Beam Dynamics in the SPL Nominal Layout

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LINAC4: Injector of SPL

Source 45keV | LEBT | RFQ 3MeV | Chopper | DTL 50MeV | CCDTL 100MeV | PIMS 160MeV

LINAC4 which presently is under construction is a normal conducting proton LINAC which is the front end of SPL.

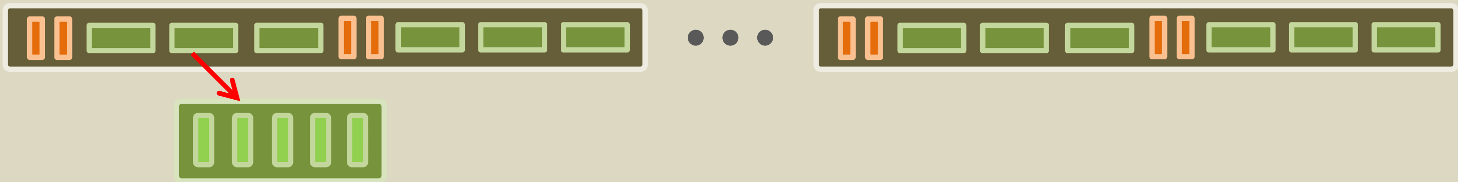
An H- source delivers 45 keV ions to magnetic LEBT which transfers and matches the beam to RFQ.

RFQ resonates at 352.2 MHz and accelerates the beam to 3 MeV, where a chopper removes some bunches (3/8) and matches the beam to DTL.

DTL is using PMQs and has a FFDD lattice in its first tank and a FODO lattice at the next two tanks.

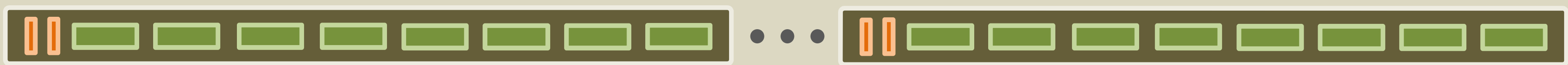
Downstream of DTL is the CCDTL which ramps the energy from 50 to 100 MeV in 7 tanks, and finally a Pi-Mode Structure brings the beam to its final value of 160 MeV.

Nominal Layout: Scheme



SPL starts from 160 MeV after LINAC4, and works at 704.4 MHz, twice the frequency of LINAC4.

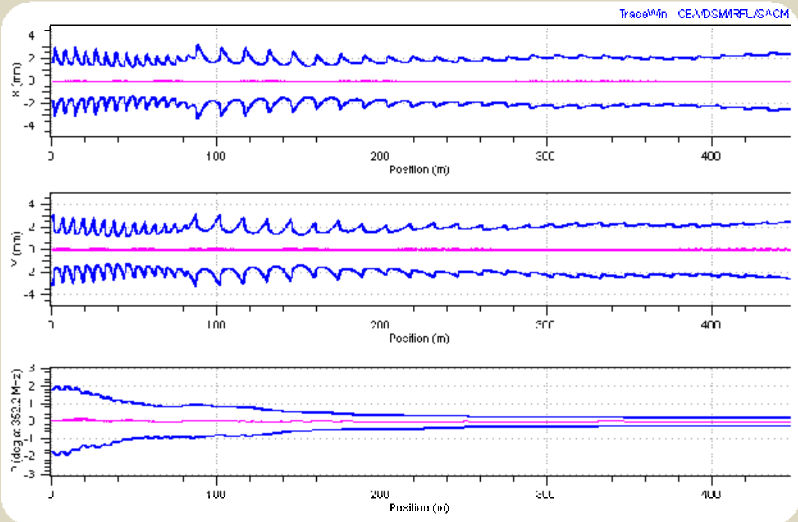
The first structure has a geometric beta of 0.65 and increases the energy to 574 MeV using 7 modules each 11.85 meters. The drift between cryo-modules is 500 mm.

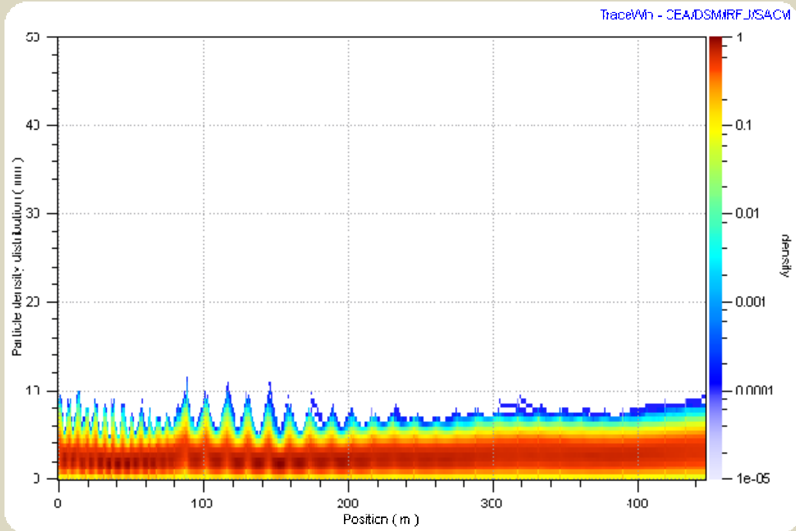


The second structure has a geometric beta of 0.92 and increases the energy to 5070 MeV using 25 modules each 13.93 meters + 0.5 meters drift in between.

Nominal Layout: Beam dynamics

Envelopes and particle densities



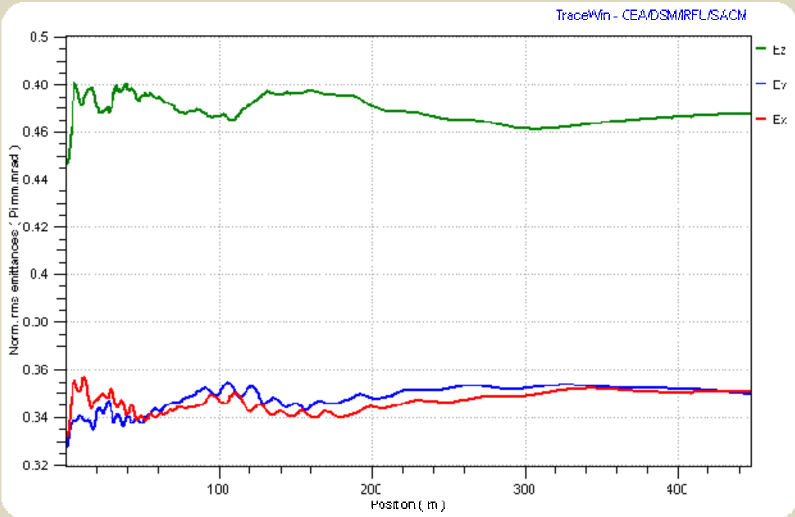


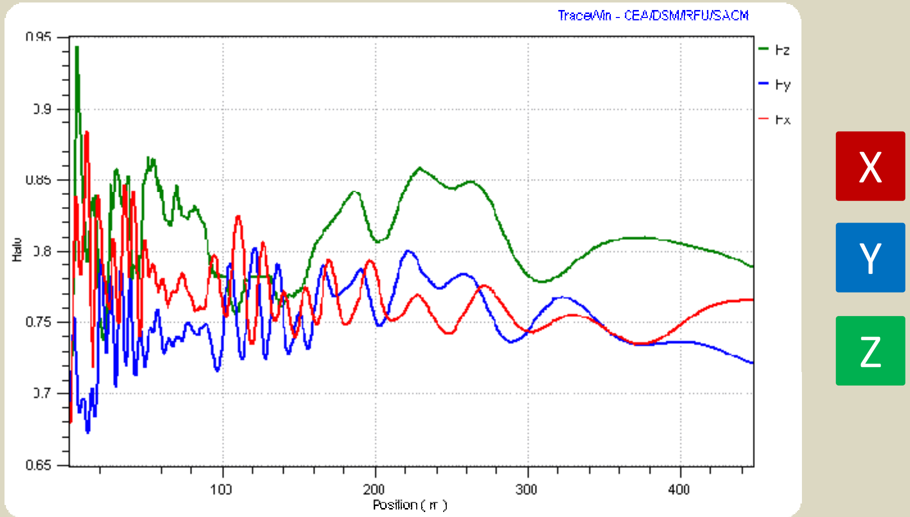
Transverse focusing is done using pairs of SC quadrupoles.

With a generated beam at the input, the particles, without error, are well within the aperture (50 mm radius)

Nominal Layout: Beam dynamics

Emittances and Halo





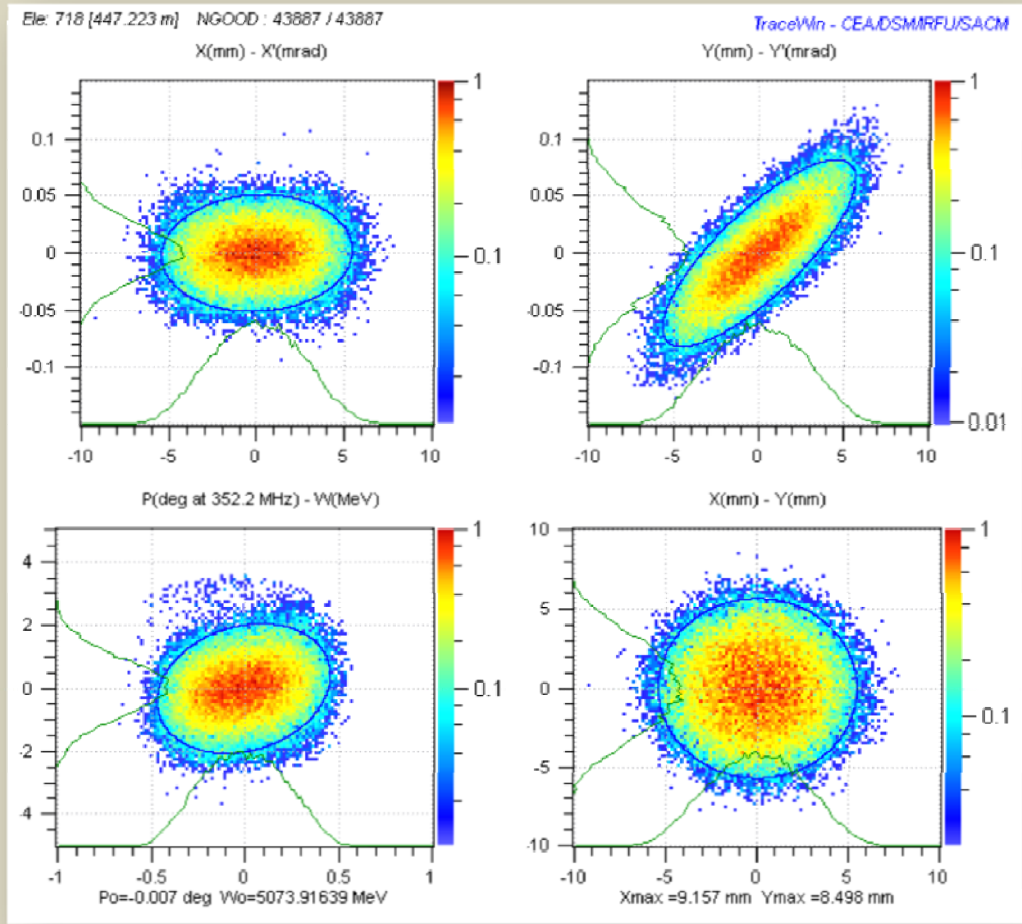
Emittances, except at the very beginning, are almost constant, with a total increase in rms values: $\Delta\varepsilon_x$ = 2.6% $\Delta\varepsilon_y$ = 3.7% $\Delta\varepsilon_z$= 7.7%

Halo oscillates around 0.78 which is the initial value of Halo for a Gaussian beam cut at 3 σ

Nominal Layout: Beam dynamics

SPL output

	Value	Unit
X_{rms}	2.4	mm
Y_{rms}	2.5	mm
ΔE_{rms}	0.919	MeV
$\Delta\phi_{rms}$ @704MHz	0.513	deg
$\varepsilon_{norm.rms}$ xx’	0.35	pi.mm.mrad
$\varepsilon_{norm.rms}$ yy’	0.35	pi.mm.mrad
$\varepsilon_{norm.rms}$ $\Delta E\phi$’	0.186	pi.deg.MeV



Nominal Layout: Error Study

Implied errors and results

Applied errors			Results of the statistical runs				
$\Delta\phi$ [Deg]	ΔG [%]	$\sigma\Delta E$ [keV]	RF phase st. dev. [Deg]	Ave. Kinetic Energy [MeV]	$\Delta\varepsilon_x$ [%]	$\Delta\varepsilon_y$ [%]	$\Delta\varepsilon_z$ [%]
0.5	0.5	55	0.28	5076 ± 1.7	0.03 ± 0.2	0.1 ± 0.2	0.2 ± 0.5
0.5	0.5	125	0.26	5076 ± 2.0	0.07 ± 0.3	0.2 ± 0.3	0.4 ± 0.6
1	1	55	0.57	5076 ± 3.6	0.2 ± 0.4	0.5 ± 0.5	1.3 ± 1.3
1	1	125	0.60	5076 ± 3.9	0.2 ± 0.4	0.5 ± 0.6	1.2 ± 1.4

55 keV energy jitter is the effect of 5% error [tilt] in PIMS field
125 keV energy jitter is due to 1% error in feeding klystrons of PIMS
Field and Phase error have a uniform distribution and Energy has a Gaussian distribution cut at $3 \times \sigma$

Transfer-line to PS2

Different schemes

Transfer-line from SPL to PS2 is a 450 meters long straight beam transfer-line. No buncher or debuncher has been included in the line for the moment.

Three different focusing schemes, all using doublets, have been designed and simulated:

1: Focusing period length equal to the focusing period in SPL (14.43 m) total of 32 periods.

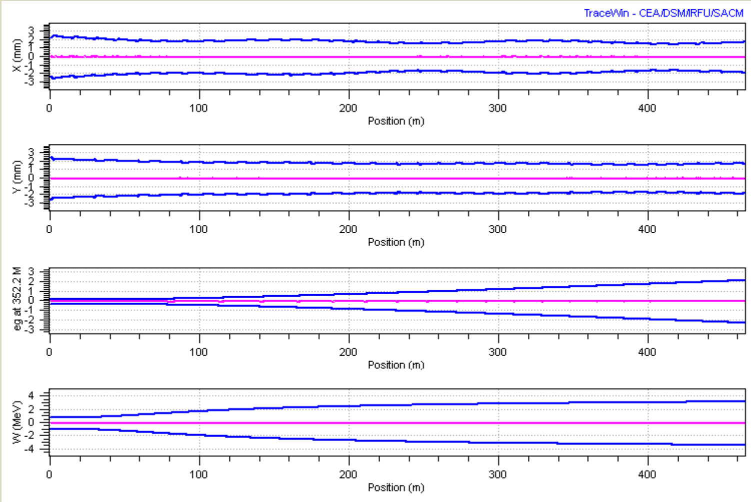
2: Focusing period length twice of the focusing period in SPL (28.86 m) total of 16 periods.

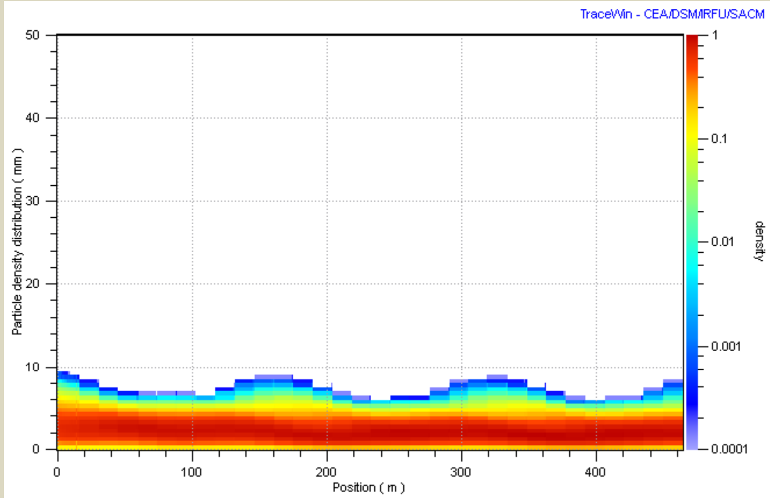
3: Focusing period length three times of the focusing period in SPL (43.3) total of 11 periods.

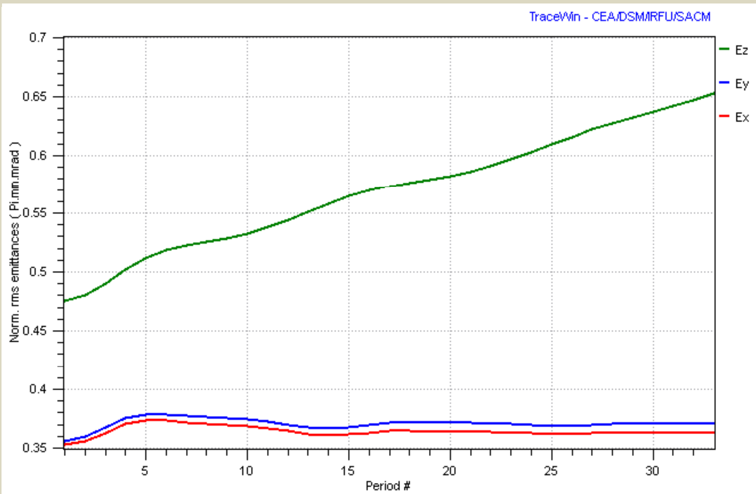
In each of the three schemes the last cryo-module of SPL has been included to match the beam to the transfer-line

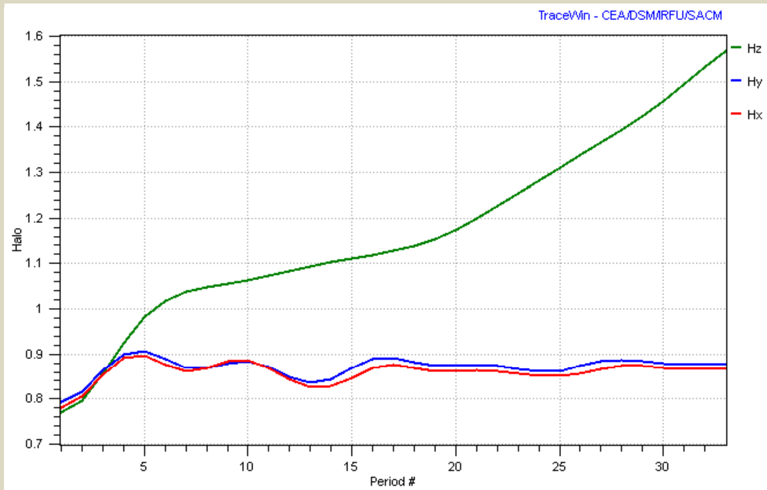
Transfer-line to PS2: Beam dynamics

Envelopes, particle density, emittances and Halos I









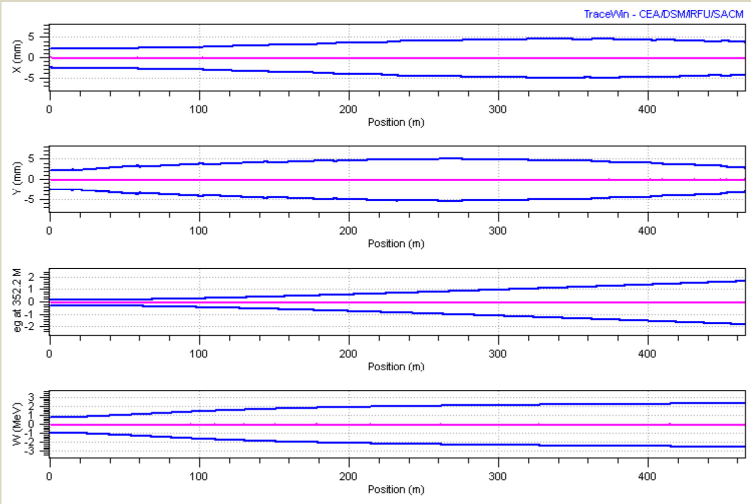
X

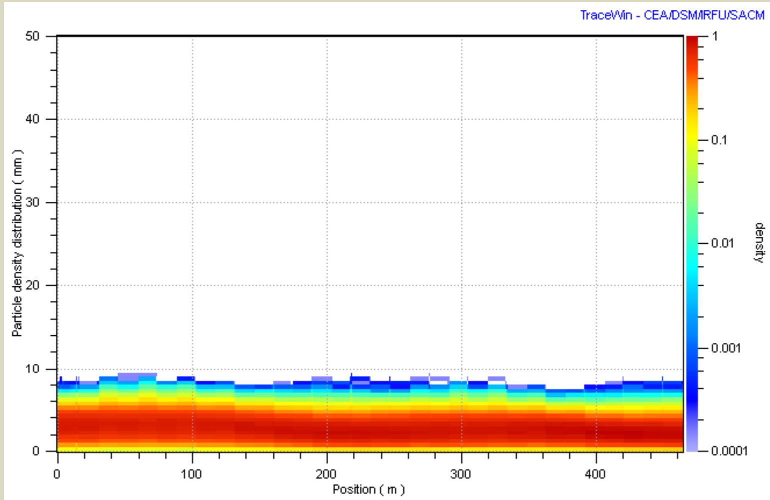
Y

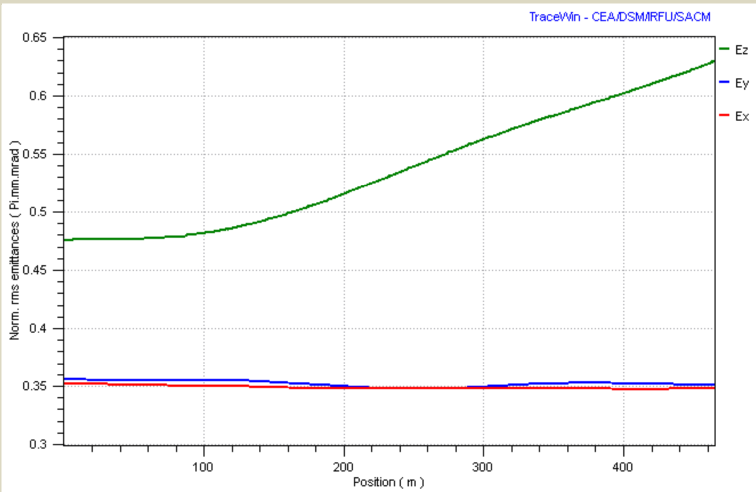
Z

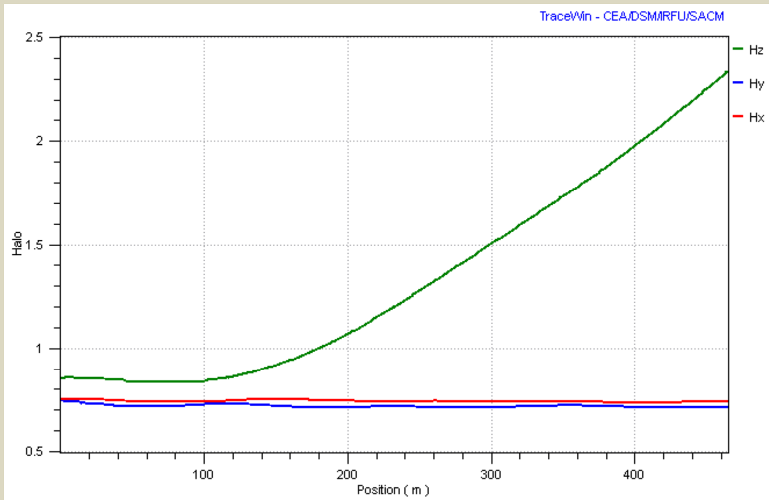
Transfer-line to PS2: Beam dynamics

Envelopes, particle density, emittances and Halos II









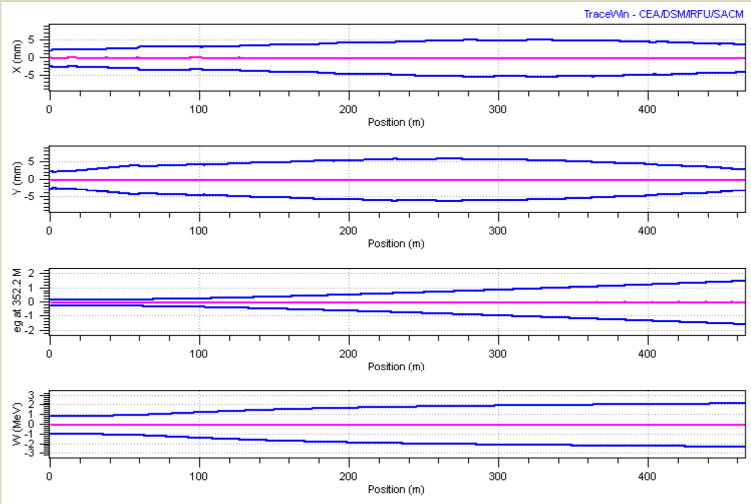
X

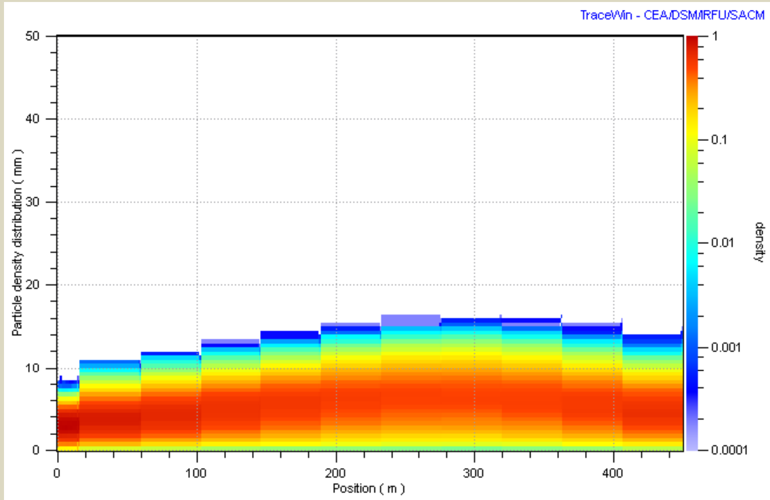
Y

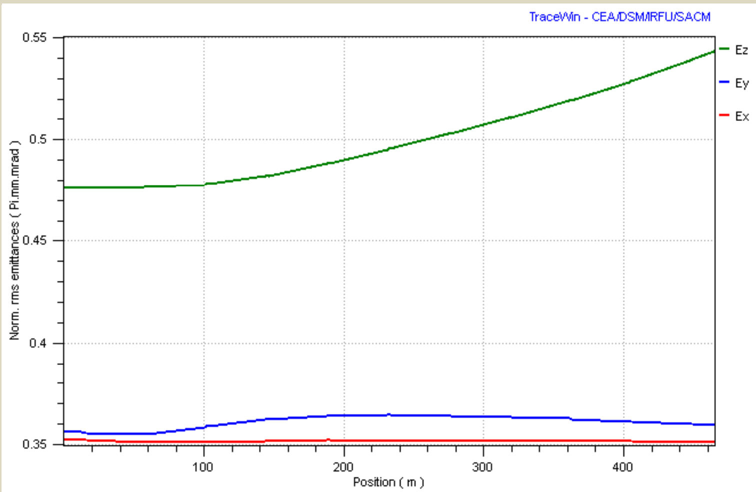
Z

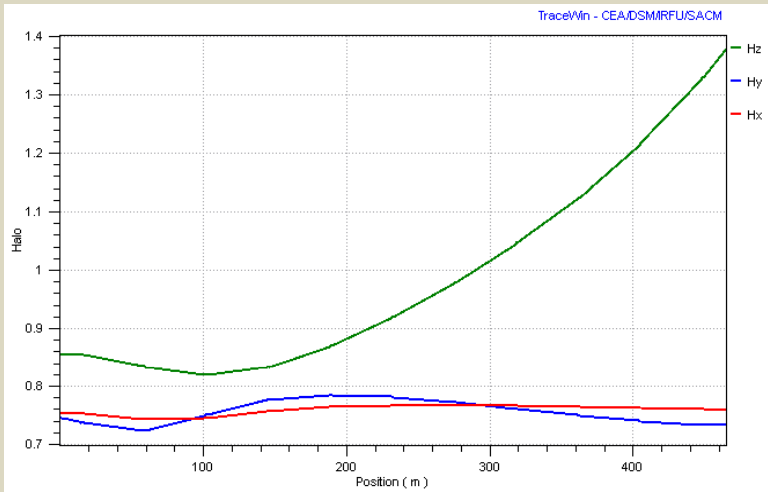
Transfer-line to PS2: Beam dynamics

Envelopes, particle density, emittances and Halos III









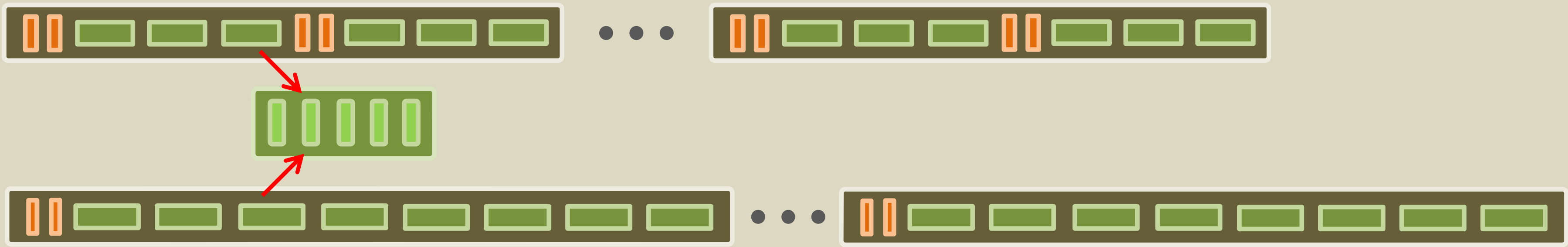
Transfer-line to PS2: Beam dynamics

Summary and Comparison

	Unit	Scheme I	Scheme II	Scheme III
R_{max}	mm	9.5	9.5	17.0
ΔE_{rms}	MeV	3.318	3.018	2.245
$\Delta \phi_{rms}$	deg	4.49	4.07	3.07
$\Delta \varepsilon_x$	%	2.9	-1.3	-0.3
$\Delta \varepsilon_y$	%	3.9	-1.6	0.9
$\Delta \varepsilon_z$	%	37.5	32.3	14.2

Adding a cavity may necessitate changing the transverse focusing scheme, at least locally, to keep the phase advance ratio between the transverse and longitudinal planes far from resonances.

Higher β_g Layout: Scheme



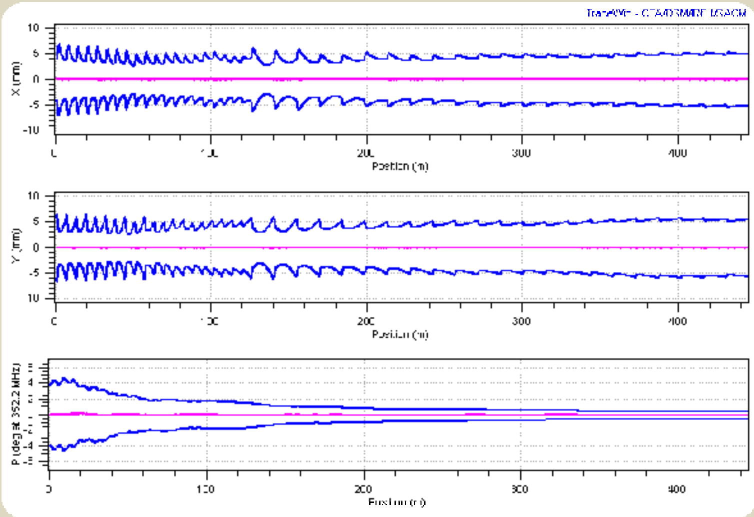
Increasing the transition energy from 574 to 806 MeV, and at the same time changing the geometric beta of cavities to 0.67 and 0.93 respectively, reduced the number of cavities by 14. The phase law and all the distances have been kept the same as nominal layout.

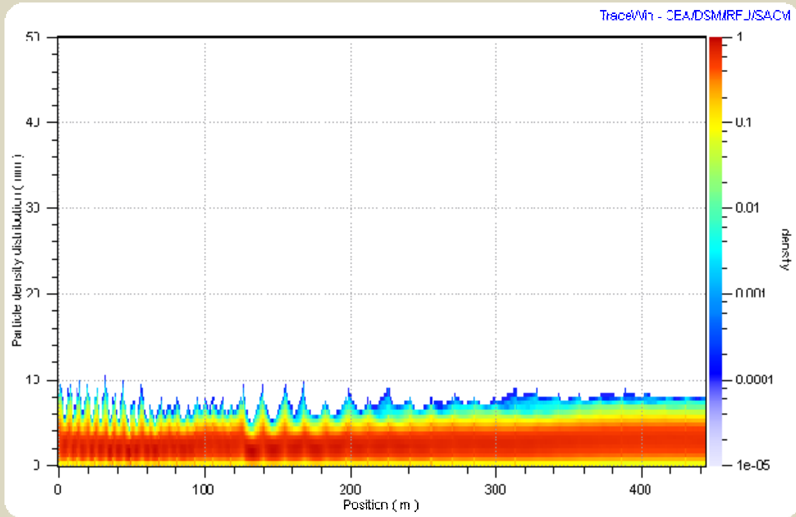
There are 30 low beta periods (6.24 m), each pair housed inside a single cryo-module of 11.976 meters. There is 500 mm drift between cryo-modules.

Total number of high beta periods is 22, each 14.516 meters long including the 500 mm drift. Final energy is 5002 MeV.

Higher β_g Layout: Beam dynamics

Envelopes and particle densities

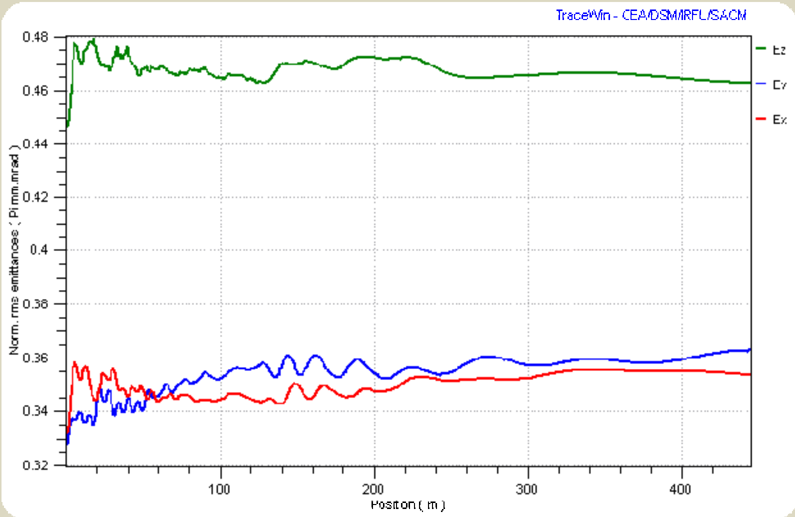


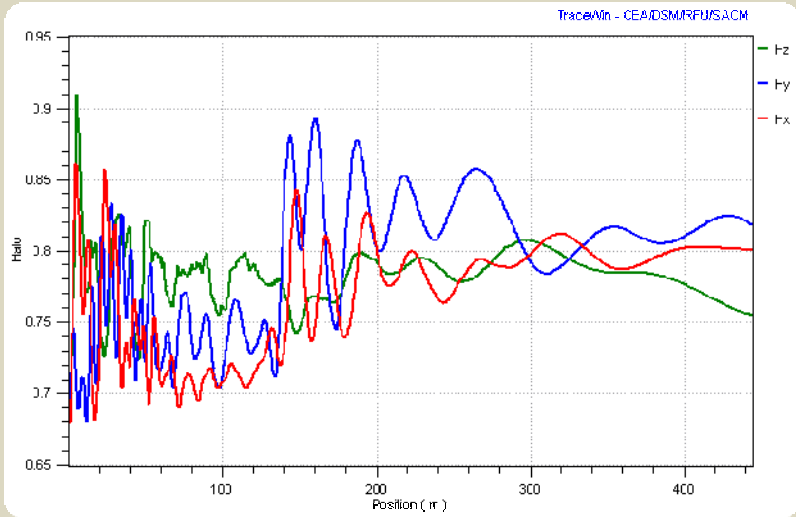


Transverse focusing is achieved using SC doublets which are housed inside the same cryo-module.
An end-to-end beam plus quadrupole error will increase the maximum size of the beam. Collimation at low energies will increase the margin between beam and aperture.

Higher β_g Layout: Beam dynamics

Emittances and Halo





X

Y

Z

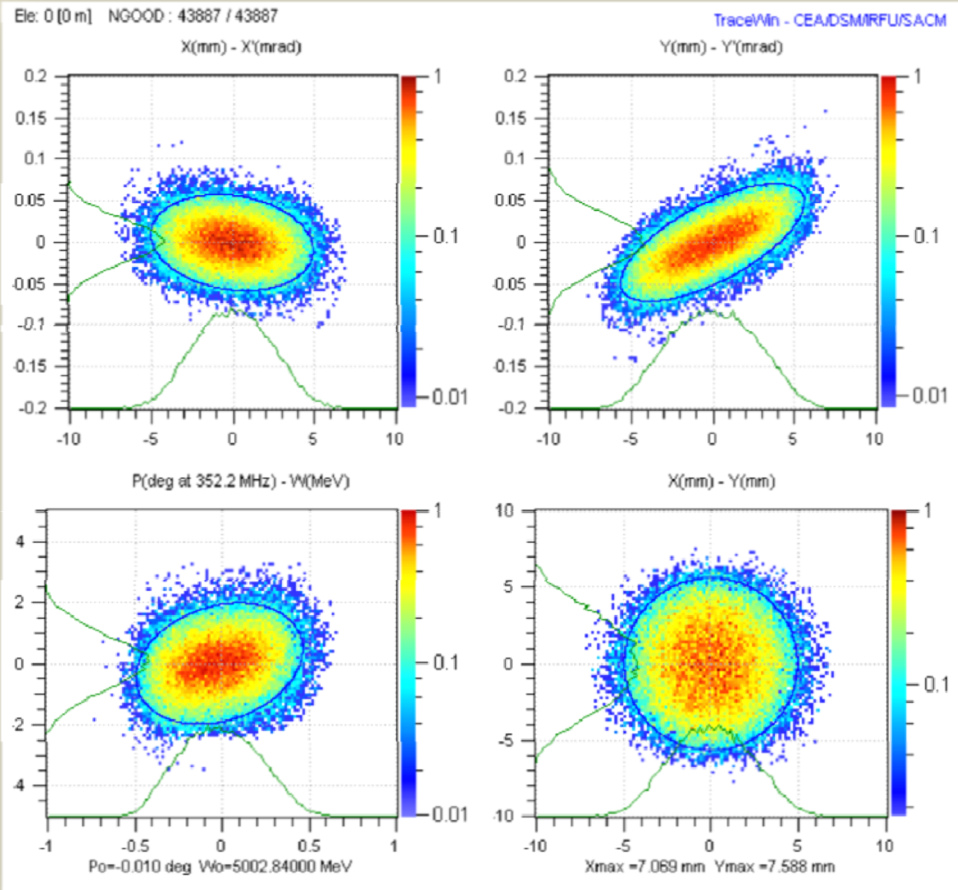
Using doublets has slightly reduced the transverse flexibility to match, and transverse emittance growth is higher with respect to nominal layout; $\Delta\varepsilon_x = 6.4\%$ $\Delta\varepsilon_y = 10.6\%$ $\Delta\varepsilon_z = 3.6\%$

Except around the matching between two structures, Halo parameter does not change a lot and the final value is still very close to the value of Halo for a Gaussian beam cut at 3 σ.

Higher β_g Layout: Beam dynamics

Optimized SPL out

	Value	Unit
X_{rms}	2.2	mm
Y_{rms}	2.5	mm
ΔE_{rms}	0.887	MeV
$\Delta\phi_{rms}$ @704MHz	0.417	deg
$\varepsilon_{norm.rms}$ xx'	0.35	pi.mm.mrad
$\varepsilon_{norm.rms}$ yy'	0.36	pi.mm.mrad
$\varepsilon_{norm.rms}$ $\Delta E\phi$'	0.184	pi.deg.MeV



Conclusion and Further Studies

- Higher β_g layout, while it might not be the best solution, indicates that there is still room to optimize the LINAC length and/or number of cavities.
- Transmission of beam from SPL to PS2 can be done using much longer periods, yet statistical runs have to be performed to prove lossless transition. Adding debunchers may require the need for stronger transverse focusing.

- Using doublets in the Nominal Layout + launching transverse and longitudinal error study.
- Matching the beam to the PS2 longitudinal and transverse acceptance.
- Reducing the emittance increase in the higher β_g layout + launching a set of statistical runs.
- Collimation of the LINAC4 beam and tracking the evolution of halo after collimation in SPL and its transfer-line(s).

Thank you for your attention, comments, and questions.