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vFFA and novel optics for muon collider accelerator complex

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UK muon collider and nuStorm meeting

Contents

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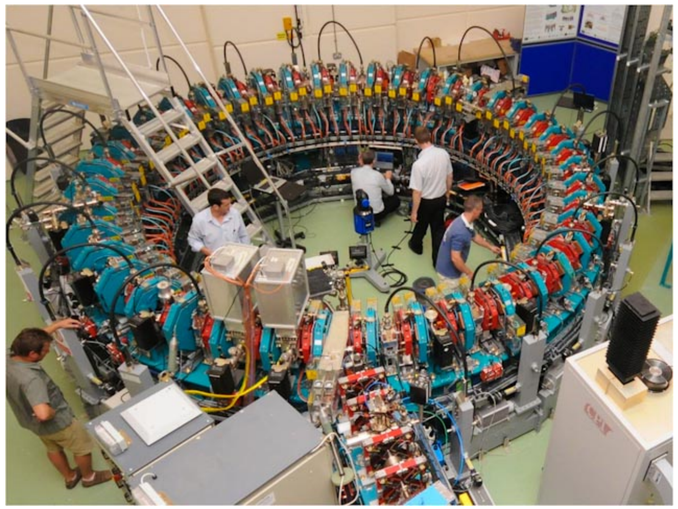
Muon acceleration and FFA developments in the UK

- Neutrino factory design study
  - Accelerator complex with a FFA as the final muon accelerator.
- Linear nonscaling FFA
  - Electron Model of Many (or Muon) Applications: EMMA.
  - It was commissioned in 2012 at Daresbury Laboratory.

- PAMELA for proton therapy.

- FFA design for ISIS-II.
  - Prototype vertical excursion FFA.
  - Feasibility study is on going.



EMMA

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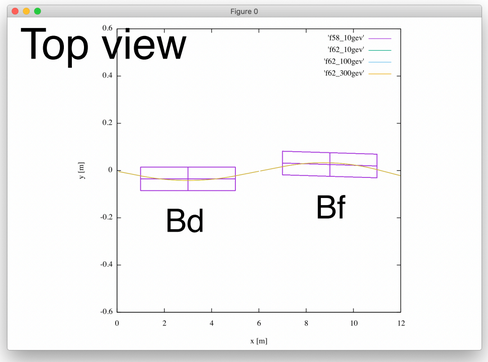
Vertical excursion FFA (vFFA)

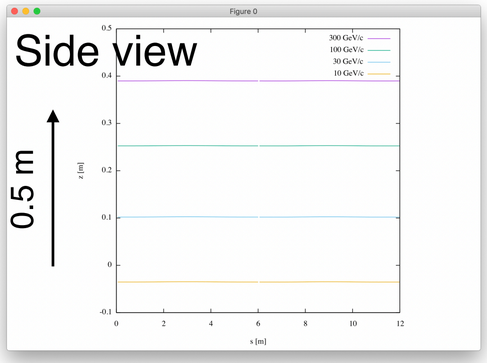
- Invented in 1955 by Tihiro Ohkawa.
- Re-invented in 2013 by Stephen Brooks.
- Orbit moves vertically when the beams are accelerated.
- **Path length is constant for all the momenta. Momentum compaction factor is zero.**
- It was called electron cyclotron
  - Ultra-relativistic particles can be accelerated continuously with fixed field magnets.

- Ideal for muon acceleration.
  - No ramping of magnetic fields.
  - No RF frequency modulation.
  - Large momentum ratio from injection to extraction, e.g. ~30.
  - Wiggling orbits to spread out neutrino.
  - Enough vertical aperture is needed.

G8. **FFAG Electron Cyclotron.*** TIHIRO OHKAWA, *University of Illinois*† (introduced by D. W. Kerst).—New types of FFAG[1] accelerators having the same orbit length for all momenta are proposed. In these types electrons, injected with an energy of a few Mev, are accelerated by a fixed frequency electric field until the radiation loss becomes serious, probably

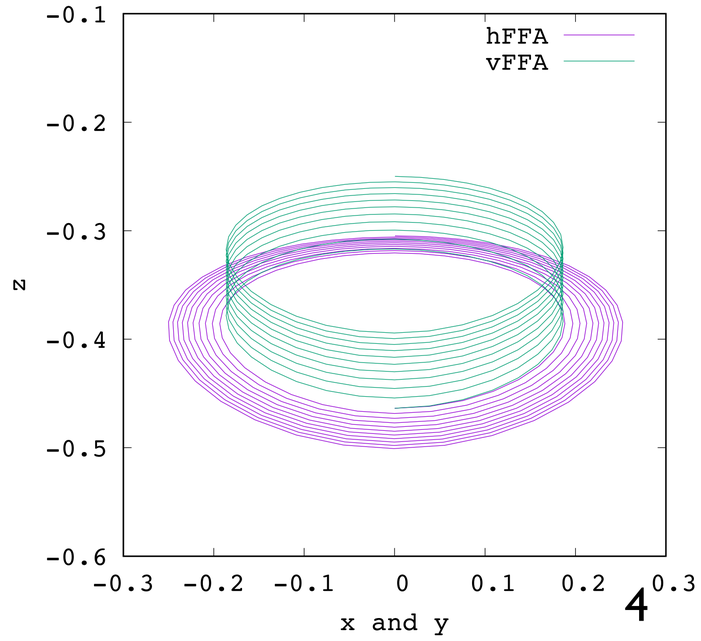
Bull. APS 30, 20 (1955)
by Tihiro Ohkawa





$$B = B_0 \exp(my)$$

m : field index
y : vertical



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Muon accelerator ring

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Design principle

- Circumference is about LHC.
- Top energy is 1.5 TeV.
- Momentum ratio from injection to top energy is about 30.
- Maximum field is no more than 10 T.
- Orbit excursion is less than 0.5 m.

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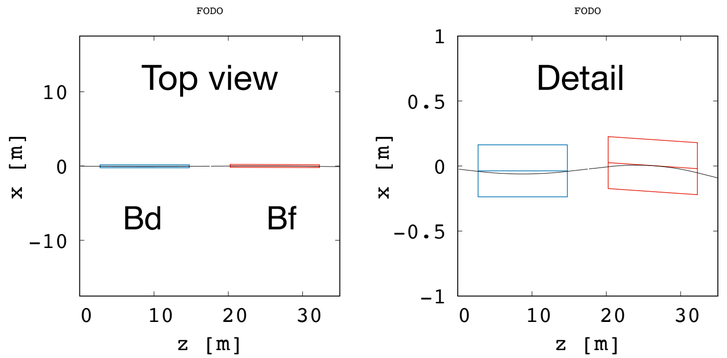
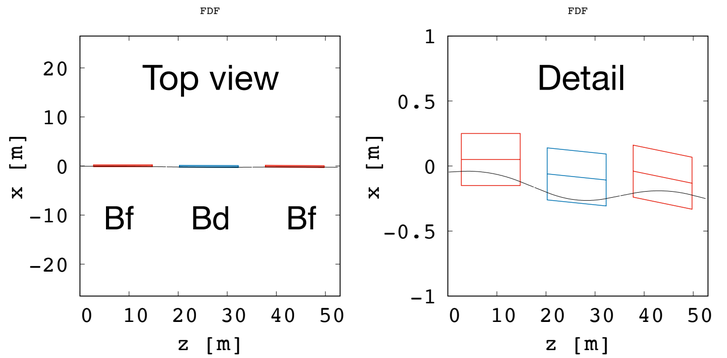
1.5 TeV accelerator in LHC tunnel

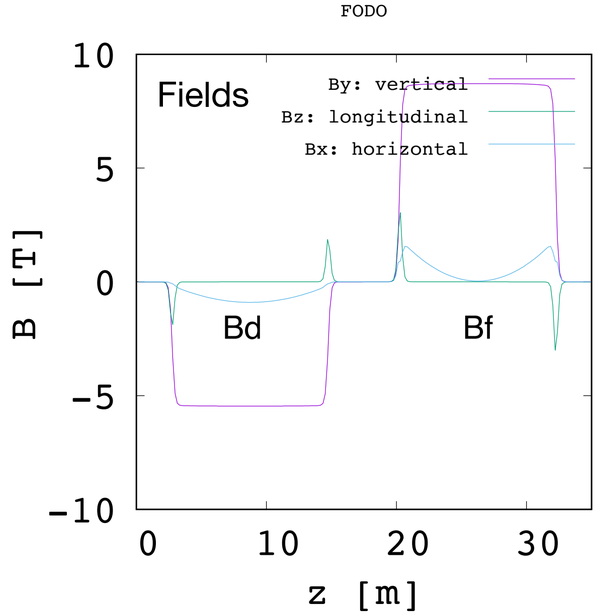
	FODO	FDF
Energy	50 GeV to 1.5 TeV	50 GeV to 1.5 TeV
Cell length	35 m	52.5 m
Magnet length	2 x 15 m	3 x 15 m
# of cell	810	540
Maximum field	8.7 T	10.6 T
Field index m	6.8	3.0
Orbit excursion	0.50 m	1.13 m
Cell tune	0.3957 / 0.0861	0.3510 / 0.1515

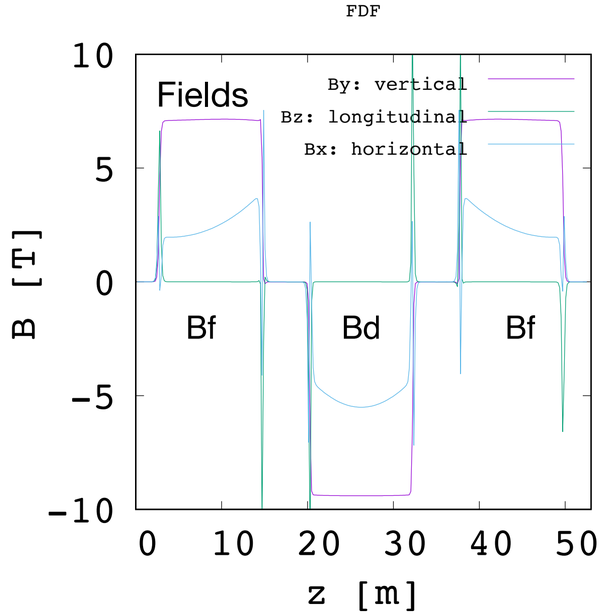
FODO



FDF







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c.f. Acceleration with RCS

Neufer and Shiltsev, JINST **13** (2018) T10003

Table 1. Muon RCS Accelerator Parameters

Scenario	"LHC-S"	"LHC-D"		"SPS"
C, km	26.7	26.7	26.7	6.9
E_{max}, TeV	7	7	4	0.45
E_{inj}, TeV	0.45	4	0.45	0.03
f_{rep}, Hz	5	4	4	20
ΔE/turn, GeV	14.0	3.5	9.2	3.7
B_{SC}, T	16	16	16	8
L_{SC}, km	4.8	7.1	2.9	0.63
B_{pls}, T	3.8	2.0	1.9	0.8
τ_{ramp}, ms	42	76	34	2.6
dB_{pls}/dt, T/s	180	52	112	615

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Muon collider ring

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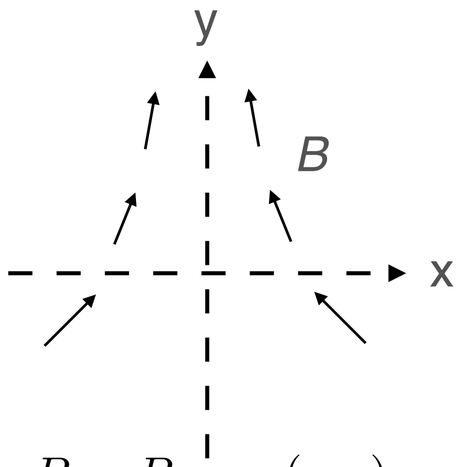
Design principle

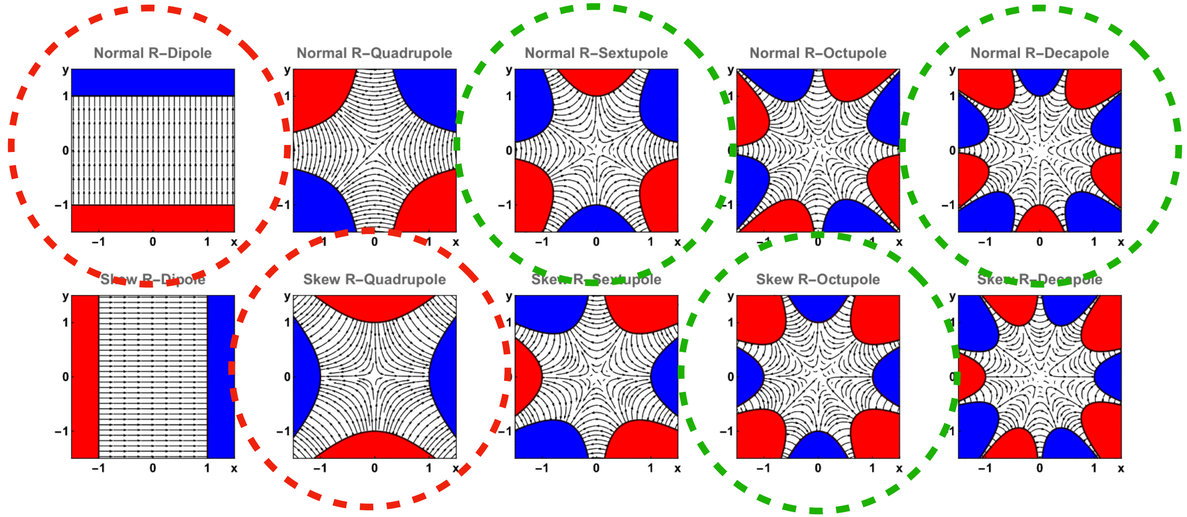
- Circumference should be as small as possible..
- Energy is 1.5 TeV.
- Momentum compaction factor is zero if required.
- Large momentum acceptance.
- Maximum field is no more than 14 T (use the same criterion of LEMMA accumulator ring).
- Follow vFFA idea but use only up to skew quadrupole.

$$\frac{B_y}{B_0} = \exp(my)\cos(mx) \approx 1 + my + \frac{m^2}{2!}(y^2 - x^2) + \frac{m^3}{3!}(y^3 - 3x^2y) + \ldots$$

Normal Dipole Skew Quad Normal Sext Skew Oct



$$B = B_0 \exp(my)$$



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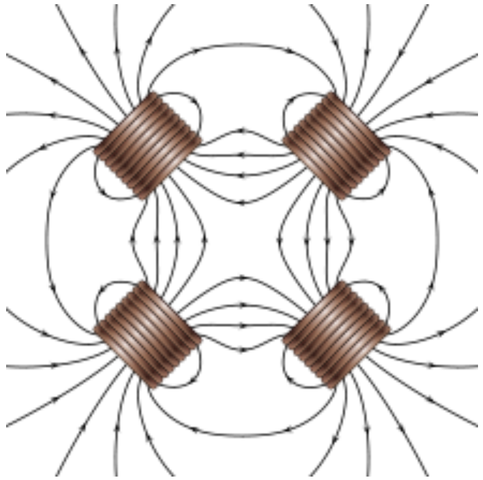
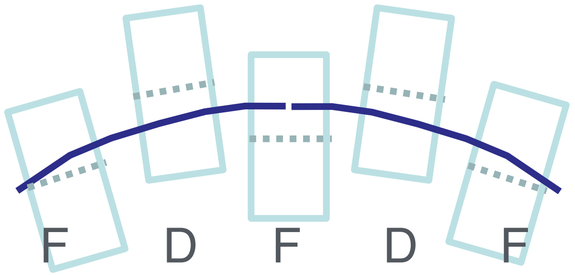
Combined function (CF) lattice

Normal quadrupole

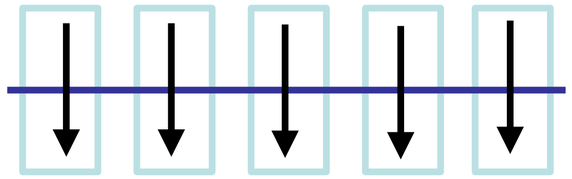
- F (normal bend) and D (normal bend) make the orbit circle.
- Vertical field get stronger **along radial direction**
- **Equilibrium orbit moves horizontally.**



Top view



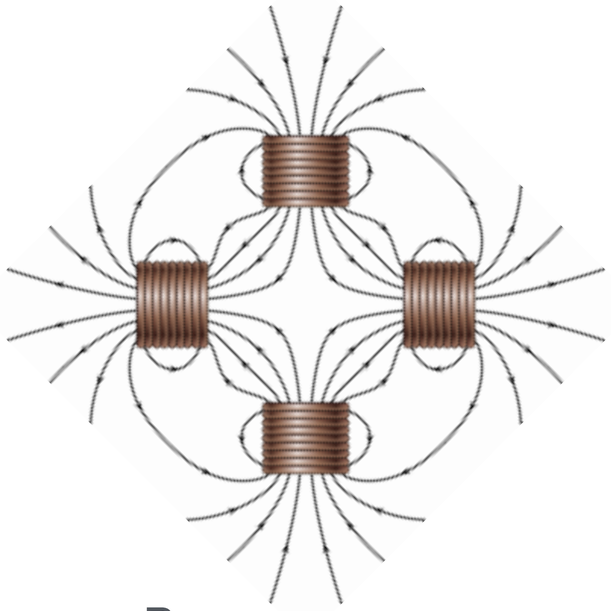
Side view



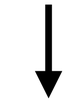
Normal CF

Skew quadrupole

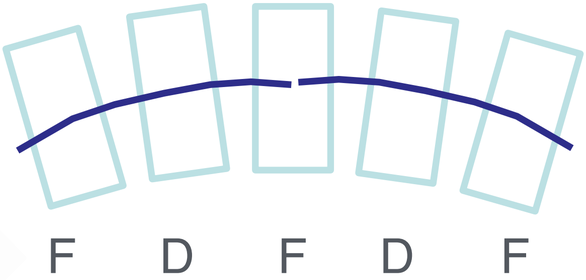
- F (normal bend) and D (normal bend) make the orbit circle.
- Vertical field get stronger **along vertical direction**
- **Equilibrium orbit moves vertically.**



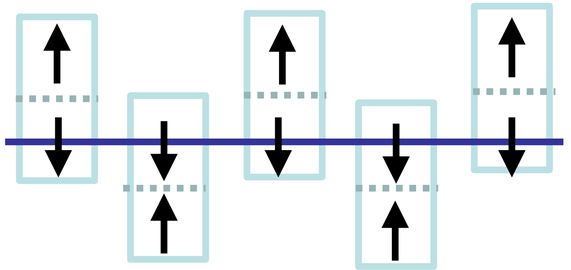
Bz



Top view



Side view



Skew CF (novel optics)

1.5 TeV collider ring

Without constraint of momentum compaction = 0.

Minimise circumference.

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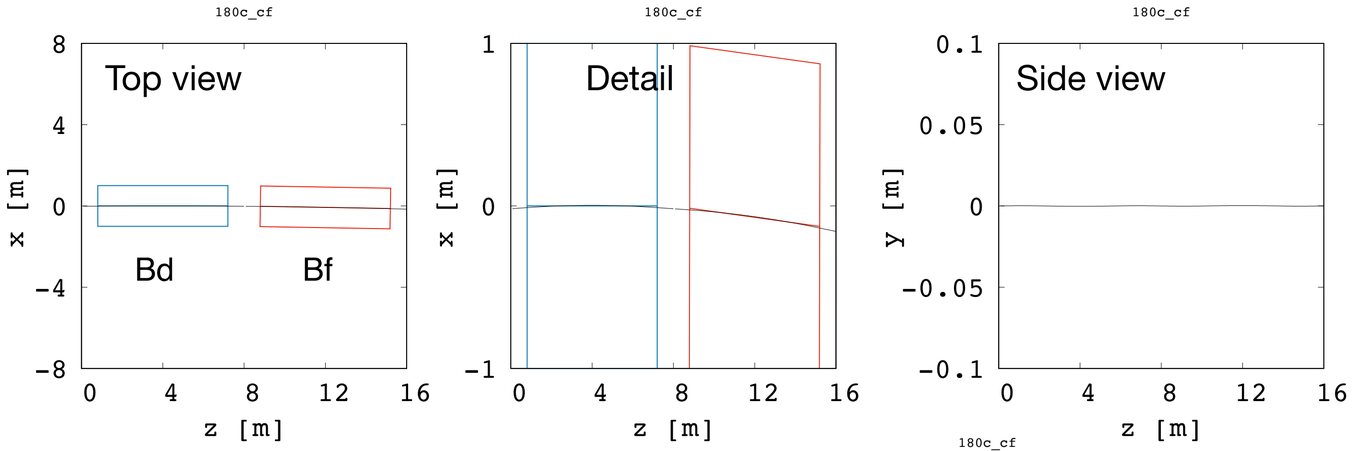
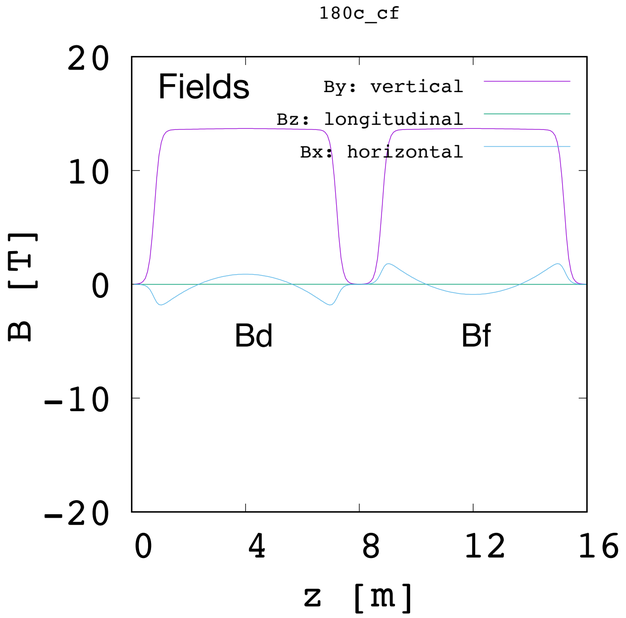
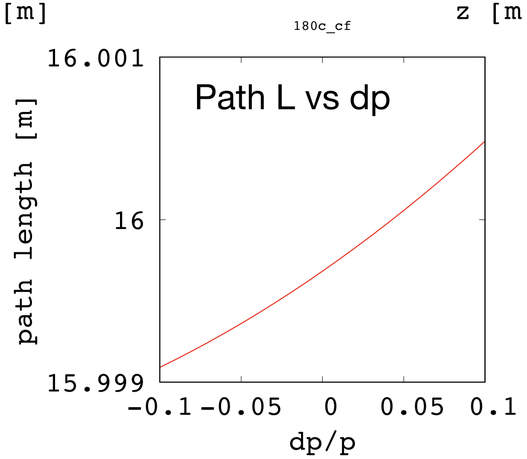
1.5 TeV collider ring

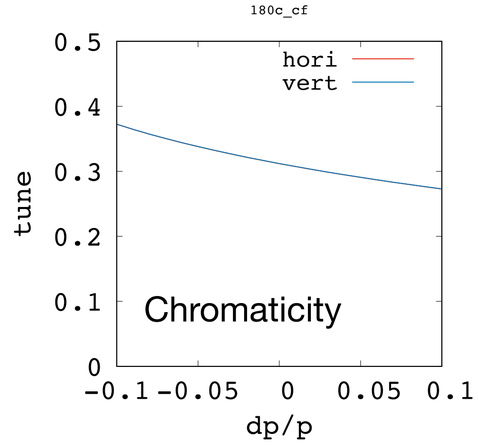
minimise circumference, arc only

	Skew FODO
Energy	1.5 TeV
Momentum compaction	4.32 x 10^{-4}
Circumference	2880 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	180
Maximum field	14 T
Field gradient	240 T/m
Cell tune	0.3119 / 0.3119









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1.5 TeV collider ring

minimise circumference, arc only

	Normal FODO
Energy	1.5 TeV
Momentum compaction	4.32 x 10^{-4}
Circumference	2880 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	180
Maximum field	14 T
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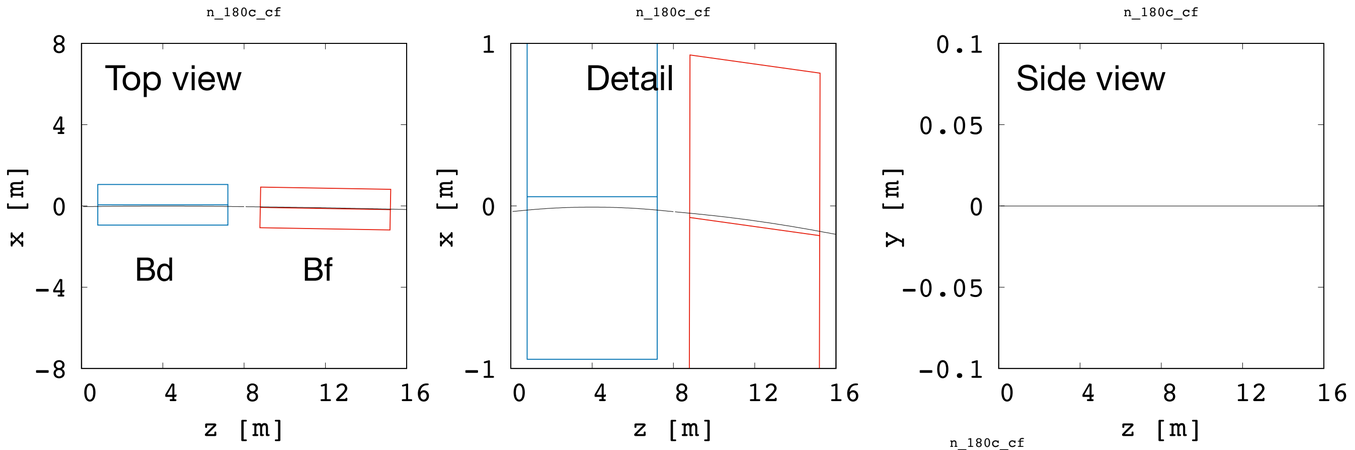

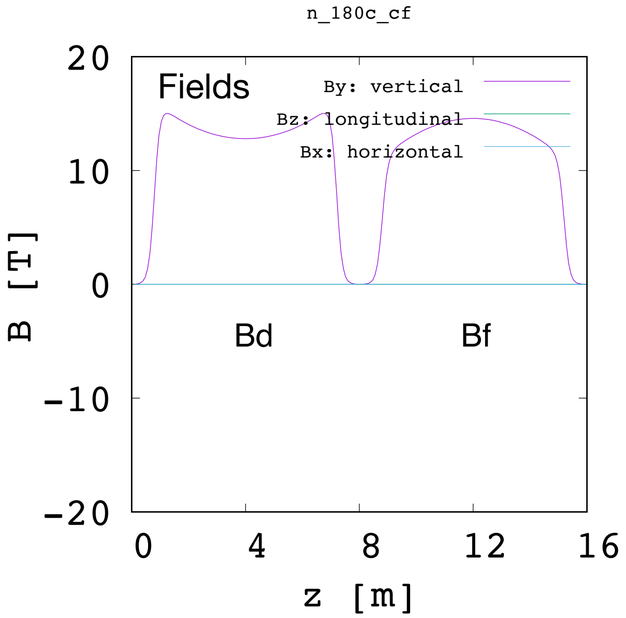

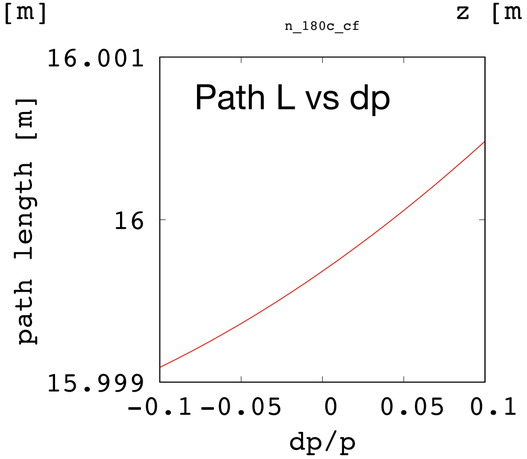

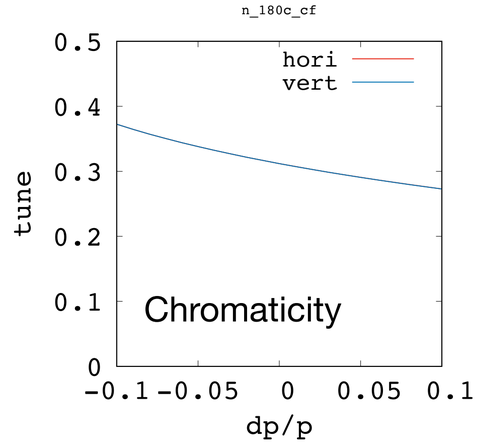

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1.5 TeV collider ring

Impose constraint of momentum compaction = 0.

Allow increase of circumference.

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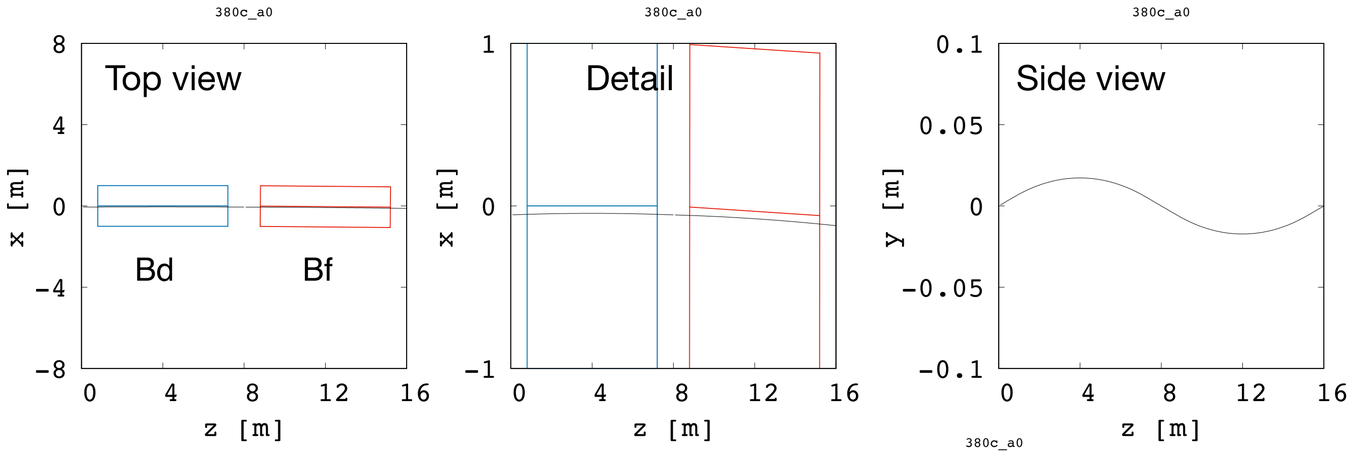
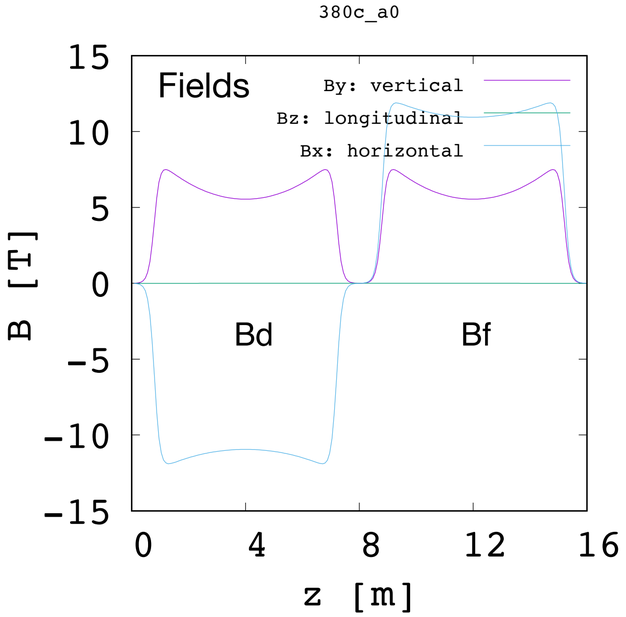
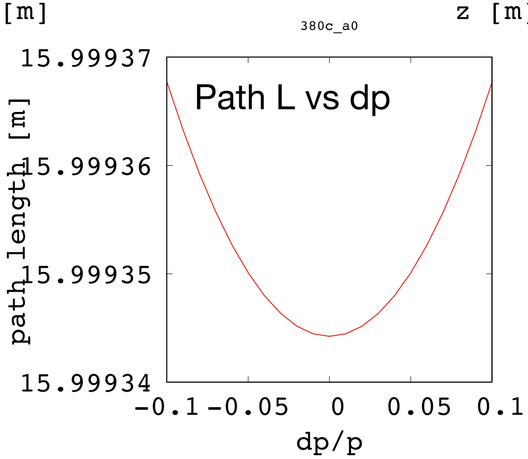
1.5 TeV collider ring

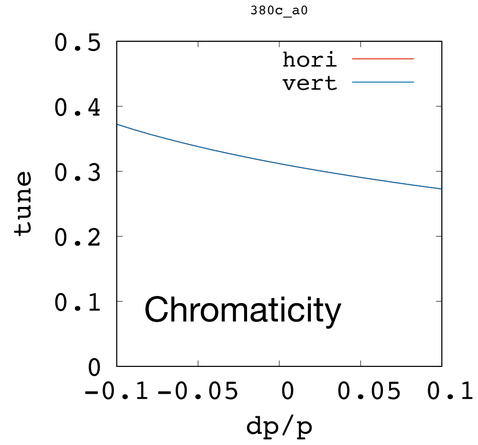
momentum comp=0, arc only

	Skew FODO
Energy	1.5 TeV
Momentum compaction	0
Circumference	6080 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	380
Maximum field	14 T
Field gradient	240 T/m
Cell tune	0.3131 / 0.3131









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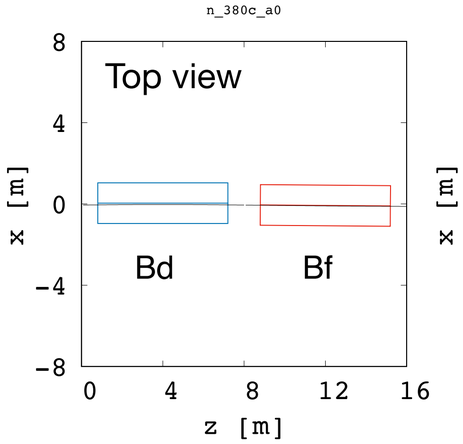
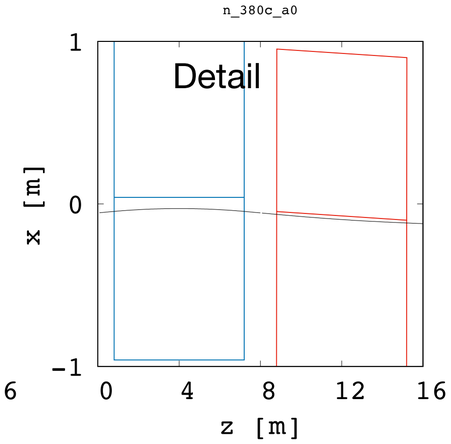
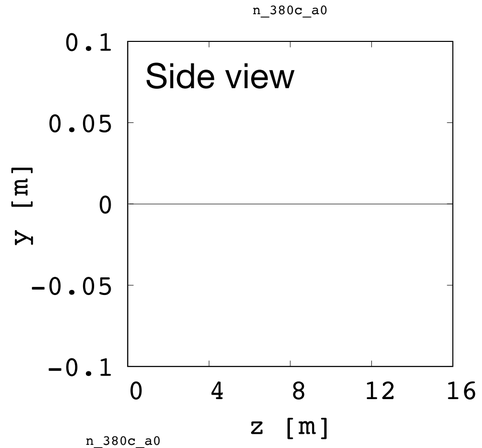
1.5 TeV collider ring

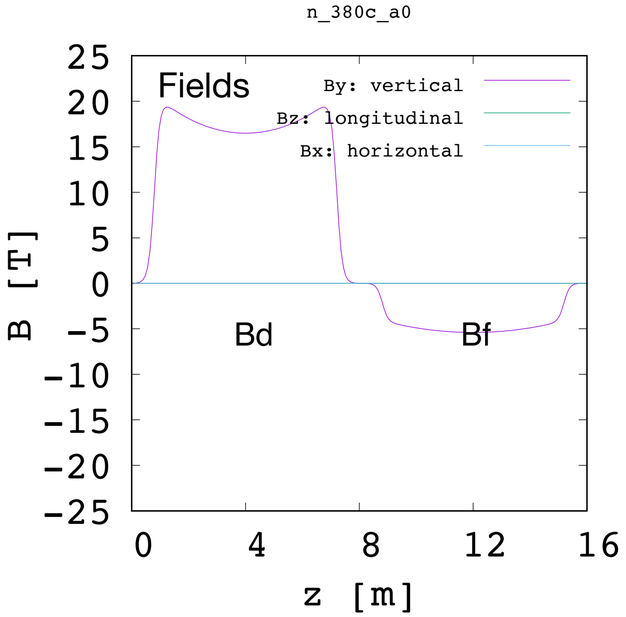
momentum comp=0, arc only

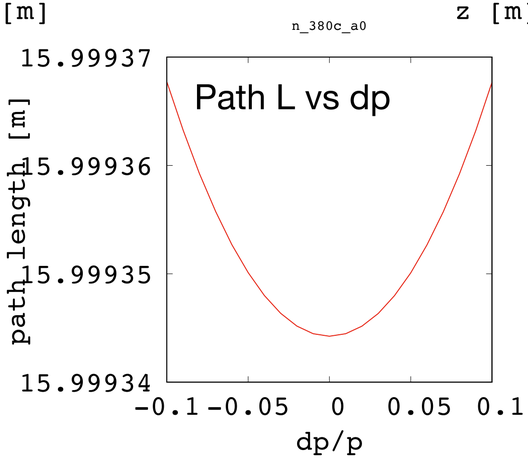
	Normal FODO
Energy	1.5 TeV
Momentum compaction	0
Circumference	6080 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	380
Maximum field	20 T
Field gradient	240 T/m
Cell tune	0.3131 / 0.3131

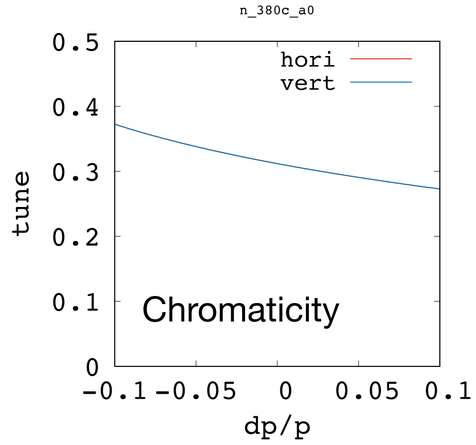












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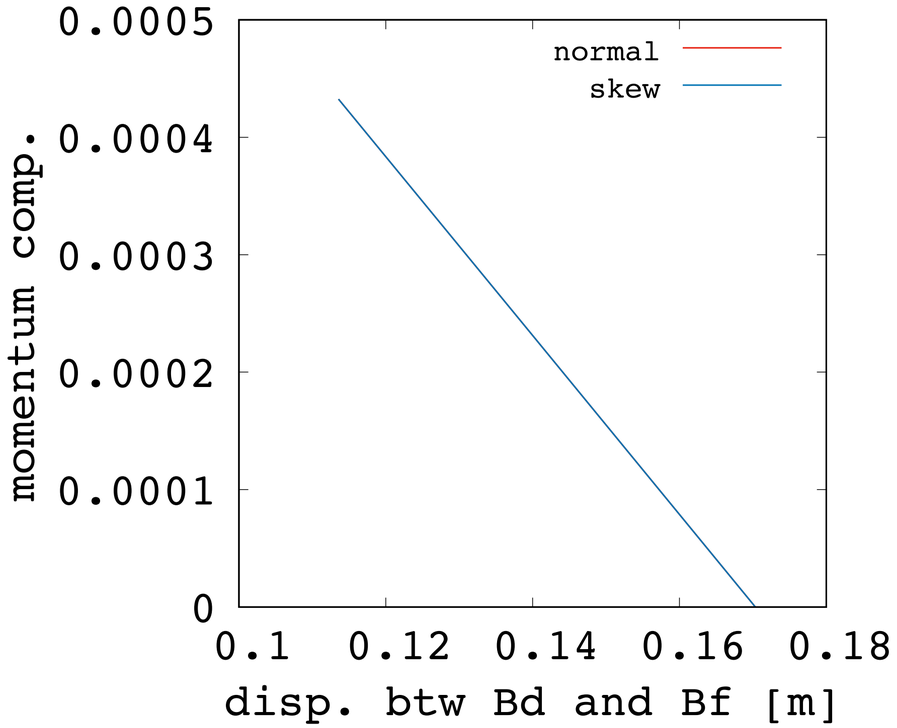
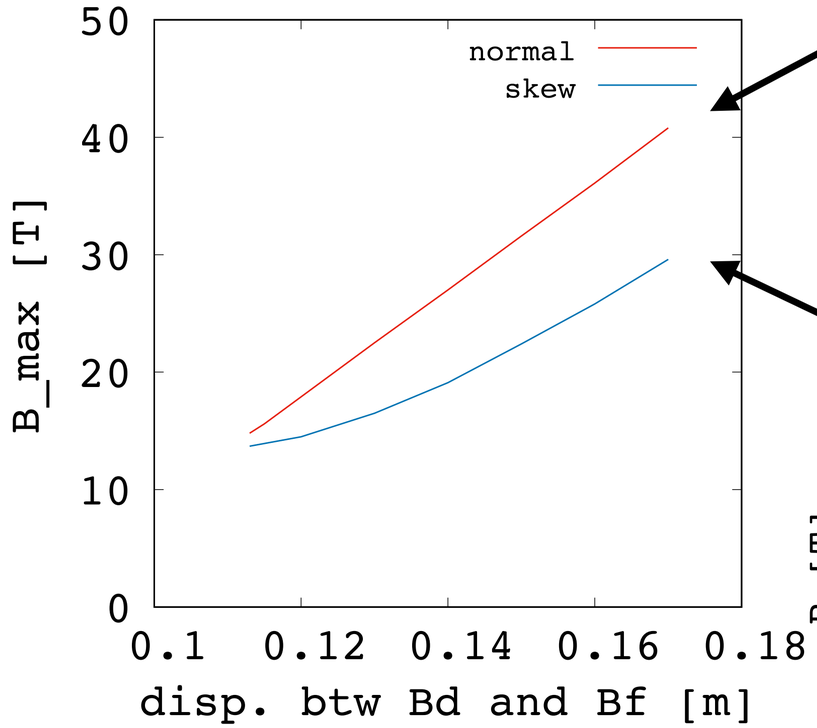
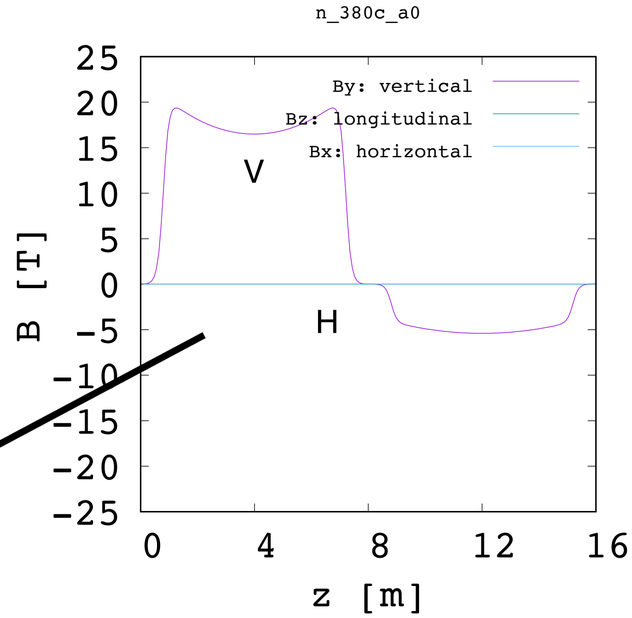
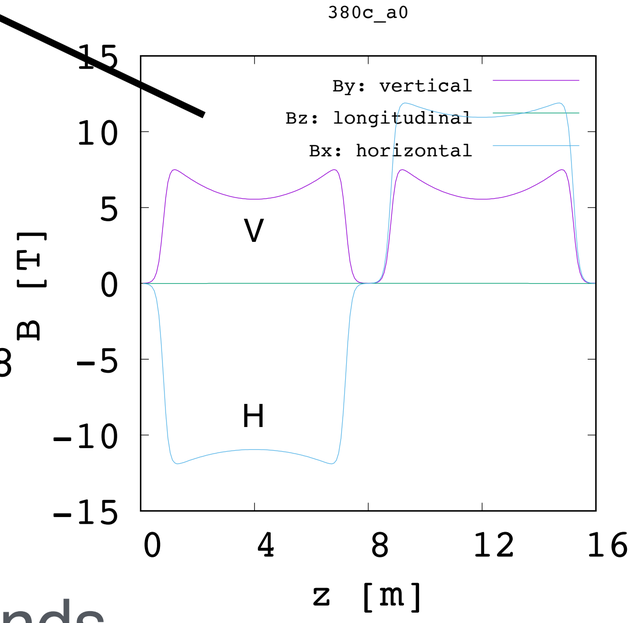
1.5 TeV collider ring

momentum compactor and maximum field strength









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Skew CF does not need negative bends.

Muon accumulator ring (LEMMA)

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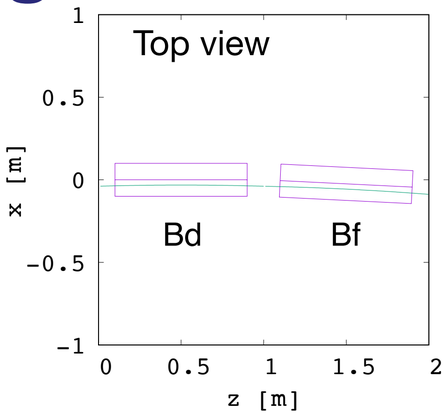
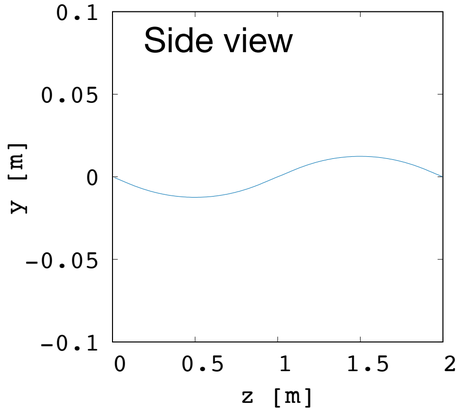
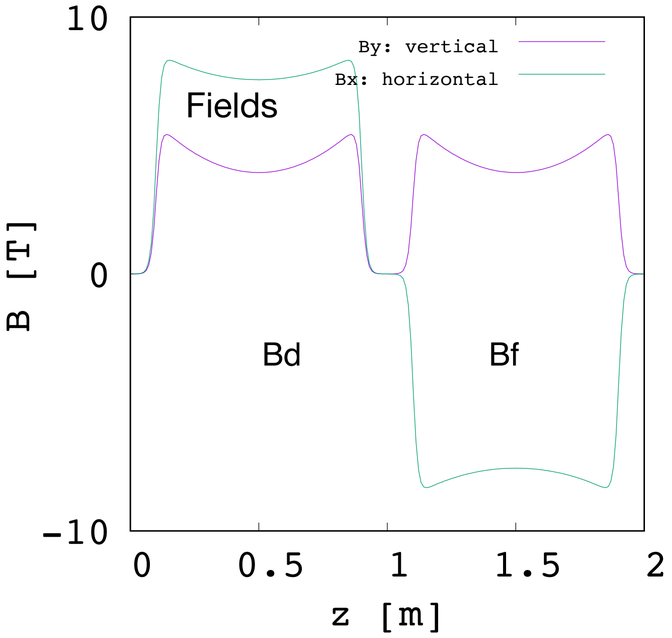
22.5 GeV accumulator ring for LEMMA

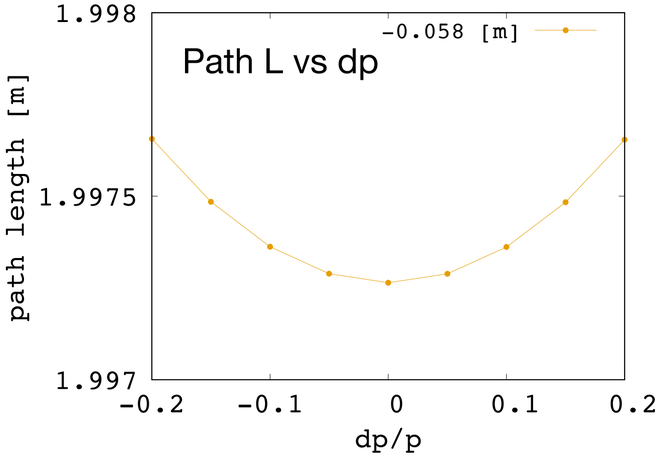
arc only

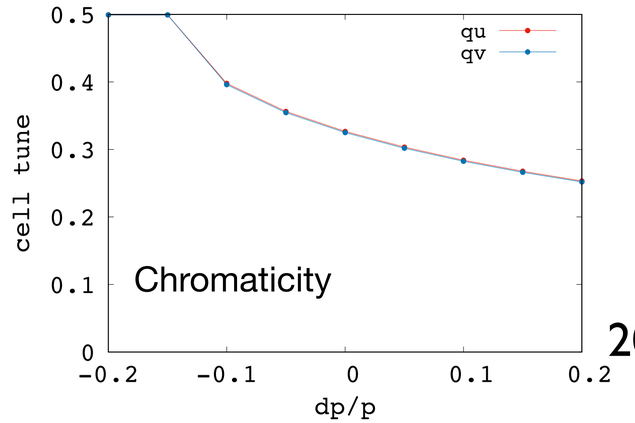
	Skew FODO
Energy	22.5 GeV
Momentum compaction	0
Arc	128 m
Cell length	2 m
Magnet length	2 x 0.8 m
# of cell	64
Maximum field	10 T
Field gradient	238 T/m
Cell tune	0.3269 / 0.3261











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Low beta insertion

skew quadrupole channel

- No design yet.

- Conventional low beta straight of normal quadrupole with 45 degree rotation.
- or Skew combined function with wiggling orbit but zero net bending.

- Under the frame with 45 degree rotation, every element for the whole ring is normal quadrupole except weak focusing at bending which give ‘skew’ in that frame.
- Normal quadrupole magnets between arc and straight will work as correction of coupling.

Proton driver

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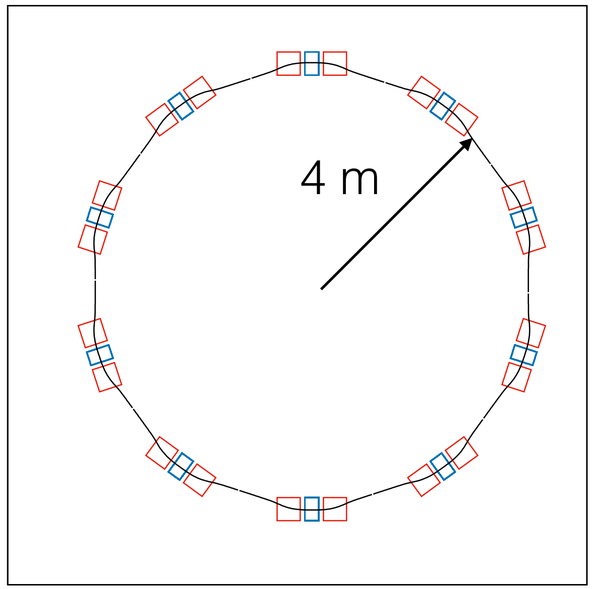
Proton driver

Not for muon facility, but as a prototype for ISIS upgrade plan

Energy	3 to 12 (17) MeV
Number of cell	10
Cell length	2.5 m
Length of Bd	0.24 m
Length of Bf	0.40 m
Space between Bd and Bf	0.08 m
Relative displacement btw Bd and Bf	+/- 0.0 m
Length of straight section	1.30 m
Fringe length L (Tanh x/L)	0.200 m
-Bd/Bf	0.2
Field index m	1.28 m^-1
Cell tune	(0.217844, 0.134228)
Order of expansion	10



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Summary

- vFFA and novel skew optics have great potential for muon collider accelerator complex.

- vFFA for muon accelerator
  - All advantage listed.
  - Negative bend increases the circumference.
  - Current design needs 8.7 T magnet to fit the ring in LHC tunnel to accelerate to 1.5 TeV

- Novel skew optics for muon collider and muon accumulator
  - Clear advantage on the required magnet strength compared with normal combined function magnet.
  - Need low beta insertion design.

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Thank you for your attention

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Backup slides

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vFFA

3D magnetic fields

All 3D magnetic fields have to satisfy the same dependence on the vertical coordinate.

$$B_z(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{zi}(x)\, y^i$$

$$B_x(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{xi}(x)\, y^i$$

$$B_y(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{yi}(x)\, y^i$$

Off mid-plane field is expanded as polynomial with *y*.

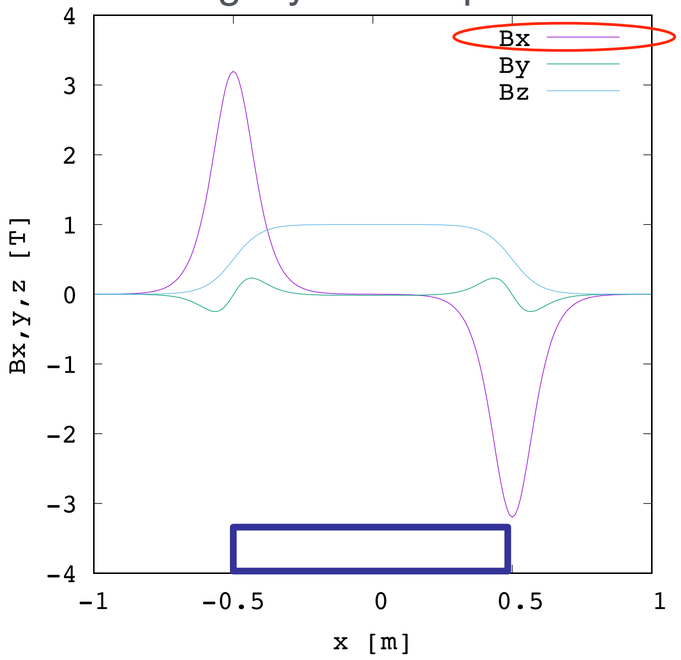
where

$$b_{z0}(x) = g(x)$$

$$b_{x0}(x) = \frac{1}{m}\frac{\partial g}{\partial x}$$

$$b_{y0}(x) = 0$$

Slightly off mid-plane



Non zero longitudinal field on mid-plane is something we did not have in a conventional accelerator.

Skew quadrupole (body) + Solenoidal field (ends)

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