DESIGNING ACCELERATOR VACUUM SYSTEMS

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Abstract
The reasons for achieving ultra-high vacuum are reviewed first, with a particular emphasis on lepton storage rings. The relationship between particle beams and their environment is also presented in terms of specifications. General considerations on the design of modern accelerators and their consequences are finally approached. Here and there, particular examples are given to illustrate the subject.

1. INTRODUCTION

Looking one or two decades back, on accelerator design and technology, one finds that vacuum is not a dominant culture in comparison with other fields such as beam optics and magnet design, or the technique of acceleration for instance.

It comes into play as a necessity that is addressed once a new machine is at a well advanced design stage. Vacuum has to adapt itself to an environment already defined. A few exceptions to such a situation could be found with the early electron-positron colliders, or the Intersecting Storage Rings at CERN which either for obvious reasons or for unforeseen ones, had to deal with ultrahigh vacuum. Progressively also came out the idea that vacuum could or should be improved on a long term operation.

To this sad picture one must add the difficulty of conducting clean and accurate experiments in the field of vacuum. Also, once a machine began to operate, beam time was usually allocated to "noble experiments" rather than to "obscure" and " unrewarding" tests.

Things began to change in the middle of the 80's and now the situation has drastically reversed in the last period with the outcome of the new e^+e^- high energy colliders, the 3rd generation of synchrotron radiation sources and the future construction of LHC. The purpose of this talk is to illustrate this evolution and to describe the new trends.

2. THE PHYSICAL AND TECHNICAL BASIS FOR THE SPECIFICATIONS OF ACCELERATOR VACUUM SYSTEMS

Before designing and building an accelerator vacuum system, one has to recognise the various reasons for achieving ultra high vacuum and the relevance of the different technologies that will be needed. In what follows, I have listed the main problems encountered in the field of e^+e^- colliders or synchrotron radiation sources. Problems somewhat similar are encountered with machines with stored proton beams. I will make a short description of each of these, thus preparing other speakers for a deeper analysis of particular cases. Most problems can be listed in five different classes.

2.1 The interaction of stored particles with neutrals

Whatever they are, atoms, molecules, shell electrons, eventually photons, the physical effects we are dealing with are:

- *A limitation of the lifetime of the stored particle beams* due to nuclear or electrons scattering as well as Bremsstrahlung on nuclei or shell electrons. Let us quote a few facts.

The cross section for Rutherford scattering (on nuclei) is proportional to Z^2, therefore argon and carbon monoxide are much more dangerous than hydrogen. Furthermore the betatron amplitude of the oscillation that results from a deflection θ from the central orbit is:

$$A = \frac{\theta}{2}\sqrt{\beta_1}\beta_2 \frac{\cos(\varphi - \pi\upsilon)}{\sin\pi\upsilon}$$

where β_1 and β_2 are the values of the betatron function respectively at the location of the scattering nuclei and at the location of observation. φ is the so-called phase advance between these two points and ν is the betatron number. If an obstacle is set at a distance d from the beam it will kill all the particles with an amplitude A larger than d. The beam gas lifetime contribution from nuclei scattering will require an integration over the machine circumference of the Rutherford scattering cross section $\sigma(\theta)$ above the limiting θ due to the obstacle, weighted by the local pressure. The dependence of the beam gas lifetime versus the distance d is of the type:

$$\tau \approx \frac{1}{d^2}$$

Usually the limitation on beam gas lifetime occurs in the vertical plane, the vacuum chamber wall being closer to the beam.

Bremstrahlung is the source of an energy loss by the particle from the beam due to a γ-ray emission. The particle loss which occurs in the horizontal plane arises from the limited energy acceptance of the machine that defines an energy window where the particle energy deviation can be accepted or even compensated.

Table 1 presents the cross section of the different processes involved when a relativistic electron interacts with residual gases.

Table 1
Interaction of ultra relativistic electrons with residual gases

- Rutherford scattering on nuclei (elastic collision)

$$d\sigma = \frac{4\, r_0^2\, Z_i^2}{\gamma_2\, \theta^4}\, d\Omega \Rightarrow \sigma_{\text{scatt.}} = \frac{2\,\pi\, r_0^2\, Z_i^2}{\gamma_2}\, \frac{\beta_1\, \beta_2}{d^2}$$

- Scattering on electrons (energy exchange)

$$\sigma_{\text{scatt}} = 2\pi\, r_0^2\, \frac{m_0\, c^2}{\varepsilon_{\text{RF}}}\, Z_i$$

- Bremsstrahlung on nuclei

$$\sigma_{\text{Br.-n}} = \frac{4\, r_0^2\, Z_i^2}{137} \times \frac{4}{3} \text{Log}\, \frac{183}{Z_i^{1/3}} \times \text{Log}\left(\frac{E}{\varepsilon_{\text{RF}}} - \frac{5}{8}\right)$$

- Bremsstrahlung on electrons

$$\sigma_{\text{Br.-e}} = \frac{4\, r_0^2}{137}\, Z_i\, \frac{4}{3}\left[Log\, \frac{2E^2}{0.8\, m_0\, C^2\, \varepsilon_{\text{RF}}} - 1.4\right] Log\left(\frac{E}{\varepsilon_{\text{RF}}} - \frac{5}{8}\right)$$

- A *dispersion over the accelerator circumference of the scattered and energy degraded particles together with their secondaries* which leave the vacuum system. They are the most important contribution to the background of the physics detectors and of the sensors. Health physics is also mostly concerned by these particles.

- *The source of a beam emittance blow-up* at low energies. The last phenomenon is however rarely observed. It is particularly important at the CERN Antiproton Decelerator where the particles are injected at 3.5 GeV/C and subsequently decelerated to 100 MeV/C.

2.2 The interaction of the stored particles with charged particles and possibly with charged micro-objects

Here we have to consider separately negatively and positively charged beams.

- *Electron beam and positive ions*

Following the ionisation of a neutral atom or molecule, the low-energy electrons will be repelled by the beam. The positive remnant charges will be attracted by the beam. This is the so-called ion trapping [1]. The increased nuclei density lowers the beam gas lifetime and the macroscopic electric field of the ions produces extra focussing forces on the stored beam. Various adverse effects can be observed: an extra tune spread of the stored particles, an increased effect of the machine non-linear resonances and a blow up of the transverse beam cross section. Ion trapping widely observed on small electron rings was considerably weakened on large electron synchrotron radiation sources. This result is obtained from the combined effect of a beam over focussing (very flat beam cross section) together with partial circumference filling [2].

Strange effects on beam lifetime are observed when small dust particles ionised by stray photons are attracted by the electron beam. They keep traversing the beam and oscillating around it. A large reduction of the beam lifetime is seen if the micro-objects resist the high temperature increase from internal ionisation by the high-energy particles. On other occasions, a fast partial destruction of the beam occurs, the micro-object being simultaneously melted away. Such phenomena were observed both at DCI, Orsay [3] and at HERA, Hamburg.

- *Positive bunched beam interaction with ions or electrons*

While much less liable to trouble, the interaction of proton or positron beams with "vacuum" can display a number of typical effects.

The proton-positive ion avalanche was observed at the ISR [4]. Following a proton collision on residual gases, positive ions are accelerated onto the vacuum chamber wall. Under ion bombardment, neutral molecules are released thus contributing to a cumulative avalanche process with infinite asymptotic behaviour under some circumstances.

The proton (positron)-positive ion instability: a leading bunch with a vertical global betatron motion will leave its print on the positive ions it creates. These will communicate to the next coming bunch a force at the betatron frequency. The successive bunches can undergo a transverse instability above a certain pressure threshold. Seen on the CERN Proton Synchrotron in the 60's, this process was revisited by Russian physicists [5]. It was never observed however until now. Note however the problem of the fast ion instability [6].

The positron-electron cloud instability. This has been seen at KEK (photon factory) [7], at Beijing (e^+e^- collider) and more recently at Argonne (APS) and at SLAC (PEP II). It is also a subject of worry for LHC. A low energy initial electron is attracted by the beam. If it crosses the orbit before the arrival of the next bunch with a sufficient energy, it will hit the chamber wall on the other side, possibly creating more than one secondary electron. In these conditions an avalanche can occur. This leads to a very strong pressure rise above a threshold current through multipactoring and possibly to beam instability.

2.3 The synchrotron radiation case

When bent by the dipole field of a magnet, relativistic electrons emit a characteristic radiation, the synchrotron radiation. The photon spectrum spans from infra-red to X-rays. Besides, synchrotron radiation is self collimated, very powerful, polarised and is time dependant due to the bunching of the particles. All these properties justify the tremendous interest of many researchers in various fields of science. The power emitted reaches Megawatt levels at LEP and still hundreds of kW in smaller machines (6-8 GeV) at ESRF, APS or SPRING 8. Such an enormous beam power must be absorbed on specially cooled copper absorbers. Large fluxes of secondaries are produced, scattered or fluorescent photons and photo-electrons. These in turn produce a strong outgassing despite UHV conditions established prior to storing a beam of particles. This is the so-called Photon Stimulated Desorption. Long term outgassing will lead to surface conditioning through a progressive depletion of the protective oxide layer from its molecule content. The cleaned surface develops a very active pumping by the walls, larger in size than the installed pumping, thus modifying the initial pressure profile along the machine [8].

Two extreme cases of synchrotron radiation exist or are foreseen : the third generation of high brilliance synchrotron radiation sources and LHC. Concerning the first one, the most important problems will be addressed in **§ 3.3.** In the case of LHC, the protons, despite their heavy mass, have such a high energy that they emit soft energy photons. These are the sources of several problems which will be dealt with by other speakers during this course.

2.4 The interaction of bunched beams with the vacuum chamber wall

The image current of a bunch of particles in the wall of the vacuum chamber vessels travels together with the bunch [10]. It is the source of problems in connection with the wall conductivity and with discontinuities of the chamber cross section. The RF fields developed by the bunch moving along the machine circumference are particularly active in bellows, RF cavities, beam kickers and protrubing absorbers. These objects couple to the bunch electromagnetic field. The excitation by the beam of local parts of the vacuum chamber that can be considered as high frequency resonators is governed by the beam frequency content and the quality factor of the circuits. Depending on the damping of the RF field induced by a bunch until the arrival of the next one, different situations will be experienced. In large machines operated with different bunch patterns, wide band and narrow band excitation will therefore occur.

Besides power dissipation in the vacuum chamber walls, one observes an increase of the bunch length with current, and of the particle energy spread due to the so-called microwave instability [11]. Transverse and longitudinal excitations of the bunch are seen. The latter occurs as a bunch centre-of-gravity motion, but internal modes can also develop altering the natural Gaussian distribution of the particles. A large effort has been gradually devoted in the most recent machines to achieve a vacuum chamber cross section as smooth as possible in order to reduce the so-called chamber impedance [12]. There is a special concern for the accelerating radio-frequency cavities that from construction have many resonating modes beside the fundamental one. Great ingenuity was shown in the design of the RF cavity impedance at the frequency of the modes (HOM), with spectacular results [13]. The residual part of the phase oscillation of the bunch centre-of-gravity motion is dealt with, using damping feedback.

2.5 Superconductive accelerating cavities

These have been the subject of much R&D, especially during the last fifteen years. The goal here is to obtain the largest possible accelerating gradients (LEP, e^+e^- linear colliders) through high quality surfaces based on elaborate construction techniques, careful surface coating and cleaning, and finally, conditioning with large pulsed RF fields [14].

Another problem encountered in RF cavities is multipactoring. Here we are mostly concerned with the multipactoring that occurs in a remote part of the cavity, the so-called energy coupler. DC voltage bias and low-secondary-emission coatings have been used successfully to overcome the trouble.

3. THE DESIGN OF VACUUM SYSTEMS

3.1 The standard technical problems

3.1.1 The chamber envelope

Three different materials have been used with success in various machines for building the vessel bodies: stainless steel, aluminium and copper alloys. Concerning the connecting flanges they are mostly of the stainless steel-copper gasket-CF type, except at KEK (Japan) and more recently at Argonne and Stanford (USA) which make use of aluminium alloys.

Different arguments were used for supporting particular choices:

- Heat conductivity in relation with bake out and cooling for the evacuation of the power from the secondaries.
- Optimisation of magnet gaps, considering also the wall thickness to withstand atmospheric pressure.
- Ease of fabrication.
- Connection of vacuum vessels with reliable flange and gasket systems.
- Availability of equipment on the market: pumps, gauges, RG analysers with stainless steel CF flanges.

None of the three materials has definitely emerged as having outstanding properties in comparison with the others.

3.1.2 The special equipment

This concerns the injection and beam kickers, the RF cavities and electrostatic beam separators, the current and beam position monitors, the feedback vessels.

Among these, the beam kickers with ceramic vacuum chambers deserve special attention. In order to reduce the beam electromagnetic field propagation outside the ceramic, a titanium coating, usually one micron thick, is made. A peculiar effect, investigated by A. Piwinski [15], thus occurs. Due to the lower propagation velocity of the E.M. field in the ceramic, a much higher longitudinal current density appears in comparison with the normal value in ordinary conductors. A correspondingly large joule power is developed which has to be evacuated.

3.1.3 The distribution of pumping in relation with the conductance of the various chamber vessels

Montecarlo programs exist to calculate the pressure profile from static or dynamic vacuum. Experimental data on the latter are becoming available on material such as stainless steel or copper, which allow to make evaluation more realistic than in the past. Finally it should be possible to add to this a rough evaluation of the effect of the wall pumping speed at various stages of irradiation.

3.1.4 Pressure monitoring

It should be emphasised that gauges and RG analysers are sensitive to several disturbing effects such as: photo-electron pick-up, photo electrons from stray photons, RF induced pick-up which requires special electrostatic shielding [16].

3.1.5 Three typical designs

We have chosen to present here three typical designs of vacuum chamber vessels for electron-positron colliders or synchrotron radiation sources. They differ mostly by the disposition of the photon absorbers.

- LEP design [17], CERN, Fig. 1

It is an extruded aluminium vessel where the photons strike directly the outer side of the chamber wall. Channels with water cooling allow the power to be removed from the primary photons and from the secondaries. When run at 130 °C they can be used for vessel bake out. Note also the extra lead shielding outside the vessel. Its sole purpose is to absorb the X-rays that escape the aluminium vessel in order to reduce the radiation level in the environment. A recess in the inner side of the chamber contains a NEG ribbon pump distributed all along the vessel.

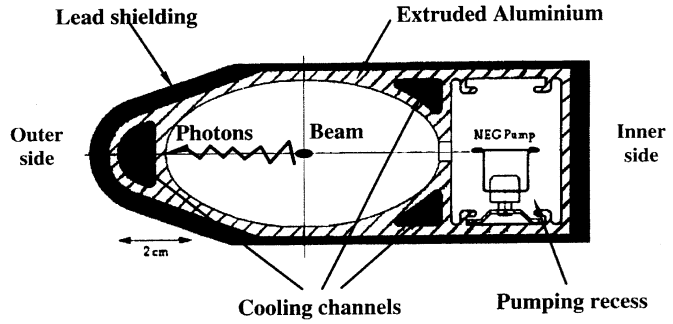

Fig. 1 LEP vacuum chamber in the arcs (cross section)

- ALS design [18], Berkeley, Fig. 2.

This is again an all aluminium vessel. In this design, full use is made, all over the circumference, of the chamber/antechamber concept. The electron beam circulates in the small particle chamber and the photons are allowed to stretch in a huge antechamber after crossing a small vertical recess. The latter decouples the particle chamber from the antechamber, from the impedance point of view. Several so-called copper crotch absorbers are put in different longitudinal locations.

- ESRF design [19], Grenoble, Fig. 3.

Here the vacuum chamber walls are made of stainless steel. Use is made of the chamber/antechamber and crotch absorber concept in the dipole vessels. In the other straight sections, longitudinal copper absorbers are brazed on the thin wall, together with outside water cooled channels. Note also the presence of two other channels with water cooling on the outside of the chamber to remove the power dissipated by the secondaries.

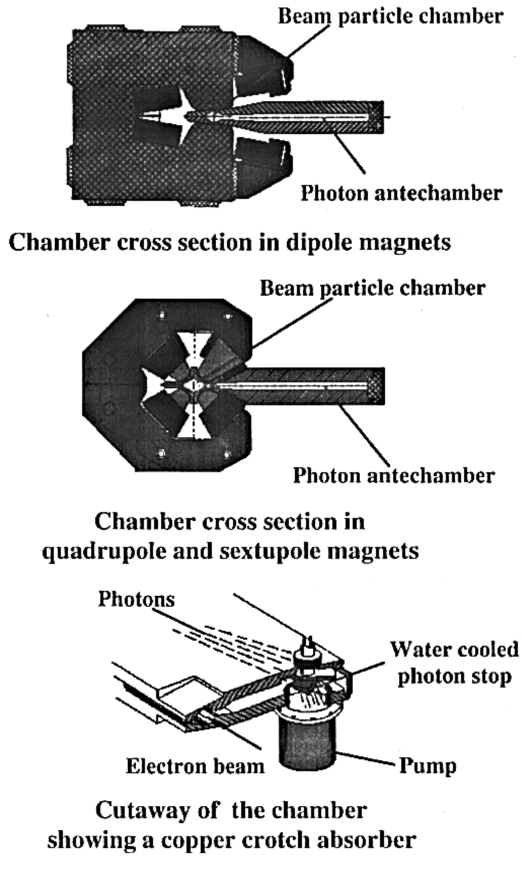

Fig. 2 ALS design. Chamber/antechamber and copper crotch absorbers

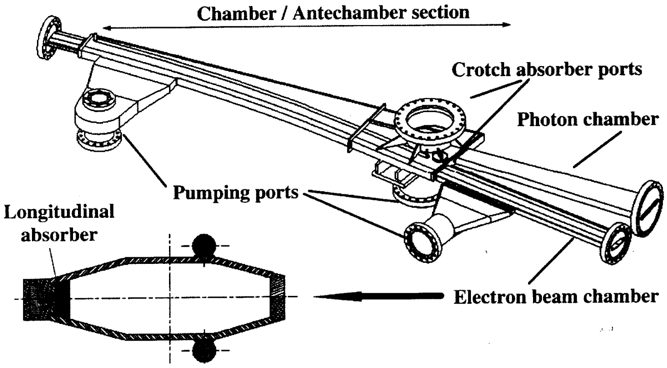

Fig. 3 ESRF mixed design

These designs have different advantages or drawbacks which would need a long discussion on comparative aspects. At the moment, all of them have given satisfaction to the users, see however § **3.3** and **3.4.**

3.2 Surface problems

3.2.1 Surface cleaning

Various surface-cleaning techniques have been developed which are adapted to the particular metal alloy used. They have become standard and are described in the 'cleaning' chapter of these proceedings [20]. Note a problem with the use of chlorides for welding stainless steel cooling pipes outside vacuum vessels. Insufficient cleaning will produce long term corrosions.

3.2.2 Surface-oxide layer and bulk

Whatever the initial preparation, there exists an oxide layer of a few tens of Å, which separates the metal bulk from vacuum. It seems that Photon Stimulated Desorption (PSD), the most powerful tool with ion bombardment, removes a number of molecules compatible with the molecule content of the outside layer. Except for hydrogen, there is no indication that one has to call for atom diffusion from the bulk to explain the photon stimulated outgassing at large photon beam doses.

3.2.3 Primaries and secondaries

There is a naive idea that desorption induced by photons comes from the primary beam. However very soon after running an e^- or an e^+ beam, degassing proceeds through the secondaries. These have several origins: the scattered primary photons which for X-rays occur mainly at glancing angle, the fluorescent photons which follow the de-excitation from the absorption of a photon by an atom, and finally the photo-electrons (and Auger electrons). The diagram of emission is very different from one type of secondaries to another. The electrons may also be deeply affected by stray magnetic fields. For a number of reasons the secondaries appear to be present practically everywhere in the vacuum vessels, see next paragraph.

3.2.4 Photon-stimulated desorption

After a normal bake out, typically 24-28 hours at 150 °C, a vacuum system (surface cleaned beforehand by suitable method) reaches ultra high vacuum, well bellow 10^{-9} mbar, depending on the surface area and the pumping speed of the system. However, the first stored beam of relativistic electrons or positrons develops a very large pressure increase, the so-called dynamical vacuum, which is observed whatever the alloy used for the construction of the vessels.

The behaviour of the PSD has been found to be very similar for all machines. In particular, it shows a gradual conditioning with the increase of the longitudinal photon beam dose, and practically all parts of the vessels are cleaned-up. One can understand this behaviour by the fact that the parts with high photon fluxes are well conditioned, the other parts with smaller fluxes being not as well degassed. The product of the local flux and the molecular yield (molecules/photon) is therefore more or less constant. It has been observed that the static pressure of a vacuum system, including water vapour, shows a large conditioning, thanks also to stray photons.

3.2.5 Multipactoring and cures

We have already dealt briefly with this subject in § **2.5.** It may occur as a two-point or a single-point effect. In the first case, two surfaces participate to the effect whereas only one participates in the second case. Electrons from secondary emission have several origins : the metal itself, the oxide layer and the molecule coverage on or within the surface layer. It is believed that multipactoring conditioning occurs from the molecule coverage which is progressively depleted with the electron bombardment. After some time, only the first two contributions dominate.

3.2.6 Surface coatings

Many attempts have been reported for different purposes and with more or less success. TiN coating of aluminium RF cavities has eliminated an otherwise indestructible multipactoring. Gold coating of vacuum vessels was reported to be no better than uncoated ones from the PSD point of view. New types of coating have been or are being investigated at CERN for LHC [21] and for achieving large distributed pumping speeds [22]. The problem of the long-term behaviour of such techniques is raised in view of the large-scale production of vessels.

3.3 New trends in accelerators design

It is not a surprise that all trends go towards increasing difficulties. Let me just briefly review the present trends before looking at their consequences in the next paragraph **3.4.**

a) For obvious reduction of construction and running cost (power bill) the goal of smaller and smaller magnet gaps, quadrupole and sextupole bores is important. In the particular case of undulator insertion devices in S.R. sources, the aim is to reach higher performances: harder monochromatic X-rays. Beam optics must follow in order to preserve beam gas lifetime and prohibitive closed orbit distorsions. However, as a result, the vacuum chamber cross section is drastically reduced.

b) Larger and larger beam currents, total or bunch current are achieved or contemplated.

c) Higher radiated power and power density are foreseen in 3rd generation synchrotron radiation sources, also from increased beam energy.

d) Higher power losses from HOM (Higher Other Modes) result also from more intense and shorter bunches.

e) Smoother vessel cross sections are required in places that were previously neglected.

f) The design of the so-called RF lined bellows, particularly sensitive to large bunch currents, has been pushed towards unprecedented but more expensive designs.

g) As a result of a), b),and c) higher density power from secondaries are expected with the adverse effects of temperature gradients which have to be limited with special cooling. This could produce vacuum vessel deformation with several consequences.

h) Finally, but for independent reasons, much tighter specifications, at the micron level, are now set for the photon and therefore the electron/positron beam stability. This difficulty cumulates with some of the above ones.

An interesting question: how far can this race go on? Before stating some physical limits to this, it is interesting to look at a certain number of consequences which we have presently to face.

3.4 The consequences of the new trends

a) Much tighter tolerances for fabrication are now required as a general result from most of the above new trends. We are now at the level of a small fraction of one mm, sometimes 100 microns for LHC for instance

b) The recourse to laser cutting, electron-beam welding and even to machining vacuum vessels from solid blocks are favoured in comparison with older types of fabrication.

c) Bake out is given up in favour of intense beam scrubbing. Dedicated beam-line experiments have clearly demonstrated this possibility. This has also been demonstrated recently with the operation of the new PEP II machines. The absence of bake out jackets, no matter how thin they are, leaves more free space between vacuum vessels and magnets. Air cooling of heat from secondaries is better achieved.

d) New problems for supports arise with the vacuum vessels becoming "spaghetti-like objects" with relatively heavy pumps attached to thin bodies with small moment of inertia.

e) New strategies for beam orbit and correction control are now developed in two stages. The mechanical design is of the so-called "girder type" with a number of critical items being precisely assembled on solid girders. These are aligned accurately so as to secure a closed orbit with all correctors being set at zero. This orbit must be safe from the point of view of the synchrotron radiation impinging only on copper-cooled absorbers. Final orbit corrections with very limited amplitude are achieved. They allow safe operation with large stored beams. When necessary realignment of girders is made with the help of microjacks.

f) Fast beam abort triggered from vacuum sensors distributed in all potentially dangerous sections is required.

g) Poor beam lifetime can be eased also by a regular topping-up of the beam current. The feasibility of this proposal has still to be demonstrated from the health point of view, as well as for preserving the quality of the experiments carried out by the users.

h) Finally the adverse consequences of small insertion-device cross sections can be overcome with adjustable vacuum chamber walls restoring some flexibility for the machine optics. This possibility has not been widely exploited yet, being subject to a number of problems raised in the above paragraphs.

i) Accurate codes for computing secondaries and their effects are becoming more and more necessary.

4. CONCLUSIONS

From vessel construction to surface problems and particle beam stability, vacuum technology for particle accelerators covers a very large number of aspects. The recent period has witnessed an evolution towards increasing complexity which brings vacuum to the forefront of accelerator technology. This situation has led to a number of experiments towards a better knowledge of the field so leading to more elaborate designs.

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