Radio-detection of ultra-high energy cosmic rays in GHz frequencies

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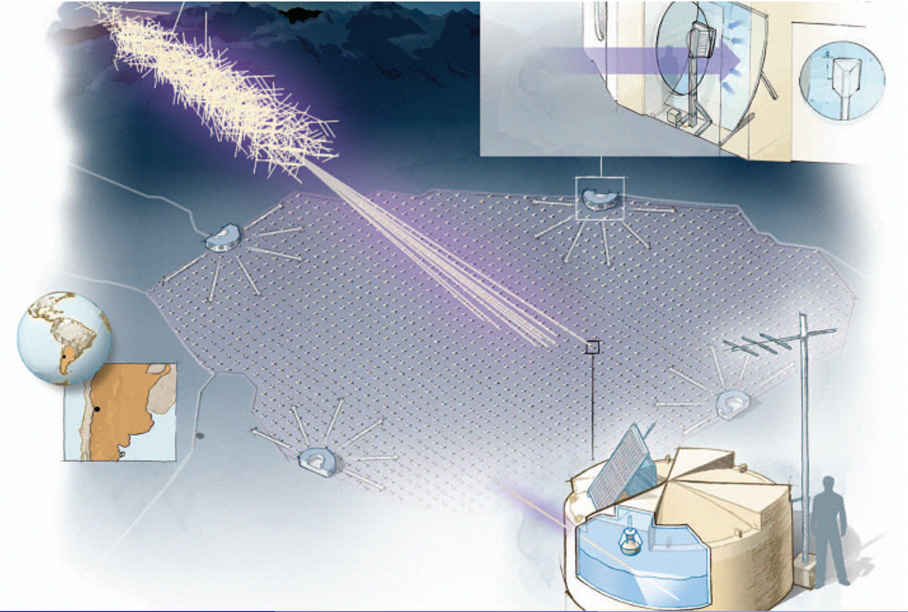
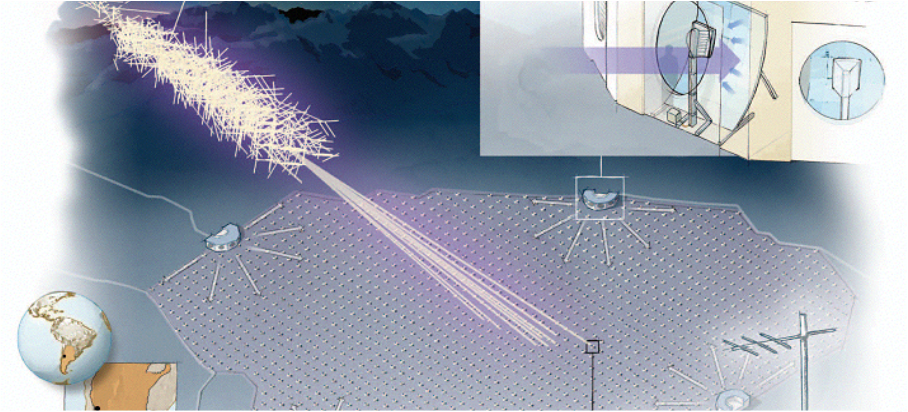
Journées scientifiques de l'Université de Nantes

Radiations induced by extensive air showers



Radiations induced by extensive air showers



- fluorescence radiation in UV and IR ranges: excited nitrogen molecules,
- geo-synchrotron and charge excess radiations in MHz range: $E > 80$ MeV,
- molecular bremsstrahlung in GHz range: low energy electrons ($E \sim 10$ eV).

$\rightarrow$ pure electromagnetic component of the extensive air shower probed for all of them

Motivation

PHYSICAL REVIEW D **78,** 032007 (2008)

Observations of microwave continuum emission from air shower plasmas

P. W. Gorham,[1] N. G. Lehtinen,[1,*] G. S. Varner,[1] J. J. Beatty,[2] A. Connolly,[3] P. Chen,[4] M. E. Conde,[5] W. Gai,[5] C. Hast,[4] C. L. Hebert,[1,+] C. Miki,[1] R. Konecny,[5] J. Kowalski,[1] J. Ng,[4] J. G. Power,[5] K. Reil,[4] L. Ruckman,[1] D. Saltzberg,[3] B. T. Stokes,[1,‡] and D. Walz[4]

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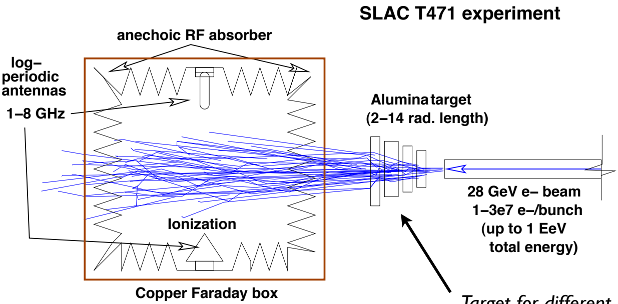
We investigate a possible new technique for microwave detection of cosmic-ray extensive air showers which relies on detection of expected continuum radiation in the microwave range, caused by free-electron collisions with neutrals in the tenuous plasma left after the passage of the shower. We performed an initial experiment at the Argonne Wakefield Accelerator laboratory in 2003 and measured broadband microwave emission from air ionized via high-energy electrons and photons. A follow-up experiment at the Stanford Linear Accelerator Center in the summer of 2004 confirmed the major features of the previous Argonne Wakefield Accelerator observations with better precision. Prompted by these results we built a prototype detector using satellite television technology and have made measurements suggestive of the detection of cosmic-ray extensive air showers. The method, if confirmed by experiments now in progress, could provide a high-duty cycle complement to current nitrogen fluorescence observations.

MBR – Molecular Bremsstrahlung Emission

- it has been observed by Gorham *et al.* using a test beam,
- low-energy electrons scattering into the EM field of neutral molecules,
- emission unpolarised and isotropic,
- GHz frequency range: 100% duty cycle and minimal atmospheric attenuation.

Beam measurements by P.W. Gorham et al. – Experimental setup

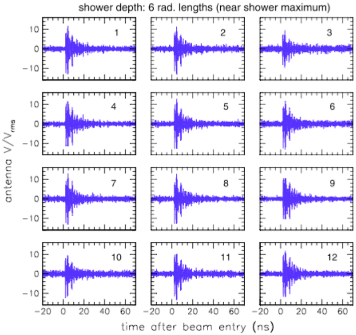


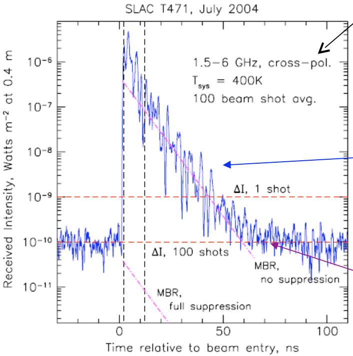
Equivalent shower energy 3.36 10^{17} eV

Target for different shower ages

Measurements at Argonne (12 MeV) and SLAC (28.5 GeV)

Beam measurements by P.W. Gorham et al. – Results (1/2)





Insensitive to radio Cherenkov

Measured signal attributed to molecular bremsstrahlung

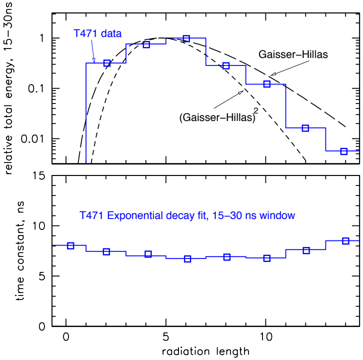
Expectation, emission enhanced by coherence

P.W Gorham *et al.,* "Observations of microwave continuum emission from air shower plasmas" Phys. Rev .D. **78**, 032007 (2008)

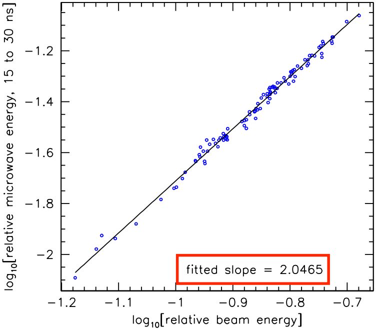
- observation of a clear signal with ~ 10 ns lifetime,
- decay constant compatible with plasma cooling (chamber crossing time ~ 3 ns).

Beam measurements by P.W. Gorham et al. – Results (2/2)

Signal scaling with shower depth



Signal scaling with shower energy



- Gaisser-Hillas function represents the electromagnetic component,
- incoherent emission: $P_{tot} = N_e \times P$ – fully coherent emission: $P_{tot} = (N_e)^2 \times P$,
- from the lab to air showers: signal level and scaling depends on plasma prop.

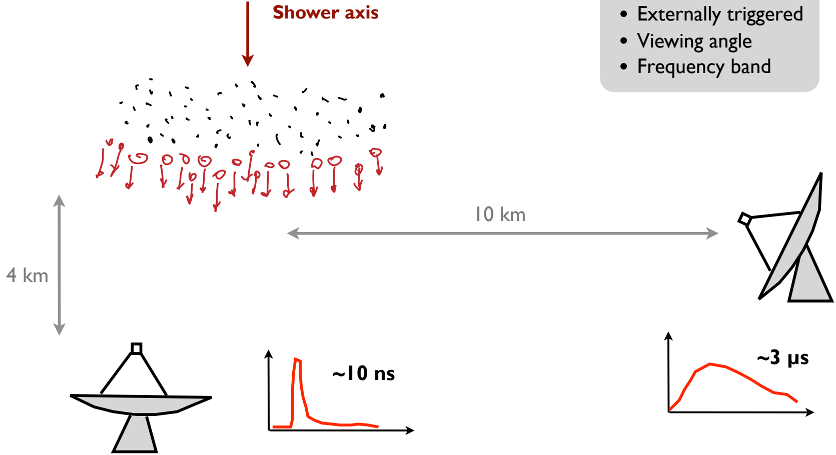
scaling indicates *partial* coherence of GHz radiation

Outline

1. **R&D activities for microwave detection of UHE cosmic rays**
   - Two different experimental approaches
   - R&D activities at the Pierre Auger Observatory
   - The CROME experiment at KASCADE-Grande
2. **Current activities to improve our understanding**
   - Two new test beam experiments
   - Optimisation of the GHz sensors
   - Improve our understanding on physics processes
3. **Conclusion**

Two different experimental approaches...

- Self-triggered
- Externally triggered
- Viewing angle
- Frequency band

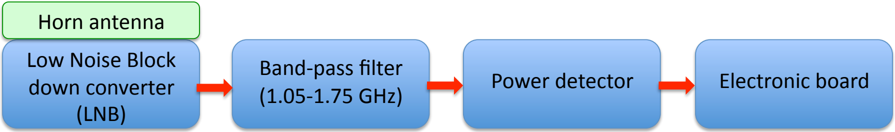


- Signal time-compressed, large peak power
- No change in frequency

- Signal similar to fluorescence pluse
- Shower profile directly measured

Courtesy: Ralph Engel.

... but a similar instrumentation to record GHz signal



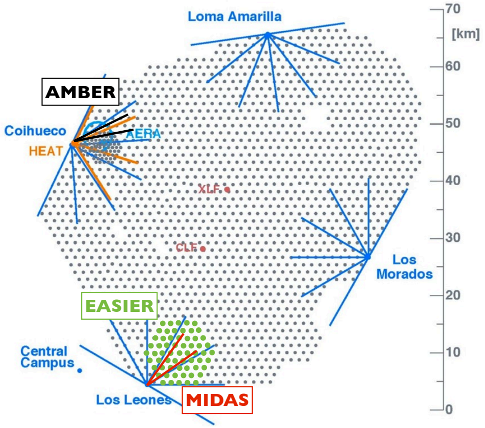
The GHz instrumentation, with two main elements

- **the Low Noise Block (LNB)** as fast receiver
  $\rightarrow$ high gain amplifier and downconverter from 3.4–4.2 GHz to 0.95–1.75 GHz,
  $\rightarrow$ gain of several tenths of dB, noise of several tenths of Kelvin.

- **the power detector** for digitisation of signal envelope
  $\rightarrow$ provides a pulse proportional to the log of the power,
  $\rightarrow$ time response τ of 10–100 ns : $P_{\rm dBm} \rightarrow P_{\rm dBm} * {\rm e}^{-t/\tau}$.

commercially available equipment – potentially low-cost

R&D activities at the Pierre Auger Observatory



Three prototypes installed at the Pierre Auger Observatory to record signals in the C-band (3.4–4.2 GHz) and the Ku-band (10.7–12.7 GHz)

→ AMBER and MIDAS (telescope setups),

→ EASIER (on-tank setup),

AMBER – Air shower Microwave Bremsstrahlung Experimental Radiometer

→ 2.4 m off-axis parabolic dish instrumented with 16 C-band feeds and 4 Ku-band feeds,

→ some feeds instrument both polarisations, 28 channels in total: $14^\circ \times 14^\circ$ at 30° elevation angle,

→ initial measurements at Univ. of Hawaii (self-trigerred),

→ moved to the Pierre Auger Observatory in May 2011 (external trigger provided),

data analysis underway, looking for coincidences with Auger array

MIDAS – Microwave Detection of Air Showers

→ 4.5 m center-focus parabolic dish instrumented with 53 C-band feeds,

→ 53 channels in total: $20^\circ \times 10^\circ$,

→ fully steerable astronomic mount,

→ absolute calibration using the signal from Sun ($T_{\rm sys}$ ∼65 K),

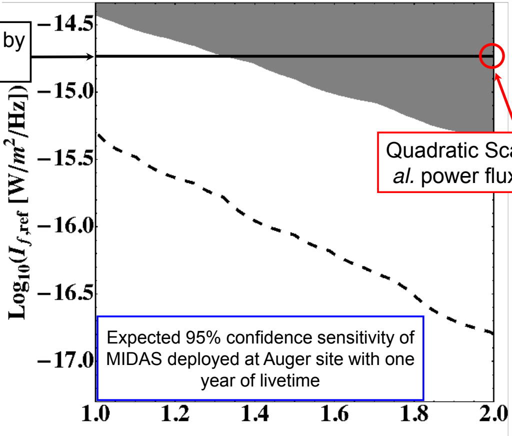
→ initial measurements at Univ. of Chicago (self-trigerred),

→ moved to the Pierre Auger Observatory in September 2012 (external trigger provided),

data analysis underway, looking for coincidences with Auger array

MIDAS – Isotropic microwave emission limits

61 days of data acquisition at University of Chicago



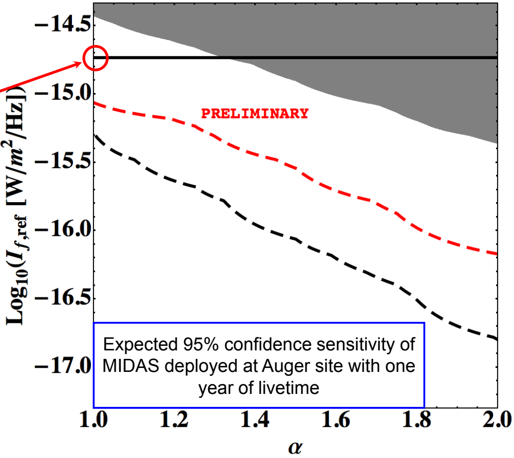
MIDAS results **exclude** a quadratic scaling for the Gorham's MBR yield

MIDAS – Isotropic microwave emission limits

66 days of data acquisition at the Pierre Auger Observatory

- Assume Chicago MIDAS Calibration

Linear Scaling at Gorham *et al.* power flux ruled out by >4σ



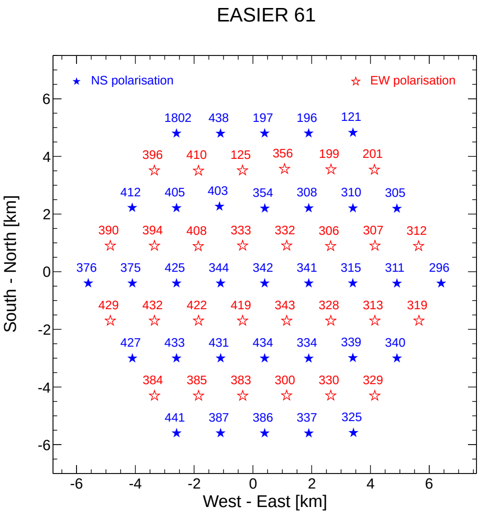
preliminary results at the Pierre Auger Observatory **exclude** the Gorham's MBR yield

Extensive Air Shower Identification with Electron Radiometers

The EASIER concept

- one antenna on a water tank, connected to one of the FADC channels,
- small collection area (0.004 m^2) and wide aperture antenna (60°),
- ... but boost from geometrical time compression,
- trigger comes from the surface detector.

EASIER – An antenna array for ~~MHz~~/GHz radio emission



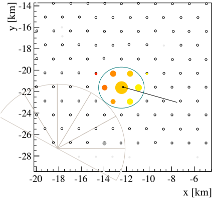
→ array completed in April 2012,

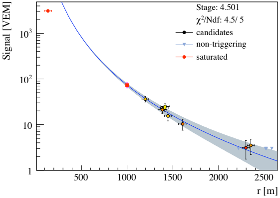
→ C-band: 3.4–4.2 GHz,

→ 2 polarisations: EW and NS,

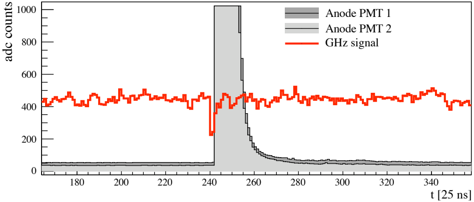
→ temperature around 100 K.

First GHz event candidate ! – $\log_{10}(\mathrm{E/eV}) = 19.12 \;/\; \theta = 29.7°$



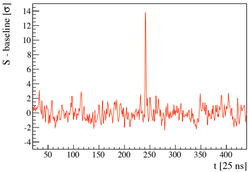


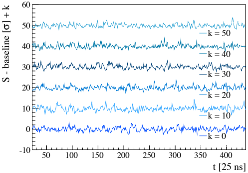
→ shower core very close to the antenna (140 m),



→ PMT saturated in the corresponding tank,

→ no signal detected in the other tanks of the hexagon,





→ first evidence of GHz radiation from an extensive air shower

EASIER – ... up to now, only 3 GHz event candidates

Event ID	E [EeV]	θ [°]	ϕ [°]	d [m]	pol.
12046376	13.2	29.7	344.6	136	E-W
20830870	17.1	55.3	33.8	269	E-W
21050180	2.6	47.4	290	193	E-W

- number of events lower than expected (if the system temperature is correct),
- short pulse lengths ($\leq$ 75 ns) and short distances from shower,
- the three events are recorded in the EW polarisation,

signal compression of an isotropic source ?

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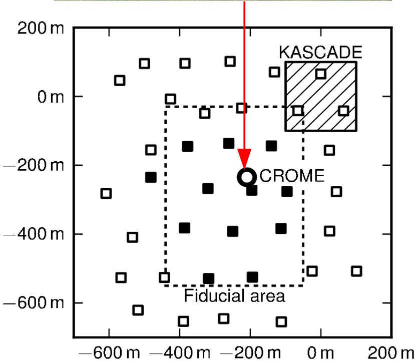
contribution from other mechanisms ?

CROME – Cosmic Ray Observation by Microwave Emission



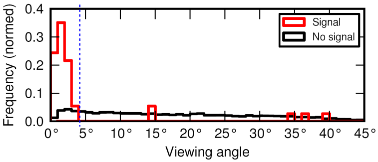
→ array of various antennas (20 kHz – 13 GHz),

→ data acquisition from May 2011 to November 2012,

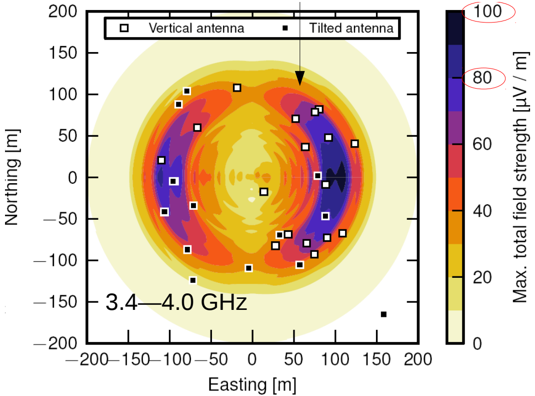
→ about 3 events above 10^{17} eV in the fiducial area per day,

→ absolute calibration by octocopter: (T_{sys} ∼50 K),

→ in a viewing angle of 4°: 32 event candidates for 30 KG showers.



CROME – Event characteristics



- → shower cores form a broken ring on ground,
- → high electric field strength at the Cherenkov ring,
- → east-west asymmetry in the field strength,
- → polarisation pattern similar to the geomagnetic emission,

the microwave emission **is not** polarised (5σ significance)

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the molecular bremsstrahlung **is not** the dominant emission mechanism

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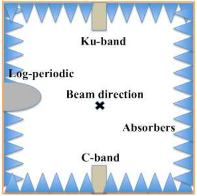
Two new test beam experiments to check previous measurements

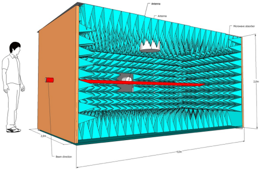
MAYBE – Microwave Air Yield Beam Experiment / Argonne

- electron energy of 3 MeV (below Cherenkov thr.),
- anechoic chamber of P.W. Gorham *et al.*,
- measurements in several frequency bands / full,
- no signal observed: limit on the MBR yield several orders below the Gorham's yield.



AMY – Air Microwave Yield / beam experiment at Frascati

- electron energy of 510 MeV produced by a LINAC,
- different pulse lengths, from 1 to 10 ns,
- several antennas in an anechoic chamber (2 m× 2 m× 4 m),
- signal observed, but could be related to another phenomenon.



towards an understanding of P.W. Gorham *et al.*'s measurements

Optimisation of the GHz sensors

→ reduce the minimum detectable signal

- *move to lower frequencies* → increases the effective area $A_{\rm eff}$
- *lower noise amplifier (LNB)* → current tests in laboratories,
- *improve the antenna design* → non-commercial solutions.

$$\text{Minimum detectable flux density} = \frac{\mathrm{k_B T_{sys}}}{\mathrm{A_{eff}}\sqrt{\tau\,\Delta\nu}}, \quad \text{with } A_{\rm eff} \propto \frac{1}{\nu^2}$$

EASIER

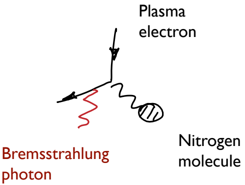
–

tests in lab in progress to choose the best design for GHz sensors

Improve our understanding on physics processes

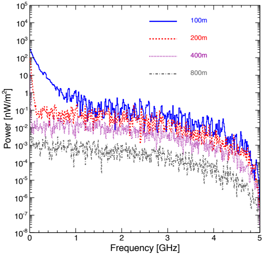
A better understanding of the MBR mechanism

- calculations of non-thermal air shower plasma,
- different estimations of absolute predictions for intensity in GHz range on the market (Karlsruhe, Orsay–Paris, Grenoble),
- preliminary results: calculated signal lower than reference flux estimated by P.W. Gorham *et al.*



An alternative to MBR: the conservative approach

- extend the mechanisms observed at MHz to GHz frequencies,
- add the effect of a realistic refractive index $\rightarrow$ time compression,
- idea explored by Scholten *et al.* (EVA), Huege *et al.* (CoREAS) and Subatech *et al.* (SELFAS).



Outline

Summary and next goals

Summary and conclusion

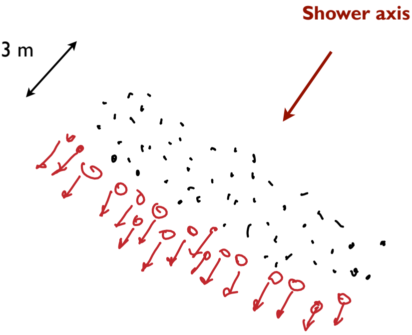
- strong signal and coherence effects found in early beam experiments, interpreted as molecular bremmstrahlung,
- microwave radiation at GHz frequencies: "calorimetric" detection with a 100% duty cycle,
- first evidences of GHz signals related to air showers in EASIER and CROME experiments,
- main physical mechanism related to this GHz radiation is not established yet.

Next goals

- improvement of the sensitivity of the GHz sensors,
- simulation of other physical mechanisms having a GHz contribution,
- better understanding of the bremsstrahlung molecular.

Backup slides
($\rightarrow$

Production of plasma region by shower particles



Plasma:

- Electrons from ionization (E_e ~ 2 - 35 eV)
- Plasma stationary (no bulk motion)
- Velocity distribution almost isotropic
- 30,000 ion pairs per MeV deposited energy

Competing processes:

- Thermalization due mainly to collisions with neutral atoms ~ 10 ns (sea level)
- Attachment of electrons to atoms by three-body processes involving oxygen ions
- Expected lifetime of plasma ~10 ns

Radio – la radio-détection à l'Observatoire Pierre Auger

L'émission bremsstrahlung moléculaire

- signal observé au SLAC sur faisceau d'électrons en 2008 *(Gorham et al.)*,
- émission non-polarisée et isotrope / signal linéaire avec l'énergie des gerbes,
- fréquences au GHz: cycle utile de 100% et faible atténuation atmosphérique.

$\rightarrow$ toujours pas confirmée par les actuelles expériences sur faisceau

EASIER 61 – Extensive Air Shower Identification with Electron Radiometers

- réseau d'antennes utilisant les cuves d'eau comme déclencheur – membre depuis oct. 2011,
- 61 antennes réparties sur 100 km^2, installation terminée en avril 2012,
- enregistre le signal radio émis dans la bande 3.4–4.2 GHz,

$\rightarrow$ premières observations d'une émission au GHz provenant d'une gerbe de particules...
.... mais nombre d'événements plus faible qu'attendu

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