LEMMA Muon Accumulator

Muon Collider Design Meeting
Beam dynamics meeting #7

2021/june/16, CERN online

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Main Messages

LEMMA stands for Low EMittance Muon Accelerator

1) LEMMA targeted a normalized emittance of **~0.040 µm.rad at 22 GeV**
In simulations we have obtained **~5 µm.rad**
Limited by the smallest ß*= 20 cm at the target, achieved with 500 T/m quads

2) LEMMA targeted a muon population of **10^{10} $\mu^{\pm}$** from 10^{16} e^{+}/s.
In simulations we have obtained :
~ **10^{9}** $\mu^{\pm}$, (Pantaleo's et al. Accumulator)
~ **10^{7}** $\mu^{\pm}$, (Blanco's accumulator)
Due to the emittance limitations we need to raise the positron rate

3) LEMMA combines three beams (e+, μ^{+}, μ^{-}) within a small 3D-space.
The positron bunches have a population of ~ 10^{12} e^{+}.
The effect of a growing (0 to 10^{9}) muon population in the same 3D-space of a high intensity positron beam has not been yet studied.

LEMMA…

2016 : P. Raimondi, M. Boscolo, M. Antonelli, R. Di Nardo published a paper on the possibility of a low emittance muon beam from e^+e^- annihilation.

M. Antonelli, M. Boscolo, R. Di Nardo and P. Raimondi, Novel proposal for a low emittance muon beam using positron beam on target, Nucl. Instrum. Meth. A 807 (2016) 101.
https://www.sciencedirect.com/science/article/abs/pii/S0168900215013364

2016~2018 : Initial studies of the positron beam

M. Boscolo, et. al. https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.21.061005

2018~2019 : A very small work group from INFN, coordinated by Alessandro Variola, was put together to evaluate the LEMMA hypothesis of a muon collider.

D. Alesini, et. al., “Positron driven muon source for a muon collider”, 2019, arxiv 1905.05747.
https://arxiv.org/abs/1905.05747

→ BLANCO, BOSCOLO, CIARMA, RAIMONDI on muon beam studies
→ In particular, Oscar BLANCO (me), muon accumulator rings, since April/2019
Grant INFN, Comissione Scientifica Nazionale 5, Bando 20069

2020 : Muon Accumulation Studies

Design of an accumulator by M. Boscolo et. al. https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.051001
Alternative based on FFA https://arxiv.org/pdf/2011.11701.pdf

Muon Production

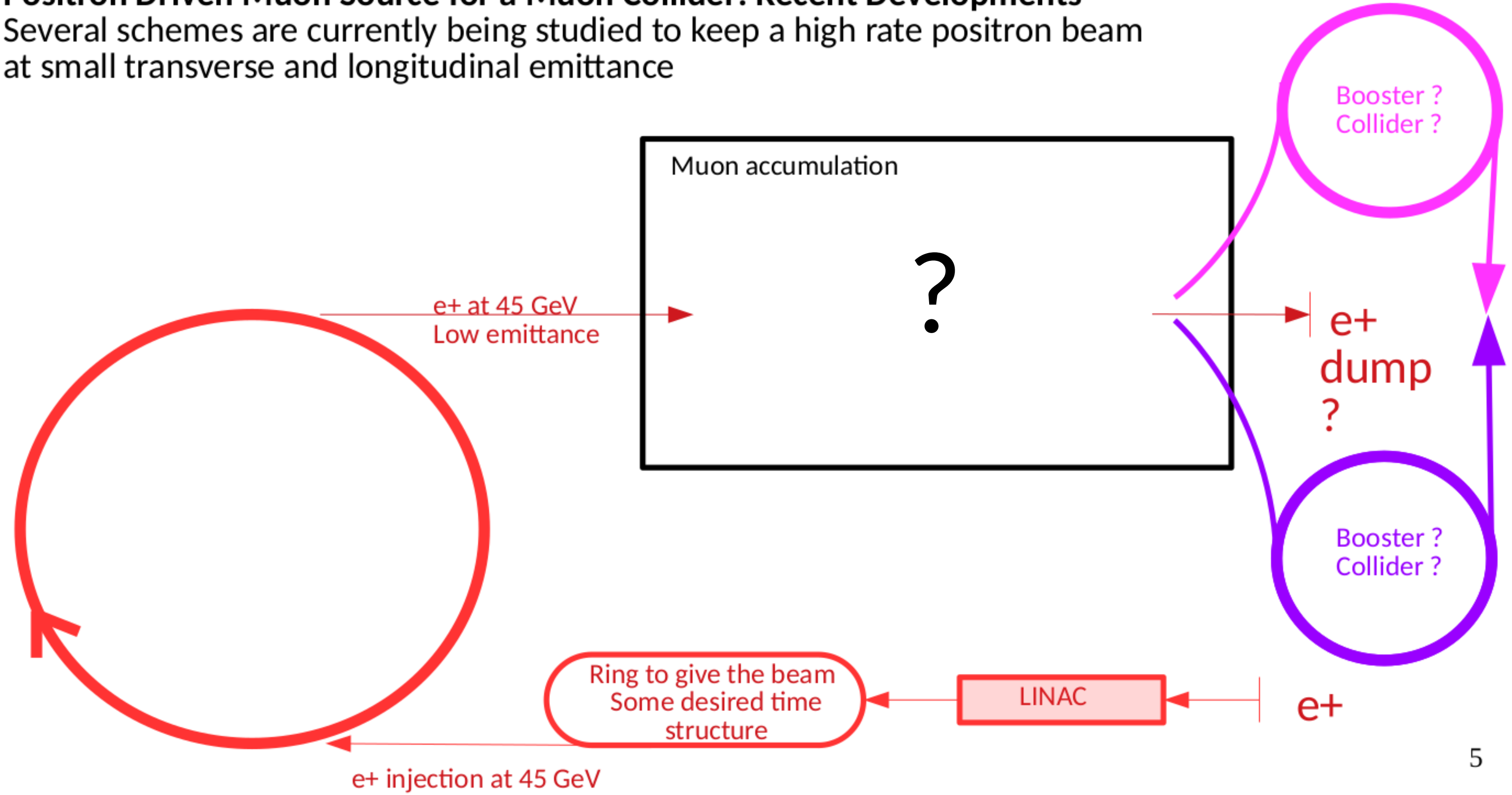
from **direct μ pair production**:

Muons produced from $\mathbf{e^+e^-\to\mu^+\mu^-}$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s}\approx$ 0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

- **Need Positrons of ≈ 45 GeV**
- $\gamma(\mu)\approx 200$ and μ laboratory lifetime of about 500 μs

OPTIONS to create a high intensity muon beam (or the black box content)

M. Biagini,et al. IPAC19. MOZZPLS2,
Positron Driven Muon Source for a Muon Collider: Recent Developments
Several schemes are currently being studied to keep a high rate positron beam at small transverse and longitudinal emittance

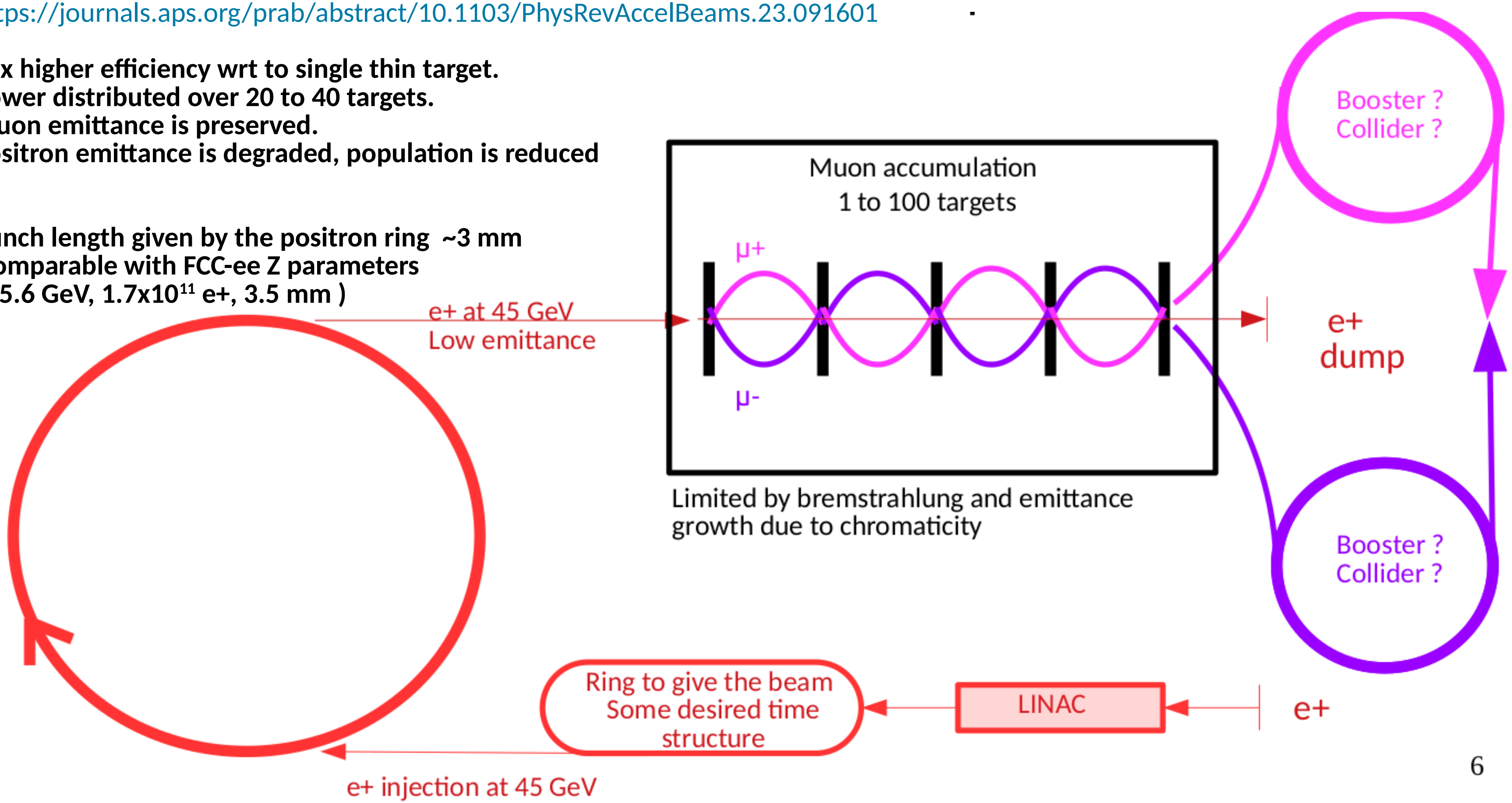


OPTIONS to create a high intensity muon beam

O. Blanco and A. Ciarma. Nanometric muon beam emittance from e+ annihilation on multiple thin targets.
Phys. Rev. Accel. Beams 23, 091601 – Published 10 September 2020
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.091601

10x higher efficiency wrt to single thin target.
Power distributed over 20 to 40 targets.
Muon emittance is preserved.
Positron emittance is degraded, population is reduced

Bunch length given by the positron ring ~3 mm
(comparable with FCC-ee Z parameters
45.6 GeV, 1.7x10^{11} e+, 3.5 mm)

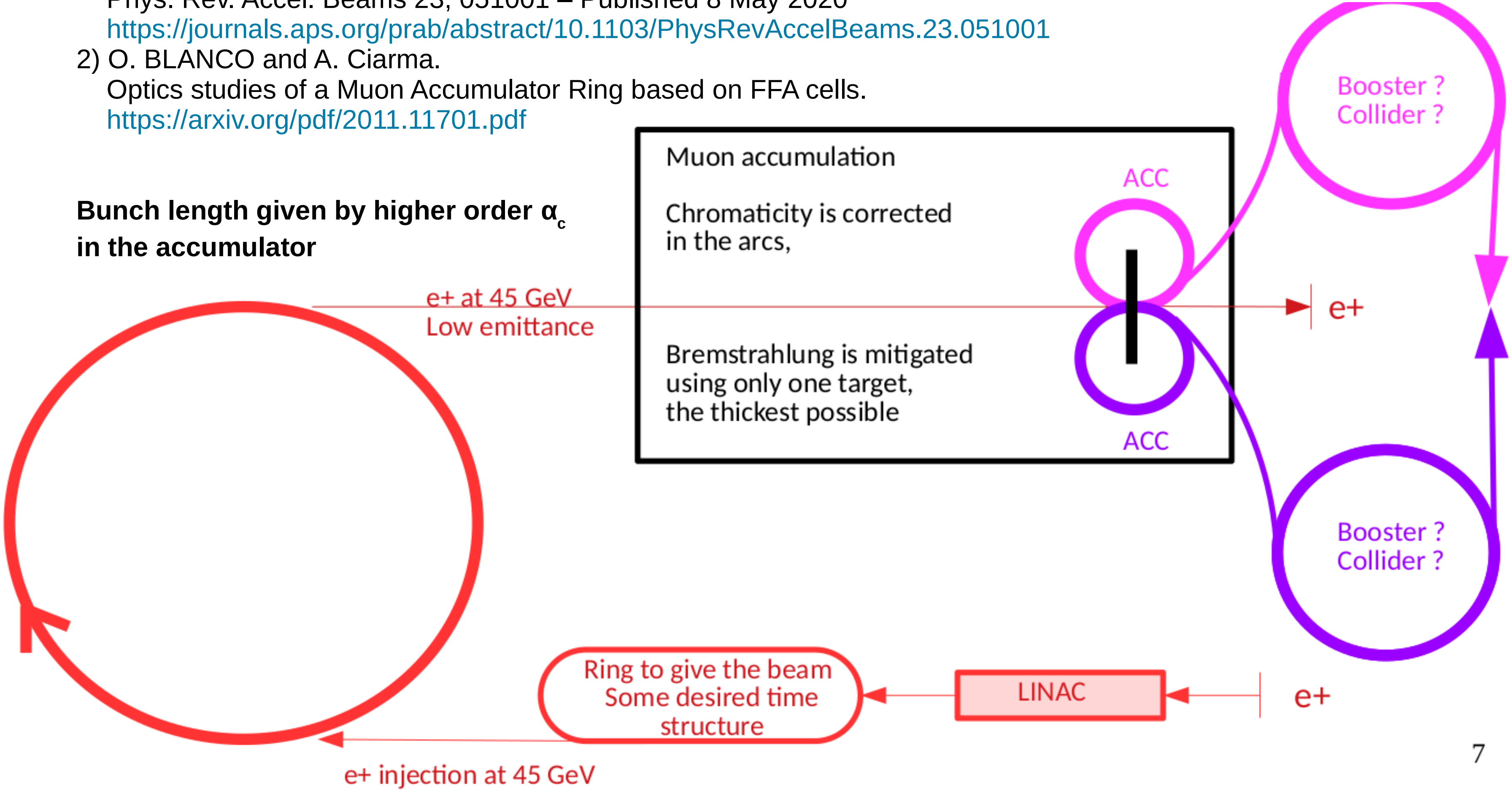


OPTIONS to create a high intensity muon beam

1) M. Boscolo et al. Muon production and accumulation from positrons on target.
Phys. Rev. Accel. Beams 23, 051001 – Published 8 May 2020
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.051001

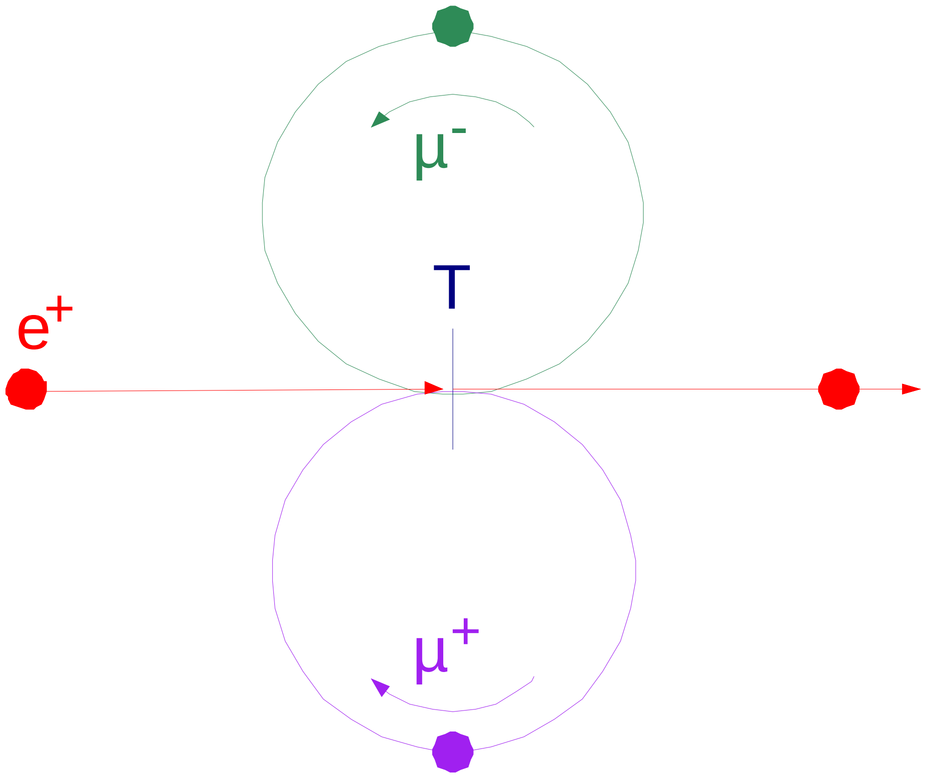
2) O. BLANCO and A. Ciarma.
Optics studies of a Muon Accumulator Ring based on FFA cells.
https://arxiv.org/pdf/2011.11701.pdf

Bunch length given by higher order α_c in the accumulator



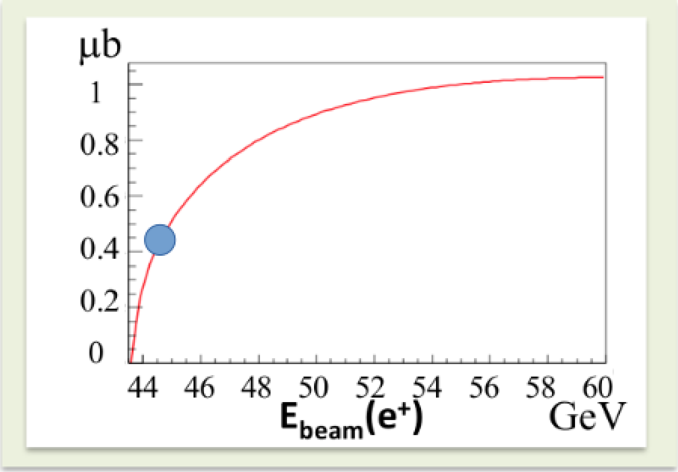
Muon Accumulator Rings

The muon accumulator rings collect and recirculate the muons produced on every positron bunch passage, increasing the muon bunch intensity

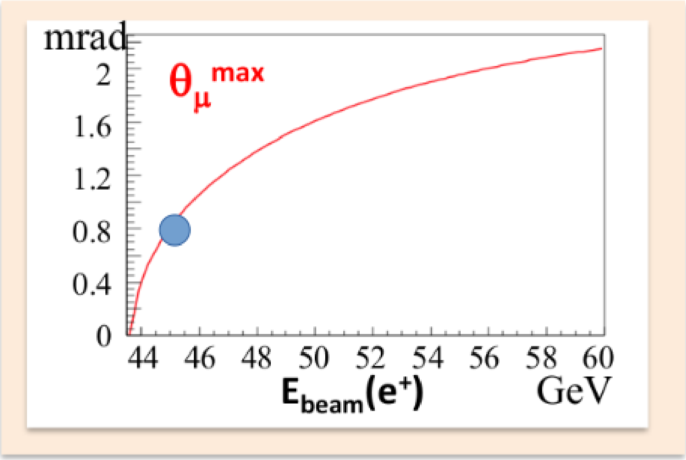


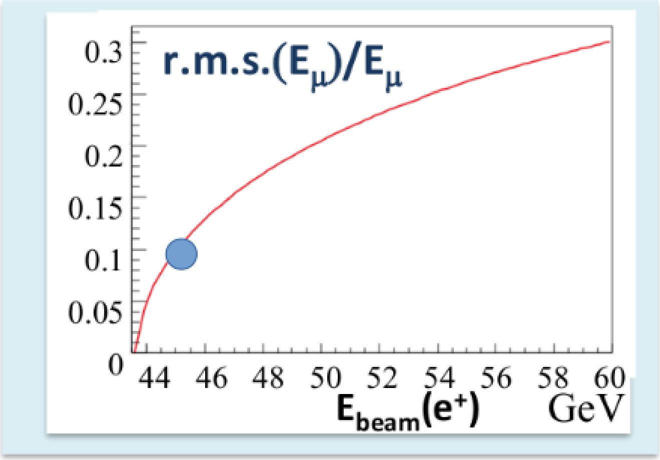
Muon transverse and longitudinal emittance depend on the e+ beam energy and size

$\sigma(e^+e^- \to \mu^+\mu^-)$

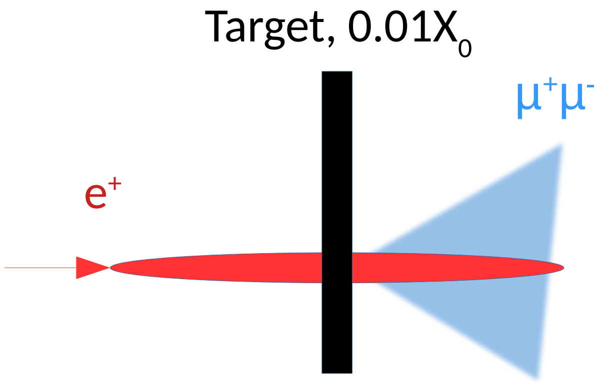


The value of sqrt(s) (*i.e.* $E(e^+)$ for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread





Muon Beam Parameters



- **Transverse emittance**
  $\varepsilon_{X,Y\,\mu} \approx \sigma_{X,Y,L\,e+}\ .\ 0.5$ mrad

- **Longitudinal emittance**
  $\varepsilon_{L\,\mu} \approx \sigma_{L\,e+}\ .\ 1$ GeV

- **Efficiency for $0.01X_0$ of material ≈ 10^{-7} μ pairs/e^+**

- Beam size at production is given by the positron beam
  $\sigma_{X,Y,L\,\mu} = \sigma_{X,Y,L\,e+}$

  We aim at producing a small positron beam size and bunch length

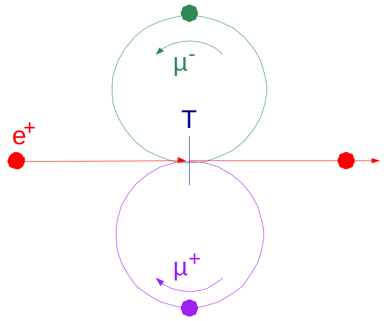
- Beam divergence and energy spread from kinematics
  $\sigma'_{X,Y\,\mu}\,(E_{e+}) \approx$ 0.1 to 0.5 mrad for E_{e+} ~ 43.7 to 46 GeV
  $\sigma_{dE/E\,\mu}\,(E_{e+}) \approx$ 1% to 20% for E_{e+} ~ 43.7 to 46 GeV

Requirements 2018 and status 2020

These requirements correspond to a muon bunch of 10^9 μ with ε_n = 40 π nm

M. Boscolo et al., “Muon accumulator ring requirements for a low emittance muon collider from positrons on target”, in Proc. 9th Int. Particle Accelerator Conf. (IPAC2018), MOPMF087. Vancouver, BC, Canada. http://accelconf.web.cern.ch/ipac2018/papers/mopmf087.pdf

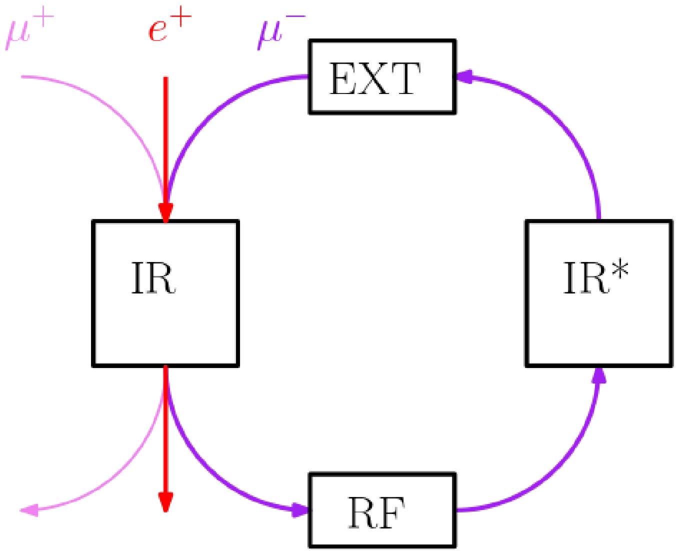
	Required 2018	**Optics Design Status**	
Small Length	60 m (1 IP)	230 m (2 IPs)	To mitigate muon decay
Large Dynamic Ap.	±20%	**±5%**	μ+μ- Production efficiency and energy spread are proportional
Low ß*	1 cm	**20 cm**	To avoid emittance growth from multiple scattering
Time of accumulation	1000~2000 turns	100~200	To get ~10^9 muons in one bunch in less than 0.4 ms (120km)



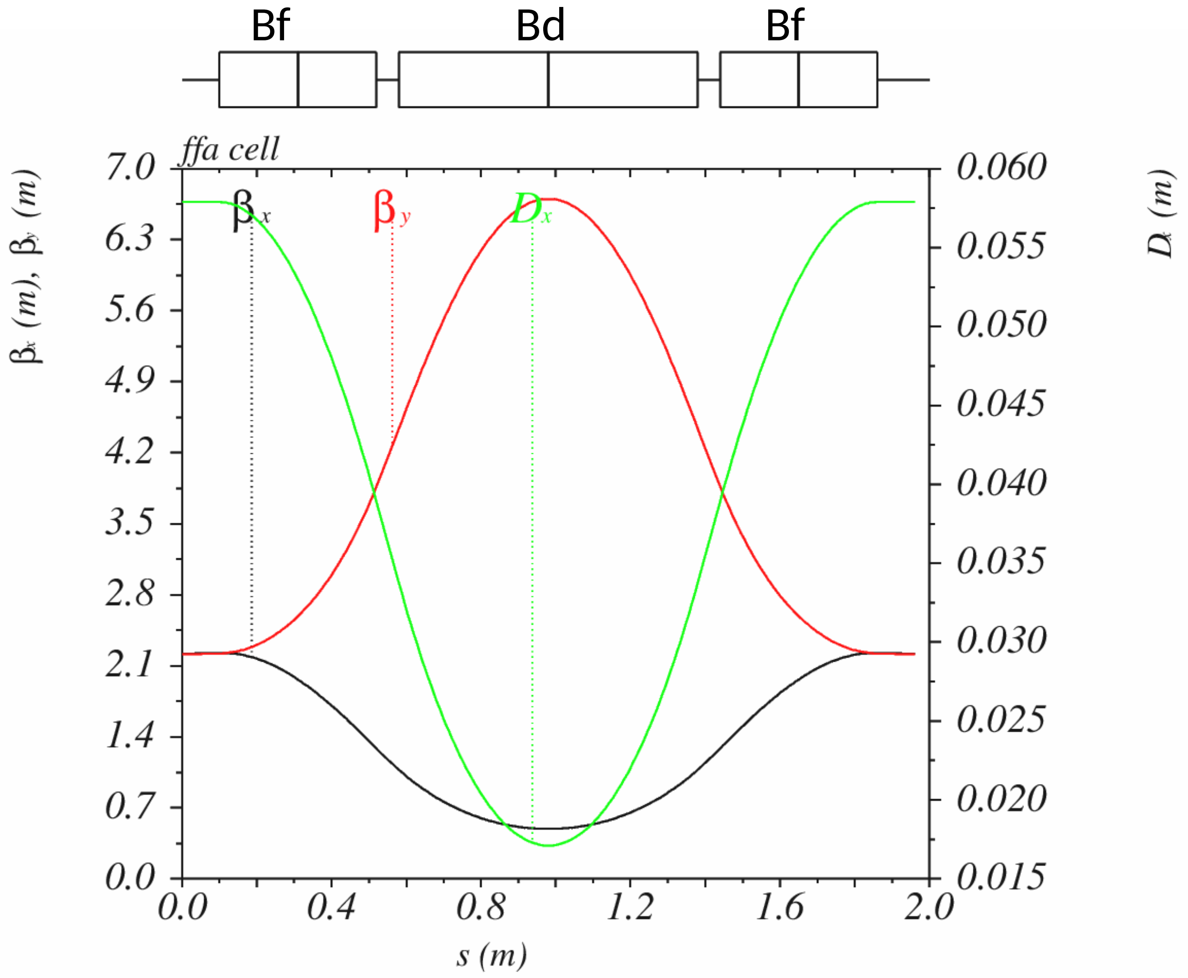
Muon Accumulator Sections

We divide the design into sections to systematically check if they achieve the requirements :

We need :
- A high momentum acceptance arc cell for the arcs
- A zero dispersion cell connecting the arcs with straigths sections
- An Interaction Region
- A radio frequency cavity region
- An extraction region



ARC CELL (more than 10% momentum acceptance)



ARC

Based on the results of A.V. Bogomyagkov. "Weak focusing low emittance storage ring with large 6D dynamic aperture based on canted cosine theta magnet technology". arxiv. 1906.09692v1
https://arxiv.org/pdf/1906.09692v1.pdf

Adapted using the Simplex method in MAD-X varying dipole, quadrupole length and strengths to get :
Minimum circumference
Low dispersion (to have magnet apertures circa 2 cm)
Minimum chromaticity
Minimum α_c
Magnet peak field of 14 T

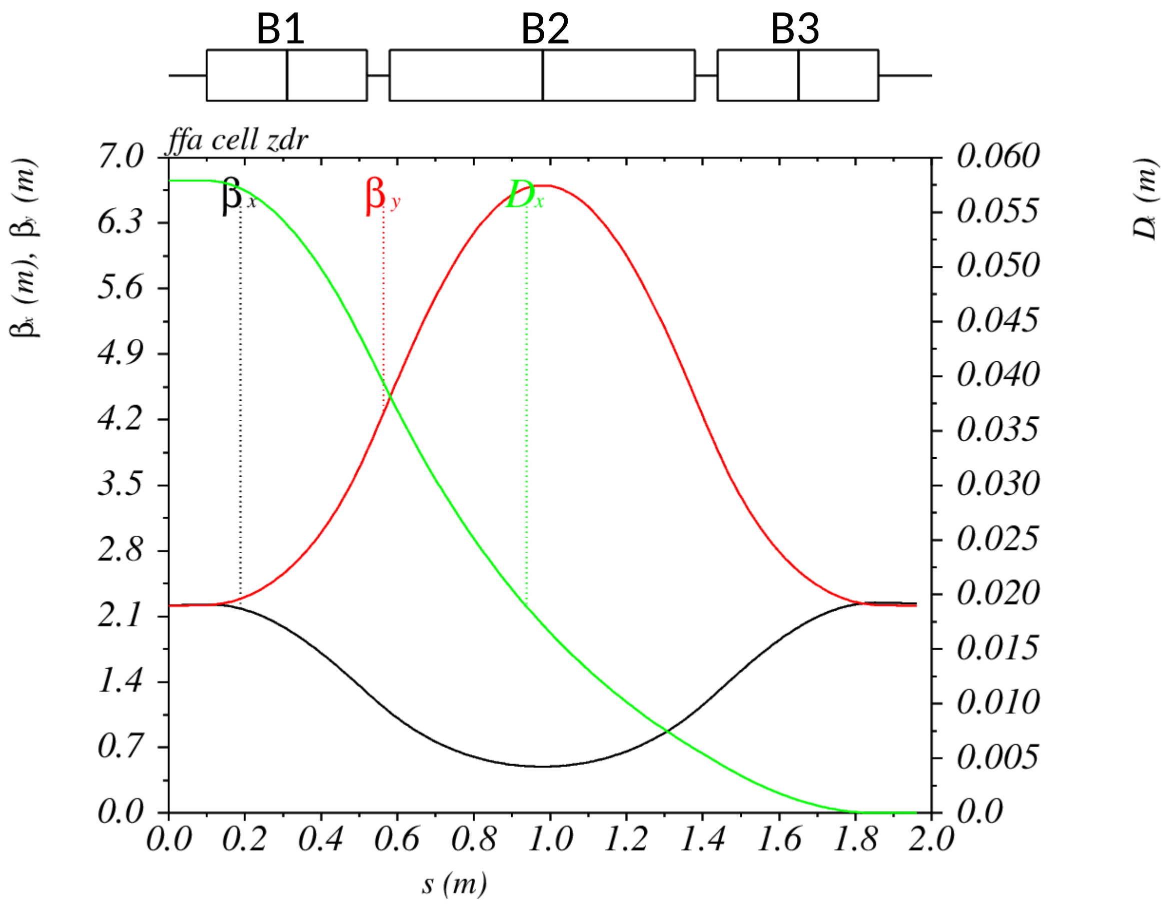
Cell phase advance (twopi units)
H/V tune of 0.1/0.3

Magnets (possibly canted cosine theta)
For a 22.5 GeV muon beam

Bf -3.1 T, 238T/m, 6.3kT/m^2
Bd 12.0 T, -183T/m, -10.7kT/m^2

Good field region of ± 1cm
Dispersion: 0.06m
Momentum Acceptance >10%
α_c = 0.3 x 10^{-3}

CELL to connect with insertions (IRs, rf and extraction)



ARC ending in zero dispersion

Trying to insert a region for the target without loosing momentum acceptance

Magnets below 14T (canted cosine theta)

B1	0.0 T,	238T/m,	8.5kT/m^2
B2	1.2 T,	-183T/m,	-13.4kT/m^2
B3	4.1 T,	238T/m,	0.0kT/m^2

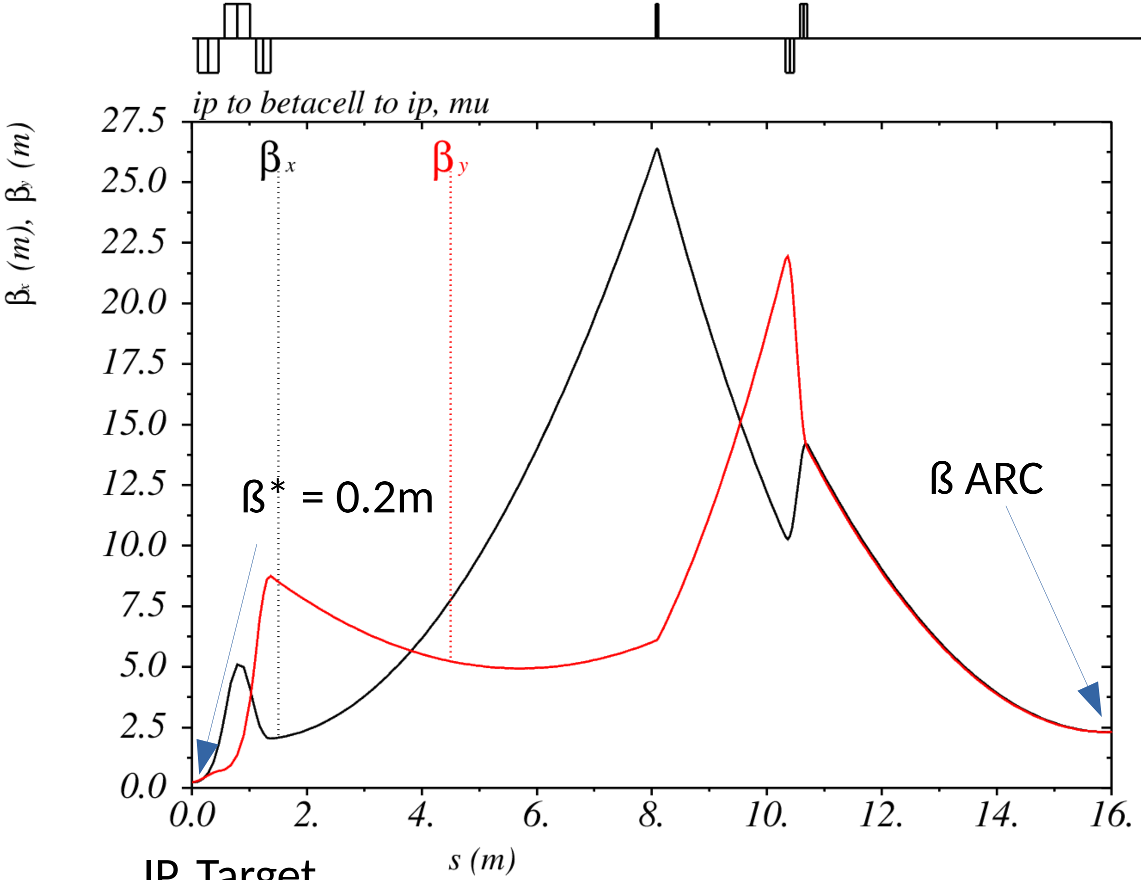
Good field region : 1cm
Dispersion: 0.06m

Momentum Acceptance >9%

Interaction Region (L*= 10cm, ß* = 20 cm over ±5% energy spread)

Inner Triplet
circa 500 T/m

Second Triplet
100 ~ 200 T/m



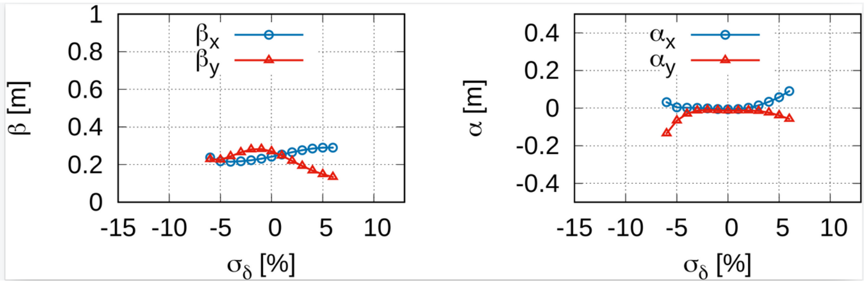
IP, Target

Interaction Region (Minimize ß*)

The Interaction Region has been designed as a first order apochromatic lattice that reduces the ß functions from 2 m to 0.2 m over +/-5% energy spread.

C. A. Lindstrøm and E. Adli, "Design of general apoc-hromatic drift-quadrupole beam lines", Phys. Rev. Accel. Beams 19 (2016)
https://link.aps.org/doi/10.1103/PhysRevAccelBeams.19.071002

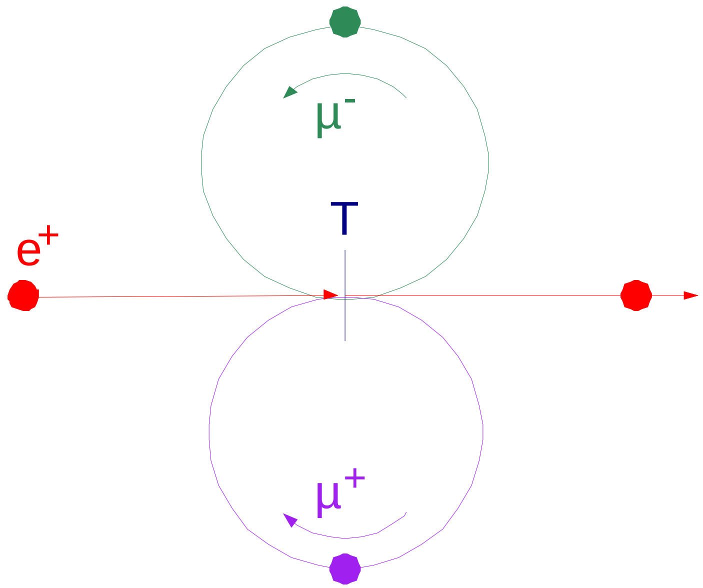
Inner Triplet Magnets at ~2T
525T/m (CLIC QD0 prototype)

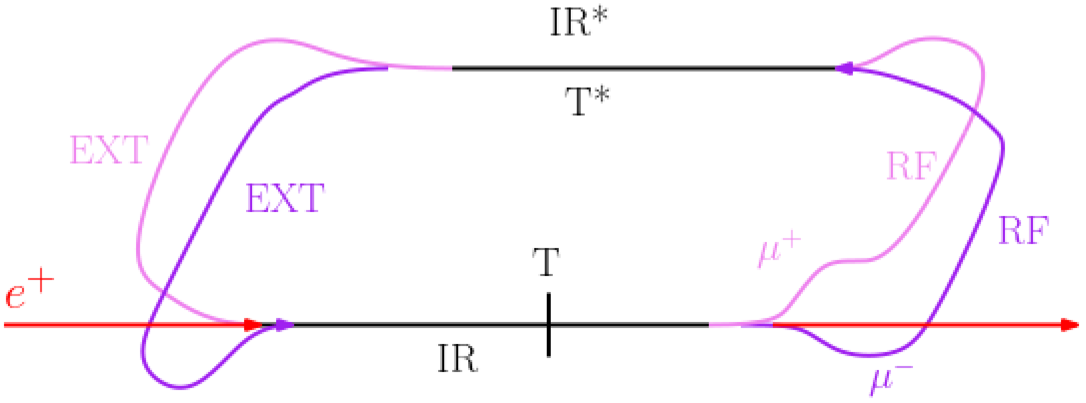


Interaction Region with Vertical Separation (1/2)

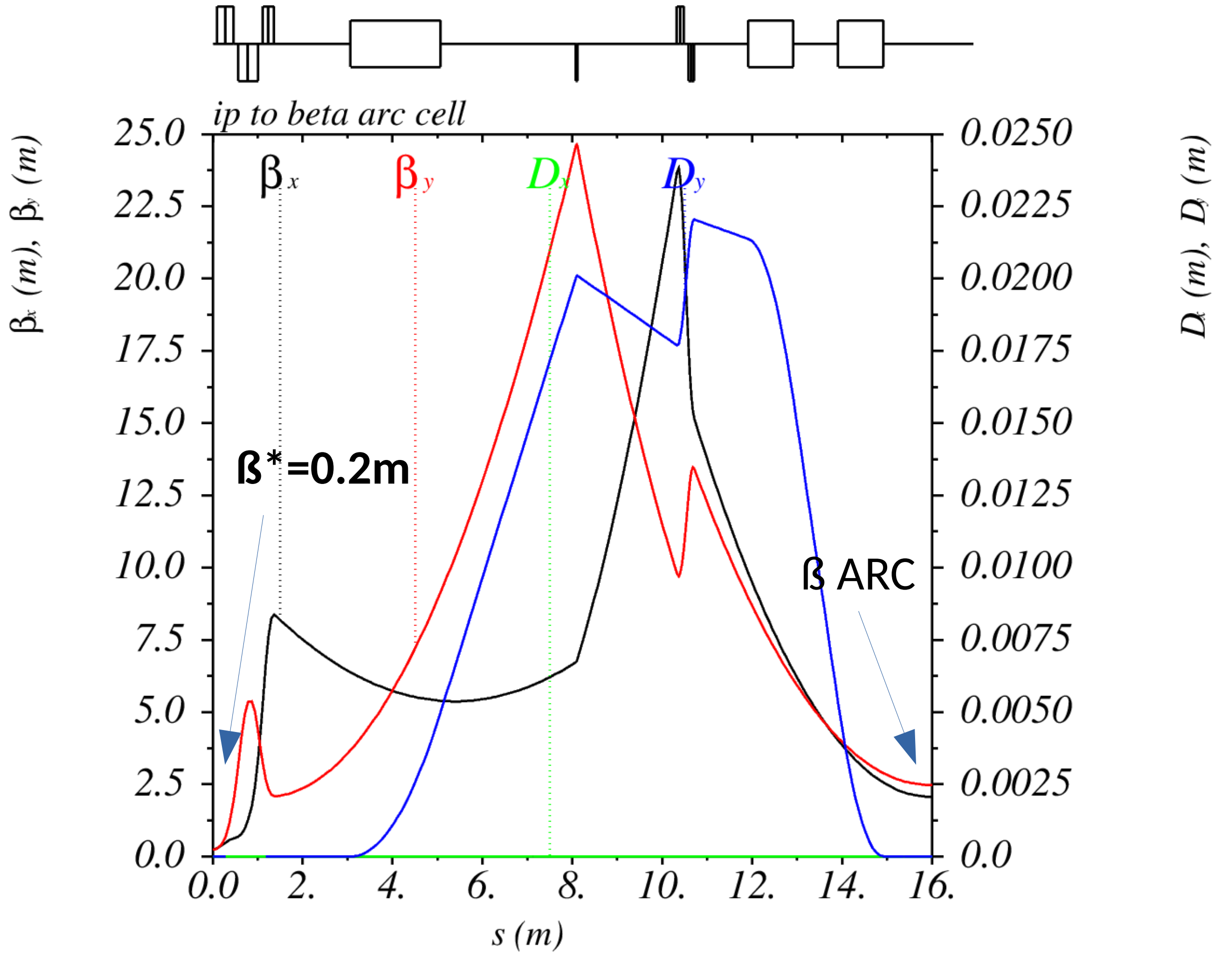
Separating the beams in the vertical plane could have several advantages

Reduce the footprint of the machine because both rings can be one on top of the other.
Allows to consider a second (or more) Interaction Region IR* for a possible second target T* given a second e^+ source, therefore,
- Reducing the distance from IP to IP
- Reducing the need for higher peak magnetic fields in the arc magnets





Interaction Region with Vertical Separation (1/2)



Interaction Region (Minimize ß*)

Inner triplet Magnets at ~2T

525T/m (CLIC QD0 prototype)
ß* = 20 cm, L* = 10 cm
Aperture Radius : 4mm
Low contribution to chromaticity
(Almost an Apochromatic design)

Second triplet magnets

100~200 T/m
FCC-like quads

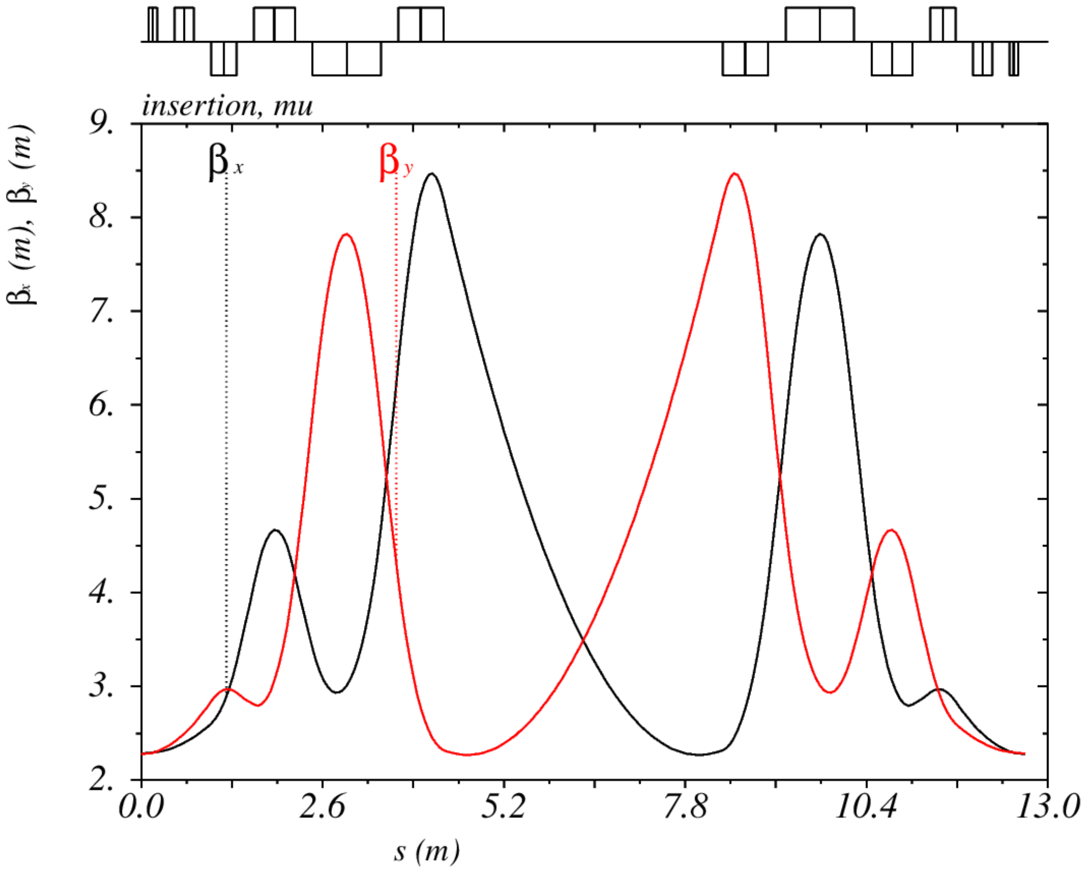
<u>Vertical dipoles < 1T</u>

To separate/combine the beams
To Minimize the positron energy loss (circa 20 MeV)
To Minimize the photon critical energy (circa 1~MeV)

We have used in total 3 vertical dipole magnets to separate the beams by more than 5 cm while cancelling vertical dispersion and its derivative with respect to s

Straigth sections for RF and Extraction Kicker

4 m for RF of ext. kicker



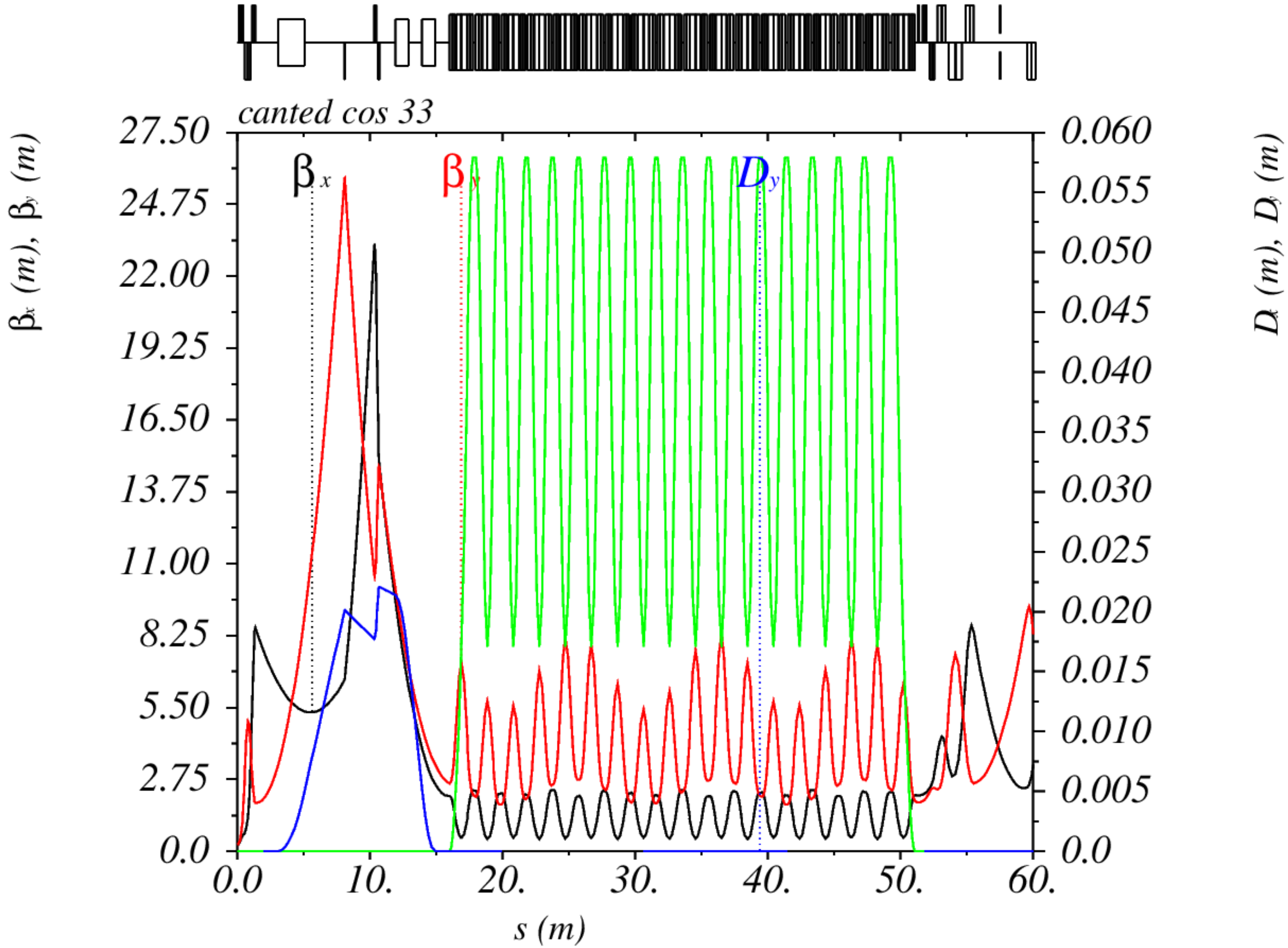
Insertion for RF or Extraction Kicker 100~200T/m

(Low contribution to chromaticity using the apochromatic design concept)

Lindstrom. Design of general apochromatic drift-quadrupole beam lines. PRAB 19, 071002, 15/JUL/2016

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.071002

Quarter of a ring …



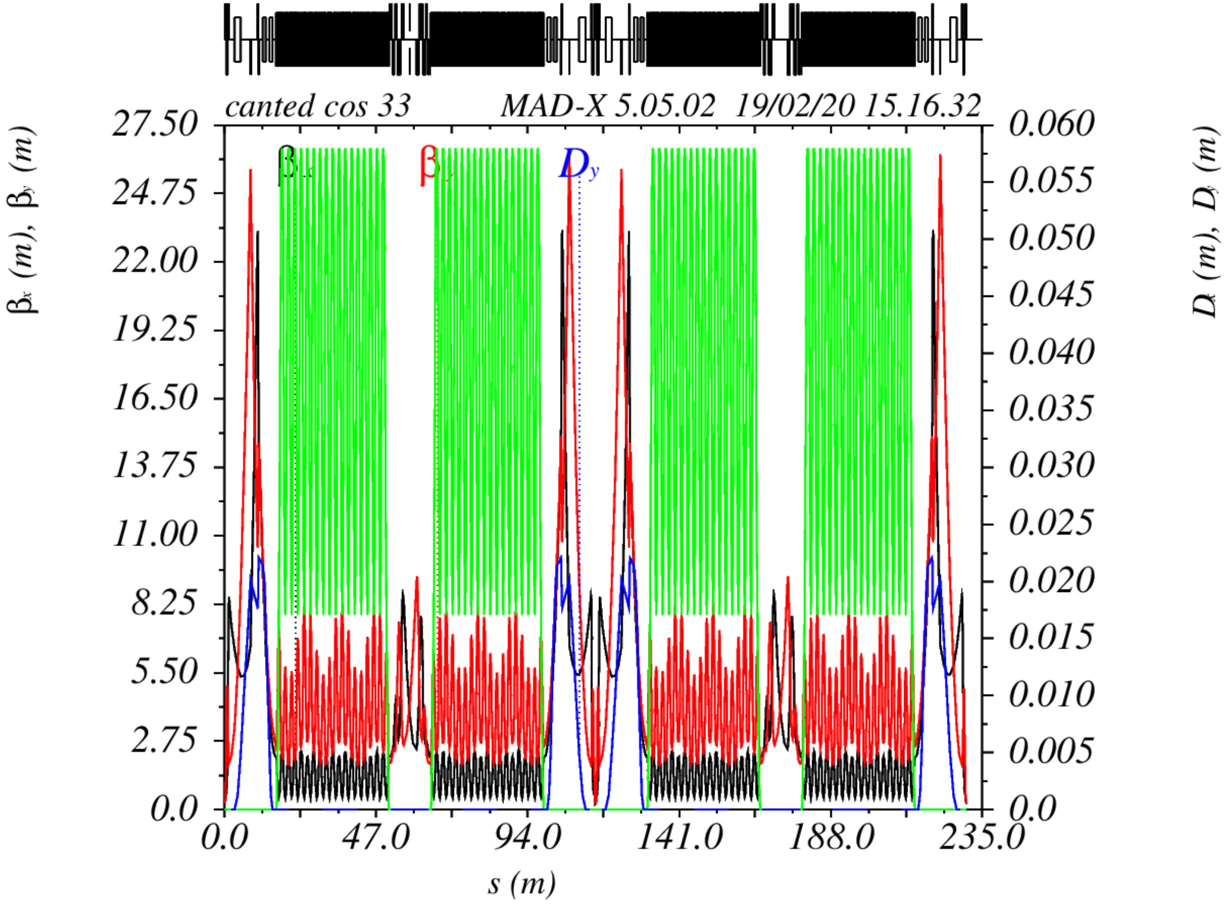
IR + ARC zdr + ARC + insertion(RF)

The energy acceptance is limited by the Interaction Region apochromatic design.

Circumference and aperture are limited by the arc peak field, assumed to be about 14 T for canted cosine type magnets.

The minimum bunch length is limited by the arc.

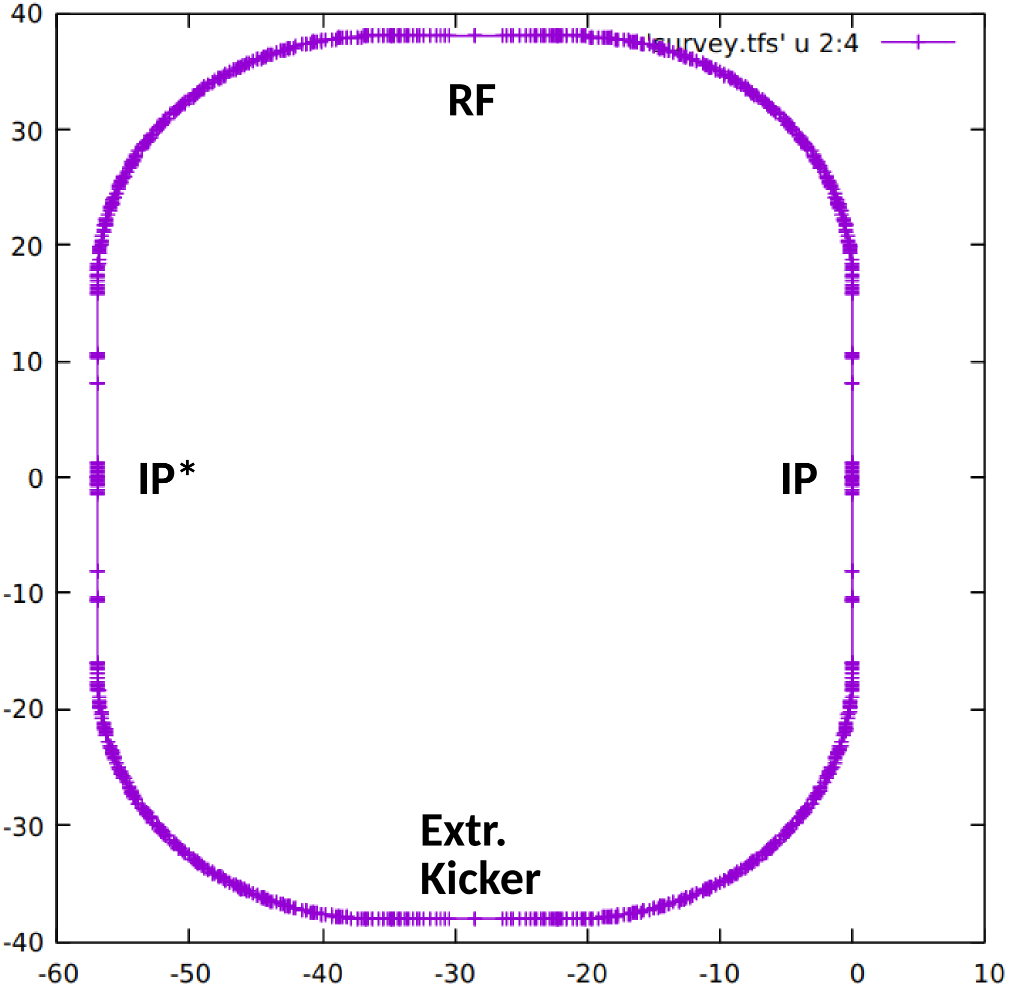
linear optics

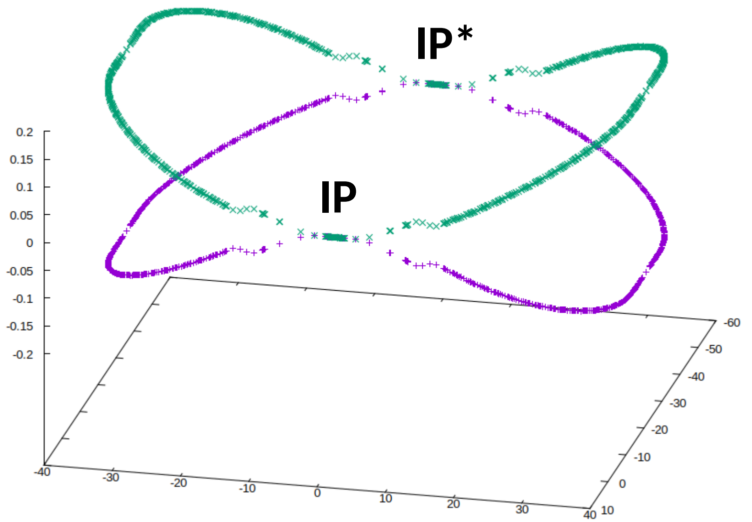


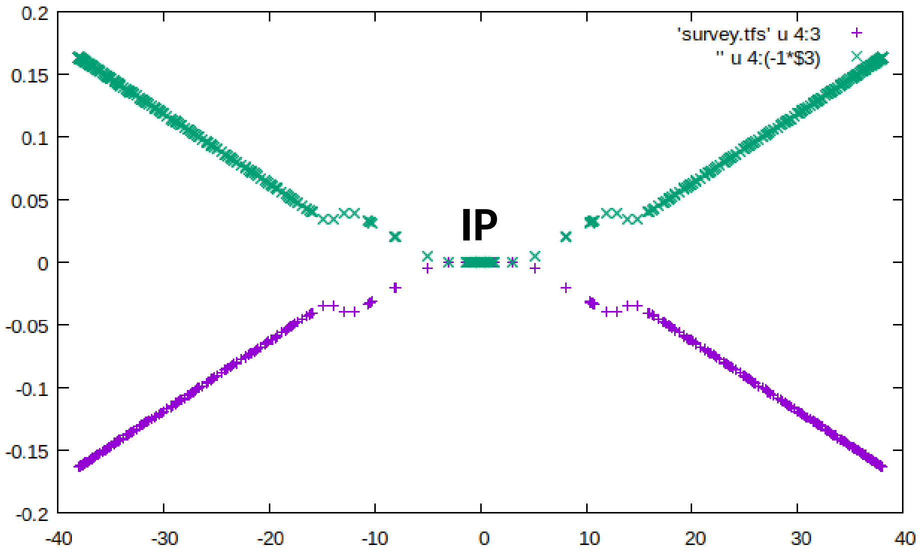
Magnets below 14T
Bd -3.1 T, 238T/m, 6.3kT/m^2
Bf 12.0 T, -183T/m, -10.7kT/m^2
α_c = 0.3 x 10^{-3}
L = 231.1 m, FFA + 2IR + RF + extr.
IR β^* = 0.2m (+/-5% e.spread)

Aperture Radius : 4mm IR + 1cm else
Dispersion: 0.06m*5% = 3 mm,
Cavity, h=600, 782MHz, 150MV
→ Mom. Accept ~ +/-5%

Survey in meters



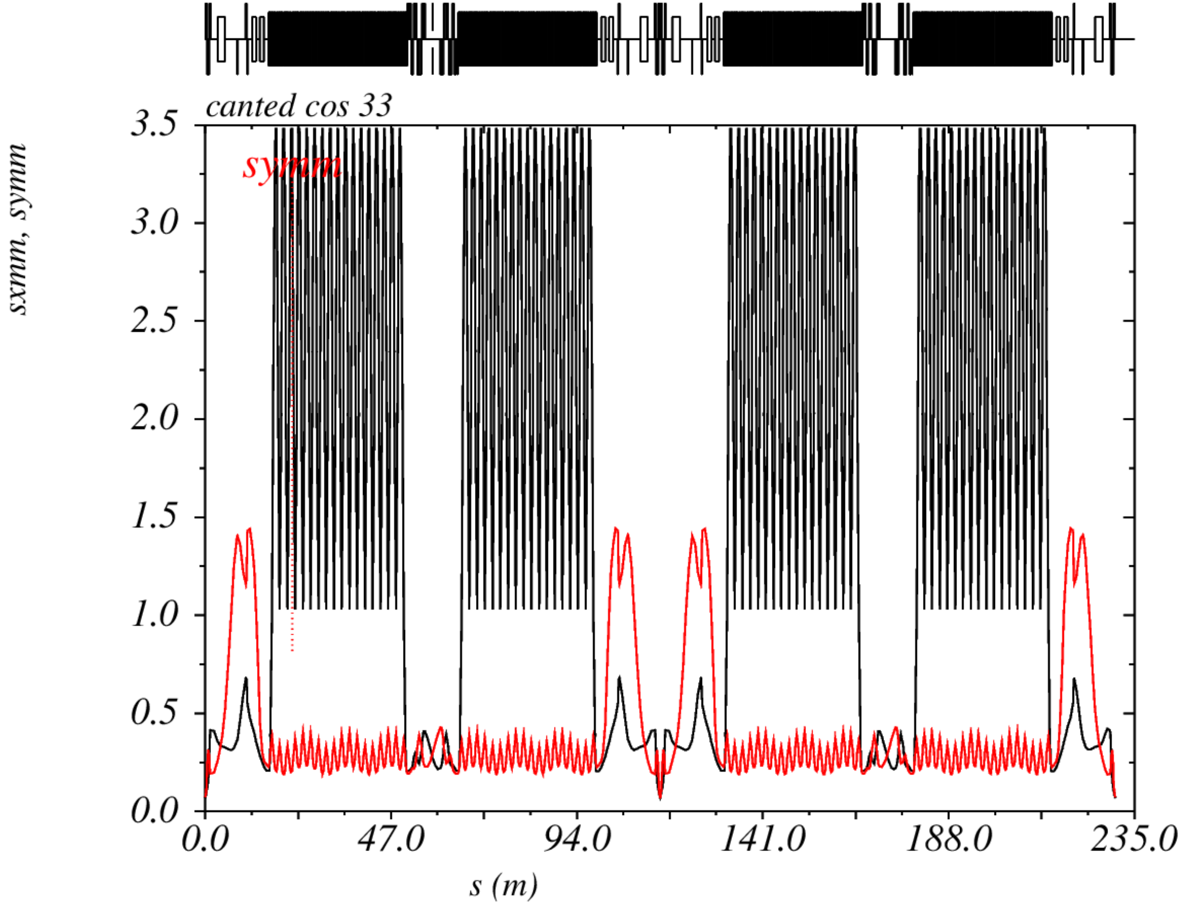




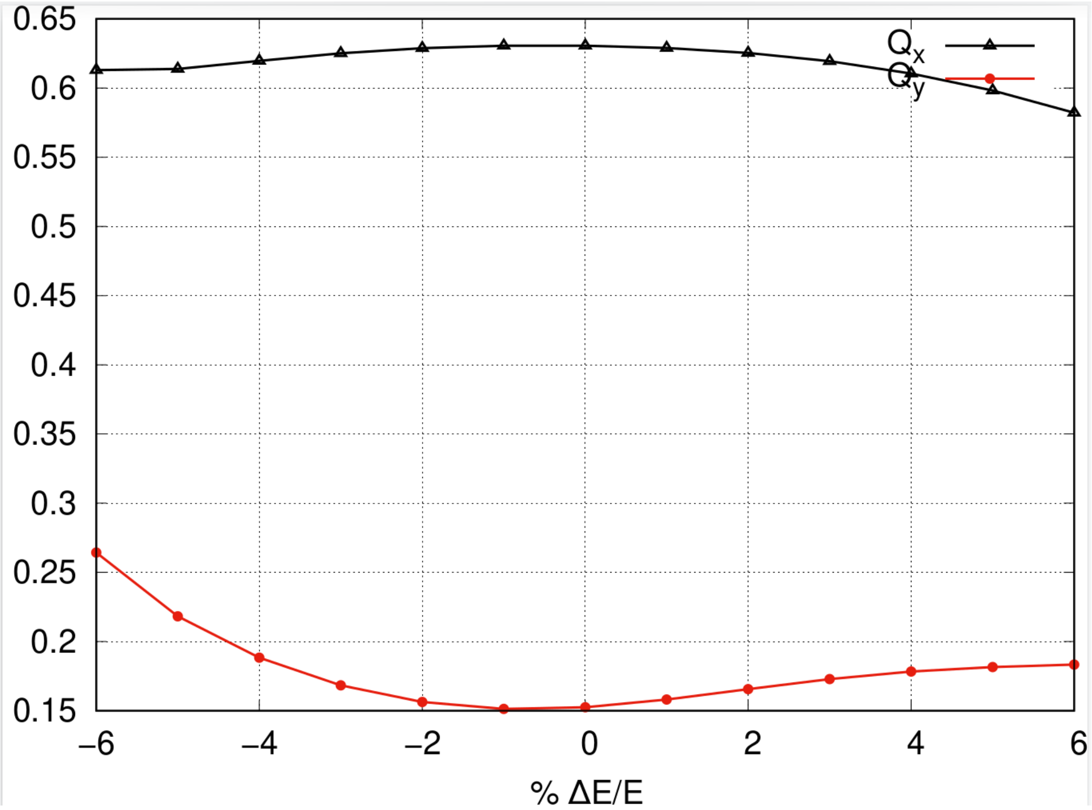
Beam size

For a normalized emittance 5 π μm (220 x 20 π nm), γ = 220, e. spread = 6%
Beam size in mm.

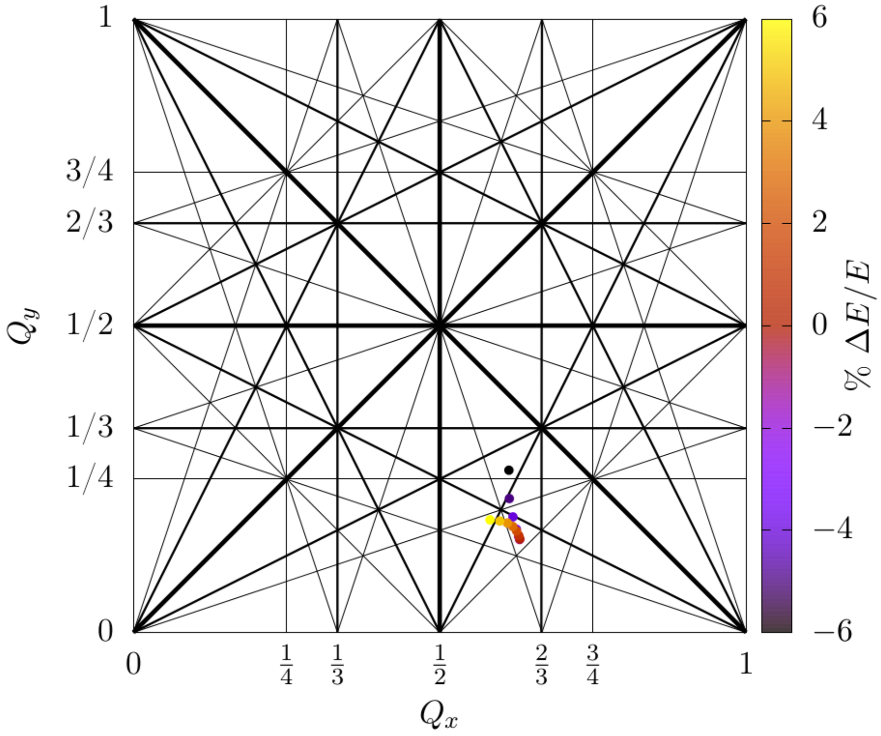
$$\sigma = \sqrt{\epsilon\beta + \eta^2\delta^2}$$



Tunes

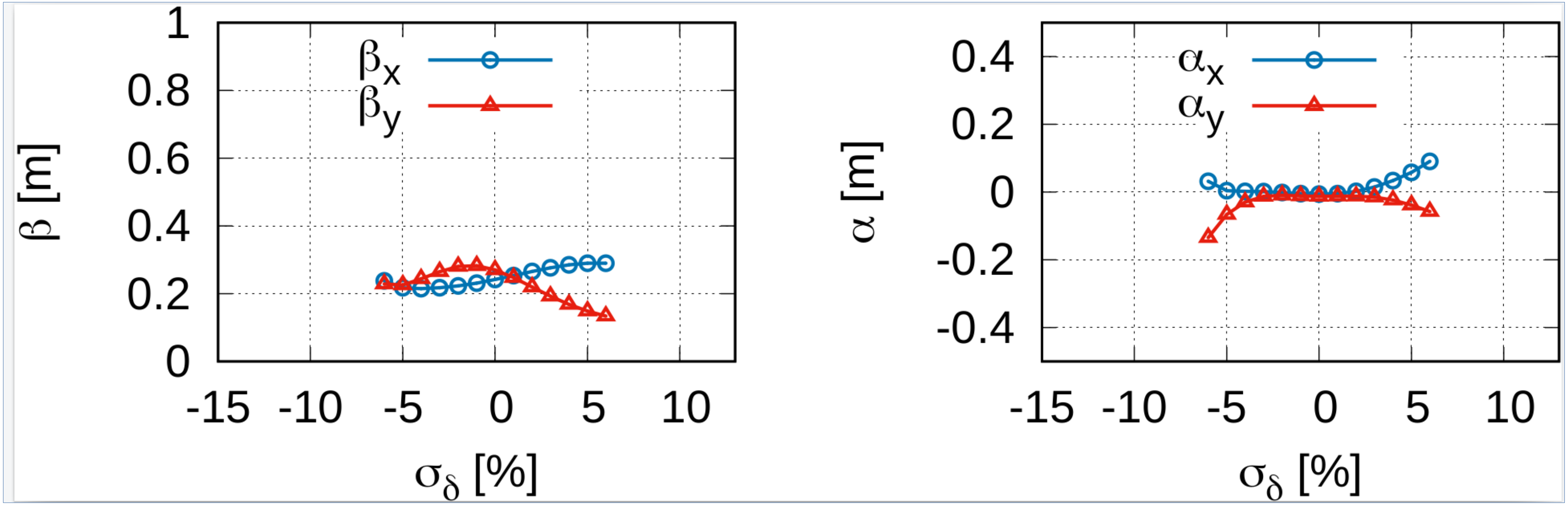


0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
−6
−4
−2
0
2
4
6
% ΔE/E
Q_x
Q_y



Q_y
Q_x
1
3/4
2/3
1/2
1/3
1/4
0
0
$\frac{1}{4}$
$\frac{1}{3}$
$\frac{1}{2}$
$\frac{2}{3}$
$\frac{3}{4}$
1
6
4
2
0
−2
−4
−6
% ΔE/E

Beta and alfa at the IP



Minimum Emittance in simulations

- Transverse (beamsize x divergence)

  geometrical = 25 π nm rad = 50 μm x 0.5mrad

  normalized = 5 π μm rad

  Achieved using quadrupoles of 500 T/m at the IP to create a ß* = 20 cm over ±5%.

  (first order apochromatic)

- Longitudinal (E. spread x bunch length)

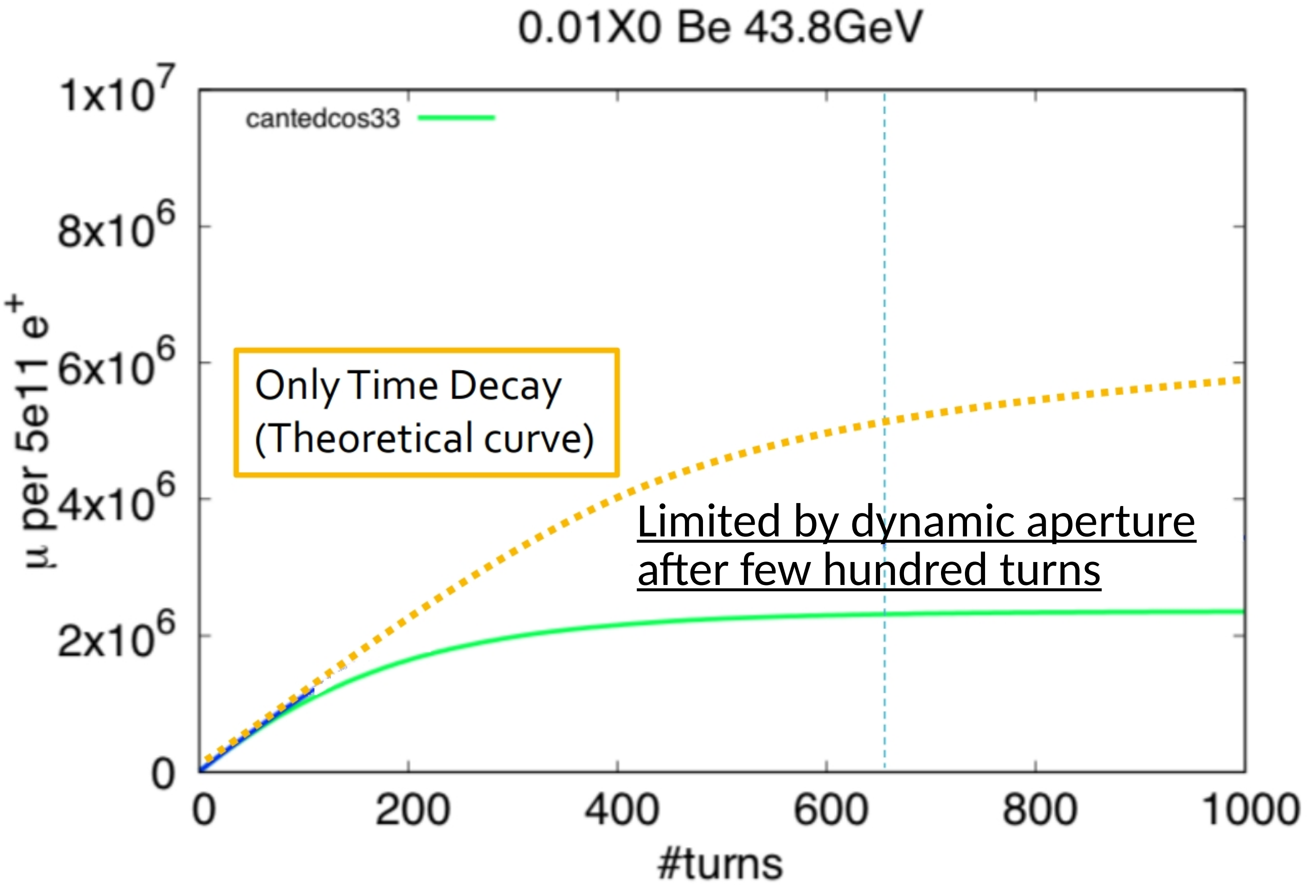
  10 π GeV mm = 0.5 GeV x 2 cm (from BLANCO's accumulator)

  3 π GeV mm = 1 GeV x 3 mm (e+ beam at 43.72 GeV and multitarget line)

  In a multitarget line the minimum bunch length is given by the positron beam.

  In the accumulator the minimum bunch length is limited by the 2nd order α_c,

Muon Accumulation



* Andrea Ciarma, MUFASA. Technical Note INFN-20-07/LNF, 2020. IINFN-LNF), Frascati, Italy.
http://www.lnf.infn.it/sis/preprint/detail-new.php?id=5456

Parameter Table

Parameter	Unit	Requirement	FFA design
Energy	GeV	22.5	21.9
Relativistic Gamma Factor	–	212.95	207.272
Length	m	60	230
Revolution Frequency	MHz	5	1.30275
Revolution Time	μs	0.2	0.7676
Energy Loss per Turn	MeV	–	3×10^{-6} (S.R.), ~ 10 (thin target)
Energy Acceptance	%	± 20	± 5
Number of Bunches	–	1	1
Bunch Population	–	10^9	2×10^6
Normalized Emittance	π μm	0.04	5 (at production), 10 (end of accumulation)
Number of IPs	–	1	1+1*
Cycles of accumulation	–	1000	< 400
Nat. Chrom. x/y	–	–	-26.8 / -29.4
Qx/Qy/Qs	–	–	25.6306 / 10.1525 / 0.0137
β^*_μ at the IP (target location)	cm	1	20
Distance from IP to first magnet, L^*	cm	–	10
α_C	–	very small	3×10^{-4}
Bunch length	mm	3	100
Straight Sections	–	–	4 (2 IPs, RF, extraction)

Issues :

1) ß* = 20 cm → 1 cm

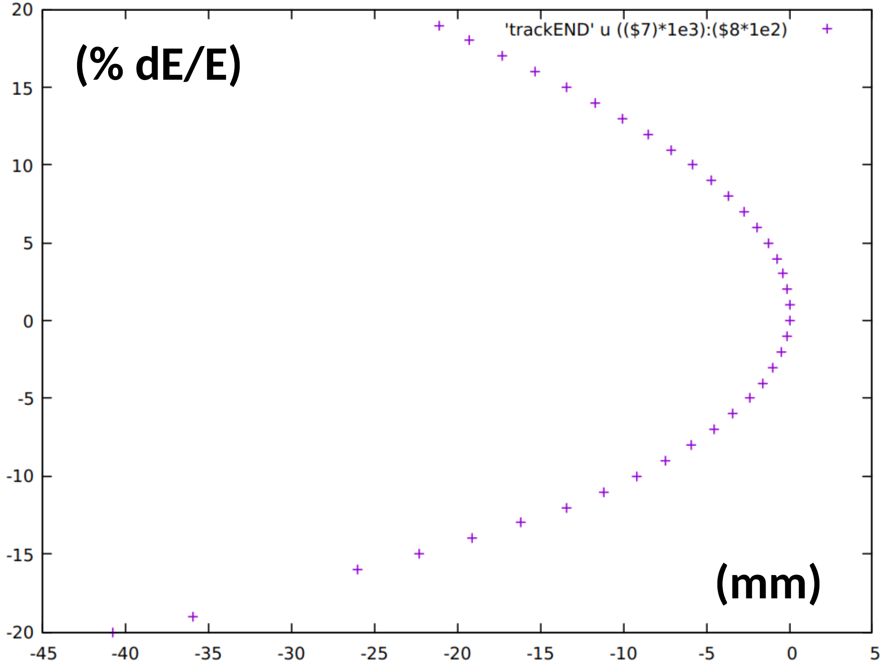
The current design uses a triplets at 500 T/m (CLIC QD0 type).
We are exploring the feasibility of higher gradient.

2) Low ß* with Energy acceptance = ±5% → ±20%

The current design is limited in acceptance by the Interaction Region section.
It seems possible to increase the energy acceptance to ±10 with a Second Order Apochromat (currently under study), however, there is no solution yet to achieve ±20% with a low ß* in the order of cm.

Issues 1) and 2) lead the design in opposite directions, and we will need to find a middle point.

3) Second order momentum Compaction Factor.



When reducing First Order Momentum Compation Factor to 10^{-4}, Second order momentum compaction is not longer negligile factor limits the energy cannot be canceled in a single cell

$$\alpha_2 = \frac{1}{C}\int \left(\eta'^2/2 + \eta_2/\rho\right) ds = DPX^2_{rms}/2 + \frac{1}{C}\sum_i DDX_{i\,.}\,\theta_i$$

D. Robin, E. Forest, C. Pellegrini and A. Amiry. “Quasi-isochronous storage rings.” Phys. Rev. E 48, 2149. Sep 1, 1993. doi:10.1103/PhysRevE.48.2149 , https://link.aps.org/doi/10.1103/PhysRevE.48.2149

One could try to reduce DPX or set sextupoles in a n-cell family, but, there is very little flexibility in an FFA to tune independently DPX or the DDX produced by sextupoles.

Other cells could be explored to check momentum compaction factors below 10^{-4}

CONCLUSIONS (1/2)

We are studying the production of low emittance muon beams from e^+e^- annihilation of a high energy positron beam on a thin target. We have achieved in simulations a normalized emittance of 5 π µm, with 500 T/m quads.

The muon production effciency is low, e.g. a bunch of circa 10^{12} e^+ to produce 10^6 µ pairs. In order to increase the muon population, we accumulate the low emittance muons produced by many (a hundred to a thousand) positron bunches.

We study the optics of a high energy acceptance accumulator.
Here we present a 231 m long optics based in FFA lattice using combined function magnets with an interaction region achieving ß* = 20 cm over ±5% of energy spread.

The 20 cm space at the IP is enough to allocate a thin target. We studied the accumulation with a 3 mm Be target. It shows that the emittance grows due to multiple scattering, therefore, we will need to further reduce ß* (meaning gradients above 500 T/m).

Although the arcs have a large energy acceptance, the IR is limited to ±5%.
One could consider to design a second order apochromatic Interaction Region with low ß* that could increase the ring energy acceptance.

CONCLUSIONS (2/2)

Another accumulator design by Pantaleo Raimondi is able to accumulate almost 10^9 μ±,
but for an emittance larger than 5 μm.rad. This is because the ring has a larger energy acceptance and combines 7 positron bunches per pass, effectively increasing the positron rate on target.

Pantaleo's ring achieves a large energy acceptance by relaxing ß*, therefore,
the beam emittance is diluted and suffers from multiple scattering with the target.

In parallel we have designed an apochromatic transport line for three beams (e+, μ+ and μ-) at two energy levels (22~GeV for the two muon beams and twice the energy for the positron beam)

The transport line:

- increases the muon production efficiency by a factor 10,
- reduces the thermomechanical stress of a single target by at least one order of magnitude
- Preserves the muon beam emittance
- Mitigates the positron beam emittance growth from multiple scattering and breamstrahlung

The transport line is benefitial in many aspects, but, its effectiveness is limited by positron bremstrahlung with the target, that reduces the population above the muon prod. Energy threshold

A combination of the accumulator+transport line, and the beam combination is yet to be studied.

MANY THANKS for your time, and also

People at INFN, ESRF and CERN who are interested in the idea.

In particular,

Andrea Ciarma, Manuela Boscolo,
Mario Antonelli, Susanna Guiducci,
Alessandro Variola, Marica Biagini
and Francesco Collamati from INFN

Pantaleo Raimondi and Simone Liuzzo from ESRF

And the Commissione Scientifica Nazionale 5 on Technological Research at INFN, Italy.

SPARE

Target

1×10^6 μ/bunch
±5% energy spread
22 GeV
ε_n = 200 x 30 nm = 6 μm

FFA fast acc.
or ERL 10 arms
20 GeV→ 200GeV
10~20 turns

FFA fast acc.
200 GeV→ 1TeV
~100 turns

FFA fast acc.
1TeV→7TeV
~600 turns

7 TeV
½ x 10^6 μ/bunch

7 TeV, 1 bunch Collider

e^+ source

43.8 GeV
100 bunches
5 x 10^{11} e^+/bunch
(104mA/bunch
From ACC length,
230 m)
5 x 10^{17} e^+/s

Emittance ~ 8 nm
Beam size ~ 60 μm

Positron to Muon Conversion

Total length : 230 m x 100 turns
Efficiency =
= 1×10^6 μ/(100turns x $5 \times 10^{11} e^+$)
= 2 x 10^{-8} μ/e^+

1%X_0 Be target

Canted Cos 33
230 m
$\beta^*\mu$ = 0.2 m
$\beta^* e^+$ = 0.5 m
L^* = 10 cm
Acceptance (±5% e.spread)

***** bunch length ~1cm *****
***** Strong e^+/weak μ beam recombination *****
***** resonance crossing *****

Low Muon Current
Fast Acceleration (10 GeV/turn)
500m x 20MV/m = 10 GV

No magnet ramping
Profiting the large FFA energy acceptance, the beam circulates from low to high energy moving radially outwards
Part of this acceleration could be also achieved with an Energy Recovery Linac (ERL)… what ever is more efficient

In fact, we need to accelerate the bunch anyways.

Circumference : 27 km
Emitt norm. ~ 10 μm
Assuming decay half of the bunch during acceleration
1 bunches of ½ x 10^6 μ,
½ x 10^{10} μ/s

$N_\mu^2 N_b/\varepsilon_n$ = $(0.5 \times 10^6)^2$ x 1 / 6×10^{-6}
= 4 x 10^{16}

Muon lifetime (at 7 TeV)
140ms → 42000km (>1000 turns)
Collision for ~ 500 turns

3 x 10^5 μ/bunch
±5% energy spread
22 GeV
ε_n = 208 x 25 nm = 5 μm

(v)FFA fast acc.
or ERL 10 arms
20 GeV→ 200GeV
10~20 turns

(v)FFA fast acc.
200 GeV→ 1TeV
~100 turns

(v)FFA fast acc.
1TeV→7TeV
~600 turns

7 TeV
1.5 x 10^5 μ/bunch

50 TeV
1 x 10^5 μ/bunch
Top-up injection

7 TeV, 1000 bunch Accumulator And 7 to 50 TeV Ramping Ring

e^+ source

44.0 GeV
1000 bunches
5 x 10^{11} e^+/bunch
(240mA/bunch
From bunch
to bunch
distance, 100 m)
1.5 x 10^{18} e^+/s

Emittance ~ 7 nm
Beam size ~ 60 μm

Positron to Muon Conversion

Total length : 323 m
Efficiency : 0.6 x 10^{-6} μ/e+
1%X_0 * 25 LLi targets

Transport line mpt104
13.455 m
β*μ = 0.2 m
β*e+ = 0.5 m
L* = 10 cm
Mu Apochrom (±5% e.spread)

Target power reduced by 25
μ bunch length equal to e^+ bunch length, few mm

Low Muon Current
Fast Acceleration (10 GeV/turn)
500m x 20MV/m = 10 GV

No magnet ramping
Profiting the large FFA/vFFA energy acceptance, the beam circulates from low to high energy moving radially-outwards/vertically.
Part of this acceleration could be also achieved with an Energy Recovery Linac (ERL).

Choice depending on efficiency

Circumference : 100 km
1000 bunches of 1.5x10^5 μ
Emitt norm. ~ 5 μm

When 1000 bunches are accum.
We Ramp in ~500 turns
→ RF cavities : 100 GeV = 5 km
5 km x 20MV/m
Mu lifetime (at 7 TeV)
140ms → 42000km
Mu lifetime (at 50 TeV)
1 s → 3x10^5 km
At 50 TeV the muon beam damps we perform TOP-UP Injection

BLANCO, 50 TeV muon accumulator. https://arxiv.org/abs/2009.02536