BUNCH PRODUCTION FOR A MUON COLLIDER

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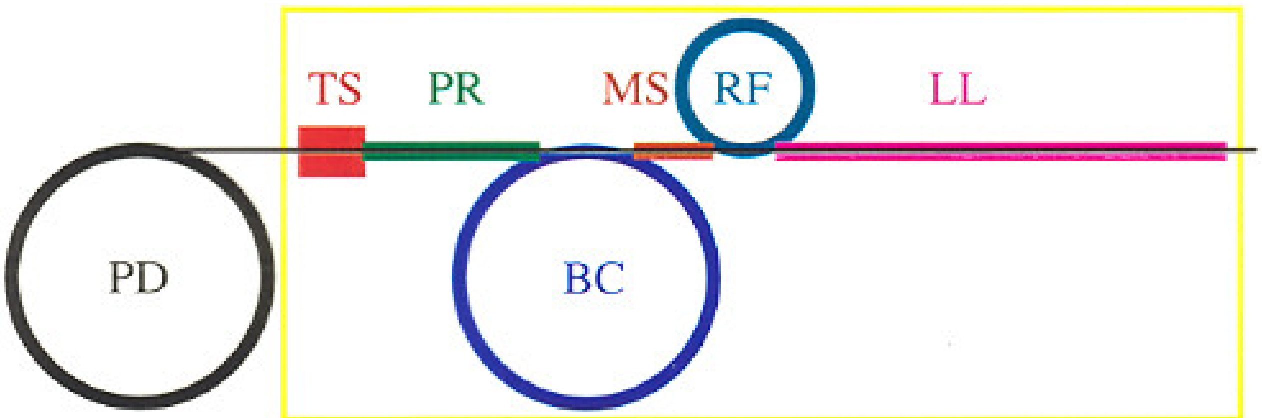
Optimal regime for a $\mu^+\mu^-$ collider

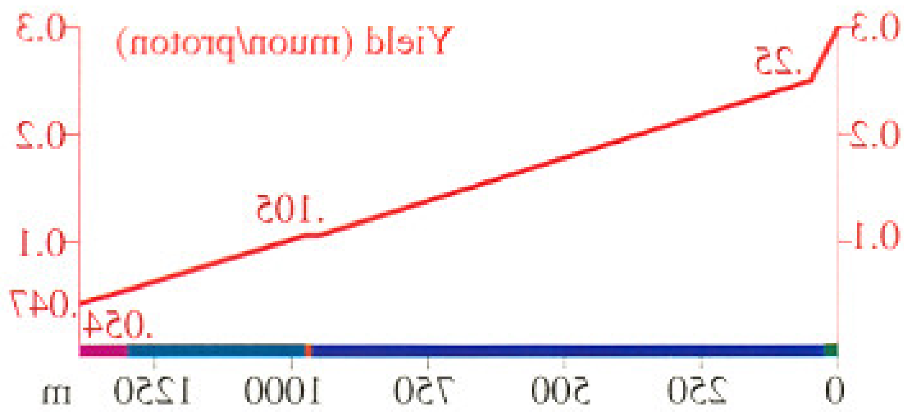
- All muons should be collected in a single bunch, because at given number of muons, luminosity is inversely proportional to the number of bunches.
- The bunch should be compressed longitudinally as fast as possible to be accepted by a high-frequency (high voltage) cooling system.
- A cooling is required at the compression because particles populate a very diffuse phase space, and initial beam length and energy spread shoud be large to capture more muons.

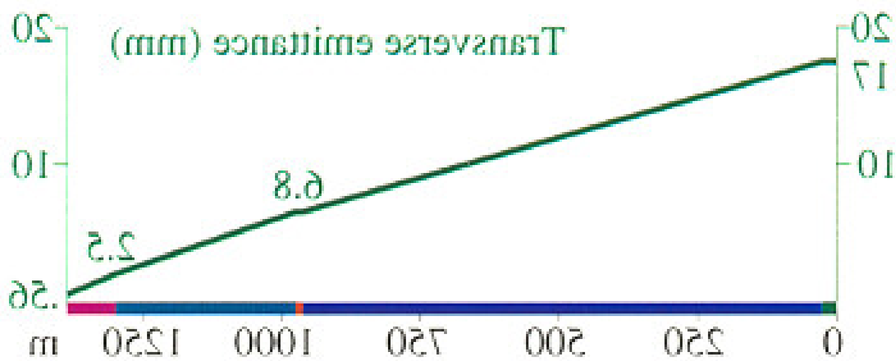
General Layout

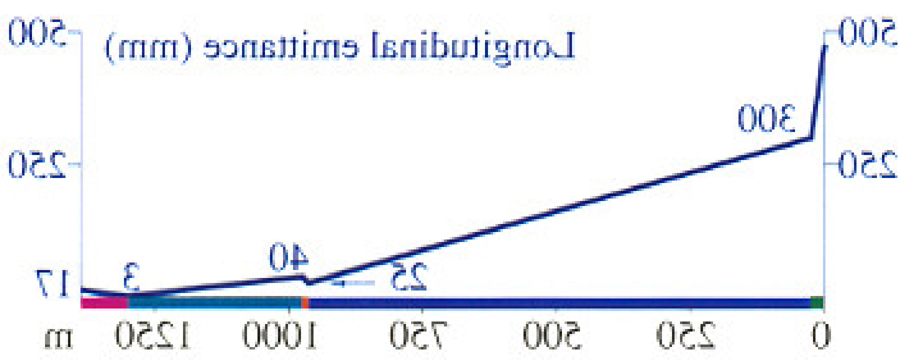


- **PD** – Proton Driver: 24 GeV.
- **TS** – Target Station: mercury jet in 20 $\rightarrow$ 4.4 T solenoid.
- **PR** – Phase Rotation channel: 20 m, 4.4 $\rightarrow$ 1.75 T, 36.37 MHz, 6.37 MeV/m, + 10 m drift.
- **BC** – Bunch Compressor: ring cooler 72.3 m, 1.75 T, 36.37 MHz, 6.37 MeV/m LH_2 absorbers, LiH wedge absorbers.
- **MS** – Matching Section: 14 m, 1.75 $\rightarrow$ 3.5 T, 203.4 MHz, 7×4.8 MV cavities.
- **RF** – RFOFO ring cooler: 33 m, ± 2.74 T, 203.4 MHz, 16 MeV/m, LH_2 wedge absorbers.
- **LL** – Li Lens cooling channel: 70-90 m, ~ 10 T Li lenses and solenoids, 201.25 MHz, 12-14 MV/m.

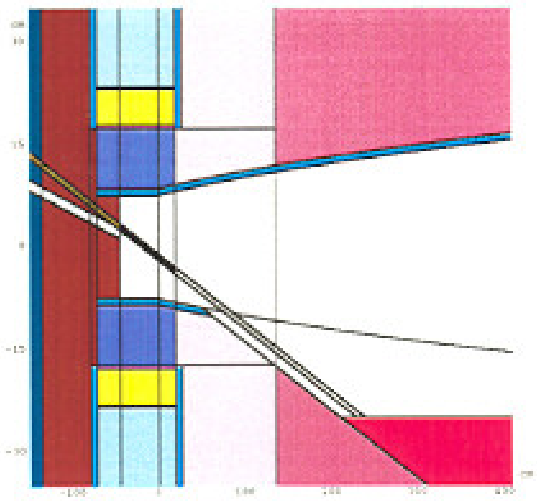
General Performances

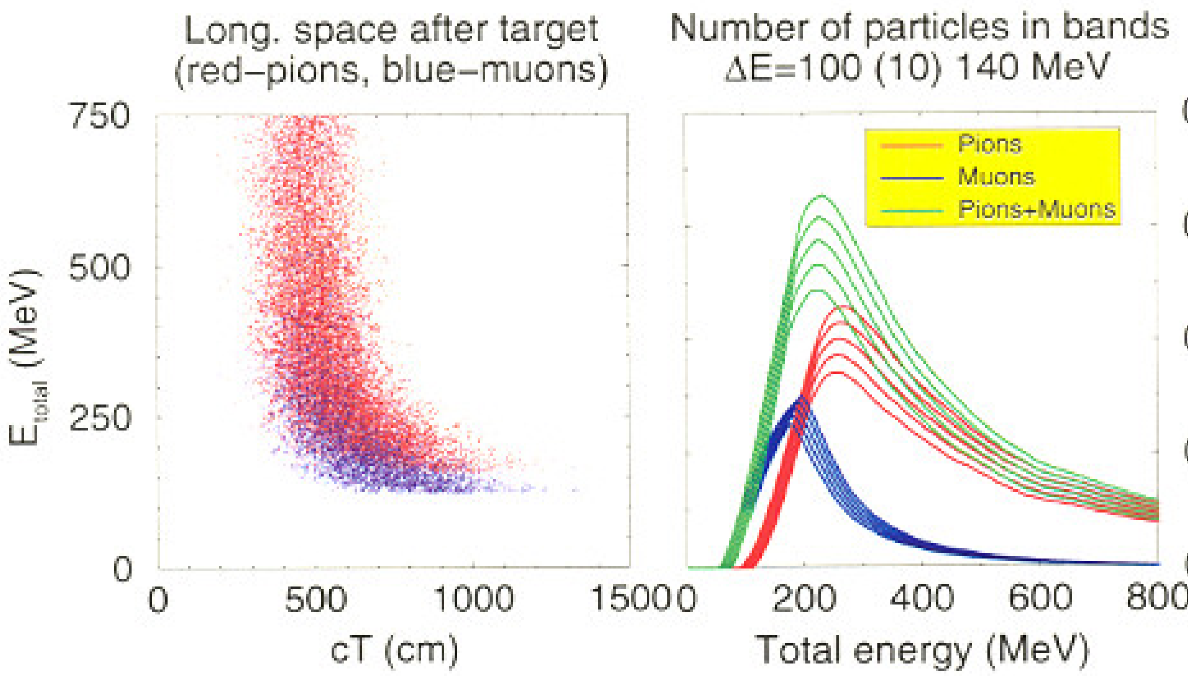






Target Station (N.Mokhov)



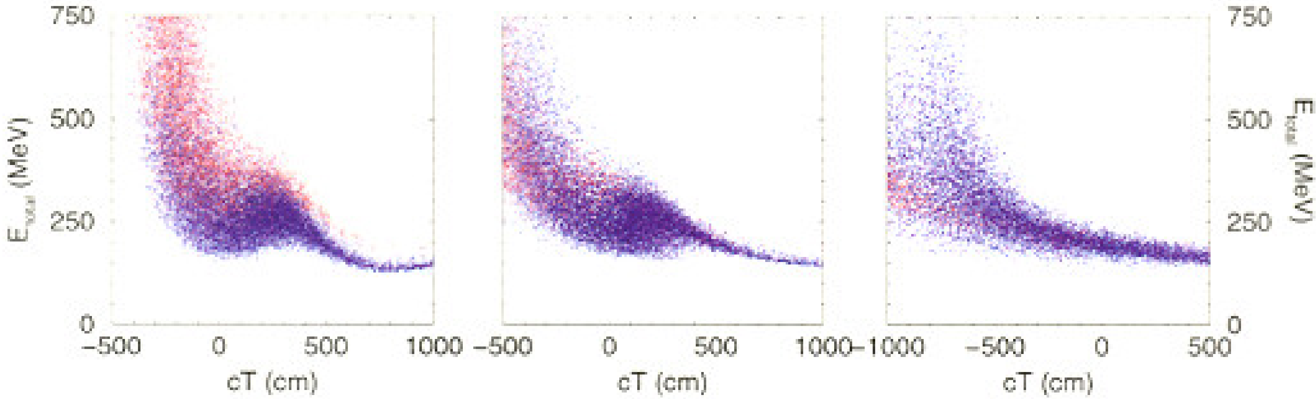


Conclusion: Phase rotation channel should be tuned on $p \simeq 200$ MeV/c.

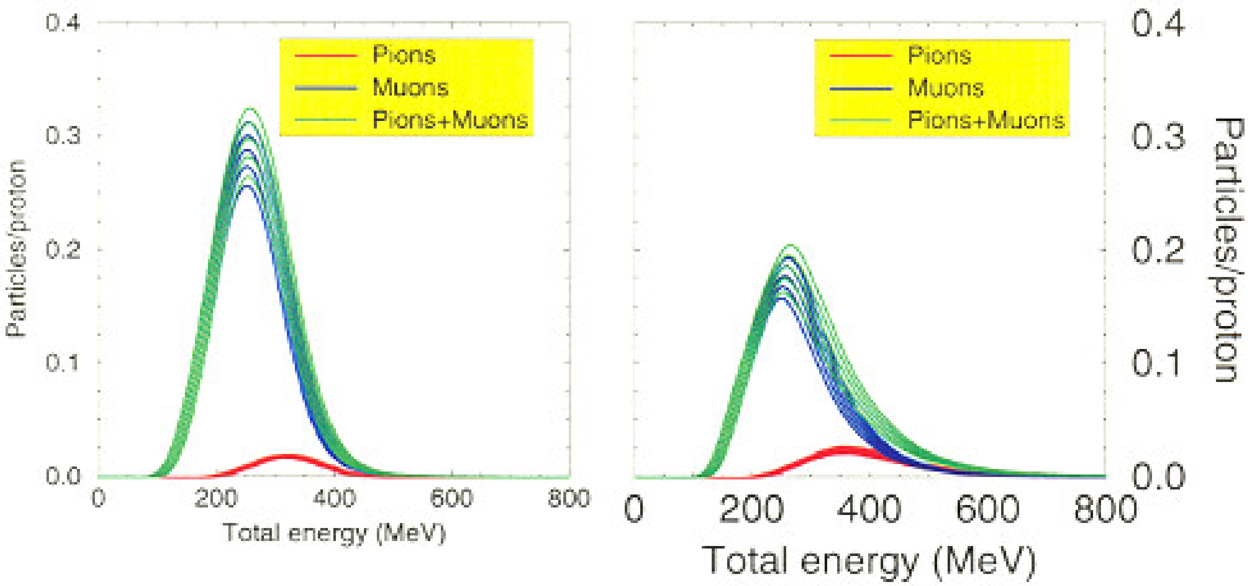
Phase Rotation - Decay Channel

- Length of rotated part of the beam is $\sim \lambda/2$.
- The same can be captured for a cooling-compression.
- Therefore it is reasonable to use the same RF both for phase rotation and bunch compression.
- Possible frequencies are $f = 3.637 \times h$ MHz:
  - ... 29.10, 32.74, 36.37, 40.01, 43.65 ...
- Presumed accelerating gradient $V' = 2\sqrt{n}$ MV/m.
- Lower frequency: more capture – slower cooling – more decay.
- Higher frequency: less capture – faster cooling – less decay.
- Optimum at $h = 10$, $f = 36,37$ MHz, $V' = 6.37$ MV/m.
- Channel: 20 m RF + 10 m drift = 30 m.
- Solenoid: $4.4 \rightarrow 1.75$ T on first 5 m.

Beam at Phase Rotation

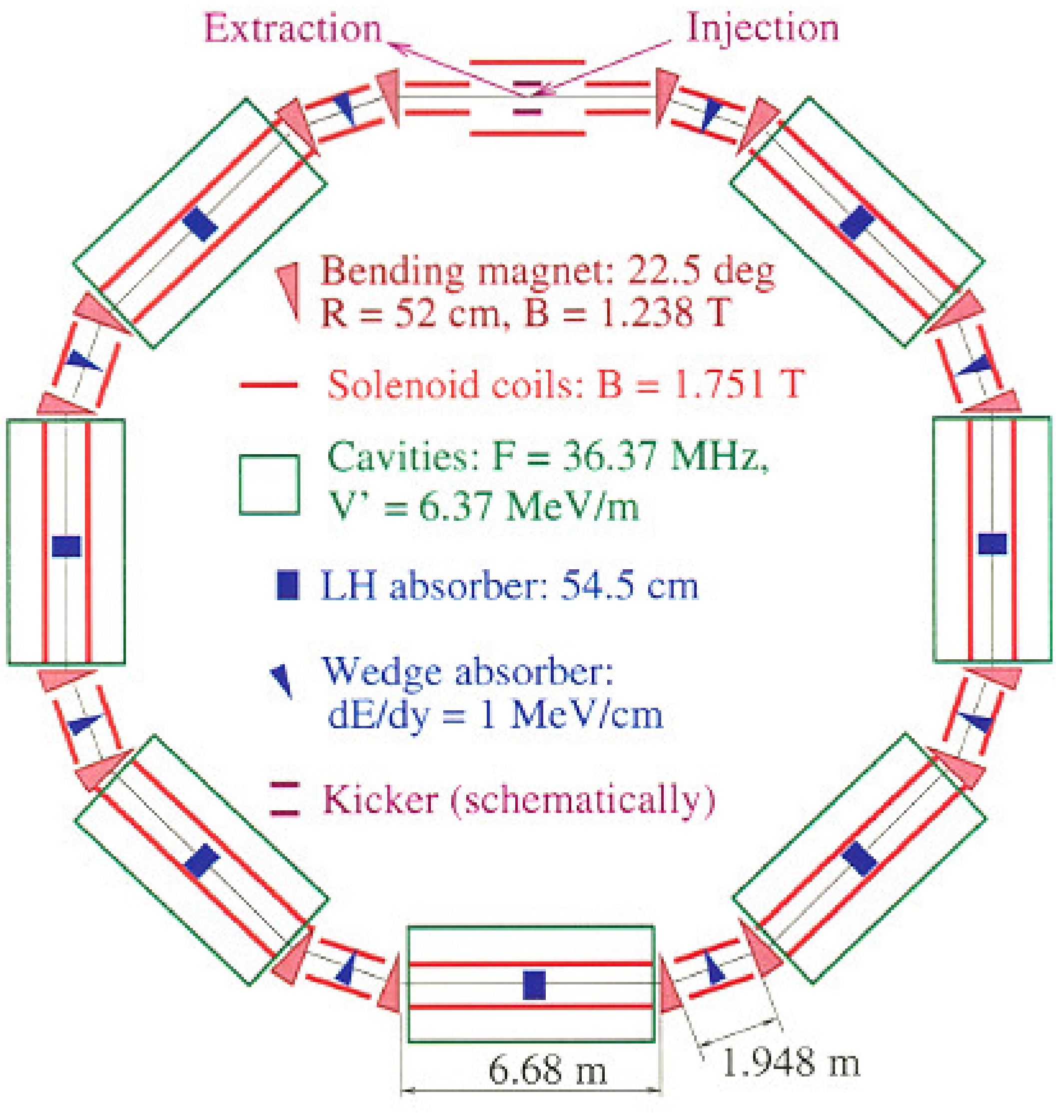


Longitudinal phase space after phase rotation (left), + additional drift (center), and after a simple 30 m drift in the solenoid without RF.



Number of particles in energy bends 100, 110, 120, 130,140 MeV at 5 m long window. Left – with phase rotation, right – without this.

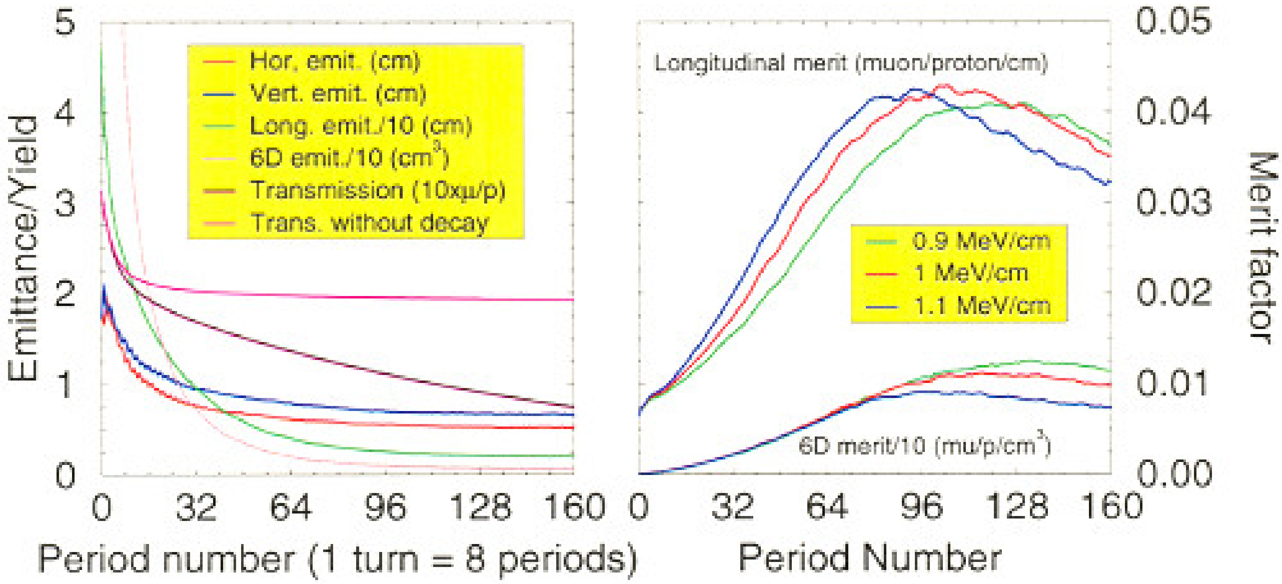
Bunch Compressor: Layout



Bunch Compressor: Parameters

Circumference	72.291 m
Nominal energy (total)	220 MeV
Bending radius	52 cm
Bending field	1.2378 T
Normalized field gradient	0.5
Length of short SS	1.948 m
Length of long SS	6.68 m
Axial field of the long solenoid	1.7506 T
Revolution frequency	3.637 MHz
Accelerating frequency	36.37 MHz
Accelerating gradient	6.37 MeV/m
Synchronous phase	30°
LH_2 main absorber, length	54.5 cm
LiH wedge absorber, dE/dy	1 MeV/cm

Beam Cooling and Compression

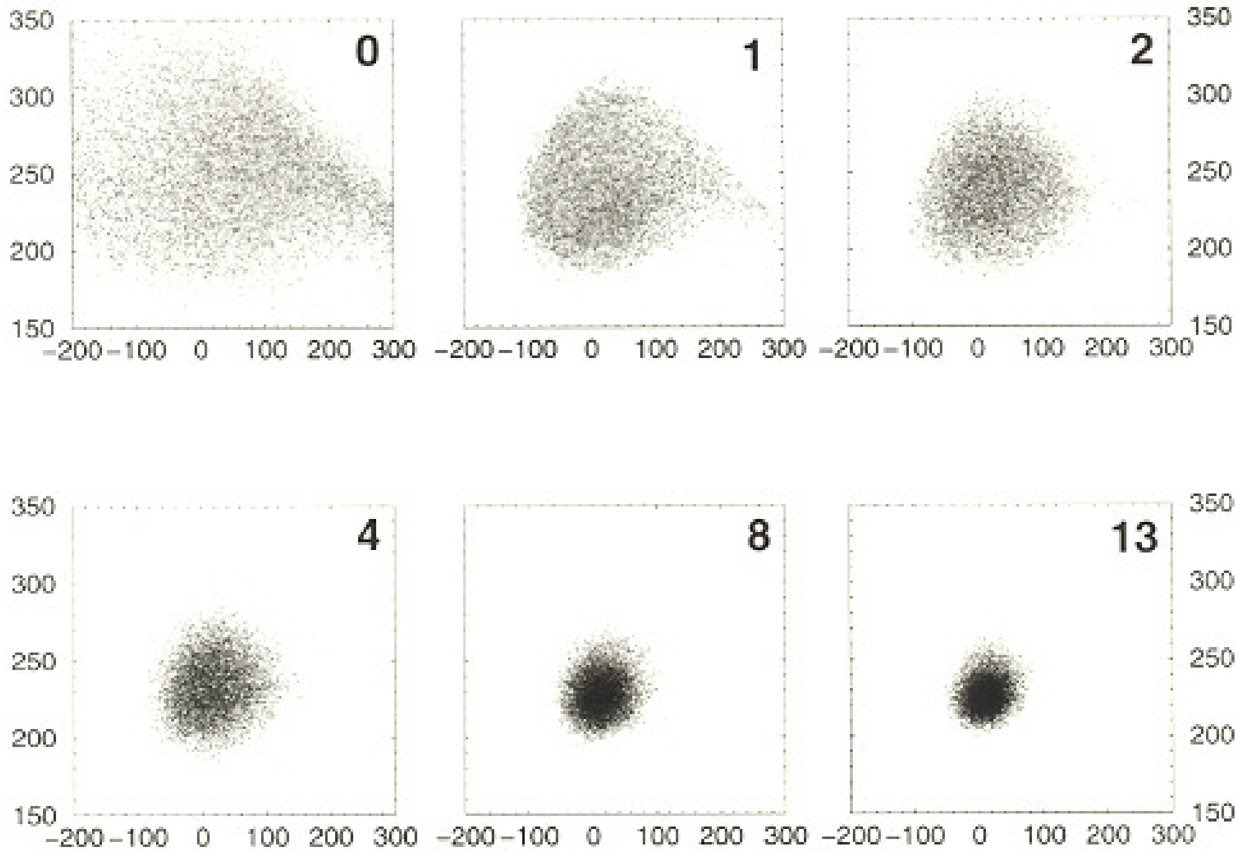


Evolution of beam parameters in the ring cooler-compressor. Left – emittances, transmission, and yield, right – merit factors.

$$\mathbf{M.F. = Yield/Emittance}$$

Parameter – gradient of energy loss in wedge absorber. The best results obtained after 13 turns at $dE/dy = 1$ MeV/cm.

Longitudinal Phase Space at the Compression



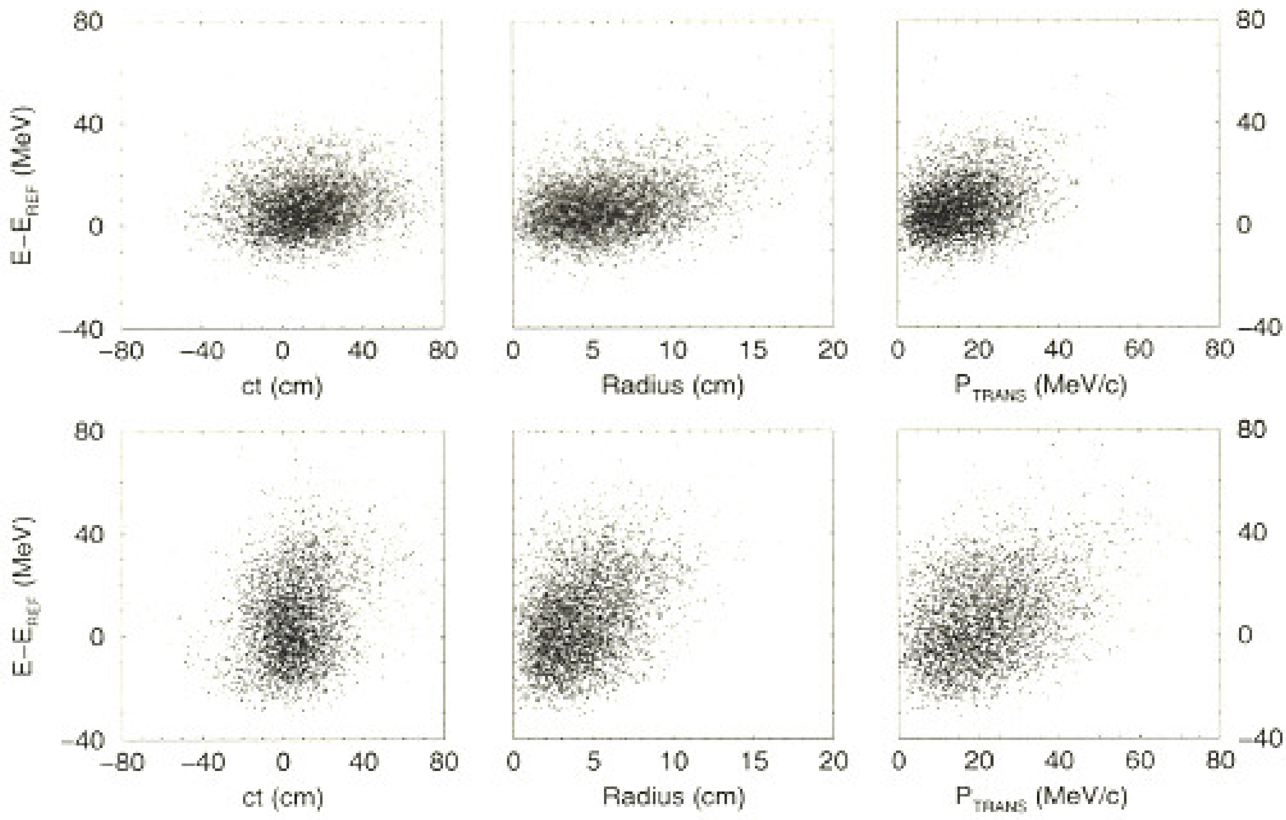
Horizontal axis – ct (cm), vertical – total energy (MeV). Number of turns is shown in each figure.

Matching of the Compressor and RFOFO Ring

- The matching is required first of all because of sharp change of FR from 36.37 to 203.4 MHz.
- Axial magnetic field should increase from 1.75 to 3.5 T.
- 14 m long matching section contains 7 cavities 203.4 MHz, 4.8 MV.
- Magnetic field increases linearly.

Longitudinal Space at the Matching

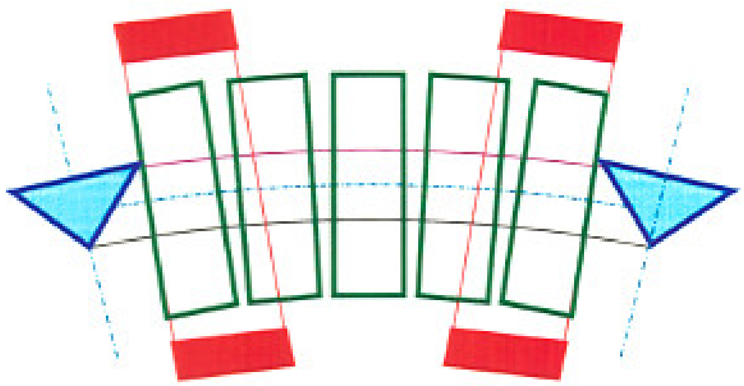
(top – before, bottom - after the matcing).



Transformation in TE plane is nonlinear because wavelength is short.

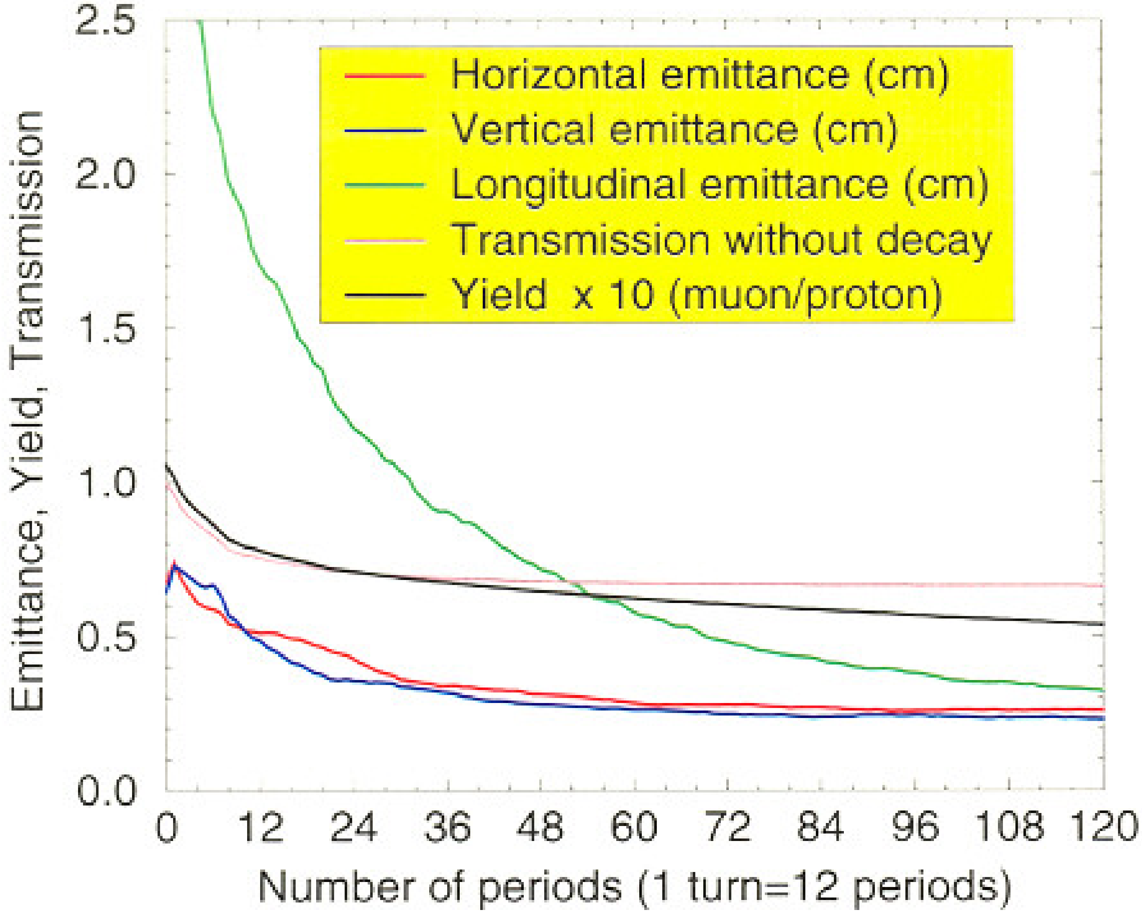
However, at lower frequency the channel is longer, and the bunch length growth because of RE and PE correlations.

RFOFO Ring – Layout and Parameters



Inner radius of coils	77 cm
Outer radius of coils	88 cm
Coil length	50 cm
Current density	± 95.27 A/mm^2
Tilting angle of the coil	± 52 mrad
Accelerating frequency	203.4 MHz
RF harmonic number	25
Accelerating gradient	16 MeV/m
Synchronous phase	33°
Absorber thickness at the center	28.5 cm
Energy loss at the center	12.52 MeV
Gradient of energy loss dE/dy	1 MeV/cm

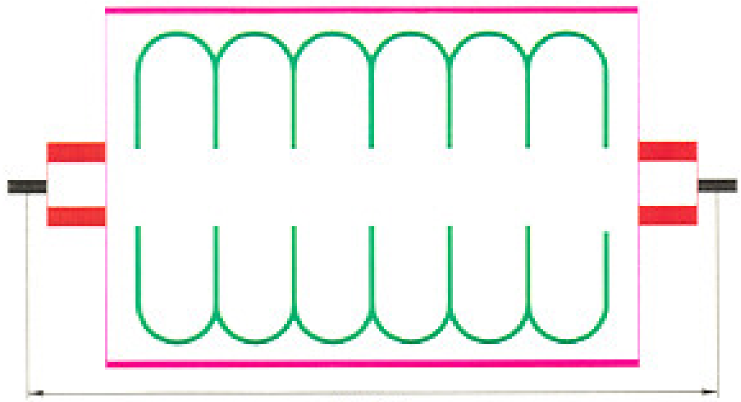
RFOFO Ring: Cooling

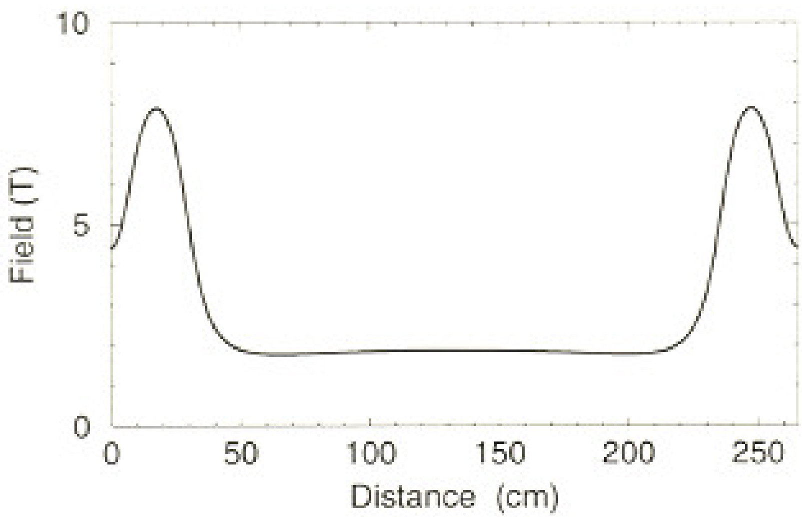


After 10 turns:

Horizontal emittance	2.6 mm
Vertical emittance	2.4 mm
Longitudinal emittance	3.2 mm
6D emittance	21 mm^3
Yield	0.054 μ/p

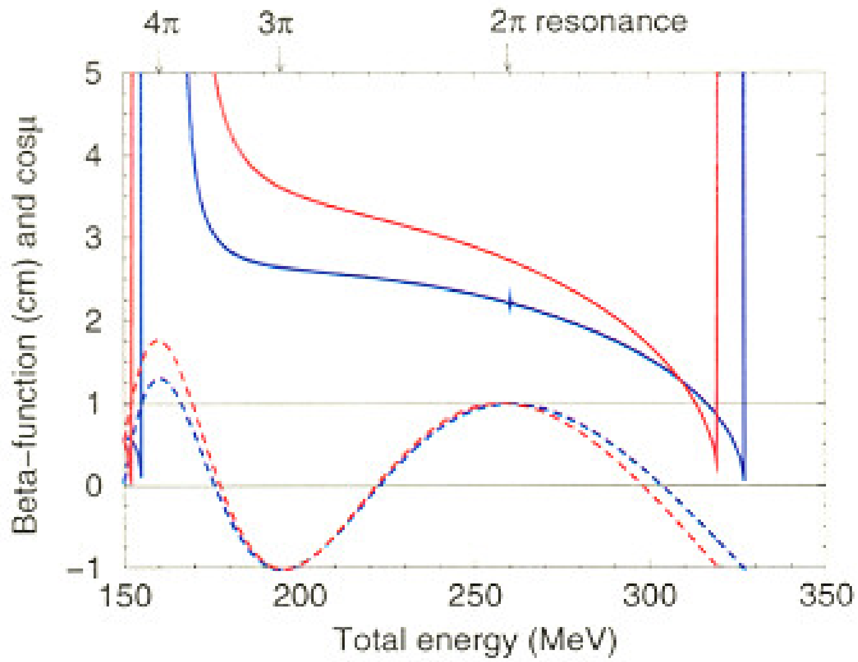
Lithium Lens Cooler



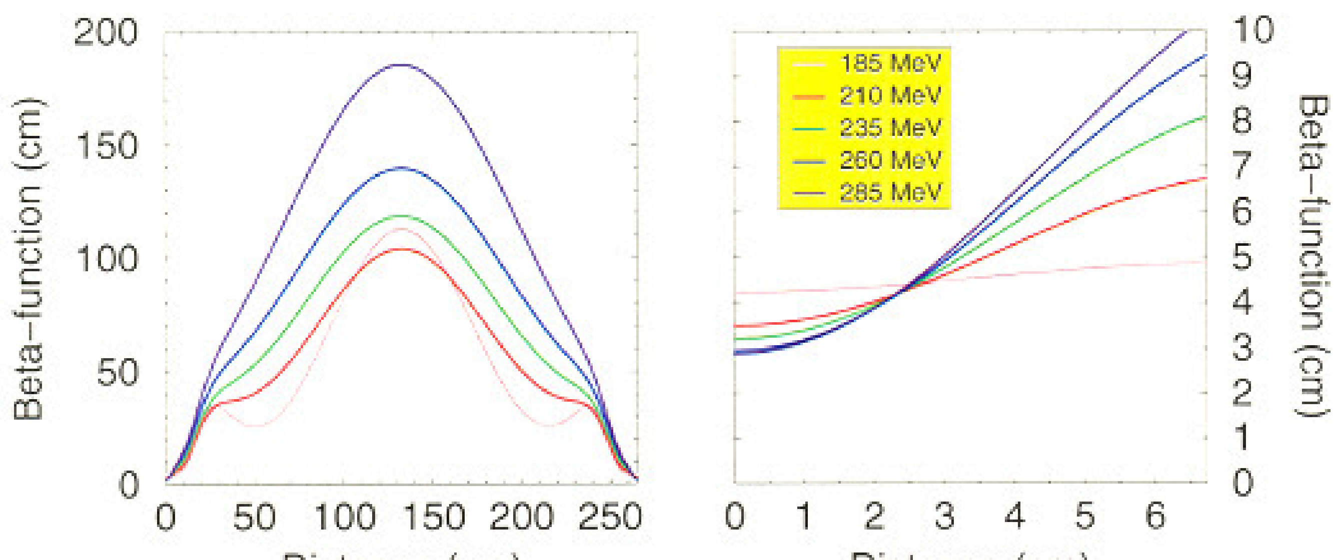


Element	Length (cm)	Radii (cm)	J (A/mm^2)
Li lens	13.45	0/3	355.0
High-field coil	22.45	6/14	84.62
Low-field coil	206.66	69/71	81.69

Li Lens Cooler: Beta-function



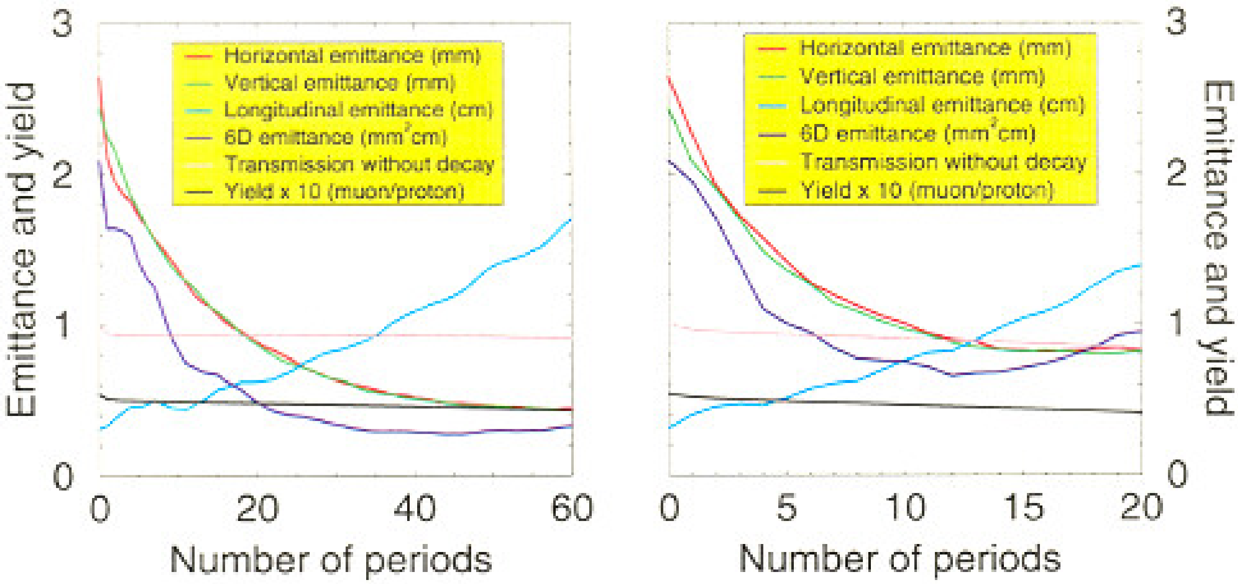
β at the lens center *vs* energy. Blue – hard edge.



β at *vs* z and energy. Left – cell, right Li lens.

Li Lens Cooler: Simulation

(right plot – longer cell, see Table below)



Element	Length (cm)	Radii (cm)	J (A/mm^2)
Li lens	38.49	0/3	512.9
High-field coil	21.81	6/14	99.84
Low-field coil	518.19	69/71	97.58

Parameter	Short period	Long period
Period length (m)	2.65	6.00
No. of periods	35	12
Channel length (m)	92.8	72.0
Trans. emittance (mm)	0.57	0.89
Long. emittance (mm)	10.2	8.3
6D emittance (mm^3)	3.0	6.6
Yield (muon/proton)	0.047	0.046

Conclusion

- Single muon bunch containing about 0.05 muons per incident proton can be obtained by means of described system.
- Its transverse emittance is about 0.6 mm what is large for muon collider.
- More transverse cooing is made difficult by a longitudinal heating.
- Therefore an introducing of emittance exchange is, probably, the most important problem.
- Muon yield is strongly restricted by decay at the bunch compression. Higher accelerating gradient is required to overcome it.
- Another serious restriction is high field matching solenoid. Longer Li lenses should be applied to use their ends with less gradient for the matching.
- Chromaticity???