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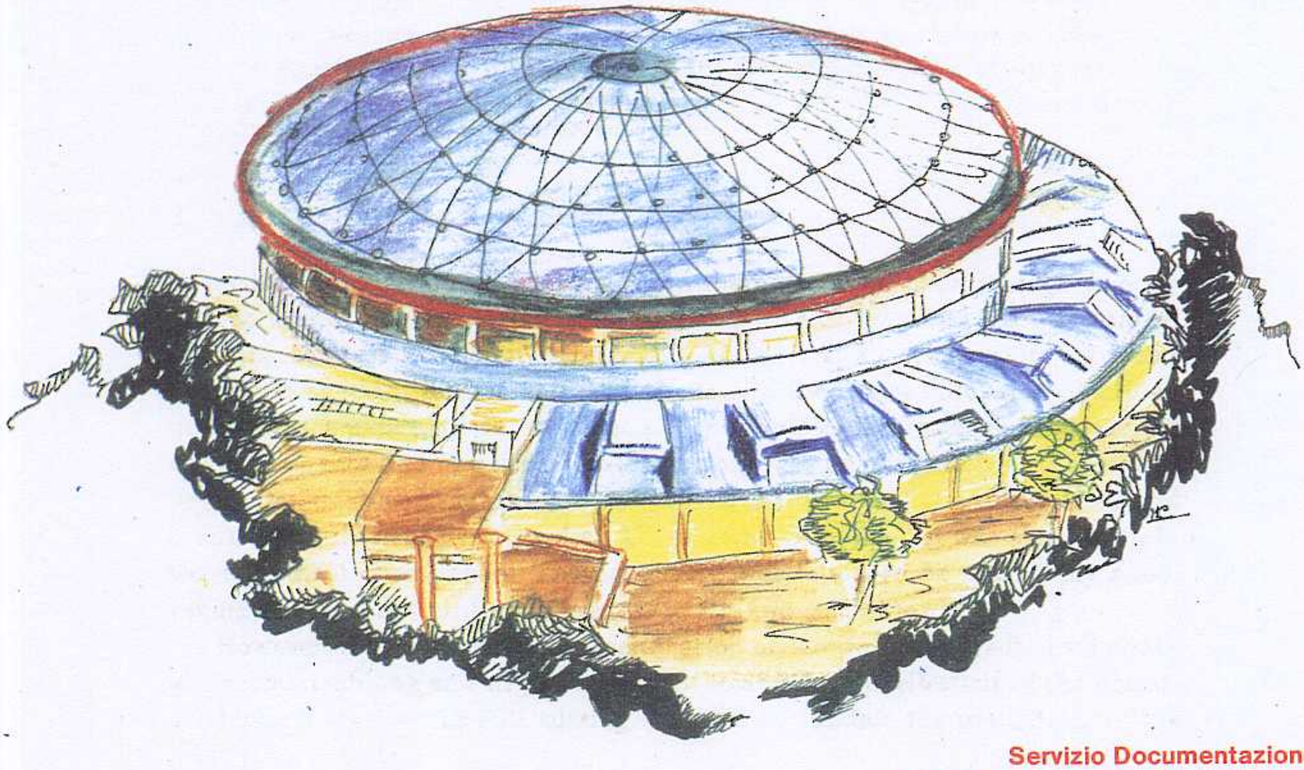

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Gas Bremsstrahlung: a Comparison of Measurements and Simulations

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Abstract

The absolute bremsstrahlung intensity generated by the interaction of the electron beam of the Adone storage ring of LNF has been measured as a function of angle and distance from the emitting straight section. Absorbed doses have been measured at various distances from the straight section by means of thermoluminescent dosimeters for a 1.5 GeV electron beam. The experiment has been simulated using the most recent version of the FLUKA code which includes a very accurate treatment of bremsstrahlung. In spite of the considerable uncertainties on the experimental value of the pressure, it has been found that the computed results are in satisfactory agreement with the results of the measurements. The experiment provided also evidence for the angular distribution of the bremsstrahlung intensity at energies in excess of 1 GeV.

1 Introduction

Bremsstrahlung produced in the vacuum chambers of electron storage rings by interactions of the circulating beam particles with the residual gas was studied by using the last version of the FLUKA code [1, 2, 3]. The results, in terms of photon spectra, fluence rate and tissue absorbed dose rate were described in a previous paper [4]. In the same paper simple equations were proposed for the fluence rate and the tissue absorbed dose rate as a function of the various parameters involved. A comparison between the results of the calculations and a dose measurement performed at Adone some years ago [5] was also shown in the aforementioned paper. The agreement was found to be reasonably good, taking into account all the differences in the two situations.

However, a firm experimental verification of Monte Carlo predictions about gas bremsstrahlung and in particular of the angular distribution of the bremsstrahlung intensity was still missing. In order to validate the predictions of the

FLUKA code and at the same time to measure directly the angular distribution of the bremsstrahlung intensity in the GeV region, an experiment has been performed at the Adone storage ring, just before the decommissioning of this machine. Matrices of thermoluminescent LiF dosimeters have been exposed at various distances downstream of a straight section. Unfortunately the only possibility of making this kind of measurements at Adone at that time has been behind a stainless steel flange about 2 cm thick.

The formulae proposed in ref. [4] were obtained in fairly ideal conditions (i.e. absence of any absorber, point-like beam, etc.) and implicitly supposing the full development of EM cascade through the use of fluence-to-maximum dose equivalent conversion coefficients, which is not at all the case for thin detectors like the LiF dosimeters. As a consequence the presented comparison has been carried out through direct simulations of the actual experimental set-up, explicitly comparing the energy deposited in the simulated dosimeters with the experimental results.

2 Experimental arrangement

The experiment has been performed in line with the straight section number 11, 613.5 cm long, of the Adone e^+ e^- storage ring. This straight section ended in a vacuum guide 190.7 cm long closed by a 1.87 cm thick stainless steel flange.

The absorbed doses have been measured by 9-by-9 matrices of thermoluminescent dosimeters placed at various distances from the end of the straight section. The range of distances covered was from 211.7 cm to 941.7 cm. The used thermoluminescent dosimeters were Harshaw Chemical Co. type TLD-700, which consists of ^{7}LiF. Their dimensions were 3.175x3.175x0.889 mm^3: the area covered by the TLD matrix was therefore 28.57x28.57 mm^2 with enough granularity to reveal the expected narrow angular distribution of the bremsstrahlung intensity at the distances where measurements have been performed. Doses have been read–out on a commercial automatic thermoluminescent dosimeter readout.

Each matrix has been constructed by drilling the housing for the dosimeters in a PVC block. The PVC sheets in front and behind the TLD were 1 mm thick. The blocks have been carefully machined in such a way that the edges could be accurately positioned along a graduated guide aligned to the straight section. The axis of the graduated guide has been aligned by means of a theodolite to the geometric axis of the straight section.

The dosimeters have been calibrated using a ^{60}Co source. The doses have been expressed in Gy in LiF, taking into account the energy absorption coefficients for air and LiF [6].

The beam energy was 1500 MeV. Its intensity has been monitored by a D.C. current transformer.

The beam position has been checked by the detection system of the Adone storage ring consisting of 21 electrostatic pick-up monitors [7]. The absolute accuracy of this system is $\leq$ 0.2 mm with respect to the center of the nearby quadrupoles, reproducibility is within 0.025 mm. The beam position measurements have been used to correct the closed orbit distortion by a least squares minimization. It must be pointed out that the beam position control system has been an essential tool for these measurements because the beam movement must be much smaller than the transverse dimension of the radiation cone.

The pressure in the vacuum chamber has been monitored using ordinary vacuum gauges (Bayard Alpert ion gauges) installed on the machine. The uncertainties on the actual value of the pressure represent the largest source of error when making an absolute comparison with the computed results.

In fact the intrinsic accuracy of the pressure readings of the Bayard Alpert ion gauges and their control units is of the order of 30%. A correction factor ranging from 1.5 to 2 must be applied to the nominal pressure reading, according to the residual gas composition. Taking into account the composition of residual gas during these measurements, this correction factor has been assumed equal to 1.7.

Furthermore the pressure readings was different in the various locations of the machine and could change during the run: difference up to a factor 1.5 between the pressure measured close to an ion pump and the one measured in the following nearest straight section has been recorded.

Other effects, the most important of which should be the ion trapping [8, 9, 10], could make the effective pressure on the path of the electrons different from the ion gauges readings.

For the purposes of the presented measurements, the reading of the ion gauge nearest to the straight section of interest, multiplied by 1.7, has been assumed as vacuum pressure in the straight section itself. We monitored that the reading was reasonably constant during the exposure of the dosimeters.

3 Monte Carlo simulation

In the simulation of the experiment we have used the FLUKA code in its most recent version [1, 2], which includes major modification to the original one [3, 11, 12], particularly in the treatment of bremsstrahlung emission, as already explained in a previous paper [4].

The straight section of Adone has been represented by an air target hit by an electron beam, with a rectangular spot 0.4×0.02 cm^2 wide.

The geometry of the experiment has been accurately reproduced, including all the thicknesses interposed between the straight section and the dosimeters (stainless steel, PVC, air).

In order to overcome the difficulties due to the low interaction probability at the operating pressure of Adone (10^{-9}-10^{-10} torr), calculations have been performed with gas density corresponding to the atmospheric pressure. The obtained results have been linearly scaled to the operating pressure.

This procedure takes properly into account the dependence of the photon yield on the residual gas pressure, but not the difference in the angular distribution due to electron scattering effects like, for instance, the multiple Coulomb scattering and the Möller scattering. The former broadens the angular distribution of the emitted photons but does not affect their number. Since the multiple scattering is practically negligible in the vacuum chamber of a storage ring, while it is responsible of large broadening of the beam at atmospheric pressure, it has been suppressed in our simulation by FLUKA. Moreover, the threshold for the Möller scattering of the electrons has been set at 10 MeV to minimize any angular deflection due to the production of δ rays (for further details about the correct procedures for scaling see ref[4]).

The code energy cuts have been set at 50 keV for charged particles and 1 keV for photons.

The absorbed doses in the TLD dosimeters have been estimated scoring the energy deposited in cartesian grids. The position of these grids as well as the dimensions of the elementary cells have been chosen in such a way to reproduce faithfully the TLD matrices used in the experiment.

In order to determine the statistical errors of the estimated values of the doses, several runs have been performed for a total number of $3{\cdot}10^6$ histories.

4 Comparison between the results of measurements and simulation

A comparison between the doses calculated in the FLUKA Monte Carlo simulations and the measured ones is given as an example in fig. 1 and fig. 2. These figures show the radial distribution of the absorbed doses for various vertical position of the TLDs, in the case of the matrices exposed respectively at 211.7 cm and 541.7 cm from the end of the straight section. Numbers have been used to denote the horizontal positions of the TLDs. All the results are normalized to one mA of current lost. For an initial beam current of 44.2 mA in the machine and a beam life of 7.39 h, such a unit corresponds to about $1.66{\cdot}10^{20}$ electrons crossing the straight section.

The reading of the nearest vacuum gauge ($8.7{\cdot}10^{-10}$ torr), multiplied by 1.7, has been assumed as the pressure to which the results of the simulation have to be scaled. However it should be noted that the readings of the other gauges of the machine during the run were in the range $6.1{\cdot}10^{-10}$ to $3{\cdot}10^{-9}$ torr. It should be stressed that, not only the absolute value of the pressure is of concern for the presented comparisons, but also a possible gradient can change the absorbed dose dependence on the distance from the straight section end.

The satisfactory agreement between the simulation and the measured results is apparent from fig. 1 and 2. It is worthwhile to point out how the narrow radiation cone predicted by the Monte Carlo has been effectively measured by the TLD matrices. To this aim, the TLDs placed in the middle of the matrix as well as the computed data for the same distances of fig. 1 and 2 are also reported in tab. 1 and tab. 2 respectively. The experimental uncertainty caused by all sources but the pressure reading has been estimated to be less than 10% for the central TLDs. Larger errors arising from the background subtraction affect the absorbed doses of the TLDs placed in the most external position in the matrices, not shown in tab. 1 and 2. The systematic error due to the pressure uncertainty discussed in a previous paragraph must be taken into account. Typical standards errors on the simulated data are of order of few % in correspondence of the maximum dose of each matrix. They range from 1.6% at the shortest distance to 6.5% for the largest one. An indication of both Monte–Carlo and experimental errors can be obtained comparing symmetrical positions in the horizontal or vertical plane in tables 1 and 2.

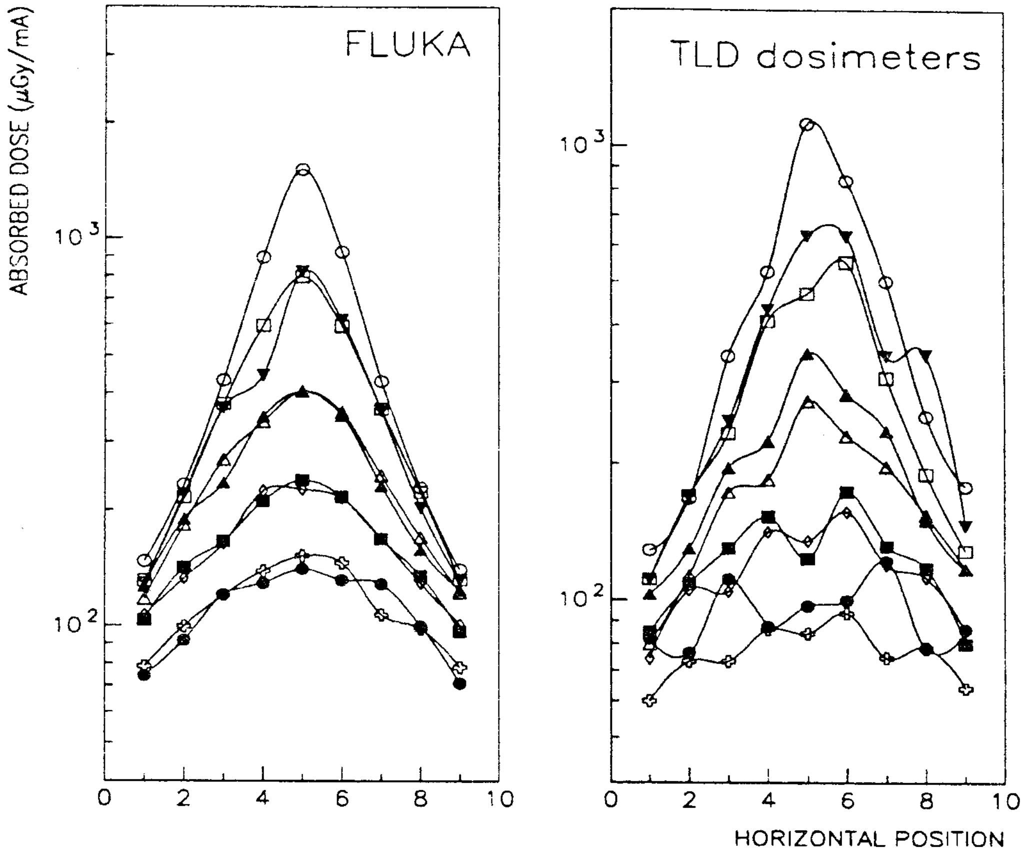

Figure 1: Horizontal intensity distribution (in terms of absorbed dose), at 211.7 cm from the end of the straight section, as a function of horizontal position for various vertical positions of the TLDs, and comparison with the results of the simulation.

Tab. 1 Experimental and computed (in brackets) absorbed doses in the TLDs placed in the middle of the matrix exposed at 211.7 cm from the straight section (μGy/mA).

195 (235)	225 (350)	250 (400)	285 (350)	235 (230)
250 (370)	435 (615)	630 (820)	630 (620)	345 (360)
345 (430)	525 (890)	1120 (1510)	840 (920)	500 (430)
230 (375)	410 (600)	470 (800)	550 (600)	310 (365)
170 (270)	185 (340)	275 (405)	230 (360)	195 (245)

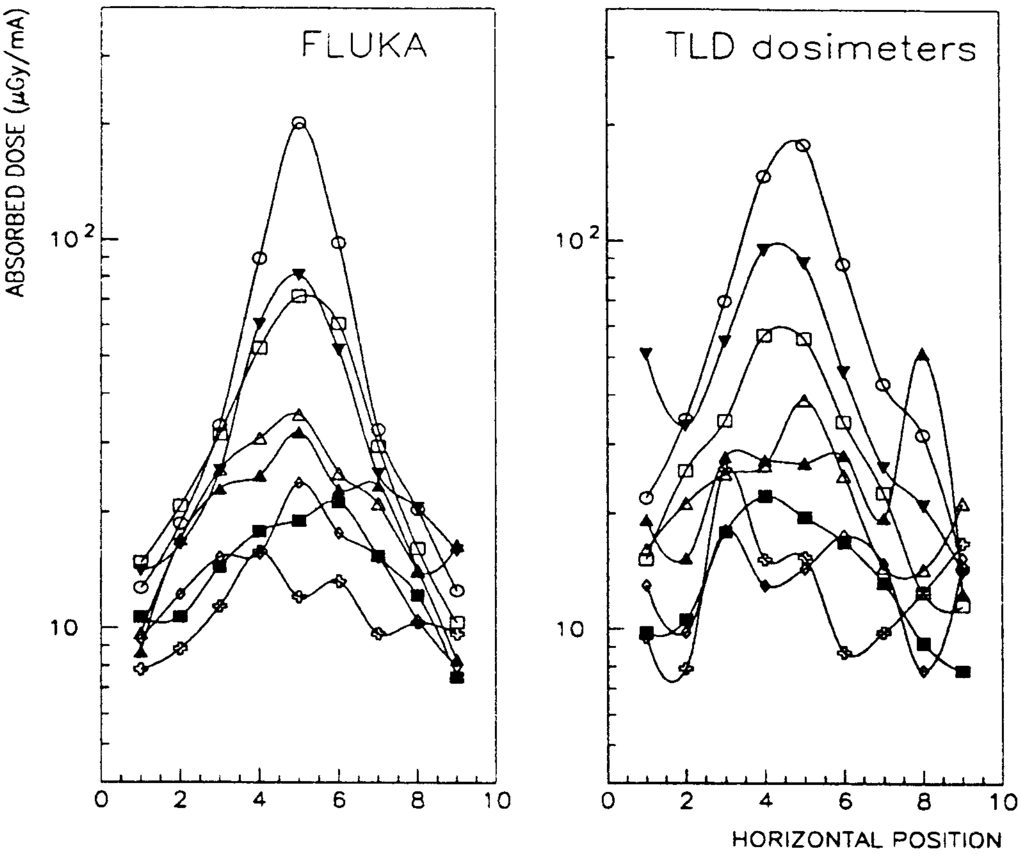

Figure 2: Horizontal intensity distribution (in terms of absorbed dose), at 541.7 cm from the end of the straight section, as a function of horizontal position for various vertical positions of the TLDs, and comparison with the results of the simulation.

Tab. 2 Experimental and computed (in brackets) absorbed doses in the TLDs placed in the middle of the matrix exposed at 541.7 cm from the straight section (μGy/mA).

28 (23)	27 (25)	27 (32)	28 (23)	20 (23)
55 (25)	95 (61)	88 (81)	46 (52)	26 (25)
70 (33)	150 (90)	180 (200)	87 (100)	43 (33)
34 (32)	57 (53)	56 (71)	34 (61)	22 (30)
25 (26)	26 (31)	39 (35)	25 (25)	14 (21)

A further comparison between Monte Carlo simulation and measured results is shown in tab. 3, and in fig. 3, where the maximum absorbed dose in each TLD matrix per mA of beam lost is shown as a function of the distance from the end of the straight section. Actually this quantity is the one needed for radiation protection purposes when assessing the shielding thicknesses required to appropriately reduce the doses due to the gas bremsstrahlung emission. However the data presented here are not completely conservative because of the incomplete development of the cascade.

Tab. 3 Maximum absorbed dose in each TLD matrix per mA of beam lost as a function of the distance from the end of the straight section.

Distance (cm)	Experimental (μGy/mA)	FLUKA (μGy/mA)
211.7	1120	1510
241.7	620	680
301.7	270	390
381.7	250	280
541.7	180	200
741.7	135	150
941.7	95	105

The general trend of the data presented in tab. 3 and in fig. 3 shows an average overestimation of about 10% of the all experimental values but two distances where the difference is larger. These differences are really within the expected experimental errors especially taking into account the systematic uncertainty on the gas pressure.

The dependence of the maximum dose rate with the distance is well reproduced by the simulation. However the expected behaviour [4], $D \propto L/d(L+d)$, where L is the straight section length and d the distance from its end, is spoiled by the presence of the stainless steel flange. In order to take into account the presence of the flange, the data have been fitted with a functional form:

$$D(d) = \frac{a}{d(L+d)} + \frac{b}{(d-l)^2} \tag{1}$$

where l is the length of the vacuum guide and the flange at the end of the straight section, and a and b the source terms for the uncollided beam and the scattered beam respectively. The fitted values from the experimental data for a and b are: a=9.6·10^{-3} Gy m^2 mA^{-1}; b=2.1·10^{-5} Gy m^2 mA^{-1}.

5 Conclusions

The absolute intensity of the gas bremsstrahlung radiation generated by a 1.5 GeV electron beam has been measured in terms of absorbed dose as a function both of the angle and of the distance from the target "vacuum" pipe.

The measured data are in substantial agreement with state-of-the-art bremsstrahlung calculations as implemented in the FLUKA Monte Carlo code. In

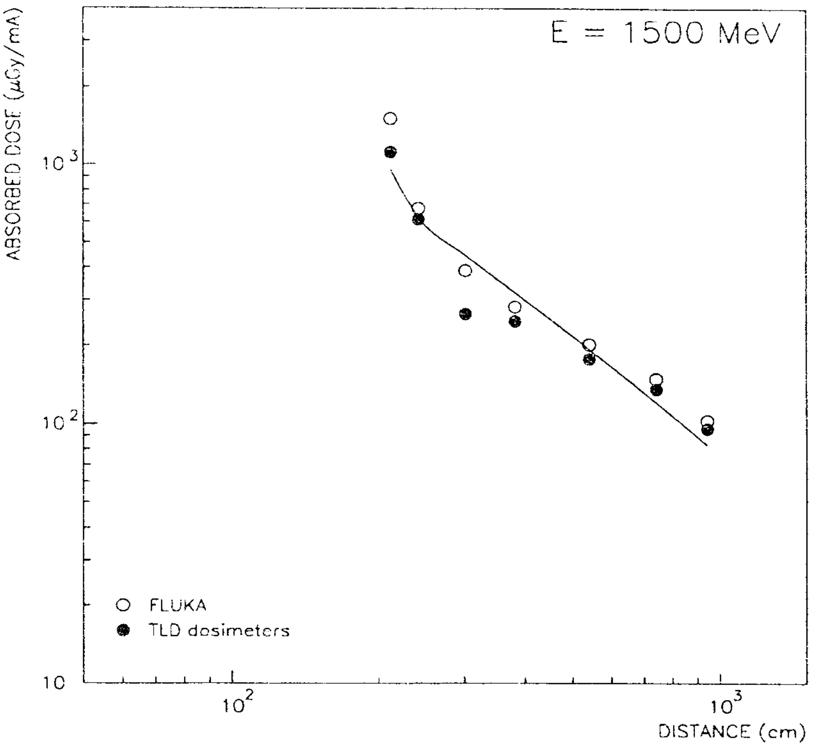

Figure 3: Maximum absorbed dose per mA of beam lost as a function of the distance from the end of the straight section. The solid line gives the best fit of the experimental data according to eq. (1).

particular the angular distribution of the bremsstrahlung intensity has been found consistent with the narrow peak predicted by theoretical expressions. Absolute comparisons are somewhat limited by the uncertainty on the effective gas pressure in the electron beam path during the measurements. However it can be concluded that the level of accuracy of FLUKA concerning the prediction of doses from gas bremsstrahlung in a storage ring is close to the best level that can be tested by this kind of experiments.

The agreement between the FLUKA predictions and the measurements provides an indirect confirmation of the validity of the formulae suggested in a previous paper [4]. However a significant difference is expected whenever experimental data obtained with thin detectors (like TLDs) are compared with the predictions of these formulae, based on standard broad beam fluence-to-maximum dose equivalent conversion coefficients, because of the incomplete development of the high energy photon cascade. Possibly a residual overestimation, even for fully developed cascades, could be there because the conversion coefficients are for a broad parallel beam, whereas the gas bremsstrahlung beam is confined to a very narrow cone. This overestimation could counterbalance possible errors due to the uncertainties on the effective value of the pressure along the path of the electrons.

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