Compressor Ring

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Contents

- Where do we go?
- Beam physics limitations
- Possible Compressor ring choices
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Where do we go?

- Tevatron Run II ends in 1.5 years
- FNAL future
  - Energy frontier -> Intensity frontier
- Project X ->

  Neutrino factory ->

  Muon collider
- Before we build machine
  - We have to anticipate coherent upgrade path
    - Energy choice
    - Initial infrastructure choice

    ⇒ Future developments
- The most general structure for Muon collider proton source
  - Linac ->

    Synchrotron (?) ->

    Accumulator ring (?) ->

    Compressor ring

Present Project X parameters

Initial Configuration Document

Linac energy	8 GeV
Max. linac current (no chopping)	30 mA
Average linac current (53 MHz chopping)	21 mA
Pulse duration	1.2 ms
Repetition rate	5 Hz
Power	1 MW

*Single pulse injection to MI, 1 of 7 pulses for 120 GeV program

Alternative Configuration Document*(preliminary)

	Stage 1	Stage 2
Linac energy	2 GeV	
Synchrotron energy, GeV	8	21
Average linac current (53 MHz chopping)	21 mA	
Pulse duration	0.35 ms	
Repetition rate, Hz	5	15
Power, MW	0.39	2.2

*Cost saving, lower linac current, 4 of 7 pulses for 120 GeV program

Boundary conditions

- Linac
  - Beam current ≤ 40 mA
  - Pulse length ≤ 1 ms
  - Repetition rate = 15 Hz
- RMS bunch length after compressed < 60 cm
- Beam is focused on the mercury target of 5 mm radius
- Rms beam size = 2 mm
- Beta-function on the target ≥ target length (~20 cm)
- Maximize beam power on the target

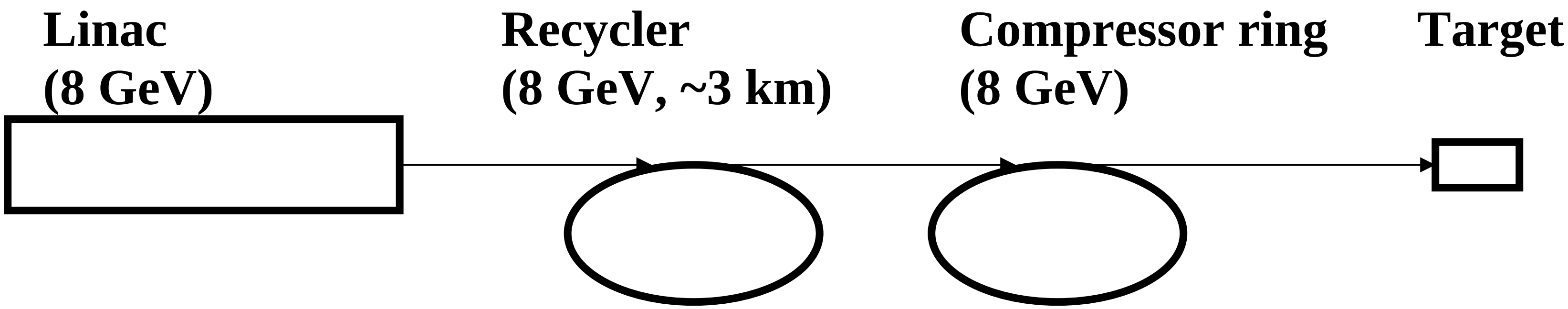
  More or about 1 MW is desirable

Main beam physics limitations

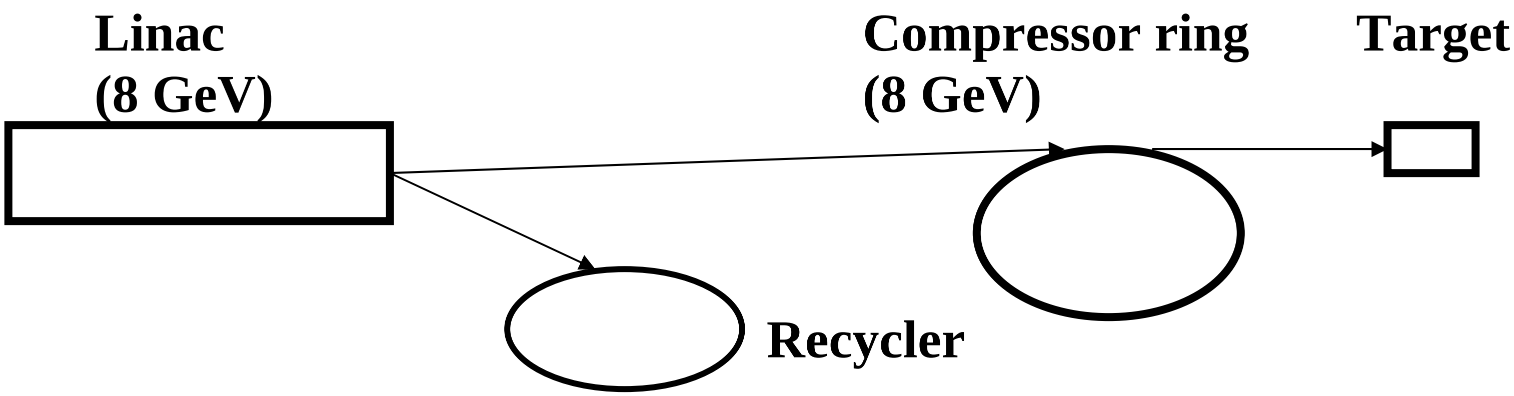
- Consistency of beam parameters through entire chain of the planned proton accelerators
- Beam focusing on the target
- Longitudinal beam stability
- Transverse beam stability
- Particle loss due to non-linear forces of the beam space charge

Choices to be considered

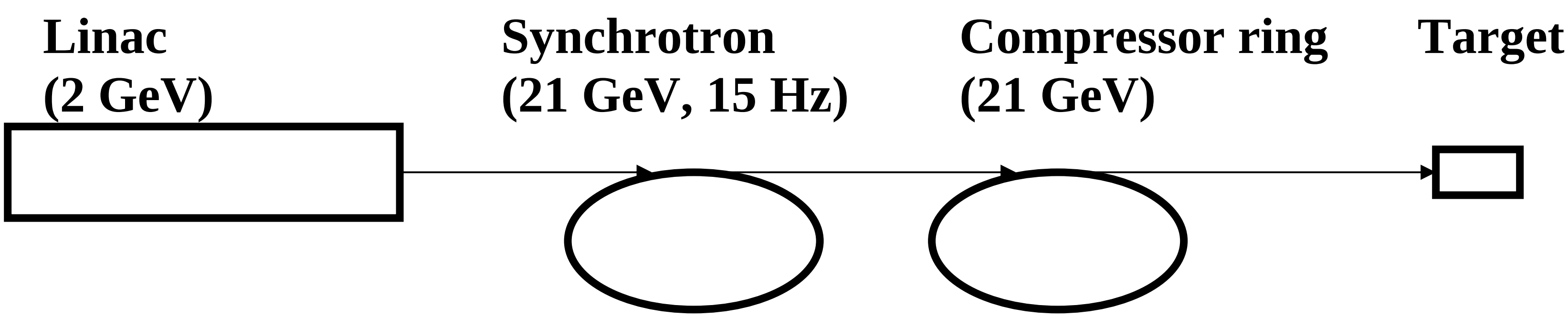
- Present Project-X with injection to Recycler + Compressor ring



- Project-X linac + Compressor ring with direct H^- strip injection

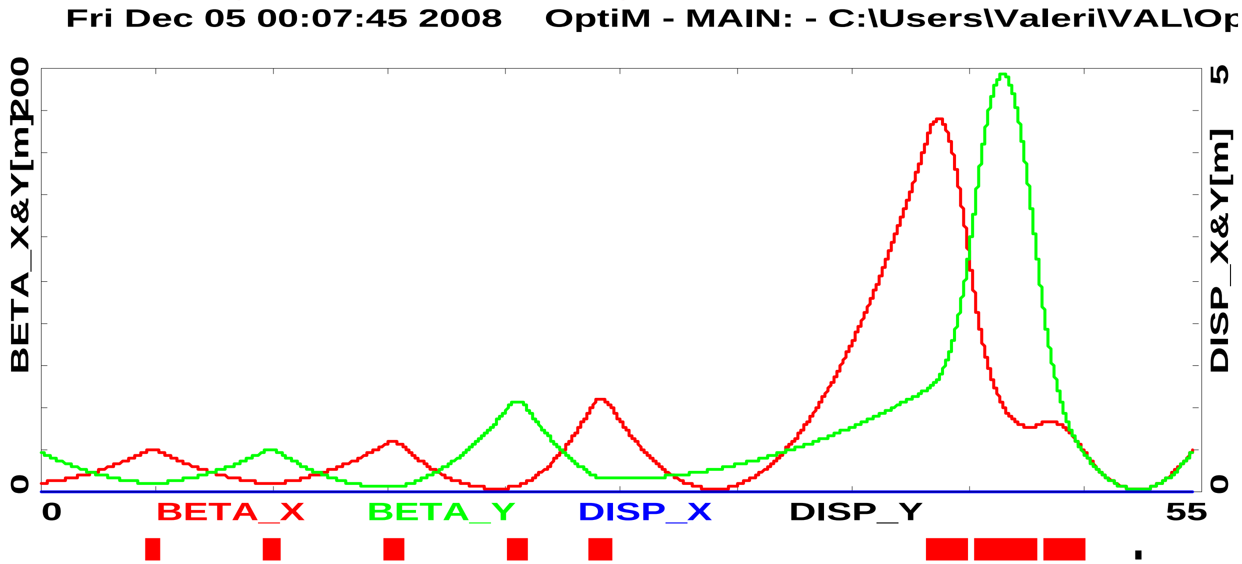


- Alternative Project-X + compressor ring

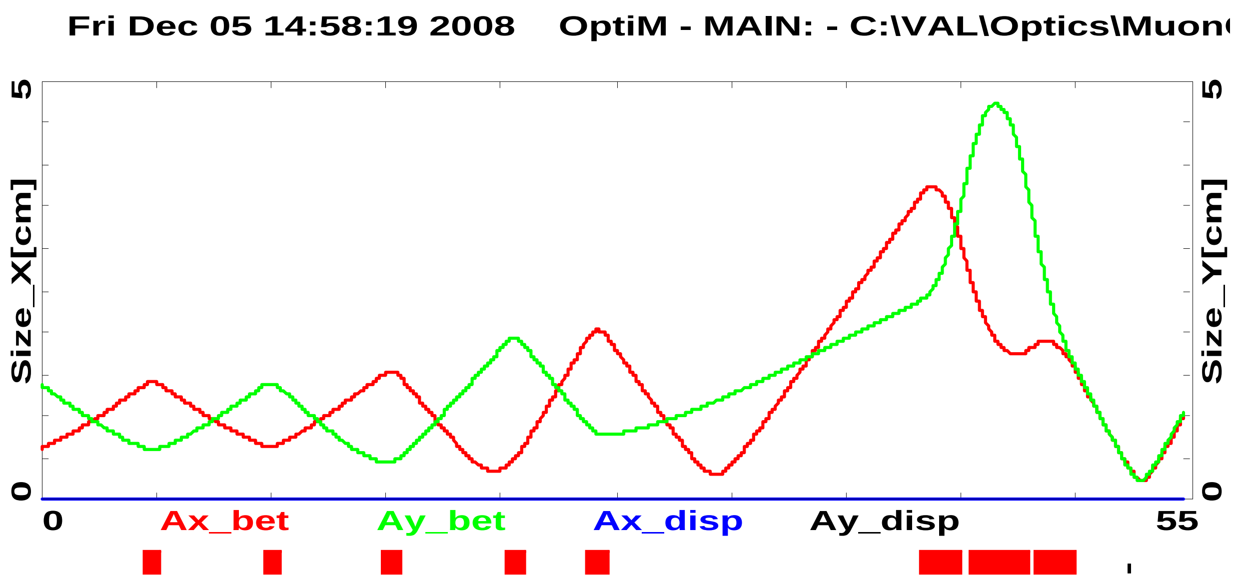


Main beam physics limitations (1)

Focusing on the target



Beta functions



Rms beam sizes (ε=10 mm mrad → $\varepsilon_{n95\%}$= 570 mm mrad)

Design requirements

Beam energy = 8 GeV

Rms beam size = 2 mm

β^* > 20 cm

$\Delta p/p \sim \pm 3\%$

Limitations of the FF chromaticity and the quad gradient result in

FF parameters

- $\varepsilon_{95\%n}$ = 570 mm mrad
- β^* = 40 cm
- β_{max} = 200 m
- Rms beam size on the vacuum window = 1.3 cm

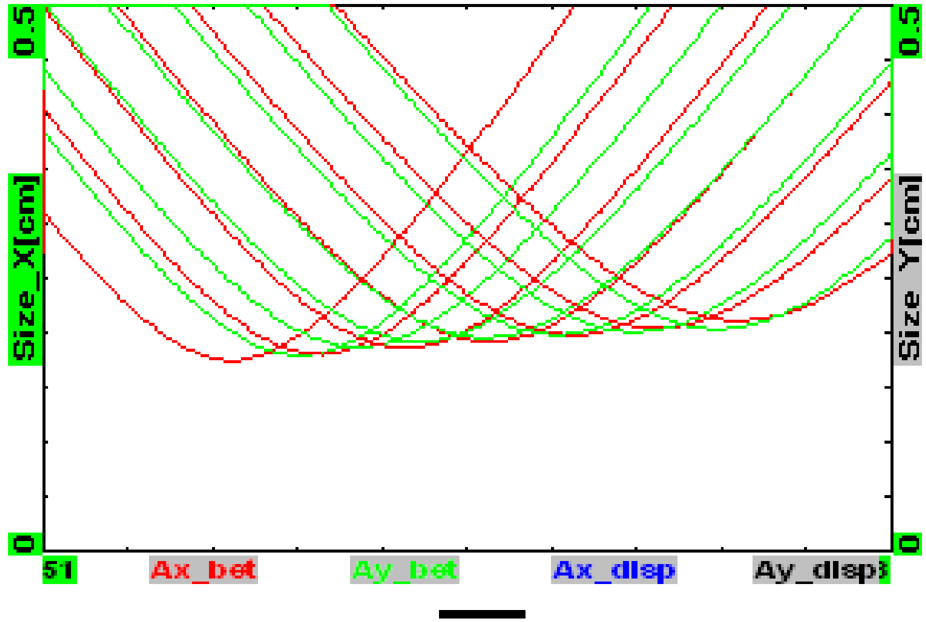
Final focus quads

	L [cm]	G [kG/cm]	***a*** [3σ+2] [cm]	B [kG]
qF	185.2	0.6	10+1	6.6
qD	282.5	-0.6	11+1	7.2
qF	185.2	0.6	7+1	4.8

Focusing on the target (continue)

Other issues

- Compensation of focusing chromaticity by sextupoles is limited because of very large beam emittance
- Beam power deposition on the vacuum window
  - Further decrease => larger $S_{target\text{-}to\text{-}window}$ => larger β_{max} => larger FF chromaticity



Beam envelopes in the target vicinity for $\Delta p/p$ = -3, -2, … 3%

- Using SC quads could reduce FF chromaticity but its usefulness is limited by desire to have large beam size on the vacuum window
- 1 MW window looks challenging but solvable problem
  - Particle flux: $dN/dt = 7.8\cdot10^{14}$ p/s; $dN/(dtdS) = 7.3\cdot10^{13}$ p/cm^2/s
  - Beryllium, d=1 mm, R=5.2 cm (4σ), dP/dS_{max} ~3.5 W/cm^2

    => ΔT = 40 K° for edge cooled window
  - Radiation hardness needs to be investigated

Main beam physics limitations (2)

Longitudinal beam stability

- For continuous beam the dispersion equation is

$$\varepsilon_n(\delta\omega) = 1 + \frac{eI_0 Z_n}{2\pi i R_0 p} \int_{\delta\to+0} \frac{df/dx}{\delta\omega + n\omega_0\eta x - i\delta} dx = 0 \quad ,$$

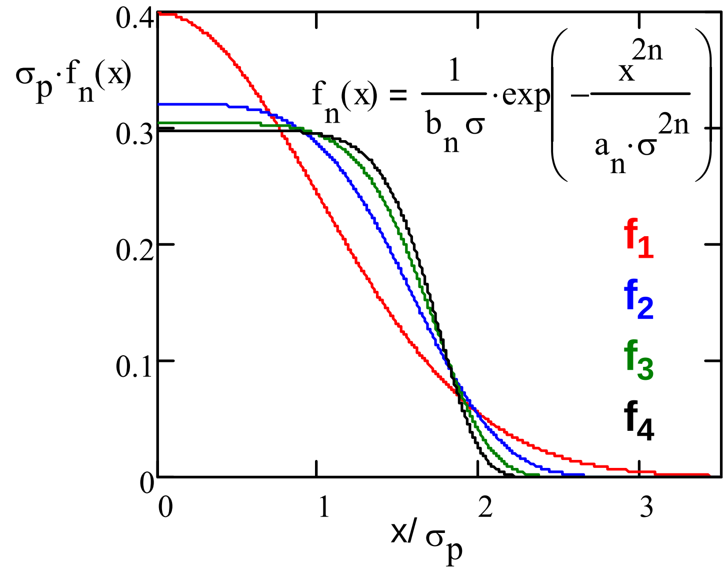
$$x = \frac{\Delta p}{p} \ , \quad \eta = \alpha - \frac{1}{\gamma^2} \ , \quad \delta\omega = \omega - n\omega_0$$

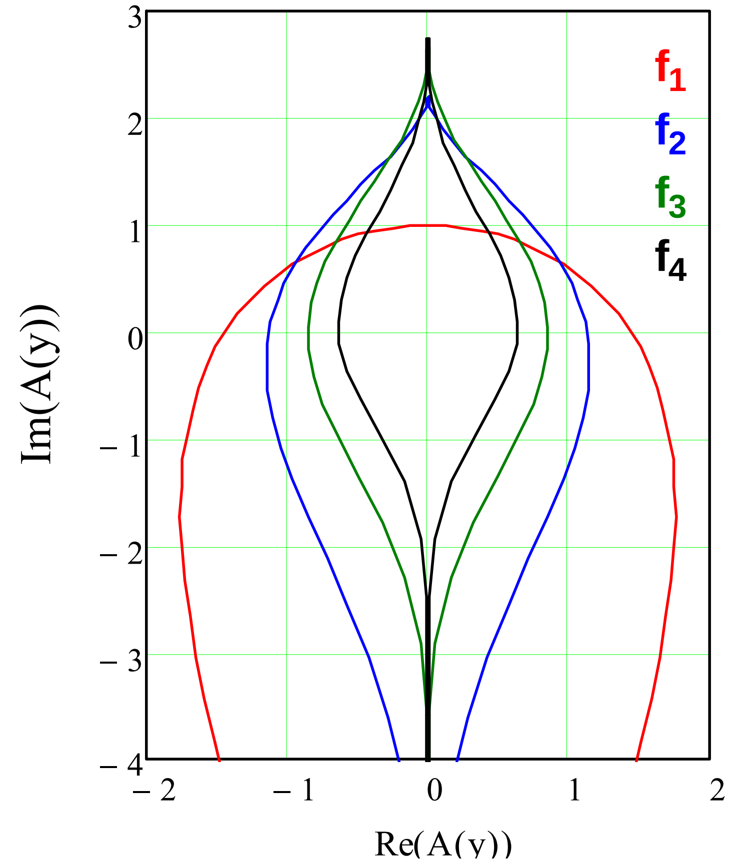
- Stability condition depends on particle distribution, $f(x)$

$$\boxed{\frac{Z_n}{n} = 2\pi\beta\eta\sigma_p{}^2\left(\frac{pc}{eI_0}\right)A(y)}$$

where $y = \dfrac{\delta\omega}{\omega_0\eta n}$, $A(y) = \left(i\sigma_p{}^2 \displaystyle\int_{\delta\to+0} \frac{df/dx}{y + x - i\delta} dx\right)^{-1}$

- There is no significant difference in stability thresholds for the cases above and below critical energy for particle distribution close to the rectangular one





Longitudinal beam stability (continue)

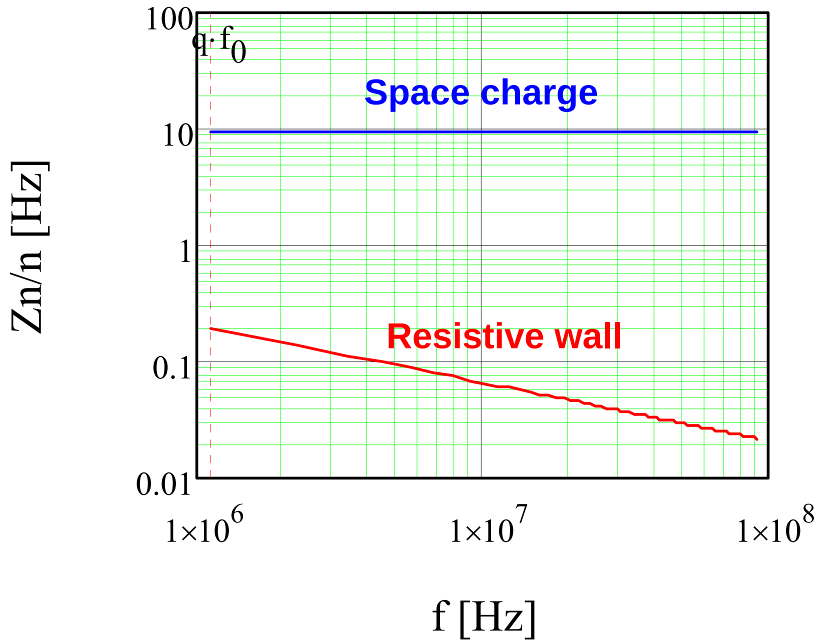
- Longitudinal impedance has three major contributions
  - Space charge
    - For round beam & vacuum chamber

$$\frac{Z(\omega_n)}{n} = i\frac{Z_0}{\beta\gamma^2}\ln\left(\frac{a}{1.06\sigma}\right)$$

  - Resistive wall
    - For round beam & vacuum chamber

$$\frac{Z(\omega_n)}{n} = \left(1 - i\,\mathrm{sign}(\omega_n)\right)\frac{Z_0\beta c}{2a\sqrt{2\pi\sigma\omega_n}}$$

  - Effect of RF cavities, vacuum chamber discontinues, etc. can be controlled by machine design and dampers (f < 100 MHz)



Copper chamber, f_0 = 1.13 MHz, a = 4.8 cm, E=8 GeV

- Space charge contribution does not depend on frequency and dominates at high frequency
  - It results very fast growth of momentum spread, $\lambda_n \approx n\omega_0\eta(\Delta p / p)$
- For high frequencies $\lambda_n >> \omega_s$, and the continuous beam theory can be used

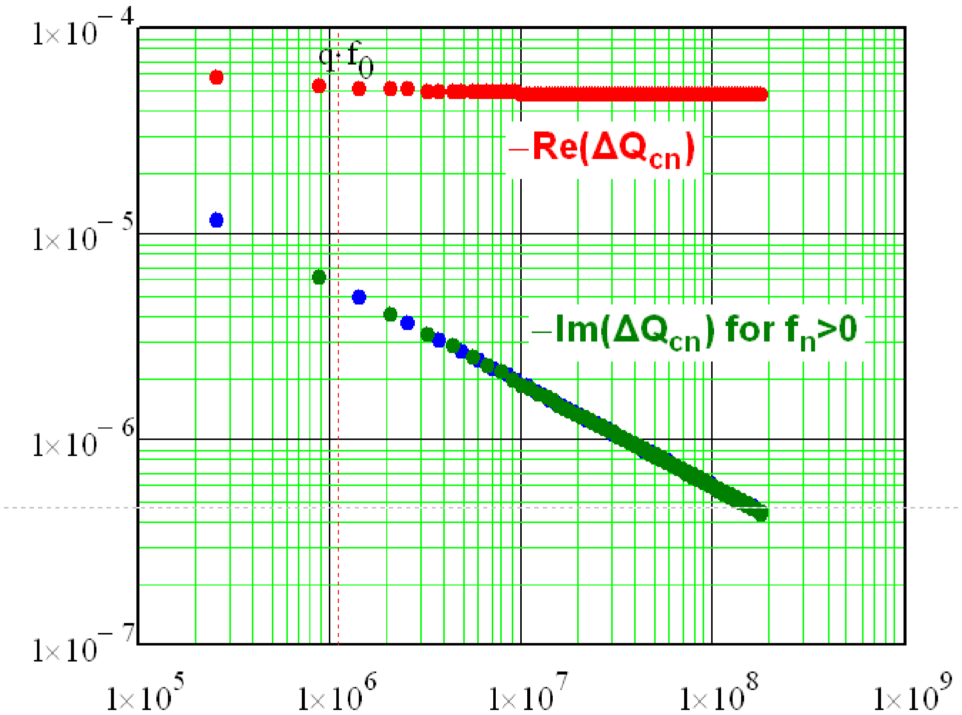
Main beam physics limitations (3)

Transverse beam stability

- Worst case estimate can be obtained for the case of the bunch with zero revolution frequency spread

$$\delta\nu_{cb} = -i\frac{r_p N}{2\pi\beta\gamma\nu}\frac{Z_\perp}{Z_0}$$ - continuous beam

$$\delta\nu \approx \delta\nu_{cb}\left(\frac{C}{L_b}\right)^{1/4}$$ - constant bunch density



Flat copper chamber, f_0 = 1.13 MHz, a = 4.8 cm, ν=5.73, C/L.b=0.235 E=8 GeV, N=5.2·10^13

- At small frequencies impedance is dominated by wall resistivity

$$Z_\perp \approx Z_0\frac{c\left(sign(\omega)-i\right)}{2\pi a^3\sqrt{2\pi\sigma\omega}}$$ - round chamber;

$$Z_y \approx \frac{\pi^2}{12}Z_\perp\ ,\quad Z_x \approx \frac{\pi^2}{24}Z_\perp$$ - flat chamber

- For short machine, high wall conductivity and large chamber size the transverse instabilities should not be a problem

Main beam physics limitations (4)

- Compressed beam has very large particle density. That results large longitudinal and transverse fields
- Both longitudinal and transverse fields drop fast with beam energy

Incoherent tune shift due to beam space charge

- Betatron tune shift is equal to

$$\delta\nu_{x,y} = \frac{r_p N_p}{2\pi\beta^2\gamma^3}\frac{C}{L_b}\left\langle \frac{\beta_x}{\left(\sigma_x+\sigma_y\right)\sigma_{x,y}} \right\rangle_s \quad , \quad \sigma_x = \sqrt{\varepsilon_x\beta_x + D^2\left(\frac{\Delta p}{p}\right)^2} \quad , \quad \sigma_y = \sqrt{\varepsilon_y\beta_y}$$

- Dispersive contribution to the tune shift can significantly reduce $\delta\nu$

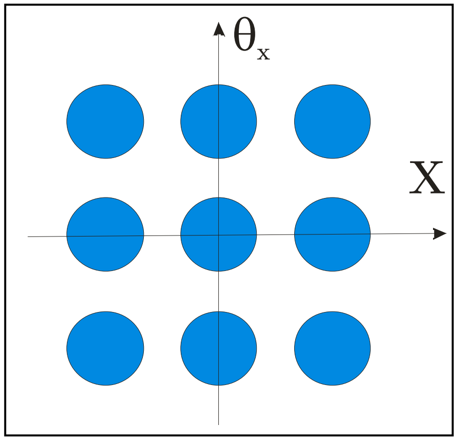
Longitudinal field of the bunch

- For Gaussian bunch

$$V_{SC}(s) = \frac{2eNC\ln\left(a/(1.06\sigma_\perp)\right)}{\sqrt{2\pi}\gamma^2\sigma_s{}^2} s\exp\left(-\frac{s^2}{2\sigma_s{}^2}\right)$$

Choice 1 – CR with Recycler beam

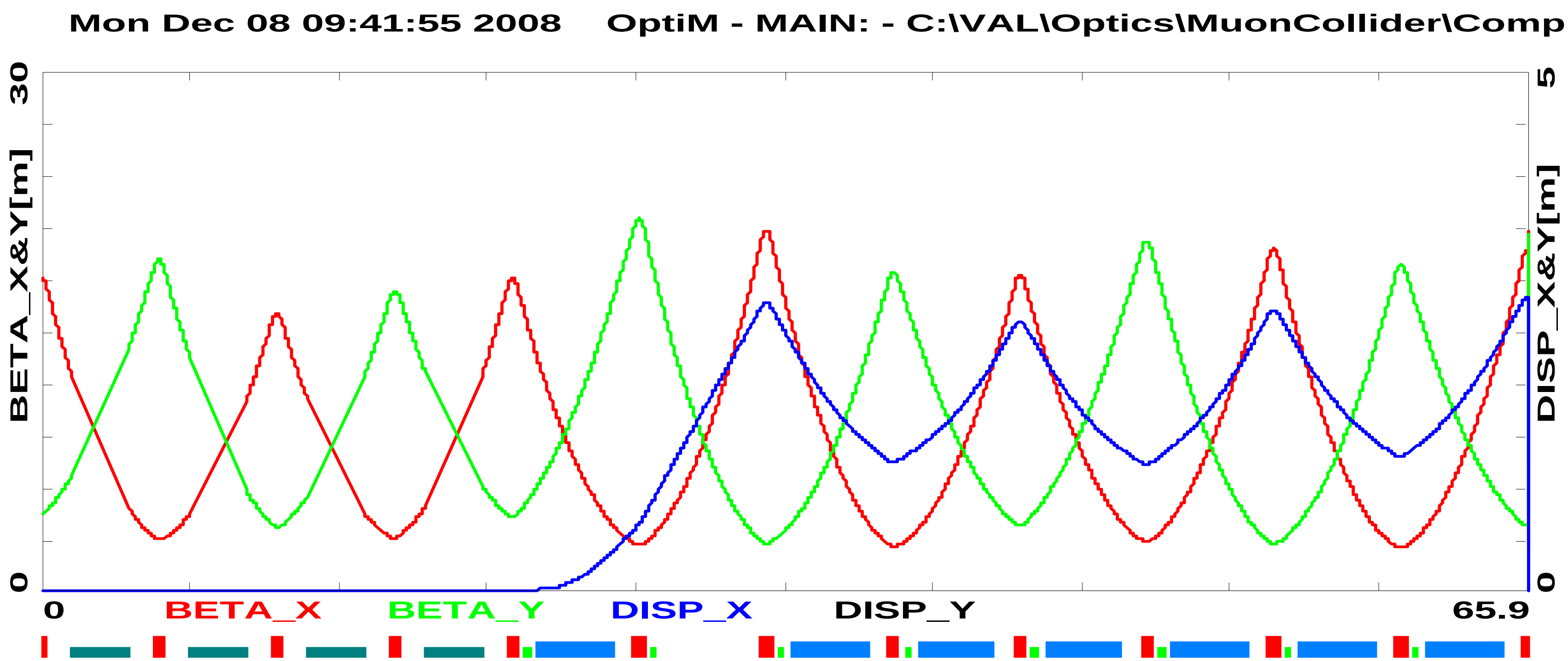
- Low longitudinal phase density of the Recycler beam is the main limitation of the beam power
  - Recycler Project-X bunch:
    $N = 2.9 \cdot 10^{11}$, $\varepsilon_s = 0.4$ eV·s/bunch (53 MHz RF)
- Only 8 bunches can be coalesced to fit to the required ε_L:
  $\sigma_s = 60$ cm, $\sigma_p = 0.1\%$, $\varepsilon_{s95} = 6\pi\, \sigma_s\, \sigma_p\, p \,/\, (\beta c)$ ~3.3 eV·s
  => 47 kW beam power on target (15 Hz, 1 bunch)
- What's wrong with Recycler?
  - Large circumference
  - Small acceptance
  - Stainless steel vacuum chamber
- Can multiple bunches be merged in transverse phase space



  - Recycler beam emittance: ε_{n95} = 25 mm mrad
  - FF limit = 570 mm·mrad
  - On paper merging ~100 bunches is allowed $(570/(2*25))^2$
  - But realistically only 4 bunches can be merged because the small phase space distance between bunches is required

Choice 2 – CR with direct strip injection from Linac

- Optics design criteria
  - Small circumference (Space charge, tr. & long instabilities)
  - Large acceptance
  - Large $\Delta p/p$ => high periodicity
  - Zero dispersion in RF cavities
  - Large slip factor to avoid microwave instability
    - It requires larger RF voltage and horizontal aperture in arcs

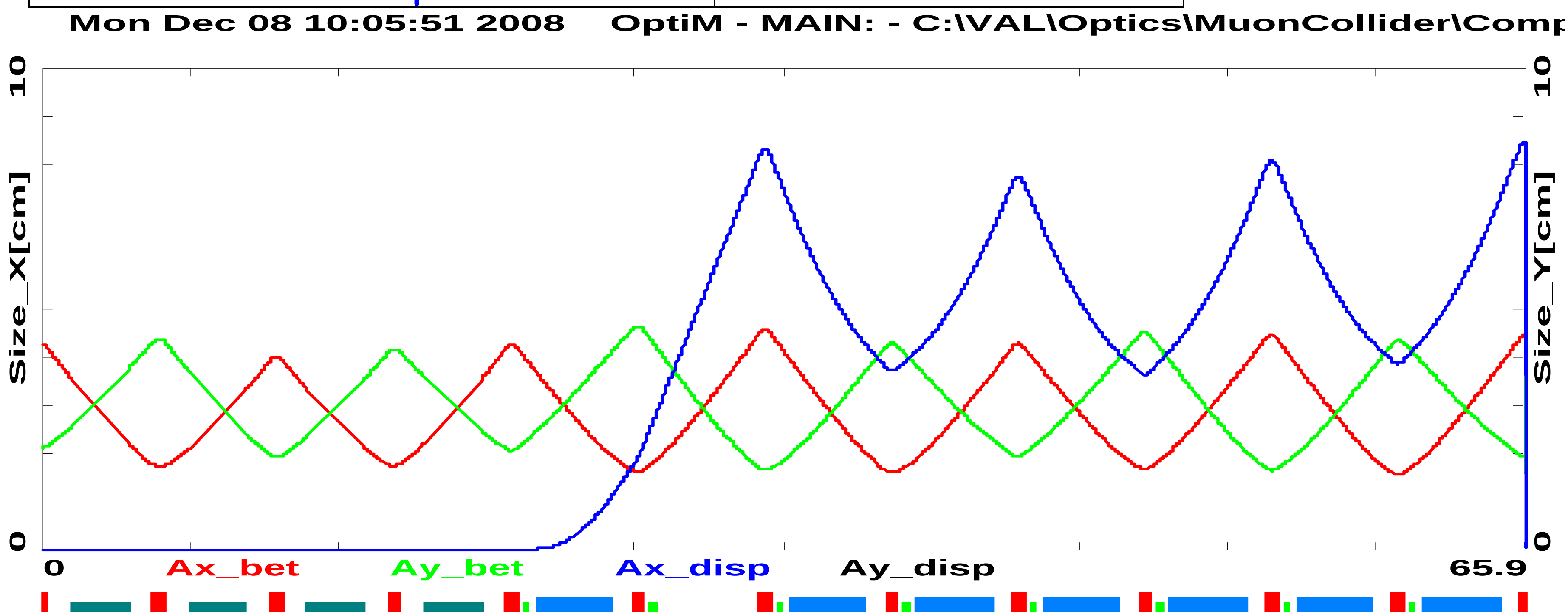


Twiss parameters for a quarter of ring circumference

Choice 2 (continue)

Main parameters of 8 GeV Compressor ring

Circumference	264 m
Tunes, ν_x / ν_y	6.42/5.42
Transition energy	3.9 GeV
Dipole field	20 kG
Acceptance	100 mm mrad
Momentum acceptance	±3%



Beam envelopes for a quarter of ring circumference (ε=100 mm mrad, Δp/p=±3%)

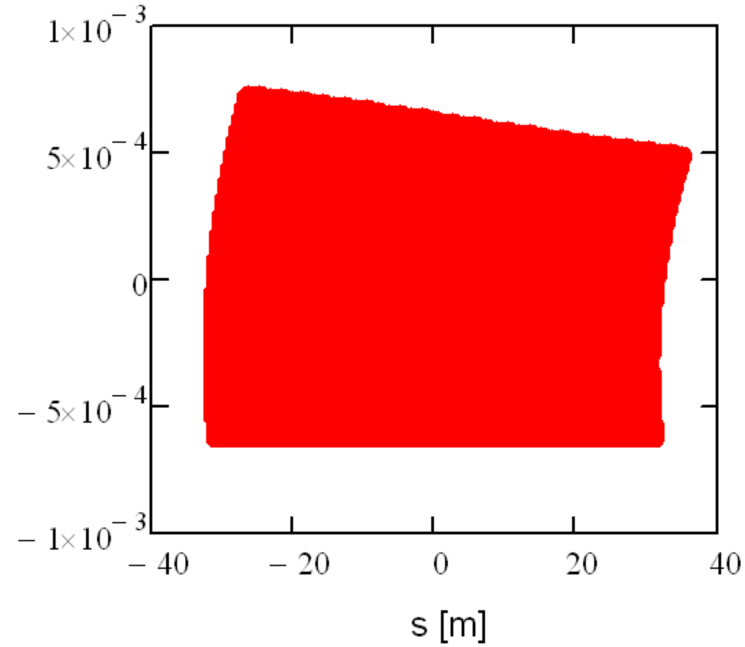
Choice 2 (continue)

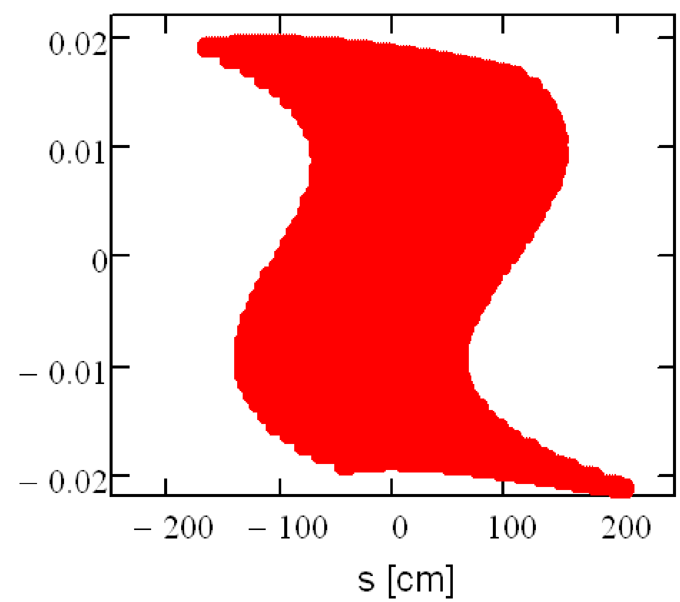
Beam injection & compression

- Micro wave instability is the major limitation of the beam power

Injection parameters

Injection type	H^- strip
Linac current, unchopped/chopped, mA	40/9.5
Linac rms momentum spread	$<2\cdot10^{-4}$
Linac energy sweep	$\pm6\cdot10^{-4}$
Filling factor, L_b/C	0.235
Total injection time	0.9 ms
DC beam current	9.4 A
Number of particles	$5.2\cdot10^{13}$
Harmonic number, h	1
RF voltage	1.5 kV
Synchrotron tune	$2.7\cdot10^{-5}$
$(Z_n/n)_{Space\ charge} = (Z_n/n)_{Stability}$	10 Ω
Beam power	**1 MW**





Longitudinal phase space at the end of injection and after compression

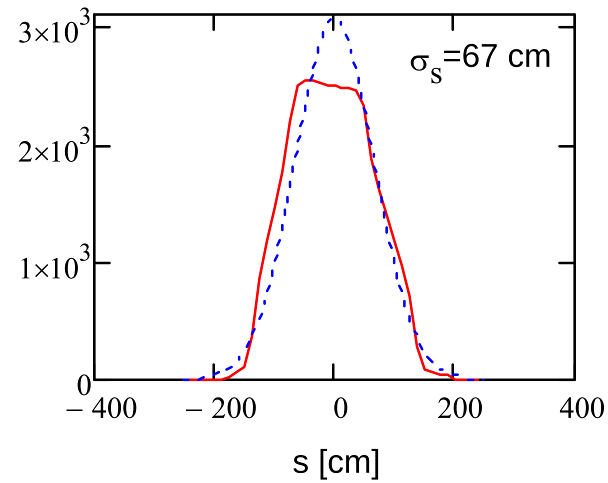
Choice 2 (continue)

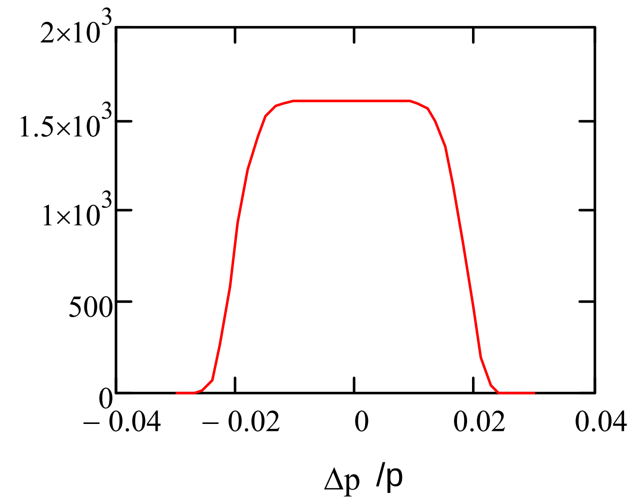
Beam injection & compression (continue)

Parameters of compressed bunch

Harmonic number, h	1
RF voltage	1 MV/turn
Max. bunch long. field	~350 kV/turn
Synchrotron tune	$6.8 \cdot 10^{-4}$
Rotation time	370 turns
RF bucket height, $\Delta p/p$	0.053
Coulomb tune shifts, $\Delta\nu_x$ / $\Delta\nu_y$	0.07/0.105
$\perp$ instability growth rate	$2 \cdot 10^{-5}$ /turn

There is not much leverage left to exceed 1MW beam power for 8 GeV proton driver (15 Hz, single bunch)

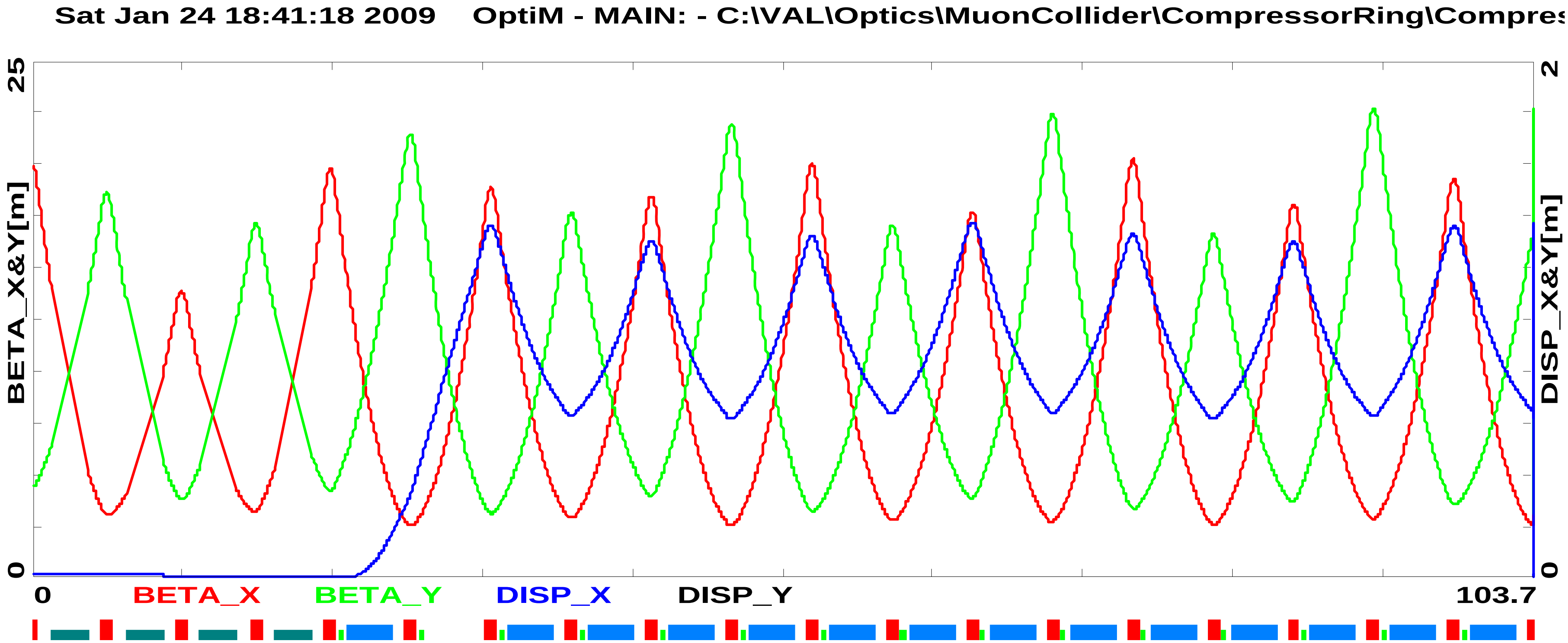




Projections of longitudinal particle distribution to s and p planes after compression

Choice 3 – CR with injection from 21 GeV RCS

- Optics design criteria
  - Small circumference (Space charge, tr. & long instabilities)
  - Two turn injection => Large hor. acceptance
  - Large Δp/p => high periodicity
  - Zero dispersion in RF cavities

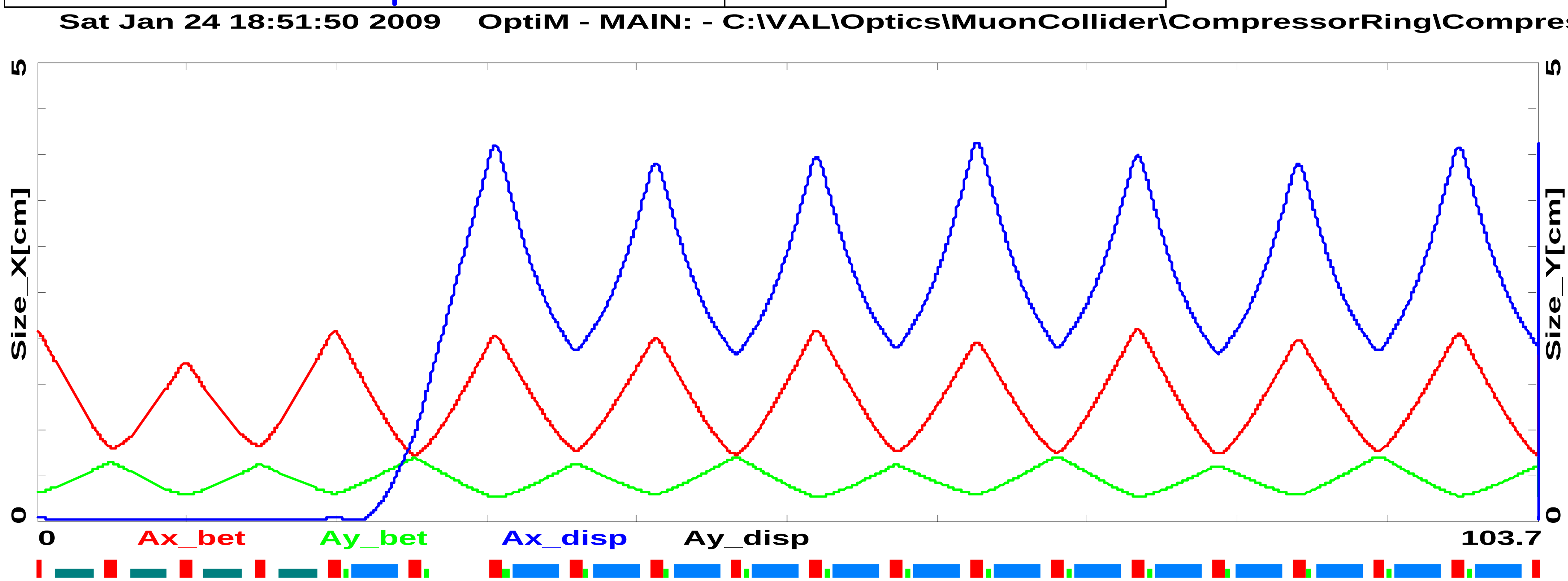


Twiss parameters for a quarter of ring circumference

Choice 3 (continue)

Main parameters of 8 GeV Compressor ring

Circumference	415 m
Tunes, ν_x / ν_y	10.79/8.79
Transition energy	7.45 GeV
Dipole field (superferic)	27 kG
Acceptance, $\varepsilon_x/\varepsilon_y$, mm mrad	500/50
Momentum acceptance	±3%



Beam envelopes for a quarter of ring circumference ($\varepsilon_x/\varepsilon_y$=500/50 mm mrad, $\Delta p/p$=±3%)

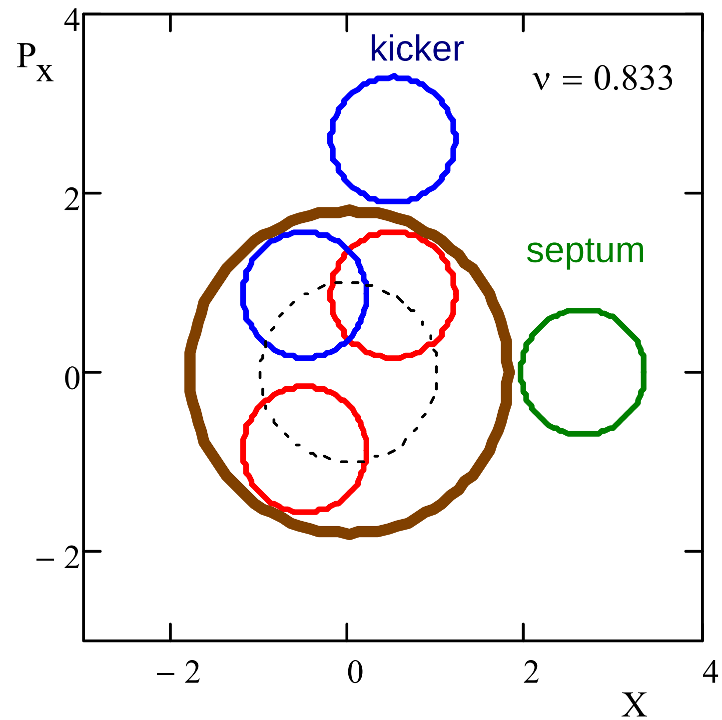
Choice 3 (continue)

Beam parameters

DC beam current, A	2.18
Number of particles	$4 \cdot 10^{13}$
Filling factor, L_b/C	0.5
Number of 53 MHz bunches	36
Particles per bunch	$1.1 \cdot 10^{12}$
Total long. emittance, eV s	10
σ_p after debunching of 53 MHz bunches	$7 \cdot 10^{-5}$
Harmonic number, h	1
RF voltage for bunch compr.	1 MV
Synchrotron tune at compr.	$2.8 \cdot 10^{-4}$
$(Z_n/n)_{Space\ charge} \approx (Z_n/n)_{Stability}$	1.5 Ω
Beam power	**2 MW**

Beam injection & compression

- 2 turn injection from RCS doubles longitudinal density
- Adiabatic bunching with consecutive bunch rotation, h=1
- Micro wave instability is still the major limitation of the beam power



Schematic of 2 turn injection presented in longitudinal phase space

Choice 3 – CR with injection from 21 GeV RCS

- 21 GeV compressor ring should allow to exceed 1 MW limit of 8 GeV choice
- The help comes from
  - Smaller number of particles per bunch (8/21)
  - Reduced effect of space charge fields as $1/\gamma^2$
- However to exceed 0.3 MW power one needs to have the longitudinal phase space density higher than is presently planned for Project-X
  - Fast accelerating rate in RCS limits a single bunch emittance to ~0.1 eV s (three fold emittance increase due to imperfections of RF gymnastic is assumed)
- 21 GeV choice also implies that the beam leaves longer time in the rings and high frequency RF is used for acceleration
  - High frequency RF and high beam intensity can provoke electron multipactoring in the vacuum chamber and, consequently, ep-instability.
    - This problem has to be addressed if RCS is preferred for Project X

Conclusions

- 8 GeV linac is a good asset for muon collider proton driver
  - It is feasible to achieve 1 MW with a single bunch mode at 15 Hz repetition rate in the specialized compressor ring
  - It looks like that other Project X infrastructure hardly can be useful for muon collider
- Further beam power increase requires larger energy
  - 21 GeV RCS looks as a good alternative
  - If chosen the problems of increased longitudinal phase space density (factor of 4) and ep-instability have to be addressed

Backup slides

Two turn injection

- Assume that after injection two injected bunches have the same amplitude but betatron phases shifted by 180 deg.

$$\begin{bmatrix} x_1 \\ p_1 \end{bmatrix} = \begin{bmatrix} \cos\phi \\ -\sin\phi_1 \end{bmatrix}, \quad \begin{bmatrix} x_2 \\ p_2 \end{bmatrix} = \begin{bmatrix} -\cos\phi \\ \sin\phi_1 \end{bmatrix}$$

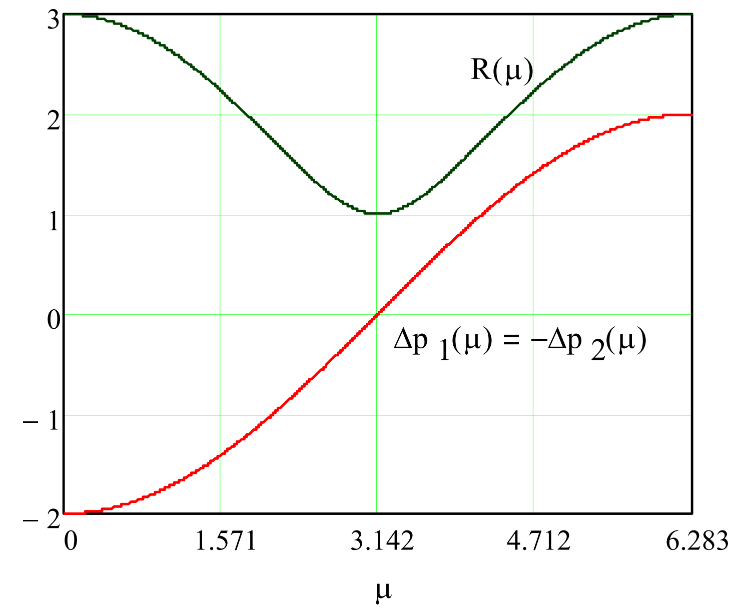
- That bounds up the initial betatron phase of injected bunch, ϕ, the kick amplitude, Δp, and the tune, μ. There are two solutions

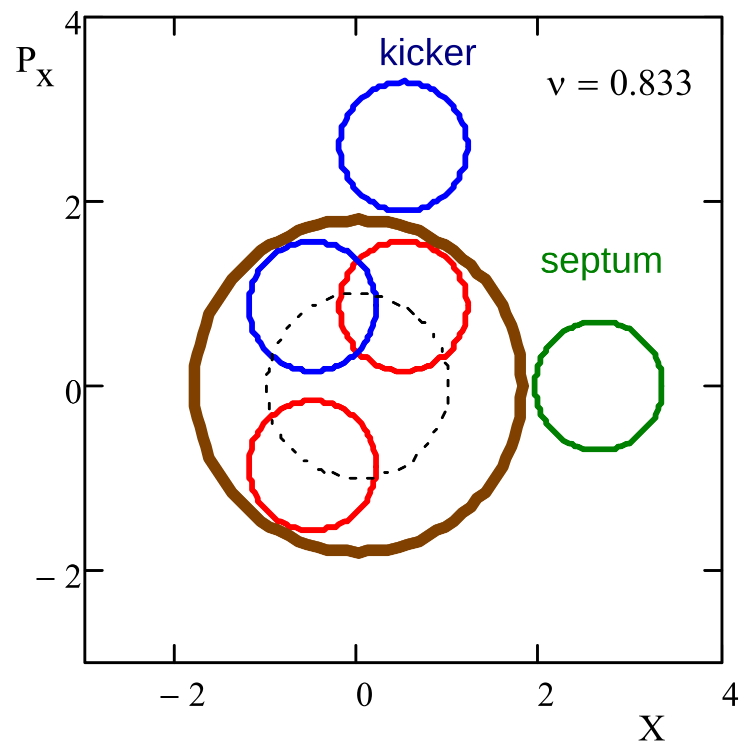
$$\phi = -\frac{1}{2}\begin{bmatrix} \mu+\pi \\ \mu-\pi \end{bmatrix}, \quad \Delta p = \frac{\sin\frac{\mu}{2} + \sin\frac{3\mu}{2}}{\sin\mu}\begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

- Corresponding betatron amplitude before the kick is

$$R = \sqrt{\cos\left(\frac{\mu-\pi}{2}\right)^2 + \left(\sin\left(\frac{\mu-\pi}{2}\right) - \frac{\sin\frac{\mu}{2} + \sin\frac{3\mu}{2}}{\sin\mu}\right)^2}$$

All distances are measured in betatron amplitude after injection

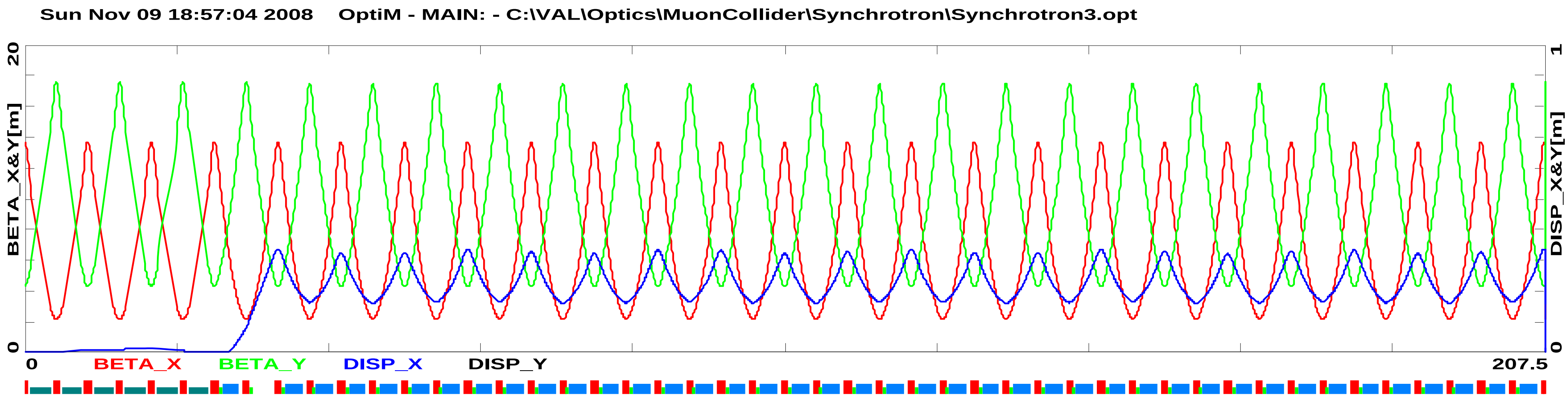


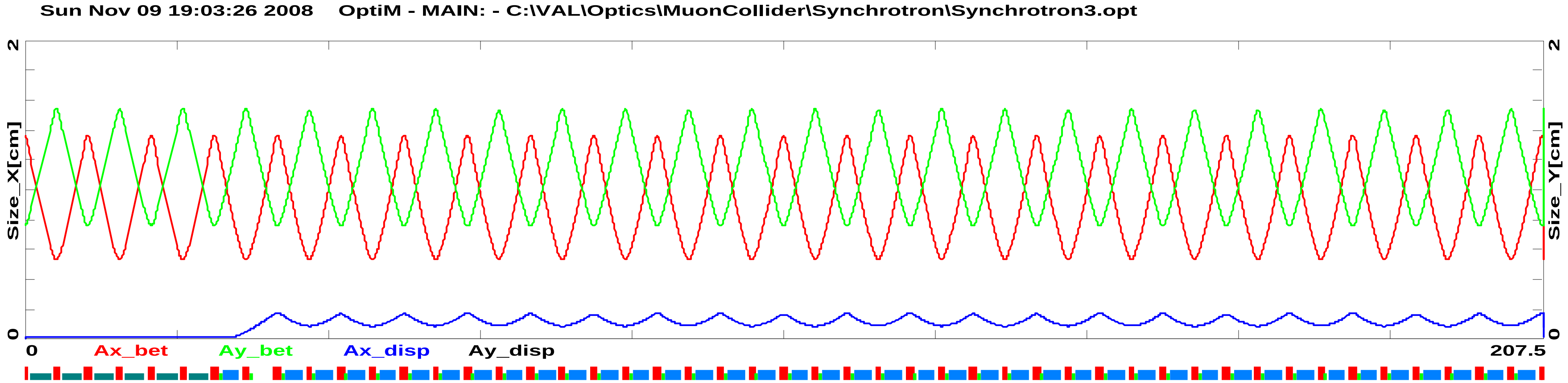


Rapid cycling synchrotron

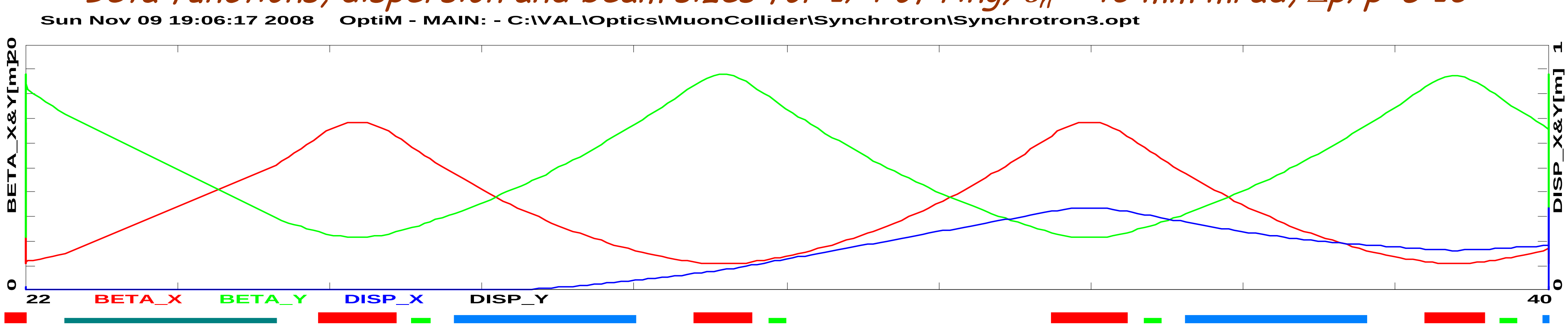
Strategy for Choice of RSC parameters

- Beam current is set to by 2 MW power of MI: I_{beam}=2.5 A
- Maximum energy – 21 GeV
  - Above MI critical energy
  - Large enough to get rid of space charge tune shift limitations
- Circumference – 1/4 of MI
  - Compromise between
    - Smallest value satisfying RCS requirements for chosen max. energy
    - Number of cycles required to fill MI
- Optics - FODO
  - racetrack
  - zero dispersion in the straight lines
  - Large tune
    - ⇒ Small momentum compaction
    - ⇒ Small beam size -> small magnets
  - Alternative choice of ring with negative momentum compaction will have larger aperture, larger magnets, more problems with vacuum chamber heating





Beta functions, dispersion and beam sizes for 1/4 of ring; ε_n = 40 mm mrad, $\Delta p/p=5\ 10^{-3}$



Dispersion is zeroed by missed dipole

Rapid cycling synchrotron (continue)

Screening of AC bending magnetic field by vacuum chamber

- Eddy currents in vacuum chamber result in a delay of bending field
  - they do not produce non-linearities if the chamber is round and has constant wall thickness

$$\frac{\delta B}{B} = -4\pi^2 ia \frac{\sigma_R ad}{c^2} f_{ramp}$$

- Heating of the vacuum chamber by eddy currents is more serious limitation technical limitation
  - The same dependence on vacuum chamber radius and thickness as the growth rate of resistive wall instability

$$\frac{dP}{ds} = 4\pi^3 \frac{\sigma_R a^3 d}{c^2} f_{ramp}{}^2 \frac{\left(B_{\max} - B_{\min}\right)^2}{2}$$

Vacuum Chamber Heating and Screening*

f_{ramp} [Hz]	E_{max} [GeV]	B_{max}[kG]	$\delta B/B$	dP/ds [W/m]
5	8	5.3	$3\ 10^{-4}$	1.6
	21	13.1		9.5
15	8	5.3	10^{-3}	14
	21	13.1		**86**

*Stainless steel, *d* = 0.7 mm, *a* = 22 mm

Rapid cycling synchrotron (continue)

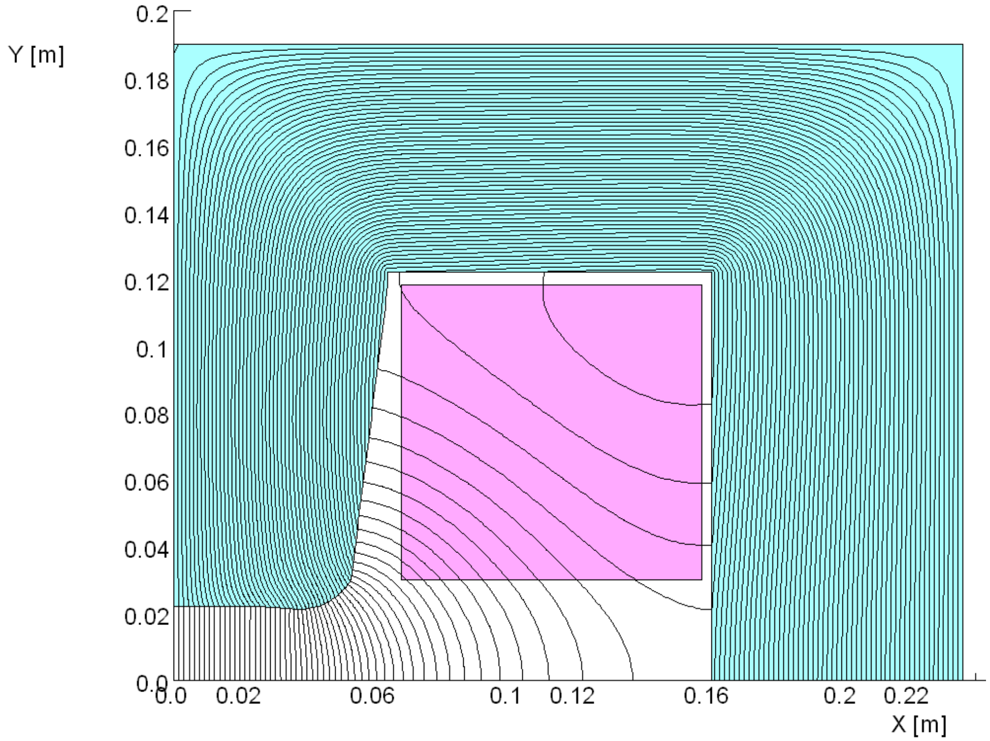
Main machine parameters

	Stage 1	Stage 2
Injection kinetic energy, GeV	2	2
Extraction kinetic energy, GeV	8	21.
Circumference, m	829.8	
γ transition, γ_t	25.04	
Ramp frequency, Hz	5	15
Total number of particles	$4.5 \cdot 10^{13}$	
Beam current at injection, A	2.5	
Betatron tunes, Qx/Qy	28.42/16.41	
Normalized 95% emittance, mm mrad	35	
Norm. acceptance at injection, $\varepsilon_x/\varepsilon_y$, mm mrad	85/65	
Harmonic number	147	
90% longitudinal emittance, eV s /bunch	0.25	
Maximum Coulomb tune shifts, KV-distr., $\Delta Qx/\Delta Qy$	0.059/0.072	
Number of bunches	137	
Natural tune chromaticity	-34/ -25	
RF voltage	3.6	2.3
Beam power, kW	390	2200

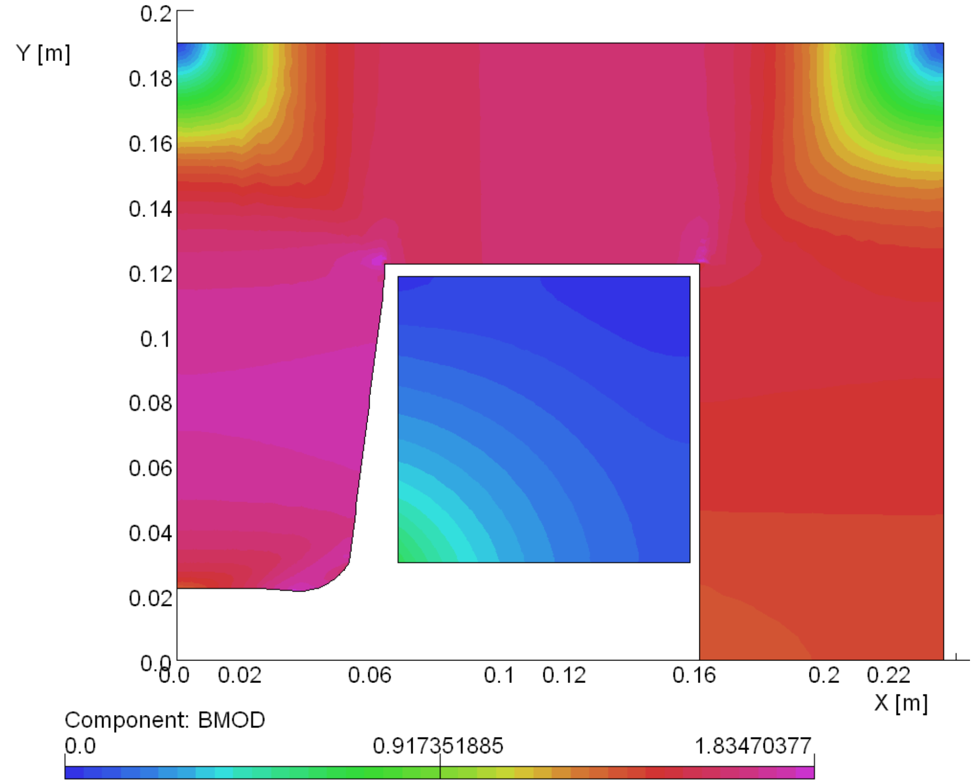
Rapid cycling synchrotron dipole (V. Kashikhin)

Peak field	T	1.3
Field at injection	T	0.12
Magnet gap	mm	44
Good field area diameter	mm	40
Field homogeneity		0.01 %
Effective length	m	2.33
Peak current	A	1000 A
Current frequency	Hz	15
Duty factor	%	100
Number of turns/pole		24
Copper conductor	mm x mm	15 x 20.2
Conductor cooling hole diameter	mm	10
Number of pancake coils/pole		2
Lamination material		M17
Lamination thickness	mm	0.35
Inductance	H	0.024
DC resistance	Ohm	0.022
Stored energy	kJ	12
Power losses rms (without eddy currents))	kW	11
Peak voltage	kV	2.5
Number of cooling circuits/magnet		2
Water pressure drop	Mpa	0.5
Water flow	l/min	7
Water temperature rise	C°	12

Rapid cycling synchrotron dipole (continue)



Magnet geometry and flux lines at peak current 1 kA.



Flux density in the core and coil.

Rapid cycling synchrotron dipole (continue)

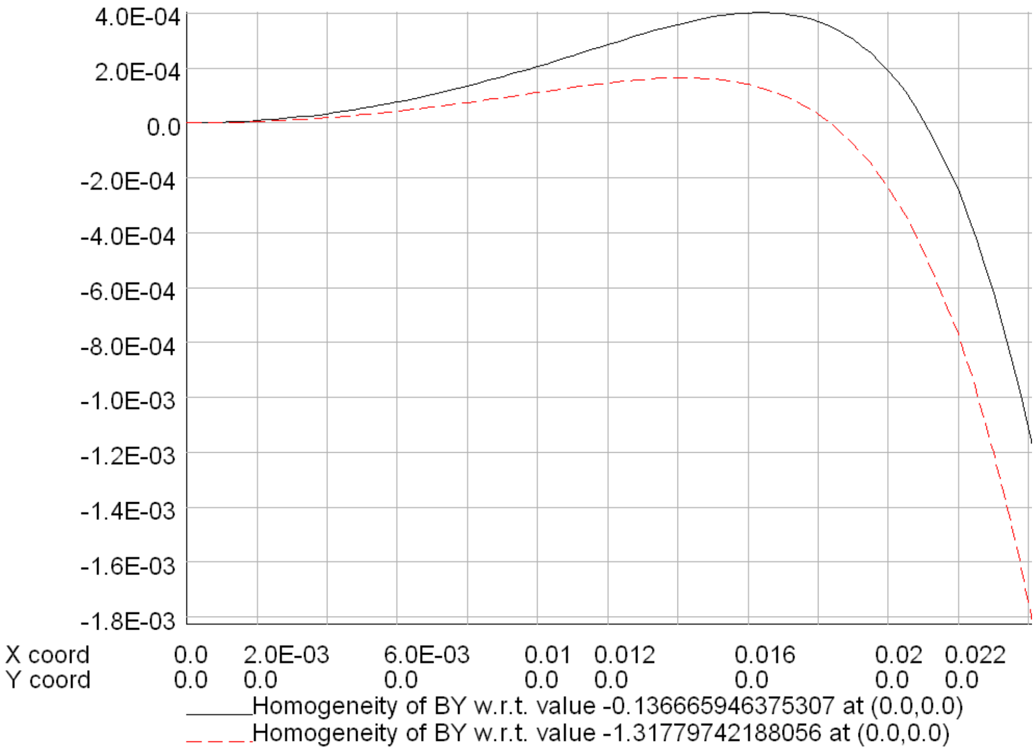
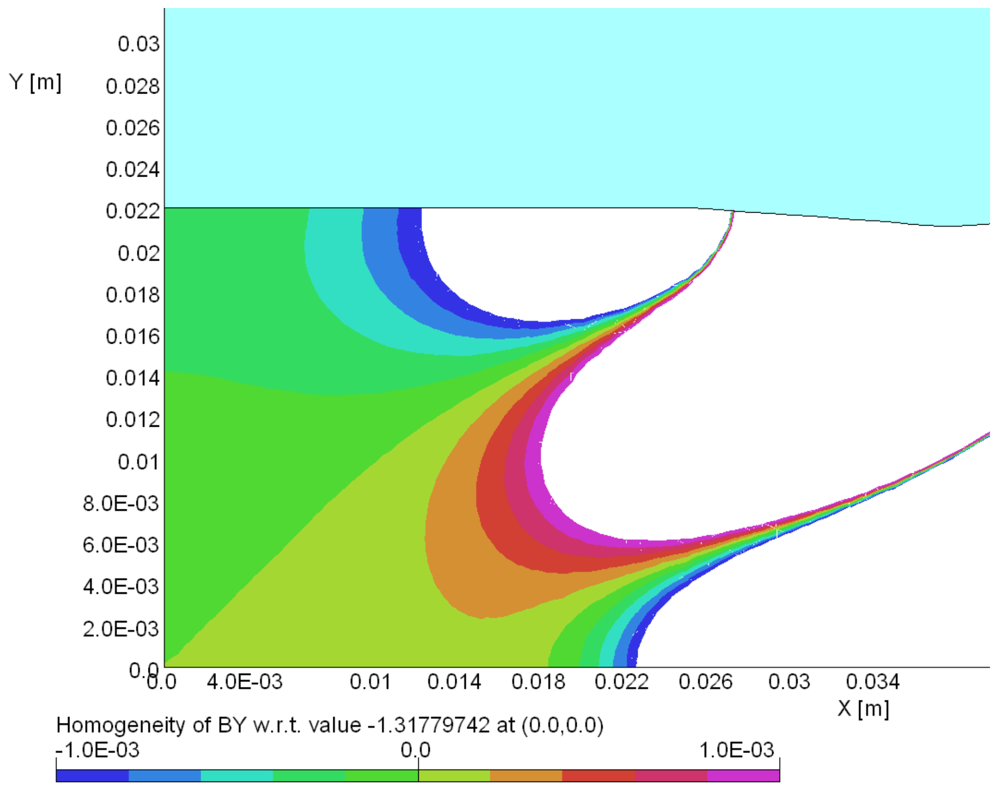
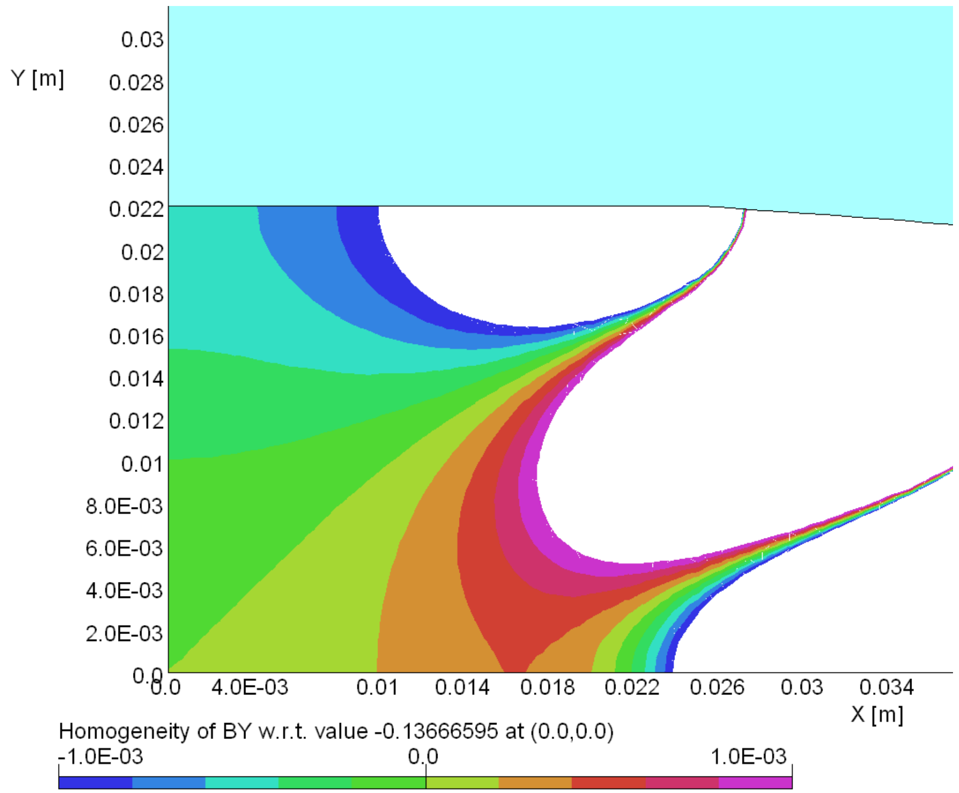


Fig. 3. Field homogeneity in the middle plane at injection (black) and extraction (red).

Rapid cycling synchrotron dipole (continue)



Field homogeneity in the magnet gap at I=1 kA.



Field homogeneity in the magnet gap at 0.1 kA.

Rapid cycling synchrotron dipole (continue)

Summary

- The dipole magnet concept was simulated using OPERA 2D package. The magnet parameters could be improved by further pole profile optimization.
- The AC magnetic field simulations should be done to estimate eddy current losses in the coils, laminated core, and beam pipe. The yoke steel properties should be properly chosen to reduce losses.
- The simulations did not take into account the core sagitta, which is 10.2mm. For the straight yoke the good field area width should be increased from 40 mm up to 50.2 mm. Another solution is to make the curved iron core. This case needs more complicated tooling and more labor for assembly.
- A possible solution is to split the straight core. Two straight half cores mounted on the support structure under the angle having common coils.