Injection (and extraction) from FETS FFA

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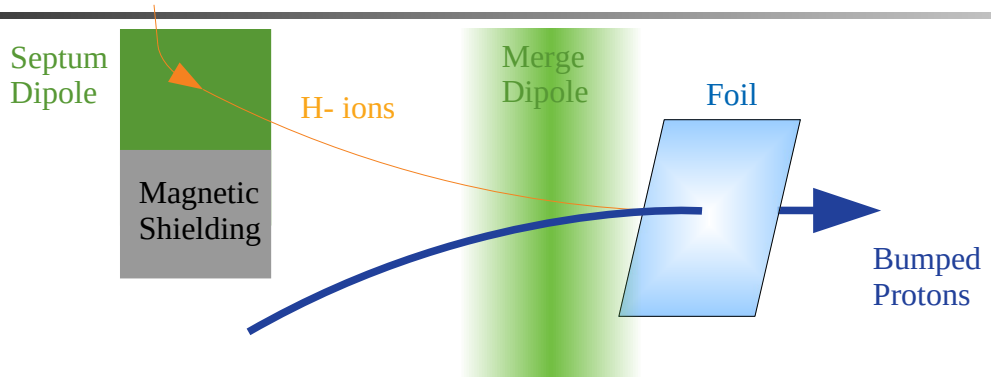
* the errors are mine, the good work is Jaroslaw’s

UKRI Science and Technology Facilities Council | ISIS Neutron and Muon Source

Charge Exchange Injection + Painting



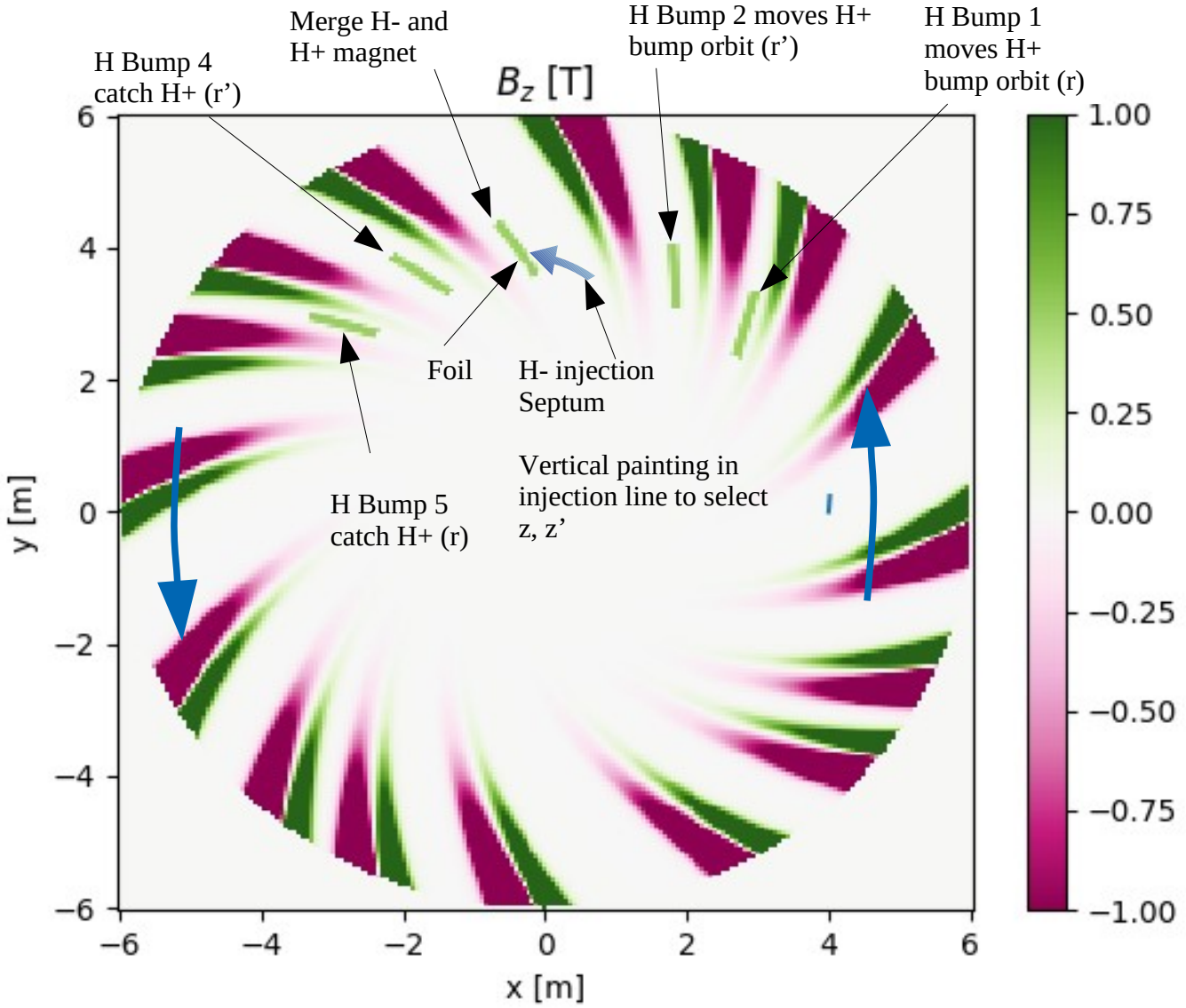
- Ion source generates Hydrogen atoms with an extra electron
  - “H-” ions
- Accelerate and inject H- on top of circulating proton beam
  - H- and protons pass through a dipole at different angles → merge
  - Pass H- through a thin Carbon foil
  - H- are ionised leaving protons
- Painting the beam enables build up of different beam shapes
  - Inject H- at distance from the circulating proton beam core
  - Develop different beams e.g. “correlated” and “anti-correlated”
- Goal: minimise protons passing through foil
- Eventually move beam off foil for acceleration

Challenges

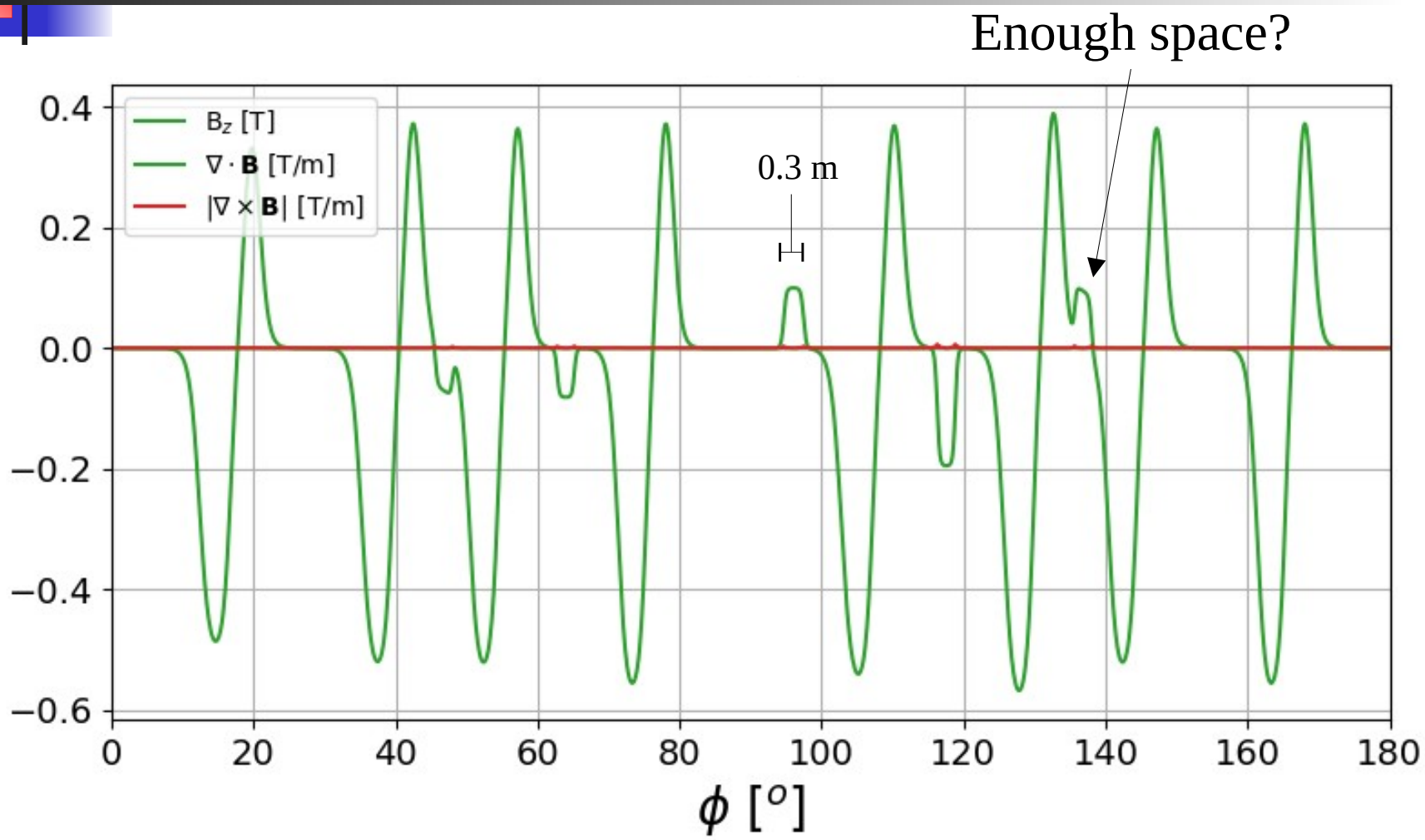
- Thin foil & foil handling issues
- Maintaining sufficient DA
- Space for septum and H- beam
  - Without disturbing main magnets
- Control/time structure of pulsed magnets
- Management of tune variation
  - Use movable extraction septum

- In the process of adopting new baseline

hFFA injection system

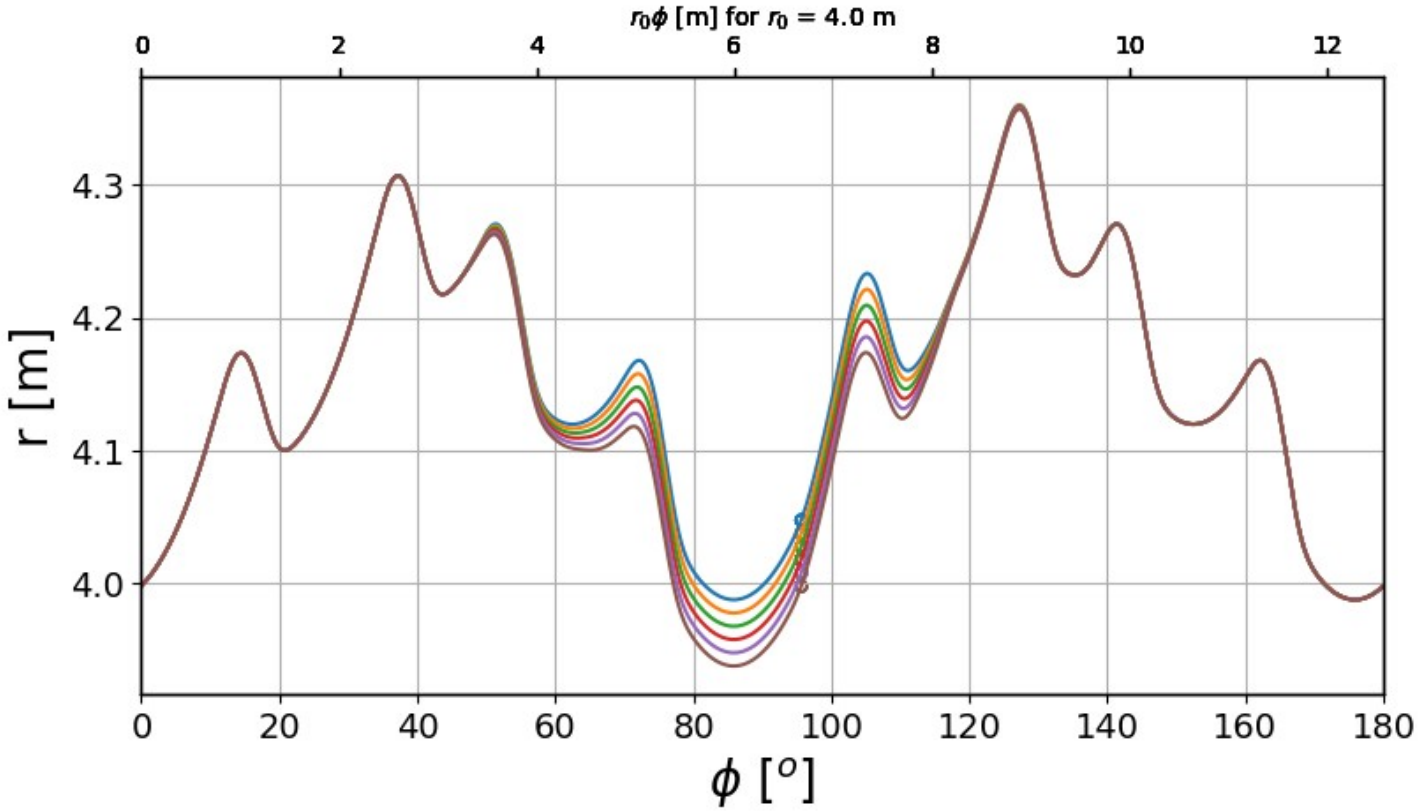


Field on the orbit

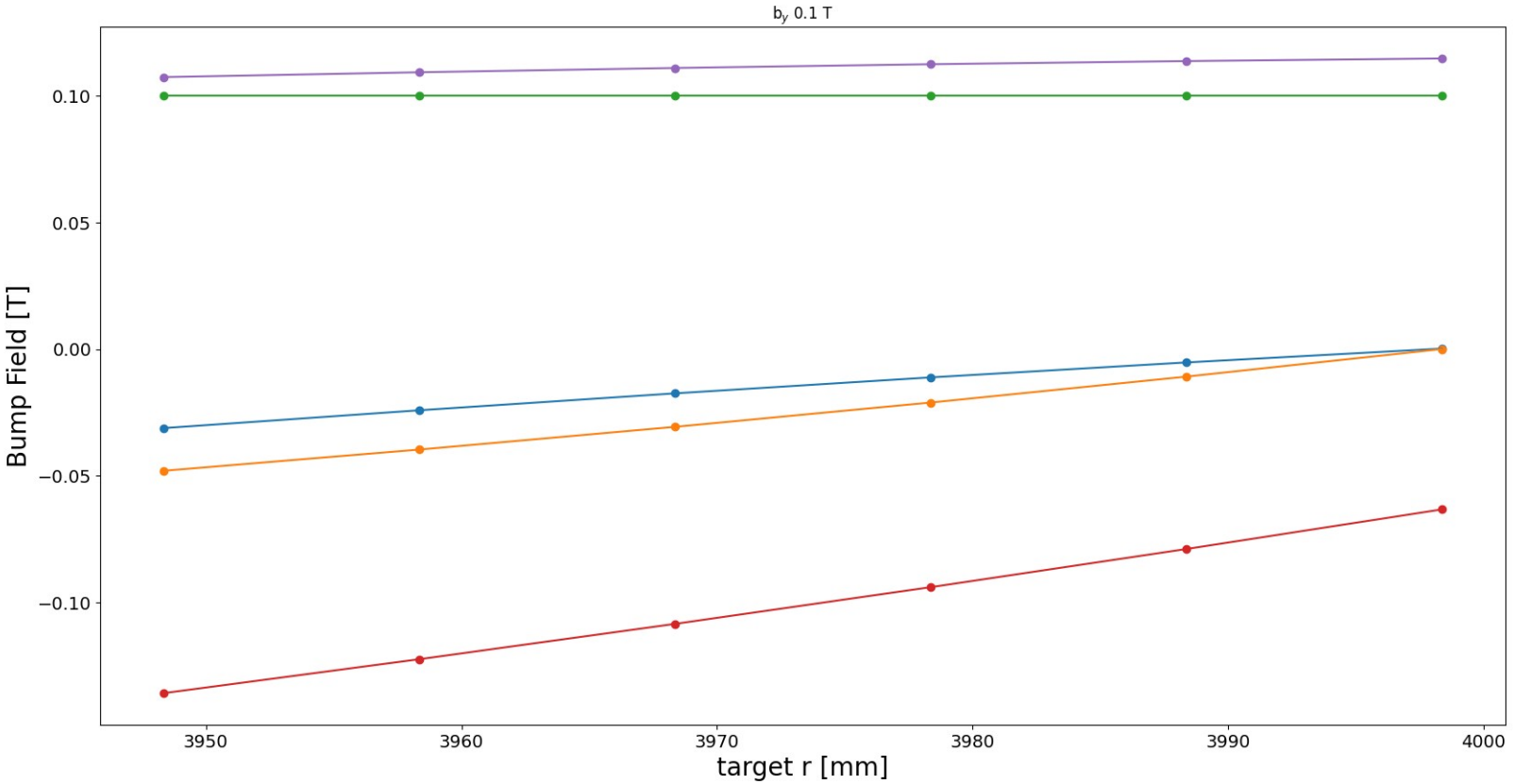


Orbits

ump

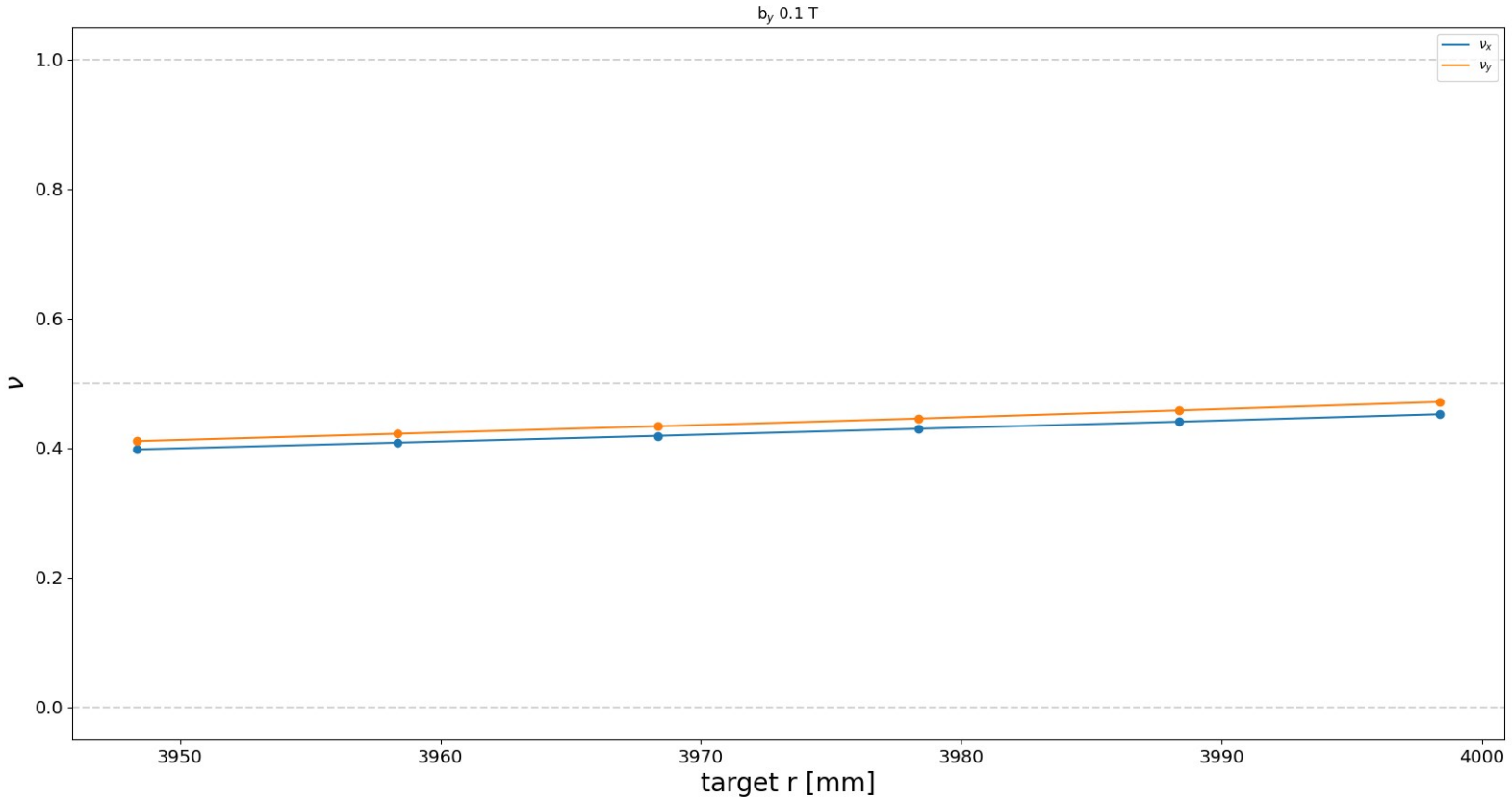

$r_0\phi$ [m] for r_0 = 4.0 m
0
2
4
6
8
10
12
4.3
4.2
4.1
4.0
r [m]
0
20
40
60
80
100
120
140
160
180
ϕ [^{o}]

Bump Field



- Bump magnet 0.3 x 0.1 m
  - Review field strength in light of new baseline

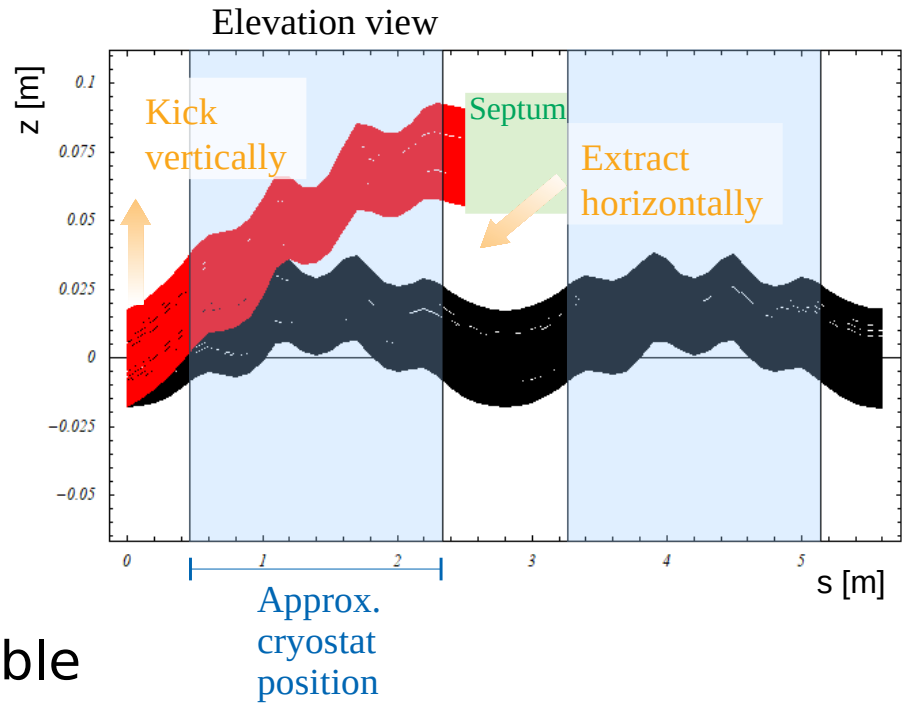
Ring Tune (Fractional)



Movie

Extraction (J. Pasternak)

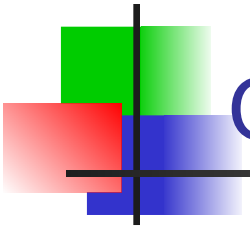
- **Extraction from vFFA**
- Extract using kicker and septum
- Kick the beam vertically
  - Required to pass the triplet
  - Acquires small radial offset
- Extract horizontally
  - Required to pass the cryostat
- Magnet parameters look reasonable
- Beam is well-controlled
  - > 3 cm separation at the septum



	Kicker	Septum
Field [T]	0.03	0.5
Length [m]	0.4	0.7
Rise time [ns	120	DC or pulsed
Flat top [ns]	470	

Extraction

- Need to redo the extraction scheme for hFFA
- Parameters
  - Change tune → change k-value → change mean dipole field
  - Orbit at the top energy moves! By 10s of cm
- Scheme
  - Kicker (maybe need two kickers)
  - Movable extraction septum
  - Bring the beam into a short extraction/diagnostics line
  - Demonstrate clean extraction



Code - OPAL

- OPAL: open source code for tracking cyclotrons and FFAs
  - Horizontal and vertical FFA with scaling to arbitrary order
  - Vertical FFA with scaling to arbitrary order
  - Variable frequency RF cavities
  - Arbitrary order multipoles with maxwellian fringe fields
  - Foil model (scattering and energy loss)
- Features coming soon
  - Python binary API for direct interface to OPAL from python
  - Time dependent/pulsed multipoles

Example PyOpal code

```
def build_ffa_magnet(self, name, b0, length, end_length):
    """
    Build an FFA magnet taking default parameters and additionally
        - name: string name of the magnet
        - b0: Nominal B0 field strength along self.r0 [T]
        - length: magnet centre length [rad]
        - end_length: length of the fringe field [rad]
    This function uses the default tanh model for the magnet definition.
    """
    magnet = pyopal.elements.scaling_ffa_magnet.ScalingFFAMagnet()
    magnet.set_opal_name(name)
    magnet.set_attributes(
        r0 = self.bend_direction*self.r0,
        b0 = b0,
        field_index = self.field_index,
        tan_delta = math.tan(math.radians(self.spiral_angle)),
        max_vertical_power = self.ffa_max_vertical_power,
        radial_neg_extent = self.dr/2,
        radial_pos_extent = self.dr/2,
        # azimuthal extent [m] defines the extent of the bounding box
        azimuthal_extent = self.cell_length,
        # magnet start [m] defines where the fringe field starts rising
        # relative to the element start
        magnet_start = 0.0,
        # magnet end [m] defines where the next element will be placed
        magnet_end = length*self.cell_length,
        centre_length = length*self.cell_length,
        end_length = end_length*self.cell_length,
        height = self.ffa_height,
    )
    if self.verbose > 0:
        print("Built magnet with b0", magnet.b0, "centre_length", magnet.centre_length, "end_length", magnet.end_length)
    return magnet
```

Note also magnet.get_field_value(...) method

set_attributes method

Direct access to attributes

Conclusions

- Phase space painting can enable high beam current injection into FFA
  - Question: to what extent can LhARA benefit from a high current injection?
- (Py)Opal code can be used to track FFAs including space charge
  - See Carl’s talk