We summarize the plans for the CERN NA63 collaboration in 2011, consisting of two separate measurements. The first is a measurement of the structured target ‘resonance’ appearing from radiation emission by electrons passing two amorphous foils positioned with separations in the range 10 – 5000 µm. By this method, the formation length for the generation of MeV-GeV radiation from multi-hundred GeV electrons - of macroscopic dimension - can be directly measured, in principle by means of a micrometer screw.

In the second measurement, we wish to investigate the radiation emission (photons and delta-electrons) from ultrarelativistic fully stripped nuclei. Both spectra of the emitted particles ($\gamma, \delta, e^-$) are expected to show clear ‘resonance’ structures arising from the finite size of the penetrating nucleus.

1) Spokesman, on behalf of the collaboration.
Structured target 'resonances'

Due to the uncertainty in the longitudinal recoil momentum taken by the nucleus from which a high energy electron scatters during bremsstrahlung emission, there is a corresponding distance over which the photon can be considered 'formed', the so-called formation length $l_f$. It is approximately equal to the distance of travel necessary for the electron to 'lag behind' the photon by one reduced wavelength, i.e. loosely speaking the photon has 'separated' from the emitting particle, see e.g. [1]. Even for GeV photons the formation length can be of macroscopic dimensions if the energy of the emitting particle is large enough

$$l_f = \frac{2E(E - \hbar\omega)}{m^2c^3\omega} = \frac{2\gamma^2c}{\omega^*} = \omega^* = \frac{E}{E - \hbar\omega},$$

where $\gamma$ is the Lorentz factor, $\gamma = E/mc^2$. The formation length is approximately equal to $2\gamma^2c/\omega$ for soft photons, $\hbar\omega \ll E$. The finite formation length of the photon—the length over which the lepton may interact again resulting in enhanced or suppressed radiation emission—is basis of the LPM effect.

In short, the LPM effect appears for photon energies where the multiple scattering over the formation length $\theta_f$ deflects the radiating particle outside the radiation cone with opening angle of the order of the inverse of the Lorentz factor, $1/\gamma$.

The LPM theory applies only to a semi-infinite target. For particle energies of a few hundred GeV, the formation length of a few hundred MeV photon becomes more than 100 microns long. In this case, e.g. a 30 micron thick target can clearly not be considered semi-infinite. By equating $\Delta t$ and $l_f$, a threshold at which the LPM theory will become insufficient can be estimated as

$$h\omega < h\omega_{TSF} = \frac{E}{\Delta t},$$

where $\lambda_c = \hbar/mc$ is the reduced Compton wavelength of the electron.

A structured or 'sandwich' target is composed of a sequence of $N$ equidistant foils of equal thicknesses, where typically the separation between the target segments is larger than their thickness. Put differently, it can be thought of as an initially homogeneous target, where sections—corresponding to what eventually becomes the separation—have been removed. In Blankenbecler’s theory [2, 3], interference mechanisms are considered for structured targets of up to 10 segments. It is shown that ‘the photon spectrum is clearly developing a peak where the formation length is approximately equal to the distance between the centers of the plates [2]. Even though those calculations are performed only for 25 GeV (and in a single case 50 GeV), they apply to the general case. Therefore, equation (1) can be inverted setting the formation length equal to the target spacing or gap width $\delta g$ leading to an onset of resonance at a photon energy

$$h\omega < h\omega_r = \frac{E}{1 + \frac{\delta g}{2\gamma\lambda_c}},$$

which for $E \gg h\omega_r$ coincides with the 'resonance condition' in a stratified medium [4, eq. (28.10')]]

In [5], Baier and Katkov treated the radiation emission from a stack of thin foils, including the LPM, polarization effects and emission from the target boundaries (transition radiation). For the general case of $N$ foils, however, they only give an explicit formula for the strong scattering, large spacing case where, in their notation, $b \ll 1$ and $T = (l_1 + l_2)/l_f \gg 1$, $l_1$ being the target segment thickness, $l_2$ the segment spacing (their eq. (2.49)) and $b = \alpha X_0/2\pi l_1$ the scattering variable. However, recently we managed to obtain a calculation for an experimentally favourable setting [6], shown below in figure 2.

From e.g. the LPM suppression it is found that the radiation intensity per unit length for scattering events in close succession is suppressed at low frequencies. Furthermore, the frequency interval which is suppressed, depends on the distance between the scattering centers—the longer this distance, the lower the suppressed frequency. It is therefore to be expected that the removal of possible scattering
centers—as in the alternative view of the structured target—results in an ‘alleviation’ of the suppression. The same picture is applicable when the formation length extends out of the target. In this case the LPM suppression continues down to frequencies corresponding to the formation length and target thickness being equal, from which point the suppression ‘lifts’ and the radiation level becomes a certain fraction of the unsuppressed Bethe-Heitler (BH) intensity. Thus, a comparison of a structured target—with an incomplete suppression—to a homogeneous one of the same thickness where the suppression is complete, will display an enhancement in radiation intensity at frequencies corresponding to the target spacings. However, such an enhancement is in a sense not really an enhancement, but a ‘lifted’ suppression, and the radiation intensity thus never exceeds the unsuppressed BH intensity. The latter observation is in accordance with our calculations based on the Blankenbecler-Drell theory, performed for various energies and target constructions, see e.g. [7]. Finally, in the view just presented, the structured target ‘resonance’ effect can be seen as a suppression-alleviation-suppression effect (where larger distances covered by the particle into the structure converts into lower frequencies).

In any case, the location of the radiation ‘peak’ from a structured target compared to a homogeneous one of the same thickness, combined with a measurement of the sub-target spacing, gives a direct measurement of the formation length for radiation.

In a previous test-run (12 hrs. of beam in spring 2009), a reference target consisting of 10 foils of 10 micron thick Ta, each pair separated by 1 mm to avoid any interference, and a structured target with the same foil thickness, but separations of 88 microns, were prepared. With the latter spacing, resonances between the foils should be possible for $\hbar \omega \lesssim 0.736$ GeV, cf. eq. (3). By measuring the structured target assembly’s full thickness with a micrometer gauge and subtracting the known amount of material, we estimated the actual mean spacing to $\delta g = 91.2 \pm 0.7 \mu m$, not far from the expected 88.1 $\mu m$. However, as shown in figure 1, no effect was found. On the other hand, a clear disadvantage with this kind of assembly is that it is at best difficult (e.g. ultrasonic waves can be imagined) to detect the actual distance between the foils, and to assure that all distances are equal to the desired tolerance.

We now propose to perform a dedicated experiment directed towards the detection of the structured target resonance. In order to avoid the problems mentioned above - and to make both the effect itself stronger and the reliability of the calculations higher - we aim to measure with only two foils, mounted on a precisely controlled translation stage, such that the internal separation between the two foils can be controlled with an accuracy of a few microns. An example of a calculation for two 20 micron thick Ta foils arranged in an experimentally relevant configuration, is shown in figure 2. It is clearly seen that as the separation is increased from 20 to 200 microns, the radiation peak moves towards lower photon frequencies.
energies.

![Graph showing energy loss vs. photon energy for tantalum with different separations.](image)

Figure 2: Calculations by Baier and Katkov [6] of the structured target 'resonance' appearing when 207 GeV electrons radiate upon passing 2 tantalum foils, each of 20 micron thickness, separated by 20, 40, 120 and 200 microns (curves 1, 2, 3 and 4 respectively). The ordinate scale is in units of $2\alpha/\pi$ and the unsuppressed Bethe-Heitler level in these units is 2.8. Similar - but not identical - resonances appear in calculations based on the formalism of Blankenbecler [8].

For this experiment we have designed and built a new target manipulator, as shown in figure 3. It is based on the 'plunger' technique developed for nuclear physics experiments, e.g. to measure lifetimes.

![Diagram of the target manipulator.](image)

Figure 3: A top view, a side view and an angled view of the target manipulator to be used for the structured target measurements. The target holder a is mounted in a damped spring-loaded gyro, such that when the target holder b is pressed against it, the foils on the holders become parallel upon contact (Contact Plane). The distance between the foils can be measured with 3 independent methods: The read-back of the translation table position, a read-out of the micrometer gauge, and a measurement of the capacitance of the two circular foils (which are electrically isolated from each other). The measurement accuracy of the foil separation is a few microns. The beam passes the Ø 15 mm holes in the holders.

Furthermore, 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 is supposed to pass is only a few microns. 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 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 [8].

1.1 Requested beam time

Since the measurement is based on the signal from a target of only 1% of a radiation length, the purity of the beam and the reduction of backgrounds are essential ingredients. Therefore, even though sufficient statistics for one beam energy under optimum conditions can be achieved within 48 hours of beam time, we request a total of 2 weeks, out of which 4 days are for setting up and calibrating the detectors, 3 days for an optimization of the beam and 7 days for the actual datataking, performed at 2 energies. Electrons of 210 GeV, gently focused at the target to a spot-size of $\phi \approx 15$ mm, with an intensity of $2 \cdot 10^5$ per burst is requested delivered to H4 in the PPE134 zone, with an MBPL installed right downstream ‘Goliath’.
2 Nuclear-size effects in radiation emission

In the addendum to our proposal [9, 10] we proposed to measure the bremsstrahlung emission from $\gamma = 170 \text{ Pb}^{82+}$ in 2011. For this task, a comparatively simple setup was proposed, and tested during week 47 of 2010. This test was primarily to measure the purity of the extracted lead ion beam, i.e. to what extent it contained fragments. As shown in figure 4 a MUltiple Sampling Ionization Chamber (MUSIC) has sufficient resolution to measure fragments down to at least $Z = 20$.

![Figure 4: A typical charge spectrum observed in the MUSIC for 18 TeV In$^{49+}$ fragmented upon the passage of a Ge target. The different elements can be clearly identified, at least down to $Z_2 = 20$ using the expected $Z^2$ dependence of the signal on charge state with a parabolic fit to the gaussian centroids versus $Z$. An adjacent averaging over 10 channels has been applied to the data points. Adapted from [11].](image)

However, during the test it was quickly realized that the extracted beam suffered seriously from a change in time-structure compared to previous ion-runs. This is due to the SPS now operating as an injector for the LHC, with a bunched beam in the machine, requiring active debunching to achieve the smooth time-structure that was delivered in the past. Such an active debunching could not be set up with few days notice. The new time-structure meant that with high probability more than one ion was extracted within the dead-time of the MUSICs, a few $\mu$s, rendering the MUSIC signals useless due to saturation.

On the positive side, the full setup was mechanically and electronically tested and proved to be well-functioning, and a more elaborate setup is therefore planned for 2011. An overview of the new proposed setup is shown in figure 5.

The enhanced setup offers several new possibilities:

- **Bremsstrahlung, $Z = 82$:** The detection of radiation emitted by Pb$^{82+}$ in the chosen radiation target (several targets mounted on a remote-controlled target wheel), where MUSIC1 measures the charge state of the incident ion and MUSIC2 verifies that the ion is still in the $Z = 82$ charge state after the radiation event.

- **Bremsstrahlung, $Z \neq 82$:** Following fragmentation in the removable fragmentation target, the detection of radiation emitted by e.g. $Z = 69$ in the radiation target becomes possible, where MUSIC1 measures the charge state of the incident ion and MUSIC2 verifies that the ion is still in that charge state after the radiation event.

- **‘Bruchstrahlung’, $Z = 82 \rightarrow Z \neq 82$:** The detection of radiation emitted by Pb$^{82+}$ in the radiation target, where MUSIC1 measures the charge state of the incident ion and MUSIC2 determines the charge state $Z \neq 82$ after the radiation event, i.e. the projectile has suffered a close collision in the radiation target leading to proton-loss while radiating.

- **Delta-electrons:** Most of these have signatures related to the finite size of the Pb$^{82+}$ projectile.
  A measurement of the intensity of delta-electrons emitted by Pb$^{82+}$ in the radiation target.

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

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
Figure 5: A figure showing the new proposed setup. The $^{82+}$ ions are incident from the left, through three scintillators - two counters $S1$ and $S2$ and one veto with a hole $S3$ - to the removable fragmentation target. The fragmentation target enables investigations of radiation emission from fragments, the charge state of which are found by MUSIC1. The ions then impinge on the radiation target. After this target, the ions are deflected using a 4 Tm magnetic dipole field (B16, MBPL installed in H4) into MUSIC2 where the charge state of the spent ion can be detected. Produced $\delta$–electrons are deviated into scintillator $S4$. Finally, the emitted photon is intercepted by a BGO (for energies 0.1-2 GeV) or lead glass (for energies 2-200 GeV) calorimeter, where $S5$ is a veto for events where the photon has converted. The deviated ions are counted in $S6$, and $S7$ is installed to avoid events with backsplash from the ions into the calorimeter.

and simply replace the electron mass by that of the ion, and likewise for the charge. This leads directly to a $Z^4 \gamma$ dependence of the energy loss per unit path-length, as e.g. shown in [12]. 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 literature [12, 13].

In figure 6, we show the significant difference expected, compared to the 'traditional' expectation [12, 13, 14]. 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 [15, 16]. 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 already at 20 GeV emission from the 33 TeV ion, the difference between the 'traditional' and the new treatment amounts to about an order of magnitude.

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. As discussed below, we aim to measure the spectrum of delta-electrons as well.

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.

2.2 Emission of delta-electrons

Generally, the energy of delta-electrons is limited by $T_{\text{max}}$ given by

$$T_{\text{max}} = \frac{2\gamma^2 \beta^2 m_e c^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \simeq 2\gamma^2 \beta^2 m_e c^2$$

(4)

where the last approximation - although typically described as the 'low-energy' approximation - in the present connection is sufficient for all practical purposes. However, the result eq. (4) is derived for a
Figure 6: The power-spectrum $\hbar \omega d\sigma/d\omega$ 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 [13, 12], and including screening with dash-dot-dot [14], 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) [16].

Upon a change to the rest frame of the ion (practically the same as the center-of-mass frame) in which the electron is incident on the ion the de Broglie wavelength $\lambda = \hbar/p$ of the incident electron becomes comparable to the radius of the nucleus $R$, i.e. $\chi \equiv R/\lambda$ becomes larger than 1 [17]. Thus, the electron will 'feel' the constituents of the ion and therefore not register it as a point-like object of charge $Ze$ (in a sense similar to the virtual photons in the emission of bremsstrahlung).

With the variable $\omega = T/mc^2$ the Rutherford cross section, governing the essentially binary collisions leading to delta-electron emission, can be written as

$$\omega^2 \frac{d\sigma_R}{d\omega} = 2\pi r_e^2 Z^2 \beta^2$$

which is a constant ($2\pi r_e^2 \approx 0.5$ barn). The perturbation result for spin-half electrons scattering in a pure Coulomb potential includes an additional factor

$$\omega^2 \frac{d\sigma_R}{d\omega} = 2\pi r_e^2 Z^2 \beta^2 (1 - \frac{\omega}{2\gamma^2})$$

in the following denoted as the approximation of a pointlike nucleus.

The cross section for a finite-size nucleus with the charge distribution assumed homogeneous within its radius is [17]

$$\omega^2 \frac{d\sigma}{d\omega} = 2\pi r_e^2 Z^2 \beta^2 \times (1 - \frac{\omega}{2\gamma^2}) \times \frac{9}{2} \left(\frac{\lambda_e}{R}\right)^2 j_1^2(R\sqrt{2\omega}/\lambda_e) \frac{\omega}{\omega}$$

where $j_1$ is a spherical Bessel function of order one, and the first two factors according to the above pertain to a point-like nucleus.

In figure 7 is shown calculations based on [17] for the generation of delta-electrons as a function of their energy in GeV, using Pb$^{82+}$ projectiles. With thick lines is shown the normalized cross sections
λ \cdot dσ/dω \text{ for } \gamma = 170 \text{ based on the finite nuclear size, homogeneously charged sphere, eq. (7), the point-like approximation eq. (6) and the Rutherford cross section, eq. (5). The additional thick line is the suppression factor, i.e. the ratio between the finite nuclear size and the point-like approximation. The suppression factor only depends on the energy of the Pb^{82+} projectile through its corresponding maximum energy transfer to the delta-electrons (purple, dash-dotted). The thin lines show the required momentum per charge in TeV/c of the Pb^{82+} projectile, to generate delta-electrons with the corresponding maximum energy (green, dash-dot-dotted) and the maximum momentum per charge in TeV/c of the Pb^{82+} presently available at the CERN SPS.

Figure 7: Calculations for the generation of delta-electrons as a function of their energy in GeV, using Pb^{82+}. The thick lines show calculations of the normalized cross sections \( \lambda \cdot dσ/dω \) for \( \gamma = 170 \) based on the finite nuclear size, homogeneously charged sphere (black, full), the point-like approximation (red, dashed) and the Rutherford cross section, \( 2πZ^2 \mathcal{r}_c^2 / \beta^2 \approx Z^2 \cdot 0.5 \text{ barn (blue, dotted)} \) [17]. The additional thick line is the suppression factor, i.e. the ratio between the finite nuclear size and the point-like approximation, which only depends on the energy of the Pb^{82+} projectile through its corresponding maximum energy transfer to the delta-electrons (purple, dash-dotted). The thin lines show the required momentum per charge in TeV/c of the Pb^{82+} projectile, to generate delta-electrons with the corresponding maximum energy (green, dash-dot-dotted) and the maximum momentum per charge in TeV/c of the Pb^{82+} presently available at the CERN SPS.

2.3 Requested beam and beam time

Due to the presence of the MUSIC detectors, which operate with a time-scale of a few microseconds, the proposed setup cannot accommodate more than about 10^5 particles per burst. Moreover, the beam has to be actively debunched before extraction from the SPS (as it was done in previous runs before 2010), since projectiles arriving at the detectors with a separation time shorter than a few microseconds, means that the event has to be discarded.
The need for a long lever arm to efficiently separate the lead ion from the radiation it has emitted, given a maximum bending power of the MBPL magnets of about 4 Tm, means that the experiments can only be performed in SPS H4. In H8, for example, there are no available zones where an MBPL can be installed with 20 metres of free space downstream.

We request 2 weeks of beam time with Pb$^{82+}$ with 3-4 momenta per charge in the range from $p/Z = 30$ GeV/c to as high as safety issues allow it, but at least to $p/Z = 200$ GeV/c.
3 Status of publications
Publications in connection with the activities of NA63:


References

[10] K.K. Andersen et al. (CERN NA63), CERN-SPSC-2009-038; SPSC-P-327-ADD-1, Addendum to Proposal