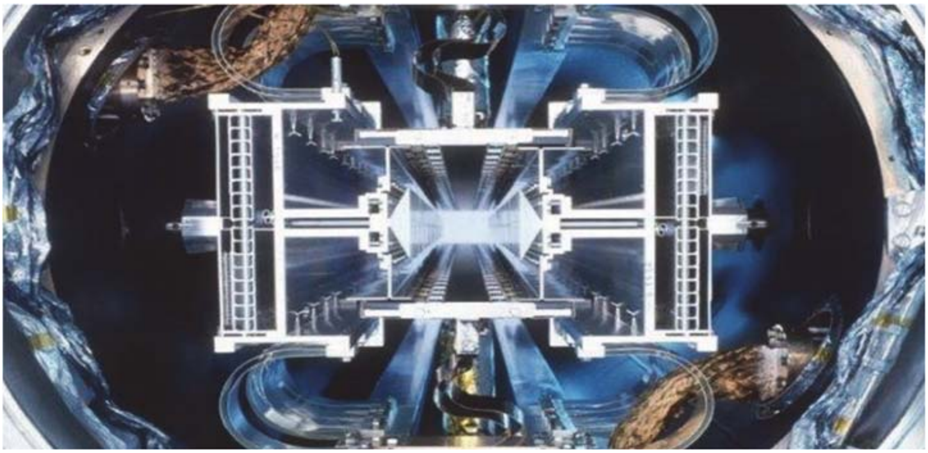

Fig. 6.6. Plunging PU in the AC, seen along the beam. The outer diameter of the vessel is 0.5 m.

The AC also required the development of 100 W *power amplifiers* for the bands 1–1.6, 1.6–2.4 and 2.4–3 GHz. These compact amplifiers were based on four power Field Effect Transistors (FET) per module and four modules per amplifier. Signal input splitting and output combination was performed with four-way elements absorbing electrical mismatches. This design was superior to the competing commercially available traveling wave tubes for several reasons: no high voltages, no cathode heating, better linearity, small phase change with amplitude and better life time [20]. The manufacture of the large series was entrusted to industry after a successful transfer of know-how.

## 6.3 Radio Frequency Quadrupole: Slowing Down Antimatter

Werner Pirkl

Many fundamental studies with antiprotons require extremely slow antiprotons, with velocities far below the kinetic energy of 5.31 MeV of the antiproton beam, extracted from the AD synchrotron [Highlight 6.7]. To this end a novel "Decelerator" was developed, a variant of the Radio Frequency Quadrupole (RFQ), which decelerated the antiprotons to 55 keV, followed by an integrated superimposed electrostatic energy correction to adjust the output energy between ~10 keV and 120 keV [21].

The RFQ is essentially a modified electric quadrupole consisting of two electrode pairs of opposite polarity, positioned at the diagonals of a square with the beam at the centre. This provides transverse focusing in one plane but causes defocusing at the orthogonal plane. Nevertheless, overall focusing can be achieved by alternating static focusing and defocusing along the beam line. Alternation *in space* can be replaced by alternation *in time*. Feeding longitudinally continuous electrode pairs with properly chosen Radio Frequency (RF) provides also overall focusing due to the changes in polarity, as W. Paul, Nobel laureate 1989, had earlier demonstrated with linear "traps".

The decisive ingredient towards the RFQ was added in the seventies by "modulating" the radial distance of the electrode tips by opposite peaks and valleys in longitudinal direction [22]. This adds a longitudinal component to the transverse field pattern. Hence, the RFQ combines transverse focusing with longitudinal acceleration in a very compact geometry. It is therefore ideally suited for pre-accelerators up to the MeV range and supplanted quickly the traditional accelerator front-ends with their huge high-voltage Faraday cages.

The suitability of the RFQ for beam *de*celeration (RFQD) was quickly recognized [23, 24]. The basic electrode structure is the same as for the RFQ. A top view of four modulated electrodes is given in Fig. 6.7. Half of two electrodes is cut away for clarity. The distance between two electrode peaks, called a double cell, has to correspond to the time the particles travel during one RF cycle, being 4.94 ns in the case of the RFQD, determined by the operating frequency of 202.56 MHz.

As the velocity of the particles decreases gradually along the RFQD that distance decreases in proportion, here by a factor of about nine, from 157 mm at the input to 17.5 mm at the output. Contrary to accelerating RFQs it is no longer possible to use 30 to 50 double cells for "soft" beam capture and shaping as those are now on the high energy side, where their much longer cell length would lead to prohibitive overall length. Instead, bunching of the beam in a single step outside and upstream of the RFQD has to be used with less than perfect efficiency. Only about half of the beam falls in the acceptance of the RFQD.

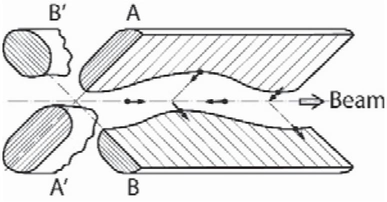

Fig. 6.7. The modulated electrodes of an RFQ; arrows show the electric field at a given moment.

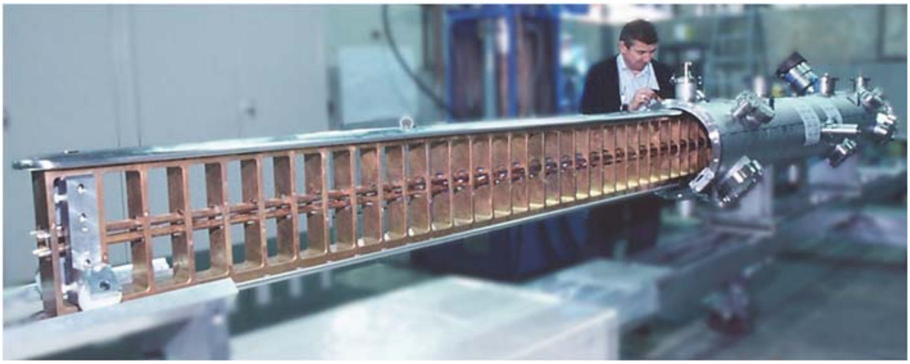

Fig. 6.8. The RFQD tank with the inner structure extracted for inspection.

The inner structure of the RFQD forms a “ladder” of length 3.4 m (Fig. 6.8). Continuous rails on top and bottom are connected by 35 rungs with the electrodes along the axis. The electrode pair A–A′ is connected to even-numbered rungs, pair B–B′ to the odd-numbered. All ladder parts are made of copper. The resulting 34 double-periodic cells are individually tuned to the operating frequency of 202.56 MHz. An RF amplifier chain (not shown) delivers the necessary RF power of more than 2 MW in 400 ns pulses at a repetition period around 300 s.

Figure 6.9 shows a cut through the RFQD in front of an even-numbered rung. Electrode pair A–A′ is firmly connected whereas pair B–B′ runs through an opening in the rung, at a distance of 10 mm to hold the RF operating voltage of 167 kV peak.

The ladder has to be mounted electrically “floating”. It is held in place by two high-voltage (HV) insulators on the top and three on the bottom, where the central one acts also as a HV feedthrough for the energy-correcting voltage of +/− 65 kV DC, see Fig. 6.9. Curved HV shields on the vertical faces, made of stainless steel, prevent discharges. The inner face of the tank with 380 mm inner diameter is copper plated to reduce the RF losses.

Initial deceleration tests were carried out with a proton beam at the University of Aarhus, Denmark [25]. Current operation at CERN yields about one million decelerated antiprotons per shot. Compared to passive deceleration by degrader foils it provides a one to two orders of magnitude higher transmission together with improved beam quality which is close to the theoretical maximum for non-cooled deceleration.