Imperial College London

Jefferson Lab

Beam dynamics in the low energy linac

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a joint work of Imperial College, JLab and RAL

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Overview

1. Linac layout and hardware design

   SC RF cavities and solenoids

2. Understanding beam behaviour

   bunch confinement and acceleration

3. Front-to-end particle tracking

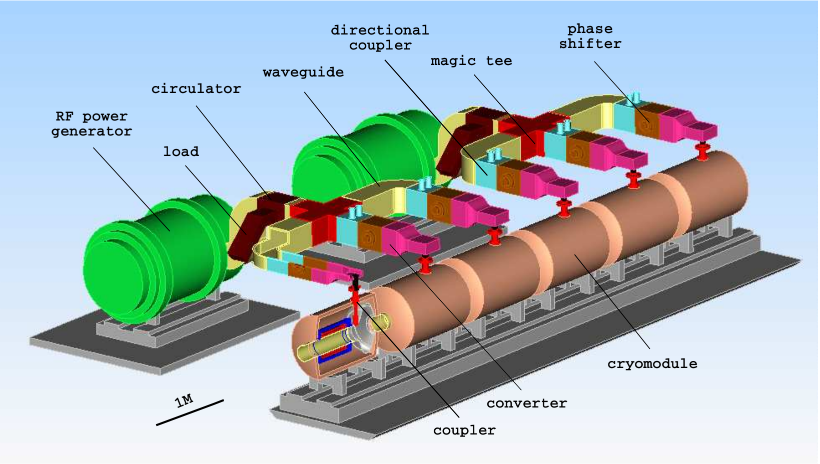
   particle trajectories and phase space

4. Conclusions

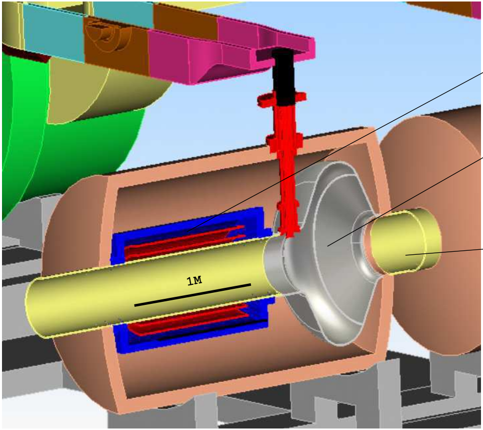
   current status and future plans

1. Linac layout and hardware design

- the linac consists of three parts:
  - *upper linac* made of 6 one-single-cell (short) cryomodules at 3 m peridicity (shown here);
  - *middle linac* made of 8 one-double-cells (medium) cryomodules at 5 m periodicity;
  - *lower linac* made of 11 two-double-cells (long) cryomodules at 8 m periodicity.



details of the short cryomodule

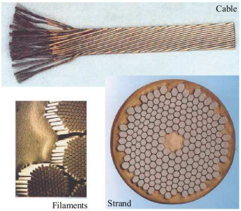


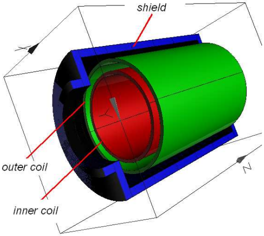
a two-shell shielded SC solenoid was modelled (Poisson/Roxie) in order to obtain a 3D realistic magnetostatic field map;

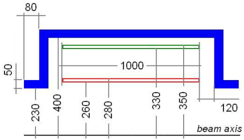
a single-cell SC RF cavity was modelled (Superfish/CST-MW/Comsol) in order to obtain a 3D realistic electric field map which was further fed into particle tracking considering various RF phases;

23 cm radius vacuum pipe

details of the solenoid design

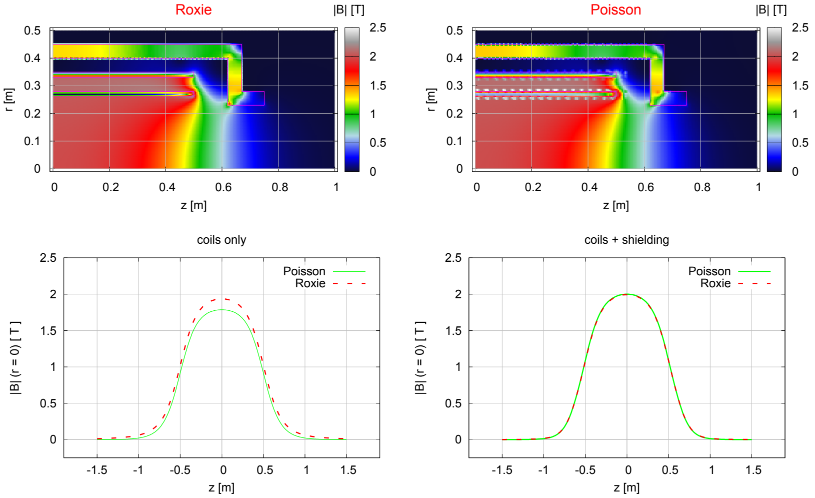






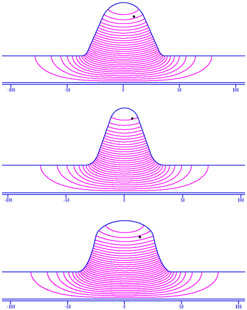
SC cable	LHC dipole	Neutrino Factory solenoid
Cable geometry [mm]	15.1 × 1.3/1.7 × 1.6/2.0	20 × 2 × 2
No. of strands	28/36	36
Strand details	diameter = 1.065 mm, Cu/SC ratio = 1.6 working temperature = 1.9 K, reference field = 10 T critical current at reference field = 1433 A/mm^2 filament diam. = 7 μm, insulation thickness = 0.12/0.15 mm	

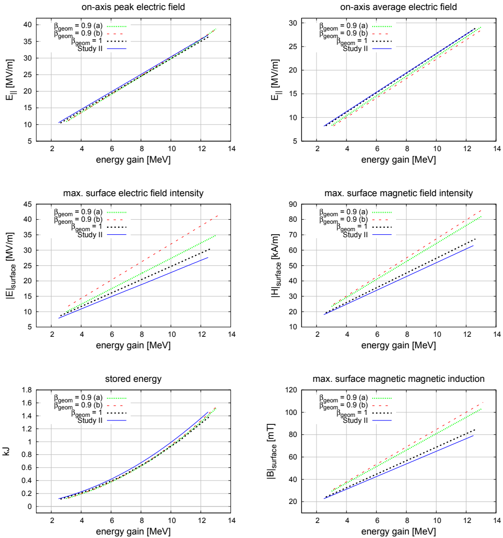
magnetostatic field map for the SC solenoid



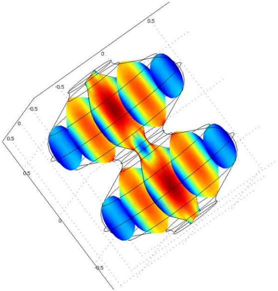
details of the RF cavity design

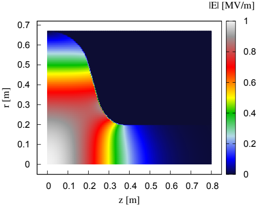
- a few RF cell layouts have been investigated with the aim of maximizing the transit time factor T and implicitly the effective energy gain ΔW, while keeping the surface electric and magnetic fields to a minimum;
- in the end $\beta = 1$ design has been choosen.





electric field maps for the RF cavity



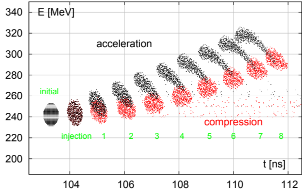


- due to the fact that the cavity length is slightly longer than half of the RF wavelength, for a peak voltage of 26.17 MeM/m a sychronous particle would gain 8.61 MeV instead of 10 MeV as intended;
- in practice, subject to the longitudinal particle distribution, the average gain will be less by 10-20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

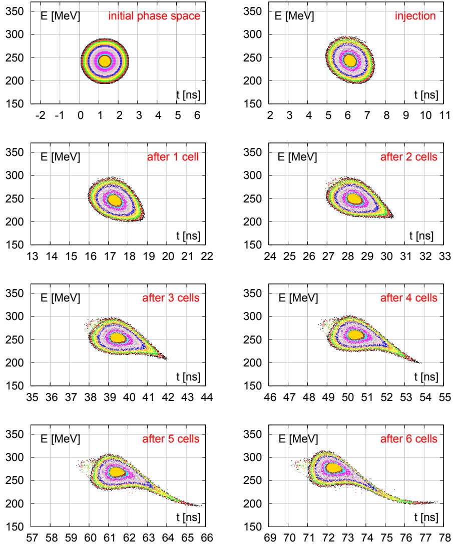
Parameter	$\beta = 1$ top	$\beta = 0.9$ middle	Study II bottom
l_{cav}[m]	0.7448	0.67034	0.8282
r[m]	0.6854	0.7042	0.6641
f_0[MHz]	201.247	201.251	198.575
Q $[10^9]$	24.67	19.6	26.7
T	0.650	0.716	0.591
$\hat{E}$[MV/m]	26.17	27.19	26.38
$\lvert E\rvert_{surf}^{max}$[MV/m]	21.70	24.87	19.75
$\lvert H\rvert_{surf}^{max}$[kA/m]	48.06	58.53	45.00
U[J]	712	772	747
$\Delta\ W^{max}$[MeV]	8.6142	9.0081	8.8466

2. Understanding beam behaviour

- single-cell RF phases have been optimized for maximum bunch acceleration and confinement separately in order to evaluate the impact onto uniform longitudinal beam distributions;



- 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 shown that only a region (golden yoke) of about 0.7 ns by 20 MeV can be preserved, passing through 201.25 MHz RF fields.

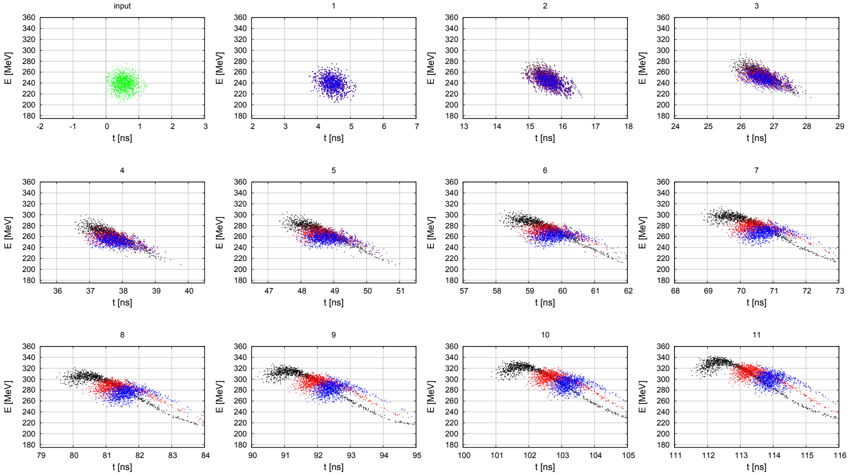


longitudinal phase space through upper linac cell types for Gaussian bunches

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.



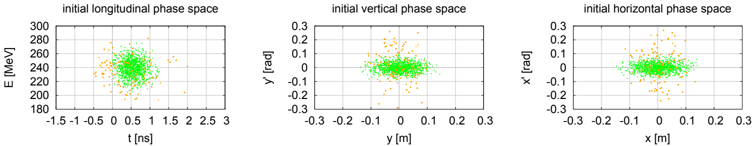
3. Front-to-end particle tracking

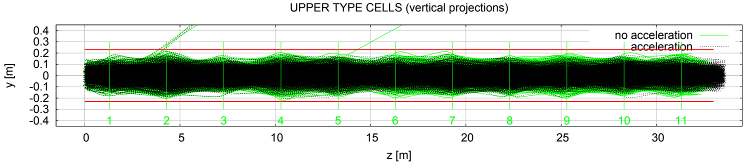
upper linac acceptances

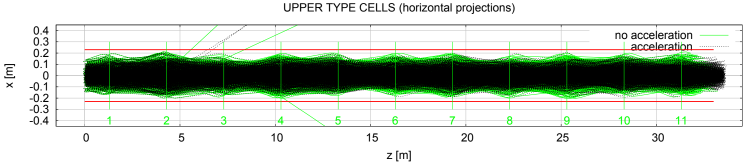
orange: beam at the end of the cooling channel

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

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



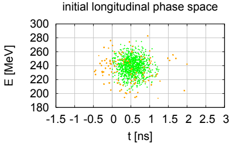


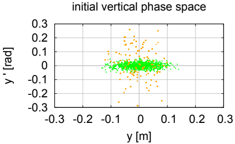


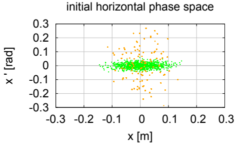
middle linac acceptances

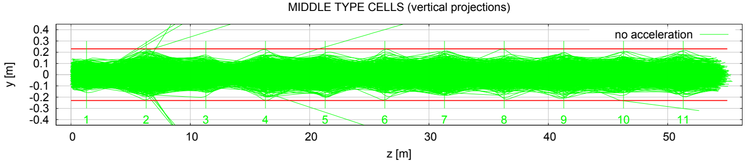
$\bar{\varepsilon}_{\perp} = 1.71\ \pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms, $\sigma_{\boldsymbol{t}} = 0.25$ ns, $\sigma_{\Delta \boldsymbol{E}} = 5$ %, <E> = 240 MeV

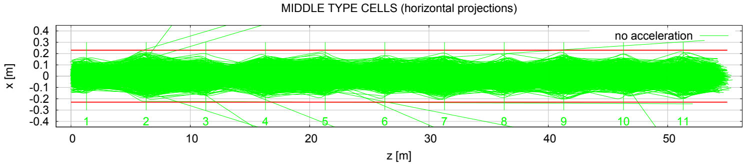
- since β functions increase, transverse acceptance must decrease to accommodate the same beam size.







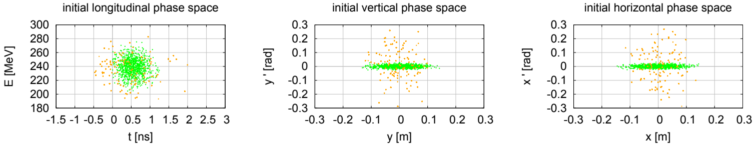


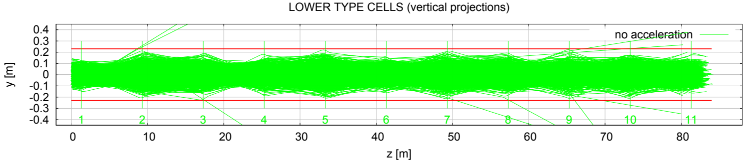


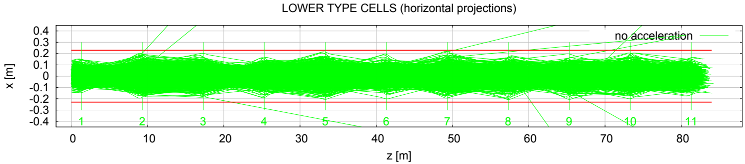
lower linac acceptances

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

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



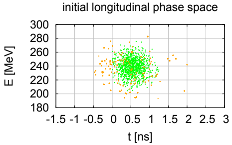


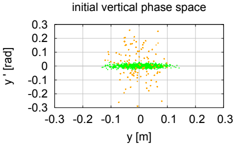


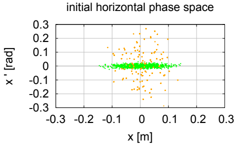
front-to-end linac tracking

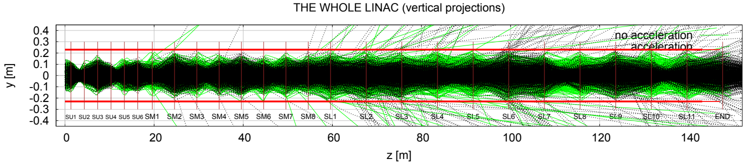
$\bar{\varepsilon}_{\perp} = 0.96\ \pi$ mm mrad and $\bar{\varepsilon}_{||} = 2.77$ eV ms, $\sigma_{\boldsymbol{t}} = 0.25$ ns, $\sigma_{\Delta \boldsymbol{E}} = 5$ %, <E> = 240 MeV

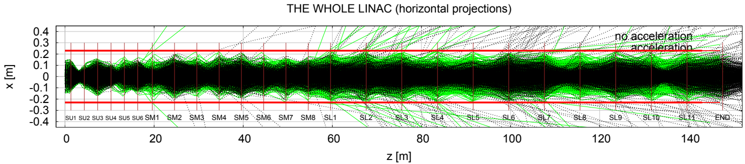
- the three β function levels are direclty correlated with the transverse beam size since $\bar{\varepsilon}_{\perp} =$ const.







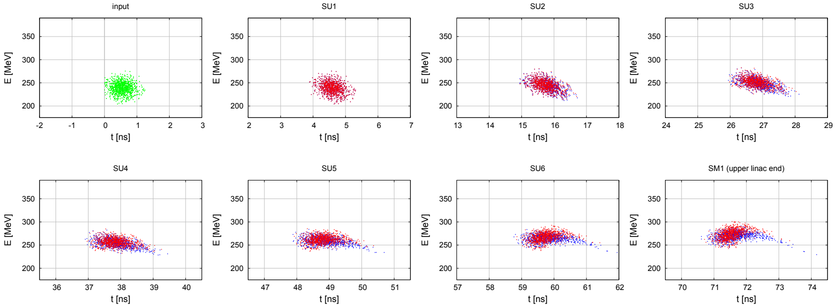




longitudinal phase space through upper linac

- 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;

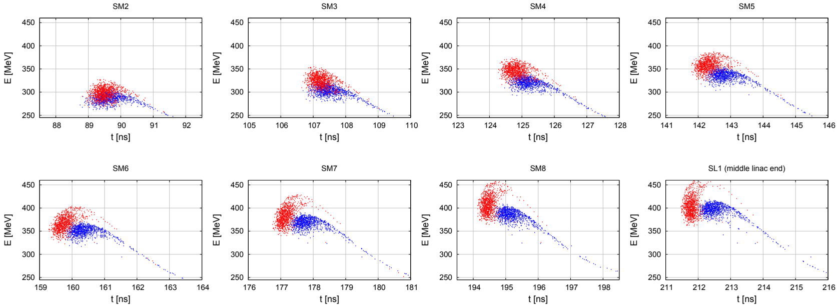
- blue (26 MV/m peak electric field) and red (33 MV/m peak electric field).



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.

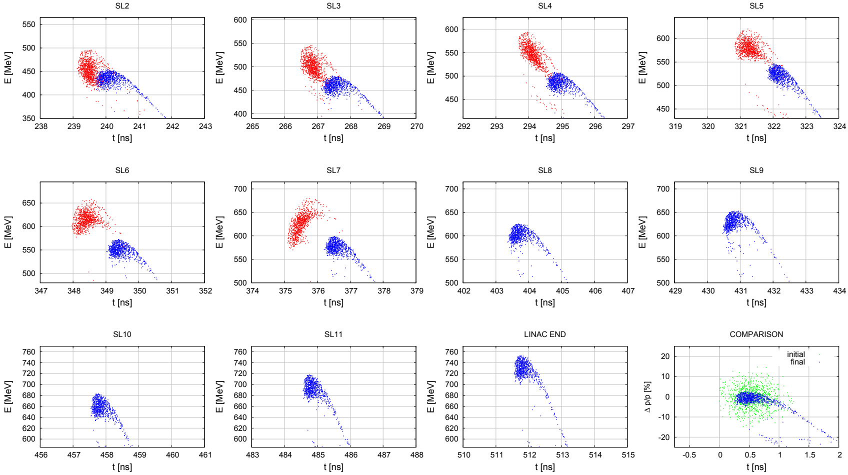


longitudinal phase space through lower linac

- 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;



4. Conclusions

- SC solenoid design acheived;
- single/double-cell SC cavity design acheived;
- particle tracking performed for the whole linac and confirmed by Optim and G4Beamline;
- RF power distribution system (waveguides, circulators, phase shifters) is scketched;
- design the chicane quadrupoles;
- have the SC RF cavity modelled with coupler ports/waveguides;
- obtain fieldmap-based β-functions for the chicane to RLA 1;
- perform particle tracking through the chicane to RLA 1 and estimate beam losses;
- design dipole/sextupole magnets for the RLA arcs;
- track the beam through the first chicane;
- decide beam diagnostics needs, types which can be used and location on the linac/chicanes/RLAs.