electrons produced by the ion and a more accurate emission spectrum from the ion itself. The target thicknesses for both Si and Pb have been chosen to yield a fragmentation of less than 5% according to earlier measurements by the group [15]. Furthermore, radiation emission from produced pairs has been shown to be negligible as the produced particles appear with energies $\gamma mc^2 \simeq 87 \pm 4$ MeV, far below the region of interest.

From figure 11 it appears that the 'radiation peak' should be detectable for several targets with a

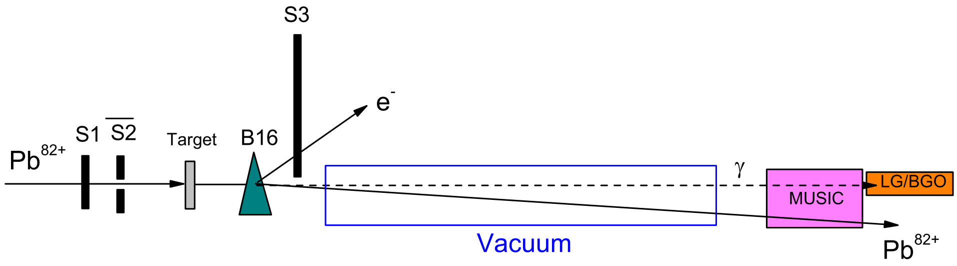
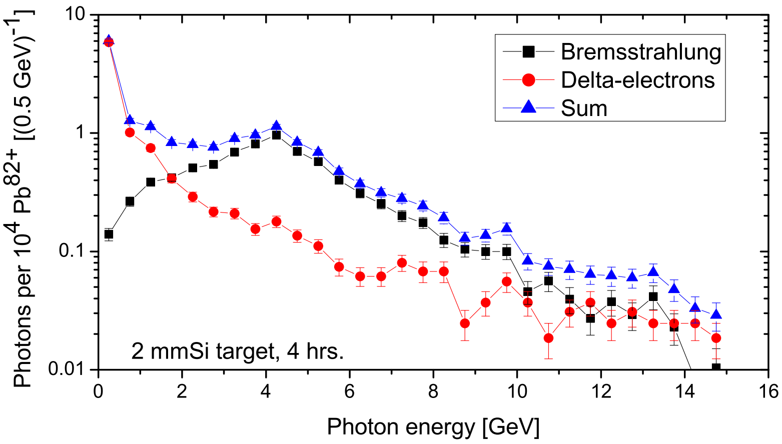


Figure 10: *A figure showing the proposed setup. The Pb*$^{82+}$ *ions are incident from the left, through two scintillators - one counter S1 and one veto with a hole S2 - to the target. After the target, the Pb*$^{82+}$ *ions are deflected using a 4 Tm magnetic dipole field (B16, MBPL installed in H4) into a MUltiple Sampling Ionization Chamber (MUSIC) where the charge state of the spent ion can be detected. Produced* $\delta-$*electrons are deviated into scintillator S3. Finally, the emitted photon is intercepted by a BGO (for energies 0.1-2 GeV) or lead glass (for energies 2-200 GeV) calorimeter.*

few days of dedicated running. We propose to measure for targets with Z values of 6, 13, 14, 29, 50, 73 and 82, mounted on a remote-controlled target-wheel. In order to prepare and calibrate the setup, estimated to take 3 days, and do the measurement itself, estimated to take 4 days in total, we therefore ask for 7 days of running with $\gamma = 170$ Pb^{82+} extracted to the SPS H4 beamline, preferably in 2011, but if safety issues prevent this [16], in 2012.

As a future development it may be envisaged to use an active crystalline silicon target, for which the restricted energy loss gives a 'handle' on the impact parameter of the impinging ion with respect to the target nuclei as shown previously by the group [17]. With such a method, the impact parameter dependence of the radiation emission process from heavy relativistic ions could be experimentally determined.



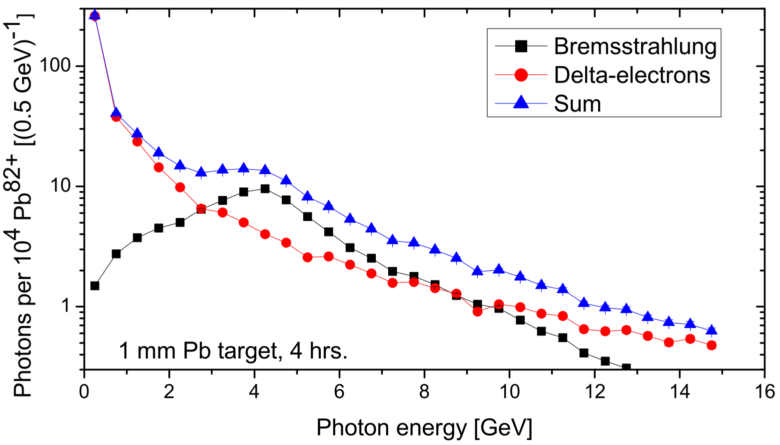


Figure 11: *Counting spectra (number of photons per 0.5 GeV per* 10^4 *incident ions) for bremsstrahlung emission from Pb*$^{82+}$*, with the condition that the nucleus stays intact during the emission process. The statistical uncertainty shown is a realistic estimate for that obtainable within 4 hours of running time, with 1 burst per minute,* 10^4 *ions per burst. The circles are for the emission of bremsstrahlung from delta-electrons produced by the ion, the squares for the emission from the ion itself and the triangles show the sum of these contributions.*

4 Efficient positron production in diamonds

In view of recent developments in the field of efficient positron production by use of crystalline targets [18, 19, 20, 21, 22], we have on a previous occasion [23] 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 (several tens of percent) 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.

In NA63 we have studied the possibility of experiments directed towards a measurement of the potential of diamond in this respect. In this connection, we have established contact with L. Rinolfi (CERN) and R. Chehab (LAL, IN2P3-CNRS) as well as one of the leading theoreticians in this area of research, V. Strakhovenko, who can do the necessary calculations for the optimization of the diamond target. However, our estimates show that such studies are excluded within the present framework of NA63, due to manpower and financial constraints related to the rather high sophistication of the required experimental setup. We do therefore *not* request beam time devoted to such a study by NA63, but continue to work on establishing a new collaboration and proposal aimed at this.

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