

CERN SPS now running as 540-GeV $\bar{p}p$ collider

The CERN Super Proton Synchrotron (SPS) has begun producing ultra-high-energy physics results in its new role as a proton-antiproton colliding-beam accelerator. At the 2nd Topical Workshop on Forward Collider Physics, held in December at the University of Wisconsin (Madison), two CERN collaborations reported their early data^{1,2} on $\bar{p}p$ collisions at a center-of-mass energy of 540 GeV.

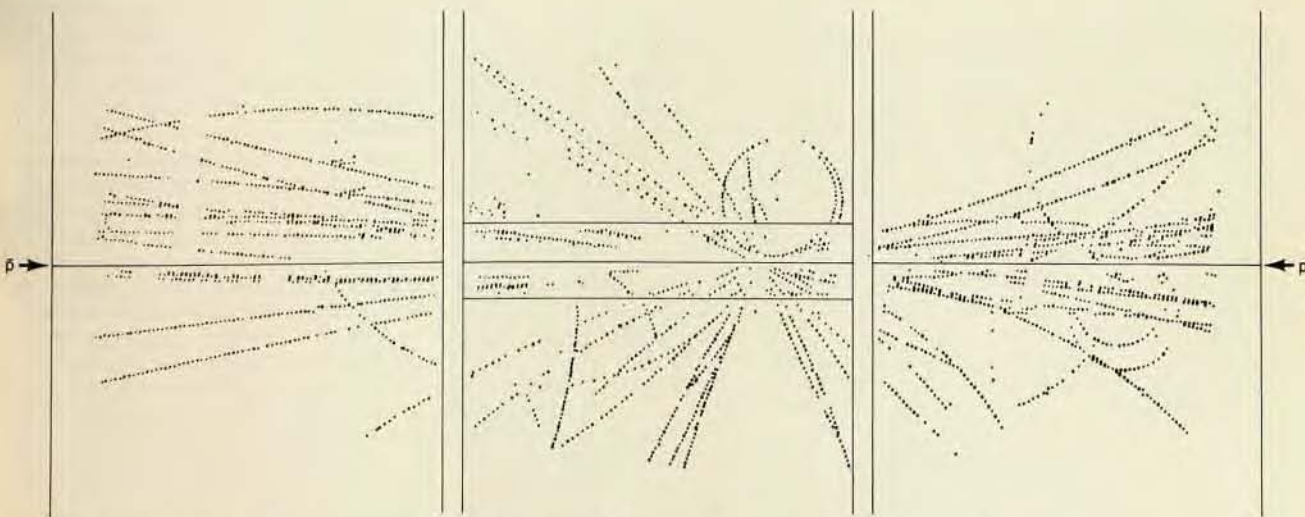
The production of these data is extraordinary on several counts. Such a collision energy is far beyond anything previously accessible at an accelerator, even with prosaic particle species—let alone *antiprotons*. The same center-of-mass energy with a fixed target accelerator would require a well-nigh inconceivable beam energy of 150 000 GeV. Proton-proton collisions at such energies had previously been studied only in rare cosmic-ray collisions. The CERN Intersecting Storage Ring has been providing pp colliding-beam events at energies up to 60 GeV for a decade. But the production of sufficiently intense antiproton beams for a

colliding-beam accelerator requires beam-cooling techniques much more elaborate than those used to concentrate positron beams for e^+e^- colliders (PHYSICS TODAY, August 1980, page 44). It is therefore remarkable that the SPS $\bar{p}p$ collider began producing data just three years after CERN took up the suggestion of Carlo Rubbia (Harvard and CERN) to modify the SPS for this purpose.³

As a fixed-target proton accelerator, the 7-kilometer-circumference SPS, which straddles the French-Swiss frontier near Geneva, has been accelerating protons to 400 GeV since 1976. But operating as a storage ring, the SPS can maintain countercirculating proton and antiproton beams in its single ring only up to beam energies of 270 GeV. Significantly higher energies would require superconducting magnets. The Fermilab Tevatron is expected to achieve 1000-GeV proton and antiproton beams (2000-GeV collisions) with superconducting magnets; but this first American $\bar{p}p$ collider is at least three years down the road.

For the moment, then, the CERN $\bar{p}p$ collider is the only accelerator capable of producing the intermediate vector bosons (the charged W^+ and W^- , and the neutral Z^0) that are believed to mediate the weak interactions. The widely accepted Weinberg-Salam-Glashow theory that unifies the weak and electromagnetic interactions predicts masses of about 80 and 90 GeV for the $W^\pm$ and Z^0 , respectively. The threshold for the production of these eagerly sought massive "weakons" (a particularly unfortunate coinage) is thus about 80 GeV in a hadron collider, where they need not be made in pairs; but because individual quarks seldom carry more than 20% of a baryon's momentum, very little production would be expected below 400 GeV.

The intermediate bosons have of course not yet been seen, but the early results reported at Madison by the UA1 and UA5 collaborations indicate some unanticipated characteristics of hadronic collisions at these high energies that may force the experimenters to rethink the triggering and data-collect-



A proton-antiproton collision at a center-of-mass energy of 540 GeV in the CERN Super Proton Synchrotron, newly operating as a $\bar{p}p$ storage-ring collider. The event is recorded in the 6-meter-long drift-chamber system of the UA1 collaboration. A 270-GeV antiproton coming from the left hits a 270-GeV proton entering right. The detector system includes six large drift-chamber modules (two central

and four forward) and two smaller modules wrapped around the collision region. The readout provides three-dimensional space points for charged tracks directly, typically 100 points per track. One can resolve two tracks 3 millimeters apart. For this early run, only half the sense wires were instrumented over 80% of the chamber volume, and the detector's magnetic field was run at 40% of its 7-kG maximum.

ing systems with which they hope eventually to find the $W^\pm$ and Z^0 .

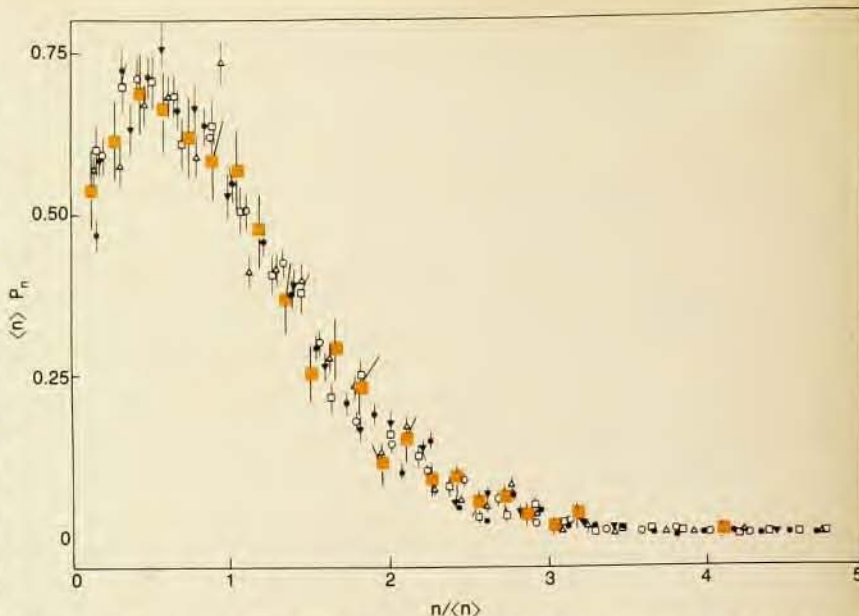
The SPS $\bar{p}p$ collider attained a sustained luminosity (collision rate per unit scattering cross section) of $2 \times 10^{27} \text{ cm}^{-2} \text{ sec}^{-1}$ in December. With a $\bar{p}p$ total cross section of about 50 millibarns ($5 \times 10^{-26} \text{ cm}^2$), this provides a collision rate of roughly 100 $\bar{p}p$ interactions per second at each of the collider's two experimental intersection regions. The luminosity is expected to reach $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ sometime this spring, Rubbia told the Madison workshop. The original design luminosity of $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ is probably not in the cards for the time being. It was based on a two-fold overestimate of the production cross section for 3.6-GeV antiprotons in the 26-GeV CERN Proton Synchrotron, which serves as the $\bar{p}$ source for the SPS collider. This lower $\bar{p}$ production rate may ultimately be offset by the fact that the SPS vacuum is significantly better than originally expected. A luminosity of $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ is expected to produce about ten W 's and one Z per day, we were told by David Cline (University of Wisconsin), organizer of the Madison workshop.

The antiprotons that are eventually accelerated to 270 GeV in the SPS are produced in collisions of the PS 26-GeV proton beam with a fixed target in front of the antiproton accumulator ring that serves to concentrate the $\bar{p}$ beam by stochastic cooling. Every 2.4 seconds a pulse of 10^{13} protons produces about 2×10^7 antiprotons with the proper energy (about 3.6 GeV) and direction for injection into the accumulator.

Stochastic cooling. The antiprotons thus injected into the AA ring are much too dispersed in energy and direction for acceleration and concentration into a beam sufficiently intense to provide adequate luminosity in the collider. As seen in the reference frame of the mean beam velocity, the original antiproton gas is far too "hot;" it must be cooled before being reinjected into the PS for preliminary acceleration on its way to the SPS.

The stochastic cooling technique employed in the antiproton accumulator ring was first suggested by Simon Van der Meer (CERN) in 1968. The large-aperture AA ring has a system of electronic beam-sensing electrodes communicating with an orbit-correcting "kicker" magnet. At a "pickup station" on the ring, the electrodes monitor the randomly fluctuating charge distribution of the antiproton beam profile. If the center of charge has strayed from the ideal orbit, a correcting signal is sent straight across the ring to the kicker on the opposite side of the AA ring in time to apply the appropriate correction when that portion of the beam arrives.

Initial tests of this cooling scheme at



Multiplicity distribution of charged particles produced in hadronic collisions (in a well-defined region of central phase space) shows remarkable scaling property when data ranging in center-of-mass collision energies from 23 to 540 GeV are plotted together in a manner suggested by Koba, Nielsen and Olesen. The colored squares are for $\bar{p}p$ collisions from the SPS collider; all lower-energy data are for pp collisions. One plots $\langle n \rangle P_n$, the probability of finding n charged particles times the mean charge multiplicity at a given collision energy, against the scaled multiplicity $n/\langle n \rangle$. This KNO scaling implies a much larger and faster growing high-multiplicity tail than one would have from Poisson statistics.

CERN, first at the ISR (1975) and then in a specially constructed small storage ring appropriately named ICE (initial cooling experiment), were so successful that the CERN management concluded in 1978 that the SPS should be converted into a $\bar{p}p$ collider with stochastic antiproton cooling.

Several notable successes in the operation of the CERN collider were reported at Madison. In December, the AA ring was cooling and storing up to 2×10^{11} antiprotons, injected at a rate about 5×10^9 $\bar{p}$ /hour. As yet only a small fraction of these accumulated antiprotons are transferred to the SPS. Ultimately one hopes to accumulate about 5×10^{11} antiprotons in the AA ring, transferring 60% of them to the SPS about once a day. The stochastic cooling is working extremely well, Cline told us. The "luminosity lifetime" of the beams circulating in the SPS is already close to its design value of 24 hours. This parameter describes the roughly exponential decay of luminosity after the SPS is filled, as a result of electromagnetic interaction between the countercirculating beams. Such interaction is minimal in dc storage rings such as the ISR, where the beams are distributed continuously around the ring. But in pulsed machines like the SPS collider, where each beam is concentrated in a few bunches, the intense electromagnetic mutual perturbation as the bunches pass through one another causes the beams, and hence the luminosity, to deteriorate

severely over the course of a day.

There had been considerable concern that these highly nonlinear beam-beam perturbations would lead to severe instabilities—perhaps even rendering a $\bar{p}p$ collider like the SPS impossible to operate. "But they've now gone a long way toward laying these concerns to rest," we were told by Fred Mills (Fermilab), one of the designers of the Tevatron $\bar{p}p$ collider. The "tune shift," the key parameter that measures the change in the operating point of the collider due to beam-beam interactions, has in fact attained its design value of 0.003. At PEP and PETRA (the large e^+e^- colliders at SLAC and DESY), by contrast, the beam-beam interactions had turned out to be much more severe than anticipated, resulting in luminosities an order of magnitude below the original design values.

The essential message conveyed to the Madison workshop by Rubbia is that "the $\bar{p}p$ collider really works!" despite its enormous complexity and the fears that had been widely harbored. There is however much work still to be done before the CERN system is operating at full capacity, Mills told us. "Low- β insertion" of the $\bar{p}$ beam has still to be accomplished under stable running conditions. That is to say, Mills explained, that the betatron oscillation wavelengths of the beam must still be reduced by about a factor of four to reduce its cross section and thus maximize luminosity. "Lots of little bugs" in the very complex beam-trans-

fer system that takes the antiprotons from the accumulator back to the PS and finally to the SPS must be dealt with so that a larger fraction of them may reach the collider. Antiprotons are precious. Getting only about two useful $\bar{p}$'s per million protons on the source target, one is loath to lose any in the transport system. At present only two bunches of protons circulate against one bunch of antiprotons in the collider. An important priority, Mills told us, is to increase this to six bunches of antiprotons and six bunches of protons.

Early physics results were reported at Madison by two experimental groups. The UA1 group is an Aachen, Annecy, Birmingham, CERN, Queen Mary College (London), Collège de France (Paris), University of California (Riverside), Rome, Rutherford Lab, Saclay, Vienna collaboration of more than 100 physicists, operating a large general-purpose detector mounted at one of the two $\bar{p}p$ intersection points on the collider ring. An 800-ton magnet provides 85 m^3 of 7-kilogauss magnetic field for the four 6-meter-long drift chambers of the central detector at the heart of the UA1 system. These drift chambers are surrounded by electromagnetic and hadronic calorimeters and muon wire chambers, covering the entire 4π solid angle around the $\bar{p}p$ collision region, with the exception of a 5-milliradian cone around the beam directions. "With its image-type readout of about 100 space points per emerging track, it's like a triggerable, digital bubble chamber," we were told by Anne Kernan, a member of the Riverside contingent.

The second group presenting SPS collider data at Madison was the UA5 collaboration of Bonn, Brussels, Cambridge, CERN and Stockholm. The two 6-meter-long streamer chambers of the UA5 nonmagnetic detector were operating in the second experimental area of the SPS collider during October and November, while the larger UA2 detector was waiting to replace it.

Both experiments have found essentially the same characteristics for the first ultra-high-energy hadronic collisions ever studied at an accelerator. The mean multiplicity of charged hadrons produced in these collisions, as measured in the streamer-chamber detector, is 27.4 ± 2 . Because this mean multiplicity is a reasonable extrapolation from the rising trend of ISR and cosmic-ray proton-proton data, it came as no great surprise.

The distribution of multiplicities about this mean, however, is another story. "We shouldn't have been surprised, but we were, when events with three times the mean multiplicity began to appear on our on-line display with astonishing frequency," Kernan

told us. Instead of the narrow Poisson distribution that many people were expecting at this energy, the multiplicity distribution has turned out to exhibit the same KNO scaling (after Ziro Koba, H. Nielsen and P. Olesen of the Niels Bohr Institute) seen at lower energies. In KNO scaling, the appropriately normalized multiplicity distribution at a given energy is a function only of the multiplicity divided by its mean value at that energy; the KNO scaling function itself is independent of energy. Thus the width of the multiplicity distribution grows with energy like the mean rather than its square root, as one has for Poisson behavior. This fact, together with the long high-multiplicity tail of the empirical KNO scaling function, implies that one will see a significant fraction of events with particle multiplicities several times the mean.

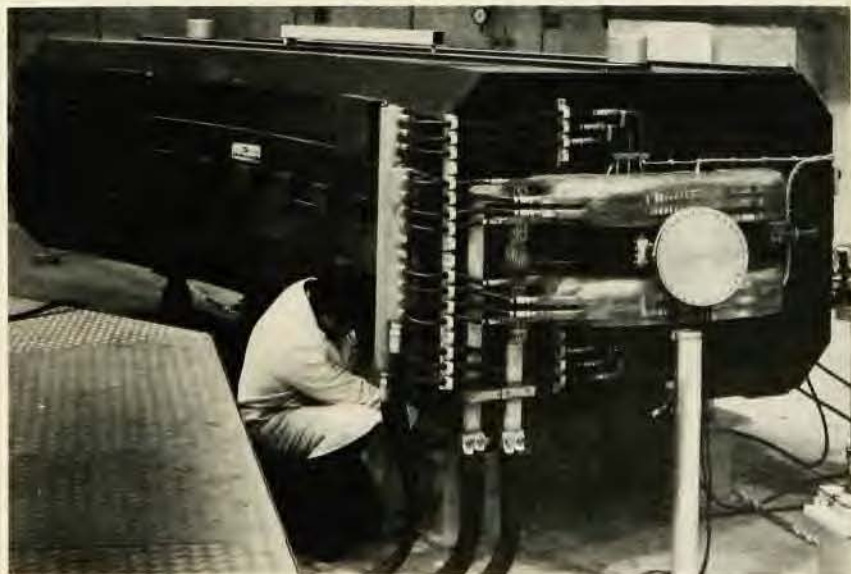
The UA1 and UA5 detectors have complemented one another well in these early collider runs. During much of the Fall data taking, only the central detector of the UA1 system was fully operational, thus providing detailed information only about tracks emerging within 30° of the plane normal to the beam direction—the so-called central region of the phase space. Although the magnetic field was not yet available to provide momentum determinations for most of the UA1 data reported at Madison, the calorimeters of the system were able to measure the energies of the centrally produced particles. The streamer-chamber detector, having neither calorimeters nor magnetic field, offers no energy information. But with the almost full 4π coverage that was lacking in the early UA1 data, the streamer chambers provided the

first complete visual records of elementary-particle collisions at these high energies.

Transverse energy. A second surprise in the collider data is the unexpectedly frequent appearance of events with very high transverse energy, and the way this transverse energy is distributed among the outgoing particles. The transverse energy of an emerging particle is the kinetic energy corresponding to the component of its momentum in the plane normal to the beam direction. In lower-energy accelerator data, the great majority of energetic particles produced in hadronic collisions tend to favor the beam directions, limiting the mean transverse energy per particle to about 300 MeV, seemingly independent of the collision energy. In the SPS collider this mean E_T , as measured in the central UA1 calorimeters, has risen to about 500 MeV.

More surprising is the fact that events with many times the mean *total* transverse energy (the sum of all E_T 's in an event) are produced at rates orders of magnitude higher than those predicted by the naive parton model. In this simplified form of the standard quantum-chromodynamic theory of hadronic interactions, high- E_T particles are produced primarily in the relatively rare "hard scatters" of quarks in the colliding hadrons. This picture predicts, furthermore, that high- E_T tracks should emerge well collimated in narrow back-to-back "jets," reflecting the directions of the two quarks after their hard collision.

The UA1 data indicate a rather different picture for the bulk of high- E_T events. Instead of being concentrated in a few jet-like particles of very high individual transverse energies, the



One of the magnets of the antiproton accumulator ring that cools and stores the $\bar{p}$ beam prior to its insertion into the PS and SPS. Note the unusually large beam aperture.

anomalously high total E_T appears generally to be distributed quite uniformly among the particles emerging in all azimuthal directions.

If more attention had been paid to a pp scattering experiment performed a year ago at the (fixed target) SPS by a Bari, Cracow, Liverpool, Munich, Nijmegen collaboration,⁴ Cline told us, the new high- E_T results from the $\bar{p}p$ collider would not have come as quite such a surprise. This lower-energy experiment had triggered on high-total- E_T events in the hope of studying jets in a segmented calorimeter that surrounded the entire 2π azimuthal range of the transverse plane. Unlike earlier experiments that had much more limited azimuthal coverage, this group found that the bulk of their high- E_T events had a non-jetlike uniform azimuthal distribution. The high- E_T event rate was much higher than that predicted by the simple parton model, and any clean jets that may have been hiding in the data were swamped by the azimuthally uniform background.

Implications. The high-multiplicity and high- E_T surprises presented by these first $\bar{p}p$ collider data appear to have significant practical as well as theoretical implications. With regard to the theory of hadronic collisions, the unexpectedly broad fluctuations in both multiplicity and total transverse energy seem to imply long-range correlations between particles produced far apart in phase space. In the more limited phase space available in lower-energy experiments, only local phase-space correlations had been clearly observed in multiparticle production.

Clean parton-model jets, it would appear, will be much more elusive in hadron-hadron scattering than in e^+e^- collisions. Geoffrey Fox (Caltech) presented a QCD-theoretical analysis at Madison indicating that both the prolific azimuthally-uniform high- E_T events and the apparently much rarer clean jets are consistent with QCD, if one takes adequate account of "gluon bremsstrahlung," the radiation of gluons by quarks when they experience high-momentum-transfer collisions. Fox emphasizes that the clean jets are still there with the proper rate and properties predicted by QCD; they are simply harder to see than one would naively have expected, given the overwhelming gluon-bremsstrahlung back-

ground.

The practical implications of the high- E_T and high-multiplicity events concern primarily the search for the intermediate vector bosons, which is, after all, the main impetus for the current race to higher energies. Because the cross sections for production of the $W^\pm$ and the Z^0 are expected to be exceedingly small, one must devise a trigger to weed out the overwhelming majority of "uninteresting" events in a hadron-hadron collider. The charged W 's can decay into hadrons or, less frequently, into lepton pairs. Because it is generally considered a hopeless task to find hadronically decaying W 's, one looks for a very high- E_T single electron or muon as a signature of the leptonic decay of the 80-GeV boson. The simplest scheme that is being considered for the SPS collider and the Tevatron is just to trigger on high total E_T in the electromagnetic calorimeters. The lesson from the first $\bar{p}p$ collider data is that such a trigger would bring along an overwhelming hadronic background. One will need, Fox suggests, a highly segmented calorimeter system that can ferret out very localized high E_T . He also warns that because vector bosons are produced in particularly violent quark-quark collisions they will be accompanied by lots of gluon bremsstrahlung.

The high-multiplicity events one must now expect at ultra-high-energy hadron colliders will require very elaborate systems of on-line data collection. Recording the data from a single event of ordinary multiplicity at the UA1 detector takes thirty thousand 16-bit words. "The first thing that happened when the UA1 energy trigger was turned on, was that 25% of the events overflowed the buffers," Cline told us. Things will get even more difficult when the luminosity is increased, he suggests. —BMS

References

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ATA: 10-kA pulses of 50-MeV electrons

Assembly of the Advanced Technology Accelerator (ATA) began in December at an isolated site 15 miles southeast of the Lawrence Livermore Laboratory. When it is completed in October (the project appears to be on schedule), the

256-foot linear induction accelerator is expected to generate repeated 10-kiloamp pulses of 50-MeV electrons—an order of magnitude higher energy than any previous induction linac capable of high current and high repetition rates.

The great majority of linear accelerators in operation today are radio-frequency, traveling-wave devices. Although such linacs can accelerate electrons to tens of *billions* of electron volts, they are severely limited in current capability. The electromagnetic field generated by the beam itself couples back into the resonant waveguide structure that provides the voltage amplification in an rf linac, generating beam-breakup instabilities when a modest current limit is exceeded. The two-mile-long Stanford Linear Accelerator, for example, is limited to electron currents of less than a hundred milliamps by such instabilities. Furthermore, the multi-gigawatt instantaneous power levels required for a high-current, high-energy linac are beyond the capacity of present rf power sources.

For the high-energy physics uses to which the SLAC accelerator is put, one is not interested in multi-kiloamp currents—only very high individual particle energies. But there are applications for which one wants extremely intense beam currents, delivering repeated multi-kilojoule or even megajoule pulses of charged particles. Although the Defense Department's primary objective in funding the ATA is to produce an experimental facility for the study of charged-particle beam propagation in air, to examine the feasibility of particle-beam weapons, such induction linacs are also of considerable non-military interest. The ATA could serve as a unique beam source for free-electron lasers. Historically, the world's first induction linac, the Astron I accelerator, was built at Livermore in 1963 by Nicholas Christofilos, to provide the high electron-beam currents required by his Astron magnetic-confinement scheme for fusion plasmas. Induction linacs are also of interest for inertial-confinement fusion with intense heavy-ion beams.

Ferromagnetic induction linacs. In contrast to an rf linac, where the electrons effectively ride an electromagnetic wave down a series of resonating cavities, in an induction linac the particles pass through an array of non-resonant cavities, each of which presents the particle with a quasi-electrostatic accelerating gap fed by a high-voltage pulse from a transmission line. One can contrive the topology of the transmission line at the gap so that the electron sees at first only the accelerating voltage across the coaxial line, and not the decelerating voltage that invariably accompanies it. But the transmission line must terminate somewhere, completing the circuit lest the energy it transports radiate away out an open end. Such a termination will produce a reflected voltage pulse of opposite polarity. If the beam passes