Imperial College London

Status of the Neutrino Factory Muon Linac

Morteza Aslaninejad, Cristian Bonțoiu, Jürgen Pozimski

Department of Physics at
Imperial College London

Second Annual Meeting of EURONU

June 1-4, 2010

Overview

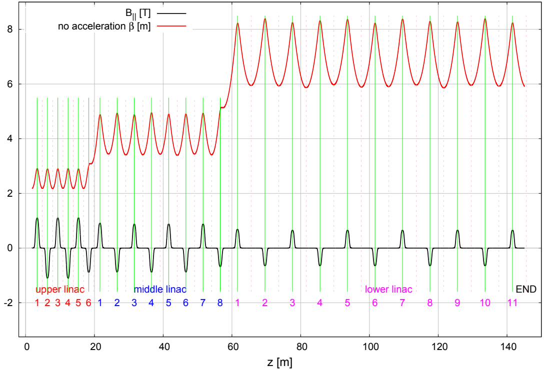
- The lattice
  layout of the three cell types, on-axis magnetic field and β functions
- The components
  design and performance of the solenoids and RF cavities
- Comparative tracking
  evolution of the transverse and longitudinal phase spaces through the three cell types
- Front-to-end tracking
  a Gaussian beam tracked through the whole linac
- Problems and solutions
  weak points of the current design and how to overcome them
- Conclusions and future work
  physics and engineering challenges coming next

The lattice

- β functions have been derived from on-axis magnetic fields for the nominal energy (240 MeV) and must be kept at the level as the muons energy increases, by rising up the solenoidal fields.

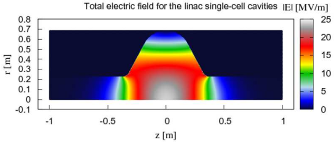
Linac section	cell length	no. of solenoids	no. of RF cells
upper	3 m	6	6
middle	5 m	8	16
lower	8 m	11	44

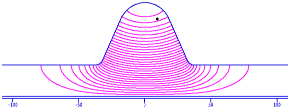
- lower linac β functions are not perfectly matched here since the transitions have to be accurate to the third digit but this has negligible impact on particle tracking.

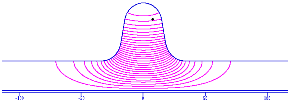


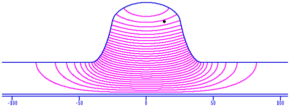
The components RF cavities

- a few RF cell layouts have been investigated with the aim of maximizing the transit time factor T and implicitly the effective energy gain ΔW, while keeping the surface electric and magnetic fields to a minimum;
- in the end $\beta = 1$ design has been choosen.







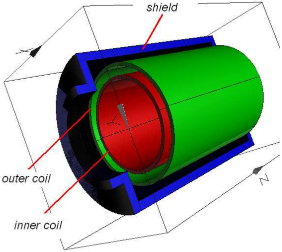


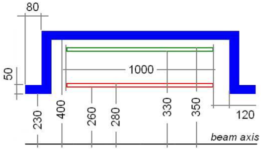
- due to the fact that the cavity length is slightly longer than half of the RF wavelength, for a peak voltage of 26.17 MeM/m a sychronous particle would gain 8.61 MeV instead of 10 MeV as intended;
- in practice, subject to the longitudinal particle distibution, the average gain will be less by 10-20 %.

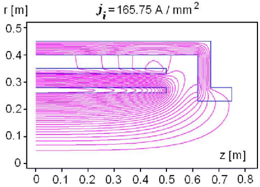
Parameter	$\beta = 1$ top	$\beta = 0.9$ middle	$\beta = 0.9$ not shown	Study II bottom
l_{cav}[m]	0.7448	0.67034	0.67034	0.8282
r[m]	0.6854	0.7042	0.6804	0.6641
f_0[MHz]	201.247	201.251	201.255	198.575
Q [10^9]	24.67	19.6	18.8	26.7
T	0.650	0.716	0.726	0.591
$\hat{E}$[MV/m]	26.17	27.19	27.83	26.38
$\|E\|_{surf}^{max}$[MV/m]	21.70	24.87	29.45	19.75
$\|H\|_{surf}^{max}$[kA/m]	48.06	58.53	61.92	45.00
U[J]	712	772	797	747
$\Delta\ W^{max}$[MeV]	8.6142	9.0081	9.1336	8.8466

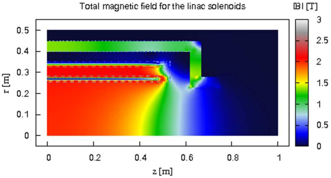
solenoids

- solenoids have been optimized in order to minimize field leackage towards the neighbouring RF cavities by designing two current-carrying shells surrounded by a 50 mm thick iron shield;
- 2D field maps have been obtained with the Poisson code and implementation into the ROXIE code is on the way in order to study the inherent superconducting effects.









Comparative tracking

- 1000 particles generated by GPT within Gaussian phase space distributions have been tracked through all cell types cells in order to determine the beam acceptances;
- the normalized rms longitudinal emittance is expressed as:

$$\begin{aligned}\bar{\varepsilon}_{||}\,[eV\,s] &= \frac{mc^2}{|q_e|}\sqrt{<t_c^2><\gamma_c^2> - <\gamma_c\,t_c>^2}\\ t_c &= t - <t>\\ \gamma_c &= \gamma - <\gamma>\end{aligned}$$

- the normalized rms transverse emittance is expressed as:

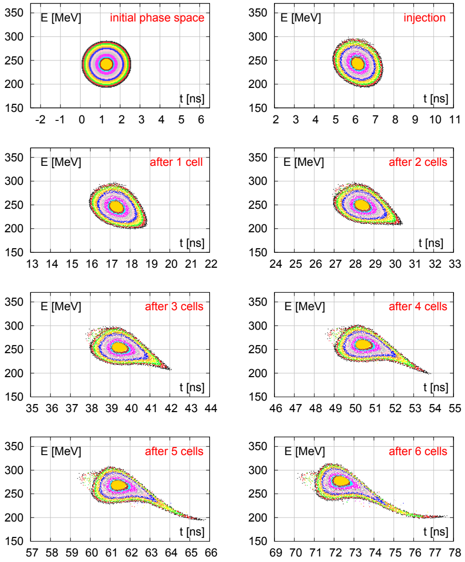
$$\begin{aligned}\bar{\varepsilon}_{\perp}\,[\pi\,m\,rad] &= <\gamma>\sqrt{\bar{\varepsilon}_x\bar{\varepsilon}_y - |<x_c y_c><x'_c y'_c> - <x_c y'_c><x'_c y_c>|}\\ \bar{\varepsilon}_x\,[\pi\,m\,rad] &= <\gamma>\sqrt{<x_c^2><x_c'^2> - <x_c\,x'_c>^2}\\ x_c &= x - <x>\\ x'_c &= \beta_x - <\beta_x>\end{aligned}$$

and similarly for y

- all tracking sessions have been performed with the GPT code making use of realistic 3D field maps.

longitudinal phase space fillamentation

- it is important to understand that since the bunch length coming from the cooling channel equals the RF wavelength (2.48 ns) its longitudinal phase space will be rapidly filamented and upon *smart RF phasing* only the core of its longitudinal distribution can be transmited till the end of the linac;
- tracking uniform beam distributions through the upper linac cells has showned that only a region (golden yoke) of about 0.7 ns by 20 MeV can be preserved, passing through 201.25 MHz RF fields;
- for Gaussian beams the transmission will be certainly more efficient.

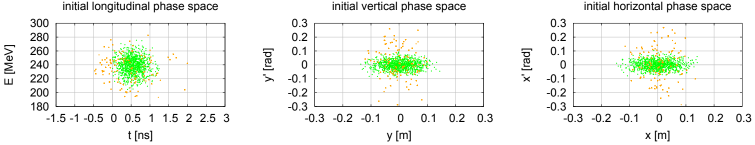


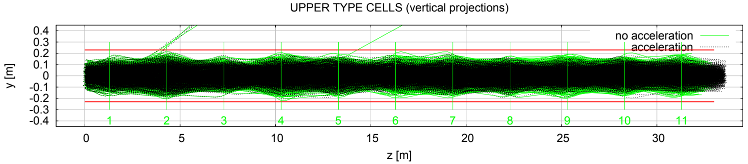
upper linac acceptances

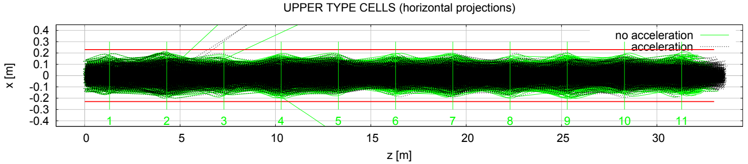
orange: beam at the end of the cooling channel

green: Gaussian beam distributions used for tracking with $\bar{\varepsilon}_{\perp} = 3.02\,\pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms,

$\sigma_{\boldsymbol{t}} = 0.25$ ns, $\sigma_{\Delta \boldsymbol{E}} = 5$ %, $<E> = 240$ MeV, $\sigma_{\beta_\perp} \approx 0.1$, $\sigma_{\boldsymbol{x},\boldsymbol{y}} \approx 5$ cm





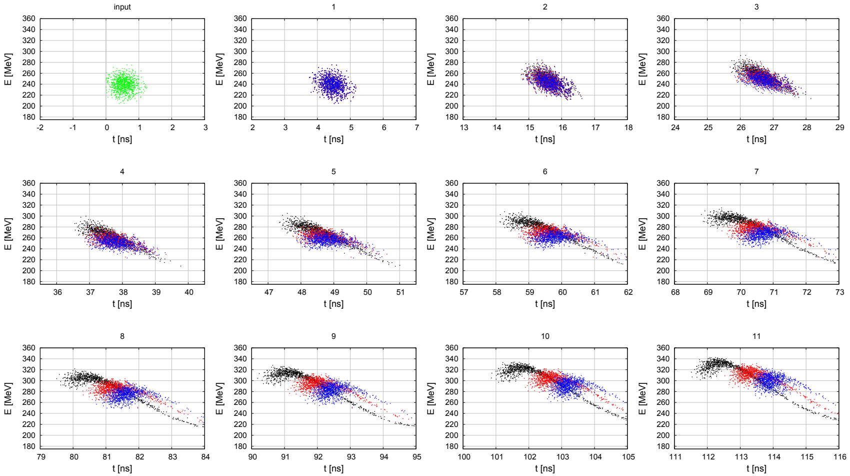


longitudinal phase space through upper linac cell types

black: each RF phase optimized for maximum average acceleration

red: all RF phases shifted backwards by 50°

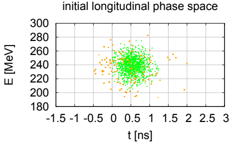
blue: RF phases shifted backwards by 60, 65, 70, 75, 80, 85, 90, 95, 100 and 105° respectively

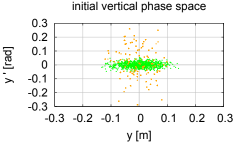


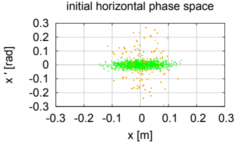
middle linac acceptances

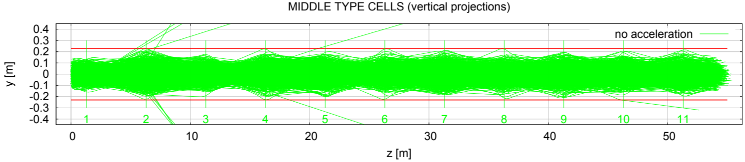
$\bar{\varepsilon}_{\perp} = 1.71\ \pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms, $\sigma_{\boldsymbol{t}} = 0.25$ ns, $\sigma_{\Delta \boldsymbol{E}} = 5$ %, <E> = 240 MeV

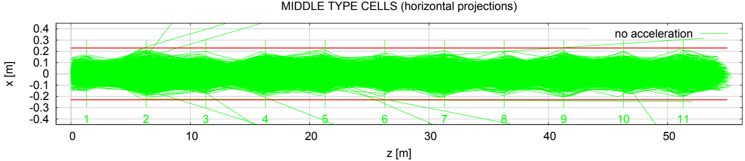
- since β functions increase, transverse acceptance must decrease to accommodate the same beam size.







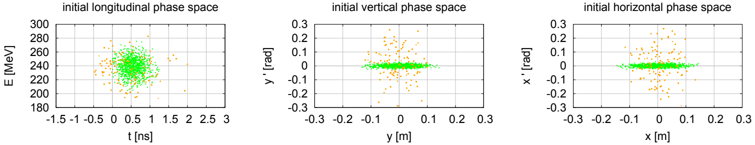


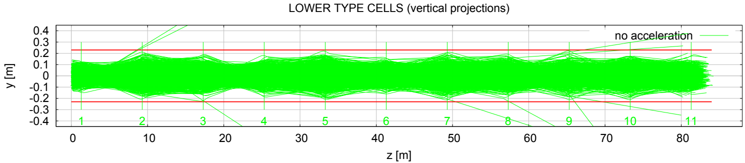


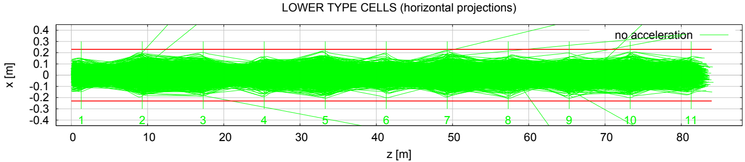
lower linac acceptances

$\bar{\varepsilon}_{\perp} = 0.96\ \pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms, $\sigma_{t} = 0.25$ ns, $\sigma_{\Delta E} = 5$ %, <E> = 240 MeV

- transverse acceptance decreased again, implicitely lowering the whole linac acceptance to this value.



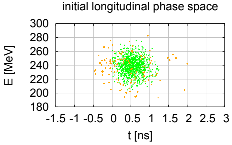


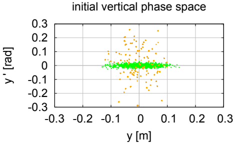


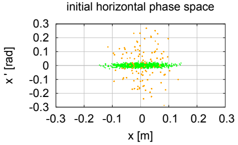
Front-to-end tracking

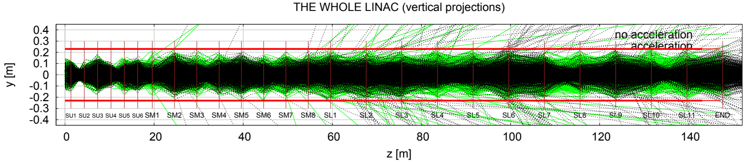
$\bar{\varepsilon}_{\perp} = 0.96\ \pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms, $\sigma_{\boldsymbol{t}} = 0.25$ ns, $\sigma_{\Delta \boldsymbol{E}} = 5\ \%$, <E> = 240 MeV

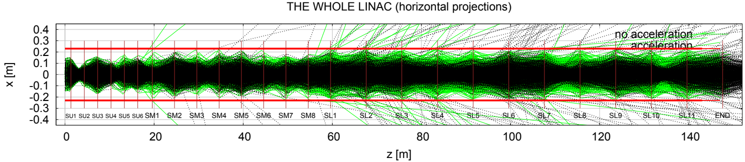
- the three β function levels are direclty correlated with the transverse beam size since $\bar{\varepsilon}_{\perp} =$ const.





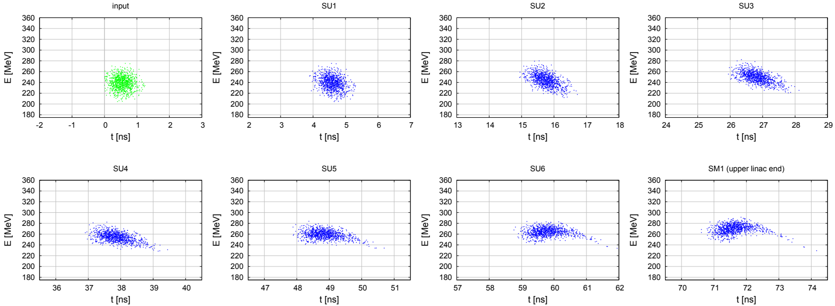






longitudinal phase space through upper linac

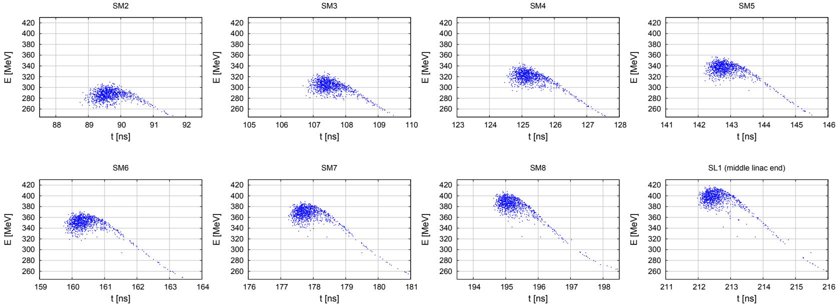
- efficient bunch compression scheme will keep most of the particles into the original phase space boundaries but the price to be paid is a poor acceleration rate, namely 5 MeV/cell at full power.



longitudinal phase space through middle linac

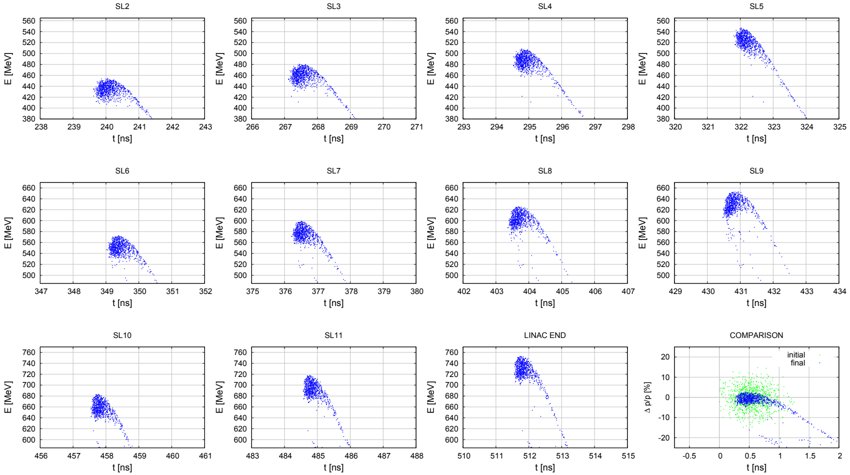
- ignoring the bunch tail, the energy spread increases from 20 MeV to 40 MeV while the bunch length remains roughly constant;

- an acceleration rate of about 8 MeV/cell has been achieved here.



longitudinal phase space through lower linac

- an acceleration rate of about 7.6 MeV/cell has been achieved here;
- since the bunch length is virtually frozen at this stage, it becomes difficult to compress the bunch energy spread (now reaching about 50 MeV) via the phase stability principle;
- the final energy is 735 MeV and not 900 MeV!



Problems and solutions

- with an average effective energy gain of about 7.5 MeV/cell there must be 66 + 22 = 88 RF cells to reach 900 MeV at the end of the linac;

- beam transverse acceptance decreased from 3.02 to 1.71 and then to 0.96 π *mm mrad* as transverse β functions increased from 2.90 to 4.93 and then to 8.25 m since the cells must be longer in order to accommodate longer cryo-modules;

- there is a significant transverse-to-longitudinal coupling, following the interplay between the finge solenoidal fields and the non-negligible muon transverse velocities (this makes their path differ in length);

- this coupling seems to be an aid when phasing the RF cells for bunch compression and thus *upper type cells* can preserve the bunch to a smaller phase space area;

- building the whole linac with *upper type cells* only would increase the transverse acceptance (by a factor of 3), improve bunch compression, eliminate the problem of matching the transitions (source of particle losses), reduce the cost of the cryomodules, keep the same amount of the RF cells at the expense of adding more solenoids;

- unless the linac lattice cells are modified, a significant effort has to be done for the design of a cooling-to-linac matching section, which may result in another linac by itself, increasing costs;

Conclusions and future work

- the whole muon linac has been simulated using Gaussian bunches and realistic field maps for solenoids and RF cavities;
- there is a visible bunch compression in what concerns the longitudinal phase space;
- the 900 *MeV* target cannot be reached but there are a few possibilities of overcoming this issue;
- for the time being cavity phasing has been done *by hand* since GPT doesn't have an algorithm to do bunch compression;
- cavity and solenoids field maps as well as the RF phasing method will be upgraded to refine the results but in principle these results are all one can get with the current lattice;
- a decision on the possible lattice changes will be taken soon after these results will be compared to previous simulations preformed with Elegant at JLab.