THE APPLICATION OF RFQs

A. Schempp Institut für Angewandte Physik Johann
Wolfgang Goethe-Universität, D-6000 Frankfurt am Main 11, Germany

Abstract

The Radio Frequency Quadrupole Accelerator (RFQ) has found wide application, not only as the preinjector linac for new high energy light ion accelerators but also in a variety of other projects. The progress in development has made ion linacs practical for medical and industrial applications including radiation therapy, isotope and neutron production, material modification and ion beam diagnostic. The paper discusses various projects together with applications in science where RFQs serve as stand alone tools like for the calibration of detectors, as decelerators or as small compact beam source for atomic physics and material research.

Introduction

Accelerators have been developed as instruments for basic research for nuclear and praticle physics. Accelerated particles were needed e.g. to cross the Coulomb barrier to study the internal structure of the nuclei. With sufficient resolution such processes cannot be studied with natural sources. In the same way accelerator applications in other fields make use of these unique probes together with the technologies involved in generating and detecting particles and reactions.

Static machines and cyclotrons were dominating the field followed by linacs and synchrotrons for higher energies and currents. The same time shift between research and applications happened in application of accelerators.

RFQs as relatively new machines have a similar phase shift between invention, prototyping, proof of principle, uses in nuclear and high energy physics machines, and applications in other fields of science.

Radio Frequency Quadrupoles (RFQ) are low energy ion accelerator structures which can efficiently transport and accelerate high current ion beams[1,2]. Acceleration is achieved by a geometrical modulation of quadrupole electrodes leading to axial components of the field. These electrodes are part of a rf resonator, excited in a TE_{210}- like mode to generate the necessary field distribution. The mechanical modulation of the RFQ-quadrupole electrodes adds an accelerating field component to the focusing channel, resulting in a structure which accelerates and focuses with the same rf fields.

Electrical focusing forces are independent of the ion velocity v_p and if rf-fields are applied, higher voltages than in a dc quadrupole system can be reached, giving a very strong focusing with a large radial acceptance. Because the focusing structure is homogeneous the accelerating and focusing cells can be very short, which makes it possible to apply the concept of adiabatic bunching [1] for converting a dc beam from an ion source into a bunched beam with a minimum of emittance growth and particle losses.

The mechanical shape of the electrodes is characterized by the aperture radii a_i, the modulations m_i, and the modulation periods L_i, as shown in fig. 1. Together with the electrode voltage U_Q it determines the acceleration and focusing fields. Therefore a voltage as high as possible (close to the breakdown voltage) and an aperture as small as possible will be chosen for a high focusing strength G U_Q/a^2 and a high ion current capability. For the same focusing strength the voltage U_Q proportional to the ratio of ion mass A to charge q: $U_Q A/q$.

The rf power N required to provide the quadrupole voltage U_Q on the electrodes is proportional to the length L_s of the structure and depends on the type and parameters of the structure and the operating frequency f. N is roughly proportional to $f^{1.5}$ while the cavity length L_S will be inversely proportional to the frequency [3], so in general the peak cavity power is the same for all frequencies and the frequency may be determined by the availability of cheap and reliable power sources.

The various applications of RFQ accelerators can be distinguished by the ion beam and rf structure properties and by the specific application which will lead to different optimizations of RFQs. The following paper describes some applications, which illustrate the progress which has been made in the last years.

× supported by the BMFT and GSI

Research applications

The RFQ dynamics and cavity design is based on the development of RFQ injectors for high energy synchrotron injector-linacs, to improve their performance both in energy and beam current. The CERN RFQ II and the ISTRA-10 linac at ITEP deliver proton beams up to 240mA with a low repetition rate [4,5]. H^--beams with up to 120mA are accelerated in the various LANL RFQs which were specially optimized for high brillance[6], while for the injection into synchrotrons beams of 50mA (BNL) and 20 mA (DESY) are used. The injectors for the JHP project at KEK [7], and for a 7 MeV proton linac at ICR [8] have higher duty factors (2%) while the only CW RFQ is the Chalk River Prototyp RFQ1 with 70 mA proton beam [9].

An important line of development is based on the technology of these injectors namely the the generation of high brilliant beams with small emittance and high peak and average beam currents. The LANL work on ATS, GTA and BEAR [6,10] has lead to important results concerning the design codes, (beam losses, emittance growth) and the technology of RFQs and other low energy linacs.

The RFQ for SSC and the CWDD are obvious descendants. The SSC RFQ (fig.1) is a low duty factor structure for 25mA H^- for which special care has been taken by including the higher order field components into the design resulting in a reduction of emittance growth [11].

The CWDD RFQ (fig.2) is a cryogenic cooled structure operating at 350MHz designed for 100% duty factor [12]. The power saving by the cryogenic operation (a factor 4 for 35K) reduces the power density in this RFQ to technically managable values. Economical operation is not the main goal of this structure which has been built by Grumman for experiments set up at ANL. So even this work might not be directly applicable in another environment, because the technology is difficult and expensive, the results are pushing forward high power ion beam technology.

Future applications, which will make use of this work are the different new projects of high power proton linacs, which can be classified as new generation of n-sources for various applications. Scaling up LAMPF with differnet bravery factors the neutrons generated by spallation are planned to be used as research tool like in the new effort for a European Spallation Source (ESS) [13] and for the nuclear waste treatment accelerators ATW, which use the high flux of neutrons for burning nuclear waste or breeding tritium [14].

An example for a straightforward application of a "standard" proton RFQ is the L3 Calorimeter Calibration RFQ [15] built by Accsys which is mounted at the L3 detector at LEP at CERN. It provides a pulsed H^0 beam (1.85MeV, 10mA, 3µsec) for injection into the magnetic field of the L3 solenoid to a Li target and will generate intense pulses of radioactive capture gamma rays to calibrate the BGO crystals of the calorimeter. The repetition rate of this RFQ, which has been operated successfully on the test stand with up to 26mA, can be as high as 150 Hz. Fig.3 shows the arrangement at the L3 detector.

Another example for a strange application is the decelerating RFQ at the PS 189 experiment at LEAR at CERN [16], which is also operational. Antiprotons stored and cooled at LEAR are extracted at 2 MeV and decelerated in a compact system with a spiral-buncher, a 4-Rod RFQ (length 1.5 m at 202MHz) and a debuncher.

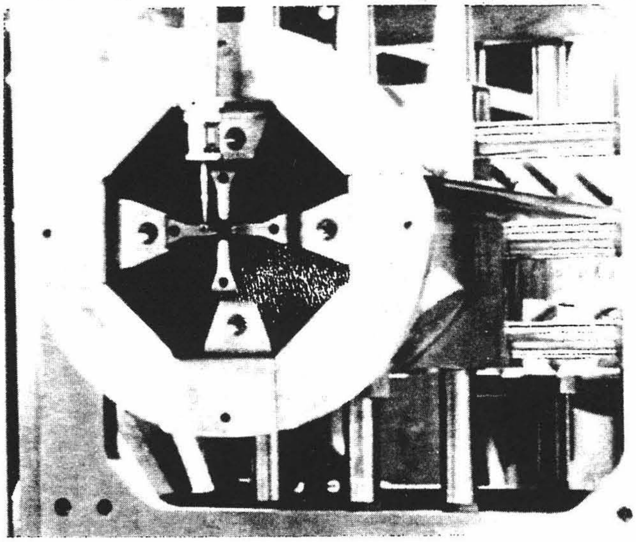

Fig.1 View of the SSC-RFQ

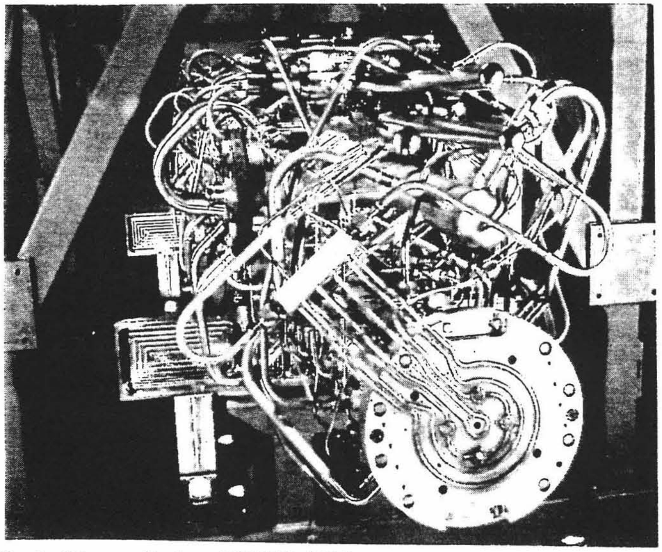

Fig.2 View of the CWDD-RFQ

The 200 keV p beam is transported to the spectrometer for high precision proton antiproton mass comparison. The acceptance of the spectrometer is very small (1πmm mrad, ± 6eV) but with help of the RFQ decelerator the counting rate has been significantly increased.

Both application show that a RFQ system matched to the environment and especially to the tight budget of the user can be applied succesfully. Like in most of these applications other solutions e.g. beams from a Van deGraff generator or putting the spectrometer on a HV platform can also be applied but either the current capability or the size of the installation are in favour of RFQs.

Most heavy ions RFQs built up to now can be classified as low current accelerators with negligable influence of space charge like the LBL Local Injector, the Saclay RFQ, the Cryring injector at MSI, LITL and TALL at INS, the CERN "oxygen" RFQ or the high duty factor HLI injector of GSI [17].

The Maxilac of GSI is still the most powerful high current heavy ion RFQ (5 mA Kr^+, 45 keV/u, 13MHz, dc 10%). Comparable RFQs work at ITHP and INS and a proptotyp of a high current spiral RFQ (27 MHz) designed for 25mA U^{2+} will undergo first beam tests soon [18].

Other RFQs under construction are the new TSR high current injector at the MPI Heidelberg [19], where two closely coupled 4-rod RFQs (each 108MHz, 3m long) will accelerate $Be^+$from a CORDIS high current ion source up to 500keV/u into the MPI spiral booster for injection into the heavy ion storage ring. The new Pb injector linac at CERN [20] will have a 100 MHz four-rod RFQ built by IFN Legnaro [21] as preinjector. Based on the experience with these accelerators, RFQs are designed for other fields of science and applications to use the compact and efficient way of generating these beams.

General Applications

Applications of RFQs in other fields of science maynot reqire design values which are on the limits of the technology but concentrate on points like reliable operation and power consumption and costs.

They also serve as injectors for synchrotrons like for the Loma Linda machine [23], the proposed 250MeV p-linac[24] and the medical heavy ion synchrotron HIMAC [25] at NIRS (RFQ: 0.8 MeV/u, 100 MHz L=7.2m, q/A>1/7) both for cancer treatment. Smaller systems with proton energies around 10-20 MeV like proposed for PET isotope production [15] are typically compact RFQ-Alvarez combinations.

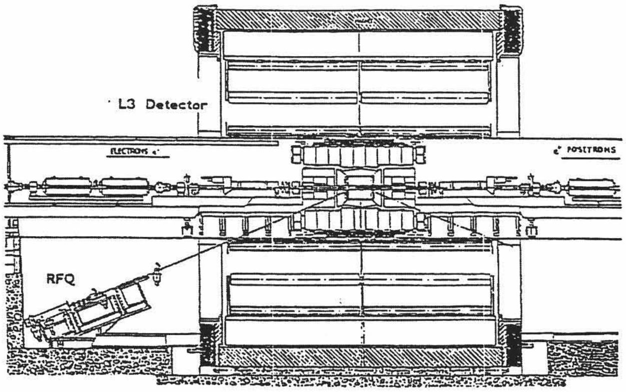

Fig.3 Layout of the L3 calibration system

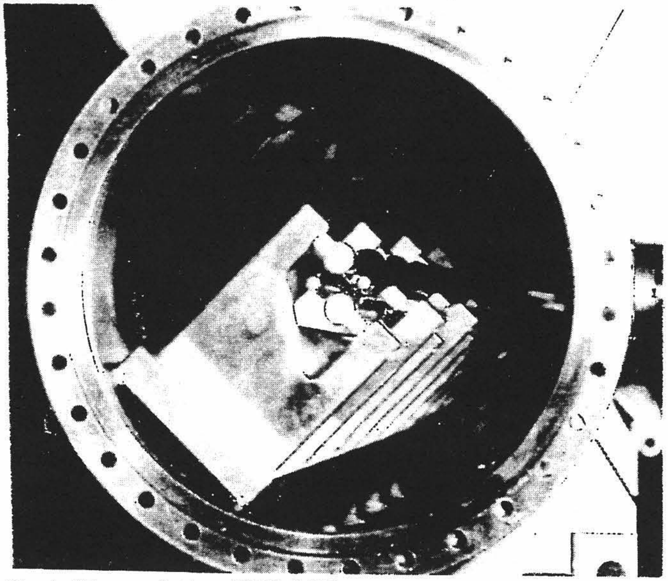

Fig.4 View of the DEC-RFQ

Another scheme has been persued by SIAC where now testing a ^3He linac consisting of three RFQs. (fig.5)[26]. A first RFQ with 1.1m length (212MHz) accelerates $^3He^+$ from 20keV to 1MeV. A stripper charges up to $^3He^{++}$, than the beam rebunched and accelerated by two RFQs operating at twice the frequency (425MHz) to a final energy of 8 MeV. The transmission of the system is not yet very high but the system has demonstrated isotope production succesfully.

Smaller systems use standard p,d RFQs between 1-4MeV and produce neutrons by bombarding Be or Li targets[15]. They are used for neutron activation analysis, cancer treatment and radiography. An example of neutron activation analysis is the detection of explosives and nuclear waste assay[26]. A typical machine like the Accsys DL1 linac is only 70 cm long (fig.5) and its 0.9MeV deuterium beam with an average current of 100µA produces appr. 10^{10}n/sec bombarding a Be target. By variation of energy and currents of the primary beam fluxes of up to 10^{12}n/sec can be produced with wide range of neutron energies.

Heavy ions are mainly used in materials science. Ion beam analysis requerires low current beams with low energy spread, which can be easily produced by van de Graaff generator, which are operating in many labs. A comparable RFQ could be used, if a debuncher cavity is attached and only a part of the beam is selected by a spectrometer. More advantagous is the RFQ if higher beam currents are needed like for material modification or implantation. Although this field is not growing as rapidly as proposed because improved ion sources together with standard implanters can supply proper beams as well, some RFQ systems are now in use[25,27].

Another RFQ application proposed by Hamm[25] is the HIBS, a very sensitive diagnostic technique for impurities in semiconductors which reqires a heavy ion RFQ for e.g. a 400 keV N beam which operates around 100 MHz.

New developments

A development which will give future applications is the work on superconducting RFQs. First experiment with short resonators showed very high electrical fields which lead naturally to cw accellerators applications [28]. Low current as for radioactive beams are possible as well as high current beams where beam losses as well as power efficiency is important[29]. A first SRFQ module has been designed at Stony Brook for heavy ion preacceleration [30]. The performance has to be comapared with the Atlas Preinjector with interdigital resonators [31]. At present one first RFQlet cavity has been testet. The fields (1MV/m) of the lead plated four-rod RFQ are not yet as high as proposed.

Work in ANL is going into high current light ions structures [32] and naturally for heavy ions like RFQs suited for tests in Atlas and for radioactive beams behind Atlas [33].

While the prototypes had shown very good results it is clear that operational structures might look different. Like shown in fig.6 a variety of possibilities of structures between pure 4-Vanes (like persued at LANL[34] and 4-rod structures is possible to give good rf properties and at the same time matchted to Nb technology and chemical treatment. While for higher frequencies modifications of the four-vane structure are investigated for lower frequencies transmission line resonators (four-rod RFQs) are under construction.

All the RFQ accelerators described up to now have fixed initial and final ion velocities v_p

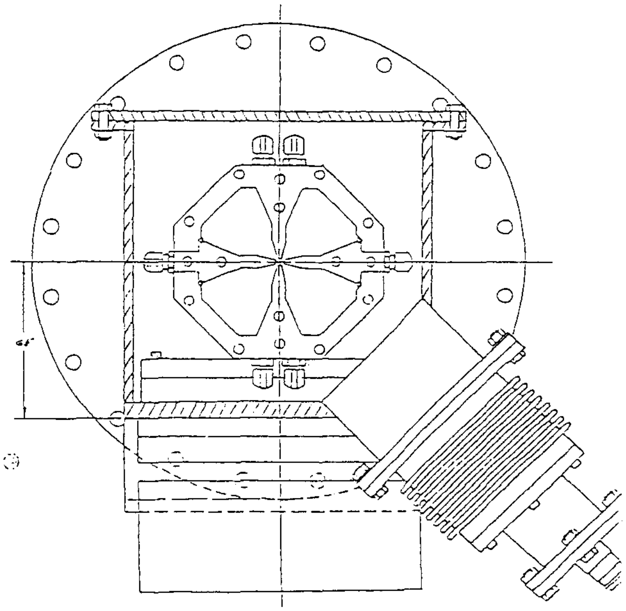

Fig. 5 Cross section of the AccSys PL1/DL1 RFQ

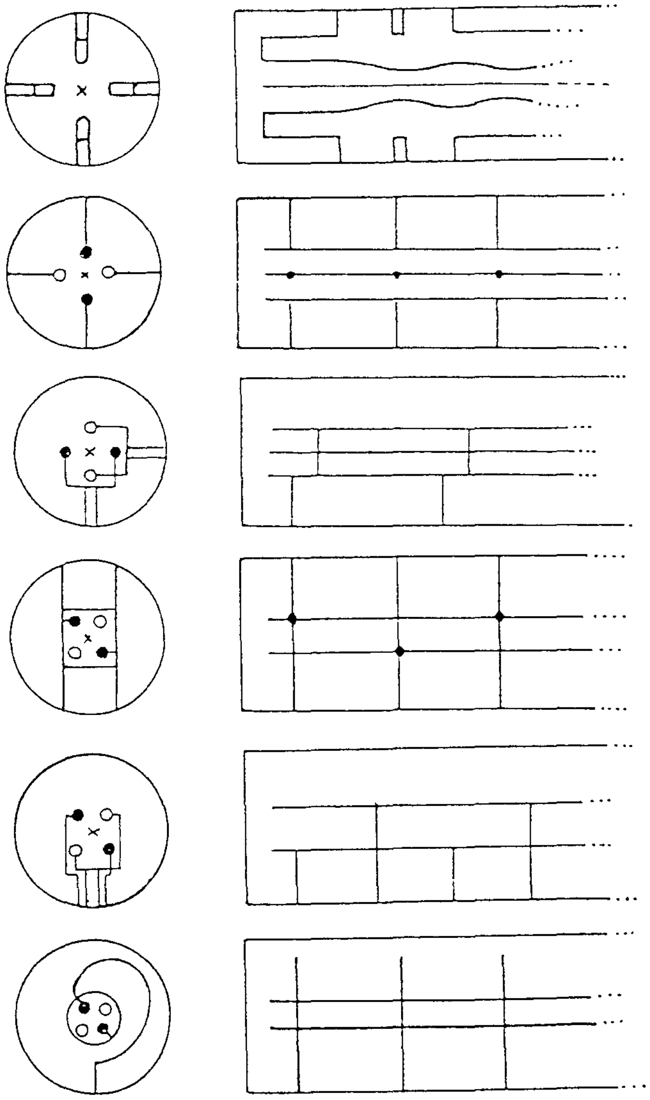

Fig. 6 Different four-rod RFQ resonator schemes

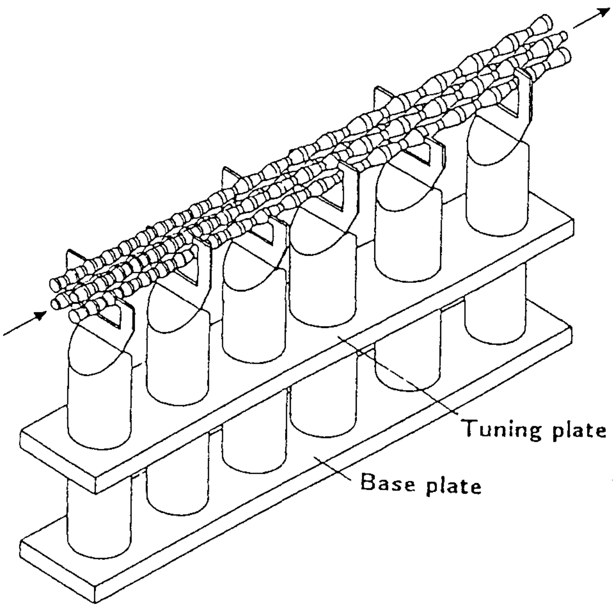

Fig.7 Scheme of a VE-RFQ

(or specific energy T/u) determined by the electrode profile. The flexibility quoted is meant to be at the design stage.

A possible way to vary the output energy T is by changing the operating frequency f : $v_p \sim f$ or $T \sim f^2$, which has been done for applications as cluster accelerator and implanter [15,27,35]. In our development of compact ion RFQs with variable energy (VE-RFQ) we use a movable short to as indicated in Fig.7 [36,37].

The cluster postaccelerator at the IPNL in Lyon is now successfully used for cluster experiments [38]. This VE-RFQ accelerates from 5-10 kev/u to 50-100keV/u (mass $m \leq 50u$).

A second VE-RFQ (in combination with a ECR source) at the IKF Frankfurt is nearly completed. It will deliver beams with $q/A > 1/6$ between 100-200keV/u for atomic physics experiments and for surface physics [39].

Work has been done on a structure to accelerate clusters up to mass m=1000u from a laser source and for a new application namely the first RFQ injector for an separated sector Cyclotron. RFQs and Cyclotrons are well matched [40] because both fixed ratios of input and output energy and energy varition is done by a change of frequency.

The Vicksi Cyclotron in Berlin will get a new injector with an ECR source on a 200 kV platform and two RFQs to replace its Tandem injector for material science work. Each VE-RFQ (80-110MHz,$q/A \geq 1/6$, T=190-360keV/u) will be 1.5m long and operate c.w. [41].

Acknowledgements

I want to thank collegues, which helped me in preparing this paper and supplied information, I am grateful espescially to W. Cornelius, R. Hamm, J. Delayen, K. Shepard, A. Todd, T. Wangler and Y. Yamazaki and apologize for not being able to give a complete survey of all activities in the field.

References

[1] I.M. Kapchinskiy, V. Teplyakov,
Prib. Tekh.Eksp. 119, No.2(1970)17,19
[2] R.H. Stokes, T.P. Wangler,
Ann. Rev. Nucl. Part. Instr. 38 (1989)97
[3] A. Schempp, Linac88, Cebaf-89001(1989)460
[4] M. Weiss, EPAC92, Ed. Front. (1992)539
[5] V.A. Andreev et al., LA12004 (1991)782
[6] S.O. Schriber, Proc. PAC91 (1991)
[7] Y. Yamazaki, M.Kihara, LA12004(1990)543
[8] T. Shirai et al., EPAC92 (1992)560
[9] G.M. McMichael, Linac90, LA12004(1990)518
[10] O. Sanders, this conf.
[11] T.Bhatia et al.,Pac91,IEEE-CH3038(1991)1884
[12] A. Todd et al., LA-12004 (1990)326
[13] S. Martin, C. Planner, EPAC92 (1992)435
[14] C.D. Bowman et al.,NIM A320 (1992)336
[15] R.W. Hamm, Linac90, LA-12004 (1990)558
[16] A. Schempp et al.,Linac90, LA12004 (1990)683
[17] J. Friedrich et al., this conf.
[18] A. Kipper et al., this conf.
[19] C.M. Kleffner et al., EPAC92 (1992)1340
[20] G. Amendola et al., EPAC92 (1992)536
[21] A. Lombardi et al., EPAC92 (1992)557
[22] F.T.Cole et al., IEEE-CH2669 (1989)737
[23] R. Hamm et al., IEEE-CH3038 (1991)2583
[24] W. Cornelius et al., this conf.
[25] R.W. Hamm, NIM B68 (1992)1
[26] L. Grodzins, NIM B56/57 (1991)829
[27] A. Schempp, NIM B56/57 (1991)1055
[28] K. Shepard, Linac90 (1991)510
[29] A. Schempp et al., Linac90 (1990)79
[30] A. Jain et al., IEEE-CH3038 (1991)2444
[31] J. Delayen, K. Shepard, LA12004 (1990)76
[32] J. Delayen et al., this conf.
[33] K. Shepard et al., this conf.
[34] T. Wangler et al., this conf.
[35] K. Tokiguchi et al., EPAC92 (1992)1705
[36] A. Schempp NIM B40/41 (1989)937
[37] A. Schempp, Linac90, LA12004 (1990)535
[38] M.J. Gaillard et al., ISSPIC6,Chicago,Sept.1992
[39] D. Hofmann et al.,NIM B50 (1990)478
[40] A. Schempp, Habschrift Univ. Frankfurt,1990
[41] A. Schempp, Int.Rep.92-12,Univ.Frankfurt 1992