Muon Acceleration

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MUTAC,
BNL, June 2000

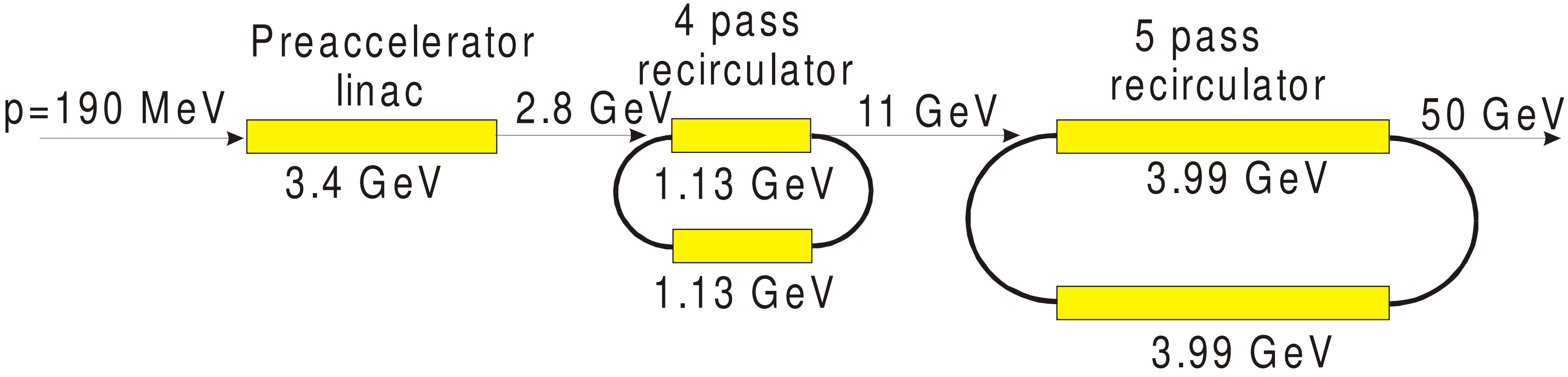
Contents

1. Machine layout and main parameters

Basic MAD Parameters

Injection momentum / kinetic energy	190/112 MeV
Final energy	50 GeV
Initial rms normalized emittance	1500 mm·mrad
Initial rms momentum spread / bunch length	0.11 / 12 cm
Number of bunches per pulse	30 × 4
Number of particles per bunch / per pulse	10^{11} / $3\cdot10^{12}$
Bunch frequency / accelerating frequency	200/200 MHz
Repetition rate	15 Hz
Beam current in micropulse	0.8 A
Beam power	360 kW

Accelerator layout



Major Points to be Addressed

1 Is it possible to accelerate fast enough to prevent a decay of muons

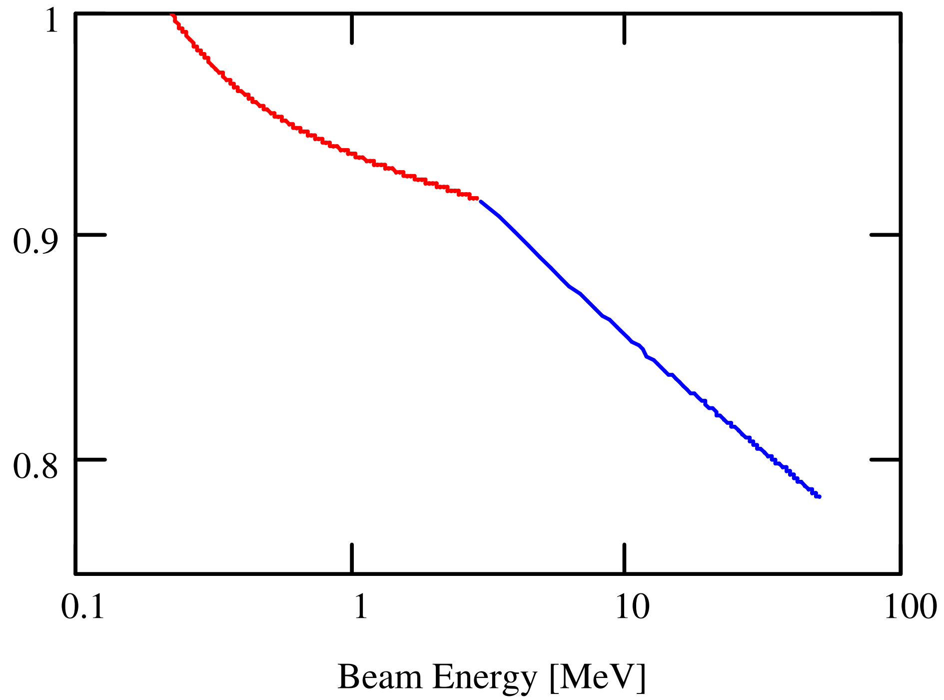
2 How to capture and accelerate a huge emittance and energy spread

- Which energy is appropriate to start recirculation
- Number of recirculation stages and number of passes per recirculator
- Lattice type and chromaticity correction
- Accelerating frequency

3 Coherent beam stability

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 depend approximately linearly on the accelerating gradient



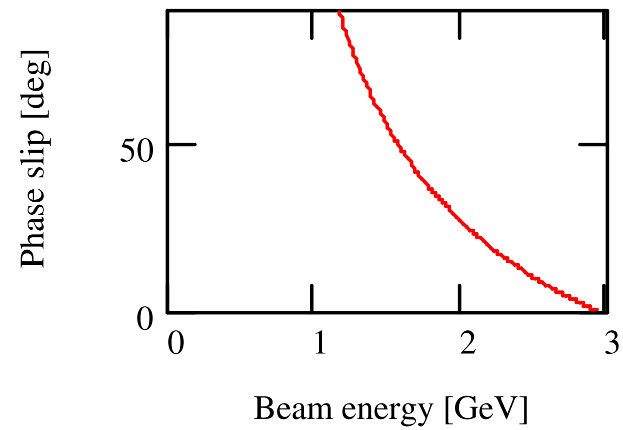
Red line – decay in linear accelerating part
Blue line – decay in recirculators

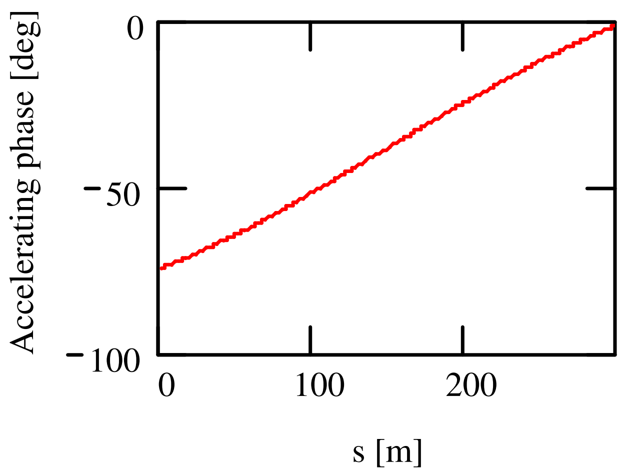
Linear Preaccelerator

1 The final energy (2.8 GeV) is set by RF phase slip for higher passes

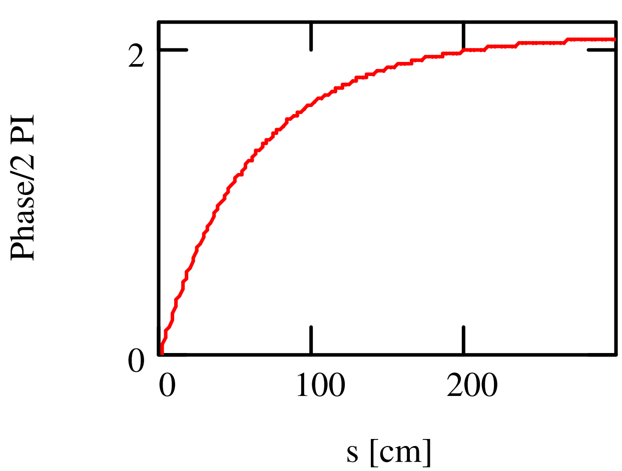
2 Longitudinal (synchrotron) motion in the initial part

- suppresses effect of non-linearities in the longitudinal phase space
- allows to perform the beam bunching
- reduces effective accelerating gradient (total voltage of 2.4 GV instead 1.9 GV)

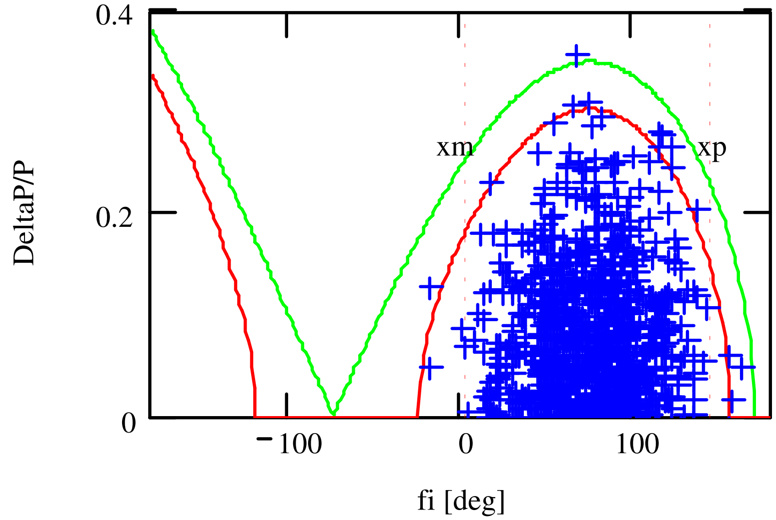


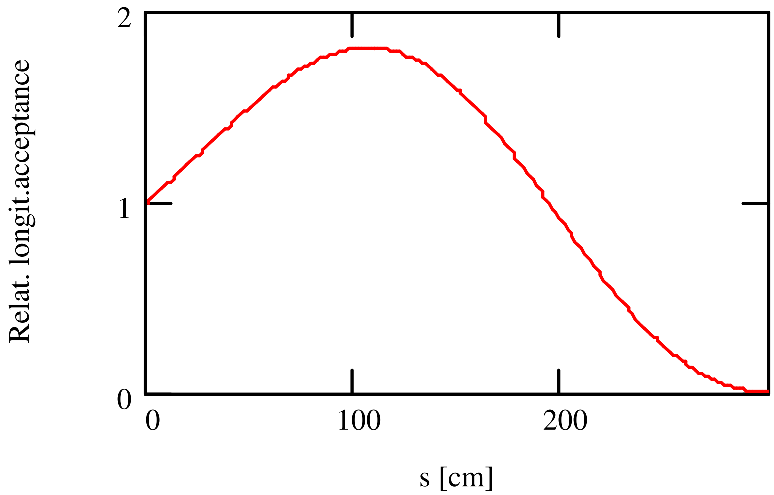


Accelerating phase along linac



Synchrotron phase along the linac





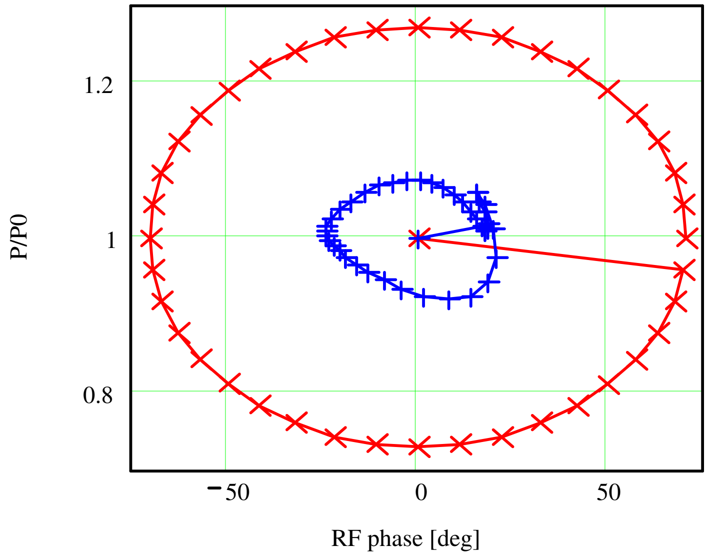
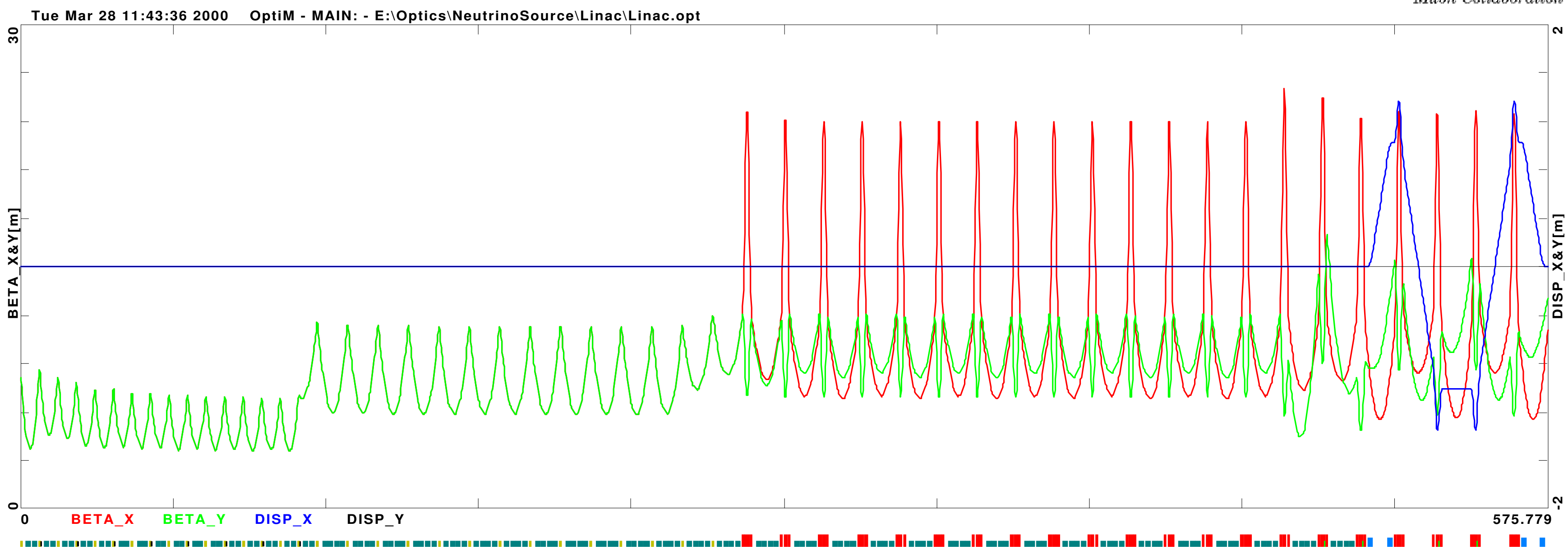


Figure 1. Separatrix size at the beginning of acceleration

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)



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 cryomodule
- 45 MV per cryomodule

30 cryomodules of 10 m length

- 4 two-cell cavities per cryomodule
- 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)

…

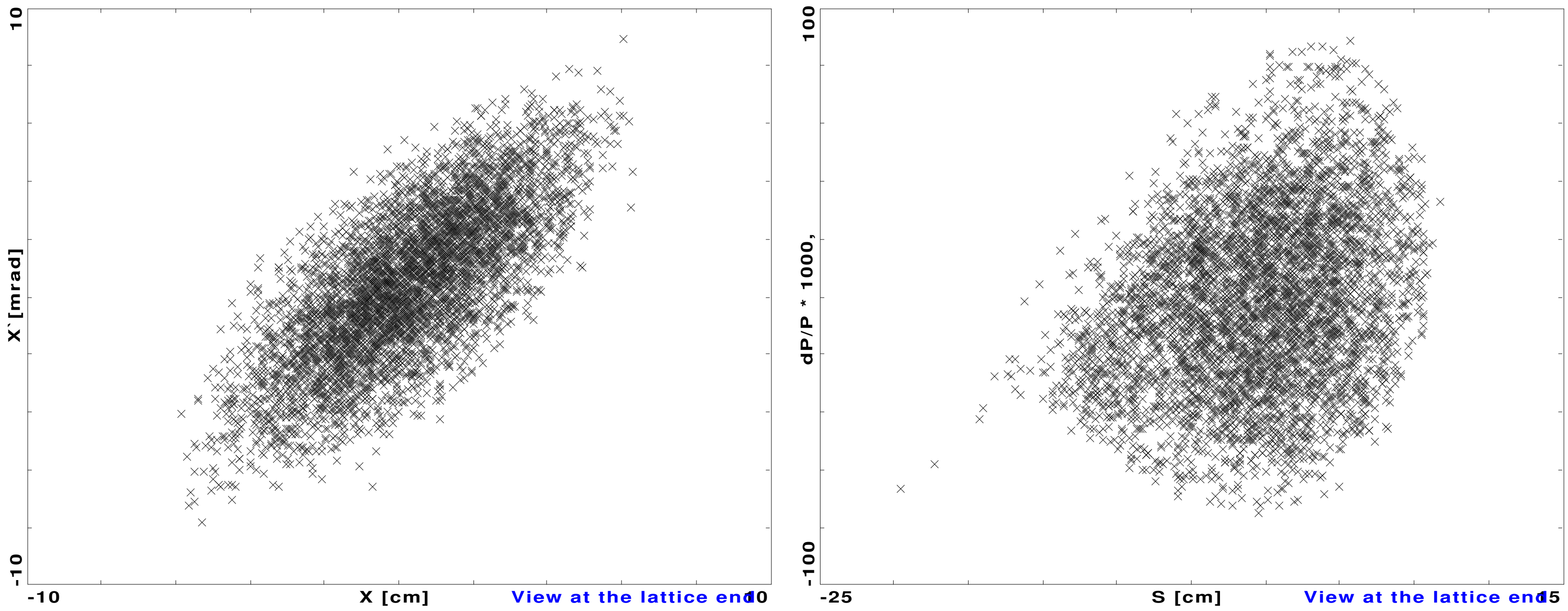
B_{21}=49 kG (L=50 cm, 2a=20 cm)

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

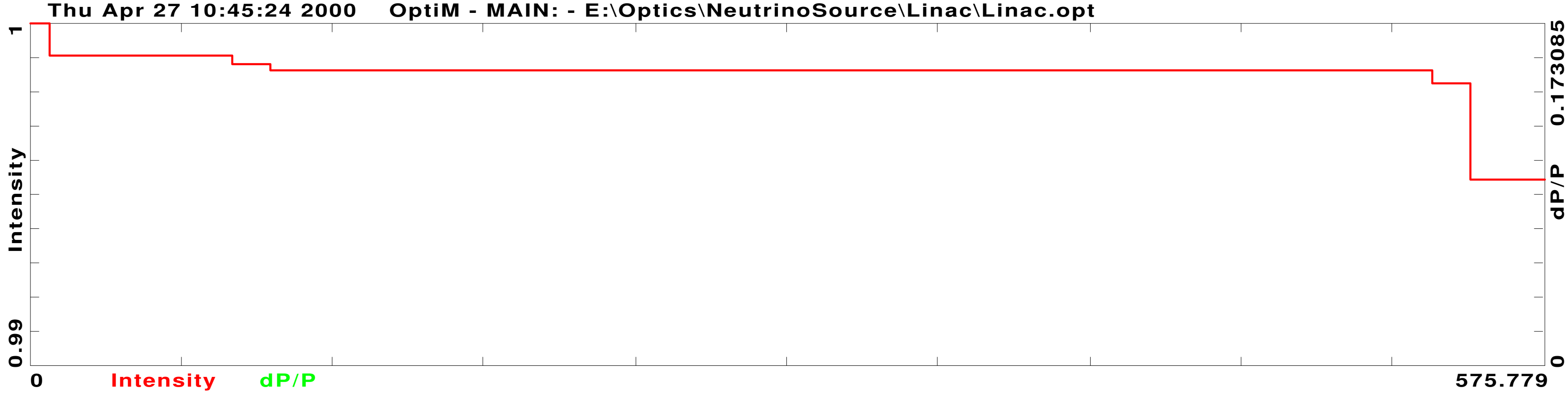
G_{D27}=-0.24 kG/cm *2 (L=60 cm)

…

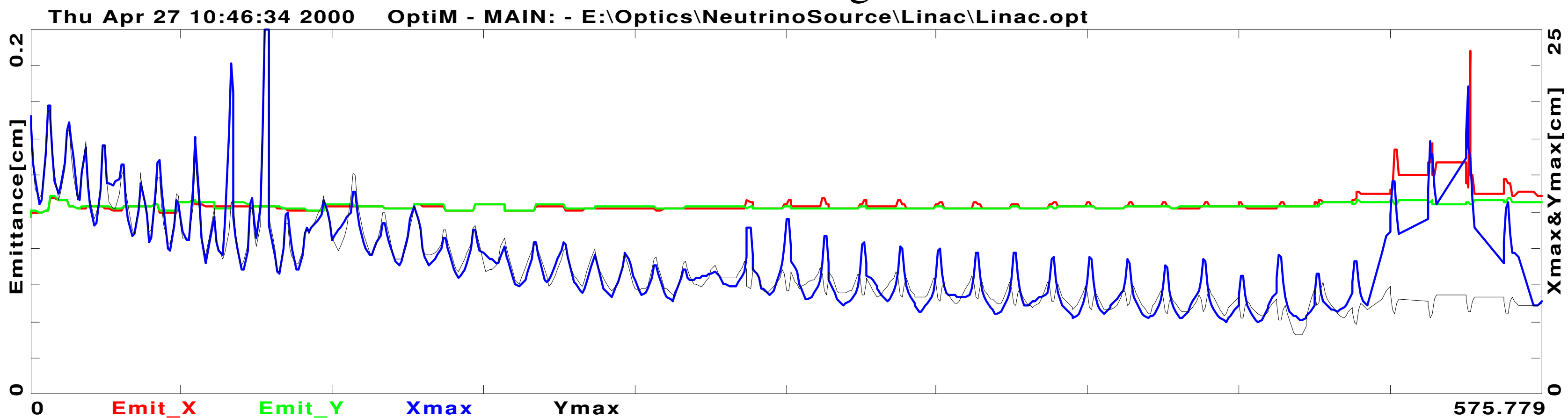
Single Particle Tracking for the Linear Preaccelerator



Horizontal and longitudinal phase spaces at the linac end



Beam losses along the linac



Rms emittance and maximum beam size (maximum particle displacement) along the linac. Rapid beam size decreases correspond to scraping of the particles with large amplitude

Tracking results for the Linear Preaccelerator

1 Initial particle distribution

- Gaussian distribution
  - Distribution truncated at 2.5 σ in 6D space
    - 30% of particles are cut from the distribution
  - Transverse rms emittance of 834 mm·mrad (1500 mm·rad normalized) is converted to 540 mm mrad after the truncation
  - Transverse acceptance of 5200 mm·mrad (9400 mm·rad normalized)
  - Rms bunch length - 12 cm
  - Rms energy spread - 0.11

2 Less than 1% of particles are lost in the course of acceleration

- transverse motion "instability" for off-momentum particles with large amplitudes

3 No significant emittance growth

- Final rms emittance - $\varepsilon_x / \varepsilon_y$ = 40 / 39 mm·mrad
  - Horizontal emittance growth – 9% (Injection chicane)
  - Vertical emittance growth – 6%
- Final rms energy spread - 0.03

4 Output acceptance

- Transverse acceptance - 430 mm·rad
- Energy spread - ±0.083

First Recirculator (RLA1)

Main parameters for the RLA1

Initial energy	2.856 GeV
Final energy	11 GeV
Number of passes	4
Total initial energy acceptance	±6%
Total final energy acceptance	±2 (4.1*) %
Initial transverse acceptance	430 mm·rad
Final transverse acceptance !!!	160 mm·rad ?
Emittance dilution (5% per arc) !!!	40% ?
Total voltage per linac	1.13 (1.23*)GV
Circumference	~840 m

*400 MHz scenario

Longitudinal dynamics in the RLA1

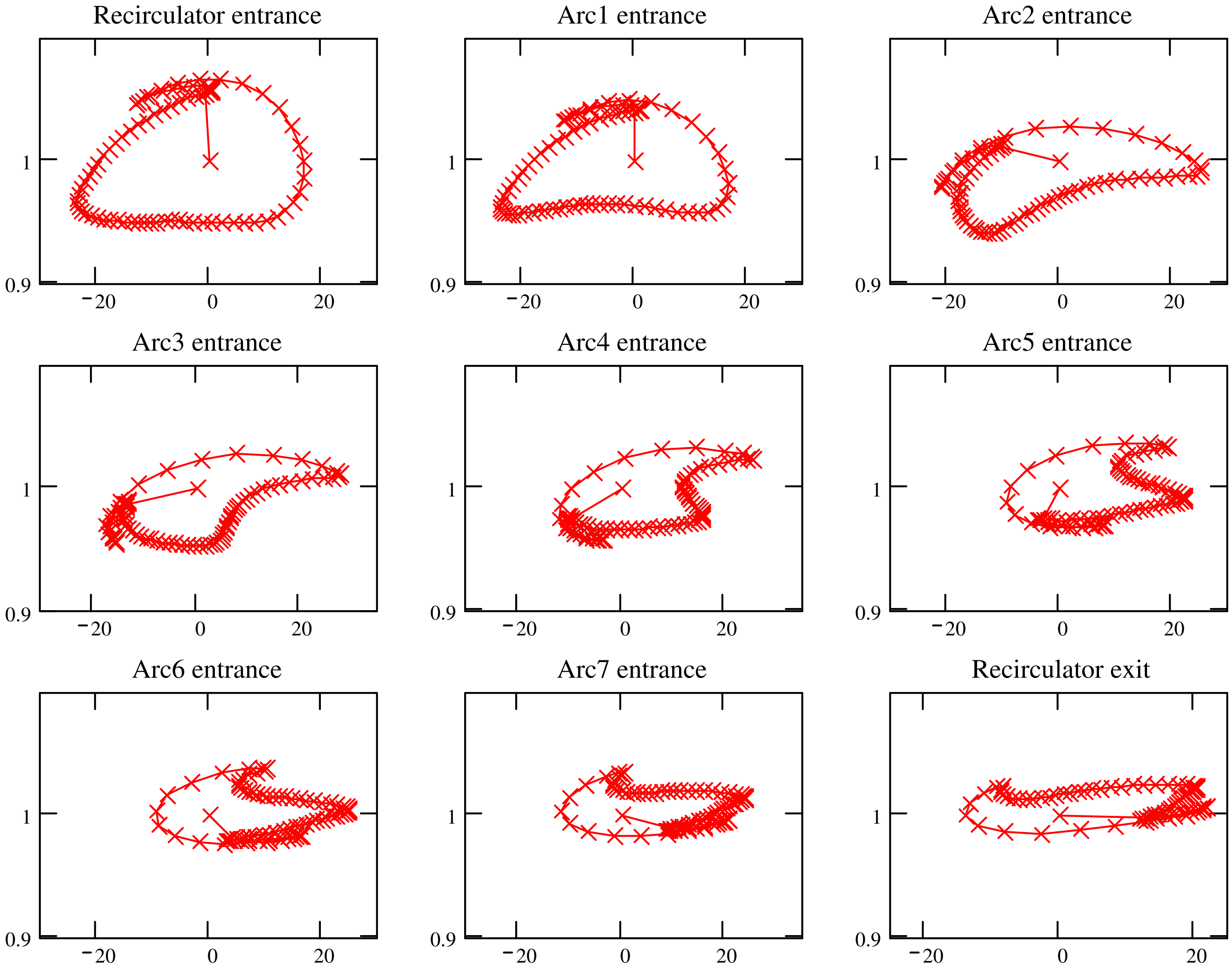
Effect of the second RLA accelerating frequency on the design of the first RLA or 400 MHz versus 200 MHz for second RLA

Parameters for acceleration in the first recirculator

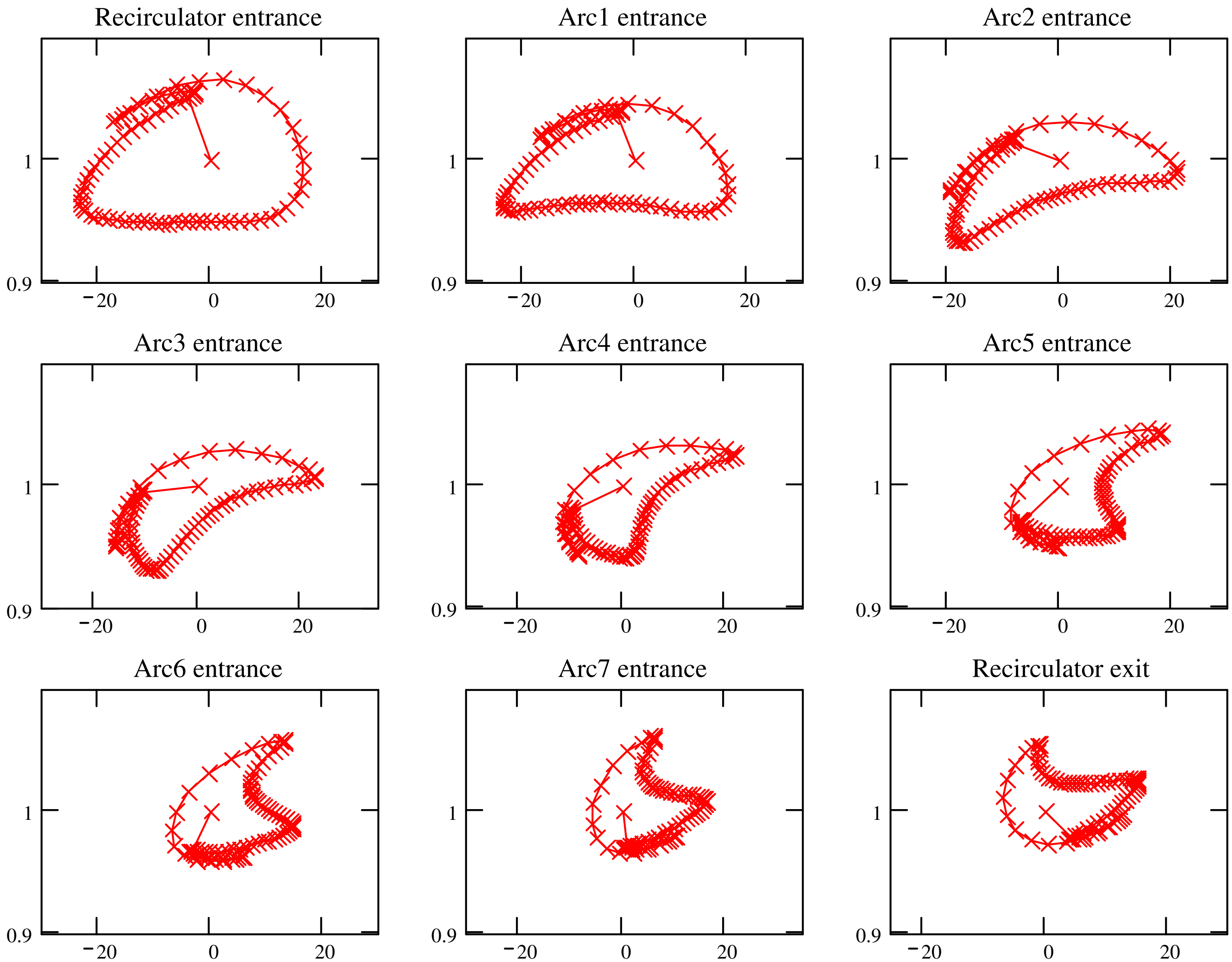
	200 MHz*			400 MHz*			
	Kinetic energy [GeV]	Gang phase [deg]	Total energy spread, $2\Delta p/p$ [%]	Kinetic energy [GeV]	M_{56} [cm]	Gang phase [deg]	Total energy spread, $2\Delta p/p$ [%]
Entrance	2.89	5	11.9	2.89		6	11.7
Arc 1	4	-26	9.3	4.11	60	-22	9.0
Arc 2	5	-26	8.7	5.25	60	-25	9.9
Arc 3	6	-26	7.5	6.36	60	-29	9.8
Arc 4	7	-26	7.5	7.43	60	-38	9.2
Arc 5	8	-26	6.9	8.40	50	-45	9.6
Arc 6	9	-26	6.1	9.26	50	-45	9.9
Arc 7	10	-26	5.1	10.13	50	-45	9.5
Exit	11		4.0	11	50		8.2

* M_{56} = 1.1 m, Total voltage per linac = 1.113 GV at 200 MHz

** Total voltage per linac = 1.227 GV at 200 MHz



Longitudinal phase space in the first recirculator, 200 MHz scenario



Longitudinal phase space in the first recirculator, 400 MHz scenario

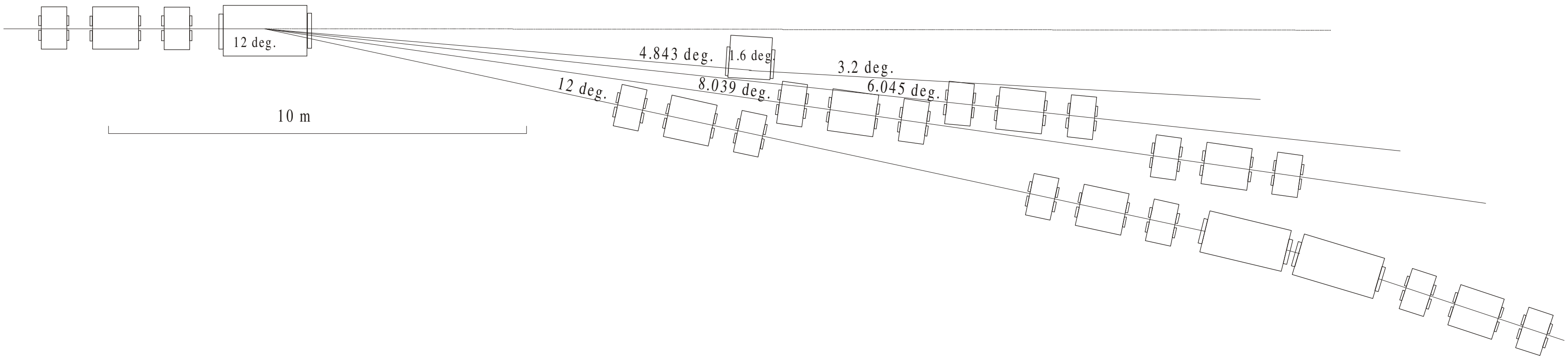
Optics for RLA1

1 General requirements for optics

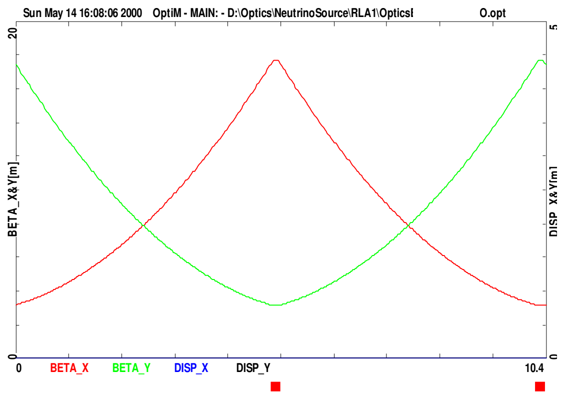
- Large energy spread
  - High symmetry lattice to accommodate large energy spread
- Large acceptance
  - Small beta-functions
- M_{56} (~1 m)
- It is a recirculator not a storage ring
  - Corrected chromaticity of the beam envelopes not tunes
    - A strategy for optics chromatic correction can be different
- 2T dipoles for highest energy arc

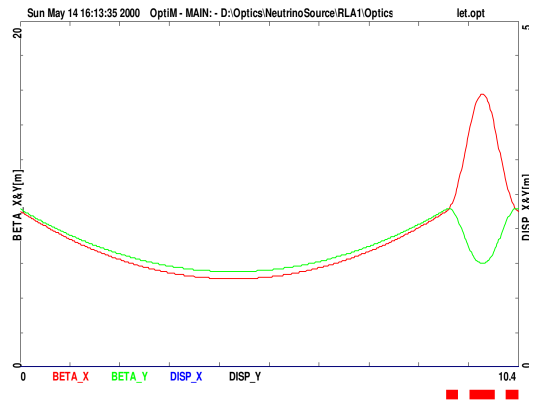
2 Spreaders and recombiners

- Horizontal
- Avoid dipoles with strongly separated beams



Choice of focusing structure

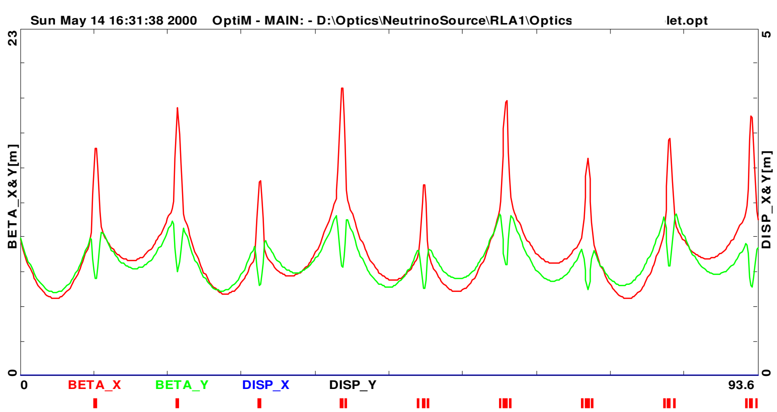




- The same length
- The same phase advance per period. $\nu_x = \nu_y = 0.25$ - effective chromaticity correction

Advantages for FODO

1. Smaller length of quads
2. Easier chromaticity correction



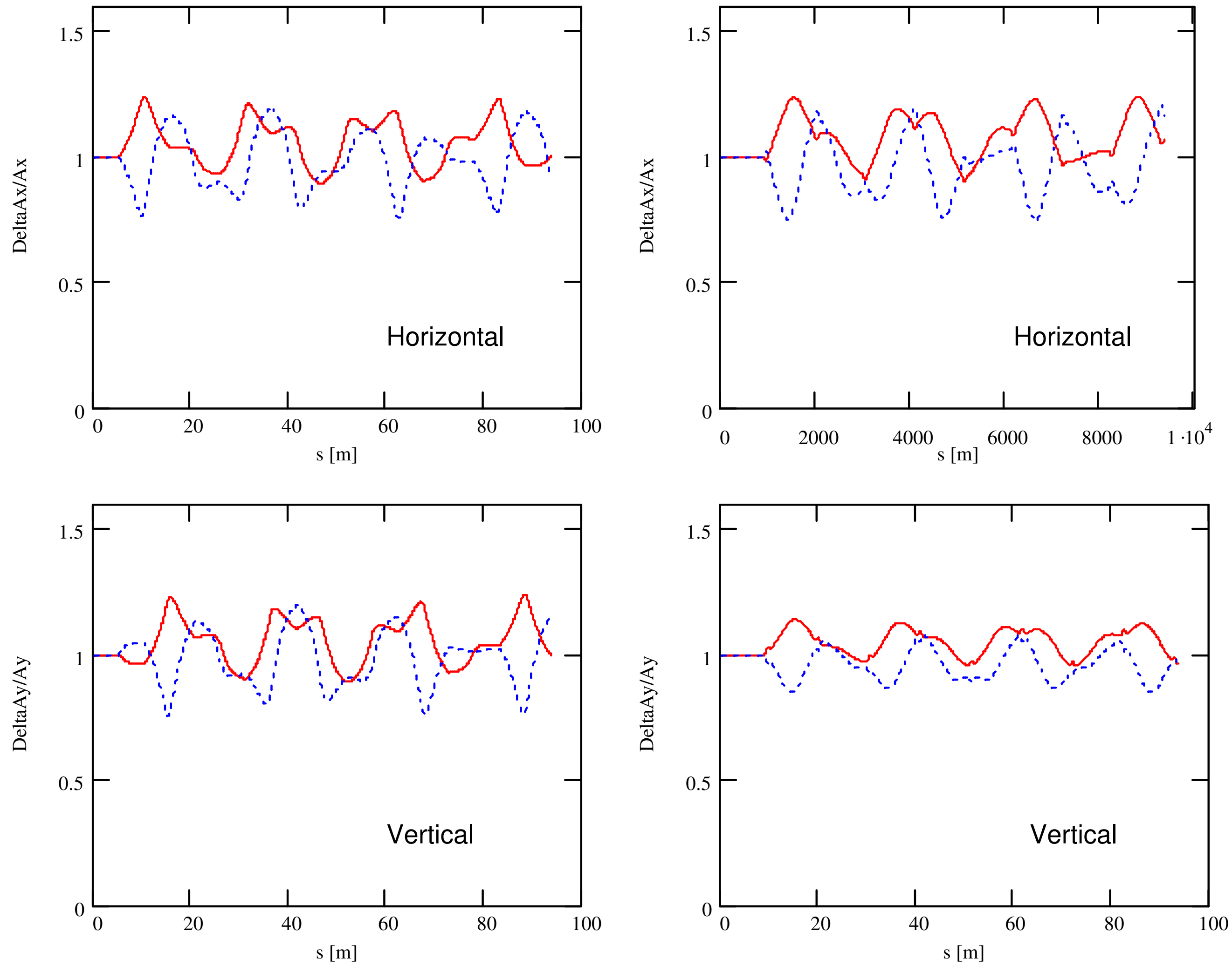
Beta-functions for momentum change of +10%
- Beam envelope oscillates but does not grow

Advantages for triplet focusing

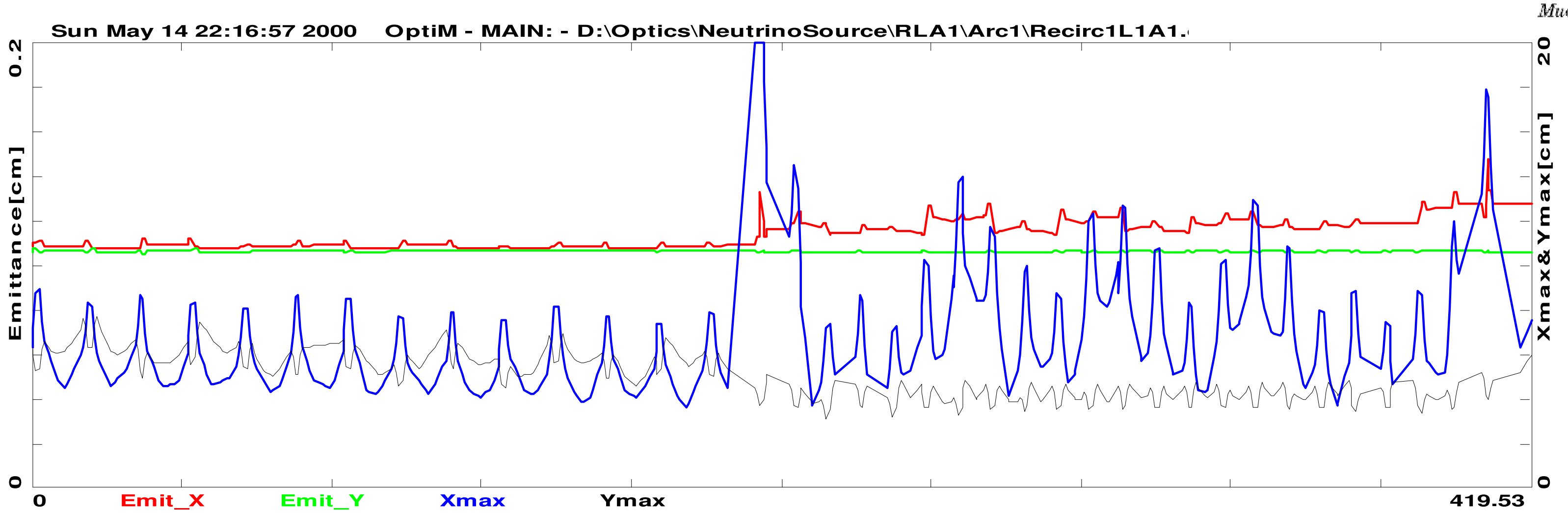
1. Longer straight sections
   - Possibility to use 10 m cryomodules
   - The only way to get simple beam spreaders
2. Smaller vertical beta-function
   - Better vertical chromatic behavior (2 times smaller the vertical beam envelope chromaticity)

FODO

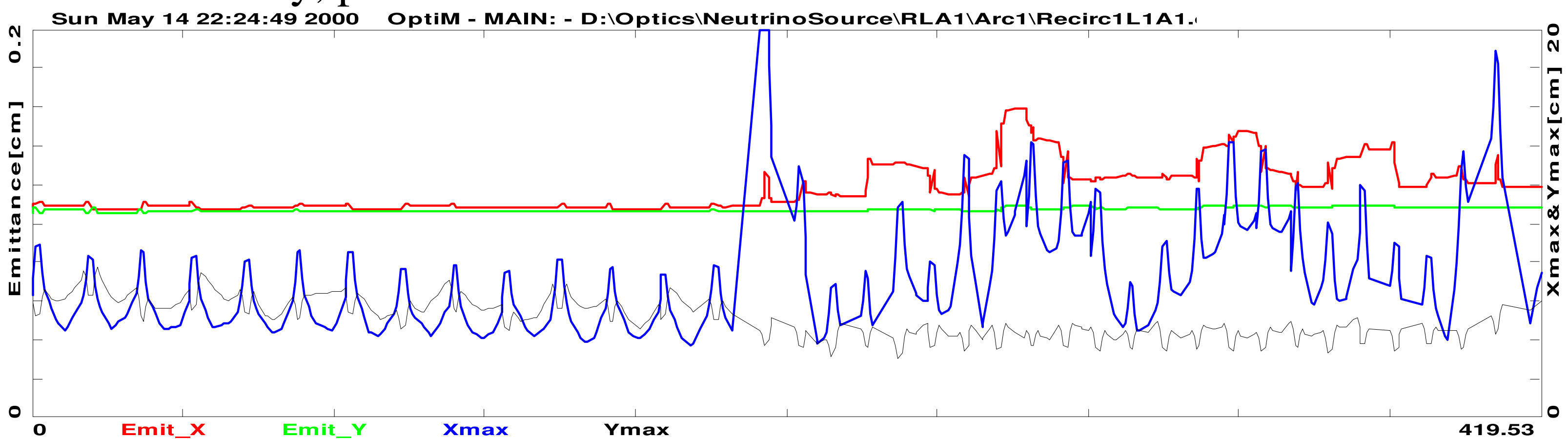
Triplet focusing



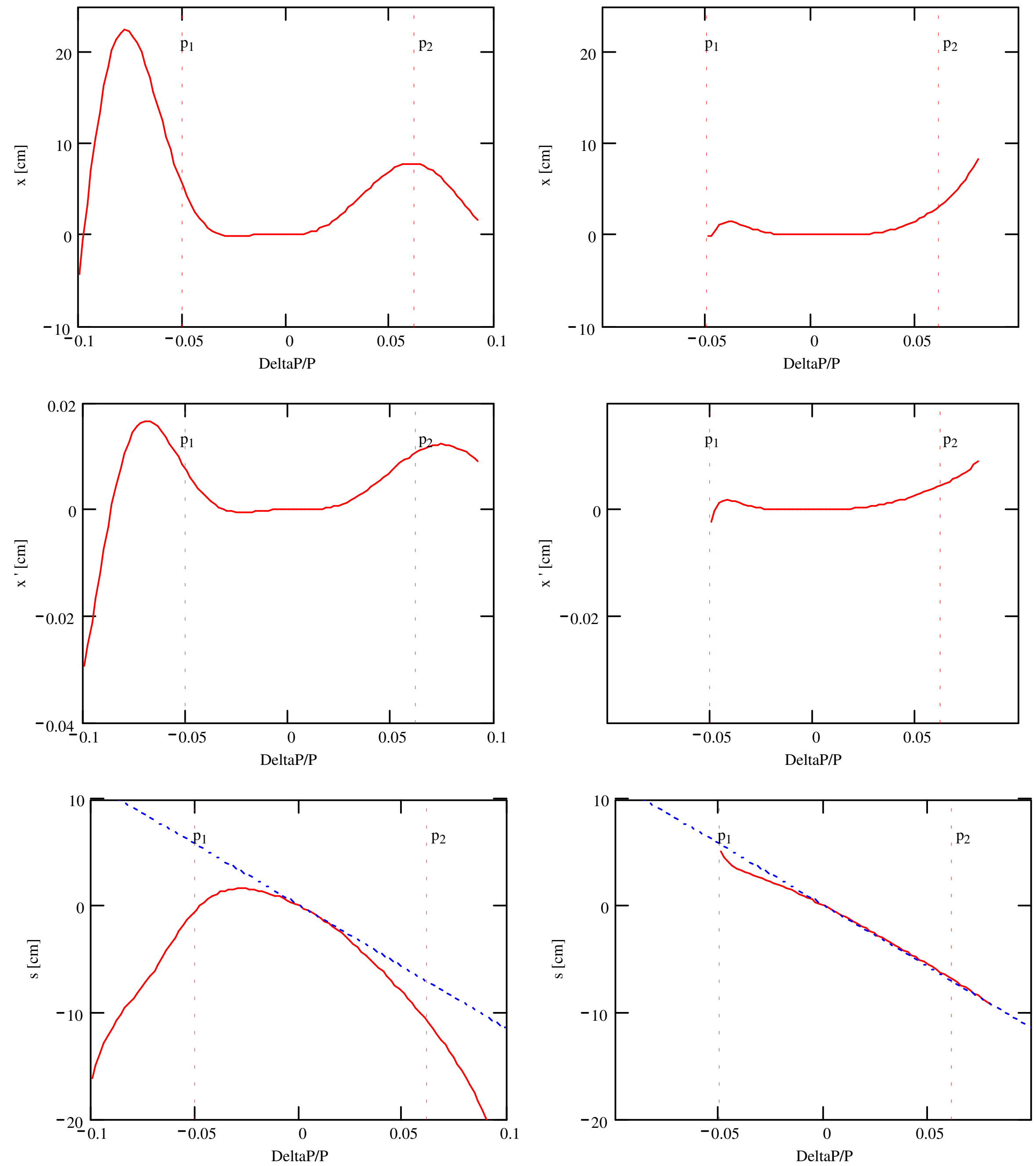
Relative beta-function change for ±10% momentum change $\beta(p)/\beta(p_0)$



Beam emittance and beam envelopes with chromaticity correction in the spreader and recombiner only, particle loss 0.2%



Beam emittance and beam envelopes with global chromaticity correction, particle loss 0.4%



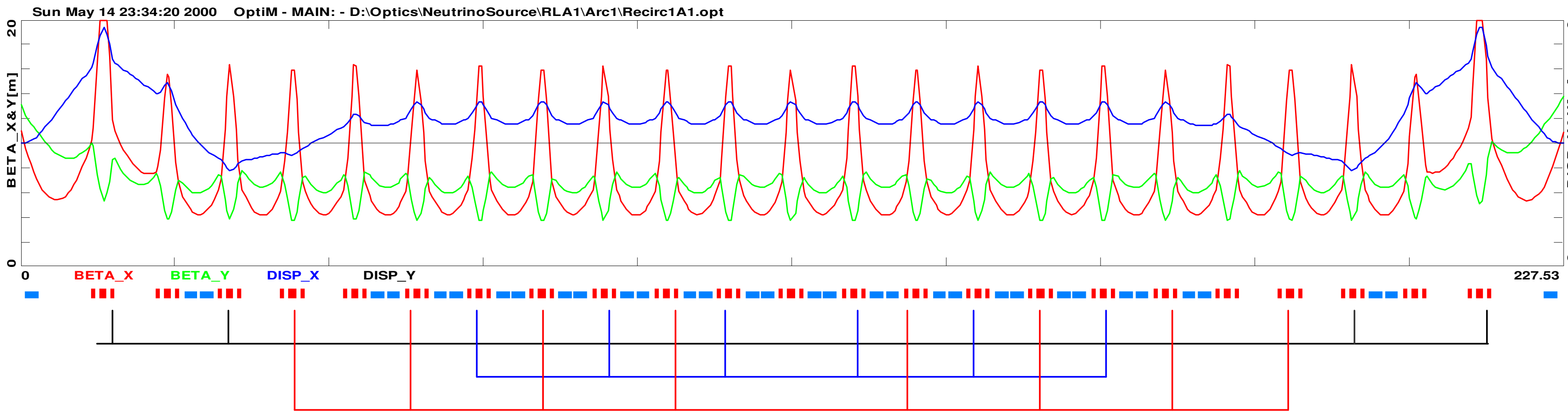
Chromaticity correction for Arc 1

Non-linearity for

- Dispersion
- Dispersion-prime
- M_{56}

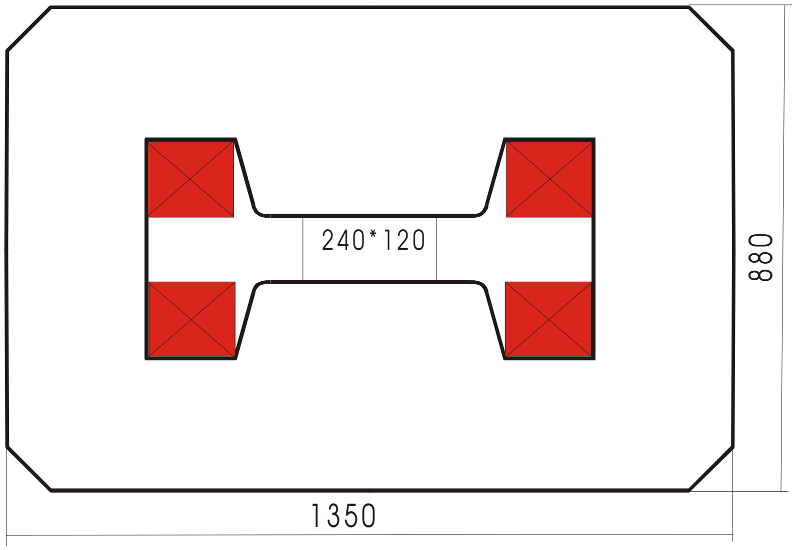
For the cases of

- no sextupole corrections
- 3 sextupole families



Scheme of sextupole correction (3 families of sextupoles)

Layout of magnets in the arcs



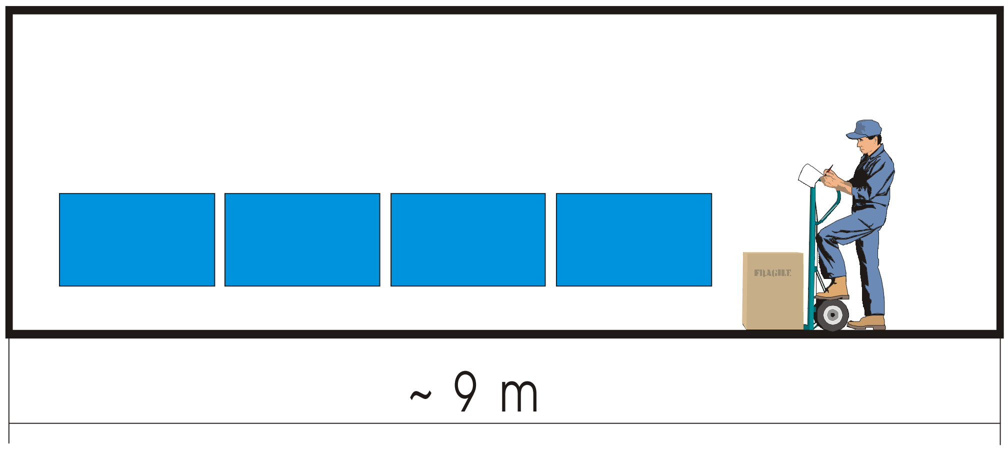
Cross-section for Arc1 dipole

Each next arc is n*1.5 m longer

⇒Distance between arcs $3*1.5/\pi \approx 1.5$ m

⇒Total width for magnets in the tunnel

$1.5*4 = 6$ m



Main Recirculator - RLA2

Main parameters

Initial energy	11 GeV
Final energy	50 GeV
Number of passes	5
Total initial energy acceptance	±2.6%
Total final energy acceptance	±0.7%
Initial transverse acceptance	160 mm·rad

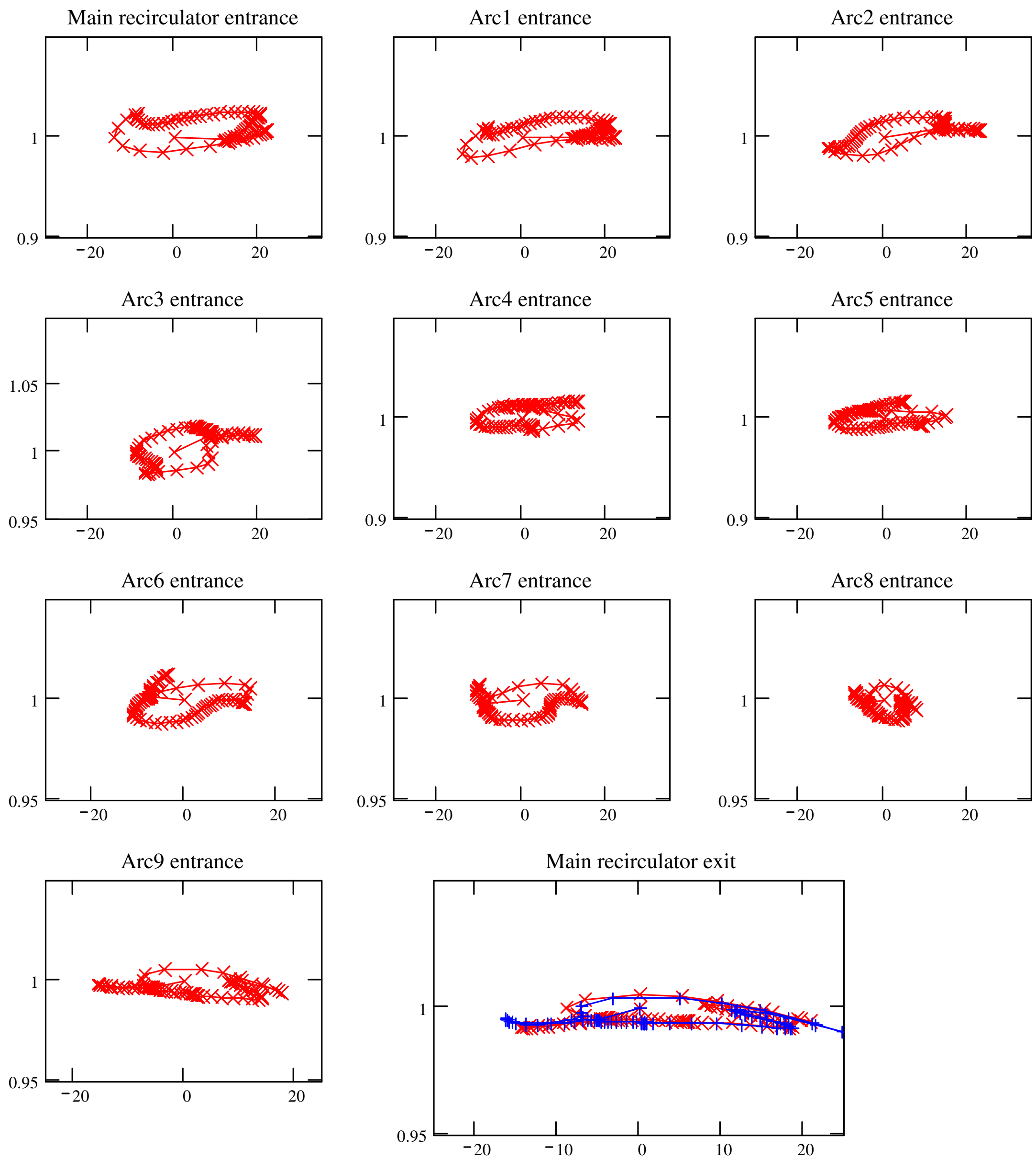
Final transverse acceptance	55 mm·rad
Emittance dilution (5% per arc)	55%
Total voltage per linac	4 GV
Circumference	~3 km

Parameters for acceleration in the RLA2

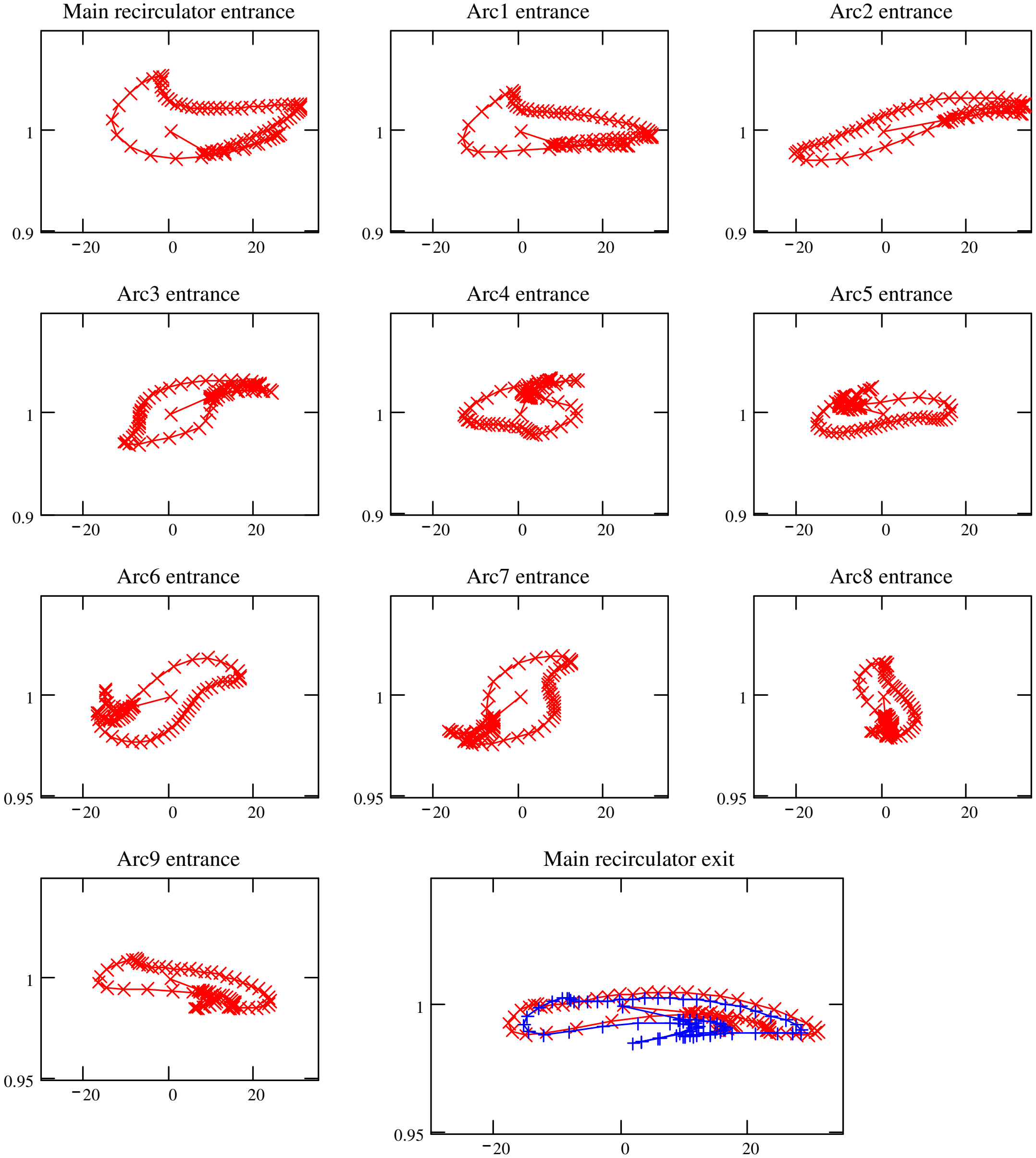
	200 MHz*			400 MHz**			
	Kinetic energy [GeV]	Gang phase [deg]	Total energy spread, $2\Delta p/p$ [%]	Kinetic energy [GeV]	M_{56} [cm]	Gang phase [deg]	Total energy spread, $2\Delta p/p$ [%]
Entrance	11.00	-5	4.0	11.00	200	-7	8.2
Arc 1	14.96	-16	4.0	15.22	200	-30	6.3
Arc 2	18.79	-16	3.9	18.9	200	-17	6.3
Arc 3	22.63	-16	3.5	22.96	200	-30	6.4
Arc 4	26.47	-16	2.9	26.64	200	-30	5.4
Arc 5	30.31	-16	2.7	30.32	200	-30	4.5
Arc 6	34.15	-7	2.4	34.00	200	-30	4.1
Arc 7	38.11	0	1.9	37.68	260	-11	4.3
Arc 8	42.10	-6	1.7	41.85	260	-16	3.7
Arc 9	46.07	-10	1.5	45.94	260	-17	2.5
Exit	50.00		1.3	50.00			1.6

* Total voltage per linac = 3.992 GV at 200 MHz, M_{56} = 2.2 m

**Total voltage per linac = 4.25 GV at 400 MHz



Longitudinal phase space in the RLA2. Blue line at the last slide shows longitudinal phase space for the last bunch of 3 10^{12} particle train. The difference in comparison with the first bunch is related to the voltage droop (0.3% per pass for 200 MHz) in RF voltage due to beam loading.



Longitudinal phase space in the RLA2. Blue line at the last slide shows longitudinal phase space for the last bunch of 3 10^{12} particle train. The difference in comparison with the first bunch is related to the voltage droop (1.2% per pass for 400 MHz) in RF voltage due to beam loading.

Important Concerns

Why SC RF?

- Large apertures in the linear preaccelerator
- The only way to get required accelerating gradient (RF generator power limit)
- Smaller voltage droop than for NC RF with the same accelerating gradient
- Positive Jefferson Lab experience verify high reliability of the SC RF but
  - ➢ To reach high reliability a by-passing of cavities must be anticipated in the design

Voltage Droop due to Beam Loading

Cannot match RF generators to the beam power because there are no RF generators with sufficient power

$\Rightarrow$ voltage droop

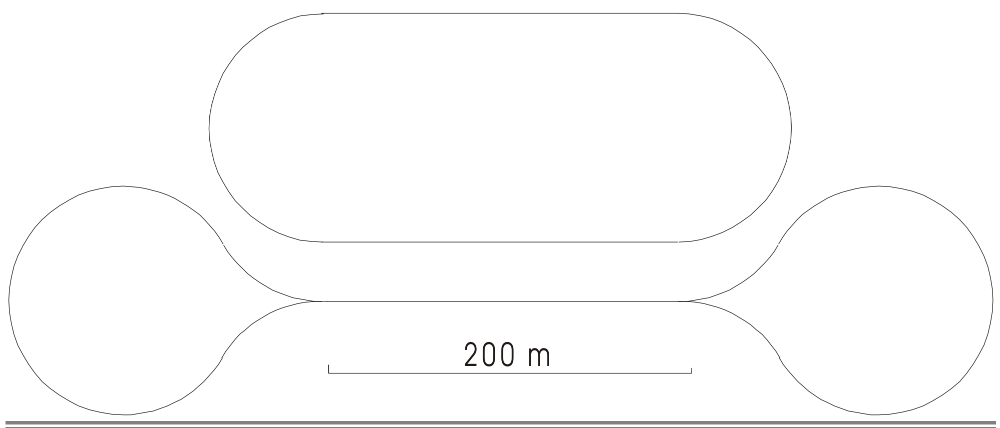
RLA1	RLA2
200 MHz 4 pass $\Delta V/V$ = 0.3% per pass $\Delta V/V$ = 1.2% for all 4 passes	200 MHz 5 pass $\Delta V/V$ = 0.3% per pass $\Delta V/V$ = 1.5% for all 5 passes 400 MHz 5 pass $\Delta V/V$ = 1.2% per pass $\Delta V/V$ = 6% for all 5 passes

- Synchrotron motion due to non-zero M_{56} prevents a loss of acceleration for the last bunch
- Dependence of beam orbit and optics on the beam current gas to be addressed in the design

400 or 200 MHz in the second RLA?

Advantages of 400 MHz	Disadvantages of 400 MHz
• Cheaper cavities • Cheapper RF generators • Smaller power consumption ○ 2.5 MW versus 10 MW average RF power for RLA2 • Easier to achieve 15 MV/m	• Difficult to handle large energy spread in RLA1 at higher passes • Larger energy droop for 400 MHz cavities

Possible layouts for recirculator



For RLA1

Linac : L=192 m

Racetrack

C=2*(192+197)=780 m

or linac takes 49% of C

Dog-bone

C=2*(192+462)=1310 m

or linac takes 29% of C

Arcs are 2.3 times longer

Total cost is smaller

RF power consumption is smaller

Muon decay 9.1% versus 5.5%

Optics & emittance growth ???

Muon Collaboration

Conclusion and Required R&D

- There are no principal physical and technical limitations to build an accelerator-recirculator for muons
- 200 MHz accelerating frequency and SC RF look well justified
- 400 MHz in second RLA is desirable but machine optics should be built to verify the possibility
- R&D to get 15 MV/m at 200 MHz
- Radiation effects on hardware (cavities, dipoles, *etc*.)
- Beam instrumentation in hard radiation environment