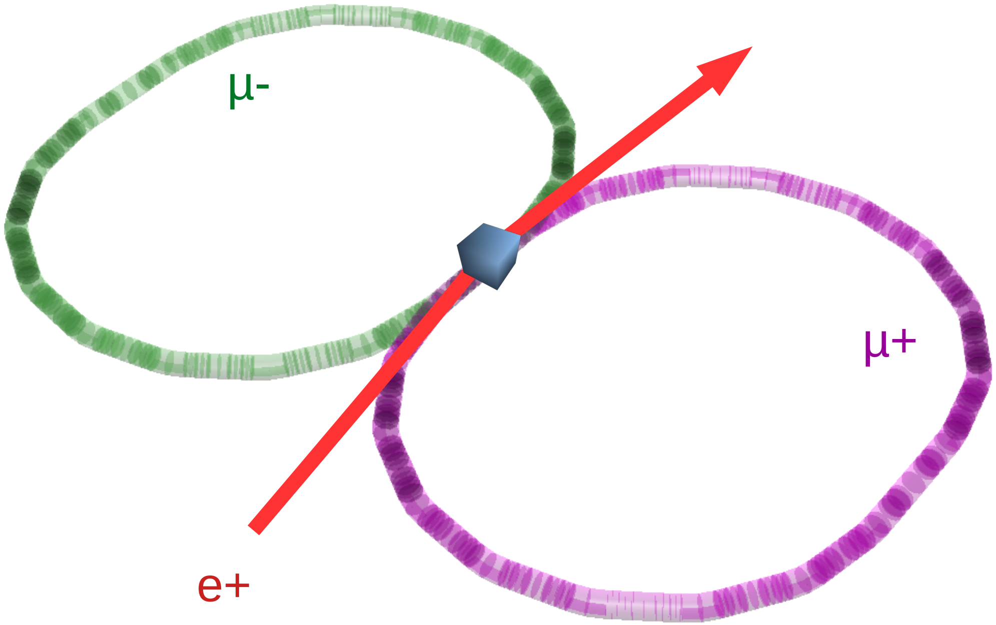
Muon Accumulator High Energy Acceptance Ring



Oscar BLANCO

Special thanks to the LEMMA team:

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

Pantaleo Raimondi and Simone Liuzzo from ESRF

8th Low Emittance Rings Workshops LER2020, Frascati/Italy, 26-30/OCT/2020

Muon Accumulator High Energy Acceptance Ring

In this presentation I will show the goals of the accumulator, the current status and issues.

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.

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 of FFA

LEMMA (Low Emittance Muon Accelerator)
It is a low emittance muon source, no cooling needed

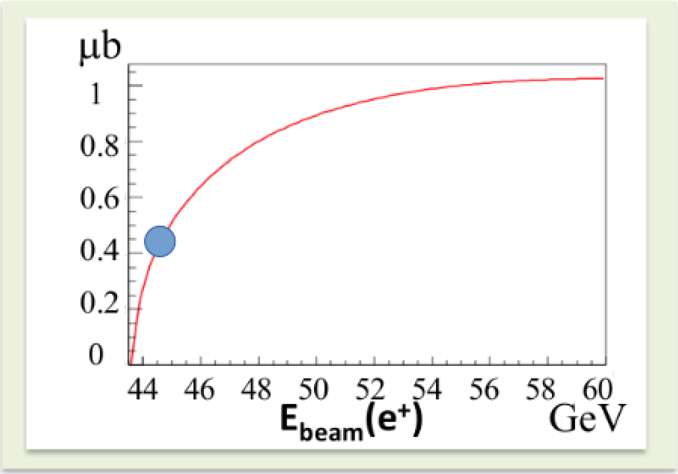
from **direct μ pair production**:

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

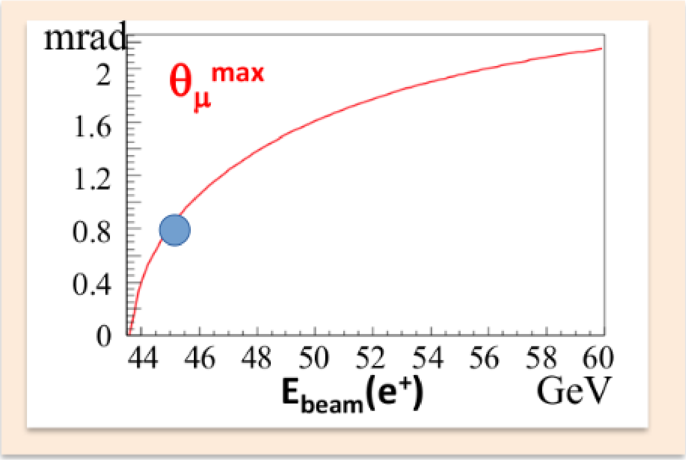
- **Need Positrons of ≈ 45 GeV**
- $\gamma(\mu) \approx 200$ and μ laboratory lifetime of about 500 μs

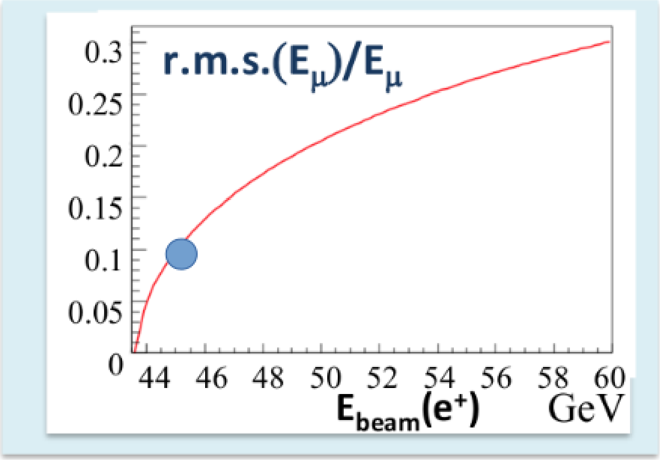
Muon transverse and longitudinal emittance depend on the e+ beam energy and size

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



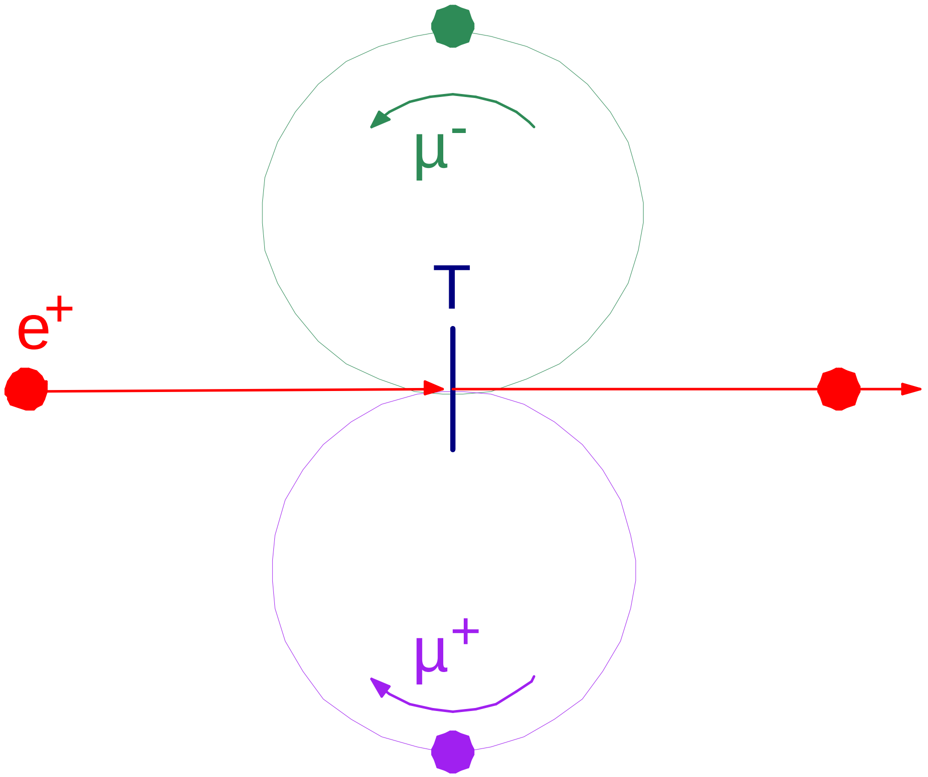
The value of sqrt(s) (*i.e.* $E(e^+)$ for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread





Muon Accumulator Rings

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

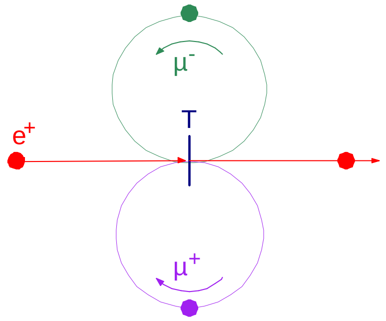


Requirements 2018 and status 2020

These requirements correspond to a muon bunch of 10^9 μ with $\varepsilon_n = 40\ \pi$ 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

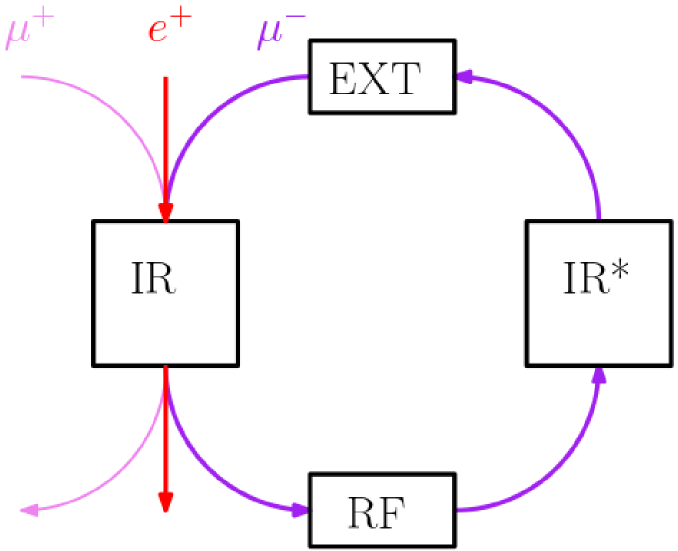
	Required 2018	**Optics Design Status**	
Small Length	60 m (1 IP)	230 m (2 IPs)	To mitigate muon decay
Large Dynamic Ap.	±20%	**±5%**	μ+μ- Production efficiency and energy spread are proportional
Low ß*	1 cm	**20 cm**	To avoid emittance growth from multiple scattering
Time of accumulation	1000~2000 turns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



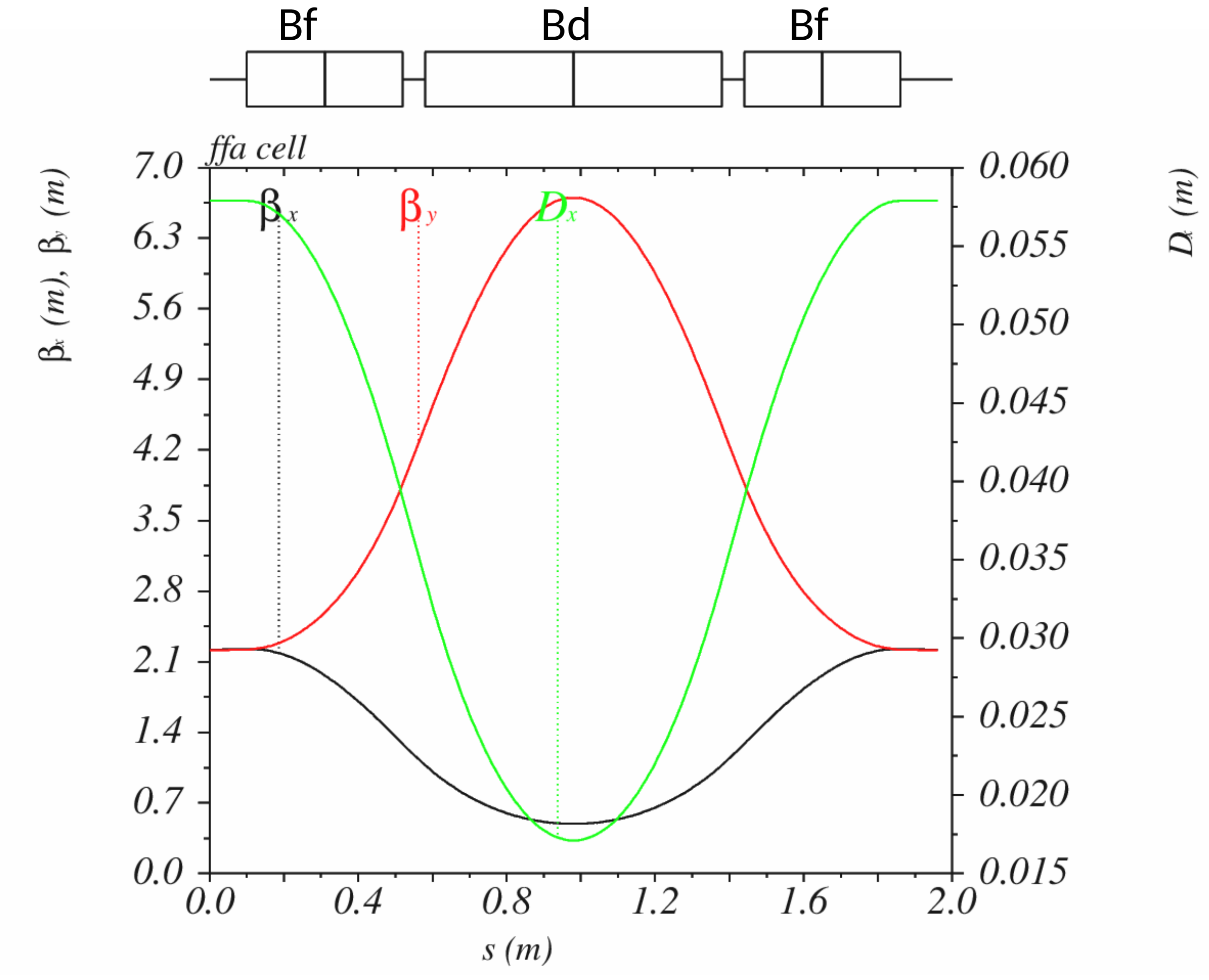
Muon Accumulator Sections

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

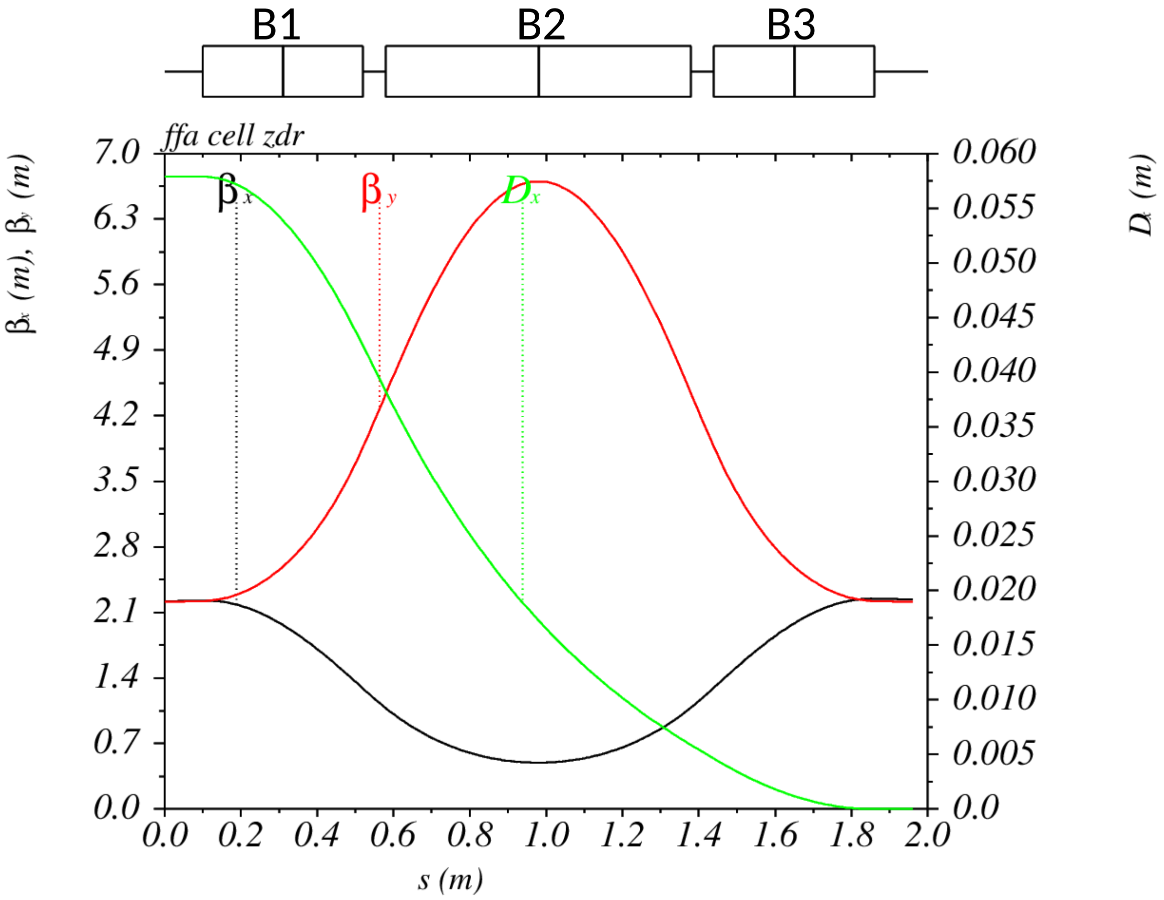
Cell phase advance (twopi units)
H/V tune of 0.1/0.3

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

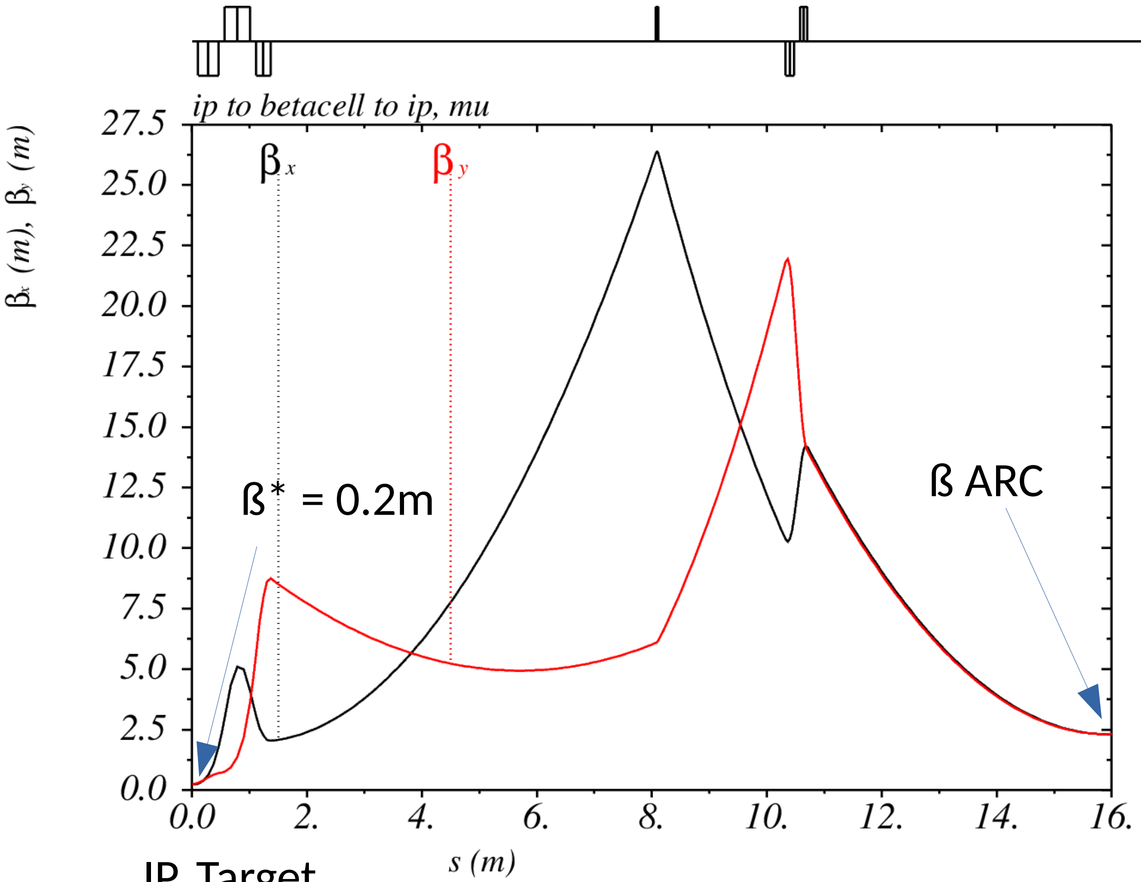
Good field region : 1cm
Dispersion: 0.06m

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



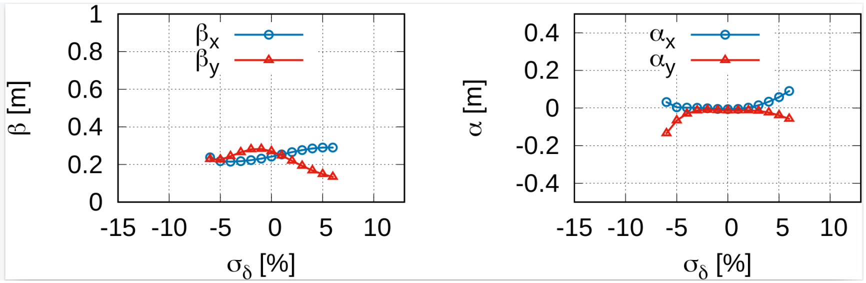
IP, Target

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 apochromatic drift-quadrupole beam lines", Phys. Rev. Accel. Beams 19 (2016)
https://link.aps.org/doi/10.1103/PhysRevAccelBeams.19.071002

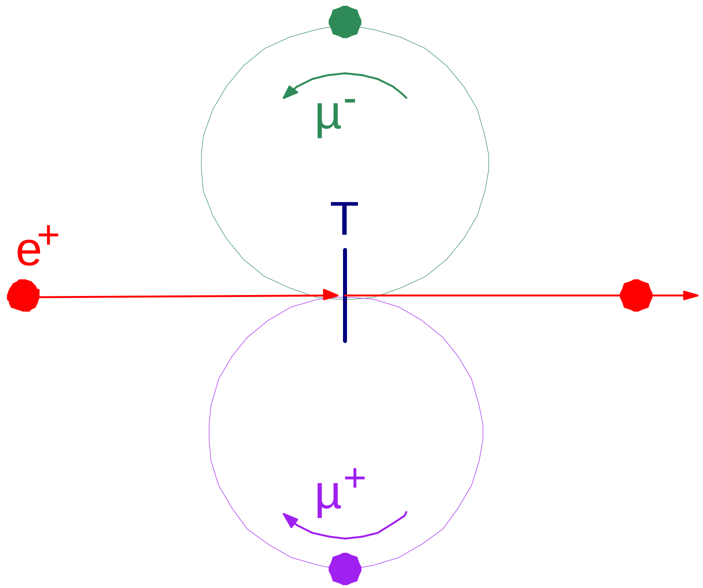
Inner Triplet Magnets at ~2T
525T/m (CLIC QD0 prototype)

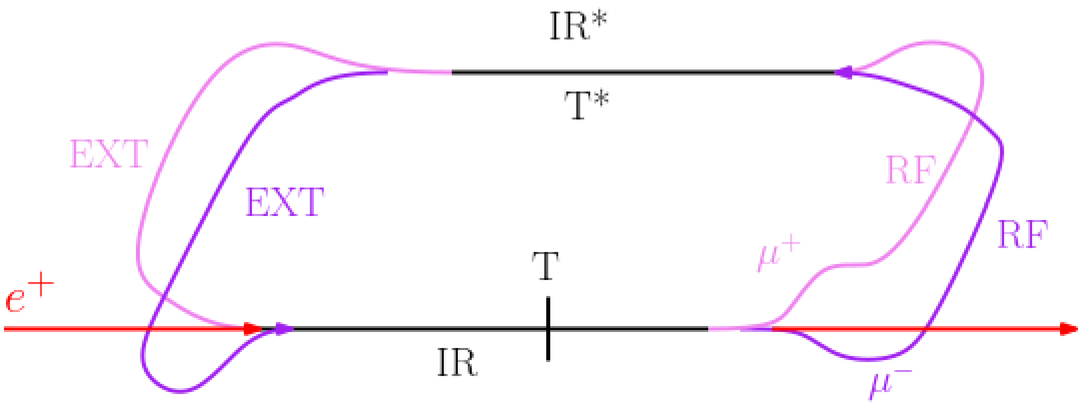


Interaction Region with Vertical Separation (1/2)

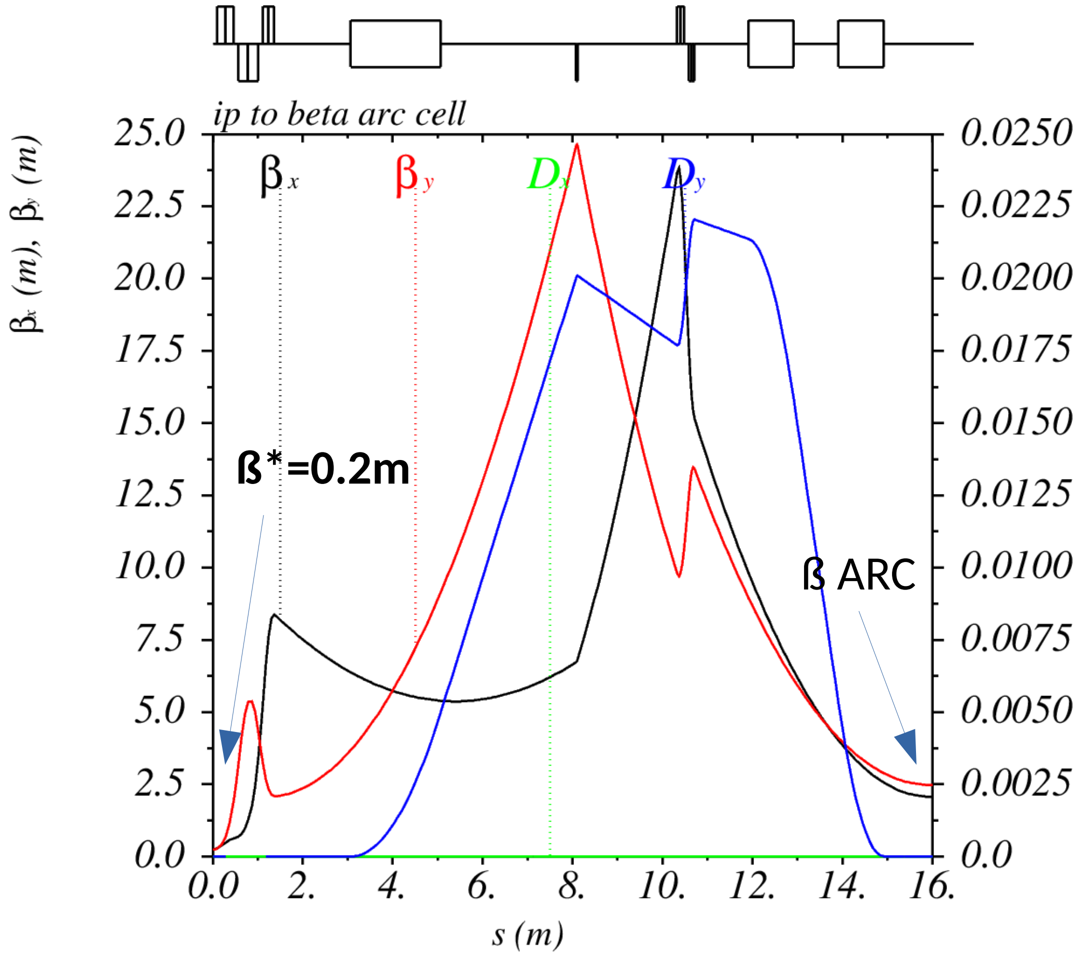
Separating the beams in the vertical plane could have several advantages

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

Vertical dipoles < 1T

To separate/combine the beams

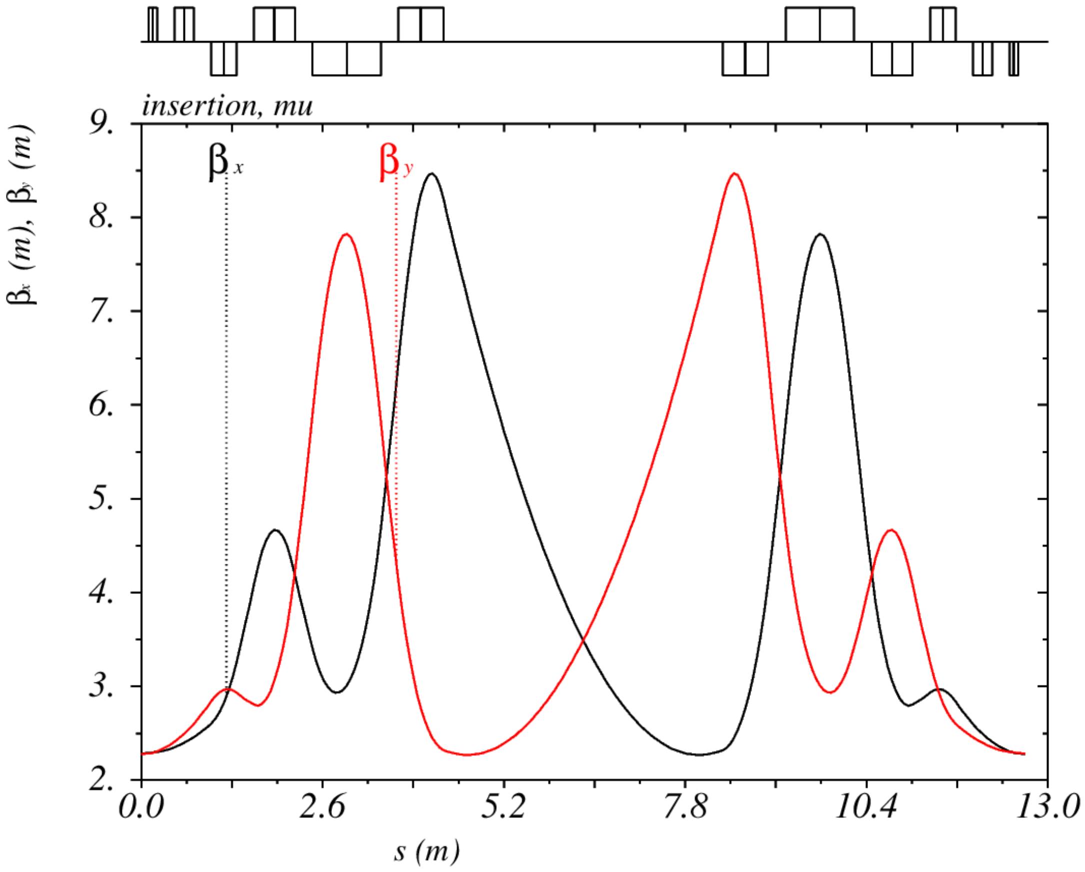
To Minimize the positron energy loss (circa 20 MeV)

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



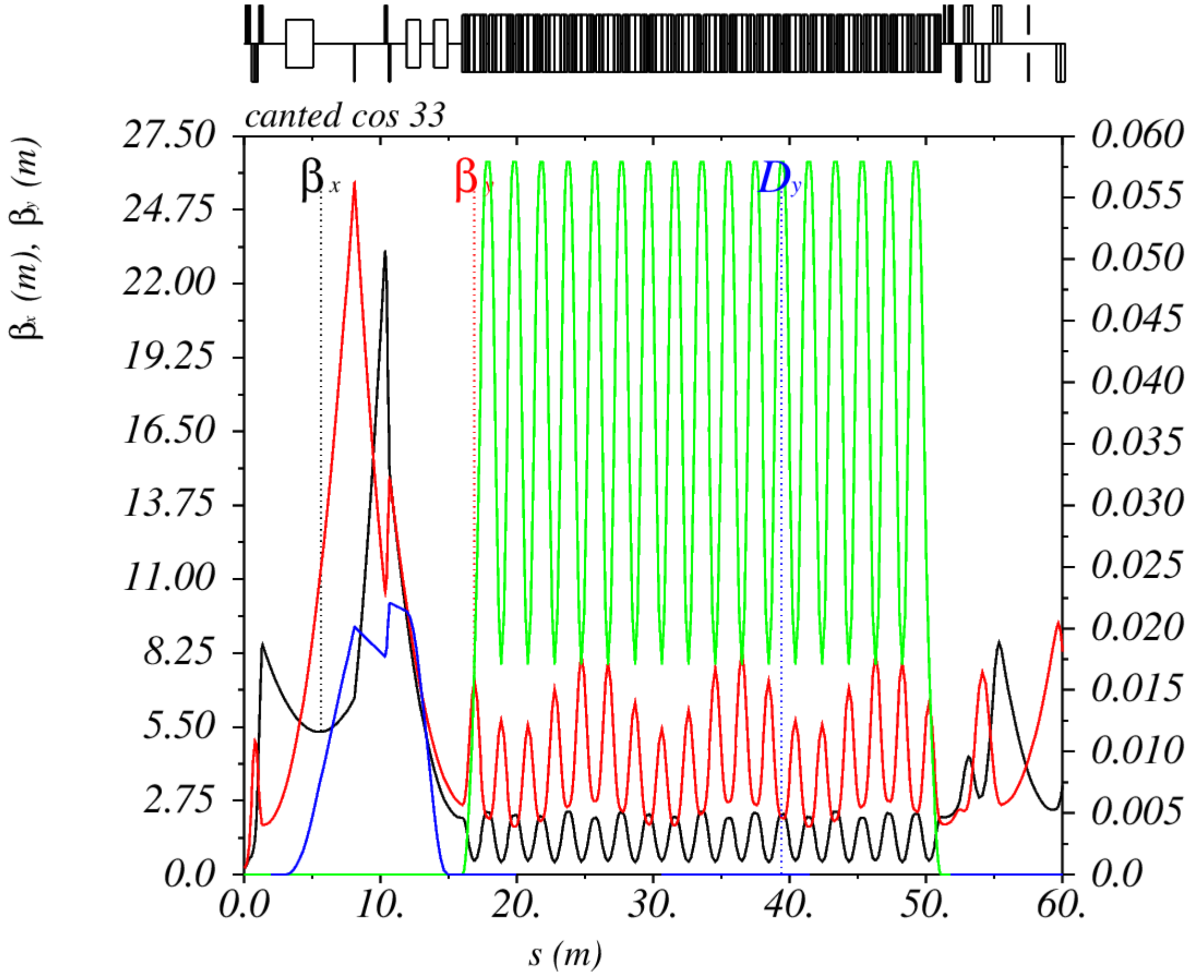
Insertion for RF or Extraction Kicker 100~200T/m

(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 …



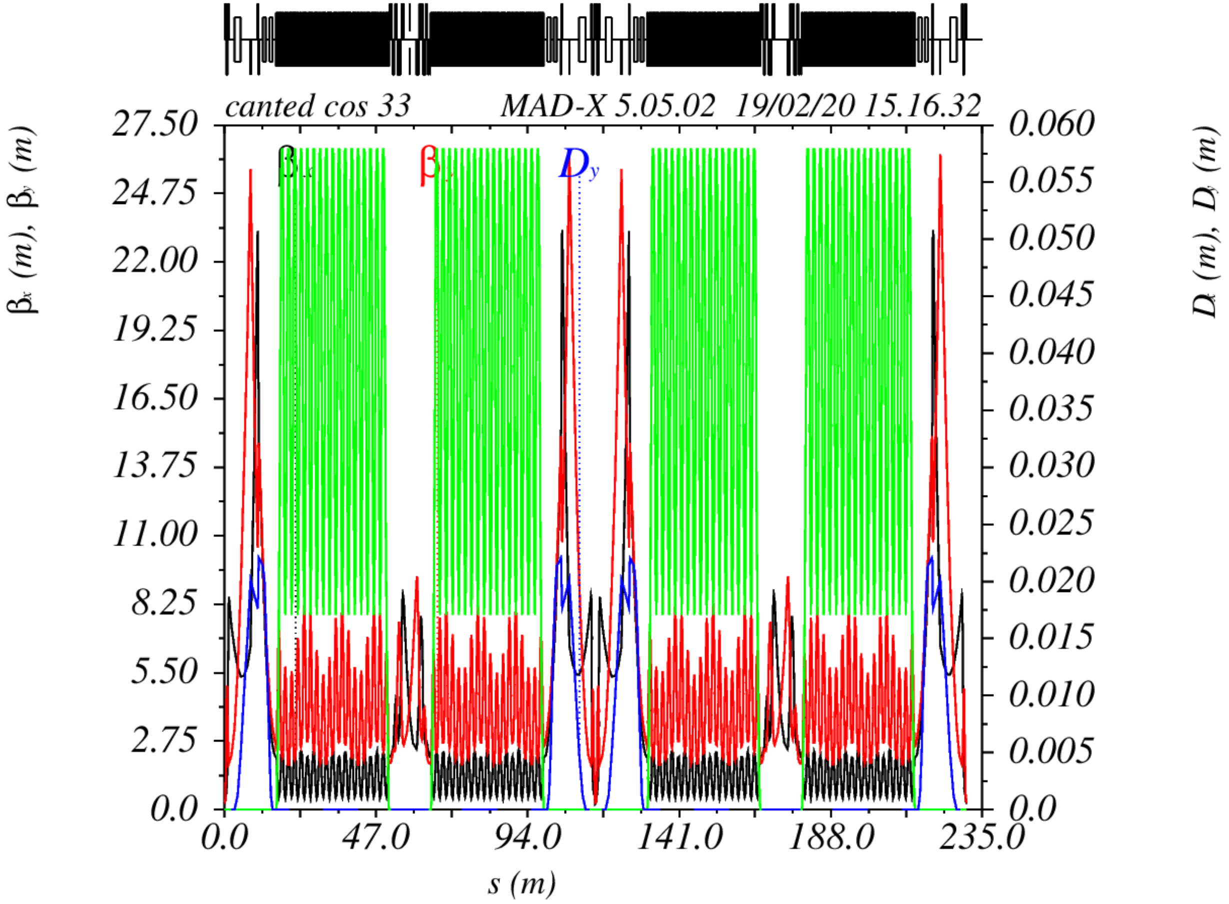
IR + ARC zdr + ARC + insertion(RF)

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.

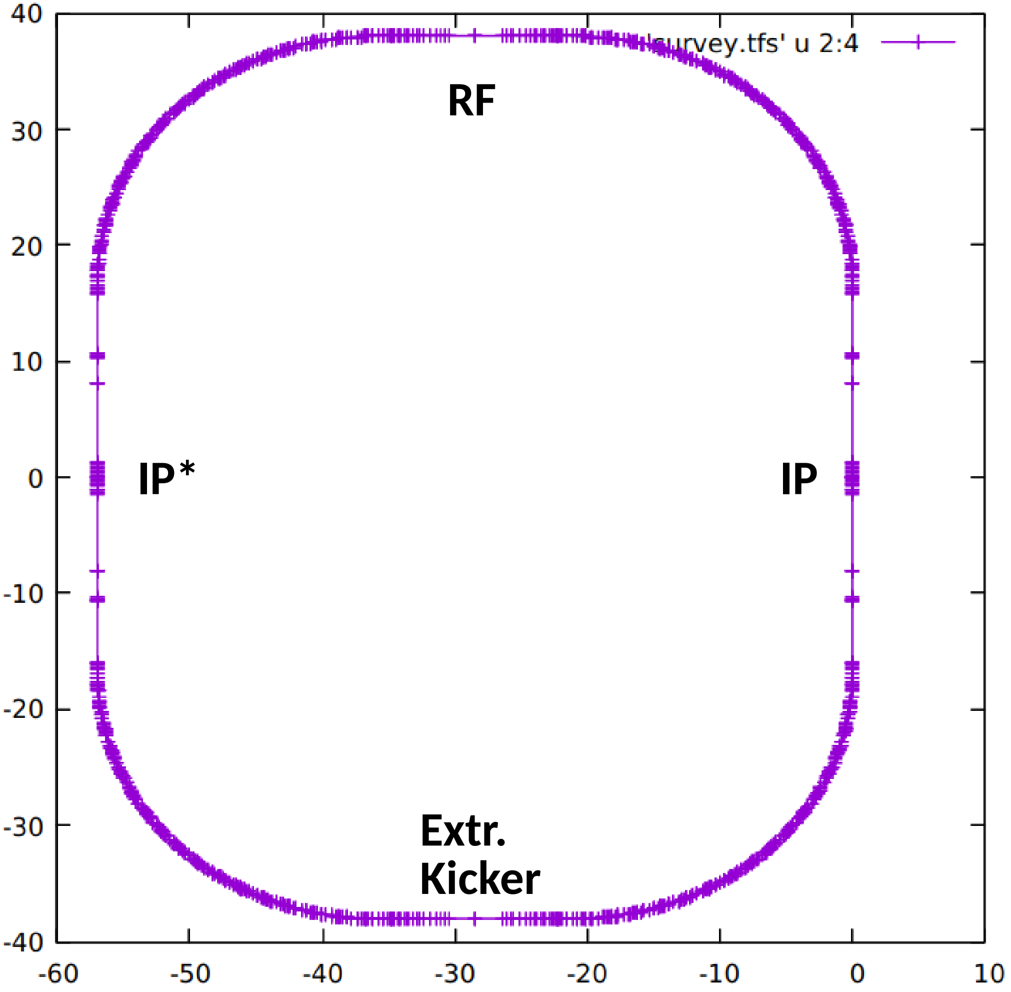
linear optics

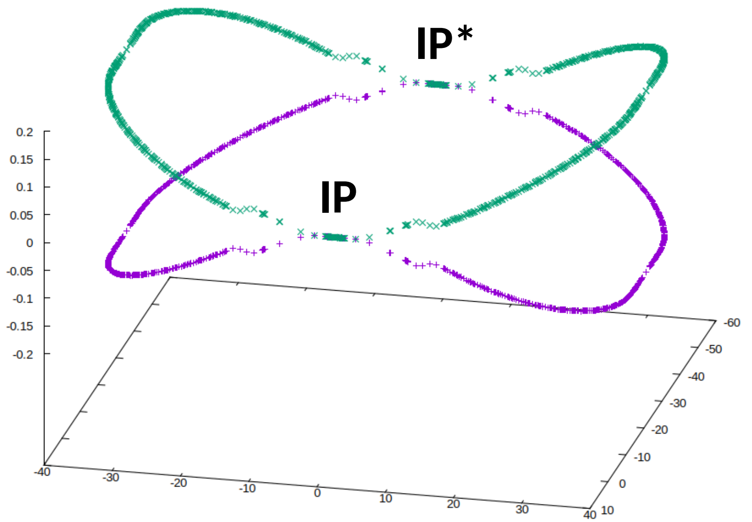


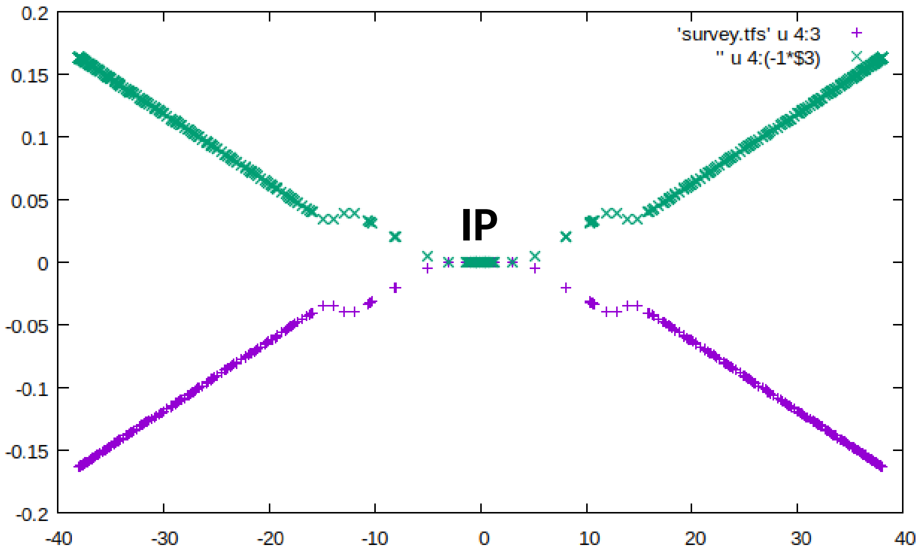
Magnets below 14T
Bd -3.1 T, 238T/m, 6.3kT/m^2
Bf 12.0 T, -183T/m, -10.7kT/m^2
α_c = 0.3 x 10 $^{-3}$
L = 231.1 m, FFA + 2IR + RF + extr.
IR β^* = 0.2m (+/-5% e.spread)

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

Survey in meters



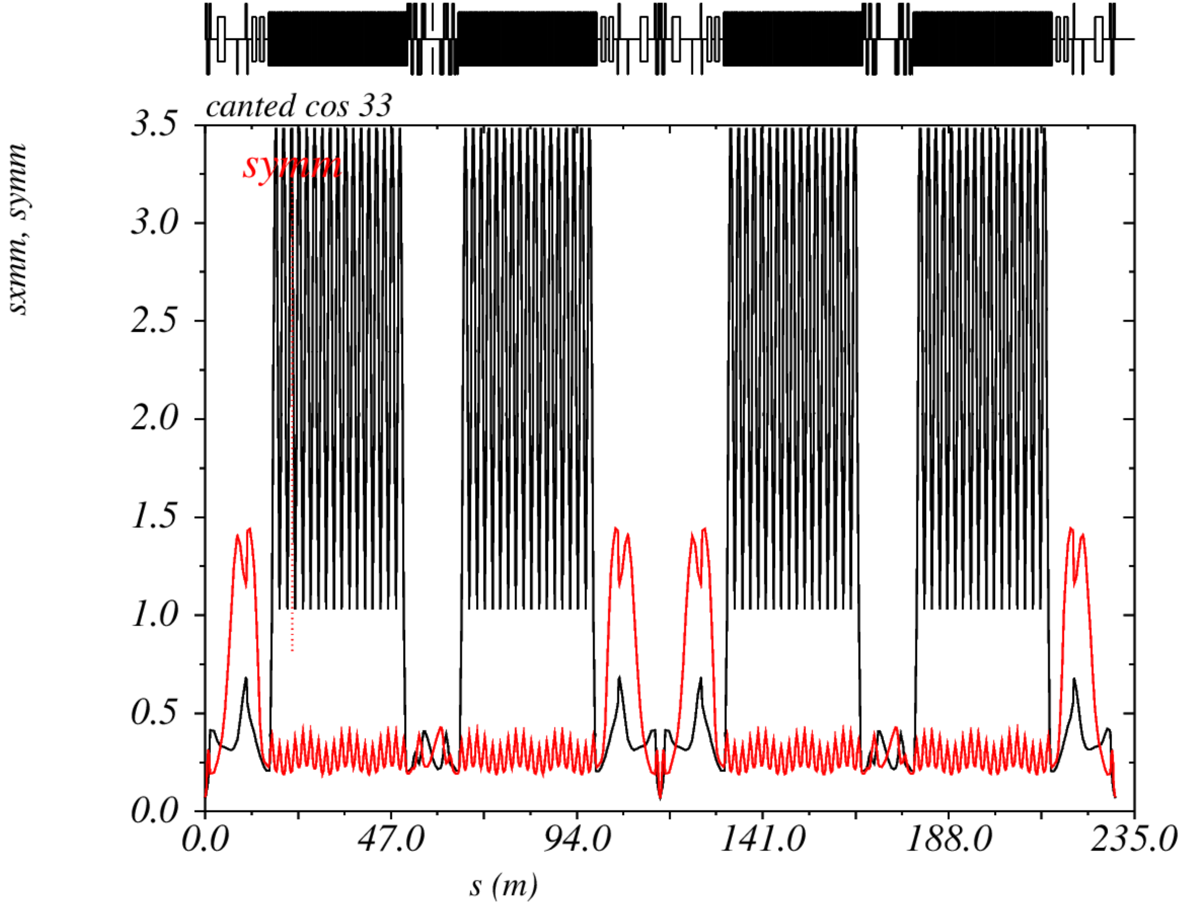




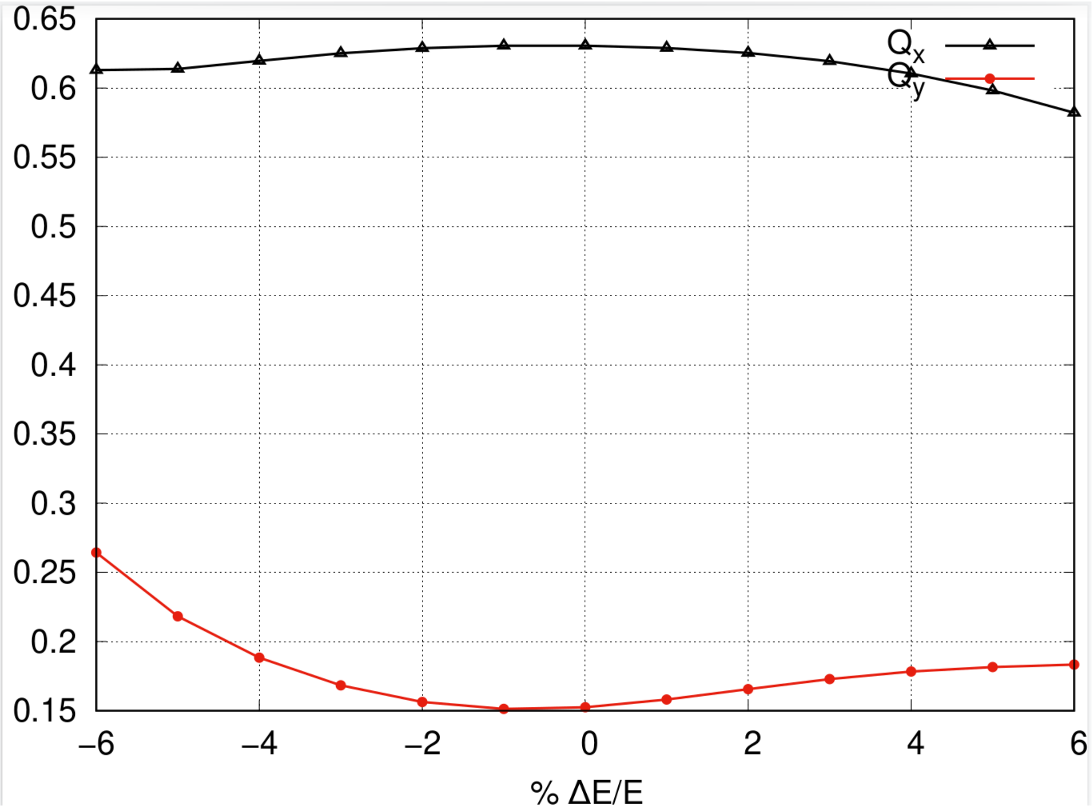
Beam size

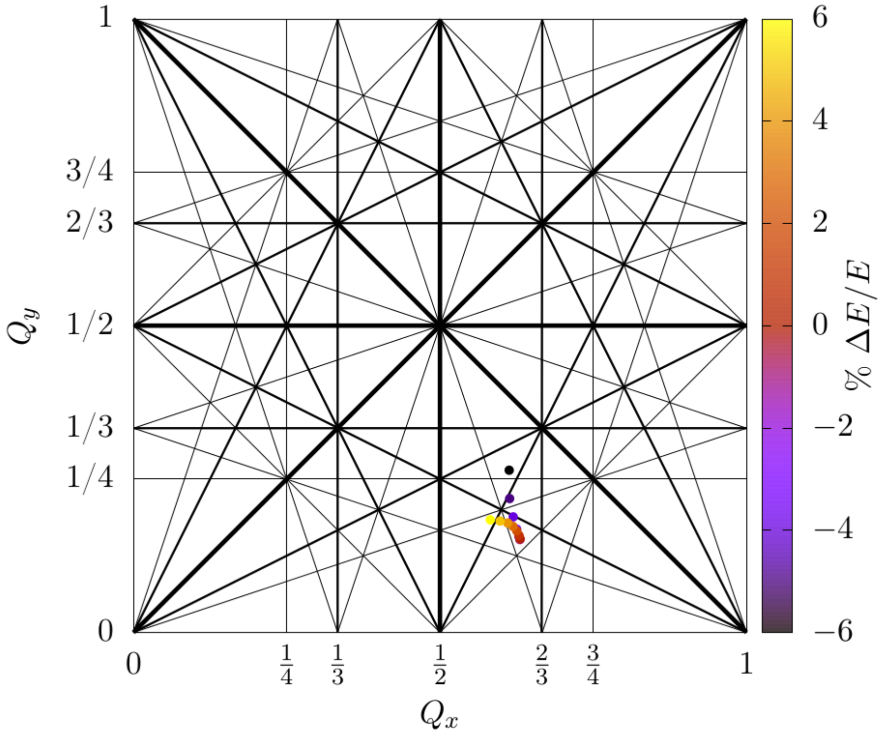
For a normalized emittance 5 π μm (220 x 20 π nm), γ = 220, e. spread = 6%
Beam size in mm.

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

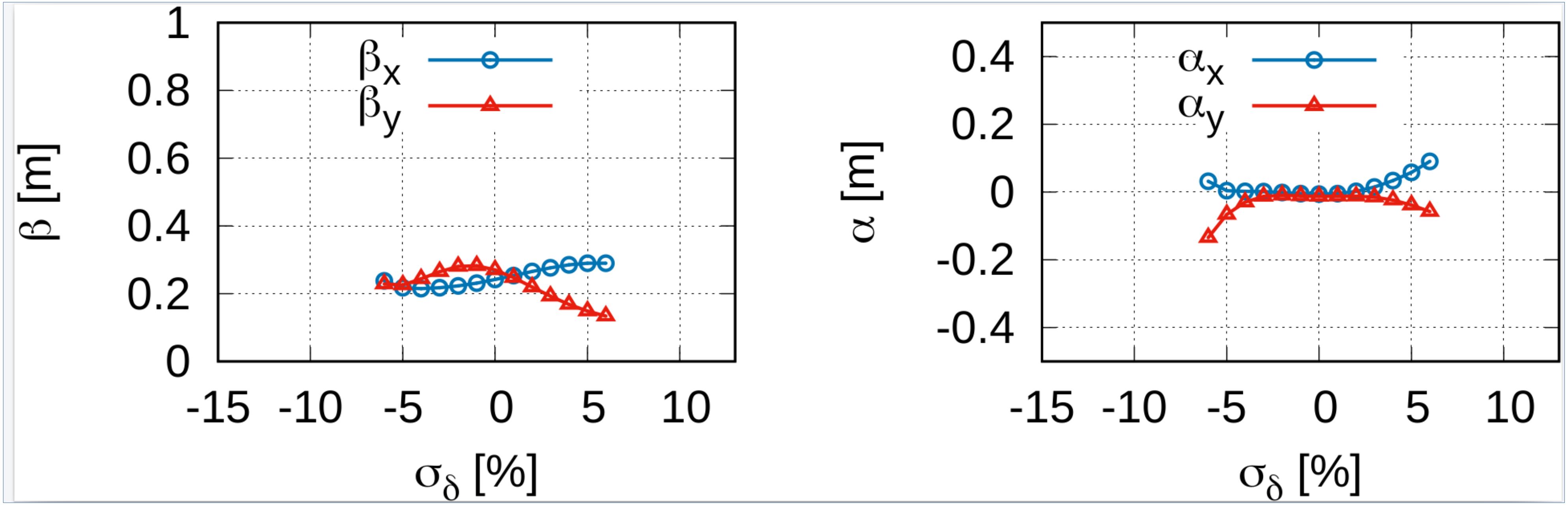


Tunes

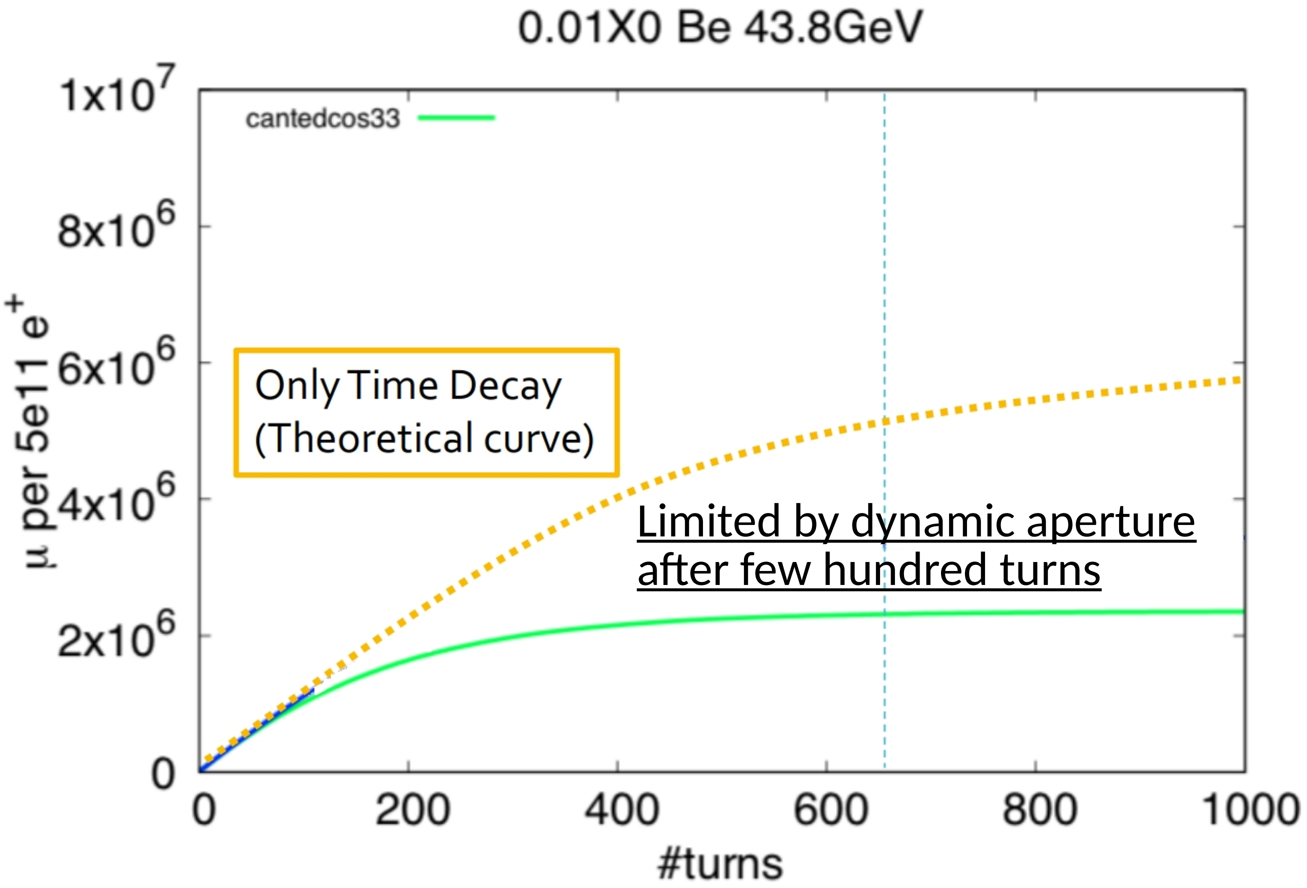

0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
−6
−4
−2
0
2
4
6
% ΔE/E
Q_x
Q_y


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

Beta and alfa at the IP



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

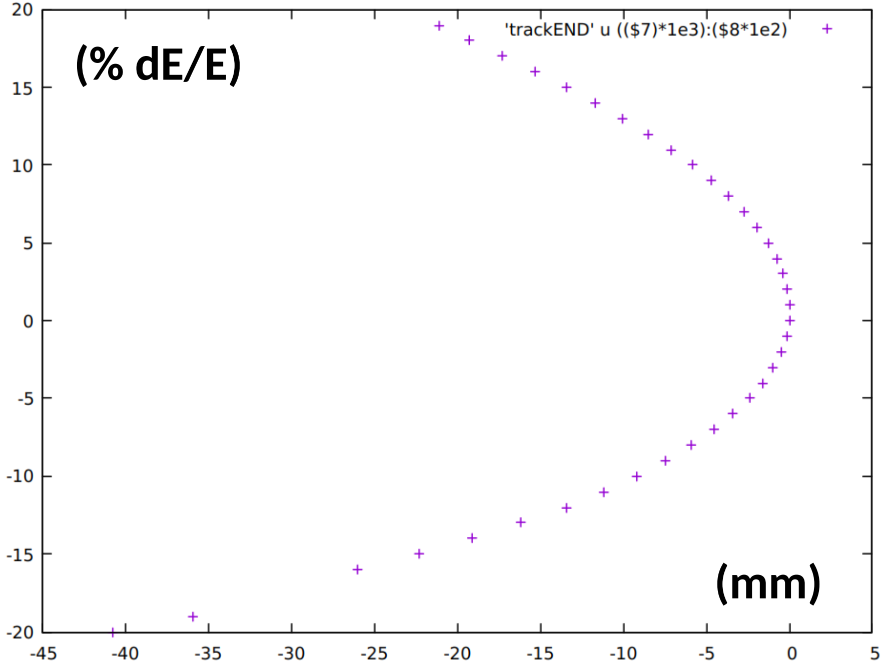
The current design uses a triplets at 500 T/m (CLIC QD0 type).
We are exploring the feasibility of higher gradient.

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

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

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

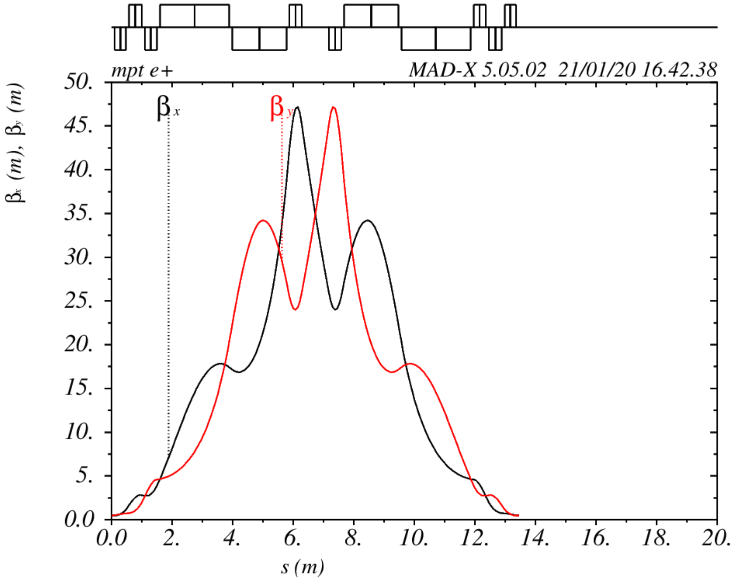
We are studying the production of low emittance muon beams from e^+e^- annihilation of a high energy positron beam on a thin target. We have achieved in simulations a normalized emittance of 5 π µm, with 500 T/m quads.

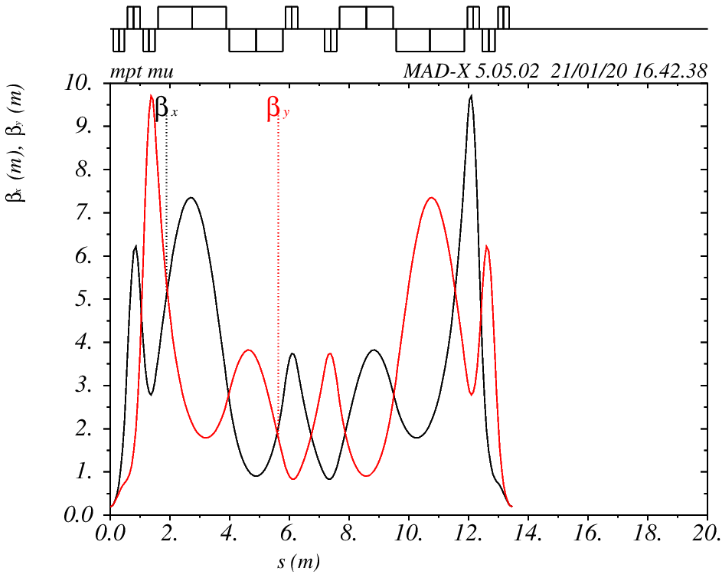
The muon production effciency is low, e.g. circa 10^{12} e^+ to produce 10^6 µ pairs. In order to increase the muon population, we accumulate the low emittance muons produced by many (a hundred to a thousand) positron bunches.

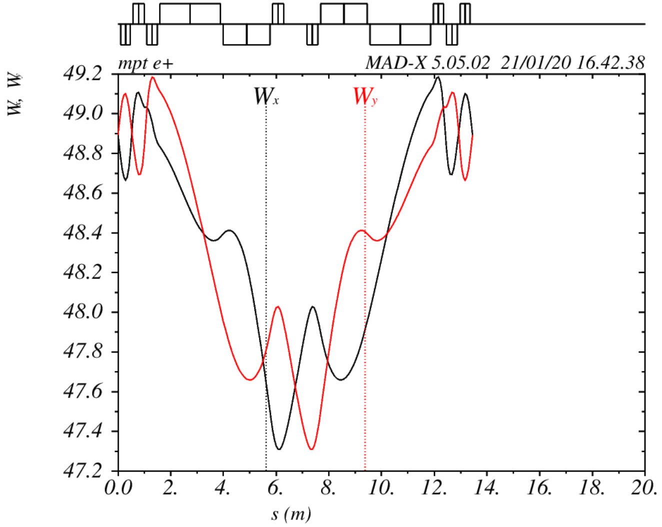
**We study the optics of a high energy acceptance accumulator.
Here we present a 231 m long optics based in FFA lattice using combined function magnets with an interaction region achieving ß* = 20 cm over ±5% of energy spread.**

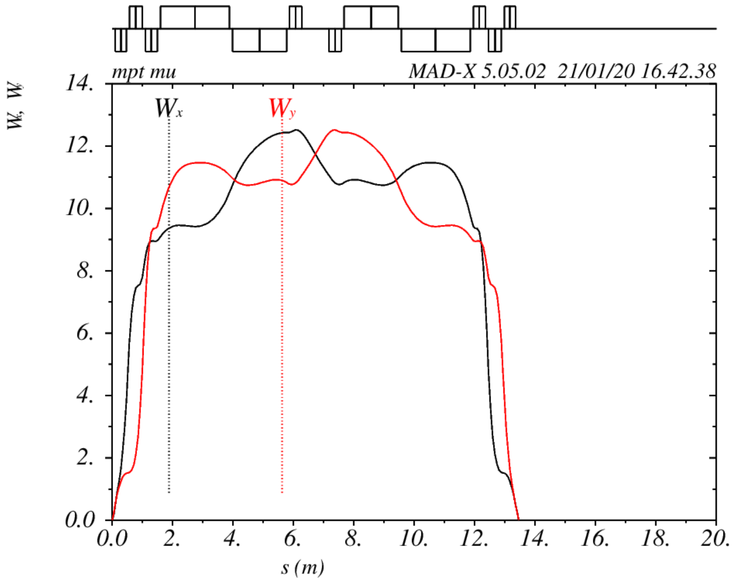
The 20 cm space at the IP is enough to allocate a thin target. We studied the accumulation with a 3 mm Be target. It shows that the emittance grows due to multiple scattering, therefore, we will need to further reduce ß* (meaning gradients above 500 T/m).

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





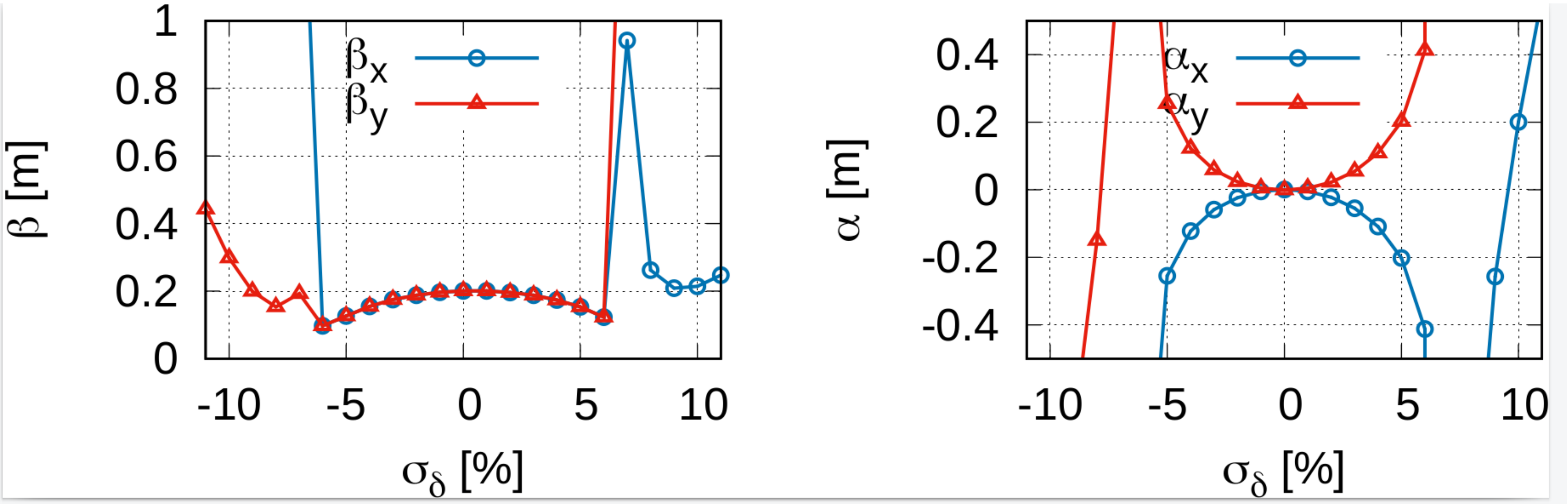




MPT104

Magnets ~2T
500T/m
Ø/2 = 4mm

Beta* = 20cm ,
±5% of energy acceptance



β [m]
βx
βy
1
0.8
0.6
0.4
0.2
0
-10
-5
0
5
10
σδ [%]
α [m]
αx
αy
0.4
0.2
0
-0.2
-0.4
-10
-5
0
5
10
σδ [%]

Variola. LEMMA Update. Muon Collider Meeting. 31/mar ~ 2/apr, 2020
https://indico.cern.ch/event/886491/contributions/3797729/attachments/2013899/3365755/AVariola_CERNWS2_2apr20.pdf

MUON ring

- - By the end of 2019 -> 150 m accumulator ring designed by P. Raimondi, optimized to get about ±10% energy acceptance, with a beta* of 2 m and a very small momentum compaction factor to preserve the longitudinal emittance.

  - in parallel study of the possible use of an FFA ring. Very small circumference of 100 m and more than ±20% energy acceptance with a similar value of beta* (2 m), however with a very large momentum compaction factor.
- Benchmarking and simulation of the FFA muon production line with MUFASA (MADX + Montecarlo code). Optimization ongoing for the working point (and energy)

  - recently -> focus on in reducing the momentum compaction factor and beta*. Obtained a 230m ring with 2 IPs done with a combination of FFA arcs and strong focusing elements below 14 T, achieving a small momentum compaction factor of the order of $3x10^{-4}$, energy acceptance of ±5%, and beta * of 20cm.

  1) The result of the accumulation simulation shows that population is limited by the energy acceptance and that emittance increases due to multiple scattering with the target(s) in few hundred turns.

  2) The current work is focused on gaining back the energy acceptance. For that we need to reduce dispersion in the arcs by one order of magnitude, have a very low chromaticity so that sextupoles don't have to run too high because of the reduction of dispersion, reduce first and second order momentum compaction factor so that the stable region in the longitudinal phase space grows, while keeping the arcs as short as possible with magnets under 16/20 T.

  3) In the long term need to further reduce the beta* by a factor 20, i.e. achieve a beta* of 1 cm that could mitigate multiple scattering over a thousand turns.

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THIS IS VERY DENSE…
I will try to go step by step