Muon Accelerator Driver for Neutrino Factory; Study II

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Talk Outline

1. Introduction
2. Machine layout and main parameters
3. Linear preaccelerator
4. Recirculator
5. Conclusions

Collaborators

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Editors Meeting for Study II,
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1. Introduction

Major Points to be Addressed

Study I

- How fast we need to accelerate to prevent a decay of muons?
- Accelerating technology (NC versus SC for cavities and dipoles)
- 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
- Site specific for Fermilab

Study II

- Increase of longitudinal and transverse acceptance
- From demonstration of main principles to more detailed optics design
  - More attention to technical details
    - SC cavities and cryo-module layout
    - Solenoid layout and shielding of solenoid field
    - Layouts for quads and dipoles
    - BPMs and tuning
    - Layouts for injection chicane, spreaders and recombiners, focusing cells
- Effect of non-linearities on the beam dynamics
  - Non-linearity of solenoidal focusing
  - Non-linearities of quads and dipoles
  - Changed phase advances per cell
- Improvements of chromaticity correction (if possible)
- Tracking through entire machine
- Coherent beam stability
- Site specific for BNL
  - 50 GeV -> 20 GeV

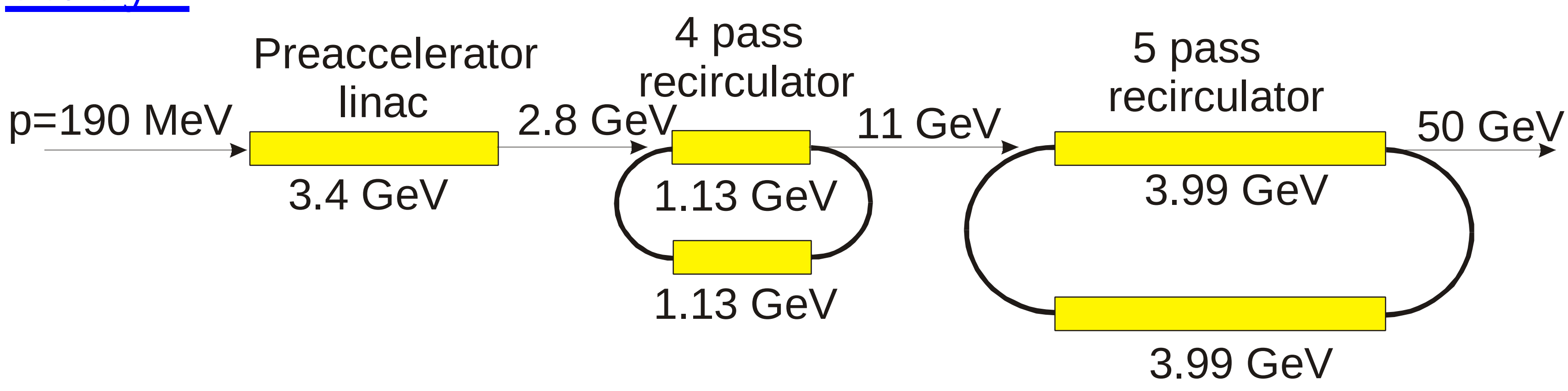
2. Machine Layout and Main Parameters

Basic MAD Parameters

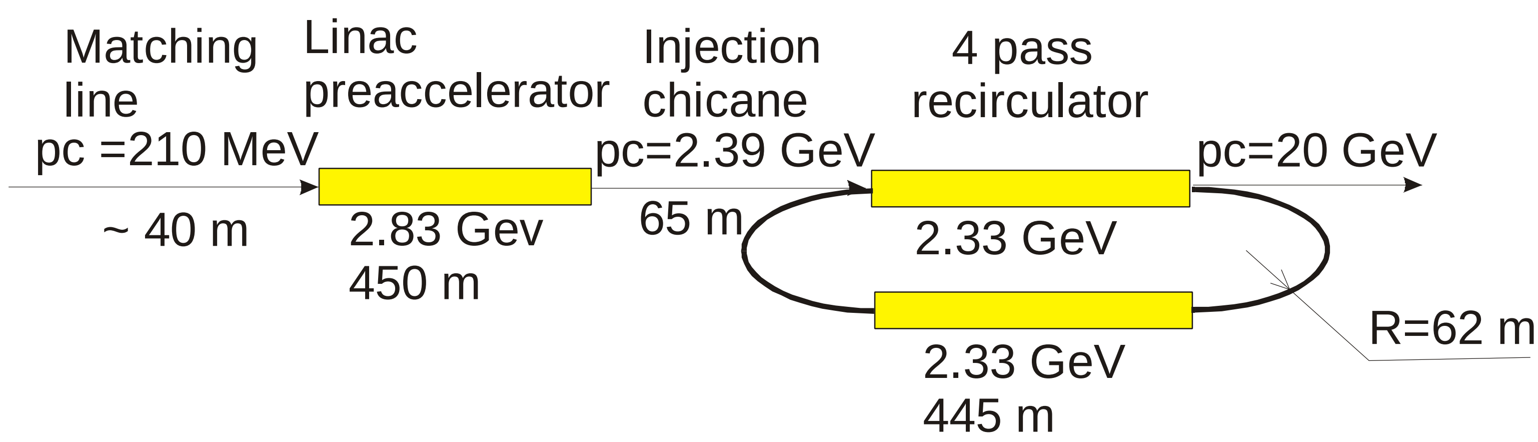
		Study I	Study II
Injection momentum/Kinetic energy	MeV	190/111.7	210/129.4
Final energy	GeV	50	20
Initial normalized acceptance rms normalized emittance	mm·rad mm·rad	9.4 1.5	15 2.4
Initial longitudinal acceptance, $\Delta pL_b/m_\mu$ momentum spread, $\Delta p/p$ bunch length, L_b rms energy spread rms bunch length	mm mm mm	148 ±0.275 ±300 0.11 120	203 ±0.275 ±372 0.11 149
Number of bunches per pulse		30 x 4	67
Number of particles per per pulse		? $3\cdot10^{12}$?	$3\cdot10^{12}$
Bunch frequency/accelerating frequency	MHz	201.25/201.25	201.25/201.25
Average repetition rate	Hz	15	15
Time structure of muon beam		15 Hz rep. rate	6 pulses at 50 Hz with 2.5 Hz repetition rate
Average beam power		360 kW	150 kW

Accelerator Layout

Study I

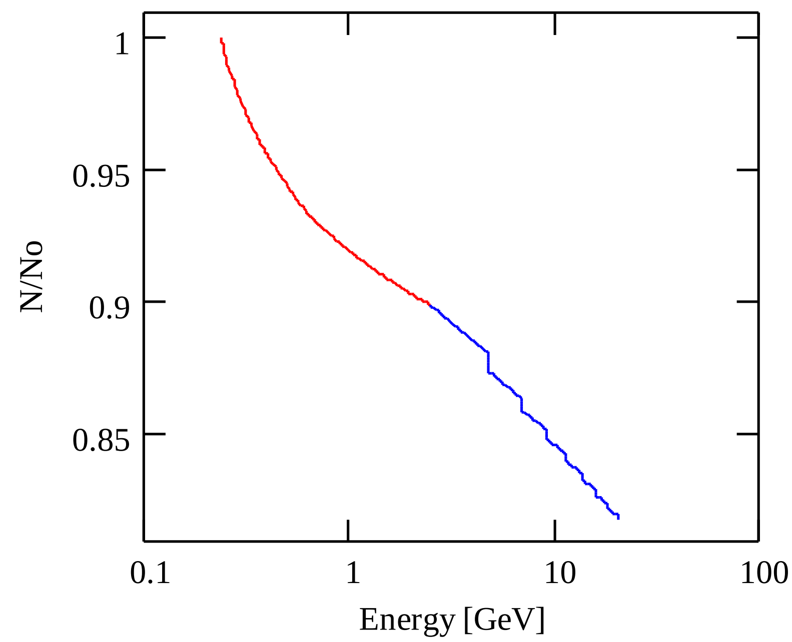


Study II



Muon Decay

- ➢ Muon decay time - 2.2 μs
- ➢ Decay losses depend approximately linearly on the accelerating gradient
- ➢ Study I
  - 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
    - ♦ That yields 22% loss for the Study I
- ➢ Study II
  - **19% loss for Study II**
    - ♦ more accurate calculations, lower energy

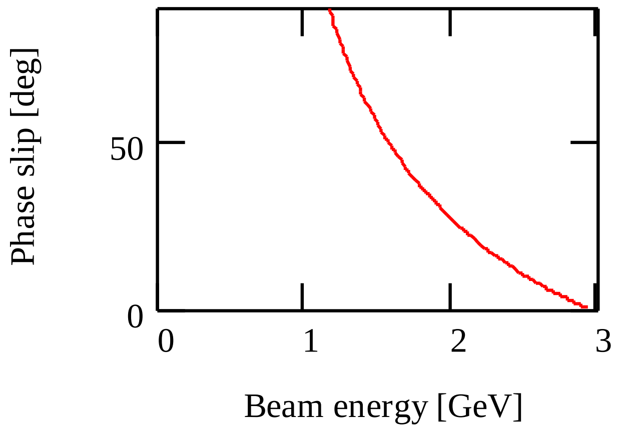


Red line – decay in the linac
Blue line – decay in recirculators

Choice of Accelerator Scheme and Technology

- High gradient acceleration and low RF frequency
  - ➢ High power RF source
    - ▪ Only choice of SC cavities allows one to reach 15 MV/m with practical RF source
- Recirculator
  - ➢ less expensive than linac and is a preferred choice
  - ➢ there are a few limitations why it can not be used at the very beginning
    - ▪ Initial beam is not sufficiently relativistic

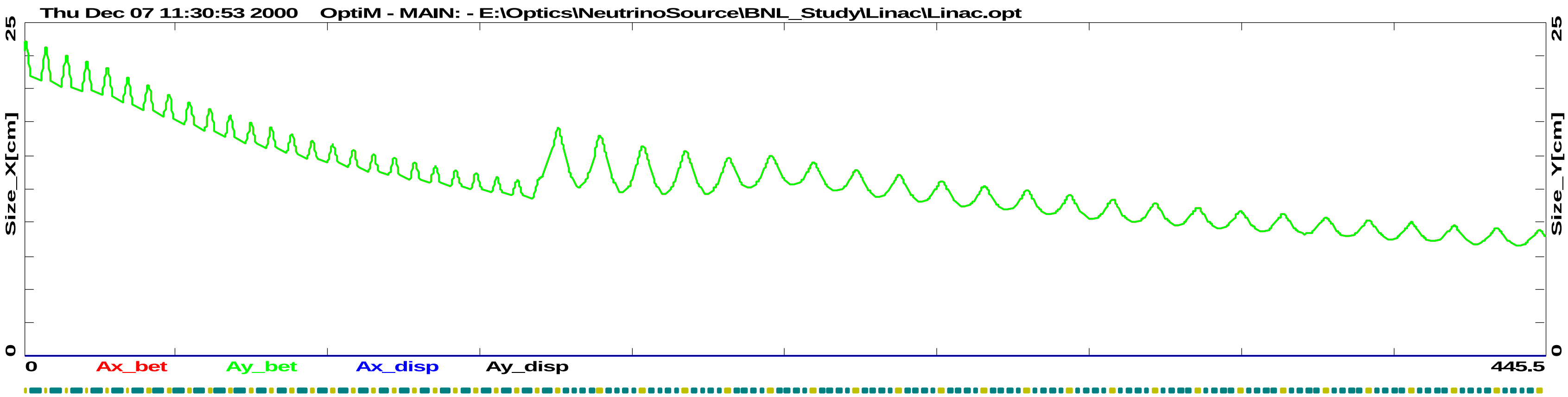
      $\Rightarrow$ phase slip for higher passes
    - ▪ Energy ratio (final/initial) should not be too large (<5-10)



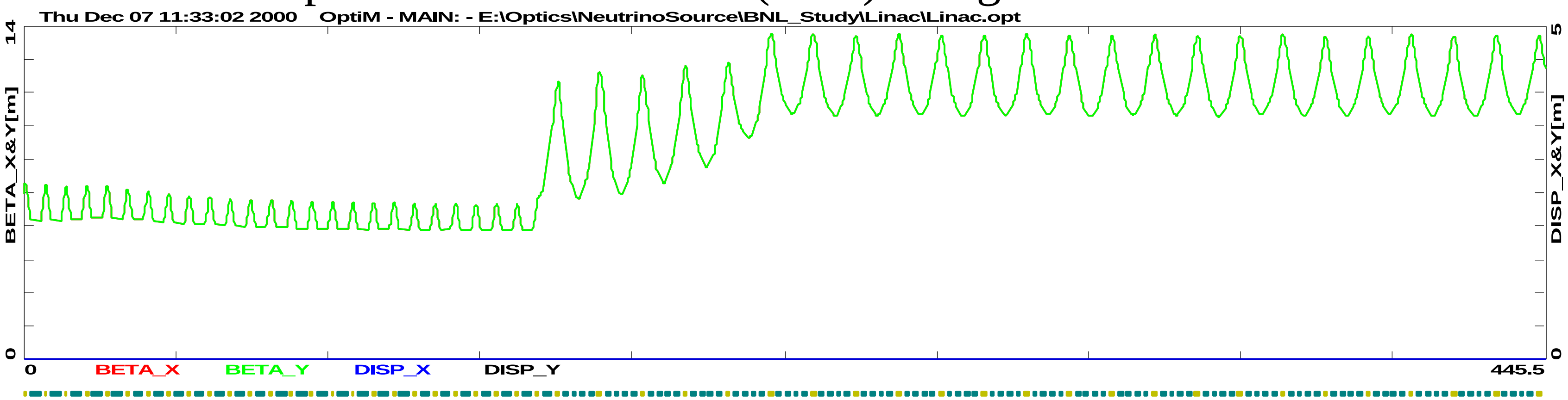
  - ➢ The number of passes should be limited to about 5 for given energy spread and emittance
- Beam transport and focusing
  - ➢ SC solenoids in the linac for beam focusing
  - ➢ NC quads and dipoles in recirculator (SC coils can be used to reduce power consumption)

3. Linear Preaccelerator

The final energy of 2.39 GeV is set by RF phase slip for higher passes

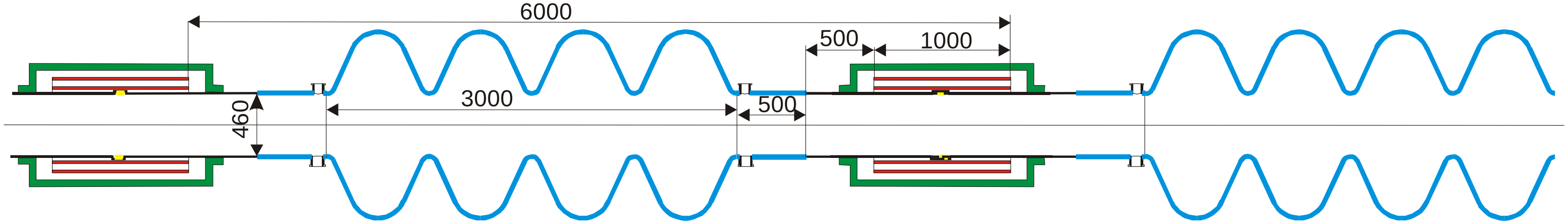


Beam envelopes of the entire beam (2.5 s) along the linear accelerator

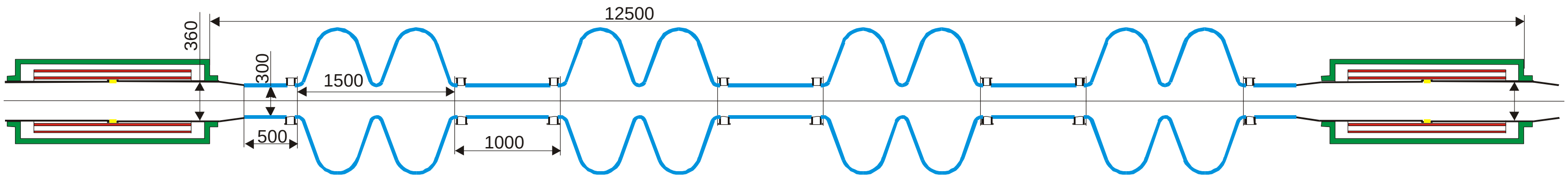


Beta-functions along the linear accelerator. Acceleration from 129 MeV to 2392 MeV

Two flavors of lattice cells and cryomodules



Short cryomodule layout



Long cryomodule layout.

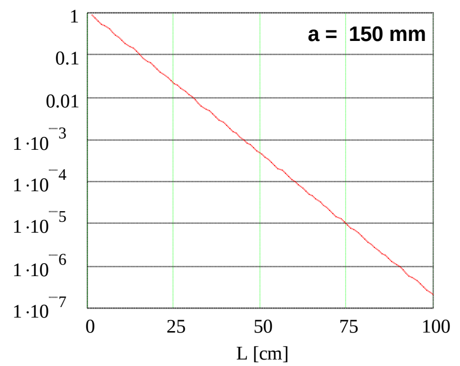
Blue - SC walls of cavities. Red - solenoid coils. Yellow - BPMs.

- Solenoidal focusing
  - saves space
  - allows one to reach very large beam emittance
- Distance between cavities and
  - RF decoupling for different cavities ($Q \approx 5 \cdot 10^5$, $d \leq 0.1/Q \approx 2 \cdot 10^{-7}$)
- Number of cells per cavity
  - Power limitation for the fundamental coupler (15 MV/m $\Rightarrow$ 500 kW/cell)

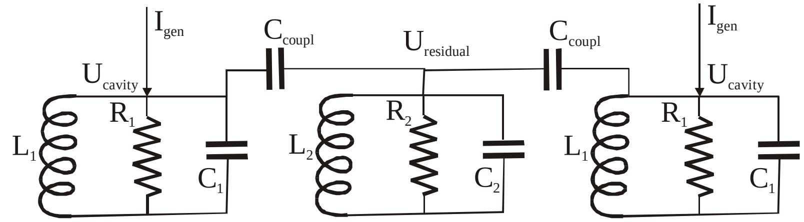
Parameters of the long and short periods of linear accelerator

	Short cryo-module	Long cryo-module
Number of periods	26	23
Total length of one period	6 m	12.5 m
Number of cavities per period	1	4
Number of cells per cavity	4	2
Number of couplers per cavity	2	2
Accelerating gradient in the cavity	10 MV/m	15 MV/m
Aperture in cavities (2*a*)	460 mm	300 mm
Spacing between cavities within one period	-	1 m
Spacing between cavities of different periods	3 m	3 m
Aperture in solenoids (2*a*)	460 mm	360 mm
Solenoid length	1 m	1.5 m
Solenoid maximum field	1.8 T	4 T

Decoupling of cavities



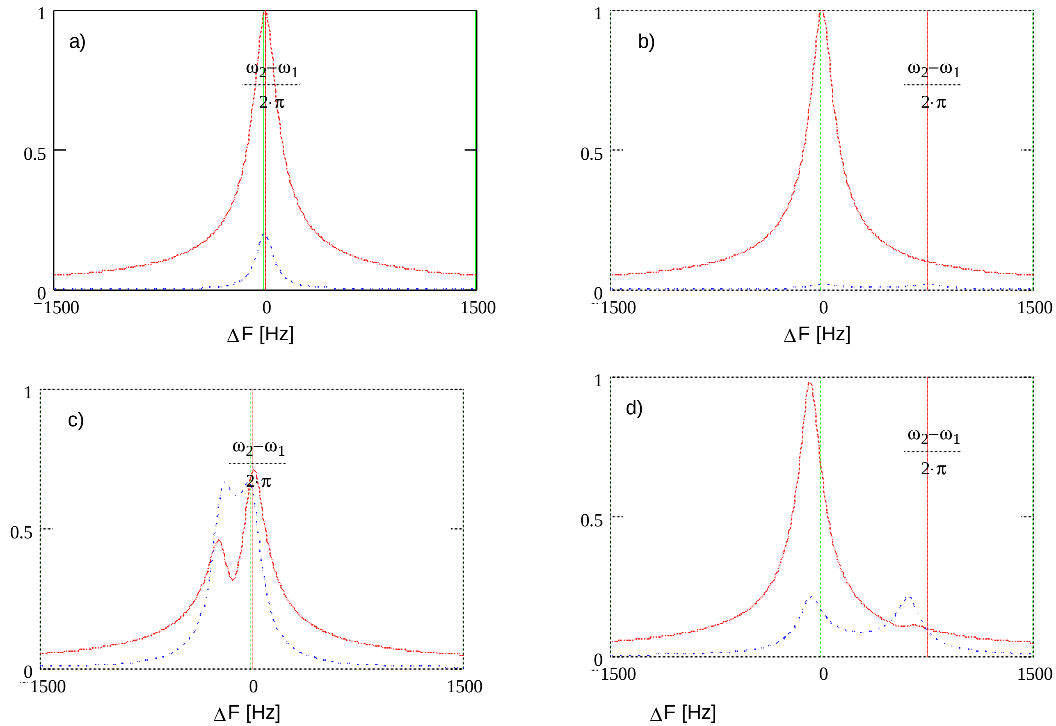
Attenuation of the electromagnetic wave between two cavities



Dependence of cavity voltage on frequency.

$d = 0.1/Q$

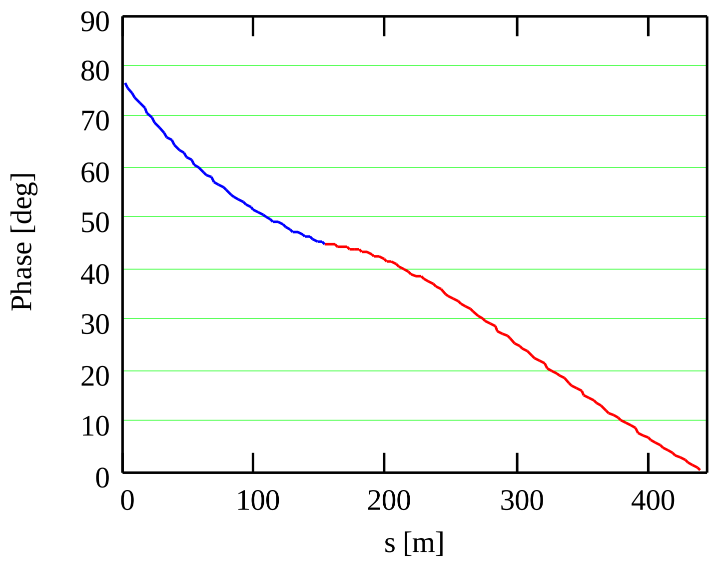
$d = 1/Q$



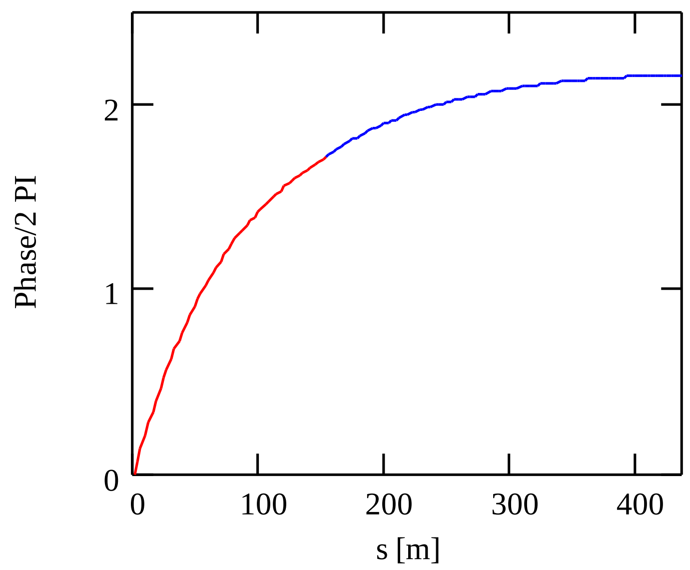
Bypassed cavity: In resonance Detuned by 5 bandwidth

Longitudinal dynamics in linac

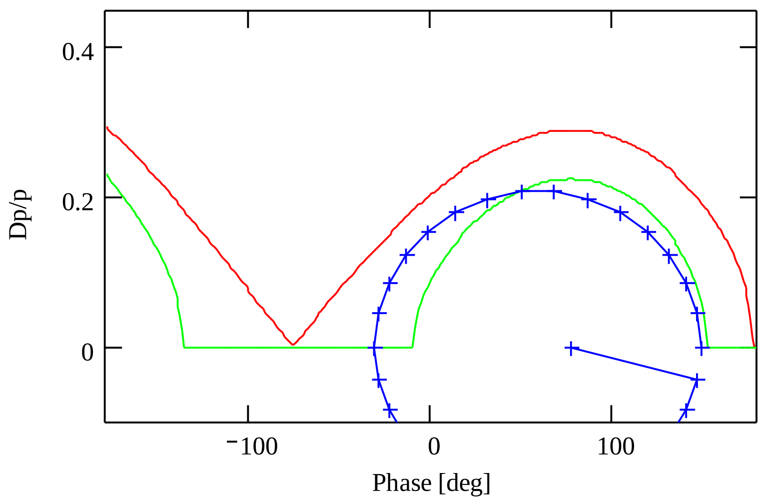
- **Longitudinal (synchrotron) motion in the initial part**
  - suppresses effect of non-linearities in the longitudinal phase space
  - allows to perform the beam bunching
  - reduces effective accelerating gradient (total voltage of 2.8 GV instead 2.2 GV)

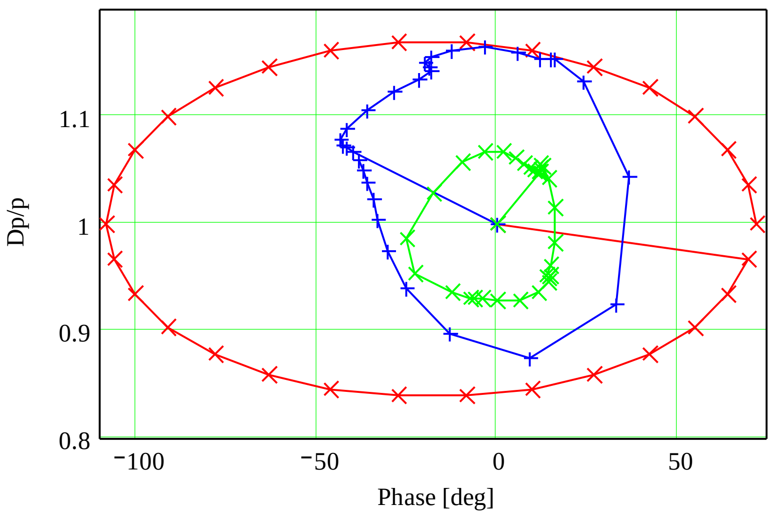


Accelerating phase along linac



Synchrotron phase along the linac



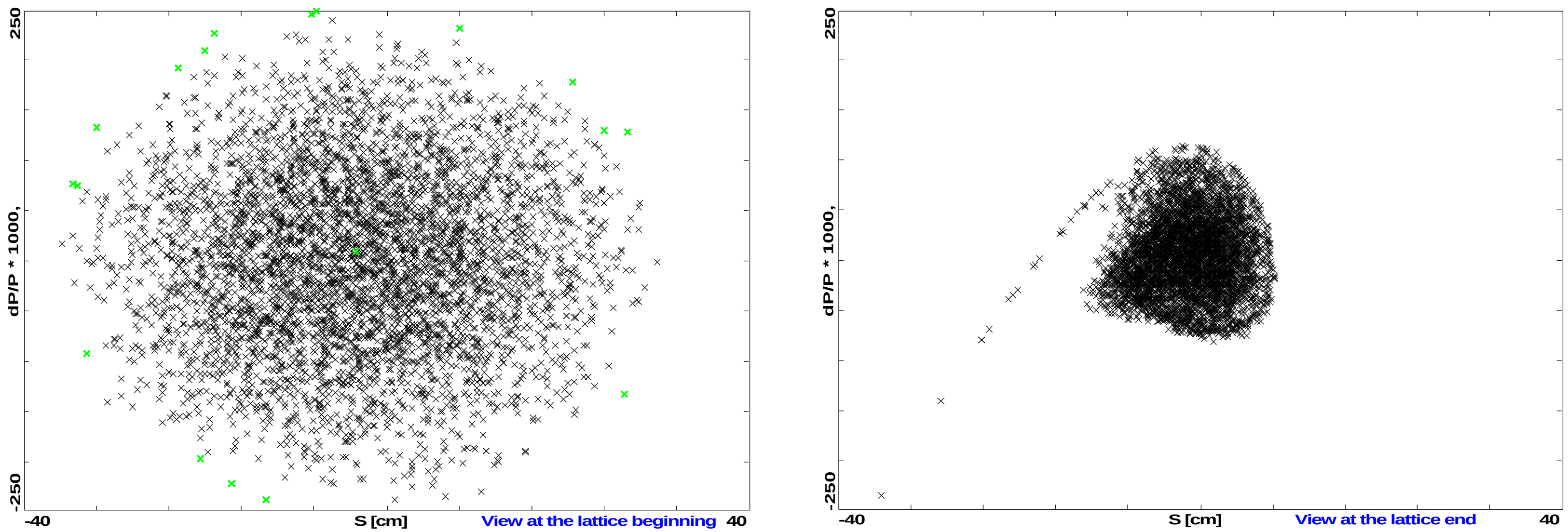


Separatrix and beam acceptance in the longitudinal phase space

- Bunch center is shifted relative to the center of potential well by -30 mm (-7.2 deg)
- In the particle tracking it was possible to increase momentum acceptance from ±0.208 to ±0.275 without significant particle loss

The boundaries of the beam phase space

- before,
- in the middle and
- after acceleration



Longitudinal emittance at the beginning and at the end of the linac

- Lost particles are marked by green color

Transverse dynamics in linac

- Focusing non-linearity
  - Focusing element length (1 m) is comparable to its aperture (R = 0.26 m)

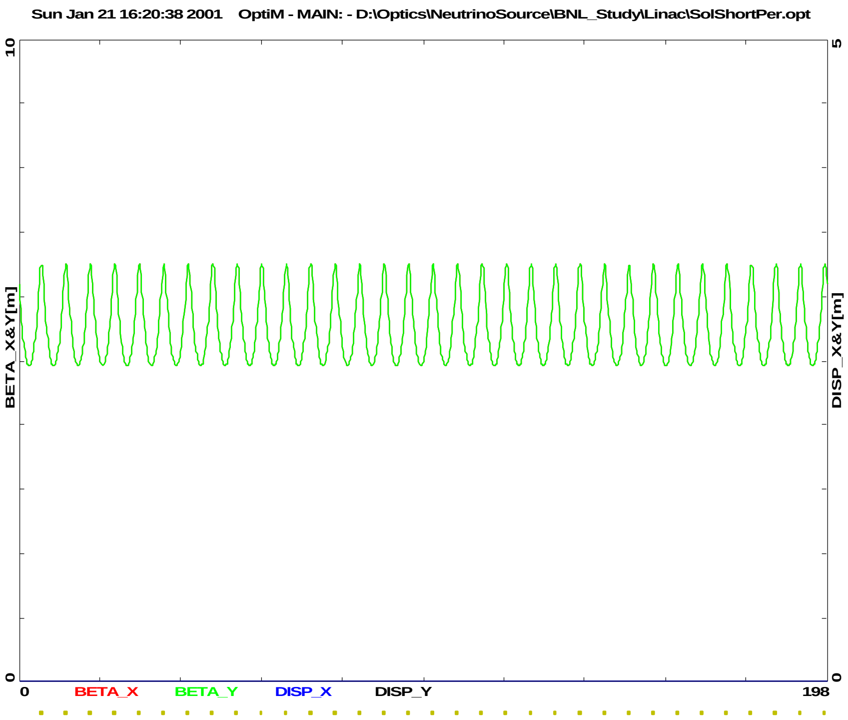
$$\frac{\Delta F}{F} \approx \frac{r^2}{2}\frac{\int B'^2 ds}{\int B^2 ds} \approx \frac{r^2}{3aL} \xrightarrow{L/r=4,\ r\approx 0.8a} 0.07$$

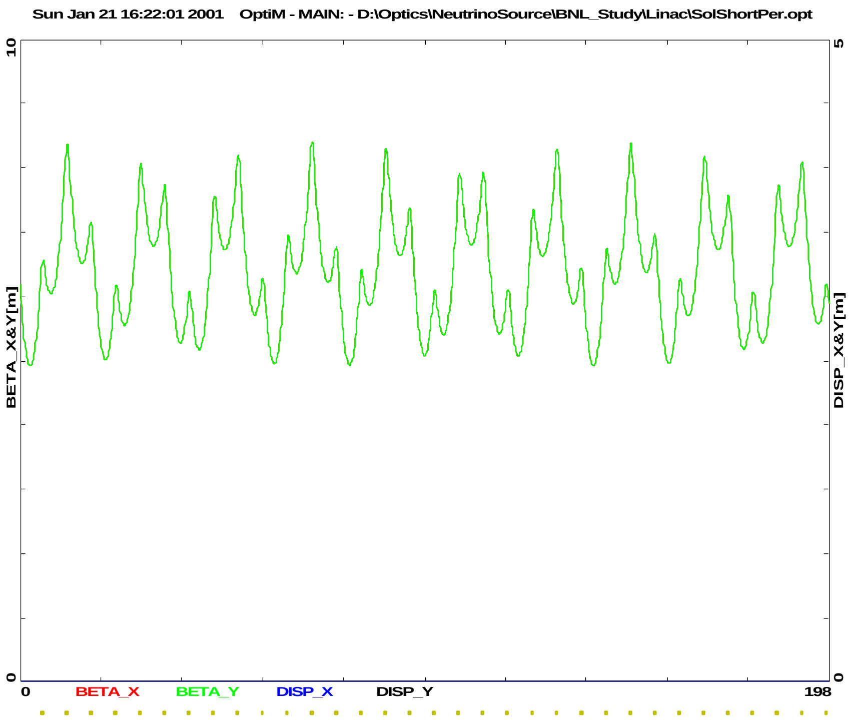
  - Length increase is limited by drop of real estate gradient
  - Aperture increase is limited by shielding of the magnetic field

    $\Rightarrow$ drop of real estate gradient
  - Fourth and six order resonances are important
  - Large energy spread $\Rightarrow$ large tune spread

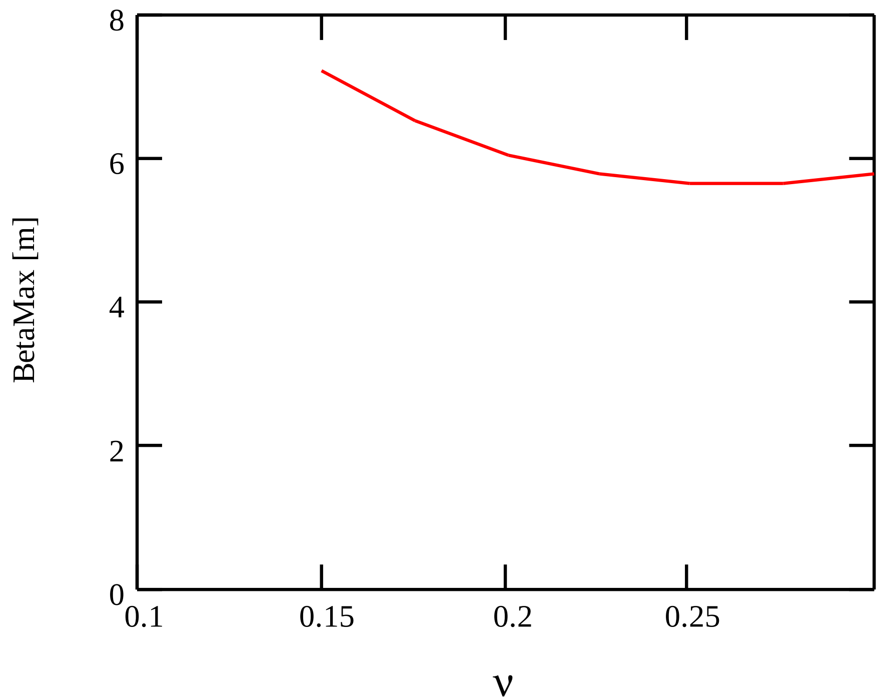
    $\Rightarrow$ Phase advance per cell is changed from 0.25 to 0.175
- Effect of large energy spread on emittance growth
  - Tracking

Choice of the Betatron Phase Advance per Cell for Linac

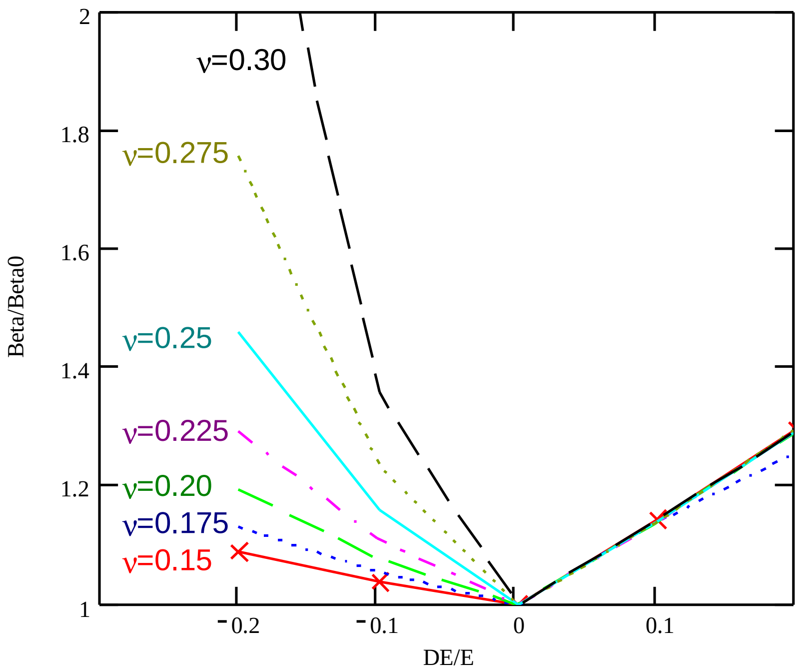




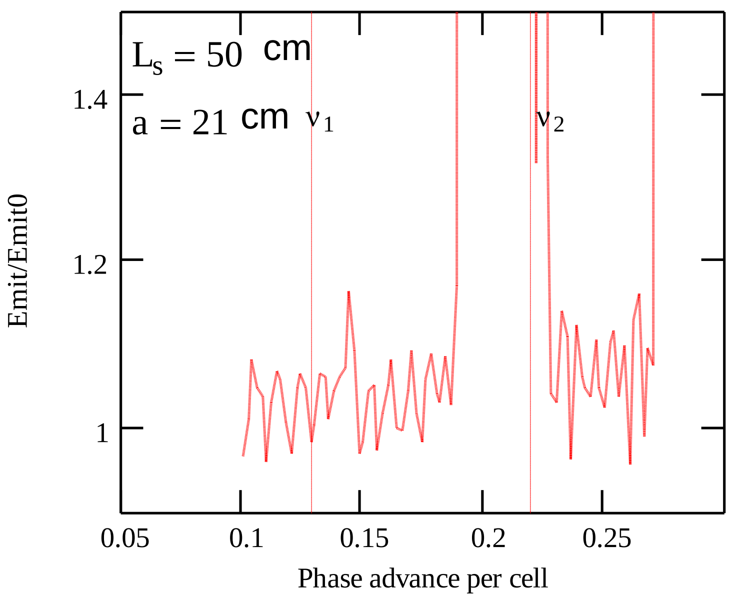
Beta-functions for the nominal energy and for energy of 20%above nominal, $\delta\nu = 0.175$.

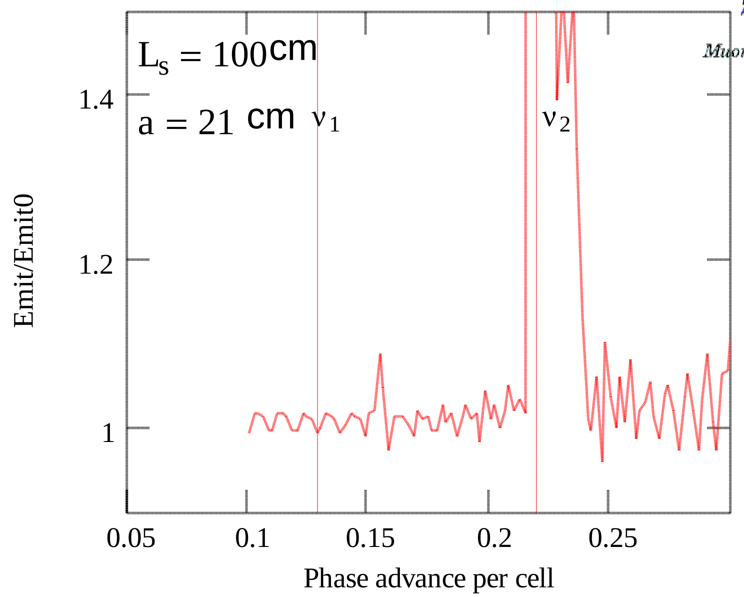


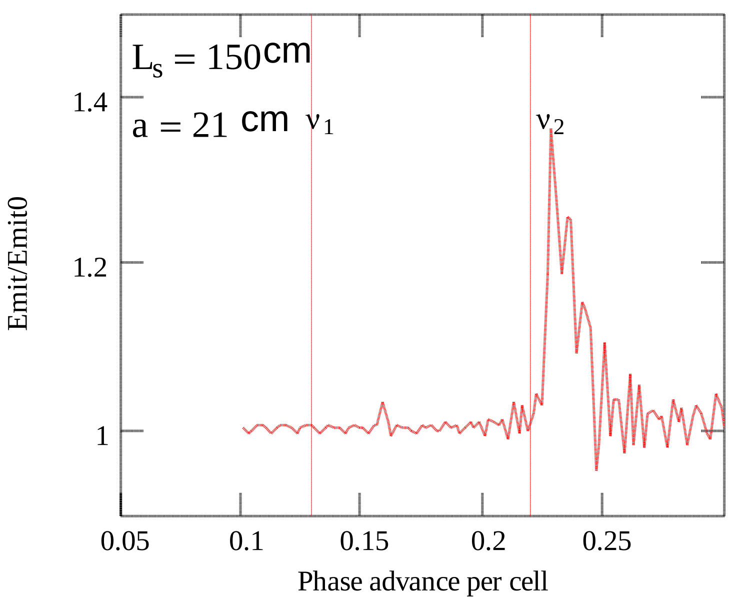
Dependence of maximum beta-function on tune advance per cell



Dependence of relative change of beta-function maximum on relative energy change for different tune advances per cell







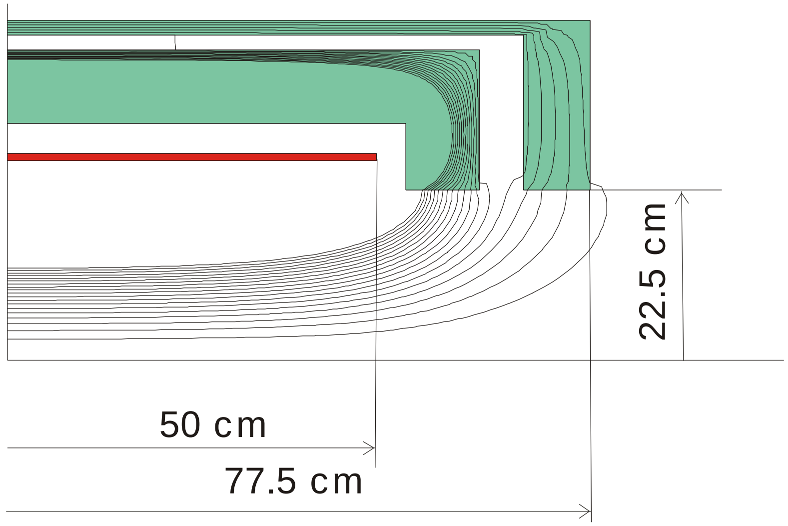
Relative emittance change after passing 50 solenoidal lenses of different length:

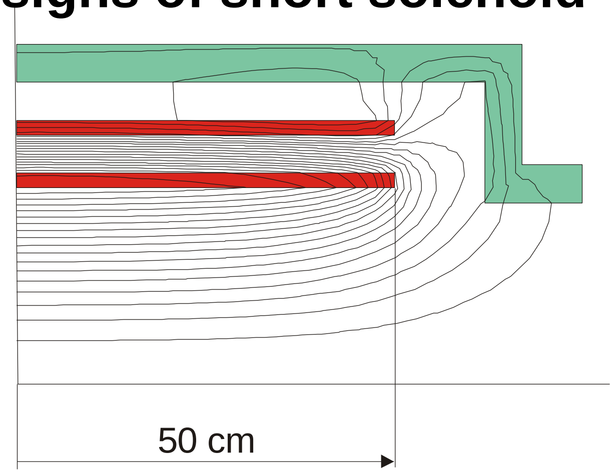
ε_n = 15 mm rad,

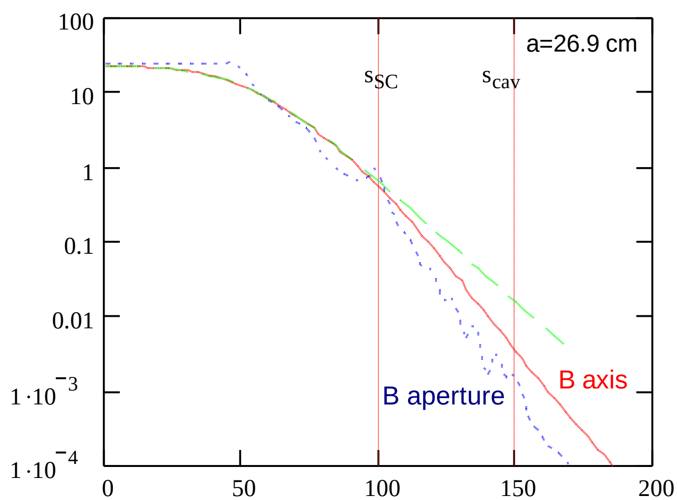
ν_0=0.175 (0.25 before !!!)

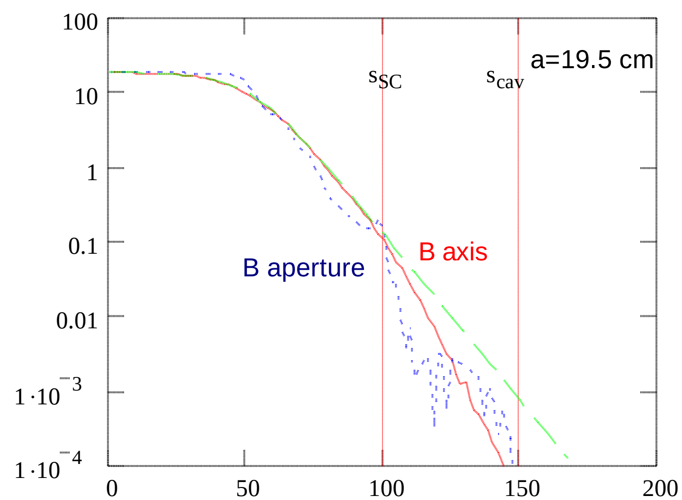
$\Delta\nu/\nu \approx \Delta p/p = \pm 26$ %

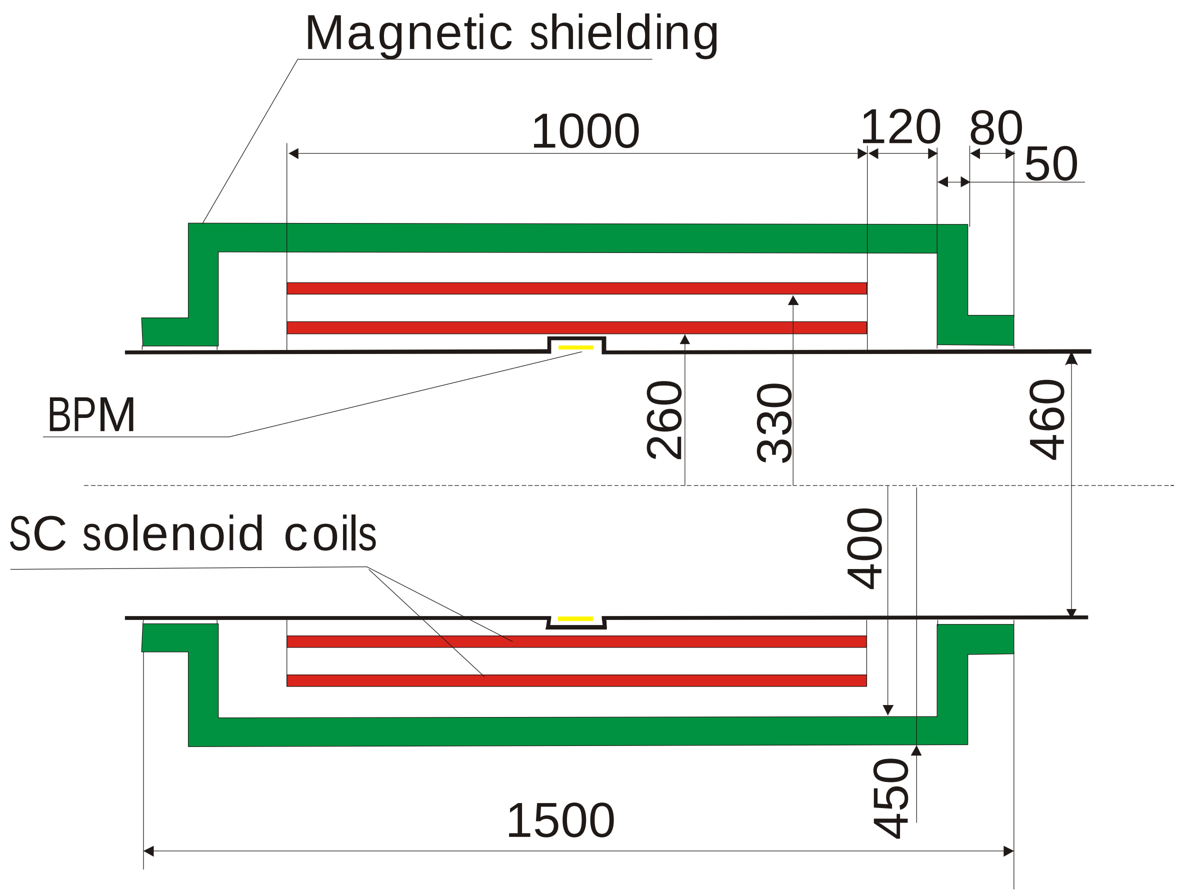
Magnetic lines and fields for two designs of short solenoid



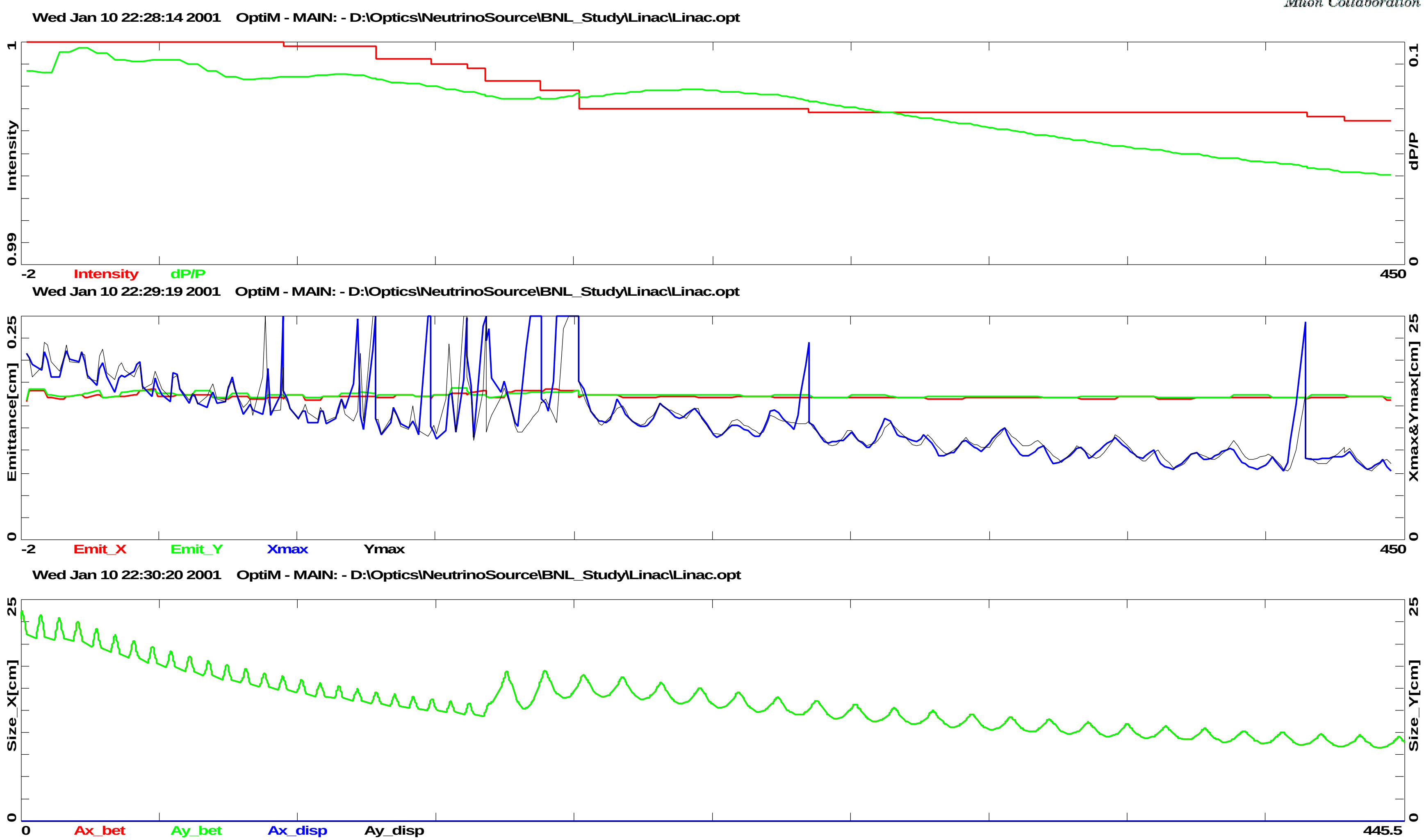






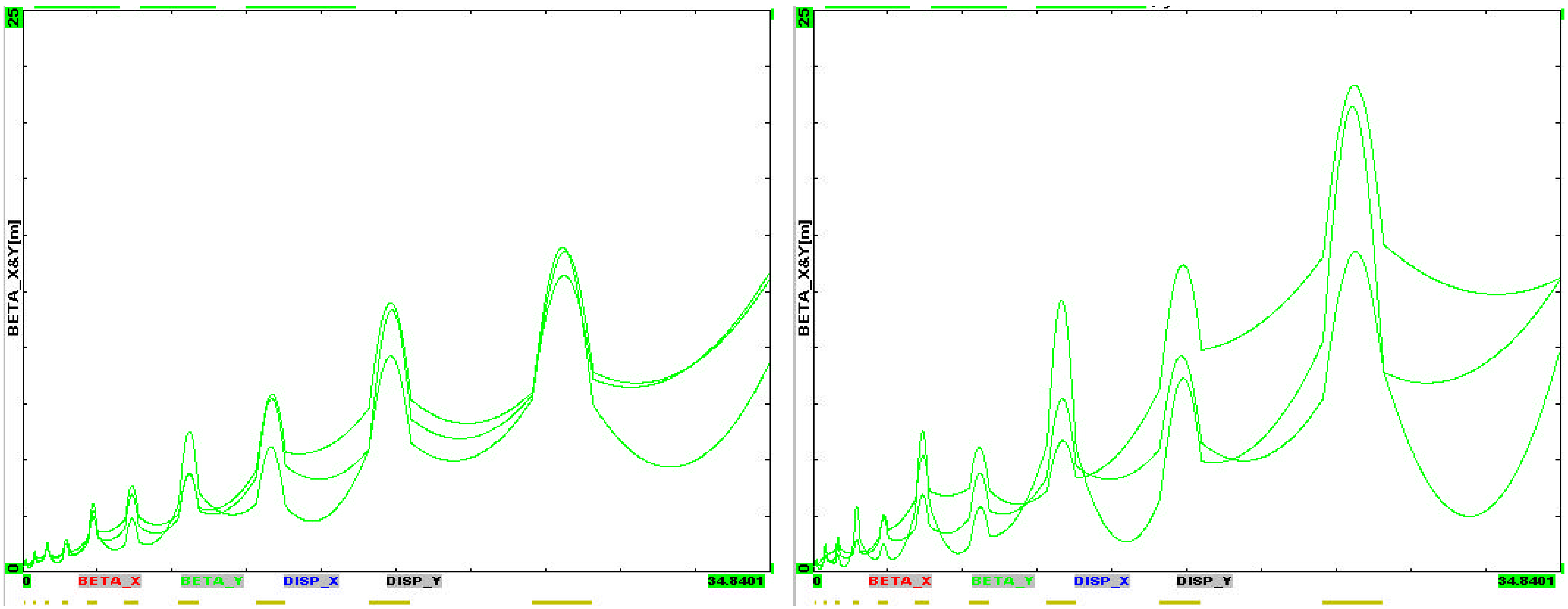


Layout of short solenoid



Beam loss, rms. emittance growth and maximum beam size (maximum particle displacement), and beam design envelope at acceptance along the linear accelerator. Rapid beam size decreases correspond to scraping of the particles with large amplitude

Transition Module from Ionization Cooling to Linac and the Chromaticity of Beam Envelopes



Beta-functions for $\Delta E/E=\pm 10\%$ and $\Delta E/E=\pm 20\%$.

Scaling: $L_{n+1} = kL_n$ (k=1.45), constant phase advance: ν = 0.195 per cell

Optimization strategy:

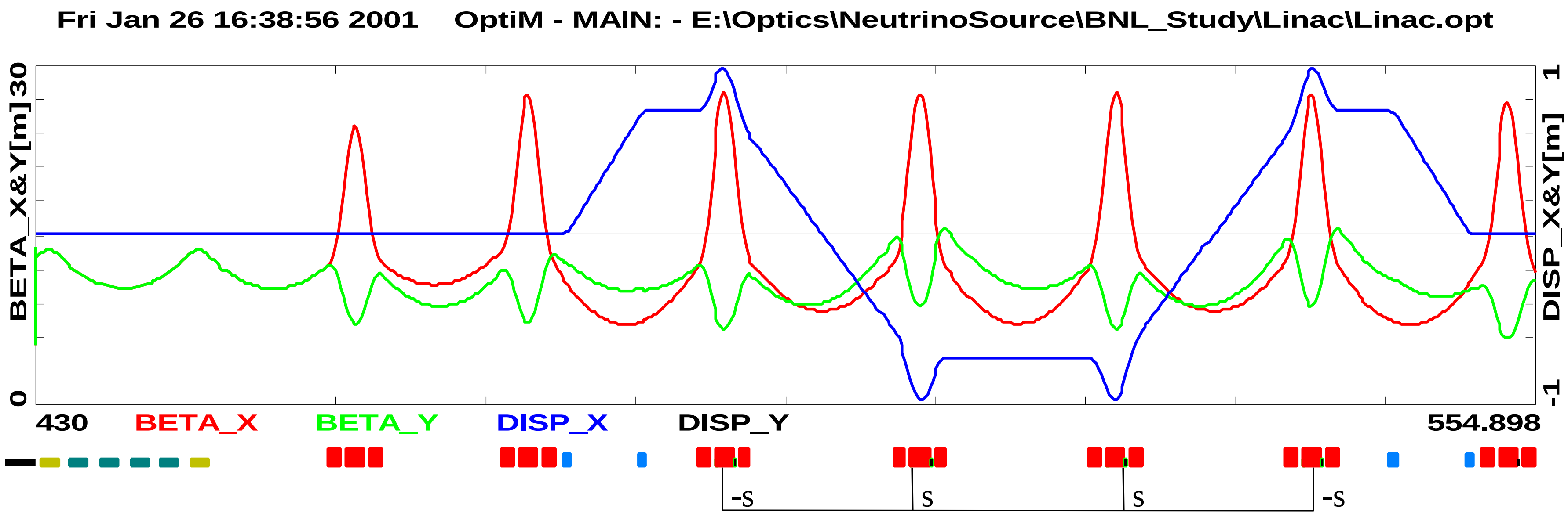
1. Determine the initial *b*-function (after the cooling) as function of energy
2. Vary phase advance per cell along as function of cell number to minimize variations of *b* - function at the end of the line

Recirculator (RLA)

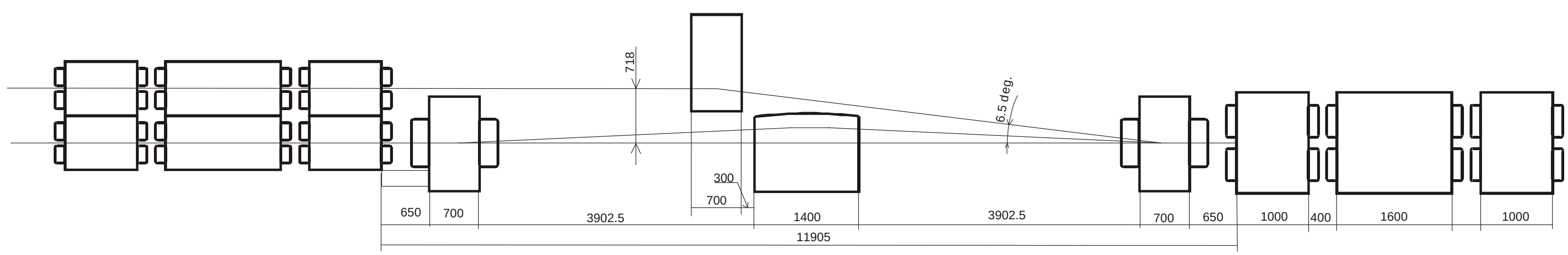
Main parameters for the RLA

Initial energy	2.3918 GeV
Final energy	20 GeV
Number of passes	4
Total initial energy acceptance	±9.2%
Total final energy acceptance	±1.9%
Initial transverse acceptance	635 mm·mrad
Final transverse acceptance, e_x / e_y	157/108 mm·mrad
Total voltage per linac	2.3347 GV
Circumference	≈1300 m

Injection to RLA



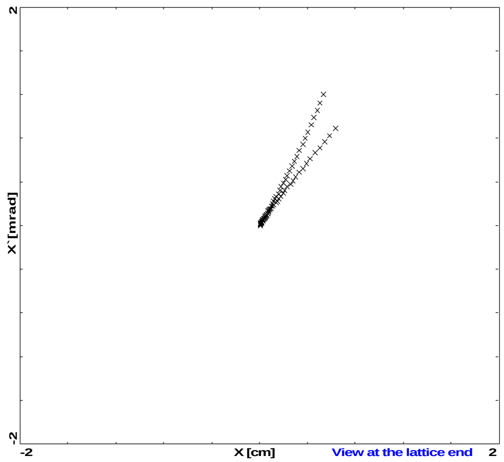
Injection chicane beta-functions and dispersions, chromaticity correction scheme

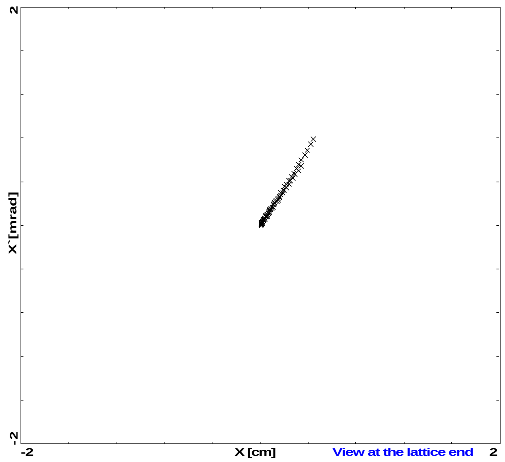


Layout of the last period of injection chicane

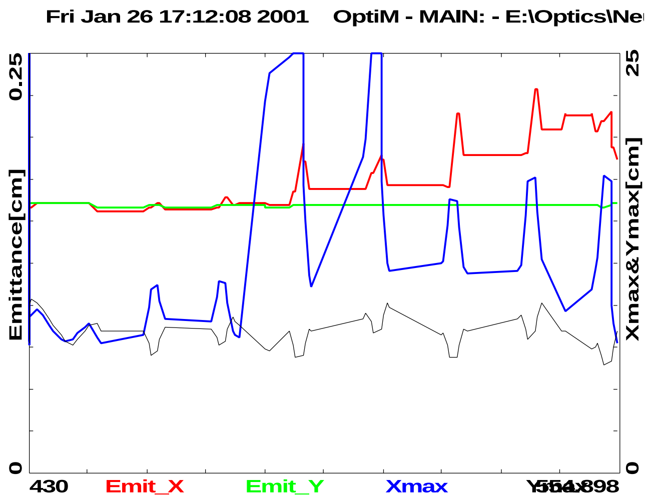
Chromatic Corrections in the Injection Chicane

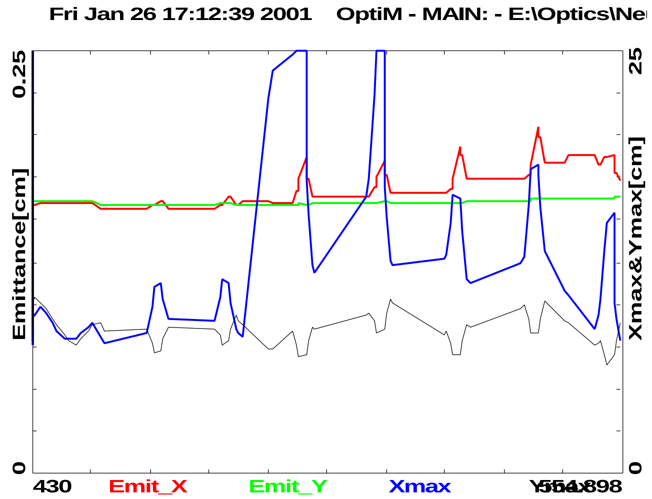
- 4 focusing quads have build-in sextupole component, SdL=0.16 kG/cm
  - ➢ it corresponds to S=1 G/cm^2 or ≈5% correction for G at r = 20 cm
- Quads are shifted by π/2 in betatron phase and their effects are canceled in linear approximation
  - ➢ 4 quads are better than 2 shifted by π (case of complete cancellation for small energy spread)
- The sextupole gradient is chosen to minimize the total emittance growth
  - ➢ It does not correspond to the best possible dispersion correction

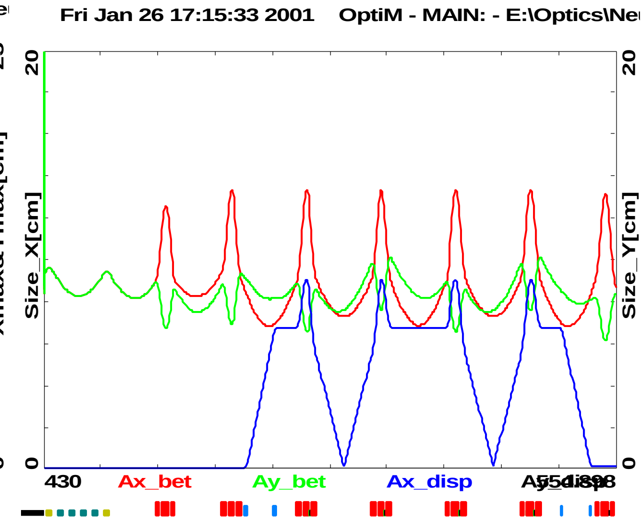


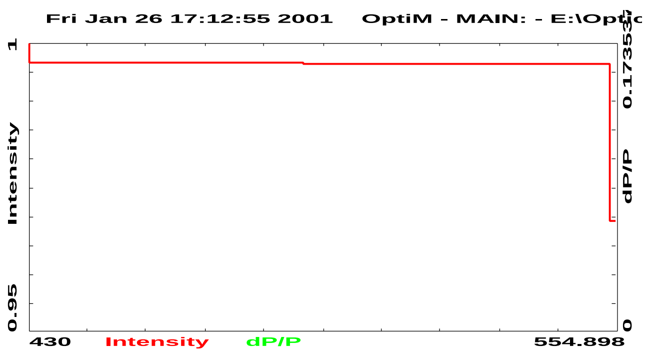


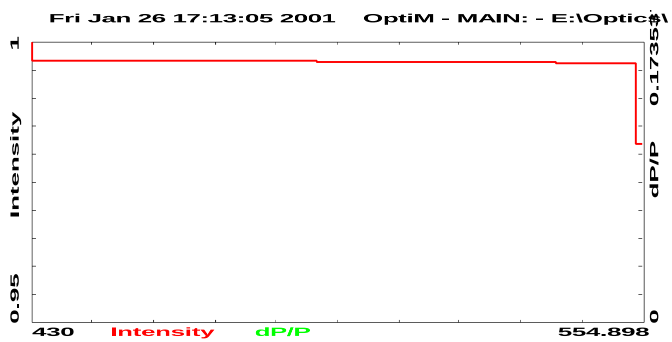
Particle displacement for uncompensated and compensated chromaticity











Design beam envelopes at acceptance

SdL=0
$\Delta\varepsilon_x$=28% ,
$\Delta\varepsilon_y$=0%
$\Delta I/I$=2.8%

SdL=0.16 kG/cm (S=1 G/cm^2)
$\Delta\varepsilon_x$=15%
$\Delta\varepsilon_y$=2.5%
$\Delta I/I$=1.4%

Beam emittance, beam envelopes and beam loss through injection chicane with and without chromatic corrections

Parameters for acceleration in the recirculator

	Kinetic energy [GeV]	Gang phase [deg]	Total energy spread, 2Δp/p [%]	Horizontal acceptance, [mm mrad]	Vertical acceptance, [mm mrad]
Entrance	2.3918	0	18.4	692	660
Arc 1	4.7265	-35	11.8	390	354
Arc 2	6.6390	-23	11.6	304	264
Arc 3	8.7881	-23	9.16	252	208
Arc 4	10.937	-19	6.57	221	174
Arc 5	13.145	-15	5.86	201	151
Arc 6	15.400	-14	4.72	187	134
Arc 7	17.665	0	4.27	178	122
Exit	20.000		3.77	157	108

M_{56} = 1.4 m,

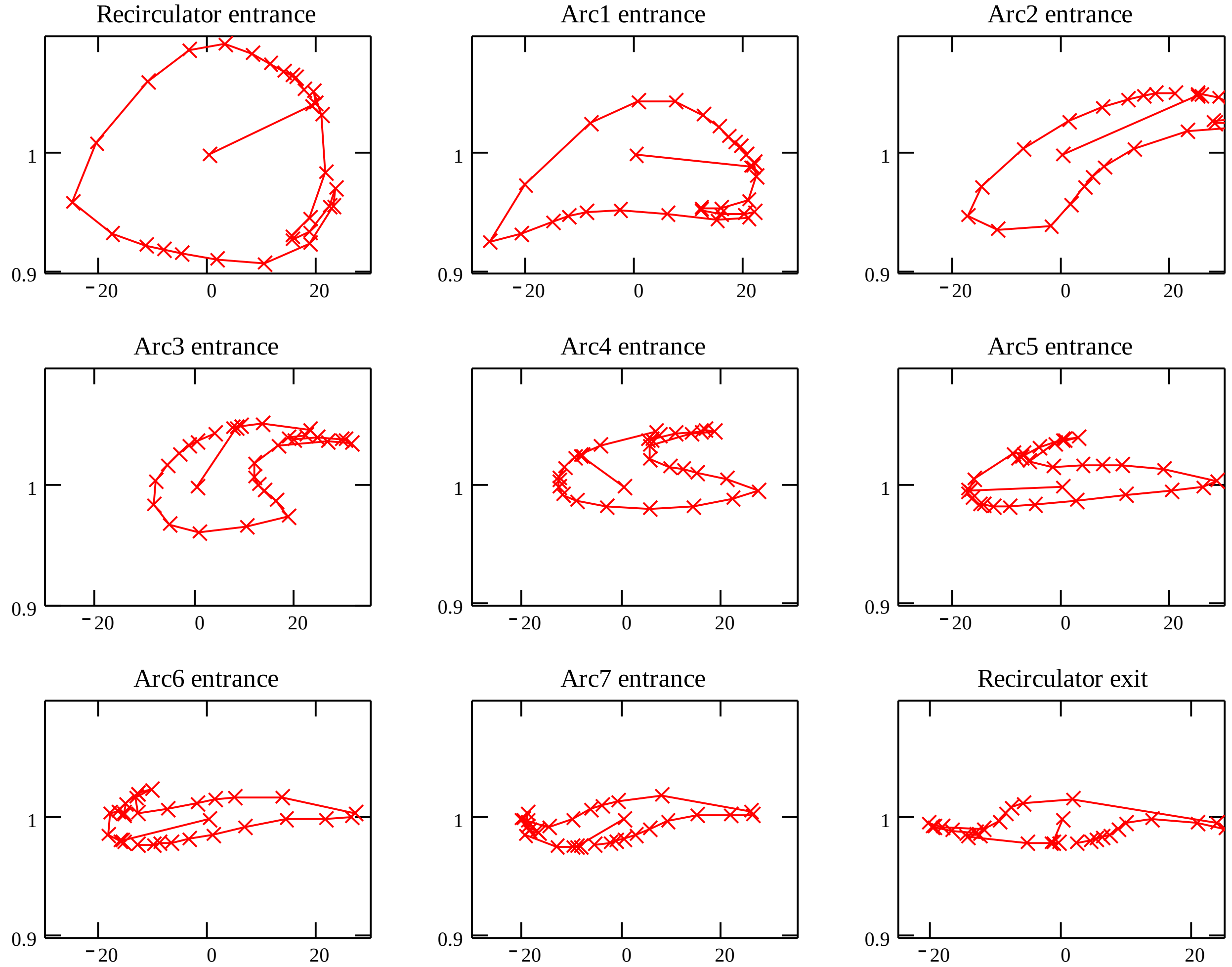
Total voltage per linac = 2.3347 GV at 200 MHz

Horizontal emittance dilution 9% per arc*

Vertical emittance dilution 4% per arc*

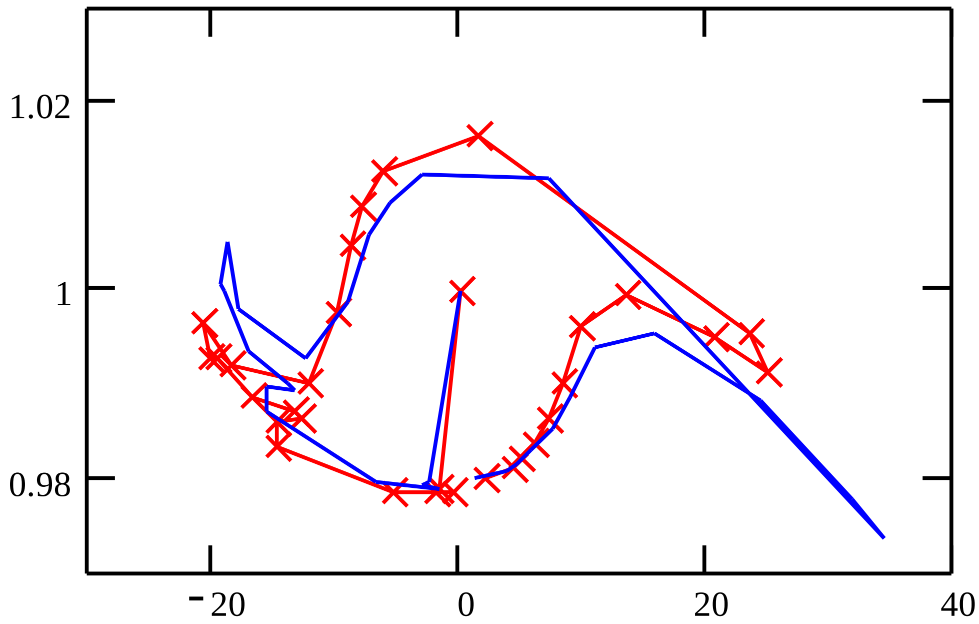
* Injection chicane is considered as an arc

Longitudinal dynamics in the RLA1



Longitudinal phase space in the recirculator

Effect of beam loading



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

The red line shows the longitudinal phase space boundary for the first bunch; and the blue line shows it for the last bunch of $3\cdot 10^{12}$ 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.

Optics for RLA1

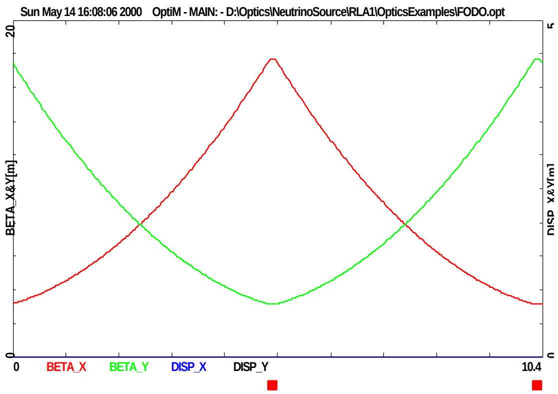
1 General requirements for optics

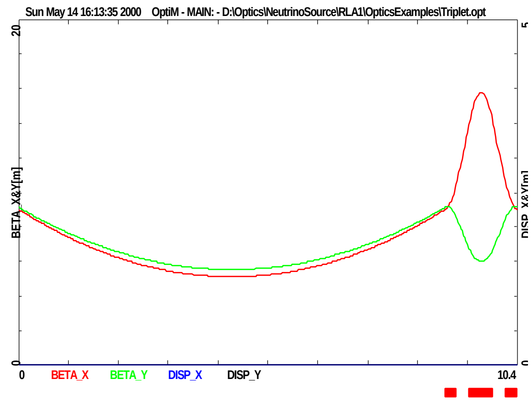
- Large energy spread
  - High symmetry lattice to accommodate large energy spread
- Large acceptance
  - Small beta-functions
- M_{56} (~1.4 m)
- It is a recirculator not a storage ring
  - Corrected chromaticity of the beam envelopes not tunes
    - A strategy for optics chromatic correction can be different
- 2T dipoles for highest energy arc
  - Arcs are already 2 times shorter than linacs

2 Spreaders and recombiners

- Horizontal
- Avoid dipoles with strongly separated beams in one dipole

Choice of focusing structure

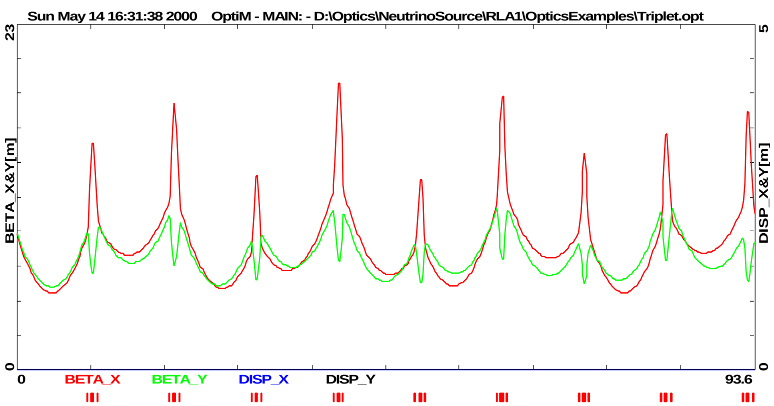




- The same length
- The same phase advance per period. $\nu_x = \nu_y = 0.25$ - effective chromaticity correction

Advantages for FODO

1. Smaller length of quads
2. Easier chromaticity correction



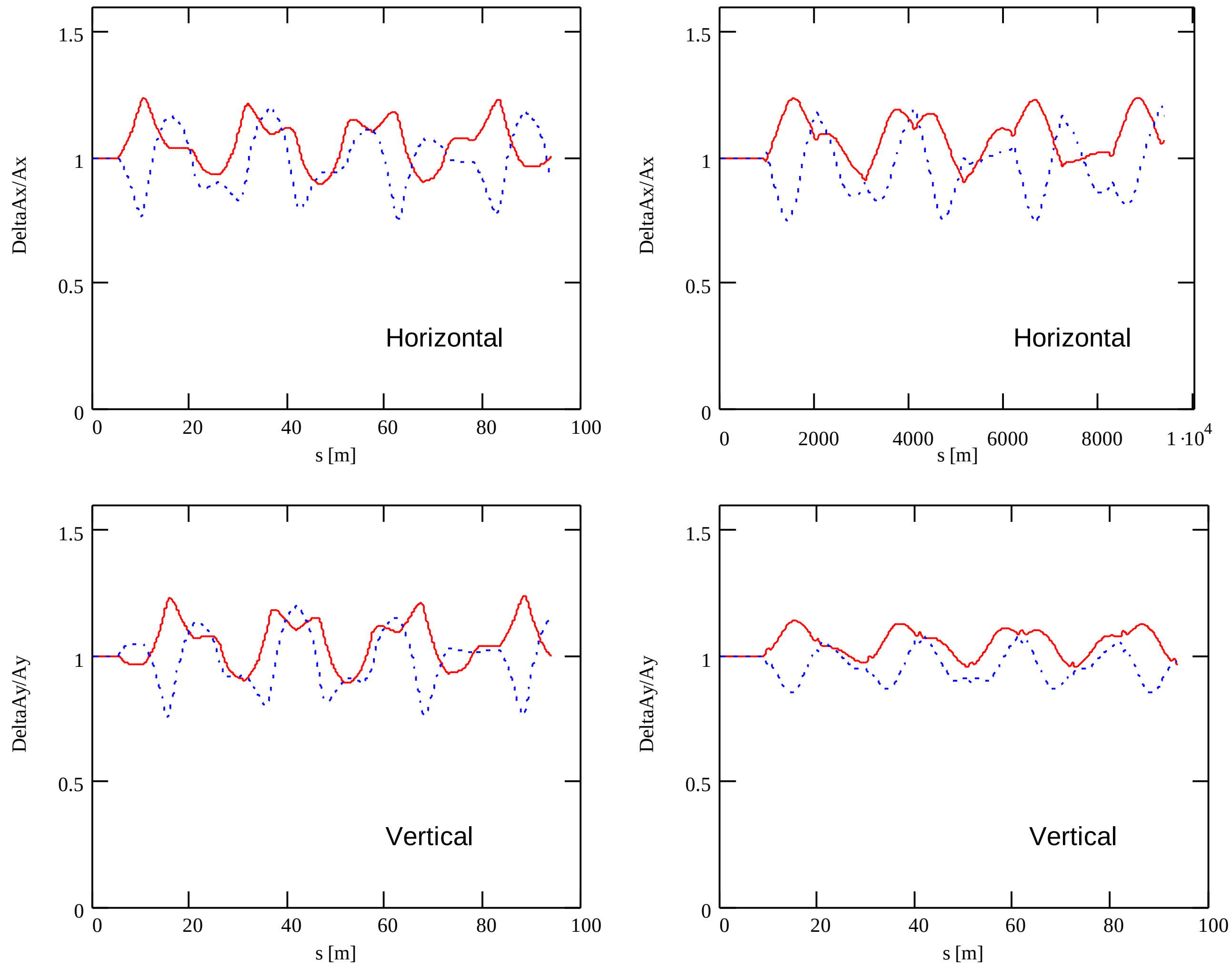
Beta-functions for momentum change of +10%
Beam envelope oscillates but does not grow

Advantages for triplet focusing

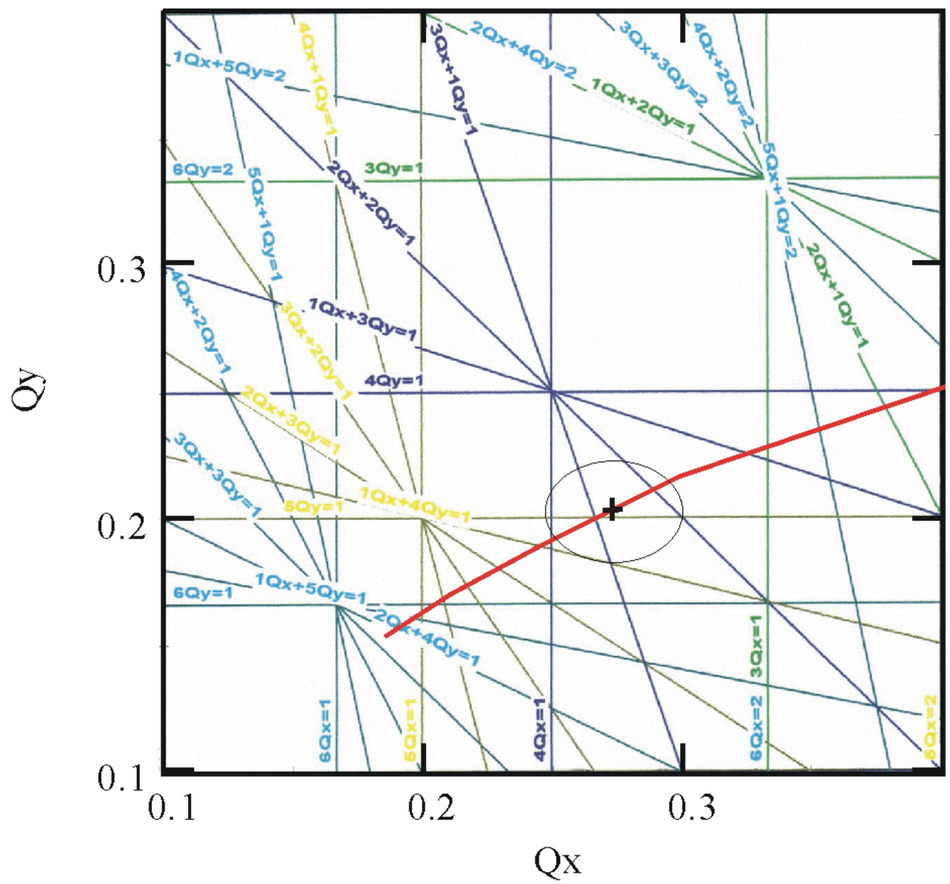
1. Longer straight sections
   - Possibility to use 10 m cryomodules
   - The only way to get simple beam spreaders
2. Smaller vertical beta-function
   - Better vertical chromatic behavior (2 times smaller the vertical beam envelope chromaticity)

FODO

Triplet focusing



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

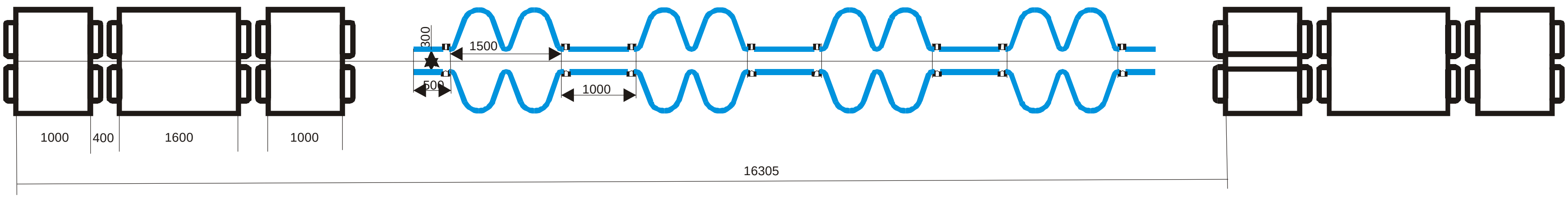


Tune diagram for 1 period of the first linac of RLA

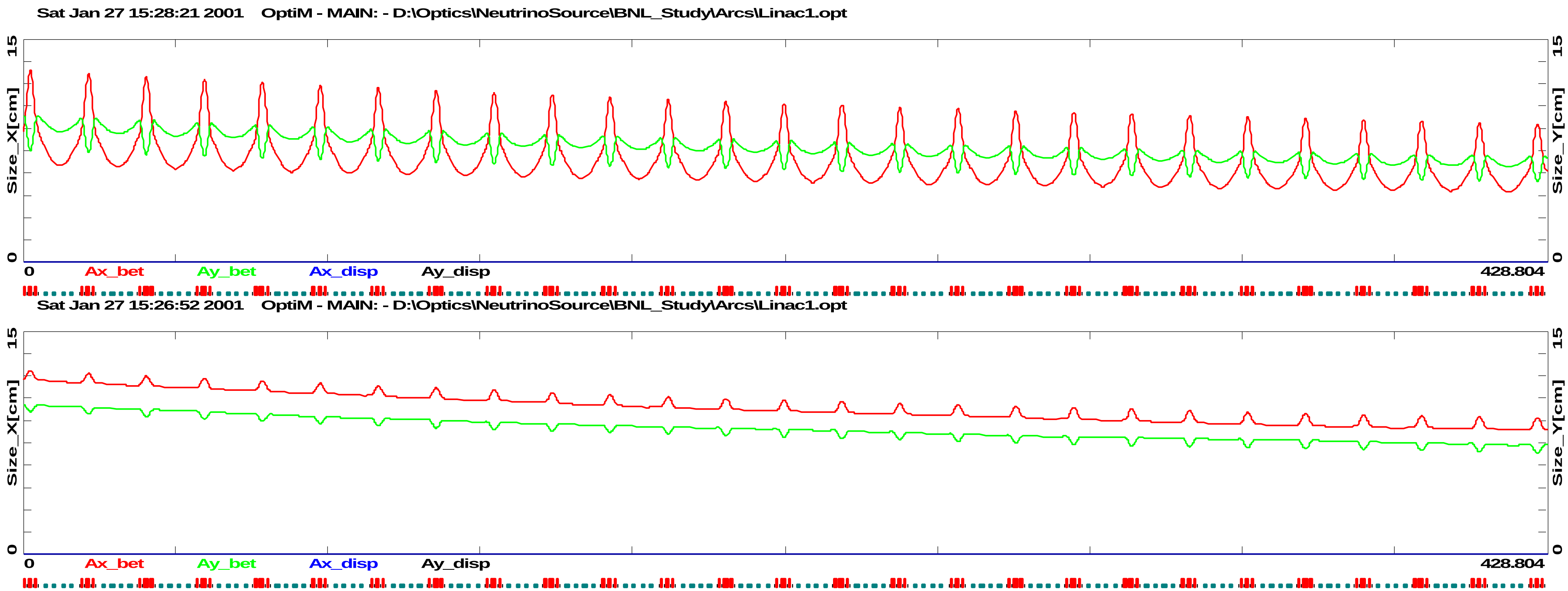
Red line shows tunes where $b_x = b_y$ for the highest energy pass

Qx=0.273, Qy=0.204

Circle corresponds 10% tune change

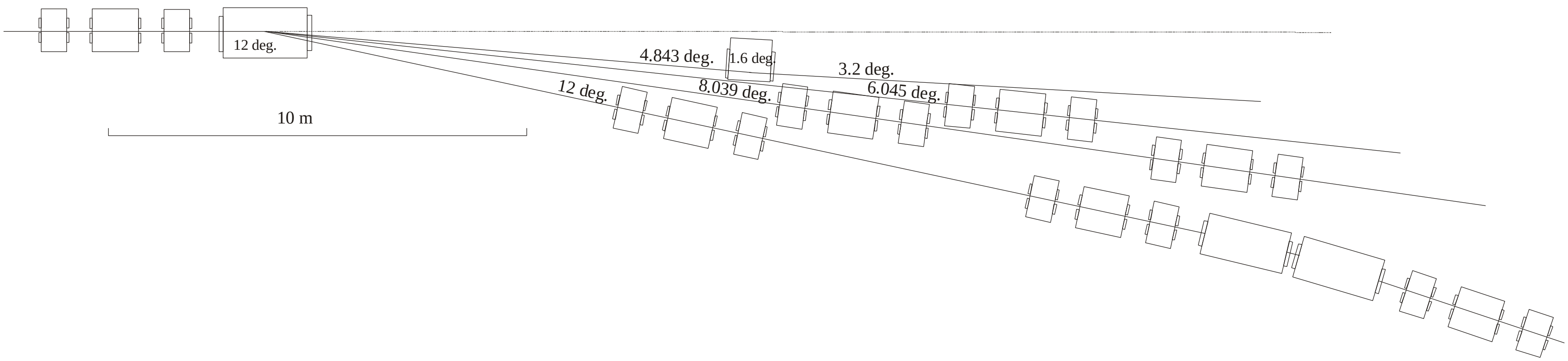


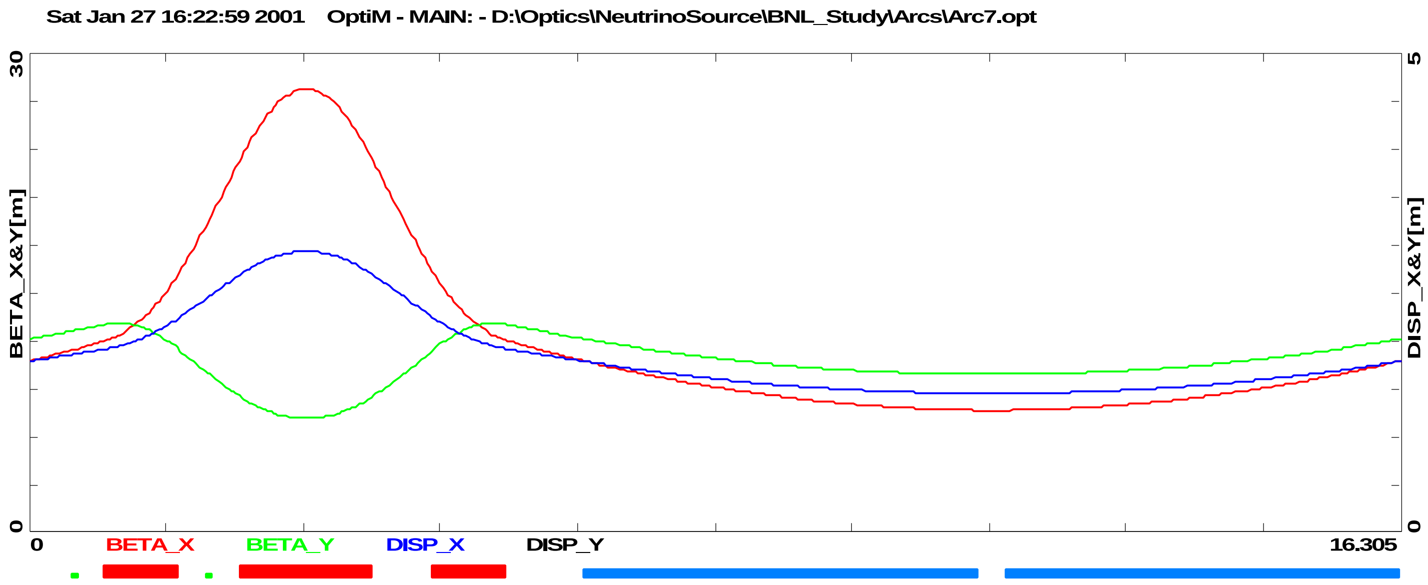
Layout of lattice period of the recirculator linac, 26 periods per linac



Beam sizes for the first and the last passes in recirculator

Spreader of Arc 1





Dispersion and beta-functions of arc period

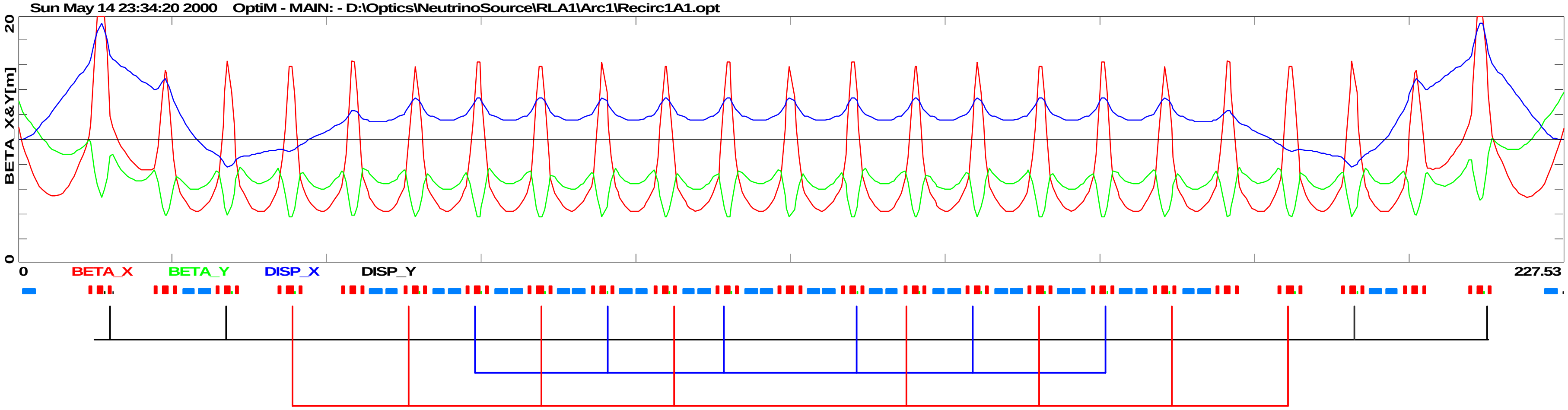
Acceptable non-linear fields of quadrupoles

	4-th order (octupole)	6-th order	10-th order
F_n	< 0.018	< 0.005	< 0.03

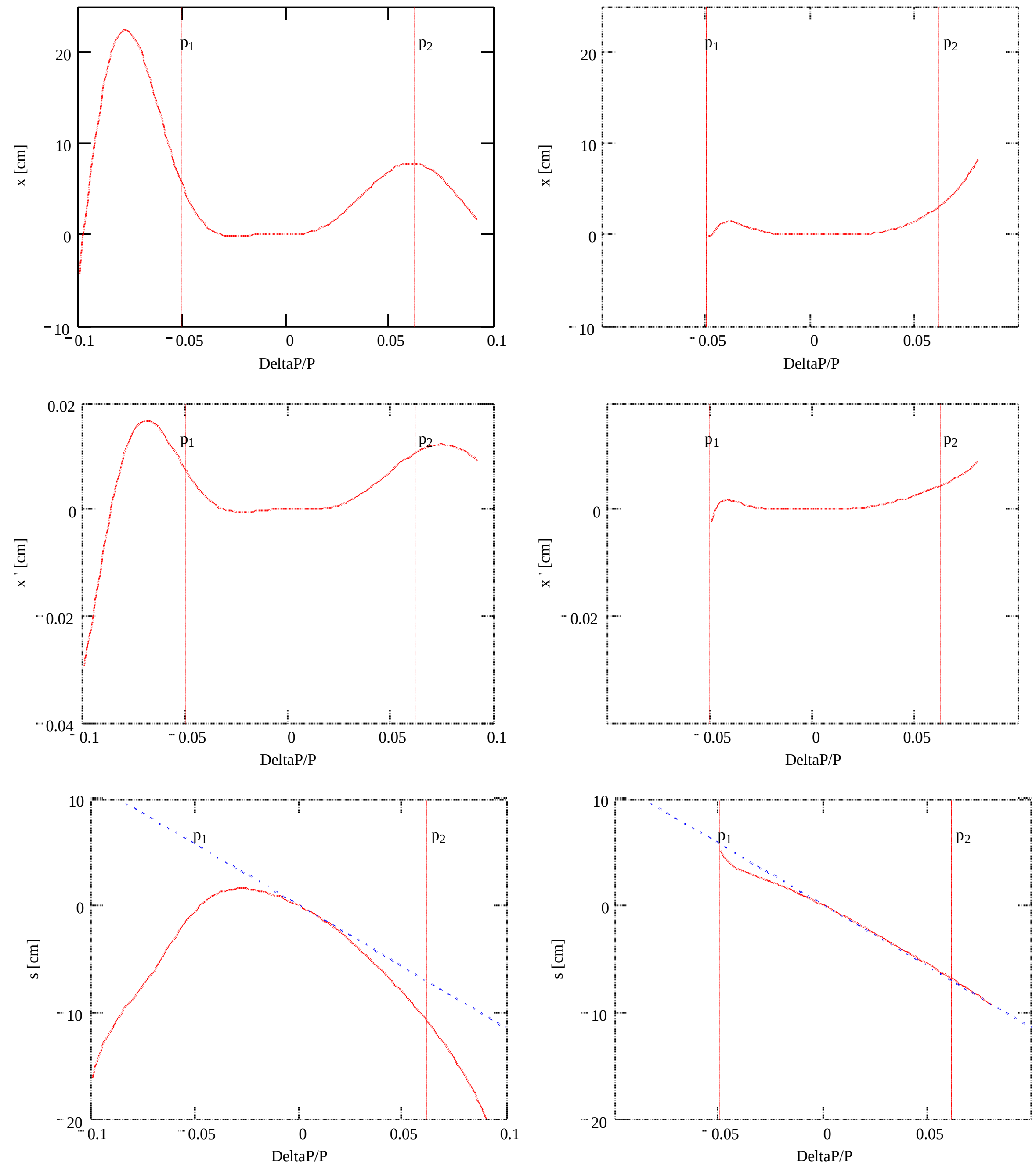
$$F_n = \frac{1}{Ga}\frac{a^{n-1}B_n}{n!}$$

a - maximum beam size in the quad

Arc 1 optics



Scheme of sextupole correction (3 families of sextupoles)



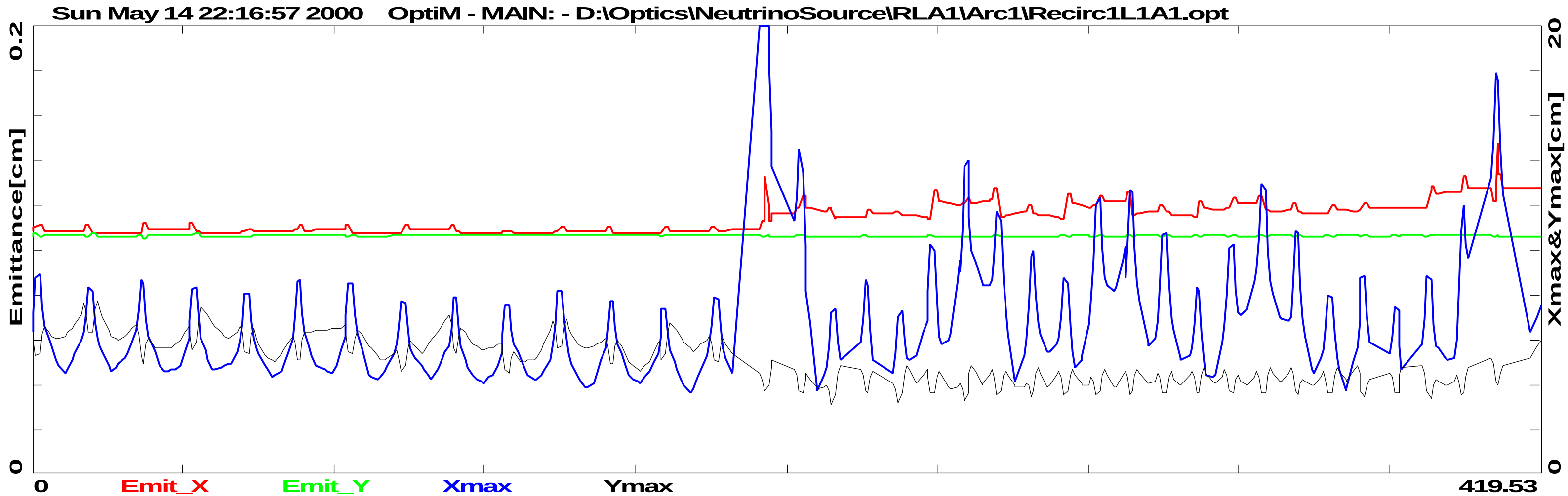
Chromaticity correction for Arc 1

Non-linearity for

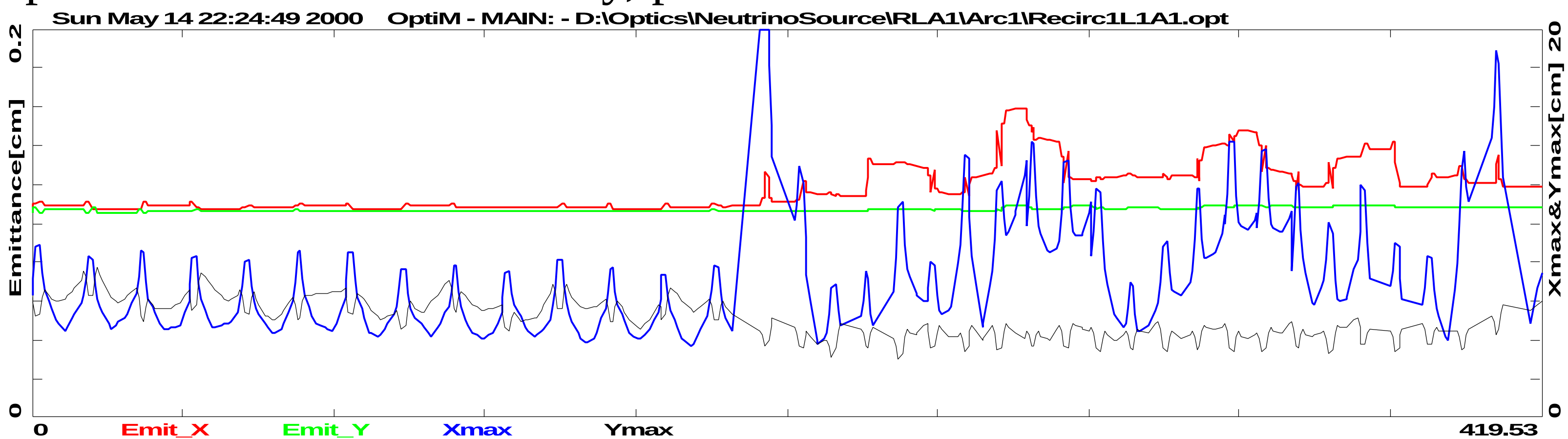
- Dispersion
- Dispersion-prime
- M_{56}

For the cases of

- no sextupole corrections
- 3 sextupole families

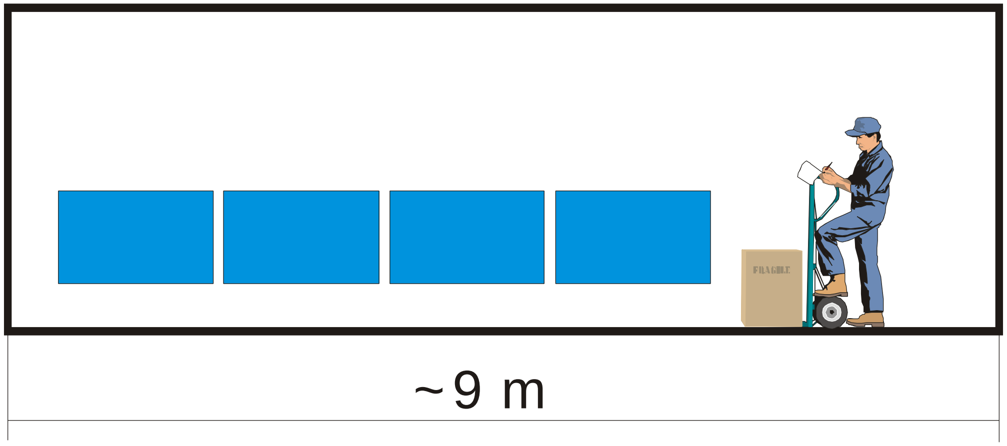


Beam emittance and beam envelopes with chromaticity correction in the spreader and recombiner only, particle loss 0.2%



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

Layout of magnets in the arcs



Conclusions

- As gar as we know there are no principal physical and technical limitations to build an accelerator-recirculator for muons
- Making use of more realistic elements (quads, cavities, solenoids, *etc*.) caused some changes of the parameters but did not exhibit principal limitations
- Optics of for arcs should be build
- Problems and solutions

Addressed problems	**Solutions**
Coupling between cavities	Decreased gradient for short cryo-modules
Shielding of the solenoid field	Two coils solenoid
Solenoid/quad non-linearity	Increased solenoid/quad length, change of betatron phase advance per cell
Decreased longitudinal acceptance due to decreased accelerating gradient	Better optimization of longitudinal motion
Increased energy spread in injection chicane	Decrease of the dispersion, better sextupole correction