

VERY HIGH PULSE-ENERGY ACCELERATORS*

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ABSTRACT

The dominant trend in the development of pulsed power accelerator technology over the last decade has been towards higher power and shorter pulse widths. Limitations in high voltage, high current switch performance, and in power flow through vacuum insulator housings led to the development of highly modular designs. This modular approach requires precise synchronization of the various modules and efficient methods of combining the power from these modules to drive a common load. The need to drive very low impedance loads led to effective ways to combine these modules in parallel. The Particle Beam Fusion Accelerator I (PBFA I)¹ and Saturn² are representative of these designs. The PBFA-II³ Li⁺ ion diode requires a higher voltage than provided by previous systems. The modules of this accelerator are arranged in stacked layers. Modules feeding each layer are added in parallel at a vacuum insulator housing and the outputs from several layers are then added in series by a self-magnetically insulated vacuum transmission line (MITL) to generate a 10 MV to 15 MV output pulse. Hermes III represents a new approach towards the efficient generation of higher voltages. It is designed to drive a 22-MV, 730-kA, 40-ns electron beam diode and combines conventional, modular pulsed power technology with linear induction accelerator concepts. High-power induction accelerator cavities are combined with voltage addition along a MITL to generate the desired output. This design differs from a conventional linac in that the voltages are added by the MITL flow rather than by a drifting beam that gains kinetic energy at each stage. This design is a major extrapolation of previous state-of-the-art technology represented by the injector module of the Advanced Test Accelerator and has proven to be efficient and reliable. The design and performance of Hermes III are presented together with a discussion of the application of this technology to the light ion beam inertial confinement fusion program.

INTRODUCTION

The field of pulsed power accelerator technology had its beginnings in the Sixties and arose from a need to develop intense, short bursts of x-rays. Initial applications included fast radiography of transient phenomena. These early systems were followed by higher power devices that created short pulses of bremsstrahlung radiation used to simulate the effects of radiation from a nuclear burst. Sandia's Hermes II⁴ accelerator is representative of this group.

The evolution of pulsed power accelerators has been driven by the programmatic needs of the different applications for this technology. Over the last decade or more the dominant trend has been towards higher power and shorter pulses. Limitations in high voltage, high current switches and in power flow through vacuum insulator feeds led to the development of highly modular systems. PBFA I and Saturn are representative of accelerators designed to produce multi-megampere pulses at about one megavolt. Each uses 36 separate pulse forming modules. In Saturn, the modules feed a common vacuum insulator stack. Their currents are added by a set of self-magnetically insulated vacuum transmission lines that deliver the power to an electron beam diode.

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PBFA II was built at Sandia National Laboratories for the light ion inertial confinement fusion (ICF) program. At peak power, it will produce a 100-TW, 15-ns, 1.5-MJ pulse to drive a 24-MV, Li⁺ ion diode. In this design, currents from the individual modules are added at each of the eight layers of a common vacuum insulator stack shown in Fig. 1. Each layer adds half of the current from nine separate pulse forming modules. A set of MITLs within the vacuum insulator stack add the voltages of the four top and bottom layers to generate 10-MV to 15-MV pulses. These two summed outputs feed a common ion diode located at the midplane of the vacuum insulator stack. Plasma opening switches located top and bottom just upstream of the ion diode provide the final stage of compression and voltage amplification to generate the 24-MV pulse required for the Li⁺ ion diode.⁵ The top and bottom opening switches must be accurately synchronized to maintain a symmetric power feed to the common ion diode load.

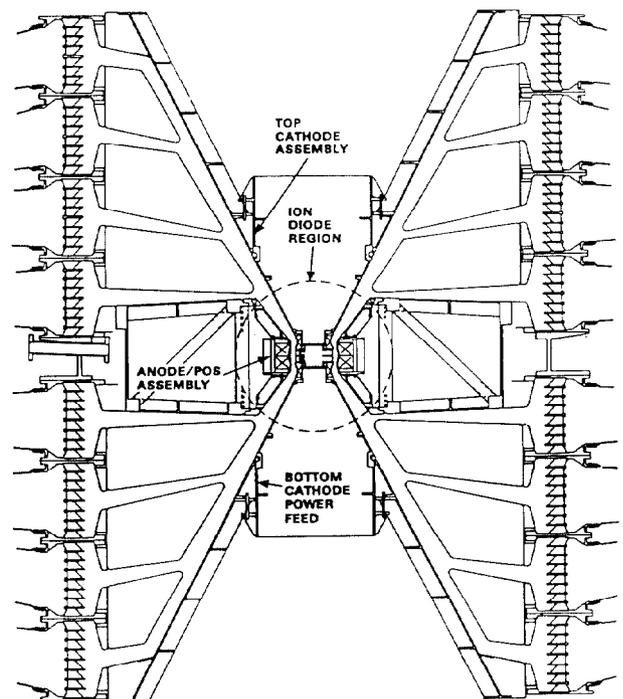


Fig. 1 PBFA II center section showing MITL structure that adds the voltages from the various levels and delivers the summed outputs to a common ion diode.

Hermes III is a 16-TW electron beam accelerator.⁶ It represents a new class of accelerators that combine state-of-the-art pulsed power designs with high power linear induction accelerator cavities and voltage addition along an extended MITL. This technology is well suited for applications requiring higher output voltage (tens of megavolts) pulses than in previous designs, with megampere level currents and short pulse widths (tens of nanoseconds). It produces the high output voltages without the inductive energy store and an opening switch used on PBFA II. This

paper describes the state of this new technology as represented by Hermes III. The design and performance of this accelerator are presented in Section II and Section III respectively. The extension of this technology to ion beam accelerators for the ICF program and other applications being pursued are discussed in Section IV.

THE HERMES III DESIGN

Hermes III is a new generation gamma ray simulator built at Sandia to provide an enhanced simulation fidelity capability for the nuclear weapons effects testing program. It generates a 22-MV, 730-kA, 40-ns pulse that powers an electron beam diode. When the electron beam is stopped in a high-Z target, it generates an intense burst of bremsstrahlung radiation. A drawing of Hermes III is shown in Fig. 2.

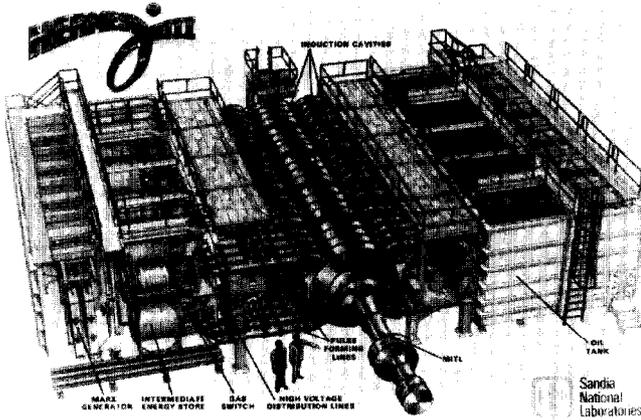


Fig. 2 The Hermes III accelerator.

Hermes III generates its output pulse by adding the pulses produced by eighty pulse forming modules in a specific parallel/series combination. The eighty individual 1.1-MV, 220-kA pulses are first added in groups of four to develop twenty 1.1-MV, 730-kA pulses that are then fed through high-power linear induction accelerator cavities. The induction cavities feed power along the length of a self-magnetically insulated vacuum transmission line which adds the cavity outputs to generate the 22-MV, 730-kA, 40-ns pulse. The output of this "adder MITL" is delivered to the electron beam diode by an "extension MITL". Figure 3 shows a cut-out view of the cavity/MITL system.

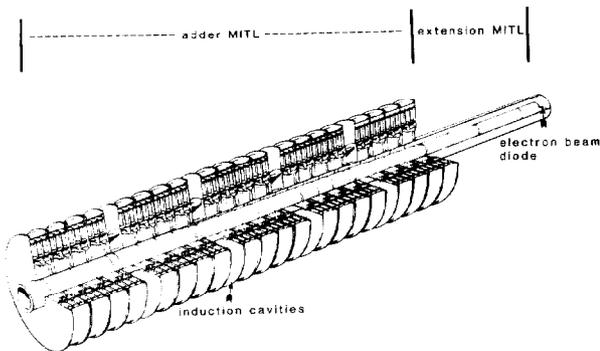
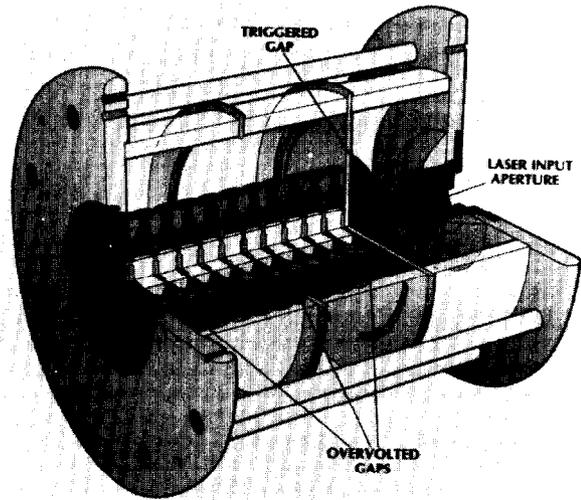


Fig. 3 Sketch showing inductive cavities, MITLs, and electron beam diode.

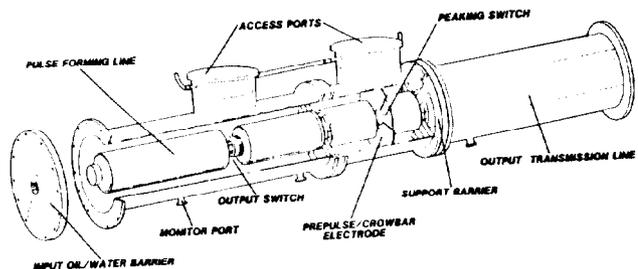
The eighty 1.1-MV pulses are generated by the synchronized switching of energy through several compression stages. The main energy store consists of ten 2.4-MV, 156-kJ Marx generators that are charged to ± 95 kV DC. The energy in the Marx generators is transferred, on command, to an intermediate energy store system consisting of twenty low inductance, water-dielectric capacitors. These self-contained coaxial units are arranged in pairs inside of the two oil-filled tanks that also house the Marx generators. The water capacitors are charged to 2.2 MV in ~ 950 ns.

The next compression stage is initiated by the command firing of twenty SF₆-insulated gas switches.⁷ These switches are each triggered by a ~ 15 -mJ laser pulse and provide for the overall synchronization of the accelerator. The output of a commercially available 900-mJ, 30-ns KrF laser unit is split into 20 different beamlets that are appropriately delayed and directed into the individual gas switches. A drawing of the multi-stage gas switch is shown in Fig. 4. The laser pulse enters the switch from one end initiating closure of the triggered stage. The remaining stages are overvolted and break down as the voltage initially across the full switch redistributes itself between gaps not yet closed. The development of these reliable, low jitter gas switches was crucial to the design of highly modular pulsed power accelerators.



4. Drawing of low jitter, multi-stage gas switch.

Each gas switch transfers energy from a water capacitor to four pulse forming lines (PFLs). A sketch of a PFL unit is shown in Fig. 5. The PFLs are five-ohm, coaxial, water-dielectric transmission lines. Each unit has a pulse-forming section, a peaking section, and an output section. Both the pulse-forming switch and the peaking switch employ self-closing water gaps. The peaking switch has a pre-pulse suppression electrode which is also part of a crowbar switch that shorts the high voltage electrode to ground and, thus, controls the output pulse width.⁸



5. Pulse forming line module.

The output from four PFLs are combined and fed to the adder MITL by one of the twenty induction cavities.⁹ Figure 6 is a sketch of a cavity cross section. Pairs of PFLs feed the left and right azimuthal transmission lines where their currents are summed. These summed pulses feed the inner azimuthal line where their currents are also added. The output of the inner azimuthal line is transmitted, through a vacuum insulator stack, to a vacuum transmission line that delivers the power to the adder MITL. The inductive isolation is provided by magnetic cores made from pre-annealed 2605CO Metglas ribbon.^{10,11}

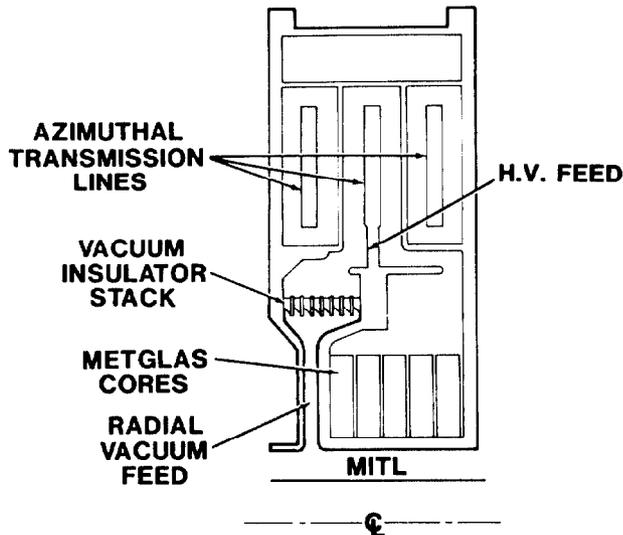


Fig. 6 Inductive cavity cross section showing azimuthal transmission lines that add the currents from four PFL modules.

The outer conductor of the adder MITL is formed by the surface of the cavity bores at a radius of 38.1 cm. This surface is interrupted at regular intervals by the cavity feed gaps. The inner conductor of the adder is formed by a cantilevered cathode stalk that is centered and aligned within the anode cylinder. The cathode stalk decreases in radius at each cavity feed along the length of the MITL, thus increasing the impedance of each MITL section. The design of the MITL system is a balanced design that requires equal power flow from each of the twenty cavities.¹² This implies that the same magnitude current flows through the entire system and that the impedance of the *n*th adder section is *n*-times the impedance of the first. The operating voltage at any location along the adder will thus be given by the addition of the voltages fed by all the cavities up to that point. The extension MITL is a constant impedance system that provides a matched output to the adder section. It includes a biconic taper that reduces the dimensions of the MITL radii to match those of the electron beam diode.

The electron beam diode is shown in Fig. 7. It is a coaxial design with an annular cathode that terminates the long cantilevered shank and a flat anode plate that terminates the extension MITL. An optimized Ti/Ta/C target is used to convert the electron beam energy to bremsstrahlung radiation.¹³

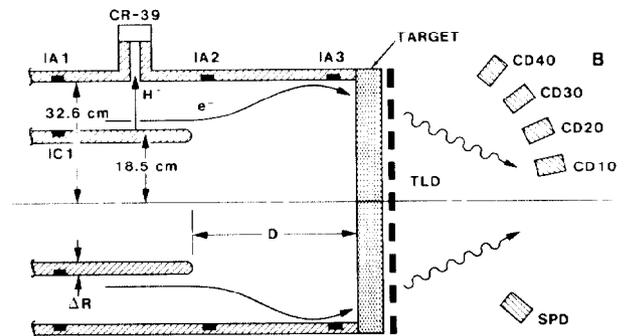


Fig. 7 Schematic of the annular electron beam diode located at end of the extension MITL.

DESIGN PERFORMANCE

The first full system shot on Hermes III was fired February, 1988. Over 400 shots were taken during the first year of testing; most at or near full power. Hermes III has met all of its performance requirements and became an operational facility one year ahead of schedule. It has fired as many as eight full power shots a day. The interval between shots is determined by experimental requirements and can be as short as twenty minutes if the accelerator vacuum is not breached to make changes to the electron beam diode. Although the design is complicated and highly modularized, Hermes III has proven to be an efficient and very reliable electron beam accelerator.

Synchronization of the eighty individual 1.1-MV pulses is critical to this design. Since the PFLs use self-closing water gaps, the overall system timing is determined by the triggered gas switches. Figure 8 shows the relative timing of the eighty 1.1 MV pulses obtained on a typical shot. One some shots, one or more of the pulses will drop out of the range of this narrow distribution due to some anomalous condition. These occasional "drop-outs" do not have a significant effect on the output pulse, however, because of the large number of input pulses used to generate the output waveform.

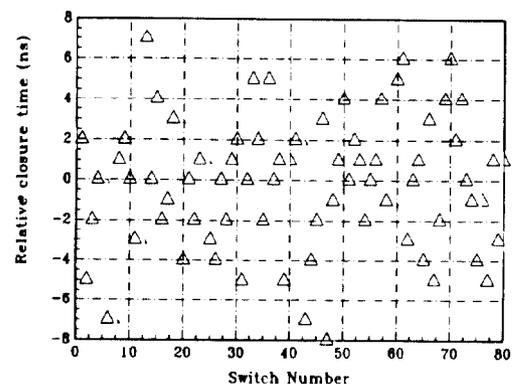


Fig. 8 Plot of the relative timing of the eighty PFL modules obtained on a typical shot.

The 17-m long, cantilevered cathode shank extends the length of the accelerator and forms the inner electrode of the coaxial "adder" and "extension" MITLs. Measurements indicate that the MITLs perform as designed. The electric fields are high enough that electrons are emitted everywhere along the length of the cathode shank. However, the

magnetic fields produced by the currents in the system are sufficiently large to prevent the electrons from reaching the anode, i.e., the MITL flow is self-insulated. The total current transported down the MITL thus has two components: a "boundary current" flowing along the MITL electrodes, and a "sheath current" consisting of electrons flowing in the vacuum gap close to the surface of the cathode shank. Measurements indicate that the total current is constant throughout the cavity/MITL/diode system. There is no evidence of any anomalous current loss. Peak voltage and current measurements indicate that each cavity contributes an equal amount of power to the output pulse. During the past year of operation the cavity/MITL system was disassembled on two occasions for inspection but have otherwise not required major maintenance.

Hermes III produces a peak dose rate of $\sim 7 \times 10^{12}$ Rads/sec² with a pulse width of 20 ns FWHM. The peak voltage at the diode is measured to be 19+2 MV by three indirect techniques that utilize parapotential flow theory, range of H⁺ ions and radiation output.¹⁴ The profile of the radiation distribution produced can be readily adjusted by changing the dimension of the anode-cathode gap in the diode. This gap can be varied over a wide range without significantly changing the load impedance. The radiation pattern produced can thus be tailored to the simulation program requirements while maintaining efficient energy transfer from the high voltage pulser to the electron beam load.

EXTENSIONS OF THE HERMES III TECHNOLOGY

Hermes III has proven to be an efficient and reliable electron beam accelerator. We have developed a conceptual design for a 47-MV, 1.2-MA, 60-ns electron beam accelerator based on the Hermes III technology. The bremsstrahlung radiation produced by this accelerator would be used to generate an intense neutron burst ($\sim 5 \times 10^{15}$ neutrons/pulse).

We also seek to apply this technology to ion beam accelerators for the ICF program. The Department of Energy is planning for a Laboratory Microfusion Facility (LMF) as the next major step in the national ICF program. Sandia's concept of a light ion beam driver for the LMF is based on the Hermes III technology. Each LMF accelerator module would deliver a ~ 32 -MV, 1.2-MA, 54-ns pulse to a Li⁺ extraction ion diode.^{15,16,17}

In an ion beam accelerator, the cantilevered shank that extends the length of the machine would form the positive electrode of the adder and extension MITLs. The electrons that form the MITL sheath current are emitted from the outer electrode. In an electron accelerator (negative polarity), the sheath electrons are all emitted from an equipotential surface. In an ion accelerator (positive polarity), this is no longer the case. The MITL flow in positive polarity is significantly more complex than in negative polarity, as shown by initial analytic calculations and particle-in-cell code simulations. A comparison of the sheath currents obtained from code simulations of a four stage system is shown in Fig. 9.¹⁸

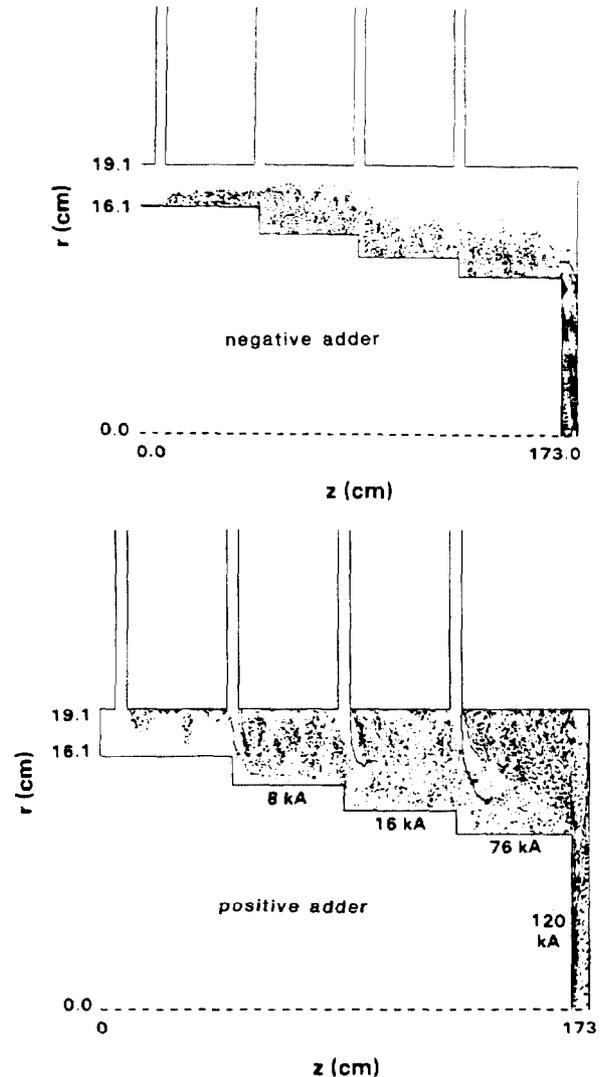


Fig. 9 MITL electron flow from simulations of four-stage negative and positive adders.

An experiment was conducted on Hermes III to investigate the feasibility of using existing hardware in a configuration suitable to power an extraction ion diode. The desired configuration was obtained simply by removing the cantilevered shank, rotating the twenty induction cavities 180 degrees about a vertical axis, and reinserting the shank. No other changes were necessary to make the inner MITL electrode positive. A reverse polarity electron beam diode was used as the load for this initial experiment. Results indicate that the power delivered by the twenty induction cavities was efficiently transported through the adder and extension MITLs. Measurements of the boundary and total currents were the principal diagnostics used in this experiment. No evidence of anomalous current loss was seen anywhere along the MITLs. Although we did not obtain a time resolved measurement of the voltage waveform at the load, peak voltages inferred from H⁺ ion range measurements indicate an 18-MV peak output at the diode for shots where this value would indicate efficient voltage addition.

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The majority of the power delivered by a ≥ 20 -MV MITL, in either polarity, is carried by the sheath current. In an electron beam diode this current forms part of the total diode current. Electrons emitted from the cathode surface at the anode-cathode gap provide the remaining diode current. In an efficient ion diode, the electron current must be reduced to the lowest value possible. This is accomplished using externally applied magnetic fields in the diode region to insulate the electron flow. Coupling power carried by the sheath current to an ion diode is, however, a much more complicated process than the coupling to an electron beam load. The complex electron flow predicted by computer simulations of a positive adder MITL may exacerbate this issue. Initial experiments using Hermes III to power an extraction ion diode are planned for this fall.

SUMMARY

The evolution of very high pulse-energy accelerators has advanced dramatically over the past two decades and has been driven by various programmatic needs. Limitations in high voltage, high current switches and in power flow through vacuum insulators led to highly modularized designs. Development of reliable, low jitter gas switches was critical for accurate synchronization of these multi module designs.

A series of accelerators built at Sandia were discussed as examples of how the pulse forming modules can be arranged in parallel, series, or parallel/series combinations to generate the output required for the specific application. Hermes III is a very reliable electron beam accelerator and generates the highest output voltage produced by a multi-terrawatt accelerator to date. Work is under way to extend this technology to higher voltage electron beam accelerators and to high-power ion beam accelerators. A key issue for ion beam applications relates to the efficiency of coupling power from the high voltage MITL to an extraction ion diode. A conceptual design of a light ion beam driver for the LMF has been developed. One LMF accelerator module would deliver ~ 3 times the power that Hermes III delivers to an electron beam diode assuming that efficient coupling between the MITL and ion diode is possible. Ion diode experiments with Hermes III operating in positive polarity are planned for this fall.

ACKNOWLEDGEMENTS

The number of people who have made key contributions to the advances in pulsed power accelerator technology described in this paper is too large to list them here. Included are personnel from government laboratories, private industry and universities in this country and abroad. I wish to acknowledge especially the contributions of Pulsed Sciences Inc. to the development of the Hermes III technology.

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