Microwave Sensors and Sensor Systems for Particle Accelerators

F. Caspers (CERN-BE-RF) with many BI related slides from R. Jones

- A few words about CERN
- An overview of classical non-intercepting electromagnetic sensors used for charged particle accelerators
- Examples of Schottky mass spectroscopy of single circulating ions
- Stochastic beam cooling, a feedback process based on Schottky signals in the microwave range
- Synchrotron light in the microwave range
- Examples of magnetic markers (NMR and FMR systems) used in accelerators
- Axion and paraphoton search in the microwave range
- Observations of hyperfine transitions in antiprotonic $^3\text{He}$ at 11GHz
- Microwave signatures from very high energy neutrinos
WHEN ENERGY BECOMES MATTER
CERN

- Founded 1954, today 21 member states
- Up to 10,000 people working at CERN, including about 2250 CERN-personnel
- Annual budget roughly one billion (10^9) SFr (not far from Euro or $ these days)
- The French-Swiss border is crossed several times by most of the CERN accelerators
The LHC at CERN – a huge scientific experiment

LHC is a particle accelerator with some superlatives:

• 26.7 km circumference;
• 4 large and several smaller experiments;
• Proton-proton collisions with an energy of up to 7 TeV per beam permitting a max. luminosity\(^1\) of \(10^{34}\text{cm}^{-2}\text{s}^{-1}\) for protons;
• 1232 supraconducting dipole magnets with 2 beampipes each and up to 8.3 Tesla magnetic field, chilled to 1.8 deg K;
• For this 96,000 kg of helium are required...

\(^1\)Luminosität erfasst die “Anzahl der Kollisionen” und beschreibt die Leistungsfähigkeit eines Colliders.
The Higgs-particle (named after Peter Higgs) is considered responsible for the mass of elementary particles – it is part of the Standard Model in physics.
The CERN accelerator-complex
Measuring Beam Position – The Principle
Wall Current Monitor – The Principle

Ceramic Insert

V
Wall Current Monitor – Beam Response

\[ f_H = \frac{1}{2\pi RC} \]
\[ f_L = \frac{R}{2\pi L} \]

C = gap capacity due to ceramic insert and fringe fields
R = external resistor, L = external inductance
Wall Current Monitor (WCM) principle

- The **BEAM** current is accompanied by its **IMAGE**
- A voltage proportional to the beam current develops on the **RESISTORS** in the beam pipe gap
- The gap must be closed by a box to avoid floating sections of the beam pipe
- The box is filled with the **FERRITE** to force the image current to go over the resistors
- The ferrite works up to a given frequency and lower frequency components flow over the box wall
WCM as a Beam Position Monitor

- For a centered **BEAM** the **IMAGE** current is evenly distributed on the circumference
- The image current distribution on the circumference changes with the beam position
- Intensity signal ($\Sigma$) = resistor voltages summed
- Position dependent signal ($\Delta$) = voltages from opposite resistors subtracted
- The $\Delta$ signal is also proportional to the intensity, so the position is calculated according to $\Delta/\Sigma$
- Low cut-offs depend on the gap resistance and box wall (for $\Sigma$) and the pipe wall (for $\Delta$) inductances

\[
\begin{align*}
  f_{L\Sigma} &= \frac{R}{2\pi L_\Sigma} \\
  f_{L\Delta} &= \frac{R}{2\pi L_\Delta}
\end{align*}
\]
The ceramic tube is coated with low resistance titanium layer, resistance: end-to-end $\approx 10 \, \Omega$, i.e. $\approx 15 \, \Omega/\square$

- Primary circuit has to have small parasitic resistances (Cu pieces, CuBe screws, gold plating)
- Tight design, potential cavities damped with the ferrite
- The transformers are mounted on a PCB and connected by pieces of microstrip lines (minimizing series inductances)
IPU and AHC – Frequency Characteristics

- A wire method with a 50 Ω coaxial setup which the IPU is a part
- Σ signal – flat to 0.5 dB within 5 decades, almost 6 decades of 3 dB bandwidth (no compensation)
- Δ signal – 5 decades (four decades + one with an extra gain for low frequencies)

![Graph showing frequency characteristics](image)

- **Σ signal**
  - BW: 300 Hz – 250 MHz (≈ 6 decades)
- **Δ signal**
  - BW: 1 kHz – 150 MHz (> 5 decades)
Electrostatic Monitor – The Principle
Electrostatic Monitor – Beam Response

\[ f_L = \frac{1}{2 \pi R C} \]
Electrostatic Pick-up – Shoebox

Linear cut through a shoebox

Highly Linear

\[ x = \frac{w}{2} \frac{U_R - U_L}{U_R + U_L} = \frac{w}{2} \frac{\text{Difference}}{\text{Sum}} = \frac{w}{2} \frac{\Delta}{\Sigma} \]

- Measurement:
  - Induced charges carried away by low-impedance circuit or sensed on a high impedance as a voltage
Electrostatic Pick-up – Button

- Variant of electrostatic PU
- Low cost ⇒ most popular
- Non-linear
  - requires correction algorithm when beam is off-centre

Transfer Impedance:
\[ Z_{T\infty} = \frac{A}{(2\pi r) \times c \times C_e} \]

Low frequency cut-off:
\[ f_L = \frac{1}{2\pi R C} \]

\[ C_e = \text{capacity of the pickup electrode to ground} \]
Button Frequency & Time Response

**Frequency domain:**
- Impedance transformers improve the low frequency levels at the expense of the high frequency

**Time domain:**
- Differentiated pulse
- Exponential dependence of amplitude on bunch length
Electromagnetic (Directional) coupler

- A transmission line (stripline) which couples to the transverse electromagnetic (TEM) beam field

\[ Z_{t\infty} = 60 \ln[(r+h)/r] \]
≡ \[ Z_0 \star [a/2\pi (r+h)] \]

- \( Z_0 \) is the characteristic impedance
- \( a, r, h, l \) are the mechanical dimensions
- \( t = l/c \) is the propagation time in the coupler
Relativistic case: Electric & magnetic fields become transverse to the direction of motion (TEM).
Electromagnetic Stripline Coupler - Principle
Improving the Precision for Next Generation Accelerators

- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ tens micron resolution for typical apertures

- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode $TM_{11}$ proportional to position & shifted in frequency with respect to monopole mode

![Frequency Domain Diagram](image)

Courtesy of D. Lipka, DESY, Hamburg
Cavity BPMs

- BPM resolution typically limited by problem of taking a difference between large numbers (2 opposing electrodes)

- Cavity BPMs have different frequency response for fundamental and difference mode
  - Aids in fundamental rejection
  - Can give sub-micron resolution.

BUT:
- Damping time quite high due to intrinsic high Q $\gg 1000$
- Poor time resolution (~100ns)
Today’s State of the Art BPMs

- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode

Prototype BPM for ILC Final Focus
- Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
- Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)
Schottky Measurements

4.8 GHz Slotted Waveguide Structure
60 x 60 mm aperture x 1.5 meters long
Gated, triple down-mixing scheme to baseband
Successive filtering from bandwidth of 100MHz to 11kHz
Capable of Bunch by Bunch Measurement

Forward coupler!
in a certain frequency band
the phase velocity of the slotted waveguides match
the velocity of the beam which is very close to c
Comparison of Ions and Protons Bunch to Bunch Spectra

Single Bunch Spectrum B1 H and B1V: **Protons vs Ions**

Single Bunch Spectrum B2 H and V: **Protons vs Ions**

Revolution frequency in LHC

Schottky bands
What type of beam structure do we have?

- **Un-bunched structure**
- **All rf buckets filled**
- **Few rf buckets filling**
- **Single bucket filling (Pilot)**
- **Special and variable pattern filling**
All RF Buckets Filled (200MHz)

- **Time domain:**
  - 200 MHz LP filter: $[V_{lp}/V_{coup}] = -0.5$ dB
  - 200 MHz / BW=12MHz BP filter: $[V_{bp}/V_{coup}] = -3.1$ dB

- **Frequency domain:**
  - almost monochromatic spectral contents ($f_0 = 200MHz$)
  - Maximal output signal: $-18.6$ dBV
 Few RF Buckets Filled (40MHz)

- **Time domain:**
  - 200 MHz LP filter: \[ \frac{V_{lp}}{V_{coup}} = -0.35 \text{ dB} \]
  - 200MHz / 12MHz BP filter: \[ \frac{V_{lp}}{V_{coup}} = -18.0 \text{ dB} \]

- **Frequency domain:**
  - Spectral contents shows all harmonics of the 40 MHz (1/25 ns)
  - BP filter selects only the 200 MHz line
Single Bunch Response

- **Time domain:**
  - LP filter
    - Bunch length = 4.8 ns \([V_{lp}/V_{coup}] = -0.0\) dB
    - Bunch length = 2.1 ns \([V_{lp}/V_{coup}] = -0.35\) dB
  - BP filter
    - Bunch length = 4.8 ns \([V_{lp}/V_{coup}] = -39.6\) dB
    - Bunch length = 2.1 ns \([V_{lp}/V_{coup}] = -24.1\) dB

- **Frequency domain:**
  - Quasi continuous spectrum
  - BP filter uses the fraction of the signal power that corresponds to its BW
Examples of Schottky mass spectroscopy
this and the following 4 slides (S.Litvinov) were provided by P. Kowina (GSI)
Examples of Schottky mass spectroscopy (2)
production storage and cooling of short lived nuclei (slide by S. Litvinov)
Examples of Schottky mass spectroscopy (3)
production storage and cooling of short lived nuclei (slide by S. Litvinov)

Production & Separation of Exotic Nuclei

Highly-Charged Ions
In-Flight separation
Cocktail or mono-isotopic beams
500 MeV/u primary beam $^{152}$Sm
400 MeV/u stored beam $^{140}$Pr, $^{142}$Pm
Examples of Schottky mass spectroscopy (4)
production storage and cooling of short lived nuclei (slide by S. Litvinov)

Recording the Schottky-noise

\[
\Delta f = -\frac{1}{\gamma_t^2} \frac{\Delta (m/q)}{m/q} + \Delta \frac{v}{v} \left(1 - \frac{\gamma_t^2}{\gamma_t^2}\right)
\]

\[
\frac{\Delta v}{v} \rightarrow 0
\]

Real time analyzer Sony-Tektronix 3066

\[\text{128 msec}\]

\[\rightarrow \text{FFT}\]

\[\text{64 msec}\]

\[\rightarrow \text{FFT}\]
Examples of Schottky mass spectroscopy (5)
production storage and cooling of short lived nuclei (slide by S. Litvinov)

**SMS: Single-ion sensitivity**

![Graph showing SMS: Single-ion sensitivity with isotopes 143m Sm and 143g Sm.](image-url)
Stochastic beam cooling (1)
invented by Simon van der Meer at CERN in 1967, Nobel price in 1984

The Nobel price was awarded to Carlo Rubbia and Simon van der Meer for "their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of the weak interaction".(quote) and also from the Laudatio: van der Meer made it possible, Rubbia made it happen.
2. Cooling, why and how?
A central notion in accelerator physics is phase space, well-known from other areas of physics. An accelerator or storage ring has an acceptance that is defined in terms of phase volume. The antiproton accumulator must catch many antiprotons coming from the target and therefore has a large acceptance; much larger than the SPS ring where the p’s are finally stored. The phase volume must therefore be reduced and the particle density in phase space increased. On top of this, a large density increase is needed because of the requirement to accumulate many batches. In fact, the density in 6-dimensional phase space is boosted by a factor $10^5$ in the AA machine.

This seems to violate Liouville’s theorem that forbids any compression of phase volume by conservative forces such as the electromagnetic fields that are used by accelerator builders. In fact, all that can be done in treating particle beams is to distort the phase volume without changing the density anywhere.

Fortunately, there is a trick - and it consists of using the fact that particles are points in phase space with empty space in between. We may push each particle towards the centre of the distribution, squeezing the empty space outwards. The small-scale density is strictly conserved, but in a macroscopic sense the particle density increases. This process is called cooling because it reduces the movements of the particles with respect to each other.
Stochastic beam cooling (3)
the text shown below is part of the Nobel lecture by S. v.d. Meer

3. Qualitative description of betatron cooling
The cooling of a single particle circulating in a ring is particularly simple. Fig. 2 shows how it is done in the horizontal plane. (Horizontal, vertical and longitudinal cooling are usually decoupled.)

Under the influence of the focusing fields the particle executes betatron oscillations around its central orbit. At each passage of the particle a so-called differential pick-up provides a short pulse signal that is proportional to the distance of the particle from the central orbit. This is amplified and applied to the kicker, which will deflect the particle. If the distance between pick-up and kicker contains an odd number of quarter betatron wavelengths and if the gain is chosen correctly, any oscillation will be cancelled. The signal should arrive at

![Diagram of betatron cooling](image)
Today stochastic cooling is an important tool for charged particle beam conditioning, its used in all 3 planes (horizontal, vertical and longitudinal).

Stochastic cooling is applied on coasting (non-bunched) and bunched HADRON beams, where for bunched beam stochastic cooling large difficulties related to inter-modulation of the front end amplifier had to be mastered.

Stochastic cooling systems are in operation at CERN, GSI, FZJ, BNL and Fermilab and further systems are planned for NICA and in the frame of the FAIR project.

Stochastic cooling is very suitable to make HOT beam tempered, and electron cooling is very well suited to make tempered beam really cold, approaching the state of beam crystallization...

There exist a considerable number of other particle cooling methods, such as ionization cooling (proposed for muons with very short lifetime), laser cooling, radiation cooling (leptons), resistive cooling (applied in traps) just to give a few examples.

Stochastic cooling has permitted to increase the “6 D phase space density” of antiprotons by more than 10 orders of magnitude...(these days)
Sir, you have PRODUCED antimatter! (creation is rather my business..)

Very suspicious ..the devil ???

We have recently created antimatter here!

During the visit of the Pope to CERN June 1982

CERN photo-8206555

Caspers  Microwave sensors  RUB March 2017
Synchrotron radiation (1)

- Synchrotron radiation occurs in any charged particle accelerator where highly relativistic particles are deflected by some bending magnet. It is nothing else than the radiation emitted by an electric charge which forced to travel on a curved trajectory due to external (usually) magnetic fields.

- Particle accelerators are used for leptons (electrons, positrons) and hadrons like protons, antiprotons and all kinds of ions from negatively charged hydrogen $H^-$ to fully stripped uranium ions.

- Leptons radiate very easily (in contrast to hadrons) and this radiation is used in all kind of synchrotron light sources for the generation very monochromatic electromagnetic radiation pulses down to a small fraction of a pico-second in length.

- The spectral range of synchrotron radiation used for research (e.g. biological and chemical processes) as well as technical applications extents from far infrared to hard $\gamma$-rays.

- Synchrotron radiation is in may cases a desired effect and also used for beam cooling (radiation cooling) in lepton damping rings. But it may be also undesired like in the CERN-LEP machine, where synchrotron radiation of the electrons and positrons at 100 GeV/c generated 2 kW average power of X-ray radiation per meter which had to be removed by water cooling of the vacuum chamber.
Synchrotron radiation (2)

- Synchrotron radiation has a lower frequency bound, namely the cutoff frequency of the first waveguide mode of the beam-pipe. Below this frequency which is typically in the GHz range the mechanism of radiation cannot become effective (no propagating waveguide modes).

- We discriminate between coherent and incoherent synchrotron radiation.

- Incoherent radiation is emitted by individual particles without having a defined phase relation to other particles in the bunch. In this case the total emitted power is proportional to the number of particles.

- Coherent synchrotron radiation is related to a defined phase relation e.g. for the case that the bunch is very short compared to the emitted wavelength. Here the complete bunch acts as a single macro-particle and radiated power is proportional to the SQUARE of the number of particles. Thus for short bunches we often have coherent synchrotron radiation in the microwave range.
Synchrotron radiation (3)

- Synchrotron radiation from infra-red to \( \gamma \) -rays has many diagnostic applications for particle accelerators such as measurement of the time structure of the beam with sub-femto second resolution as well as measurement of the transverse and longitudinal emittance.

- But also at the low end (microwave) synchrotron radiation is applied now as a diagnostic tool...e.g. for measuring the time structure.

Example of a 60-90 GHz detector with horn antenna mounted next to a visible light extraction port

From: G. Rehm et al.
ULTRA-FAST MM-WAVE DETECTORS FOR OBSERVATION OF MICROBUNCHING INSTABILITIES IN THE DIAMOND STORAGE RING, Proceedings DIPAC 2009 Basel

Abstract:
The operation of the Diamond storage ring with short electron bunches using low alpha optics for generation of Coherent THz radiation and short X-ray pulses for time-resolved experiments is limited by the onset of microbunching instabilities. We have installed two ultrafast (time response is about 250 ps) Schottky Barrier Diode Detectors sensitive to radiation within the 3.33-5 mm and 6-9 mm wavelength ranges. Bursts of synchrotron radiation at these wavelengths have been observed to appear periodically above certain thresholds of stored current per bunch.....
Magnetic markers in accelerator magnets

- For proper control of the accelerating cycle in many cases magnetic marker is required, which at the start of the ramp gives a pulse like signal. This is required in order to compensate for hysteresis effects in the iron of the magnets which leads to deviations from the desired field (remanence). The actual B-field vs time is then usually determined via an integrator on the signal of field pickup-coil in the magnet.

- In the early days (50 years ago but at the CERN Proton synchrotron still in use) one had “peaking strips” to provide a pulse when the magnetic field of the ramp passes though a pre-defined field level.

- NMR probes (about 42 MHz/Tesla, Nuclear Magnetic Resonance) are in use as magnetic markers (CERN booster and SPS but they require a rather homogeneous field. In addition when running in the “Peaking strip” mode the trigger signal for starting the subsequent field integrator is not always reliable since its single shot readout. (of course in normal operation NMR probes work very well)

- As a good alternative the FMR (FerriMagnetic Resonance, 28 GHz/Tesla) has been identified. Essentially this is a single sphere monocrystal YIG filter with a (high) Q-value around 1000 and very low temperature coefficient obtained by special orientation of the single crystal YIG with respect to the DC or ramped B-field

- In contrast to the NMR the YIG marker is VERY insensitive even to large field gradients and provides a very reliable output signal for fast magnetic ramps (1T/s)
Example of an FMR magnetic marker

General view of the CPS reference magnet

Detailed view of the CPS reference magnet beampipe removed

FMR probe at beam position

Figure 59: FMR signal at 800 G in the U101
Axion and paraphoton search with microwaves

The “light shining through the wall” (LSW) experiment:

According to theory a microwave cavity in a strong magnetic field should generate “AXIONS” = \( \Phi \)
and without DC magnetic field just PARAPHOTONs = hidden photons = \( \gamma' \)
Both types of particles are supposed to easily penetrate any shielding and reconvert to microwave photons in a second cavity nearby

- Idea: exploit microwave cavities instead of optical resonators
  [Hoogeveen ‘92; Jaeckel,Ringwald’07; Caspers,Jaeckel,Ringwald ’09]
- With current technology, expect increased sensitivity in certain mass range
- First test experiments have already been done (Livermore; Perth), or are being set-up (Daresbury; Yale)
Searching for Axions (ALPs) and Hidden Photons with “Photon regeneration experiments”

- **Hypothetical** elementary particles
  - Their existence is strongly motivated in theoretical physics:
    - Excellent candidate for **dark matter**
    - Can explain the abundance of matter over antimatter
    - Can solve the "**strong CP-problem"** – an important issue in the current formulation of the standard model (CP=Charge –Parity)

- **Theory predicts:**
  - Photons (any wavelength) can spontaneously convert into ALPs= and vice versa -- if a strong magnetic field is present
  - An energized cavity will couple energy to a passive cavity by ALP radiation
  - This is exploited in a “Light Shining through the wall” [=LSW] experiment to probe the existence of ALPs (ALP=axion like particle)
Inside the magnet

- Why optical fibres
  - Much better EMC shielding than coaxial cables
  - Compatible with waveguide-style feedthrough filters
  - We have to deal with more than 300 dB isolation
  - There is roughly 1 MegaWatt reactive power in the transmitter cavity (=+90dBm)
  - With 10 microHz resolution bandwidth and about 3 dB system noise figure we are at -220 dBm on the receiver side

Outside the magnet

Shielding box containing the detecting cavity

Connected by optical fibres

WISP = Weakly interacting small particles
The CERN resonant WISP search (3)

Required to work well in the magnet at 3 Tesla! Several design iterations were necessary!
Superconducting MRI magnet

3 Tesla

Made accessible for us on weekends

University of Geneva, Brain & Behaviour Laboratory,
Magnet could not be ramped down!

→ Only non-magnetic tools and components allowed to avoid the “Missile effect”
CROWS exclusion results for paraphotons [June 2013]

Results published in the Journal “Physical Review D”
Abstract

We report on the first experimental results for microwave spectroscopy of the hyperfine structure of $\bar{p}^3\text{He}^+$. Due to the helium nuclear spin, $\bar{p}^3\text{He}^+$ has a more complex hyperfine structure than $\bar{p}^1\text{He}^+$ which has already been studied before. Thus a comparison between theoretical calculations and the experimental results will provide a more stringent test of the three-body quantum electrodynamics (QED) theory. Two out of four super-super-hyperfine (SSHF) transition lines of the $(n, L) = (36, 34)$ state were observed. The measured frequencies of the individual transitions are $11.12559(14)$ GHz and $11.15839(18)$ GHz, less than 1 MHz higher than the current theoretical values, but still within their estimated errors. Although the experimental uncertainty for the difference of these frequencies is still very large as compared to that of theory, its measured value agrees with theoretical calculations. This difference is important because it is proportional to the magnetic moment of the antiproton.

Keywords: antiprotonic helium, microwave spectroscopy, hyperfine structure, three-body QED

First observation of two hyperfine transitions in antiprotonic $^3\text{He}$

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Hyperfine transitions on antiprotonic $^3\text{He}$ (2)

Figure 1: A schematic drawing of the laser-microwave-laser method. The dashed arrows indicate the laser transitions between the SHF levels of the radiative decay-dominated state $(n, L) = (36, 34)$ and the Auger decay-dominated state $(n, L) = (37, 33)$ of $p^3\text{He}^+$. The wavy lines illustrate the microwave-induced transitions between the SSHF levels of the long-lived state.

Figure 3: Drawing of the central part of the experimental setup, a cross-section of the cryostat.
The experimental technique is a three-step process, referred to as \textit{laser-microwave-laser spectroscopy} (Fig. 1). After antiprotonic helium is formed, the atoms in the hyperfine substates are in thermal equilibrium and the states are all equally populated. Therefore, at first a population asymmetry between the SSHF substates of the measured radiative decay state \((n, L)\) needs to be created. This depopulation is induced by a short laser pulse which transfers the majority of the antiprotons from one of the HF states of the radiative decay-dominated, metastable parent state to the Auger decay-dominated, short-lived daughter state \((f^+\text{ transition in Fig. 1})\). The bandwidth of the laser is narrow enough so that the \(f^-\) transition is not excited. Therefore the antiprotons in the other HF state are not affected, which results in the desired population asymmetry. The antiprotons in the short-lived daughter state annihilate within a few nanoseconds. Afterwards, a microwave frequency pulse, tuned around the transition frequency between two SSHF \((\bar{p}^3\text{He}^+)^3\) substates of the parent state, is applied to the antiprotonic helium atoms. If the microwave field is on resonance with one of the SSHF transitions, this will cause a population transfer and thus a partial refilling of one of the previously depopulated states. Then, a second laser pulse is applied again to the same transition \((f^+)\) as before, which will again result in subsequent Auger decay of the transferred atoms and annihilation of the antiprotons. Thus, the number of annihilations after the second laser pulse will be larger if more antiprotons were transferred by the microwave pulse.

Figure 5: Scan over the microwave frequency for two of the four SSHF transitions for the \((n, L) = (36, 34)\) state of \(\bar{p}^3\text{He}^+\), at a target pressure of 250 mbar. Each transition is fitted with Eq. 2. The frequencies of the measured transitions are \(11.12559(14)\ \text{GHz}\) and \(11.15839(18)\ \text{GHz}\). The dashed curve shows a simulation using collision rates obtained from comparison between experiment and simulation.
Microwave signatures from very high energy neutrinos (1)

Microwave diagnostics in the high MHz to several GHz range is also applied for measuring tracks of very high energy neutrinos (above 10^{12} eV) in air and in matter e.g. the ICECUBE experiment.

The **Askaryan effect** is the phenomenon whereby a particle traveling faster than the phase velocity of light in a dense dielectric (such as salt, ice or the lunar regolith) produces a shower of secondary charged particles which contain a charge anisotropy and thus emits a cone of coherent radiation in the radio or microwave part of the electromagnetic spectrum. It is similar to the Cherenkov effect (from Wikipedia).

1960’s: **Askaryan** predicted that the resultant compact cascade shower (1962 JETP 14, 144; 1965 JETP 21, 658):

- would develop a local, relativistic net negative charge excess
- would be coherent (P_{rf} \sim E^2) for radio frequencies
- for high energy interactions, well above thermal noise
- detectable at a distance (via antennas)
- polarized – can tell where on the Cherenkov cone
Microwave signatures from very high energy neutrinos (2)

Microwave diagnostics in the high MHz to several GHz range is also applied for measuring tracks of very high energy neutrinos (above $10^{12}$ eV) in air and in matter e.g. the ICECUBE experiment.

Askaryan Effect: SLAC T444 (2000)

- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> avoid RF transition radiation
- RF backgrounds carefully monitored
  • but signals were much stronger!

From Salzberg, Gorham, Walz et al. PRL 2001

Sub-ns pulse, Eq-p≈ 200 V/m!

Courtesy: P. Gorham
Conclusion

- For beam diagnostics in particle accelerators electromagnetic sensors operating from DC to well beyond the microwave range are and indispensable tool and modern accelerators cannot run without this kind of diagnostic.

- Stochastic beam cooling, a mixture of microwave based beam diagnostic and correction, has made important contributions to physics. This technique corrects the movements of individual particles. On average each simply charged particle (e.g. proton) passing through a stochastic cooling pick-up just gives off a single microwave photon per passage.

- Microwave diagnostic can see a single charged particle circulating in a storage ring and also a single particle (e.g. antiproton) oscillating in a trap.

- Also for auxiliary systems of particle accelerators such as magnetic markers, RF and microwave related systems (e.g. nuclear- and ferri-magnetic resonance) are relevant.

- Microwave diagnostics is also an important tool for different kinds of experiments (antimatter related) in the vicinity of accelerators.

- Other high energy physics experiments (axion and neutrino search) also rely on sophisticated microwave diagnostics.

- And last not least: RF and microwave power systems are the indispensible working horse for virtually ALL particle accelerators used these days.