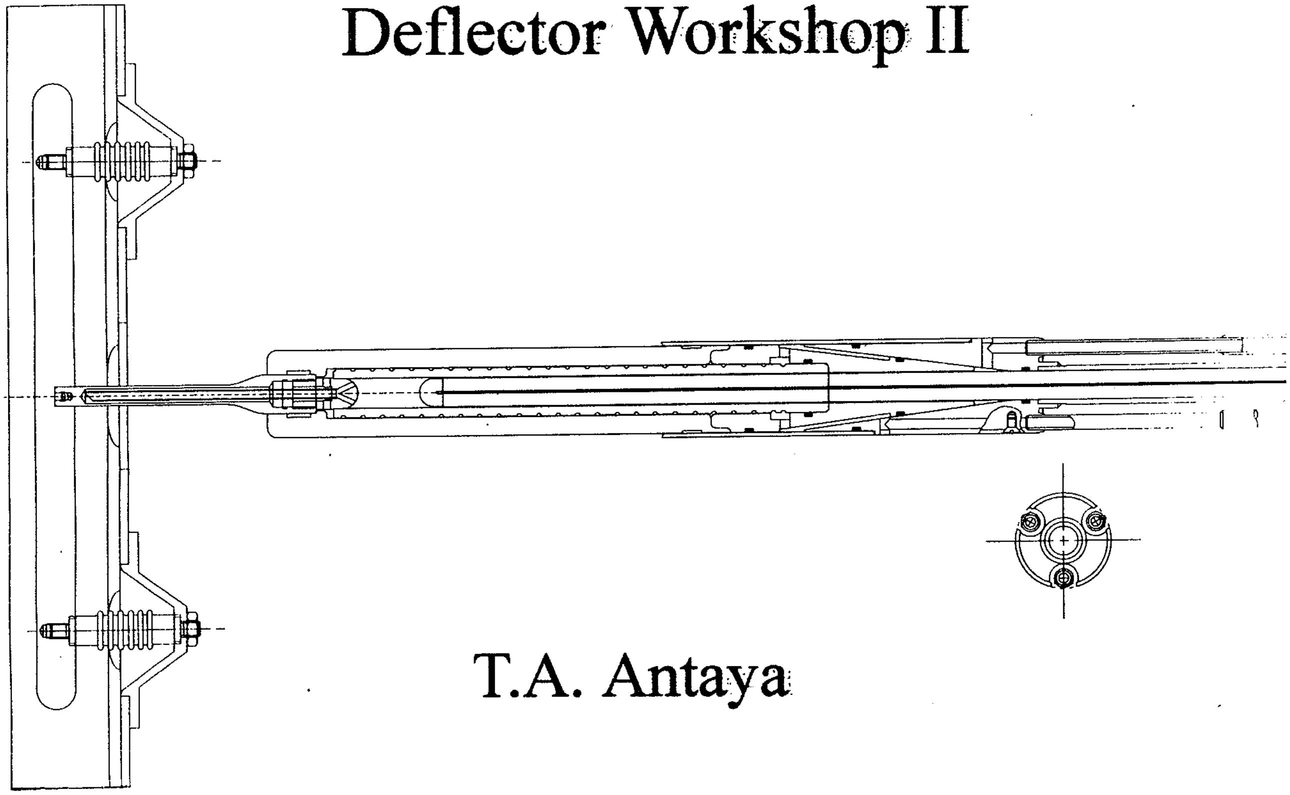
Michigan State University

National Superconducting Cyclotron Laboratory

Compact Superconducting Cyclotron Deflector Workshop II



T.A. Antaya

MSUCP-77

Compact Superconducting Cyclotron
Deflector Workshop II

27-28 Sept. 93
MSU/NSCL--East Conf. Room

Tentative Agenda:

Monday 27 Sept	AM - Progress Reports: Texas A&M (Rogers) Chalk River (Diamond) NSCL (Antaya / Poe)
	Lunch - Owen Graduate Center
	PM - Desc. of Radial HV Feed thru Test
	3:00 pm - D. May, Seminar TAMU K500
Tuesday 28 Sept	AM - Start K500 HV Test
	11:00 am - J. Wills, Seminar ECR--Tandem
	PM - Continue Test
	(3:00 pm - K500 Upgrade Meeting)

Other Activities

Monday	Ramp K1200 Deflectors to 70 kV
	^{106}Cd^{26+} / K1200 Development (Dallas Cole - Vacuum Atten. Measurement)
	SCECR /High Intensity Oxygen -all day (Keith Harrison)
Tuesday	SCECR /High Intensity Krypton -all day (Keith Harrison)

OUTLINE

Performance Table

B. Rogers, TAMU

B. Diamond, Part 1, Review - Cyclotron Deflector Operation

B. Diamond, Part 2, HV Research

T. Antaya, Present NSCL Deflector Development Effort

D. Poe, K1200 O2 Conditioning Experience

COMPACT SC CYCLOTRON DEFLECTOR
PROGRESS - OCTOBER 1993

	Conditioning Limit B = 0 RF = 0 No Beam	Operating Limit RF ON B at Int. Levels Beam Extracted
TAMU K500 E1, E2 Titanium Shoe W Sparking Plates slotted 'Barrel' Macor Insulators Horizontal Gap: 6.25 - 6.5 mm Vertical Gap:[?] 90 MΩ Surge Resistor 3 - 30 MΩ resistors Resistance inside HV Rod w/ O_2 Ballast Gas	90 kV (one went as high as 100 kV!)	65 kV 68 - 70 kV
TASCC K400 Cyclotron E.P. SS shoe E.P. SS Sparking Plates Greened Alumina Insulators Horizontal Gap: 5 mm Vertical Gap: 10 mm 24 MΩ water gap surge resistor No Ballast Gas	95 kV	80 kV
NSCL K1200 E1, E2 Anodized Alumina Shoe SS Spark Plates Fluted Macor Insulators / Ti end caps Horizontal Gap: 6 mm Vertical Gap:[?] 16 2/3 MΩ 1 External Resistor Surge Resistance in PS w/ O_2 Ballast Gas	unknown	65 kV 80 kV

B. Rogers, TAMU

A. Coatings

Al_2O_3 : High purity Al surface (.9999), coating obtained at Mel Fall Titanium Finishing (P.O. Box 22, East Greenville, PA 18041), get cracked surface grain structure if lower parity is used

TiO : No cracks, first micropolish, then bath-etch, $\varepsilon = 70$ % 160 kV/cm

TiO at 7mm gap - 1st operation is good to great and achieved 70 kV- required O_2 glow discharge conditioning first

Observations on Coatings

1. Coatings Require Conditioning - Technique:

Set P = 40 microns

Negative voltage on shoe

Set current limit to 0.5 mA

Allow sparking for 20-30 min

2. Main problem - once shoe sparks at high voltage, the coating is damaged and is non-recoverable

⋆ must strip off layer and start over

B. Identical Metals

1. Two Stainless Steel electrodes ordered but not here yet

2. Housing and spark shields

Titanium	Reliable
W spark plate 65 kV	
6 1/4 - 6 1/2 mm	Beams of Deuterons > 60 MeV/n have been achieved in K500

3. Failures of new Insulators

We precondition insulators in Cyclotron : B=0 reach 90 kV at $2 \cdot 10^{-5}$ T

Then, with B on, oxygen ballast, reach 68-70 kV in operation
(⋆ D. May - one went to 100 kV)

Purpose of oxygen ballast gas - observe zero leakage current → suppressing field emission [?]
(⋆ B. Diamond - observe same for O_2 ballast except after some time, high leakage current returns. Have tried also H_2 ballast, where emission drop is permanent.)

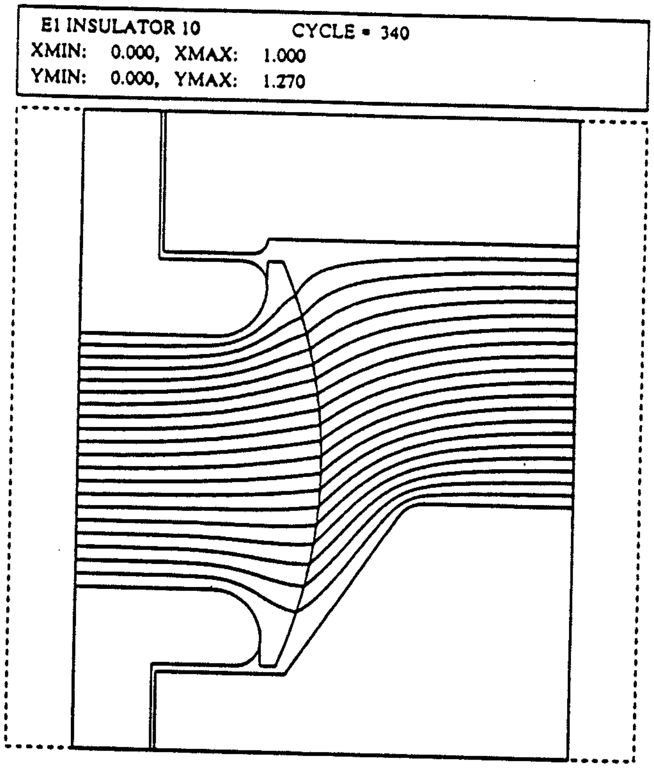
C. New Insulators

E1

Material : Macor

End caps glued on with high density 3M epoxy
Failure Mode : punch thru from ends thru center

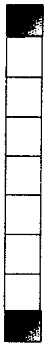
⋆B Field helps operation of these insulators



Above: with this type of insulator, marks are observed at the position of maximum voltage gradient

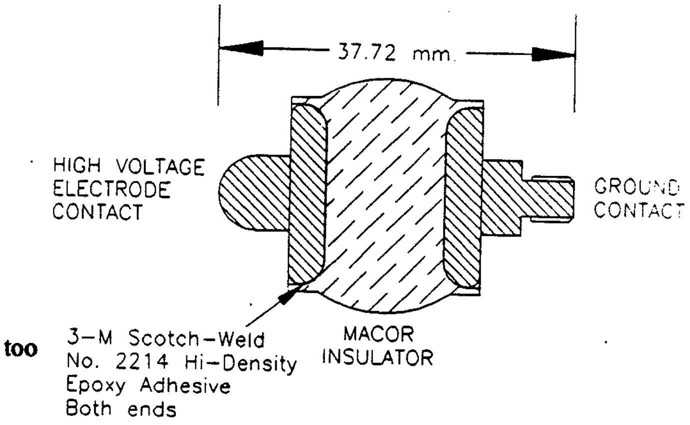
E2 : shorter version of E1 above

PREVIOUS DESIGNS



GROOVED SAPPHIRE:
Failure Mode: plate down sides and fail
(B. Diamond - "Brown = Hydrocarbons")

Another test design: `Big Bob' - it coated too



INSULATOR STATUS

Q(TA): Running now in K500   How long? E1 since Christmas

Macor vs. Mycolex - Comment B. Diamond. In studies at Chalk River, we observed the following voltage hold limits:

Macor	**100 kV**
Mycolex	**60 kV**

WHERE LIMITS NOW?

Insulators   okay to 70 kV; failure at 75 - 78 kV

(D. May - when we repair deflectors, fresh insulators are always used)

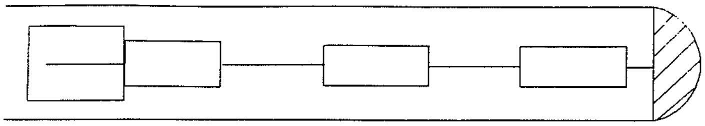
Have run 65 MeV/n beams for ≥ week

Attempt to run at 70 MeV/n RF failed: main insulators Vac seals which used Viton o-rings, and breakdown with RF sparking

HV Rod:

standard glass rod - can melt with RF because of poor conductivity

90 MΩ at shoe end (3 x 30) M Ω resistors



Cable - Graphite loaded coax with center conductor removed operating at
Because of the 90 MW surge resistance, the deflector voltage can be lowered if the leakage current is significant

Cables - 2m long

Power supplies are low stored energy supplies. We estimate stored energies of:

PS 1.5 Joule
Def 0.25 Joule

B. Diamond , Part I, Review - Cyclotron Deflector Operation

Goal: 150 kV / cm Any B, Any RF

In situ, the constraints are:

Vertical Gaps, H.V. Electrode to Sparking Plates, are 25 mm.

B - 2.5 to 5 Tesla

r_g = 0.18 mm 70 kV, 5 T
0.31 mm 70 kV, 3 T

Power Density $\propto B^2$

RF Heating

Vacuum Contamination

Design

RF cracks hydrocarbons, carbon deposition on deflectors results in increased leakage

Fixed position - extract at same radius

Deflector is located in dee

Sparking Plates upper 3 piece center removed
lower 1 piece

Septum 1 " high

Gap 5mm

New Design : Jan-Feb 1993,
Monolithic Cu base rail tried, - allows for both gap and beam inner radius adjustment
upper rail removed
This design did not work

HV Feed 12 MΩ - cm water

Glued Teflon liner in main alumina insulator - drilled out after assembly

2 cm water gap

Greening (Cr_2O_3) of insulators results in a surface with an S.E.C. < 1!

Typical Failure Mode:
HV Feed, after 4 - 5 months of operation, due to water leak in the Butt joint in the Teflon liner at center of the main insulator

One unusual vacuum fault: we have 2 radial probes - there is software protection on probe, this code opened a probe gate valve connected to atmosphere (1.5 in diam), blew all the carbon foils in the cyclotron

Carbon contamination lowered peak voltage that could be achieved in the deflector

Operating Characteristics:

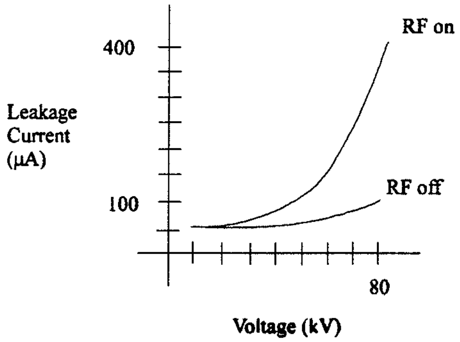
130 - 150 kV/cm 4 months at a time

We condition to 80 kV @ 2 T

Hydrocarbon Contamination:

Deflectors are conditioned with RF Off and a leakage current of 50 μA @ 80 kV is obtained

With RF on, we observe a large increase in leakage current:



Infer RF is breaking hydrocarbon molecules and that these are getting to the deflectors.

Q(TA) - What is the roughing vacuum, are there cold traps on lines?

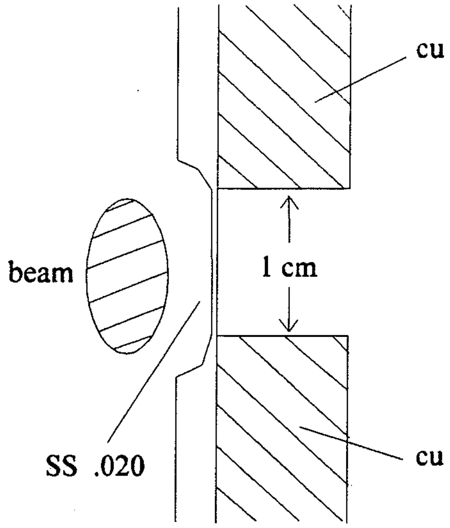
Hydrocarbon Source? - It is historical: Possible contamination sources are

⋆ trim rods, sliding seals

we have 2 Cryopanels in upper dees, and with these high 10^{-7} T vacuum can be achieved. But with the Turbos only 10^{-5} T.

High Power Septum Development

Rails - lip is higher and is made of thick copper

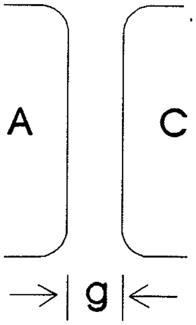


Summary: Present TASCC Deflectors

95 kV	5 mm	B = 0
100 kV	6 mm	B = 2 T
85 kV	5 mm	2 T
80 kV	RF on, magnet on at intermediate levels	

B. Diamond, Part 2, HV Research

Schematic: small test stand



g: small gaps, approx. 1mm

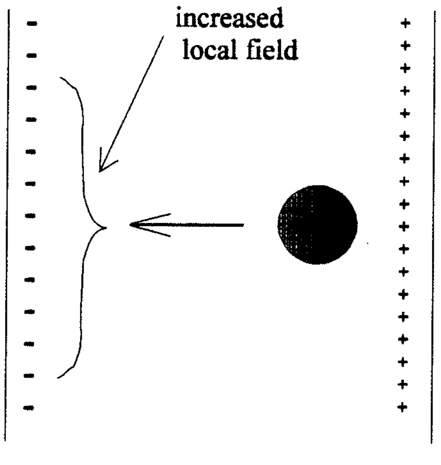
Goal - increase V

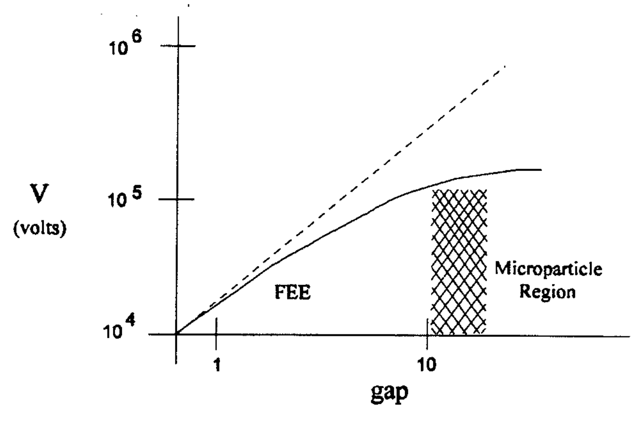
Point emitters are well characterized, but what about

Broad Area Electrodes ???

Generally one observes that $E_{max} << E_{point}$ Why?

TOTAL VOLTAGE EFFECT - **breakdown limit depends on total voltage**





TASCC Small Test Stand **Operating Limits: Neg Bias :100 kV , Bi polar: 200 kV**

⋆ Variant - double negative test: Bring both up to -65 kV to degas electrodes then turn one down

We believe that microdischarges between electrodes do this degassing.

This degassing comes only from small parts of the surface and consists of H_2 + hydrocarbons, because we observe O, $H_2O \approx$ const.

What is the nature of this process discharge?

Q: Is it a Desorption / Spark process or Spark / Heating / Outgassing process?

Clue: we observe no precursor electrons (x rays) before this discharge onset, hence No Spark is Observed so Desorption ions must come first from a direct voltage process.

∴ We observe a sudden emission of gas

→ high enough pressure to induce Townsend discharge

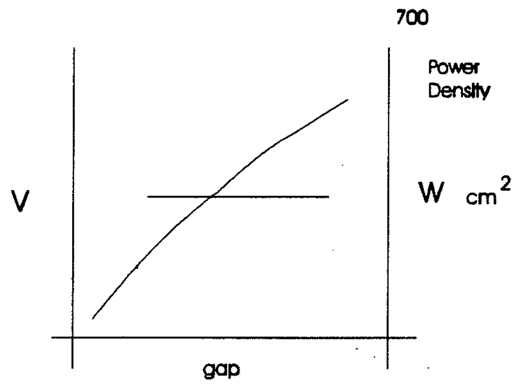
- no spark
- X rays distributed over entire ion pulse

⋆ Import - use slow conditioning and therefore avoid microdischarge driven sparks during conditioning

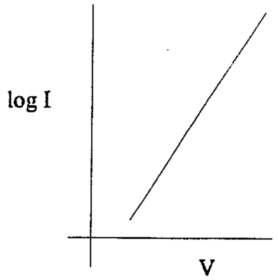
FIELD EMISSION & TOTAL VOLTAGE EFFECT

SLAC Code calc * - spike 4 µsec long has E av ≈ 100 MV/m

⋆Thermionic Emitter Characteristics:



⋆ Field Emitter - - x 10 in current for a few % change in V:



Transition to Field Emission in Double Negative Exp: for a 1 mm gap, this transition occurs at $\Delta V = 20$ kV, when using A. P. Cu cathode and anode

(E.P. ≡ Electro polished)
(A.P. ≡ Abrasive polished)

⋆ [Slac Electron Trajectory Code - Calculation]

Mixed Mode Effects

AP Cathode EP Anode	Transition at $\Delta V \sim 20$ kV
E.P. Cathode A.P. Anode	Transition at $\Delta V \sim 23$ kV

Vacuum annelling, H annelling, then E.P. (Double Negative Exp)

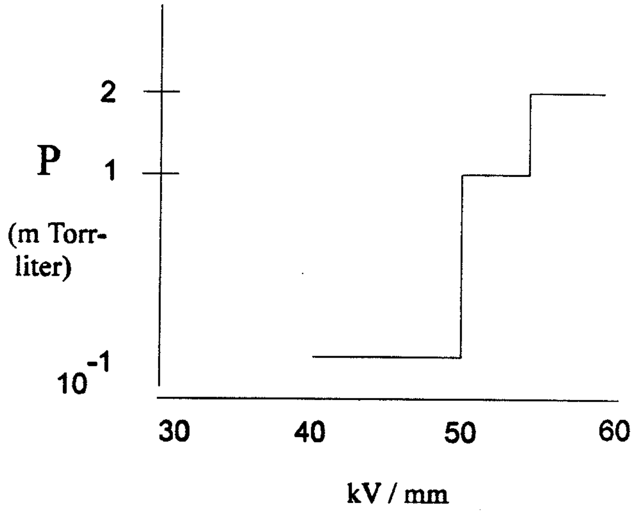
1 mm gap   The transmission shifts to higher voltage:

Transition : 37 kV → 43 kV → 48 kV → 53 kV

and we reached 75 kV before sparking limited!

⋆ In these experiments, both the anode and cathode are stable and cooled

GAS DESORPTION vs. VOLTAGE



T. Antaya Present NSCL Deflector Development Effort

We have identified four areas in which to work on:

1.) Cyclotron Operating Environment: vacuum, B, RF

2.) Insulator Voltage Holding: mechanical, electrical, conditioning

3.) Metal - Metal Sparking: field emission, micro-discharges, sparking damage

4.) Beam Effects: heating, secondary electrons

CYCLOTRON OPERATING ENVIRONMENT

- Run beams over most of K1200 h=1 operating diagram
- Deflector failure hard to diagnose
- Previously only one K1200 -- E1, E2 set - during repair, everything must be corrected so failure systematics hard to get

Solutions:

1. Build complete spare set - have ready to install

   Other Advantages

   - large scale systematic tests i.e. new insulator design etc
   - can avoid having to work on hot deflectors

2. Use K500 Cyclotron as Deflector Test Stand

K500 AS DEFLECTOR TEST STAND

1. K=250 5mm Deflector Test

Design study for K250 proton therapy cyclotron requires 100 kV/cm performance

5 mm gap should be sufficient for proton beam -- not expected to be intensity limited

Set up two deflectors

K500 E1 : 5 mm gap, 5/16 in. straight Macor Insulators

K500 E2 : 5 mm gap, 3/8 in. Fluted Macor Insulators

Performance - E1 50 kV, difficult conditioning, high leakage current
E2 60 kV, easy conditioning

The new fluted insulators are once agian found to be superior to the standard NSCL deflector insulators.

2. W.C. K1200 HV Feedthru (More on this later)

3. Deflector Designs for High Beam Power - Ultimate Goal

- We assume HV limit problem will be solved !

- We need very high intensities for our ECR / K500 / 1200 coupling proposal !

INSULATOR VOLTAGE HOLDING

Problem - we had several insulator types, which was best?

Solution - Tested one of each type in TASCC small test stand as a quick 'survey' of performance [W. Diamond, et.al,. MSUCP69, Dec 1992]

Found:

a. Insulators are more stressed by B=0 conditioning

b. Single insulators can take several hours to condition to HV, depending on material properties

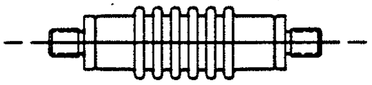
c. Standard NSCL Macor / Titanium could fail at 60 kV - this is just where deflectors often failed in practice - could these failures then be insulator limited?

d. Two designs were superior:

- Fluted Macor: reached test stand limit (100 kV) easily
- Greened Alumina: reached test stand limit easiest

FOLLOW UP

1. We adopted **Fluted Macor** design into K1200 deflectors in Jan. 1993:



1.24" LONG X .375"/.500" DIA. FLUTED
MACOR with TITANIUM BUTTONS

- there have been no K1200 deflector failures in 1993

- we have operated with beam at 80 kV (6 mm gap)

2. We are developing Greened Alumina as next step in upgrading insulators

- interchangeable with Fluted Macor type in working deflectors

- shrink fit endcaps eliminate brazing /alignment problems

- Greening technique done in house (From TASCC recipe - Thanks!)

- Several were sent to TASCC for evaluation - results are available on two:

#1	130 kV	(-75 kV / +55 kV)
#4	130 kV	(-80 kV / +50 kV)

- Spare E1, E2 will be assembled with Greened Alumina Insulators

METAL - METAL SPARKING

Present Configuration K1200 E1, E2 :

- anodized aluminum shoes
- SS sparking plates - abrasive polished
- E1A housing has W.C. copper spark plates
- vertical clearance:
- gap: 6 mm
- surge resistance: 16 2/3 MΩ
- surge resistance located in power supplies, cable length 3m.

Operation

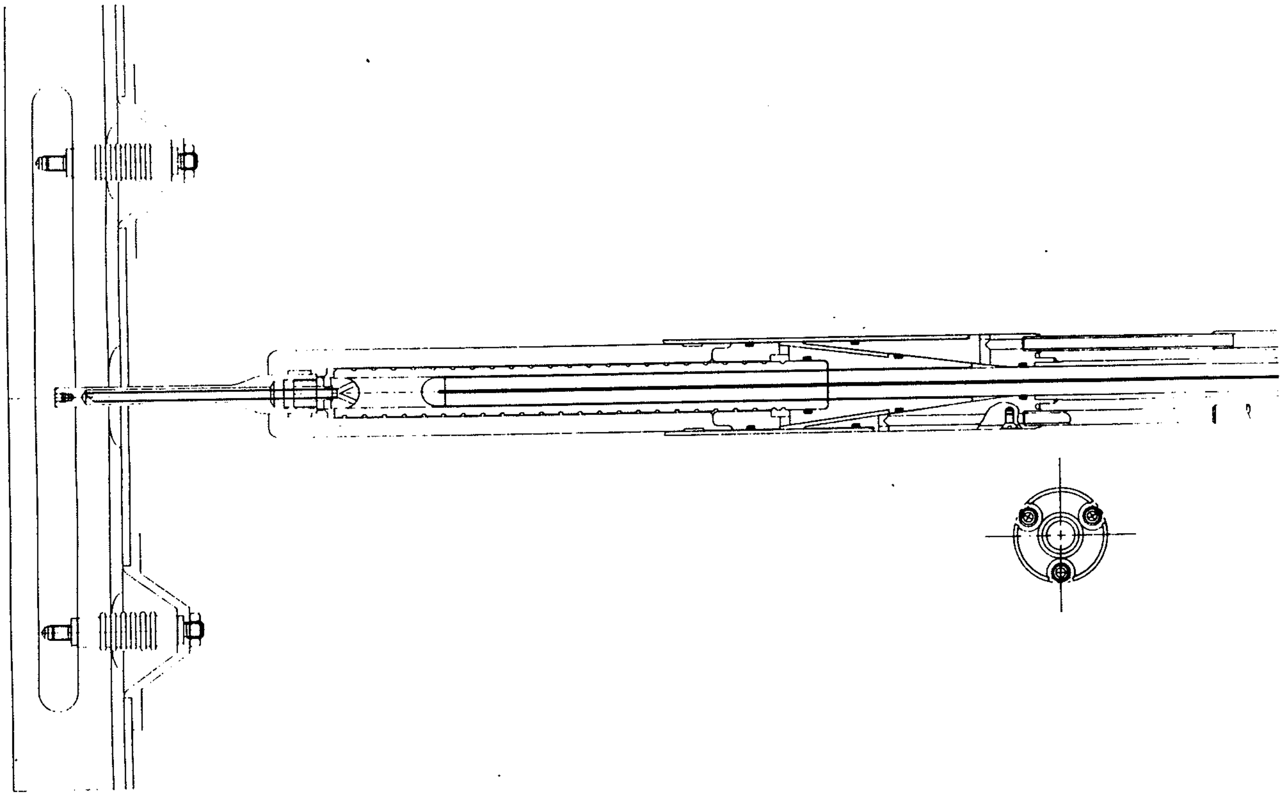
- since changing to Fluted Macor insulators, this Metals System seems okay
- HV feed can get hot - cable welds to housing bore at deflector shoe connector
- W.C. sparking plates on E1A appear to help when beam current is high
- When leakage current goes up, a precursor to sparking O_2 ballast is added at deflectors to recover low leakage state
  [D. Poe will discuss - later this meeting] We try to operate with leakage $\leq 10\mu A$ on either deflector

Next Effort : W.C. HV Feed Why?

- compact water gap surge resistance at deflector shoe
- water cooling to HV rod end - known hot spot
- future direct shoe water cooling - but must first solve technical problem of HV connection at hinge

Present Status

- Assembled and ready to test in K500 [Hopefully during this Meeting!]
- Have built short / straight prototype deflector as a load for this testing
  - has all features of deflector problem but lacks large size and curvature of operating deflectors
- Using building LCW (only 4 MΩ • cm) - building closed loop cooling system



BEAM EFFECTS

K1200 Beam Heating

- observe slow increase in leakage current on E1 and E2 when high intensity (≥ 200 eμA) high energy (70 -80 MeV/n) beams are run

- sensitive to quality of cyclotron extraction tune: either E1 or E2 can be adversely affected
  Good tune - can extract 500 - 600 eμA

we have not yet started to work on this problem - but we see the K500 as an ideal test stand for this work

WATER COOLED SHOE SHOULD HELP THIS

WATER COOLED SPARKING PLATES SHOULD HELP

Ultimately new septum designs for high beam power dissipation will be required

D. Poe K1200 O_2 Conditioning Experience

We at NSCL have had good fortune in reconditioning both deflectors by means of a high pressure oxygen reconditioning technique. This method consists basically of flooding large amounts of oxygen into the deflectors and running a voltage on them with the vacuum interlock bypassed. The vacuum in the cyclotron is about 5 to 10 x 10^{-4} Torr during this operation, and we run in the 50 - 60 kV range during this. The current limits on the supplies are at 100 microamps, and we let the current go where it will within this range. This will usually restore an ailing deflector in about fifteen minutes at most, and it seems equally effective for failures due to high beam and high voltage. After about fifteen minutes, he may turn the gas back to normal, and performance is generally restored.

Operationally, we have set a limit of ten microamps of dark current as a set point to trigger action on the part of the cyclotron operator. If this point is reached, he will shut off the beam and proceed to flood the deflector with oxygen by opening a manual valve to attain a vacuum in the 5 to 10 x 10^{-4} Torr range. The deflector vacuum interlock can be bypassed for a thirty minute interval from the control console (after which it automatically re-enables). This keeps the voltage of both deflectors on, as well as the water on E1, so both may be treated at once. He will then set the voltage to 55 kV and let it run. Sometimes the current will decrease to a fraction of a microamp, sometimes it will oscillate in the ten to thirty microamp range, and sometimes it will go to 100 microamps and the voltage will drop due to the current limit.

We are faced with the prospect of trying to understand these phenomena. One possibility is this: the deflector shoes are made of aluminum and they are anodized, that is, they have a layer of aluminum oxide on the surface. The reasoning behind this is that the oxide layer is nonconducting and will presumably help limit the emission of electrons from the surface of the shoe. Any damage to the shoe from a spark or excess beam will provide a point from which electron can be emitted, and it may be that we are able to re-oxidize a damaged patch.

Another possibility is that the oxygen simply cleans off whatever dirt is currently causing difficulties. It may be that thin layers of metal are deposited on the insulators during operation. The oxygen may perform the function of oxidizing this metal creating a nonconductor. We might be able to test this with hydrogen. Hydrogen is used to reduce oxides in metal ores industrially. The ore is heated in the presence of hydrogen, the oxygen in the oxides combines with it, and the result is water and a metal. The hydrogen might have the effect of making the oxide conducting again (i.e., high current after treatment).

We have often thought that conditioning occurs because positive ions may be made out of the gas, which then may be accelerated by the electrical potential with enough energy to abrade away a sharp point. If so, it may be that this process is accelerated with high pressure. In that case, the process should work well with Argon.

We often find that the deflectors go bad when we run large amounts of beam through them, and we are able to recondition them by this method. We also find that they are much more tolerant of high beams if we run them slightly out from the position of maximum transmission. A possible interpretation of these phenomena is that we cannot tolerate much beam hitting the shoe itself. If there is a source of charged particles emanating from the spot where the beam hits the shoe, we would expect some of them to drift around the shoe along the equipotential lines and in the direction of E x B, bringing them around eventually to the insulators. It may be that we can tolerate no such source of charged particles, and that the high pressure oxygen creates a new sealing layer over such a spot. Such a bad spot may well remain bad when the beam is removed, and only recover with treatment.

O_2 Conditioning Discussion

D. May	-	For sapphire we use Argon For Macor we use O_2
R. Rogers	-	H_2 Glow Discharge is Bad
W. Diamond	-	Pure Metals - O_2 not helpful in long term because high emission comes back - H_2 gives similar, permanent effect