LhARA FFA- beam physics update

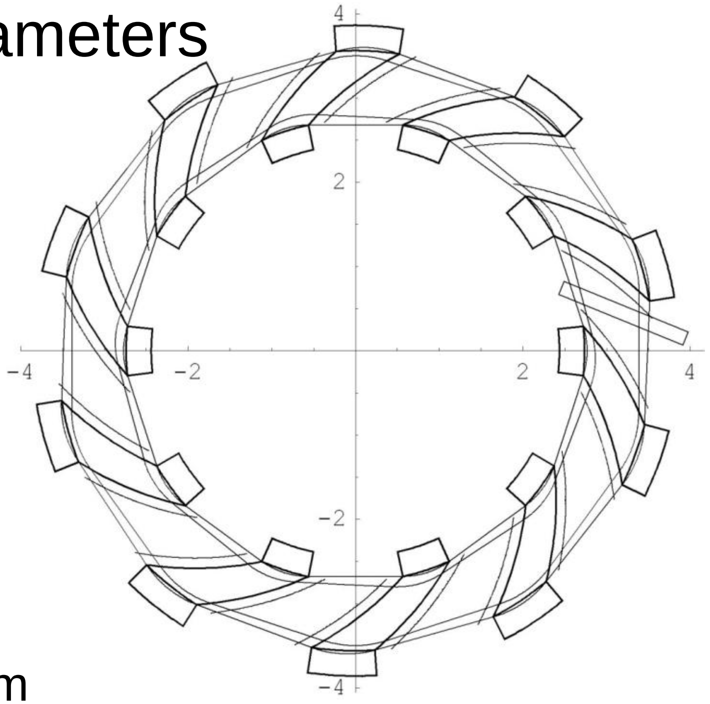
J. Pasternak

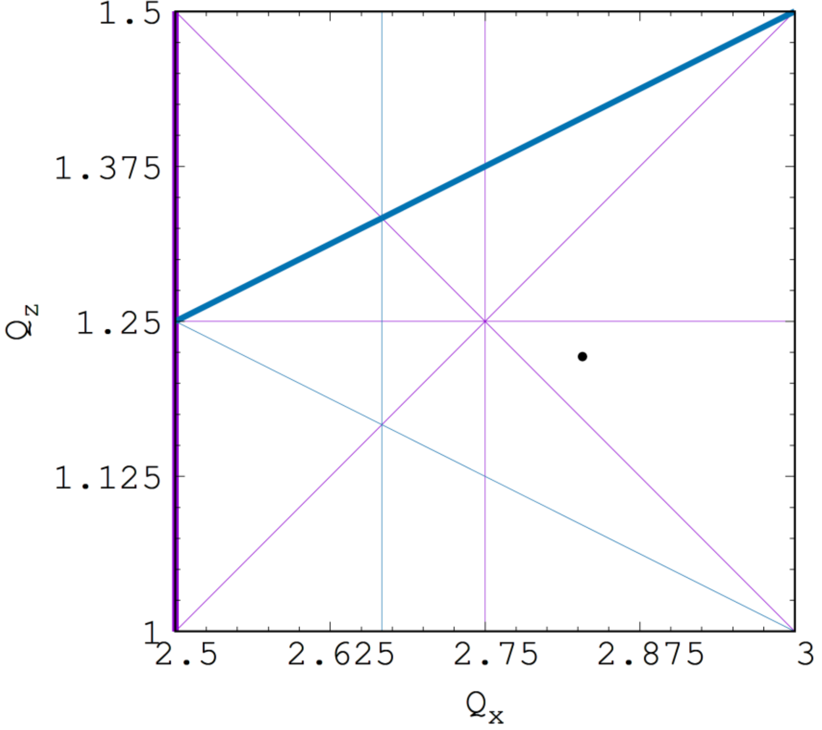
10/01/2024, FETS FFA/LhARA joint collaboration workshop, RAL

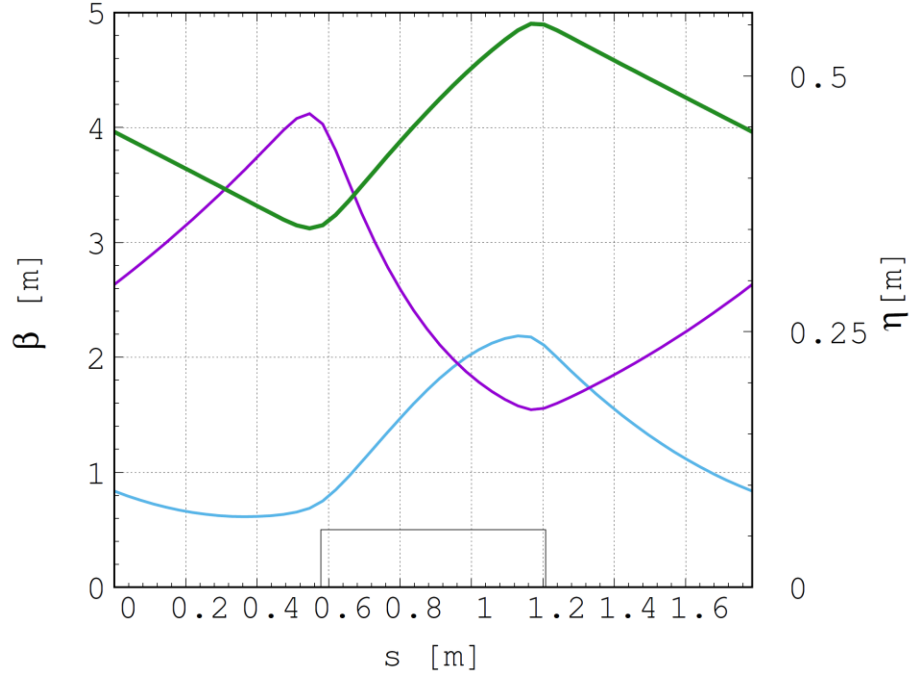
Outline

- LhARA FFA baseline
- Variable energy FFA
- Lessons from RACCAM
- LhARA double spiral FFA candidate
- New injection line
- Conclusions

LhARA FFA baseline ring parameters







- Lattice type single spiral scaling FFA
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8 protons
- Range of other extraction energies possible
- Other ions also possible

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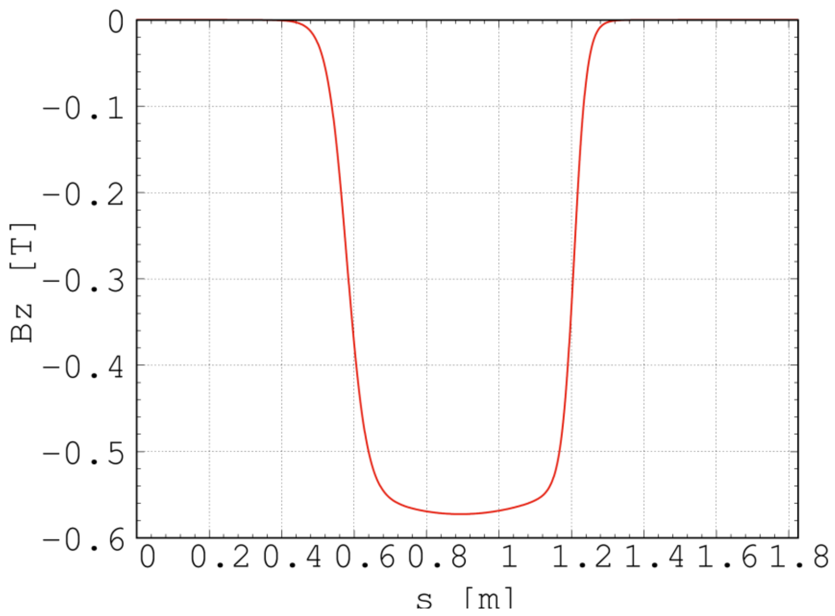
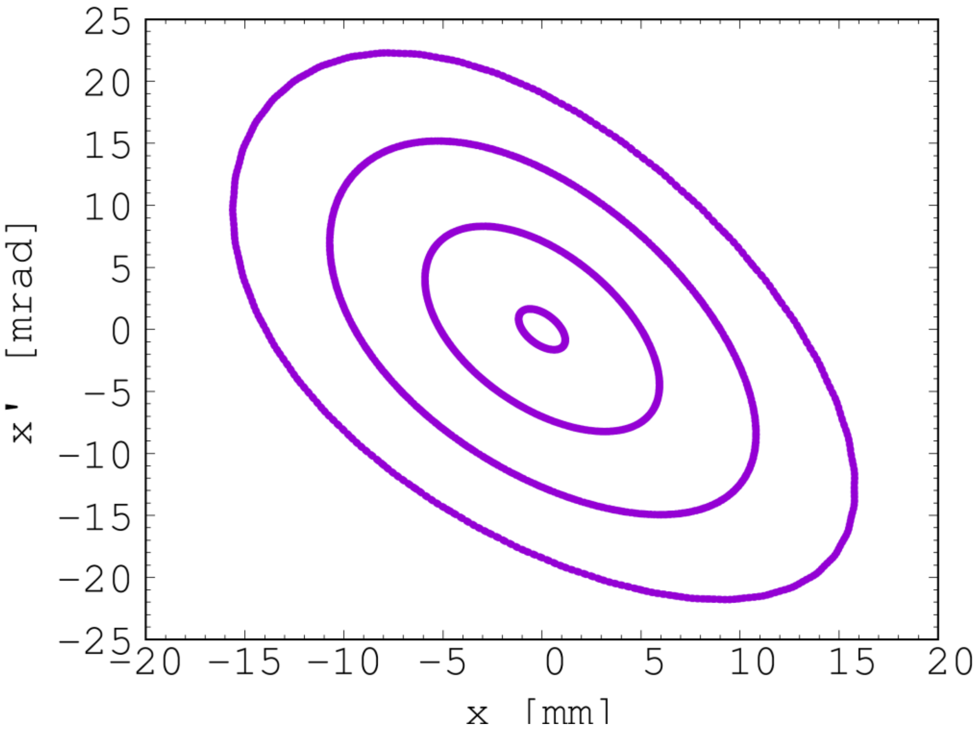
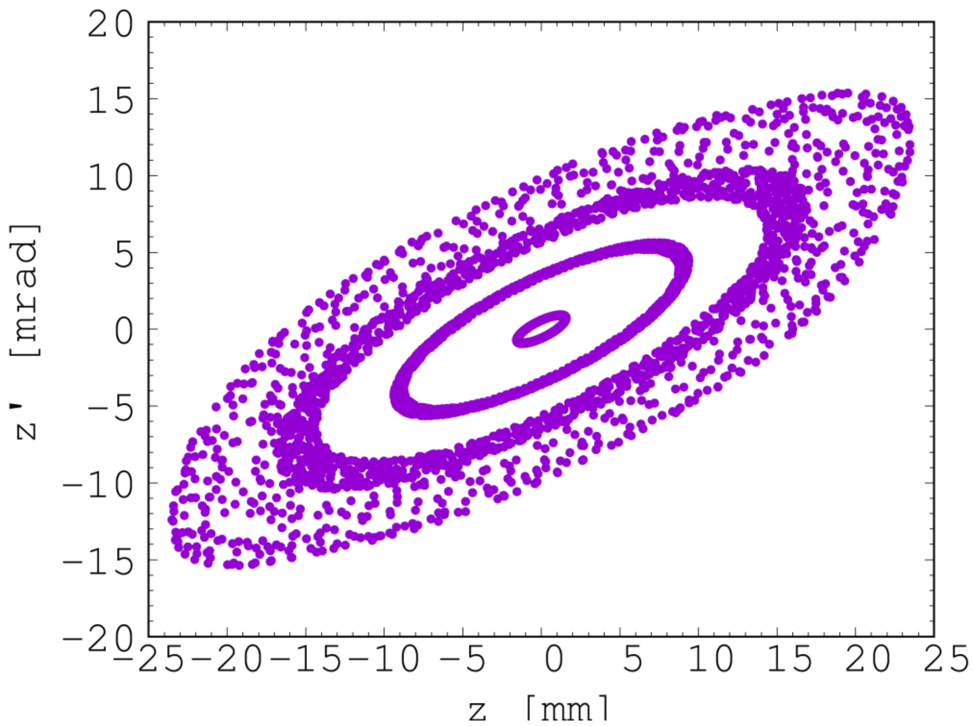
LhARA Ring Tracking

- Performed using proven stepwise tracking code (FixField)
- It takes into account fringe fields and non-linear field components
- Results show dynamical acceptances are large
- No space charge effects included yet



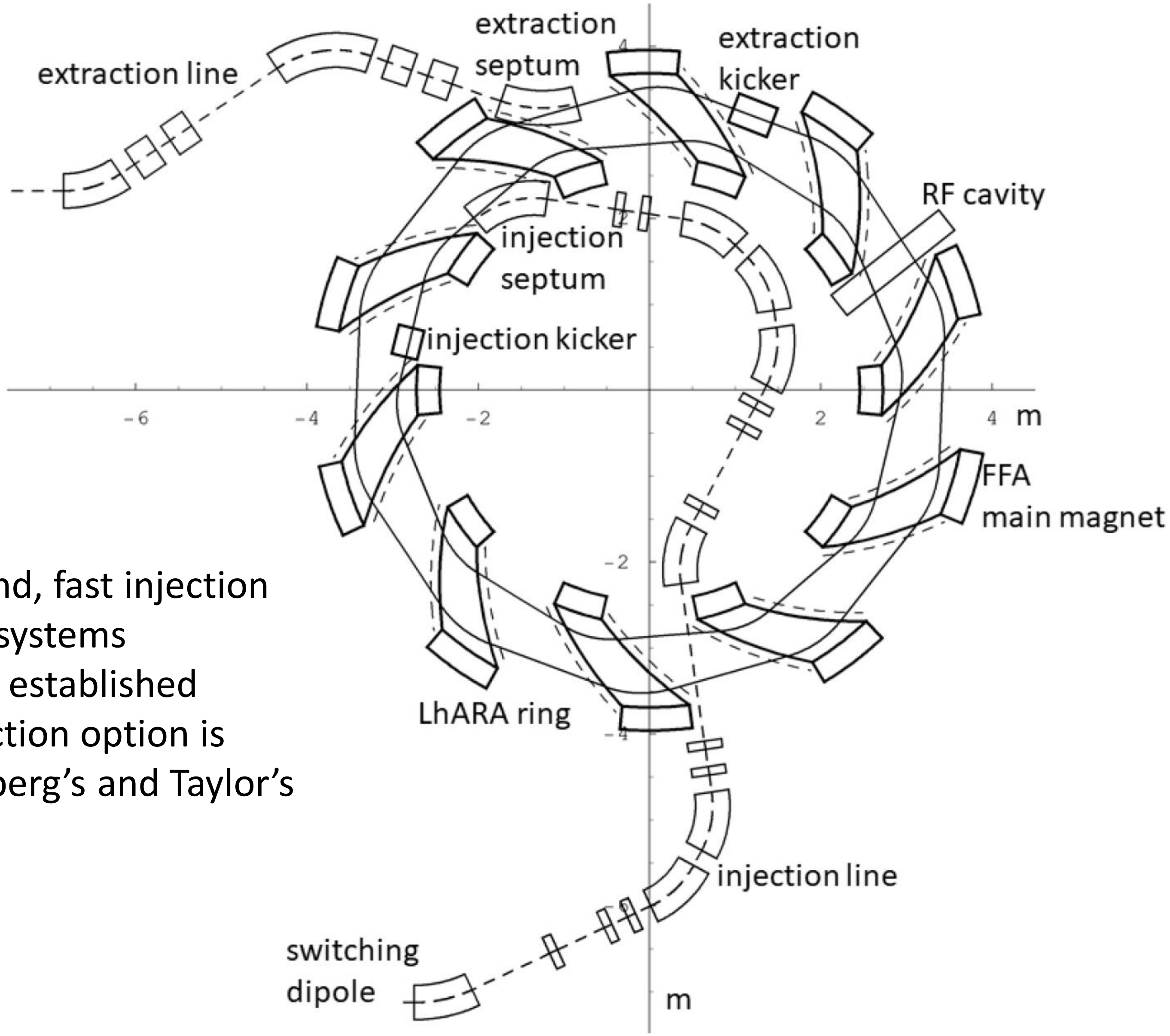




FFA Ring with subsystems

Parameter	unit	value
Injection septum:		
nominal magnetic field	T	0.53
magnetic length	m	0.9
deflection angle	degrees	48.7
thickness	cm	1
full gap	cm	3
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	1.12
magnetic length	m	0.9
deflection angle	degrees	34.38
thickness	cm	1
full gap	cm	2
pulsing rate	Hz	10
Injection kicker:		
magnetic length	m	0.42
magnetic field at the flat top	T	0.05
deflection angle	mrad	37.4
fall time	ns	320
flat top duration	ns	25
full gap	cm	3
Extraction kicker:		
magnetic length	m	0.65
magnetic field at the flat top	T	0.05
deflection angle	mrad	19.3
rise time	ns	110
flat top duration	ns	40
full gap	cm	2

- Injection line and, fast injection and extraction systems parameters are established
- The slow extraction option is possible (Steinberg's and Taylor's work)

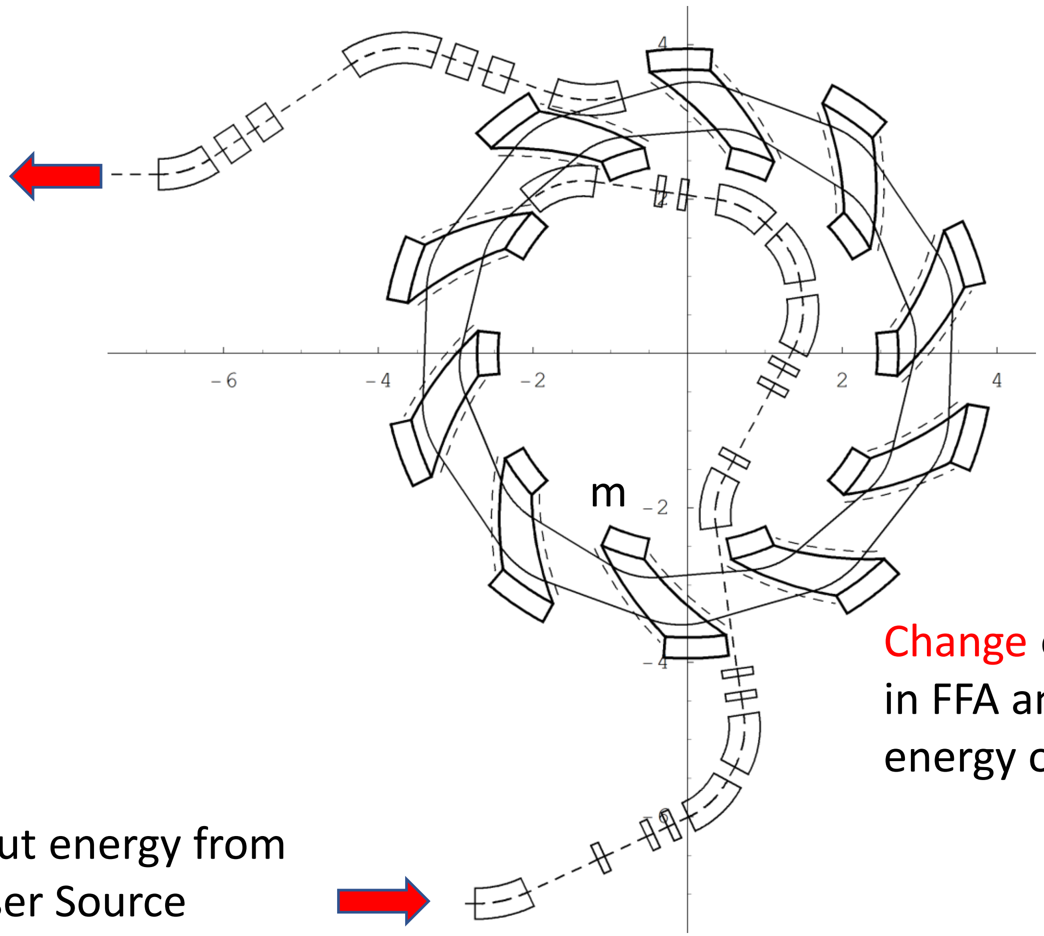


Energy Variability using Laser Accelerated Ions

Variable extraction energy from FFA within 1 s (20-127.4 MeV) at fixed geometry

+

pulse by pulse variation with kicker could be implemented



Change of the value of magnetic field in FFA and transfer lines for a specific energy operation (laminated magnets)

Variable input energy from the Laser Source (multiple ions are possible)

Some RF scenarios for various modes

- Main proton mode: h=1, V~0.5 kV, (4 kV to accept ±2% energy spread at injection, 15-127.4MeV, 2.89 – 6.48 MHz
- Min energy proton mode: h=2, 1.68-15 MeV, 1.95-4.83 MHz
- Main carbon mode: h=1, 3.77-33.4MeV/u, 1.46 – 3.55 MHz
- Min energy carbon mode: h=4, 0.42-3.77 MeV, 1.95-4.83 MHz

Some parameters

- Total proton bunch length in in-vitro station at Stage I 5.3ns (for comparison)

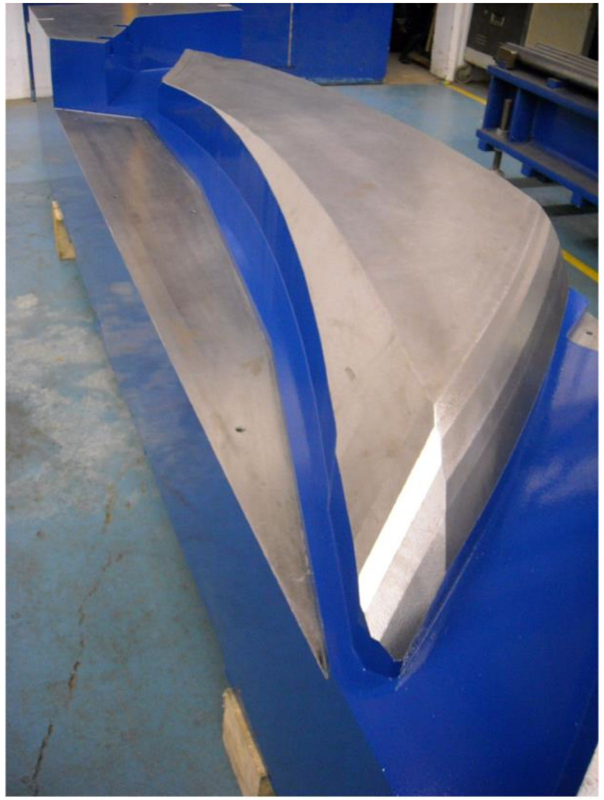
- Bunching factor at injection to FFA 0.023
- Total proton bunch length at injection to FFA 8.1ns
- Total relative energy spread at injection to FFA $\pm$2%
- Incoherent space charge tune shift at injection to FFA ~-0.8
- Beam intensity for proton beam ~10^9
- Proton bunch length at extraction from FFA 41.5ns
- Beam intensity for carbon beam ~10^9 /12
- Carbon bunch length at extraction from FFA 75.2ns

Challenges of variable energy opeartion

- Flexible RF system -> MA cavities
  - Ferrite loaded cavities may be an option as well with lower power consumption?
- Flexible power supplies
  - Should be ok?
- Stable tunes for all operating modes
  - It is already challenging to achieve stable tunes for a single mode, hmm…

What did we learn from RACCAM?

- Singlet scaling spiral FFA magnet
- Gap-shaping
- Variable chamfer
- It can be manufactured!



Yoke shape		Parallelepiped
Lamination thickness	(mm)	1.5
Gap shape		$\propto 1/r^{\kappa},\ \kappa \approx 5.2$
Gap at 3.46 m	(cm)	4
Gap at 2.794 m	(cm)	11.6
Overall dimension L× W× H	(mm)	2913 × 579 × 1230
Good field region	(m)	$2.9 \leq r \leq 3.3$
Total weight of magnet	(t)	18
PS voltage	(V)	159
PS current (180 MeV operation)	(A)	200
Total water flow	(litres/min)	12.13
Water temperature, in/out	(°C)	24/44

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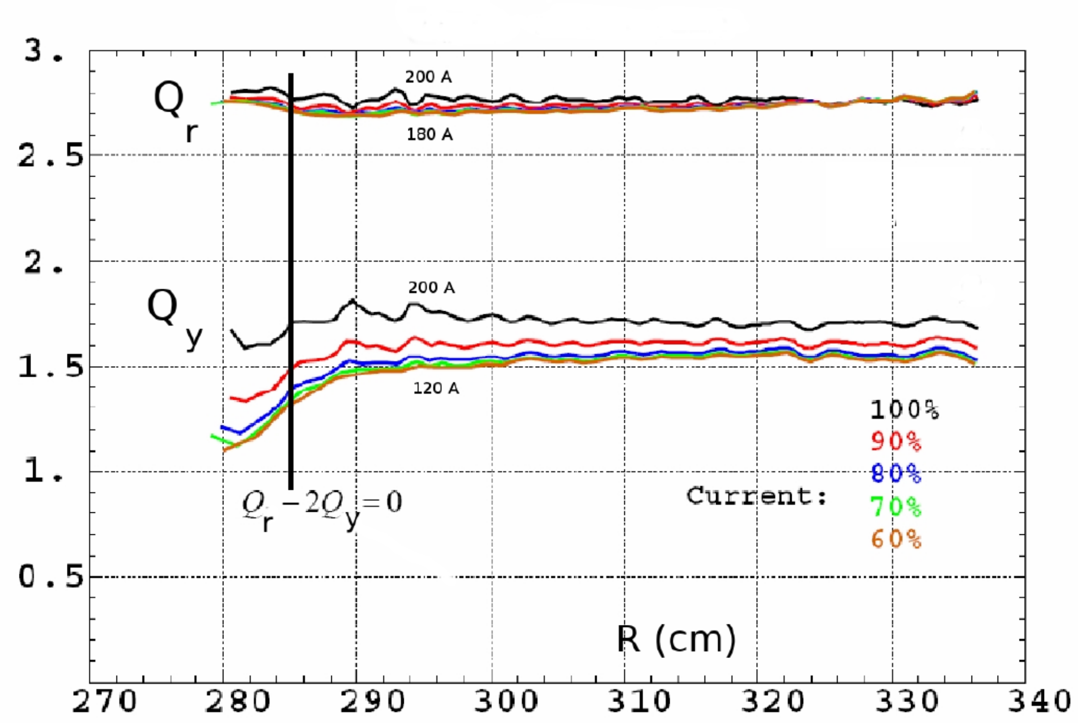
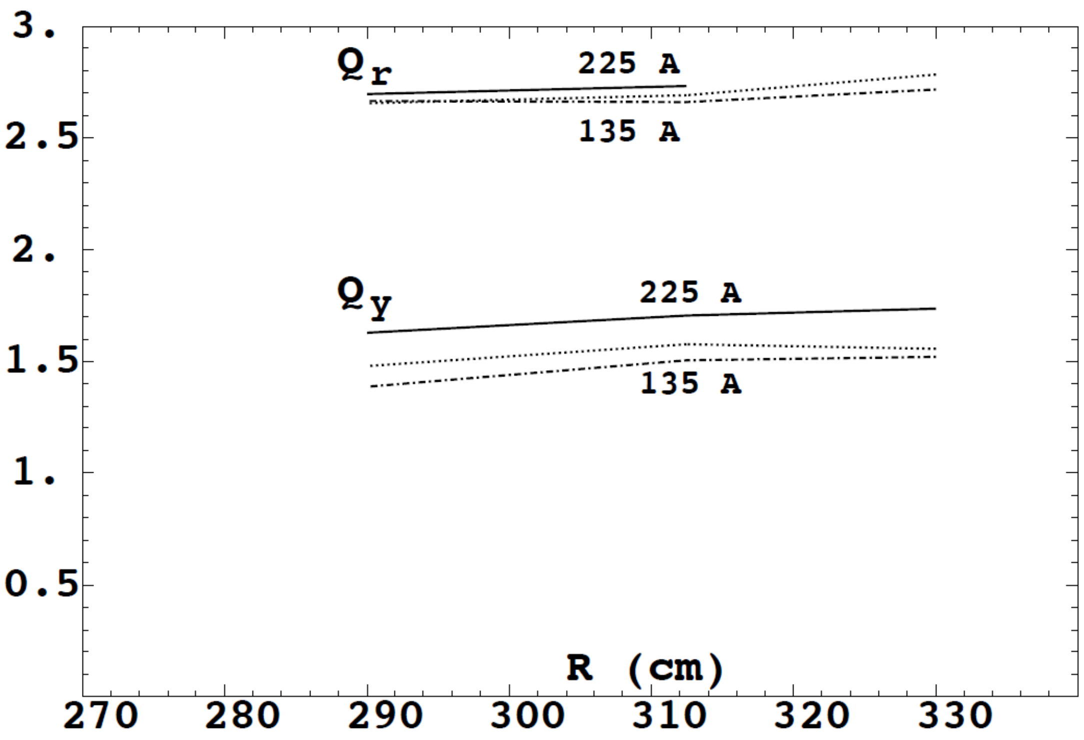
RACCAM tune behaviour at different field levels



Simulated field



Measured field

- Horizontal tune is relatively flat and changing only at the highest current
- Effect on the vertical tune is much stronger
  - Effect on the shape and the mean value
  - Effect is clearly visible at the high current and tend to be very small below 80% (is this approximately where LhARA FFA could be?)

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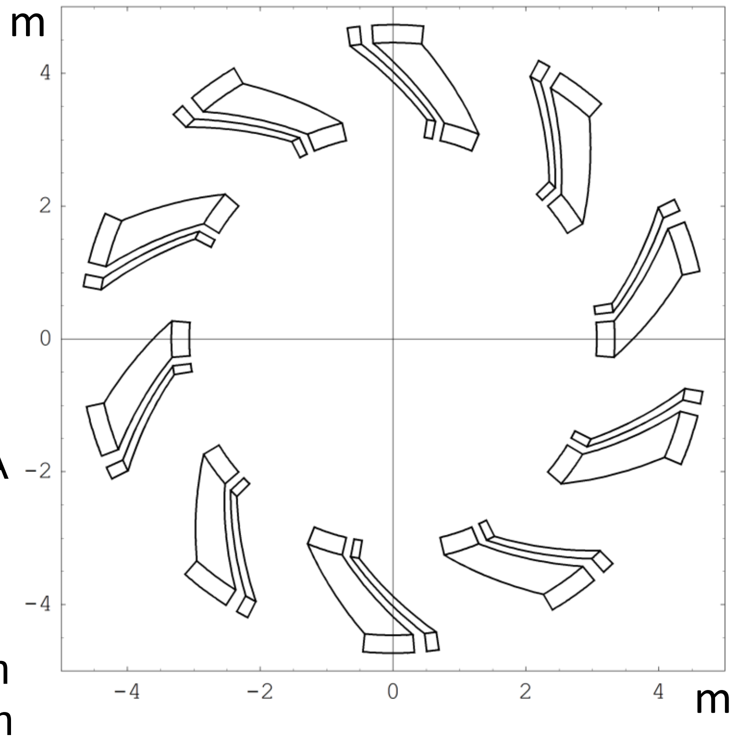
For similar discussion on the field level for flat gap, distributed coils magnet, see Enzo Kuo's talk

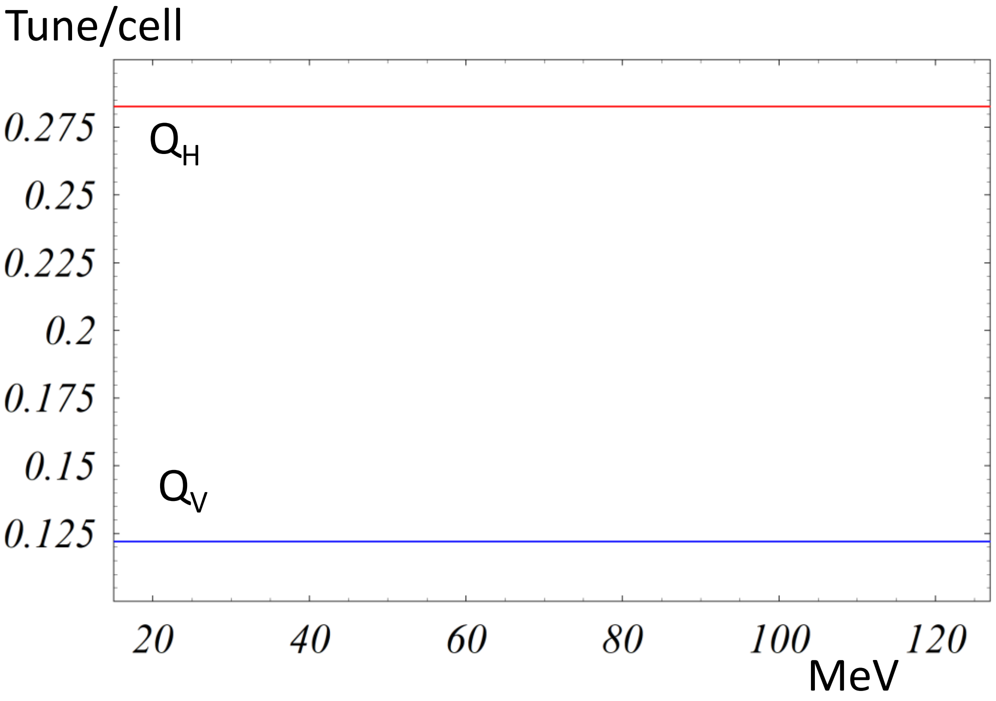
Issues

- RACCAM type machine sits in the designed working point forever
  - What if we want to change the tune?
  - What if we need the specific horizontal tune for the slow extraction?
  - Wha if we need to move away from the resonance?
- Solution could be the singlet with distributed conductors (FETS FFA-like)
  - It should be possible to scale the magnetic field
    - This scaling cannot be as simple as in the case of the gap-shaping magnet
  - It should be possible to change the working point (both tunes together in correlation)

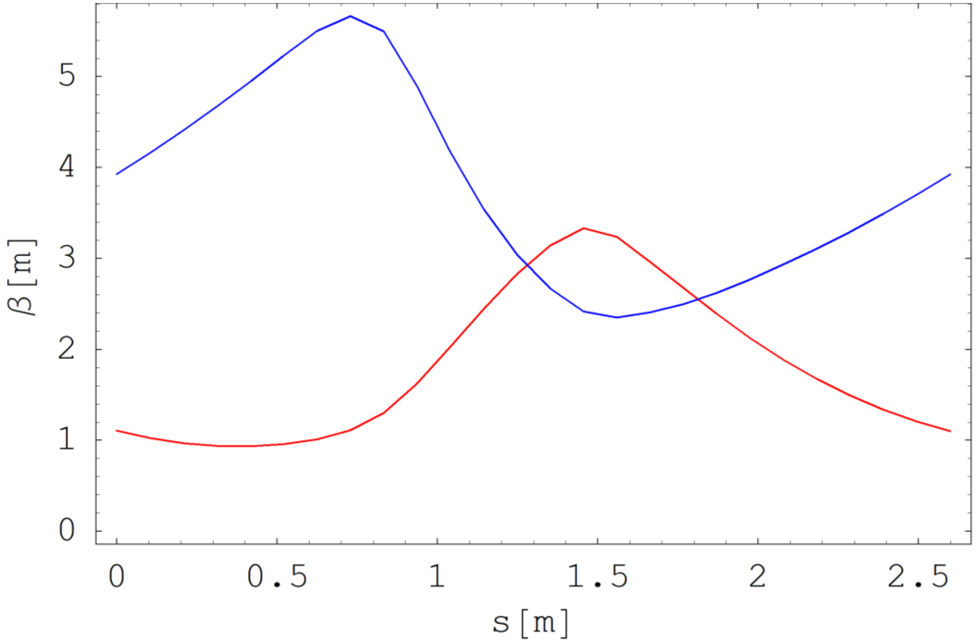
  - What if the full variability of both tunes independently is needed?
    - For example, if the effect of scaling on the vertical tune is very strong

LhARA double spiral baseline candidate, Ff configuration (nominal tune)





- Lattice type — double spiral scaling FFA
- N — 10
- k — 5.26
- Spiral angle — 45.87°
- R_{max} — 4.14 m
- R_{min} — 3.55 m
- (Qx, Qy) — (2.83, 1.22)
- B_{max} — 1.5 T
- p_f — 0.386
- Max Proton injection energy — 15 MeV
- Max Proton extraction energy — 127.4 MeV
- h — 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.37 – 5.47 MHz
- Bunch intensity — few×10^8 protons
- Range of other extraction energies possible
- Other ions also possible



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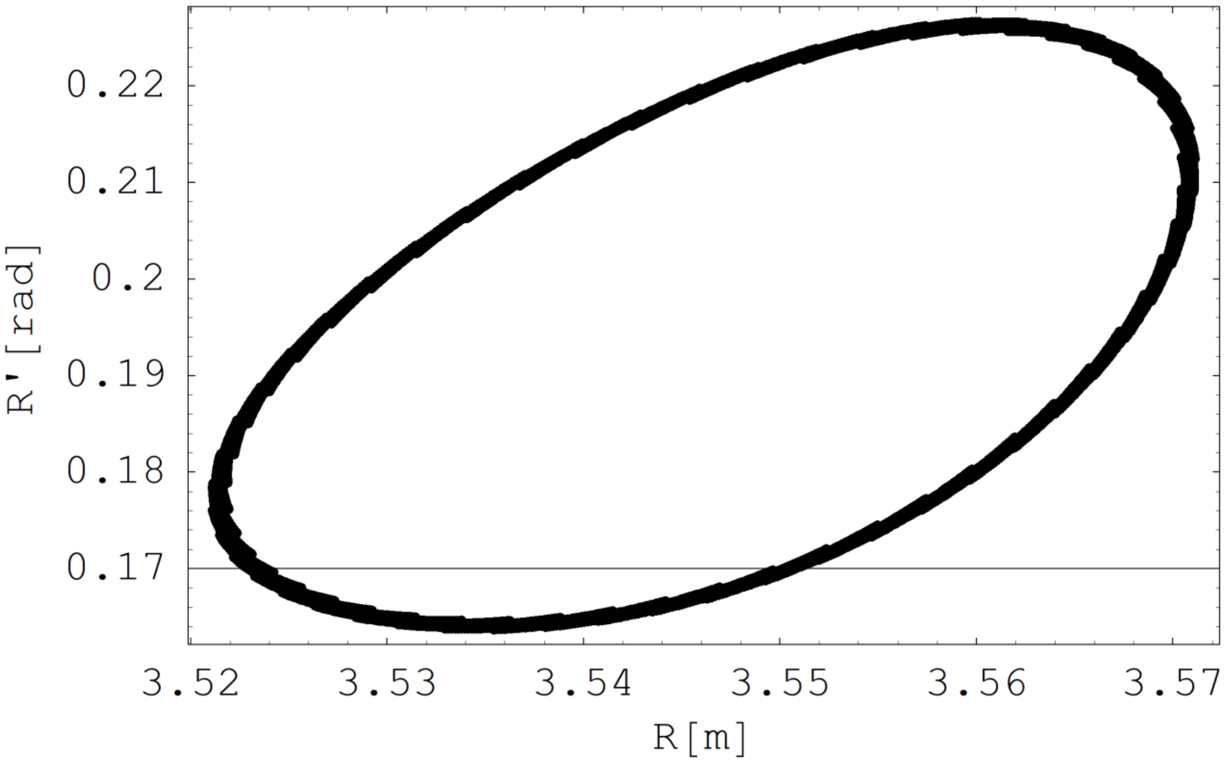
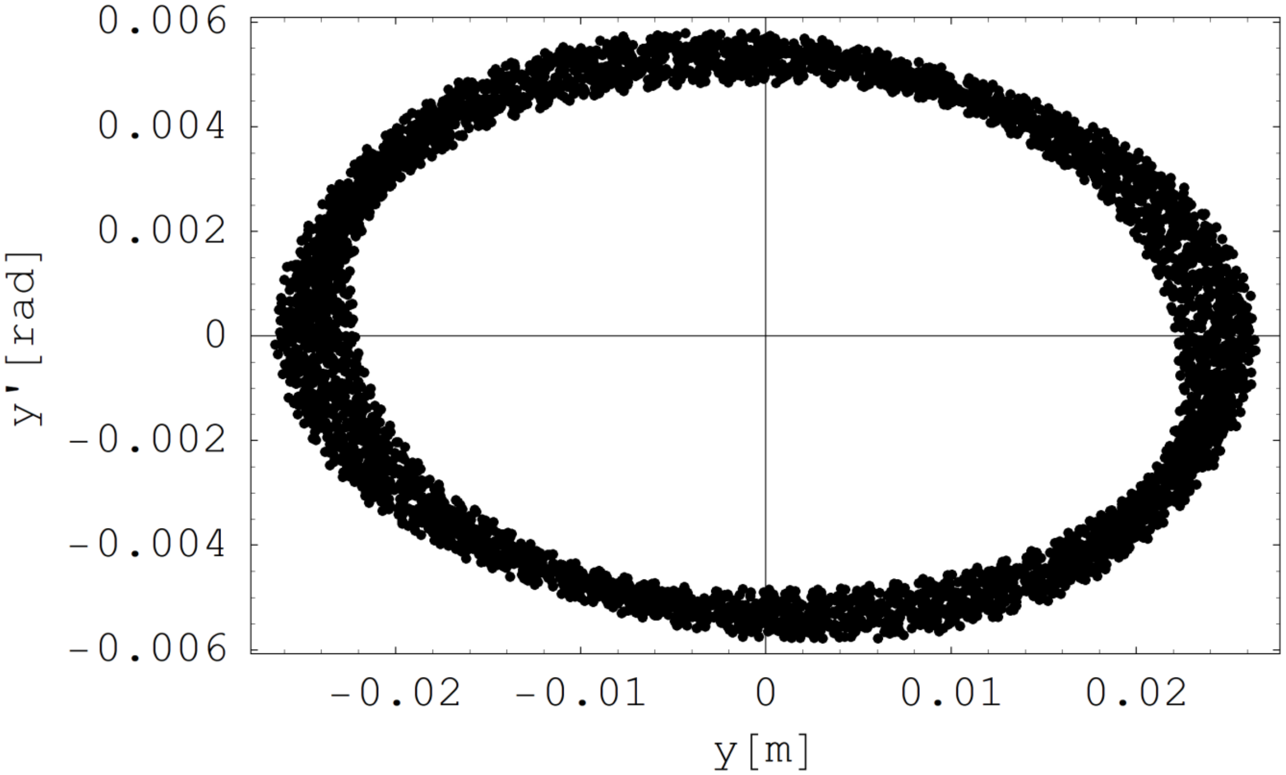
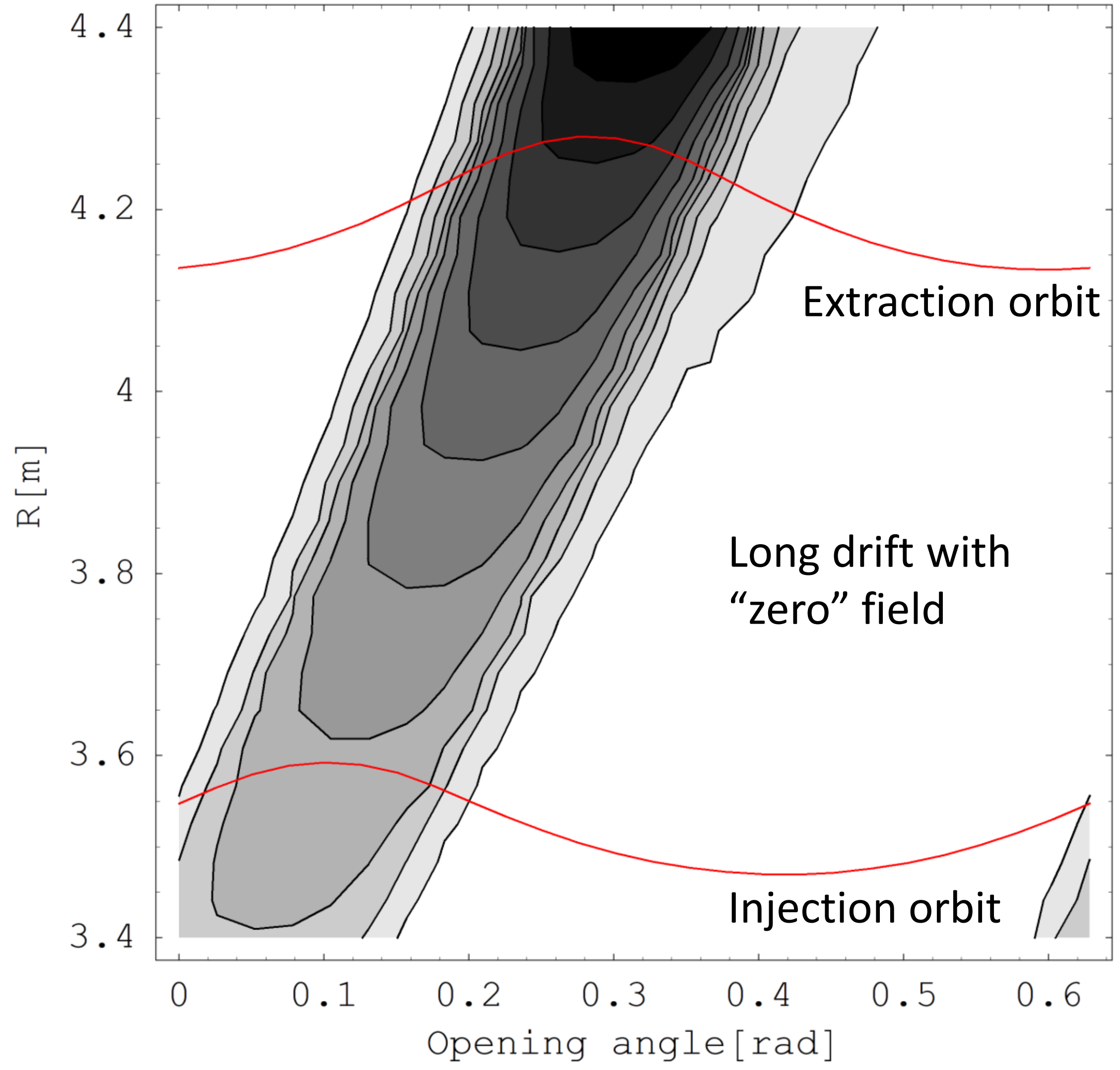
DA studies in double spiral candidate (Ff, nominal tunes)

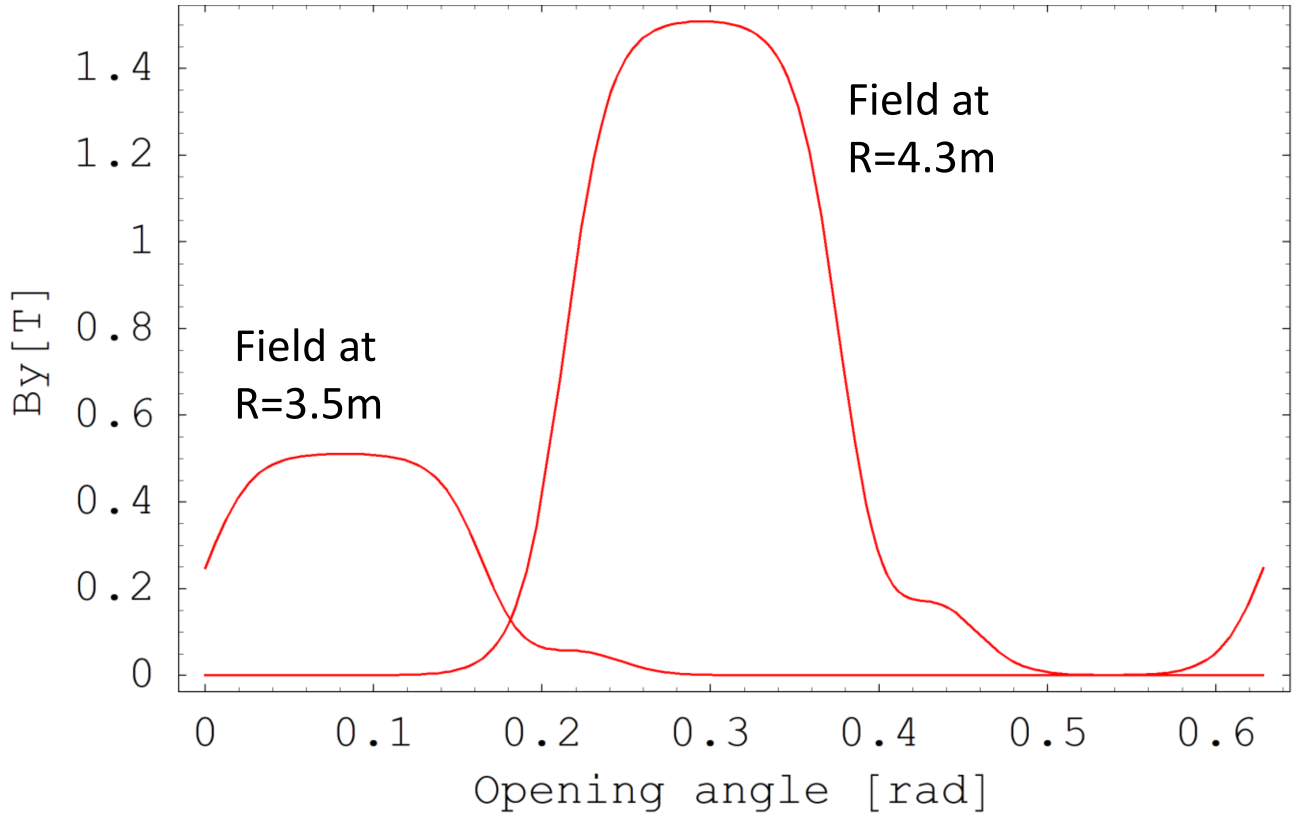




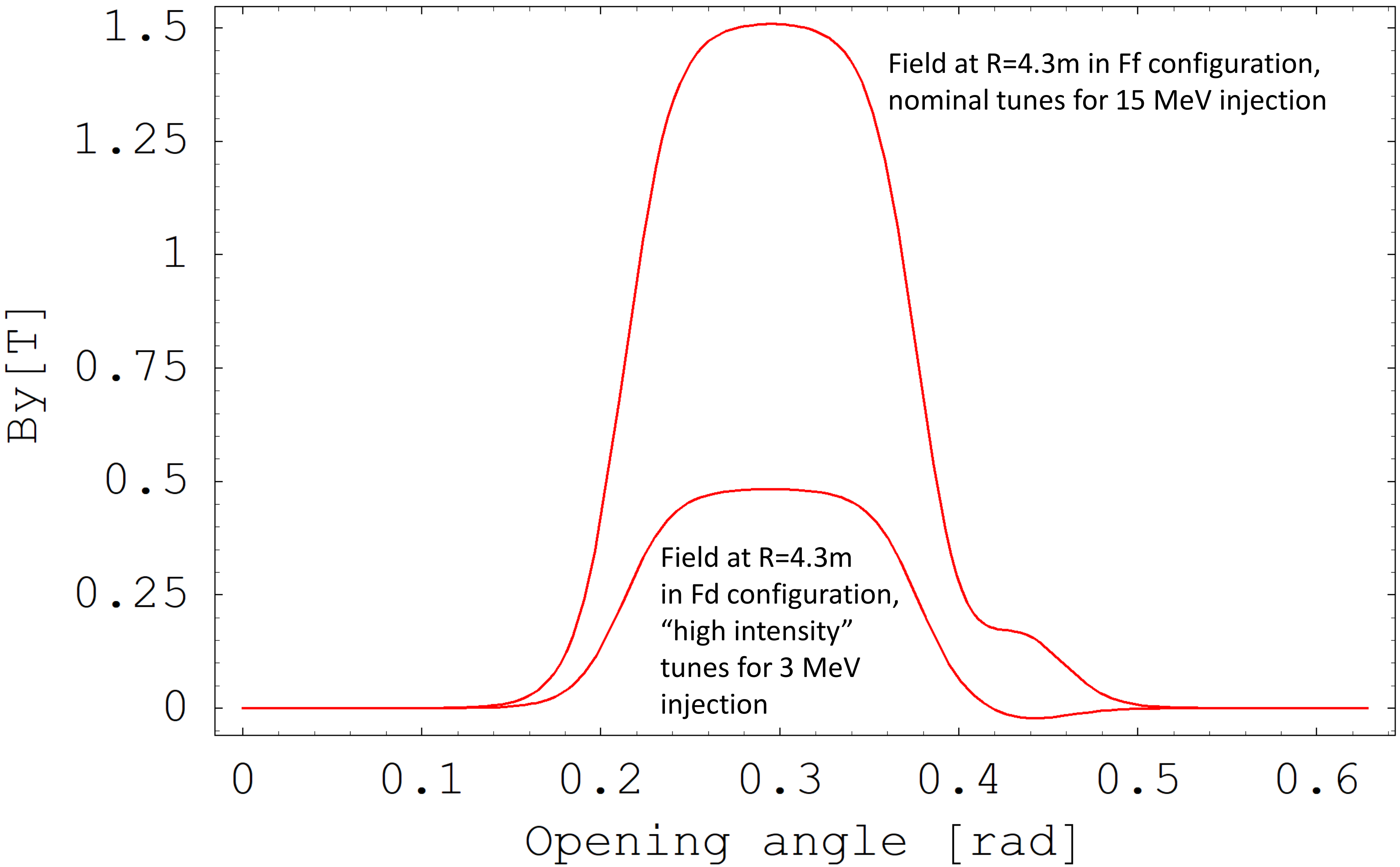
Tracking studies show sufficient DAs in both transverse planes

B field in double spiral candidate (Ff, nominal tunes)



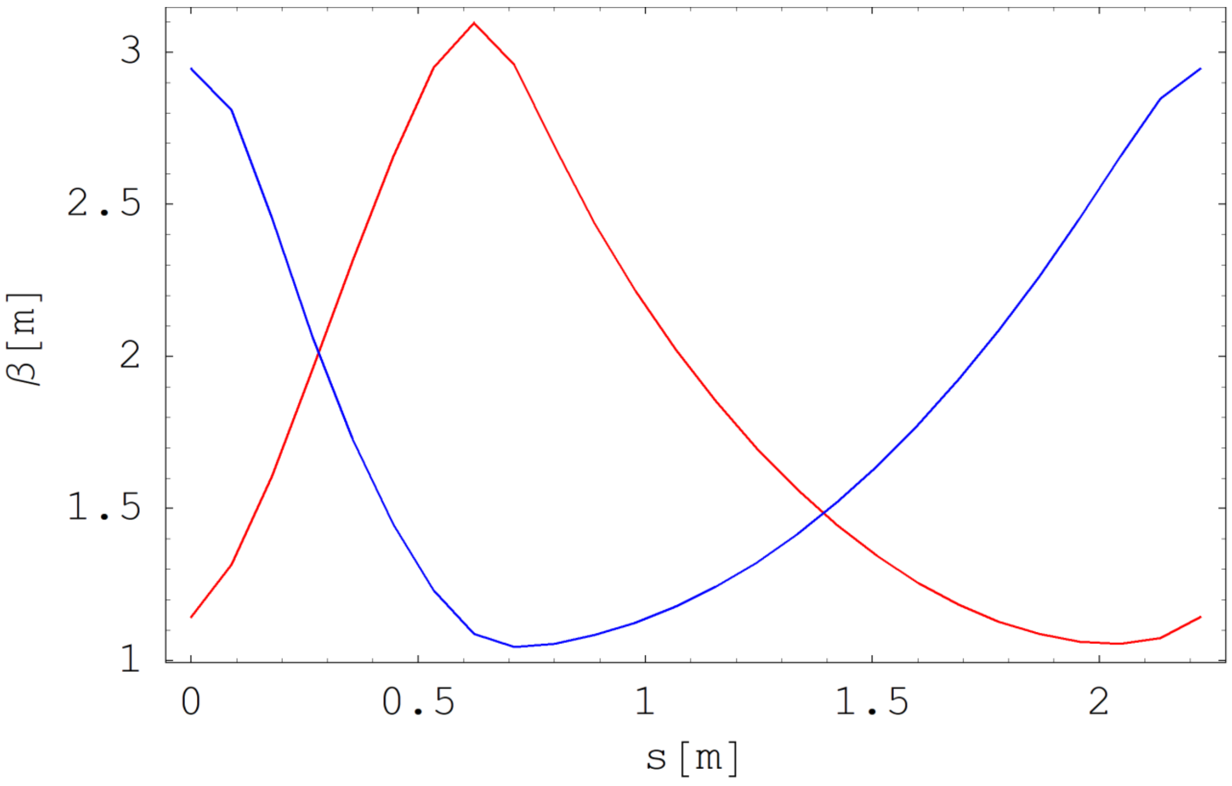


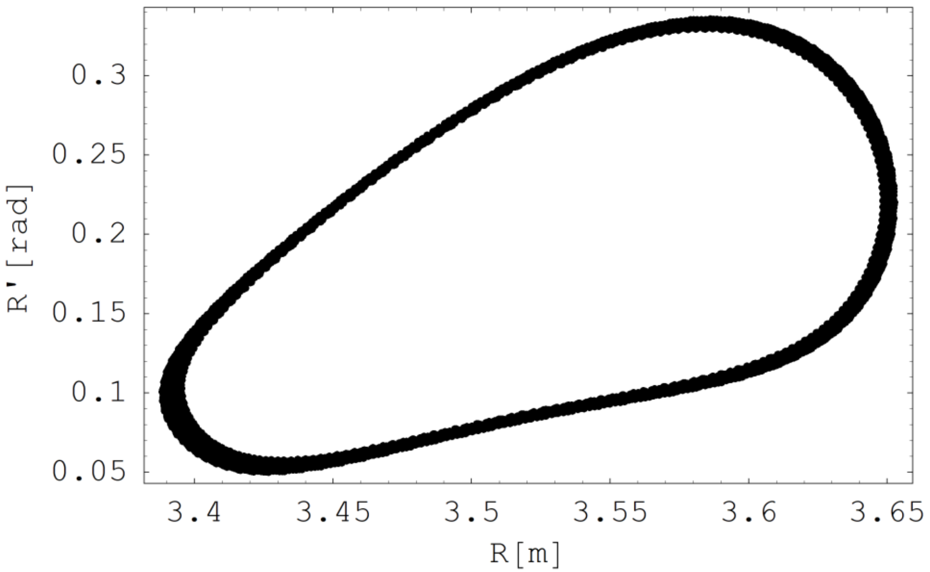
Ff vs Fd configurations (nominal tunes vs “high intensity” tunes)

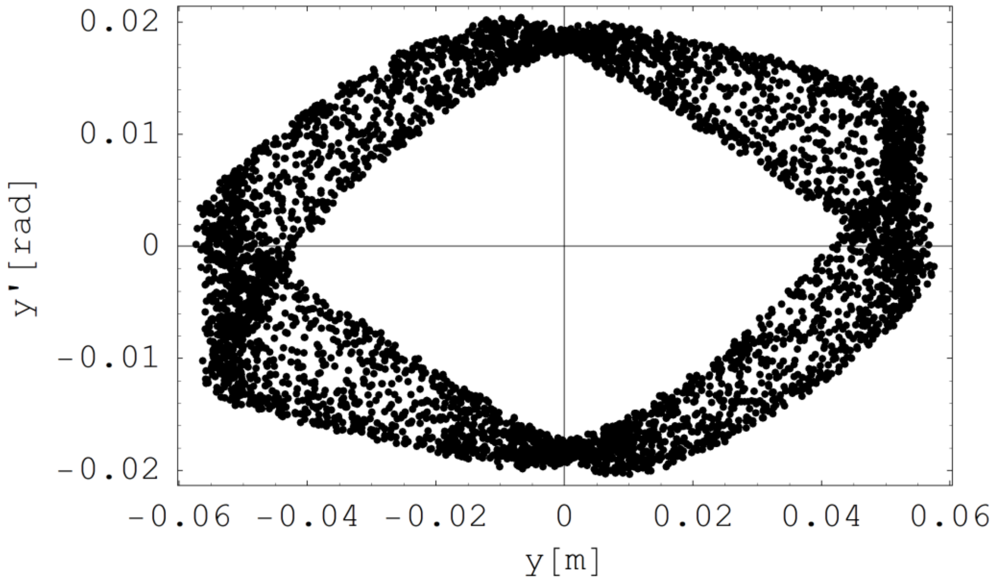


- Geometry of the doublet is informed by the FETS-FFA developments
- Second magnet can be considered as an “active clamp”
  - Effectively changing the flutter function
- It allows to vary the vertical tune in a wide range
- When polarity switched with respect to the main F magnet “f” turns into “d”.
- Allows to test double spiral concept in the focusing-defocusing configuration
  - It could be set at “high intensity” tunes (both tunes close to each other), which may allow for space charge experiment

Optics and DA studies in double spiral candidate (Fd, "high intensity" tunes)

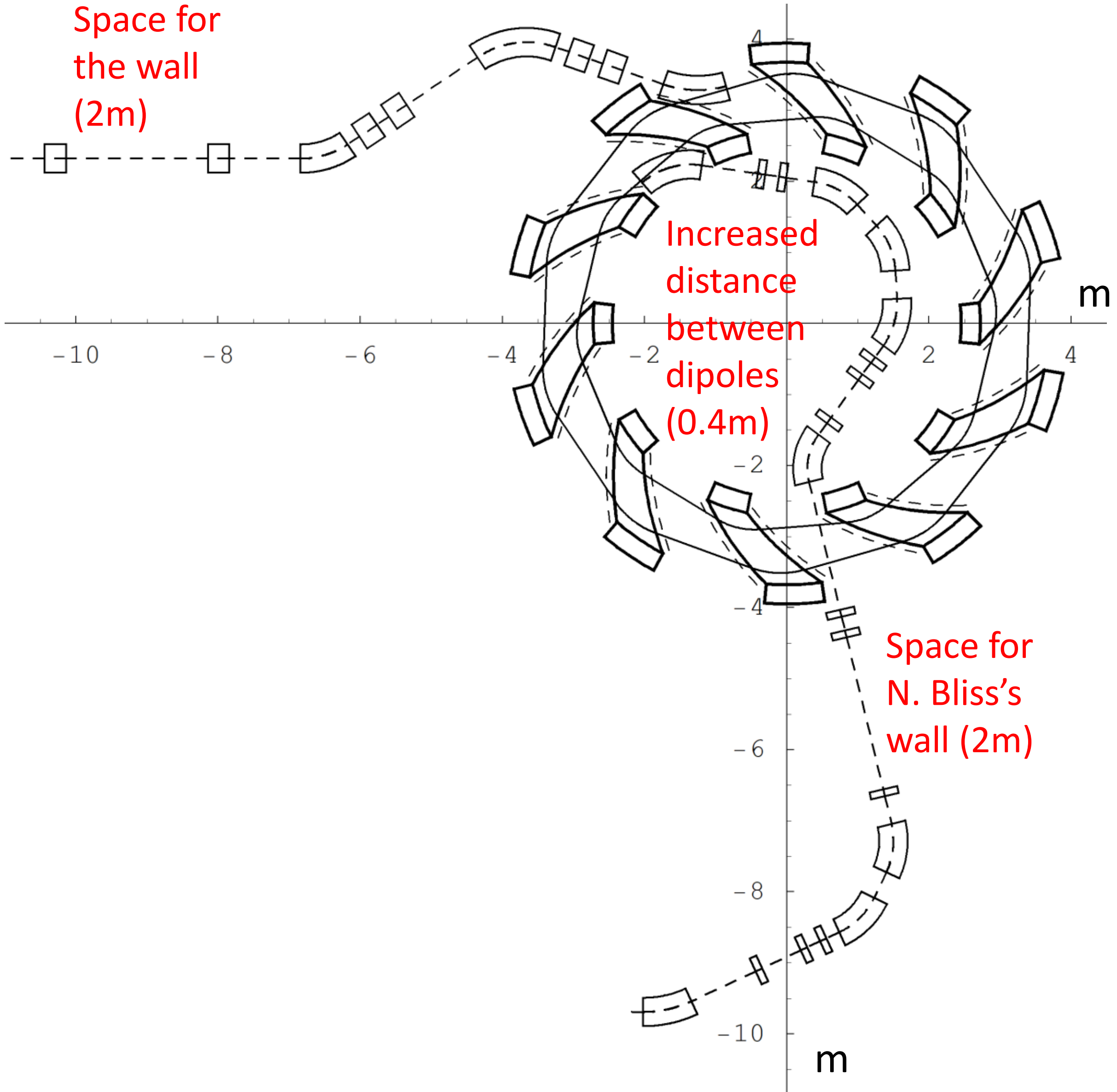


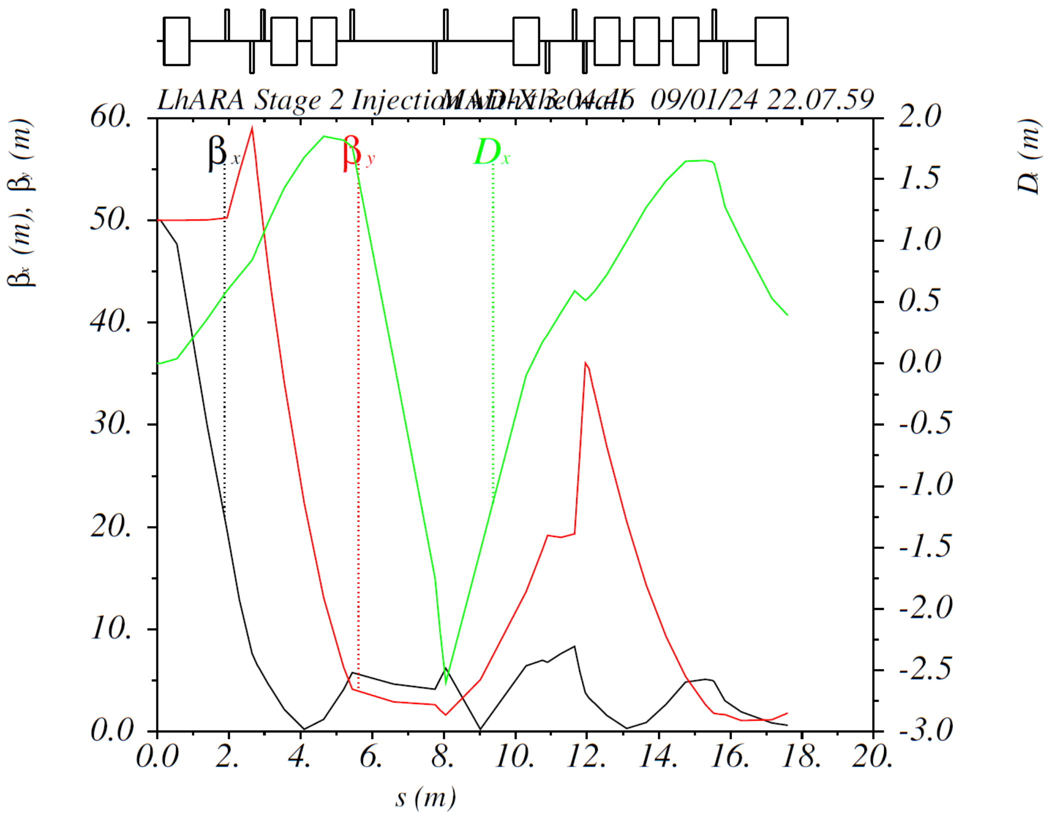




- "High intensity" tunes: (Q_H, Q_V)=(2.22,2.19) provide similar betatron functions
- This working point is limited to low energy
- DAs are larger than in the nominal working point
- We could perform space charge experiments
  - Beam is space charge dominated at injection due to the short bunch length from the laser source

New injection line for the baseline





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Conclusions

- LhARA at Stage 2 requires a variable energy FFA
- The cost effective, single spiral scaling FFA chosen for the baseline shows a good performance in tracking studies
  - New injection line has been recently designed
- The magnet design for the singlet may be realised by
  - Gap-shaping solution (RACCAM-like)with fields below saturation level with a frozen working point
  - Distributed conductors (using technique similar to FETS- FFA)
    - Allows to vary tunes in correlation
- Alternative double spiral scaling lattice was proposed
  - Allows for the independent tuning of both tunes over a wide range
  - Allows to work with a nominal tune (2.83, 1.22) in the Ff configuration
  - Allows to obtain working point with both tunes close to each other (2.22,2.19) at low injection energy (3 MeV) in Fd configuration
    - May be suitable for space charge experiments