

A Reference Concept for ADS Accelerators¹

Alex C. Mueller

CNRS-IN2P3, Institut de Physique Nucléaire, Orsay, France

Email: mueller@ipno.in2p3.fr

Abstract. Accelerator Driven Systems (ADS) for transmutation of nuclear waste require multi-megawatt power proton accelerators of exceptional reliability. A study for such a machine has been recently performed as part of the FP5 EC contract PDS-XADS, "Preliminary Design Study of an Experimental ADS". A reference solution, based on a linear superconducting accelerator with its associated doubly achromatic beam line has been worked out up to some detail. For high reliability, the design is intrinsically fault tolerant, relying on highly modular "derated" components associated to a fast digital feedback system. Operational aspects like maintenance and radioprotection were investigated, a consolidated budget calculated, and a roadmap given for the remaining R&D and construction. The present paper gives a short review of the established facts and findings.

1. Introduction

One important aspect of sustained growth is the long-term availability of energy resources and their environmental impact. The European Commission's Green Paper: *towards a European strategy for the security of energy supply* [1] takes into consideration **all** exploitable resources and substantial share of nuclear power. It is often advocated for its negligible contribution to global warming and economic competitiveness. However, it is also heavily debated because of the long-term environmental burden of nuclear waste from the present-generation light-water reactors. Therefore, transmutation of the long-lived radioactive waste is of high interest. Both critical and sub-critical reactors are potential candidates as dedicated transmutation systems. Critical reactors, however, loaded with fuel containing large amounts of minor actinides (Americium and Curium) pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fractions. A sub-critical system using externally provided additional neutrons is very attractive since it allows maximum transmutation rate while operating in a safe manner. Coupling a proton accelerator, a spallation target and a sub-critical core, the name **ADS**, for Accelerator **D**riven **S**ystem, is used for such a reactor.

A few years ago, a **T**echnical **W**orking **G**roup (TWG) was created by the advisors to several European Research Ministers in order to elaborate a report on ADS technology. The TWG concluded by presenting in 2001 a "European Roadmap" towards ADS technology [2], advocating, the construction of an experimental facility, "XADS", for the 2015 horizon. Triggered by an initiative of the TWG members, the project PDS-XADS, **P**reliminary **D**esign **S**tudy of an **eX**perimental **ADS**, was funded by the European Commission in 2002. Performed by 25 partner organisations, including university groups, large research institutes and industrial firms, one important aspect of the study was the identification of future R&D needs. PDS-XADS [3,4] contained 5 Working Packages (WP), and 3 versions of an **eX**perimental ADS were studied: a molten-metal (eutectic Pb-Bi) and a gas cooled ADS of 100 MW_{th} class, and a smaller-scale (30–50 MW_{th}) system based on the MYRRHA project of SCK Mol in Belgium. WP1, "Global coherence" assured the overall approach to the project, WP2 concerned the safety of these hybrid nuclear systems, WP3 elaborated the accelerator, WP4 the design of core and target, and WP5 the system integration.

¹Work accomplished within the European Commission Contract N° FIKW-CT-2001-00179, "PDS-XADS"

2. The Accelerator Working Package of PDS-XADS

At the start-up of the PDS-XADS project, the main initial specifications for the accelerator system have been defined by WP1. From this, WP3 has assessed the main requirements and the corresponding technical answers. Coordinated by CNRS-IN2P3, the following institutions collaborated on the the six deliverables of WP3: ANSALDO (I), CEA (France), CNRS-IN2P3 (France), ENEA (Italy), Framatome ANP (France), Framatome GmbH (Germany), IBA (Belgium), INFN (Italy), ITN (Portugal), University of Frankfurt (Germany). WP3 issued the following "deliverables", (responsible organisation in parenthesis):

- Requirements for the XADS accelerator and the technical answers (CEA).
- Potential for reliability improvement and cost optimization of linac and cyclotron accelerators (INFN).
- Accelerator: feedback systems, safety grade shutdown & power limitation (CEA).
- Accelerator: radiation safety and maintenance (CNRS).
- Definition of the XADS-class reference accelerator concept & needed R&D (CNRS).
- Extrapolation from XADS accelerator to the accelerator of an industrial transmuter (INFN).

The PDS-XADS contract arrived at term in October 2004. The subsequent sections chapters aim at giving a synthetic view of the facts and findings as far as the accelerator is concerned. It includes a short description of the required R&D. The latter has been incorporated in the FP6 project EUROTRANS which just started at the time of writing (April 2004).

3. Main Specifications for the XADS Accelerator

The main specifications for the XADS accelerator are summarized in Table 1 showing that it belongs to the category of "HPPA" (high-power proton accelerators). HPPA are presently very actively studied (or even under construction) for a rather broad use in fundamental or applied science [5, 6]. Compared to other HPPA, many requirements are similar, but it is to be noted that the reliability specification, i.e. the number of unwanted "beam-trips", is rather specific to ADS. Therefore, the WP3 studies had to integrate this stringent requirement from the very beginning, since this issue could be a potential "show-stopper" for ADS technology in general.

3.1. Beam Energy

The TWG had stated that the physics of spallation and of energy deposition favours an energy of the order of 1 GeV. Moreover, *"however, as the mission of the XADS plant is a global demonstration of the operation and safety and not the industrial operation for waste transmutation, cost considerations could favour the choice of a lower energy. In any case, a lower limit of about 600 MeV can be set in order to have a reasonable efficiency in neutron production and an affordable beam load on the target window"*. Thus, the XADS-accelerator was designed for 600 MeV, but with the requirement that the concept should be upgradeable in energy and keeping in mind that the smaller-scale ADS only requires 350 MeV protons.

3.2. Beam Intensity and Time Structure

The beam intensity can be deduced from the multiplication factor of the sub-critical assembly and the thermal power of the ADS reactor. The PDS-XADS studies showed, that for a power level of $P_{\max} = 100$ MW, and a core load with MOX type fuel and with a multiplication factor

$k_0=k_{\max}=0.98$, the proton beam current needed at 600 MeV is about 2 mA average. Considering a core multiplication factor of $k_0=0.90$ as an extreme lower limit, the current would rise up to about 10 mA. Higher currents had at least conceptually also be considered for the XADS accelerator in order to demonstrate also the feasibility of industrial operation. Further, the effective level of beam intensity depends on the actual XADS fuel core design and specific fuel cycle, as well as on the practical feasibility, operability and relevant safety issues which are linked to the target-core coupling. Based on all these considerations, the accelerator was designed for a maximum current of 10 mA.

TABLE 1: XADS SPECIFICATIONS FOR THE PROTON BEAM

Proton beam parameters	Nominal values
Max. beam intensity	6 mA CW on target (10 mA rated)
Proton energy	600 MeV (including 800 MeV upgrade study)
Beam entry	Vertically from above preferred
Number of beam trips	Less than 5 per year (exceeding 1 second)
Beam stability	Energy: $\pm 1\%$, Intensity: $\pm 2\%$, Size: $\pm 10\%$
Beam footprint on target	Gas-cooled XADS: circular \varnothing 160 mm LBE-cooled XADS: rectangular 10×80 mm MYRRHA: circular, "donut" \varnothing 72 mm
Intensity modulation	0.2 ms "interruptions" in CW beam for neutronics measurements, repetition frequency 0.01-1 Hz

Concerning the beam time structure, operation in CW (RF) mode has a certain number of advantages. A thorough and quantitative analysis has been made, e.g. for the EURISOL driver [8] leading to recommend the CW mode: reliability is enhanced because of the lower peak power for the same average power, mechanical stress from Lorentz forces vanishes in the superconducting cavities, R&D effort is significantly lower, and the machine is simpler and more flexible. Concerning the subsequent subcritical system, a continuous beam is also the favoured solution. Indeed, the thermo-mechanical stresses on the beam window, the target and the sub-critical assembly, are much lower. However, a pulsed operation of the accelerator is not impossible. The time scale of pulsing can indeed be shorter than the thermal inertia of the different components of the target and the reactor. Further, pulsing enables on-line measurements of the sub-criticality level through dynamic neutron flux analysis [9], this point is considered as important in order to ensure a safe operation of the XADS. Therefore, WP3 recommended to choose a CW operation mode for the XADS accelerator, the RF continuously applied on the RF structures, while the beam intensity could be modulated by macro-pulsing.

4. Choice of the Basic Accelerator Concept

The reliability requirements are essentially related to the number of allowable beam trips. Frequently repeated beam trips can significantly damage the reactor structures, the spallation target or the fuel and, also, decrease the ADS plant availability. From WP1, the maximum acceptable duration of a beam trip was specified to 1 s. Longer breakdowns of the beam should not occur more frequently than 5 per year. Given the state-of-the-art in accelerator reliability, this requirement is highly challenging, and could become a "show-stopper" for ADS technology. The suitable design strategies developed to cope with this crucial requirement are described below in some more detail.

Up to now, only sector-focused cyclotrons and linear accelerators (LINACs) are able to provide beam currents in the mA domain. The 600 MeV cyclotron of PSI [10] delivers about 2 mA on a routine basis, and from this, it is felt in the cyclotron community, that an extrapolation to 5 mA is safe. However, reaching up to 10 mA is more questionable, and might require two cyclotrons with the beams being funnelled together. A (given) cyclotron also cannot be expanded in energy, so that boosting the energy from 600 to 800 MeV, as specified by WP1 would require the full replacement of the final and main stage, an absolutely not cost effective operation. The industrial transmuter needing about 1 GeV, the intrinsic limit of the very working principle of a cyclotron is reached, because the proton is becoming too relativistic. Even for a well optimized extraction system (losses well below 10^{-3}), the hot spot created by μA of lost protons is a serious radiation hazard in contrast to the quest for hands-on maintenance. Furthermore, the requirement to provide pulses for neutronics measurements is a major difficulty for a cyclotron of such power. None of all these limitations are present in a LINAC which can reach 100 mA intensities without an intrinsic energy limit.

The chosen strategy to implement reliability relies on *over-design, redundancy and fault-tolerance* [11]. This approach requires a highly modular system where the individual components are operated substantially below their performance limit. In contrast to a cyclotron, a superconducting LINAC, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, important for radioprotection and maintenance issues. For all these reasons, WP3 concluded that the cyclotron solution for an XADS presents a number of difficulties if not impossibilities: funnelling, pulsing, beam trips, double-machine scheme, intrinsic current limitation, activation, energy upgrading that precludes this solution. Therefore, the reference solution discussed below is a superconducting LINAC [12].

Finally, it should be noted this assessment is corroborated by the one of OECD/NEA [13]: *Cyclotrons of the PSI type should be considered as the natural and cost-effective choice for preliminary low power experiments, where availability and reliability requirements are less stringent. CW linear accelerators must be chosen for demonstrators and full-scale plants, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.*

5. The XADS reference accelerator

The proposed reference design for the XADS accelerator, optimized for reliability, is shown in Figure 1. The LINAC and its associated beam-line are discussed in the subsequent sections.

5.1 The LINAC

The LINAC uses an ECR source and normal conducting RFQ as injector followed by warm IH-DTL or/and superconducting CH-DTL structures up to a transition energy. Then a fully modular superconducting LINAC accelerates the beam up to the final energy. Below the transition energy, fault-tolerance is guaranteed by means of a "hot stand-by" spare. Above this energy, *spoke* and, from 100 MeV on, *elliptical* cavities are used. Beam dynamic calculations showed that an individual cavity failure can be handled without loss of the beam. Another remarkable feature of the concept is its validity for a very different output energy range: 9 cryomodules of $\beta=0.65$ cavities for 350 MeV; for 600 MeV, simply 10 more cryomodules have to be added (7 with $\beta=0.65$ and 3 with $\beta=0.85$) and 12 additional ($\beta=0.85$) boost the

energy to 1 GeV. Therefore, already the small-scale XADS accelerator is fully demonstrative not only of the 600 MeV XADS (and could be converted to it), but even for an industrial machine. The performance of first prototypical cavities has been measured to exceed the specifications for the XADS by a very comfortable *over-design* safety margin [14].

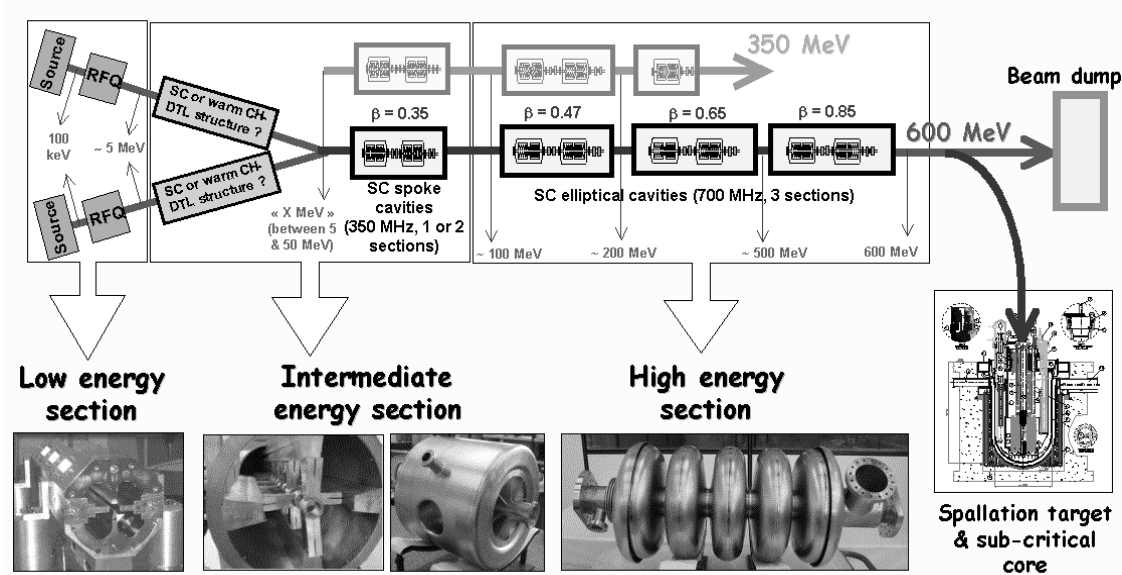


FIG. 1. XADS reference accelerator layout: a doubled injector accelerator is followed by a fully modular spoke and elliptical cavity superconducting linac. Photos of typical cavity prototypes are shown in the lower part. From left to right: RFQ, CH structure, Spoke, Elliptical 5-cell.

5.2 The Beam Transport Line

The objective of the transport line is to safely inject the proton beam onto the spallation target with the specified footprint. A doubly achromatic module composed of two 45 degrees bending dipoles and three focusing quadrupoles has been designed. With scaled magnetic rigidity, the same layout can be used at 350 MeV. Overall, such a double-achromat is non-dispersive. Thus, the beam position at the target is independent on energy variations, and the beam size independent on the energy spread. Thus, spread and central energy fluctuations from the accelerator will have no effect at the target. The system is however dispersive in the region situated between the two dipoles. Position and size monitors located in this region will be able to provide information on proton energy variations, and to trigger a feedback system. The footprint is obtained by raster scanning. The pencil-like beam is deflected by fast steering magnets operated at frequencies of 50 to a few hundreds Hertz, and acting in the two transverse directions. Various shapes (rectangular, circular) and various particle distributions (uniform, parabolic...) are achievable. Four raster magnets will be operated synchronously and independently so that the beam will be always moved at the target if one magnet fails. Redundant fault detection circuits will monitor the magnet current and the magnetic field to ensure proper operation and to shut down the beam in case of necessity. Similar systems are used in cancer therapy where they meet the stringent requirements for medical use.

5.3. Maintenance strategy and radiation protection

Proper maintenance has to guarantee that the *over-design* margin does not deteriorate and that a proper amount of redundant equipment is regularly restored if partial failures have occurred. Lost equipment has to be replaced at a regular basis, and it is of prime importance to ensure that the supervising control system regularly undergoes a complete performance check to

ensure that it can replace components-at-fault by readjusting the operational parameters of the overall machine. These requirements request the development of an expert system, able, while the accelerator is running and delivering nominal beam, to precisely identify and locate equipment that has started to loose rated performance, and/or that is out-of-order and to be replaced or repaired. This system provides the database for the scheduled maintenance periods of repair and/or replacement of deteriorated or faulty equipment. This fastest possible way of preparing the maintenance procedure also is in-line with the ALARA (As Low As Reasonably Achievable) principle for the concerned personnel. Indeed, many conditions for the ALARA principle, like enough working place and quick disconnection of sub equipments are actually the very much the same that are asked by an optimization of the reliability.

The shielding calculations for the XADS accelerator had to be in line with the general radiation protection philosophy, based on the recommendations from the ICRP publication n°60 [15] that have been adopted in the European decree Euratom/96/29. The goal of the shielding design of the XADS accelerator was therefore to guarantee that, under normal operational conditions, the added integrated dose to anybody working around the XADS accelerator will be extremely small, i.e. comparable or smaller than the natural background of 1 mS/y. To obtain this goal, the shielding calculations were made using conservative (= pessimistic) normal beam loss assumptions, and assuming an “occupancy factor” of 1, that means that a person will be present during 2000 hours per year immediately behind the shield wall where maximum dose rates exist. The design dose rate was 0.5 μ Sv/h. The shielding defined for the normal operational conditions, must further guarantee that extra exposure created from abnormal conditions stays sufficiently low, in order not to jeopardize the main shielding objective, i.e. keep the total integrated dose from the operation of the XADS accelerator to any person below the natural background. The exposure from activated accelerator components is minimized by keeping normal beam loss in the accelerator small and the integrated power of accidental beam loss as low as possible via a powerful accelerator interlock system.

6. Reliability focused R&D Programme

The broad field of applications covered by HPPA accelerators is at the origin of remarkable R&D effort presently underway world-wide. The study, design and testing of the main components of these new generation linear accelerators have contributed to a good synergy by developing complementary activities between many laboratories. The XADS accelerator can profit from this general background and even built on it quite directly. However, a dedicated R&D programme is needed for the requirement of an extremely low number of beam trips.. In this spirit, the participants to WP3 have elaborated such a program, focused on reliability and fault tolerance design. It is included the 6th FP EUROTRANS project, started in April 2005.

6.1. Injector and Intermediate Energy Section

Concerning the injector section, a thorough campaign to test the reliability of every component of the injector, operated over a long period of time (e.g. a continuous run of a few months) will be performed "full-scale" with IPHI. Presently under construction in France [16], IPHI which combines an operational ECR source with a 6 m long RFQ will deliver, in 2006, its 3 MeV high intensity beams (10 – 100 mA). Some basic R&D is required for the subsequent sections, up to 100 MeV, in order to assess a solution simultaneously reliable and economical. While superconducting components should in principle be deployed from the lowest possible energies on, "the warm option" has nevertheless to be studied carefully and

prototyped for two reasons. First, if the transition energy to the superconducting structures is higher than the RFQ output. Secondly, while room-temperature structures have large RF losses, their development risk is low (well established technology). The superconducting resonators considered within WP3 are short and modular in view of the reliability strategy. First cavity prototypes for the intermediate section are presently successfully tested [14, 17]. It is therefore important to push these developments for spoke- and CH- structures, by adding helium tanks and power couplers. The final aim of all these developments is to assess the best technical option for the intermediate section of the XADS accelerator based on established demonstrated performance. It might well be a combination of several technologies.

6.2. High-Energy Section and RF System

R&D is already going on since a few years in Europe on superconducting elliptical cavities at a frequency of 704 MHz. Nevertheless, the demonstration of the full technology is not yet accomplished, because it is important, besides the development of the bare superconducting cavity, to build prototypes of each auxiliary system needed for the cavity operation in a real environment (power coupler, RF source, power supply, RF control system, cryogenic system, cryostat...). This requires a full-scale prototype of an accelerating module in which all these elements included. The construction of a module with a given beta value (e.g. $\beta = 0.5$) can be considered as a rather general proof-of-principle of the technology, since the higher beta modules are very similar. Moreover, tests with RF at nominal power (although without beam), could be done and used for specific studies dealing with the XADS reliability issue, like the completion of the RF control system procedures in case of a cavity failure. This system has to react with enough speed to retune the whole accelerator, in order to recover nominal beam conditions in a short time (less than 1 second) and to ensure the fault-tolerance principle. Digital techniques are necessary to meet the speed and software configuration requirements.

7. Possible Roadmap

Consecutive to the advanced technology R&D programme, described in section 6, the construction of the accelerator of the XADS facility typically may take 7 years. This estimate was based on industrial studies and experience gained from the construction of similar facilities like ESRF, SOLEIL and SNS. The PDS-XADS study estimated a cost, prior to routine operation, of about 300 M€ has been estimated for the 600 MeV machine, including in-house and external man-power as well as infrastructure investments of 30 M€. Considerable savings are possible if the energy is lower, and the injector not doubled. As concerning operation costs, the concept of using superconducting technology from a very low energy range on is most cost effective. It is hoped that the R&D program within EUROTRANS will not only provide answers related to the accelerator performance in the critical area of reliability/availability, but may even allow to relax on some of the presently rather conservative specifications, with positive impact on the price.

8. Concluding Remarks

Within the 3 year contract PDS-XADS, a generic and robust technical solution for the XADS accelerator has been developed. A superconducting LINAC, with its associated doubly-achromatic beam line, has been found to constitute an optimal technical solution. This LINAC is suited for all different versions studied within PDS-XADS, and it is also representative for an industrial machine. It is reliable through the rigorous implementation of a highly modular

system with de-rated components operated in a fault-tolerant way. The well-controlled beam dynamics behaviour also allows a straightforward concept for the radioprotection. The same collaboration which made the studies reported here will now continue, within the FP6 project EUROTRANS, a vigorous R&D program concerned with the reliability aspects of the XADS accelerator. It is aimed at being compatible to a vision where the European demonstrator could be launched at the beginning of FP7, still rather in-line with the TWG roadmap.

Acknowledgments

The author, coordinator of WP3 of PDS-XADS, acknowledges the work of all his colleagues of the WP3 collaboration on which this short summary paper is based.

References

- [1] EUROPEAN COMMISSION Green Paper: "Towards a European strategy for the security of energy supply", COM (2000) 769 and http://europa.eu.int/comm/energy_transport/library/livre-vert/livre-vert-en.pdf
- [2] RUBBIA, C. et al., "A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration", ENEA, Rome (2001), ISBN 88-8286-008-6.
- [3] ABDERRAHIM, H.A., CARLUEC, C. and MUELLER, A.C. in ref. [5], 3rd meeting
- [4] Benoit Giraud, "Principle Concepts of the XADS Designs in the 5th FP, in ref. [7]
- [5] OECD Nuclear Energy Agency, International Workshops on Utilization and Reliability of High Power Proton Accelerators (HPPA):
 1st Meeting, October 13-15, 1998, Mito, Japan, ISBN 92-64-17068-5
 2nd Meeting, November, 22-24, 1999, Aix-en-Provence, France, ISBN 92-64-18749
 3rd Meeting, May, 12-16, 2002, Santa Fe, NM, USA, ISBN 92-64-10211-6
 4th Meeting, May, 16-19, 2004, Daejeon, Republic of Korea, in press.
- [6] International Workshop on Physics with a multi-MW proton source, CERN, Geneva, 25-27 May, 2004, <http://physicsatmwatt.web.cern.ch/physicsatmwatt>
- [7] Proceedings of ICRS 10/RPS2004, May 2004, Funchal, Madeira Island, Portugal, <http://www.itn.mces.pt/ICRS-RPS> and Radiation Protection Dosimetry (2005) in press.
- [8] <http://www.ganil.fr/eurisol>
- [9] RIMPAULT, C. et al. "Core instrumentation and reactivity Control of the experimental ADS", International Workshop on P&T and ADS Development, SCK Mol, Belgium (2003), http://www.sckcen.be/sckcen_en/activities/conf/conferences/20031006/cd/
- [10] STAMMBACH, Th. et al., Nucl. Inst. Meth. B113 (1996) 1.
- [11] PIERINI, P. in ref. [5], 4th meeting.
- [12] SAFA, H. "Design of a XADS linear accelerator", in proceedings quoted ref. [9].
- [13] "Summary of Working Group Discussion on Accelerators", in ref. [5], 3rd Meeting.
- [14] JUNQUERA, T., "Status and Perspectives of the R&D programs for the XADS accelerator", in proceedings quoted in ref. [9]
- [15] Recommendations of the International Commission on Radiological Protection, ICRP Publication 60. Annals of the ICRP 21(1-3) Pergamon Press, Oxford, 1991
- [16] BEAUVAIS, P.Y., "Recent Evolutions in the Design of the French High Intensity Proton Injector (IPHI)", European Conf. on Particle Accelerators, EPAC 2004, Luzern, Switzerland, <http://accelconf.web.cern.ch/AccelConf/e04/PAPERS/TUPLT053.PDF>
- [17] MIELOT, C., in ref. [4], 3rd meeting