Tevatron Beam Separator R@D

- **Overview**
- **Activities at MP-9 since Feb 2004**
  - Construction of polarity switches
  - Assembly of HV power supplies (180kV and 250 kV)
  - Construction of separator production facility (clean room, test cave,…)
  - Separator assembly
  - Conditioning at higher voltages
  - Electrode material R&D
- **Plans for 2006**

<u>**People Involved:**</u>

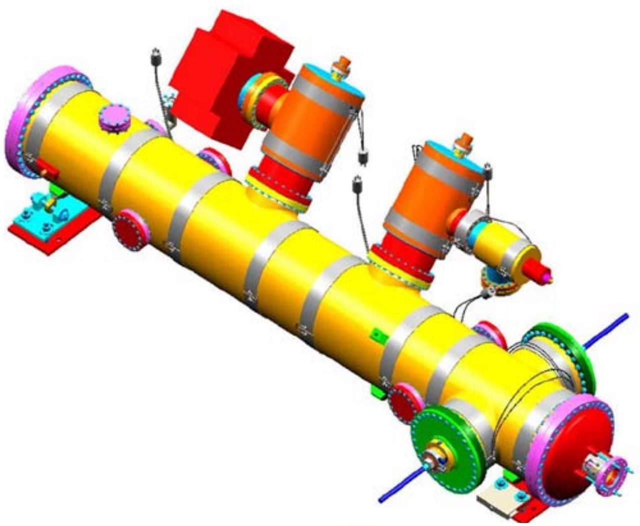
AD

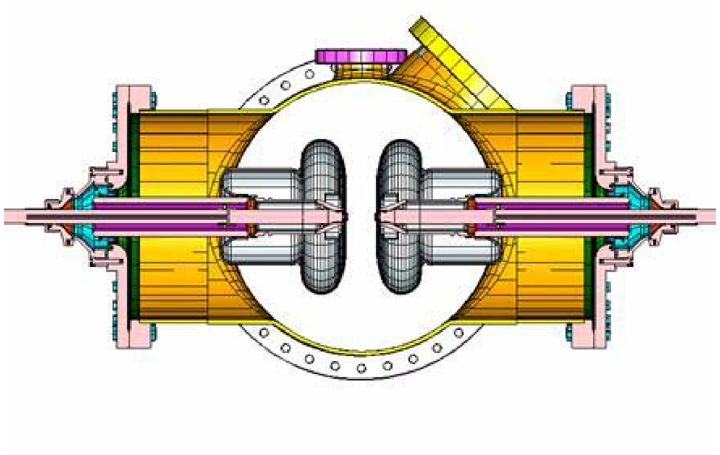
<u>R. Moore</u>, D. Bollinger, B. Hanna, J. Johnstone, R. Meadowcroft, S. McCormick, T. Sen, V.Shiltsev, J. Walton

TD

<u>P. Limon</u>, L. Alsip, R. Bossert, M. Chlebek, D.Conolly, L.Elementi, G. Kobliska, A.Makarov, O. Prokofiev, G. Smith, D.Sorensen, J. Wittenkeller, J. Zweibohmer,

TeV Separator Spark history





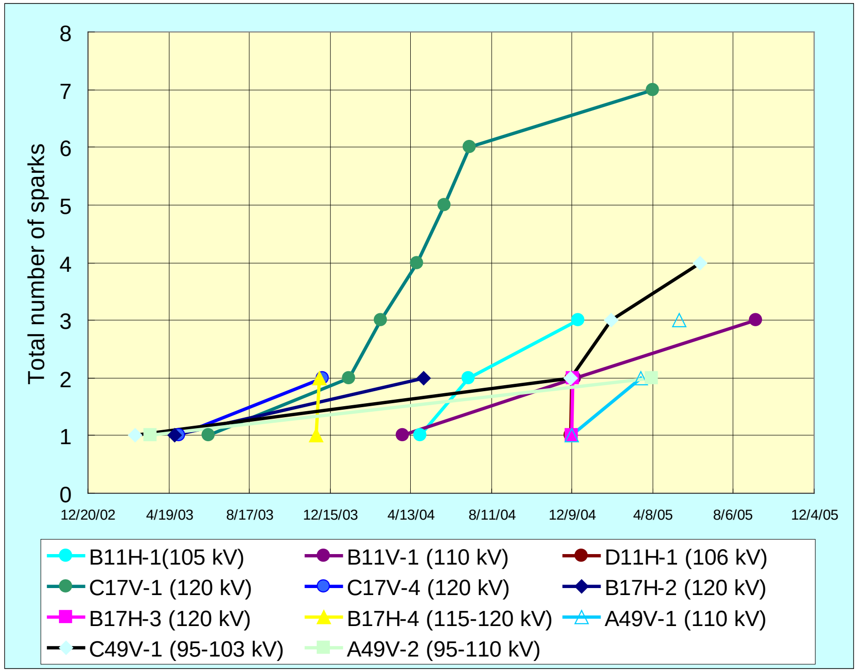
Electrode length – 101.25"
Electrode gap – 50 mm
Maximum voltages – up to 120 kV / plate)

Electrostatic separators used to put p-bars and protons on different orbits ("helices) to avoid beam interactions. 24 separators grouped into 13 stations around of ring.

Fermi news:

… Tev separator sparked and kicked out the last bunch…
… C17 separator started sparking…
… TeV vertical separator sparked 3 times…
…. store 4078 quenched due to separator spark…
…. separator sparks caused loss of luminosity and then…

Operational losses due to separator sparks in 2004-2005 are about 2 weeks (~10k$/hr).



Separator R&D Program

- Motivating Higher Voltage Operation

  Separation on ramp limited by voltage

  Can B17H, C17V run @ 150 kV for few min with acceptable spark rate?

  During HEP stores, IP separators run at ~100kV

  Running @ 120 kV seems to be a realistic goal 20% more voltage ⇒ 20% more separation

  Can IP separators run @ 120 kV for many hours with acceptable spark rate?

- Conditioning at higher voltages

  Conditioned up to 150 kV during original production
  Now conditioning spare separators at up to 180 kV
  Obtaining nice data on spark rate vs voltage

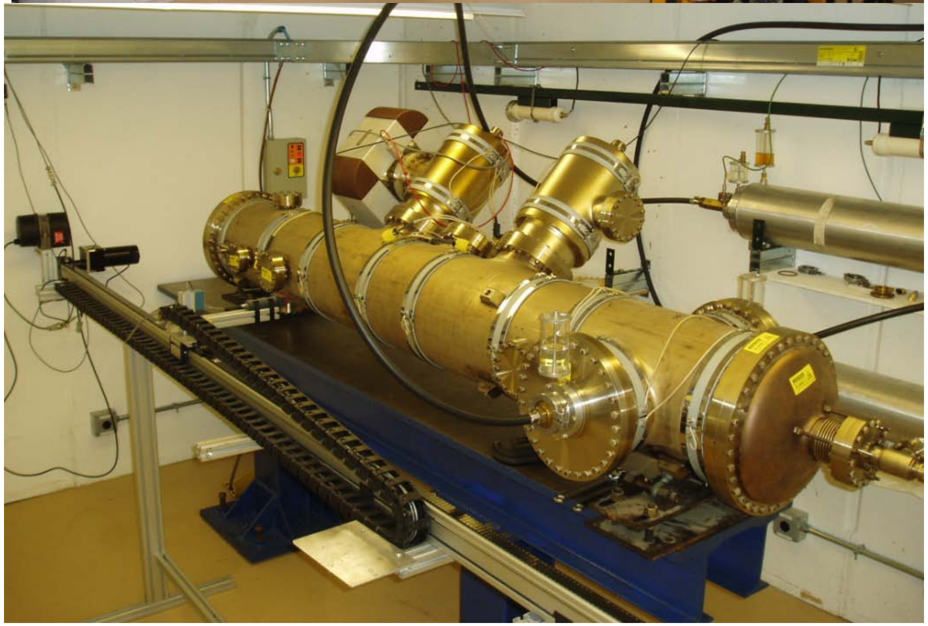
- Try new electrode material

  Test separator reassembled with electropolished stainless steel electrodes
  Assembly separator with Ti electrodes

- Goals

  Improve separator performance and reliability
  Reach 1 spark/year at voltages 150 kV per plate (6.0 MV/m)

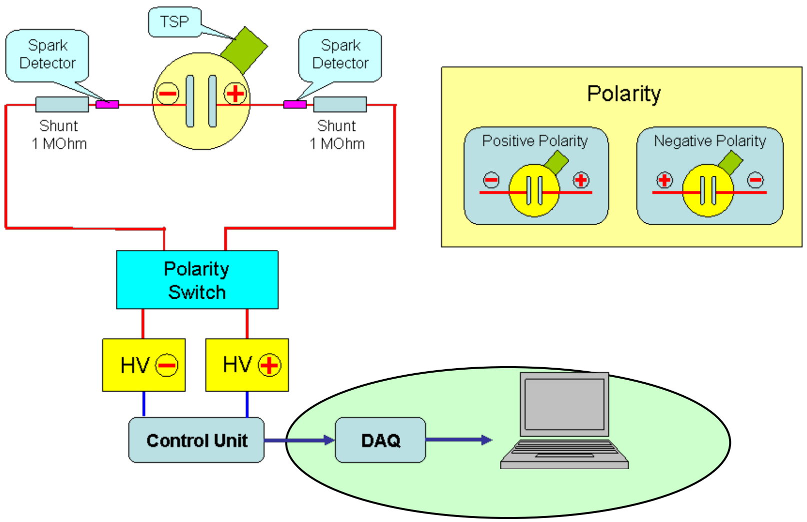
Conditioning Test Facility at MP-9

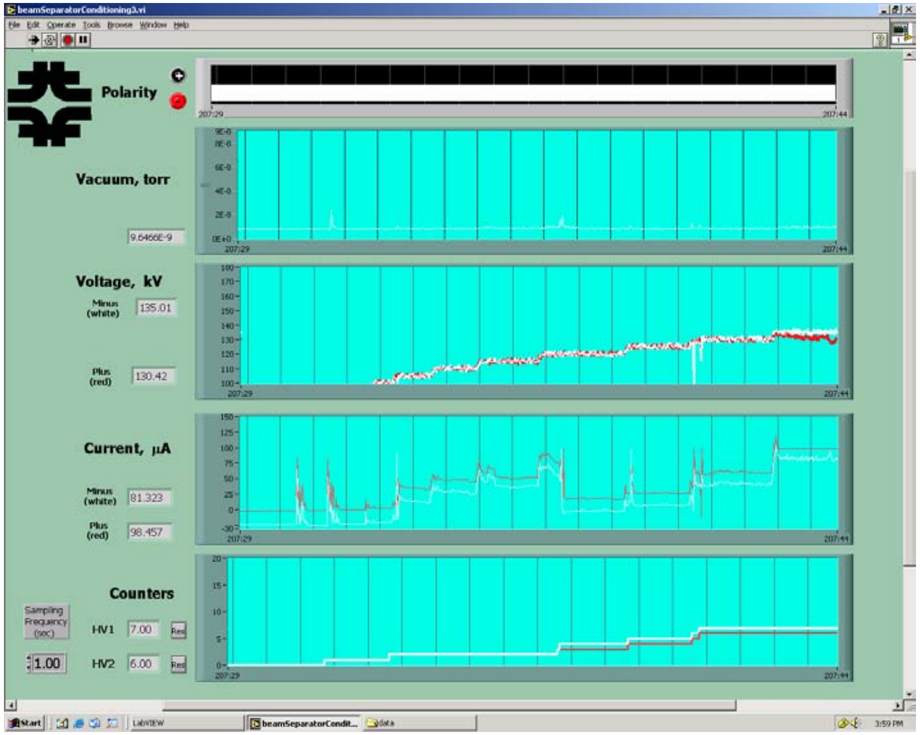


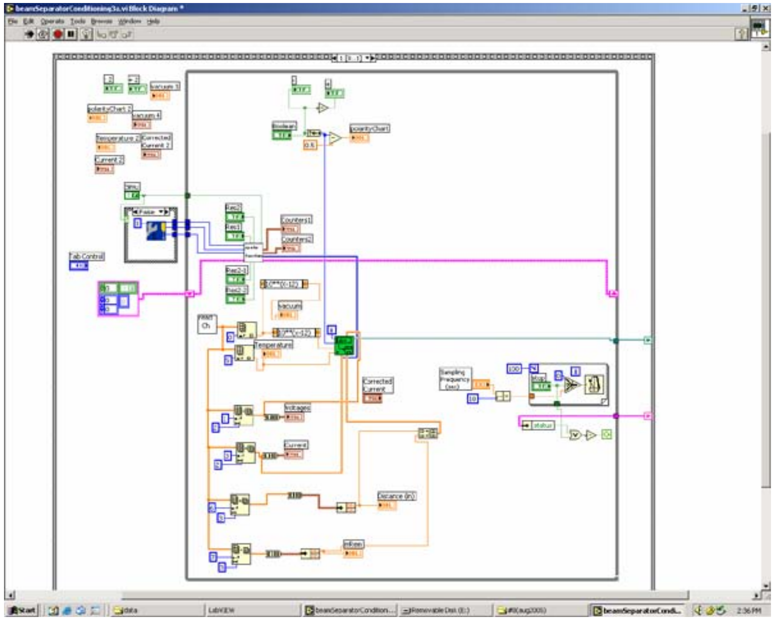
New factory was constructed at MP- 9 for separator production.
Facility include a clean room class 10000, baking oven, conditioning cave, automatic setup for radiation scan and measuring system.

Automatic Measurement Setup

Measuring scheme







Automatic setup was developed and constructed by D.Conolly and L.Elementi.

Measured parameters:

- **polarity**
- **voltages, currents, sparks**
- **pressure, temperature**
- **radiation, hot spot position**

Conditioning Procedure

The high voltage was applied on 2 electrodes with following combination:

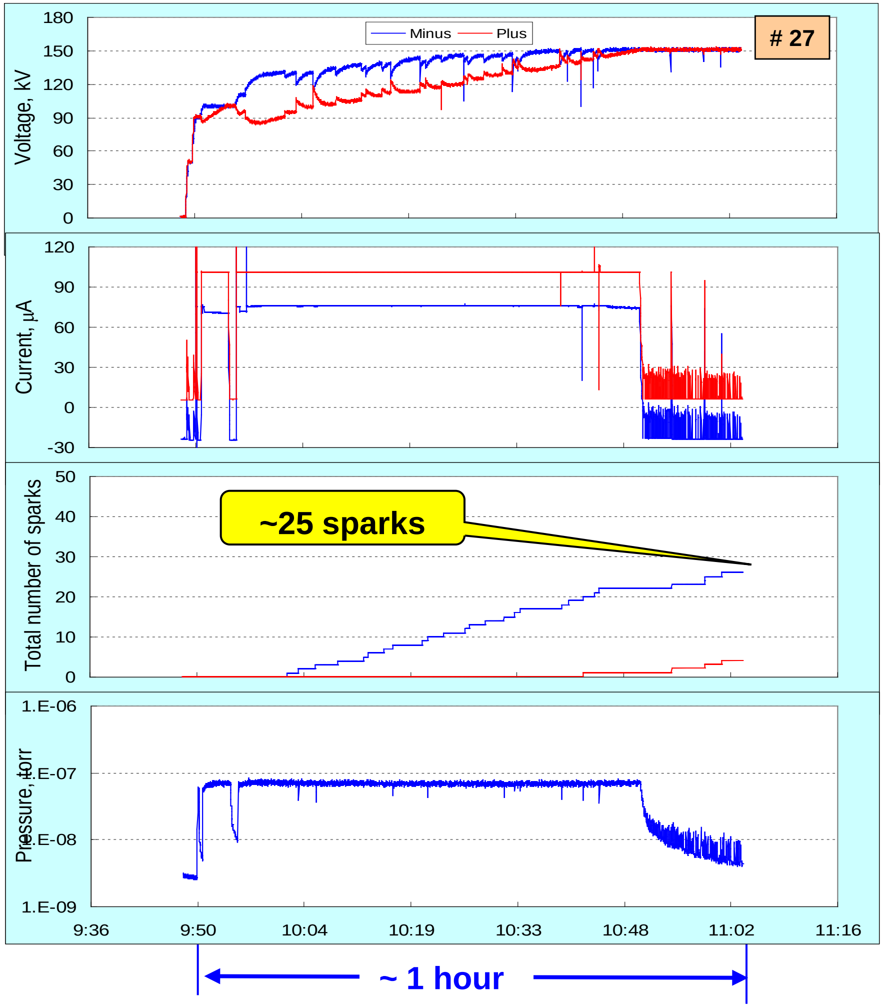
- **(-150kV, 0), (0, +150kV) → change polarity → (0, -150kV), (+150kV, 0)**
- **(-150kV, +150kV) → change polarity → (+150kV, -150kV)**
- **(-170kV, +170kV) → change polarity → (+170kV, -170kV)**
- **(-180kV, +180kV) → change polarity → (+180kV, -180kV)**

(-150kV, 0), (0, +150kV) → change polarity → (0, -150kV), (+150kV, 0)

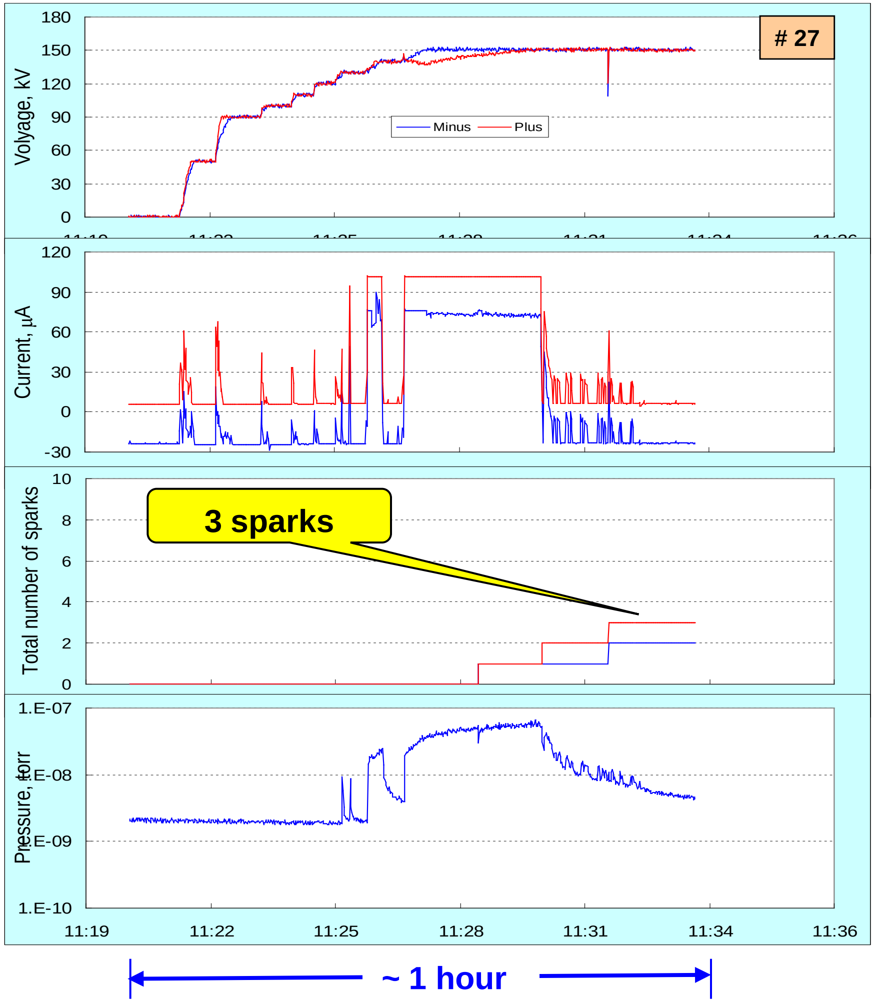
 # 27

Conditioning at 150 kV (July 13, 2005)

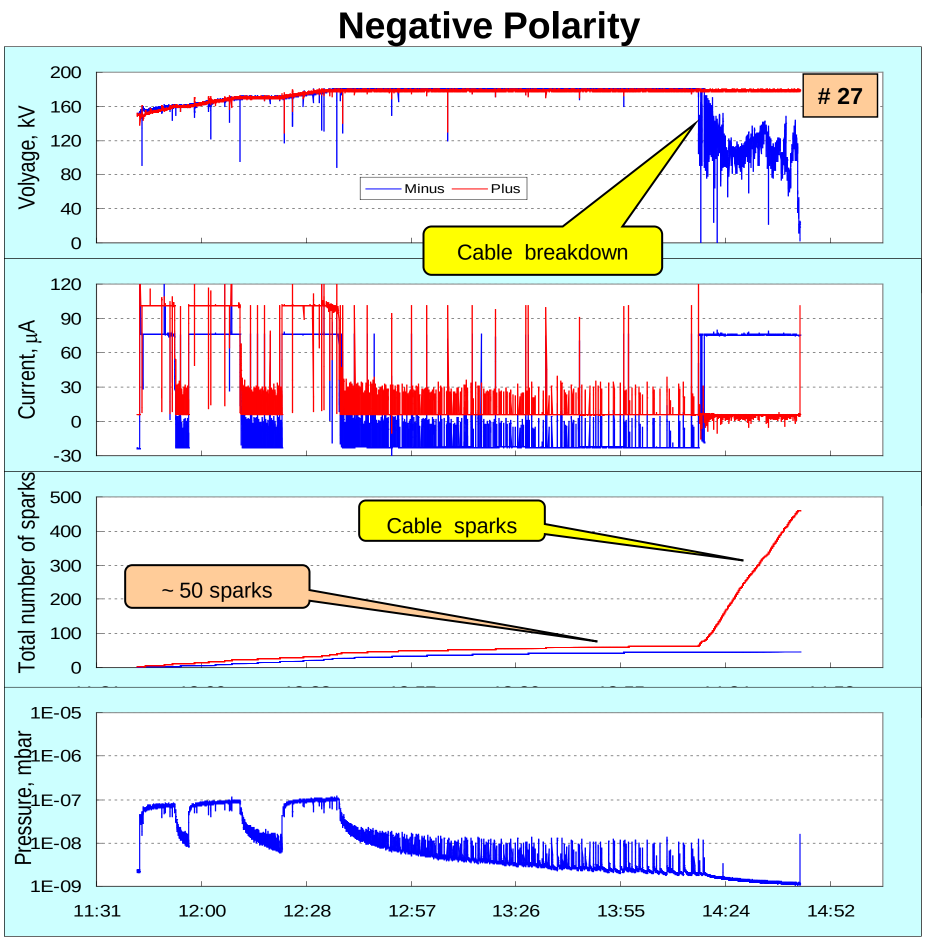
Positive Polarity



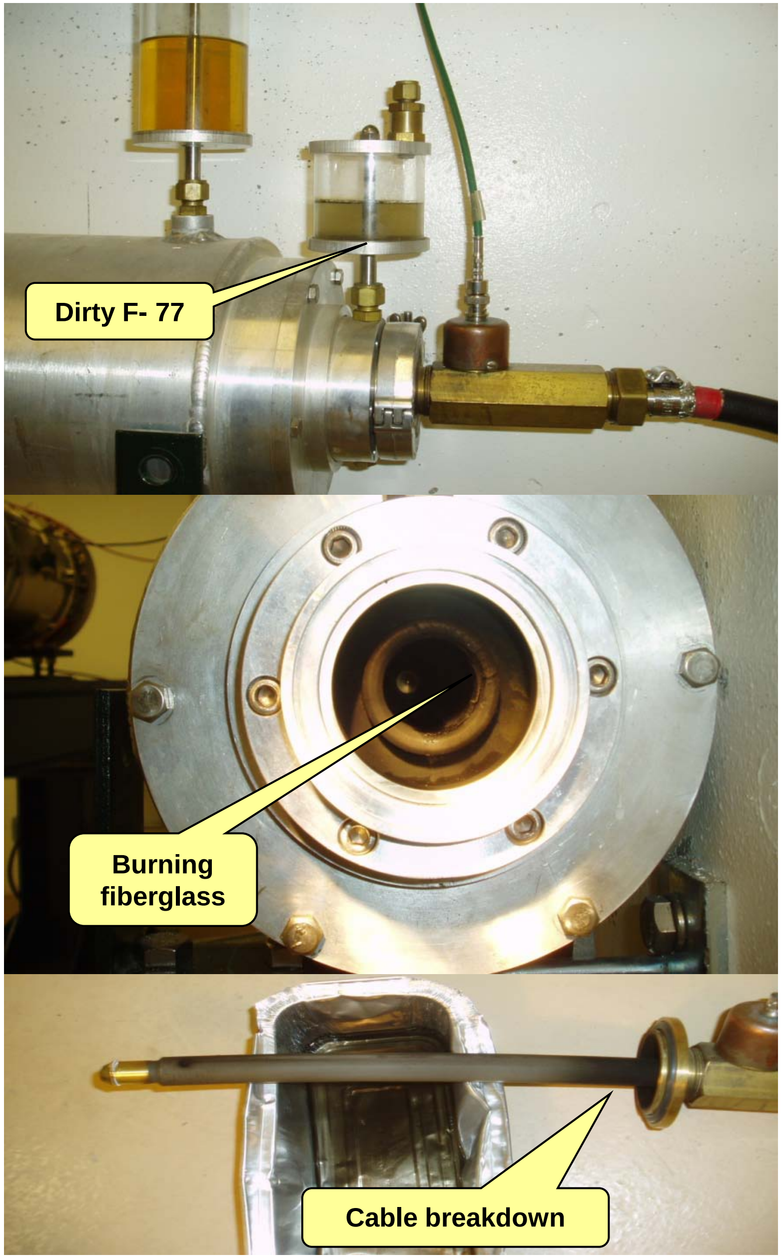
Negative Polarity



Conditioning (Negative Polarity) at 150 - 180 kV (July 13, 2005)



~ 3 hours



Conditioning separators at up to 180 kV:

- conditioning much more quickly (hours vs days)…
- …at a cost – damaged HV cables, 1 MOhm shunt, control unit, HV power supply, a polarity switch….

Safety, Procedures, Travelers, Instructions

Beam Separator Test Facility at MP-9

Hazard Analysis

Prepare
Peter Limon Pro
anc
Oleg Pro

September

Sept. 20, 2004

Tecl

Beam Sep

Standard

for Separator

Fermi National Accelerator Laboratory
Batavia, IL 60510

TEVATRON BEAM SEPARATOR
HIGH VOLTAGE
CONDITIONING TESTIN
TRAVELER

Reference Drawing(s)

Tevatron Beam Separator Final A
2214-ME261545 Horizonta
2214-ME261546 Vertical

Project# / Task #:	Job #:
Released by:	Magnet/Device
Date:	Scan Pages:
Prepared by: B. Jensen, O.Prokofiev	
Title	Signat
TD / E&F Process Engineering	Bob Jensen/Designee
TD / E&F Assembly	Glenn Smith/Designee
TD / E&F Project Physicist	Oleg Prokofiev/Design
TD / E&F Project Physicists	Peter Limon/Designee

From sood@fnal.gov Wed Oct 13 16:18:50 2004
Date: Wed, 13 Oct 2004 15:18:44 -0500
From: Romesh Sood <sood@fnal.gov>
To: Bob Kephart <kephart@fnal.gov>, Yarba Victor <yarba@fnal.gov>
Cc: Limon Peter <pjlimon@fnal.gov>, Prokofiev Oleg <prokofoe@fnal.gov>, Romesh Sood <sood@fnal.gov>, Apollinari Giorgio <apollina@fnal.gov>
Subject: Phase- I ORC Recommendations For The MP9 Electronics Beam Separator Conditioning & Test Setup

Dear Bob, Victor,

The MP9 Electronics Beam Separator Conditioning & Test Setup is now ready to commence *Phase-1* full operation (_*Phase-1 with no power on access*_).* *In addition to a comprehensive written Hazard Analysis, the TD-Support Department conducted a thorough safety analysis of all potential hazards listed below:

cal - High Voltage Power Supply,
tion Radiation,
anical Safety, and
ical Safety

e MP9 user group in
ts, and emergency
hat all electrical safety
ipment, have been
, a comprehensive LOTO
oon Jim Garvey has trained
enn Smith, Roger Rojo Jr., and
safely.

exposure is a real
o grant a limited _*Phase-1
the cave enclosure until a
pply and high voltage

TECHNICAL DIVISION
ENGINEERING AND FABRICATION GROUP
LOCK OUT/TAG OUT PROCEDURE

re Number: TD-512045	**Document EFG-Elec-**	**Revision Number & Date:**
y (Knowledgeable person) kofiev Date: 9/28/04	**Organization** TD EFG	**Extension** 6636
by: arvey Date:	**Organization** TD Support	**Extension** 4160
by: Kephart Date:	**Organization** TD HDQ	**Extension**
: identification/description atic Beam Separator MP-9 Test Facility		
: **pose of this procedure is to identify the specific hazardous energy sources associated with this nt and the methods used to lock and tag them out to allow safe servicing. This procedure is an ntation of Fermilab ES&H Manual, Chapter 5120, and titled Control of Hazardous Energy for Personnel Safety.**		

GENERAL INFORMATION

Scope:
These procedures cover the Lockout/Tagout steps that are to be performed on the Glassman High Voltage Power Supplies and control system of Electrostatic Beam Separator MP-9 Test Facility before inserting, removing, moving, or otherwise handling exposed ends of the high voltage cables in the test cave used to supply power to the Beam Separators, and to restore the system following this work to an operational ready condition.

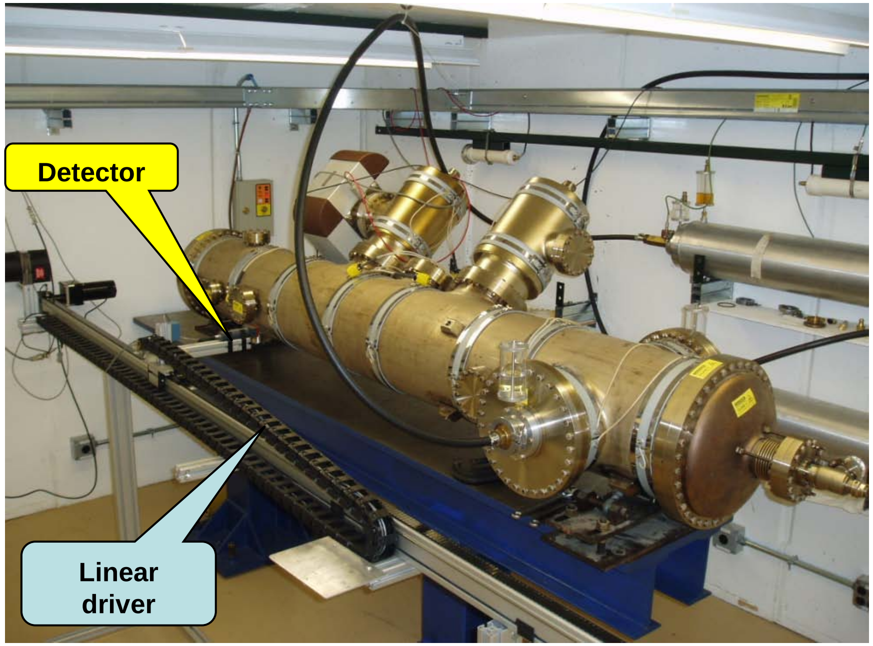
Special Concern:
This LOTO action is required before changing out beam separator assemblies, removal or re-connection of the high voltage cables, or other maintenance work where there is an exposure to the employee from the high voltage power supplies.

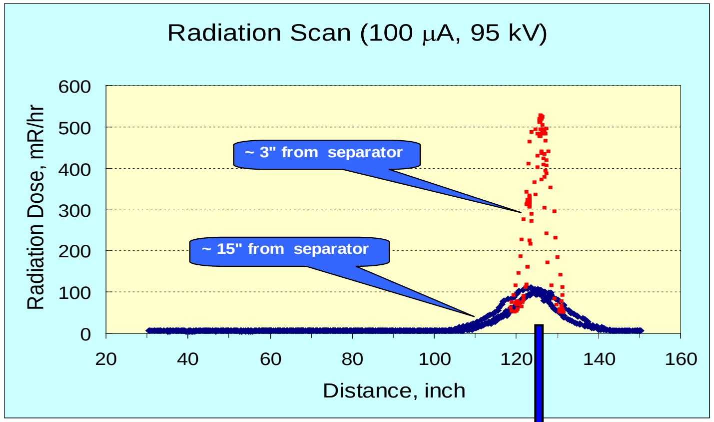
Qualification of Workers:

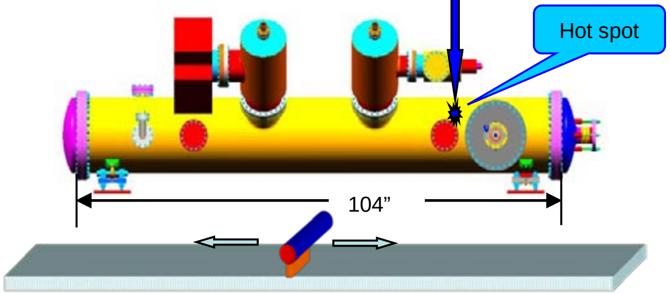
Authorized Individuals
LOTO Level II training is a pre-requisite to performing this procedure. Workers who are annually certified in this written procedure will be classified as “Authorized Individuals” in this document. A list of qualified individuals will be posted at the location of the LOTO keylock box.

High Voltage Knowledgeable Persons
Only personnel who have the knowledge and experience to work on high voltage power supplies are to be classified as a “high voltage ps knowledgeable person” capable of trouble shooting the system.

Automatic Setup for Radiation Scan

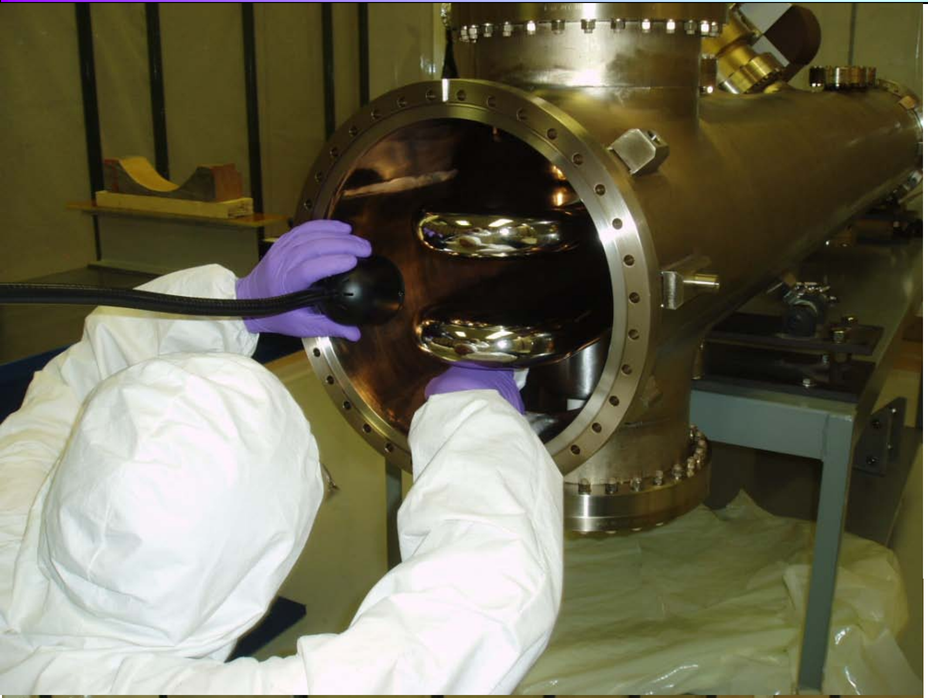


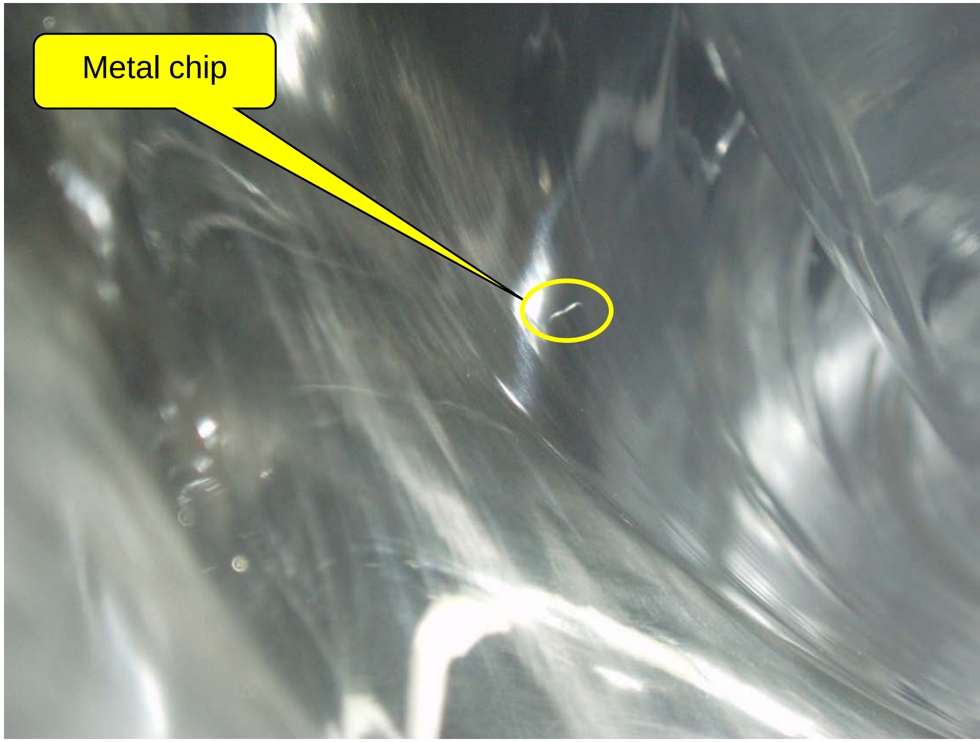




The automatic scan significantly simplified the radiation scan procedure and improved a safety environment at MP-9. In the previous conditioning facilities to do X-ray scan the interlocks to the cave must be bypassed and a minimum of 3 people were needed for radiation survey (one person is outside of cave and adjusts voltages, the other two people are separator expert who will perform the scan and Radiation Safety person to monitor a situation).

Separator Opening and Cleaning (July 12, 2005)





Found silver plated metal chip ~ ¼” long

Results of Conditioning Tests

A list of Separators conditioned at MP-9

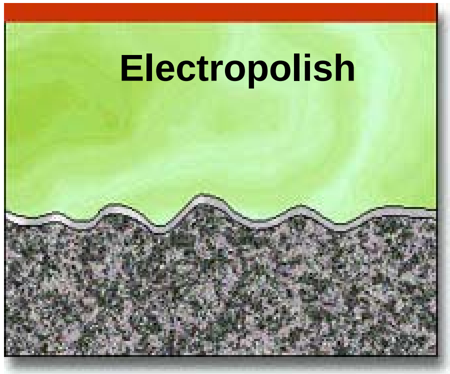
- # 28, horizontal, hand-polish SS (Jan - Feb, 2005)
- # 6, vertical, electro-polish SS (Apr - Jun, 2005)
- # 27, vertical, electro-polish SS (Jul – 05)
- # 4, horizontal, hand-polish SS (Jul – 05)
- # 8, vertical, electro-polish SS (Aug-Nov, 2005)

 # 29, hand polish titanium electrodes under construction

Electropolishing Process Verses Mechanical Polishing

Roughness: 4 - 40 microinches
(depends from abrasive grit number)

Mechanical polishing is an operation designed to prepare a metal surface for electropolishing or to satisfy non-critical surface roughness requirements. Mechanical polishing reduces all surface ridges, microprotrusions, pits and discrepancies to provide a homogeneous appearance and roughness.



Roughness: 2 - 5 microinches

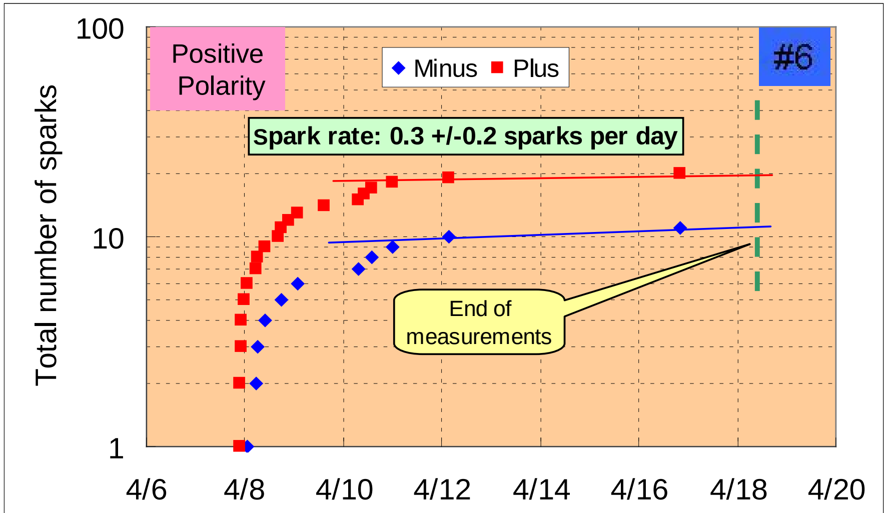
Electropolishing (used since early 1950's) is the electrochemical removal of microscopic irregularities or diminution scratches, burns and unwanted harp edges from metal surfaces. Typical material removal is .0001"- .0004"
per surface.

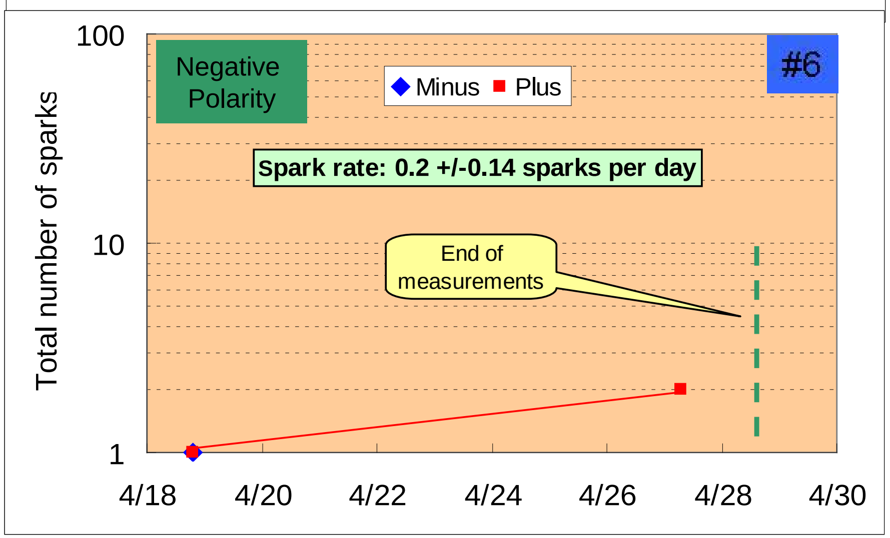
Smoothness of the metal surface is one of the primary and most advantageous effects of electropolishing.

Electropolishing should improve separator performance.

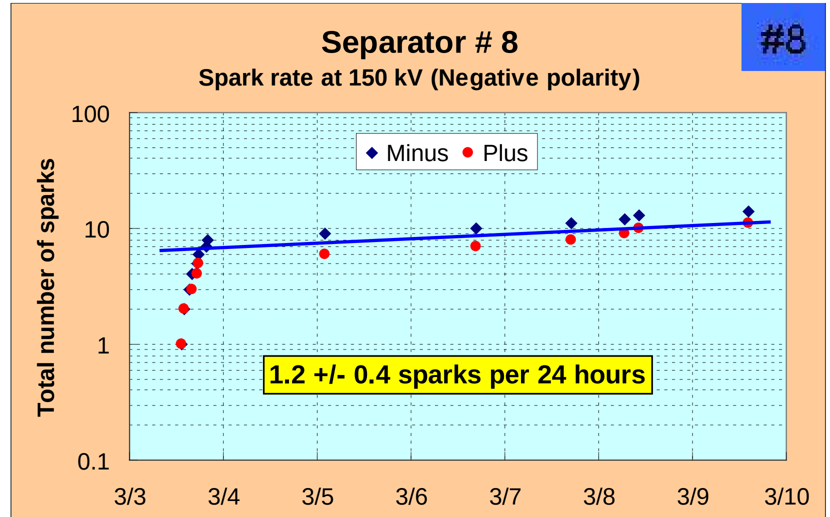
Conditioning at 150 kV: Spark Rate for # 6 and # 8

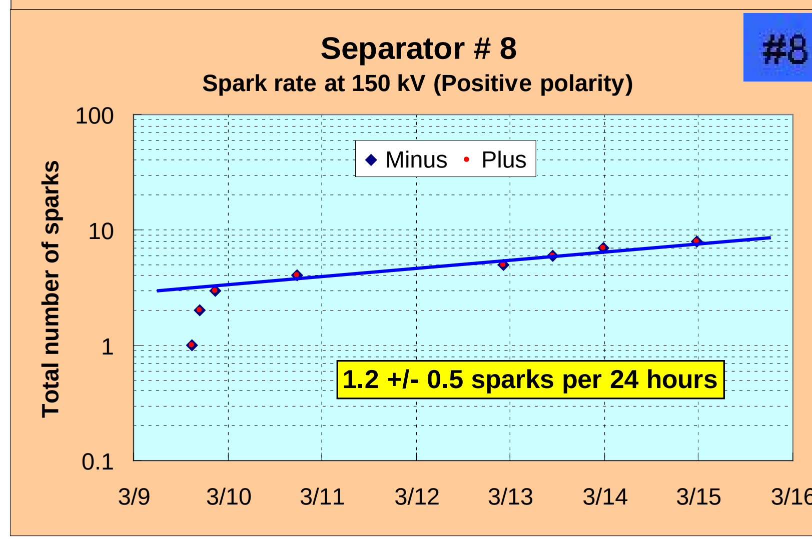
Electro-polished electrodes





Hand-polished electrodes



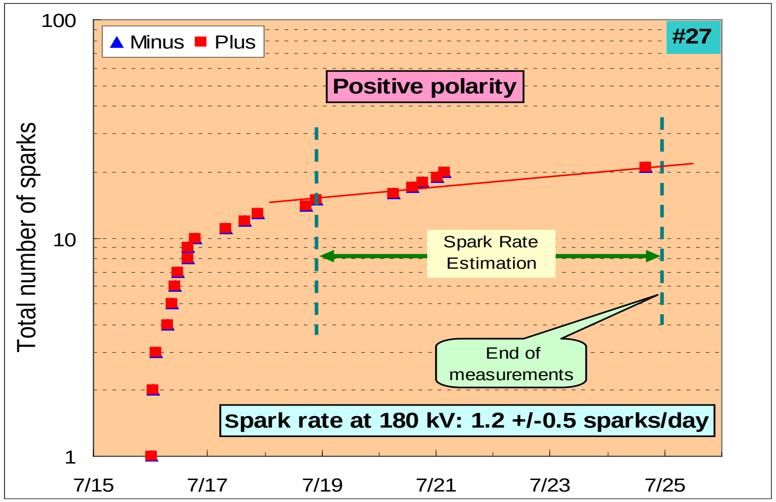


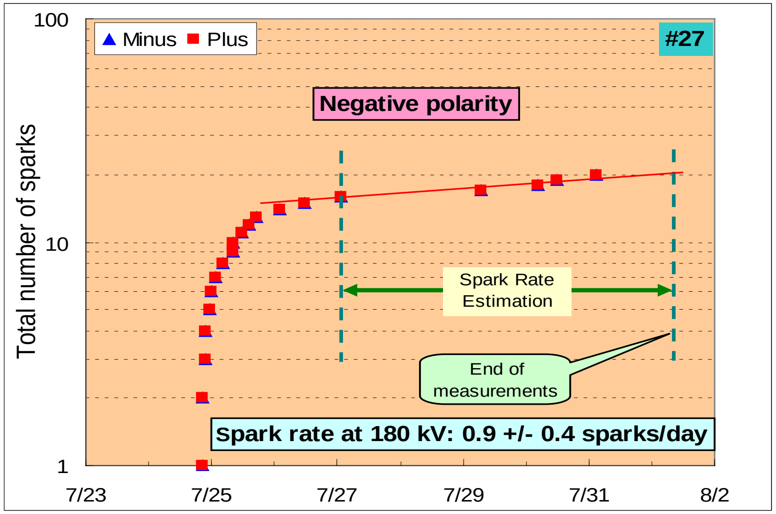
Spark Rate at 150 kV

- #6 (electro-polished) : 0.25 +/- 0.15 per day
- #8 (hand-polished) : 1.2 +/- 0.3 per day

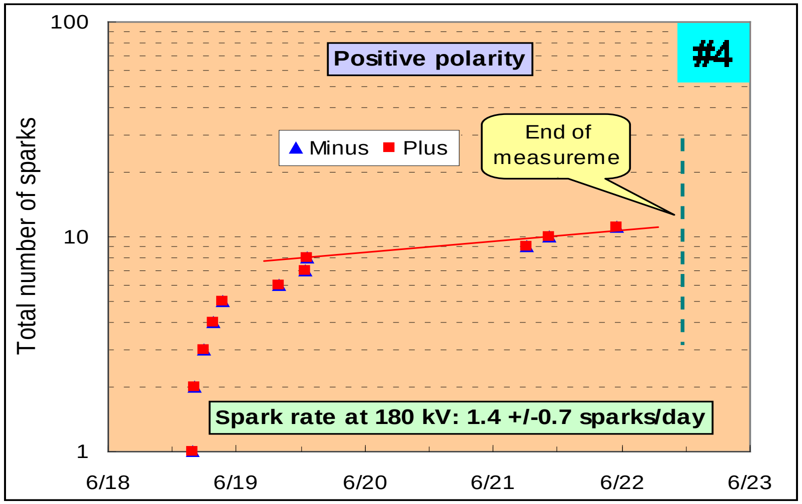
Conditioning at 180 kV: Spark Rate for # 4 and # 27

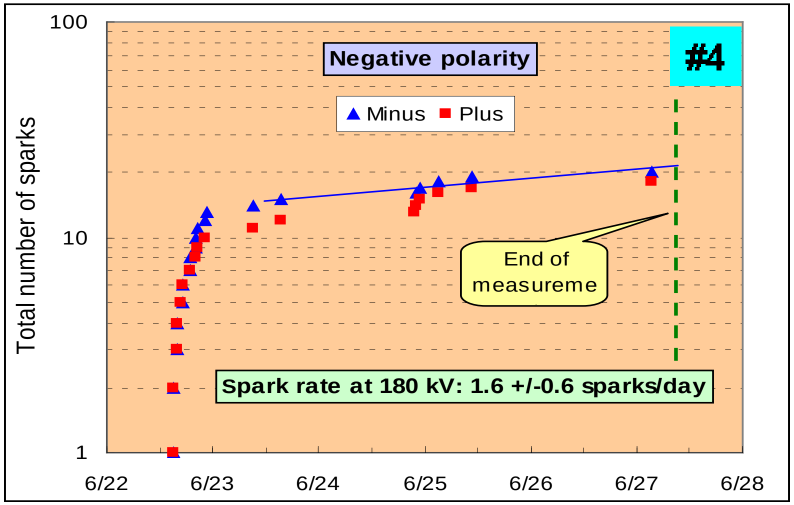
Electro-polished electrodes





Hand-polished electrodes



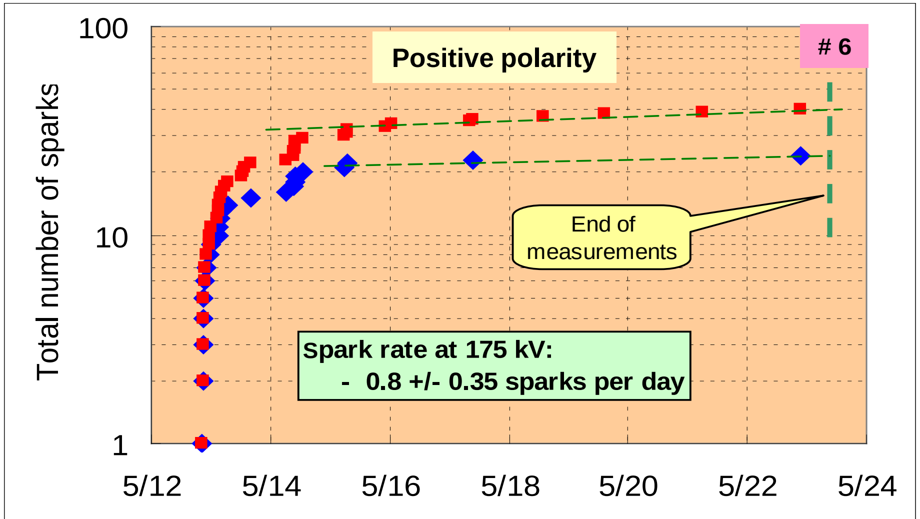


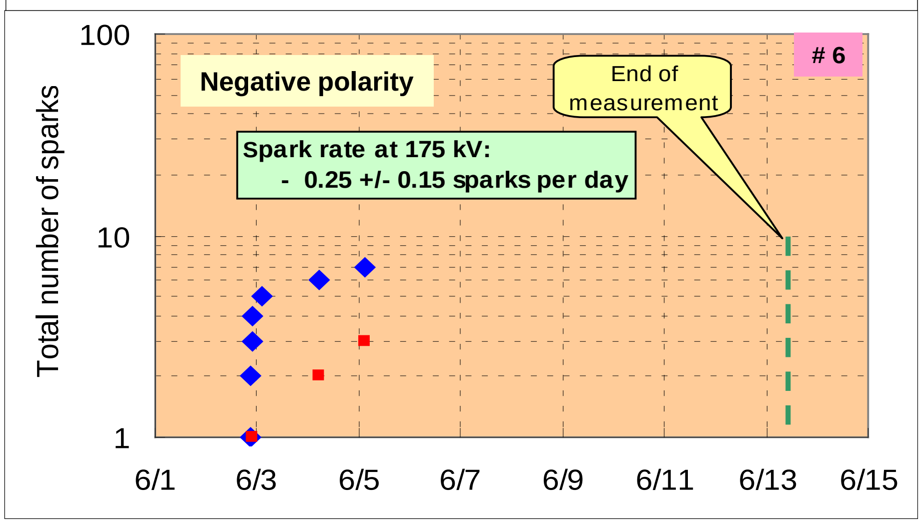
Spark Rate at 180 kV

- ➢ # 27 (electro-polished) : 1.0 +/- 0.3 per day
- ➢ # 4 (hand-polished) : 1.45 +/- 0.35 per day

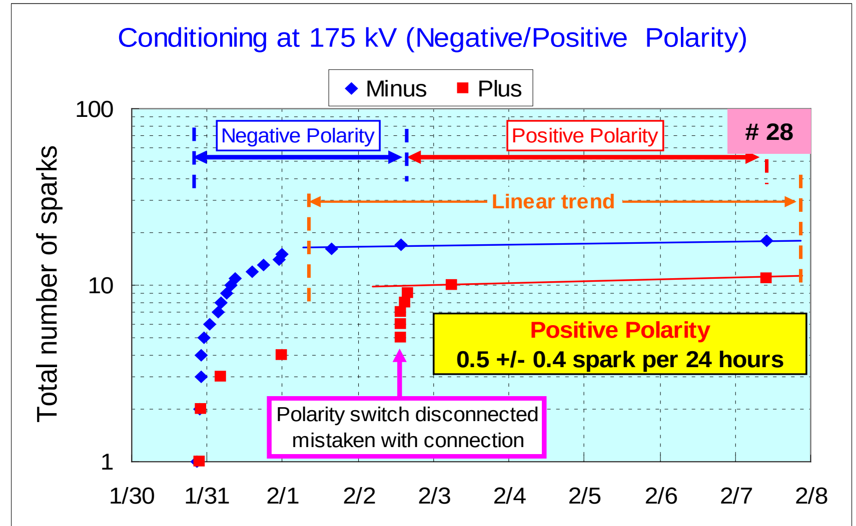
Conditioning at 180 kV: Spark Rate for # 6 and # 28

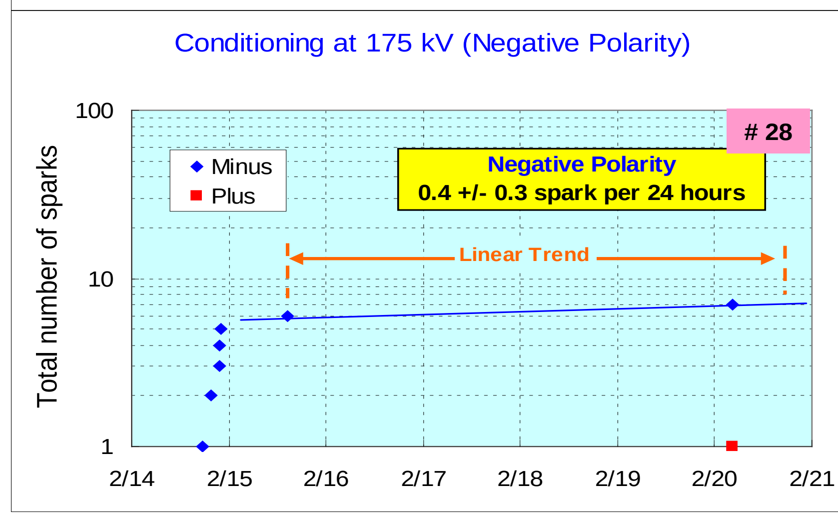
Electro-polished electrodes





Hand-polished electrodes

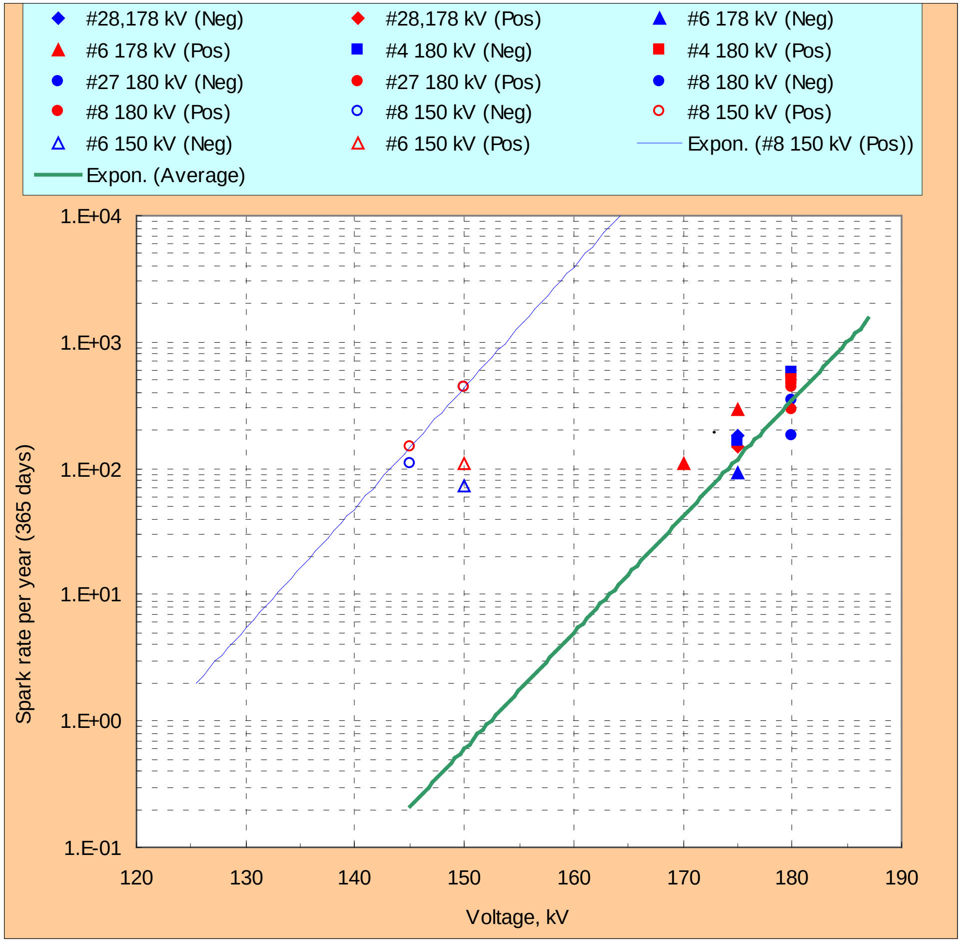


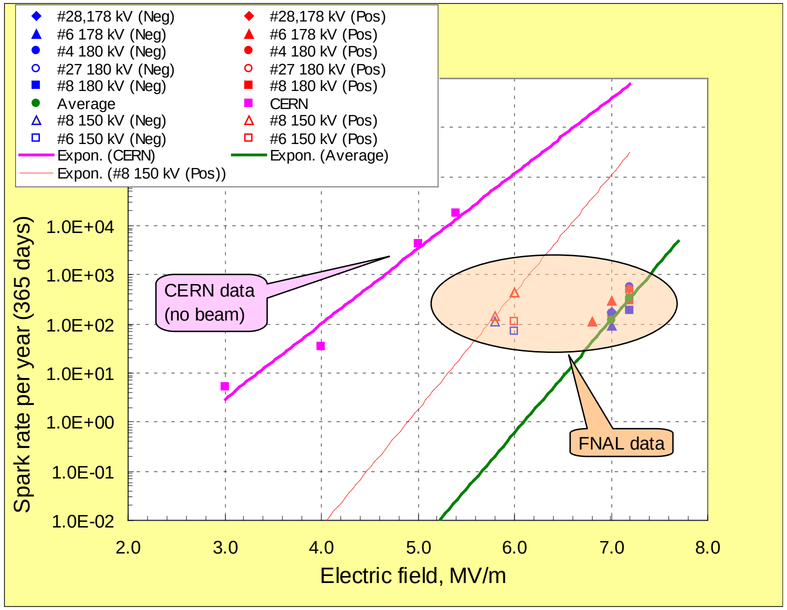


Spark Rate at 175 kV

- # 6 (electro-polished) : 0.35 +/- 0.15 per day
- # 28 (hand-polished) : 0.45 +/- 0.25 per day

Conditioning at 180 kV: Spark Rate Summary





For comparison CERN data were included

CERN design:

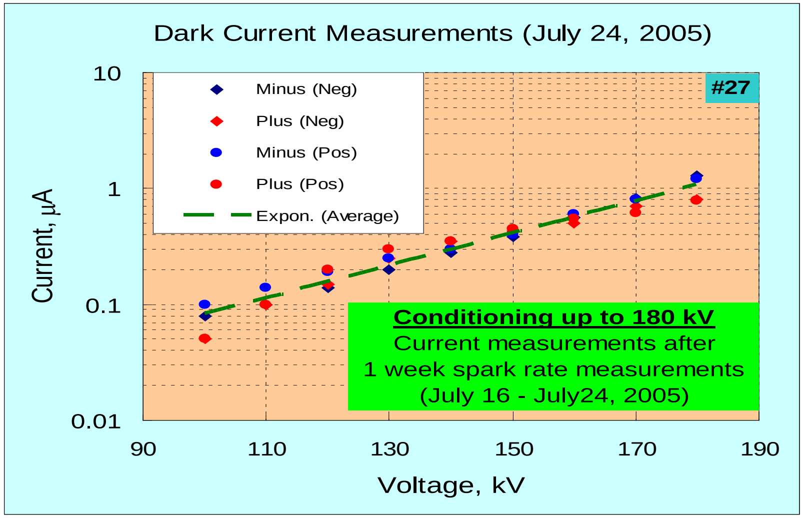
- 6 cm separation
- 4 m long electrodes
- 26 cm electrode width
- Polished with Scotch - Brite “very fine 320” to satin finish

Conditioning at higher voltages decreased spark rate (10 kV up → spark rate down ~ 10 times)

Expected spark rate at 150 kV for separators conditioned at 180 kV will be less than 1 spark per year or about 3 order of magnitude less in comparing with separators conditioned just at 150 kV.

Summary of Dark Current Measurements

Electro-polished electrodes

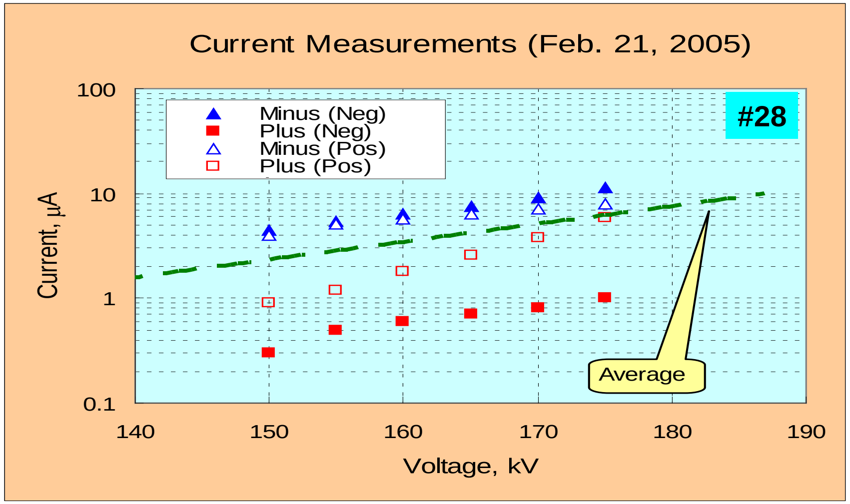


#6

Conditioning up to 178 kV
Current measurements after
1 month spark rate
measurements
(May 13-June 13, 2005)

Hand-polished electrodes

#4



Dark current at 180 kV

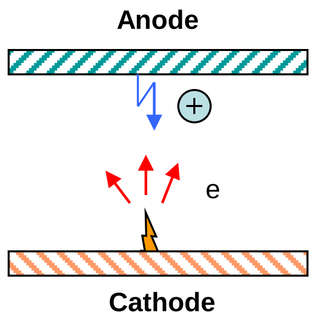
- **# 6 and #27 (electro-polished) : ~1.0 µA**
- **# 4 and #28 (hand-polished) : ~ 10 - 20 µA (neg. polarity)**

High Voltage Electrical Breakdown in Vacuum

It is generally agreed that a vacuum breakdown is a vapor arc, taking place in material evaporated from the electrodes. Evidence is the observation of localized light during breakdown and electrode material transferred across the gap.

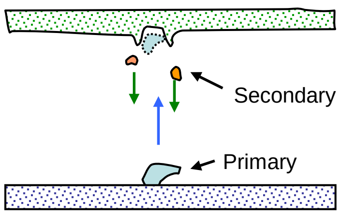
❖ **Electron field emission mechanism for initiating the breakdown**

According with this model, electrons are assumed to be field emitted from the tip of microprotrusion at an isolated site on the surface of broad-area cathode.
Question: where is the metal vapor produced at the anode or cathode?
Is it enough power to vaporize anode material by field emitted electrons bombarded anode or positive ions produced at the anode lead to rupture of the cathode or that resistive heating on the cathode causes them to melt and ultimately to vaporize. This mechanism dominates at gaps less than 2 mm.



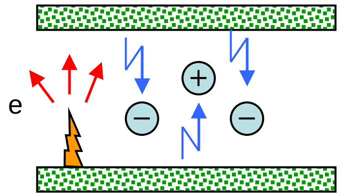
❖ **Microparticle or "clump" model**

Clump of loosely adhesive material is drawn across the gap by the electric field so as to strike the opposite electrode with enough energy to produce high local temperature in the electrode or clump material with melting and vaporizing.
Pre-operational electrode surface will be characterized by having a finite number of microscopic particles. These will originate from various stages of mechanical polishing, and may be in the form of either impurity particle of polishing material or dust particles. Another source of microparticles are those originated from thermal instabilities at either the cathode or anode "hot" spot. For uniform gaps the breakdown voltage should vary as the square root of the gap spacing. The model is dominated at large gaps.



❖ **Ion exchange mechanism**

This mechanism is assumed to be initiated by say random positive ion created in the gap that is than accelerated by the field to generate further negative ions on impact with cathode, which subsequently generate more positive ions on impact with the anode etc. Thus, if the ion multiplication factor > 1, the process will develop in the breakdown mode. It is very sensitive to chemicals contaminations.



The breakdown consists of many complicated and complex phenomena with no single process involved.

Electrode Conditioning Process

Any conditioning process is to safely quench as many as possible of the sources of breakdown current and "primary" microparticle events.

- "Current" conditioning

The applied voltage is increased in small steps such that the prebreakdown current is allowed to stabilize at each steps before progressing.

Separators were conditioned at current limits about of ~100 μA.
Voltages increased step by step of 2 - 10 kV . Voltages applied in following combination:

(-150kV, 0), (0, +150kV) → change polarity → (0, -150kV), (+150kV, 0)
(-150kV, +150kV) → change polarity → (+150kV, -150kV)
(-170kV, +170kV) → change polarity → (+170kV, -170kV)
(-180kV, +180kV) → change polarity → (+180kV, -180kV)

- "Gas" conditioning

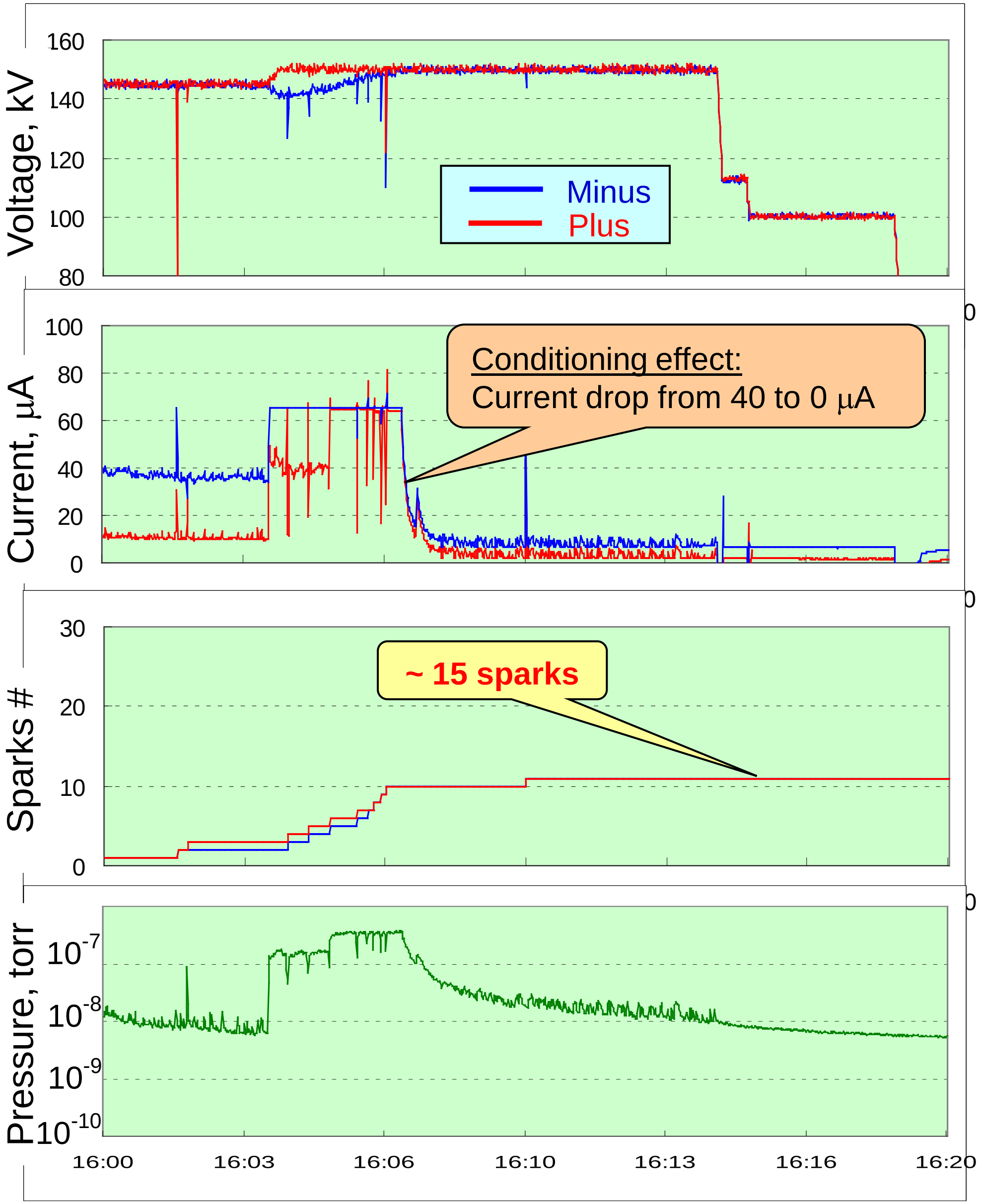
The gas normally used for this process is He, Ar, N_2, O_2, H_2 and the phenomenon has been traditionally interpreted in terms of the blunting of metallic emitters by action of high energy gas ion.

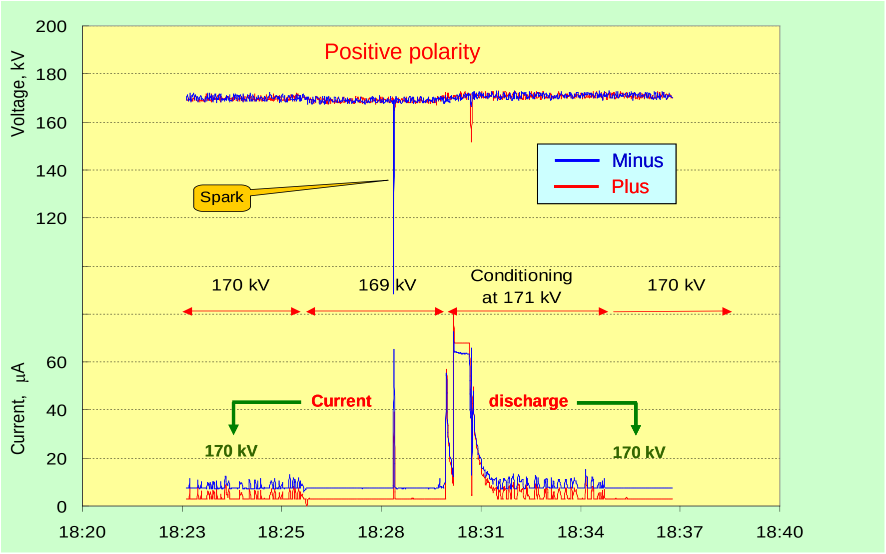
In our case a residual gas was used for "gas" conditioning at pressure around 10^{-6} torr.

- "Spark" conditioning

This technique is also known as "spot knocking" is to remove cathode emission sites or spots by arc erosion. It is also efficient in eliminating microdischarge and decreases the incidence of microparticle process.
Spark conditioning is effective way to decrease a separator dark current (hot spots).

Current Conditioning Effects





The disappearance of random charge transients or "microdischarges" from the predreakdown current during its stabilisation is frequently cited as evidence in support of the suppression of microparticle activity in the gap.

Current conditioning at higher voltages is effective way to eliminate microdischarges

Summary of Conditioning Tests

- New process for conditioning at higher voltages was well defined and tested.
  A procedure became much more quickly (hours vs days).

- 5 beam separators # 4, 6, 8, 27 and 28 were conditioned at 180 kV

- A detailed data were obtained on dark current and spark rate dependence vs voltage
  Conditioning at 10 kV higher decrease spark rate roughly 10 times

- A measured average spark rate:
  - at 180 kV → 1.0 +/- 0.2 sparks/day
  - at 175 kV → 0.3 +/- 0.1 sparks/day

- Estimated spark rate at 150 kV for separators conditioned at 180 kV is ~ 0.6 spark/year.
  Is it completely meet to technical specs (1 spark/year) requested by AD.

- Parameter comparison for hand polish and electropolish separators shows:
  - no big difference in spark rate at 175-180 kV but for 150 kV spark rate for electropolish separator is better for few times
  - a total number of sparks is roughly the same for both hand polish and electropolish separators that indicates an equal number of primary microparticles
  - dark current for electropolish separator almost 10 times better in comparing with handpolish

- Conditioning separator # 29 with titanium plates is the next
  Assembly almost completed (waited for HV feedthrough)
  New HV power supply prepared for testing

Plans in 2005 - 2006

- **Prepare and install 5 separators conditioned at 180 kV during next long shutdown in March 2006**

  3 separators will replace old ones and 2 will be install at new location to improve a beam separation in the arc

- **Continue R&D on separators**

  Complete construction and testing a separator with titanium plates

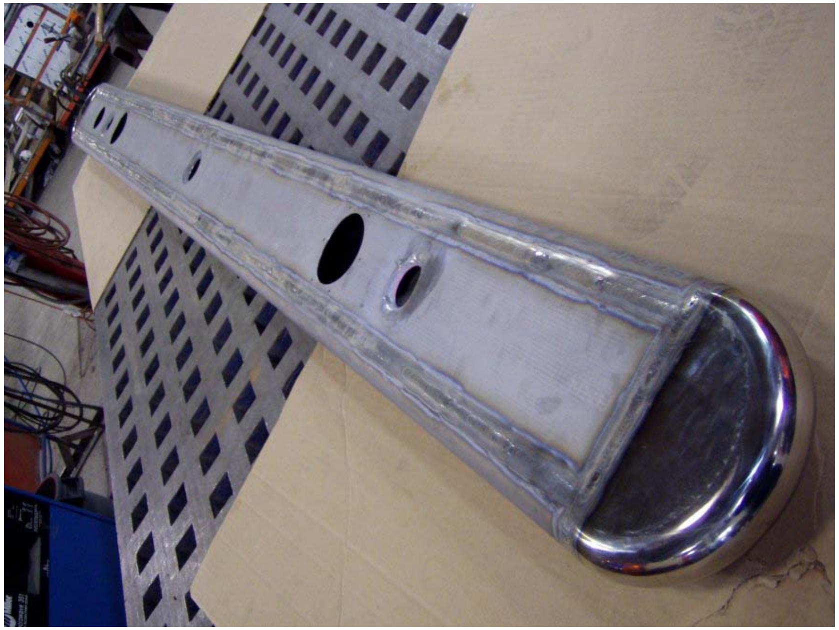
  Higher voltage conditioning up to 200kV (new 250 kV power supplies)

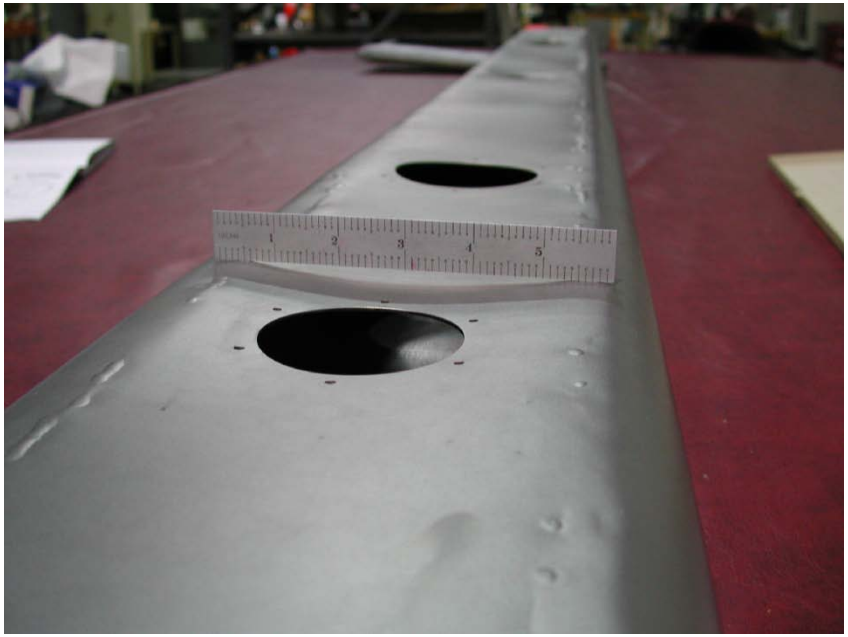
  Long term studies of separator performance at 180 kV (deconditioning effect)

  Reconditioning of 3 separators removed from Tevatron after shutdown

  Keep 4 separators as spare to swap in for installed separators after 2006

Titanium Plate Production

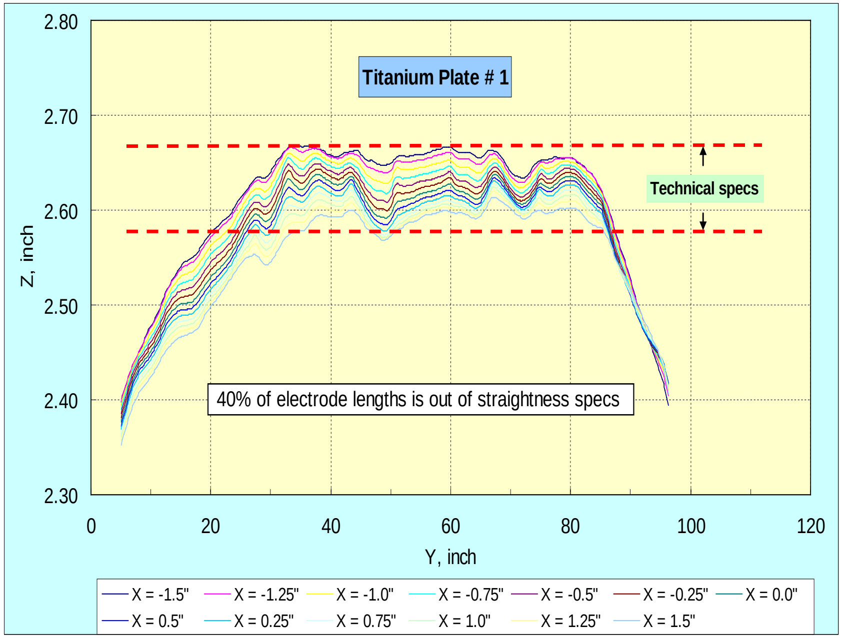




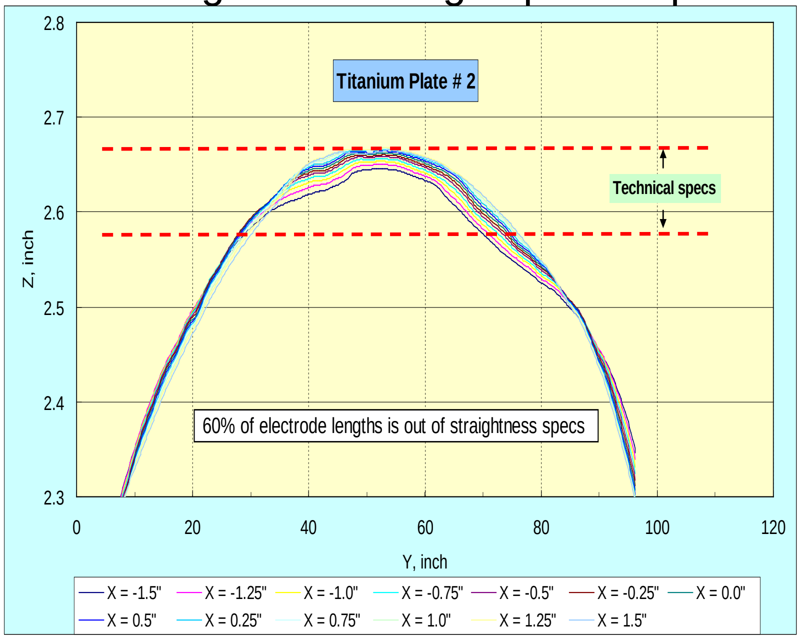
Titanium, like all metals, is susceptible to certain welding defect and deformations. However, the range of possible defects for titanium is much more than for stainless steel. The surface preparation and adequate gas shielding is crucial for titanium welding.

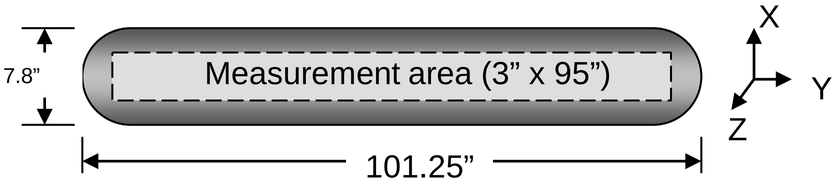
Titanium Plate : Front Face Straightness Measurements

Straightness along separator plate



Straightness along separator plate



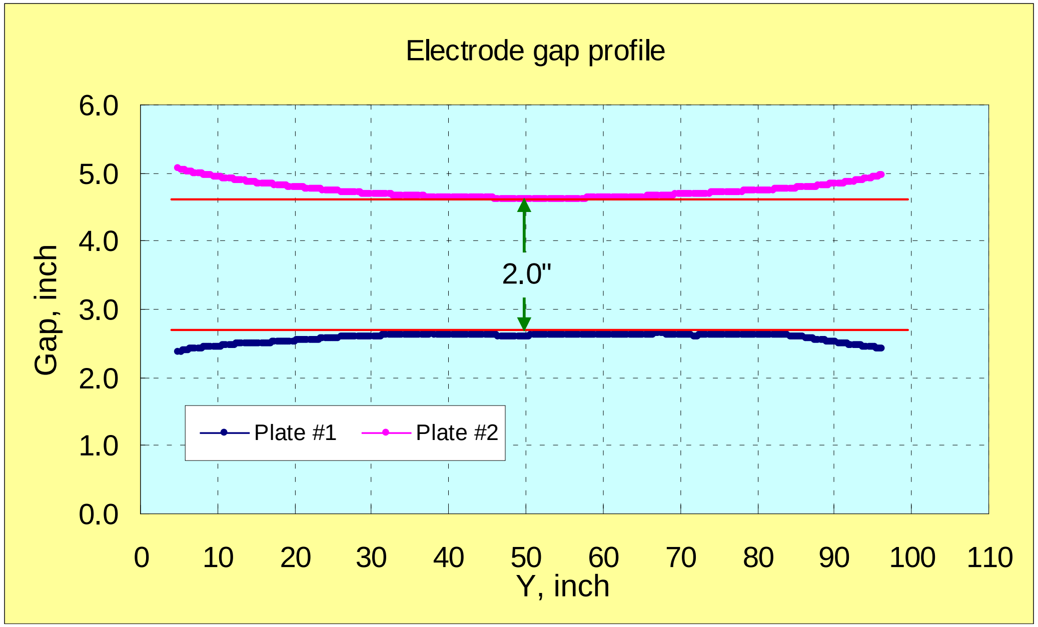


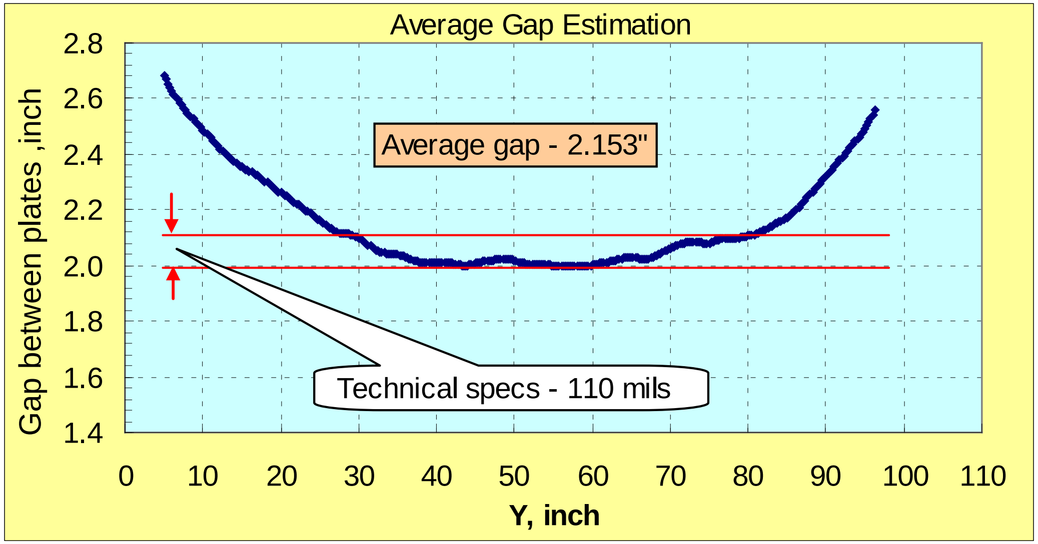
Technical specs:

- straightness → 80 mils for 92.6”
- flatness → 20 mils for 3.0” square

The results of two titanium plate production with using hand weld are not good.
A plate deformation and porosity in weld metal is out of technical specs.
About 40%-60% of electrode length is out of straightness technical specs.
A sag correction is possible but may make damage (crack) electrode.

Electrode Gap Estimation

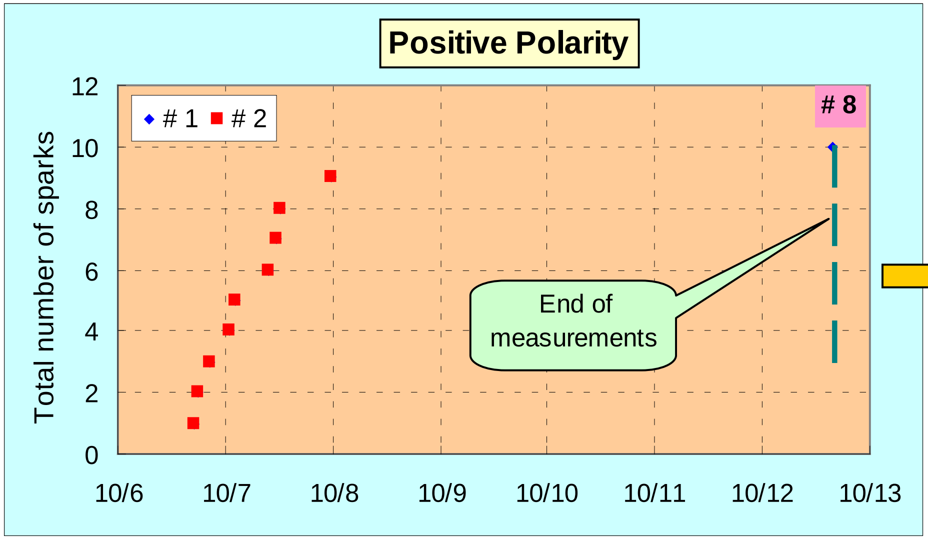


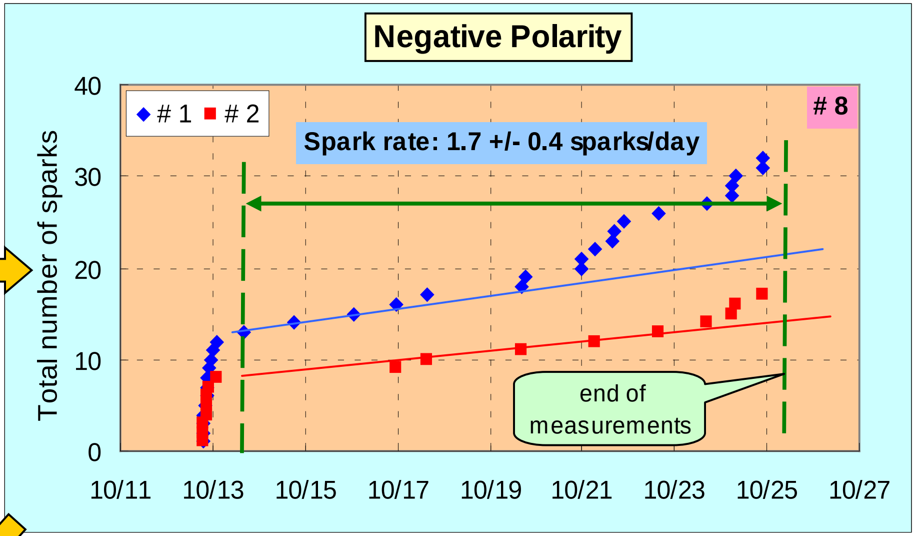


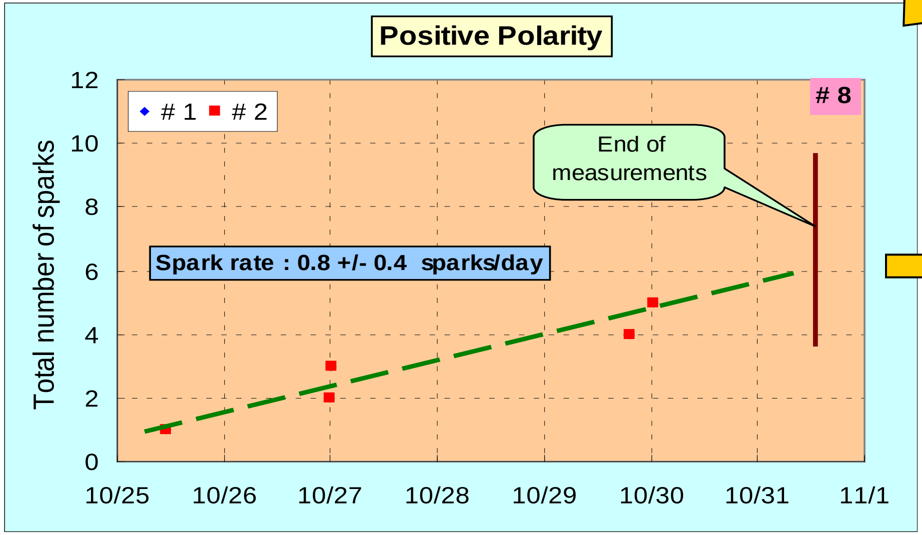
Effective electric field will be less from nominal for about 7.7% due to electrode deformation

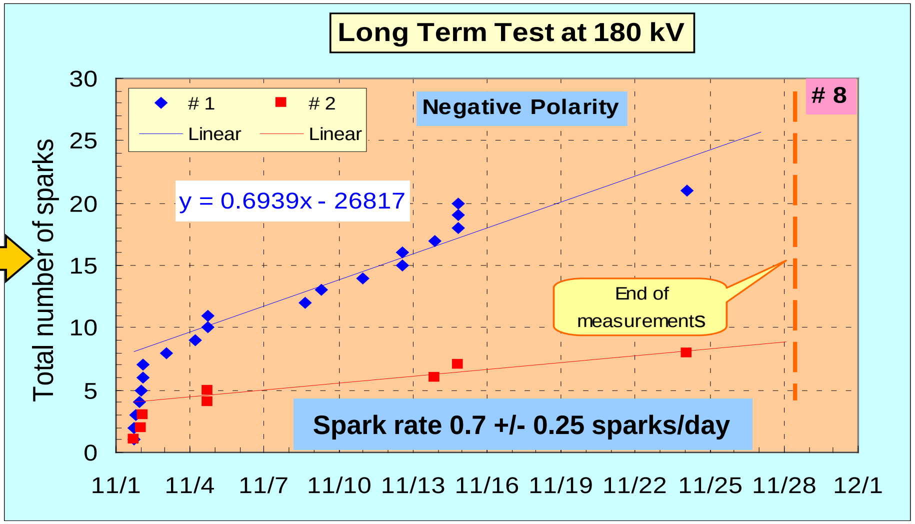
This efforts is only R&D, future production should be done with more consideration of titanium manufacturing technology.

Long Term Measurements at 180 kV









Long term separator performance and reliability at 180 kV
There is no any evidence of deconditioning / degradation effect.