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An International Survey of the Operation of DC Electrostatic Particle Separators

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Science Research Council

Nimrod Experimental Facilities Group
Rutherford High Energy Laboratory
Chilton Didcot Berkshire
1971

SBN 90237616 0

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SCIENCE RESEARCH COUNCIL

AN INTERNATIONAL SURVEY OF THE OPERATION OF DC ELECTROSTATIC PARTICLE SEPARATORS

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ABSTRACT

During a recent tour of accelerator laboratories in the USA the opportunity was taken to find out the operating techniques in use at Brookhaven, Argonne and Berkeley to compare them with those in use at the Rutherford Laboratory.

A visit was also made to CERN to establish the techniques at present in use there.

A questionnaire was prepared and this was completed by discussion at each of the laboratories visited. The attached sheets are those completed questionnaires.

Nimrod Experimental Facilities Group
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January 1971

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BROOKHAVEN NATIONAL LABORATORY

Number of Separators operational - Eight in 4 beam lines.

Electrode materials used - Glass cathodes, stainless steel anodes. (Type 304 St.St.)

Operational Voltages - 600kV on a 10 centimetre gap with a glass electrode, 500kV on a 10 centimetre gap with metal electrodes, to 350kV on a 5 cm gap, though 450kV has been found to be possible, voltages of 650kV have led to breakdown of the lead-in insulators.

Operation Temperature - $100^{\circ}C \pm 5^{\circ}$ measurement is made with a thermocouple to meter relay from the electrostatic shield. There is one of these thermocouples per tank. The temperature is then controlled by a hand operated Variac.

Electrode gap currents permitted - 200 μamps.

Sparking rates - one to two an hour.

Conditioning Procedures - The voltage is stabilized at 25kV on one electrode and the voltage increased on the other to a maximum of 200kV, with the maximum current stabilized to 200 μamps. The procedure is then repeated on the other electrode and finally both electrodes together to a maximum of 370kV all at low pressure.

Conditioning Times - With a new separator being conditioned for the first time a period of five to seven days is required to reach a level of 500kV with a spark rate of one an hour or less. A separator in use needs eight to twelve hours after it has been turned off for one or two days and if the shutdown has been prolonged a period of twenty-four to thirty-six hours is needed.

Time is available for conditioning during one or two days of each week during the period set aside for development and maintenance of the accelerator. It is not normally necessary to use beaming time for

conditioning the separators.

Period of operation - Normal operating period is 5 days.

Operating Pressure - between two and six times 10^{-4} torr. The normal operating pressure is kept low, ie on the left hand side of the pressure plateau.

'Bleed' Gas used - 'dry' nitrogen.

Magnetic Fields - It is found necessary to cycle the crossed magnetic field to re-establish the electric field.

NOTE: If the negative polarity voltage is brought on first (at less than 50kV) after a spark off, recycling of the magnetic field is not necessary.

Vacuum Pumps - are Turbo-molecular, 260 litres per second; one pump is used on each tank and no liquid nitrogen trap is used.

Insulators - Stand-off (electrode) - 99% alumina, with recessed corrugated sheds and mounted in such a way that there is no bending moment transferred to the insulator from its end fixing.

Insulators - lead-in. Normally run at a maximum of ±300kV with experience of failures when run above this voltage (using heated glass cathodes).

The connection of the cable to the socket is effected by a metal cap over the end of the cable, the adjoining volumes being filled with ordinary transformer oil. Cables between power supplies and lead-in connections are restricted in length to 25 feet.

Staff - It is normal practice at Brookhaven to have one operator for each beam line. At the present time they appear to have - 15 technicians responsible to 2 lead electricians who are in turn responsible to an engineer. Of these 15, 4 are mechanical, 2 are vacuum and 9 are electrical and they are used as follows:

There are 8 operators on shift (2 per shift) working on 3 DC beams and 1 RF beam simultaneously with the additional men as required taken from the men working on days. The day men include 3 working on electrical installation modification and maintenance, 2 vacuum technicians engaged on the same and a further 2 men working on the RF deflector development (over the last 2 years there has been a drop from 25 men to 15).

Note: After July 1 1971 there will only be four men on shift (1 per shift). This includes the operation of the RF separated beam as before.

These men cover all electrical installation back to the building supply and all leak testing. The main workshops are used for all machining, survey, rigging and all services are connected to the separator by other groups in water, air and the cross-field magnet power supplies.

ARGONNE NATIONAL LABORATORY

Number of separators operational - Nine, composed of one triple module (one 10' and two 20' separators), one double (two 20' separators) and four single modules (three 10' and one 15' separators). Also working to assemble for operation one 5' separator acquired from Princeton-Pennsylvania Accelerator.

Electrode materials used - Glass cathodes, some flat plate and others 'slumped' to give approximately a 4" radius to the electrode edges. Anodes in type 304 stainless steel.

Operational voltages - 550kV on 4", 3-5/16" and 3" gaps. 500kV on 2-5/16" gap.

Operation temperature - 105°C. No measurement or variable control is applied. Power load is the only parameter.

Electrode Gap currents permitted - 100 μamps.

Sparking rates - 1 per hour.

Conditioning Procedures - Assymetrical then symetrical, by stabilizing voltage at 50 to 75kV on one electrode and increasing the voltage on the other, limiting the current to 200 amps until a maximum of 175kV is reached. This is then repeated on the other electrode and finally the voltages raised together. The pressure is then raised to the 10^{-4} torr range and high pressure conditioning carried out for one to two hours.

Conditioning times - A new separator conditioned for the first time requires 7 to 10 days to establish a working voltage and satisfactory spark rate, 3 days to stabilize the temperature and vacuum and the remainder for increasing the voltage. An operational separator requires a period of 2 hours to restore the performance to an acceptable level. Again time is available during the accelerator cycle due to development or breakdown of other equipment and every opportunity is taken to make use of these changes.

Period of operation - 7 days.

Operating pressures - normally between 2 and 8 times 10^{-4} torr. The pressure is normally kept to the left hand side of the pressure curve.

'Bleed' Gas used - Nitrogen.

Magnetic fields - it is not found necessary to cycle the magnetic field to enable the electric field to be re-established.

Vacuum pumps - oil diffusion pumps, 10" diameter, one per tank with water cooled chevron baffles and a liquid nitrogen trap between the pump and separator tank.

Insulators - Stand-off (electrode) - use the standard Berkeley insulator which is 97% alumina with recessed corrugations and a screwed fitting on each end. These are being replaced by a larger insulator which has a different end fixing but again it is 97% alumina. There are at least 4 insulators supporting each electrode, there being 6 where 20' electrodes are fitted. Insulators appear to operate reliably to a maximum of 375kV.

Insulator - lead-in - operates at $\pm$ 300kV with an absolute maximum of $\pm$ 325 as above this level failure of the insulator has occurred. The connection between cable and socket is via a metal cap over the end of the cable. Surrounding volumes are filled with vacuum dried transformer oil.

Staff - Separator operation is covered by one of the four men on the operations shift team with five teams covering the shifts, plus two separator specialists working normal hours. These are responsible to a systems manager who in turn is responsible to a professional engineer. This engineer is also responsible for the over-all safety of the ZGS division.

The men of the shift team operate all three experimental areas (two proton and one meson). Each team consists of at least one electronic, one electrical and one mechanical technician.

All major repairs are passed on to the two specialists and miscellaneous members of the two shift teams working normal hours.

Installation is supervised by separator staff with rigging, surveying and services installation carried out by other staff. (All separators are presently filled with LN_2 from a piped-in house system from large tankers located outside the experimental buildings).

Assembly is carried out by the four separator specialists always available during normal hours, assisted by other staff as available from the experimental hall teams.

BERKELEY - LAWRENCE RADIATION LABORATORY

Number of separators operational - Three, all single tank, one 10' long, two 15' long. A further three are also available - one 15' and two 10'.

Electrode materials used - Glass cathodes with 'slumped' profile giving approximately a 4" radius to the electrode edge opposite stainless steel type 304 anodes.

Operational voltages - 590 to 610kV on 2" and 4" gaps.

Operational temperature - 105°C ± 10° with no measurement or control of the heaters other than power input.

Electrode Gap currents permitted - of the order of 100 μ Amps (200 μ Amps, including divider drain).

Sparking rate - ¼ per hour.

Conditioning procedures - Assymetric and then symetrical ageing. Stabilized voltage on one electrode at 50kV and then increasing voltage on the other, the current being stabilized to level quoted above. Repeated on the opposite electrode and then both aged together.

No high pressure ageing is carried out. Occasionally only symetrical conditioning is carried out.

After conditioning to 350kV to 380kV across the gap at low pressure during the day shift, the voltage is then dropped to 340kV during the afternoon and night shifts and left at low pressure overnight preparatory to operating at 600kV at high pressure in the morning.

When the possibility arises due to stoppages of the accelerator or breakdown of other beam line equipment the opportunity is taken to condition the separator in that beam line.

Conditioning times - With a new separator, after the temperature and vacuum has stabilized it is only necessary to low pressure condition

for 8 hours to reach a satisfactory level of spark rate at ± 300kV. With an operational separator a period of 2 to 4 hours for low pressure conditioning is normally used to recondition the separator.

Period of Operation - 7 days

Operating pressures - 8×10^{-4} torr to 1.2×10^{-3} with the pressure set for running on the extreme right of the pressure plateau.

'Bleed'Gas used - either Argon or 'dry' nitrogen are used.

Magnetic fields - The magnetic fields need to be recycled to enable the electric field to be re-established.

Vacuum pumps - oil diffusion pumps, 7" diameter with a pumping speed of 1500 litres/second using 1 on each separator tank. A liquid nitrogen cooled trap is fitted above the pump.

Insulators - Stand-off (electrode) - Material - alumina (97% or better) with recessed corrugations and a cavity in each end. Installation is by means of a screwed fitting vacuum brazed on to each end. There are a minimum of 4 supporting each electrode with 6 being used on the longer electrodes. No failures of any kind have been experienced.

Insulators - lead-in, these operate at a maximum of 300-310kV, despite this failures occur by tracking along the outside. Lead-ins are replaced 2 or 3 times a year. The connection between 600kV cable and socket is made without the use of a plug but by means of a metal cap fitting over the extreme end of the cable and held by clamping the outside circle of conductor forming the core. The socket is then filled with vacuum dried transformer oil (Shell Diala). Cables are not restricted for length and the normal seems to be approximately 50 feet.

Any machining required is carried out by central workshops with small items being covered by the separator technicians.

Electrical support is provided from a separate group and all design

effort is supplied by the design office.

Staff - Operationally one man covering 24 hours a day and weekends on an on-call basis; practical as calls outside normal hours are few. Dewar changes, needed every 12 hours, are carried out by the maintenance machinists on shift for other duties. All vacuum maintenance and routine maintenance of vacuum gauges and power supplies is carried out by the operations man who also assists when repair work is needed and also assists and supervises installation and repair of mechanical services.

Survey and rigging effort is supplied from another team as is the installation and removal of the power supplies and 600kV cables and all control cables.

Assembly of a new separator is carried out by a main workshop as are all major repairs - it is estimated 6 man/weeks (2 men for 3 weeks) are needed to strip, clean and reassemble a separator.

Design at the moment is static although a new lead-in insulator is envisaged estimated to require $1\frac{1}{4}$ men on design plus 10% of the time of a senior engineer.

RUTHERFORD LABORATORY

Number of separators operational - Six, one 33' long, three 23' and two single modules 13' long.

Electrode materials used - Glass cathodes and stainless steel type "Immaculate 5" anodes though we have one separator with all metal electrodes.

Operational Voltages ±375kV on 15 cm, ±300 on 8 cm and 10 cm and ±250 on 10 cm.

Operational temperature - $70^{\circ}C \pm 1^{\circ}$. The electrode temperature is set up to be as constant as possible along the length of the electrodes and referred against a thermistor mounted on the electrostatic shield. This is then used to control the temperature inside the tank compensating for ambient changes via a thyristor control circuit.

Electrode gap currents permitted - 40 μamps.

Sparking rates - 1 per hour.

Conditioning Procedures - The voltage is stabilized on one electrode at 50kV and progressively increased on the other within the limitation of gap current as above. The procedure is then repeated on the other electrode and then both are conditioned together again with the gap current limited to 40 μAmps. The pressure is increased to the 10^{-4} torr range and conditioning carried out at this pressure for a further period by 'sparking'. The voltage is then reduced to the operational level. As we have suffered stand-off insulator failure over ±300kV the voltage is limited to this level and, where this is also the operating voltage, the pressure is reduced (ie to the left hand side of the curve) until sparking occurs. This has the effect of broadening the pressure plateau.

Conditioning times - With a new separator a period of 14 days is needed to reach an operating level of ±250kV - including the time necessary to stabilize the vacuum and temperature. Where a separator

is in use a period of 2 to 4 hours is needed to recondition. The whole of this procedure is controlled by an automatic box which only requires to be set up at the commencement of the conditioning and adjustments made at intervals. This means high pressure ageing can be extended when time is available and measurements show this increases the 'operational life' of the separator between reconditioning. When the separator is not required during operational periods the opportunity is taken to condition, in this way beaming time is not lost due to the need to recondition separators.

Period of operation - 17 days (3 week accelerator cycle, less time for maintenance and development).

Operating pressures - 3×10^{-4} to 1×10^{-3} torr.

'Bleed' gas used - 'dry' nitrogen.

Magnetic fields - need to be recycled to re-establish the electric fields after a spark has occurred.

Vacuum pumps - Turbo-molecular, 500 litres per second normally two per separator. In addition a nitrogen trip is used inside the separator, this greatly reduces pressure recovery times particularly during low pressure conditioning.

Insulators - Stand-off (electrode) - 50% alumina with felspatic porcelain with a flange at each end for clamping, two insulators being used to support each electrode.

Insulators - lead-in. Made of HT porcelain with recessed corrugations. No failures have occurred under normal operation. The connection between cable and socket is by means of a mineral filled epoxy resin plug, the volumes between being filled with a heavy oil (Cantona 170). This oil is vacuum dried and heated during filling of the socket, the oil being circulated for 24 hours in this state.

Recording - A six-channel recorder is included as part of the control rack, this records continuously the voltage and current on each

electrode, the pressure inside the tank and above the vacuum pump and, in addition, an event marker records each spark. This enables any gradual rise in current or drift in pressure to be seen before trouble arises and means a close watch can be kept by a technician despite his visiting the separator only once each shift.

Staff - There is a separator operations team with 2 men on days and 5 men on shift, these men also operate liquid hydrogen targets, beam line vacuum equipment, hazardous gas equipment and provide a service on polarised targets, and cover general safety of these experimental halls. One of the technicians on days also supervises the assembly of and major repairs to separators in a separate workshop. This workshop also provides support for development of separators and research into electrical breakdown in vacuum; the normal complement is 2 craftsmen these are increased in number when the work demands it.

The operations team install, commission, operate and maintain separators in beam lines calling on the services of specialist teams as required. Rigging support and surveying is provided to them, as are all mechanical services, to a point adjacent to the separator. They then complete the installation, connect to the beam pipe system and install the vacuum pumps. All vacuum leak detection and routine maintenance is carried out by a central vacuum section, they also calibrate and maintain the vacuum measurement equipment.

The electrical installation of both the EHT cables, control cables and power supplies is carried out by an electrical technician and supporting craftsmen, but the filling and circulation of the insulating oil in the lead-in plug and socket assembly is covered by the separator team.

Liquid nitrogen is delivered to each separator by a general service and is connected and removed from the separator by the operations team.

CERN - MEYRIN

Number of separators operational - Four, two 10 metres long and two 2 metres.

Electrode materials used - Anodized aluminium cathode opposite a stainless steel anode of type 304 stainless steel.

Operational voltages - These vary from 700kV across 11 cm in a 10 metre separator through 750kV across 11.5 cm to 700kV across 7 cms in a 2 metre separator and 800kV across 8 cms in another 2 metre separator.

Operational temperature - Ambient as the anodized alumina cathodes do not require heating.

Electrode gap current permitted - A maximum of 40 μAmps and this is reduced further to 30 μAmps for the shorter separators.

Sparking rate - varies from one spark every 2 hours to a few per hour (only for the 6M sep.). With the short separators, particularly those in restricted places, a maximum of 1 per hour is allowed before reconditioning.

Conditioning Procedures - The state of the separator is first assessed by applying voltage to either plate in turn; depending upon the result of this test, symetrical or assymetrical ageing is then carried out automatically by means of an electronic box which regulates the current while increasing the voltage. The current may be set to a pre-determined level at the onset and the voltage increased within this current limitation. A continuous record of both the negative and the positive voltages is kept or one polarity and the separator pressure. High pressure conditioning is only carried out during the early conditioning periods.

Conditioning times - The conditioning time for a newly built separator is a matter of two or three weeks, during this time both low and high pressure conditioning is carried out as needed to enable the voltage

to be increased. With an operational separator to reach a level of 100kV/cm while limiting the internal current to 30 μAmps a period of 10 to 25 hours is needed depending on the condition of the separator.

Period of Operation - The accelerator operates on a 3 week cycle and during this period no conditioning is necessary and experience has shown this period can be extended.

Operating pressures - These vary slightly with the different separators, giving a pressure plateau with the 2 metre from 2×10^{-3} torr to 1×10^{-3} torr at 700kV (on a 7 centimetre gap) through 2×10^{-4} to 7×10^{-4} torr with 500kV in the 6 metre to 3 to 5×10^{-4} torr in the 10 metre.

The deterioration rate of the separator is measured by quoting the rate of reduction of the width of the pressure plateau against time (ie 5×10^{-5} torr/100hrs) to enable a comparison to be made of the different separators.

No crossed magnetic fields along the length of the separator tanks are used, the correction being applied by a bending magnet at each end of the separator. In the future crossed fields will be used with the 1 metre separator.

Vacuum Pumps - Both oil diffusion and turbo-molecular pumps are used, the oil diffusion being Gallilao with a pumping speed of 300 litres/sec used with the 6 and 10 metre separators, there being a liquid nitrogen trap placed between the separator tank and the vacuum pump. Two pumps are filled to each 10 metre separator and one to the 6M.

The turbo-molecular pumps are fitted to the 2 metre separators and have a pumping speed of 140 litres per second, one pump is fitted to each separator and no liquid nitrogen trap.

Insulators - With the 97% alumina insulators now filled there have been no electrode stand-off insulator failures. These have a screwed fitting fitted to each end by a potting method using pure tin. These

operate at a voltage of 450kV. Above this level failures have occurred with a lead-in insulator and H.T cable although one electrode has been run at levels of 450kV with the 2 metre separator and 500kV with the 6 and 10 metre separators. The connection of the cable is by means of a plug and socket as in the case of the Rutherford Laboratory, the oil is heated to dry it prior to charging the socket, the socket being pumped prior to and during the filling process to ensure no bubbles remain in the insulating oil.

Future Programme - During the next year, the number of separators in operation will increase, beginning with one 6M early in 1971 (12 cm at 660kV) followed by a further 2M in July (720kV across 6 cm) and then a further 2 (one 6M and one 10M), leaving a final total of 8 operational separators.

Staff - The operation is controlled by 1 engineer who is also responsible for power supplies and cooling water for beam transport elements and the maintenance of magnets. To assist him he has a technical assistant with an electrical training and 2 technicians, one electrical and one vacuum trained. These in turn are supported by 2 electro-mechanical craftsmen.

When a separator is being installed, rigging and surveying assistance is supplied as is the connection of all mechanical services. Leak detection is carried out and vacuum equipment installed and maintained by the separator team who also supervise the installation of all adjacent beam pipes, collimators, cut-offs etc.

All electrical installation of both H.T cables, control cables and normal power supplies is done by the separator team (they also provide a service to the main machine installing and maintaining 25 power supplies and their associated control and operating racks and also to the separator development section for these power supplies).

During silent hours support is provided by a team of floor operators, these can deal with the minor problems and call in the separator specialists when they cannot deal with the trouble.

Liquid nitrogen is supplied to the working areas by a general site service with 2 dewars adjacent to each separator. These are connected to the separator and removed by the separator team or floor operators.

The building of new separators and initial conditioning is carried out by a separate group, however, assistance is provided as necessary by members of the separator team.

GENERAL OBSERVATIONS ARISING FROM THE SURVEY

The main area of difference appears to be in allowable currents during both high and low pressure conditioning. Both CERN and RHEL limit the electrode current to 30 μAmps and 40 μAmps respectively while in the American laboratories it varies between 100 and 200 μAmps. In America all conditioning is done manually, so this current may be exceeded quite easily during the process of raising the voltage as small differences, while increasing the voltage, can give rise to large increases in current. Both at CERN and the RHEL conditioning is done under automatic control, the voltage being raised within pre-set current limits.

Experience has shown us that these larger currents can cause damage to insulators. In our case it has always been with the electrode stand-off insulators. At CERN in the early days trouble was experienced with stand-off insulators but since changing the material to 97% alumina no further trouble has been experienced. High voltage lead-in insulators have been run at voltages up to 450kV, above this level failures have occurred. No stand-off insulator failures have ever been experienced in the States, they have always used a 97% alumina insulator developed at Berkeley.

From this record it would appear alumina insulators will stand considerable sparking without damage and are completely reliable in operation, whereas the 50% alumina insulators in use at the Rutherford Laboratory are operating at their limit. The other benefit with the use of alumina is the greater allowable temperature tolerance, which is in use at Berkeley up to 105°C, while temperatures of 80°C and above can lead to failure with the 50% alumina insulator.

There is also one common design feature with all the alumina insulators they possess an internal cavity with a hemi-spherical shape at each end. In use this cavity will cause the electric field at the triple junction of vacuum-insulator and electrode to be lowered, thus protecting this most vulnerable point.

High voltage lead-in insulators, those in use at all the laboratories visited in the States, have failed repeatedly at voltages between 300 and 350kV. Both at the Rutherford Laboratory and CERN these insulators appear to be satisfactory up to 450kV and at the Rutherford Laboratory no failures have occurred in service under normal conditions.

How much of this is due to the design and socket connection and how much to restriction of allowable electrode currents is difficult to establish. However, on the separators used for development work, where the electrode currents are not so tightly controlled, signs of incipient damage have been seen at voltages in excess of 350kV. Arising from this, recent development has produced a H.V lead-in that has been tested satisfactorily at 500kV.

Turbo-molecular vacuum pumps are being used to replace oil diffusion pumps by the majority as and when the occasion makes that possible. General agreement was reached that the cleaner vacuum conditions achieved led to an increase in separator performance and at CERN and Brookhaven have led them to dispense with their nitrogen cold traps. At the Rutherford Laboratory the cold trap has been dispensed with where it does not significantly effect the performance and life of the separator. (The cold trap used at the Rutherford Laboratory is much more effective in use than those elsewhere, as it is inside the body of the separator and not outside the tank above the vacuum pump). The use of the turbo-molecular pump has also led to an increase in the operational life of a separator (in between conditionings) and this can be significant, where the accelerator runs are longer, as in the past this has necessitated conditioning during operational beaming time.

ACKNOWLEDGEMENTS

I wish to acknowledge the assistance and enthusiasm of the staffs involved at the various laboratories, particularly R Loper at Brookhaven, D Roman at Argonne, R Force at Berkeley and L Danbey at CERN for their help in compiling this survey. The help and support of Dr W A Smith of the Rutherford Laboratory has also been invaluable.