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REQUESTS FOR FUTURE EXPERIMENTS IN LEAR IN VIEW OF LEAD IONS FOR LHC

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1. INTRODUCTION AND SUMMARY OF THE REQUESTS

The first series of machine experiments (4 runs of roughly 1-2 weeks each, performed between December 1994 and April 1996 [1-4]) was aimed to test all aspects of ion accumulation for the LHC that can be addressed in the present configuration of Linac 3 and LEAR. Important and encouraging results were obtained, concerning e.g.: the cooling of heavy ions, charge exchange with cooling electrons and with the residual gas, machine lattices suitable for multi-turn injection and cooling, optics of the transfer line and ramping of the Linac 3 energy required for the novel method of combined injection into longitudinal and transverse phase space [5]. Also, new diagnostics devices and software methods for heavy ion cooling and stacking were developed.

However, these tests had to be seriously limited in time and scope as the main duty of LEAR was to supply high quality antiproton beams to its users. In fact important problems relating to ion accumulation could not at all be addressed because the configuration required for multi-turn injection is not compatible with slow extraction for the antiproton experiments. It emerges from Table 1 that a factor of 600 in intensity has to be gained. Thus multi-injection and stacking as well as effects related to cooling and handling of the high intensity have to be demonstrated.

After completion of the antiproton programme (foreseen for the end of this year) LEAR can be "reconfigured" for a second phase of tests as an ion accumulator. Based on the experience gained we propose the changes for the test next year which will then permit us to finalise the design of a "state of the art" cooling and accumulation ring. These changes, which involve relocation of existing and the construction of some new elements, are discussed in the body of this note.

For convenience we give here a summary of the main arguments. The work to be done follows from our objectives for next year which are to test:

- Multi-turn injection into horizontal and longitudinal phase space;
- Cooling and stacking of the large emittance/large momentum spread pulse resulting from the multi-turn process;
- Accumulation of a number (10-20) of pulses such that the influence of collective effects becomes apparent;
- Acceleration of the beam such that beam behaviour and cooling at different energies can be tested;

The main hardware implications can be summarised as follows:

- For a clean test of the horizontal/longitudinal injection we may need a dedicated energy ramping cavity installed after the stripper in the Linac 3 transfer line.
- To monitor the injection and stacking process, we recommend the improvement and some additional diagnostics devices in the transfer line and maybe in LEAR.
- Multi-turn injection in LEAR requires relocation of the electrostatic septum and the installation of two additional fast bumpers (two bumpers are already installed!).
- Optimisation of the injection leads to special optics conditions ($D \approx 5$ m, $\beta_h \approx 1.0$ m) in straight section 1 which due to the required lattice symmetry are then also present at the electron cooler in SS3. Optimisation of the cooling leads to optics functions ($D \approx 0$, $\beta \approx 5$ m) which are incompatible with injection. It is for this reason that we recommend to move the cooler to SS2 where characteristics different from the injection section can be obtained.
- To upgrade the cooling force we recommend an increase of the cooling length (from 1.5 m at present to 3 m). This implies the removal of two sextupoles from the cooling straight section, which is feasible because for the "cooling optics" ($D = 0$) these have anyway no influence on the chromaticity.
- To accumulate a high intensity stack it is important that Linac 3 and the pulsed elements of the transfer line can be cycled fast (10 Hz or at least 3 Hz, provided that the beam lifetime permits slower stacking). Some additional hardware is necessary to deal with the high intensity stack.
- To improve the beam lifetime and therefore the LEAR vacuum.
- For the acceleration tests: some upgrade of the rf system and of the bending and quadrupole supplies may be necessary.

These modifications will allow us to perform a fairly complete test of the ion accumulation for the LHC. Only partial tests are possible if one or several of the improvements are not made.

Although our immediate objectives are the tests next year, we have regarded all items in the spirit that they should serve for the final use of LEAR for the LHC later on.

Table 1 - Main objectives of the lead ion accumulation in LEAR

			Required	Obtained
Linac 3 repetition time		[s]	0.1	1.2
Flux of ions injected		[ions/μs]	2.6×10^6	1.8×10^6
Injected beam	ε_H^*	[μm]	0.2	0.3
(normalised	ε_V^*	[μm]	0.2	0.3
emittances)	$\Delta p/p$		0.2×10^{-3}	0.3×10^{-3}
Stacking time		[s]	2	
Cooling time		[s]	<0.1	<0.1
N_{ions} total			$0.3\text{-}1.2 \times 10^9$	5×10^6
After cooling	ε_H^*	[μm]	1	0.4
(normalised	ε_V^*	[μm]	0.5	0.2
emittances)	$\Delta p/p$		0.5×10^{-3}	0.15×10^{-3}
Acceleration time (4.2→ 14.8 MeV/u)		[s]	1	-
LEAR cycle time		[s]	3.6 (4.8 s can be considered as an alternative)	-
Linac momentum ramping			±0.3%	±0.4%
Transfer line longitudinal acceptance			±0.5%	±1%

2. COMMENTS ABOUT THE LINAC ENERGY RAMPING FOR 1997 STUDIES

LEAR requirements for multi-turn injection with Pb ions in view of LHC are a relative momentum variation of ±0.4% during a ramp of 30 to 60 μs whilst keeping the beam momentum dispersion within 0.02% at 1 σ. The dynamic beam energy variation works in principle by synchronous ramping of the tank 3 amplitude and the debuncher phase as reported in Ref. [4].

From the results of this MD one can conclude the following:

- Operating the *debuncher* alone to obtain the required momentum variation, one finds that there is no voltage left to focus the beam; even if higher voltages were available, the resulting energy spread would still be considerably increased (contrary to the dedicated energy corrector proposed below).
- Using the amplitude of *tank 3 in combination with the debuncher* phase, the dynamic beam energy variation works in principle (the ±0.4% change in beam momentum needed have been obtained), but a blow-up of momentum dispersion is found for the rf settings tried out during this MD (more than 1.5 times the nominal momentum spread of 0.02% *dP/P* at 1 σ with unacceptable tails at the low energy end). Disregarding the approximately 25% beam intensity in the tails of the momentum distribution, one does obtain the same momentum dispersion for all energies. The requirement of a minimum ramp of 30 μs has been tried but is not met.

- However, simulation shows that one should come to better results. Therefore, investigations are underway (and machine studies are foreseen) in order to find out whether or not one could reach the required parameters with the present set-up.
- In the case of unsatisfactory performance of the ramping made with tank 3, one would need a dedicated energy corrector cavity placed close to tank 3 output, where the beam is very short and non-linear effects are reduced to a minimum. The cavity design could be close or identical to existing material, in this case it could also be used as a spare.

2.1 Linac Pulsing

It is foreseen for the project to pulse the linac at 10 Hz (compared to the actual 0.8 Hz). Some study is needed to decide what should be done in the linac and in the LEAR injection line to make this possible (e.g. certain pulsed power supplies will perhaps have to be changed).

3. LES MODIFICATIONS DE LA MACHINE LEAR

3.1 Général vide

Pour améliorer le vide, il faut augmenter la vitesse de pompage et mieux l'adapter aux gaz résiduels lourds et difficiles à pomper. Il est prévu d'ajouter là où cela est possible des pompes NEG ou des parois froides, mais rien n'est vraiment défini pour l'instant.

3.2 Section droite 1

Dans cette section, le septum électrostatique est déplacé au centre de la section pour l'injection multitours, le groupe de pompage primaire est replacé, deux bumpers sont ajoutés et le kicker de mesure de Q est déplacé.

3.3 Section droite 2

Si l'electron cooling reste en section 3, il suffit alors de replacer les éléments de correction multipolaires qui étaient installés avant Jetset. Quelques modifications dans la section courte 21 sont réalisés.

Si l'electron cooling vient en section 2 et s'il est allongé, il faut enlever les sextupoles XFN21 et 22 et installer l'electron cooling, modifier la chambre à vide des quadripôles, réaffecter certaines alimentations, etc.

Dans les deux cas, il faut éventuellement (cela dépend de la maille) envisager de rajouter un kicker pour le damper.

3.4 Section droite 3

Si l'electron cooling reste mais est allongé, il faut enlever les sextupoles XFL31 et XFN32 et modifier la chambre à vide des quadripôles.

Si l'electron cooling est déplacé en section 2, il faut installer les éléments de la section 2 avec les éléments de correction multipolaires et réaffecter les alimentations.

3.5 Section droite 4

Il n'y a en principe rien à changer au niveau des éléments.

3.6 Dipoles principaux

Les pertes par recombinaison (échange de charges, recombinaison radiative ou di-électronique) ou à l'injection se faisant principalement dans les dipôles principaux, il faut soigner le pompage et le dégazage à l'étuvage.

Suivant la position de l'electron cooling, il faut intervertir ou non la position des éléments de détection des bendings 20 et 30.

Un résumé des travaux correspondants est donné en Appendice 1.

4. INSTRUMENTATION

4.1. Transfer Line

The existing instrumentation in the Linac 3 - LEAR transfer line is inappropriate for use with Pb ions. At the moment we only have one secondary emission grid (SEMgrid) situated in the middle of the E0 loop and a number of luminescent screens along the transfer line.

For the future we would like to equip a second SEMgrid station with the slow electronics needed to measure the Pb ion beam profile. The position chosen is at the end of the E2 line (to replace either MGHV11 or MGHV12) so that the injection matching could be checked.

The signals from the luminescent screens have also been difficult to interpret as the screens have been damaged with age. We envisage to replace all the screens and to install CCD cameras at each position for analysis of the beam profiles.

Beam current transformers (BCT) will also have to be replaced if we want to be able to evaluate the transfer efficiency along the line. Having the same characteristics as the BCTs installed in the Linac 3 - PSB line, three monitors could be placed near to or in place of the existing BCTs used for (anti)proton operation.

4.2 LEAR Machine

In principle the LEAR machine is well equipped for measuring the properties of the circulating Pb beam. Schottky pick-ups, ionisation profile monitors and position pick-ups (when the intensity is high enough) have all been used successfully in previous machine experiments. The only element that could be modified is the x-ray detector installed on the electron cooler. The present installation is rather cumbersome and requires a regular supply of liquid nitrogen. AmpTek have recently produced a solid state x-ray detector, the XR-100T, which does not require any form of cryogenics. Complete with a thinner beryllium window, this would be the best suited detector if we were to pursue our investigations of the recombination process.

5. REQUESTED WORK ON THE ELECTRON COOLER

The stored ion intensity is expected to be substantially increased such that the space charge and IBS effects have to be taken into account. It is therefore very likely that the cooling forces have to be increased. This is the reason why we foresee a doubling of the cooler drift tube length.

As mentioned in Section 1, the cooler has to be moved in SS2 where one can hope to find optimal optic conditions ($\beta \approx 5$ m, $D \approx 0$), independently of the injection parameters.

An important point is to have uniform vacuum pipe diameters in order to reduce the natural neutralisation. This is proposed to be done except for the gun which would require more substantial and expensive work.

Owing to longitudinal injection, the cooler energy has probably to be ramped in real time with an additional power supply. Due to the electron beam space charge it is essential to have no dispersion at the cooler.

5.1 Lengthening of the Cooler Drift Space

It is intended to double the length of the drift space. This should induce a reduction by a factor of 2 of all the cooling times, or obtain the present cooling force with less space-charge effects. Secondary effects may appear which justify the tests.

The additional solenoid will be taken from the present test bench.

The lengthening implies some actions on LEAR, as described in Section 3. One expects the insulation of the drift tube from ground but this is not mandatory.

Since new correction coils have to be built (for example end effect coils) a measurement of the magnetic field along the ion trajectory must be done prior to the installation on LEAR.

5.2 Displacement of the Cooler in SS2

Presently the cooler is located opposite to injection such that the machine parameters at the place of injection and at those of the cooler are the same by symmetry. This is very inconvenient for stacking and cooling. We can take as an example the dispersion D which must be large for an optimised stacking detrimental to the cooling process itself.

Therefore, in the present configuration stacking and cooling cannot be optimised together. as a consequence it is proposed to move the cooler from its actual position in SS3 to SS2. Moreover, the suppression of the sextupoles in SS2, when lengthening the cooler, is less penalising the LEAR properties.

For the final project the electron cooling has to be in SS2 anyway. Many of the other changes also depend on the location of injection versus cooling.

Considering the duration of the experiments, the cheapest way to do this move is to lengthen the existing cables (solenoids BBC, correction coils, high voltage...) and to displace the water cooling system.

A way to power the compensation solenoids independently of the cooler solenoid exists.

5.3 Electron Cooler Vacuum Chamber

In the 1996 shutdown the vacuum chamber in the electron cooler collector solenoid was modified to have an internal diameter of 140 mm. This was done in order to reduce the level of natural neutralisation of the electron beam space charge which occurs due to the difference in vacuum chamber diameters. This has proved to be very successful and the electron beam is now much more stable [4].

To further reduce this natural neutralisation the same modification will have to make on the gun side. This will involve a redesign of the NEG pump chamber, the neutralisation electrode and the toroid vacuum chamber.

6. ADDITIONAL ITEMS

6.1 Hardware to Deal with High Intensity

Some specific hardware is necessary to deal with the high intensity stack. The active damping system of LEAR together with part of the "stochastic cooling system" used as a wideband damper is required to counteract instability of the stack. For this purpose a number of elements has to be relocated and additional ones have to be introduced (as already mentioned in Section 3 above) to find an acceptable phase advance even when the optical properties are changed.

The strong electron cooling which is necessary to transport the newly injected particles into the stack has a tendency to "overcool" the core. In fact stack emittances of 5-10 μm (rms) and $\Delta p/p$ of 0.5×10^{-3} are required to avoid excessive space-charge effects and instabilities. Without care, equilibrium emittances smaller than theses values can arise. One method which we propose to deal with this problem is selective heating of the stack. To this end rf noise is applied on transverse and longitudinal kicker electrodes over a limited band at a suitable betatron sideband and a revolution harmonic, respectively. This noise is shaped in bandwidth and amplitude, to lead to heating inside with negligible effect outside the stack.

For momentum heating the "noise system" developed for the ultra-slow extraction can probably be adapted. For the transverse heating, components of the stochastic cooling system can be recuperated, but other electronics (synthesizers, tunable filters...) have to be developed.

6.2 Acceleration

It is desirable to test the rf acceleration of the ions as considered in the feasibility report [6]. The range from 4.2 to 14.8 MeV/u requires no special hardware, except a minor upgrading of the "low energy" magnet supply R22L to reach a rise rate of 0.3 T/s, which will allow us to perform the cycle 4.2 - 14.8 - 4.2 MeV/u in 1.6 s.

Acceleration to 64.4 MeV/u mentioned as an option in Ref. [6] necessitates an extension of the frequency swing of the rf system (f_{max} = 5.4 MHz for h = 4 instead of 5.3 MHz at present). In addition the "high energy" magnet supply R5 has then to be used with faster rise time (B rises from 0.3 T to 1.2 T in 1 second).

A large part of the acceleration tests can be performed with protons. We believe that fast extraction of the ion beam is not a critical item. It is therefore proposed to leave the rf cavities in their present place (SS4) for the tests in 1997 and to postpone modifications required for fast extraction (with a fast kicker and a spetum magnet, installed in either SS4 or alternatively in SS1) until a decision on the potential relocation of the lead linac has been taken.

7. CONCLUSIONS

As seen in the previous chapters the requested work on LEAR is done in view of new experiments to be made with lead ions in LEAR in 1997. It is expected to cope, at least partially, with the objectives given in Table 1 and to be in a better position to finalize the design of the ion injection scheme for LHC. In case of success, a large part of the work done for these experiments can be re-used in the future.

A next future step will be to determine the cost and the manpower required to fulfill all the items mentioned in this paper.

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[5] S. Maury and D. Möhl, *Combined Longitudinal and Transverse Multiturn Injection in Heavy Ion Accumulator Ring*, PS/AR/Note 94-12, 1994.

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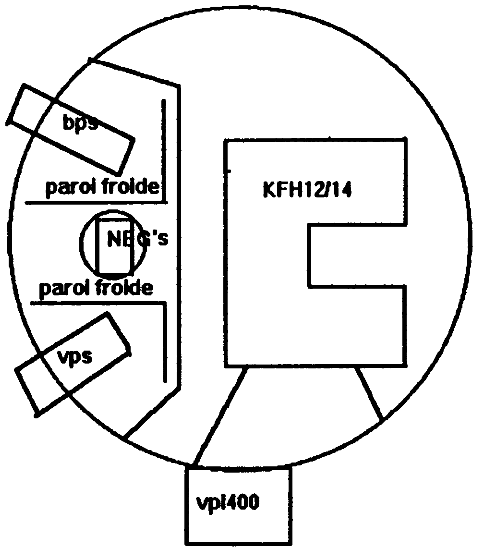
APPENDICE 1 : RÉSUMÉ DES MODIFICATIONS SUR LEAR

SECTION DROITE 1

éléments	actuellement	en 1997
MGHV14, SMH12	centre SL1	à enlever mais à conserver pour le futur. perte 1 VPI 400 et 2 VPS + connexion VGP, jauges VGI,Penning...,RGA,mise à PA
Seh11	SS1	extrémité aval au centre de SL1. on a donc 1VPI 400 et 2VPS Raccordement avec ch. à vide SMH11 contenant connexion VGP avec vanne DN200, piquages penning,....,mise à PA, RGA Insérer un NEG? Raccordement avec tank MGHV12
SS11	il y a SEH11	nouveau bumper(contre quad) et KCHV12(mes. Q) actuellement en SS12
SS12	MSHV12, KVHV12	nouveau bumper(contre quad?) idem SS42,21 avec VGI,VPI 60,VPS MSHV12 reste (coté bending) démonter ligne extr.? on perd 1 VPI 400 et 2 VPS mais on ajoute 1 VPI60 et 1 VPS
KFH12-14	KFH12-14	insérer NEG (2 cartouches =2500l/s) insérer paroi froide(voir croquis)?
ligne E2		changer NEG , installer NEG dans chambre avant pu ou dans MGHV11/13



SECTION 2 AVEC ECOOL

éléments	actuellement	en 1997
de UEHV21 à UEHV 22	SL2	à transférer en SL3
XFN21 et XFN22	contre quad. F	à enlever et à conserver
SS21	bumper et KCMV21	mettre bumper contre quad et KCMV21 contre bending.
SS22	Kquad22 +UWB22 +VVS206	enlever vanne VVS206 Voir croquis secteurs vide
SL2		installer ecool 3m avec sol. compensations, ueh's, vannes, (est-ce nécessaire de conserver dhn's et d'avoir 2 bobines sur les dev pour ajuster l'orbite?). Si le solénoïde est toujours on pour l'opération avec ion on peut utiliser deh's et dev's pour compenser les toroïdes mais aussi pou ajuster la trajectoire dans ecool(cas 1). Dans ce cas il faut revoir le câblage des timings. Dans l'autre cas il faut faire 2 bobines dev ou "couper" les actuelles en deux(cas 2).
câblages		alim SMH12 câblée sur solénoïdes de compensation en série(avec gfa's? et timing idem solénoïde ecool) alim qsk23/24 cablées sur dev's(si cas 2 avec timing deh's) alim xfn21/22 cablées sur dhn's(cas 2) alims ex-xdl23/24 câblées sur dvn's(cas 2). (câbles en place) alim actuelles câblées sur deh's (manchonnage des câbles et/ou changer leur parcours) uehv ; utiliser les câbles actuels(longueur à vérifier)
connexion eau		ecool système à déplacer qsk sur deh's découpler sol. de comp. du sol. principal.
sécurité alims		câblage sol. comp. vers alim smh12 câblage deh's.
kicker cooling utilisé en damper large bande		installer dans chambre dev un kicker ou utiliser le kcm21 en kch suivant maille et avance de phase.
vide		améliorer vide ecool ,NEGS (cryo?) câblage vanne 20x à la place vvs206?
damper kicker		installer dans chambre Qfn/Qdn 22 un kicker(si ce mode est choisi et si l'avance de phase est bonne pour la maille considérée) installer les lignes coaxiales et l'électronique correspondantes

SECTION 2 COMME ACTUEL

élements	actuellement	en 1997
SS21	bumper et KCMV21	mettre bumper contre quad et KCMV21 contre bending.
SS22	Kquad22 +UWB22 +VVS206	enlever vanne VVS206? Voir croquis secteurs vide
QSK's	installés	à installer dans une position favorable pour la compensation ou l'excitation des résonances de couplage linéaire.
SL2		ré-installer les sextupoles xdls23/24 (seules utiles les skews) câbler avec les câbles existants. connecter ref. eau
st. cooling		éventuellement installer une ucv à la Caspers pour beta=0.094 si ucv31 ne va pas
vide		améliorer la zone RGA , installer une pompe cryo?
damper kicker		installer dans chambre Qfn/Qdn 22 un kicker(si ce mode est choisi et si l'avance de phase est bonne pour la maille considérée) installer les lignes coaxiales et l'électronique correspondantes

SECTION 3 AVEC ECOOL

éléments	actuellement	en 1997
UCV31	UCV31	transformer en pu à la Caspers.
XFL31 et XFN32	contre QFN's	à enlever et à conserver.
SL2		installer ecool 3m avec sol. compensations, ueh's, vannes, DEV,DEH (est-ce nécessaire de conserver dhn's et d'avoir 2 bobines sur les dev pour ajuster l'orbite?). Si le solénoïde est toujours on pour l'opération avec ion on peut utiliser deh's et dev's pour compenser les toroïdes mais aussi pou ajuster la trajectoire dans ecool(cas 1). Dans ce cas il faut revoir le câblage des timings. Dans l'autre cas il faut faire 2 bobines d'eV ou "couper" les actuelles en deux(cas 2). le déplacement des éléments de chaque côté de ecool est de 750 mm(voir câbles, tuyaux d'eau, etc..),voir plan
câblages		alim SMH12 cablée (puissance et sécurité) sur solénoïdes de compensation en série (avec gfa's? et timing idem solénoïde ecool) alim xdl31/xfn32 cablées sur dvn's(cas 2) uehv ; utiliser les câbles actuels (longueur à vérifier)
connexion eau		découpler sol de compensation du solénoïde principal.
vide		améliorer vide ecool , NEGS (cryo?)

SECTION 3 SANS ECOOL

éléments	actuellement	en 1997
UCV31	UCV31	transformer en pu à la Caspers.
SL3		installer ex- "uehv21,dev21,dhv22,qsk et vide idoine avec pompage,NEGs..." installer ex-xdls23/24 en xdls33/34
câblages		uehv's avec câbles de la SL3 câbles puissance et sécurité à déplacer de SL2 en SL3 dvn21 avec cable xds31 xdl33/34's avec câble dhn's qsk's 31/32 avec câbles dev31/32 (existe-t-il un câble sécurité?)
vide		améliorer la zone RGA , installer une pompe cryo? ne pas installer de vannes ?

SECTION 4

éléments	actuellement	en 1997
KFH42		installer au moins un NEG,. Ceci implique un piquage D200 sur couvercle.
vide		améliorer la zone RGA , installer une NEG (cryo?) démonter les ch. à vide cavité 41 et 42 pour changer les jacquettes d'étuvage

BENDING'S

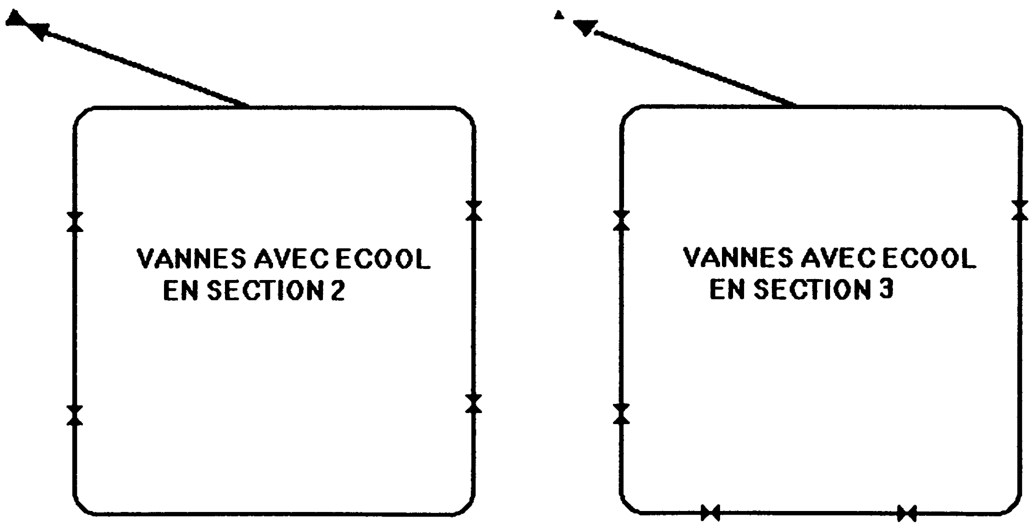
éléments	actuellement	en 1997
BHN10		NEG dans VPI 400? paroi froide pour capter dégazage dû à pertes injection**
BHN20		NEG dans VPI 400? si ecool secteur 2 -installer mesure H0 sur hublot avec guide de lumière et PM. -installer détecteur Pb 53+ -enlever BIPMH's -paroi froide pour capter dégazage dû aux pertes ions recombinés** si ecool secteur 3: un seul BIPMH? et/ou remplacer/tourner les galettes microcanaux
BHN30		NEG dans VPI 400? si ecool secteur 3 -installer mesure H0 sur hublot avec guide de lumière et PM. -laisser détecteur Pb 53+ -paroi froide pour capter dégazage dû aux pertes ions recombinés** si ecool secteur 2: ....-installer un seul BIPMH? et remplacer/tourner les galettes microcanaux
BHN40		NEG dans VPI 400? adapter uch40 pour 0.094MeV/c.(toutes pu en séries devraient donner un facteur 1.4 en en rapport signal/bruit)

**** A l'injection les pertes sont inévitables et provoquent du dégazage . Dans le cas de l'injection monotour ces pertes ont lieu dans le bending BHN10. Dans le cas de l'injection multitour il faudrait analyser où les pertes se font pour la partie du faisceau linac3 avant et après le processus d'injection (voir pendant). Il serait bon à l'endroit des pertes d'optimiser le pompage pour éviter un point haut de pression. Il serait même souhaitable qu'un obstacle froid soit l'intercepteur. Est-ce les ions plombs eux-mêmes (ralentis et non collés contre les parois) qui perturbent la durée de vie des ions plombs circulant. Il en va de même pour les ions plombs recombinés qui sont perdus dans le bending en aval de l'refroidisseur-électron.**

AUTRES IDEES

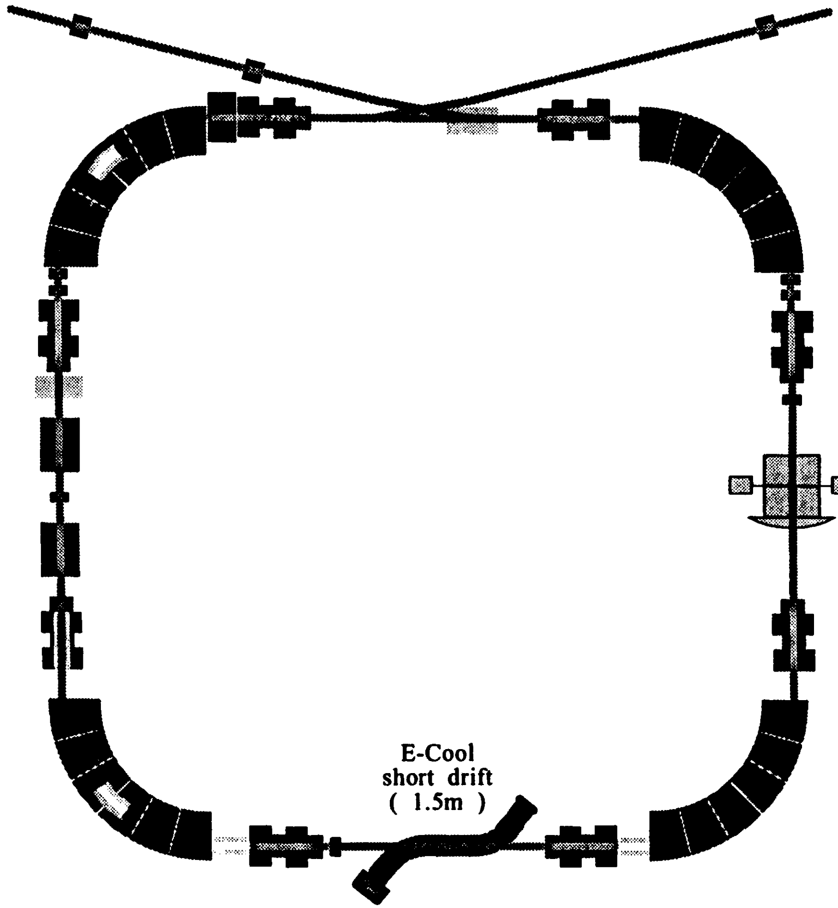
éléments	actuellement	en 1997
quads pour résonance		2 quads de compensation de résonance 2Qh,v=p, si la maille le demande(qh,qv~n+0.5) et si les trims ne peuvent pas le faire (p résonance)
réduction de l'impédance de la machine($Z_{//}$/n~40Ω actuel.)		éviter les résonances dues à certaines connections vide ou à de gros tanks

VANNES A VIDE EN 1997

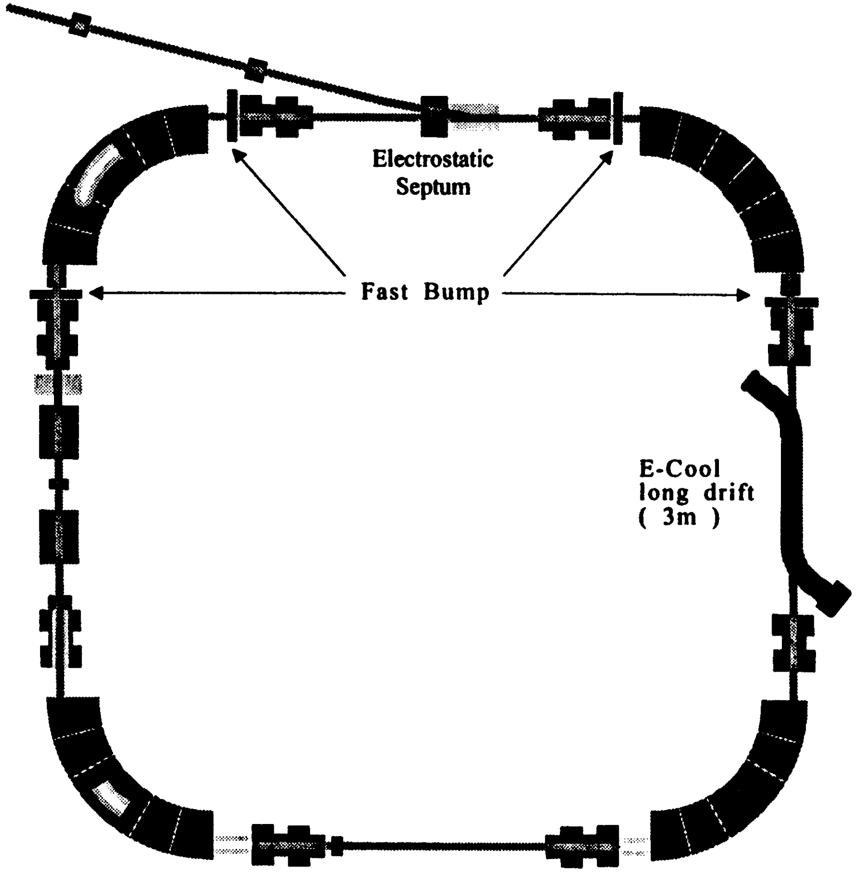


<u>ETUVAGE:</u> Compte tenu des modifications les canaux auront une signifiacation différentes. Y-at-il assez de canaux préavaux ensection 2 pour installer ecool. Probablement ila avait été prévu beaucoup de canaux supplémentaires pour Jetset.(à vérifier)

The Lear machine layout in 1996



The Lear machine layout in 1997



Distribution

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