CONCLUDING REMARKS

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Abstract

The time period since the 17th International Conference on Cyclotrons and their Applications in 2004 is characterized by significant achievements. Several new installations started operation. Upgrade programs are under way at many laboratories and new facilities are in construction or in an advanced development stage, especially in the fields of radioactive beams and hadron therapy. The present paper is an attempt to summarize the state of art and the trends emerging from the most recent activities.

GENERAL OVERVIEW

The most spectacular achievement since the last Conference was certainly the start of the operation of the RIKEN radioactive beam facility RIBF with the worldwide first superconducting Ring Cyclotron SRC. Already the first experiments with the 345 MeV/A $^{238}U^{86+}$ beam led to the discovery of a new neutron rich element, ^{135}Pb. With its 8300 tons the SRC is the heaviest cyclotron ever built. Since major components have been constructed without the intermediate step over model tests the successful realization of the RIKEN complex demonstrates also in an impressive way the power of the presently available computational tools.

The superconducting approach is now well established in the design of modern cyclotrons. The first commercial superconducting cyclotron for proton therapy (ACCEL/VARIAN) based on the NSCL concept has started routine operation at PSI. Future superconducting medical cyclotrons will be able to accelerate Carbon ions up to 400 MeV/A. Collaborations between research institutes and an industrial manufacturer have been established to address this challenge (IBA, JINR, LNS). The basic idea is to take advantage of the small difference of the charge to mass ratio of Z/A=1/2 light ions up to $^{12}C^{6+}$ to design a cyclotron able, with small and fast readjustments, to deliver alternatively different species to the specific gantries. Protons of 260 MeV are extracted by stripping of H_2^+, positive ions by electrostatic deflection.

With the diminishing support of the low energy nuclear physics most of the variable energy cyclotrons suitable for the acceleration of protons, deuterons and a-particles up to 60-70 MeV/A have been decommissioned in the last decades. The demand of such beams for the investigation and the production of new medical isotopes is one of the reasons for the construction of new machines with very interesting features. A fixed field, fixed frequency machine will accelerate H^- and D^- as well as H_2^+ and $^4He^{2+}$ and will be equipped with both charge exchange and electrostatic extraction systems (IBA/Nantes). The charge exchange extraction allows to boost the proton intensities at a level of several hundreds µA, far above the limit characterizing previous cyclotrons in this energy range. Multiple extraction systems are or are being installed at various laboratories, where in addition, the acceleration of heavier ions is also considered (e.g. JINR, VINCA).

An impressive variety of new ideas characterizes the studies dealing with the FFAG concept. Basic characteristics like scaling, linearity, isochronism, particular lattice design are discussed in the light of possible application as muon or hadron accelerators. Concentric arrangements of FFAG are considered to accelerate protons and Carbon ions at energies suitable for hadron therapy. The KEK 150 MeV scaling FFAG is a prototype for a medical accelerator, a similar machine at Kyoto University is part of an ADS project. At KURRI a FFAG storage Ring with an emittance-energy recovering internal target (ERIT) for BNCT is in development. The test of a magnet for a spiral scaling FFAG with varying magnetic field is in preparation in the frame of the French RACCAM project. The non-scaling approach is considered in several new proposals. A 20 MeV, non-scaling electron FFAG named EMMA has been funded and will be tested at STFC Daresbury. The BNL concept of a high power proton driver has been extended by the introduction of the harmonic jump concept, which would reduce the technical difficulties with the rf system, and also allow for CW operation or high repetition rates.

Besides new developments the dynamism of the cyclotron community is also well demonstrated by its ability to adapt existing facilities to the needs of new users. Cyclotrons, some of them several decades old, become the backbone of new or extended facilities, e.g. as generator or accelerator of radioactive beams, or as main components of medical centers. Refurbishment programs for key components (e.g. at GANIL, TRIUMF, IUCF, Texas A&M) in order to warrant reliable operation over a further couple of decades have been undertaken. New and upgraded radioactive beam facilities like RIKEN RIBF, ISAC I & II, SPIRAL, DRIBS, NSCL, EXCYT, KVI offer a very broad spectrum of ion species in a wide energy range and open exciting research opportunities in nuclear physics and other fields. Very ambitious ongoing developments and projects (e.g. SPIRAL 2 with a deuteron driver, ISAC II with new targets and post-accelerators, photofission complex) promise a bright future in this field. Let note in passing that a remarkably broad know-how in accelerator technology is available at RIB facilities since they combine cyclotrons with a variety of other accelerator like Tandem, RFQs and Linacs.

The highest beam power delivered on a neutron spallation target is still achieved at the PSI cyclotron complex and continues to be improved. Control and minimization of the beam losses is not only an issue with high energy MW proton beams. The potential for damages caused within milliseconds by the miss-steering of a kW beam of heavy ions (or of low energy protons) is also considerable. An example of improved controls and diagnostics is discussed in a KVI contribution.

It is not possible to give credit to all development and upgrade programs presented at the Conference. Highlights were certainly the progresses reported in much detail by laboratories setting a particular emphasis on educational aspects and on the acquirement of in-house expertise (CIAE, VECC).

Reports on the successful conversion of former research laboratories to dedicated medical facilities (ISL, IUCF) showed that this option means a fundamental change in the operation philosophy, including e.g. the redesign of the control systems, the implementation of new diagnostics or the inforcement of new regulations.

The demand for higher beam intensities doesn't only call for more powerful components like sources, extractors or strippers. The problems associated with personal protection, activation and radioactive waste management become a major issue in the design and the operation of accelerators and target stations. They have been shortly addressed at this Conference and will certainly take more space in the future.

Accelerators used at multi-user facilities, for patient treatment or for commercial purposes, have to satisfy high expectations in respect to their availability and reliability. Cyclotrons can be proud of their record. However, since everyone uses different definitions, the figures reported are confusing. Nevertheless, the up-time of 98% during 10 weeks of operation at 1.2 mA achieved by the ACSI TR30 shows what might become a standard in the future. The JYFL K130 cyclotron was operated during 7500 hours in 2006, which is an excellent figure for a multi-use research installation. Medical cyclotrons are expected to operate 52 weeks per year, i.e. maintenance becomes an affair of single days and repairs an affair of hours. The specifications on procedures, component design and redundancies are defined accordingly. For example, PSI requests that the beam interruption caused by an exchange of the extractor should last less than 4 hours.

In the following we discuss briefly the most recent advances in a few specific fields.

ION SOURCES

Presently, external sources based on the ECR technique are the solution of choice for the efficient production of almost every kind of ions. While small sources using permanent magnet are considered e.g. for 12C6+ beams, the generation of intense highly charged heavy ion beams is best achieved with superconducting sources working at high, single or dual, frequencies (18/28 GHz). Progress reports on VENUS, SECRAL, SuSi, and MS-ECRIS have been presented. VENUS started operation at the LBNL 88-inch cyclotron in September 2006. It demonstrates that, considering the gains in intensity and energy of the accelerated beam, this third generation of ECR ion sources is up to two orders of magnitude more efficient than the best conventional ones. The up-to-now successfully applied scaling laws suggest that a fourth generation of sources operated at higher frequencies (37 GHz feasible in MS-ECRIS, eventually 56 GHz in future sources) may lead to a further increased of the performances. However there are concerns that the limit of the magnet technology might set an end to this approach. Since plasma heating by microwaves is far from being fully understood it was suggested that more effort should be invested in basic investigations. A refinement of the techniques, e.g. by the selective exploitation of the most efficient oscillating modes, may have a better pay-off than a brute force approach.

The target/source system is a key element in the production of radioactive beams with the ISOL method. Impressive progress has been achieved in this field (e.g. at TRIUMF, GANIL). The target has to stand the load of the primary beam but must reach a temperature allowing for the escape of the products. New designs based on cylindrical Ta containers and composite target materials are very promising. Operation with a 500 MeV, 100 μA proton beam has been demonstrated. Different ionization methods are in use or in an advance online testing phase. An ECR source without permanent magnets, which will not survive in this environment, is a good future option. A very attractive method is the laser source: it has an excellent selectivity if the ionization process goes over two steps.

A very interesting development is the NSCL ion stopper. Radioactive ions from the fragment separator are slowed down by Si degraders and stopped in a cyclotron-like device filled with helium gas at low pressure. The ions can be extracted from the center of the device by guiding electric fields and used at keV energies or fed into a post-accelerator.

BEAM INJECTION

The space charge limit of a cyclotron depends strongly on beam parameters defined at the injection and during the first turns of acceleration. For high intensity cyclotrons with radial injection appropriate bunching allows for the generation of bunches with, simultaneously, small phase width and momentum spread. There are evidences that this technique is also applicable with rebunchers between the acceleration stages, thus relaxing the extremely challenging requirements on flat-topping systems in high power machines.

The use of external sources in compact cyclotrons for high intensity beams made it necessary to reconsider the design of the axial injection systems and of the central region. This is illustrated by the large number of contributions on this subject. All new designs use spiral inflectors. The inclusion of space charge in various models shows that the intensity limit with this technique may be below 2.5 mA in a small H- cyclotron, the losses occurring essentially in the vertical plane. The space charge dominated bunching in this injection scheme has been investigated, also, e.g. with the disk model.

The transport of the beams from ECR sources still suffers from a lack of understanding of the extraction mechanism which leads to beam shapes difficult to handle with the usual optical elements. Nevertheless, refined image-based tuning techniques made it possible to increase the intensity from the NSCL K=1200 cyclotron by a factor of 4 over the period 2003-2006.

ACCELERATION AND EXTRACTION

The losses due to the interception of the beam by the extraction device set the intensity limit of a cyclotron. Therefore special attention is paid to achieve separate trajectories or at least to reduce the density of overlapping turns in designing the rf resonators or dees in such a way that the maximum of the acceleration voltage is applied at large radii. In new compact machines up to 4 stems are implemented to achieve this goal. In any case, the load on the septa remains a serious problem, especially with heavy ions where it is strongly localized. Besides improvements like active septum cooling and improved geometries provision has to be made for quick and safe replacement of this strongly activated component (shielding boxes, handling with manipulators).

Systematic investigations performed at JINR demonstrate the high efficiency of the stripping extraction of heavy ions from AVF cyclotrons. The extraction efficiency of the sum of all charges is nearly 100%; for a single charge state it varies between 20 and 100% depending on species and energy.

With the extraction of protons by stripping of H_2^+ a 400 MeV/A ^{12}C medicine cyclotron can be used for proton therapy, too. Allowing for two turns after stripping at a convenient position it is possible to extract and focus 260 MeV protons into a common beam line to the gantries (JINR/IBA). In the LNS 300 MeV/A proposal, protons of this energy can be extracted in one turn.

STRIPPERS

The acceleration of heavy ions to very high energies request strippers between the acceleration stages in order to increase the Z/A ratio. The life time of the foils used up to now is very limited at the intensities of very heavy ion beams achievable nowadays. Therefore new approaches are intensively investigated (e.g. at RIKEN). Rotating systems and liquid films are promising solutions. In the latter case, it is expected that the use of Li instead of silicone oil will increase the allowed deposited power up to 10 kW cm^{-2}.

APPLICATIONS

The main field of applications discussed at this Conference was the use of cyclotrons for hadron therapy. The spot scan technique is the method of choice for the treatment of moving tumours. The way it is applied depends on the gantry design and on the genuine properties of the accelerator. The pros and cons of different accelerator schemes (classical cyclotron, FFAG, synchrotrons, combined cyclotron/linac) were presented in a panel discussion. If from the therapy point of view a fast, continuous tumour painting is preferred the cyclotron as a CW machine is the best choice. It is suitable for various modes of operation, since with appropriate equipments (source control or deflecting plates, internal or external kickers) every desirable intensity modulation or time structure has been demonstrated. The disadvantage is the need of a higher current in connection with a degrader to adjust the energy. The cyclinac promises to be much faster in performing this operation, but it is controversial if this is really needed. The synchrotron is not appropriate for fast painting: the dose is applied by discrete shots. The compactness of the cyclotron may be an advantage in respect to the building and infrastructure costs. However, superior cost effectiveness is also claimed for the other approaches: in fact, realistic numbers supporting such statements, e.g. prices offered by different contractors for a specific project, are not available. While the cyclotron is well established in the domain of proton therapy, the facilities for Carbon therapy in operation or currently planned are synchrotron based. This reflects indeed the availability of a given technology at the time a choice had to be made and the know-how at the involved institutions. Since cyclinacs and cyclotrons for Carbon therapy are in an advanced development stage they will probably become the best options in the near future.

The BNL work on non-scaling FFAG led to the proposal of a gantry with dramatically reduced weight by the use of very compact multi-function superconducting magnets operated at a fixed field.

The number of cyclotrons dedicated to the production of medical isotopes is steadily increasing. To date up to 250 reaction products have been investigated in respect to their suitability for radiology or pharmaceutical use. Production routes using also deuterons, ^3He and α-particles look very promising. Besides basic investigations the development of target systems able to accommodate high intensity beams is a main effort in this field.

THE CONFERENCE

All contributors deserve a special thank for the high quality of their presentations. It is very encouraging to see how fast and at which level this “old” accelerator technology is still developing.

The Sicilian sun, the excellent foods and wines, the many contacts and discussions during the coffee breaks under the palm trees in front of the sea, all this made this meeting a very enjoyable event. But first of all the perfect organisation by Luciano Calabretta and his team was the key to the success of this Conference.