FETS-FFA lattice and extension to higher energy

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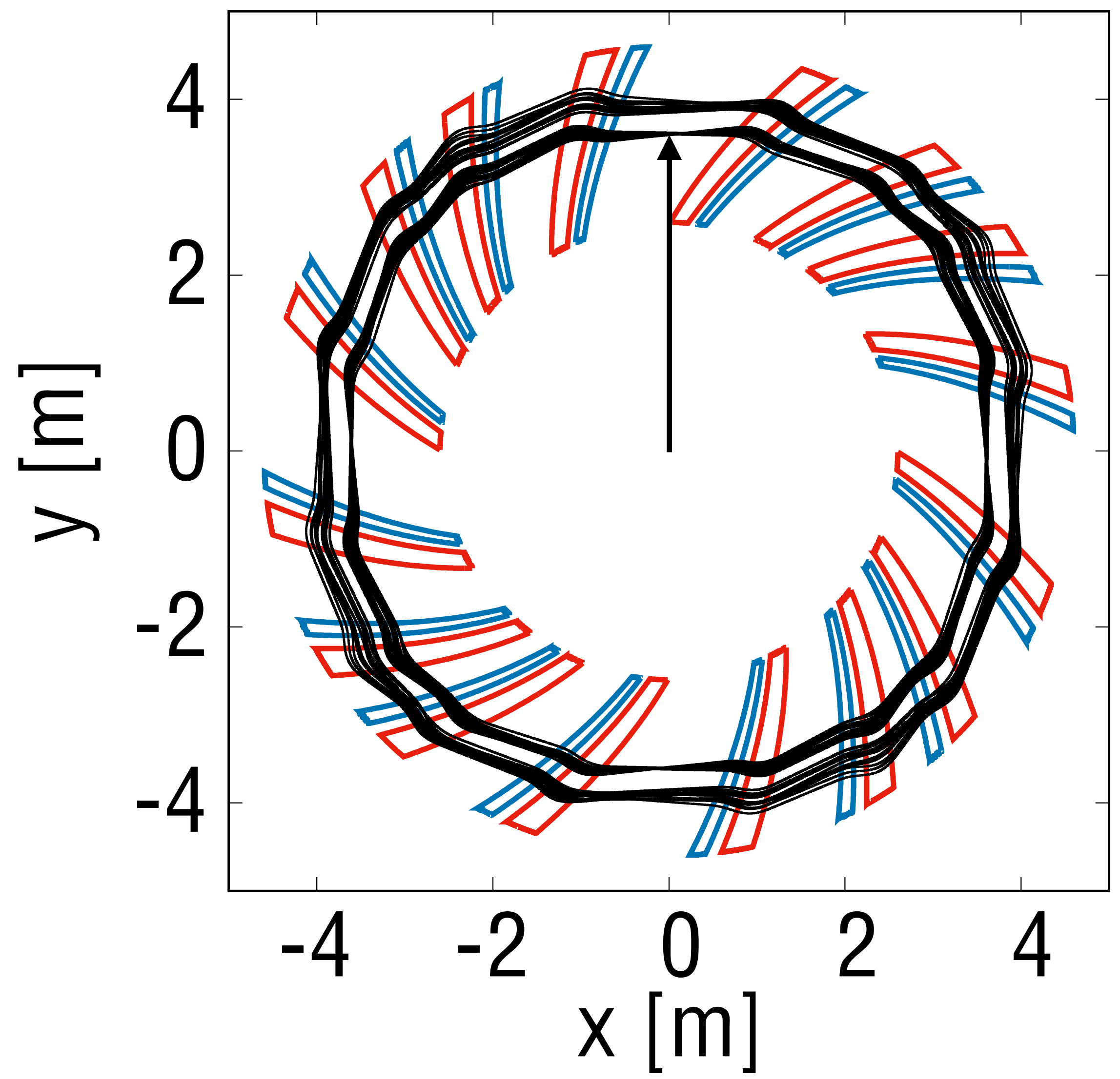
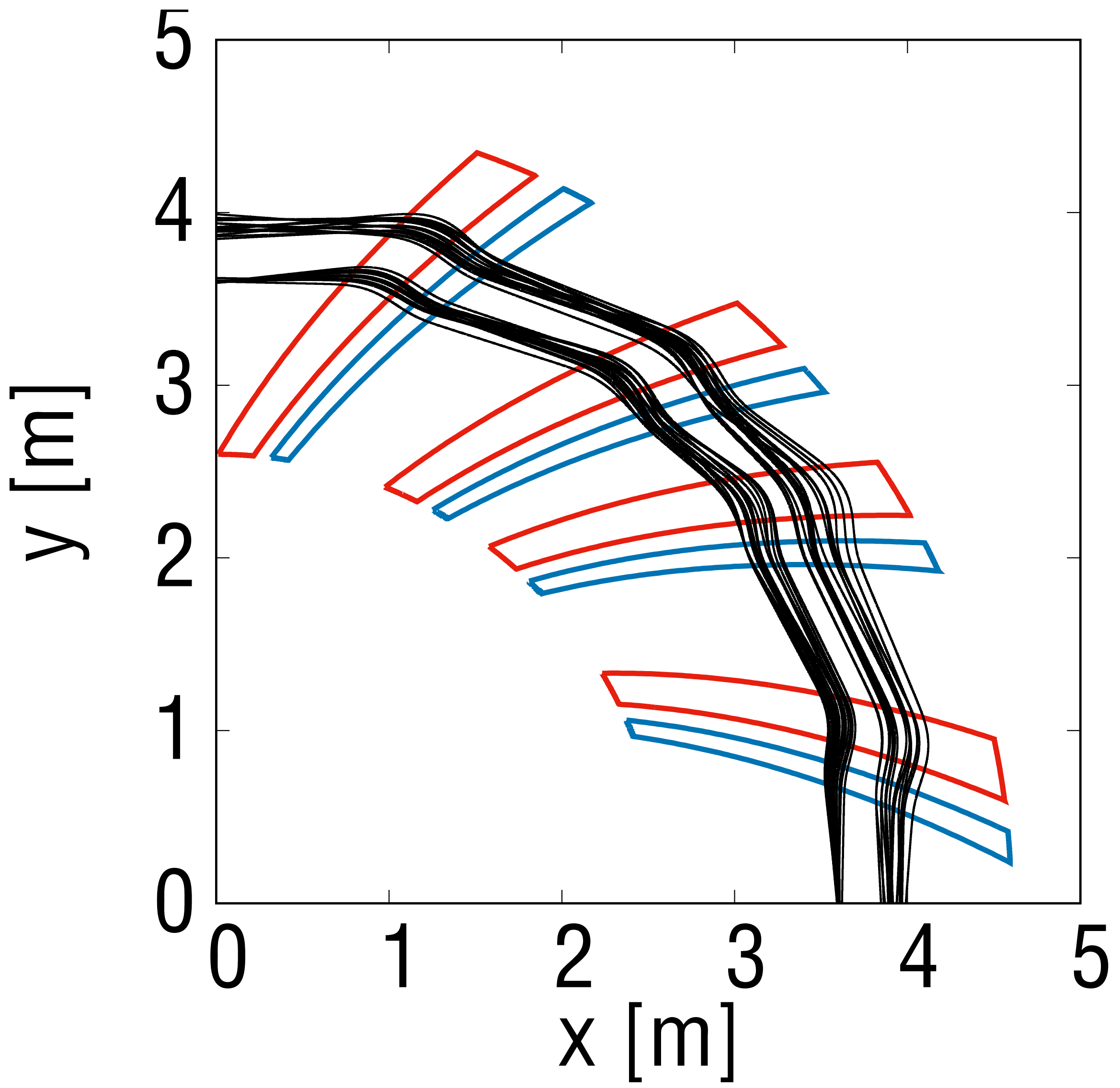
ISIS-II/LhARA common themes

FETS-FFA lattice

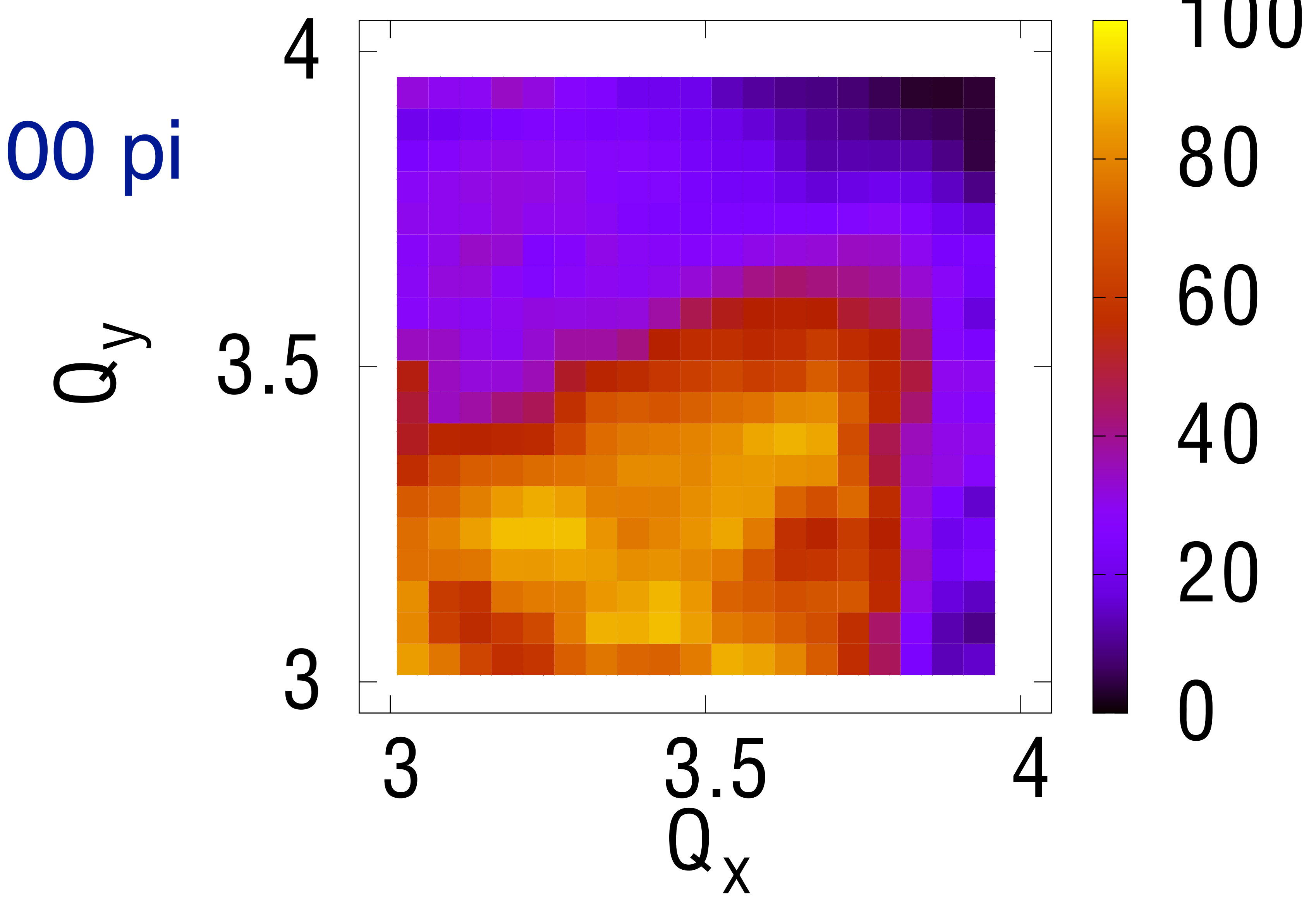
FETS-FFA lattice (latest)

- 4-fold superperiod lattice
- Orbit radius at injection at drift space is 3.6 m.





Dynamic aperture is ~100 pi mm mrad at maximum.



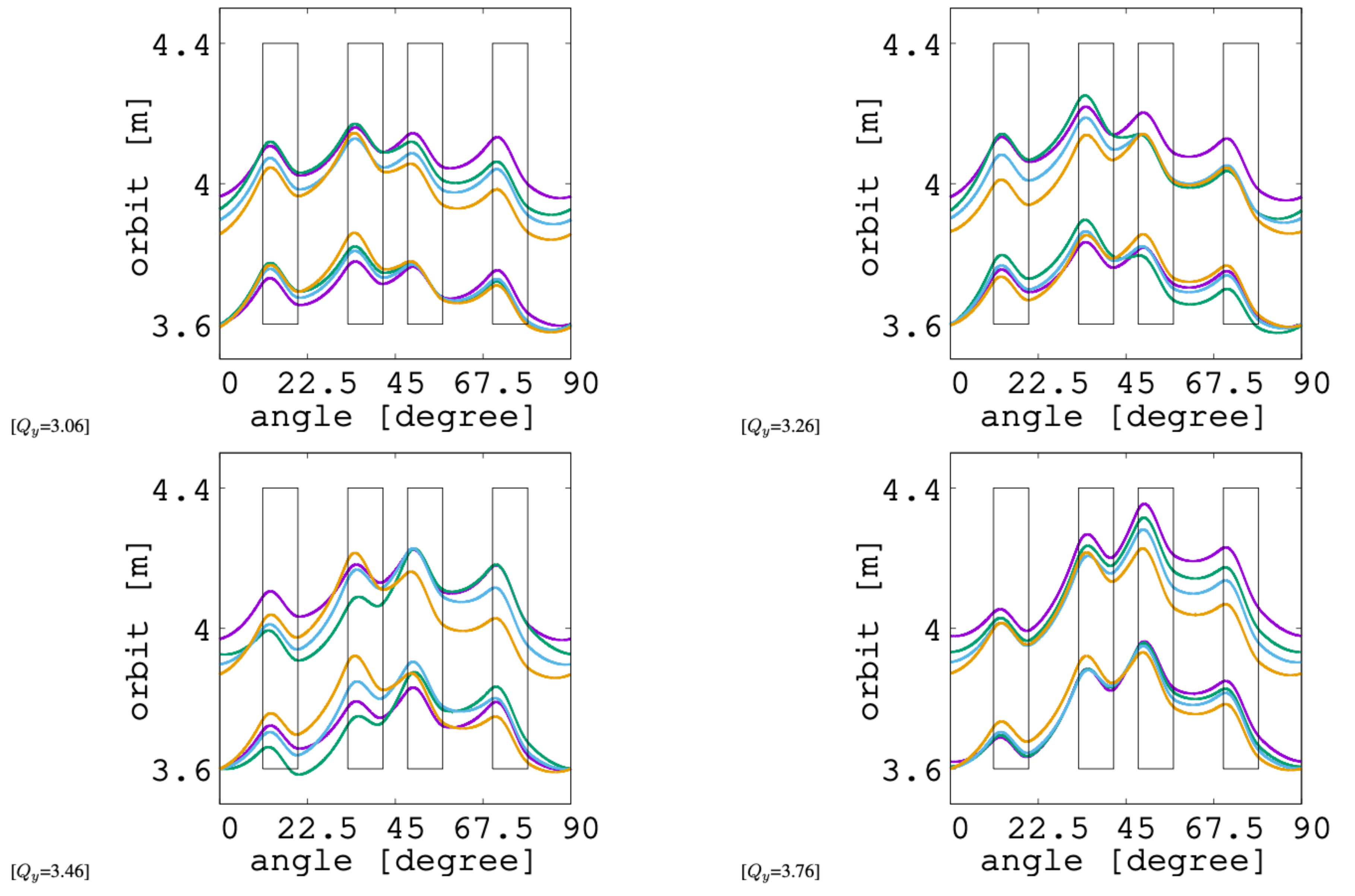


Figure 2.8: 3 MeV and 12 MeV orbits for 16 operating points.

	doublet 1	doublet 2	doublet 3	doublet 4
r_{min} [m]	3.5835	3.7143	3.6684	3.5900
r_{max} [m]	4.1688	4.2695	4.3561	4.2324
orbit excursion [mm]	585	555	688	642

Table 2.2: Horizontal beam size and acceptance

	normalised [π mm mrad]	un-normalised [π mm mrad]	Physical size [mm]
beam core	10	125	±20
collimator acceptance	20	250	±28
physical acceptance	40-80	500-100	±40-57

Table 2.5: Vertical beam size and acceptance

	normalised [π mm mrad]	un-normalised [π mm mrad]	Physical size [mm]
beam core	10	125	±16
collimator acceptance	20	250	±23
physical acceptance	40-80	500-100	±32-45

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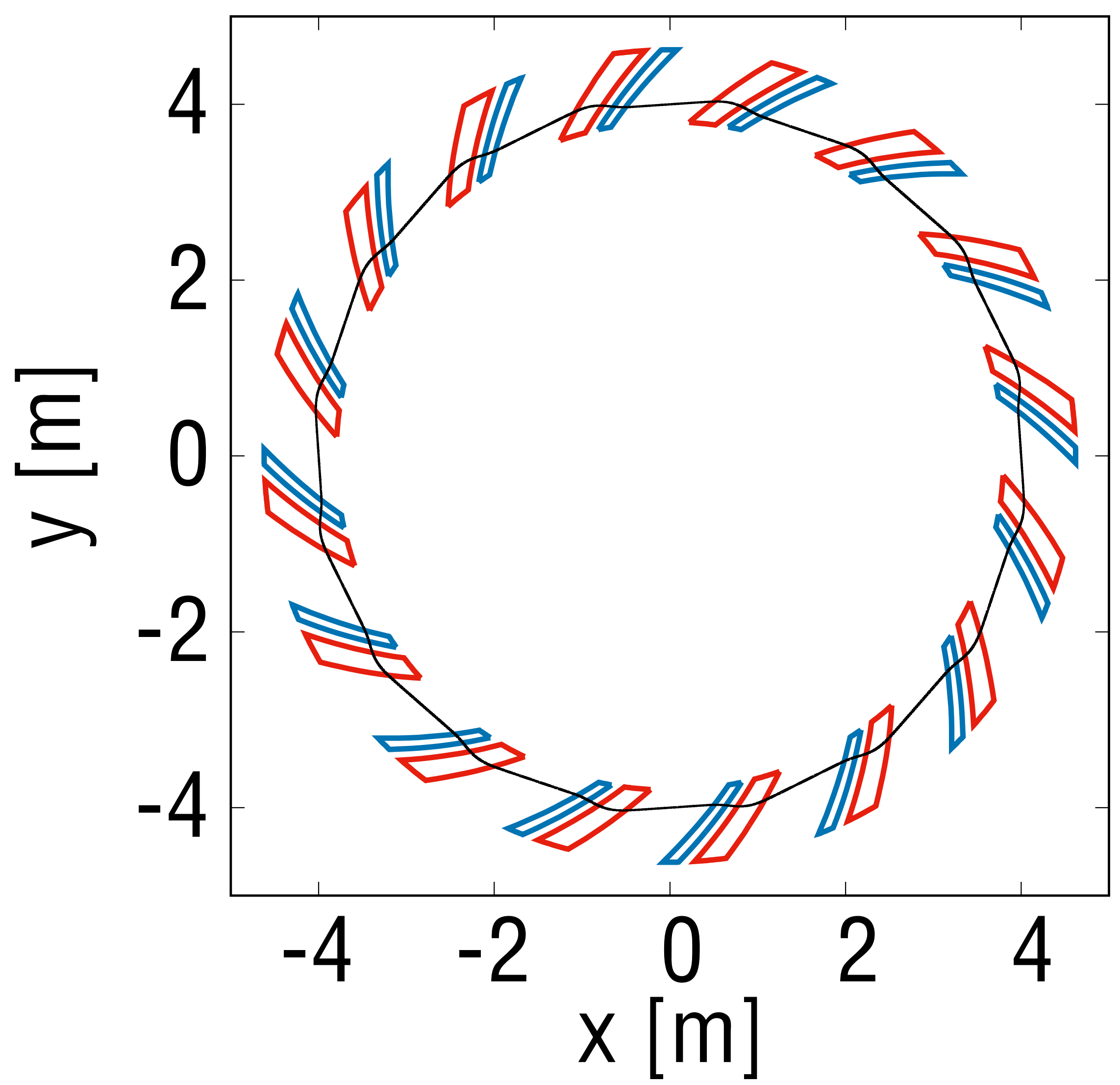
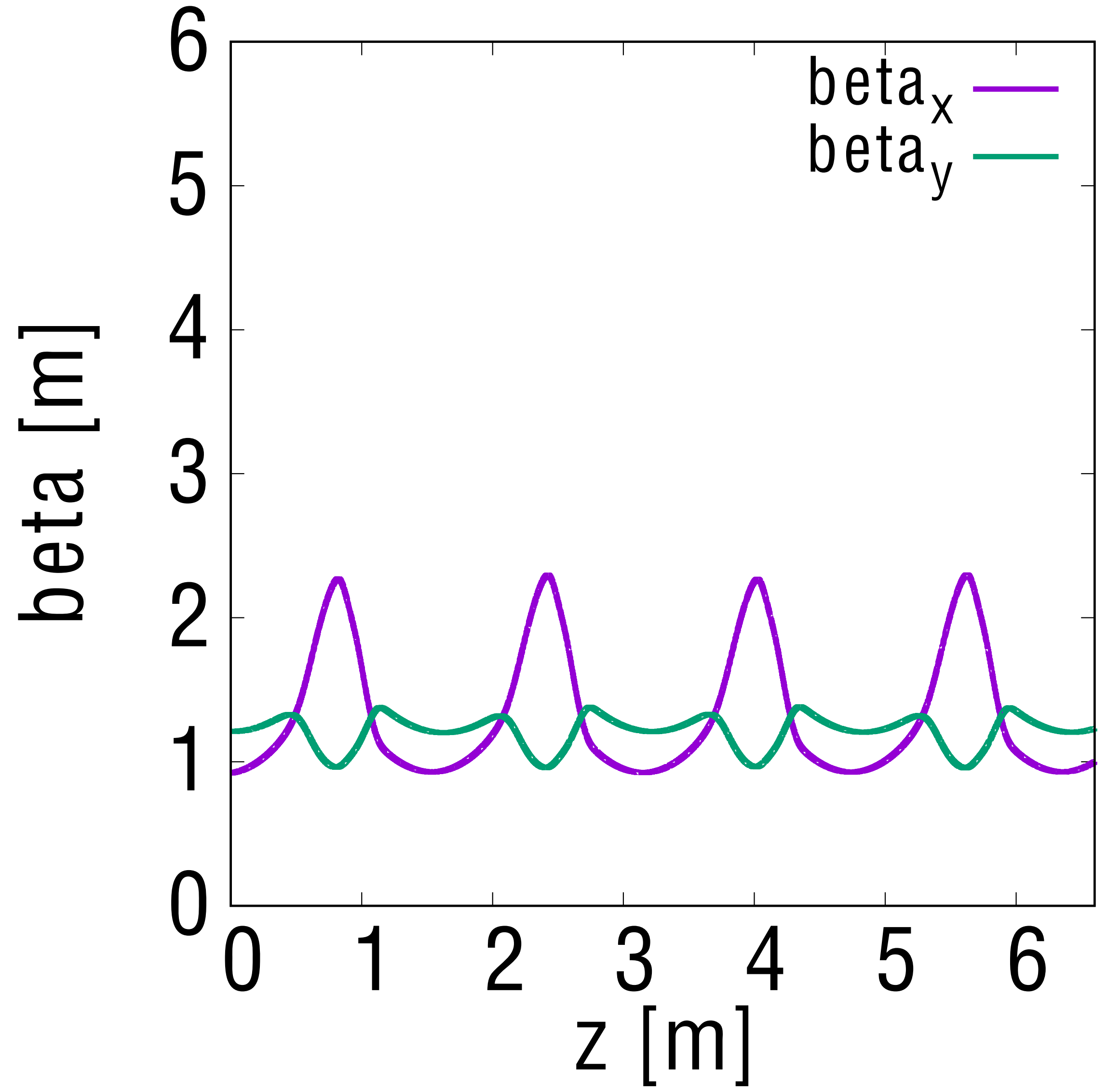
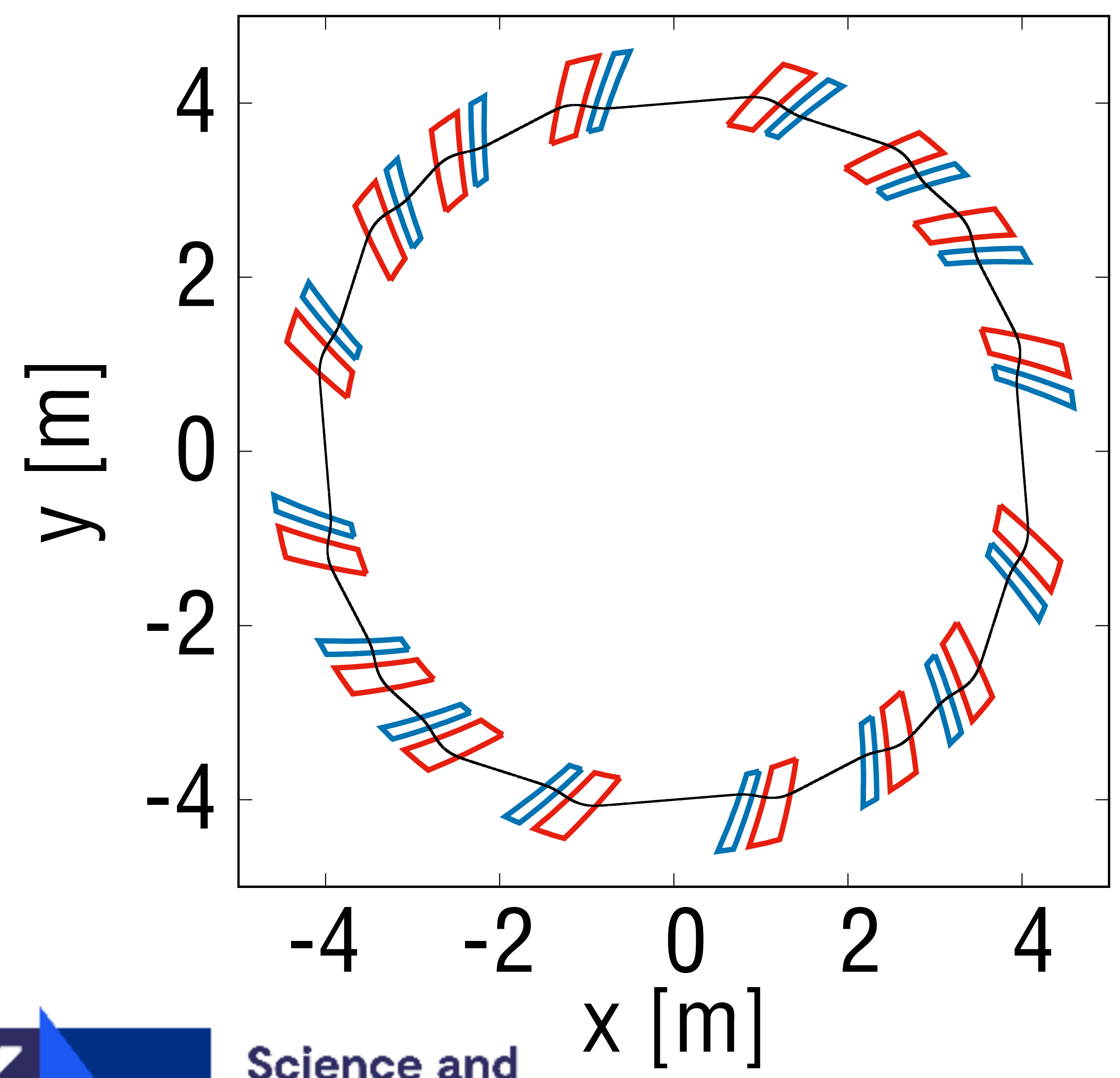
Baseline lattice changed!

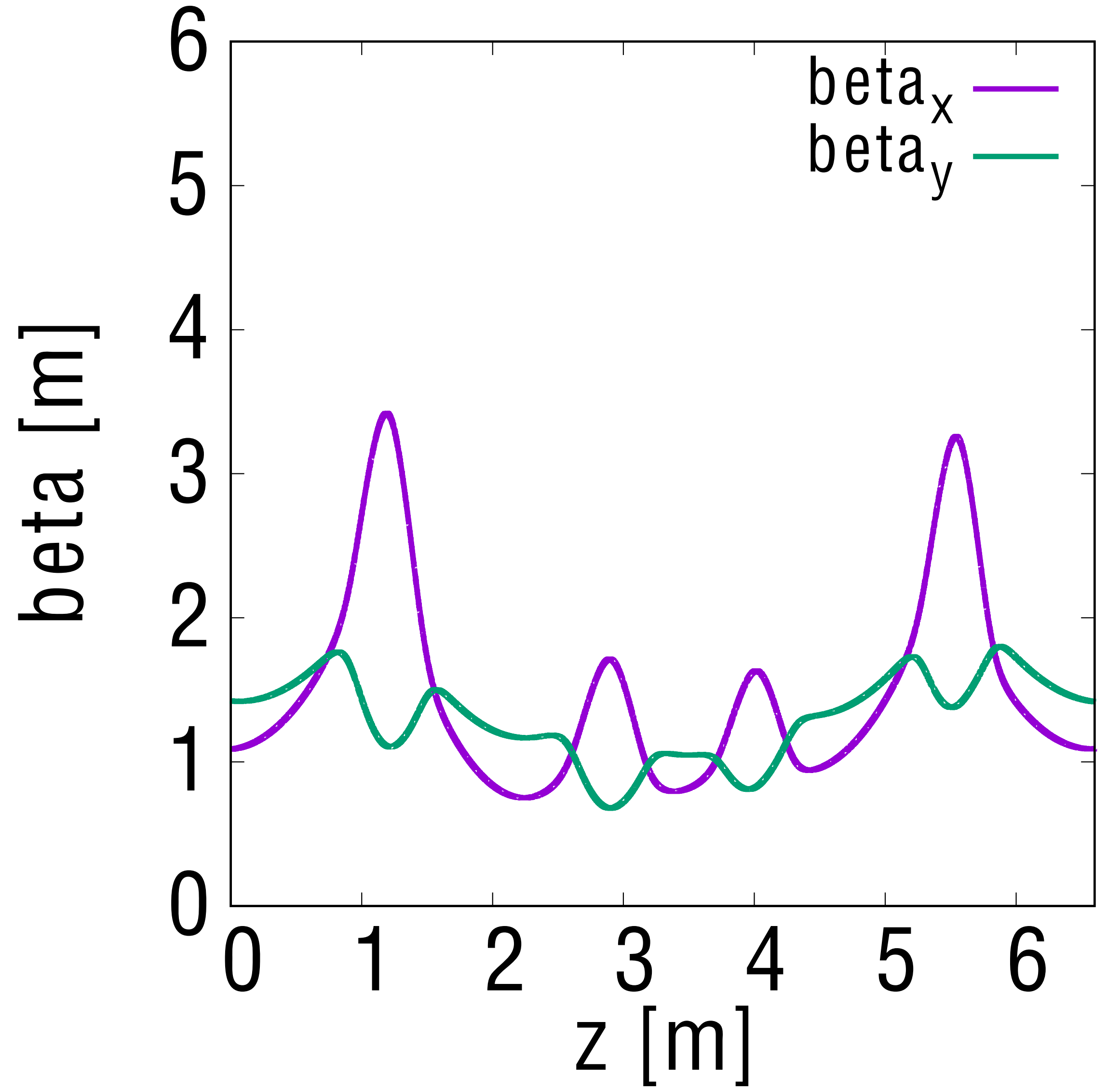




16-fold symmetry

Straight length: 0.95 m
Dynamic aperture: 110 pi mm mrad
Field index k: 8.00
Spiral angle: 45 degree
Magnet families: 2





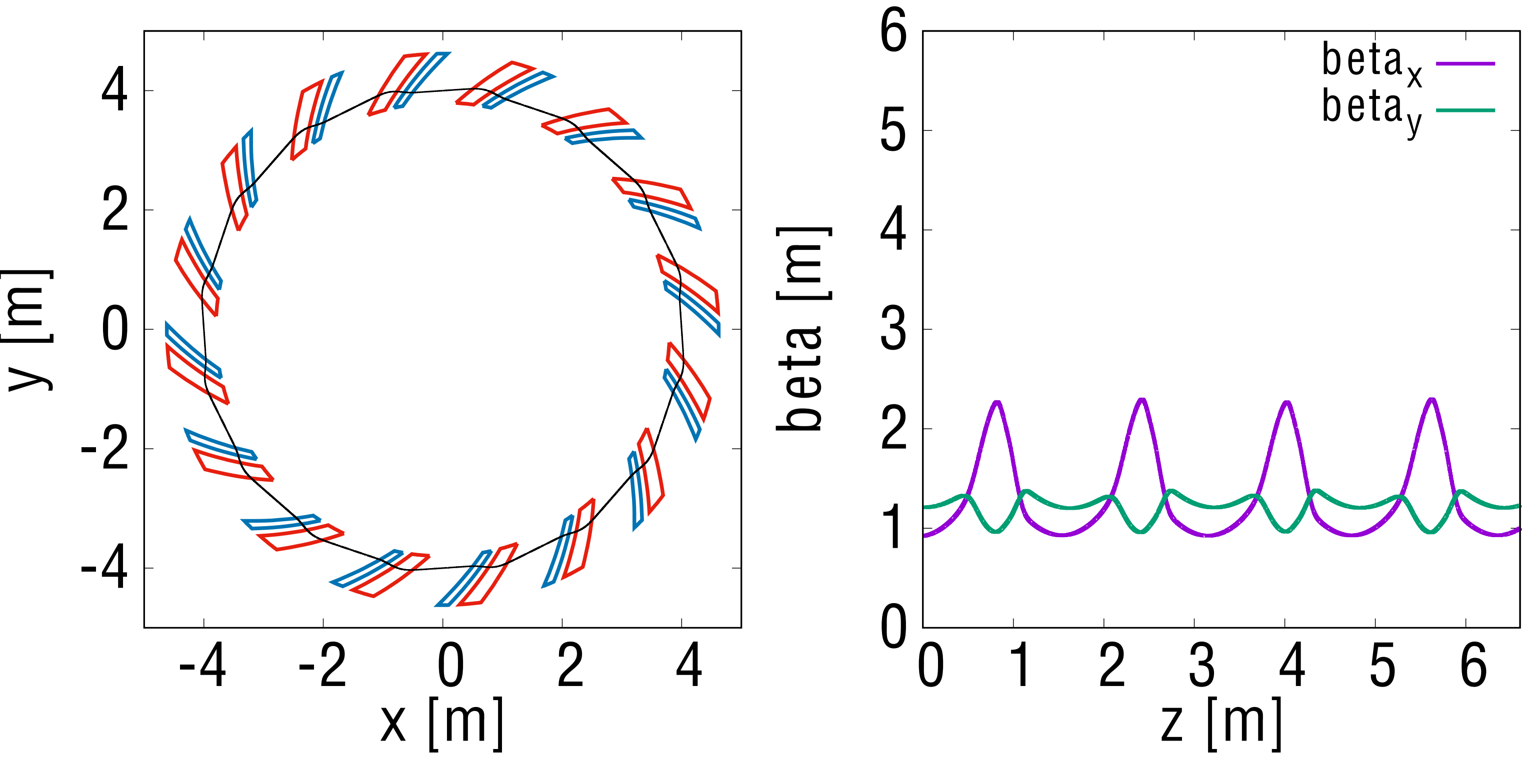
4-fold symmetry

Straight length: **1.55 m**, 0.90 m, 0.45 m
Dynamic aperture: 80 pi mm mrad
Field index k: 7.40
Spiral angle: 30 degree
Magnet families: 8

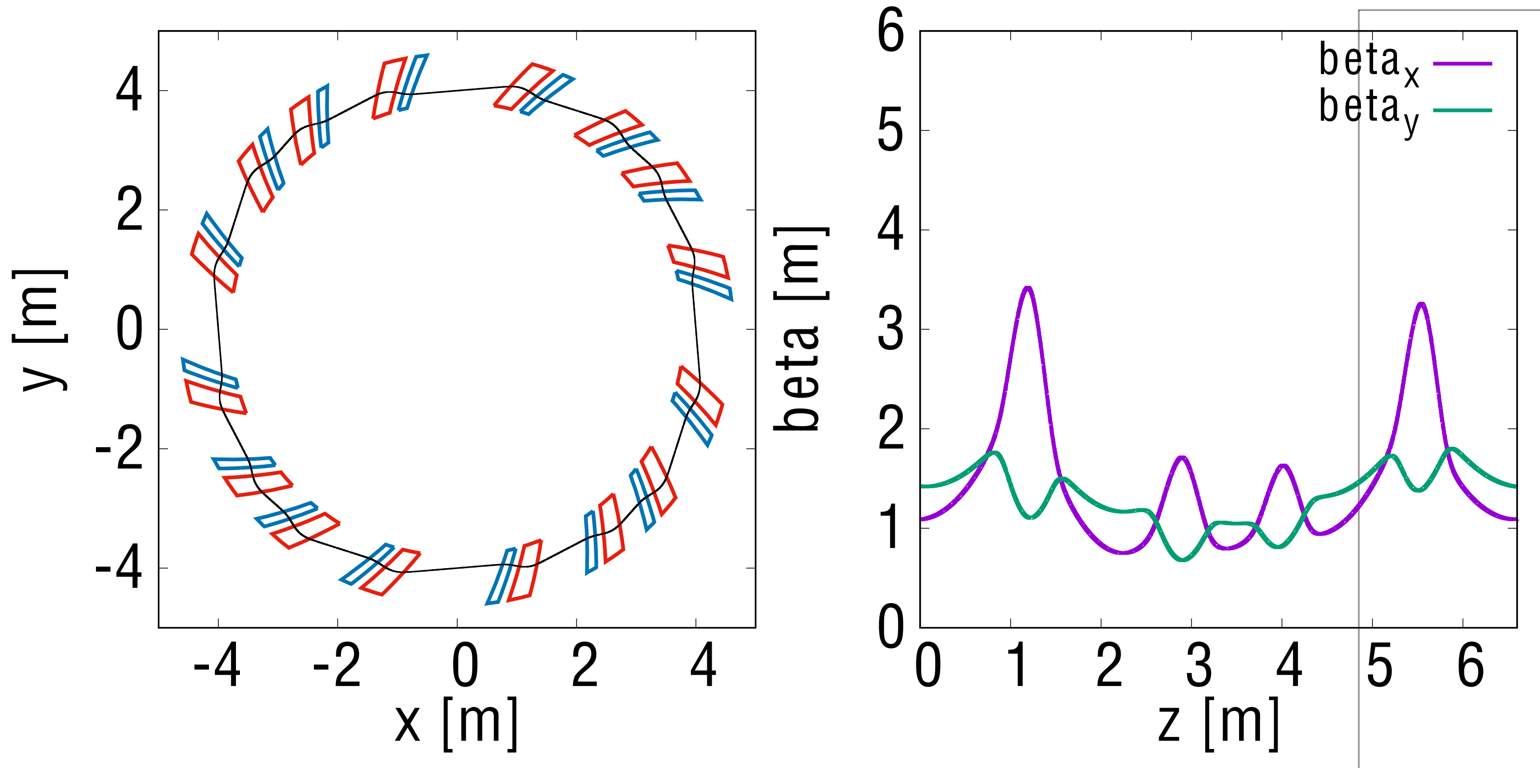
Horizontal beam size is larger.

Comparison between FETS-FFA and LhARA

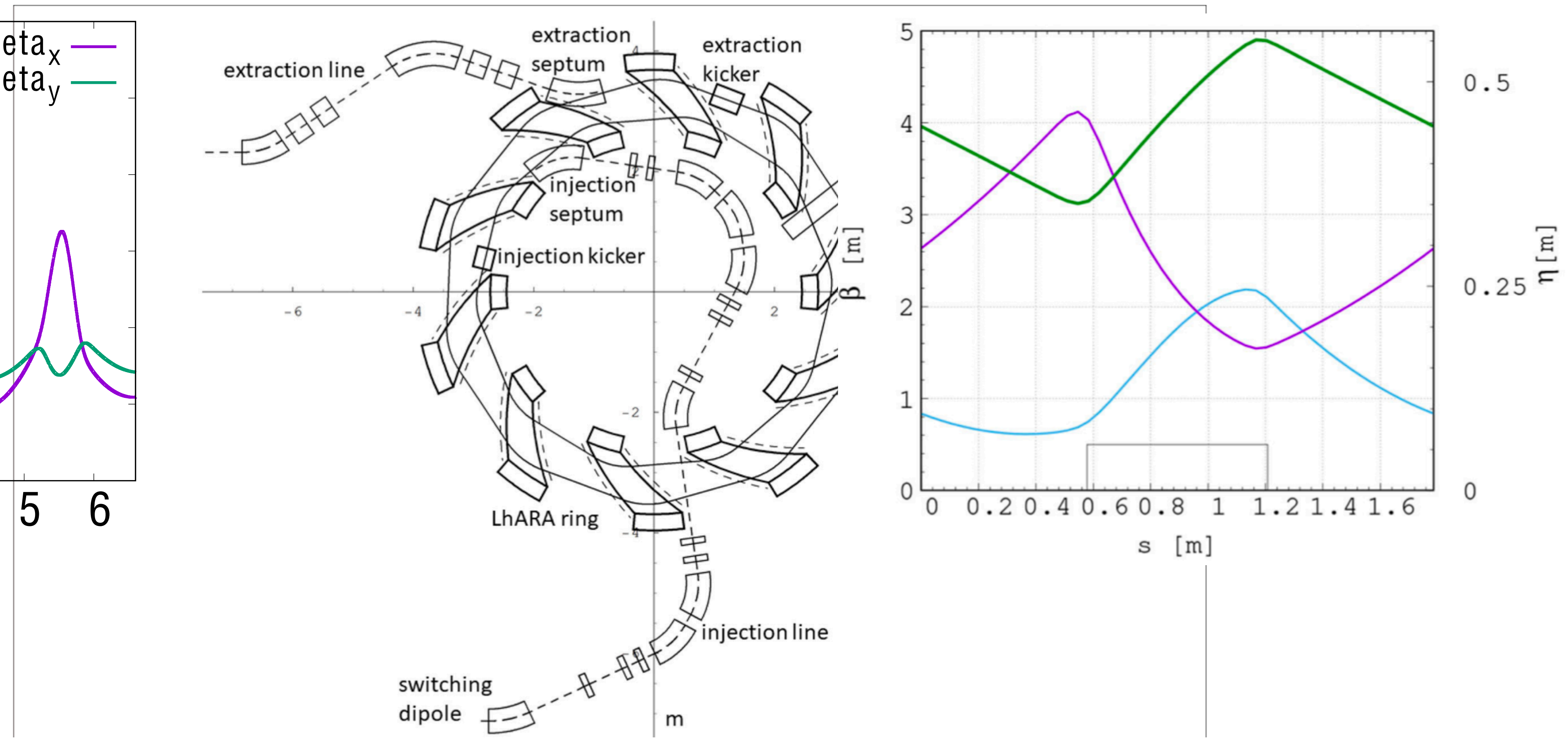
FETS-FFA (16-fold sym)



FETS-FFA (4-fold sym)



LhARA



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Goals (success criteria)

FETS-FFA	LhARA
Demonstrate a **high intensity FFA operation** with minimum beam loss.	Demonstrate acceleration of **multiple ions** with **variable energy** (and variety of time structure for Stage 1).
• Transverse emittance and aperture - **Large** • Momentum spread - **Small** • Pulse length - **micro second** • # of particles - 10^{11} protons	• Transverse emittance and aperture - **Small** • Momentum spread - **Large** • Pulse length - **micro second** • # of particles - 10^{9} protons

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Parameters (physics)

	FETS-FFA (16-fold sym)	FETS-FFA (4-fold sym)	LhARA	notes
Momentum	**p: 0.075 - 0.151 GeV/c [3 - 12 MeV]**	<- same	**p: 0.168 - 0.504 GeV/c [15 - 127 MeV]** C^{6+}: 0.173 - 0.505 GeV/c	**x 2.3 at inj** x 3.3 at ext
Radius	4.0 - 4.42 m	4.0 - 4.8 m (now 3.6 - 4.4 m)	2.92 - 3.48 m	
Number of cell	16	4 per s.p. and 4 s.p makes a ring	10	
Lattice	**Doublet (FD) spiral**	<- same	**Single (F) spiral**	
Magnet packing factor	F: 0.20, D: 0.10	<- same	F: 0.34	
Nominal total and cell tune	**(3.41, 3.39)** (0.213125, 0.211875)	<- same	**(2.83, 1.22)** (0.283, 0.122)	
Number of particle	**A few 10^{11} protons**	<- same	**10^9 protons**	~1/100
Physical emittance	**125 pi mm mrad (100%)**	<- same	**0.41 pi mm mrad (RMS)**	~1/1000
Dynamic aperture	> 1250 pi mm mrad	<- same	> 300 pi mm mrad	
Momentum spread	**A few 0.1%**	<- same	**+/- 2% at inj** **+/- 0.5% at ext**	
Initial bunch length	~300 ns	<- same	8.1 ns (right after injection)	~1/100
Space charge tune shift	-0.3	<- same	-0.8	~10

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Parameters (hardware)

	FETS-FFA (16-fold sym)	FETS-FFA (4-fold sym)	LhARA	notes
Maximum field	**0.9 T**	**1.4 T (to be lowered)**	**1.4 T**	Definition may be different
Spiral angle	45 degree	30 degree	48.7 degree	Spiral angle
Magnet families	**2**	**8**	**1**	Magnet families
Nominal k-value	8.00	7.40	5.33	Nominal k-value
Field index k and spiral angle	k = 6 - 11 and 45 degree	k = 6 - 9 and 30 degree	k = 5.33 and 48.7 degree	Tuneability is essential for FETS-FFA
Magnet gap	~ 120 mm	<- same	47 mm	
Repetition of RF	100 - 120 Hz	<- same	10 - 100 Hz	
RF frequency	1.8 - 3.4 MHz	<- same	2.89 - 6.48 MHz	
RF voltage	6 kV	<- same	4 kV	
Straight length	0.95 m	1.55, 0.90, 0.45 m	1.21 m	Straight length

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Extension to higher energy with 16-fold symmetry lattice

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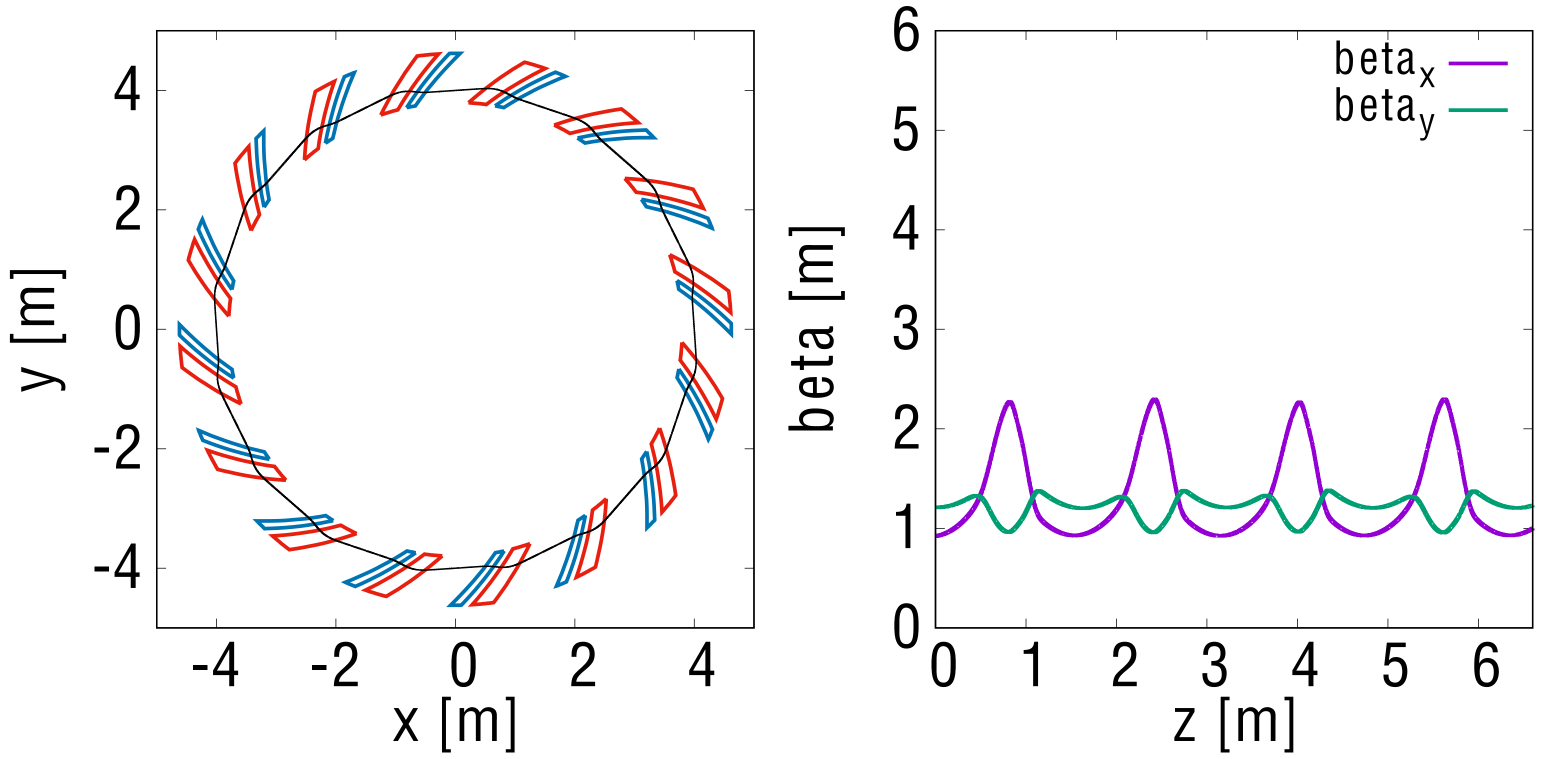
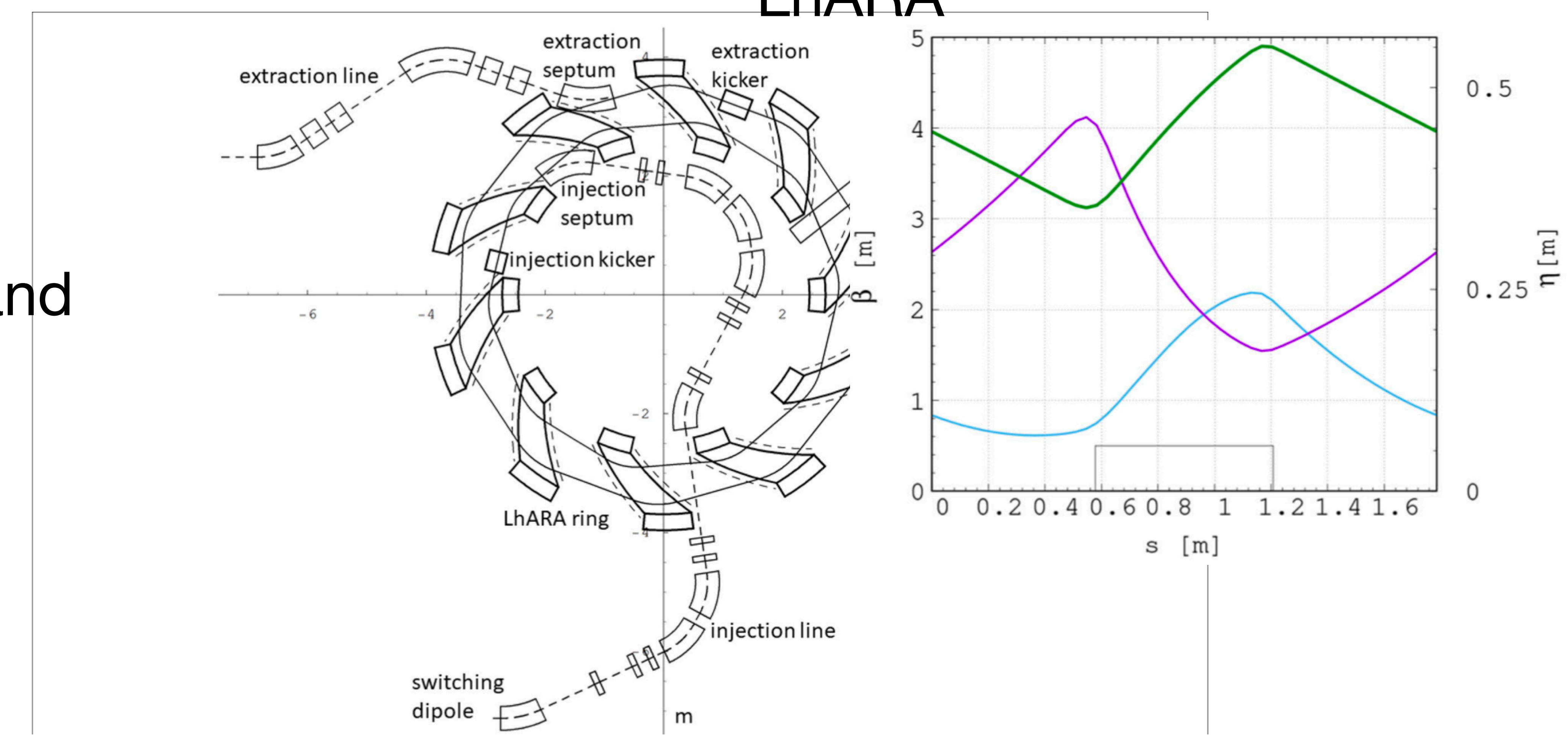
Can FETS-FFA and LhARA share the design?

FETS-FFA (16-fold sym)



and

LhARA



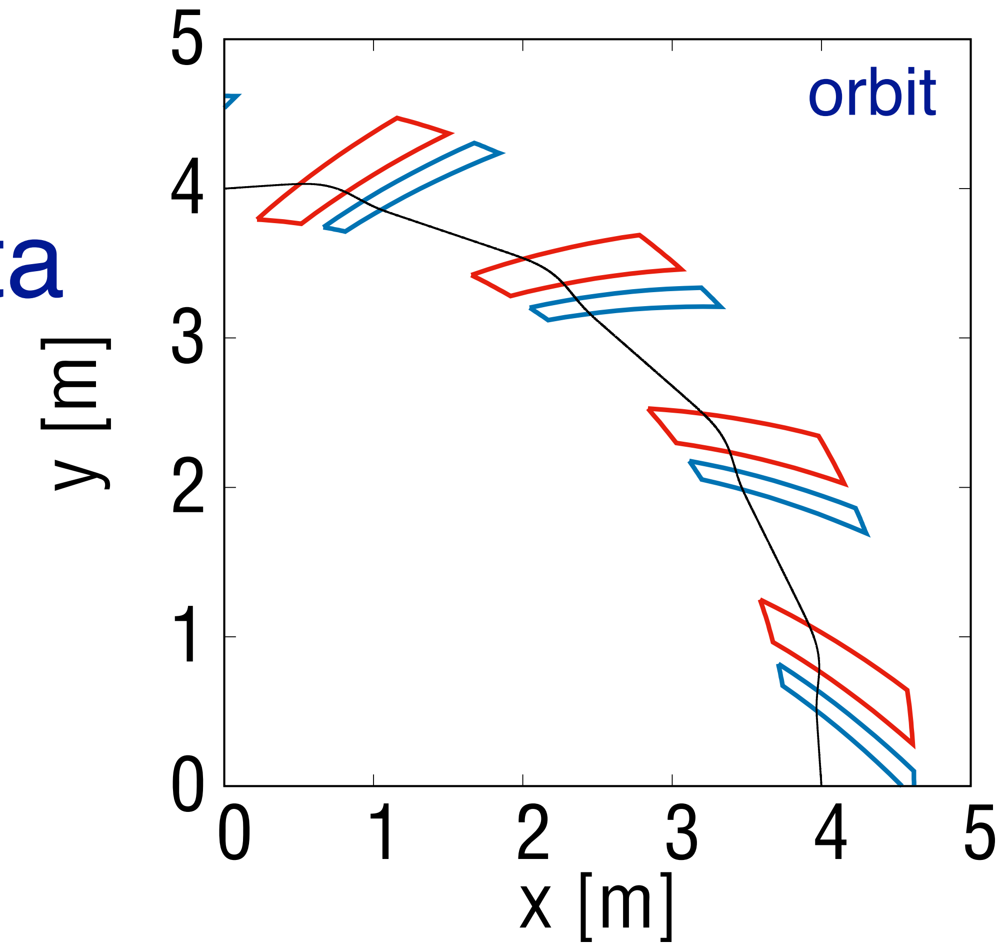
- Both lattices look similar (spiral FFA), but
  - FETS-FFA has more constraint, i.e. tune choice (Qx~Qy) for high intensity operation.
  - FFAS-FFA uses doublet (normal and reverse bend) while LhARA uses singlet (normal bend only).

- Due to reverse bends, injection and extraction momentum have to be lower in FETS-FFA with similar circumference.
  - At injection, particle momentum is x2.3 higher in LhARA.

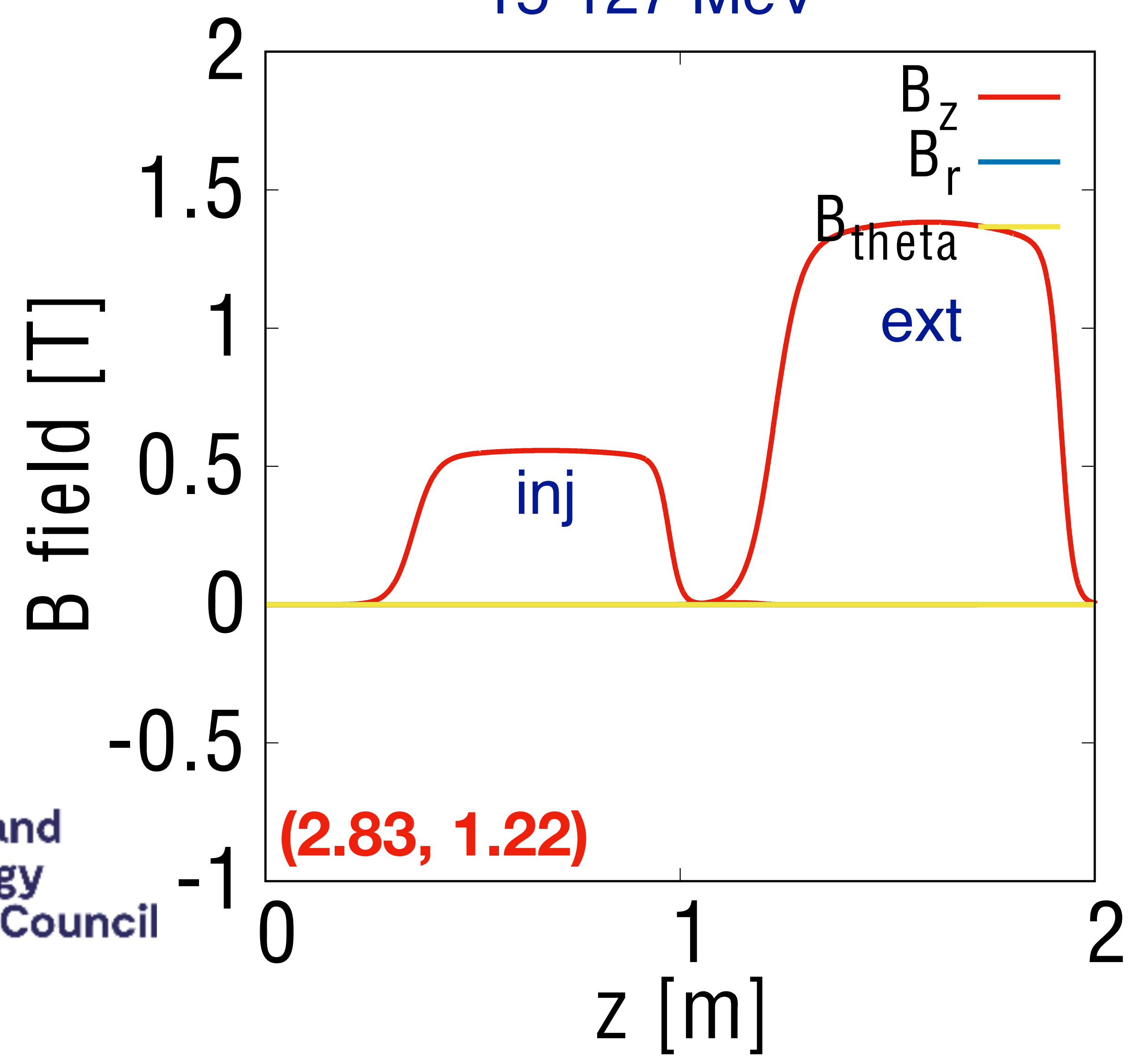
Is it possible to FETS-FFA lattice for higher momentum?

Eliminate reverse bends

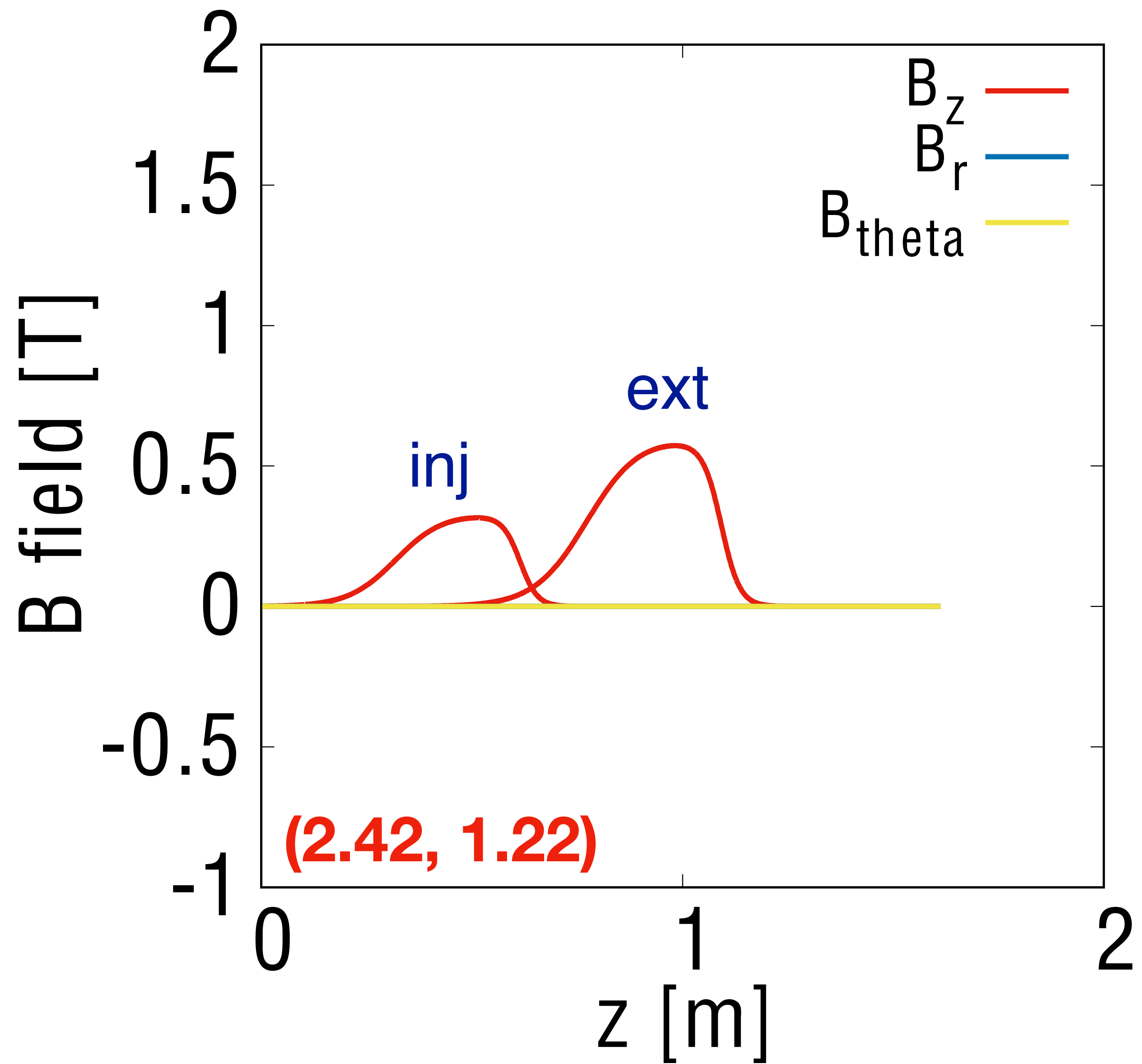
- Very roughly, a normal magnet bends \theta and a reverse magnet bends -0.25\theta
  - Net bend = \theta - 0.25\theta = 0.75\theta (nominal FETS-FFA design).
- Without a reverse bend,
  - Net bend = \theta
- Momentum can be 33% more or energy 78% more.
  - FETS-FFA 3 - 12 MeV lattice can accept up to **21 MeV**.
- If the maximum field of the magnet is ~1.4 T instead of ~0.9 T, the top energy could be higher
  - Another gain of a factor 2 makes **~50 MeV**.



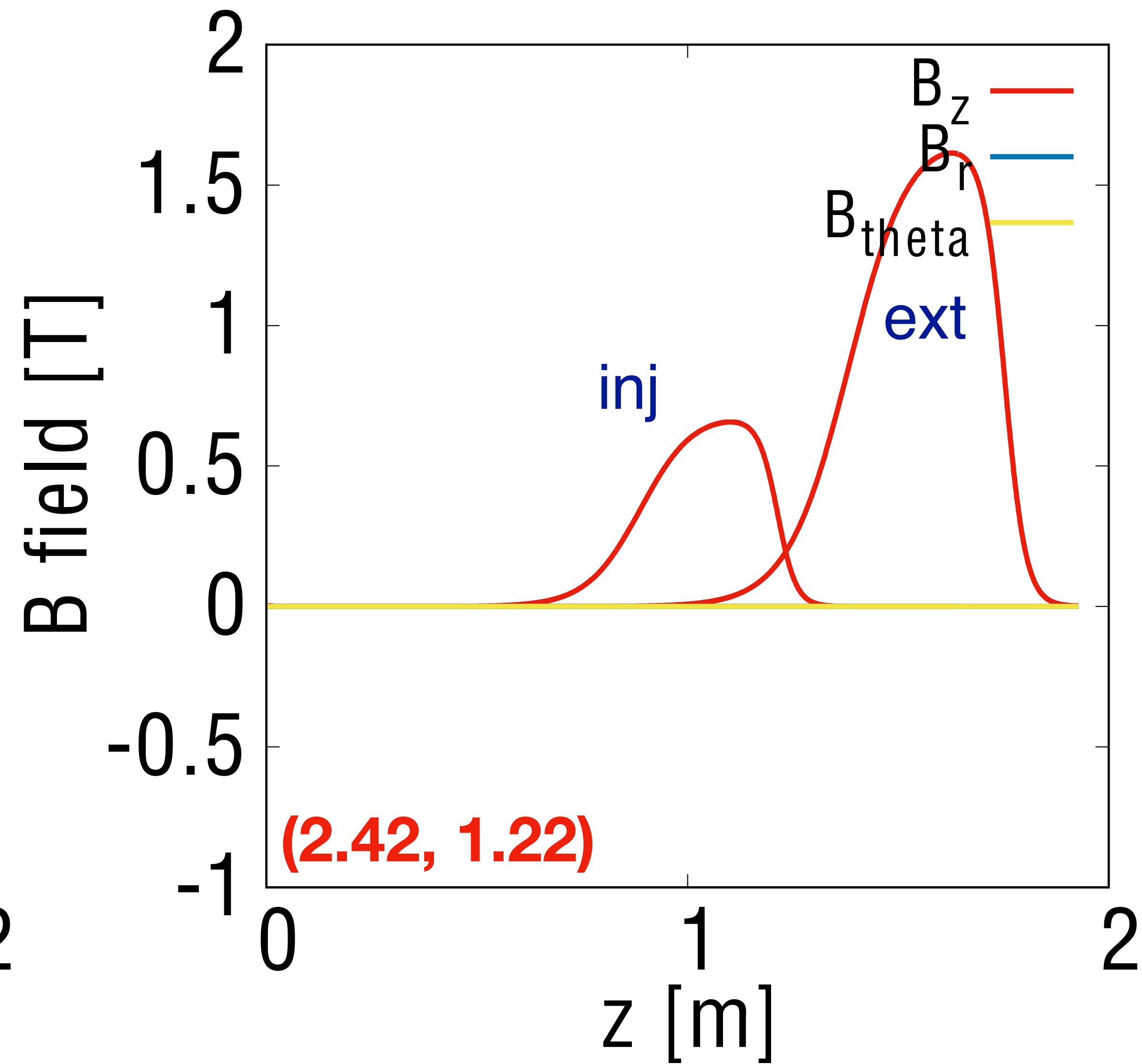
LhARA (Bf only)
15-127 MeV



FETS-FFA (Bf only), asymmetric tune
3-12 MeV



FETS-FFA (Bf only), asymmetric tune
15-127 MeV



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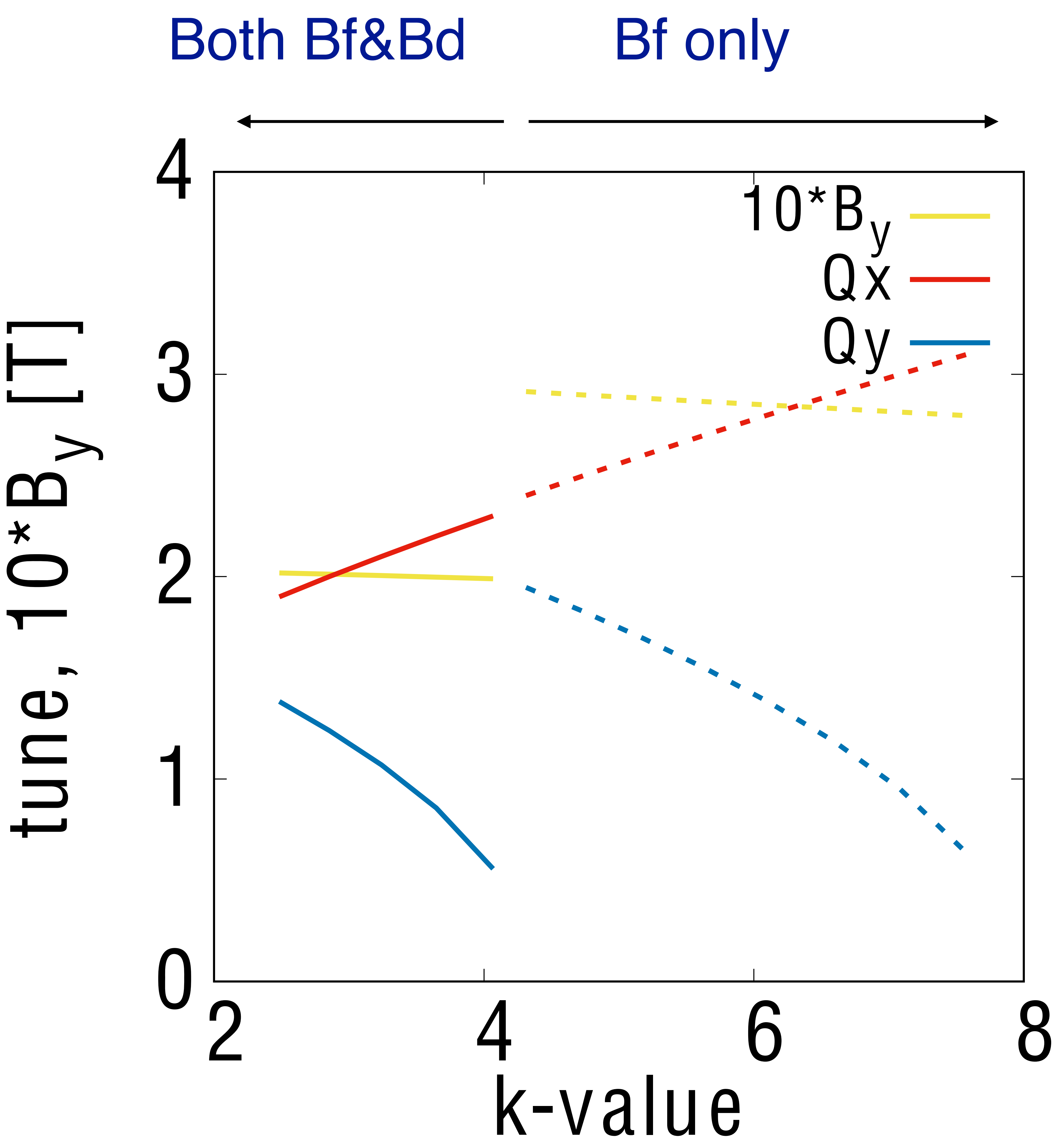
How about using both Bf and Bd as normal bends?

- Very roughly, a normal magnet bends \theta and a reverse magnet bends -0.25\theta
  - Net bend = \theta - 0.25\theta/2 = 0.75\theta (nominal FETS-FFA design).
- With both Bf and Bd as normal bends,
  - Net bend = \theta + 0.25\theta = 1.25\theta
- Momentum can be 67% more or 2.8 times higher in energy.
  - FETS-FFA 3 - 12 MeV lattice can accept up to **34 MeV.**

- However, field gradient k-value has to be smaller.
  - Orbit excursion is roughly doubled when k change from 6 to 3.
  - Unless the magnet aperture is wider than the baseline design, the max energy is limited by horizontal aperture.
  - Max energy is similar to Bf only lattice.
- k-value becomes smaller because the edge angle is smaller.



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Extension to higher energy with 4-fold symmetry lattice

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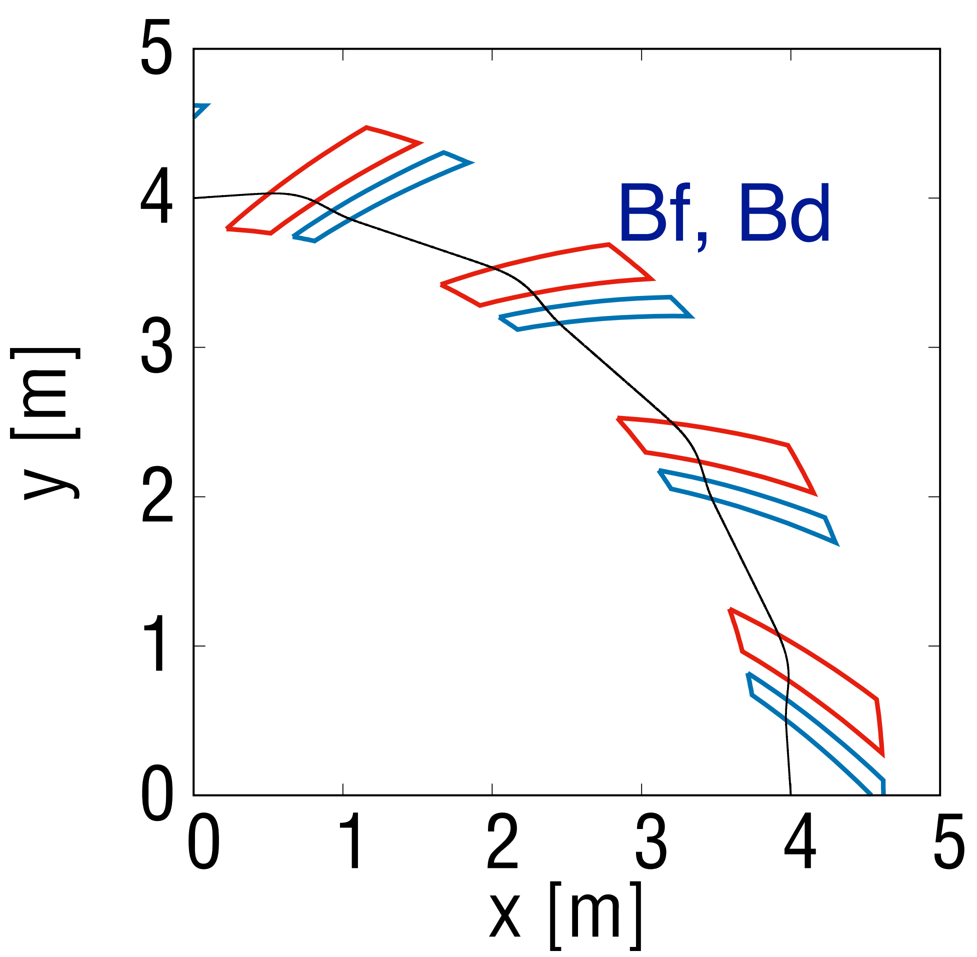
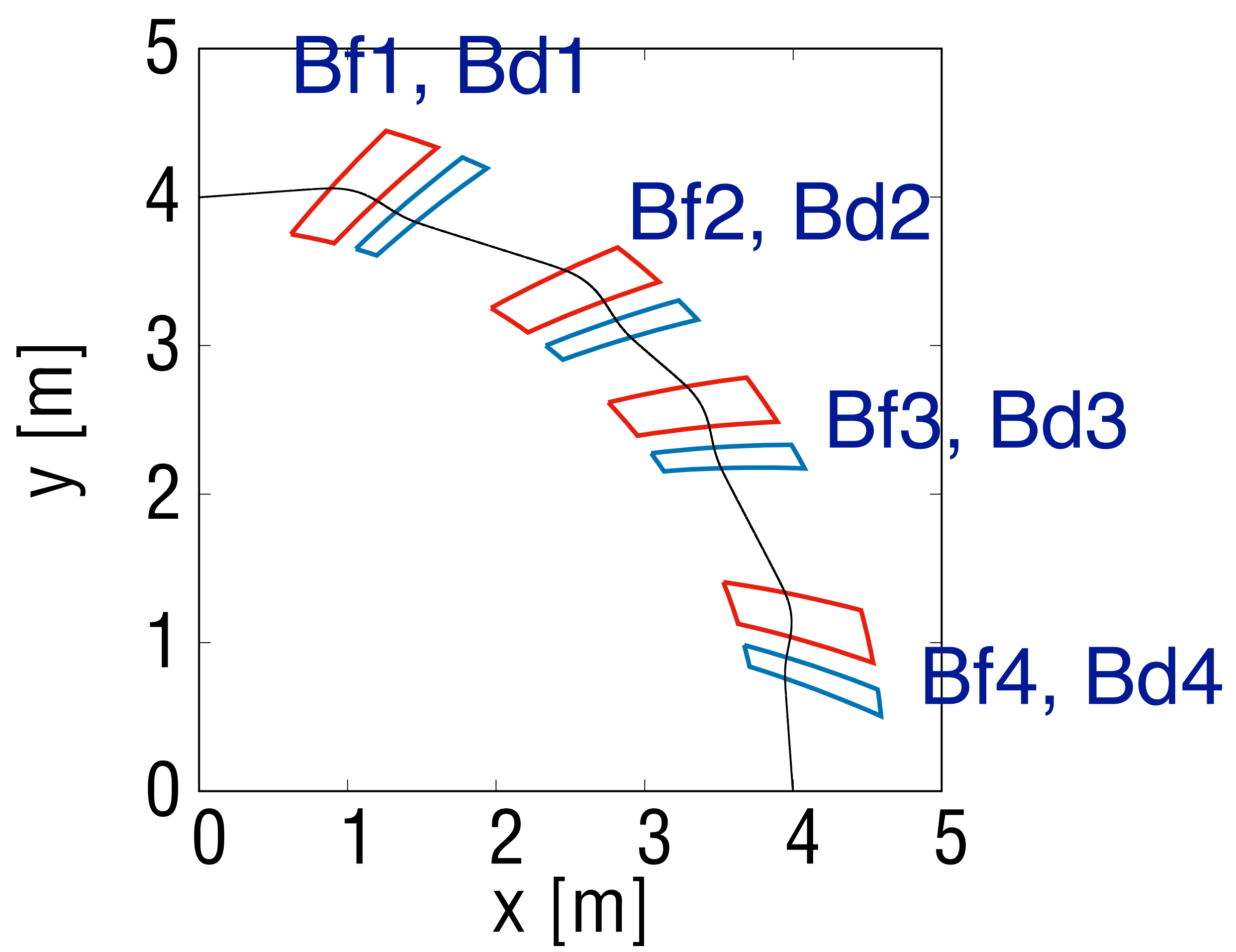
FETS-FFA baseline is now 4-fold lattice

- FETS-FFA lattice evolved since I have done the calculation in the previous pages.
- Main differences which have an impact to this study is
  - Spiral angle is now 30 degree (45 degree before).
  - Maximum field is 20~30% higher than before.

- On the other hand, the number of magnet families is 8 (2 before).
  - We could test many different excitation pattern. Previously only (Bf,0) and (Bf,Bf’).
  - e.g. (Bf1,0, Bf2,0, Bf3,0, Bf4,0), (Bf1,Bf1’, Bf2,Bf2’, 0,0, Bf4,Bf4’), etc.





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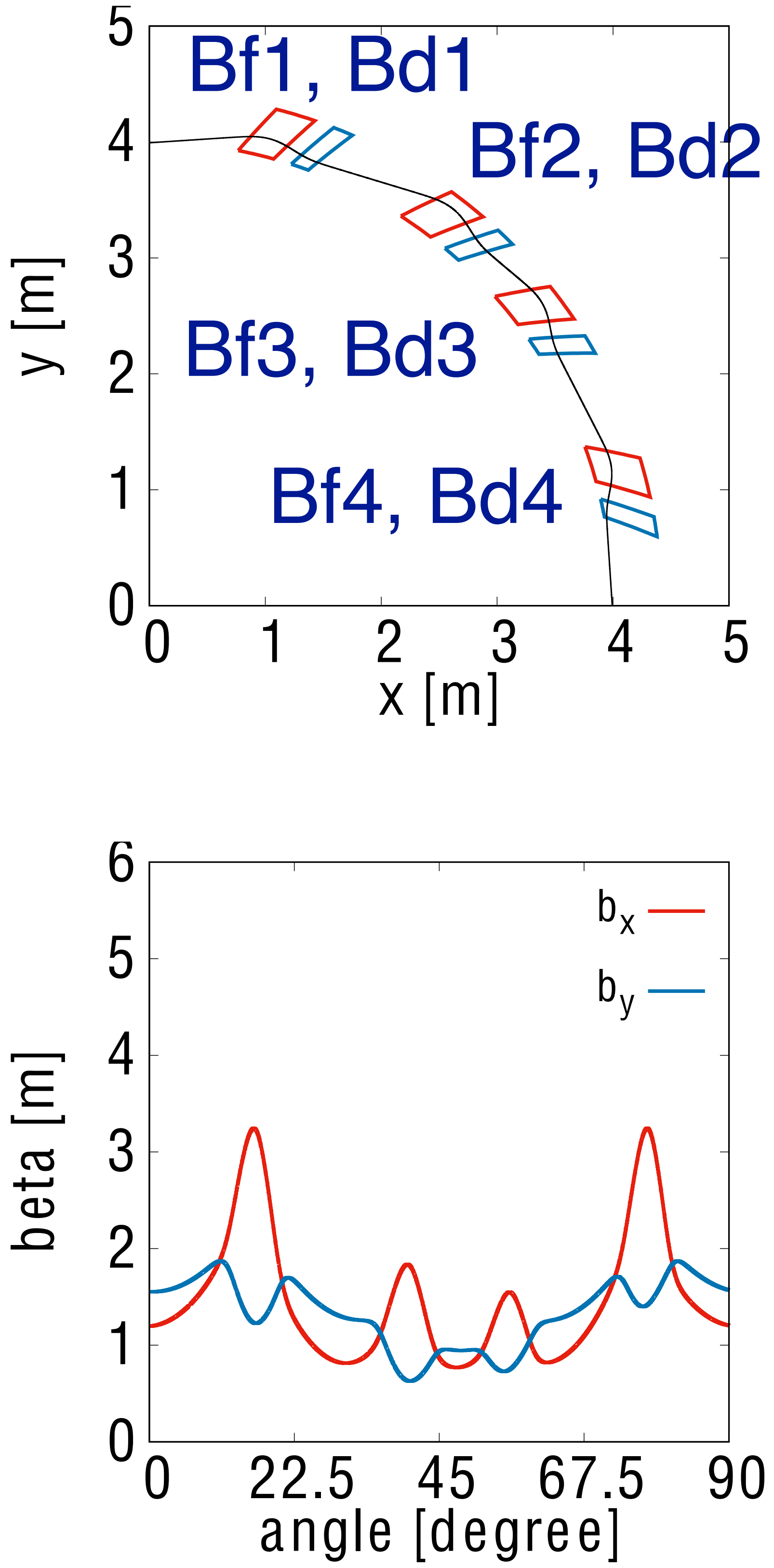
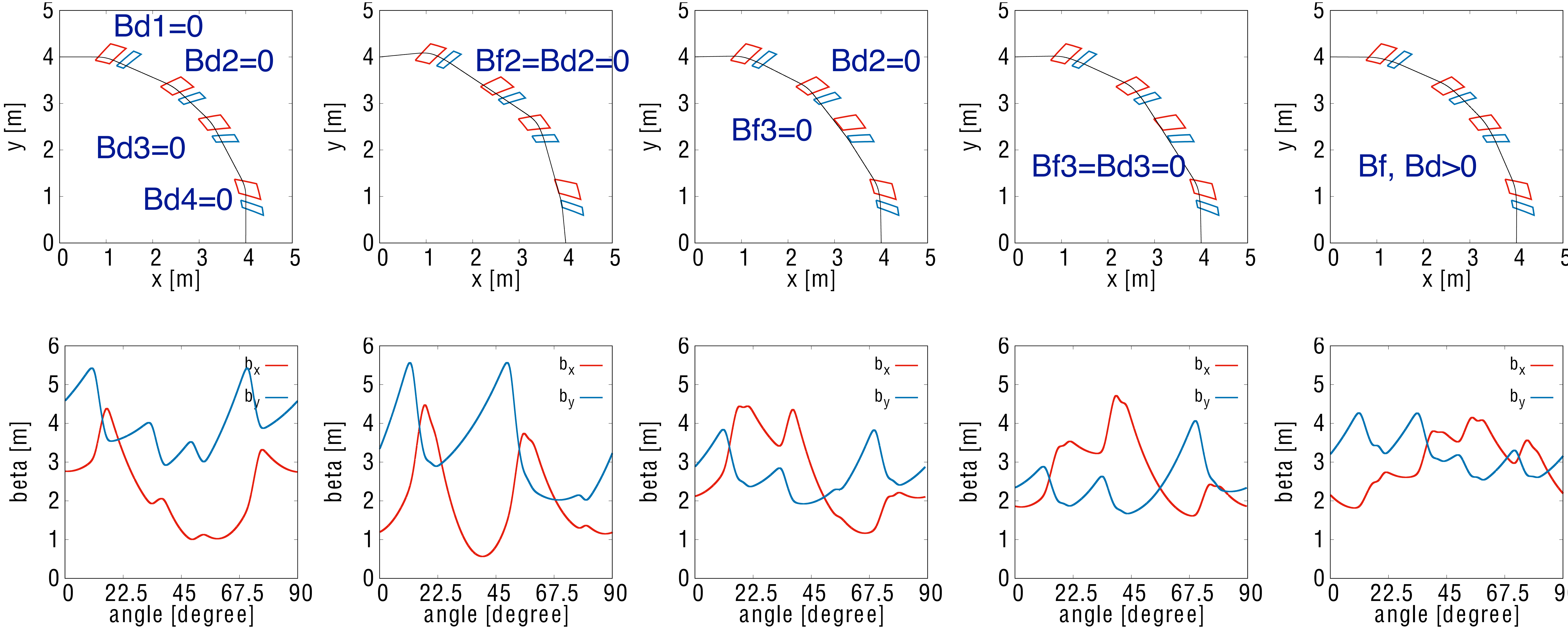
5 different ways of operation (no reverse bend)

FETS-FFA



(3.41, 3.39)
k=7.49
12 MeV

Possible ways to extend maximum energy



(2.18, 1.05)
k=3.59
19.5 MeV

(2.87, 1.35)
k=5.07
19.7 MeV

(1.84, 1.57)
k=2.04
20.0 MeV

(1.68, 1.77)
k=1.55
20.2 MeV

(1.48, 1.31)
k=1.06
30.9 MeV*

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* Injection energy has to be above 20 MeV.

Without constraints of maximum beta function

FETS-FFA

Possible ways to extend maximum energy

(3.41, 3.39)
k=7.49
12 MeV

(2.18, 0.51)
k=4.5
41 MeV

(2.19, 0.26)
k=3.8
36 MeV

(1.65, 1.45)
k=1.5
32 MeV

(1.68, 1.52)
k=1.5
34 MeV

(1.49, 1.09)
k=1.1
61 MeV*

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* Injection energy has to be above 40 MeV.

Conclusion

Conclusion

- By eliminating reverse bend magnets or change the polarity of reverse bends, top energy of FETS-FFA can be higher than 12 MeV.
- 16-fold symmetry lattice (with modest increase of magnetic field) can accept beams up to ~50 MeV.
- 4-fold symmetry lattice (new baseline) can accept beams up to ~40 MeV
- or ~60 MeV but injection energy has to be more than 15 MeV or vacuum aperture has to be larger.

Thank you for your attention

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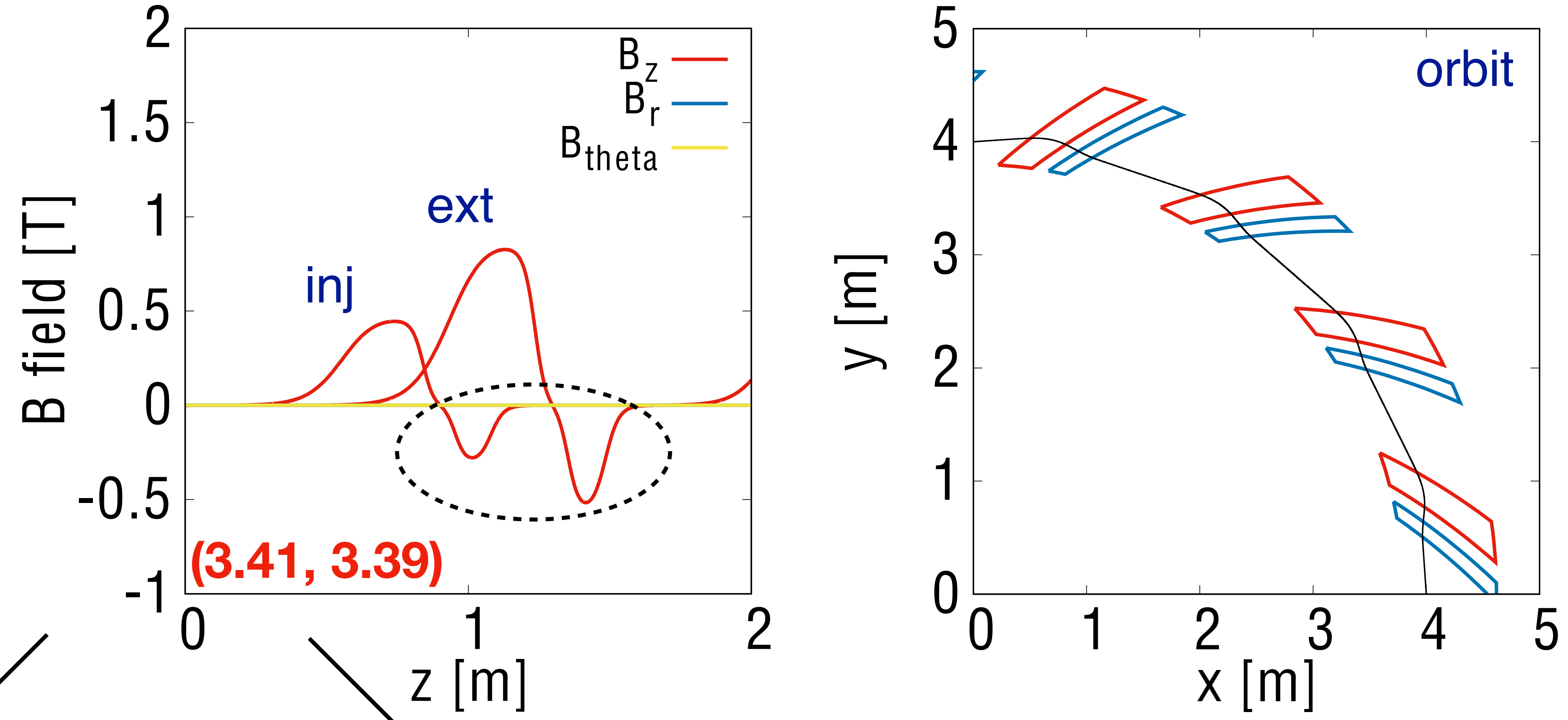
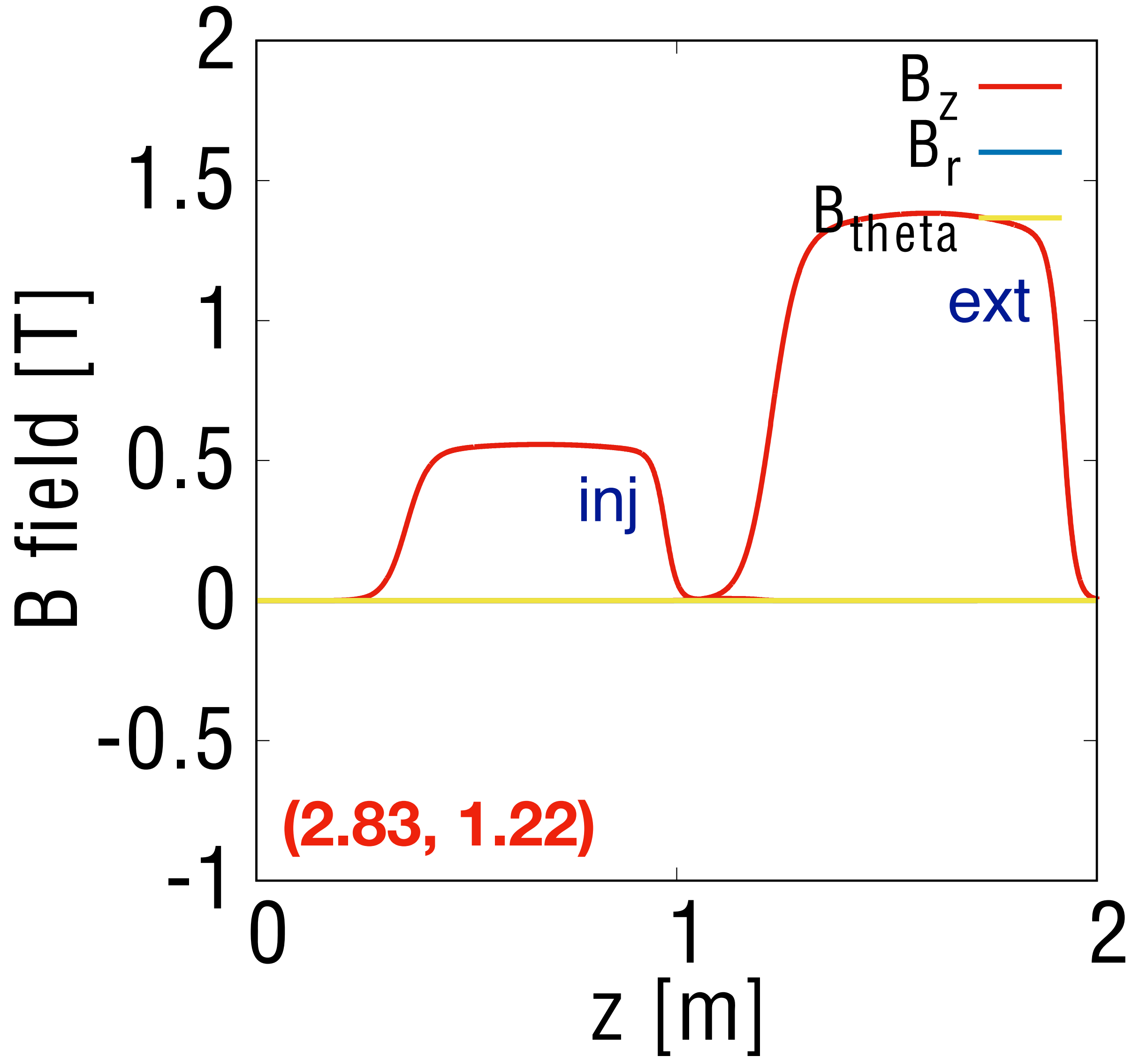
An option to increase momentum range in FETS-FFA

Eliminate the reverse bends. Make the strength zero.
Similar to LhARA lattice with only normal bends.

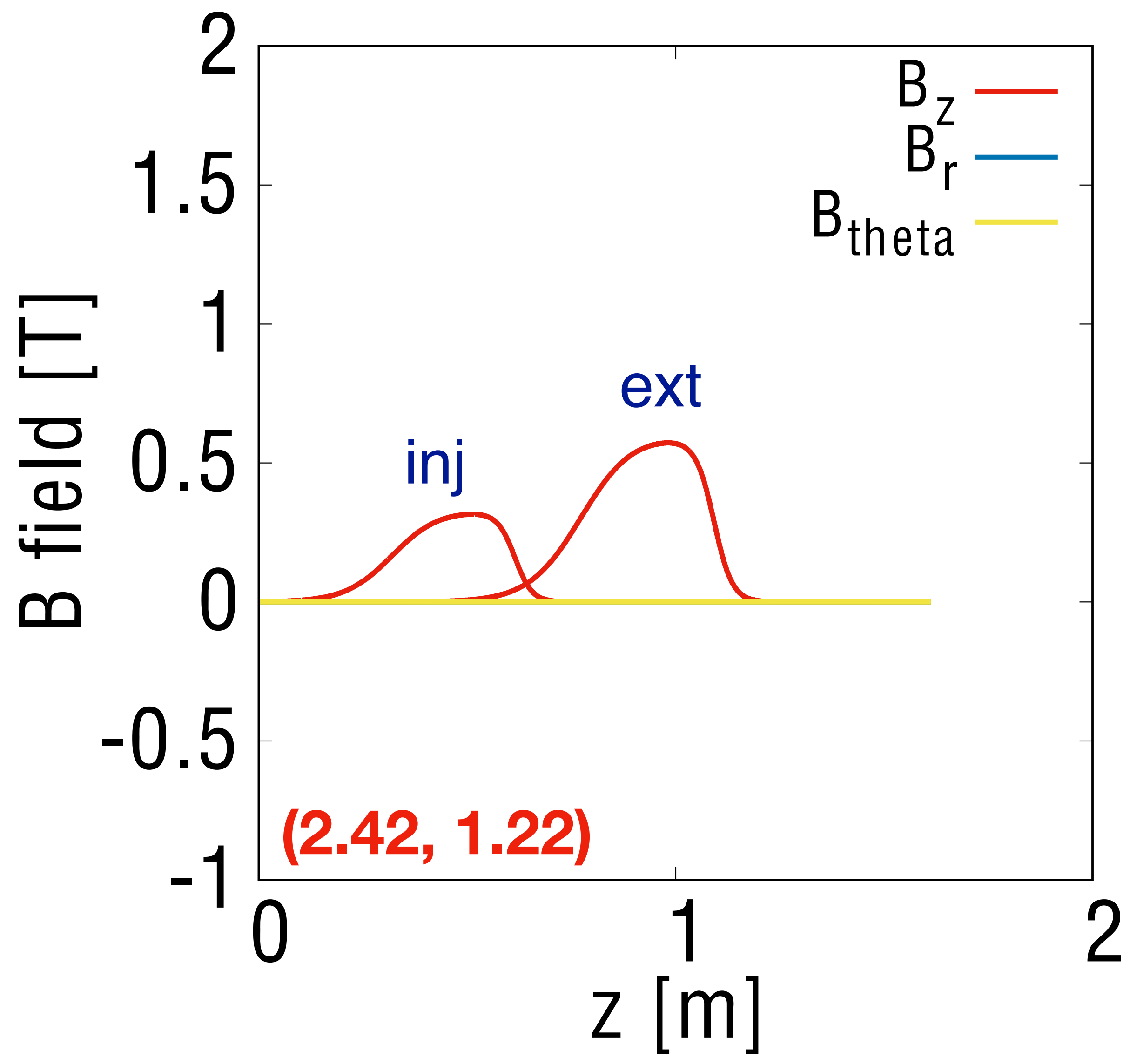
FETS-FFA (Bd and Bf)



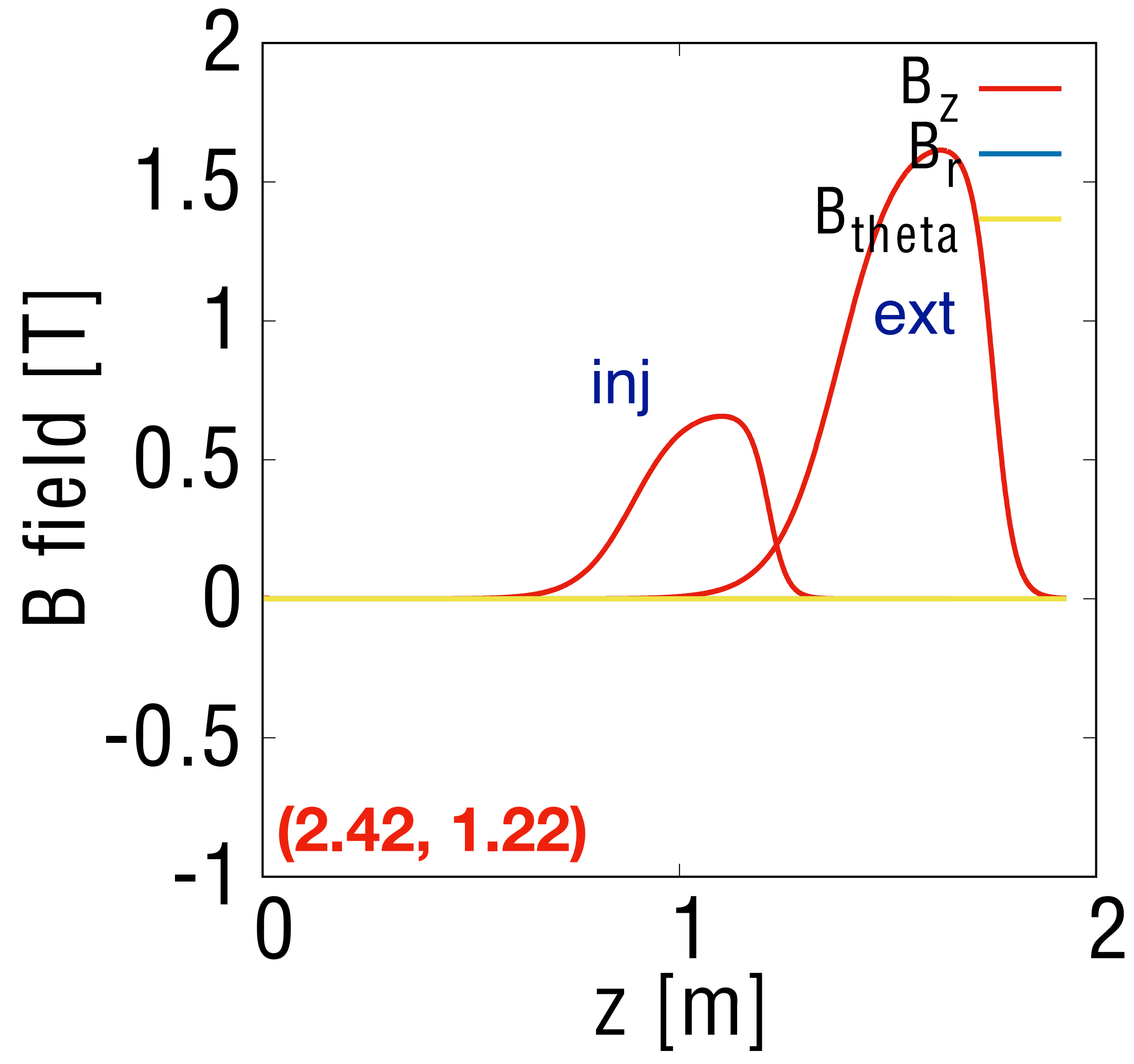
LhARA (Bf only)
15-127 MeV



FETS-FFA (Bf only), asymmetric tune
3-12 MeV



FETS-FFA (Bf only), asymmetric tune
15-127 MeV



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References

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https://indico.stfc.ac.uk/event/487/contributions/3923/attachments/1375/2428/FFA2022_JPasternak_LhARA.pdf

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My personal summary

- FETS-FFA is a more demanding FFA: double (FD) spiral, tuneability, space charge mitigation, etc.

- Hardware development goals are similar.

- If we have a decent design of FETS-FFA, it will work for LhARA **except momentum acceptance** is not enough.

- LhARA design requirements can be satisfied to some extent with (minor) modifications of FETS-FFA.
    - **Increase maximum field.**
    - Increase good field region to accommodate momentum ratio of 3 (FETS-FFA is 2).
    - Single turn injection system without charge exchange.

- Have to redo the calculation for 4-fold symmetry baseline lattice.

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