THE ALPI SUPER-CONDUCTING ACCELERATOR UPGRADE FOR THE SPES PROJECT[*]

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Abstract

The SPES project at Laboratori Nazionali di Legnaro foresees the construction of a RIB facility based on a fission target driven by a 40 MeV proton beam. After the ^{238}U carbide target the 1+ charged ions will be selected by a high resolution mass spectrometer, charge enhanced by a charge breeder and accelerated up to 10 MeV/A for ^{132}Sn. The present configuration of the Legnaro super-conducting accelerator complex (PIAVE injector and ALPI main accelerator) fits the requirements for SPES post acceleration too. Nevertheless an upgrade of its performances both in overall transmission and final energy is needed and a solution which minimizes the impact on the present structures will be presented.

INTRODUCTION

The super-conducting linac ALPI [1] is injected either by a XTU tandem or by the s-c PIAVE injector [2][3]. The linac (at the present 64 cavities and a total voltage of 48 MV) is build up in two branches connected by an achromatic and isochronous U-bend (Fig. 1). ALPI period consists in one triplet and 2 cryostats (4 cavities in each cryostat), and a diagnostic box (profile monitor and Faraday cup) in between.

The PIAVE-ALPI complex is able to accelerate beams up to A/q = 7. Higher A/q ions suffer from a too low injection energy to the medium-β cryostats, where the RF defocusing is too strong and the beam gets easily lost onto the cavity beam ports. In the last few years the average cavity accelerating field (E_{acc}) has been enhanced by more than a factor of two with respect to the original design value [4]. The strength of the focusing lenses on the other hand, has remained the same (20 T/m). Therefore, even for 6 < A/q < 7 it is hard to design a proper longitudinal beam dynamics such that it will not cause problems on the transverse plane. To fully exploit the available acceleration gradient, some improvements are required in the layout of both PIAVE and ALPI.

Referring to the cavity performances of Tab. 1 (expected in the next years), three subsequent upgrade scenarios may be envisaged, each one representing a step forward in the final energy (Fig. 2) and beam quality: 2009 for stable beams (funded), an intermediate and a final upgrade within the SPES project (not yet officially funded). For SPES, the Radioactive Ion Beam at 37.1 keV/A will be injected into PIAVE line upstream the SRFQs.

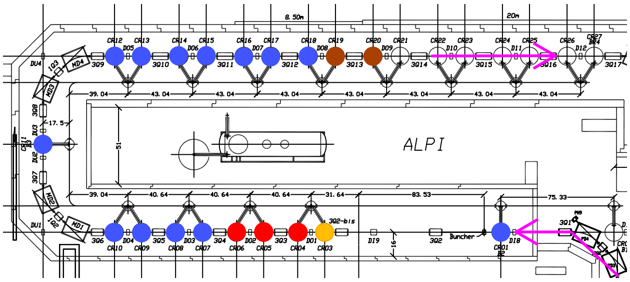

Figure 1: ALPI plan for 2009. The beam coming from PIAVE injector passes through the low-β (in orange and red), medium-β (blu) and high-β (brown) cryostats.

The beam dynamics of each scenario has been optimized for 4 < A/q < 7 thanks to several runs of PARMELA [5]: the beam behavior in the low-energy branch is highly nonlinear due to the high gradients and strong Bessel components of the fields inside the cavities, therefore, in such conditions, simulation programs like Trace3D are simply ineffective.

Table 1: ALPI cavity performances for the upgrade scenarios. E_{acc} in MV/m.

cryostat	#	2009	inter	SPES I	SPES II
low-beta (β_o = 0.047 *and* β_o = 0.056), 80 MHz					
CR01-02	8	n/a	n/a	6	n/a
CR03	4	5	6	6	6
CR04-06	12	3.5	6	6	6
medium-beta (β_o = 0.11), 160 MHz					
CR07-18	44	4.2	4.5	4.5	4.5
high-beta (β_o = 0.13), 160 MHz					
CR19-20	8	5.5	5.5	5.5	5.5
CR21	4	n/a	5.5	5.5	5.5
CR22-23	8	n/a	n/a	n/a	5.5
total number		68	72	80	80

THE 2009 STATUS

The first ALPI cryostat (CR03) gently focuses the beam coming from PIAVE to the following cryostat. Hence, only a small acceleration is given to the beam by CRO3. The E_{acc} values of the following low-energy branch cavities are

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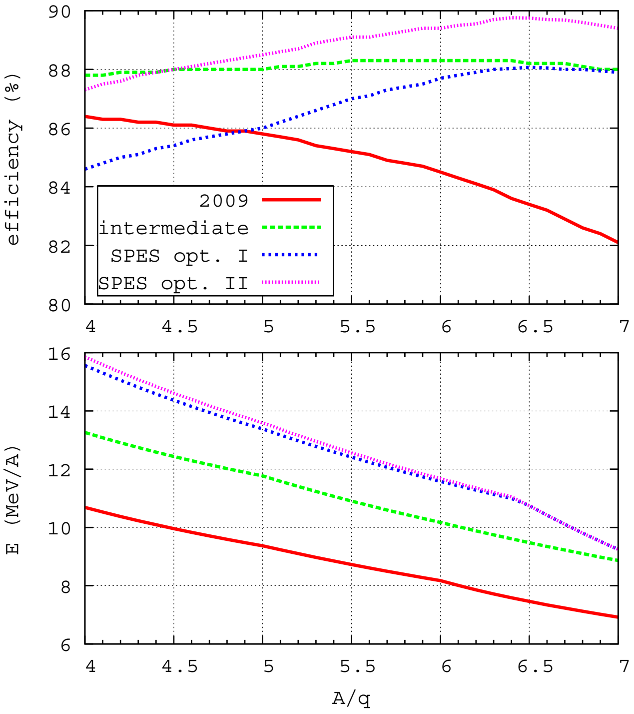


Figure 2: Accelerator efficiency and final energy for the different scenarios. The efficiency is here defined as E [MeV/A] * A/q * V^{-1}. For A/q ≥ 6.4 the final energy is limited by the 3 T·m max. rigidity in dipoles.

chosen as function of the A/q and the beam dynamics has been optimized for A/q = 7, where its main limit is the maximum gradient of the magnet before the last period (3Q5). For 6 < A/q < 7, the E_{acc} of CR09 and CR10 are raised and the maximum field is obtained for the configuration of A/q = 6. For 5 < A/q < 6, the E_{acc} is lowered by a less steep function than the linear A/q scaling, because the longitudinal match can be found by changing specific synchronous phases. For A/q = 5 the beam dynamics limit (i.e. long. phase advance and RF defocusing) is reached. Finally, for 4 < A/q < 5 E_{acc} scales like A/q. Given this optimization, it results that for A/q = 4 the acceleration efficiency is at its maximum. More low-β cavities are needed in order to accelerate larger A/q in a more comfortable way.

THE INTERMEDIATE UPGRADE

To enhance the low-β gradient, a new 80 MHz buncher is needed in front of the first ALPI period. Consequently an additional quadrupole triplet must be placed before CR03. The first period E_{acc} values are scaled by A/q up to A/q = 6, whereas the remaining ALPI low-energy branch E_{acc} are scaled up to A/q = 5. The acceleration is much more efficient than before and the final energies exceed 9 MeV/A. The higher beam rigidity requires the triplets to be replaced (20 T/m→30 T/m) both in the low and in the high-energy branch.

THE FINAL UPGRADE

The present PIAVE layout (Fig. 4(a)) is very compact, with the SRFQ cryostat immediately followed by the two QWR cryostat periods with external doublet focusing. The period is kept as short as possible, especially to reduce the longitudinal phase advance. This solution presents a weak point: the lack of a separate function matching line between the two sections. In the present set-up the first cavity is used as buncher and this results in a residual longitudinal emittance increase; as a consequence, the first part of the acceleration in ALPI is troublesome and longitudinal losses cannot be avoided. Moreover, the transverse transport is such that it causes 40% vertical emittance increase (Tab. 2). Finally, the first available beam diagnostics is located only after the second QWR period.

New Injector Layout

To improve the situation, a new layout (see Fig. 4(b)) of the line downstream the SRFQs is proposed.

Bunching section. A new low-energy n-c buncher and a quadrupole singlet must be installed. The singlet must be placed at the x-plane waist between the SRFQs and the buncher itself, in order to reverse the transverse beam divergence without affecting the quadrupole symmetry. This means that the beam dimensions are almost equal inside the cavity. After the buncher, 2PQ5 doublet focuses the beam at the first QWR cavity and the round condition should be achieved while setting the singlet field appropriately.

New cryostats. In the present PIAVE beam dynamics the synchronous phases are employed in a alternating ”funnel” scheme, $(-90| + 60| + 30| - 25)$ $(-20| - 20| - 20| + 20)$ and, in order to obtain the required longitudinal acceptance, the QWRs are set to lower E_{acc} values than the best achieved cavity performances. To overcome the problem, a shorter longitudinal and transverse period must be designed. A good solution is the periodic structure à la ISAC-II (TRIUMF) [6]: each cryostat houses 4 QWRs and a compact s-c solenoid (max 9 T) in the middle. Because of the dimensions of the cryostat and the solenoid, the effective longitudinal period comprises two cavities and it is half the transverse one. Hence, all the synchronous phases can be set to −30 and $E_{acc} \simeq 5.2$ MV/m for A/q = 7 are employed. Moreover, a short space for beam diagnostics is available between the modules. This diagnostic box, combined with

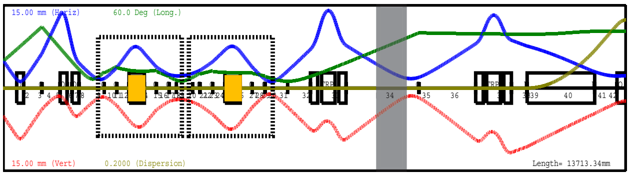
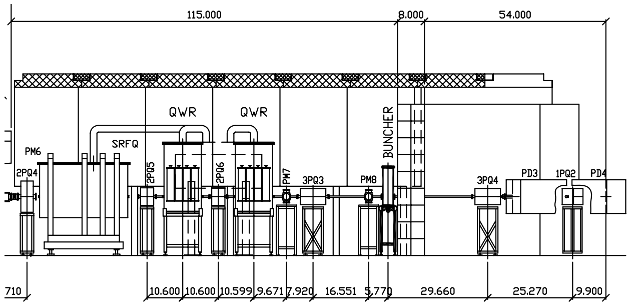
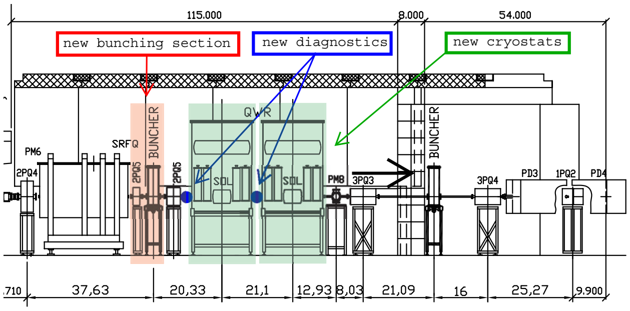


Figure 3: Beam dynamics for the new PIAVE layout from the SRFQ output to the quad singlet of the achromatic bend to ALPI.



(a) Present layout.



(b) New layout.

Figure 4: PIAVE injector layout comparison.

the one placed after 2PQ5, will be used for checking the transverse match parameters and, in particular, the roundness of the beam before it enters the first cryostat. Table 2 shows the results for the new layout: the even envelopes (Fig. 3) inside the cavities do not produce the any significant emittance growth and the final energy is increased by ~ 20%.

New HEB1 location. The n-c rebuncher HEB1 will be slightly moved downstream in order to obtain a parallel longitudinal beam transport along the bend to ALPI.

Table 2: PIAVE beam dynamics results. Emittances are in mm.mrad.

	SRFQs	present	new	*var.*
$\varepsilon_{x\ rms\ norm}$	0.100	0.102	0.105	*+3%*
$\varepsilon_{y\ rms\ norm}$	0.100	0.138	0.105	*-24%*
$\varepsilon_{z\ rms\ norm}$	0.060	0.163	0.066	*-60%*
E (MeV/A)	0.59	1.24	1.45	*+17%*

ALPI Upgrade Options

I. Low-β upgrade. The new period before CR03 can be filled with the two cryostats recovered from PIAVE. The last two low-β cryostats can be required to work at E_{acc} = 6 MV/m up to A/q = 5. This way, the acceleration efficiency would be favorable to the heaviest ions, whereas the lightest ones would suffer from an excess of low-β cavities. However, this allows to transport the beam efficiently even if some low-β cavities were out of order.

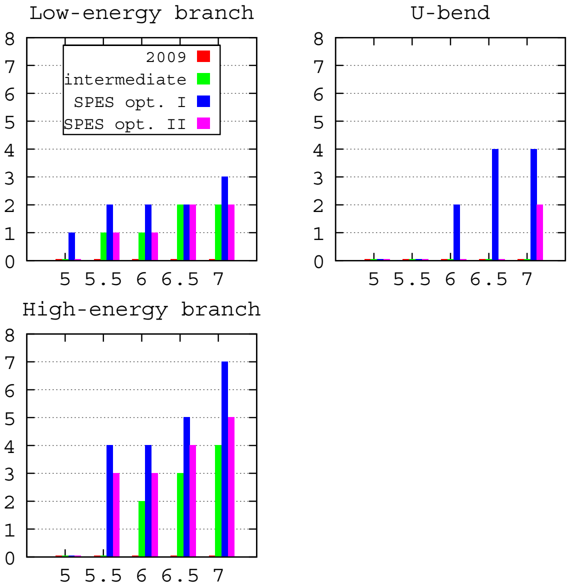


Figure 5: Number of quadrupole triplets that need to be replaced (20 T/m→30 T/m) in the various scenarios as function of A/q.

II. High-β upgrade. Alternatively, the two cryostats could be placed downstream the high-energy branch. This way, the number of cavities would be more effectively divided among the three optimum betas an the final energy for the lightest ions would be slightly enhanced.

CONCLUSIONS

As shown in Fig. 2, in the second and third scenario the heaviest ions are accelerated in a increasingly efficient way. It is worth to point out, however, that the maximum magnetic field of the dipoles (1.6 T) in ALPI and in the extraction lines limits the performances of the SPES scenario for A/q ≥ 6.4.

SPES option I is the most demanding scenario from the point of view the magnetic quadrupole replacement (Fig. 5). The only way to keep the existing magnets in both the U-bend and the high-energy branch is to use a stripper foil, as described in [7]. As a major consequence of this, the final energies increase by 30% at the cost of a lower transmission, depending on the selected charge state probability (15 ~ 20% for the heaviest ions).

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