CYCLOTRON PERFORMANCE AND NEW DEVELOPMENTS

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Abstract

New developments in the design and use of cyclotrons are reported. Past decades have shown that cyclotrons can well be adapted to a large variety of applications in very different fields. Cyclotrons worldwide are employed in scientific experiments in atomic, nuclear, particle and solid-state physics, but also in medical and industrial applications. As the most compact accelerator the cyclotron is the ideal choice whenever size or economical factors become essential. New projects for e.g. cancer therapy or heavy ion production are presented and new initiatives for the production of high power beams for accelerator driven reactor systems (ADS) are discussed.

1 INTRODUCTION

The cyclotron is not only a very compact and hence economical accelerator but also a versatile tool. This makes it the preferable choice for both, research, where flexibility is important, and applied work, where it is important to optimally adapt the accelerator to its particular use.

The close link between the development of cyclotrons and their use is also seen in the history of cyclotrons. Fig.1 shows the number of cyclotrons of different types as it developed since their invention as “apparatus for multiple acceleration of light ions to high speed” in 1931 by E.O.Lawrence and M:S:Livingston [1]. The development has seen many limitations that seemed to hinder further development and a successful use of this type of accelerator. New strategies were found and new ideas were employed in order to remove the limiting problems. In 1937 H.E.Bethe and M.E.Rose [2] predicted that 12MeV protons or 34MeV alpha particles would be the highest obtainable energy from a cyclotron, because the flat pole in the “*classical cyclotrons*” could not provide both axial focusing and the isochronous acceleration of relativistic particles. In response to user demand (the predicted existence of pions and muons) the concept of frequency modulation was introduced. In 1945 the first *“synchrocyclotron”* was built and allowed to accelerate beams up to 1GeV, but intensities were limited due to the pulsed operation. Only with the introduction of Thomas focusing by azimuthally varying magnetic fields both limitations could be removed. Now the *“sector focused cyclotron”* was a unique and versatile instrument that could be tailored to a large variety of uses. “*Separated sector cyclotrons”* were built in order to produce very high fluxes of secondary particles (pions, muons and neutrons) and also used in large facilities for heavy ion physics. *“Superconducting cyclotrons”* allowed to reduce the size and weight of cyclotron magnets by more than an order of magnitude which was important for large heavy ion beam facilities and an essential advantage in some typical medical applications. Finally the exploding number of *cyclotrons for commercial application* demonstrates the actual trend of cyclotron development.

In the present paper some new initiatives are discussed. In medical applications the development of a 250MeV cyclotron for radiation therapy with proton beams, is an urgent step in order to bring this advanced technique into hospitals. Several projects of radioactive beam facilities (RIB) aim at the production of beams of nuclei away from the line of stability for experiments in nuclear physics and astronomy. At the Paul Scherrer Institute, Switzerland (PSI) the 590MeV cyclotron facility has been upgraded and is routinely operated at 1MW beam power as driver for the spallation neutron source SINQ. As a possible future application, several proposals to generate about 10MW of beam power using cyclotrons in accelerator driven reactor systems (ADS) for energy generation or transmutation of nuclear waste are presented.

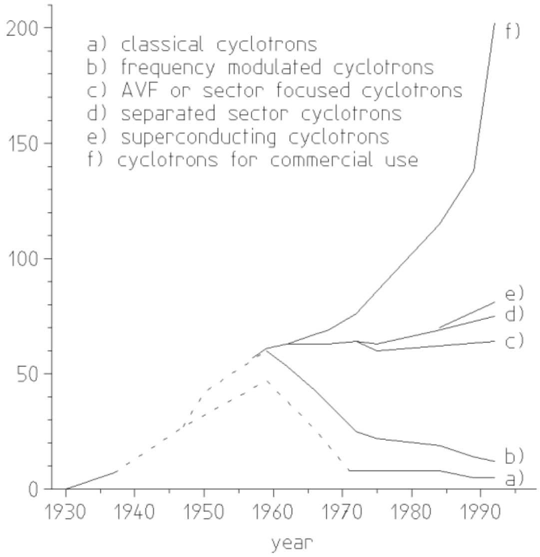

Figure 1: Number of cyclotrons of different types as it developed since the first cyclotron was built in 1931.

2 COMMERCIAL APPLICATION OF CYCLOTRONS

The commercial use of cyclotrons covers a large variety of applications. Best known are small cyclotrons for the production of radioisotopes, in most cases for medical use, as e.g. positron emission tomography (PET). It is interesting to note that the big growth of the market for such dedicated cyclotrons, as seen in Fig.1, came only about 10 - 20 years after the first experiments in the field. This is the time needed for the development of the corresponding technology on the side of the application as e.g. the PET tomograph itself.

The development in the field is accompanied by the demand for higher beam intensities. A firm in the USA produces ^{103}Pd-seeds for prostate cancer therapy with 18MeV protons and a total beam intensity of 28mA using 14 cyclotrons each delivering 2mA onto an internal target. In order to avoid unwanted activation of the machine a high intensity extracted beam would be preferable. A large number of small commercial cyclotrons accelerate H^-, negative H-ions, so that the beam can be extracted easily using a stripper foil installed at the extraction radius with the benefit of low beam losses. A new very interesting development in this direction is the work at IBA (Ion Beam Application) in developing the self-extracting cyclotron as example of an uncritical industrial machine. This type of cyclotron has a very sharp transition of the internal isochronous magnetic field to the fringe field, so that the beam drops out of the machine without deflector. With a 14MeV proton cyclotron it was demonstrated that up to 2mA can be extracted with a transmission of 70-80% [3].

3 MEDICAL CYCLOTRONS

The challenge of medical applications is not to build a suitable cyclotron, but to find the technical solutions, that best account for economical factors like low price, high reliability and simplicity of operation and maintenance. It is important to see the cyclotron as part of a dedicated facility. Not counting buildings, the investment for the cyclotron is about half of the whole facility, the power use about one fourth.

Proton therapy is widely acknowledged to be a very effective method for the destruction of cancer cells. More than 30’000 patients have been treated mostly using beams from research facilities. It is now an important step to apply this advanced therapeutic method in hospital-based clinics. A proton beam of 250MeV is necessary to penetrate 35cm of human tissue, 70MeV for a treatment in the eye. Beam currents for therapy are far below 1µA. After extraction the beam is degraded and collimated. Depending on the application only a small portion is applied to the patient. An isochronous cyclotron is probably the simplest and most cost effective way to produce such a beam. In the list given by D.T.L.Jones [4] 15 out of 22 existing facilities use cyclotrons.

The first cyclotron for this application on the market was the CYCLONE 235, developed in 1991 by IBA in collaboration with Sumitomo Heavy Industries [5]. It is a 4-sector 235MeV proton cyclotron with a special magnet design. In order to keep the size compact, the magnet has an elliptic gap, which allows working with hill fields as high as 2.9T still using room temperature coils. The elliptic gap produces also a fringe field with a steep falloff, which makes beam extraction easier. The pole diameter is 2.24m, the full outside diameter 4.3m, the beam extraction radius 1.08m and the weight 210t. The magnet gap is 96mm at the centre, but narrows down to 9mm at extraction, which has caused problems with beam loss due to vertical excursions. The cyclotron is optimised for easy operation. It is controlled by 7 tuneable parameters in order to allow operation by the medical personnel. Such a cyclotron is installed at the Massachusetts General Hospital (MGH) in Boston and another in Japan. The cyclotron in Japan has gone into clinical use in 1998 and the Boston machine in 2001. 80 patients have been treated so far.

Newly put on the market by a collaboration of ACCEL and Michigan State Univ. (MSU) is a superconducting 250MeV cyclotron [6]. This design puts more weight in minimal size of the magnet and minimal power needed for the cyclotron. Also a high priority is set on a good beam quality, a high extraction rate and fast beam control, partly in view of future spot-scanning techniques. The cyclotron will first be installed at PSI (a research lab) as a prototype for a hospital-based facility, with commissioning expected in 2004. The magnet has an outside diameter of 3.2m, an extraction radius of 0.83m and it weighs 90t

Many existing cyclotrons are partly used for proton therapy as listed in Table 1. Proton beams around 70MeV are used for a very successful treatment of melanomas in the eye, beams around 200MeV for treatment in the body. The given number of patients treated is taken from the summary on the PTCOG homepage [7]. New initiatives are the Midwest proton radiation institute (MPRI) using the Indiana separated sector cyclotron [8] and a design study of a 400MeV/u-superconducting cyclotron at MSU for therapy using heavy ion beams [9]. Many cyclotrons are also used in neutron therapy [4].

Table 1: Proton therapy centres

Location	Energy [MeV]	Patients treated	Beam time
Harvard synchrocycl., Ma USA	160	9067	90%
Synchrocyclotron Orsay, France	200	1894	65%
NAC, South Africa	200	408	16%
Gustav Werner cycl., Uppsala	200	236	20%
PSI, Switzerland	230	99	n.a.
NCC, Kashiwa, Japan	235	new	100%
MGH Boston, Ma USA	235	new	100%
MPRI Bloomington, In. USA	200	new	
PSI Philips cycl., Switzerland	70	3429	10%
Centre Antoine Lacassagne Nice	65	1590	85%
Clatterbridge, UK	62	1102	80%
Davis, CA, USA	60	284	
HMI Berlin, Germany	72	236	18%
Chiba, Japan	70	133	
TRIUMF in Vancouver, Ca	72	57	

4 RADIOACTIVE ION BEAM FACILITIES

The growing interest in radioactive beams, in high power heavy ion beams or in beams of the most massive nuclei has stimulated several new cyclotron projects. Cyclotrons are exceptionally well suited for the acceleration of heavy ions. The energy per nucleon E/A depends quadratic on the charge to mass ratio of the accelerated ions. It is given by $E/A = K\cdot(Z/A)^2$ and K itself also depends quadratic on the magnetic rigidity of the cyclotron magnet, $K\approx(B\cdot R)^2$. Hence the demand for heavy ion beams in nuclear physics research has influenced the development of large cyclotrons in a significant way. Separated sector cyclotrons were employed in large heavy ion facilities with the possibility to strip the preaccelerated ions to higher charge states between the stages of the accelerator chain. Superconducting cyclotrons were built in order to reduce the size of such facilities. The development of ECR ion sources was largely stimulated by the need of high charge states from the source for acceleration in cyclotrons. Pioneered in Louvain-la-Neuve, Belgium, new cyclotrons were built for the acceleration of unstable nuclei produced in existing facilities.

The most impressive project is the expansion of the RIKEN accelerator research facility to become the radioactive ion beam (RIB) factory [10]. The goal is to reach an energy per nucleon of 400MeV/u for ions up to Ar- and 350MeV/u for U-beams. Three additional separated sector cyclotrons are planned to be added to the existing K=540 cyclotron as an energy booster. The first, the fixed frequency ring cyclotron (fRC) has a K-value of 520 and is employed as a charge state booster that allows to fully ionise even uranium-beams. The second, the intermediate ring cyclotron (IRC), is a 4-sector, K=980 separated sector cyclotron with an extraction radius of 4.15m using room temperature magnets. The final stage is a K=2500 superconducting ring cyclotron (SRC) reaching a magnetic rigidity of 8Tm. The extraction radius is 5.36m and the 6 separated sector magnets have superconducting coils in order to reach a higher magnetic induction. The construction of these extremely large sector magnets and the handling of the enormous forces on the coil are a substantial technological task [11].

In 1994 Michigan State University (MSU), which operates two superconducting cyclotrons, the K=500 and the K=1200-cyclotron, started an upgrade of the facility by coupling the two cyclotrons. The K=500-cyclotron was completely refurbished and can now be used as an injector for the K=1200. The range of energies from the K=1200 remains unchanged in the coupled cyclotron system, but beam currents can be substantially raised, because the more intense lower charge states from the ion source can be used. Also some energy limits for heavier ions are raised. The maximum energy per nucleon is 200MeV/u. The coupled system successfully started operation in 2001 [12].

GANIL in Caen, France, operating two coupled K=380 cyclotrons, is upgrading the facility for high-intensity heavy ion beams, which are to be used for the production of radioactive species for acceleration in the newly commissioned cyclotron CIME. With a 5kW argon-beam the goal of 6kW beam power could almost be reached [13], after increasing the acceleration voltage in order to reduce longitudinal space charge effects (see chapter 5 for a detailed discussion of this effect).

5 THE PERFORMANCE OF THE 1MW BEAM AT PSI

At present the PSI separated sector cyclotron facility and spallation neutron source holds the world record in beam power with the maximum beam current of 2mA at an energy of 590MeV, corresponding to 1.18MW beam power. The facility operates routinely at a level of 1.8mA for about 5000h per year.

An extraction efficiency close to 100% is the key point in the development of high power cyclotrons. Three strategies have been followed: 1) the acceleration of H^- and extraction by stripping (e.g. the TRIUMF cyclotron in Vancouver, Canada for energies up to 520MeV), 2) the separated sector cyclotron, first proposed be Willax et al.[14] for PSI and 3) the separated orbit, cyclotron with individual channels for guiding, focusing and acceleration of the individual orbits (e.g. TRITRON in Munich, Germany as a ‘proof of principle’ machine).

The separated sector cyclotron facility at PSI was commissioned in 1974 as one of the first meson factories with the aim to reach 50-100kW beam power for the production of intensive meson beams. The facility has been upgraded to beam currents up to 2mA for the PSI spallation neutron source SINQ. The concept of separated magnets allows installing large and efficient high Q-value cavities for a fast acceleration of the beam. Due to the high acceleration voltage the orbits are well separated up to the extraction radius (Fig.2), so that the beam can be extracted by means of a conventional electrostatic deflector (septum and HV-electrode) with practically zero beam loss. The annually averaged beam loss at around 1.5mA beam current is as low as 0.01% (Fig.3), which helps to keep the activation of the machine at tolerable levels for easy maintenance. The disadvantage of the separated sector concept is, that it is difficult to extend the cavities to the centre of the cyclotron. Hence the beam must be injected at an intermediate energy from a preaccelerator stage. At PSI this is a 0.87MeV Cockcroft Walton generator and the Injector 2, a 72MeV injector cyclotron.

At this high intensities space charge effects have to be accounted for. Since cyclotrons do not have longitudinal focusing properties, the longitudinal space charge forces impose a limit, $I_{lim,}$ on the beam current. As shown by W.Joho [15] the acceleration voltage seen in one revolution, V_{acc}, is very effective to shift this limit upwards, I_{lim} is proportional to V_{acc}^3. Indeed a 3rd order dependence of the beam current limit was observed when the acceleration voltage was raised during the upgrade of the facility [16].

Making use of this strong dependence on the acceleration voltage a further upgrade of the facility is planned. New cavities are developed that shall replace the old ones starting 2004. The new cavities are made out of Cu instead of Al and are expected to operate at a 30% higher voltage, which would allow raising the beam current to even 4mA [17].

In the injector cyclotron Inj2 the space charge effects are stronger due to the lower energy. In order to avoid a limitation on the beam current, this cyclotron is operated in a new regime, where the beam is longitudinally matched by injecting with a circular bunch of equal dimensions in radial and longitudinal direction. This regime makes the beam insensitive to space charge forces. Under space charge dominated conditions in a cyclotron, such a circular bunch is a stable configuration with favourable conditions [18,19,20,21], especially at high beam intensities. The bunch remains circular due to the strong radial-longitudinal coupling and space charge forces can, therefore, not distort it. The phase width of the beam at extraction is extremely small and the beam profile is compact and does not have long tails. It is assumed that these properties of the beam also contribute significantly to the excellent performance of the next stage, the 590MeV cyclotron.

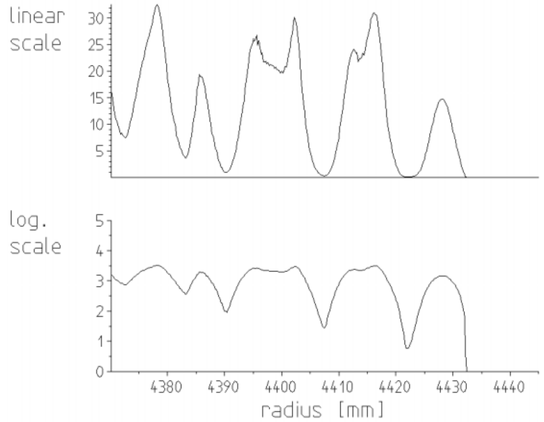

Figure 2: Beam profiles of the last 12 turns in the PSI Ringcyclotron at a beam current of 1.8mA as measured with a radial probe equipped with a thin carbon wire.

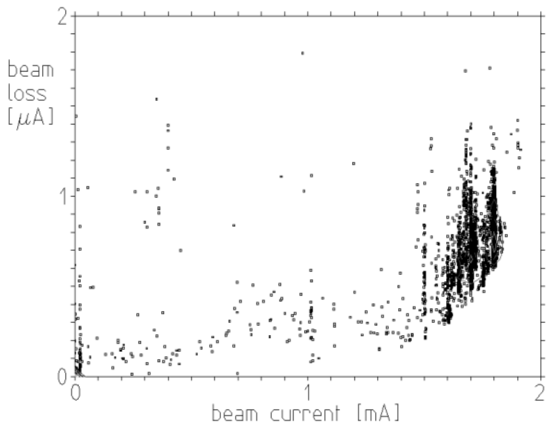

Figure 3: Beam loss at extraction from the PSI Ring in function of the extracted beam current. Plotted are data taken in 10-minute intervals during routine operation of the facility at 1.5-1.9mA in July 2000.

6 HIGH POWER CYCLOTRONS FOR ACCELERATOR DRIVEN SYSTEMS

High power cyclotrons could also play an important role in the development of accelerator-driven nuclear power systems (ADS). In this application a subcritical nuclear assembly is driven into criticality by adding neutrons from a spallation neutron source generated by a high power accelerator. The beam power needed for this application is expected to be in the range 10-30MW depending on the structure of the assembly used and the particular aim. This could be energy generation using the Thorium-cycle (energy amplifier), energy production by burning spent nuclear fuel, the reduction of radiotoxicity of waste by transmutation of particular isotopes (fission products, minor actinides or transuranium isotopes) or a combination of some of those applications.

Again the accelerator has to be viewed in the context of the facility it serves. Several cyclotron properties are favourable for this application. Economical factors like small size and high power efficiency (because the acceleration voltage is repeatedly used in all turns) keep both investment and operation cost low. The cyclotron is well suited for the acceleration of high beam currents. It is a DC machine with continuous beam, reducing the charge in a single beam bunch, and due to the strong radial-longitudinal coupling space charge forces tend to keep the beam bunch together, especially if operated with circular bunches. This is in contrast to accelerators with longitudinal focusing where space charge forces tend to spread the particles throughout the bucket.

The availability of the beam is an important issue in ADS. Due to the complexity of accelerators the standard in nuclear power plant of only a few scrams per year will never be reached, but the reliability could be considerably improved with proper design and a corresponding spare part policy. Depending on the final design of an ADS spallation target and its core it might be advantageous to have a farm of 10MW cyclotrons with an additional complete cyclotron as spare accelerator. Several factors would favour such a multi-beam arrangement. i) The peak power on the beam entrance window to the spallation target could be reduced, ii) the neutron flux distribution inside the target volume better be adapted to the materials to be incinerated, iii) the beam power economically be adjusted to the change of criticality with time and iiii) the availability of the beam could almost be continuous and allow for easy maintenance and repair. Such a solution might also be economically acceptable, since 40% of the investment goes into the installed beam power.

While in the USA and in Japan the accelerator for ADS is foreseen to be a linac, several proposals to use cyclotrons have been brought forward in Europe. Based on extrapolation of the performance of the PSI facility a tentative layout of a 10MW separated sector cyclotron (1GeV, 10mA) has been proposed using the same technology as in the 590MeV cyclotron [20]. The 10MW cyclotron is larger, its magnet has 12 instead of 8 sectors and it has 8 instead of 4 cavities for the acceleration of the beam. The resulting high acceleration voltage sets the longitudinal space charge limit mentioned above to higher than 10mA. As injector a 120MeV separated sector cyclotron would be used similar to the one at PSI and also be operated under longitudinally matched conditions as described above.

P.Mandrillon et al. have investigated a 10MW cyclotron (1GeV, 10mA) for the energy amplifier also closely based on the PSI design [22]. As injector two 10MeV cyclotrons (one for 5mA H^-- and one for 5mA p) and an intermediate 120MeV separated sector cyclotron are foreseen. Y.G.Alenitsky et al. from DUBNA propose a 8MW 10-sector cyclotron (800MeV,10mA) with a 15MeV preinjector cyclotron and an intermediate 60MeV separated sector cyclotron as injector [23]. The space charge effects in the intermediate cyclotrons, however, seem to be rather strong and a longitudinal matching at the injection energy of 10MeV or 15MeV could be difficult to achieve.

Even with an extraction efficiency as high as demonstrated in the PSI facility, the activation of such a cyclotron would reach a considerable level. A dedicated facility for ADS, however, has to be well equipped to handle activated parts and the experience at PSI has shown that the dose to service personnel can be kept in reasonable limits with a proper design for easy handling under activated conditions.

In order to further reduce beam loss at extraction L.Calabretta proposed to accelerate H_2^+ and extract the beam by stripping [24]. After passage through the stripper foil two protons emerge and exit the cyclotron following a trajectory with half the bending radius of the original H_2^+. The most recent projects of high power cyclotrons for ADS are based on this new extraction strategy. For the MYRRHA project, Belgium, IBA works on a design of a 700MeV cyclotron for the acceleration of 2.5mA H_2^+ delivering 5mA 350MeV protons to a spallation neutron source [25]. The project TRIGA of an ADS prototype in Italy plans to use a 220MeV, 1mA H_2^+-cyclotron [26].

7 CONCLUSION

The cyclotron is a unique tool, for many applications. It is a versatile instrument that can well be adapted to the particular use. Its excellent performance even at the highest beam intensities makes it also a competitive choice in future applications in accelerator driven transmutation technologies.

REFERENCES

[1] E.O.Lawrence and M.S.Livingston, "Apparatus for the multiple acceleration of light ions to high speed", Phys. Rev. 40 (1932) 19.
[2] H:E:Bethe and M.E.Rose, "Maximum energy obtainable from cyclotron", Phys. Rev. 52 (1937) 1254.
[3] W.Kleeven et al., "The self-extracting cyclotron", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.69.
[4] D:T:L:Jones, "Present status and trend of heavy particle therapy", Proc. 15th Int Conf. on Cycl. and their Appl., Caen 1998, p.13.
[5] Y.Jongen et al., "The proton therapy system for the NCTP", Nucl. Instr. & Meth. B113 (1996) 522.
[6] M.Schillo et al., "Compact superconducting 250MeV cyclotron for...", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.37.
[7] Particle Therapy, http://www.p-therapy.web.psi.ch/
[8] V.Anferov et al., "The Midwest proton radiation institute at the Indiana University cyclotron facility", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.27.
[9] J.Kim et al., "Design study for a superconducting cycl. for heavy ion therapy", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.324.
[10] Y.Yano et al., "RI beam factory project at RIKEN", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.161.
[11] A.Goto et al., "Progress on the sector magnets for the RIKEN SRC", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.319.
[12] F.Marti et al., "Commissioning of the coupled cyclotron system at NSCL", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.64.
[13] E.Baron et al., "High intensity heavy ion beams ..... at GANIL", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.431 and private comm.
[14] H.A.Willax, "Status Report", Proc. 3rd Int Conf. on secctor-focused cycl., CERN 63-19, 1963, p.386.
[15] W.Joho, "High intensity problems in cyclotrons", Proc. 9th Int Conf. on Cycl. and their Appl., Caen 1981, p.337.
[16] Th.Stammbach, "The PSI 2mA beam & future applications", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.423.
[17] M.Bopp et al., "Upgrade concepts of the PSI accelerator RF-systems...", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.300.
[18] A.Chabert et al., Proc. 7th Int. Conf. on Cycl. and their Appl., Zürich, 1975, p245 and IEEE Trans. NS 22-3 , 1975, p.1930.
[19] C.Chasman et al., N.Instr.&Meth. 219, 1984, p.279.
[20] Th.Stammbach, "High intensity problems revisited or cycl. operation beyond limits", Proc. 15th Conf. on Cycl. and their Appl., Caen 1998, p.369.
[21] S.Adam, "Space charge effects in cyclotrons", 14th Int. Conf. on Cycl. and their Appl., Cape Town 1995.
[22] N.Fietier and P.Mandrillon, "", 14th Int. Conf. on Cycl. and their Appl., Cape Town 1995, p 462.
[23] Y.G.Alenitsky et al., "A high current cyclotron complex for.ADS", Proc. 16th Int Conf. on Cycl. and their Appl., East Lansing 2001, p.434.
[24] L.Calabretta et al., "A superconducting ring cyclotron to deliver high intensity proton beams", Proc. 7th Europ. Part. Acc. Conf., Vienna 2000.
[25] Y.Jongen, "High intensity cyclotron development at IBA", ICFA High intensity beam Workshop, Chicago 2002, http://www-bd.fnal.gov/icfa/workshops/20/
[26] Europ.Roadmap for Developing ADS in Nucl. Waste Incineration, ENEA 2001, ISNB 88 8286-008-6, p.78