CONTINUED MONITORING OF THE CONDITIONING OF THE FERMILAB LINAC 805 MHZ CAVITIES*

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Abstract

We have reported previously on the conditioning of the high-gradient accelerating cavities in the Fermilab Linac [1, 2, 3, 4]. Automated measurements of the sparking rate have been recorded since 1994 and are reported here. The sparking rate and the fraction of beam pulses lost to RF faults continue to decline. X-ray data from the cavi-ties suggest a slight worsening of the surfaces.

INTRODUCTION

Fermilab commissioned the seven, high-gradient 805 MHz RF accelerating modules in 1993, which gave this Linac the ability to send 400 MeV H-Minus ions to the Fermilab Booster. In order to achieve the desired acceleration, gradients of up to 8 MV/m were required, which led to maximum surface gradients of nearly 40 MV/m: 1.4 times the “Kilpatrick Limit”. These high fields caused some concern about RF breakdown leading to beam loss and to excessive X-ray exposure.

After seventeen years, the change in the rate of these breakdowns has stabilized at a level well below the original specifications.

THE MEASUREMENTS

Automated measurements of the sparking rate of each of the seven 805 MHz RF cavities in the 400 MeV Fermilab Linac have been collected since April 1, 1994. Also, we have automatically recorded the number of beam pulses lost each day, presumably due to RF breakdown in one or more of the cavities, beginning in 1994.

We have measured the X-ray production rate as a function of the power levels in one cavity on several occasions over these years.

Sparking Rate

The sparking rate is measured continually at the 15 Hz repetition rate of our RF system using an automated DAQ computer program. These data are recorded daily. We record the number of RF pulses for each of the seven 805 MHz cavities and the number of times an RF pulse at that cavity was ruined by an RF breakdown/spark. We have experimented with various ways of detecting sparks in the cavities, and have determined that watching for abnormal reverse power from the cavity is the most reliable.

The Overall Rate

Table 1 shows the median number of sparks per day for each of the years we have been accumulating data. Usually, there are about 1.296x10^6 RF pulses in a day (24 hours at 15 Hz pulse repetition rate).

Table 1: Median number of sparks per cavity per day

Year	Days	M1	M2	M3	M4	M5	M6	M7
1994	245	75	*	105	33	40	14	0
1995	307	56	*	63	13	20	11	1
1996	295	126	35	44	14	27	10	1
1997	236	93	25	30	9	22	6	1
1998	153	87	10	12	11	12	8	2
1999	237	51	11	23	7	10	5	1
2000	267	40	21	19	4	8	8	0
2001	268	61	12	22	3	9	6	0
2002	306	44	21	43	6	5	9	0
2003	244	27	19	41	7	9	9	0
2004	238	*	6	31	3	9	13	0
2005	296	17	4	39	3	12	15	0
2006	252	9	2	18	1	4	6	0
2007	211	5	1	13	2	5	6	0
2008	285	5	1	16	4	7	7	0
2009	277	2	1	13	1	4	6	0
2010	167	2	1	7	1	3	3	0

* Missing data. “0” indicates that more than half of the days had no sparks.

The “Days” column represents the number of days counted—a minimum number of 7E5 RF pulses in a day is applied. There is no indication that sparking is correlated among the cavities. Thus, one would expect that the sum of the values in each row represents the median number of sparks in the entire Linac per day.

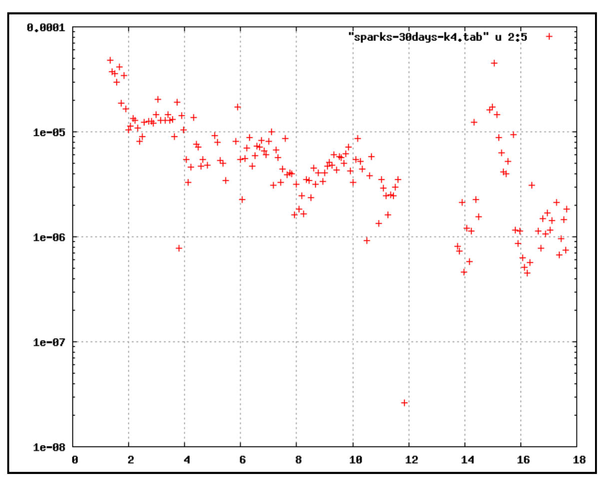

Figure 1: Module 4 (of 7) sparking rate per 30-day interval, since 1993.

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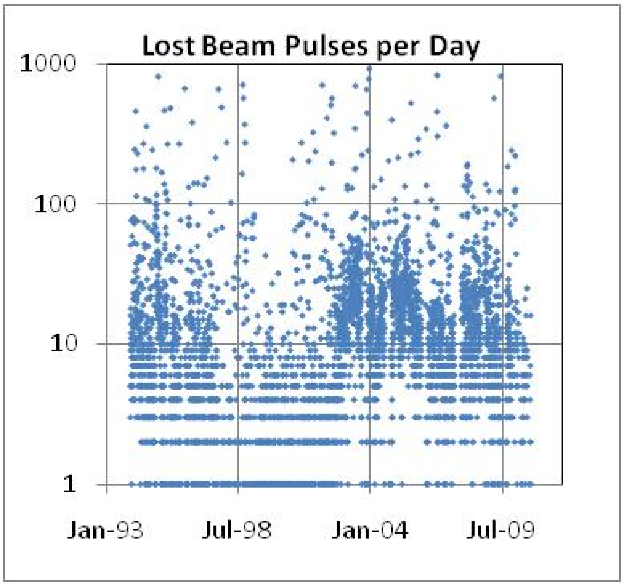

Figure 2: Count of lost beam pulses per day.

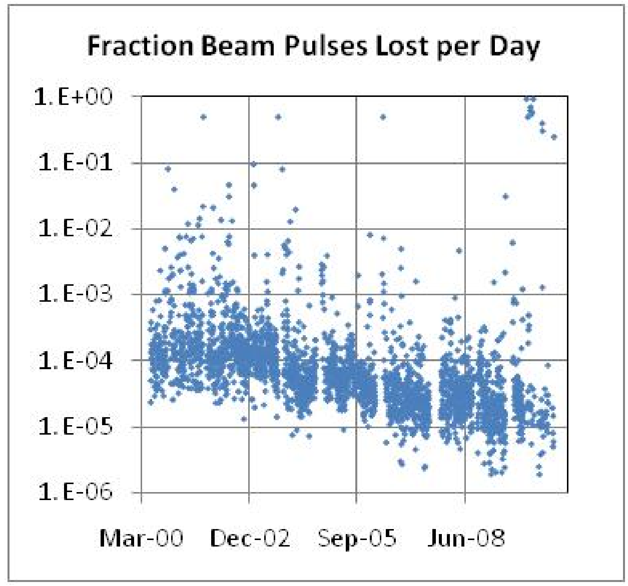

Figure 3: Fraction of beam pulses lost per day.

Rates per Cavity

In the previous paper [4], it was reported that there is evidence the sparking rate was levelling off. This was from the analysis from Module 3's sparking data. At this time we can say that the sparking rate of Module 3 has, indeed, stabilized at about $5x10^{-5}$ sparks per second (about 3 sparks per day). Modules 6 and 7 have also leveled at about $5x10^{-6}$ sparks per second.

The sparking rate of the other three modules continues to decrease. Modules 1 and 2 have a sparking rate of about $1x10^{-5}$ Hz, and Module 4 has reduced to $2x10^{-6}$ Hz, see Figure 1.

Since the beginning of 2010, we have had 4344 sparks in the Fermilab Linac. This datum represents 170 days when the Linac was running, or 2.2E8 RF pulses, thus an observed average sparking rate of about one spark per hour.

Lost Beam

We began counting the number of lost beam pulses per day in 1994, shown in Figure 2. The number of lost beam pulses per day reduced substantially to its lowest level at the time of the publication of the previous paper on this topic in 2000.

Since 2003 and the advent of the Fermilab high-intensity neutrino program, the Linac has delivered in excess of 500000 (5E5) 400 MeV beam pulses to the Booster. For much of 2010, almost half of the 15 Hz RF pulses in the Linac have contained beam. Prior to 2003, the typical number of beam pulses per day was about 30000.

In 2000, we started an automated count of the number of 400 MeV beam pulses in the Linac. To remove the effect of the varying number of beam pulses in a day, the fraction of the beam potential beam pulses that were lost is shown in the Figure 3.

A clear decrease in the fraction of beam pulses lost per day is seen.

X-Ray Measurements

The X-ray production of Module 5 has been measured four times over the last 18 years: 1992, 1996, 2000, and 2010. The measurements of the x-ray production are consistent with the assumption that it is produced by dark current emission from the high field areas of the cavity as described by the Fowler-Nordheim equation. The data are shown Figure 4.

The 1992 data were taken with a single detector placed approximately four feet transversely from the center of the module, between sections 2 and 3. The rest of the data were taken with four detectors placed approximately 1 foot transversely from the center of each of the four sections of the module. The 1992 data have been multiplied by four (assuming a quasi-line source) to suggest the proper relationship to the other data that have not been transformed. The detectors used for the measurements have a time constant of 20-40 seconds. When taking the measurements in 2000, the cavities remained at each new power setting for 30 minutes before the data were recorded. In 2010, the power settings were held for only 2-3 minutes due to time constraints. Because this was not enough time for the detectors to settle at the new values, the data for each power setting were fit to an exponential and the asymptotic values were derived.

The source of the dark current is an emitting area that is assumed to be a microscopic protrusion or dielectric impurity. In either case a local enhancement in the electric field (Em) occurs that is related to the average field by $\beta = Em/E0$. We fit the data from each detector to the Fowler-Nordheim equation for an RF field that describes enhanced field emission [5].

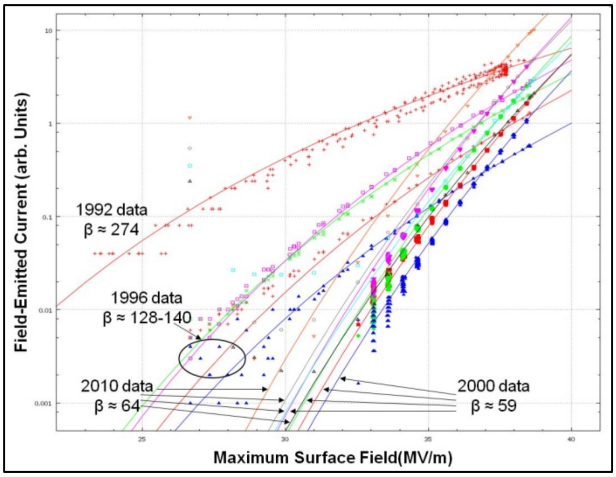

Figure 4: Field emission of Module 5 as a function of surface field.

$$j_F = \frac{5.7\times10^{-12}\times10^{4.52\phi^{-0.5}}}{\phi^{1.75}} A_e(\beta E_0)^{2.5} \exp\left(-\frac{6.53\times10^{9}\times\phi^{1.5}}{\beta E_0}\right)$$

where ϕ is the work function in eV, E0 is the macroscopic surface field in V/m, and Ae is the area of the emitting site(s). We fit our data to this form using MINUIT [6] with the free parameters being β and a term proportional to A_e. These data are shown in the table on the next page.

In these data, see Table 2, we see relative stability in the X-Ray data from the last measurement, 10 years ago. The area terms have decreased by an order of magnitude, but the beta terms have increased by less than 10%. If the betas have truly increased, then this would indicate a slight degradation of the surfaces of the cavities. However, given the timescale over which this has occurred, we see no threat to their future performance.

CONCLUSION

Measurements suggest that the conditioning of the Fermilab Linac continues to improve or has stabilized, even after 18 years of operation. These measurements are:

- Automated detection of cavity sparks
  - The sparking rate in the Fermilab 805 MHz, 400 MeV Linac has reduced to approximately one cavity spark per hour of RF operation. This is a substantial reduction since 2000: one spark every 17 minutes.
- Fraction of beam pulses lost due to cavity sparks
  - Approximately 2 in 1E5 beam pulses is lost due to a cavity spark—far below the design criterion of 1 in 1000 and an order-of-magnitude decrease from 2001, the first full year of the automated counting of the beam pulses in the Linac.
- X-Ray emission
  - The size of the sites in Module 5 that are emitting x-rays has decreased by a factor of ten over the last decade, but the electric field enhancement factor has increased.

If this trend of infinitely improving conditions in the Fermilab Linac ever stops, we hope to be around to report on it at a future Linac conference.

Table 2 : Fit results for field emission of Module 5

Data set	*Area term*	*β*
1992	$1.0\times10^{-12}\pm4\times10^{-14}$	274±1
1996_1	$8.8\times10^{-9}\pm3\times10^{-10}$	128±0.3
1996_2	$3.6\times10^{-9}\pm1\times10^{-10}$	140±0.3
1996_3	$2.2\times10^{-9}\pm8\times10^{-10}$	133±2.9
1996_4	$1.7\times10^{-8}\pm3\times10^{-10}$	129±0.2
2000_1	0.37±0.04	59.5±0.2
2000_2	0.80±0.06	58.8±0.1
2000_3	0.30±0.06	59.1±0.4
2000_4	1.29±0.07	58.8±0.1
2010_1	0.044±0.03	64.7±1.5
2010_2	0.15±0.09	63.1±1.4
2010_3	0.052±0.028	63.6±1.2
2010_4	0.139±0.108	65.0±1.8

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