Acceleration Issues and Design

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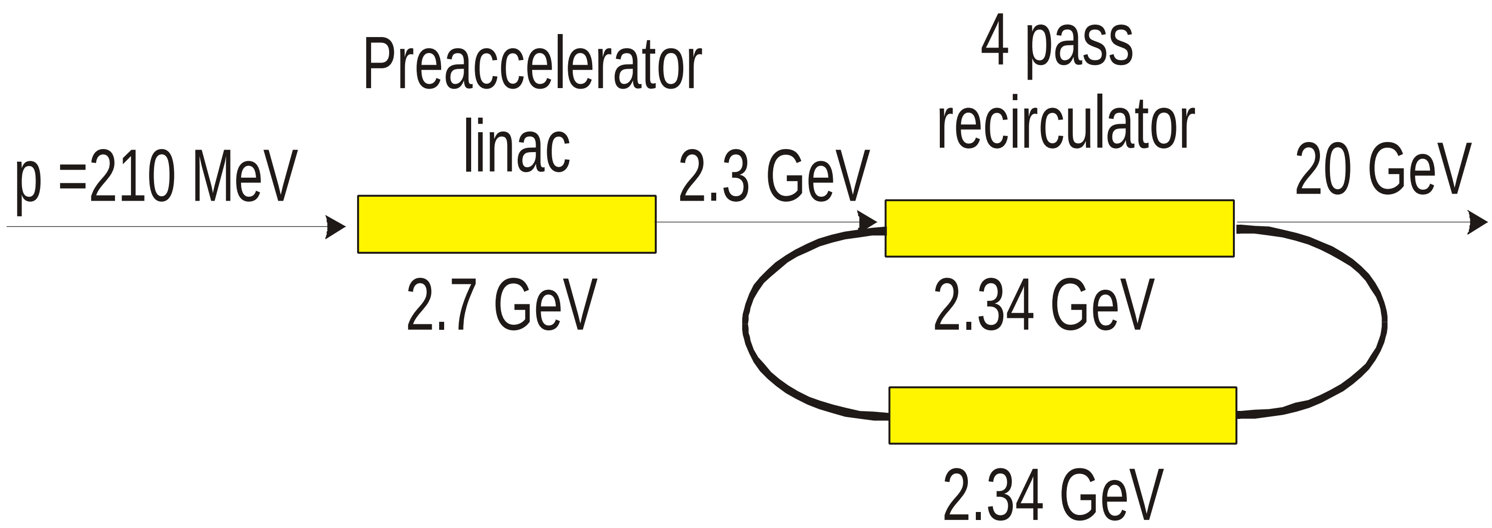
Machine layout and main parameters

Basic MAD Parameters

Injection momentum/Kinetic energy	210/130 MeV
Final energy	20 GeV
Initial normalized acceptance	9.3 (15?) mm·rad
Initial longitudinal acceptance, $\Delta p L_b/m_\mu$ L_b $\Delta p/p$	150 mm ±290 mm ±0.26
Number of bunches per pulse	67
Number of particles per bunch/per pulse	$4.4\cdot10^{10}$ / $3\cdot10^{12}$
Bunch frequency/Accelerating frequency	201.25/201.25 MHz
Average repetition rate	15 Hz
Pulse structure	6 bunches at 50 Hz with 2.5 Hz rep.rate
Beam Power	150 kW

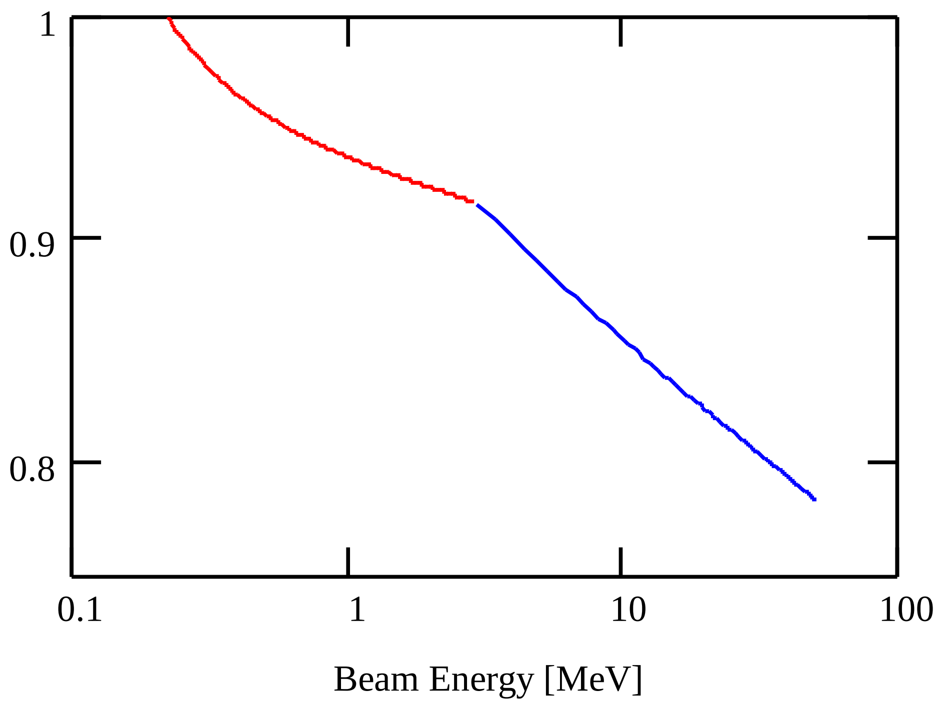
MAD layout



Preaccelerator
linac
4 pass
recirculator
p =210 MeV
2.3 GeV
20 GeV
2.7 GeV
2.34 GeV
2.34 GeV

Muon Decay

- ➢ Muon decay time - 2.2 μs
- ➢ Accelerating gradient of 15 MV/m
  - Real estate accelerating gradient in linac – 8.2 MV/m
  - Real estate accelerating gradient in recirculators – 3 MV/m
- ➢ Decay losses depends approximately linearly on the accelerating gradient



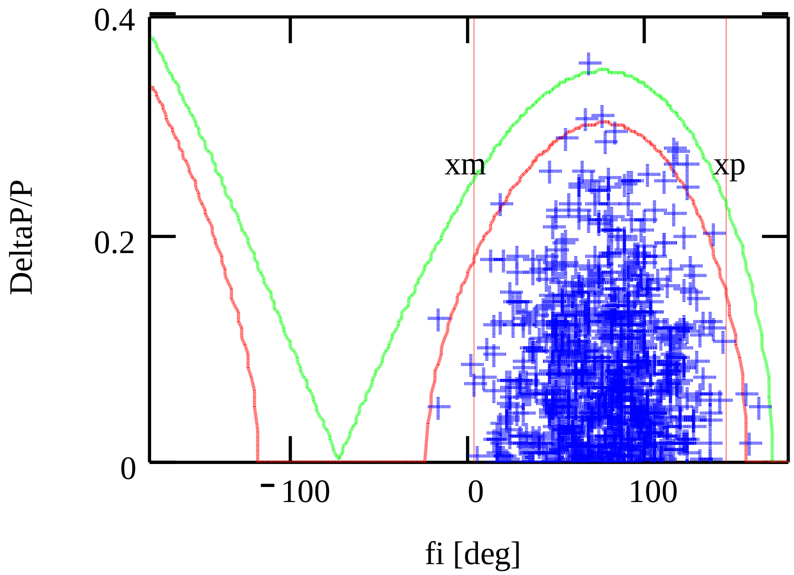
Red line – decay in linear accelerating part
Blue line – decay in recirculators

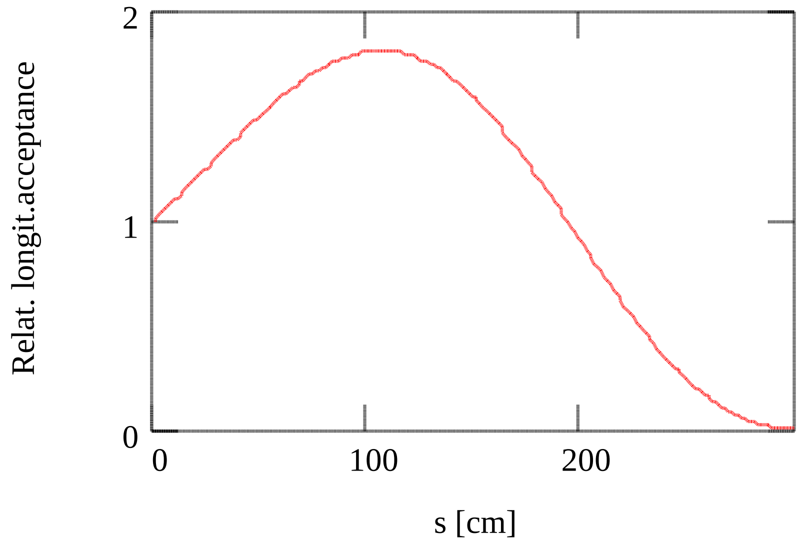
Linear Preaccelerator

1 Acceleration from 130 to 2300 MeV
2 Longitudinal dynamics is well understood
- Synchrotron motion in the initial part
  - suppresses effect of non-linearities in the longitudinal phase space
  - allows to perform the beam bunching
  - reduces effective accelerating gradient (2.7 GV instead 2.2 GV)

3 Accelerator final energy of 2.3 GeV is determined by
- RF phase slip
- Sufficiently small emittance and energy spread to be injected to the recirculator
- Ratio of initial and final energies at first spreader
- Difference in focusing for the first and last passes

4 RF
- SC two cell cavities
  - Short cryo-modules - 2 cavities, ~5 m
  - Long cryo-modules - 4 cavities, ~10 m
- frequency choice - 200 MHz
  - To capture the required longitudinal phase space
  - Voltage droop due to beam loading
    - 0.6% per pass for 200 MHz for $6 \cdot 10^{12}$ particle train





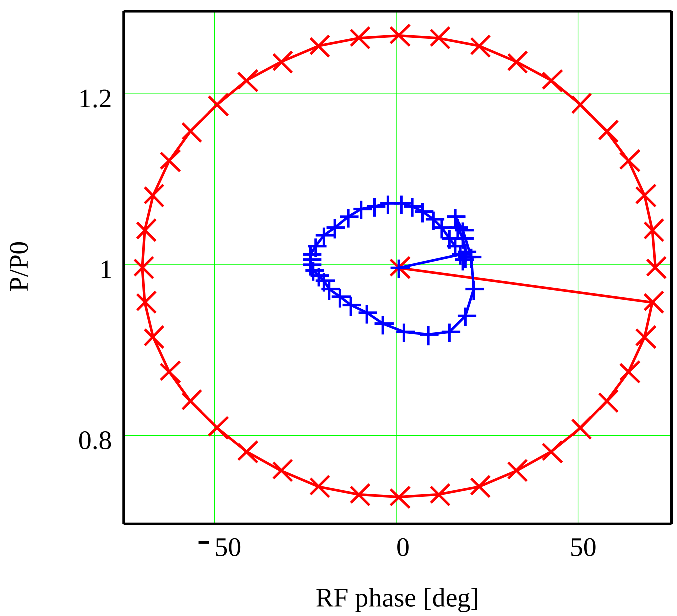
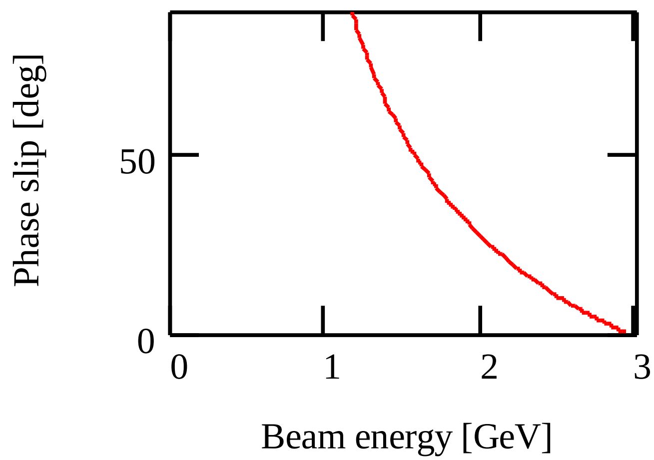


Figure 1. Separatrix size at the beginning of acceleration

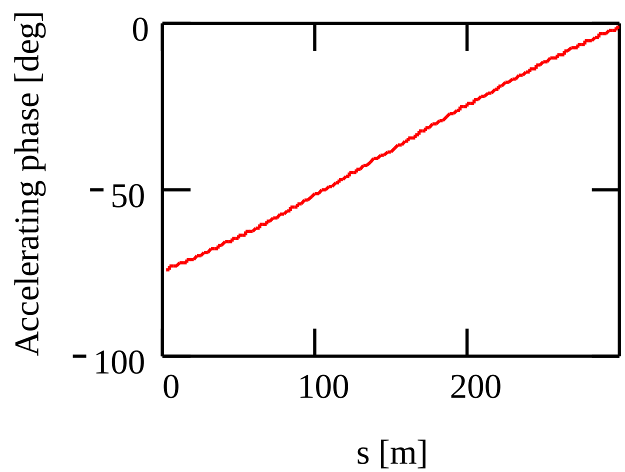
Figure 2. Relative size of longitudinal acceptance along linac

Figure 3. Phase space before and after acceleration for particles at 2.5σ (95% of particles)

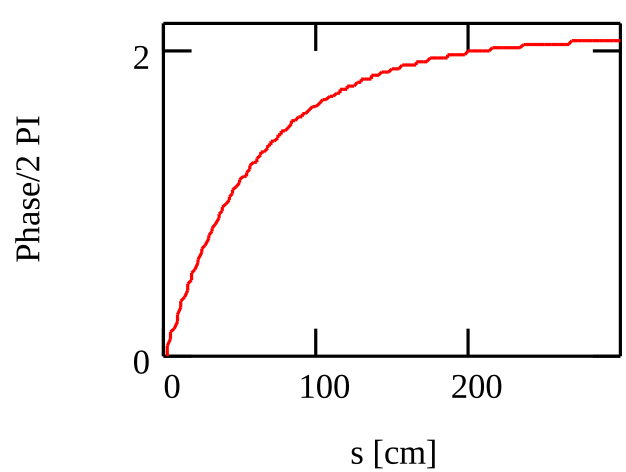
Longitudinal Dynamics in the Linear Preaccelerator



Phase slip dependence on
the beam energy yields
final linac energy
to be ≥2 GeV



Accelerating phase along linac



Synchrotron phase along the linac

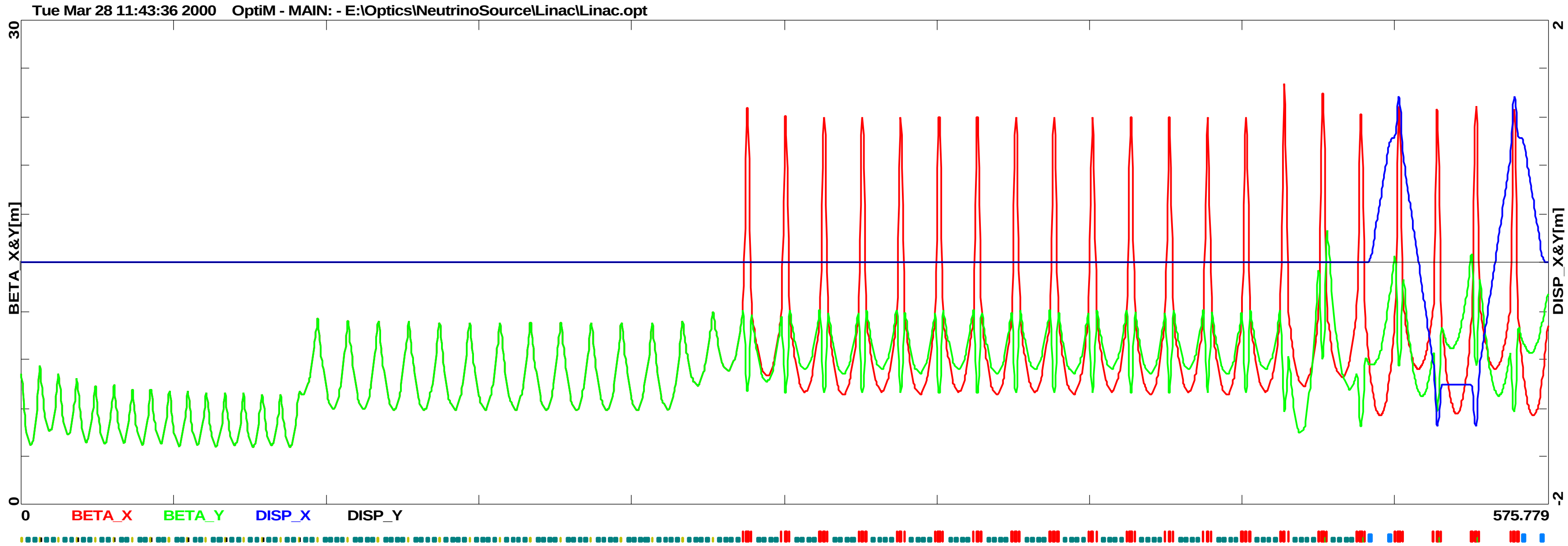
5 Transverse dynamics

- large beam size due to huge emittance
- Strong transverse focusing ($b_{max} \leq 15$ m)
- strong time dependent focusing in the RF cavities
- focusing is limited by the increase of effective longitudinal mass due to transverse particle momentum ($b_{min} \geq 3$ m). $\left(\frac{\Delta b_{\parallel}}{b_{\parallel}} \approx -\frac{1}{2} q_{\perp}{}^{2}, \quad m_{eff} = \sqrt{m_{m}{}^{2} + p^{2} c^{2}} \right)^{2}$
- Solenoidal focusing
  - Focusing non-linearity

    Focusing element length (~ 1 m) is comparable to its aperture (0.4 m)

$$\frac{\Delta F}{F} \approx \frac{r^2}{4} \frac{\int B'^2 ds}{\int B^2 ds} \xrightarrow{a \approx L/\ 2} \frac{r^2}{5L^2} \xrightarrow{L/r=5} 0.01$$

  - Shielding solenoid’s field



Beta-function in linear preaccelerator; acceleration from 112 MeV to 2856 MeV

RF

15 MV/m accelerating gradient

16 cryomodules of 5 m length

- 2 two-cell cavities per cryo-module
- 45 MV per cryomodule

30 cryomodules of 10 m length

- 4 two-cell cavities per cryo-module
- 90 MV per cryomodule

Maximum beam size in the cavity R=20 cm

Focusing

B_0= 7.5 kG (L=50 cm, 2a=40 cm)

B_1=10.5 kG (L=50 cm, 2a=40 cm)

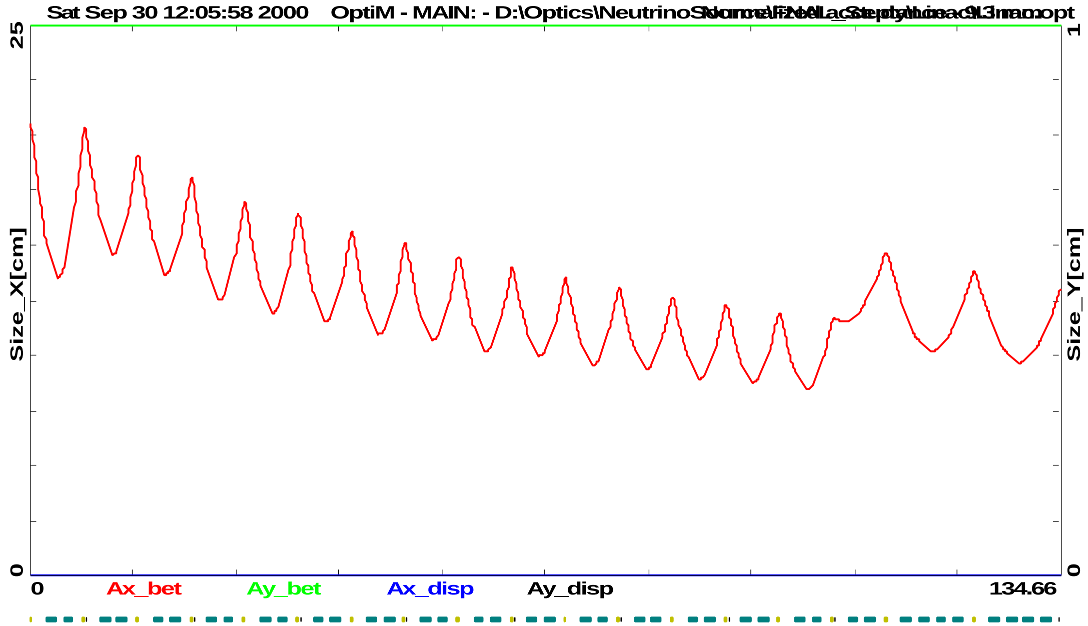
…

B_{21}=49 kG (L=50 cm, 2a=20 cm)

G_{F27}=0.24 kG/cm (L=110 cm)

G_{D27}=-0.24 kG/cm *2 (L=60 cm)

…



Beam size for the acceptance of 9.3 mm at the linac front-end

Maximum beam size in cavities $2a$ = 34 cm

in solenoids $2a$ = 40.5 cm

➢ If the acceptance needs to be increased from 9.3 to 15 mm

- (1) Need to know exact aperture available for the beam in SC cavities
  - ♦ Non-linearities of cavity focusing can be real show-stopper
- (2) If the use of 2 cavity cryo-modules is not sufficient
  - ♦ 10-15 single cavity cryo-modules
    - ➢ 3 m versus 5 m or
    - ➢ solenoids incorporated into criomodules - magnetic shielding
  - ♦ Significant drop of the accelerating gradient

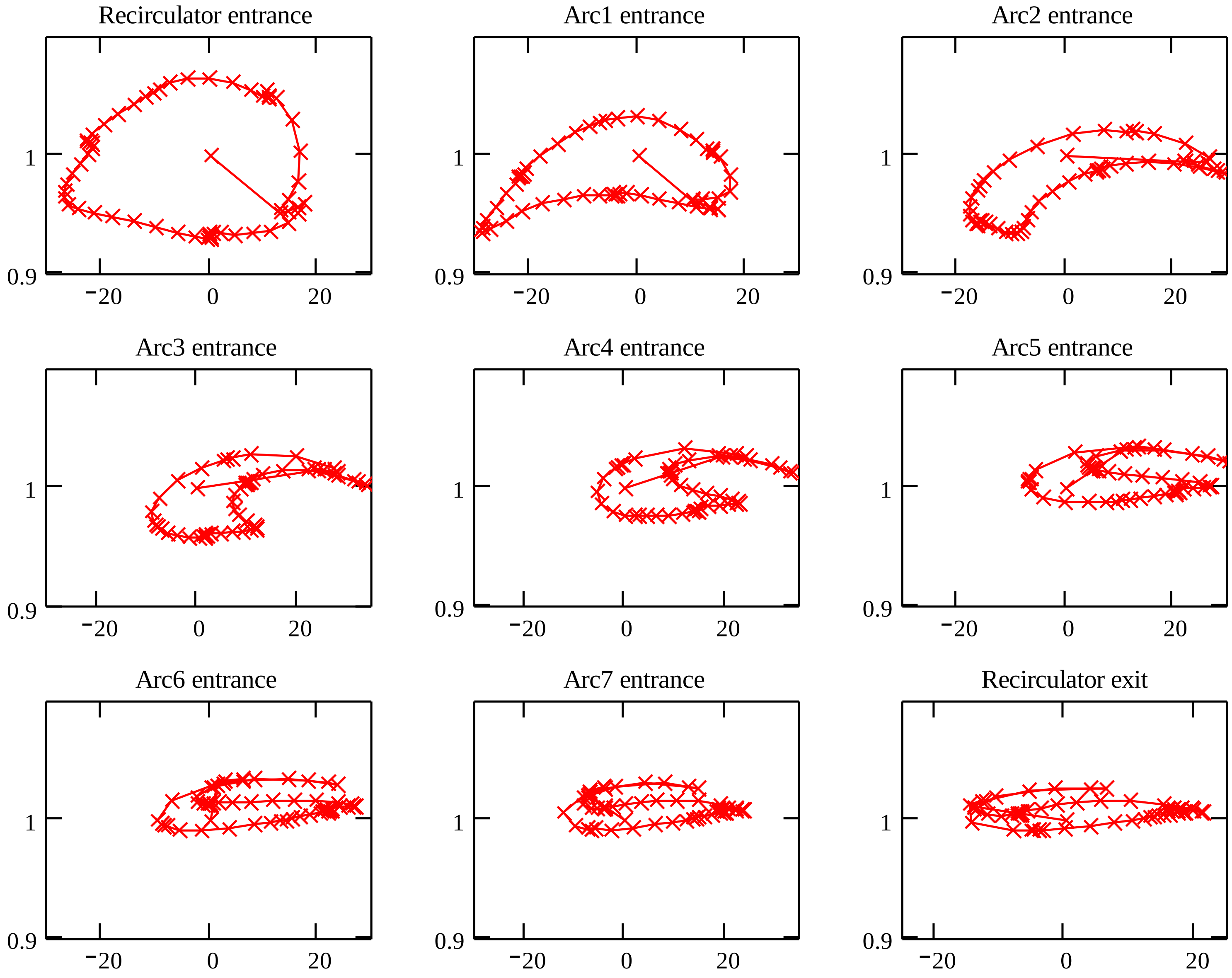
Main parameters for recirculation arcs and linacs

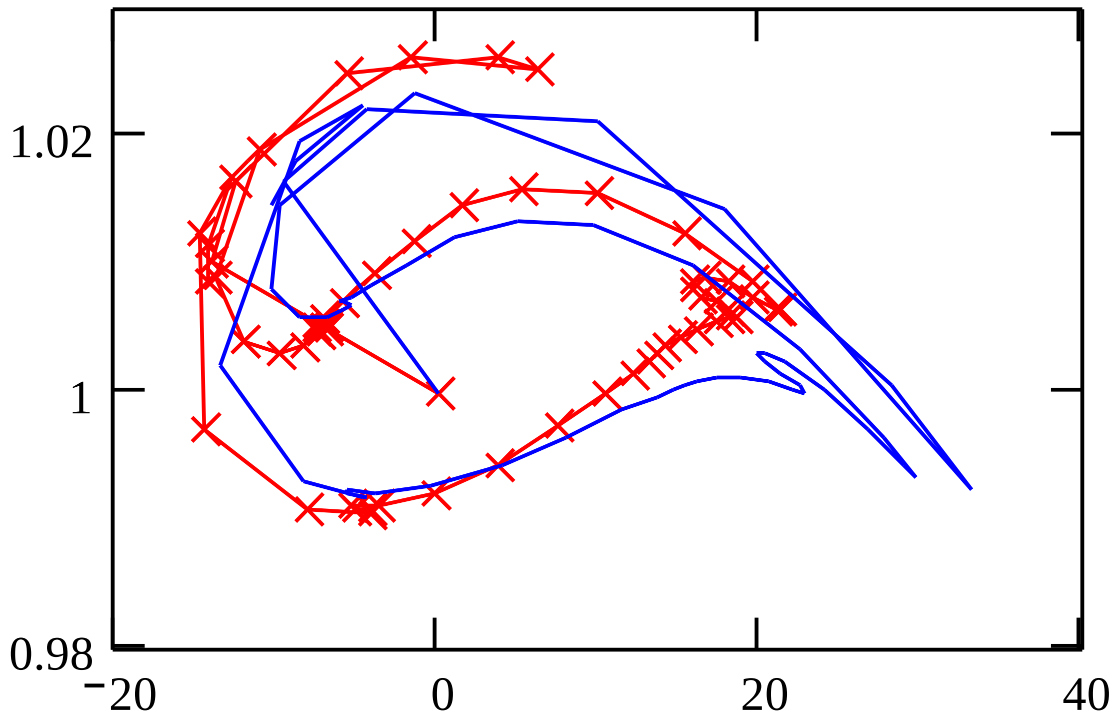
	Initial Energy [GeV]	Initial total energy acceptance	Transverse acceptance*, X&Y [mm·rad]	Gang phase of the linac [deg]
	2.3	±6.8%	410	-4
Arc 1	4.7	±4.9%	230	20
Arc 2	6.9	±4.4%	172	22
Arc 3	9.1	±3.5%	142	22
Arc 4	11.3	±2.8%	124	22
Arc 5	13.6	±2.4%	113	22
Arc 6	15.8	±2.2%	106	10
Arc 7	18.1	±2.0%	101	10
	20	±1.8%	98	

M_{56}=1.3 m

* Emittance dilution of 100%, $\left(e_n = e_{n0} 2^{n/8}\right)$

Longitudinal dynamics

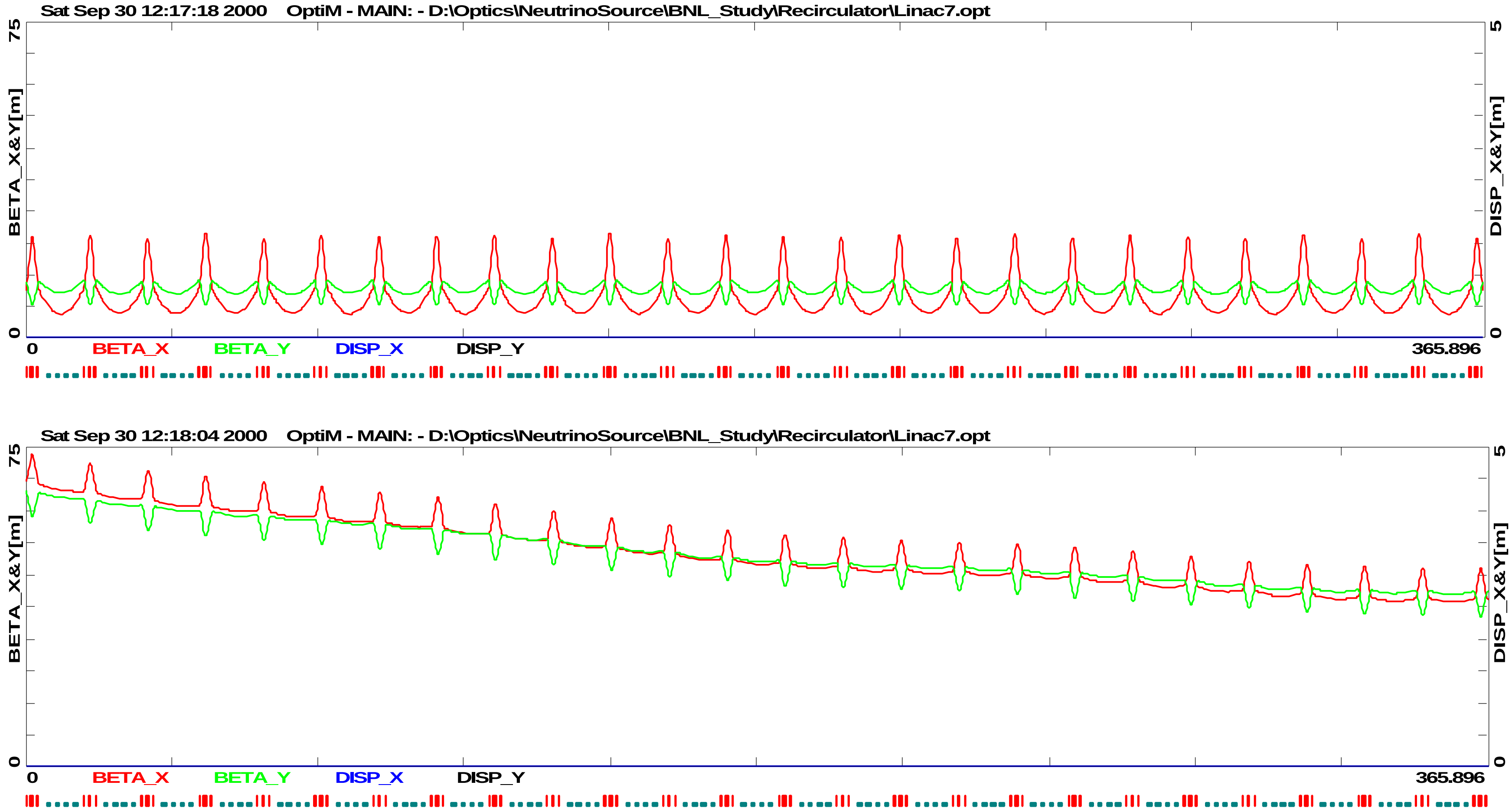




Effect of beam loading

$\Delta E/E = 6\cdot 10^{-3}$, $N_\mu = 6\cdot 10^{12}$

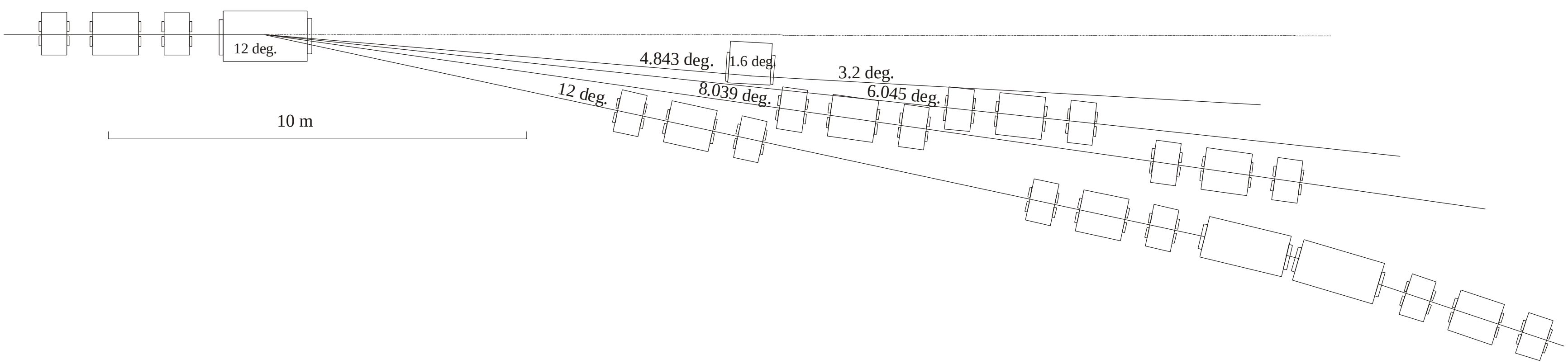
Blue line at the last slide shows longitudinal phase space for the last bunch of $6\ 10^{12}$ particle train. The difference in comparison with the first bunch is related to the voltage droop (0.6% per pass for 200 MHz) in RF voltage due to beam loading.



Beta functions for the first and last passes in recirculator

Design choices

- General optics choices
  - ➢ Rotationally phased 90° high-periodicity triplet focusing
- Spreader-recombiners matching region
  - ➢ Single step, non-dispersion suppressed horizontal spreader/recombiner
    - Vertical spreader non-visible for given emittance and energy spread
  - ➢ Sextupole corrections to correct the beam envelopes, and dispersion



- Arcs
  - ➢ 2T dipoles for highest energy arc
  - ➢ Sextupole corrections to correct the beam envelopes, M_{56} and dispersion

Conclusion & Questions

- Linac
  - Need help from RF folks
    - Cavity & RF coupler geometries (beam aperture)
    - Cryomodule sizes
    - Requirements for magnetic shielding
  - Additionally need to take into account
    - non-linearity of solenoidal focusing in tracking
    - conceptual magnetic design of solenoids (shielding &non-linearity)
- Recirculator
  - There is no principal requirements to push dipole field beyond 2 T
    - Conventional dipoles and quads
    - Conceptual design for quad and dipoles design
  - Spreader recombiner concept - horizontal
    - Triplet focusing is the only way to achieve beam separation without huge dipoles in spreaders and recombiners
  - Need concept for quad and dipoles design (high radiation)
  - Help in tracking study with real non-linear elements
    - Non-uniform acceleration in linacs
    - Machine tuning procedure
- Multi-particle effects
  - Estimates for BBU
  - Estimates for the space charge effects