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1 GeV リニアック検討資料

1 GeV LINAC DESIGN NOTE

題目 (TITLE) Kilpatrickの放電限界に関するメモ

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概要 (ABSTRACT)

キルパトリックの放電限界は加速空洞の設計等に於て比較用の基準値として使用されている。この式の導出、有効性に関して調べた事をまとめてみた。

KEY WORDS:

Ion source, RFQ, DTL, CCL, Magnet, Monitor, Beam Dynamics,
Transport, Vacuum, Cooling
Klystron, Low level rf, High power rf, Modulator
Control, Operation, Radiation, Others

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Kilpatrick break down criterion に関するメモ

1. Introduction

高周波加速空洞などを設計する際、空洞表面の最大電場の値はKilpatrickの放電限界(ref.1)を単位としてその何倍という形で設定される事が多い。Kilpatrick は通常の電界放出により電極表面から放出される電子の数がイオンの multipactering により増加させられてbreak down が生じると考えた。

金属表面からの電界放出される電流量は$I(A/m^2)$は

$$I \propto E^2 \exp(-k_1/E) \quad , \quad E\text{ ; electric field} \qquad K_1\text{:const.}$$

電流量は衝突するイオンのエネルギーにも比例している。(ref.9)

$$I \propto W$$

したがって　$I \propto WE^2 \exp(-k_1/E)$　となる。

放電がある一定電流 Ic 以上で生じるならば、この境界値はK_2を定数として

$$K_2 = WE^2 \exp(-k_1/E) \quad (1)$$

と表せる。K_1とK_2は実験データに上式をあてはめて求められている。

$$k_1 = 1.7 \times 10^5 \text{ (volt/cm)},$$

$$k_2 = 1.8 \times 10^{14}$$

（RFの場合）

後述するV^*を単位としたW/V と V/V^* の関係

$$W/V = (2/\pi) V/V^* \quad (2)$$

V;電極に印加する電圧(volt),

W;イオンの到達可能な最大運動エネルギー

を（1）に代入する。（gap spacing や周波数の影響はすべてV^*の中に入っている。）

結果は(ref.2,3)

$$f = 1.643 \times 10^4 E^2 \exp(-0.085/E) \text{ 。} \quad (3)$$

単位は、f (MHz) , E(MV/cm)　である。

Eが大きいときは

$$E(MV/m) = 25\ [\ f(GHz)\ ]^{1/2} \quad (4)$$

で表せる。(ref.4)

（直流の場合）

$W/E = g$ という関係から

$$gE^3 \exp(-k_1/E) = k_2 \quad (5)$$

である。この時 $W=V$ である。

2. Meaning of V^*

1組の平行平板電極間に周期電場Eを印加する。極板間にイオンが存在するとそのイオンはEに振られて周期運動を行なう。イオンが極板にぶつかると表面から2次電子が放出される。従って特定の印加電圧と周期の時、Eの半周期でちょうど1つの極板からもう1つの極板表面までイオンが到達するような状況になると、半周期毎に2次電子生成が起こる。そして最終的には発生した電子群によりスパークが起こる。

以下、電場 $E = E_0 \sin \omega t$、電極間隔 g (cm)、イオン質量 M (kg)、イオン電荷 e ,極板は x=0 と x=g にあるとして ref.7&8 に従って上記の共鳴が生じる条件の計算を進めていく。

運動方程式は、

$$m\, d^2x/dt^2 = eE_0 \sin \omega t \qquad (6)$$

である。イオンが x=0 を離れる時の RF の位相を ϕ する。即ち時刻 $t=\phi/\omega$ で極板を離れる。そのさいの初速度は $dx/dt=0$ とする。

この初期条件での共鳴条件はイオンが他方の極板の位置 x=g に到着する時間差が $\Delta t=(2n-1)\pi/\omega$ (即ち時刻 $t=(2n-1)\pi/\omega+\phi/\omega$)になる事である。

(6) を1回積分する。

$$m\, dx/dt = -(eE_0/\omega) \cos \omega t + A$$

$t=\phi/\omega$ のとき $dx/dt=0$ なので $A=(eE_0 \cos \phi)/\omega$。従って

$$m\, dx/dt = (eE_0/\omega)\,(\cos \phi - \cos \omega t) \qquad (7)$$

再度積分する。そして $t=\phi/\omega$ のとき x=0 なので

$$m\, x = (eE_0/\omega)\,((t-\phi/\omega)\cos \phi + (1/\omega)(\sin\phi - \sin \omega t)) \qquad (8)$$

(7) に共鳴条件 $t=(2n-1)\pi/\omega+\phi/\omega$ を代入すると x=d でイオンの運動量 $P_{x=d}$ は

$$P_{x=d} = m\, dx/dt_{x=d} = 2eE_0 \cos \phi \quad . \qquad (9)$$

同様に(8)に共鳴条件 $t=(2n-1)\pi/\omega+\phi/\omega$, x=d を代入すると

$$m\, d = (eE_0/\omega^2)\,((2n-1)\pi\cos \phi + 2\sin\phi) \quad . \qquad (10)$$

運動エネルギーを W とすると、W は初期位相 ϕ にのみ依存する。即ち

$$W = P^2/(2m) = (2e^2E_0^2/m\omega^2) \cos^2\phi \qquad (11)$$

である。

ϕ に関する制限は以下の通り。

a). $t=\phi/\omega$ で $d^2x/dt^2>0$. 故に $0<\phi<\pi$ 。

b). $t=(2n-1)\pi/\omega+\phi/\omega$ で $dx/dt >0$. 故に $-\pi/2<\phi<\pi/2$ 。

従って $0<\phi<\pi/2$ となる。

(10) に $E_0=V_0/g$ を代入し V_0 に関する形に書き直す。

$$V_0 = \frac{m(g\omega)^2}{e} \frac{1}{(2n-1)\pi \cos\phi + 2\sin\phi} \qquad (12)$$

(11)より運動エネルギー最大は $\phi=0$ の時で

$$W_{max}=2e^2E_0^2/m\omega^2 \qquad (13)$$

となる。この時の印加電圧は(12)より、

$$V_0 = \frac{m(g\omega)^2}{e} \frac{1}{(2n-1)\pi} \qquad (14)$$

.

(14)式で　n=1、かつイオンが陽子の場合を Kilpatrick はV^*として使用した。
ただし $\omega=2\pi c/\lambda = c/ƛ$ (c ：光速) として

$$V^* = \frac{mc^2}{e} \frac{(g/ƛ)^2}{\pi} \qquad (15)$$

（蛇足）

(12)をϕ に関して微分して極値を求めると共鳴条件をみたすV_0の最小値が分かる。

$$dv_0/d\phi = -\frac{m(g\omega)^2}{e} \frac{(-(2n-1)\pi \sin\phi + 2\cos\phi)}{((2n-1)\pi \cos\phi + 2\sin\phi)^2} = 0.0 \qquad (16)$$

故に、

$$\cot\phi = (2n-1)\pi/2 \qquad (\text{即ち}n=1 \text{ の時 } \phi=32 \text{ deg.})$$

である。　従って、(12) に$\phi = \cot^{-1}(2n-1)\pi/2$ を代入する。

$$V_0(\min)= \frac{m(g\omega)^2}{e((2n-1)^2\pi^2+4)^{1/2}} \qquad (17)$$

同様に(12)に$\phi=\pi/2$ を代入することにより最大値が求まる。つまり

$$V_0(\max)= \frac{m}{e}\frac{(g\omega)^2}{2} \qquad (18)$$

この時、極板に到達したイオンの運動エネルギーは 0 である。
multipactering は印加電圧が$V_0(\min)$ と$V_0(\max)$ の範囲内のとき生じる。

3. The relation between W/V and V/V*

W_{max} をV^* で書き換えると

$$W_{max}=2e^2E_0^2/m\omega^2 = 2e^2V_0^2/(m\omega^2g^2) \qquad (\text{Jule})$$
$$= 2e\,V_0^2/(mg^2\omega^2) \qquad (\text{eV})$$
$$= (2/\pi)\,V_0\,(V_0/V^*)$$

故に、　$W_{max}/V_0 = (2/\pi)(V_0/V^*)$　(19)

(19)が Kilpatrick論文の Fig. 3の左側直線部分に対応する。周波数を下げるか、印加電圧Vを上げるとDC条件に近ずき W/V* は 1 に近づく。この時ϕは関係なくなる。

4. Kilpatrick limit

イオンとして陽子を考える。

$$V^* = \frac{mc^2}{e}\frac{(g/\lambda)^2}{\pi} = \frac{mc^2}{e}\frac{4\pi^2(fg)^2}{\pi c^2}$$

$$= \frac{938.3\times10^6\times4\pi}{(2.998\times10^{10})^2}(fg)^2$$

故に、

$$V^* = 1.31\times10^{-11}\, g^2 f^2 \quad (\text{単位は volt, g:cm, f:Hz}) \qquad (20)$$

$E_0 g=V_0$ と(20)を(19)に代入して整理すると

$$W_{max} = 4.85\times10^{10}\, E_0{}^2/f^2 \qquad (eV) \qquad (21)$$

(21) を (1)式、$WE^2\exp(-k_1/E)=k_2$ ($k_1=1.7\times10^5$ volt/cm, $k_2=1.8\times10^{14}$)
の中に代入すれば $f(MHz)=1.64\times10^4 E^2\exp(-0.085/E)$ (E:MV/cm)が求まる。

5. Recent data

SLAC で測定されたS,C 及び X-band cavities (disk-loaded type)の Peak break down surface field の周波数依存性 (ref.5)は

$$E(MV/m) = 195\,[\,f(GHz)\,]^{1/2} \qquad (22)$$

である(Fig.1を見よ)。絶対値は（2）式の4倍である。

さらにITEP(ref. 6) により球形及び円盤状の電極をもちいたsparking limit の測定がある。($f=6.25$MHz,10^{-3}-10^{-4} Pa) 2枚の円盤状電極の結果は Kilpatrick の結果とよく一致し銅の球面状電極では放電限界は高い。しかし後者の場合でもギャップ間隔が広いほど放電電圧は減少している。(Fig.2)

電場が非常に高くなった場合、直接的な電子の電界放出が効いてくる。Fowler-Nordheim 方程式 (ref.5)によれば GV/m のオーダーで有意になる。(Fig.3)
RFの波長が 1cm (300 GHz)位になると高周波による表面加熱 (ref. 5)により電子が出てくる。(Fig.4)

(参考文献)

ref.1 W.D.Kilpatrick , Rev. Sci. Inst. 28 (1957) 824
ref.2 S.W.Williams, et al. '79 LINAC conf. 144
ref.3 S.W.Williams, et al. IEEE Trans. Nucl. Sci. 28 (1981) 2967
ref.4 P.B.Wilson, SLAC-PUB-3674 (1985) 18
ref.5 G.A.Loew, SLAC-PUB-4647 (1988) 2

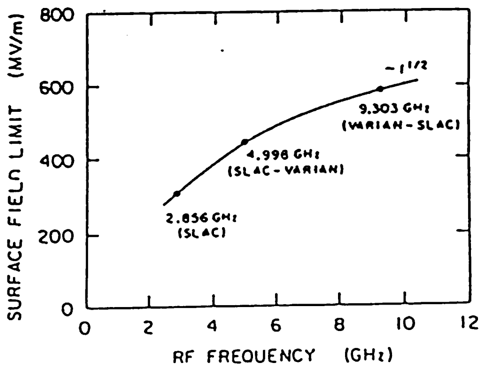
ref.6 A.V.Bodylev et al. ITEP 156-88
ref.7 A.J.Davis MPS/Int. LIN 69-13 (1969)
ref.8 S.Hunphries Jr. "Principles of Charged Particle acceleration" (1986) John Wily & Sons
ref.9 H.C.Bourme et al. Phys. Rev. 92 (1953) 847

Table ~~9~~ 1. Experimentally obtained gradients.

	S-band Disk-loaded ($2\pi/3$-mode)	S-band With nose cone (π-mode)	C-band Half-cavity	X-band Half-cavity	X-band Disk-loaded ($2\pi/3$-mode)
Frequency, f (MHz)	2856	2858	4998	9303	11424
Total length (cm)	24.5	10.5	1.507	0.806	26.25
Filling time* (μs)	0.77	1.0	0.172	0.082	0.028
Pulse length (μs)	1.5-2.5	1.5-2.5	3.5	3.8	0.025†
Peak power input (MW)	~ 47	~ 10	0.8	1.2	200†
Peak surface field, E_s (MV/m)	312	340	445	572	305†
Corresponding traveling-wave accelerating field‡	144	157	205	267	140†

104.97mm 60.02mm 32.2mm

*For critical coupling in the case of standing-wave structures.
†Preliminary results.
‡Assuming SLAC structure, working in the traveling-wave mode, in which $E_s/\overline{E}_{acc} = 2.17$.



~~Fig. 5.~~ Peak breakdown surface fields measured as a function of frequency.

Fig. 1

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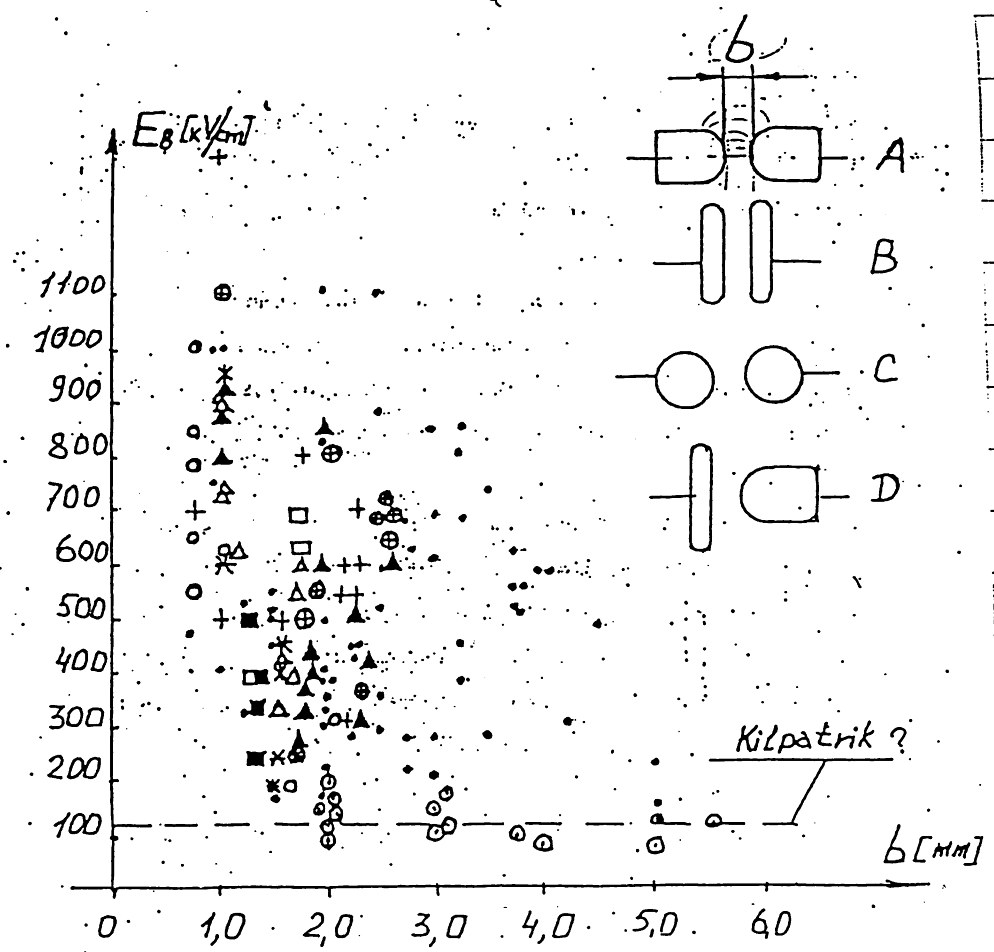

Fig. 2

~~Fig. 4~~. Electric field strength of the first breakdown: • – copper electrodes (A,C,D); ⊙ – copper electrodes (B); o – copper electrodes with Ti – coating (B); □ – copper electrodes with W – coating (C); ■ – duralumin electrodes with W – coating (C); Δ – copper electrodes with Mo – coating (C); ▲ – duralumin electrodes with Mo – coating (C); ✱ – copper electrodes with stainless steel coating (C); ⊕ – duralumin elecrodes with stainless steel coating (C); + – copper electrodes with Ni – coating (C); ⊕ – duralumin electrodes with Ni – coating (C).

Field emission current density
(Fowler-Nordheim equation)

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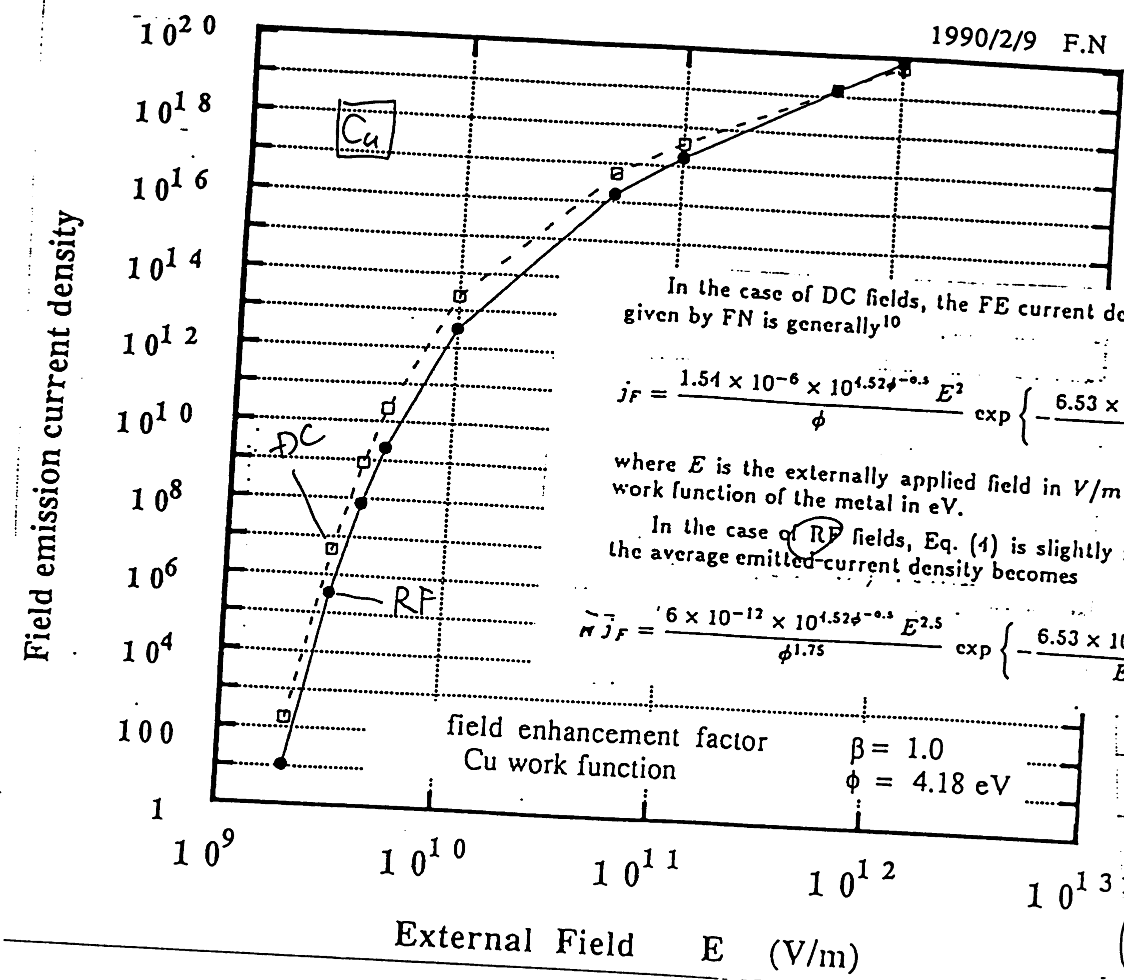


In the case of DC fields, the FE current density in A/m^2 given by FN is generally[10]

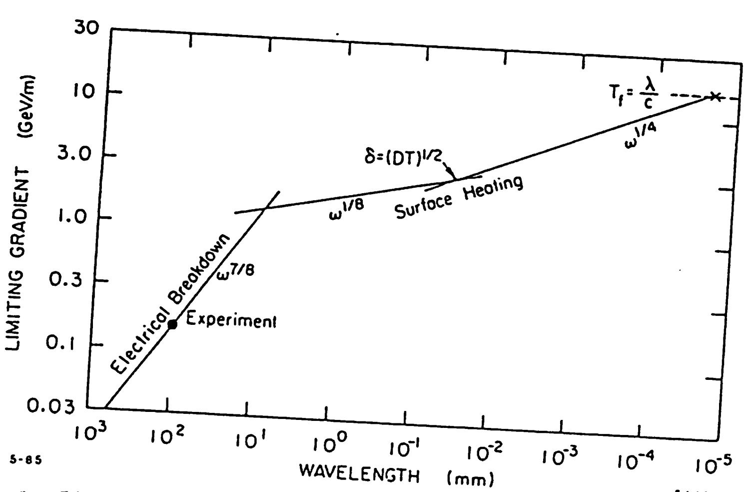
$$j_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\phi^{-0.5}}\, E^2}{\phi} \exp\left\{ -\frac{6.53 \times 10^9 \times \phi^{1.5}}{E} \right\}, \quad (4)$$

where E is the externally applied field in V/m and ϕ is the work function of the metal in eV.

In the case of RF fields, Eq. (4) is slightly modified and the average emitted-current density becomes

$$\bar{j}_F = \frac{6 \times 10^{-12} \times 10^{4.52\phi^{-0.5}}\, E^{2.5}}{\phi^{1.75}} \exp\left\{ -\frac{6.53 \times 10^9 \times \phi^{1.5}}{E} \right\}. \quad (5)$$

Fig. 3



~~Fig. 3~~. Limitations on gradient as a function of wavelength due to electric field breakdown and surface heating in a SLAC-type disk-loaded structure.

Fig. 4

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THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 28, NUMBER 10 OCTOBER, 1957

Criterion for Vacuum Sparking Designed to Include Both rf and dc*

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(Received May 31, 1957)

An empirical relation is presented that describes a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and rf or dc voltages are used. The criterion applies to a range of surface gradient, voltage, gap, and frequency that extends over several orders of magnitude. Current due to field emission is considered necessary for sparking, but—in addition—energetic ions are required to initiate a cascade process that increases the emitted currents to the point of sparking.

SPARKING is defined, for the purposes of this paper, as an abrupt major dissipation of stored electrical energy across a gap between two metal electrodes. Vacuum is to be considered in terms of a gaseous mean free collision path that is greater than the electrode-gap spacing; Paschen's rule relating electrical breakdown to gap and pressure is not applicable. The proposed criterion concerns "practical" vacuums of 10^{-3} to 10^{-7} mm Hg pressure, and metal electrodes that are not especially prepared, and does not include the presence of external magnetic fields. Under these circumstances, vacuum sparking generally occurs at much lower voltages than would be expected if field emission were the mechanism for initiation.

A concentrated effort was focused on vacuum sparking at 200 Mc, from which the following principal conclusions emerged[1]:

(a) At 200 Mc, no vacuum sparks occur below a threshold electrode-surface gradient.

(b) An inherent total (finite) number of vacuum sparks is characteristic of a particular electrode-surface gradient. As the gradient is increased, the inherent total becomes larger rapidly, apparently exponentially—the exponential coefficient determines the rate of "cleanup" or the "cleanliness" of the electrode surfaces. Therefore a conditioning process can apparently elevate the threshold.

(c) Different electrode metals—Pb, Cu, Al, Au, Mo, Rh, and C—have similar thresholds with only minor variations. However, if there are small traces of oil on the electrodes, the exponential coefficient is very large, and a deluge of sparks occurs above the threshold.

(d) The maximum energy of an ion incident on an electrode is severely limited by the applied frequency—

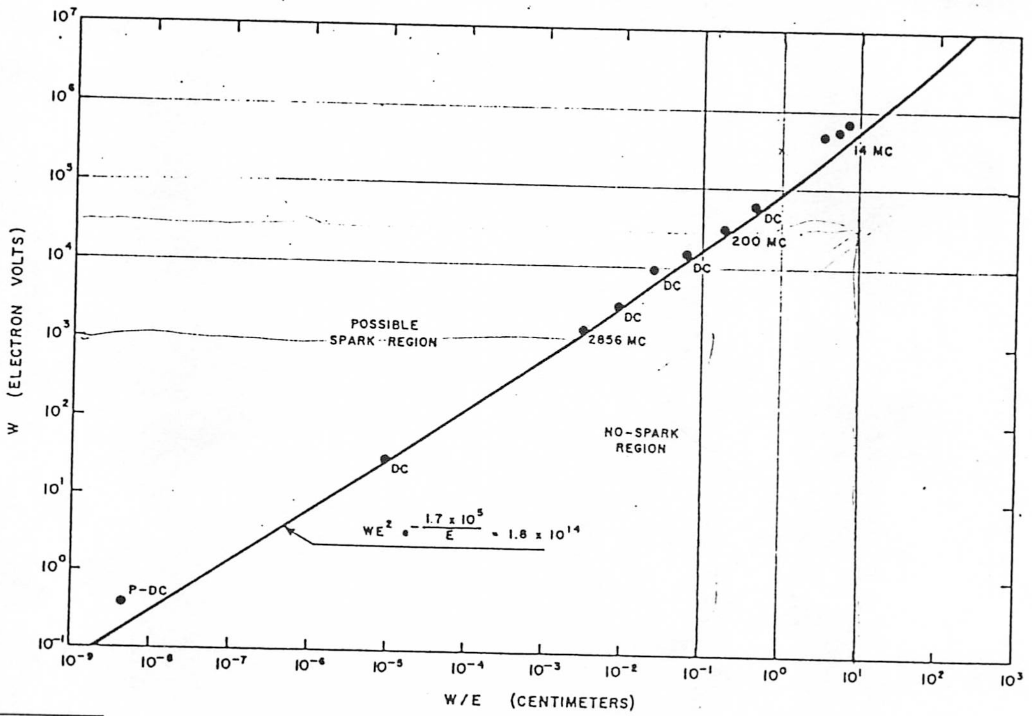

FIG. 1. W is the maximum ion energy at the cathode, in electron volts. For dc, W corresponds to the applied voltage, and W/E is the gap spacing for plane parallel fields. For rf, W is a function of frequency and gap (see text).

* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] W. D. Kilpatrick, "Sparking and x-rays in a mercury-pumped vacuum system," UCRL-1907 (August, 1952).

this effect was later used to separate gradient and voltage effects.

A criterion was constructed that utilized several investigators' experiences, data, and theories.[2–5] Consider the probability of field-emitted electrons,[6] together with a linear dependence of secondary-electron emission upon ion energy.[7] Then there follows

$$W[E^2 \exp(-K_1/E)]=K_2,$$

where W is the maximum possible ionic energy (dc or rf) in electron volts, and E is the electric cathode gradient. K_1 was established as 1.7×10^5 volts per cm, and K_2 as 1.8×10^{14}. This criterion includes rf, dc, and pulsed dc, and specifies an upper limit for no vacuum sparking. The above relationship of $W\sim E$ is presented graphically as Fig. 1 and Fig. 2.

If is difficult to compare this result with those of other investigators in the vacuum spark field, because of the consideration here of the existence of a threshold rather than of the degree or probability of sparking. However, pertinent dc data are available from Kisliuk[8] and Beams,[9] and from check points by the author.[10]

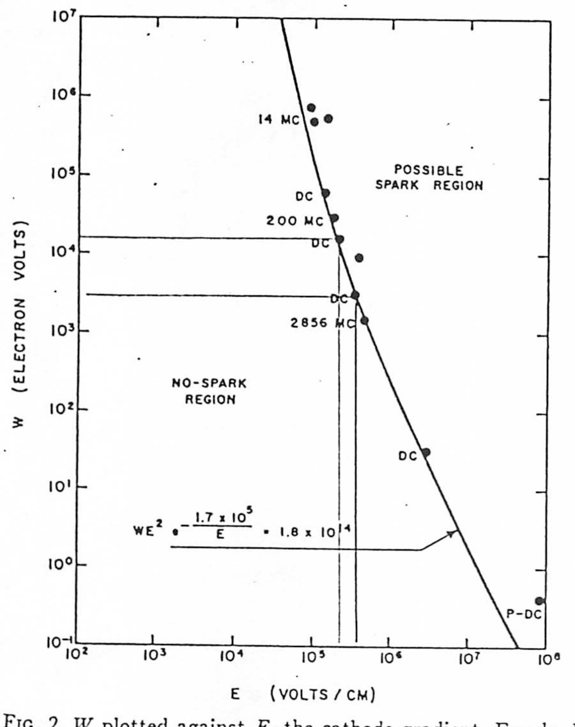

FIG. 2. W plotted against E, the cathode gradient. For dc, W corresponds to the applied voltage; for rf, W is a function of frequency and gap.

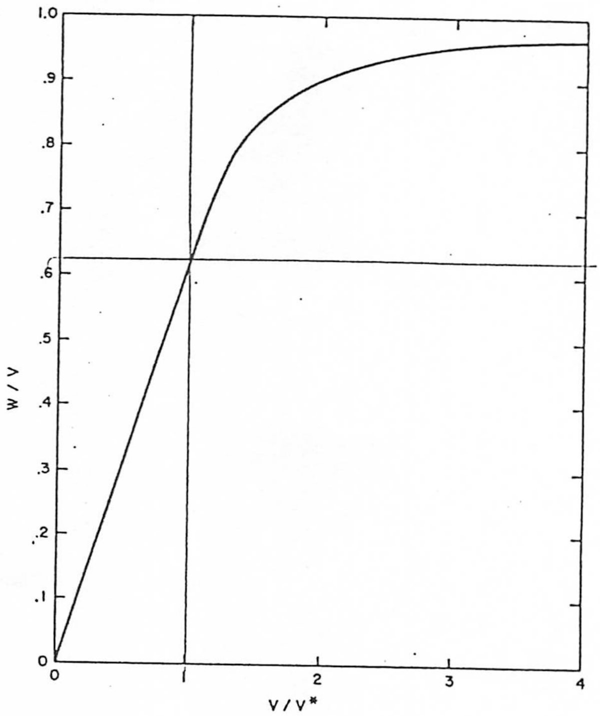

FIG. 3. Graph for ion transit-time correction. For plane parallel fields, $V^*=(g/\lambda)^2M_0c^2/\pi q$. For computing the maximum cathode ion energy, where $\nabla\cdot E$ is not ≈0, the calculation of W or V^* is without reference.

For pulsed dc, data by Dyke and Trolan[11] can be interpreted as a combination of cathodic evaporation (equivalent to energy transfer by ionic bombardment) and field gradient, where both are required to produce vacuum sparks. In the rf case, the maximum possible ionic energy must include transit-time and phasing effects. Figure 3 is included for estimating W when voltages V of frequency f are applied to gap g. The quantity V^* is introduced for dimensionless units of applied voltage V and is defined as

$$V^*=(g/\lambda)^2(M_0c^2/\pi q)$$

where $\lambda=\lambda/2\pi$, $\lambda(=c/f)$ is the propagation wavelength in free space, and q is the elementary charge of a particle with M_0c^2 rest energy in electron volts (M_0 specified throughout as the mass of atomic hydrogen).[12] Threshold vacuum sparking data for rf are available from Panofsky,[13] Chupp and Heard,[14] and Kilpatrick.[1] Con-

[2] L. Cranberg, J. Appl. Phys. 23, 518 (1952).
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[11] W. P. Dyke and J. K. Trolan, Phys. Rev. 89, 799 (1953).
[12] For derivation of a similar equation for electron transit-time multipactor, see Mullett, Clay, and Hadden, "Multipactor Effects in Linear Accelerators and Other Evacuated RF Systems; and a New Cold Cathode Valve," Atomic Energy Research Establishment (AERE GP/R 1076, H.D. 983) Harwell (1953).
[13] W. K. H. Panofsky (private communication, concerning sparking at 200 Mc with details in UCRL-2321, 11, September, 1953).
[14] W. W. Chupp and H. G. Heard, "Spark damage and high-voltage breakdown of metals in vacuum at 14 megacycles," UCRL-1962, Jan., 1954.

sistent with the sparking criterion and $V/V^* \leq 1$, the threshold voltage varies as the square of the applied frequency.

The vacuum spark described here possesses many properties similar to those of a conventional gas discharge between metal electrodes, but the generated gas has a transient pressure as well as a spatial distribution during the spark onset. It is also possible to raise the threshold slightly above the criterion level by outgassing or by dissipating gas-generating impurities from the electrode surfaces.

ACKNOWLEDGMENTS

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Method for the Generation of Very Fast Light Pulses

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(Received May 31, 1957; and in final form, July 22, 1957)

A method is described in which a visible or infrared light beam is repeatedly reflected between a rotating and stationary mirror system. The resulting sweep speed is proportional to the number of such reflections. Light pulses of 4×10^{-8} sec duration were measured. A considerable increase in the sweep speed appears feasible. Various applications of the system are mentioned.

Light chopping devices using rotating mirrors to measure the lifetime of excited states or the transient response of detectors are applicable to a wide range of radiation wavelengths. The minimum achievable light pulse width is, however, limited to several tenths of a microsecond for systems of moderate complexity. Pulse widths as small as 10^{-9} sec have been attained, albeit with a system requiring air turbine drive, shaping slit widths of 0.02 mm, and a flash lamp source with resulting limitations to duty cycle and spectral range.[1] There still exists, therefore, a need for a simple method of generating fast pulses of light in a wide range of the spectrum. The following system yields, for given conditions of rotary speed and slit definition, considerably narrower pulse widths.

The method consists of surrounding a rotating multisided mirror by a set of stationary mirrors (see Fig. 1). This assembly is so adjusted that the collimated light from the source is repeatedly reflected between the central and the stationary mirror planes. Each face of the mirror rotating with angular velocity ω adds 2ω to the rotational speed of the emerging light beam. If δ is the linear extent of an intensity distribution in the image field, the corresponding sweep time τ of the light pulse is then given by

$$\tau=\delta/2N\omega R \quad (1)$$

where N is the number of faces on the rotating mirror and R its distance from the image. In addition to the internally reflected beam, one obtains also, at intermediate mirror positions, a singly reflected beam. These two images can, however, be separated by inclining the last stationary mirror somewhat so that the beams sweep in different planes.

The hexagonal arrangement shown in Fig. 1 was used to measure the very short time constants for the rise and decay of certain photoconductive processes such as occur with gold-doped germanium in response to radiation between 2 and 9 μ. Application of the system to the infrared has, of course, the advantage that intensity losses amount to only a few percent, even

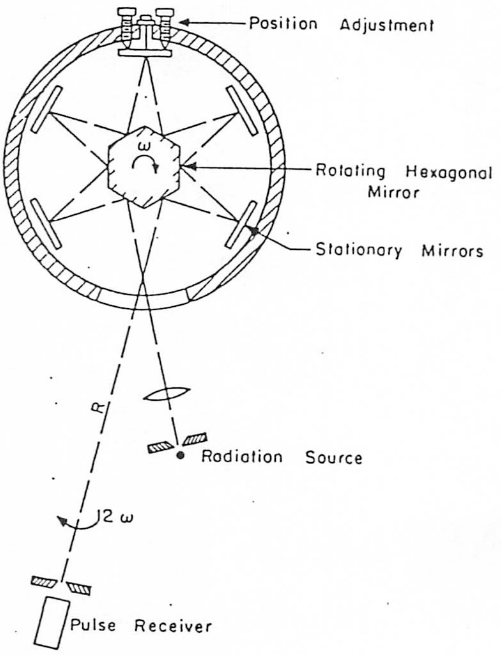

Fig. 1. Scheme for the generation of very fast light pulses.

[1] Cladis, Jones, and Wickersheim, Rev. Sci. Instr. 27, 83 (1956).

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VOLTAGE BREAKDOWN IN A 420 MHZ RFQ STRUCTURE*

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Summary

Designs for Radio Frequency Quadrupole (RFQ) accelerators of reasonable length require operation with surface fields above the threshold of Kilpatrick's Sparking Criterion.[1] A cavity was designed using SUPERFISH to test the validity of this criterion and to determine operating limits for the Los Alamos Proof-of-Principle (POP) RFQ. The testing was done near 420 MHz, with varying qualities of surface finish on the electrodes. The experimental set-up and procedure are described, as are the data and results. A method of calibrating the test is presented.

Introduction

The experimental series known as the Sparking Test has been completed. The usefulness of this test relates to the focusing-gradient selection and voltage-breakdown safety factors for RFQ designs near 420 MHz. The data also are applicable to general accelerator design where high fields are a concern.

An RFQ's expected performance is strongly dependent on the maximum surface field chosen for its design. It is important to select the highest field levels consistent with avoiding voltage breakdown. As the operating field increases, the radial acceptance, the rate of energy gain, and the current-carrying capacity are all increased.[2] Higher surface fields also allow for shorter accelerator designs.

The series comprised three tests. In the first, the high-voltage electrode finish was a machined surface hand-polished with 320-grit aluminum oxide paper. These electrodes were chemically polished to remove a mil of the surface for the second test. For the third measurement, these electrodes had about a mil of copper electroplated onto the surface. In each case, measurements were made to determine the surface rms microfinish and the breakdown fields at 420 MHz.

Background Information

For this work, sparking is defined as an abrupt change in the dissipation of energy stored as electric field across a gap between electrodes. The field magnitude required to initiate sparking depends on the electrode geometry, RF frequency, vacuum properties, and the nature and condition of the electrode surfaces. For gradients less than 10 MV/cm, the electron current caused by field emission is small. Field-emitted electrons in the gap, however, accelerate to strike the cathode, causing the emission of neutral gas atoms and electrons from that surface. The result is a localized expanding volume of increasing gas pressure, ionization within this volume, increased emission from back-bombardment, more gas, more ions, and so on. Such a cascade process may result in spark formation, causing an abrupt change in the stored energy to occur.

Kilpatrick's Sparking Criterion defines the frequency for which sparking may occur at a given gradient:

$$f = 1.64 \times 10^4 E^2 e^{-0.085/E}$$

where
f = frequency in MHz
E = gradient in MV/cm.

Thus, at 420 MHz, sparking is predicted at 19.7 MV/m. The conditions for which this Criterion applies are:

- single-gap sparking
- no effects involving the quantity of stored energy
- vacuums of 10^{-3} to 10^{-7} mm mercury
- metal electrodes not specially prepared
- no external magnetic fields.

The usefulness of this relation is that it determines a threshold below which no sparking should be observed during, or prior to, conditioning of the electrodes. This lower limit may be raised by procedures such as outgassing, electrode preparation, or spark cleanup.

The work presented here differed from Kilpatrick's test in several respects. First, the RFQ configuration had not one gap but four, as shown in Fig. 1. Second, the magnetic field component near the electrode tips was nonzero, although small. Third, the metal electrodes were prepared to maximize the field stand-off. Thus, the results were not directly correlative to Kilpatrick's. Rather, Kilpatrick's was used as the unit of measure for a test that employed a special geometry and nonexotic but modern vacuum and fabrication technique.

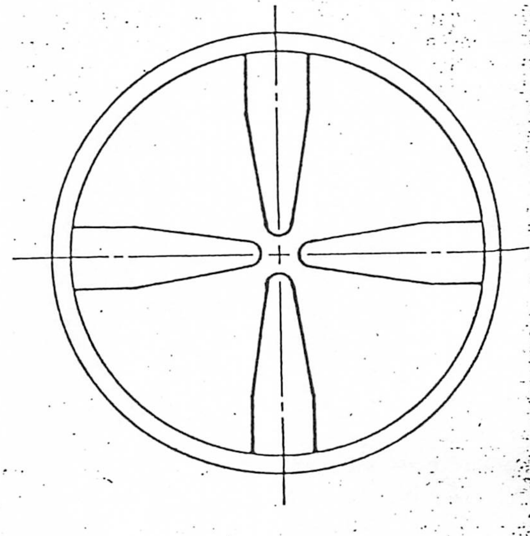

Fig. 1. Sparking cavity configuration.

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