DESIGN CRITERIA FOR HIGH VOLTAGE, HIGH CURRENT ACCELERATING COLUMNS

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Summary

A continuing development program has increased the reliability of two 100% duty factor single-stage accelerating columns at the Chalk River Nuclear Laboratories. Experiments on the two columns have included studies in gap voltage, accelerating gradient, extraction geometry, electrode materials and shape, column bleed current, insulator design, and the effect of backstreaming electrons. A set of design criteria for accelerating columns, based on these experiments, has been formulated. While the reliability of the existing single-stage columns has been improved, the criteria can best be satisfied by a two-stage accelerating system with ion species separation and beam shaping between a low voltage ion source and the main accelerating column.

Introduction

The Chalk River Nuclear Laboratory is investigating high-voltage, high-current accelerator technology to establish the feasibility of converting fertile materials to fissile nuclear fuel in an accelerator-based breeder.[1] Requirements are for a 1-GeV, 300-mA, 100% duty factor proton beam with very high reliability,[2] but existing dc injector technology is as yet inadequate for this application.

Two accelerators have been available at the Chalk River Nuclear Laboratories for injector technology studies. One is the 750-keV, 100-mA dc, H^+ injector for the High Current Test Facility (HCTF).[3] The injector has operated at up to 50-mA total beam, with beam-induced high-voltage breakdowns being the predominant problem. The other accelerator is the 300-keV, 25-mA dc, D^+ accelerator for a 4 x 10^{12} n/s Fast Intense Neutron Source (FINS).[4] It has operated at 40-mA total hydrogen beam and 30-mA total deuteron beam, again with beam-induced high voltage breakdown problems. Some initial experiments on these machines have been previously described.[5,6]

Experiments aimed at improving the reliability of the two dc accelerators have led to a set of design criteria which could be used for accelerator breeder, neutron generator, and fusion research applications.

The Problem

An accelerating column will typically voltage-condition readily with no beam present, but will spark down when ion beams are being accelerated. Its performance can be improved by gradually increasing the accelerator current, i.e. the column will "current-condition". Interruptions in beam production are short but they may be intolerable to the overall facility.

Figure 1 schematically shows the number of runs observed as a function of the duration of each run for two kinds of problem: inter-electrode sparks and microdischarges, which give an exponential distribution, and surface breakdowns on the ceramics, which give a peaked distribution. Generally the effects are superimposed, although usually the HCTF results follow an exponential-like pattern, while FINS follows the peaked function or distribution. The average time in a series of runs decreases with higher current, accelerating voltage, and externally measured radiation.

Observations

Figures 2 and 3 show the latest, most successful versions of the HCTF and FINS columns. Some experiments and observations on these columns are now discussed.

It was found that electron beams of 10-50 μA, accelerated from a filament at the ground end of the FINS column with the ion source removed, gave the same external radiation level and produced the same breakdown rate as did typical ion beams.[5] The energetic electrons produce bremsstrahlung inside the column. The experimental configuration was varied and the breakdown effect was shown to be related primarily to the ceramic. It is postulated that electrons created on the ceramic surface by bremsstrahlung via the photo-electric effect charge the surface and provoke breakdowns. Ultraviolet light from the ion source or beam plasmas could do the same thing. Operation of a FINS column whose electrodes were 1.5-mm thick stainless steel was greatly improved by addition of 6-mm thick copper plates positioned to shield the ceramics from x-rays generated at the ion source. Operation was further improved with 12-mm thick copper electrodes.

The HCTF ceramics, and early versions of the FINS ceramics, are right circular cylinders with a notch at the ceramic-metal-vacuum interface (see Fig. 2). The HCTF ceramics have suffered only a few damaging tracks on the vacuum side. However, two early versions of the FINS column suffered extensive track damage whether or not the ceramic-metal-vacuum interface was shielded by electrodes. Convolutions on the inner surfaces of two later FINS columns (see Fig. 3 for geometry) have prevented any track damage from occurring, possibly because the bands of high and low electric field on the ceramic surface created by the convolutions tend to stabilize surface charges. The presence of ceramic in a complicated electrode configuration can greatly influence the equipotential distribution; the convolutions can be used to reduce electric fields on the adjacent electrodes. Electrostatic analysis of the latest FINS column (Fig. 3) using an electron gun code from SLAC[7] (neglecting surface charge) shows the convoluted ceramic shape to be close to optimum.

All the FINS and HCTF columns have used ≥ 95% Al_2O_3 ceramic insulators bonded with either polyvinyl acetate or Torr-Seal epoxy (from Varian Associates). One FINS column glazed on both inner and outer surfaces has been operated. In all the columns, radiation damage has yellowed the ceramic material in places where x-ray bombardment is high. The color fades slowly (over months) if the ceramic is not in use or if it is heated. No difference in operation can be attributed to the insulator materials; however, the glaze makes cleaning the column much easier and prevents the adherence of metal if the column is rubbed accidentally.

The ceramic-to-metal vacuum interface in a column can emit electrons which start breakdowns. Dependence of column reliability on bond properties can be greatly reduced through use of metal electrodes to reduce electric fields in the bond region. This approach has worked well on FINS, with the convolutions on the ceramics assisting in the field shaping.

Given restraints such as available ceramic sizes and choice of accelerating gradient, the electrodes must be designed to minimize surface electric fields - particularly on the cathode surfaces. A useful guideline is the Kilpatrick criterion for vacuum sparking.[8] For ease of use in dc applications, substitution of $E = \alpha V$ eliminates the peak cathode surface electric field E. This leaves a universal equation relating the Kilpatrick sparking threshold voltage V to the voltage-independent, geometry-dependent parameter α. In practice, α is found analytically (for simple geometries) or by using the modified SLAC electron gun code[7] to solve for surface fields for given applied voltage. Then, the sparking threshold voltage is found from the universal curve of V vs α. At present, the FINS and HCTF columns operate with surface fields less than or equal to the Kilpatrick limit on anode surfaces and 0.7 times the limit on cathode surfaces. These columns voltage-condition readily without beam and operate better than columns with lower safety factors.

While long acknowledged as being an excellent material for high voltage electrodes, titanium (or Ti6Al4V alloy) appears to be unsuitable in the hydrogen atmosphere of a proton accelerator. Here, titanium hydride forms on electrode surfaces, leading to outgassing during beam spills and formation of titanium hydride microparticles that possibly loosen and cause voltage breakdown. Materials tests done on smaller experimental setups at CRNL showed molybdenum, stainless steel and copper to be superior with either ion beams or electron beams (equivalent to typical backstreaming electron currents in proton accelerators) present. Molybdenum is preferred because it has good thermal conductivity and does not sputter. The most recent HCTF column uses mainly stainless steel and TZM molybdenum alloy. FINS has operated well with copper electrodes provided that no abrasives were used in fabrication. (Abrasive-treated copper exhibits many microdischarges in the presence of ion beams.) This restriction on abrasives probably also applies, to a lesser degree, to the harder electrode materials.

Voltage and gradient effects have been studied. On the HCTF, a change from a column gradient of 3.1 MV/m (with Pierce geometry over the first 200 kV) to a uniform column gradient of 2.1 MV/m over 750 kV gave a modest improvement in reliability. Also, with fixed 50 kV per ceramic, a change from 100 kV to 200 kV between adjacent accelerating electrodes gave slightly improved reliability. Originally, FINS used a single 300 kV, 2.7 MV/m gap. A single 1.8 MV/m gap operated no better. It now has three 100 kV gaps and an average gradient of 2.5 MV/m.

Column bleed currents of 0.25, 0.5 and 2.25 mA gave the same reliability in the HCTF. A bleed current of 800 μA instead of 250 μA made the FINS column more tolerant of column problems, such as electrode microdischarges, but did not significantly improve reliability. Apparently, electrons and gases produced by beam spills cause breakdowns before electrode potentials are significantly perturbed.

The bad effects of beam spill on column reliability imply that knowledge and control of ion optics in a column must be good. However, computer codes now used for beam optics analysis have trouble modelling halo on beams from non-uniform plasma surfaces. Work on this problem continues at CRNL. In the meantime, beam optics in FINS is controlled by a passive shaped-focus plate replacing the original biased, Pierce extraction electrode. The HCTF column has a Pierce extractor for beam focusing, followed by a uniform gradient column.

Design Criteria

A set of design criteria for accelerating columns formulated from the foregoing experimental results is outlined in Table I.

Discussion

Figures 2 and 3 show the present configurations of the HCTF and FINS columns. The criteria of Table 1 have been incorporated into the HCTF as far as possible, subject to existing mechanical and operational constraints. The FINS column was subject to fewer constraints, and follows the criteria more closely.

The column criteria above can best be satisfied by a two-stage system in which the ion beam is first extracted from the ion source, focused, magnetically analyzed, and stripped of high emittance components and then in the second stage accelerated to the required total energy. The RTNS accelerators at Livermore,[9] and a recent FMIT injector proposal[10] (400 kV version) use two-stage designs.

Table I

Desirable Features of High Current, High Voltage Accelerating Columns

Feature	Remarks
A. Good Electrode Design	
- use accelerating gradient of $\lesssim$ 2.5 MV/m	
- choice of voltage per gap should be $\sim$ 100 to 200 kV, subject to ease of satisfying the remaining electrode design requirements	- this gives a column diameter to electrode gap ratio convenient for incorporating the required shielding from x-rays and allows convenient shielding of ceramic-to-metal joints
- use massive electrodes	- shields ceramic from x-rays and reduces ceramic charging
- minimize surface fields on electrodes using electrostatic analysis and a sparking criterion	- reduces sparks and microdischarges
- hide the ceramics from direct or reflected ultraviolet light from the ion source or beam plasmas	- reduces ceramic charging
- water-cool or heat-sink all electrodes	- reduces outgassing and effects of beam spill
- use electrodes to hide the ceramic-to-metal bond	- reduces electric fields where electrons may be produced
- select electrode material and finish to suit application (molybdenum seems best; <u>no abrasive should be used</u>)	- aids voltage stand-off with or without beam
B. Good Ceramic Design	
- use convoluted ceramics, designed using electrostatic analysis	- prevents track damage, stabilizes charge distributions, reduces fields on adjacent electrodes
- standard materials and bonding agents are suitable	
C. Minimize Electron Backstreaming and x-rays	
- effective electron trap required	- prevents downstream space-charge electrons from entering column
- use a very stiff electron trap power supply, or do not have trap electrode as one side of a high voltage gap	- reduces chance of losing electron trap during high voltage transients
- locate the first restrictive beam aperture downstream from electron trap	- avoids production of secondary electrons in the column
- reduce beam spill by making column bore as large as possible	- reduces column voltage perturbations, secondary electron production, and electrode heating and outgassing (but may harden bremsstrahlung spectrum)
- pump gas as efficiently as possible (use pumping slots and large bore)	- reduces electron and ultraviolet light production from ion-molecule collisions
D. Other Considerations	
- magnitude of bleed current not critical	- any beam spill creates electrons which cause breakdowns before voltages are significantly perturbed
- examine beam spill in the column over entire operating range (by computer analysis if possible)	- may show problems from space charge, mixed ion beam, high emittance components, or change of focusing with beam current
- avoid PIG discharge regions, and avoid crossed E and B fields	- prevents stable electron orbits
- minimize the area of electrodes at high voltage, put highest electric fields on-axis	- reduces sparking probability

The advantages of a two-stage system are many. Coupling between the ion source and main column is reduced, so that operation of one is not compromised by operation of the other. The gas loads can be differentially pumped to remove source gas and optimize space-charge neutralization in beam drift regions, yet allow very high vacuum (hence low electron production) in the main acceleration column. The system can be selectively opened to air without venting the whole system and losing high voltage and current conditioning of the remaining components. Backstreaming electrons passing through the main column can be intercepted by a low-Z shielded dump. Electrical power is saved by dumping the unwanted portions of the beam at low voltage. Beam spill in the main column is much reduced by the prior removal of unwanted ion species and high emittance components.

Conclusions

The design criteria described in this paper are the result of extensive experimental work on two accelerating columns with very different operating conditions. Application of the criteria has markedly improved operation of the columns.

Two-stage accelerators appear to have the best configuration for production of high voltage ion beams, but design criteria such as those presented here must be carefully applied to realize the potential of two-stage accelerators for reliable operation.

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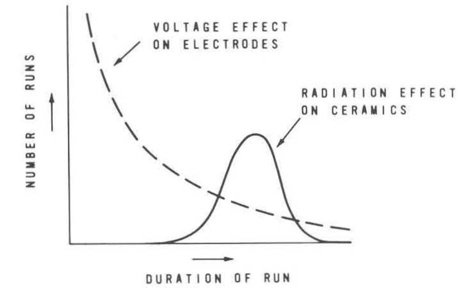

Fig. 1 Distribution of the number of runs as a function of the duration of each run.

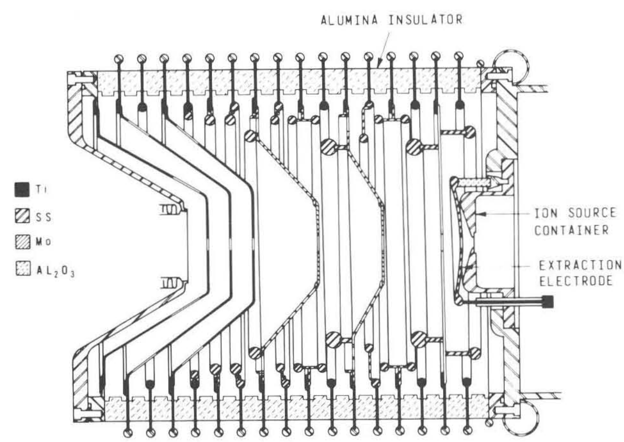

Fig. 2 Cross-sectional view of the HCTF injector column.

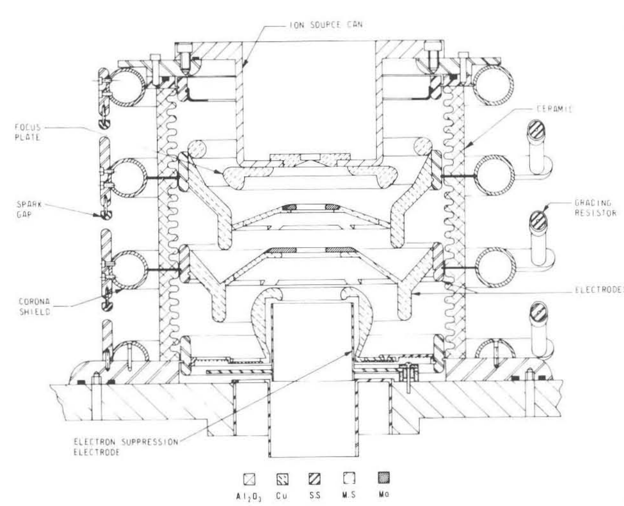

Fig. 3 Cross-sectional view of the FINS accelerating column.

Discussion

West, RHEL: To avoid breakdown problems, should we perhaps move towards lower gradients and incorporate permanent magnet quadrupoles inside the column accelerating structure?

Hepburn: I have seen designs which did that. They essentially had meters for acceleration with solenoids or whatever; it is a different approach. But with 300 milliamps and 1% duty factor, space charge is an enormous problem. Then, you try to get the ions going, you obviously accelerate them as quickly as possible.

West: Well, my point is that we've seen that permanent magnet quadrupoles are a reality and they are there to match to a particular beam space charge defocusing.

Hepburn: I do not know what they will do to the electrical design of the column if they are insulating or conducting. If they are conducting, it means that you cannot have thin electrodes - you have to have an electrode long enough to incorporate each magnet, which is a radical departure, that I would be interested to try.

Curtis, FNAL: Do I understand properly, that you have included all your design criteria in the last column figure which you showed? Have you attempted to put up to 100 mA through this column?

Hepburn: The answer to the first question is, not quite. We have no cooling on the electrodes, and I would prefer to be able to machine them out of molybdenum instead of copper. As for the improvement we have been able to make on FINS, the first column operated - it was very similar to a short section of say the high current test facility column, or Los Alamos' column. That operated for a few milliamps for a few minutes between spark downs. We've got that up to 40 milliamps for half an hour or an hour.

Curtis: You have not reached your 100 milliamp goal yet?

Hepburn: I'm sorry - you are confusing the two machines.

Curtis: Right, but have you tried for a higher current in that particular column?

Hepburn: No, I'm limited by target problems at the moment.

Curtis: Right.

Grand, BNL: I wonder if it would be relevant right now to ask anyone in the audience if they have any present knowledge of the status of John Osher's column, which is relevant to this talk?

Clark, LBL: Yes, it is a medium gradient column, with large aperture. He has had trouble with backstreaming from the gas - ionization of the column gas, but I don't know any other current information.

Unidentified voice in audience: They have increased the pumping in the dome substantially - theirs is a two stage system, and they have increased the pumping substantially and done much better. I think - this is a vague memory - about the order of 100 milliamps 100 kilovolts.

Grand: And what gradients do they have in the column?

Same unidentified voice in audience: That I don't know, but I do know they are seeing one thing we've seen on all our columns: a yellowing of the ceramic, which I assume is radiation damage. They are getting that and they are also getting the peak type of run distribution, where the run durations cluster around a mean value. I would recommend going to look at the ceramics and the shielding in the column for that one.

Bentley, NEN: What was the time scale on that graph of peaking of the runs?

Hepburn: On the first FINS column it was a few minutes average and on later ones it has gone up to an hour or two hours, so it is a function of how good your column design is.

Bentley: There was a paper on Osher's column at the Particle Accelerator Conference in San Francisco. They had increased pumping on the upstream end of the column and put in a trap at the high voltage end of the column to protect against slow ions going into the column, and I think everything was operating fine as of that point.

Hepburn: Again, beam spill. On the question of reliability: The 750 kv set has operated up to 50 milliamps with runs up to an hour. The problem there seems to be the arc transient during turn-on. It means the extractor is not matched during the first current pulse - that is, difficulty in turning on, not really reliability.