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BOVET
Claude SL

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - MT DIVISION

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Pressure measurements and helium leak detection in the LHC cold bore using the electron current from ionization of the gas by the proton beam

A. Poncet

Abstract :

This note considers the problem of measuring the residual gas pressure in the LHC. With a cold bore at 1.9 K acting as a large cryopump, helium leak detection is a problem which conventional gauges cannot solve. As was done in the ISR and the Antiproton Accumulator the electron current from ionization of the gas by a debunched test proton beam at injection energy could provide a means to measure gas densities and detect helium leaks.

CERN
1211 Geneva 23, Switzerland

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PRESSURE MEASUREMENT AND HELIUM LEAK DETECTION IN THE LHC COLD BORE USING THE ELECTRON CURRENT FROM IONIZATION OF THE GAS BY THE PROTON BEAM

A.PONCET

1. The problem of measuring the gas pressure in the LHC cold bore

With a cold bore at 1.9 K and a beam screen at 4.5 to 10 K acting as large cryopumps,the LHC proton beam will normally encounter at startup a very low static gas density,difficult if not impossible to measure with conventional means:
$P_{RT} \leq 10^{-13}$ Torr,measured at Room Temperature (RT),with low H2 coverage (cf the LHC pink book in ref.1)

The dynamic pressure rise due to photodesorption of gas molecules from the walls by synchrotron radiation will be initially at most a few 10^{-11} Torr,measured at RT:
$P_{RT} \leq 10^{-10}$ Torr, if the beam is switched on at full intensity,into a virgin cold bore (i.e. with no previous cleaning). Note that although pessimistic,this pressure is still sufficiently low to be not very easily measurable. It would require modulated Bayard Alpert gauges of good quality,baked at 300 C during the pumpdown of the machine.

As the beam screen surface coverage by the gas released by the photon bombardment increases,the gas density rises,due to secondary desorption . In the absence of beam,the base pressure will rise following the species's adsorption isotherms. With 1-5% at least of its surface covered with holes, the beam screen will have sufficient pumping action to limit the bore pressure at 5 K at 10^{-10} Torr,i.e. $P_{RT} \leq 10^{-9}$ Torr.

This pressure is of course easily measurable with ionization gauges.However it should not happen very often,if provision is made to raise the beam screen temperature from time to time to desorb the accumulated condensed gas.In the absence of Helium leaks,one would really question the need to use ionization gauges: located at RT,they would hardly measure the true cold gas density.**Would they operate at 2-5 K? Would the power they dissipate (~Watt) be acceptable for the cryogenic system ?**

2. Helium leaks and pressure front propagation

Helium leaks in the cold bore of a magnet (superfluid helium from the magnet itself,or supercritical helium leaking from the screen's cooling channels) have to be avoided by all means in the LHC.This is more true than in any other machine such as RHIC or SSC, even though the difficulty not to have leaks is much greater, due to the by far larger complexity and the presence of pressurised superfluid helium around a cold bore submitted to faraminous quench forces. Concerning helium II ,it could be (although yet not proven) that due to its superfluidity the leak rate through some particular material defect be larger than in the case of normal liquid helium (itself much more unfavourable than normal gaseous helium at RT).

The reasons for this strong statement pertain to the following facts,some of which are unique :

a) LHC is at the limit in terms of **pressure bump instability**. Any surface coverage due to leaking helium will increase the molecular yield from ion impact beyond the tolerable limit.

b) unlike other machines where a few pressure bumps from leaks can be tolerated from the point of view of beam lifetime, one single pressure bump in LHC could lead to the loss of enough protons into the SC coils **to cause magnet quenches**,preventing the machine to even simply operate. If this happens,the location of the quenching magnets will not easily point at the position of this pressure bump in the machine. Therefore,there must be a mean to quickly find pressure bumps,i.e. leaks.

c) In case of a leak in ,say, the middle of a half cell , it may take several days , weeks or even months before any pressure change becomes noticeable at an eventual gauge located at the nearest pumping manifold,25 m away.

The reason for this comes from the fact that the cold bore and its beam screen are large cryopumps : gas leaking-in condenses instantaneously as it progresses over fresh surfaces down the pipe;as the surface coverage increases behind this front,the adsorption isotherm pressure rises dramatically. This leads to a slowly progressing sharp pressure front.

As an example,from a theoretical paper by J.P.Hobson and K.M.Welch[2] applied to RHIC at BNL,the pressure front resulting from a leak of 10^{-8} Tl/s at 4 K would travel at a speed of a few meters per day. After having travelled 25 m away from the leak (several days to fill the LHC half cell),the average pressure over 50 m would be in the 10^{-9} Torr range.

We note of course that the presence of a beam screen with pumping holes in the case of LHC should modify the picture : the larger overall pumping surface (roughly 2 times) and,mainly ,the higher adsorption capacity of the cold bore at 2 K (compared to the 5 K RHIC cold bore) will result in an additional slowdown of the front propagation.

To fix ideas,as indicated in annex 1, a 10^{-8} Tl/sec Helium leak at 2 K in LHC,eventually undetectable at Room Temperature during routine quality control (because it would be below the detection limit of 10^{-11} Tl/s),could lead to enough proton losses to provoke magnet quenches after 11 days.**The leak would then feed an helium plug of 2 10^{-8} Torr extending over 10 m.Hypothetic gauges located every 50 m would not detect it for an additional 15 days.**

3. Electrons from ionization : an elegant answer to the problem

Like in the ISR (where this was done first[3]) ,the AA and EPA,the species which result from ionization of the residual gas by the particles can be collected on biased electrodes if they are trappable by the beam, thus providing a current proportional to the gas pressure. With its positive space charge,a proton beam such as the LHC one (0.53 A, 87 V beam potential at injection energy) traps a large number (~50%) of the electrons from ionization events **,if it is debunched.**

These electrons drift longitudinally under the action of the beam potential variation due to the modulation of the beam size. In magnets the magnetic field (quadrupole or dipole) fixes the azimuthal drift velocity and direction ,opposite for electrons born on either side of the beam center line.The drift velocity at the LHC injection energy is of several hundred km/s,thus giving **an instantaneous response** on a remote collecting electrode (see annex 1).

To fix ideas, table 2 in annex 1 gives the numbers for an LHC half-cell (50 m) at 530 mA beam current: the electron current collected at its extremity **would be at least 7 10^{-12} Amps for an average 4K pressure of 10^{-14} Torr** (~10^{-7} Amps at 10^{-10} Torr).

This current is easily measurable ,provided it is not hidden by a larger photo-emission current on the positively biased electrode,such as the one resulting from synchrotron radiation impact. On the EPA[4] ,which has very similar synchrotron radiation parameters (critical energy,photon flux) than the LHC at top energy,it has been possible to shield a special clearing electrode from the photon flux from 10^{-6} Amps down to 10^{-10} Amps,thus allowing the measurement of ion currents. However this may not be possible or convenient for the LHC. However at injection energy,no such risk exists,due to the very low photon energy (see attached table).

Therefore for vacuum diagnostic purposes,a test proton beam injected in the LHC could be debunched,the pressure read in all half-cells (using for instance a positively (<1kV) biased electrode of low impedance,as in the EPA design),and then dumped.

As outlined in annex 1,given the large difference between ionization and nuclear scattering cross-sections (~6 orders of magnitude),this clearing current/leak detection system will be several orders of magnitude more sensitive than the beam loss detection system.

4. Technical feasibility

The question of using the BPMs (as in the AA) has been raised.In the actual design the stripline is grounded on one side.To use the BPM as a clearing electrode would entail the necessity of a second feedthrough to isolate from ground,to introduce a bias voltage. If it turns out to be inconvenient or too difficult to use the BPMs, **special electrodes could be designed.** In that case one would use the **tri-axial technology developed for the AA**[5],which allowed measurement of clearing currents as low as 10^{-12} Amps on electrodes biased at 1kV,a voltage probably more than sufficient to extract all electrons drifting in a LHC test DC beam.

There is plenty of free space in the short straight section's interconnect with the adjacent dipole.Installing clearing electrodes there wouldn't be difficult; it would then mean a resolution of 50 m for leak localisation. As sketched in figure 1,the electrode lead could be fitted **in the rough-pumping duct** connecting the cold bore vacuum to the external world.This would permit the installation of the tri-axial feedthrough on the manifold of the external rough-pumping station,and thus avoid the need to use a cryogenic feedthrough on the cold bore tube.

To minimize the beam coupling impedance (and therefore resistive losses at 1.9 K),the same design as the one adopted for the **CERN EPA can be chosen**: namely,ceramic electrodes coated with a high resistivity paint.These have been shown to have negligible impedance [13].

With ~50 m spacing between electrodes,the clearing current system will have a resolution in leak localization capability of a half cell (i.e. 4 magnets).However,as hinted in annex 1 assymmetries in current reading on neighbouring electrodes might provide a finer resolution.

5. Aknowledgements:

P.Tavares (LNLS-Brazil) has contributed (and still does) actively to the calculations of electron dynamics in the LHC beam,taking into account dipole fringe field effects. F.Pedersen and L.Soby have provided ion and electron clearing currents measurements on the AA,in view of the applicability of the idea for LHC.Some more work is needed to fully correlate measurements with theory.

6. References:

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ANNEX 1

Estimates of the ionization electron currents in the LHC

1) Electron production on the residual gas:

The following LHC parameters are used:

Table 1: LHC parameters

Top energy (GeV):	Et	7540	normalised emittance (micro.m):		Eps	3,75
inj.energy(GeV):	Ei	450	transverse beam sizes :			
gamma (top):	gt	8036	y=sqr(Bhv*Eps/gt)	top	y (m)	0,00022
gamma(inj):	gi	480	x=y+D.alpha (H)	top	x (m)	0,00066
bend. radius (m):	ro	2700	y=sqr(Bhv*Eps/gi)	injection	y (m)	0,00089
nr of bunches	n	2835	x=y+D.alpha (H)	injection	x (m)	0,00133
part / bunch	N	1,00E+11	Revolution freq	(Hz)	f	11253
current I (mA):	I	510	Screen radius	(m)	a	0,02
circumference (m):	C	26659	RMS bunch length	(m)		0,075
maximum betas (m)	Bhv	172,8	distance btw bunches	(m)		9,40
minimum betas (m)	Bhv	30,3	Field x radius	(T.m)	B .ro	24300
maximum dispersion (m)	Dx	2,02	magnetic field (T)		B	9,00
minimum dispersion (m)	Dx	0,98	momentum compaction		α	2,94E-3

At injection energy where there is no synchrotron radiation induced desorption,the residual gas is composed solely of hydrogen.In case of leaks,then Helium from magnet cryostats or beam screen cooling tubes may exist.

At equilibrium the total electron current produced for one metre of beam path and one Ampère of proton beam current is:

$$I_e = \sigma_i n_m \text{ (A)}$$

n_m ,the molecular density,is $n_m = 9.7\ 10^{24} \dfrac{P(Torr)}{T(K)}$ [mol/m^3]

The hydrogen and helium total ionization cross-sections[6] for a proton beam of 450 GeV/c are given in Table 2,together with the maximum possible electron currents produced per metre of beam path,per Ampère of beam current,and per Torr of Hydrogen or Helium at 5 K (temperature of the beam screen):

Table 2: expected electron currents from ionization

Gas	Hydrogen	Helium
ionization cross-section(m^2)	$3\ 10^{-23}$	$2.07\ 10^{-23}$
total ionization current (A/m.A.Torr)	58	40
beam channelled current (A/m.A.Torr) (i.e.50%)	29	20

Electrons are produced with a continuous spectrum of kinetic energies.Only those with kinetic energies at the time of creation lower than the beam electrostatic potential on axis V(r=0) will be trapped and channelled by the combined action of magnetic fields and the longitudinal beam potential to the nearest electrode.For a bi-gaussian beam of RMS beam sizes x (horizontal) and y (vertical) at the center of a round pipe the potential on axis is [10]:

$$V(0) = \frac{I_{beam}}{2\pi\varepsilon_0 c}\left(0.577 + \ln\left(\frac{2a^2}{(x+y)^2}\right)\right)$$

with I_{beam} the beam current and a the beam screen inner radius .With the LHC parameters of Table 1,the maximum beam potential on axis at injection energy is 0.17 Volts per mA of beam (i.e. 87 Volts at 510 mA).

A detailed calculation for the nominal LHC parameters[6] shows that ~ 50% of the electrons produced in the ionization process are trapped inside the beam. It can be shown[7] that this percentage is weakly dependent on the beam potential (~ln ($V^{1/2}$));thus at small beam currents of 10 mA or more (yielding beam potentials above ~2 Volts) it should not be significally different,as measurements done on the CERN AA have shown[8].

2) Electron dynamics

Electrons trapped in the beam have a thermal velocity ,feel the transverse and longitudinal electrostatic beam potential,have a cyclotronic motion around magnetic field lines,drift along the beam path under the combined action of electrostatic and magnetic forces in dipoles and quadrupoles,etc...A detailed analysis is presented in reference 6.

Table 3: Typical electron velocities in nominal LHC beam[9]

Average thermal velocity along beam path at 5 K (no fields)	$v_{th} = \sqrt{\frac{2kT}{\pi . m_e}}$	**13.5 km/s**
cross field drift,average velocity in dipoles	$v_d = \frac{E}{B}$	**50 km/s**
gradient drift in quadrupoles (W_{kin}=0.1 eV)	$v_d = \frac{W_{kin}}{eB^2}\frac{\partial . B}{\partial . x}$	**125 km/s**
velocity along beam path due to beam size modulation dV_o/dz=0.09 V/m (=W_{kin})	$v_l = \sqrt{\frac{2W_{kin}}{m_e}}$	**180 km/s**