

OPERATION OF A FIVE-STAGE 40,000-CM²-AREA INSULATOR STACK AT 158 KV/CM

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Abstract

We have demonstrated operation of a 3.35-m-diameter insulator stack at 158 kV/cm with no total-stack flashovers on five consecutive Z-accelerator shots. The stack consisted of five +45°-profile 5.715-cm-thick cross-linked-polystyrene (Rexolite-1422) insulator rings, and four anodized-aluminum grading rings shaped to reduce the field at cathode triple junctions. The width of the voltage pulse at 89% of peak was 32 ns. We compare this result to a new empirical flashover relation developed from previous small-insulator experiments conducted with flat unanodized electrodes. The relation predicts a 50% flashover probability for a Rexolite insulator during an applied voltage pulse when $E_{\max} e^{-0.27/d} (t_{\text{eff}} C)^{1/10} = 224$, where E_{\max} is the peak mean electric field (kV/cm), d is the insulator thickness (cm), t_{eff} is the effective pulse width (μs), and C is the insulator circumference (cm). We find the Z stack can be operated at a stress at least 19% higher than predicted. This result, together with previous experiments conducted by Vogtlin, suggest anodized electrodes with geometries that reduce the field at both anode and cathode triple junctions would improve the flashover strength of multi-stage insulator stacks.

I. INTRODUCTION

Sandia National Laboratories is proposing to design and build a 40-MA z-pinch accelerator (ZX) for inertial-confinement-fusion, equation-of-state, plasma-physics, and high-energy-density-physics experiments. The machine would also serve as a testing facility for pulsed-power research required to develop higher current (~80 MA) drivers. The ZX design would build upon experiments performed on the Proto-II,¹ Saturn,² and Z³⁻¹¹ accelerators, which have delivered 5, 8, and 20 MA to z-pinch loads, respectively.

To optimize the ZX design, we are conducting a series of experiments to improve the understanding of the

performance of large-area multi-stage insulator stacks. Results of the first series of experiments are reported in Sec. II. In Sec. III, we use small-insulator-flashover data¹²⁻¹⁸ to develop a new empirical flashover relation. In Sec. IV, we compare the relation's predictions with Z-stack measurements, and previous results obtained by Vogtlin¹⁹ with anodized electrodes and an anode plug.²⁰

II. Z-STACK EXPERIMENTAL RESULTS

The Z accelerator³⁻¹¹ has thirty-six modules which deliver power to four insulator-stack levels at the accelerator's water-vacuum interface. Nine modules deliver power to each of the four levels. The source impedance of nine modules in parallel is 0.48 ohms. For the stack-flashover experiments, only the modules connected to the uppermost level were operated. This level, shown in Fig. 1, consisted of five +45°-profile 5.715-cm-thick 3.35-m-outer-diameter cross-linked-polystyrene (Rexolite-1422) insulator rings,²¹ and four 0.9525-cm-thick hard-anodized-aluminum grading rings.⁶ The stack electrodes and grading rings were shaped to reduce the field at cathode triple junctions 15% below the value that would have been obtained with flat electrodes. All insulator and electrode surfaces were machined to a roughness with a root-mean-square value $\leq 81 \mu\text{m}$.⁶

On five consecutive Z shots (#334-338), the total stack did not flash during the application of a 4.52-MV 93-ns-FWHM voltage pulse. The shots were taken at pressures between 6.1×10^{-6} and 1.8×10^{-5} torr. The stack had been subjected to a pulse with peak voltage ~3 MV on the previous 333 shots. After each of the 338 shots, the stack

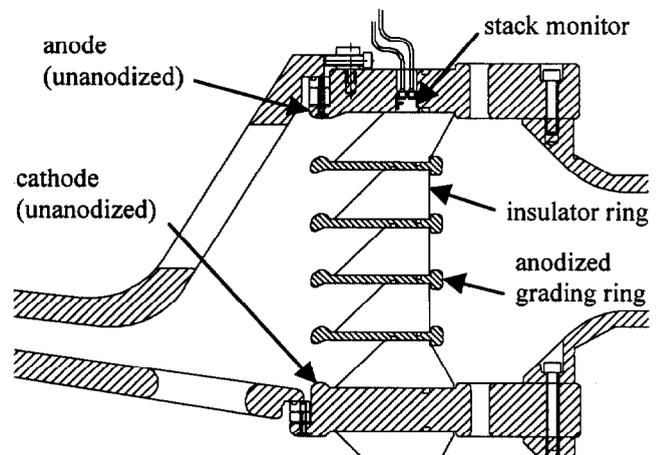


Figure 1. The uppermost stack level of the Z accelerator.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE JUN 1999	2. REPORT TYPE N/A	3. DATES COVERED -	
4. TITLE AND SUBTITLE Operation Of A Five-Stage 40,000-Cm2-Area Insulator Stack At 158 Kv/Cm		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Mission Research Corporation, Albuquerque, NM, USA		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited			
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.			
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15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	
			18. NUMBER OF PAGES 4
			19a. NAME OF RESPONSIBLE PERSON

was opened to atmospheric pressure, and the insulator rings were cleaned with Scotch-Brite™ (#96), ethyl alcohol, and TexWipes™ (TX 309). (The bottom ring was also regularly cleaned with 400-grit sandpaper.) None of the stack (or MITL) components were oiled for any of the shots.

Shots #334-338 were taken with no MITL electrodes or any other load hardware attached to the stack; hence the magnetic field at the plastic vacuum interface (~1 mT, due to displacement current) was orders of magnitude less than required for magnetic flashover inhibition. There were also no sources of charged particles or ultraviolet radiation, except for those inherent to the stack itself when operated at high voltage.

Six D-dot and three B-dot monitors were used to measure the stack voltage and current.²² All monitors were located on a 1.651-m radius, as shown in Fig. 1. The D-dots were located at 20, 100, 140, 220, 260, and 340 degrees; the B-dots at 60, 180, and 300 degrees. The six D-dot and three B-dot signal averages for shot #338 are presented in Figure 2.

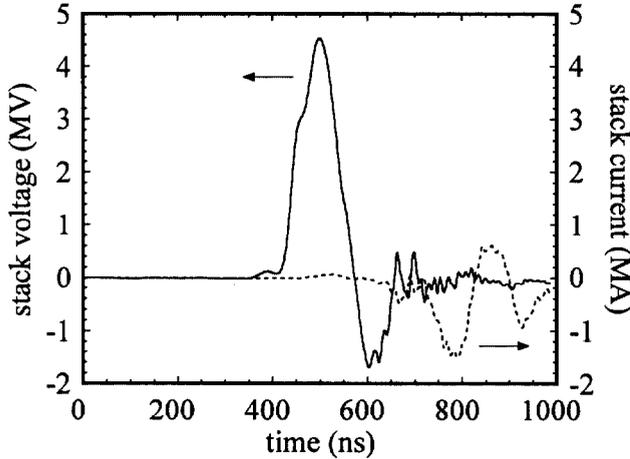


Figure 2. The stack voltage and current on Z-shot #338.

III. THE NEW RCM RELATION

To facilitate comparison of these results with previous measurements, we develop a new insulator-flashover relation. We begin by considering a large population of +45°-profile insulators, each with thickness d and unit length, subject to a voltage pulse $V(t)$ where $V(t) = 0$ for $t < 0$. We define $N_{\text{unit}}(0)$ as the size of the population and $N_{\text{unit}}(t)$ as the number of insulators that survive until time t without flashing. We make the simplifying assumption that the insulator failure rate is a function of the mean applied electric field $E(t) \equiv V(t)/d$, and that this function can be approximated as a power law:

$$\frac{1}{N_{\text{unit}}(t)} \frac{\partial N_{\text{unit}}(t)}{\partial t} = - \left(\frac{E(t)}{k} \right)^{\beta} \quad (1)$$

where β and k are independent of t . Integrating Eq. 1 gives

$$s_{\text{unit}}(t) = \exp \left(- \frac{1}{k^{\beta}} \int_0^t E^{\beta}(v) \partial v \right) \quad (2)$$

where $s_{\text{unit}}(t) \equiv N_{\text{unit}}(t)/N_{\text{unit}}(0)$ is the survival probability.

We now consider a large population of circular insulators, each with thickness d and circumference C (where C is greater than unit length), subject to the voltage pulse $V(t)$. We define $N(0)$ to be the size of the population, and $N(t)$ the number that survive until time t . We model each insulator as C insulators in parallel, each with thickness d and unit length.²³ Assuming the initiatory flashover mechanism operates independently in each of a ring's unit-length components, the survival probability $s(t) \equiv N(t)/N(0)$ can be expressed as:

$$s(t) = s_{\text{unit}}^C(t). \quad (3)$$

Combining Eq.'s 2 and 3 gives:

$$f(t) = 1 - \exp \left(- \frac{C}{k^{\beta}} \int_0^t E^{\beta}(v) \partial v \right) \quad (4)$$

where $f(t) \equiv 1 - s(t)$. The failure probability $f(t)$ equals 50% when

$$E_{\text{max}} \left(\frac{t_{\text{eff}} C}{\ln 2} \right)^{1/\beta} = k \quad (5)$$

where

$$t_{\text{eff}} \equiv \frac{1}{E_{\text{max}}^{\beta}} \int_0^t E^{\beta}(v) \partial v \quad (6)$$

is the effective pulse width.

We determine β and k empirically using the insulator-flashover results listed in Table 1. These were obtained with +45°-profile uncoated polymethyl methacrylate (PMMA) and cross-linked polystyrene (Rexolite) insulators operated at $\leq 10^{-4}$ torr, between flat parallel uncoated electrodes, with no external sources of charged particles or ultraviolet radiation, and a magnetic field due only to the displacement current that charges the capacitance defined by the insulator and its electrodes.¹²⁻¹⁸ This set of conditions matches those of the Z experiments with two exceptions: the Z stack included coated (anodized) grading rings, and the Z electrodes were shaped to reduce the field at cathode triple junctions. (We later compare the Table 1 data with the Z results, and to those obtained by Vogtlin with anodized electrodes and an anode plug.)

We use four constant-insulator-thickness subsets of the data in Table 1 to determine β : the 0.5-, 1.0-, 1.27-, and 1.5-cm results, which have the largest range of pulse widths. The value of β that best fits each set is approximately 10. Setting $\beta = 10$, we observe that, for the data in the Table for which $d \geq 0.5$ cm, k is approximately proportional to $\exp(0.27/d)$ where d is in cm. (This

Table 1. Summary of +45°-profile uncoated PMMA and Rexolite insulator-flashover measurements conducted at pressures $\leq 10^{-4}$ torr, with flat uncoated electrodes and no external sources of charged particles or ultraviolet radiation, and effectively no magnetic field.

reference	material	E_{\max} (kV/cm)	d (cm)	t_{eff} (μs)	C (cm)	k_{RCM}	$t_{89\%}$ (μs)	A (cm^2)	k_{JCM}
Anderson ¹⁵	PMMA	405	0.6	0.00979	20	228	0.0100	20	254
Glock ¹²	PMMA	295	1.257	0.00493	19.99	195	0.00533	35.54	175
Milton ¹⁴	PMMA	1100	0.254	0.000631	14.91	247	0.000778	5.36	395
Milton ¹⁴	PMMA	651	0.508	0.000507	14.11	242	0.000495	10.14	231
Milton ¹⁴	PMMA	523	0.762	0.000739	13.31	240	0.000920	14.35	213
Milton ¹⁴	PMMA	444	1.016	0.00112	12.52	230	0.00152	17.98	201
Milton ¹⁴	PMMA	417	1.27	0.00147	11.72	233	0.00178	21.05	197
Milton ¹⁴	Rexolite	417	1.27	0.00147	11.72	233	0.00178	21.05	197
Milton ¹⁴	PMMA	346	1.59	0.00736	10.71	235	0.00880	24.09	216
Milton ¹³	PMMA	313	1.27	0.00627	11.72	202	0.00797	21.05	190
Milton ¹³	PMMA	365	0.254	0.134	14.91	140	0.164	5.36	319
Milton ¹³	PMMA	315	0.508	0.163	14.11	209	0.181	10.14	299
Milton ¹³	PMMA	278	0.762	0.330	13.31	235	0.433	14.35	316
Milton ¹³	PMMA	242	1.016	0.487	12.52	231	0.619	17.98	298
Milton ¹³	PMMA	196	1.27	0.519	11.72	197	0.658	21.05	248
Milton ¹³	Rexolite	223	1.27	0.723	11.72	232	0.902	21.05	297
Vogtlin ^{16,18}	PMMA	522	0.5	0.000836	10.37	196	0.00103	7.33	202
Vogtlin ^{16,18}	PMMA	471	0.75	0.000836	9.58	210	0.00103	10.16	189
Yamamoto ¹⁷	PMMA	238	0.5	10.0	7.85	223	11.8	5.55	426
Yamamoto ¹⁷	PMMA	179	1.0	10.0	9.42	223	11.8	13.33	350
Yamamoto ¹⁷	PMMA	164	1.5	10.0	11.00	227	11.8	23.33	339

scaling must become invalid at sufficiently small values of d; it appears to fail at 0.254 cm when $t_{\text{eff}} \sim 0.1 \mu\text{s}$.)

Defining $k_{\text{RCM}} \equiv ke^{-0.27/d} = E_{\max} e^{-0.27/d} (t_{\text{eff}} C / \ln 2)^{1/10}$, we include in the Table values of k_{RCM} . The average value for PMMA, excluding both 0.254-cm results, is 221; the standard deviation is 16 (7%). The average value for Rexolite is 232. Hence for $d \geq 0.5$ cm, $f(t) \approx 0.5$ when:

$$E_{\max} e^{-0.27/d} \left(\frac{t_{\text{eff}} C}{\ln 2} \right)^{1/10} = \begin{cases} 221 \pm 16 & (\text{PMMA}) \\ 232 & (\text{Rexolite}) \end{cases} \quad (7)$$

We refer to Eq. 8 as the restricted Charlie Martin (RCM) relation since strictly speaking, it applies only to the data in the Table with $d \geq 0.5$ cm. We note that, for the PMMA measurements, t_{eff} ranges from 0.5 ns to 10 μs . Fig. 3 plots E_{\max} as a function of $e^{0.27/d} (t_{\text{eff}} C / \ln 2)^{-1/10}$.

To compare the data in Table 1 with the original JCM-scaling prediction²⁴ ($E_{\max} t_{89\%}^{1/6} A^{1/10} = k_{\text{JCM}}$, where $t_{89\%}$ is the full width in μs of the applied voltage at 89% of peak, and A is the area in cm^2 of the vacuum-insulator interface), we include in the Table $t_{89\%}$, A, and k_{JCM} . For the PMMA results in the Table with $d \geq 0.5$ cm, the average value of k_{JCM} is 256; the standard deviation is 71 (28%). Fig. 4 plots E_{\max} as a function of $t_{89\%}^{-1/6} A^{-1/10}$. It appears the data are more consistent with RCM scaling; however, we note the JCM relation was developed before most of the measurements in the Table were taken.

Assuming RCM scaling, Eq. 4 gives the cumulative failure probability for a single insulator ring (selected randomly from a large population.) Following ideas

developed by Smith²⁵, we calculate the RCM probability that all of the rings in an n-stage insulator stack flash between times 0 and t is given by:

$$F(t) = \int_0^t \dots \int_{t_{n-2}}^t \int_{t_{n-1}}^t n! \left(\prod_{i=1}^n \frac{\partial f_i}{\partial t_i} \right) \partial t_n \partial t_{n-1} \dots \partial t_1 \quad (8)$$

where

$$f_i(t) \equiv 1 - \exp \left(- \frac{C}{k^\beta} \sum_{j=1}^i \left(\int_{t_{j-1}}^{t_j} (g_j E(v))^\beta \partial v \right) \right) \quad (9)$$

and $t_0 = 0$. Assuming that, if one or more rings flash, the voltage redistributes itself equally across the remaining unflashed rings, and neglecting azimuthal-transit-time effects,²⁵ $g_j = (n/n+1-j)$. Imperfect redistribution would increase, and transit-time effects decrease, the effective values of g_j .

IV. APPLICATION OF RCM TO THE Z-STACK AND VOGTLIN RESULTS

Assuming Eq.'s 7-9 apply to the Z stack, we estimate that the total-stack-flashover probability is 81% for the conditions described in Sec. I. The measured value is $\leq 17\%$, which suggests $k_{\text{RCM}} \geq 276$, or $\geq 19\%$ larger than the value given by Eq. 7 for Rexolite. We speculate the difference is due to the anodized grading rings in the Z stack, and Z's electrode geometry, which reduced the field at cathode triple junctions.

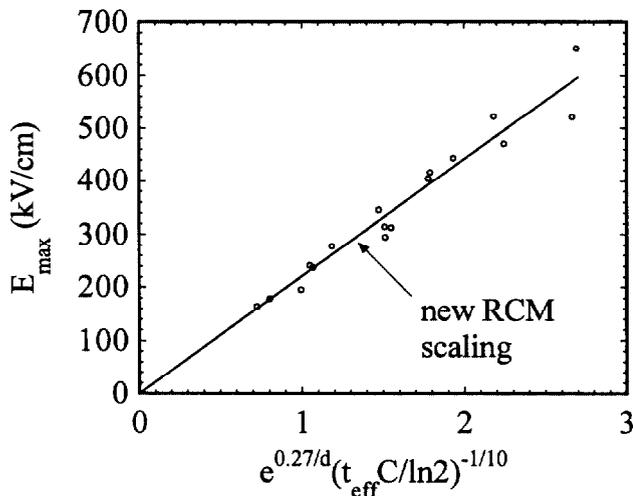


Figure 3. E_{\max} as a function of $e^{0.27/d} (t_{\text{eff}} C / \ln 2)^{-1/10}$ for the PMMA data in Table 1 with $d \geq 0.5$ cm. For these measurements, t_{eff} ranges from 0.5 ns to 10 μs .

Measurements by Vogtlin of the flashover-strength of an insulator with anodized electrodes and an anode plug¹⁹ (which reduced the field at the anode triple junction²⁰) also exceeded the value predicted by Eq. 7. Vogtlin observed that a 1-cm-thick +45° Lexan insulator with $t_{\text{eff}} = 67$ ns and $C = 8.80$ cm did not flash when $E_{\max} = 391$ kV/cm, indicating $k_{\text{RCM}} \geq 294$ under these conditions. (We note the flashover strength of Lexan is less than that of PMMA and Rexolite when tested under identical conditions, for $t_{\text{eff}} \sim 0.6$ μs .¹³)

The Z-stack and Vogtlin results suggest anodized electrodes with geometries that reduce the field at both triple junctions would improve the flashover strength of multi-stage insulator stacks. Additional experiments are needed to develop a new flashover relation more appropriate to these conditions.

V. ACKNOWLEDGMENTS

The authors wish to thank R. Altes, W. Beezhold, J. Boyes, R. Brockman, P. Corcoran, D. Dalton, T. Dinwoodie, G. Donovan, D. Fehl, G. Feltz, J. Fockler, C. Guthrie, D. Heath, C. Jeffs, K. Jones, J. Kellogg, M. Kernaghan, H. Kishi, J. Lee, M. K. Matzen, H. McGovern, C. Mendel, Jr., J. Mills, L. P. Mix, W. Moore, G. Mowrer, D. Muirhead, T. Mullville, M. Pelock, D. Petmecky, B. Peyton, J. Potter, J. Poukey, J. Powell, K. Prestwich, J. Ramirez, P. Reynolds, D. Rice, G. E. Rochau, T. Romero, J. H. Seamen, D. Seidel, A. Seth, A. Sharpe, J. Slopek, S. Speas, P. Spence, S. Summers, D. Van De Valde, R. Wavrik, L. Wilson, the Z and Saturn Operations Groups, C-Lec Plastics, Votaw Precision Technologies, Team Specialty Products, and Prodyn Technologies for invaluable contributions. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-ACO4-94AL85000.

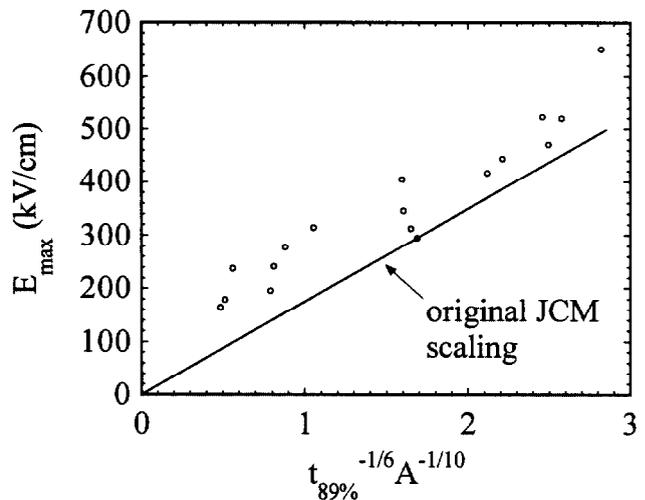


Figure 4. E_{\max} as a function of $t_{89\%}^{-1/6} A^{-1/10}$ for the PMMA data in Table 1 with $d \geq 0.5$ cm. The original JCM relation²⁴ ($k_{\text{JCM}} = 175$) is also plotted.

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