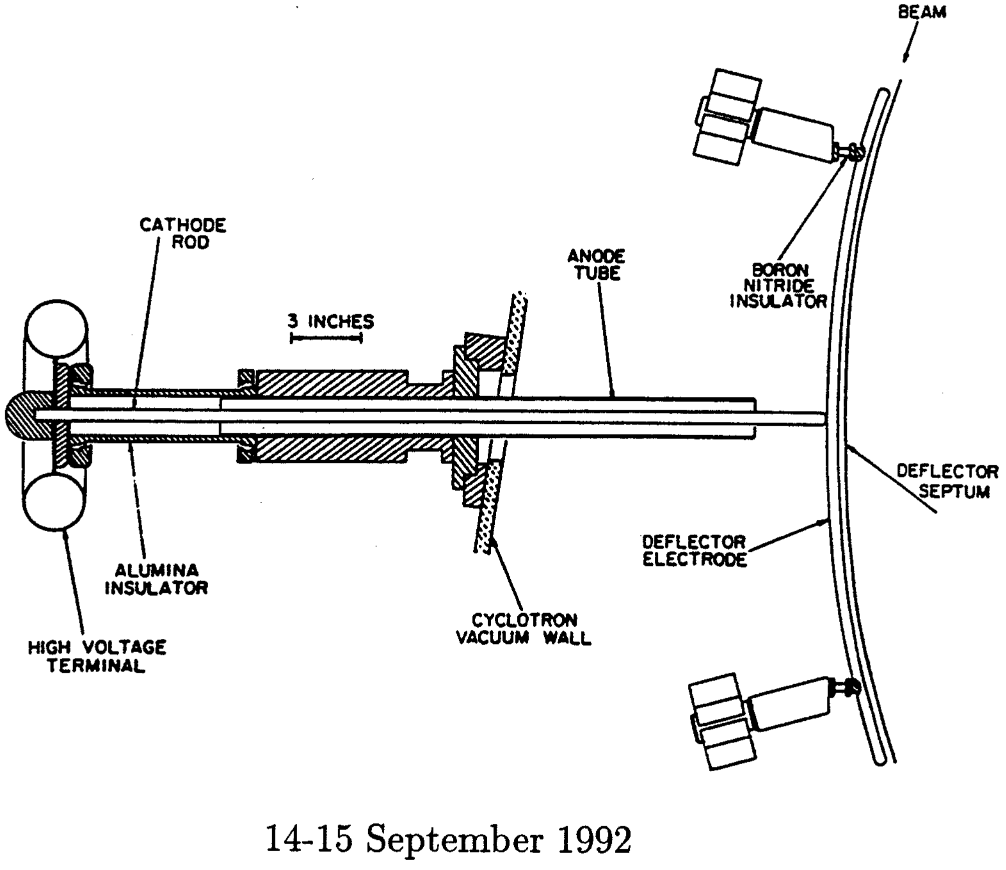
Workshop on High Voltage Deflectors For Superconducting Cyclotrons

B. Rogers, Chairman

Cyclotron Institute
Texas A&M University



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Anodized Titanium Deflector Demonstration

A K500/E1 style deflector with anodized titanium shoe and sparking plates was assembled and tested during this Workshop.

At 9:00am on Monday, the assembly and installation of the deflector was observed. Both the shoe and sparking plates had been electropolished and hard anodized prior to assembly. The shoe had a grainy, rough, gray surface finish. The sparking plates had a smoother, shiny finish. The shoe was assembled using 'fat' Mycalex insulators. Mycalex is a glass-mica composite similar to MACOR, but softer with reputedly better sparking properties. The insulator end caps, also anodized titanium, were affixed in insulator end recesses using high density epoxy.

The TAMU/E1 deflector test stand consists of an Alpha Scientific Magnet modified for an E1 deflector housing with a standard TAMU high voltage feed thru. The test stand includes magnet and high voltage power supplies, turbo- molecular pump, and an O_2 gas feed system. The HV supply can be current or voltage regulated.

In voltage regulation mode, the high voltage current limit was set at 50 eμA. The magnet produces 0.7 tesla at the deflector insulators. The high voltage feed thru has a glass center conductor enclosing a resistive high voltage cable (standard cable with the center conductor removed) in series with a 250 kΩ resistor, for a total series resistance of 0.5 MΩ between the power supply and deflector assembly. The test stand includes lead glass view ports at both deflector ends which reduce the x-ray dose from the deflector assembly to background levels.

After roughing to $\approx$ 80 microns, O_2 glow discharge conditioning commenced at B=0 and I=0.5 mA @ 700 V. Lower pressure operation increases the conditioning voltage, but results in etching of the electrode ends. The glow discharge cleaning process is continued for a period of three hours. This period may be overly long but appears to insure good performance. The glow discharge cleaning causes the change in appearance of the anodized titanium surface from a soft white color to the rough gray color.

Before oxygen discharge cleaning, which was done prior to the workshop, the newly anodized titanium electrode was only capable of supporting a voltage of 20 - 25 kV before the onset of sparking, this with no magnetic field applied. After cleaning, the electrode was able to reach 100 kV with no magnetic field. Application of the magnetic field resulted in the onset of sparking at the 40 kV level which could then be slowly increased to a level of approximately 65 kV. Attempting to go beyond this level resulted in sparks which caused damage to the center insulator in the form of tracking which gave a high level of drain current.

Additional cleaning of the electrode with oxygen appeared to correct the leakage problem for a short time but ultimately the deflector had to be disassembled so the insulator could be cleaned mechanically.

The deflector was reassembled with the anodized aluminum electrode. This electrode had not been previously used. The spark shields were not changed and the same insulators were used. The aluminum electrode reached 50 kV before the oxygen discharge was used. After three hours in the oxygen bath and overnight pumping to a vacuum of 4x10e-7, the electrode reached 89 kV but could not go beyond that voltage because of sparking in the region of the input insulator, this without magnetic field. Application of the field resulted in the onset of sparking at the 50 kV level with a damaging spark at the 55 kV level that reduced the voltage holding capability to 35 kV. A further cleaning with oxygen and changing of the high voltage input rod to include 30 MΩ of resistance resulted in the electrode reaching 86 kV with the magnetic field before a spark apparently damaged a region around the output insulator. This concluded testing until the deflector could be disassembled and inspected.

Peter Miller
National Superconducting Cyclotron Laboratory
Michigan State University

History of Deflectors in MSU Superconducting Cyclotrons

History of Deflectors in MSU Superconducting Cyclotrons

K500 S.C. cyclotron concept: "Like the 50 MeV cyclotron"

Differences:
1. Smaller magnet gap — 2.5" for deflectors
2. Higher B
3. Cryostat crosses median plane.
4. Deflector moves.

Consequences for deflectors:
1. Less space available
2. Sparks are more concentrated

Deflector R+D 1976-80
- Electrode material — chose St. Steel
- HV feed
- Support insulator design
- Eliminate water cooling

Testing of the essential elements of the design is in progress. We are reporting high voltage experiments which have tested the median plane feedthru.

At the same time the maximum field in the feedthru will be 172.9 kV/cm, 22% higher.

The chosen high voltage feedthru design, shown in Fig. 1, consists of a coaxial arrangement of cathode and anode. The cathode, fabricated from a 0.5 inch diameter rod, is the

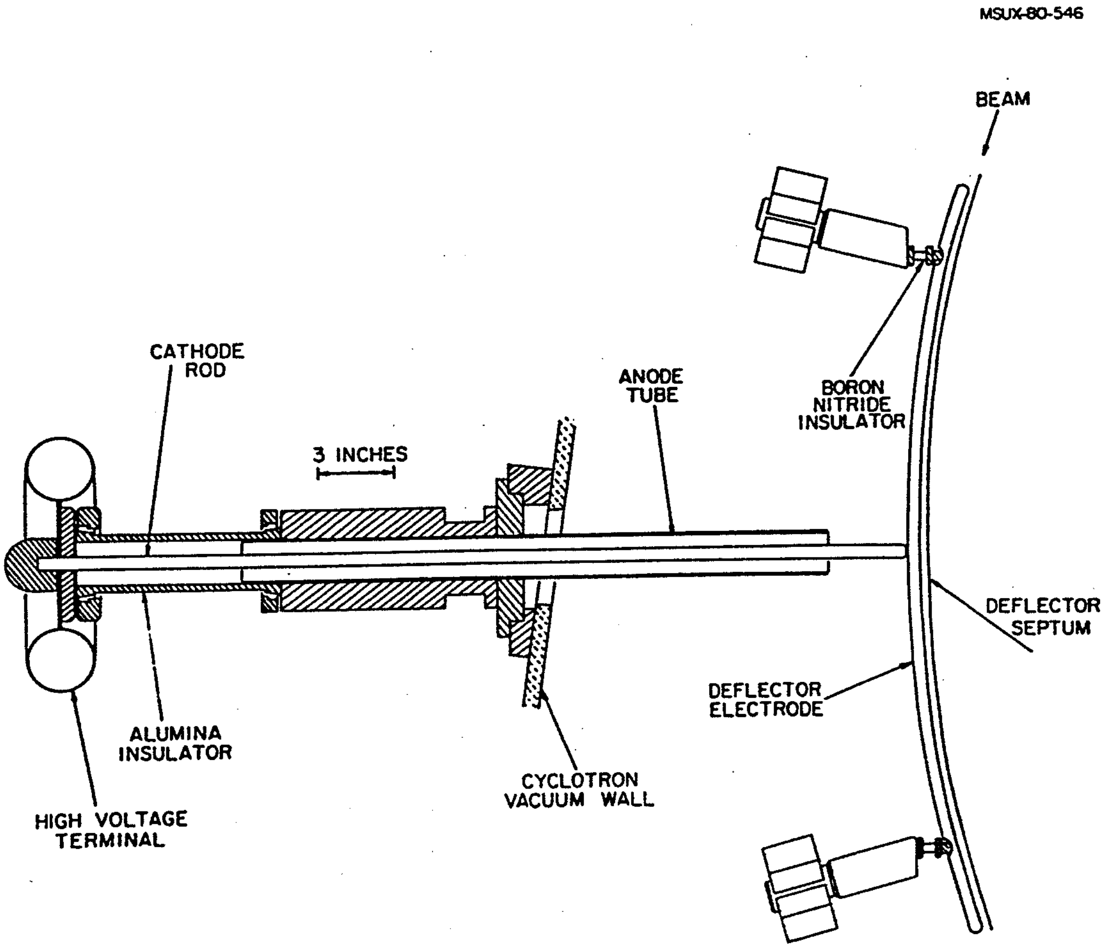
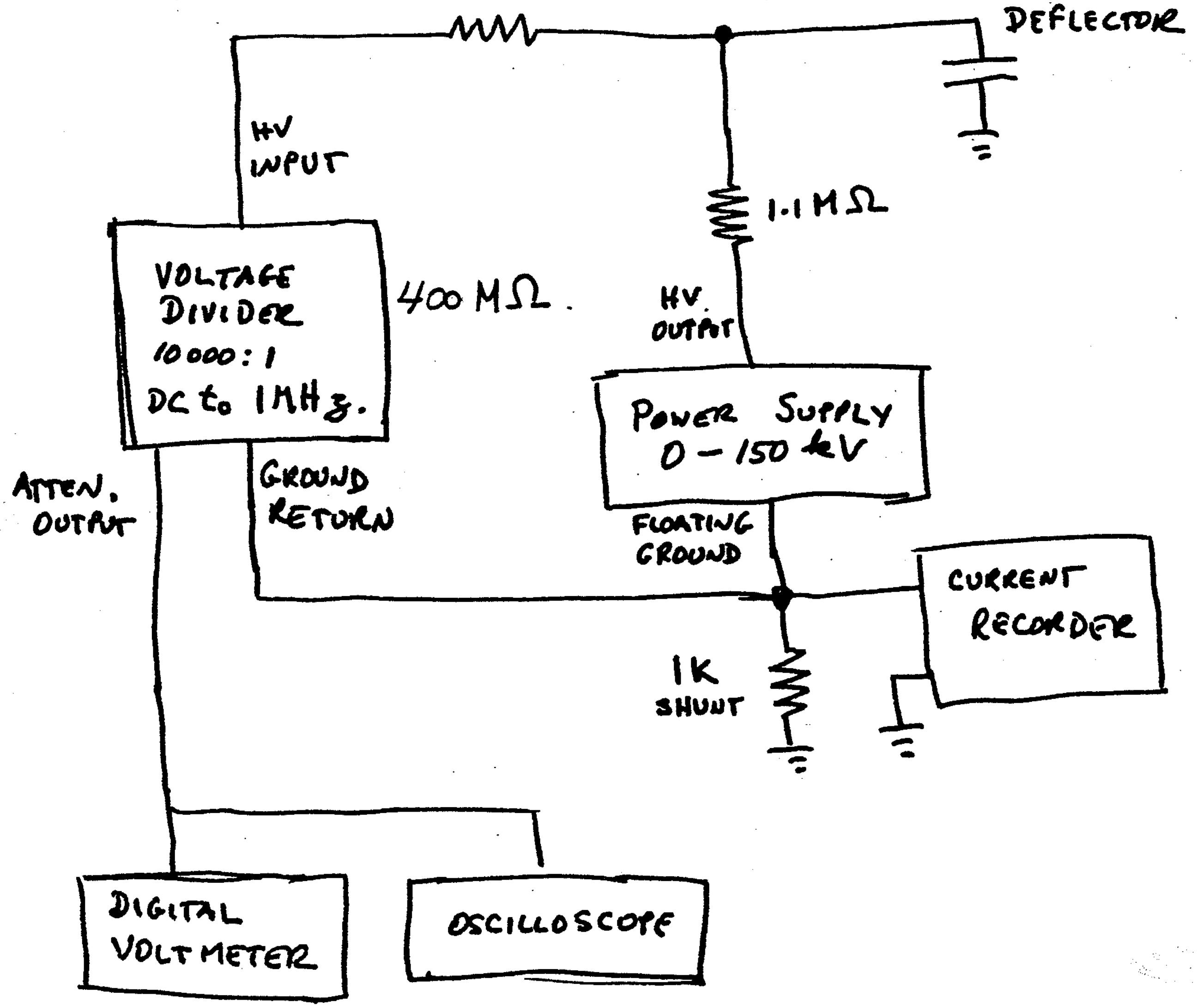
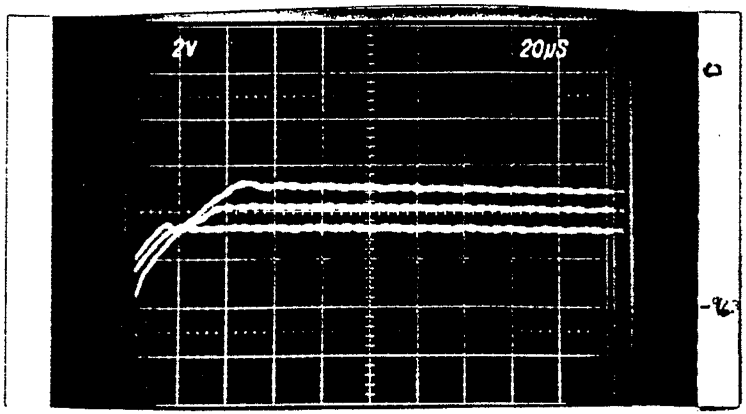
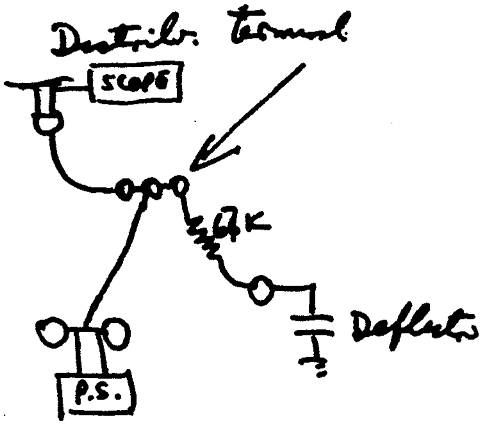


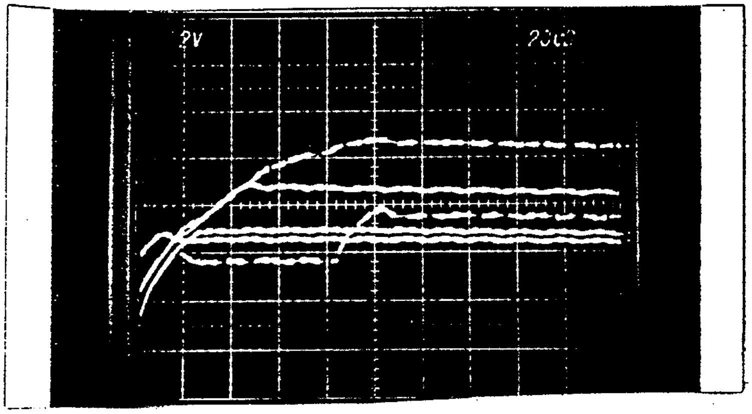
FIG. 1. Diagram of the high voltage feedthru and electrostatic deflector as installed in the 50 MeV cyclotron for the high voltage tests. The K-500 design feedthru supplies an existing deflector electrode. The length of the feedthru, measured from the high voltage terminal to the deflector electrode, is 32 inches, and will increase to 44 inches in the K-500 cyclotron. Both titanium and stainless steel anodes have been tested.


DEFLECTOR
HV INPUT
1.1 MΩ
VOLTAGE DIVIDER
10000:1
DC to 1MHz.
400 MΩ.
HV. OUTPUT
POWER SUPPLY
0 - 150 kV
ATTEN. OUTPUT
GROUND RETURN
FLOATING GROUND
CURRENT RECORDER
1K SHUNT
DIGITAL VOLTMETER
OSCILLOSCOPE

28 Feb 80







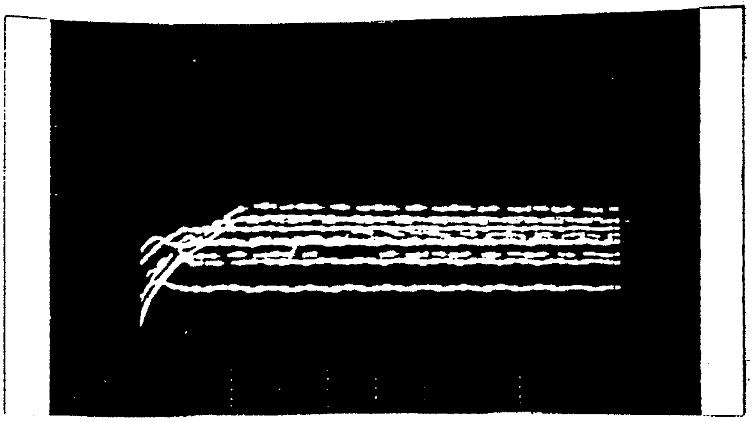
RC min ≈ 20μsec

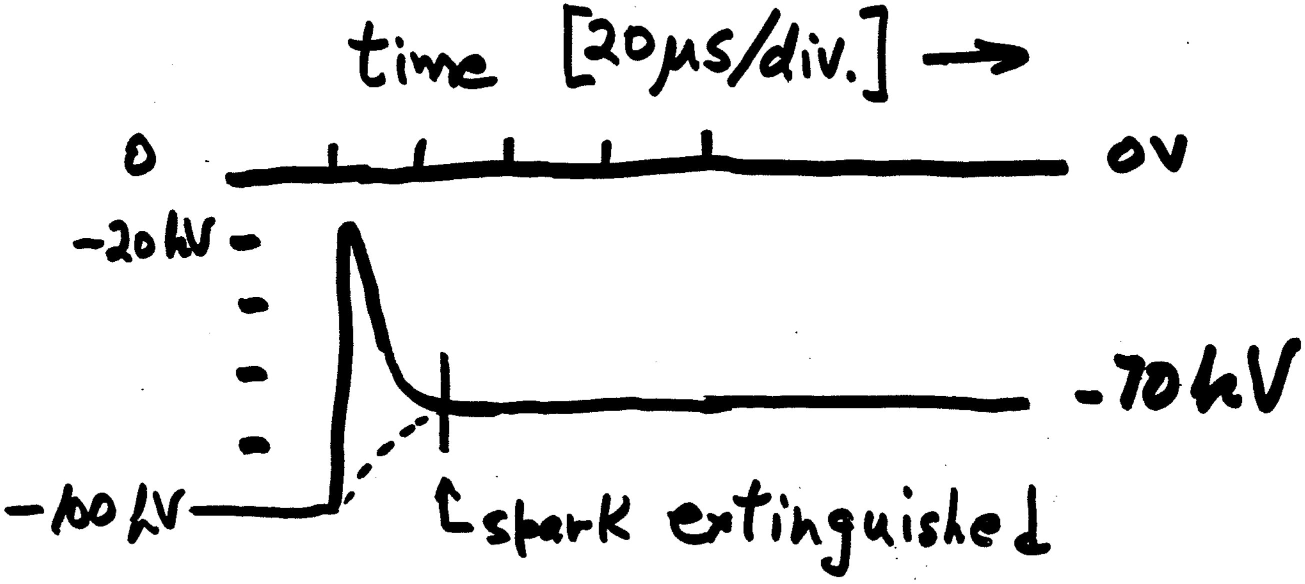
$$C = \frac{20\mu sec}{67K} = 300\ pf$$

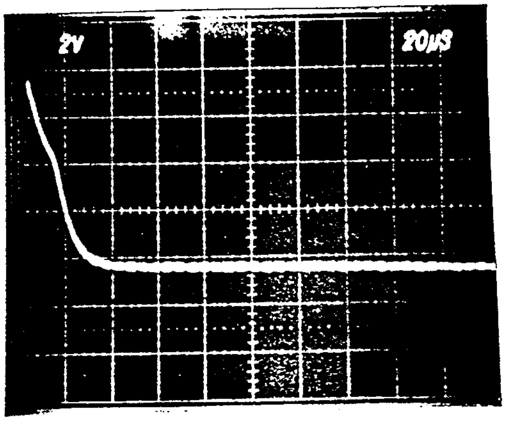
Stack has 16 units of 3600pf each

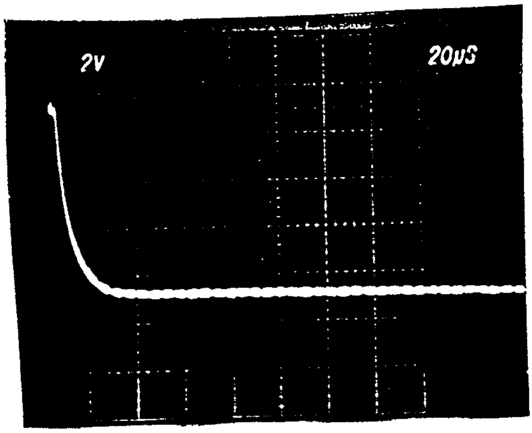
$$\frac{3600}{16} = 225\ pf$$

75pf extra due to terminals.



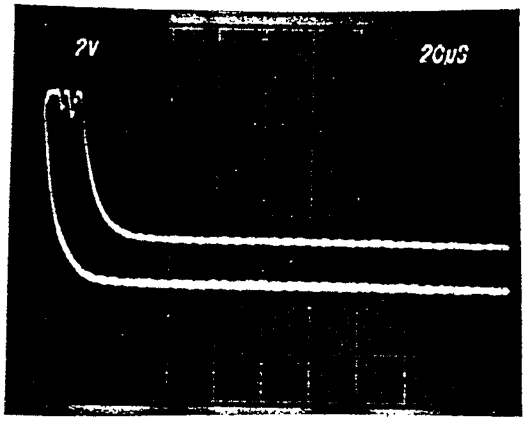

time [20μs/div.] →
0
0V
-20kV
-100kV
-70kV
[spark extinguished]

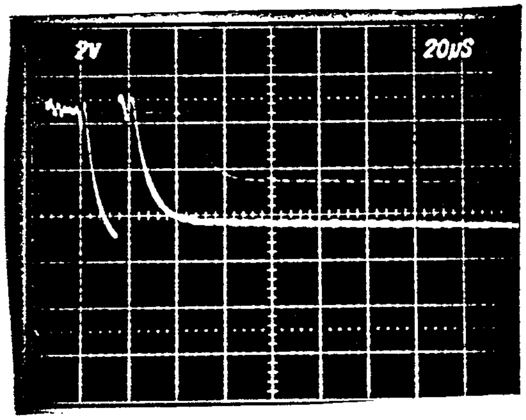




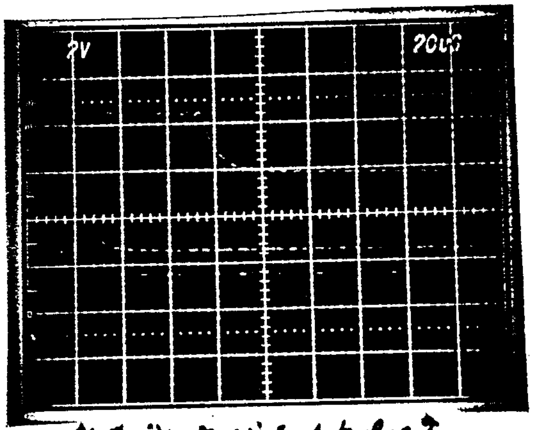
99.6 kV

28 Feb 80
Deflector term.

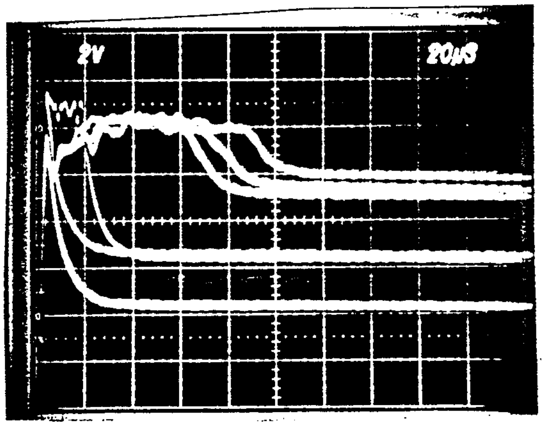




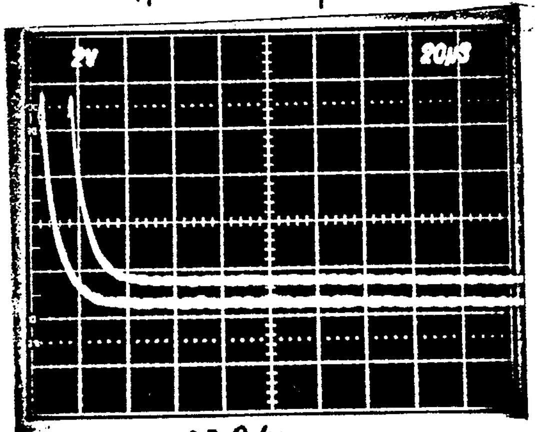
107.2 kV
.85 mA



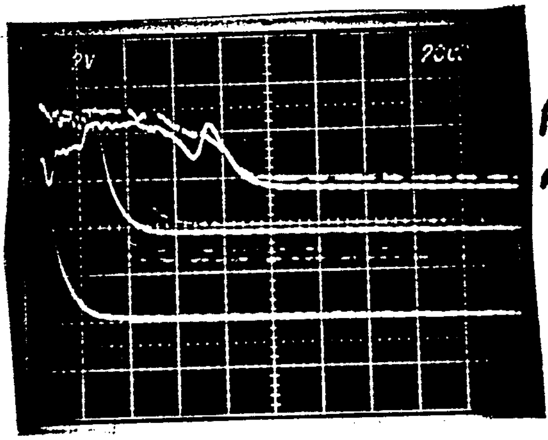
OL trip on widest pulse ?



105.18 kV



103.9 kv



pot 710
~113 kV

Deflector Conditioning Performance in 50 MeV Cyclotron

Summary 11 March 1980 and 24 March 1980

1. Electrodes seem to be capable of at least 104 kV.

2. Plastic feedthrough insulator sparks in vacuum at about 98 kV.

3. Short insulators with no corona rings, midplane hole, spark at about 98 kV.

4. 500 K current limiting resistor is beneficial, comparable to 67 K.

5. H2 glow cleaning is beneficial to electrodes--don't know about insulators.

6. Conditioning from vacuum break takes 1 day.

7. Power supply trip senses average current, does not trip on most sparks (averaging time >= 17 ms).

8. Spark protection is provided by resistor string.

9. Vacuum spark lasts 5-100 microsec.; spark seems to go out with high voltage present (50-80 kV). Not necessary for power supply terminal to discharge before spark ends (Not true in air).

10. Power supply terminal ripple is about 0.27% rms, sine wave, f=62-67 kHz.

11. Deflector ripple is reduced below 0.01% rms by a filter.

12. Dark current should be less than 10 microamp for stable opertion--higher values tend to go with sparking.

13. Dark current fluctuations are about +- 10% peak to peak (0 to 10 Hz band) at all current levels.

14. Power supply output capacitance is 370 pf.

15.Deflector capacitance is about 80 pf.

16. Titanium spark anodes will burn through with repeated sparking and 67 K resistor. Get pits formed but no holes with 500 K.

17. External terminals will support 134 kV. Voltage divider up to 120 kV max.

18. Boron nitride rods with corona caps can take more voltage than feedthru (about 100 kV).

19. Dark current can be conditioned down by sparking, but it grows back.

20. Dark current is not a repeatable function of voltage.

21. 1.1 meg resistor seems to prevent damage from sparks.

22. Vacuum sparks extinguish in about 4 microsec at V=15 kV.

23. After letting up to N2 twice, dark current increses with voltage and grdually recovers, often without sparking (outgassing?).

24. Gross heating by sparks is not a problem even with dark current of 30 microamp--checked by cooling period--no change in dark current.

25. Deflector works OK with no water on sparking plates.

26. There is an air leak in spark plate water circuit, which raises the deflector pressure--Nolen says high pressure is good for holding voltage.

27. 24. Also demonstarted by 24 March power supply record, 100 kV at up to 30 microamp. Wiped terminals, current didin't change, so must be deflector current.

K500 Deflectors 1982 – 1988

3 insulators each

Coaxial HV feed
  Sliding rod – changed to Ti tube
  180 kV/cm max.

Built test stands

Peak field studies
  Electrode shape gives 180 kV/cm peak when working field is 140 kV/cm
  Led to modification of shape of cathode in K1200.

econd and a leakage current limit of 50
leakage current goes above the set
voltage is decreased by 4% per tenth
il the current drops below the set

the insulators come out discolored,
ed d sometimes broken after a few
se in the cyclotron they are suspected
gely responsible for the limited
e. Each deflector shoe is supported by
ators, two in compression and one in
They are alumina 0.3" in diameter and
long. We have tried metallizing the
e insulators and soldering metal end
compressive ones to reduce insulator
his may have made operation slightly
le but the results are not very well
e to the wide range of performance of
ors.
all diameter of the voltage feedthrough
ssitated by the small median plane
n of the superconducting coil is also a
of the deflectors. It is not unusual
tor sparks to be in this tube rather
actual deflector housing. The ID of
(grounded) tube is 1.2" while the OD of inner
) conductor is 0.4" leading to an
eld of 178 kV/cm at the surface of this
ctor at the design voltage of 100 kV.
ied both titanium and stainless steel

/o adjustable current limit has been purchased for use with these test stands and to determine the advantages of the current limiting feature. Various cleaning and polishing methods for the various deflector components will also be tried. Different conditioning procedures, leak rates, and leak gasses will be evaluated. New deflector shoes (cathodes) of titanium are currently being made in the shop. The idea of using a ceramic

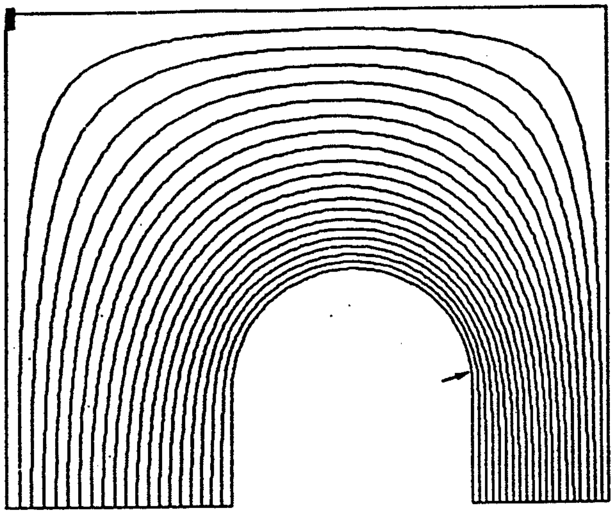
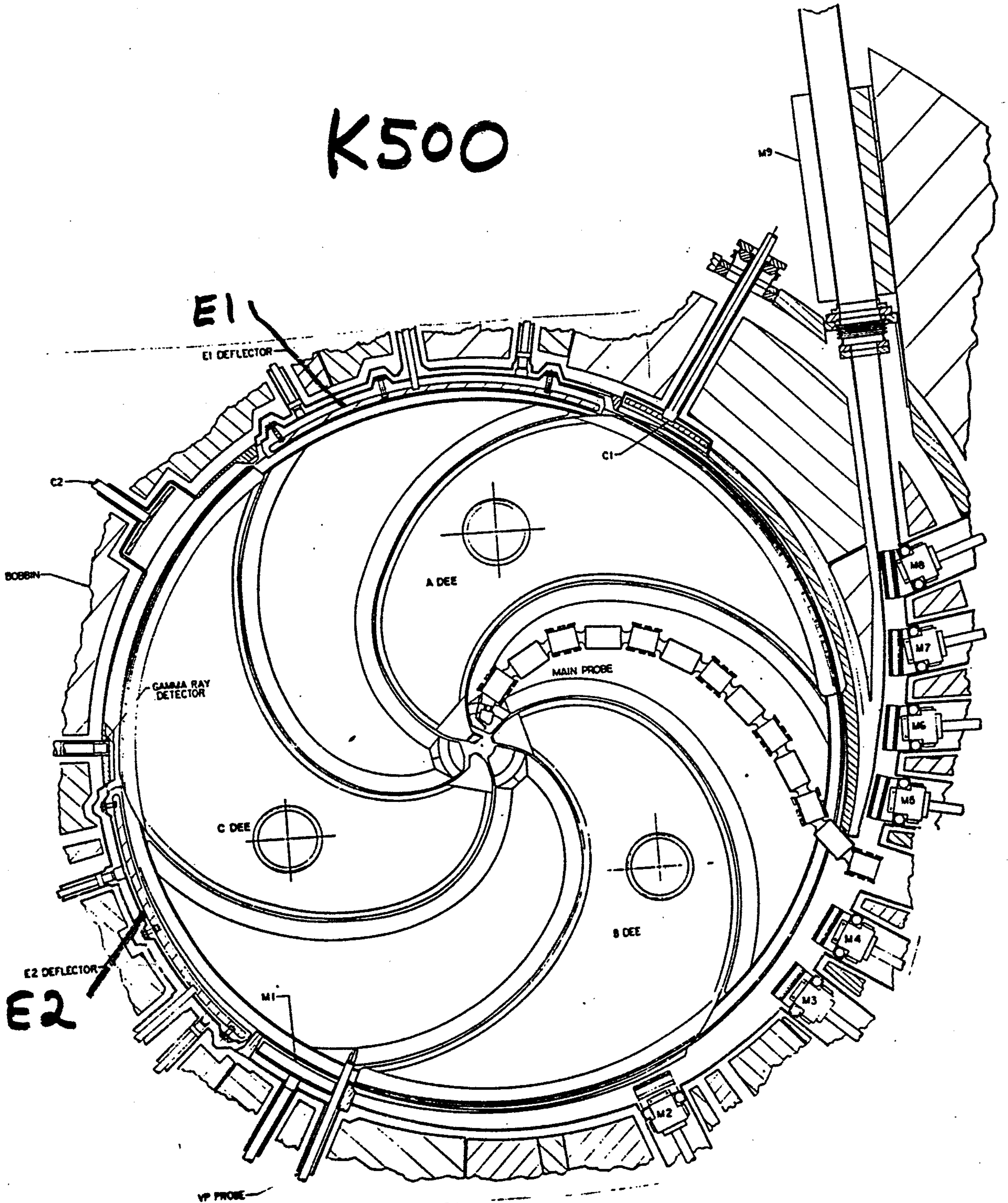
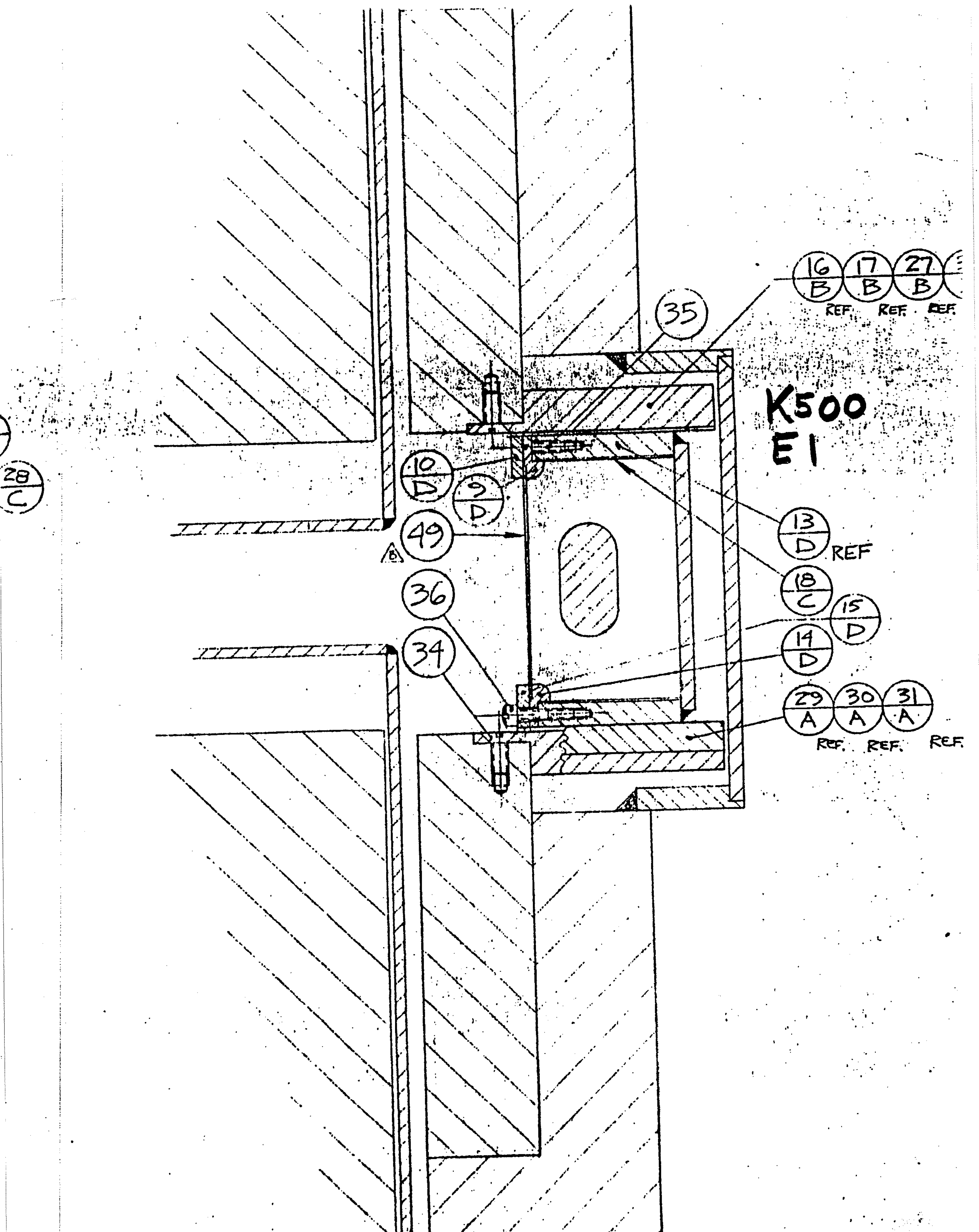
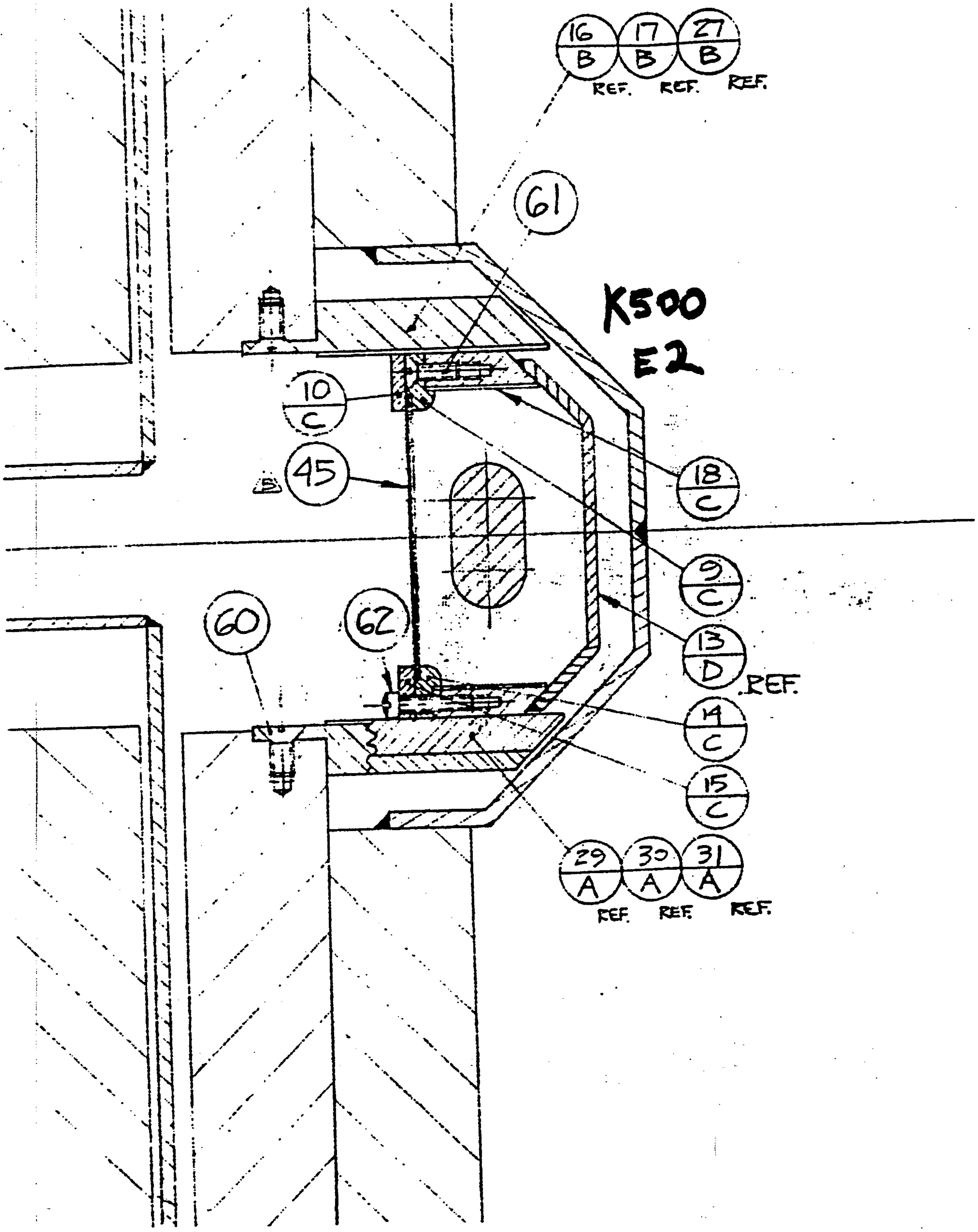


Fig. 1. Electrostatic calculation showing the equipotentials surrounding the deflector shoe with the present geometry. With a field of 140 kV/cm on the median plane, the peak field (at the arrow) is 180 kV/cm.

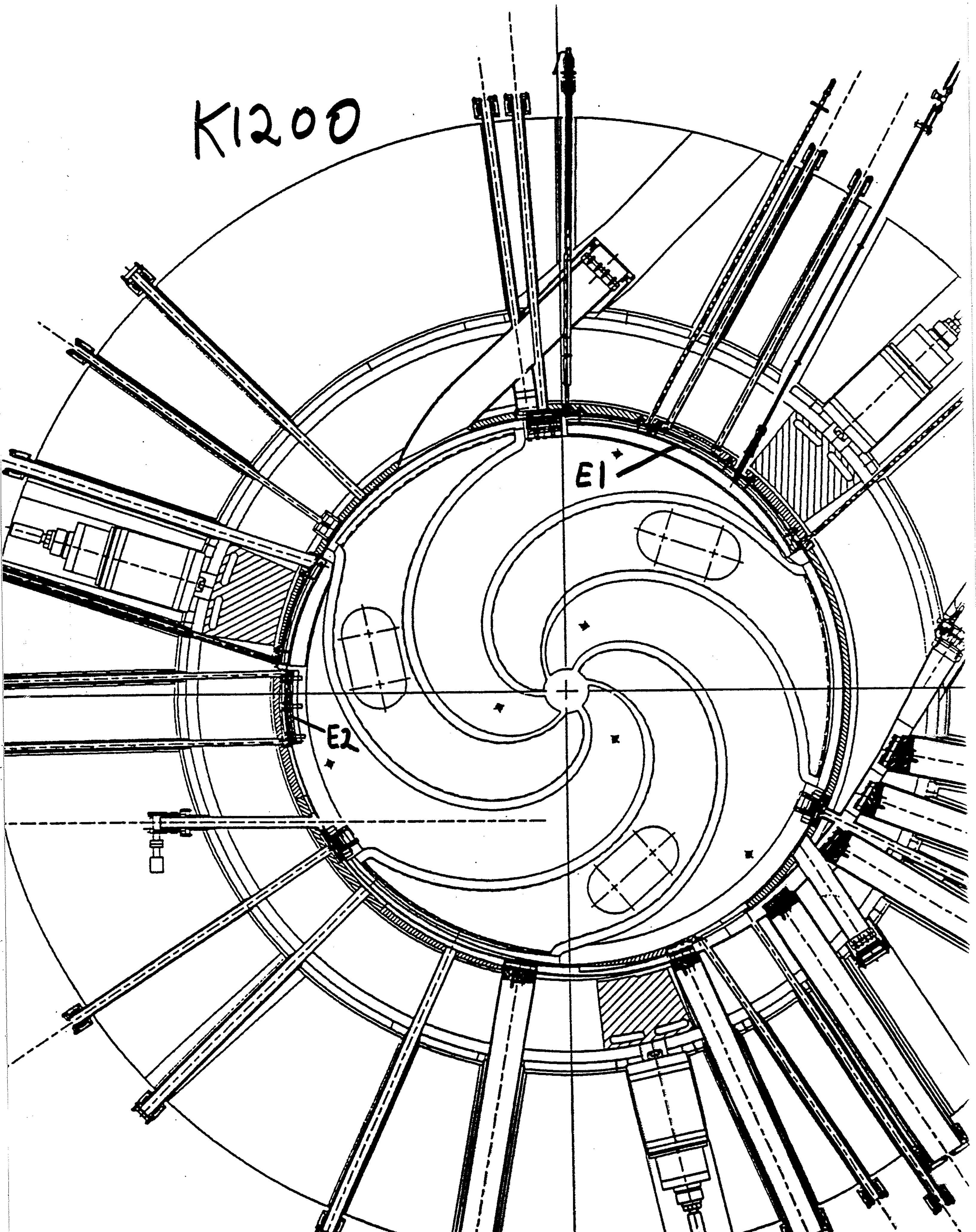
K500


E1
E1 DEFLECTOR
M9
C1
C2
BOBBIN
A DEE
MAIN PROBE
GAMMA RAY DETECTOR
M8
M7
M6
M5
C DEE
B DEE
M4
M3
E2 DEFLECTOR
E2
M1
M2
VP PROBE


16/B REF
17/B REF
27/B REF
35
K500
E1
28/C
10/D
9/D
49
B
13/D REF
18/C
15/D
14/D
36
34
29/A REF
30/A REF
31/A REF

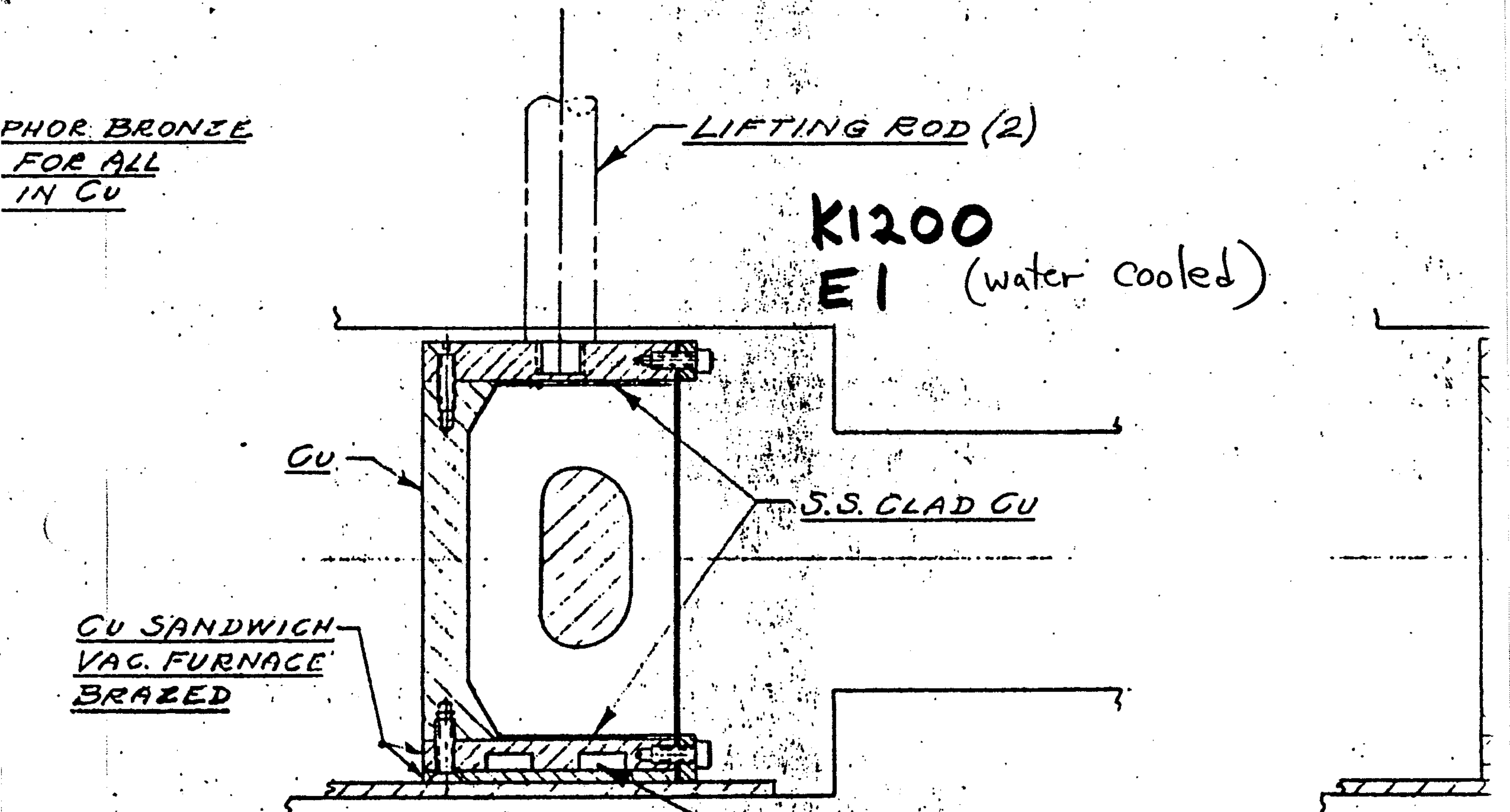

16/B REF.
17/B REF.
27/B REF.
61
K500
E2
10/C
45
18/C
9/C
13/D REF.
60
62
14/C
15/C
29/A REF.
30/A REF.
31/A REF.

K1200



W F-F
"A" HEAD

VIEW G-G
TYPE "B" HEAD



K1200
E1 (water cooled)

SECTION C-C

K1200 Deflectors 1989 –

Minimize Damage from Sparking
$50 M\Omega + 0.6 M\Omega$ in cable – Rogers

Minimize Leakage Currents
Coating cathode – $\begin{cases} \text{varnish} \\ \text{anodize} \\ \text{glass} \end{cases}$

Support insulators
Sapphire – good up to 60 kV. Some have glow mode, draw current.

Insulator mounting
midplane gap tested — avoid E×B current.
Corona caps – shield braze joints on metal end buttons

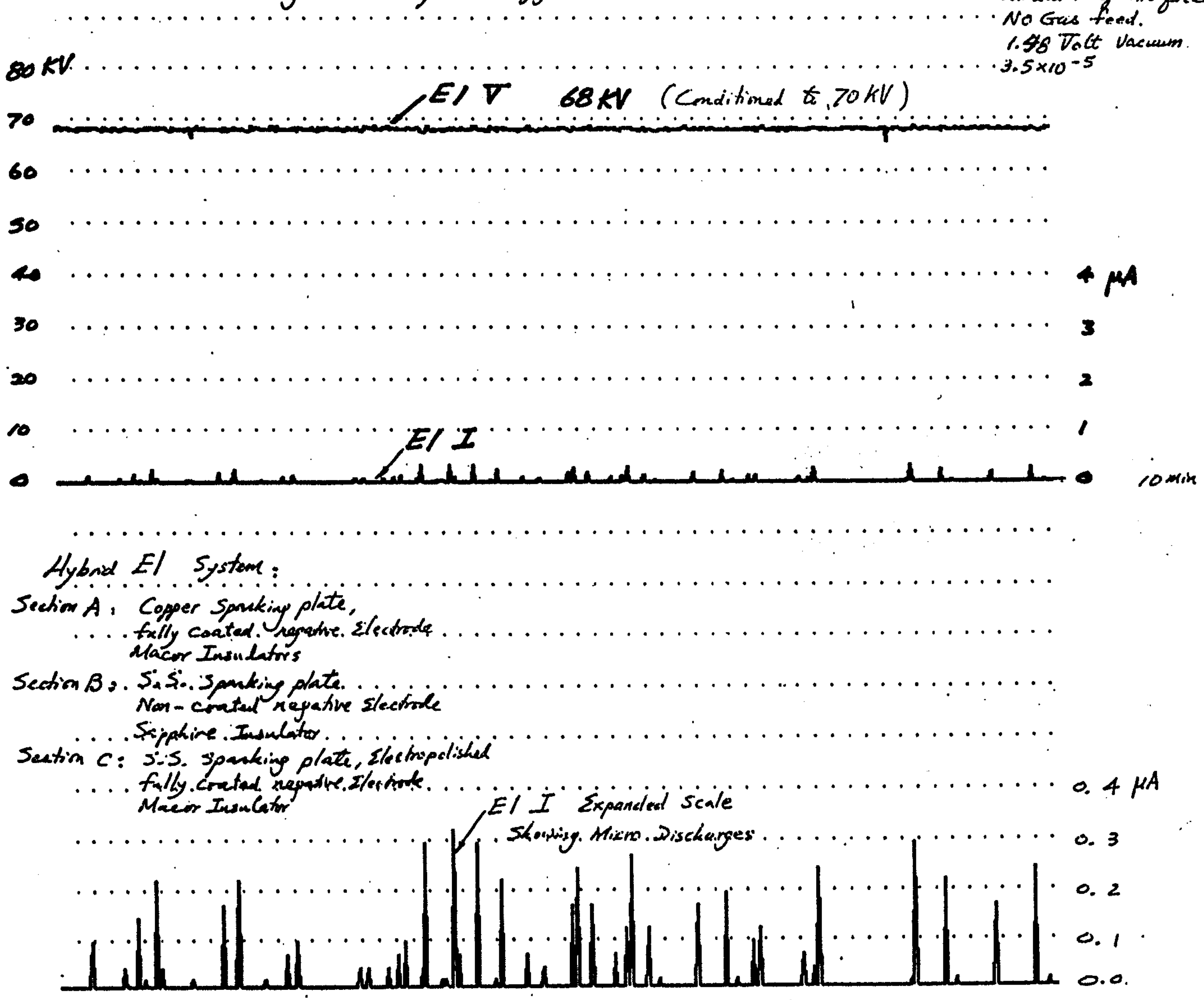
Magnetic field and gas effects

Water cooling added to housing – 1992
E1 A

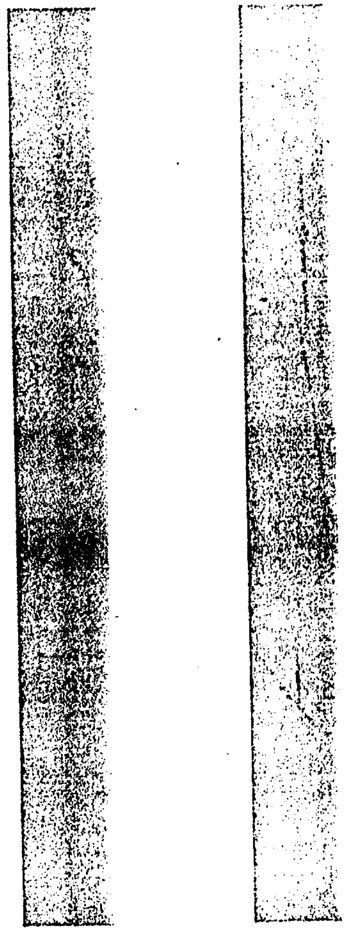
Deflector test stand was converted to study a fast-timing cyclotron.

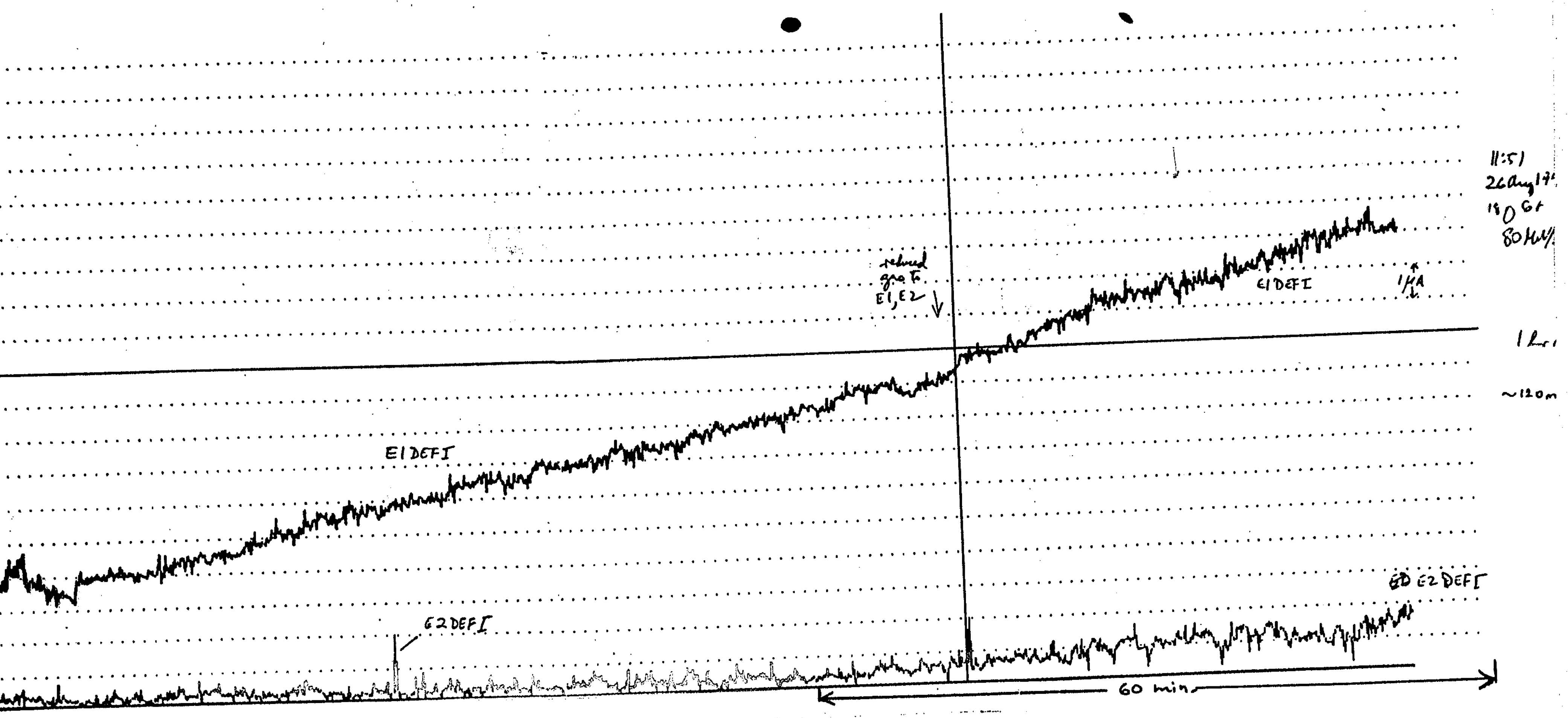
Working Toward Higher Energy Ion Extraction

Feb. 23 - 24, '92
without magnetic field.
No Gas feed.
1.48 Volt Vacuum
3.5×10⁻⁵



Hybrid EI System:
Section A: Copper Sparking plate, fully coated negative Electrode Macor Insulators
Section B: S.S. Sparking plate. Non-coated negative Electrode Sapphire Insulator
Section C: S.S. Sparking plate, Electropolished fully coated negative Electrode Macor Insulator



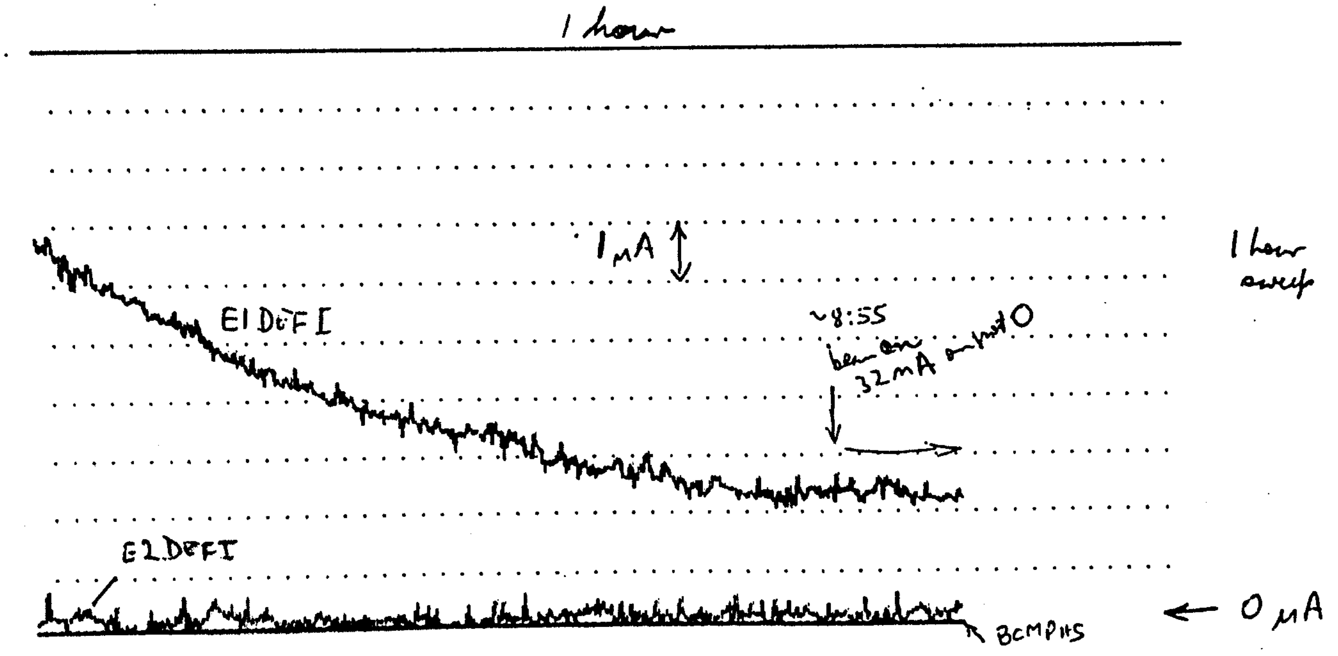

reduced
gain to
E1, E2
E1DEFI
E1DEFI
1μA
11:51
26Aug17
$^{18}O^{6+}$
80 MeV/
1 hr
~120m
E2DEFI
E2DEFI
60 min

9:00 AM

26 Aug 1991

80 MeV/n

$^{18}O^{6+}$



Advances 80 kV achieved

HV feed K500 ~60 kV max.

K1200 >80 kV

Stainless steel spark anodes best
(sparks must be avoided)

Insulating coating on cathode
glass and aluminum oxide being tried
Use of glass to attach insulator to cath.

Series current limiting resistor

Water cooled housing and beam stop (first sect.)

Ongoing work

Dust control

Cathode coatings < anodized Al E1 under const. / glass

Insulator design

More cooling (other sections)

Goals

Run 84 kV on 6 mm gap reliably

Increase the beam power capability for specific beams, like ^{18}O, desired for secondary beam production.

William Diamond
Chalk River Laboratories

Deflector Operation in the Compact Cyclotron

Deflector Operation
in the
Compact Superconducting Cyclotron

- Tight space constraints

  ≈ 25 mm between H.V. electrode and sparking plate

- Strong magnetic fields

  2.5 to 5 Tesla

  (mm)

  r_g = 0.18 at 70 kV and 5 T
  r_g = 0.31 at 70 kV and 3 T

- Power density in a spark $\propto B^2$

- RF heating

  – residual rf fields heat deflector
  – heated electrodes reduce performance

Deflector Design Goals

Ultimate Goal

100 kV across 7 mm gap

⟹ 140 – 150 kV/cm gradient

at 2.5 – 5.0 Tesla

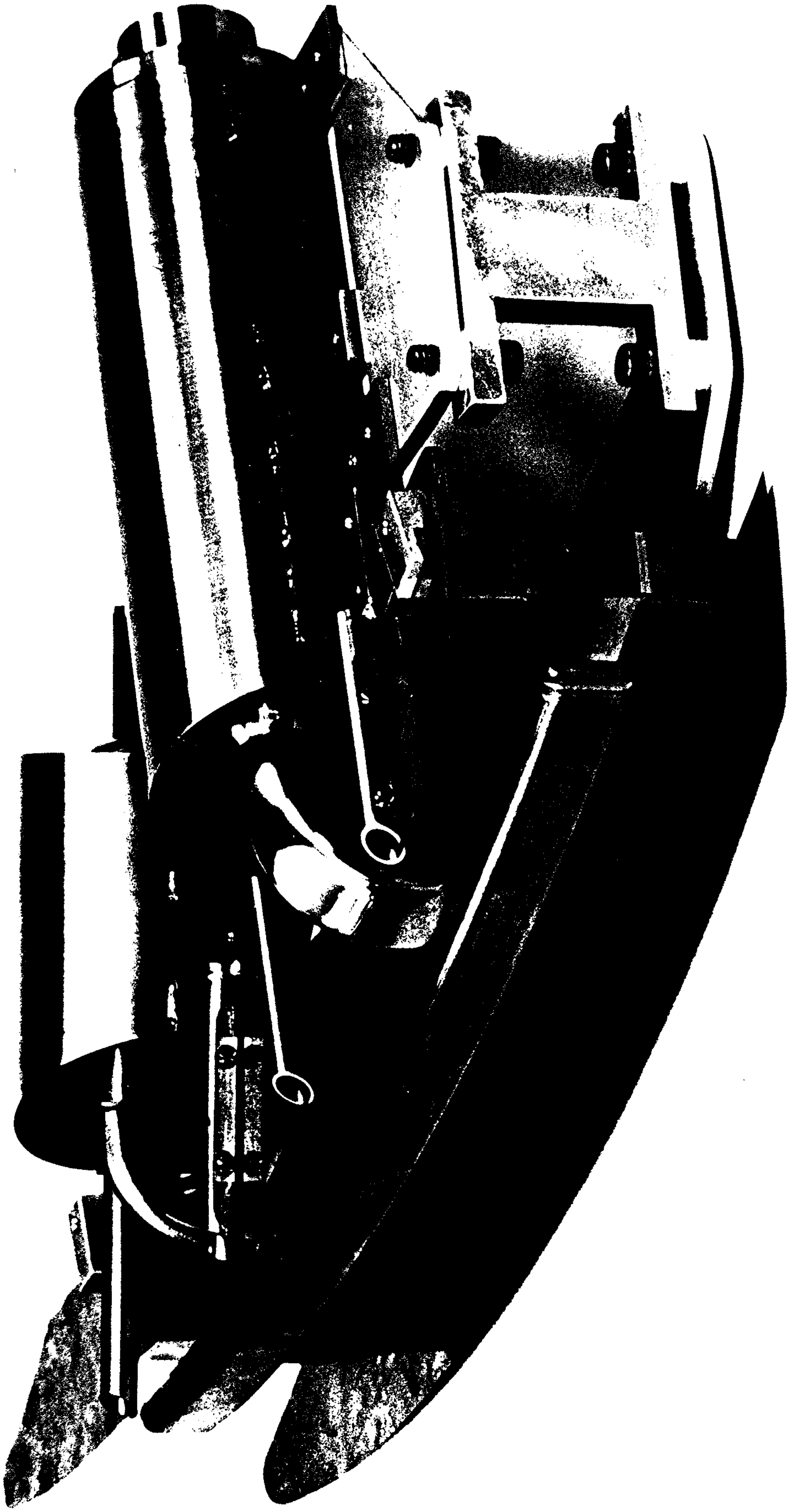
with up to 100 kW of RF power

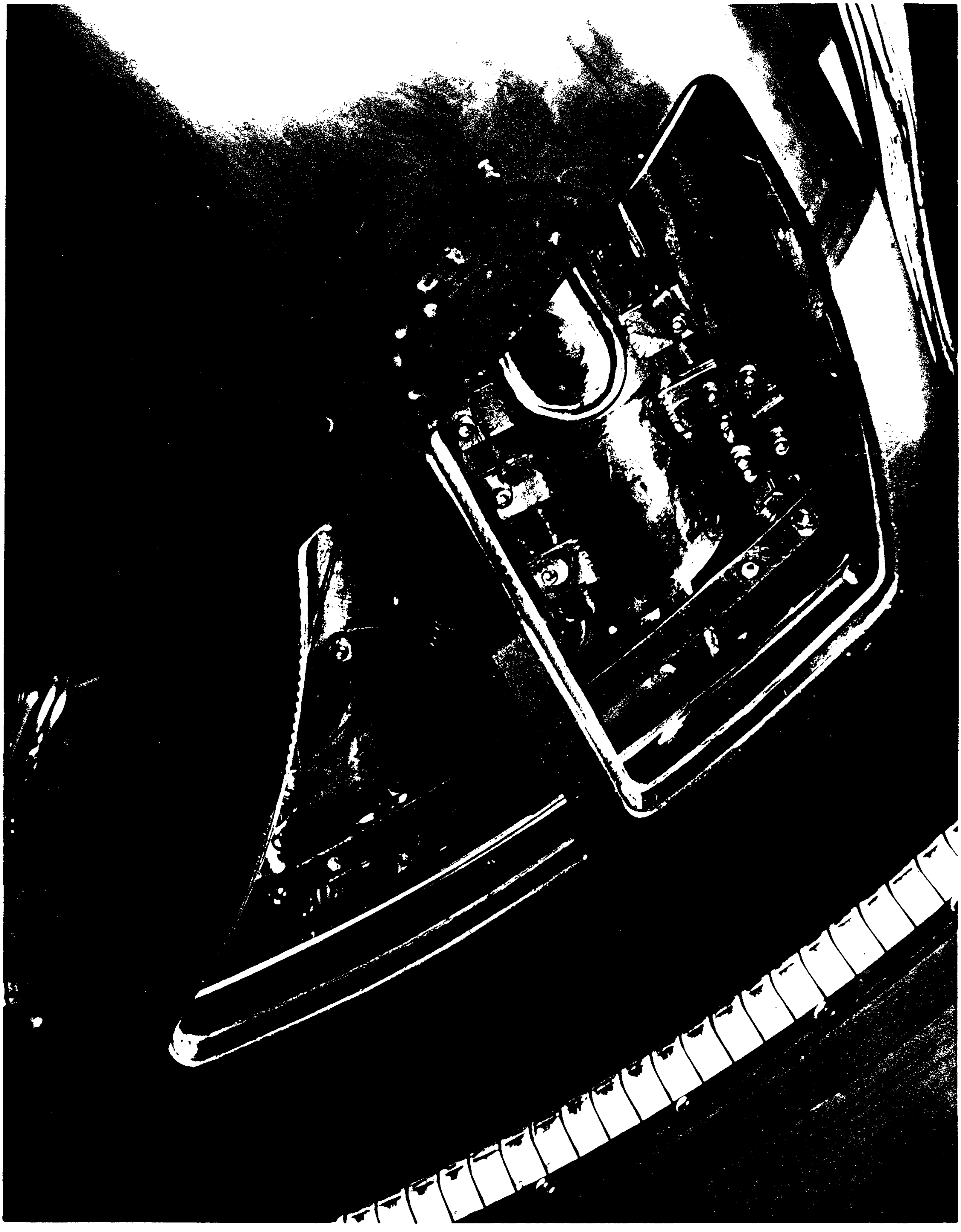
Intermediate Goal

75 – 90 kV across 5 – 6 mm gap

⟹ 150 kV/cm gradient

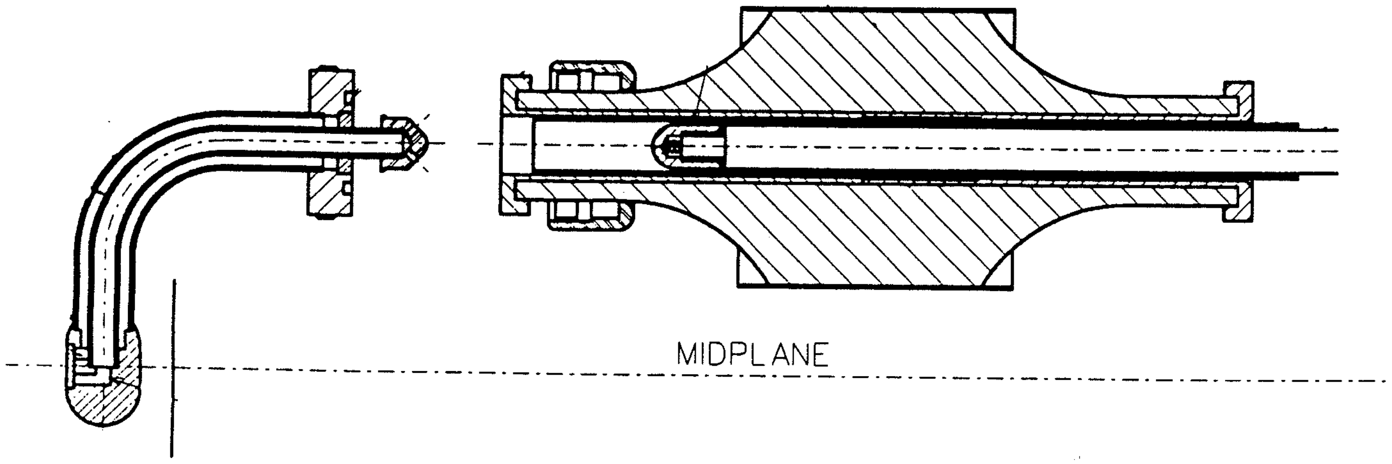
at any magnetic field or RF power



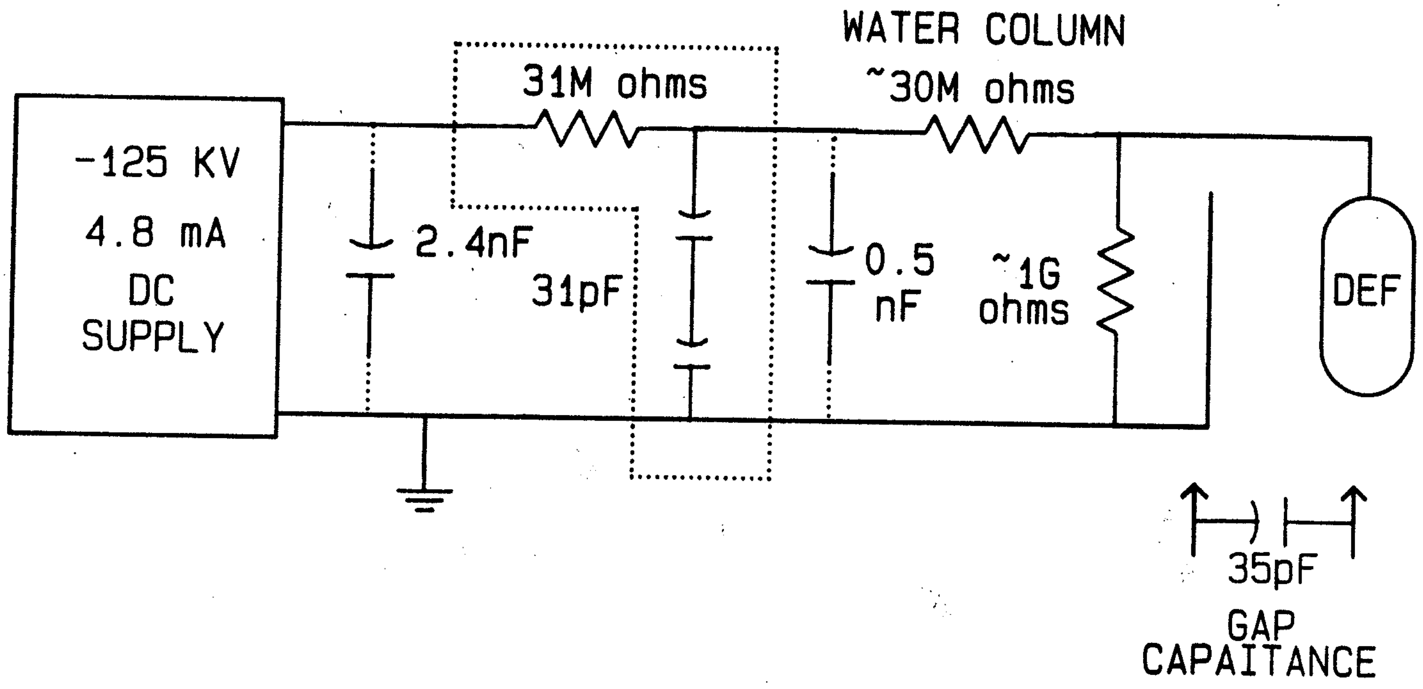


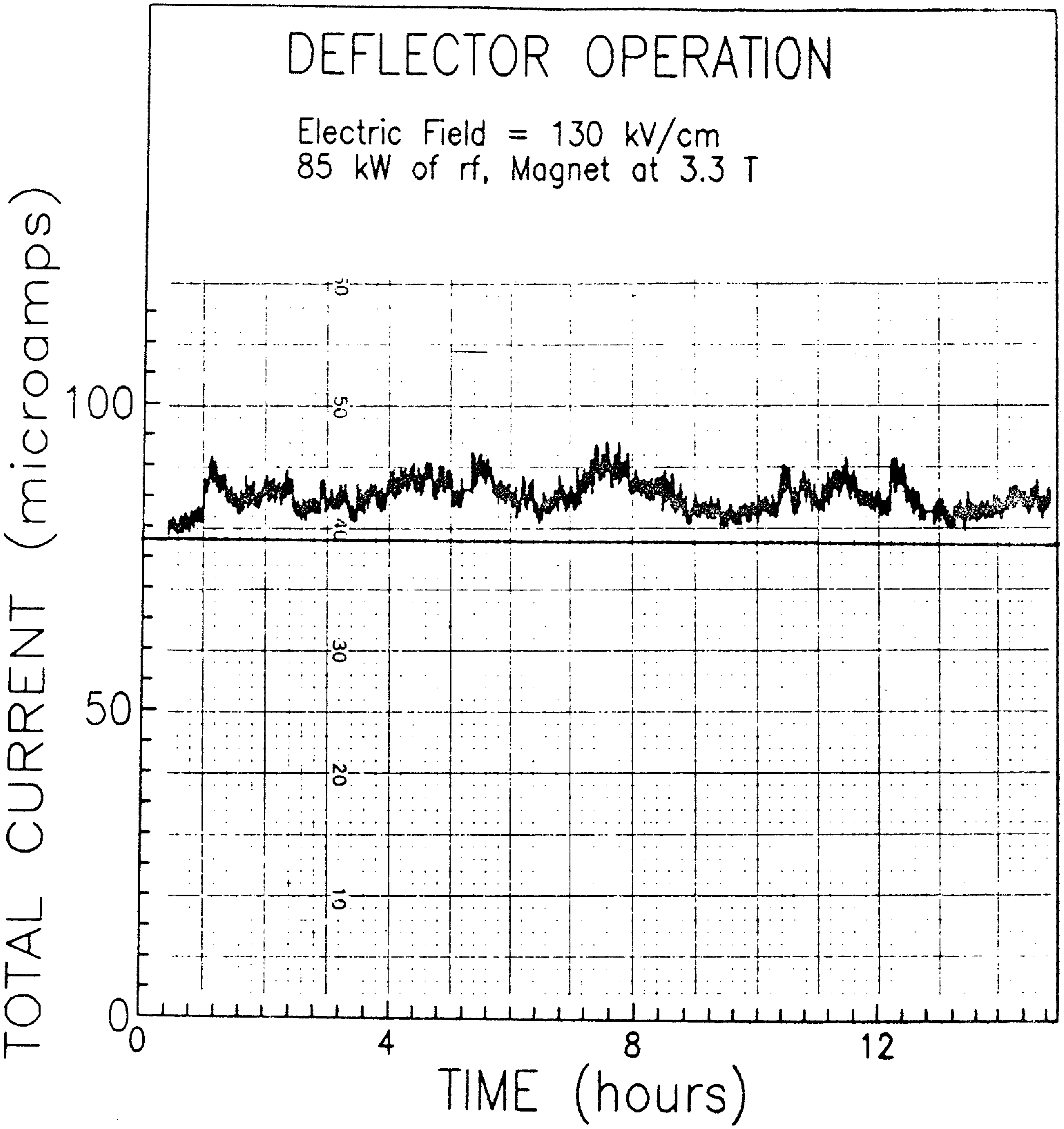
9103-20449-2

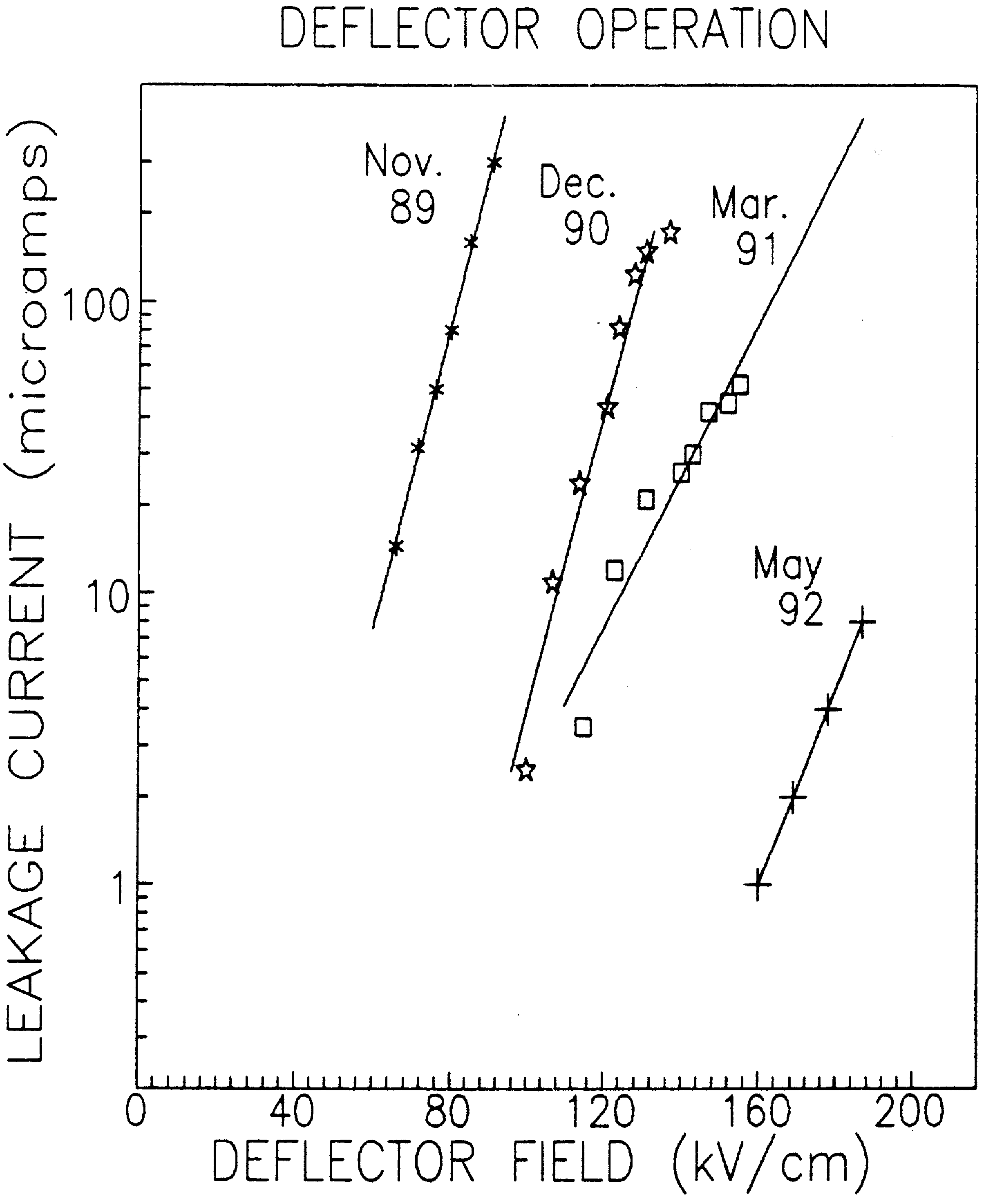
ATOMIC ENERGY OF CANADA LTD - RESEARCH CO.
CHALK RIVER, ONTARIO



WATER COOLED DEFLECTOR


WATER COLUMN
~30M ohms
31M ohms
-125 KV
4.8 mA
DC
SUPPLY
2.4nF
31pF
0.5
nF
~1G
ohms
DEF
35pF
GAP
CAPAITANCE


DEFLECTOR OPERATION
Electric Field = 130 kV/cm
85 kW of rf, Magnet at 3.3 T
TOTAL CURRENT (microamps)
100
50
0
TIME (hours)
0
4
8
12
60
50
40
30
20
10


DEFLECTOR OPERATION
LEAKAGE CURRENT (microamps)
DEFLECTOR FIELD (kV/cm)
Nov. 89
Dec. 90
Mar. 91
May 92
100
10
1
0
40
80
120
160
200

Summary

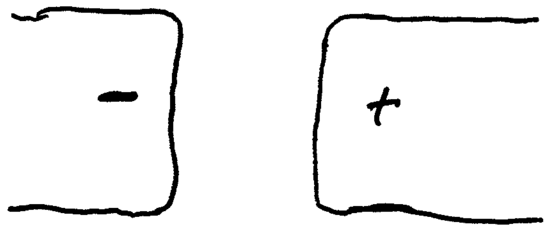
- Water-cooled cathode + stainless-steel sparking plates and septum are best
- Stainless-steel parts are best electropolished
- High-power r.f. is more detrimental than very strong magnetic fields
- Alumina insulators operate very reliably

Achieved

- 94 kV across 5 mm gap with magnet off
- 85 kV across 5 mm gap at 2 Tesla
- 80 kV with r.f. and magnet at intermediate operating levels
- Generally reliable, routine operation at 130 - 140 kV/cm

William Diamond
Chalk River Laboratories

High Voltage Test Stand Studies and Results



V ↑

What happens as we increase V ?!

In Practice

We make a collection of observations (with a wide range of sophistication). To infer some of the effects.

Two main things can happen

(1) Field Emission Electrons are pulled from the cathode. This is a tunneling phenomena, originally believed to occur from large E-field enhancement at sharp points or defects in the cathode surface. Now believed to occur at insulator inclusions or possibly metal - insulator - metal interfaces
Studied for many years but still not

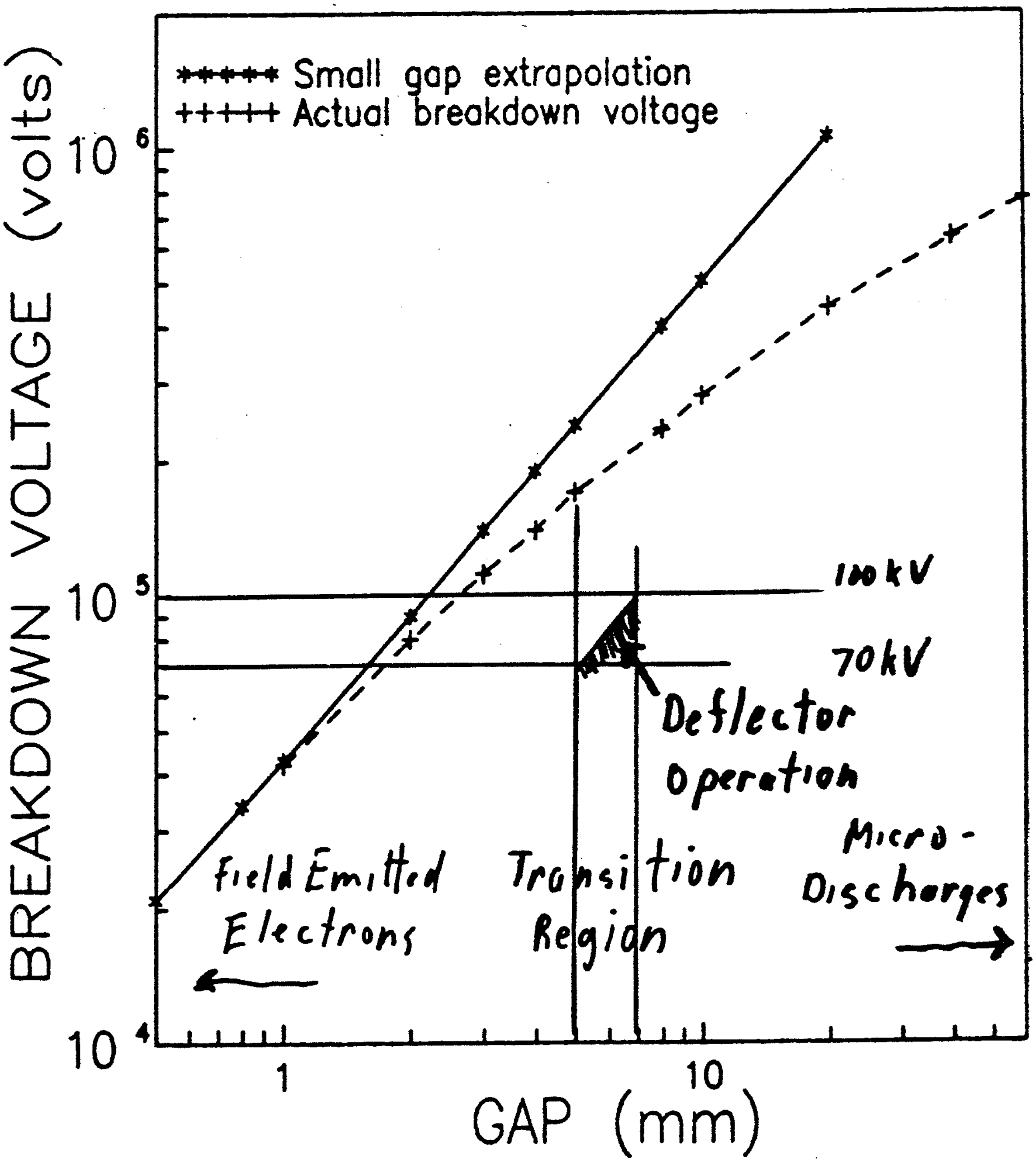
Other main effect is from
μ discharges

These are much less studied than
FEE

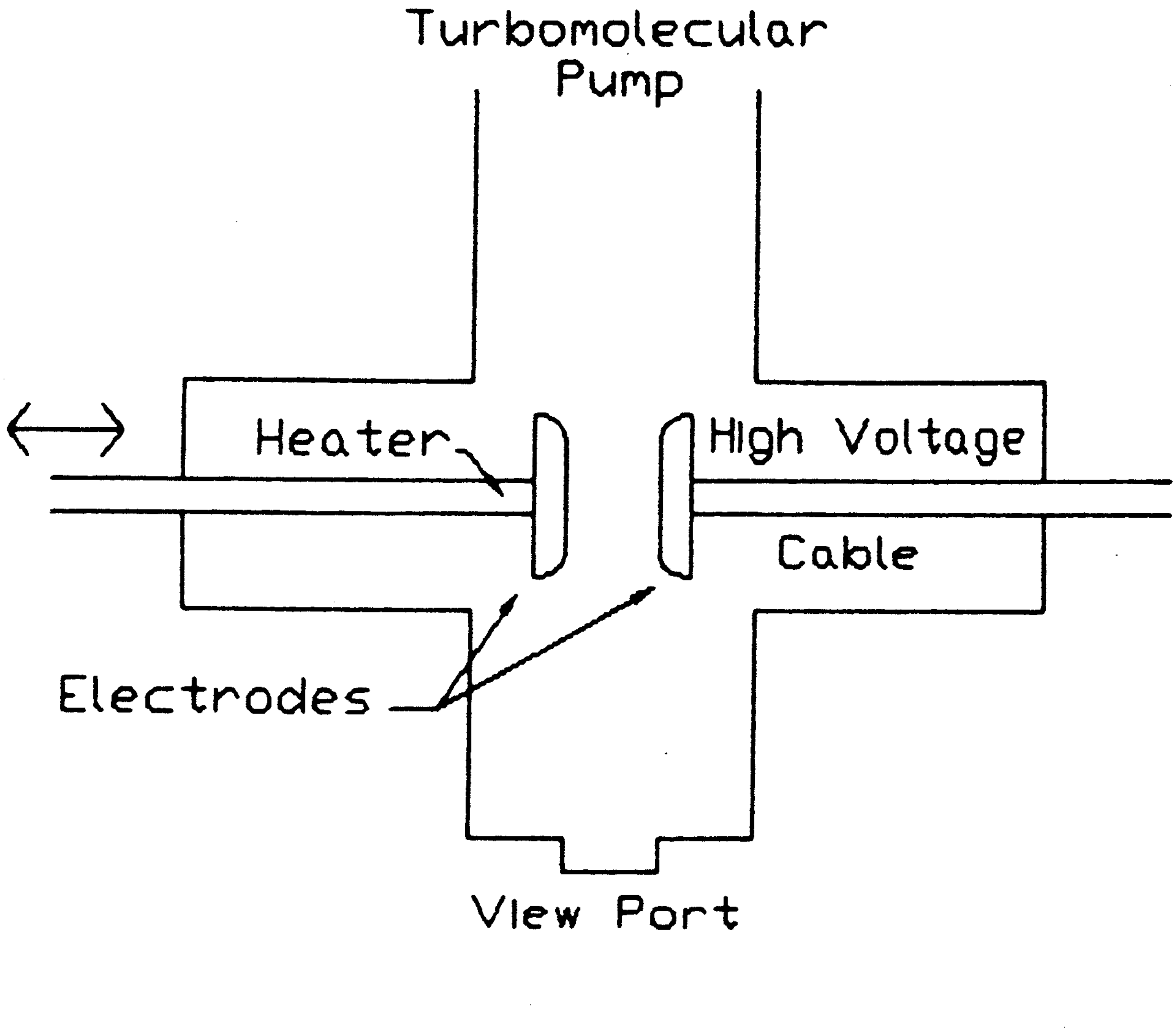
But they are the dominant mechanism
of breakdown as the gap increases

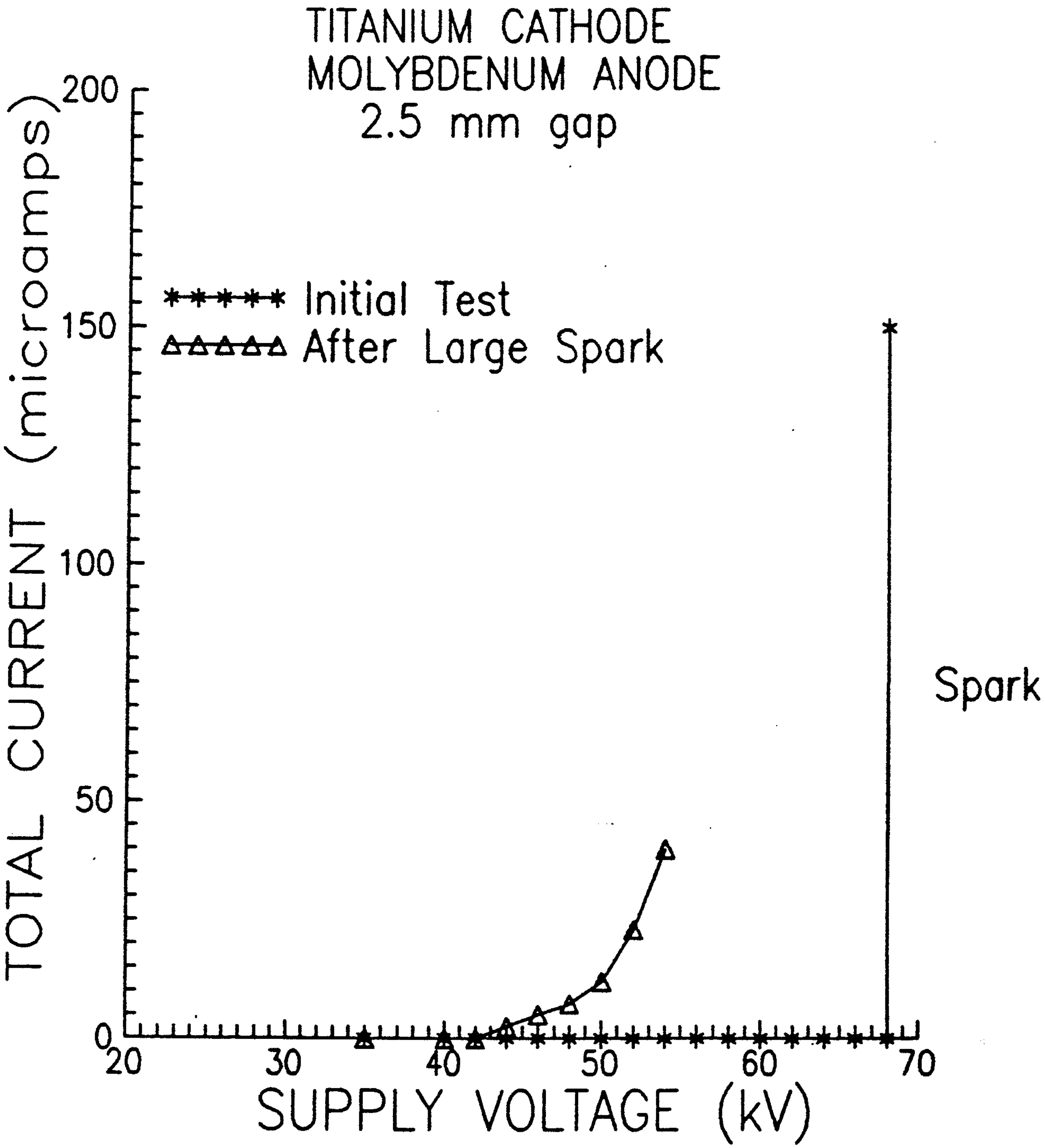
Produced by clumps of material pulled
from 1 surface by electrostatic
fields, crossing the gap. and
vapourizing on impact on the
opposite electrode

They produce a gas burst on impact
and possibly damage to the electrode
that they impact on. This damaged
site may serve as a region of FEE.
If gas pressure is high enough — may
initiate a spark



Small gap extrapolation
Actual breakdown voltage
BREAKDOWN VOLTAGE (volts)
10^6
10^5
10^4
1
10
GAP (mm)
100 kV
70 kV
Deflector Operation
Field Emitted Electrons
Transition Region
Micro-Discharges


Turbomolecular Pump
Heater
High Voltage
Cable
Electrodes
View Port


TITANIUM CATHODE
MOLYBDENUM ANODE
2.5 mm gap
TOTAL CURRENT (microamps)
200
150
100
50
0
Initial Test
After Large Spark
Spark
20
30
40
50
60
70
SUPPLY VOLTAGE (kV)

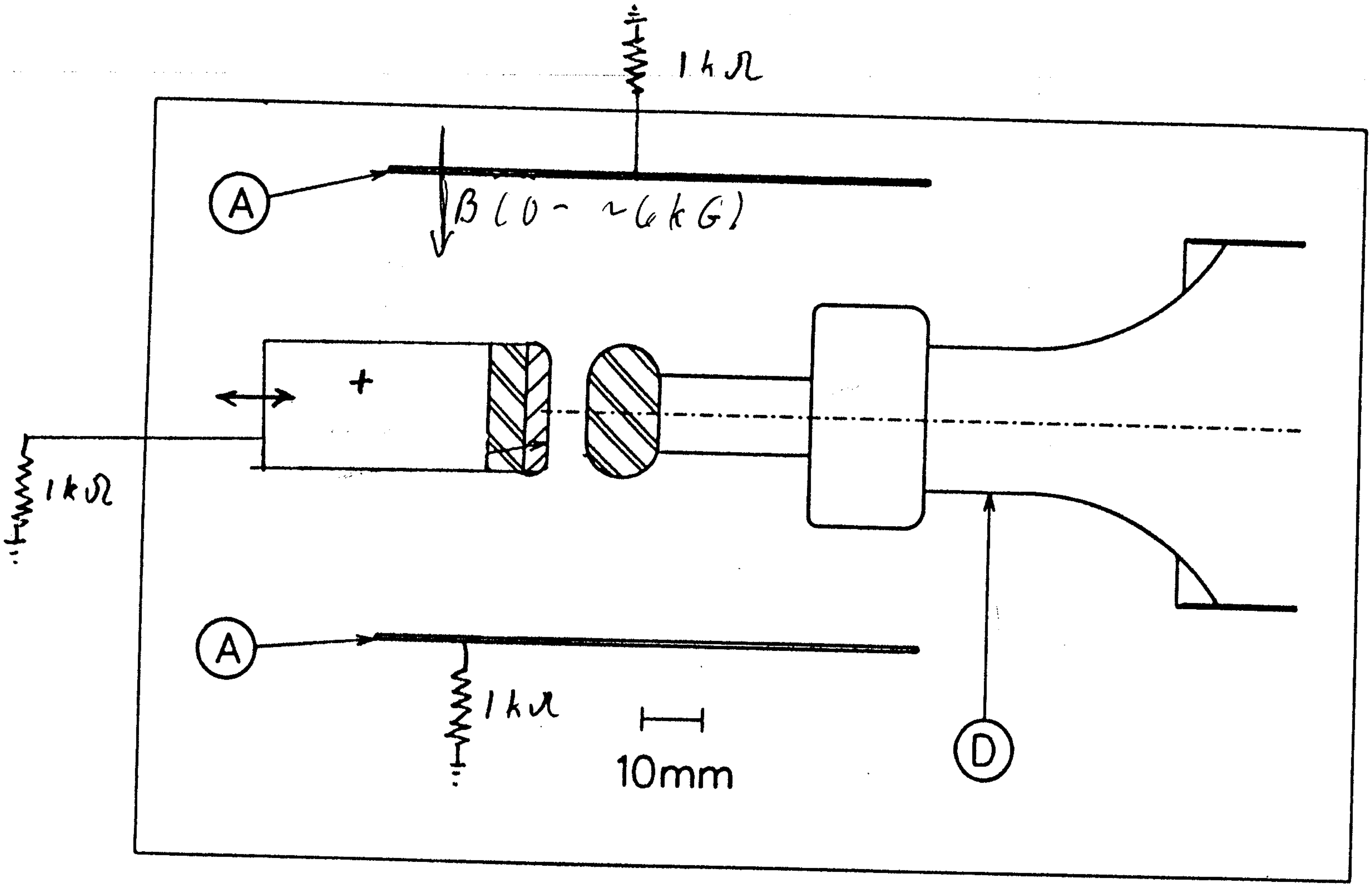
Breakdown Voltage for Parallel Electrodes at a 2.5 mm Gap

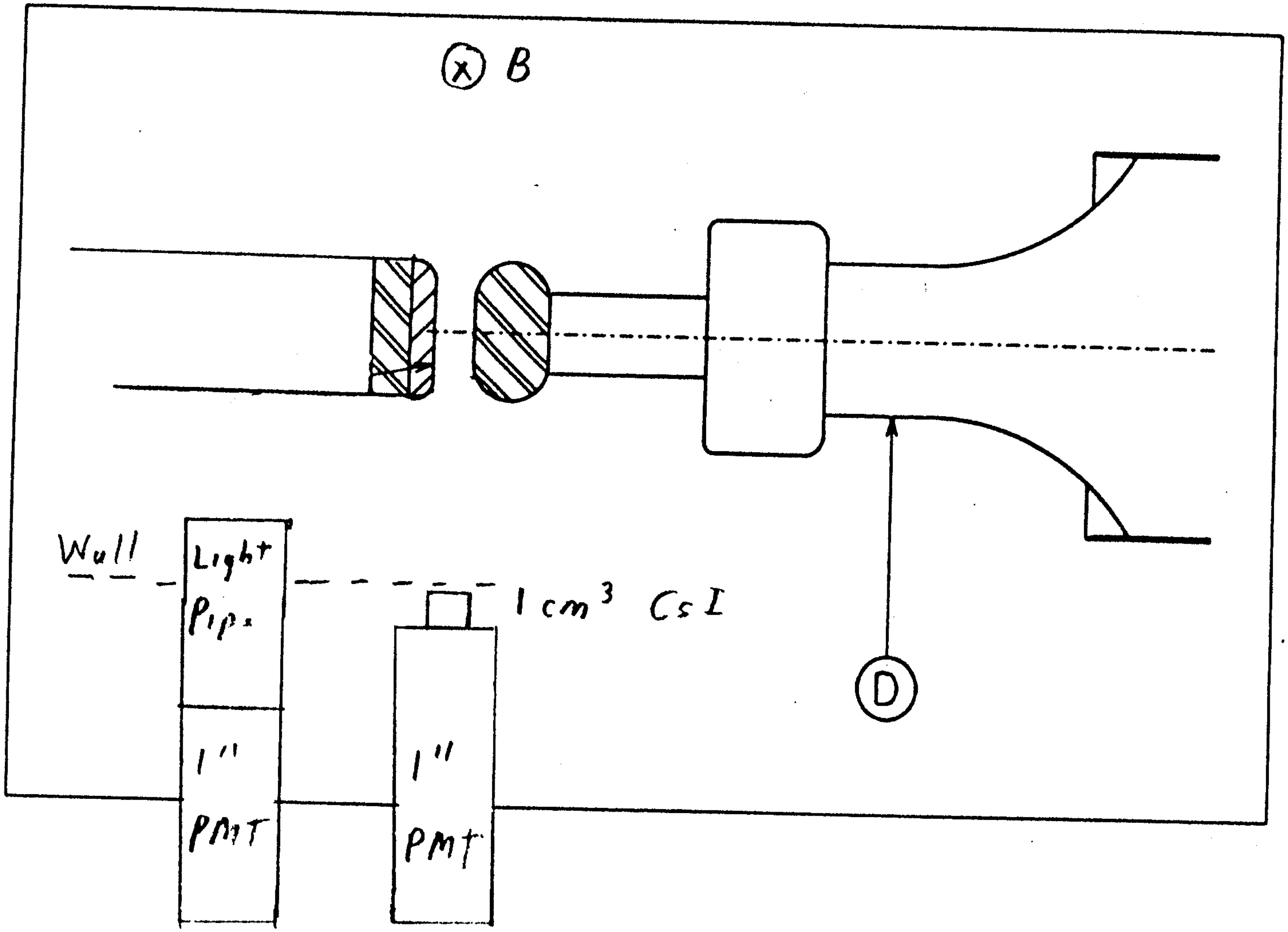
Cathode Material	Anode Material		
	Copper	Stainless Steel	Titanium
Copper	64	92	98
Stainless Steel	74	96	110
Titanium	72	88	110

Breakdown Voltage for Parallel Electrodes at a 2.5 mm Gap

Effects of Electropolishing

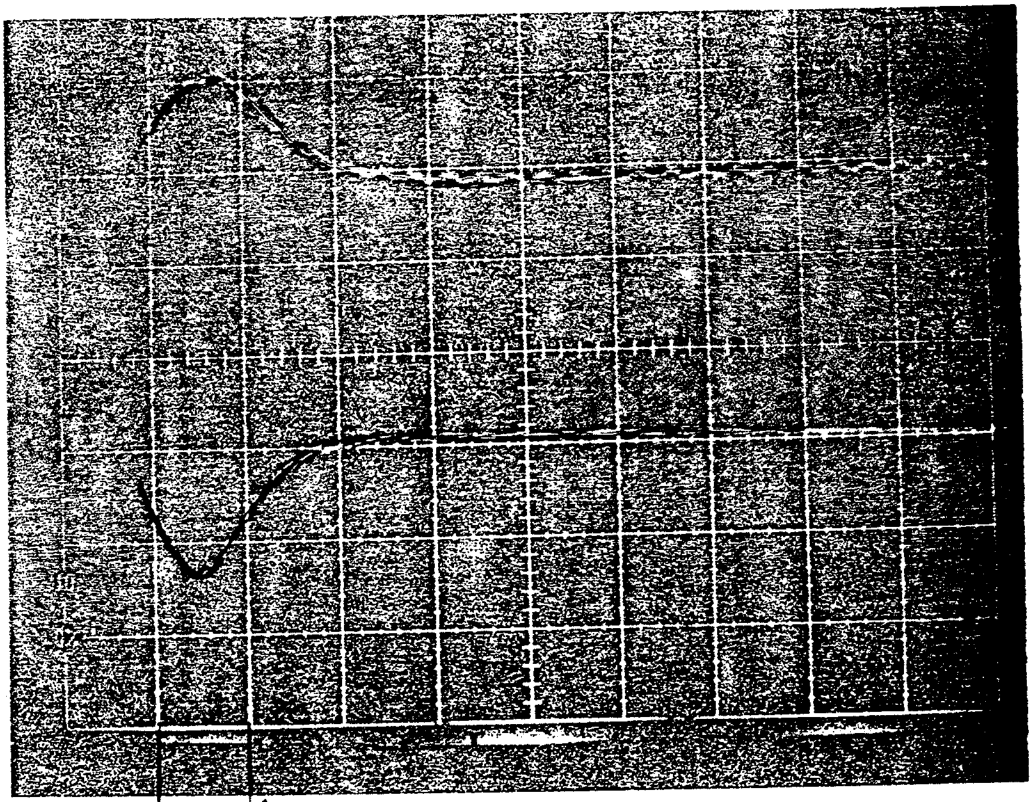
Cathode Material		Anode Material			
		Copper		Stainless Steel	
		EP	Not EP	EP	Not EP
Copper	EP	98, 96	64		
	Not EP	85			
Stainless Steel	EP			97	
	Not EP	94, 94			

1 kΩ
A
B (0 ~ 6 kG)
+
1 kΩ
A
1 kΩ
10mm
D


⊗ B
D
Wall
Light Pipe
1''
PMT
1 cm³ CsI
1''
PMT

Typical μ discharge just after V↑
Magnet on

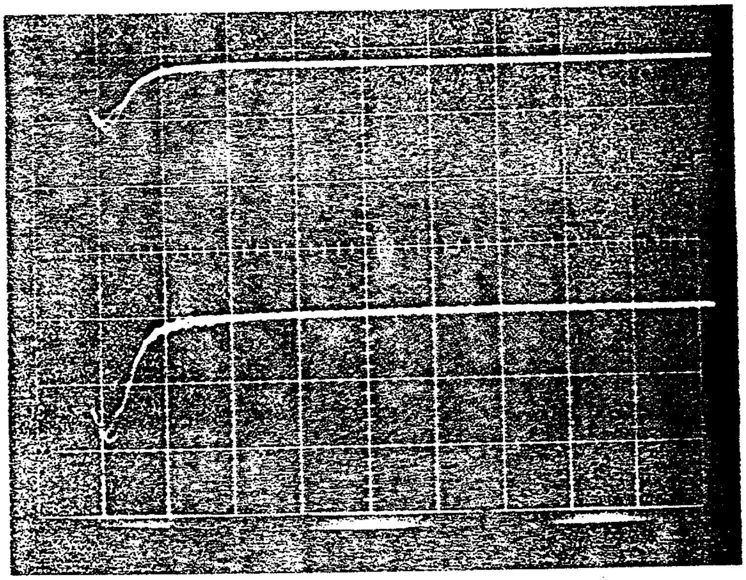
Top Isept

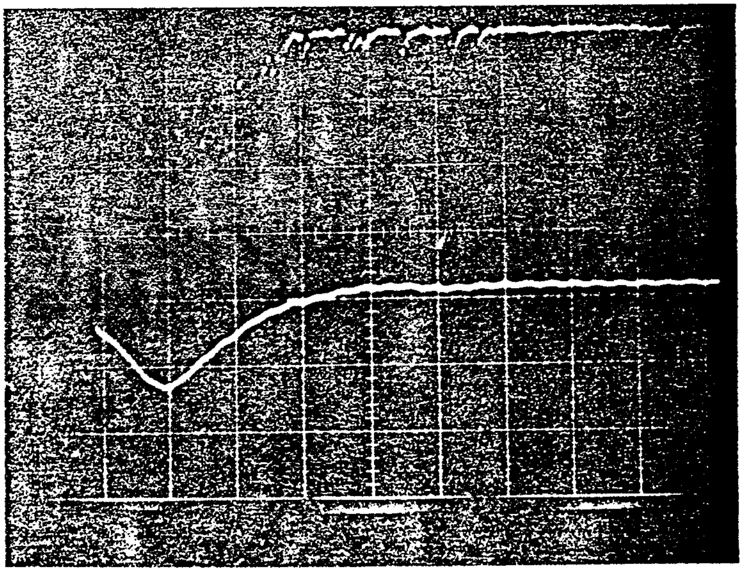


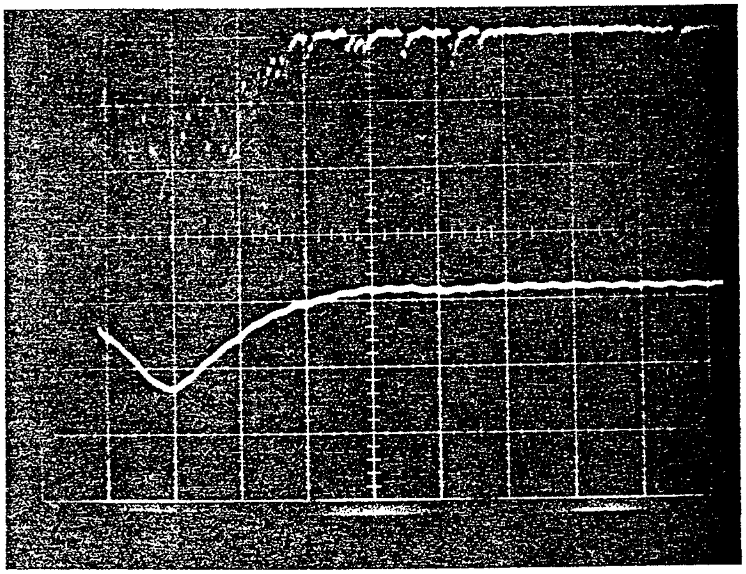
→| |← 50 μsec

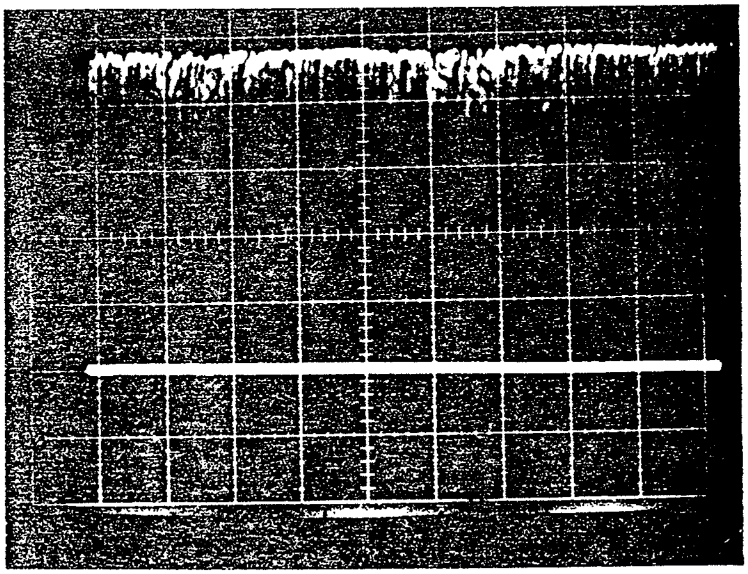
Bottom LSP at 50μA/div

Comparison of light output and x-ray output

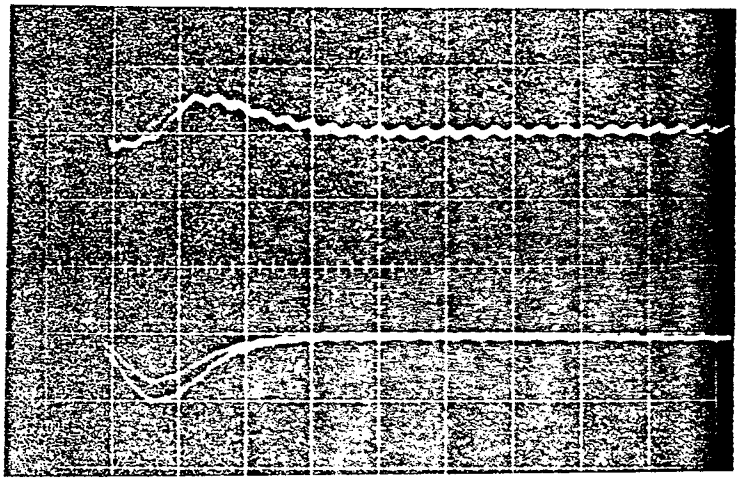








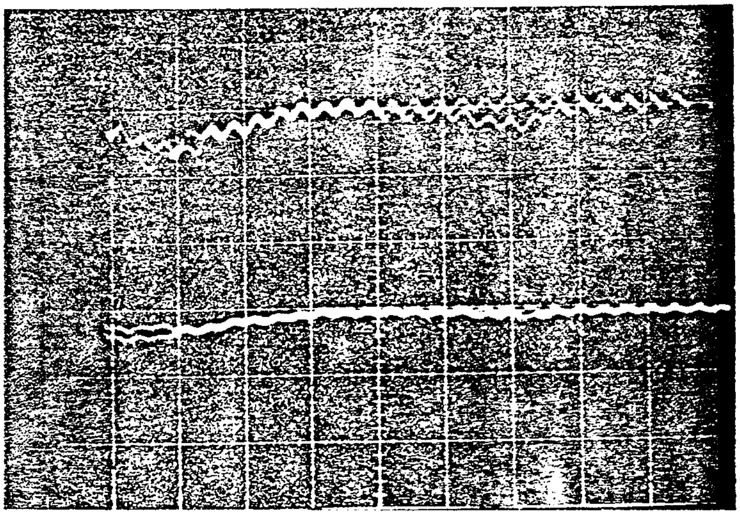
As Magnetic Field is Increased
At 70 kV



I = 0 A

Sept
10 μA/div

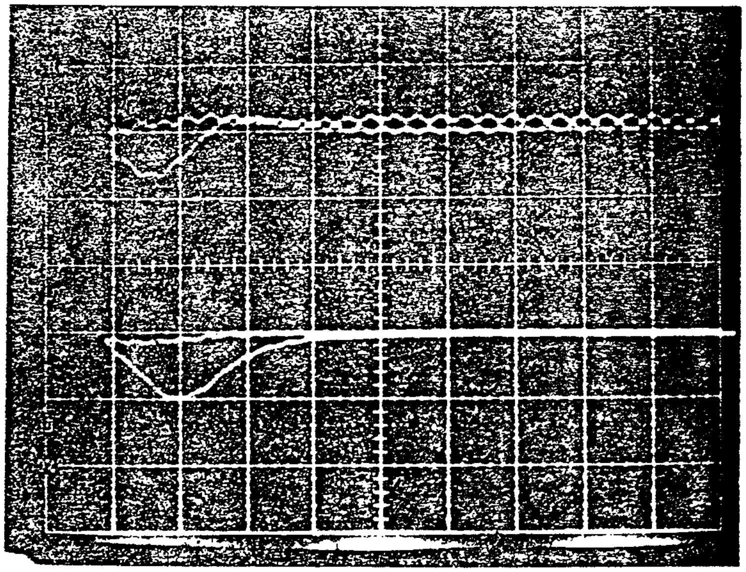
USP 10 μA/div



I = 3½ A

septum 5 mV/div

USP 10 mV/div

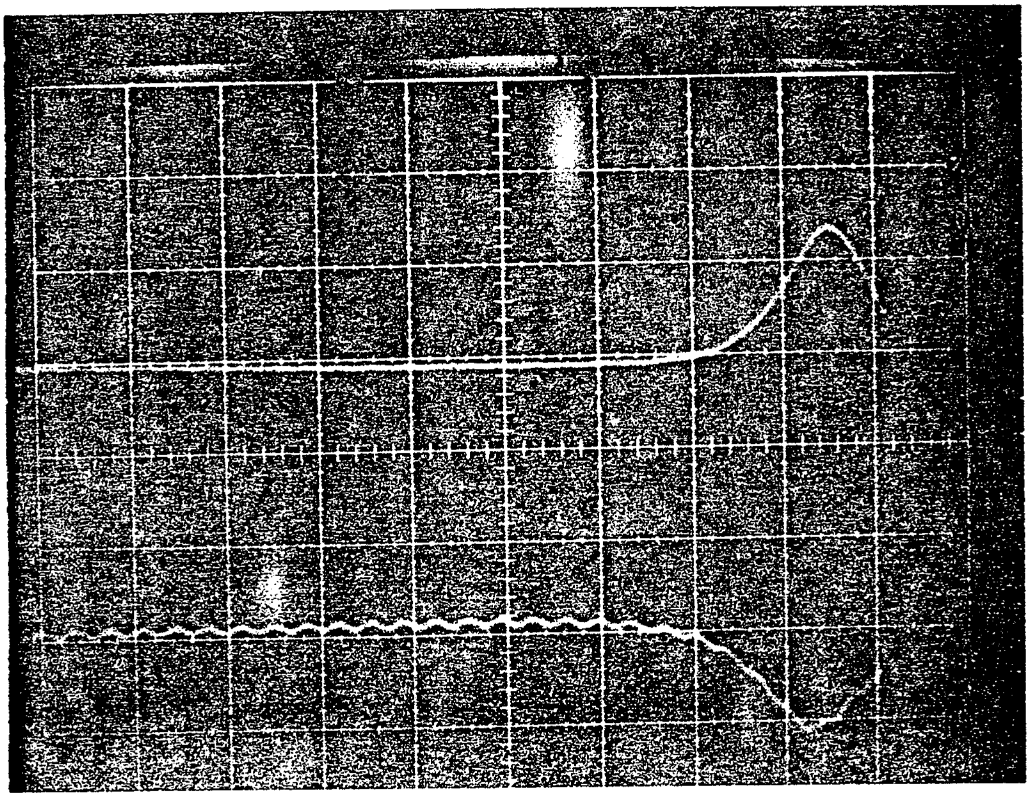


I = 5 A

Septum 10 μA/div

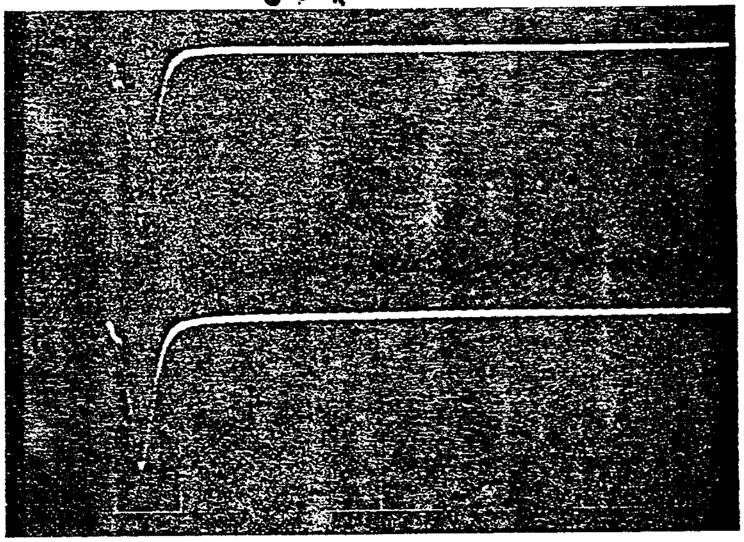
USP 20 μA/div

50 μsec



E.P. SS Anode
copper Cathode
gap = 1.5 mm

6.5 kV

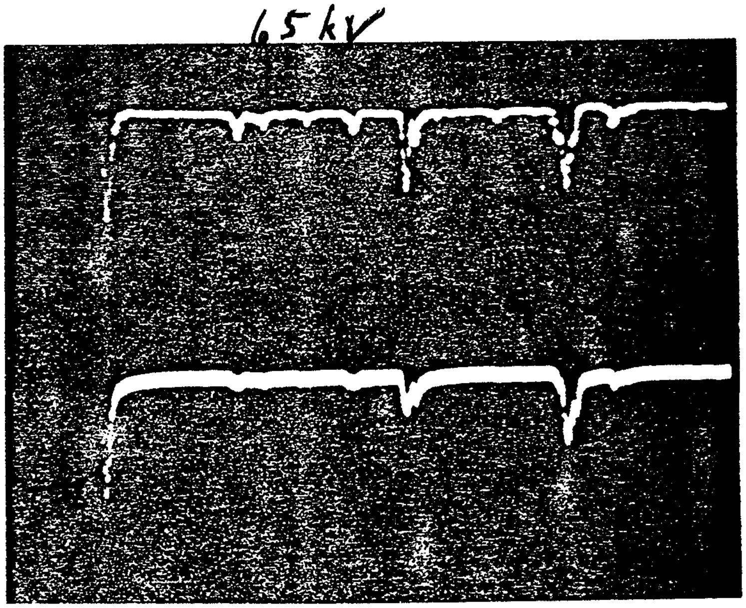


PMT

Septum

100 μsec

6.5 kV



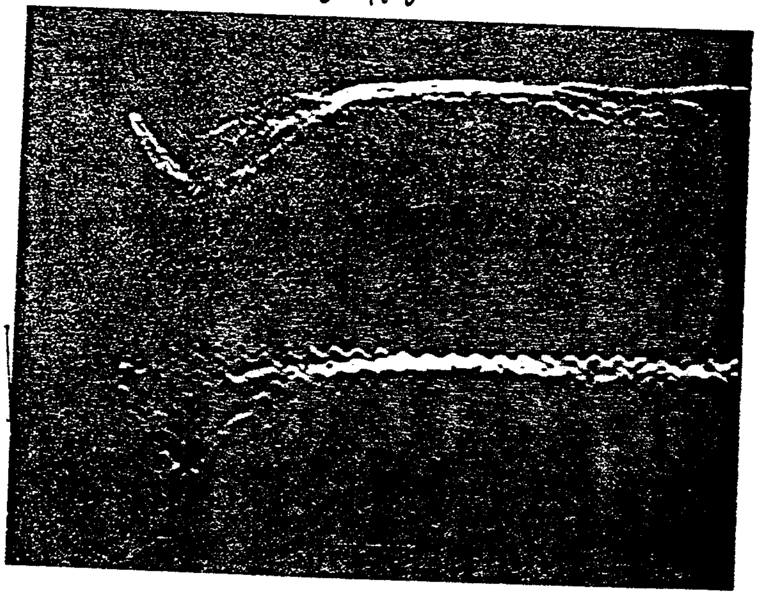
PMT 10 mV/div

Septum 5 mV/div

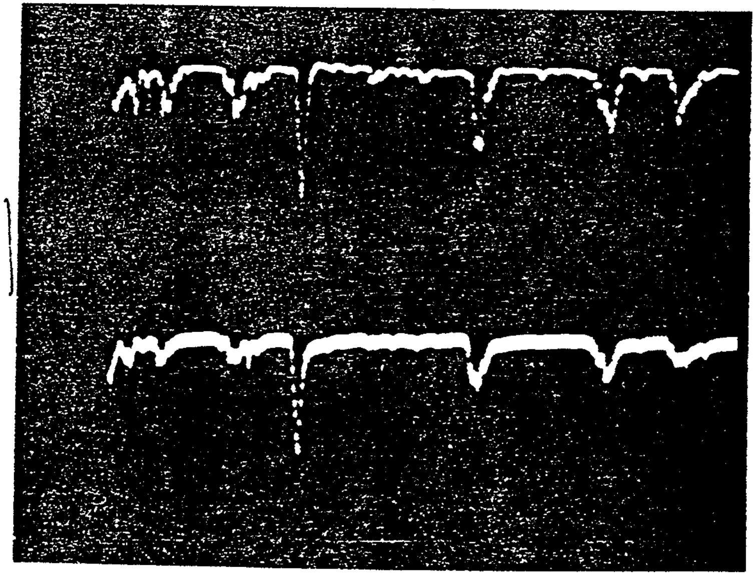
1 msec/div

Copper Anode
SS Cathode
y ≈ 3mm

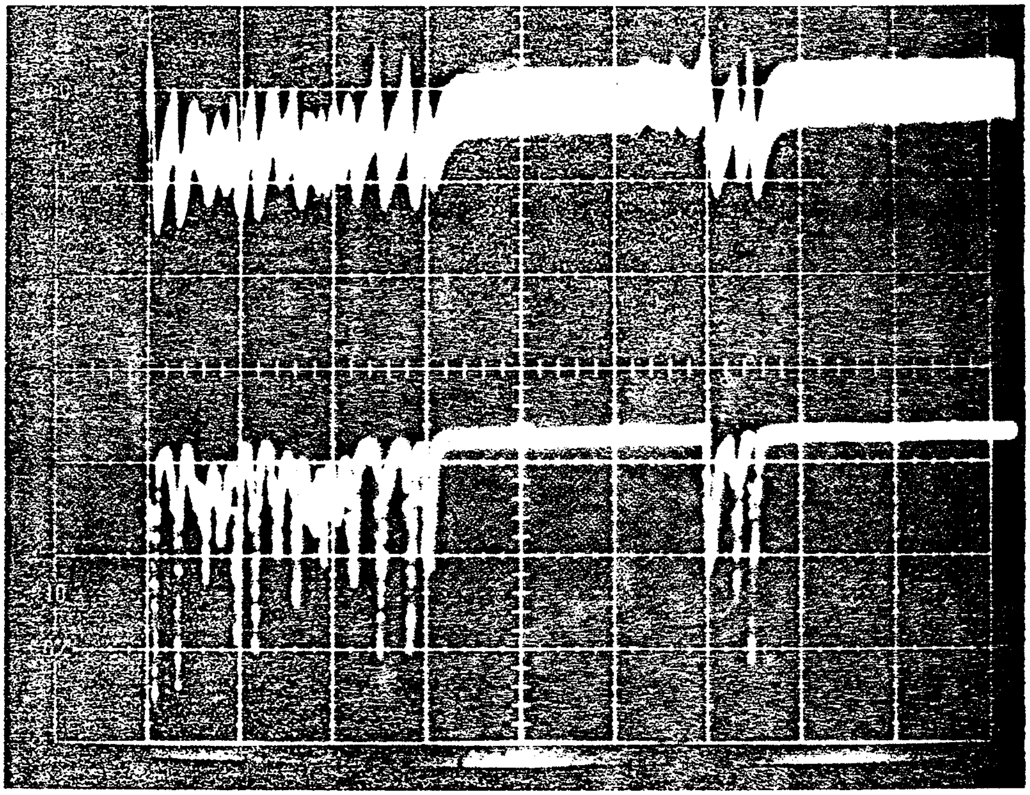
50 kV



70 kV

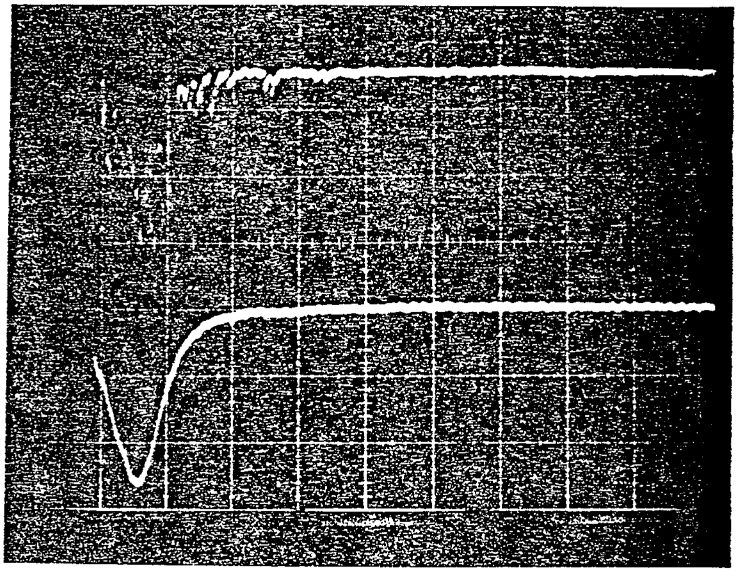


Multiple μdischarges


Sept

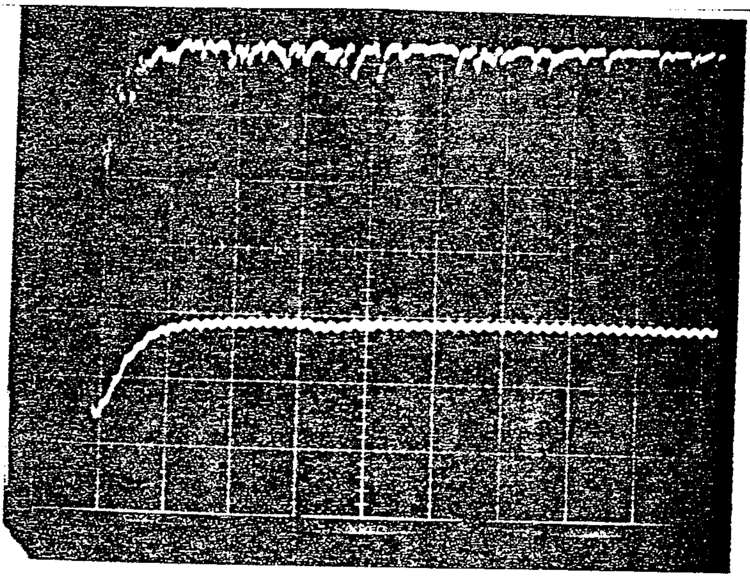
USP

5 msec /cm



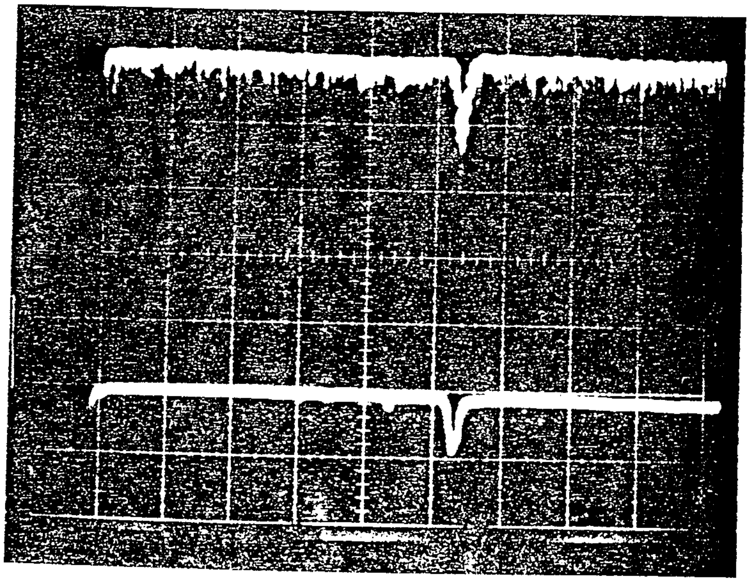
60 kV

Top CsI 10mV/
Bottom USP $\frac{100}{5}$mV/
100 μsec/



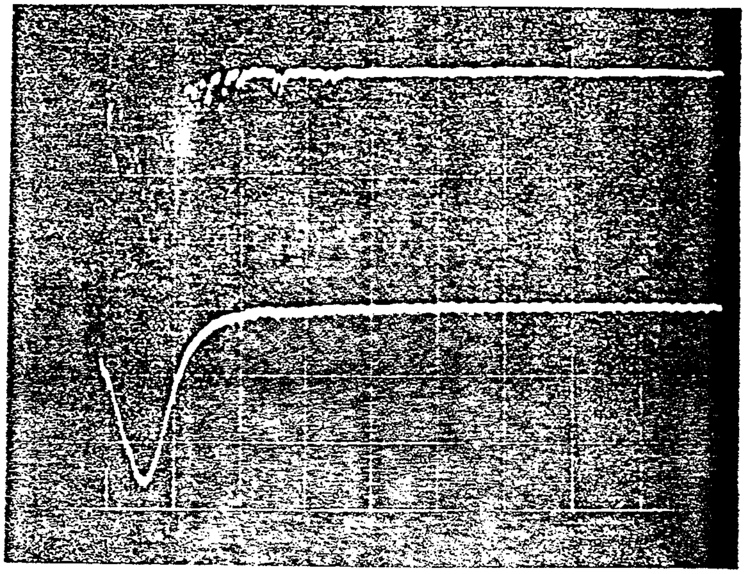
70 kV

Top CsI 20mV/
Bottom USP 20mV/.
100μsec/



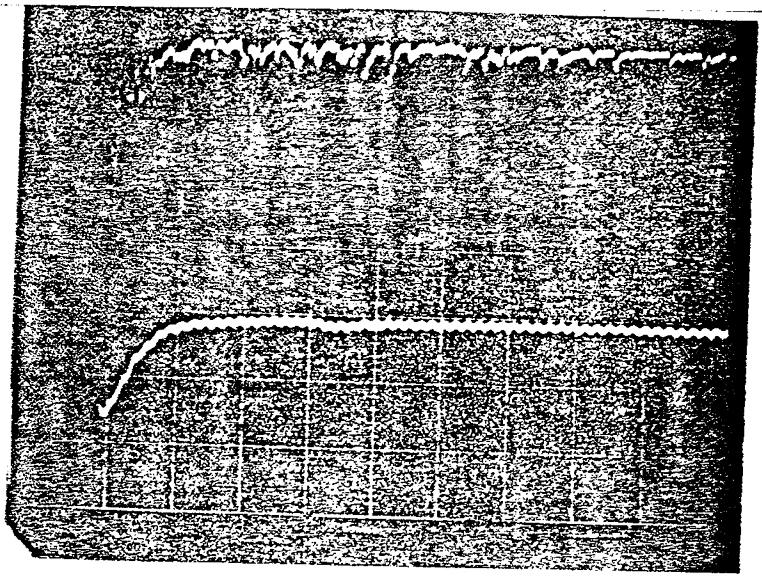
80 kV

Top CsI 20mV/
Bottom USP 20mV/
1 msec/



60 kV

Top CsI 10mV/
Bottom USP $\frac{100}{5}$mV/
100 μsec/

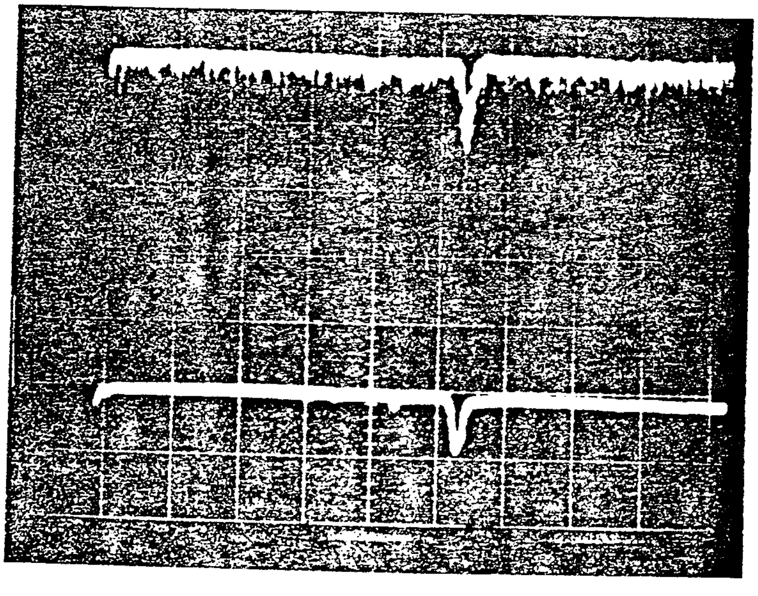


70 kV

Top CsI 20mV/

Bottom USP 20mV/.

100μsec/



80 kV

Top CsI 20mV/

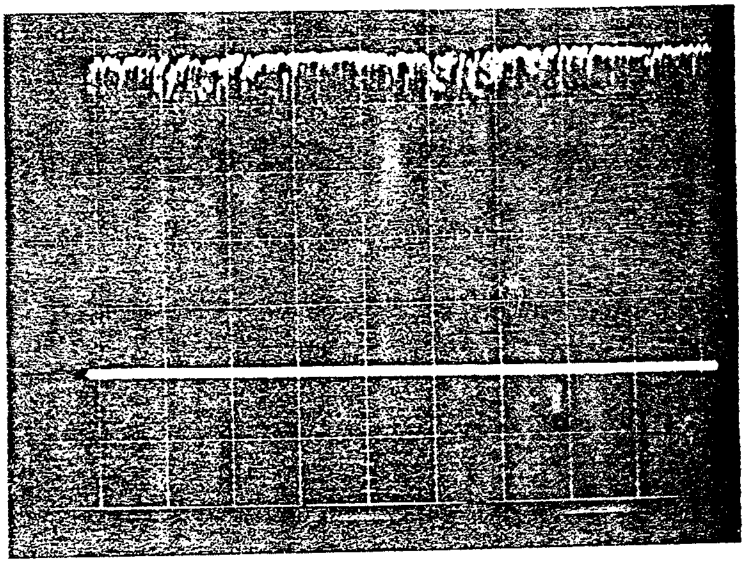
Bottom USP 20mV/

1 msec/

Titanium Electrodes

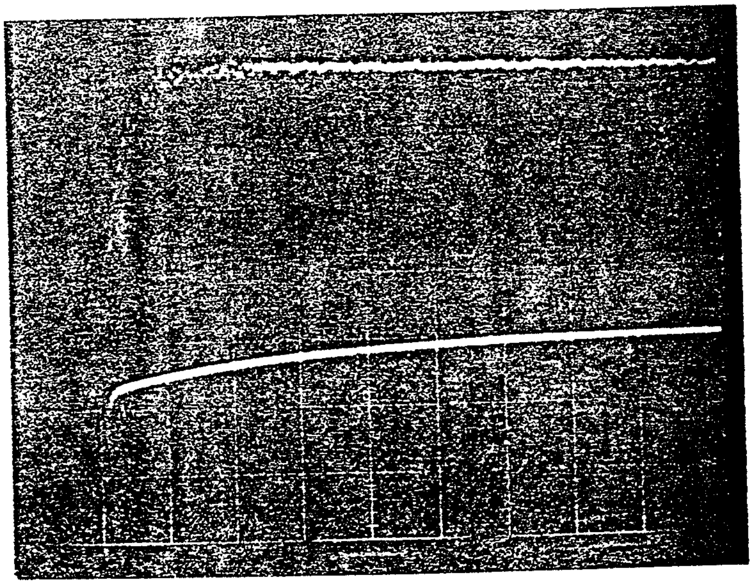
gap ≈ 3mm

45 kV

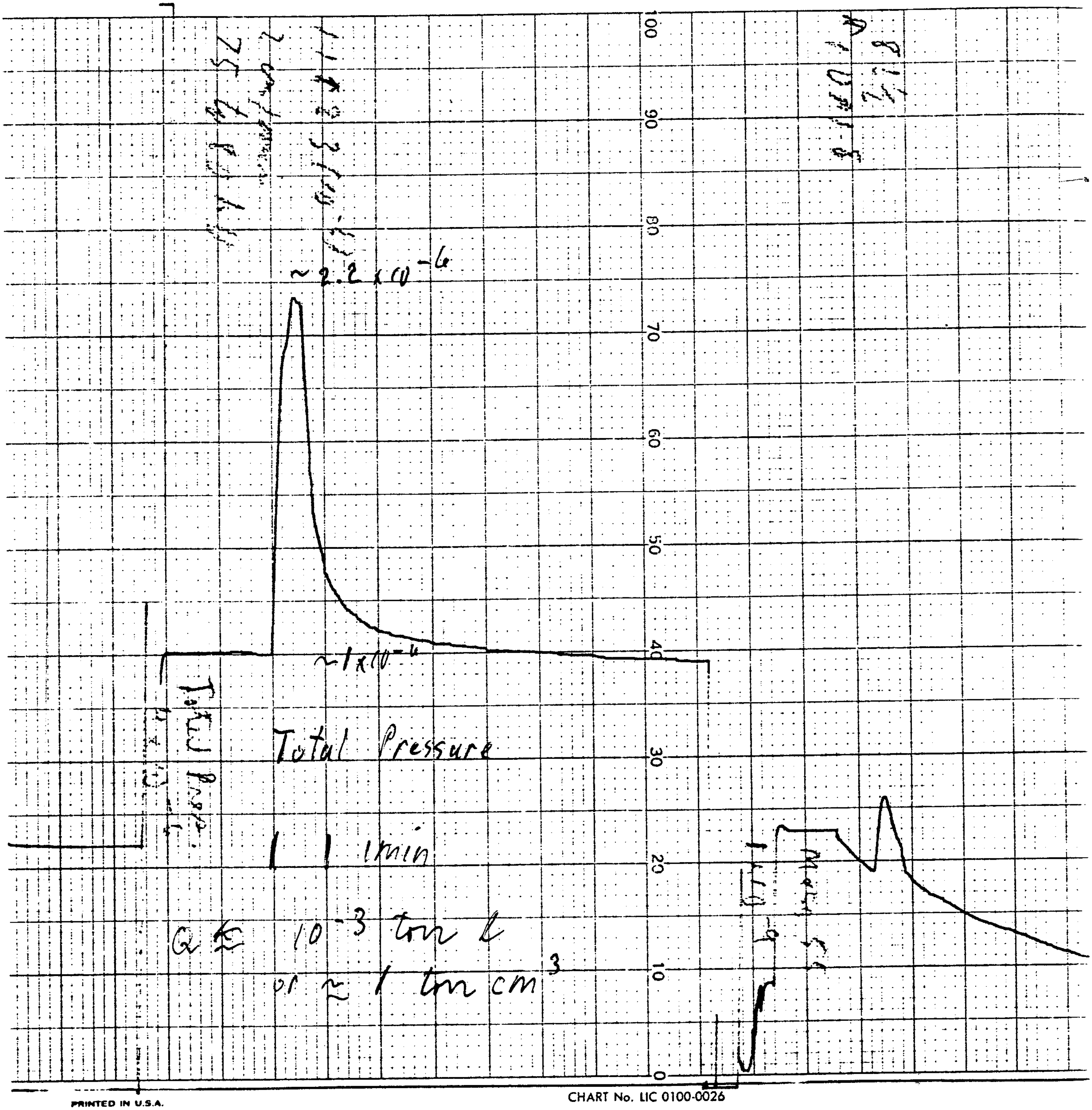


CsI at 10mV/div

USP at 5μA/div



Typical Spark



Total Pressure

| | 1 min

$Q \cong 10^{-3}$ torr l

or $\cong 1$ torr cm^3

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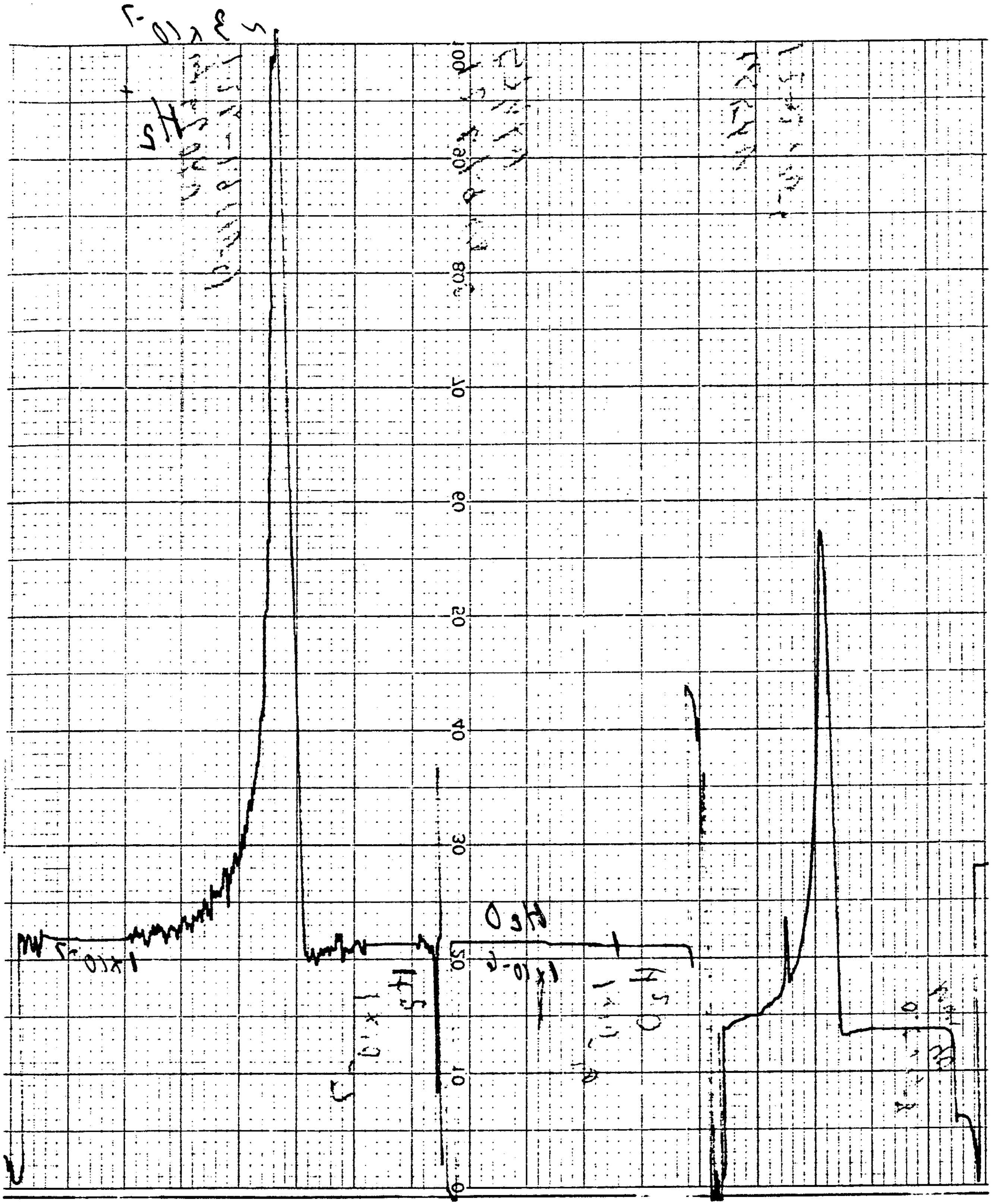
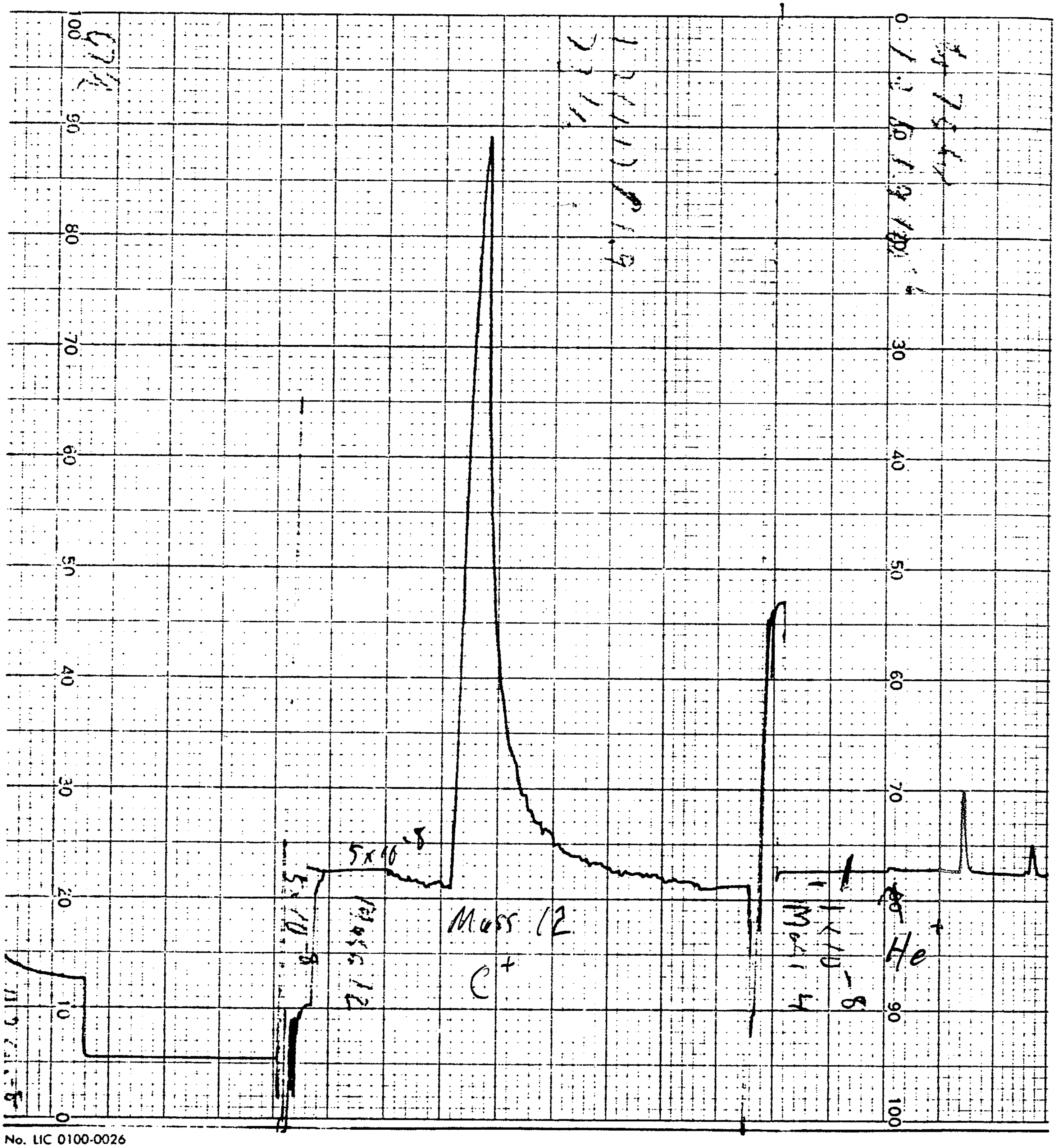
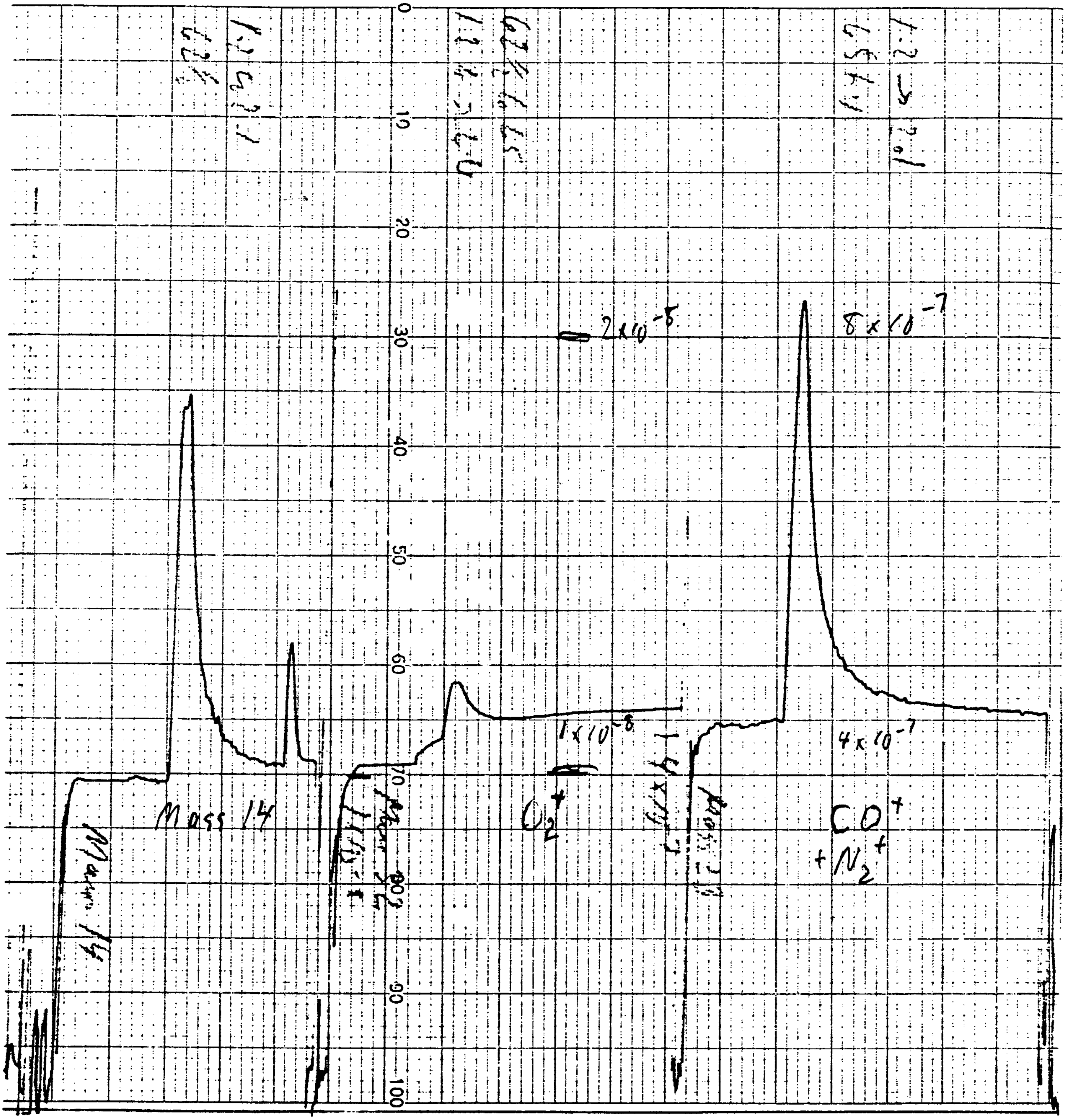
CHART No. LIC 0100-0026


~3x10-7
H2
1x10-7
H2O
1x10-6
100
90
80
70
60
50
40
30
20
10
0
CHART No. LIC 0100-0026



No. LIC 0100-0026



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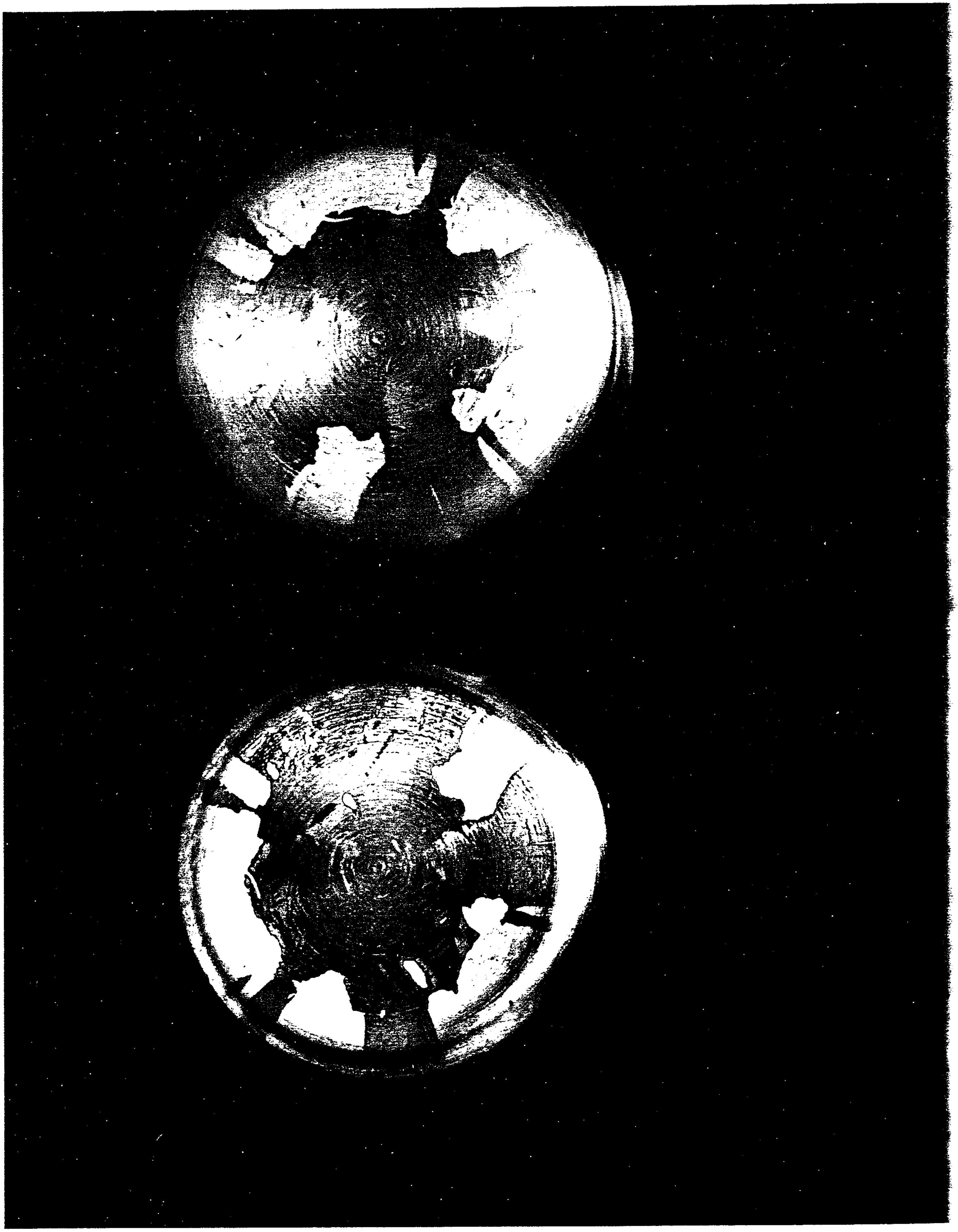
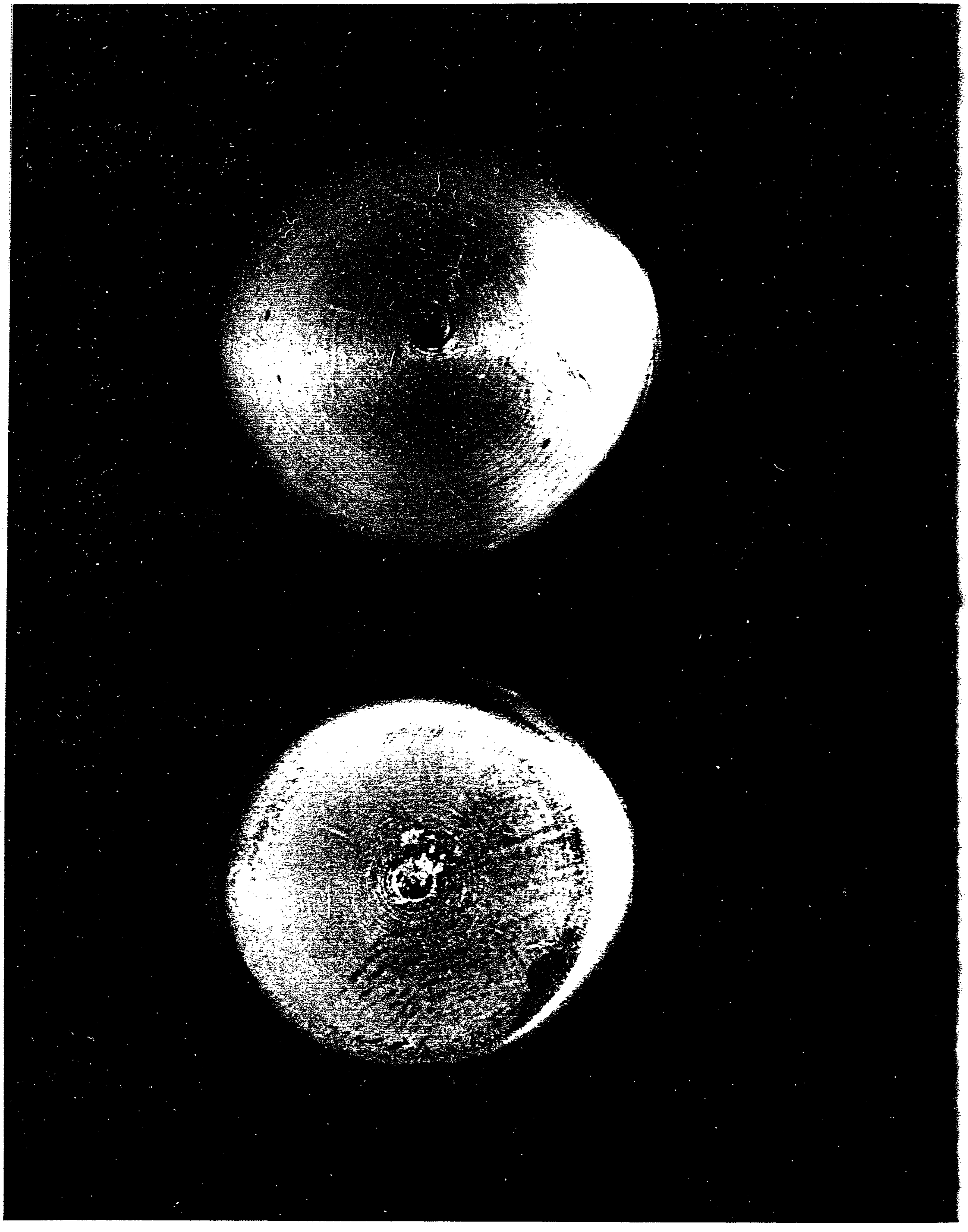
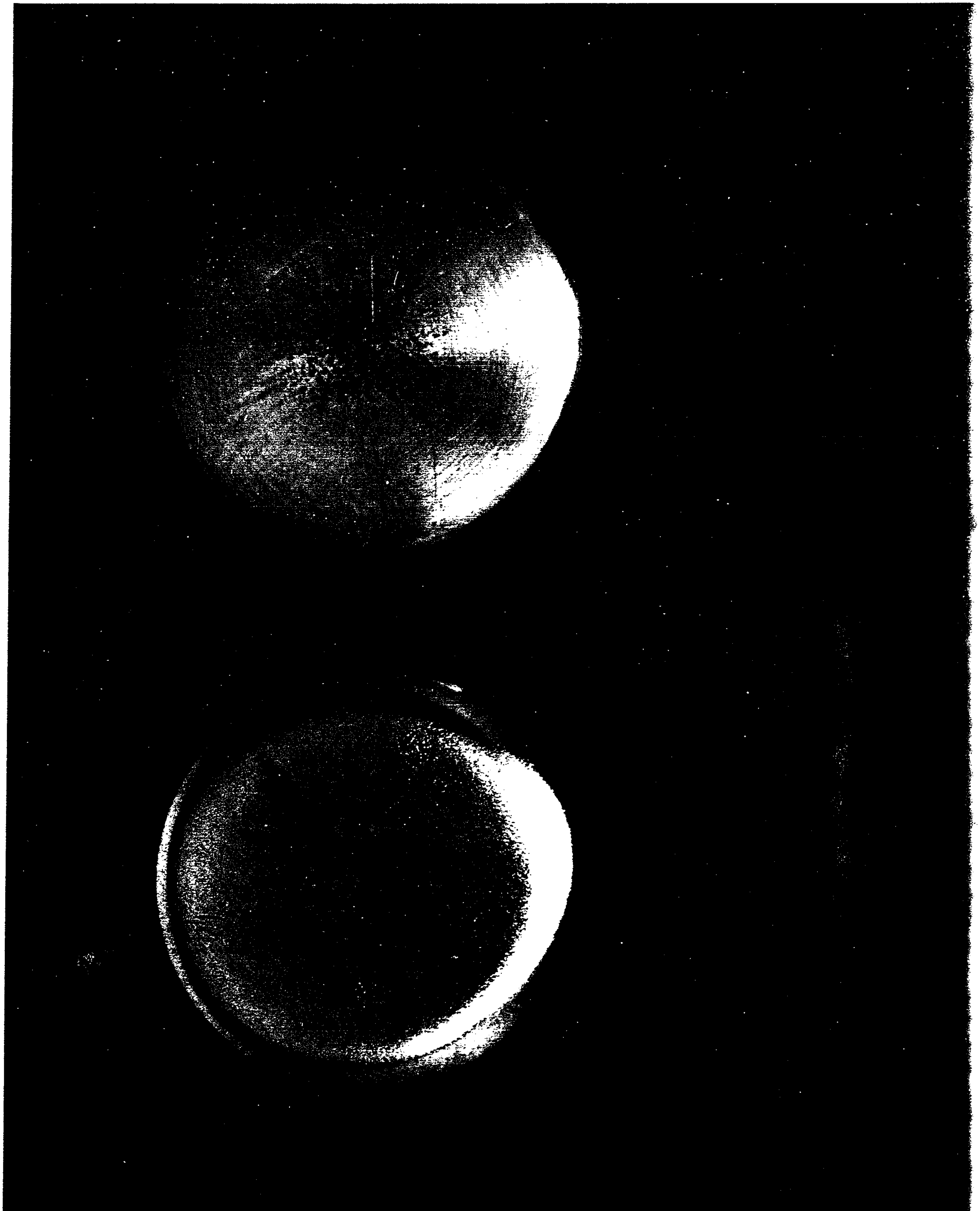






Summary of R & D

- Deflectors operate in transition regime
- Both field-emitted electrons and microdischarge activity may cause breakdown
- At low E-field, microdischarges more important

Microdischarges

- Originate from either anode or cathode
- Produced by transport of clump of material across the HV gap
- Have charge-density of originating electrode
- Are not bent significantly by B-field
- Anode-originated microdischarge more damaging
- Can produce direct cathode damage or deposit a particle on cathode that produces high FEE current
- Exponential increase in FEE current may set maximum usable E-field

At Impact...

- Gas burst produced
- May damage impacted surface
- May trigger spark that also damages surface

David Poe
National Superconducting Cyclotron Laboratory
Michigan State University

An Alternative Deflector Design

An Alternative Deflector Design

David R. Poe MSU-NSCL September 1992

We are just beginning a project to try making a deflector of unusual design. We are planning to try to make a K500 E2 deflector of this design, and if it works there, to try an E2 for the K1200. (E2 is mechanically simpler than E1).

The idea is to get away from the usual design wherein one supports the shoe with cantilevered insulators, and instead support the shoe with insulators above and below the shoe. The insulators would fill the entire space above and below the shoe, so they would be objects as large as the shoe. (This idea works better in our superconducting cyclotrons than it would in a conventional machine, since we have such a vertical space limitation.) There would be no insulators at the back of the shoe, only the high voltage feedthrough would be there.

Admittedly, this might or might not work too well, but some of its potential advantages I can list:

> Many of the problems with which we are familiar in deflectors are caused by the acceleration of electrons and positive ions between the shoe and the ground plates above and below. The design philosophy here is that all space vertically above and below the shoe be filled with insulator, so as to deny particles the possibility of acquiring kinetic energy. Any design for a hinged deflector, such as the K1200 E1, would have to still try to fill the space in the hinge area as well as possible.
>
> The insulators would be mechanically much stronger than those of a conventional design, so there should not be such an air of delicacy as with the present cantilevered designs. It might even prove possible for it to keep running with cracks in it, if voltage holding is still possible.
>
> There would be more heat flow through the insulators than in the present designs. This would provide some passive cooling of the shoe as well as making the insulators more rugged thermally; any given amount of power is more easily dissipated, due to the large heat capacity as well as the high conductivity.
>
> In the median plane of the cyclotron, particles may experience an E cross B drift parallel to the face of the shoe. (Off the median plane, E X B has vertical components.) These particles may then stike and damage the insulators. The vertical support design bypasses this problem.
>
> Many of the problems which can be thought of as edge effects of the insulators would be gone. These are the problems associated with trying to make electrically flat surfaces with no sharp edges as transition pieces between conductors and insulators.
>
> Some experience says that glass coatings or anodized aluminum is good due to the inability of electrons to freely move in the insulator. These insulators constitute a very thick coating in the vertical direction.

Right now, I picture making a shoe with a hole for the high voltage rod, but none for the insulators. The back plate of the deflector housing has only the feedthrough hole for the high voltage rod, but no "cups" to support insulators. We would probably first try MACOR for the insulators, machining them out of large pieces to match the curve and shape of the shoe. Locating the insulators in position is problematic; probably we will machine a channel in the sparking plates just deep enough to hold the insulators in position, though one might imagine screws (nonconducting ?) into the base of the insulators.

It might be necessary to solder the shoe to the insulators to avoid the slight gap at the contact point. I would like to avoid this if at all possible, as it is best to keep maintenance problems simple, so we will try it just fitting snugly.

There are some obvious potential problems with this design. The large surface area of the insulators would probably allow much more current to flow, which might or might not be a problem, but the more rugged construction would hopefully allow this. Also, the surfaces of the insulators are approximately parallel to the magnetic field, although it is unclear just what shape to make them. The direction of the magnetic field might help a discharge to begin and sustain itself inside the insulator.

There are many questions which one may ask, such as:

What are the best materials to use for insulators, shoes and sparking plates?

Will all of this dielectric increase the stored energy enough to increase the spark damage?

What is the best shape for the insulators? Should one try to make them follow the shape of the field, or perhaps deviate as far as possible therefrom?

What should be the angle between the surfaces of the insulators and those of the shoe and sparking plates at the points where they join?

Should the insulators be fluted?

Should we consider "graying" the insulators to assure uniform gradients along them?

Does any of this matter very much at all, or do all such geometries act about the same?

If this is a good idea, why hasn't it been done before?

We at MSU may be able to answer some of these questions in the coming months, and we may even end up with a workable deflector.

Timothy Antaya
National Superconducting Cyclotron Laboratory
Michigan State University

Beam Loading of Deflectors
(and other observations)

PRESENT PERFORMANCE K1200 + ECRs

$H_2^+ \longrightarrow {}^{40}Ar^{16+}$

- Maximum Energy limited by Cyclotron Voltage Limits
  - S= not problem
  - RF voltage limit above where we routinely operate
  - deflectors marginal
- Maximum Intensity - various limits

$\approx Kr \longrightarrow U$

- Maximum Energy Limited by Ion Sources
- Maximum intensity Limited by Ion Sources or Injection Rigidity

DEFLECTORS – Many Puzzles

- M3 Deflector Test stand – routinely $\boxed{50-100\%}$ higher voltage achieved

- $\vec{B}=0$ conditioning and/or adding gas $\boxed{\text{Heals}}$ high $\vec{B}$ damaged deflectors

- Slow Conditioning results in high initial performance but little long term gain

- Operating Deflectors with beam generally lowers performance

LONG STANDING PUZZLE FOR T. ANTAYA

1. EARLY K500 + PIG

$54 \frac{MeV}{A}$ H_2^+ beam @ ≈ 1 μA

Result: E1 damaged

2. LATER K500 + PIG

$35 \frac{MeV}{A}$ $^{14}N^{5+}$ 2 eμA @ 26.5"

- 1eμA extracted } No observed damage
- 1eμA lost (E1) }

3. Contrast – Tissue inhibited beam extraction <u>completely</u> after a K500 shut down

100 watts is really very little power!

BEAM DEGREDATION OF DEFLECTORS

this workshop:

1. P. Miller showed deflector current growth with beam on
2. D. May observed correlation with poor extraction efficiency
3. B. Diamond noted improved performance with water cooled cathode

HEATING ?

PROBLEM <u>CAN NOT</u> BE SIMPLE HEATING

(IF SO – SOLUTION TRIVIAL)

WHAT ARE THE OBSERVABLES ?

↑ leakage current
↑ sparking
I threshold
time constants • • •

WHAT'S THE PHYSICS ?

HEATING → ENHANCED F.E.E.
→ SHAPE DISTORTION, FIELD ENHANCEMENT
→ INSULATOR FAILURE
→ OUT GASSING

IONIZATION → SEC
→ CONTAMINANT GAS

PHYSICAL DAMAGE ? • • •

CATESTROPIC FAILURE – WHAT DO YOU REPAIR ?

IN SITU HEALING – WHAT CAUSES THE RECOVERY ?

PROPOSE TEST:

- NSCL K1200
- Operate 10% macroscopic duty factor
- O^{6+} beam from SCECR
- $E \approx 80 - 100$ MeV/A
- $I \approx 0 - 10$ eμA Extracted

  - PEAK CURRENT HIGH
  - AVERAGE POWER LOW
  - RAISE DUTY FACTOR
    (will be limited by radiation)

Low darkcurrent → 100 kV/2mm gap
SiO2 sputtering deposition
High sec. not problem

1991 PAC
San Francisco

RF BREAKDOWN TEST OF SiO$_2$ COATED COPPER ELECTRODES *

D.Sun, P.Datte, W.W.MacKay and F.R.Huson
Texas Accelerator Center[†], 4802 Research Forest Drive,
The Woodlands, TX 77381

Abstract

RF breakdown test results with copper and SiO$_2$ coated copper are presented. The results show that SiO$_2$ coating can withstand an rf field as high as 100 MV/m at 471 MHz without sparking and depress the field emission.

Introduction

For high gradient accelerators, rf voltage breakdown is one of the major factors which impose the limits on the maximum field gradient. Since Kilpatrick proposed his semi-empirical criterion for rf breakdown limit in the 1950's [1], several experiments have been conducted to test the rf breakdown limit at various frequencies. But up to now the mechanism of rf breakdown still remains unclear. Different metals were tried to increase the breakdown limit, but there is no substantial increase. The surface coating of rf cavities was proposed to be a possible way to increase the breakdown limit far above the electron multipactoring limit [2][3].

Field emission is another detrimental factor for operation of high gradient accelerators, since it can induce breakdown, consume extra rf power, cause wakefields and possible excitation of unwanted modes of oscillation in the accelerating structures. So the research on how to depress the field emission for high gradient accelerating structures is needed.

In this paper we report our research on the possibility of SiO$_2$ coating of copper electrodes. Our interest is to investigate what improvement could be made in the depression of the field emission and increase of maximum field gradient by SiO$_2$ coating.

Experiment Setup

The test setup is shown in Figure 1. A reentrant type resonant cavity is used which consists of two demountable halves and two movable electrodes. The gap and resonant frequency can be changed easily by moving two electrodes. The electrodes are composed of two parts: body and end cap. The end caps to be tested are screwed onto the bodies. A small area of each end plate of the cavity was coated with titanium to depress possible multipactoring. The cavity is partially water cooled.

Two rf probes are mounted at different positions to monitor rf power transmitted into the cavity. Also, the ratio of the two probes' measurements is used to detect other possible modes which may be excited at higher power levels. Seven thermocouples monitor the cavity's temperature at various positions.

An x-ray spectrometer is set up for the measurement of maximum rf field and field emission in the gap. This x-ray spectrometer consists of a NaI detector, a LeCroy 3001 multichannel analyzer, a LeCroy 4608C discriminator, an HP 5314A universal counter and an IBM PC.

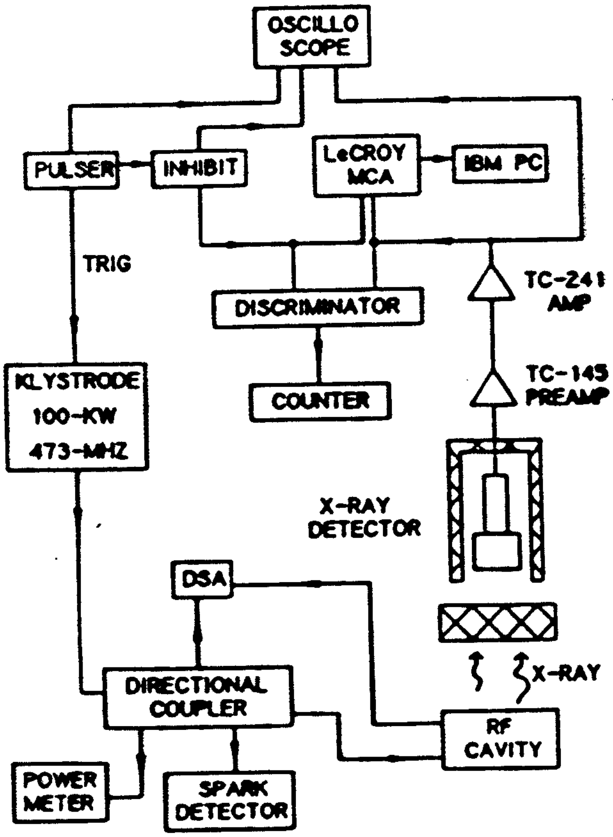


Figure 1. Experiment Setup.

An EIMAC 2KDW60LA klystrode is used as an rf power source providing 8-50 μs long pulses with a repetition rate of 10-100 Hz [4]. The forward and reflected powers are monitored with a calibrated four port directional coupler, a Tektronix 602A digital signal analyzer and an HP 408A power meter. Also the reflected signal is sent to a spark rate counter.

The rf cavity is in a high vacuum chamber which is

---

pumped by a 500 L/sec turbo pump, a liquid nitrogen cold trap and a mechanical pump. The vacuum feedthrough for the main rf coaxial transmission line is made with a Teflon insulator and a Viton O-ring.

Experimental Procedure

The pure electrode end caps were made of OFHC copper. They were carefully polished to less than 3 μm finish and ultrosonically cleaned. After cleaning, several copper end caps were coated with SiO_2 thin films by electron beam evaporation. The thickness of SiO_2 is 400 nm. The refractive index of SiO_2 is 1.543. Before and after each test the Q and SWR of the cavity and attenuation of rf loops were measured several times with an HP8753B network analyzer. The x-ray spectrometer was calibrated with gamma ray standards (^{133}Ba,^{57}Co,^{137}Cs, and ^{22}Na). To compare the field emission, we measured the x-ray intensity at several field levels with both pure copper and SiO_2 coated copper electrodes. The rf frequency was 471 MHz. The rf pulse length was 8 μs, and the repetition rate was 100 Hz. All tests were done after the vacuum chamber was pumped to less than $3\text{x}10^{-7}$ torr.

The maximum electric field in the cavity was determined by two methods: pick up loop and x-ray spectrum. The pick up loop method determines the maximum electric field by the expression:

$$E_{max,exp} = E_{max,theo}\left[\frac{Q_{exp}P_{exp}}{Q_{theo}P_{theo}}\right]^{1/2} \qquad (1)$$

where $E_{max,theo}$, Q_{theo} and P_{theo} are the theoretical maximum electric field, Q factor and corresponding dissipated power as calculated by SUPERFISH, and Q_{exp} and P_{exp} are the experimental values.

Since the real field distribution and oscillation modes at high electric field can be different from either those measured at low field level or those calculated by SUPERFISH, it is necessary to employ another method to ensure the accurate determination of the real maximum electric field in the gap. The x-ray measurement is used to determine the maximum energy obtained by the field emitted electrons. The high energy end of the x-ray spectrum (Bremsstrahlung) corresponds to the amplitude of the rf voltage in the gap. The maximum electric field is determined by deviding the voltage amplitude with gap length.

The total intensity of the x-rays can be used to determine the current density of the field emitted electrons by the following expression:

$$I = CjZV^{m} \qquad (2)$$

where I is the total intensity of the x-ray, C and m are constants, Z is the atomic number of the electrode material, j is the electron current and V is the voltage between electrodes. The x-ray intensity can be determined by the spectrum if the other parameters are fixed.

Experimental Results

1. Breakdown limit

The breakdown started at a field level of 97-100 MV/m with the SiO_2 coated electrodes. This sample was first tested up to 81 MV/m [5]. After the first test, the cavity was opened and the electrode surfaces were visually checked. There was no trace of sparking. Afterward the samples were kept in the ordinary atmosphere for seven months and were tested again. The samples showed good repeatability until the first spark occurred at 97-100 MV/m. After the spark occurred, the signals from x-ray spectrometer were heavily piled up, which indicated a dramatic increase of field emission. After the cavity was opened, there were two small pits seen on the electrode surfaces, similar to those of pure copper electrodes. Except for those two pits, the SiO_2 film remained undamaged. As we previously reported [5], with pure copper electrodes, the sparks started at a electric field of about 60 MV/m. The maximum field of pure copper electrodes can be maintained at a level of 120 MV/m after a long time careful conditioning, but there are a lot of spark traces left on the surfaces after tests.

2. Field emission

Figure 2 shows the x-ray spectrum from SiO_2 coated copper and the pure copper electrodes at an rf field of 42.5 MV/m. The pure copper electrodes had been conditioned and operated at various field levels up to 120 MV/m for a long time. The x-ray spectrum was taken after operations of more than 100 hours. In order to avoid pileup of the x-ray signals, we had to increase the shielding of the x-ray detector with increase of rf field, but at each field level, the same shielding was used for both pure and SiO_2 coated copper electrodes. Table 1 lists the total counts of x-ray signals normalized by the total effective counting time at three different rf field levels. The data shows that the total normalized x-ray counts of the pure copper sample is about 20 times more than that of SiO_2 coated copper.

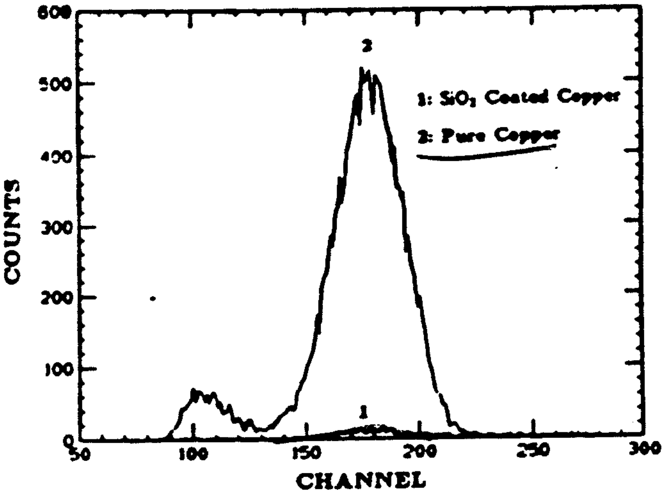


Figure 2. X-ray spectrum at rf field of 42.5 MV/m

TABLE 1
Normalized Total Count

rf field (MV/m)	total counts per second		ratio
	pure Cu	SiO_2 coated Cu	
42.5	2120	104	20.4
67.5	3643	148	24.6
85	4488	86	52.2

Conclusion

1. The above reported results show that the SiO_2 coating can increase the rf breakdown starting level up to 97-100 MV/m. The Kilpatrick limit at 471 MHz is 20 MV/m. This means that SiO_2 coating may provide a method for keeping the electrode surface free of damage during high field gradient operation.

2. The SiO_2 coating can reduce the field emission. Compared with the pure copper electrodes which were used for more than 100 hours, the total normalized counts of the x-ray signals can be decreased up to 20 times. This could improve operation of accelerators at high field gradient by reducing the dark current.

also:

Thin 400 um

Q: What About DC?

References

† TAC at HARC is a consortium of Rice University, Texas A&M University, the University of Texas, Prairie View A&M University, Sam Houston State University and the Baylor College of Medicine MR Center.

1. W. P. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both rf and dc," Review of Scientific Instruments, 28 (10), 824 (1957).

2. W. Peter, "Vacuum Breakdown and Surface Coating of rf Cavities," J. Appl. Phys. 56 (5), 1546 (1984).

3. B. Hoeneisen, Internal Report No.2, Instituto de Fisica Universidad de Guanajuato, 1987.

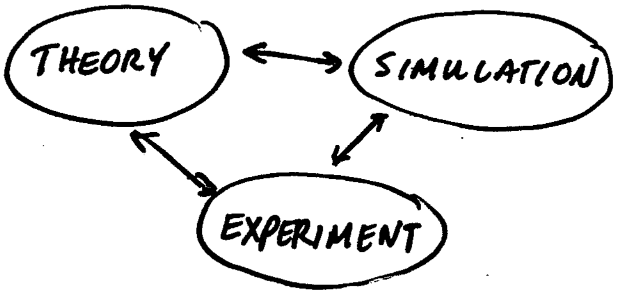
4. W. W. MacKay, *et al.*, "Operation of a 473MHz Pulsed Klystrode Power Source," Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 1990, pp. 186.

5. D. Sun, *et al.*, "Voltage Breakdown Test At 473 MHz," Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 1990, pp. 216.

PROPOSE TEST :

- Fabricate set of CRNL electrodes
  - various materials : Cu, SS, Ti
- Apply Various treatments
  - none, hand polishing , E.P.
- Grow SiO_2 Layers on Some in ECRIS
- Run in CRNL test stand

MOST AREAS OF ACCELERATOR PHYSICS:

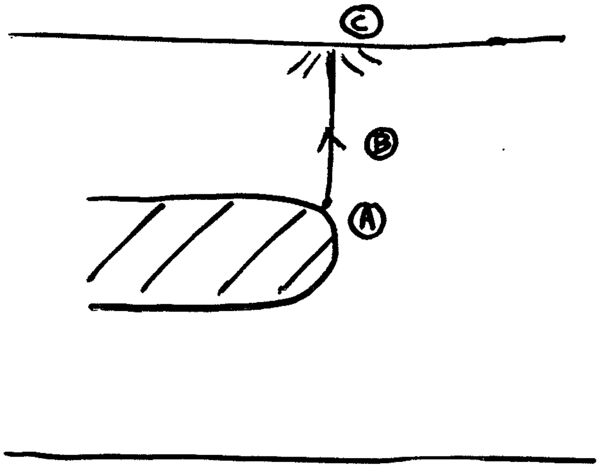


WHY is THIS NOT TRUE FOR DEFLECTOR RESEARCH ?

STEPS :
more complex
more expensive
more critical
} GAINS SMALLER !

WHAT CAN BE MODELLED ?

PROPOSE - MODEL HIGH $\vec{B}$ SPARKING



Ⓐ F.E.E. ϕ, T, B, V ...

Ⓑ ELECTRON Ray Tracing w/ Space charge

Ⓒ Energy Deposition

E/A, S.E.C., Ion and cluster production

DEFLECTOR DEVELOPMENT COMPLEX PROBLEM

SHOTGUN APPROACH:

1. LINK 3 PROGRAMS TIGHTLY
   - A. MATERIALS STUDIES/ SYSTEMATICS
     - CHALK RIVER TEST STAND
   - B. FULL SCALE TESTS – LEADING CONCEPTS
     - TAMU TEST STAND
   - C. PROOF OF PRINCIPLE TESTS
     - MSU K500 Cyclotron
2. REGULAR COMMUNICATIONS EMAIL
3. ADD THEORETICAL EFFORT
4. Establish Data Base

EXAMPLES :

1) POE'S  DEFLECTOR

- Don't attempt Full scale at NSCL
- BUILD SMALL SCALE TEST at CRNL
    - Faster, loss effort

2) ROGER'S ANODIZED/E.P. TITANIUM E1

- TEST w/ BEAM AT NSCL

(• not mission disruptive either lab)

3) SiO_2 vs Anodizing vs EP
- grow SiO_2 in CPECR
- Matrix (Cu, SS, Ti) x (SiO_2, EP, Anod.)

at CRNL (• excellent diagnostics available)

4) K1200/E2 for K500/E2

- TEST AT TAMU

(• don't reassemble MSU/M3 T.S.)

Timothy Antaya
Workshop Summary

Two observations have hit me. First, a large body of knowledge and technical know-how is needed to pursue the development of high voltage electrostatic deflectors. One must simultaneously be several specialists, and that of course is an impossibility.

My second observation is that recent work, particularly Diamond's systematic studies at Chalk River, have resulted in enormous progress. We will all be looking to apply those results and others to our own particular deflector instances over the next few weeks and months.

Rogers drew our attention to the questions of surface treatment and conditioning, through an effective demonstration of the anodize titanium E1 deflector operation in the TAMU test stand. I hope that we at MSU will be able to take advantage of this facility in the future.

Test stands allow us to 'take apart' the deflector problem, but we need to be able to 'put it all together' while still operating our respective facilities. The causal linkage between test stand data and 'in cyclotron' performance must be more clearly demonstrated. The K500 cyclotron at MSU may play an important role as an intermediary in this process.

Miller traced the development of deflectors for the K500 and K1200 at NSCL. The differences–smaller gap, higher B, provision for deflector motion, have perhaps a bit more significance now then when he started R&D at MSU in 1976. Poe made the most unusual suggestion: massive vertical insulator supports. Perhaps it works, perhaps it does not work–in any case, many such new ideas need to be proposed and considered.

All mentioned the urgent need for further research and development, and the only question is how best to proceed? Let me just say that I hope we proceed on all fronts simultaneously, by working together on these very challenging questions. To reiterate, one scheme for accomplishing this would be to:

1. Link the 3 programs tightly
    - A. Materials Studies/Systematics–CRL Test stand
    - B. Full scale tests of *leading concepts*–TAMU Test stand
    - C. *Proof of principle* tests–NSCL K500
2. Open regular communications (via E-mail).
3. Add a theoretical effort.
4. Establish a database.

Of course we should not forget our colleagues at AGOR and Milano/ Catania, who were not able to attend this workshop. Though just assembling their superconducting cyclotrons now, they no doubt will soon face many of the same issues when they attempt extracted beams.

In closing, on behalf of the visitors, I would like to thank Bob Rogers and the staff at the Cyclotron Institute for their hospitality and making this, the 1st High Voltage Deflector Workshop for Superconducting Cyclotrons, such a great success.

Timothy Antaya