Planning for the Generation-X Radio Cherenkov Test Beam Experiment

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Abstract. We outline plans for future test beam experiments on coherent radio Cherenkov radiation, in particular those induced by hadronic showers at laboratory facilities. A high degree of symmetry, exploitation of exact solutions and exact features of radiation, and deliberate over-determination of observables are intrinsic to the experimental design.

I TEST-BEAM X

Coherent Radio Cherenkov radiation is a fascinating phenomenon which underlies the most sensitive known mechanism for the detection of ultra-high energy particle showers [1,2]. The process is exploited for the detection of neutrino-induced showers in cold Antarctic ice in the prototype RICE array [3]. RICE now uses more than a dozen radio receivers probing the region of neutrino energies of about 1 PeV and above. The project has recently generated a preliminary limit on ultra-high energy (UHE) neutrino fluxes, reported at this meeting [4]. Detection of showers in other radio-transparent substances such as rock-salt are also under consideration; in addition, the coherence and sensitivity of the radio regime suggest other uses which may lead to new technologies of high-energy particle detection.

Yet no experiments have been conducted to measure radio emission from hadron-induced showers. To order of magnitude, one expects that radio emission from PeV hadronic showers and electromagnetic showers are comparable, because almost all of the energy ends up at the "bottom" of the energy distribution with charge imbalances that are "order unity", namely 10-20%. But hadronic showers involve substantial uncertainties. Hadronic showers are sufficiently different from electromagnetic showers that independent tests should be done: the vast range of energies involved in a UHE shower and the intrinsic complexity of strong interactions make Monte Carlo estimates less reliable than corresponding electromagnetic shower calculations. Indeed, calculations for RICE thus far [3] have conservatively omitted the hadronic contributions.

We have developed a test-beam proposal which can be used both for hadronic or electromagnetic circumstances, and which takes into account experience gained from the previous generation of experimental work. A chronic problem has been the comparison of experiments done in near-field regime with idealized calculations sometimes limited to the asymptotically far regime. Another difficulty is the separation of different kinds of radiation, treated by textbooks as independent phenomena, which tend to mix in real experimental circumstances. Finally, the geometry of any particular experimental setup, while well-designed and clean on some criteria, may end up being very troublesome for radio-frequency optics.

We deal with the difficulties by planning from the bottom up with a high degree of symmetry and theoretical predictability. Certain configurations of beam and conductors lead to exact solutions to the electrodynamics: we engineer the experiment along these lines. We don't bother to separate out the pieces identified in textbooks so long as we get productive results in the end. Some features of the solutions are highly detailed, while others are as general as Gauss' Law: we recognize this, and take into account the limitations of theory. The experimental setup is arranged to give a high degree of internal self-calibration, so as to be hardly dependent on external standards. Indeed we plan the experiment with a high level of empirical *over-determination* of observables. Our philosophy is that when observables are over-determined by relations between the observations themselves, then the results are less subject to theory assumptions and also more amenable to systematic de-bugging.

The scheme we present is a first outline for a test-beam study exploiting the possibilities of symmetry and merging theory and experiment as much as possible step-by step: and if things go as conceived so far, would make a "pretty" experiment of high quality and intrinsic interest.

Some Helpful Experimental Predecessors: The combination of high energy physics with radio technology involves many orders of magnitude in energy and many challenges. Our work follows several efforts over the last few years aimed at verifying the effects of *radio-coherence* with laboratory test beams. We happily acknowledge the open communications and cooperative processes so important to the field. Alice Bean and Ilya Kravchenko [5] conducted informal experiments on SLAC electron beams in the mid 1990's. They saw radio pulses consistent with the total charge flowing past. Doug McKay did the theory work. Mary Anne Cummings, Paul Schoessow, and others [6] recognized the need for a hadronic test beamtest project at Fermilab. They conceived a novel concrete target arrangement, and succeeded in getting the lab's support. Several years ago Dave Besson [7] worked with Al Odian and paved the way for an electron test beam project at SLAC, conceiving a scheme with antennas buried in sand targets and box geometry to release radiation and inhibit reflections. The early efforts culminated recently in two experiments, conducted at the ANL wake-field facility and SLAC, which convincingly demonstrate that the important features of coherence have been observed in electromagnetic shower evolution [8,9]. These experiments are also discussed at this meeting by Saltzberg et al [9].

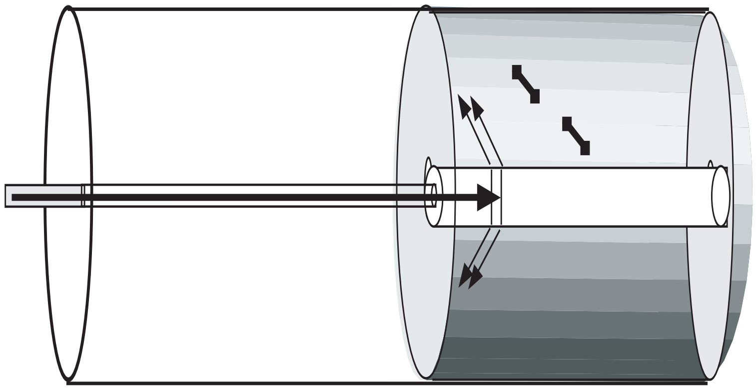

FIGURE 1. Schematic layout of the Tank. The accelerator beampipe (left side) feeds an evacuated dielectric beam pipe entering a field pre-form region with conducting boundary conditions. The length of this region of "free space" is adjustable. The tank proper (gray cylinder) contains an inner target pipe. The target pipe is illustrated empty; the tank is illustrated full. Radio receivers (black bowties) are placed at various locations inside the tank; causality is exploited. The illustration shows Cherenkov radiation (arrows) forming from the boosted Coulomb charge under free space conditions inside the target pipe.

II CONCEPTUAL OVERVIEW: THE TANK

The basic experimental set-up is dictated by the symmetry of the electrodynamics. The fields of steadily moving charges have basic symmetry along the beam direction or z-axis, and azimuthal symmetry about the beam. Shower evolution breaks the z-translational symmetry, but we retain as much z-symmetry as possible for empty target calibration purposes, explained momentarily. These observations lead to our basic design of a cylindrical tank containing a co-axial, independent hollow "target pipe". Both the tank and the target can be filled independently with dielectric fluid, or operated empty, in several combinations to be discussed. Radio antennas are placed at various locations in the tank with facilities to move any particular receiver from place to place without changing connections. We plan to use very small, very inefficient dipole antennas: the small size allows precision of placement, while fields from intense particle beams are so large that we can tolerate inefficiency. The scale of things is set by the scale of shower development: for 100 GeV showers induced by a Fermilab proton beam, we need dimensions "of order meters" of tank length and diameter. However the design "re-scales" easily, and we are also considering smaller models, on the scale of tens of centimeters, that might serve for lower energy tests or prototyping.[1]

The Tank and target-pipe arrangement allows many combinations of measurements with the same apparatus and receivers.

The combinations include the case of *Empty Target-Empty Tank*, in which the beam simply passes freely though the target pipe (evacuated for this purpose) and excites the antenna with a pulse of radio-frequency fields. The beam has been treated as a nuisance in previous experiments. We propose to use this case for calibrating the receivers. The pulse of radiation is obtained by Lorentz-transforming the Coulomb fields, or solving the wave equation directly: sometimes these fields are not recognized as "radiation", although in high energy physics the correspondence is well established, and well exploited in the "equivalent photon approximation". In more detail, the Fourier transformed electric fields,

$$\vec{E}_\omega(\vec{x}) = \int dt\, e^{i\omega t} \vec{E}(\vec{x}, t)$$

of a charge e moving with speed v, boost γ, are given by

$$\begin{aligned}
\vec{E}(\omega, \vec{x}) &= -i\omega \vec{A}(\omega) - \vec{\nabla}\phi(\omega); \\
E_\omega(\vec{x})_z &= -\frac{2iQ\omega}{\epsilon v^2\gamma^2} \exp\left(i\frac{\omega}{v}z\right) K_0\left(\frac{\omega\rho}{\gamma v}\right); \\
E_\omega(\vec{x})_T &= \frac{2Q\omega}{\epsilon v^2\gamma} \exp\left(i\frac{\omega}{v}z\right) K_1\left(\frac{\omega\rho}{\gamma v}\right),
\end{aligned}$$

where ρ is the transverse distance to the axis, and $\gamma^{-2} = 1 - \epsilon(v/c)^2$. The free-space fields are given by dielectric constant $\epsilon = 1$; otherwise use $\epsilon(\omega)$ appropriate to the medium. Note the argument of the Bessel function: dependence on the dimensionless ratio $\omega\rho/(\gamma v)$ causes the transverse size of the fields to scale like the boost parameter γ. When $\gamma \gg 1$ the fields may be comparatively flat out to surprisingly large distances.

Depending on frequency, the case of $\gamma \gg 1$ of relativistic beams also forces the Bessel functions to be practically evaluated at zero argument: and for $\omega \to 0$ the electric field is impeccably determined by Gauss' Law. Applying Gauss' Law in the frequency domain can be done by converting a surface integral into a time integral: for an infinite cylinder surrounding the beam, write

$$\begin{aligned}
\oint \vec{E} \cdot d\vec{S} &= 4\pi Q_{encl}/\epsilon; \\
\int d\vec{S} \cdot \vec{E} = \int_{-\infty}^{\infty} dz 2\pi\rho E_T &= \int dt 2\pi\rho E_T(\rho, t)/v; \\
E_{\omega,T}(\rho; \omega \to 0) &= \frac{2Q}{\epsilon v\rho} \exp\left(i\frac{\omega}{v}z\right).
\end{aligned}$$

We have assumed ϵ is evaluated in a region where it varies slowly. While the Bessel functions have the details, we see that the fields for $\omega\rho/(\gamma v) \ll 1$ are flat

1) We thank Peter Gorham for suggesting this point.

in frequency, absolutely normalized, kinematic, and known as well as the accelerator physicists know the total charge in their beam, creating a highly accurate opportunity for calibration.

The next simplest combination is *Empty Target/Full Tank*, in which the boosted Coulomb field "refracts" into the dielectric tank medium, creating Cherenkov radiation. The radiation here is over-determined, while exhibiting all the coherence features of the subsequent combinations: *Full Target/Empty Tank*, and *Full Target/Full Tank*. Here the new feature is shower evolution. As the hadronic (or electromagnetic) shower evolves, the net electromagnetic current which produces radio emission evolves. The current will be predicted by Monte Carlo routines such as GEANT. Elsewhere there are discussions of radio emission from an evolving, coherently radiating radio source in the near or "Fresnel" and far transition regimes [10] and the asymptotically far regime [11]. The *Full Target/Empty Tank* allows investigation of shower evolution which is probed by the free-space propagating radio fields. Since the shower current is the only new thing compared to the previous case, we will be able to tell if the Monte Carlo is valid, comparing data to data. The *Full Target/Full Tank* will use buried receivers just like RICE, and is overdetermined after the previous measurements.

Obviously there are many measurements that can be made with a single, calibrated antenna which is moved about inside the tank, both transversely and longitudinally. We also plan to use ganged receivers, which can directly determine the Cherenkov angle by timing differences, and we can measure the speed of waves propagating in the medium, among other things. Before we go too far, however, we must caution that the boundary conditions can be considered with more care, which is "Part Two" of the theory planning.

More on Boundary Conditions: and Making Movies: In the discussion so far we neglected to mention the breaking of z-symmetry by the front edge of the tank, and the exit of the beam from the beampipe upstream.

The very broad transverse field profile of a relativistic beam (dependence on $\omega\rho/(\gamma v)$) makes the experimental hall a potential unwanted part of the boundary conditions. To control this, the Tank design includes a "pre-forming" hollow cylindrical conducting extension the same diameter as the tank. There is nothing in the preform but air (or maybe another, similarly cheap dielectric) and a length of dielectric evacuated beam pipe. The preform cylinder sits upstream of the tank and is designed to get the incoming fields into a known configuration before they hit the front surface of the Tank. If the pre-form region is sufficiently many wavelengths in extent, the boundary conditions are well established: we can check this by changing the length of the preform, so we don't need to rely on theory. There will also be a pulse of transition radiation from the beam's upstream emergence from the metallic beampipe: this may be controlled with an adiabatically tapered concentric absorber. The longitudinal locations of the tank, the end of the preform cylinder, and the metallic beampipe are all adjustable, creating many freedoms for consistency check.

The boundary-value problem for moving charges inside a conducting cylinder is easy: potentials are a combination of $K_0(\omega\rho/(\gamma v))$ and $I_0(\omega\rho/(\gamma v))$. Deviations from azimuthal symmetry should be small, but if any exist they are smoothly described with K_m and I_m series we also developed.

The problem of fields inside a cylinder meeting a plane boundary of dielectric at the front surface of the tank is the main complication. We solved this using the techniques for transition radiation emphasized by Bolotovsky (see his talk at this meeting) and others [12]. First, there is no particular reason to decompose the fields into those standard species of transition radiation, boosted Coulomb or Cherenkov radiation, which is sort of impossible anyway: the terminology of textbooks does not apply to real experiments. (Plus, we only want the fields whatever they are called.)

Second, the front and back boundaries of the tank are handled by Bessel series. These series have been set up by exact analytic algebra, with some care to get the solutions for forward-moving waves downstream from the tank. The sums over the series are seriously complicated: however, the finite frequency response of receivers made an otherwise infinite series converge with gratifying rapidity. Nevertheless, the operations in the frequency domain can be treacherous, because various backward and forward reflections hinge on properly deforming contours, and one must be careful.

To make sure we knew how to do this, we went the full route of making "movies", which seem to be the ultimate test of proper causal behavior of the complicated Bessel series. The movies in real space/real-time show the Coulomb field entering the Tank, reflecting from the front and "ringing" inside the Tank cavity, and exiting the Tank to re-form on the far side. The ringing, traveling wave has been observed before in the context of wake-fields [13].

In these calculations and in the whole experimental plan, causality is a great help. The complications from the Tank front surface cannot propagate through the dielectric medium faster than light speed in the medium. The leading fields of a Cherenkov pulse near the charge are very much like the free space fields. We knew this in advance, but made the calculations anyway, because they are beautiful, and worth doing well.

III SUMMARY

The self-calibrating features of empty-empty mode in our design promise measurements of high absolute accuracy. The various over-determined cases, measured in free space or medium, should help the eternal experimental difficulty of "getting things right". However certain details remain open, and make it hard to be firm on the level of accuracy achievable. One important detail is the nature of the dielectric fluid. We have considered water, because it is cheap, well-characterized and not-too-attenuating on the regime of GHz and below. Water is admittedly a complicated dielectric, and some colleagues shudder, but we have researched the dielectric properties and find hydrophobia unwarranted. Other radio-friendly fluids exist and are under consideration. Activation of the material is a consideration: this is another reason that we minimize the volume exposed to the beam with the target pipe. Activation of the antennas does not seem to be a problem. Worries raised in the workshop, that a pulse of 10^{11} particles with 100 GeV (say) might modify the dielectric properties, create a momentary plasma state, or do something unpredictable for the radio signal, have a simple answer: if that happens, it is just what we all want to know, both for Monte Carlo validation, and for RICE, where one of these days we might see a neutrino of equivalent super power make a loud radio splash.

Acknowledgments: Support by NSF and DOE, Division of High Energy Physics, and NSF Division of Polar Programs for the RICE project is gratefully acknowledged. We thank our colleagues attending the meeting for many useful discussions: in particular Boris Bolotovsky, John Learned, Al Odian and Peter Gorham were very helpful.

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