Modelling H- Injection and Painting in Vertical and Horizontal FFAs Using OPAL

C. T. Rogers*, A. Adelmann

*chris.rogers@stfc.ac.uk

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Science and Technology Facilities Council | ISIS Neutron and Muon Source

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FFAs for high power proton machines

- Acceleration of high power protons comes in 3 flavours
  - Cyclotrons
  - Linacs
  - Synchrotrons
- Cyclotrons
  - No pulsed magnets → energy efficiency
  - Large magnet apertures
- Fixed Field Accelerators (FFAs) are like cyclotrons, but
  - Increase bending field with momentum → more compact
- FFAs have never been used for high power proton acceleration
  - Proposed as an option for ISIS upgrade in ~ 2030s
  - Would like to test concepts in small prototype ring
    - 4 m radius
    - 3-12 MeV energy
  - Short injection straights → challenging injection

Horizontal and vertical FFAs

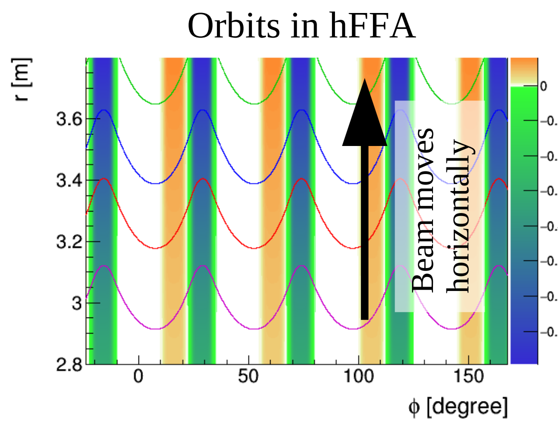
- Two types of FFA considered in this talk
  - Horizontal orbit excursion (hFFA)

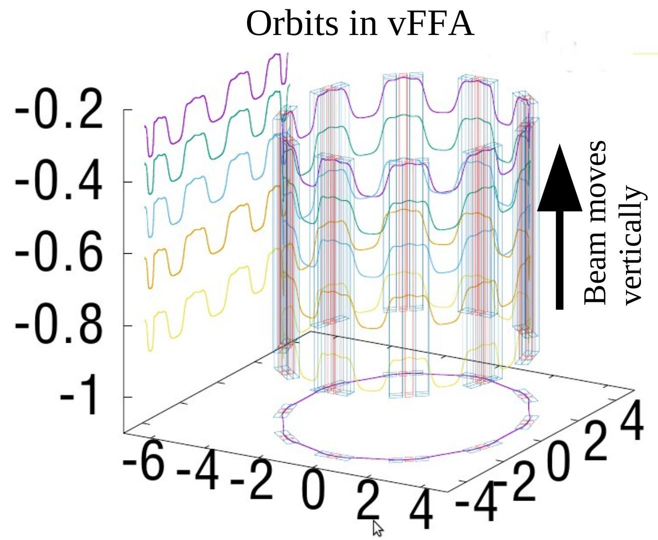
$$B_z(r,\phi,z=0) = B_0(\psi)\left(\frac{r}{r_0}\right)^k$$
$$\psi = \phi - \tan(\delta)\ln(r/r_0)$$

    - Beam moves horizontally as momentum increases
  - Vertical orbit excursion (vFFA)

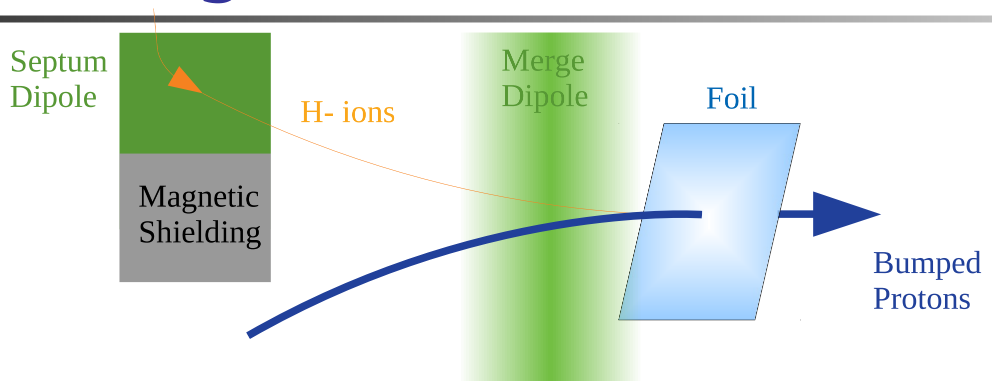
$$\vec{B} = \vec{B}_0(r,\phi)\exp(mz)$$

    - Beam moves vertically as momentum increases
    - Strongly coupled optics
- FFAs not isochronous
  - Variable frequency RF
  - High power → accumulate a beam
    - Charge exchange injection
    - Phase space painting





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

Object Oriented Parallel Particle Library (OPAL)

OPAL is a versatile open-source tool for charged-particle optics in large accelerator structures and beam lines including 3D EM field calculation, collisions, radiation, particle-matter interaction, and multi-objective optimisation

https://gitlab.psi.ch/OPAL/src/wikis/home

- OPAL is built from the ground up as an HPC application
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the MAD language with extensions
- OPAL is written in C++, uses design patterns, easy to extend
- The OPAL Discussion Forum:

  https://psilists.ethz.ch/sympa/info/opal
- International team of 11 active developers and a user base of O(100)
- The OPAL sampler command can generate labeled data sets using the largest computing resources and allocations available

The Active OPAL Developer Team

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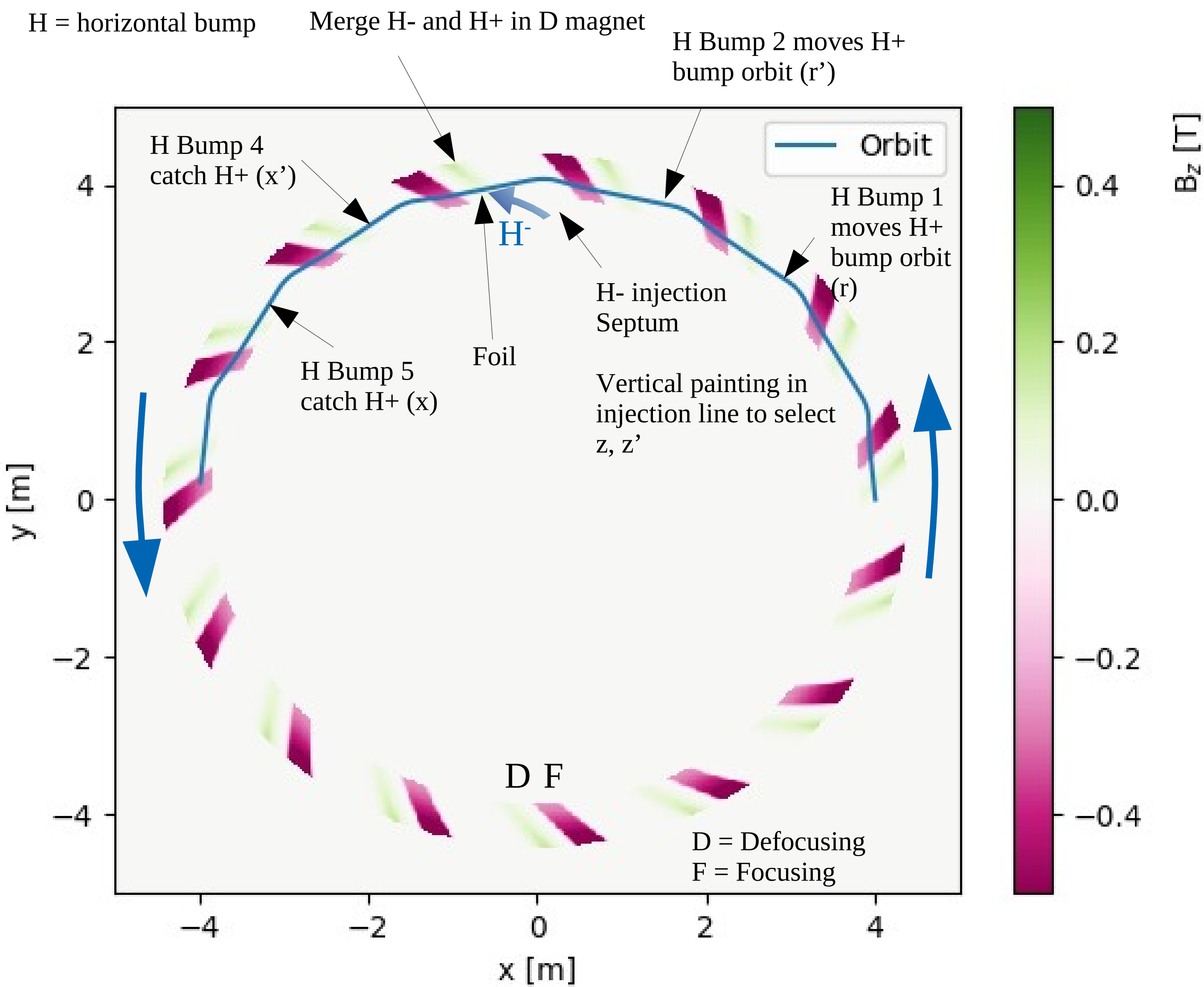
Features Implemented in OPAL

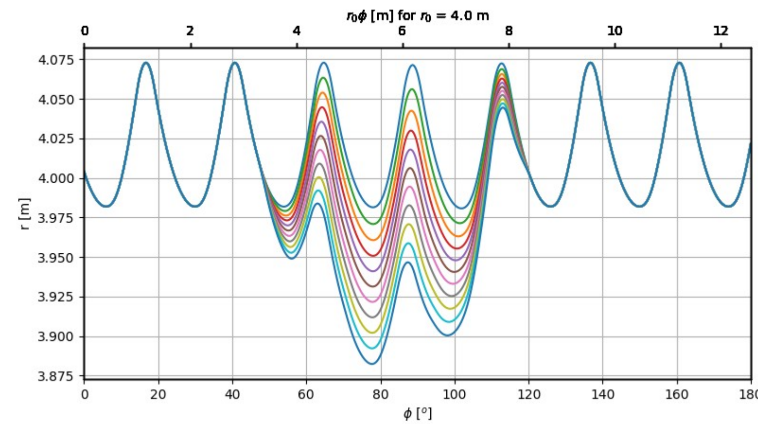
- Features now implemented in OPAL-cycl
  - Horizontal and vertical FFA with scaling to arbitrary order
  - Vertical FFA with scaling to aribtrary order
  - Variable frequency RF cavities
  - Arbitrary order multipoles with maxwellian fringe fields
  - Foil model (scattering and energy loss)
- Features coming soon
  - Python binary API for direct interface to OPAL from python
  - Time dependent/pulsed multipoles

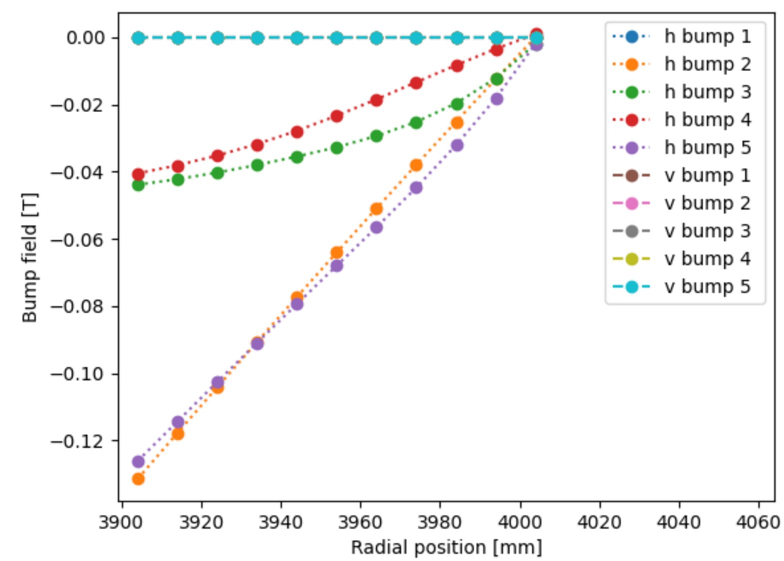
Horizontal FFA



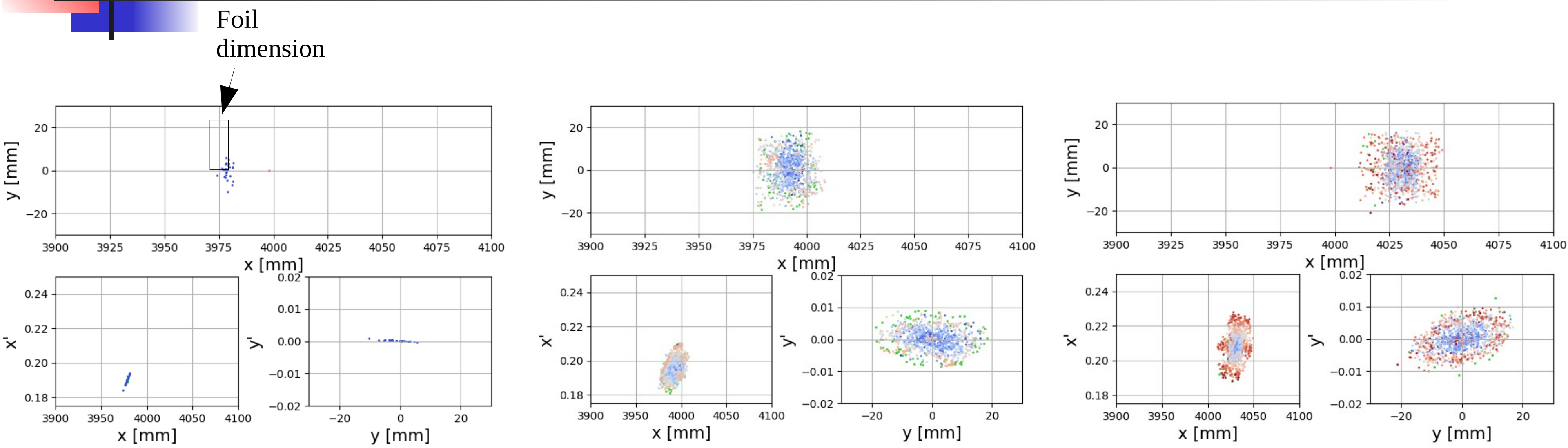
Inject from inside – using D magnet

- Use bump magnet to distort closed orbits
  - Movement of circulating proton beam over 100 mm
  - 0.1 m long bump magnets
  - Max field ~ 0.12 T
- Tune distortion is constrained to maintain sufficient DA





Injection process

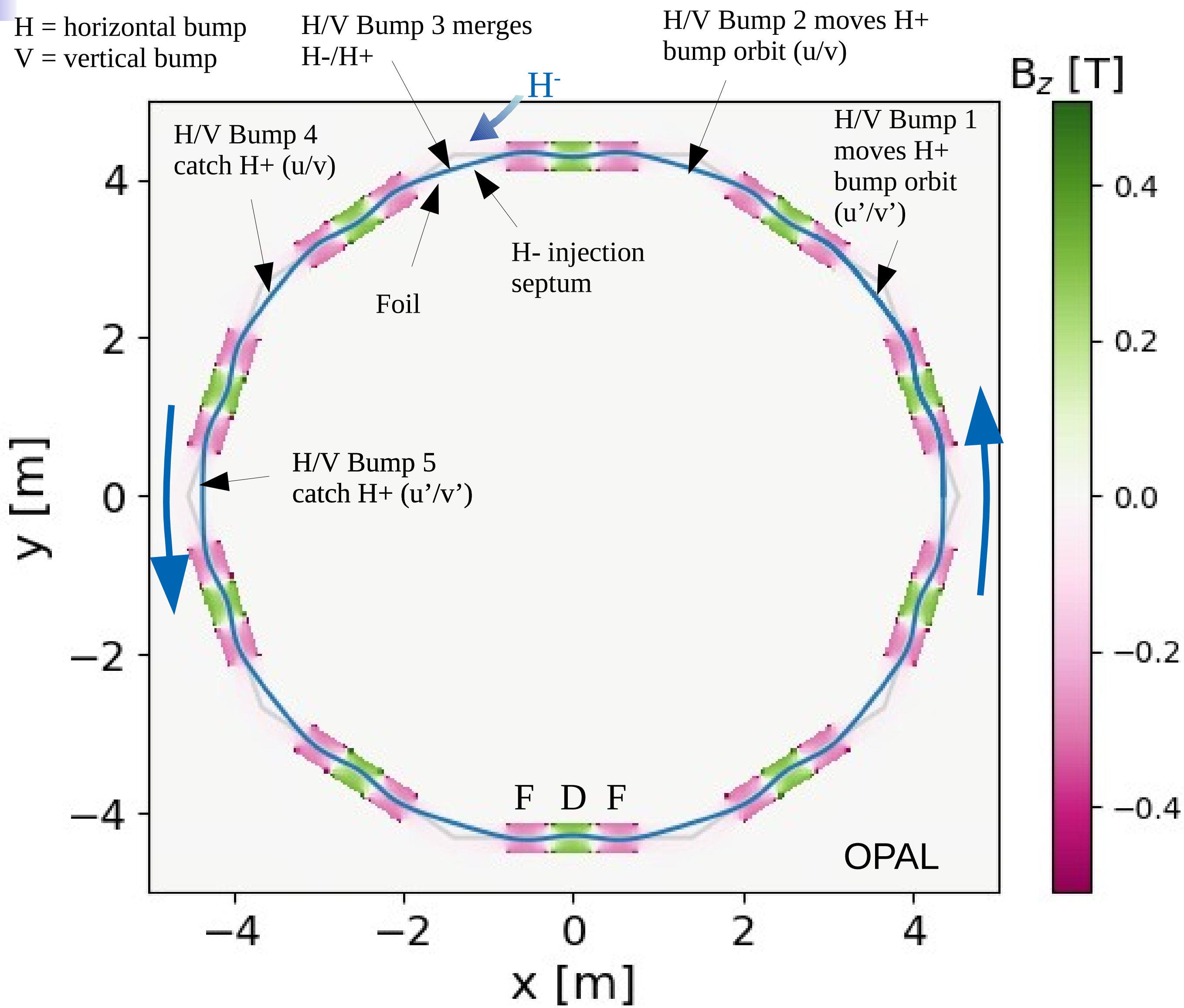


- Inject H^-
- Sweep H^- beam up
- Sweep H^+ close orbit horizontally

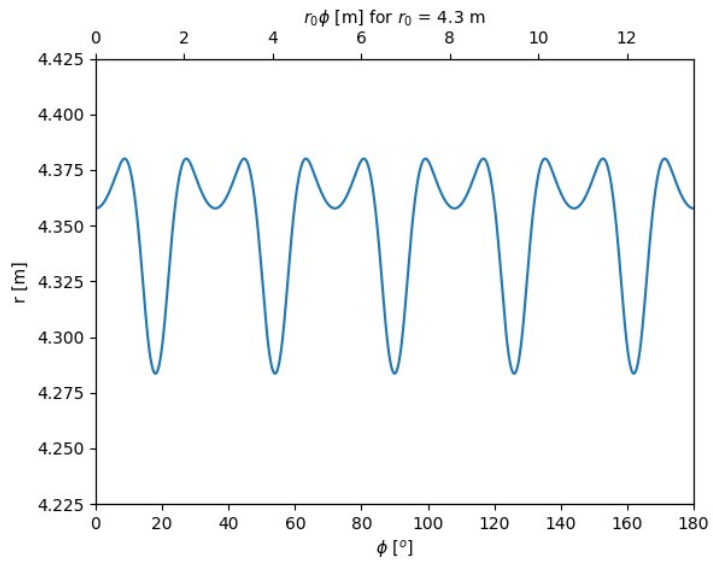
- Paint full phase space

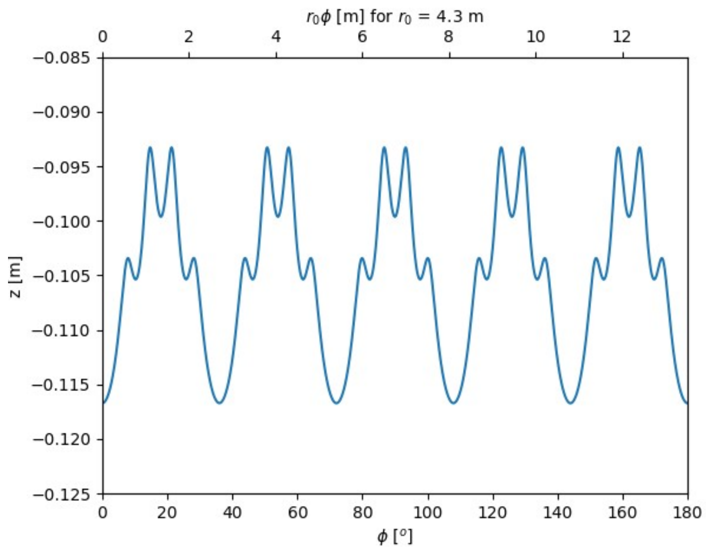
- Collapse bump
- Beam moves clear of foil

Vertical FFA



Tracking simulation - vFFA

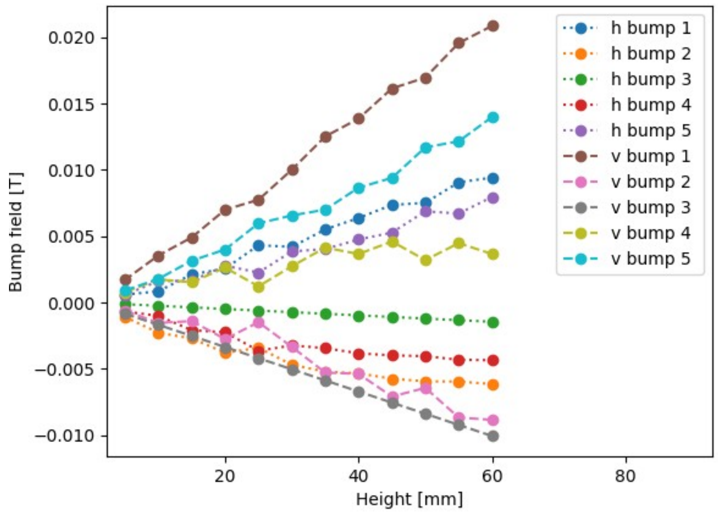


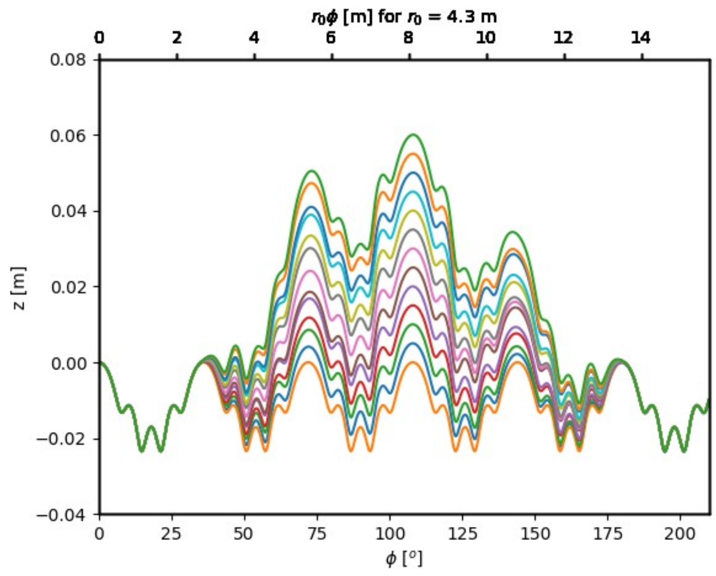


- vFFA has strongly coupled optics, from Maxwell's equations
  - Skew quadrupole focusing in magnet body
  - Solenoid focusing in magnet fringe field
  - Vertical kick in fringe field if beam is not perfectly central

Injection simulation - vFFA

- Use bump magnet to distort closed orbits
  - Now we need both horizontal and vertical bumps
- Challenging to achieve sufficient DA with good orbit separation
  - Have not tried using F magnet to separate orbits!





Conclusions

- OPAL has been extended to model FFAs
- OPAL has been extended to model fully 4D injection systems
  - Including e.g. pulsed magnets and RF
  - Features coming to user space soon!
- Studies of injection in a small test ring
  - HFFA
    - Good closed orbit separation
    - Sufficient DA
  - VFFA
    - Move proton orbit arbitrarily in x-y plane
    - Still looking for good DA with sufficient orbit separation
    - Idea to use foil in F magnet to get orbit separation (WIP)