Compressor Ring

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Where do we go?

- Tevatron Run II ends in two 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

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

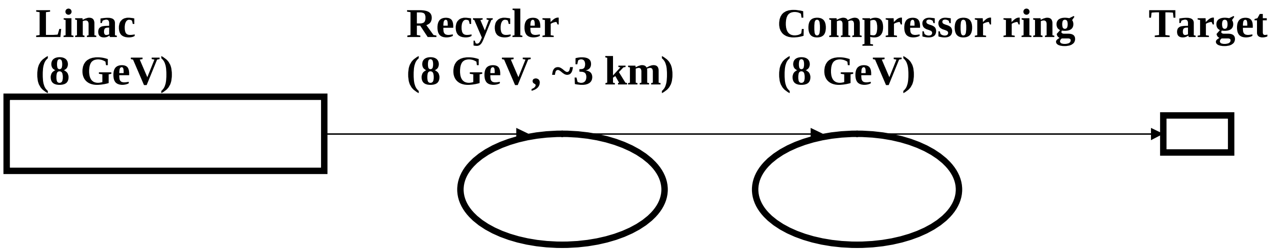
  More or about 1 MW is desirable

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



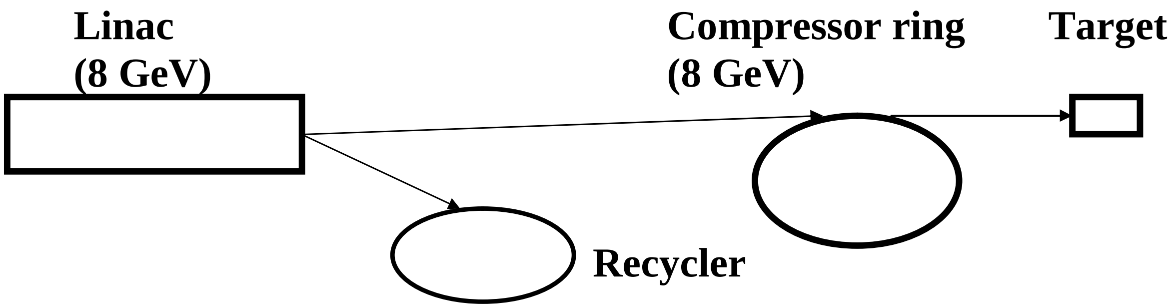
Linac
(8 GeV)

Recycler
(8 GeV, ~3 km)

Compressor ring
(8 GeV)

Target

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



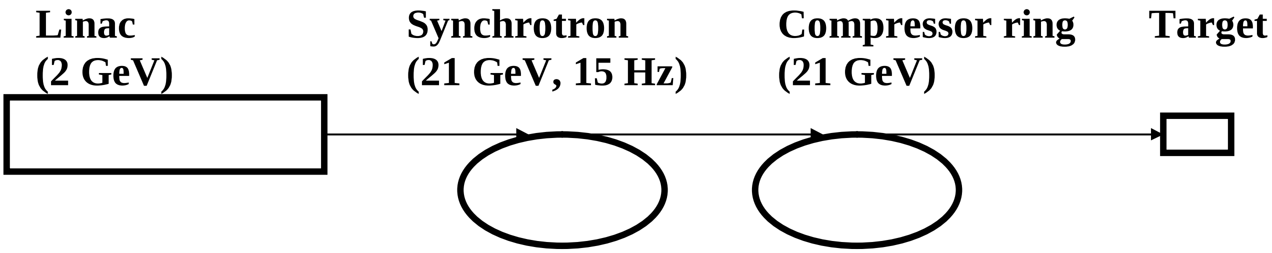
Linac
(8 GeV)

Compressor ring
(8 GeV)

Target

Recycler

- Alternative Project-X + compressor ring



Linac
(2 GeV)

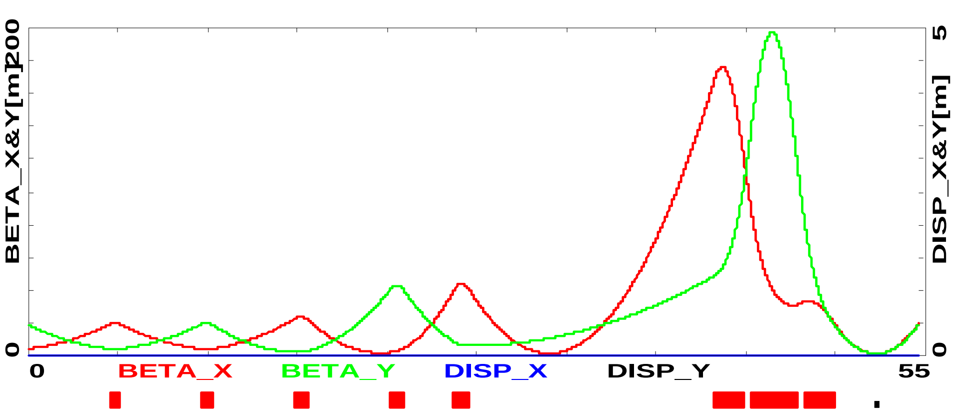
Synchrotron
(21 GeV, 15 Hz)

Compressor ring
(21 GeV)

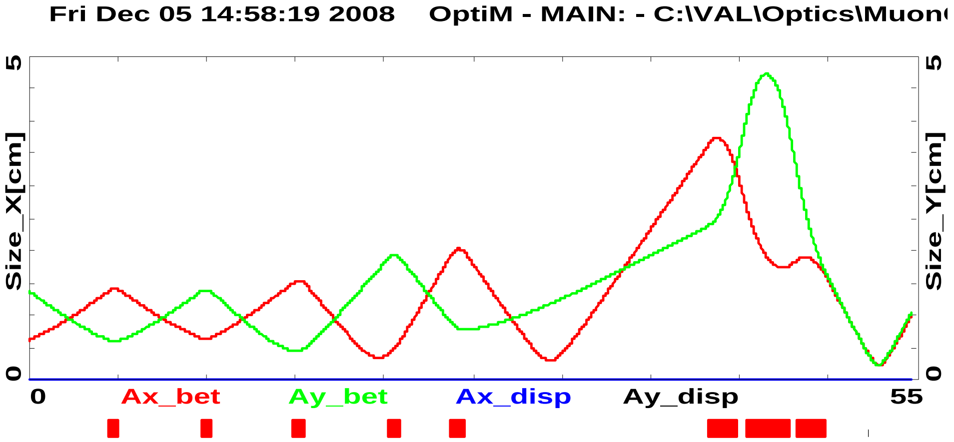
Target

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

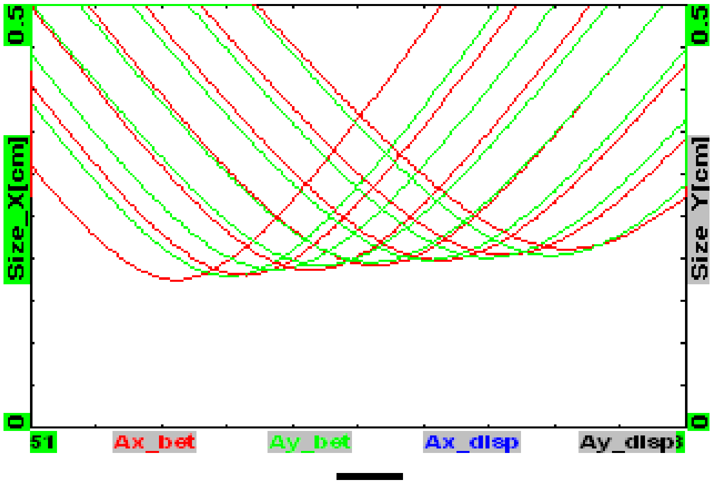
Final focus quads

	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 $S_{\text{target-to-window}}$ => 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

$$\varepsilon_n(\delta\omega)=1+\frac{eI_0Z_n}{2\pi i R_0 p}\int\limits_{\delta\to+0}\frac{df/dx}{\delta\omega+n\omega_0\eta x-i\delta}dx=0\quad ,$$

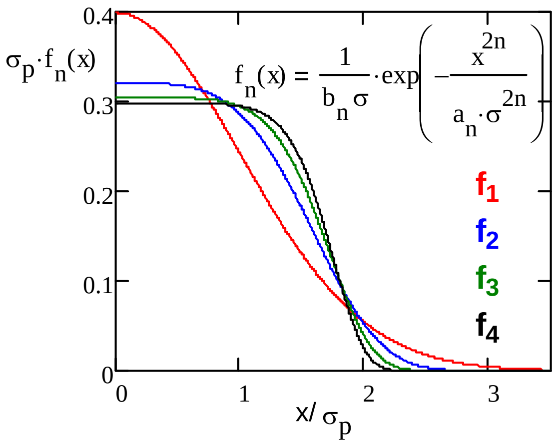
$$x=\frac{\Delta p}{p}\ ,\quad \eta=\alpha-\frac{1}{\gamma^2},\quad \delta\omega=\omega-n\omega_0$$

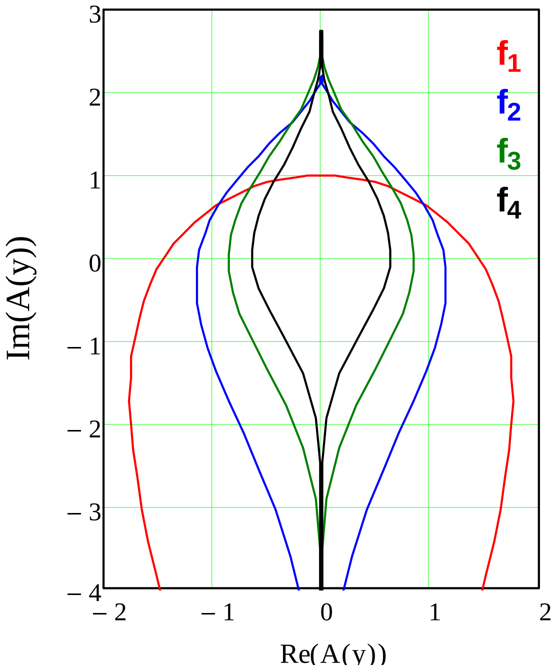
- Stability condition depends on particle distribution, $f(x)$

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

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

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





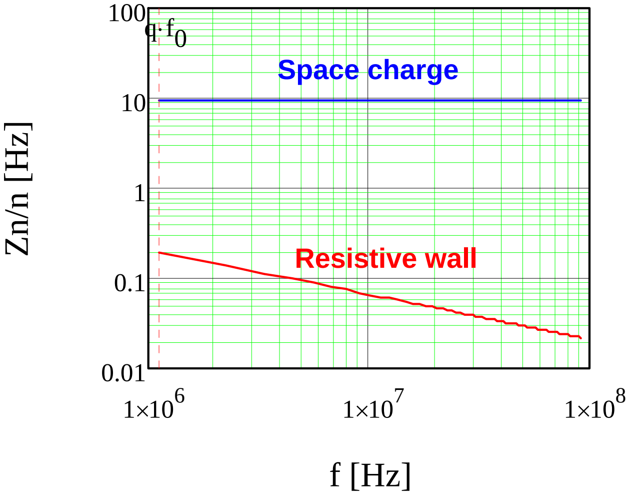
Longitudinal beam stability (continue)

- 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

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



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

  - Effect of RF cavities, vacuum chamber discontinues, etc. can be controlled by machine design and dampers (f < 100 MHz)
- Space charge contribution does not depend on frequency and dominates at high frequency
  - It result very fast momentum spread growth, $\lambda_n \approx n\omega_0\eta\left(\Delta p / p\right)$
- 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

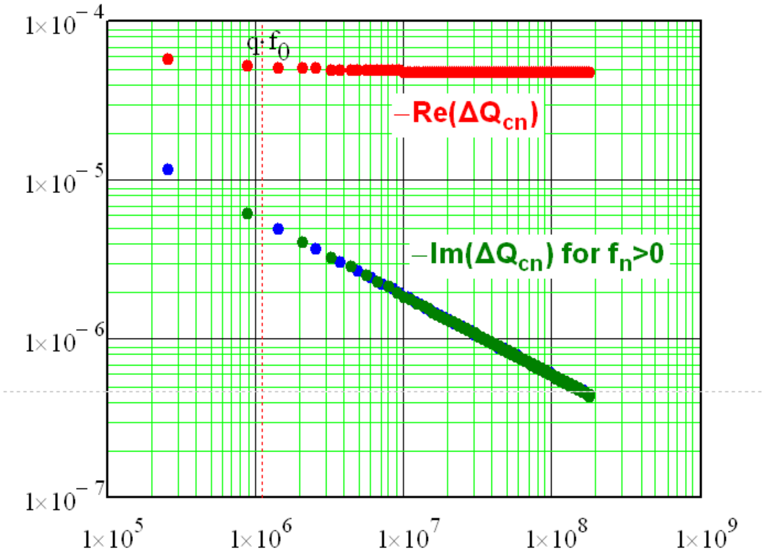
$$\delta\nu_{cb} = -i\frac{r_p N}{2\pi\beta\gamma\nu}\frac{Z_\perp}{Z_0}$$ - continuous beam

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

- 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



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}

- 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

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

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

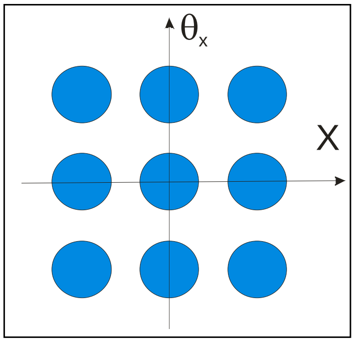
Longitudinal field of the bunch

- 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

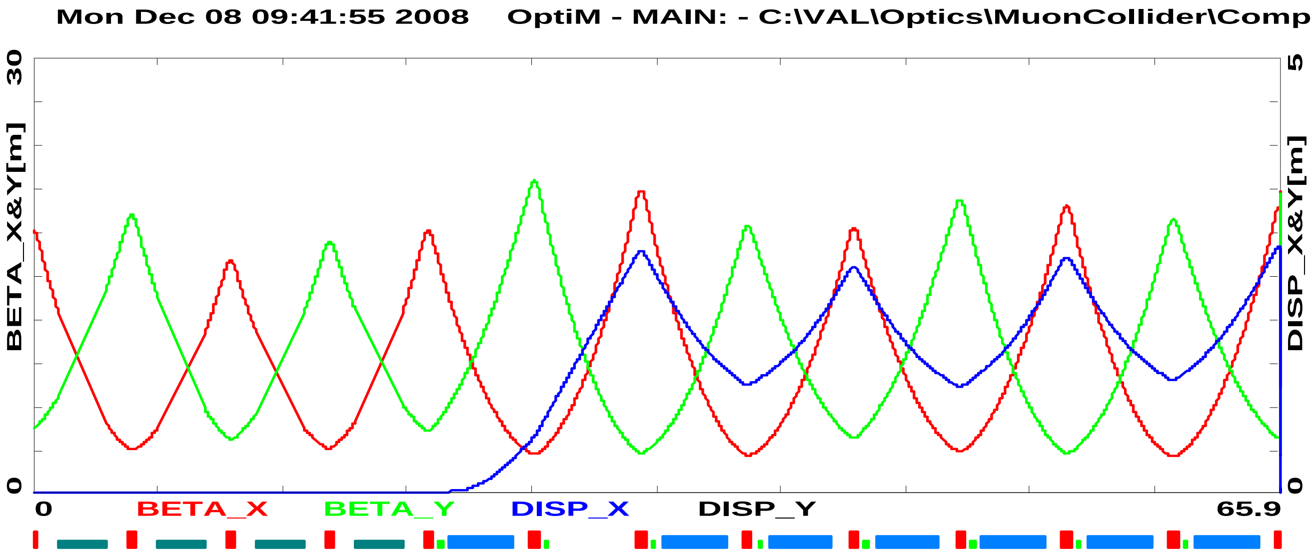
- Low longitudinal phase density of the Recycler beam is the main limitation of the beam power
  - Recycler Project-X bunch:
    $N = 2.9\cdot10^{11}$, $\varepsilon_s = 0.4$ eV·s/bunch (53 MHz RF)
- Only 8 bunches can be coalesced to fit to the required ε_L:
  $\sigma_s = 60$ cm, $\sigma_p = 0.1\%$, $\varepsilon_{s95} = 6\pi\,\sigma_s\,\sigma_p\,p\,/\,(\beta c)$ ~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: $\varepsilon_{n95} = 25$ 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

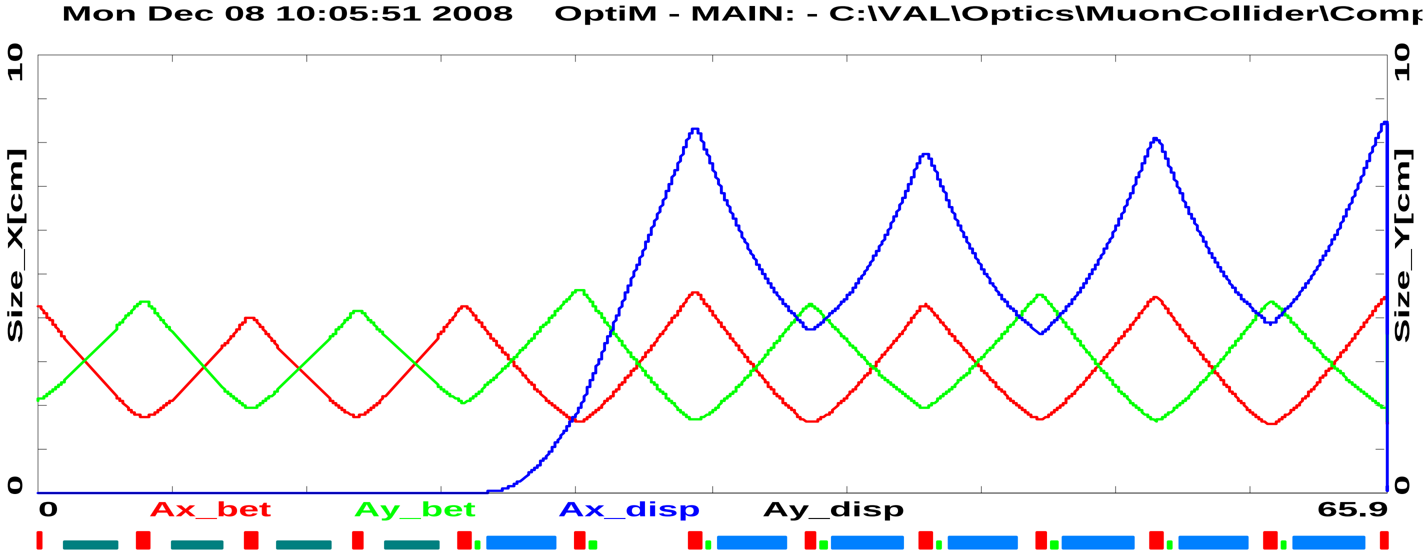


Twiss parameters for a quarter of ring circumference

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, $\Delta p/p$=±3%)

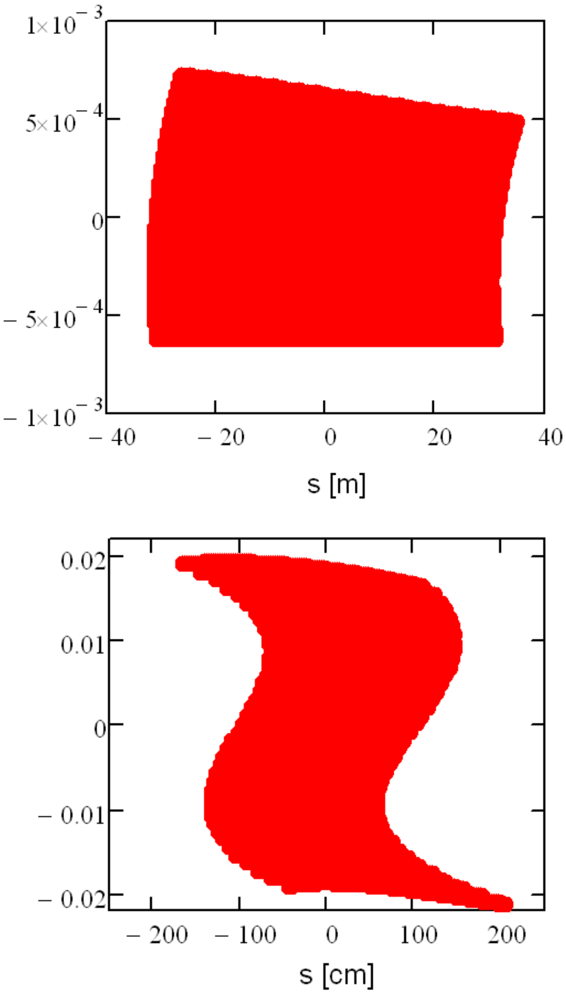
Choice 2 (continue)

Beam injection & compression

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

Injection parameters

Injection type	H^- strip
Linac current	40 mA
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	$2.7\cdot10^{-5}$
$(Z_n/n)_{\text{Space charge}} = (Z_n/n)_{\text{Stability}}$	10 Ω
Beam power	**1 MW**



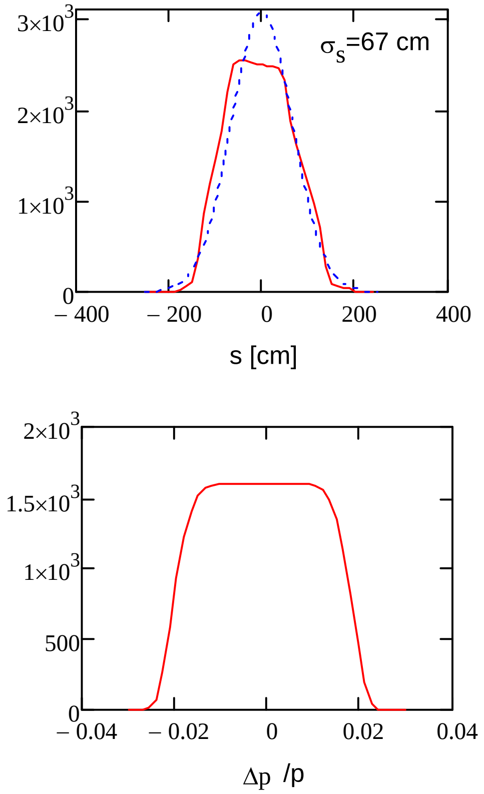
Longitudinal phase space at the end of injection and after compression

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	$6.8\cdot10^{-4}$
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	$2\cdot10^{-5}$ /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

- 21 GeV compressor ring allows 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
- This choice also implies that the beam leaves longer time in the ring and high frequency RF is used for acceleration
  - High frequency RF and high beam intensity 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