The Low Energy Beam Transport and RadioFrequency Quadrupoles

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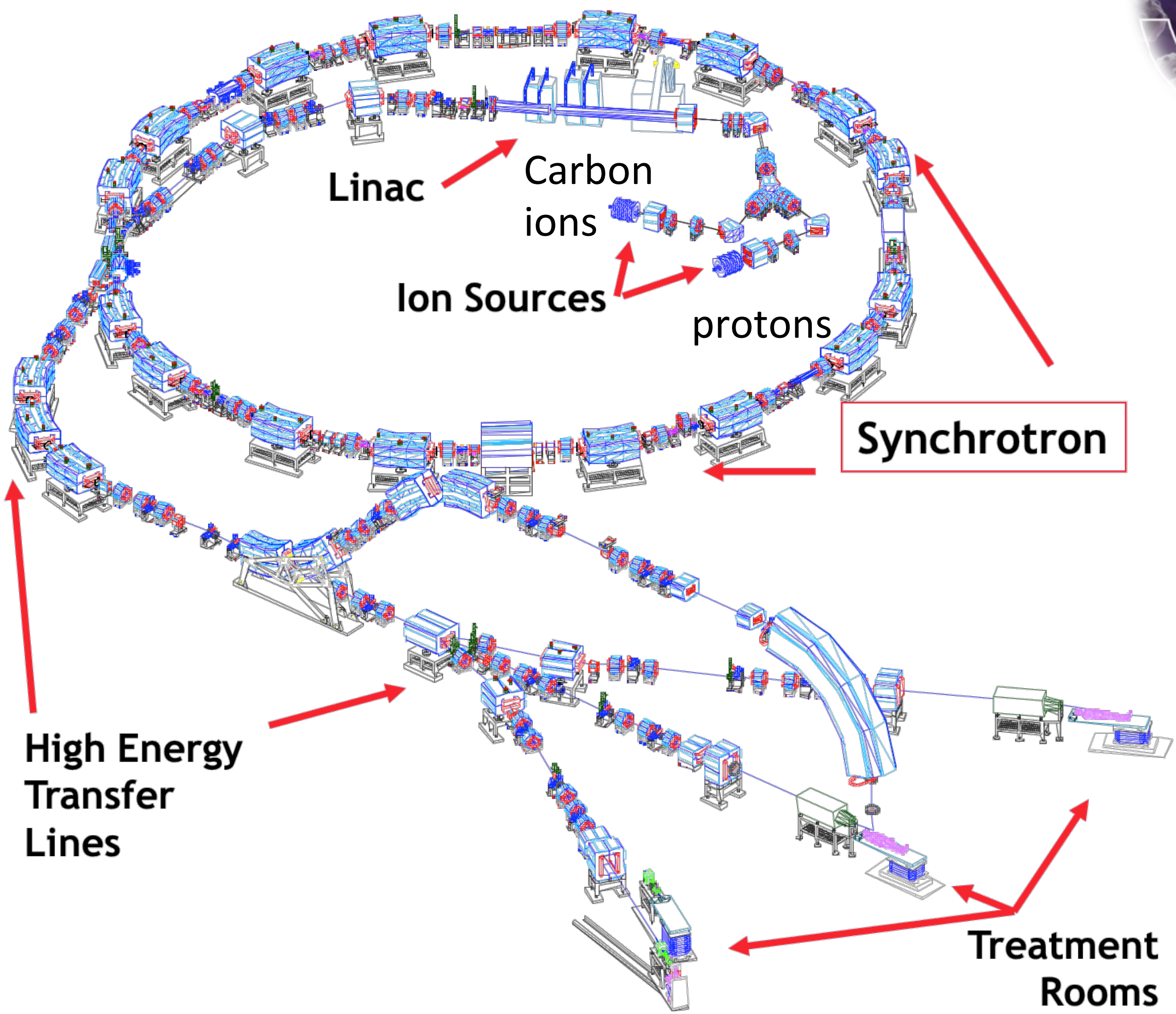
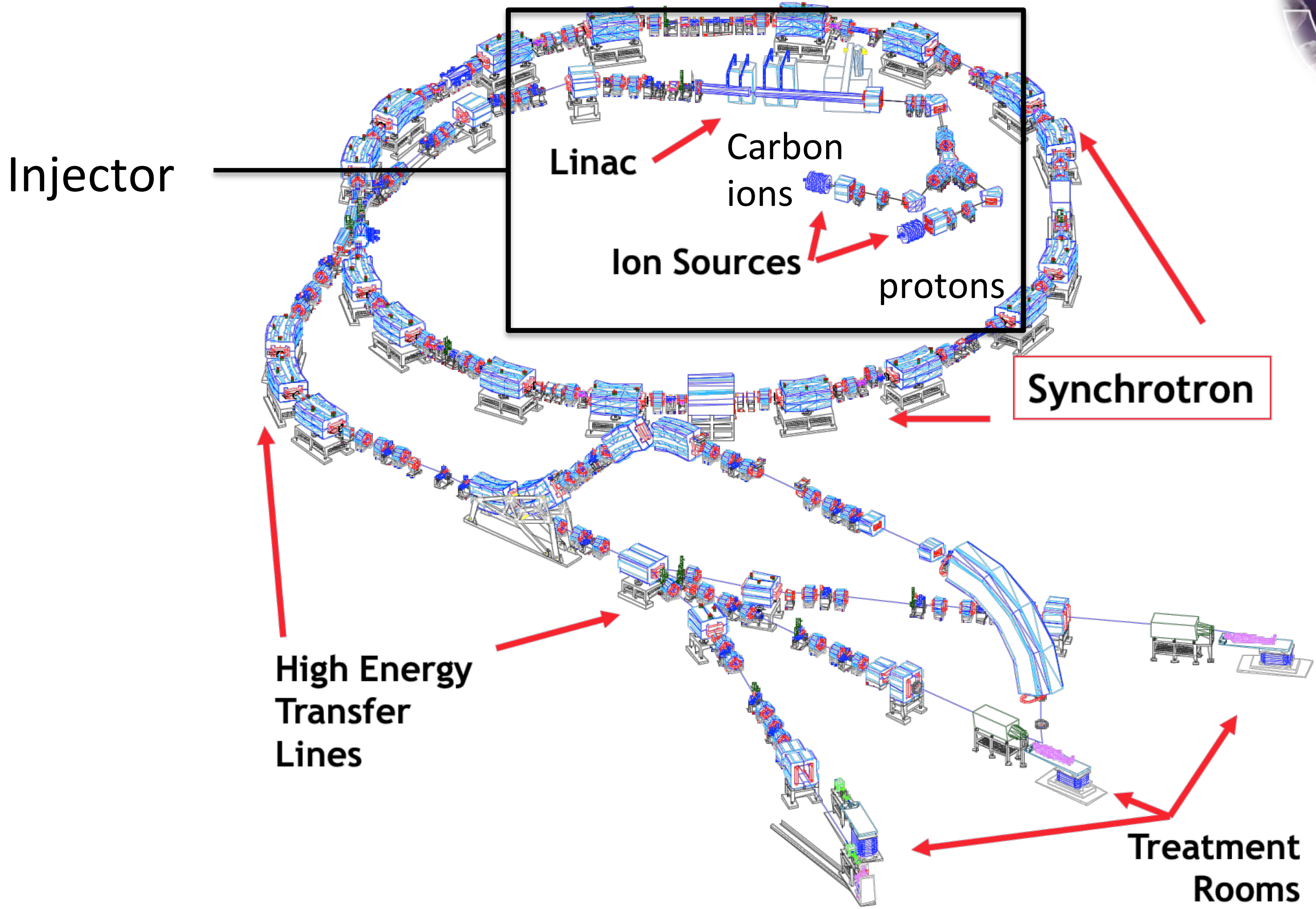
Injection

- Need to transport beam from ion source to accelerator:
  - Only cyclotrons can take beam at extraction energy (~10 keV).
  - Synchrotrons need minimum energy (~7 MeV) to match minimum revolution frequency (frequency of RF).
  - Linacs need to deal with high space charge before acceleration.
- This part of the accelerator is called the ***injector***.

CNAO Layout


Linac
Carbon
ions
Ion Sources
protons
Synchrotron
High Energy
Transfer
Lines
Treatment
Rooms

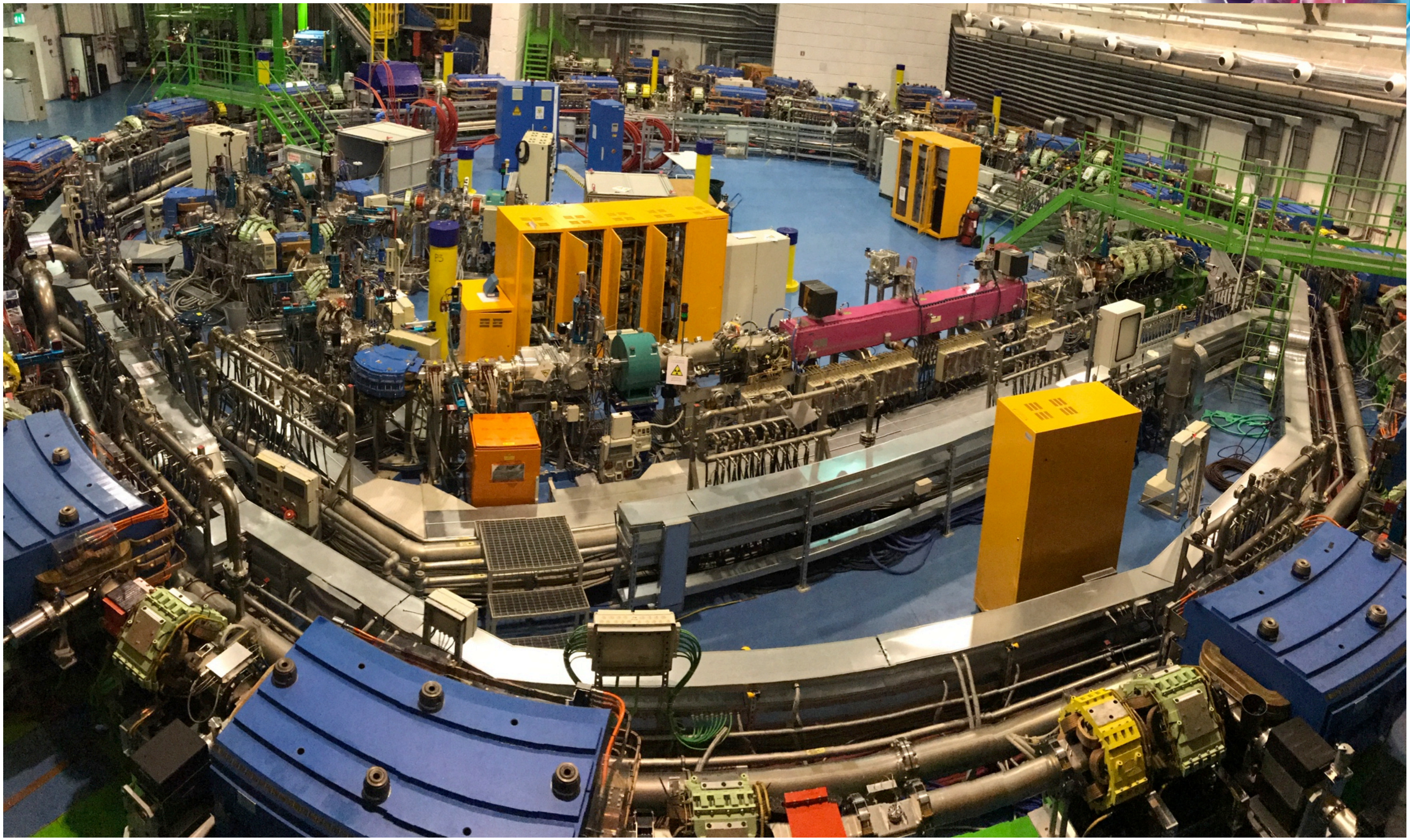
CNAO Layout: Injector



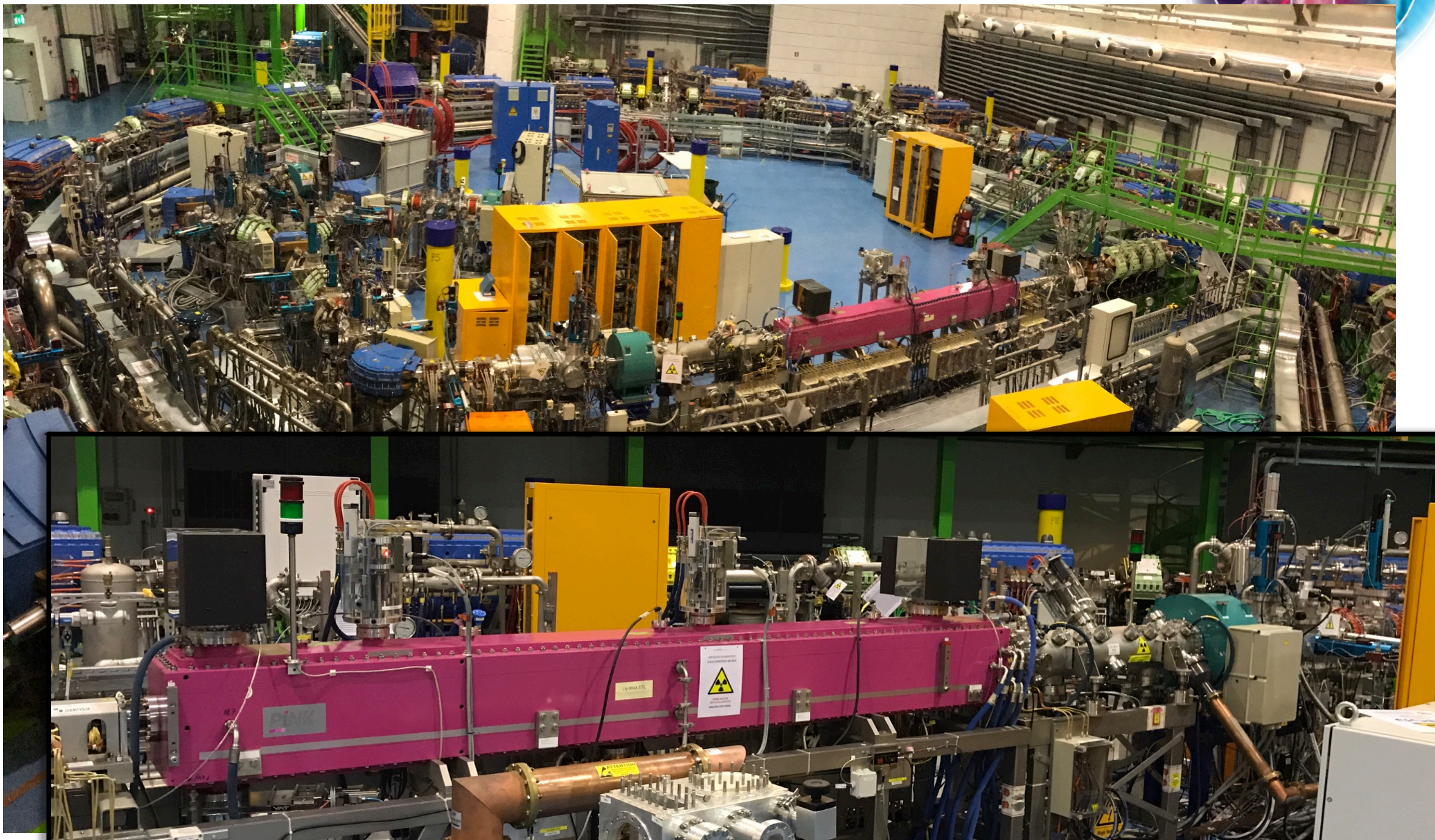
Injector Components

- The injector consists of several distinct parts:
  - The ***Ion Source***, which creates the beam.
  - The ***Low Energy Beam Transport*** (LEBT) takes the beam from the ion source to the first accelerating structure.
  - The ***RadioFrequency Quadrupole*** (RFQ) is the first accelerating stage that increases the energy whilst maintaining strong focussing.
  - The ***Linear Accelerator*** (Linac) provides greater acceleration with less focussing.

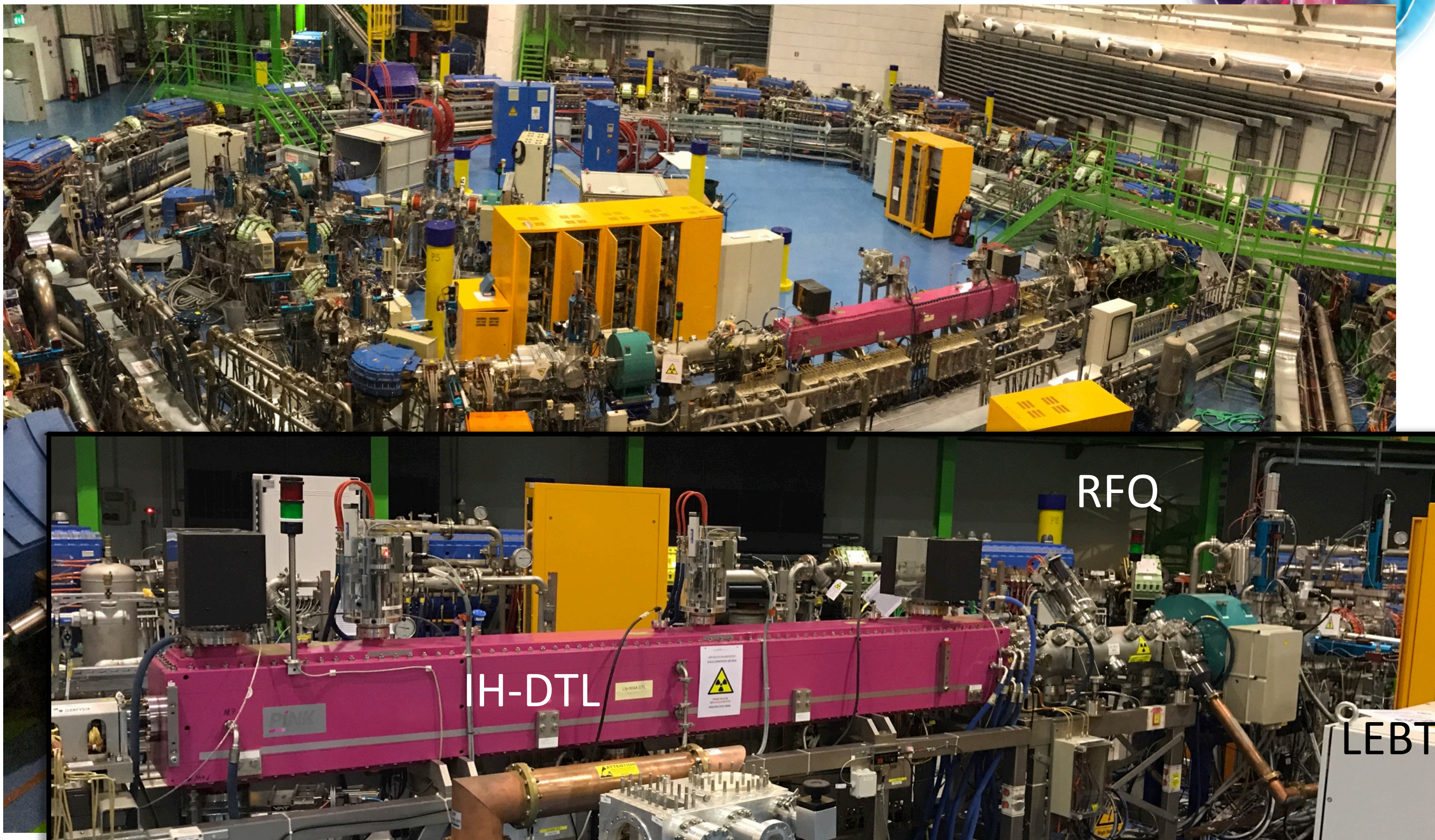
CNAO Injector



CNAO Injector



CNAO Injector



Beam Transport Requirements

- Emittance **must** be preserved:
  - Easy to make it worse.
  - Very hard to make it better without losing beam.
- Treatment current is ~1 nA:
  - For cyclotron, this is the ***Continuous Wave*** (CW) extracted current.
  - Synchrotron current is >1 mA, with slow extraction to achieve treatment current.
- For synchrotron injector, at low energies we have to deal with ***space charge***: natural Coulomb repulsion in beam leads to emittance blow-up.
- Therefore: focus hard, accelerate fast, transport carefully and measure as you go…

1st Rule of LEBT Design:

Don’t f*** up the emittance…

2nd Rule of LEBT Design:

Don’t f*** up the emittance…

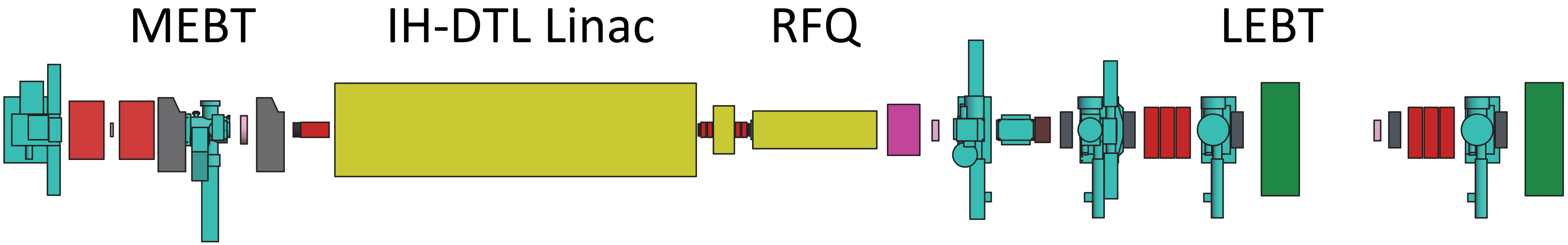
3rd Rule of LEBT Design:

Get the beam to the right energy for synchrotron injection… before you f*** up the emittance…

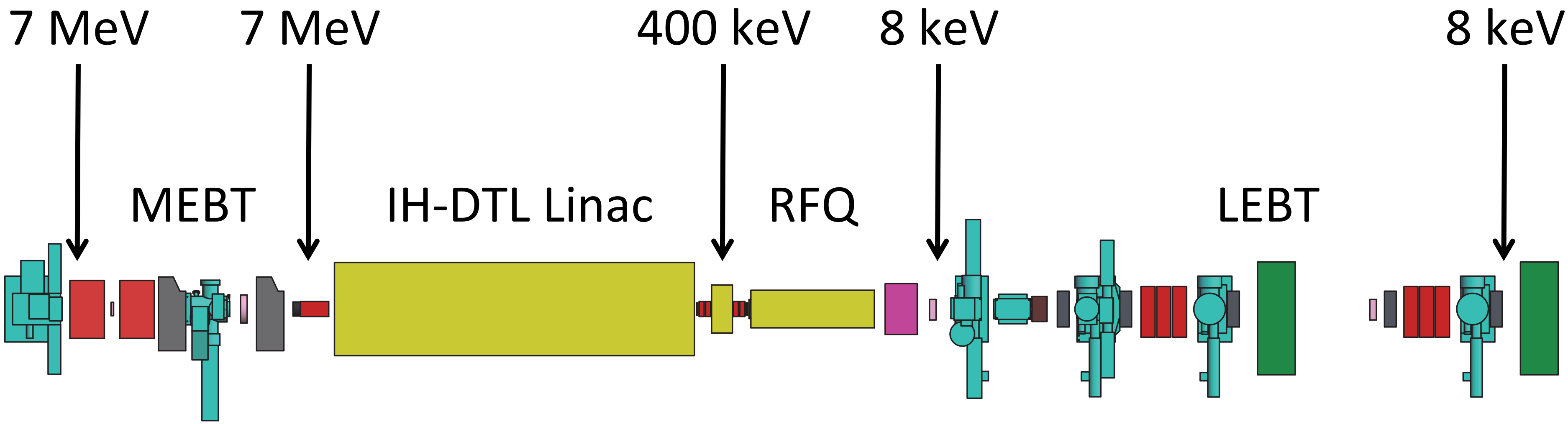
4th Rule of LEBT Design:

If you f*** up the emittance,
work out why…

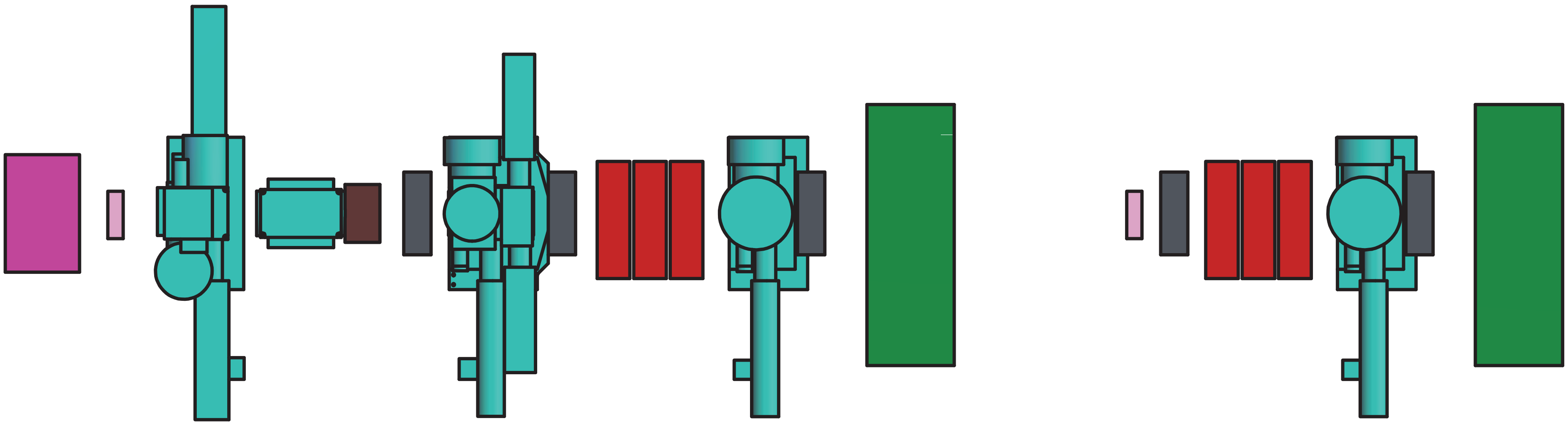
MedAustron Injector



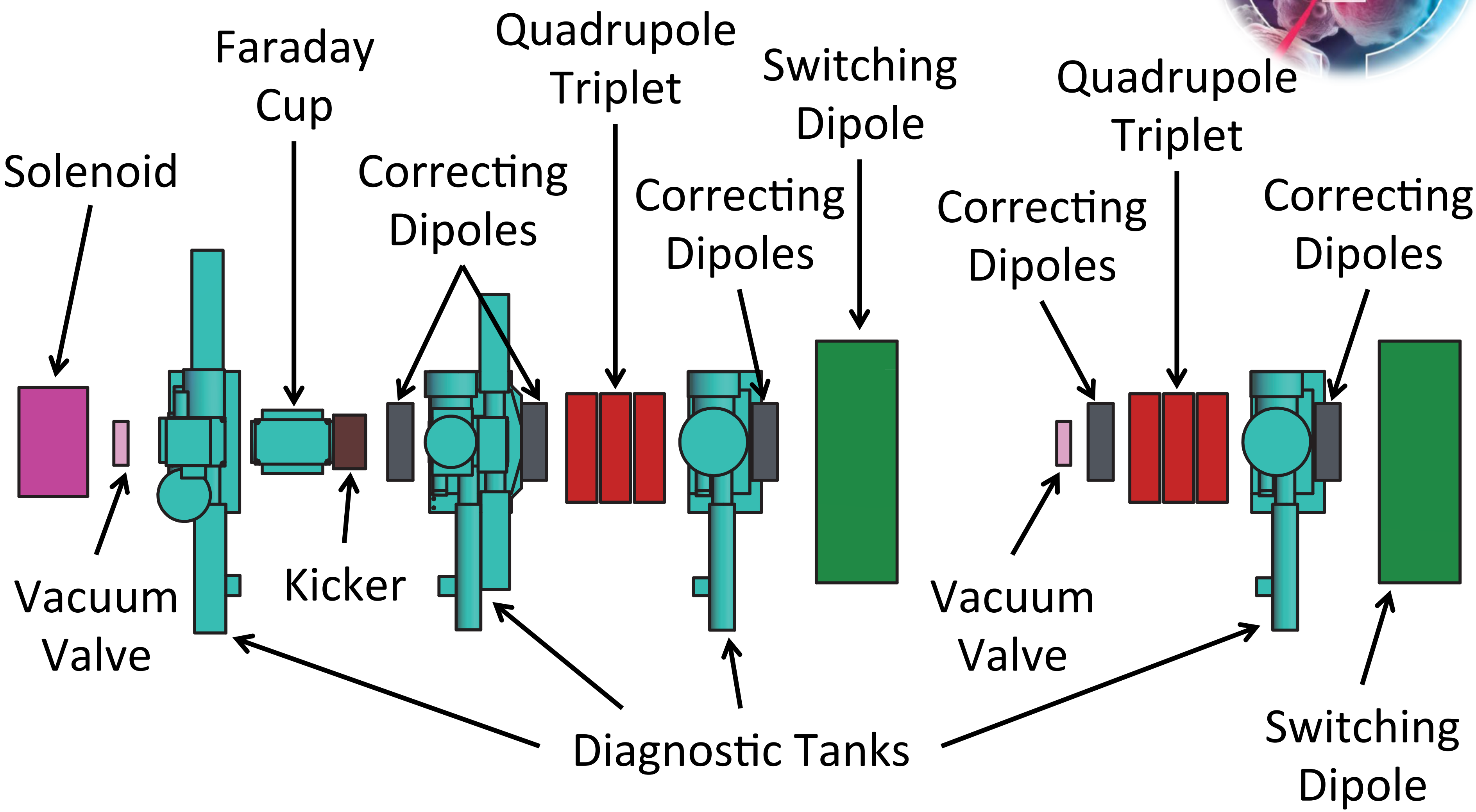
MedAustron Injector



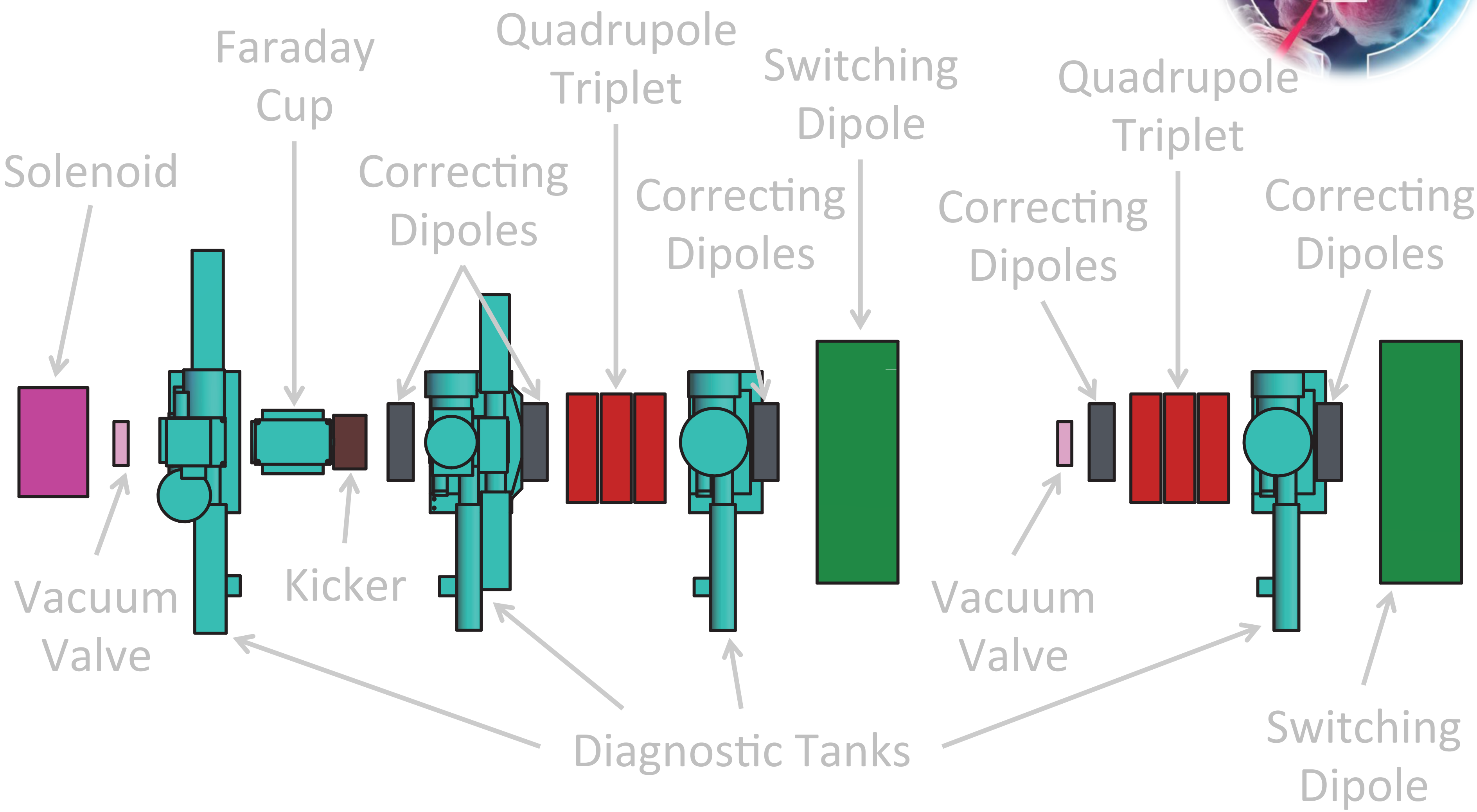
MedAustron LEBT



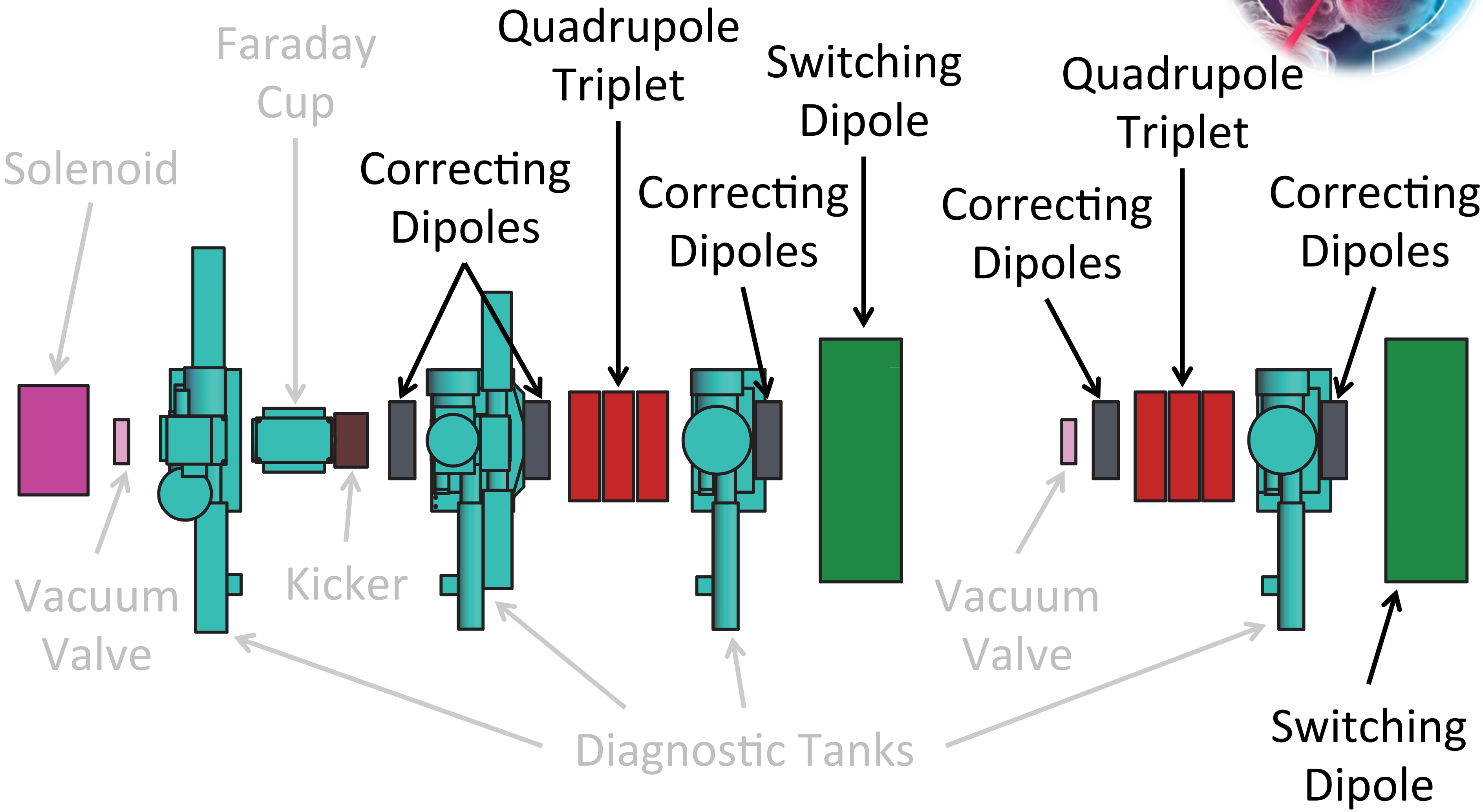
MedAustron LEBT



MedAustron LEBT: Magnets



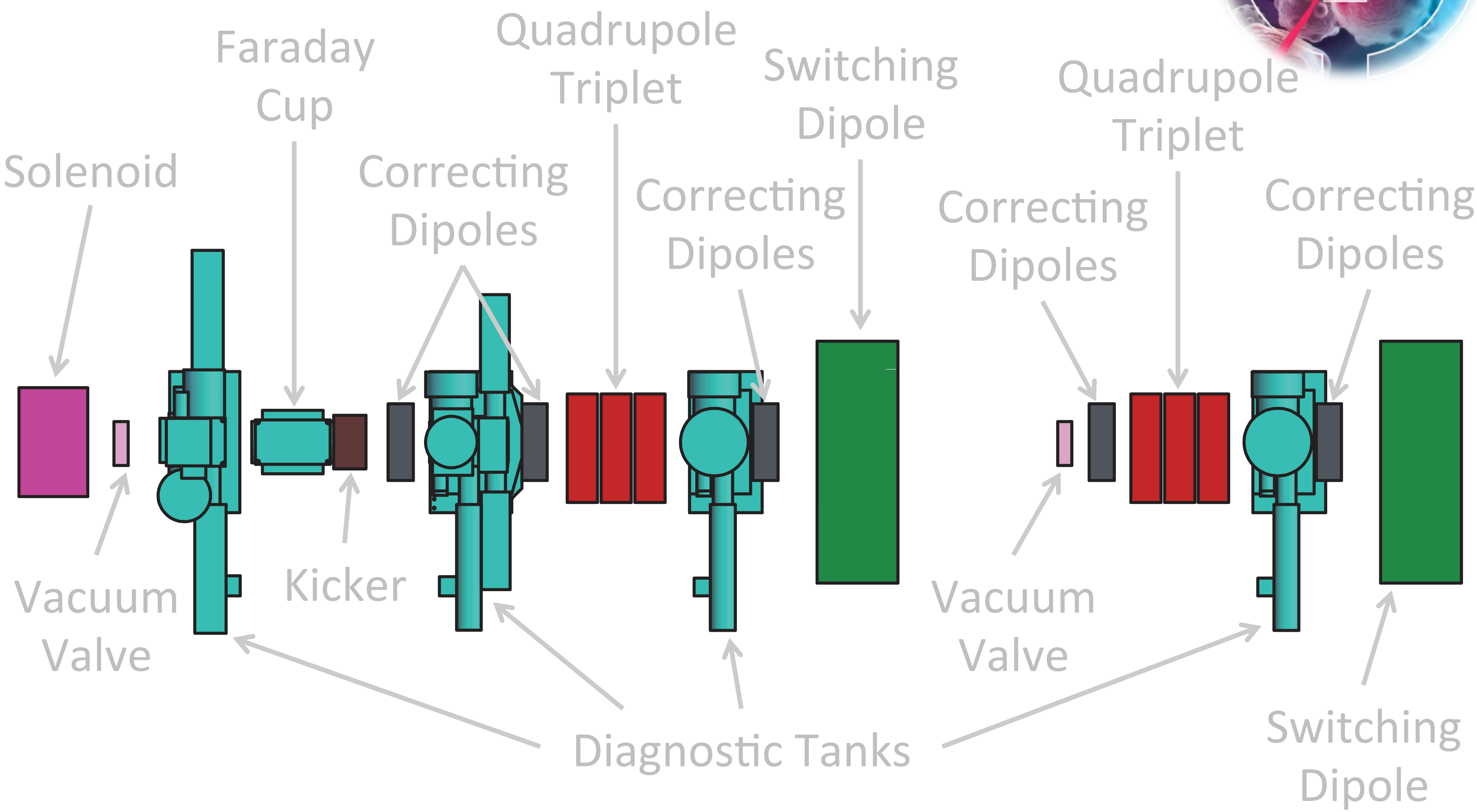
MedAustron LEBT: Magnets



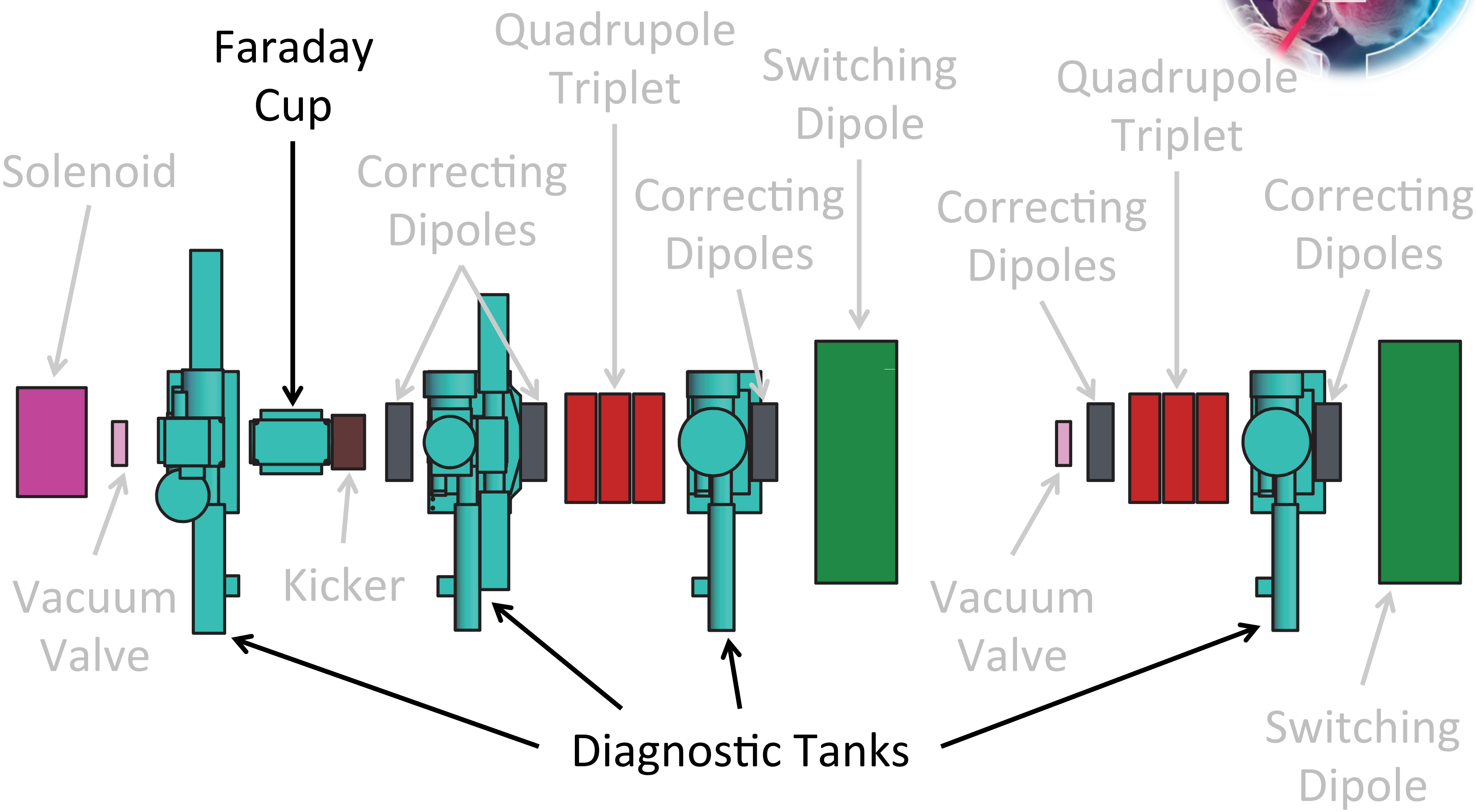
Magnetic Elements

- Initial switching dipole brings multiple beams onto single injector beam axis.
- X & Y correctors at regular intervals to steer slow beam through LEBT.
- Quadrupole triplets give beam transverse focussing:
  - Single quadrupole only focuses in **1 plane**.
  - Quadrupole pair (FODO) focuses in **both planes** but **beam profile asymmetric**.
  - Quadrupole triplet (MedAustron FDF) gives **symmetric beam profile**.

MedAustron LEBT: Diagnostics



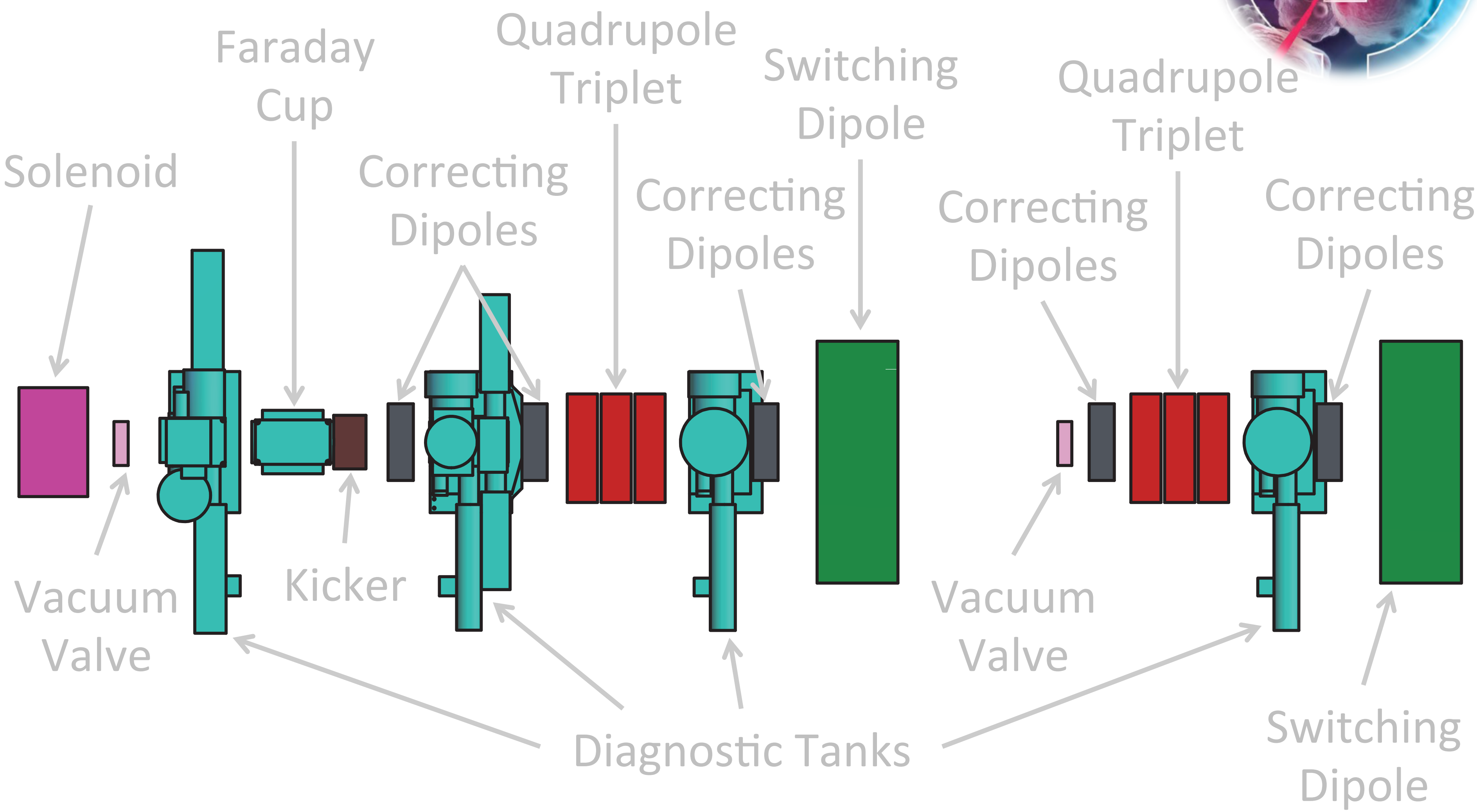
MedAustron LEBT: Diagnostics



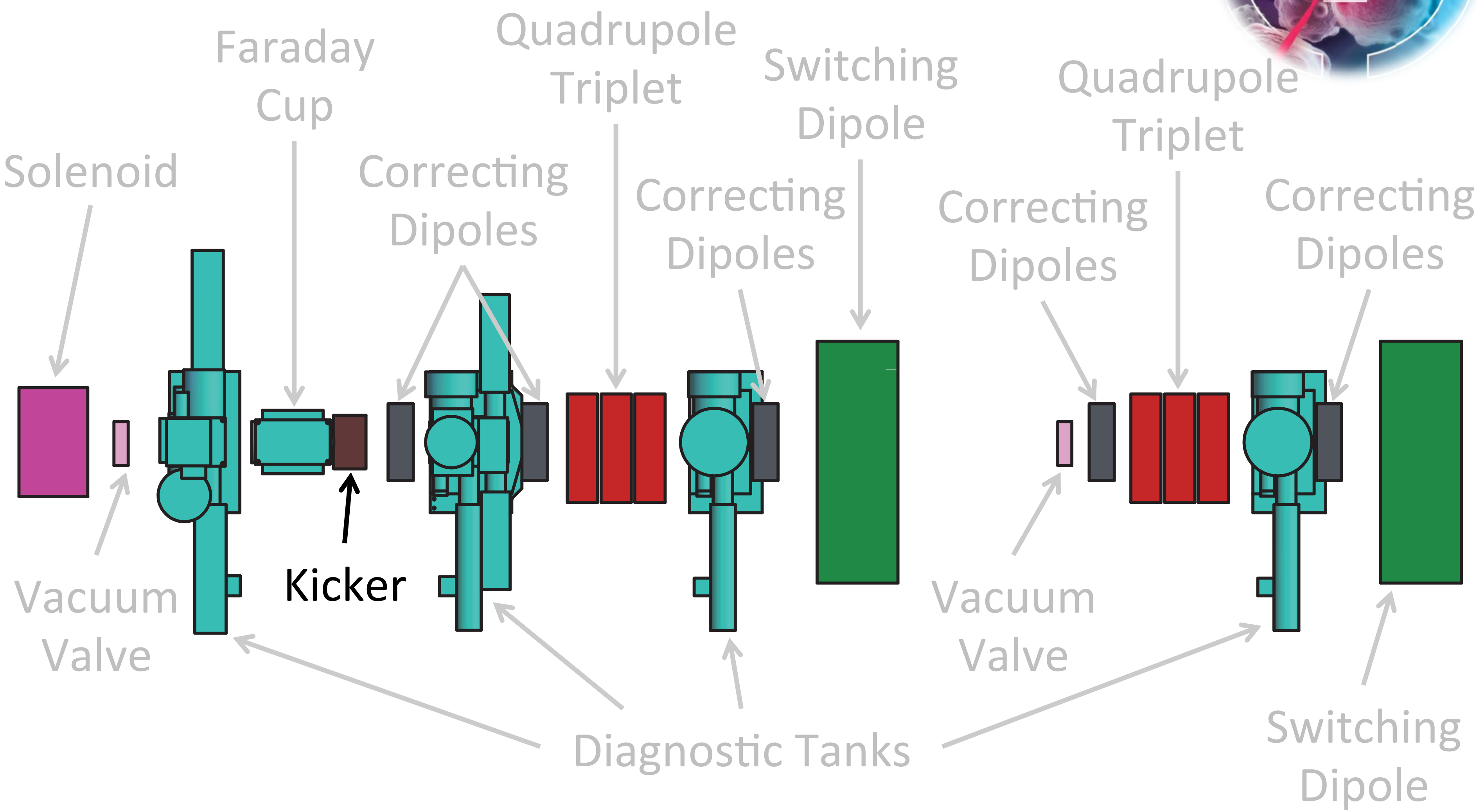
LEBT Diagnostics

- Many diagnostics used in LEBT to measure beam position, current, profiles and emittance:
- Non-destructive:
  - Beam position monitor (BPM): position.
  - Wire scanner: profile (only slightly destructive…).
  - Toroid (current transformer): current.
- Destructive:
  - Slit-slit scanner: emittance.
  - Faraday cup: charge.
  - Harp monitor: profile.

MedAustron LEBT: Kicker



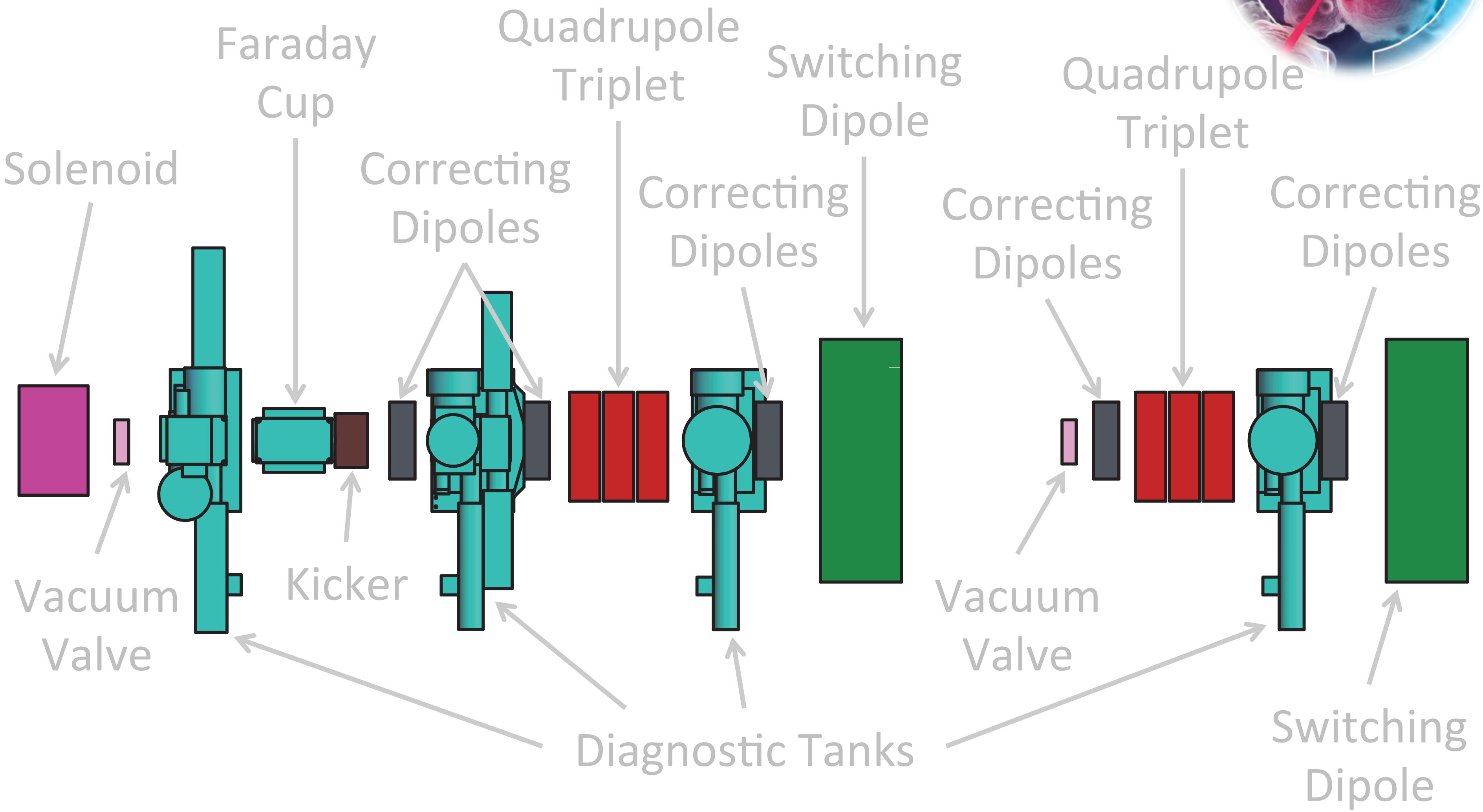
MedAustron LEBT: Kicker



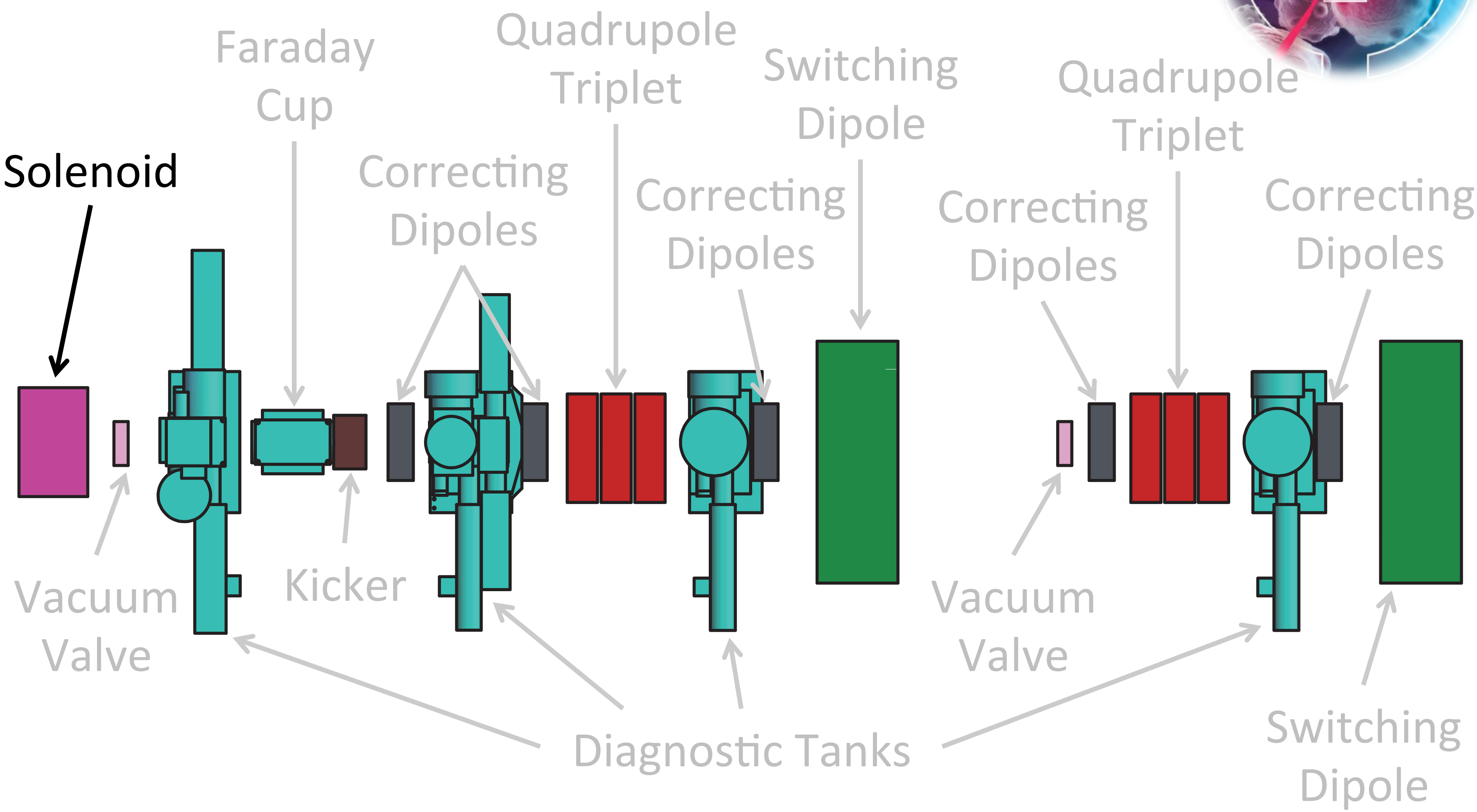
Kickers

- All the magnetic elements in the beamline relatively slow:
  - Iron takes time to change field.
  - Superconducting magnets even slower.
- Need a fast element to rapidly redirect beam:
  - Kickers normally electrostatic.
  - High voltage applied to parallel plates gives rapid deflection.
- Kickers much higher voltage than magnets and less stable, so only used in these special circumstances.

MedAustron LEBT: Solenoids



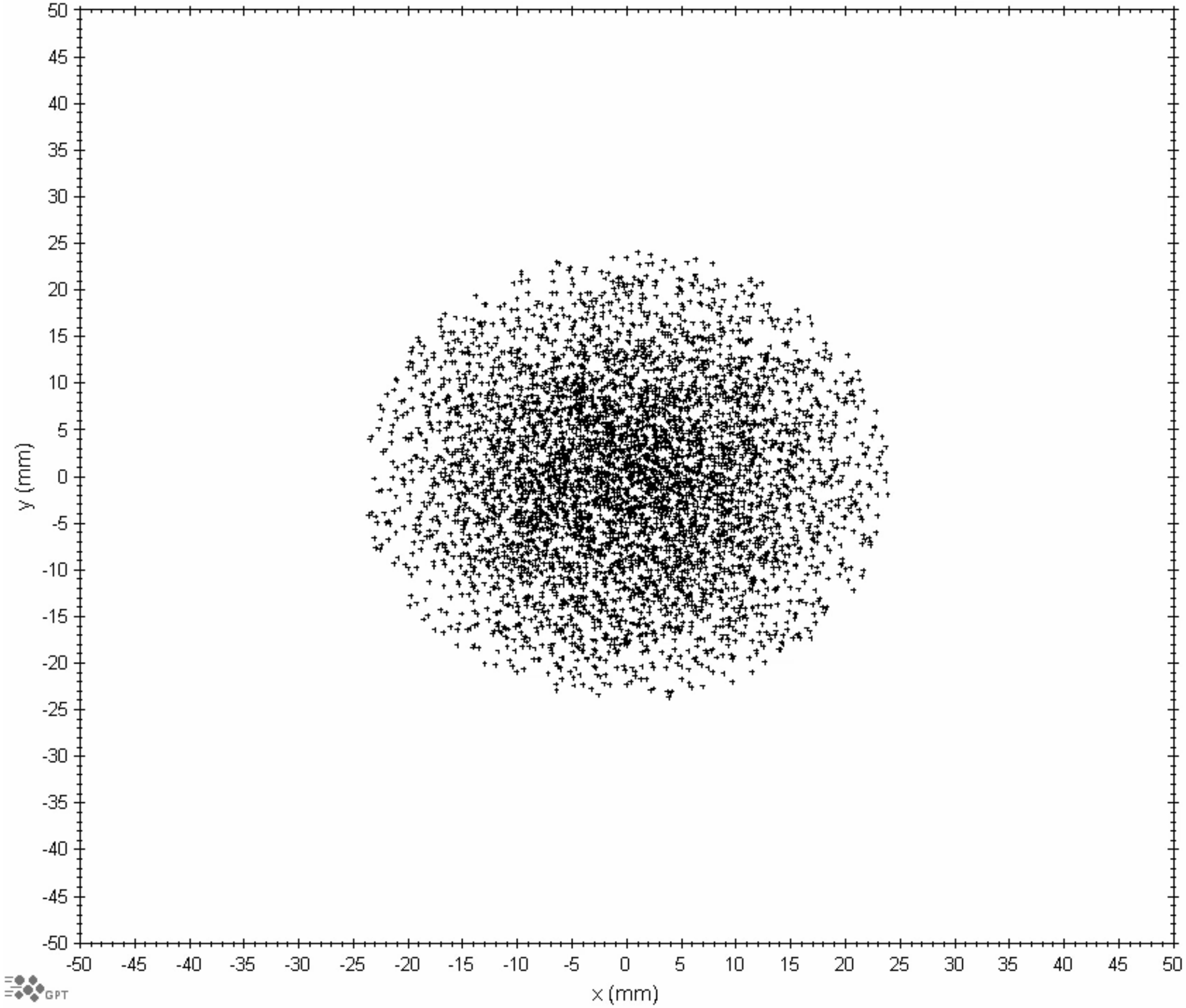
MedAustron LEBT: Solenoids



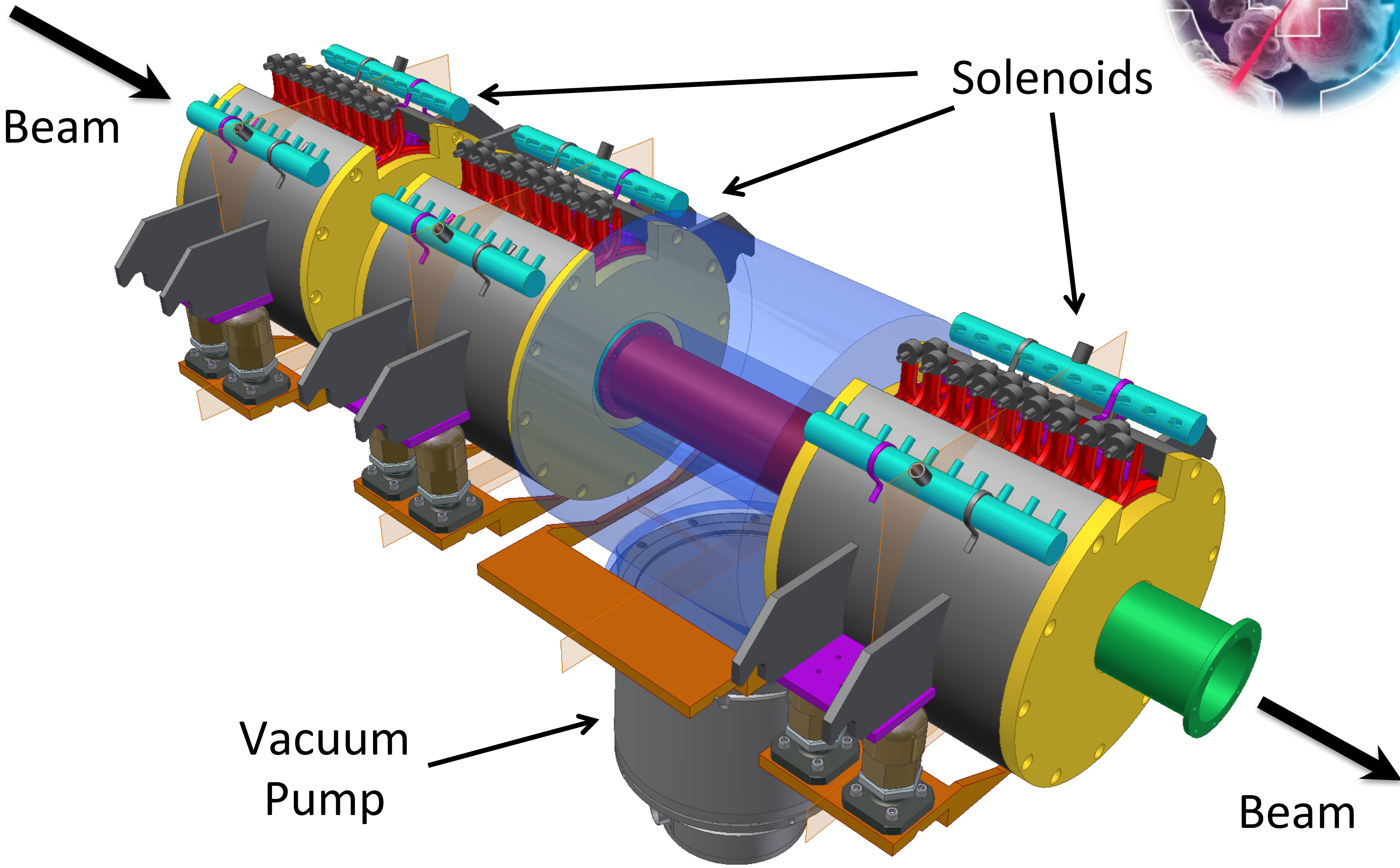
Solenoids

- For injection into RFQ, beam needs to be focussed **symmetrically**.
- At low energies **solenoids** are used:
  - In solenoid field, radial motion leads to azimuthal acceleration.
  - Particles then spiral round magnetic field back towards beam axis.
- At high beam currents (CERN Linac-4: 60 mA peak) LEBT contains **only** solenoids to combat enormous space charge.
- Need to be used carefully:
  - Overfocussing causes tails on emittance distribution.
  - These tails lead to emittance growth: must be avoided!

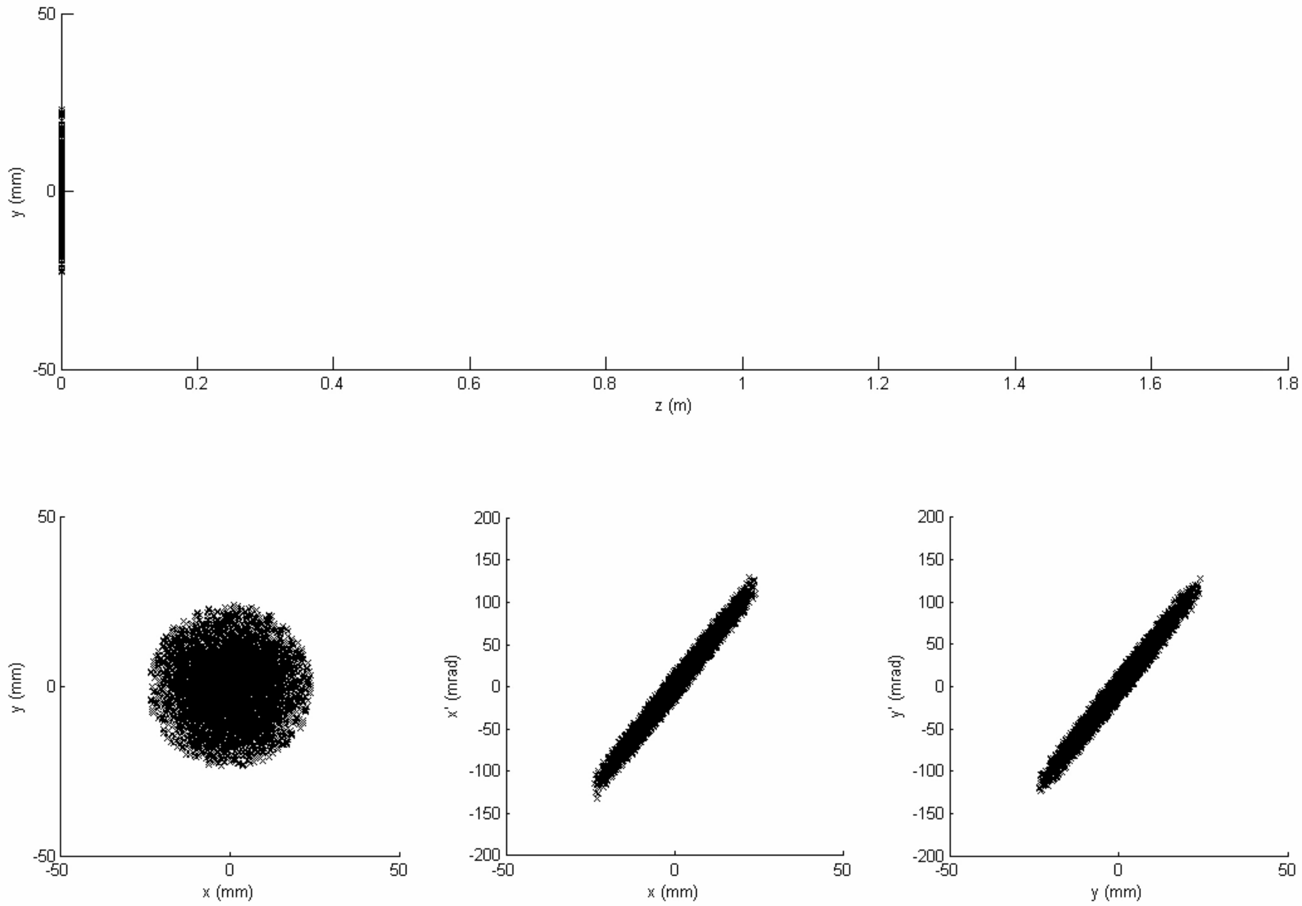
Single Solenoid Focussing



FETS 3-Solenoid LEBT



FETS 3-Solenoid LEBT

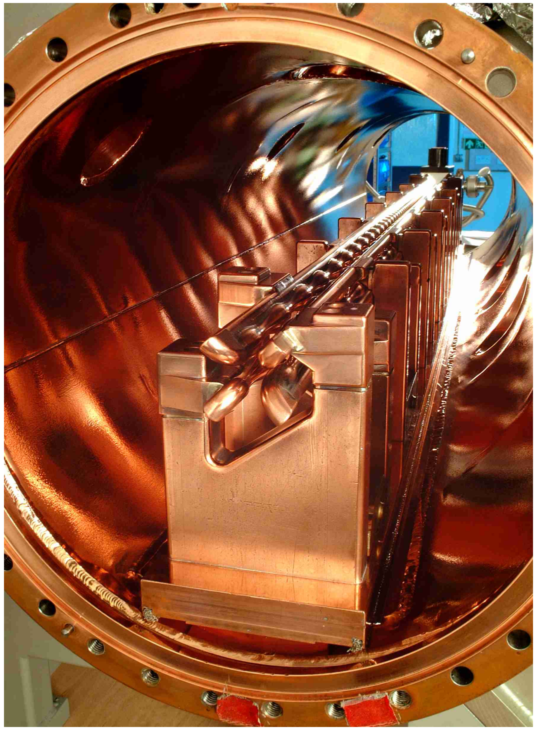


Low Energy Acceleration

- At low energies, two requirements compete for space:
  - To combat space charge and prevent emittance growth, need lots of transverse focussing.
  - To reduce space charge, accelerate quickly.
- These two both need the same space!
- Use an accelerator that combines continuous transverse focussing with capture and acceleration: the **RadioFrequency Quadrupole** (RFQ).

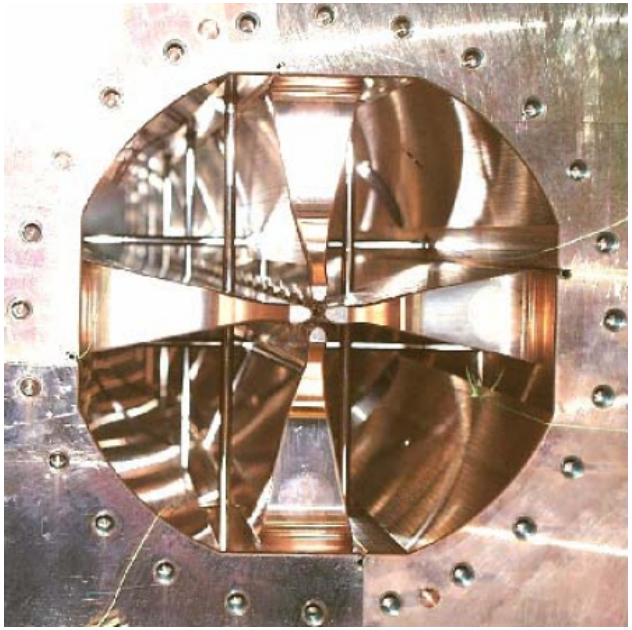
RadioFrequency Quadrupoles

RFQ's accelerate, bunch AND focus all at once!



2 types: 4-rod and 4-vane

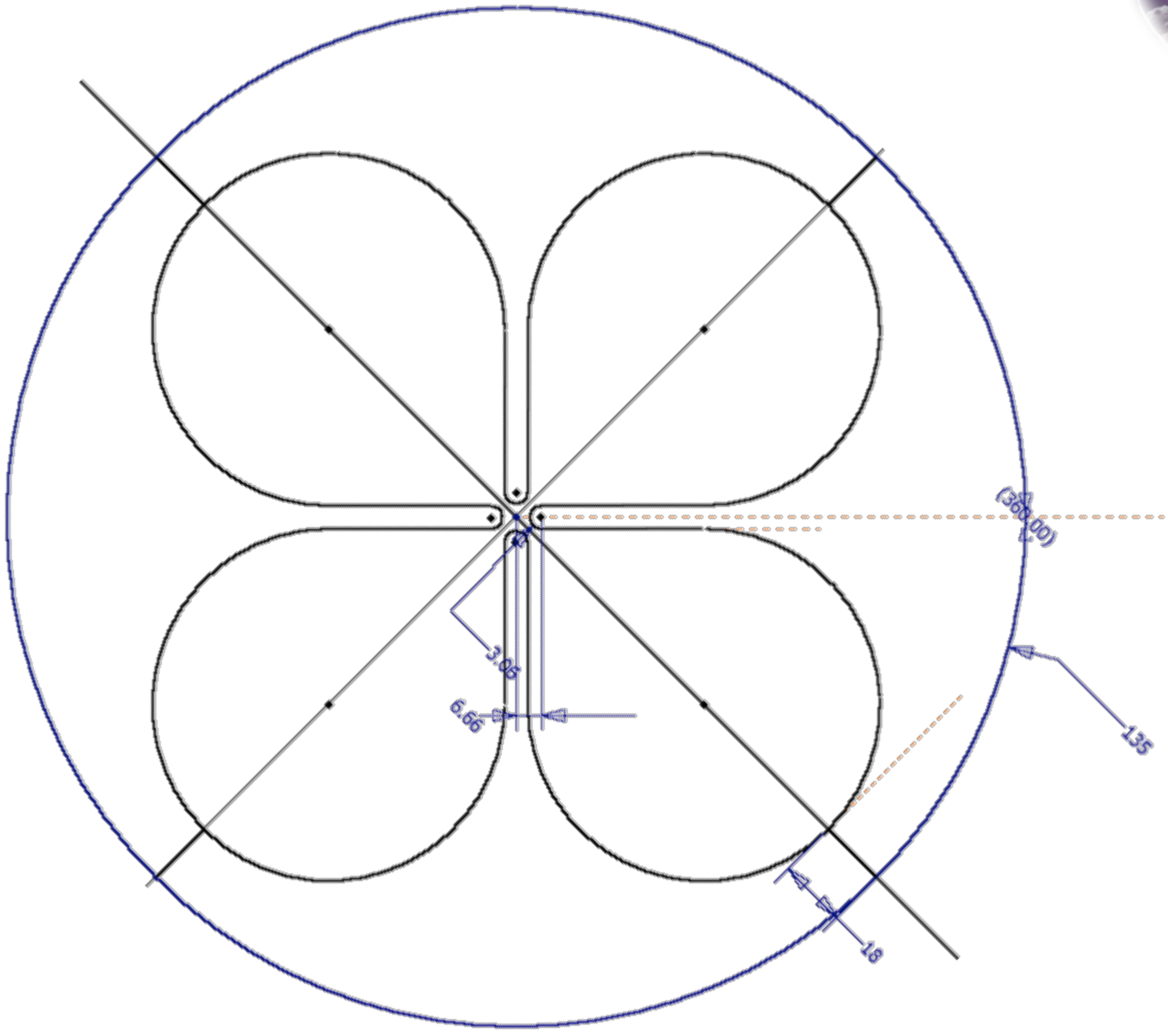
4-rod RFQ



4-vane RFQ

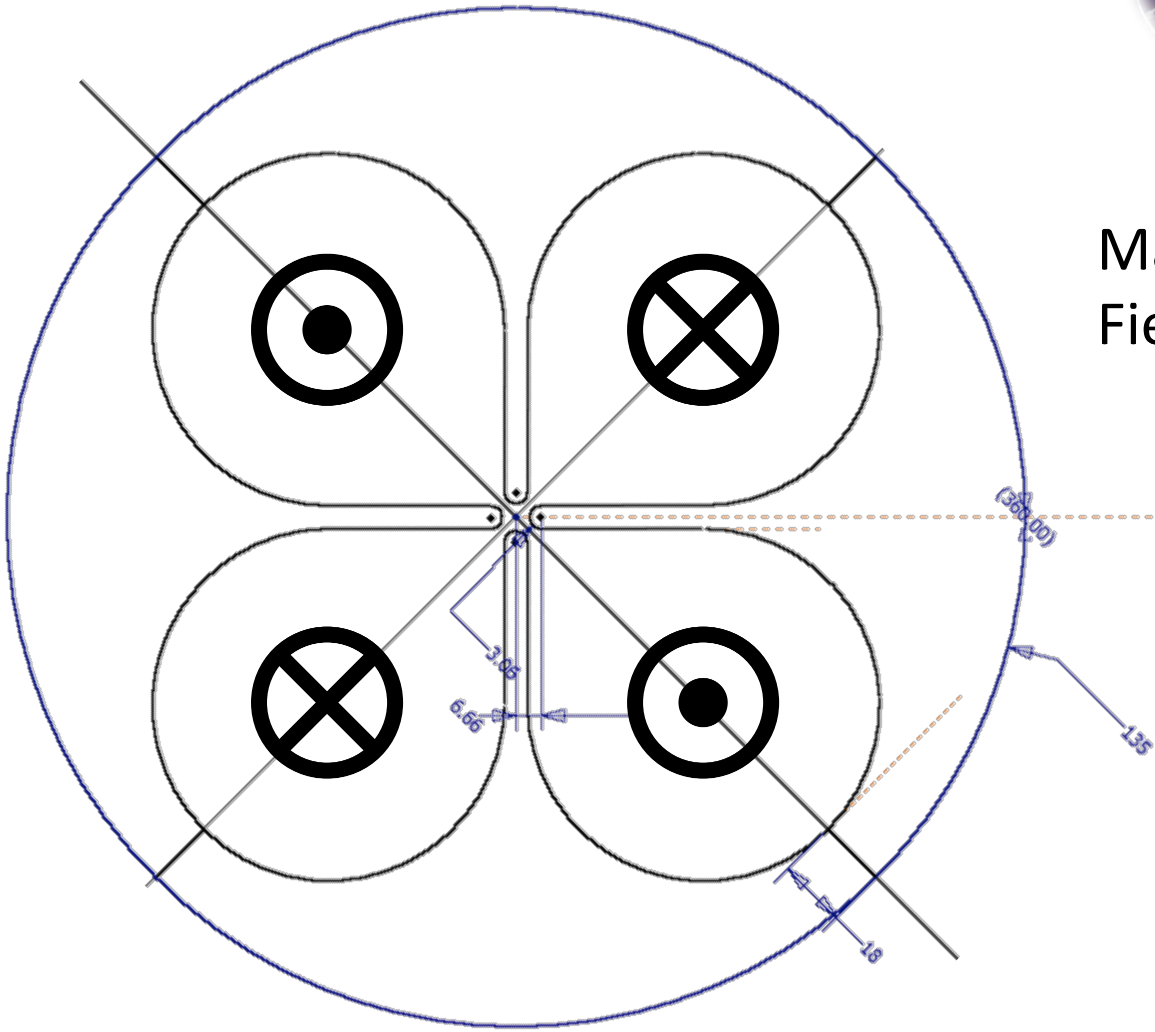
RFQ E- and B-Fields

4-vane RFQ
structure



RFQ E- and B-Fields

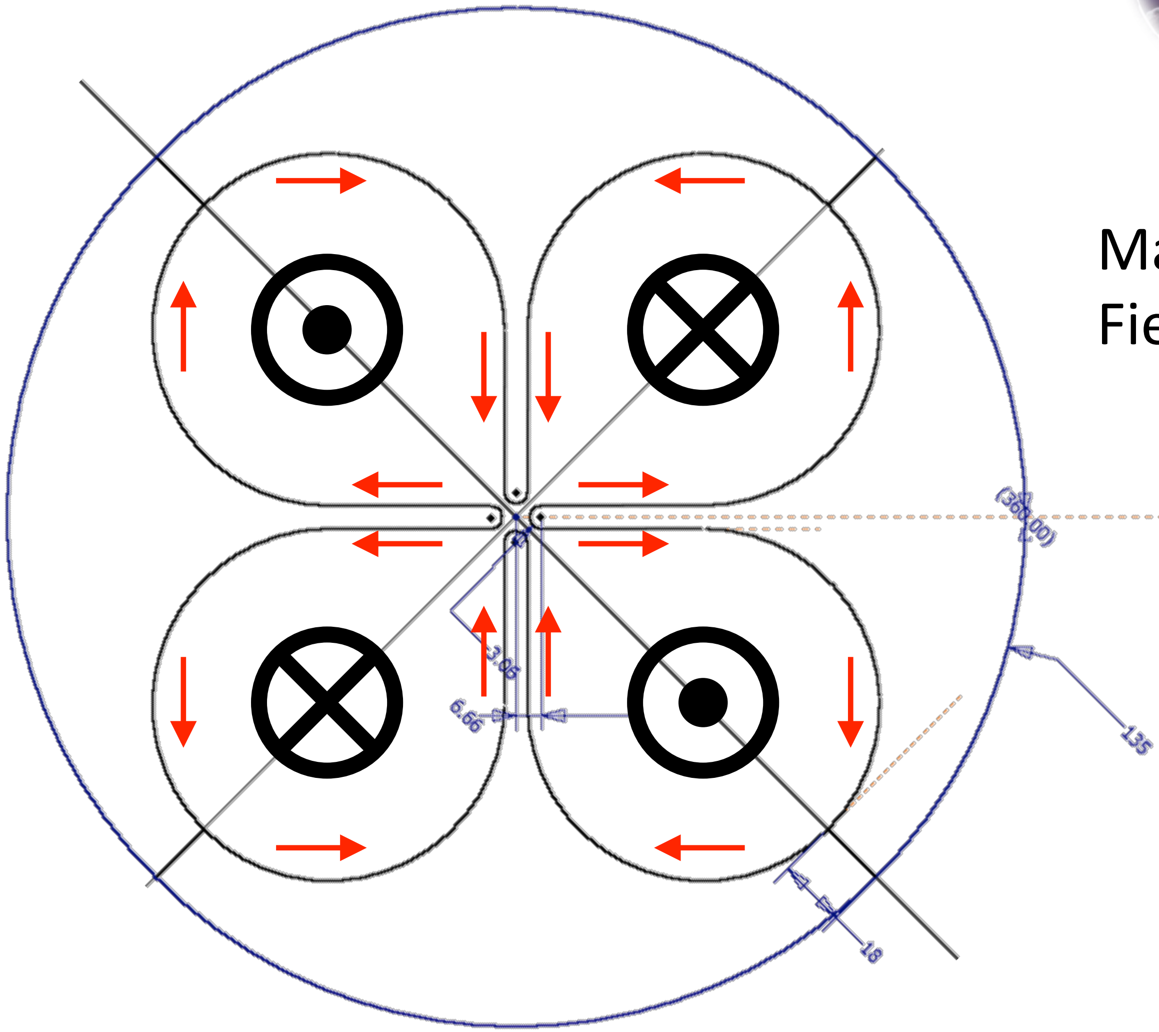
4-vane RFQ structure



Magnetic Fields

RFQ E- and B-Fields

4-vane RFQ structure

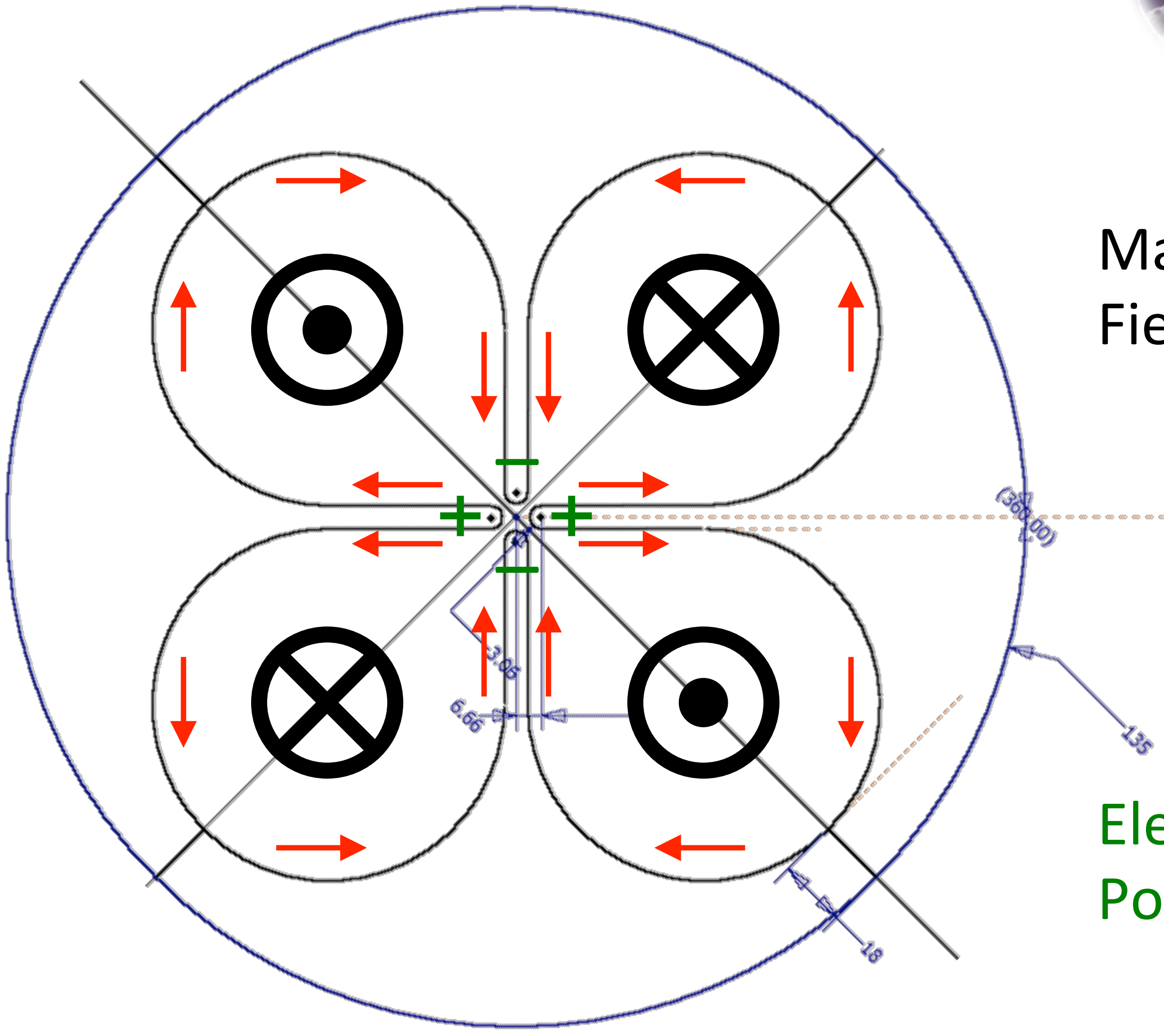


Magnetic Fields

Surface Currents

RFQ E- and B-Fields

4-vane RFQ structure

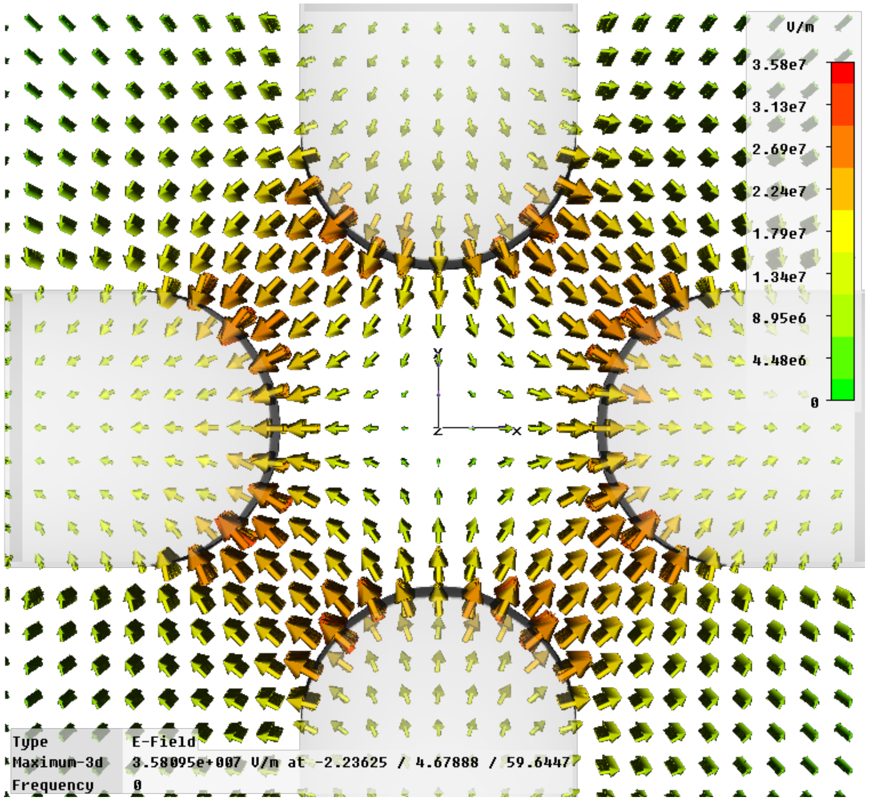


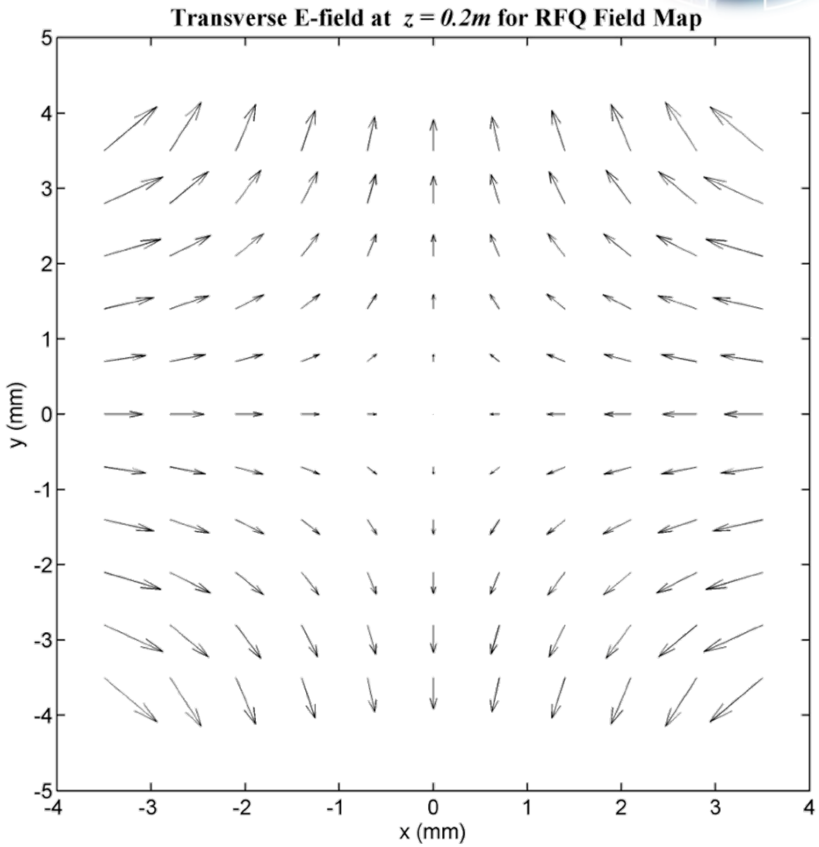
Magnetic Fields

Surface Currents

Electric Polarities

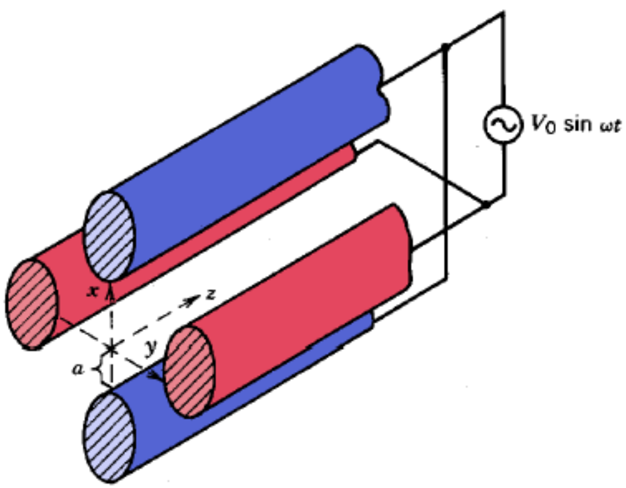
RFQ Vane Tip Fields





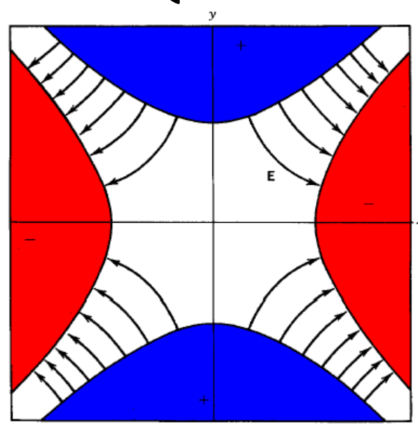
RFQ Transverse Focussing

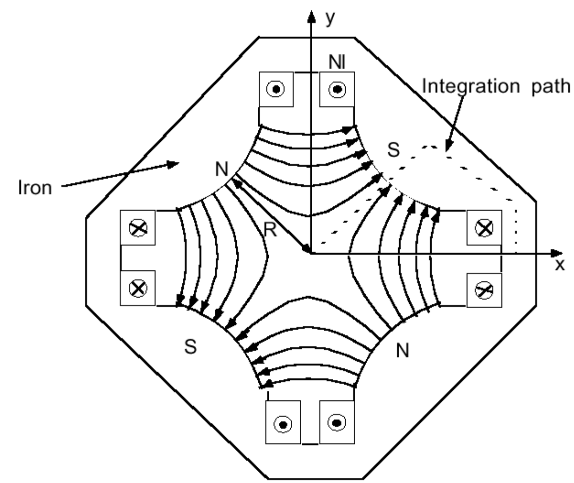
- RF field causes positive/negative charges on pairs of vanes.
- Since field varies with time, alternate focussing/defocussing mimics FODO.



RFQ vane tips

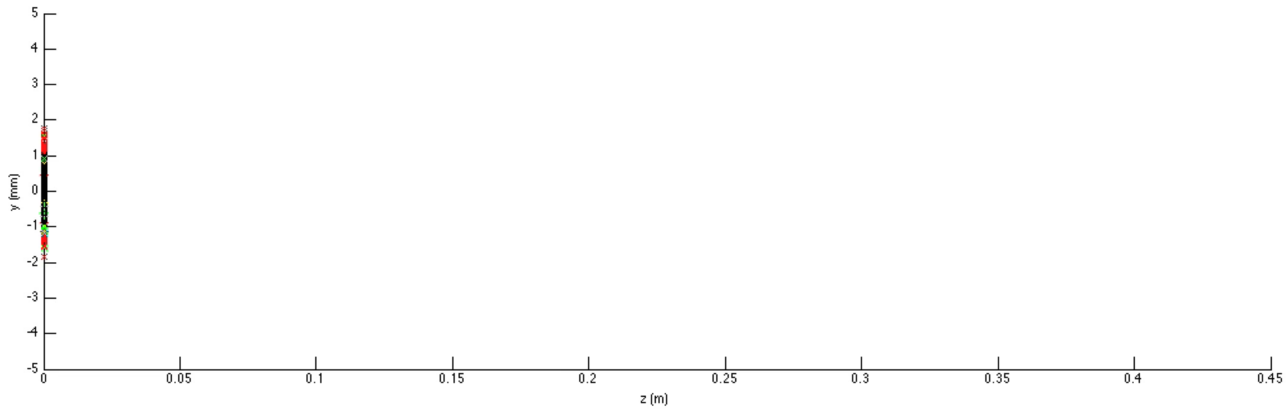
RFQ E-field

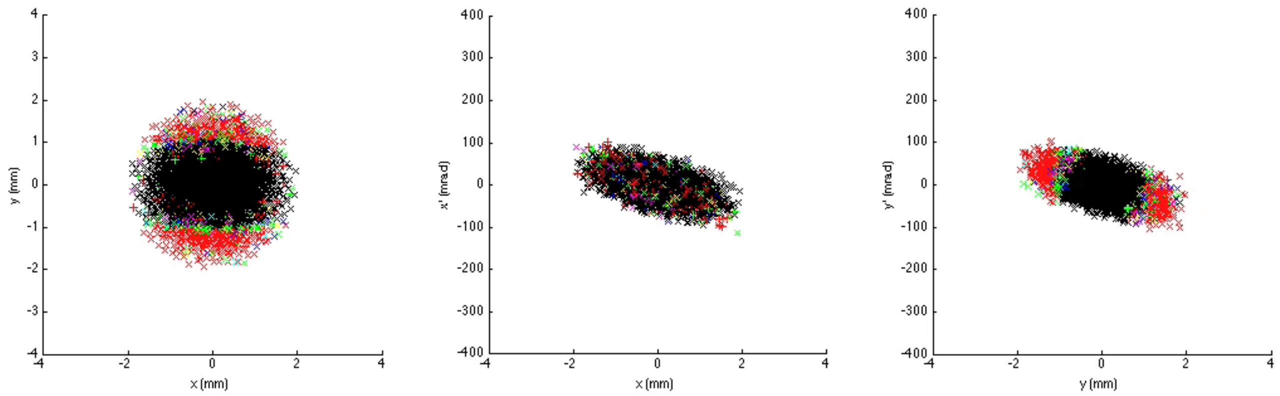




Standard Quad

RFQ Transverse Focussing

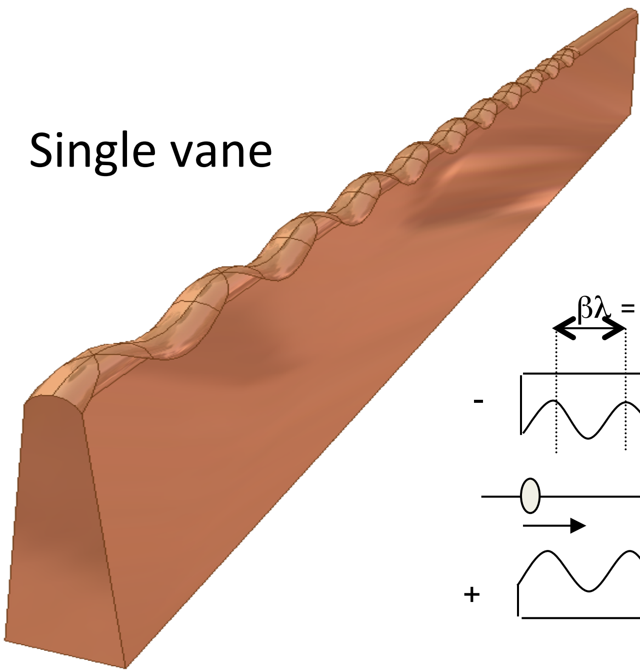




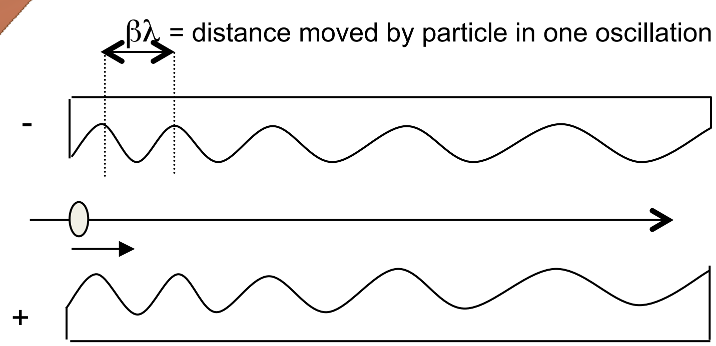
RFQ Acceleration/Bunching

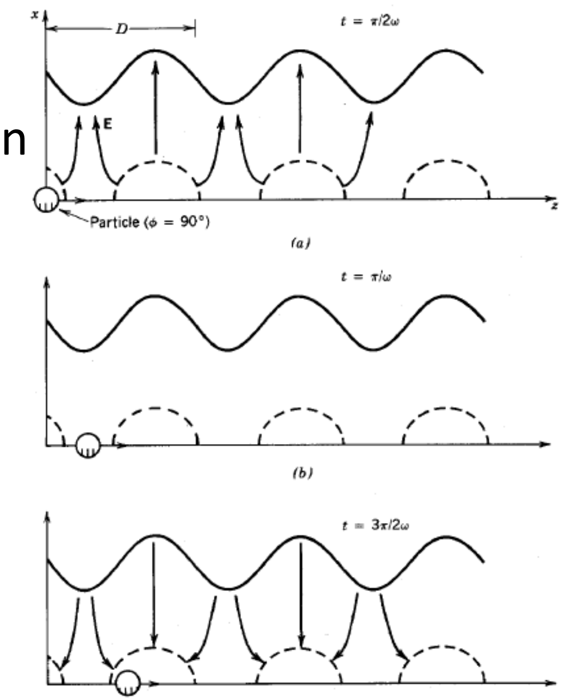
- RFQ vane tips modulated longitudinally.
- Curved field lines produce longitudinal field: acceleration and bunching.

Single vane



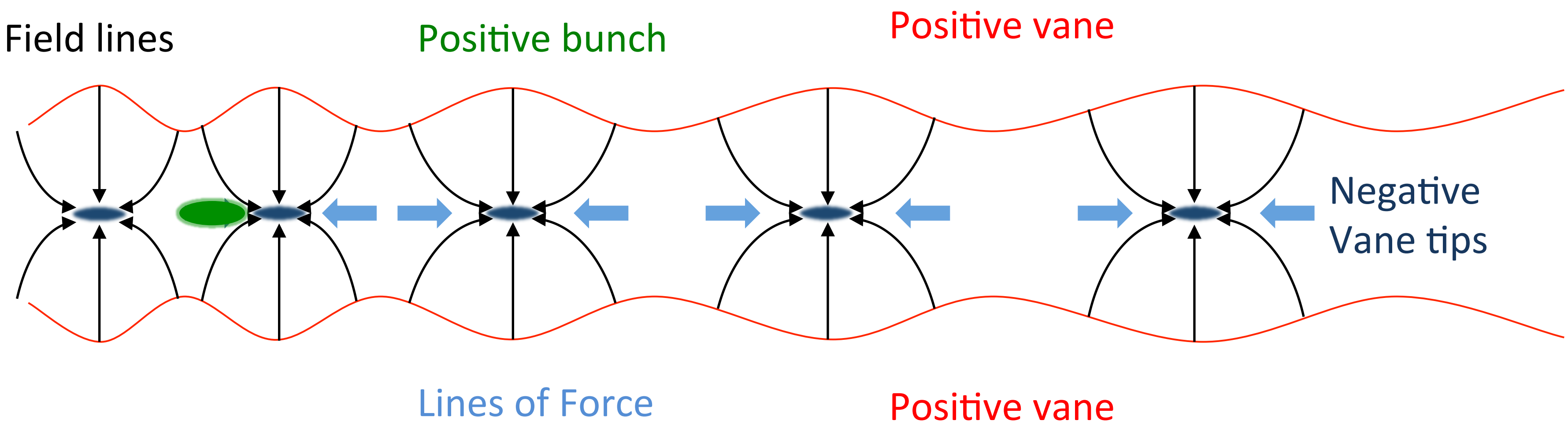
Alternate modulation gives acceleration





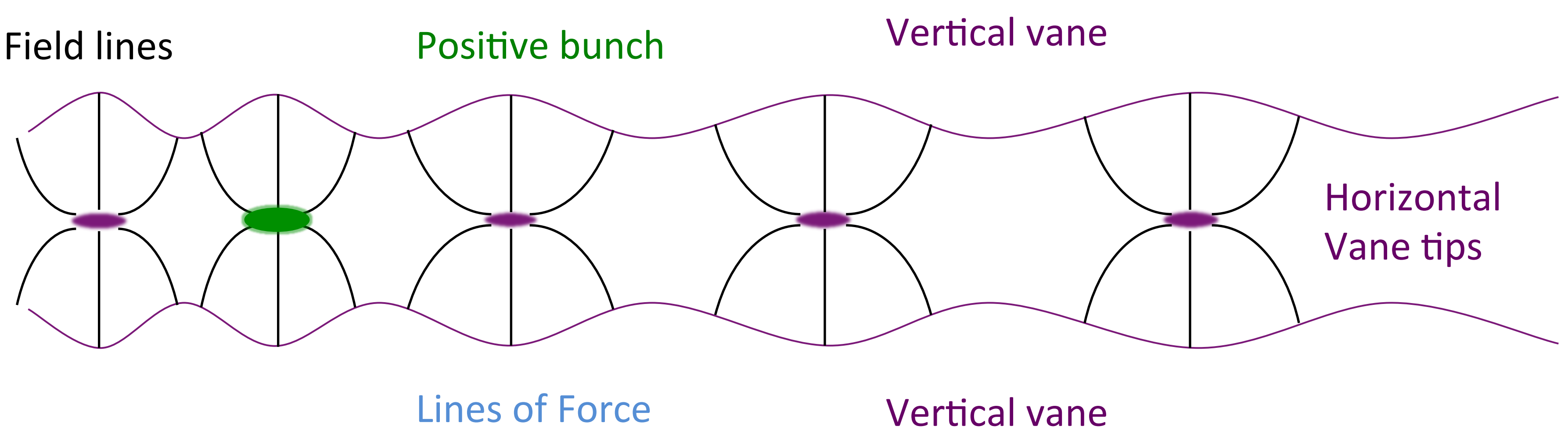
RFQ Field Lines

- On-axis field gives longitudinal force from curved vanes, plus time-varying.
- Vertical vanes initially positively charged, horizontal vanes negatively charged.
- Bunch feels accelerating force from curved field lines.



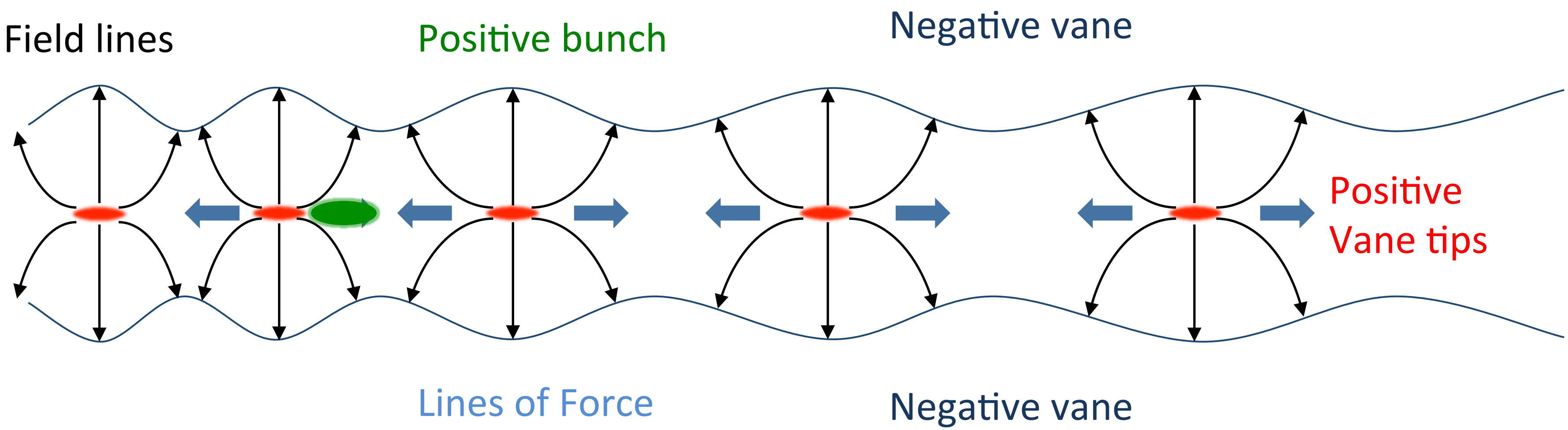
RFQ Field Lines

- After a quarter RF period, RF field drops to zero.
- Bunch feels no accelerating force.



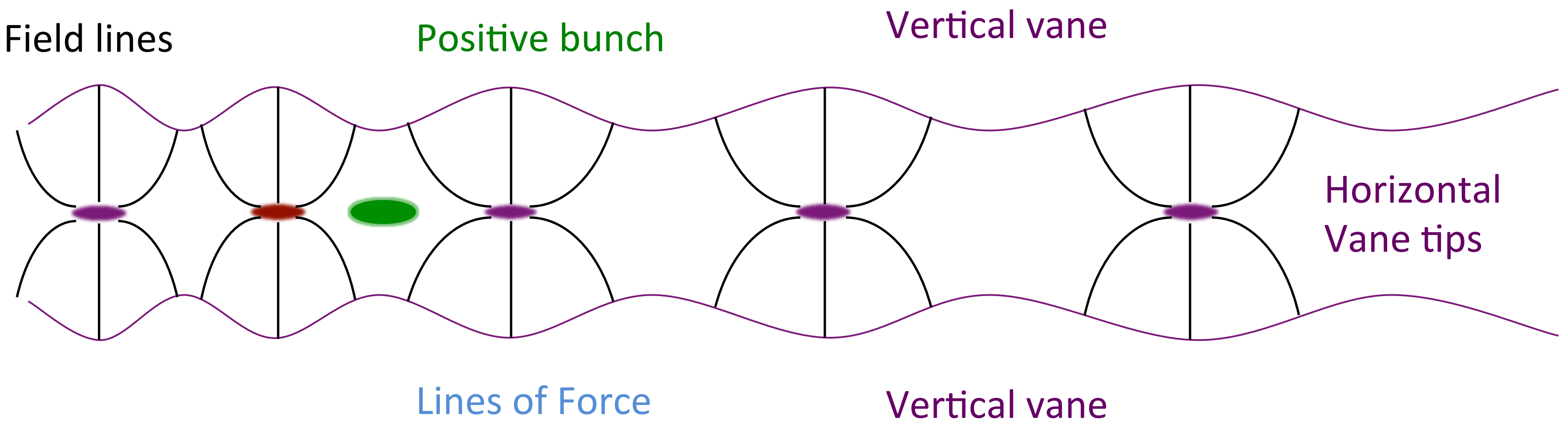
RFQ Field Lines

- After a half RF period, RF reaches maximum again but sign is reversed.
- Vertical vanes now negatively charged, horizontal vanes positively charged.
- Bunch feels accelerating force from curved field lines again.



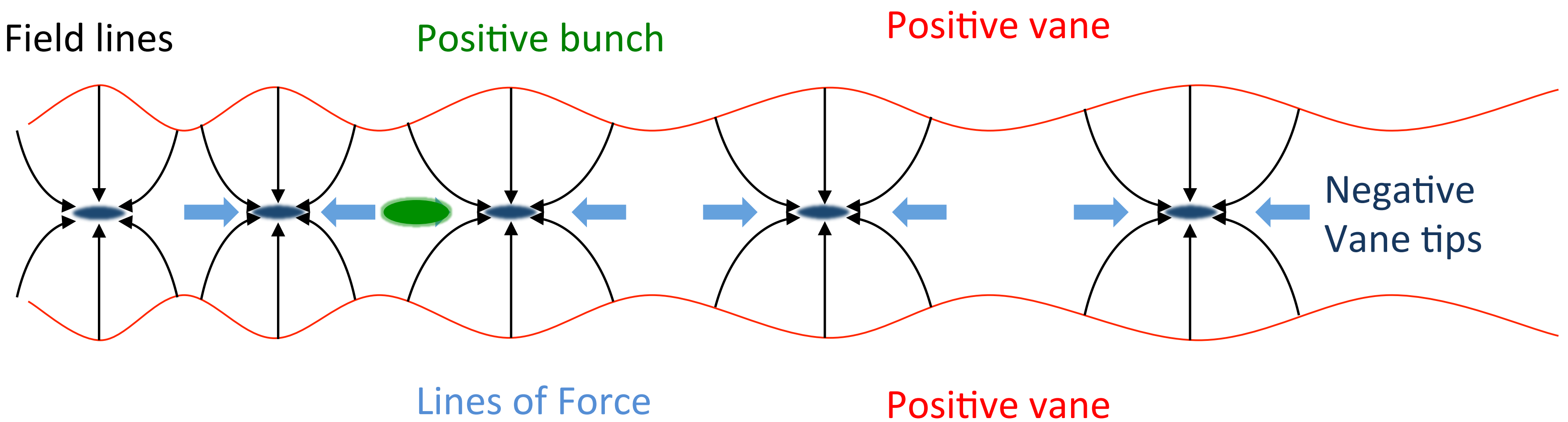
RFQ Field Lines

- After three-quarters of an RF period, RF field drops to zero again.
- Bunch feels no accelerating force.



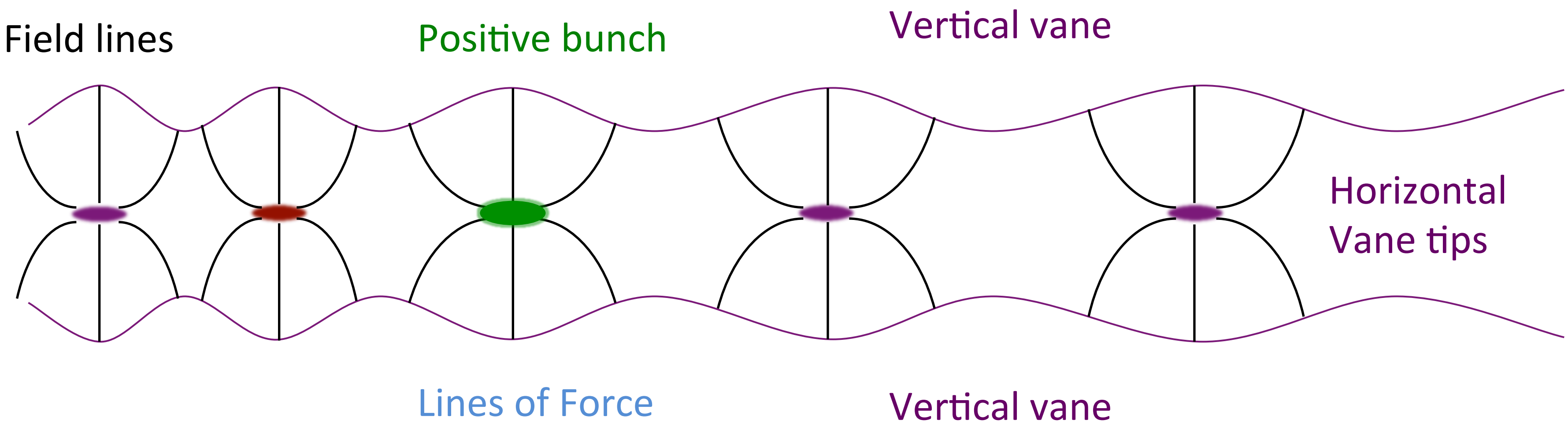
RFQ Field Lines

- After a full RF period, RF reaches maximum again but sign of field reverts to original direction.
- Vertical vanes again positively charged, horizontal vanes negatively charged.
- Bunch feels accelerating force from curved field lines again.



RFQ Field Lines

- And so we continue…



RFQ Field Lines

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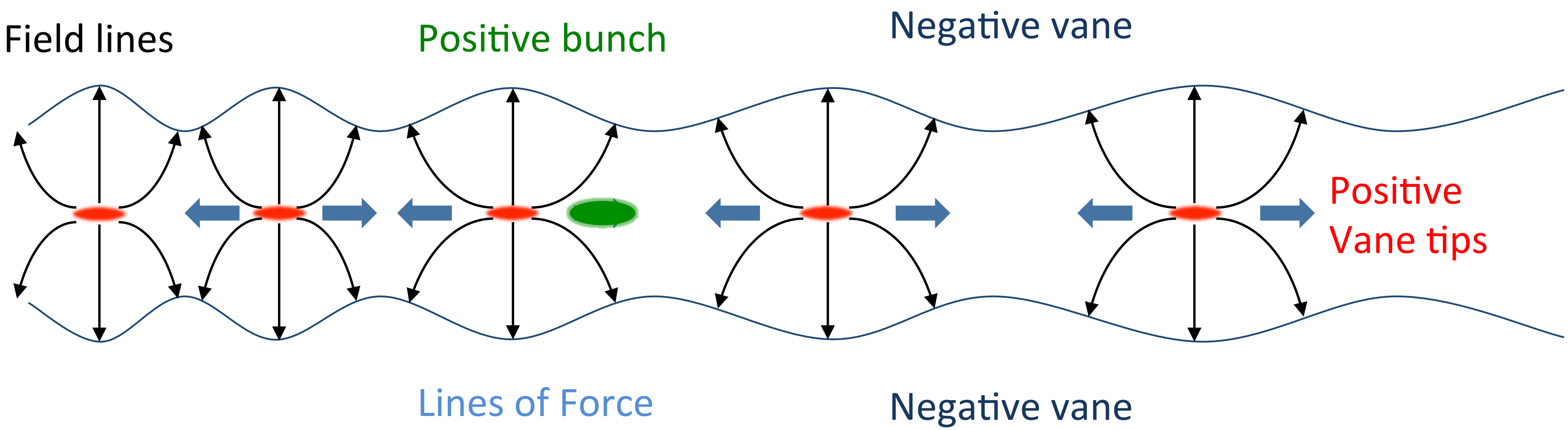

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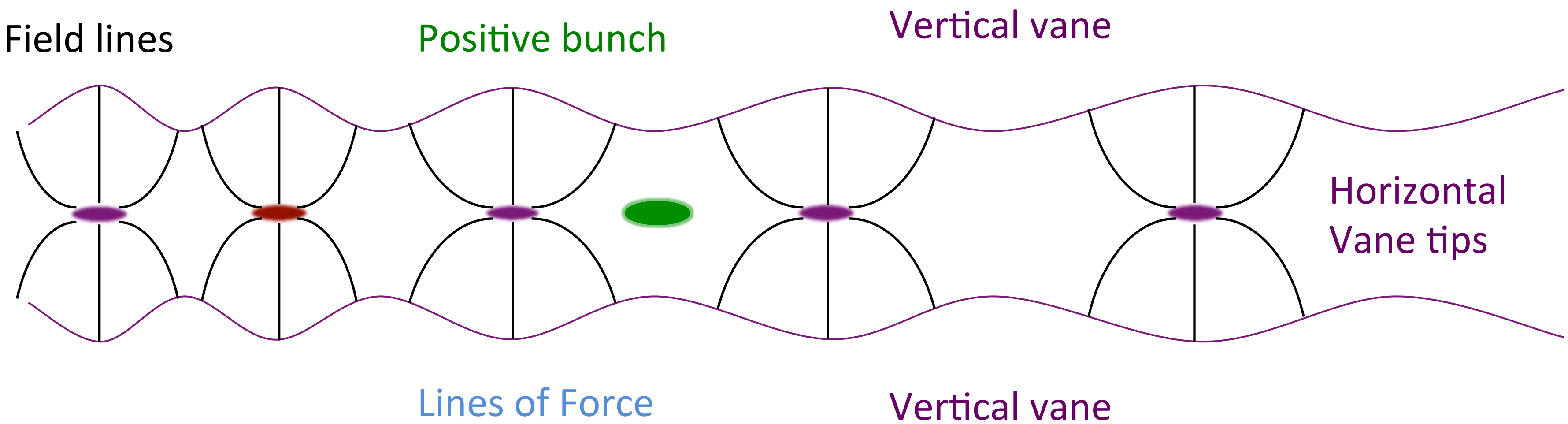

RFQ Field Lines

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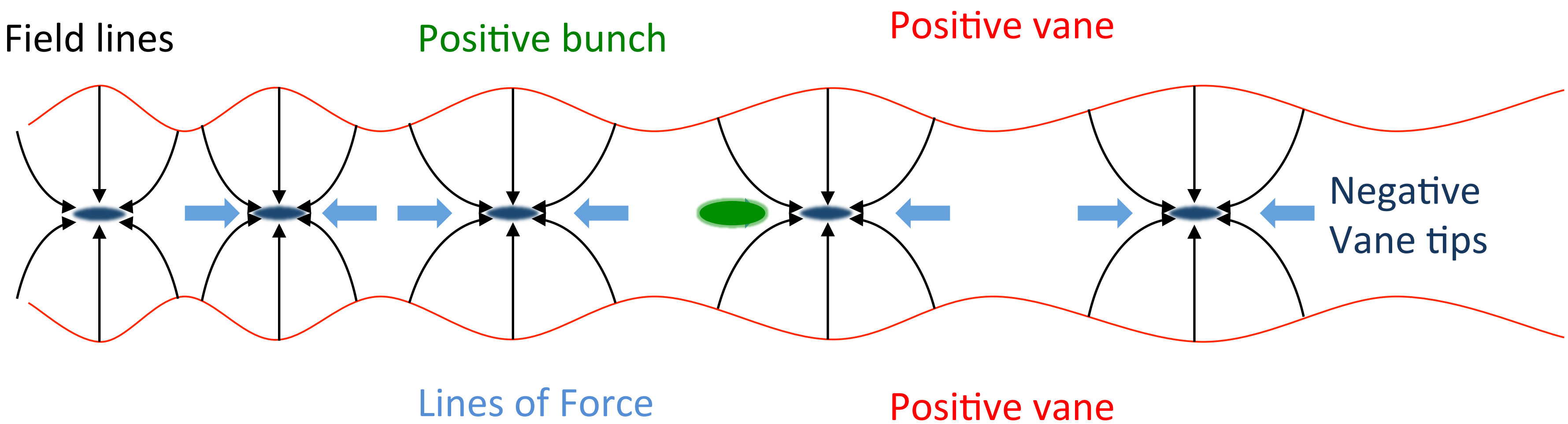

RFQ Field Lines

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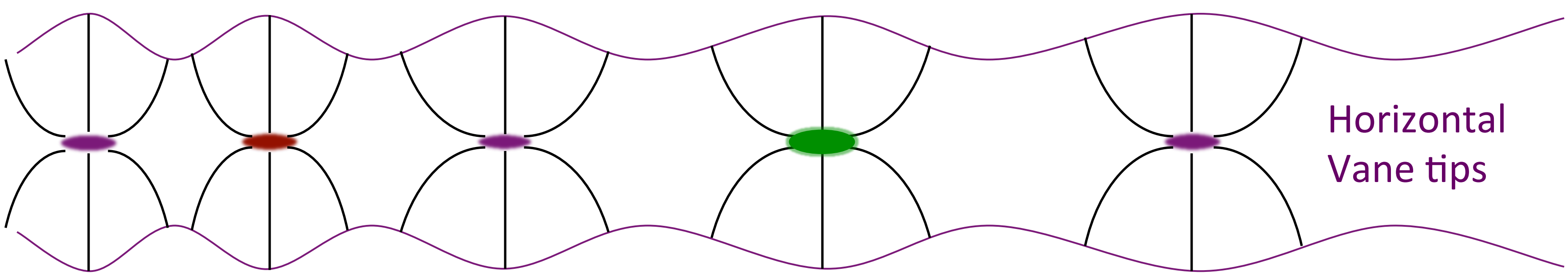

RFQ Field Lines

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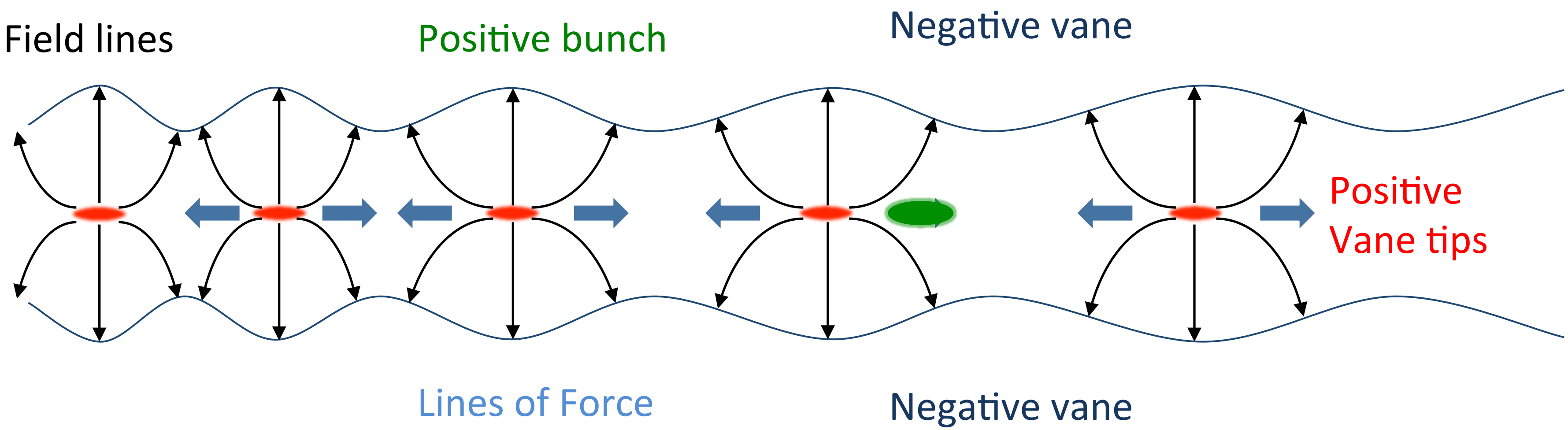
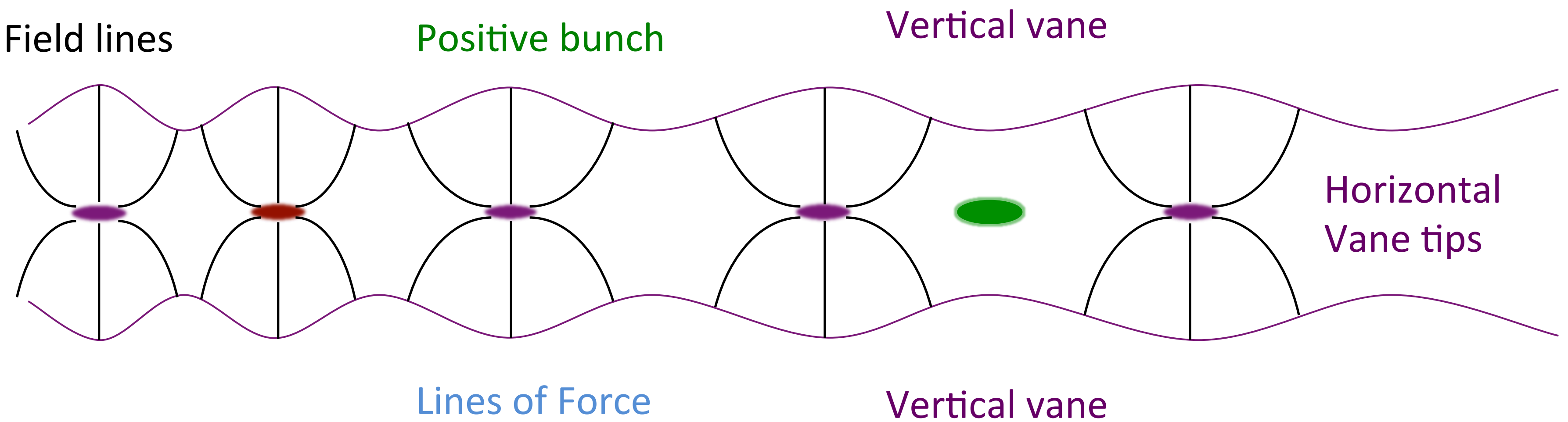


RFQ Field Lines

- And so we continue…



RFQ Field Lines

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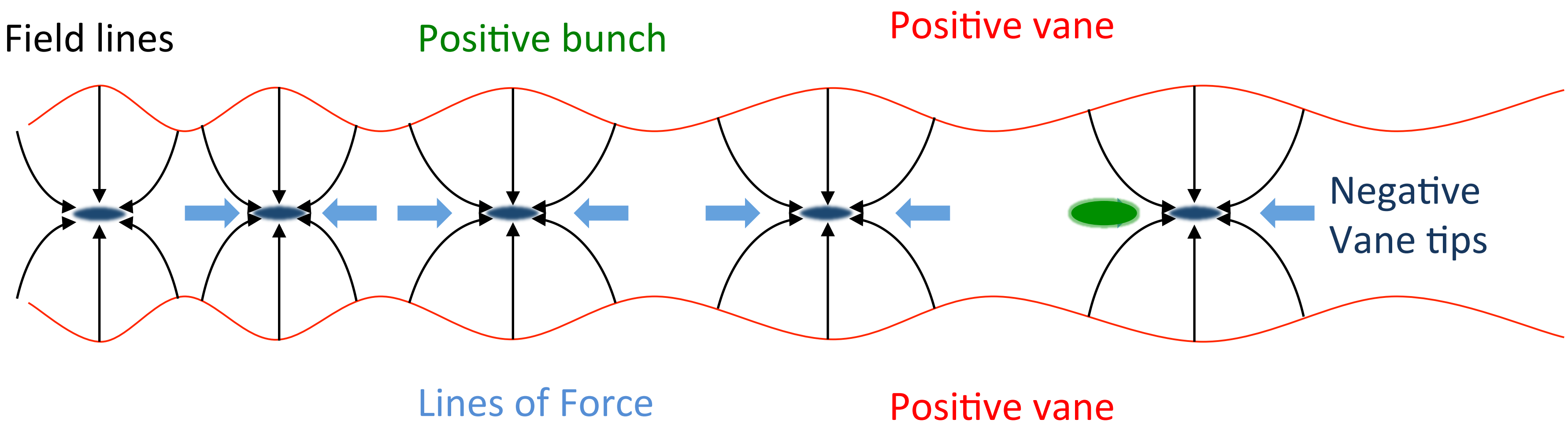
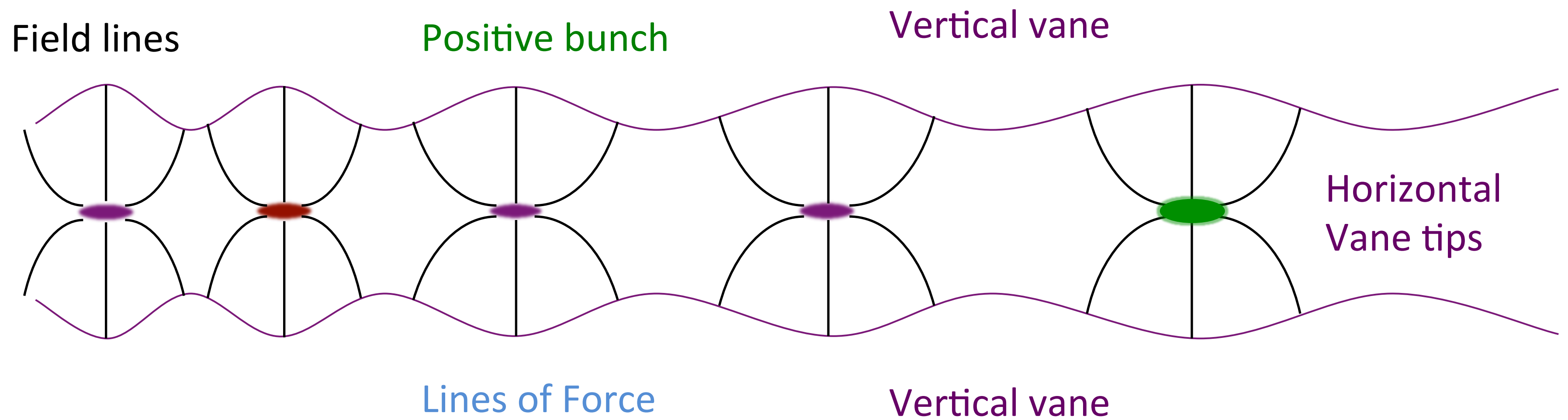


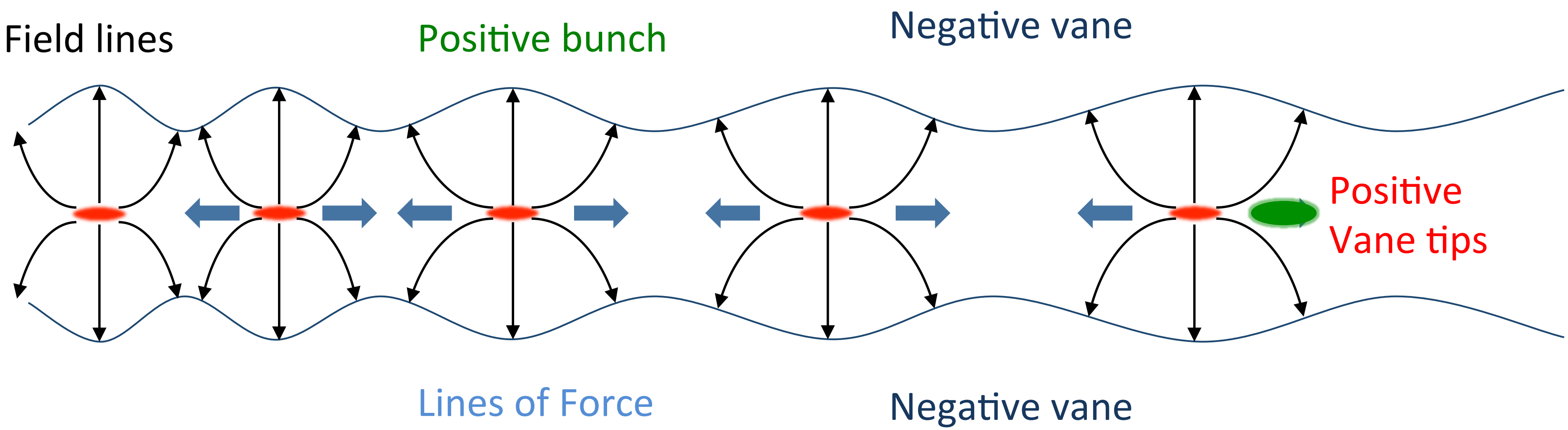
RFQ Field Lines

- And so we continue…



RFQ Field Lines

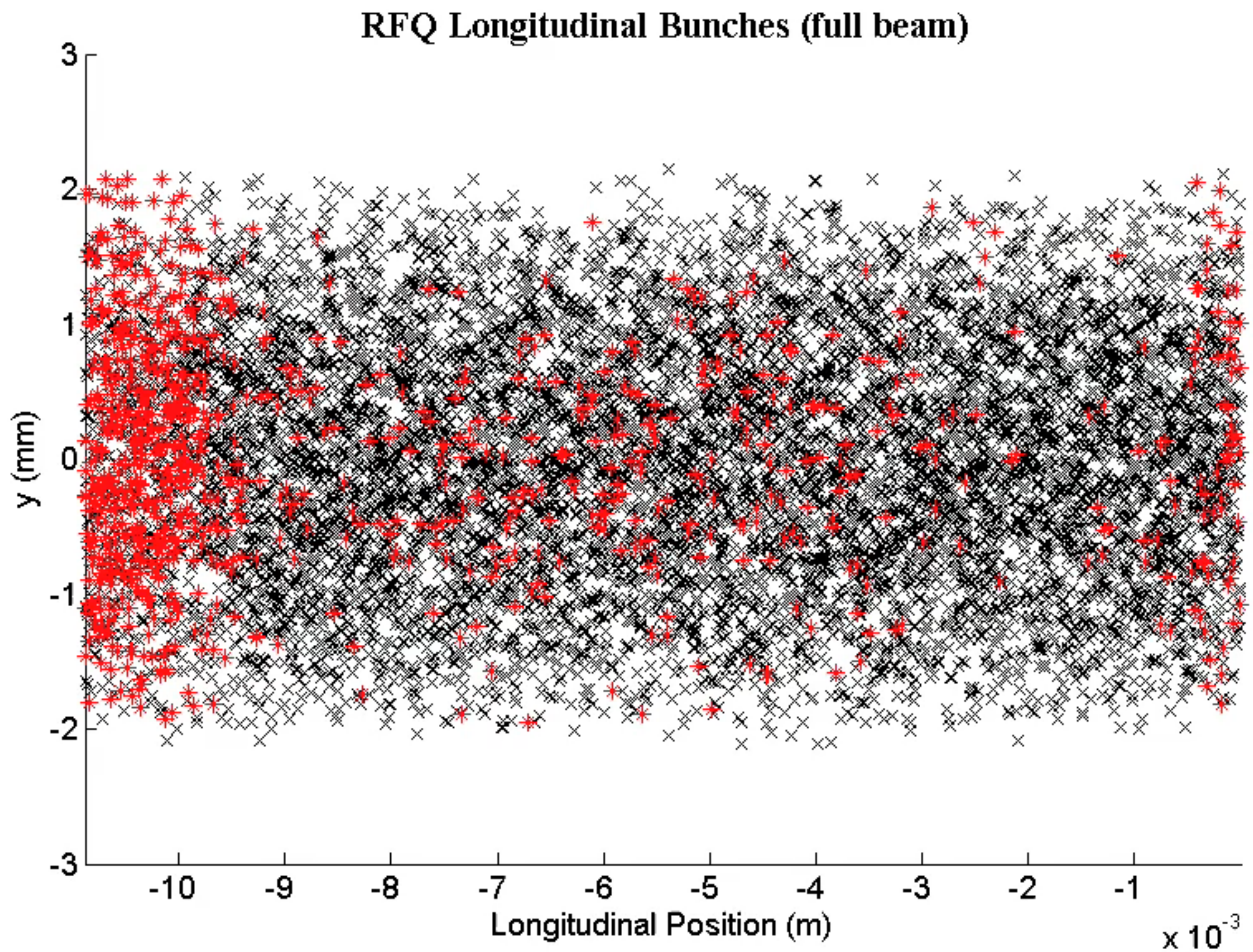
- And that’s how an RFQ accelerates the beam!



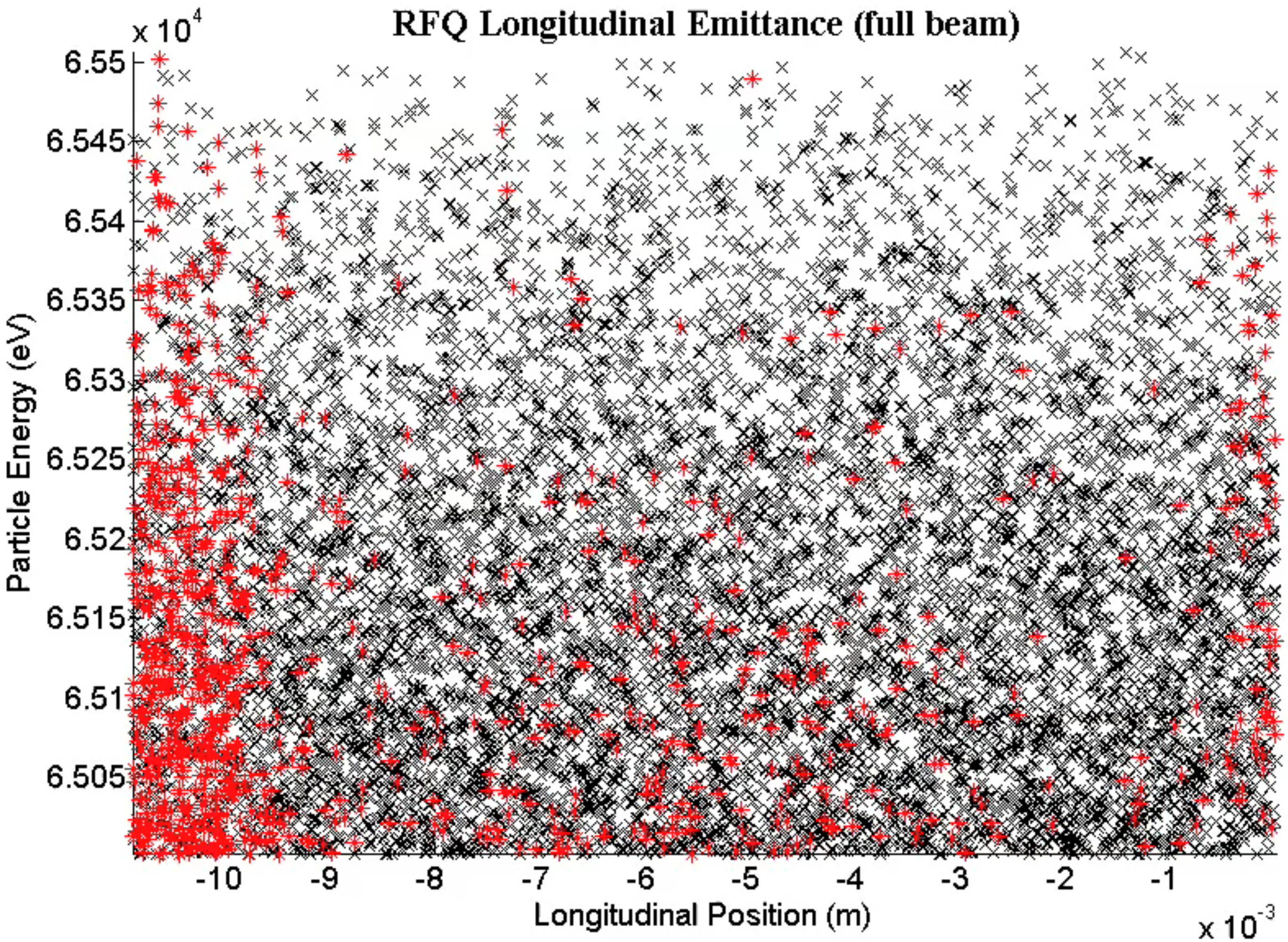
Longitudinal RFQ Sections

- An RFQ has 4 longitudinal sections:
  - The **Radial Matcher** takes the beam from the solenoid and introduces it slowly to the varying RF field between the vanes.
  - The **Shaper** forms bunches from the continuous beam by "shaping" the longitudinal emittance.
  - The **Gentle Buncher** squeezes the bunches gently to allow RF capture and starts the process of acceleration by shifting the phase.
  - The **Accelerator** takes the fully captured beam and accelerates it to the output energy.

FETS 4 m RFQ Bunch: Z-Y



FETS 4 m RFQ Bunch: Z-E



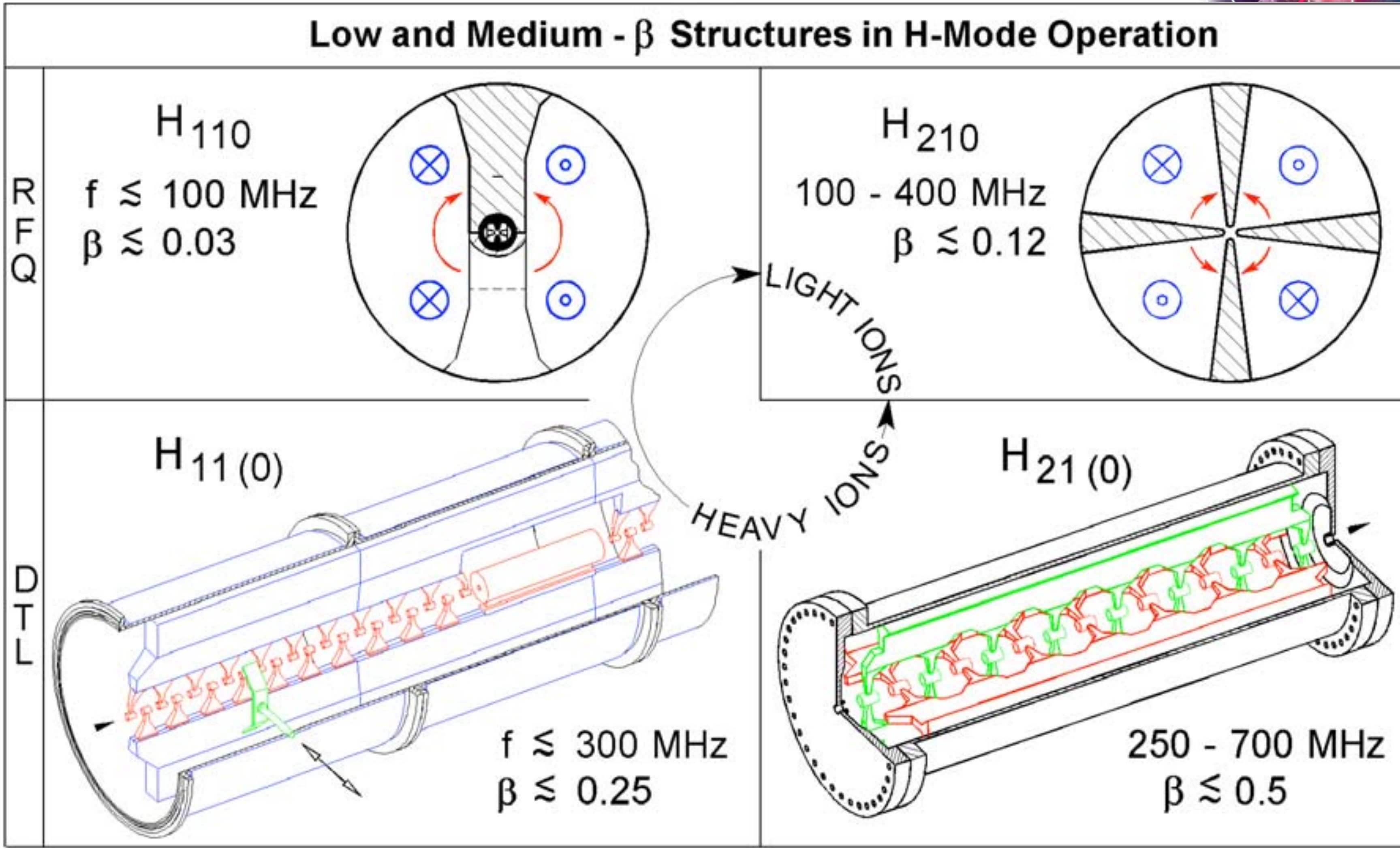
From LEBT to MEBT

- For medical synchrotron injectors, RFQ accelerates particles up to 400 keV per nucleon.
- Need to inject into ring at 7 MeV/u.
- RFQ great at low energy but acceleration inefficient.
- Switch to "normal" linear acceleration once space charge no longer dominant and beam bunched.

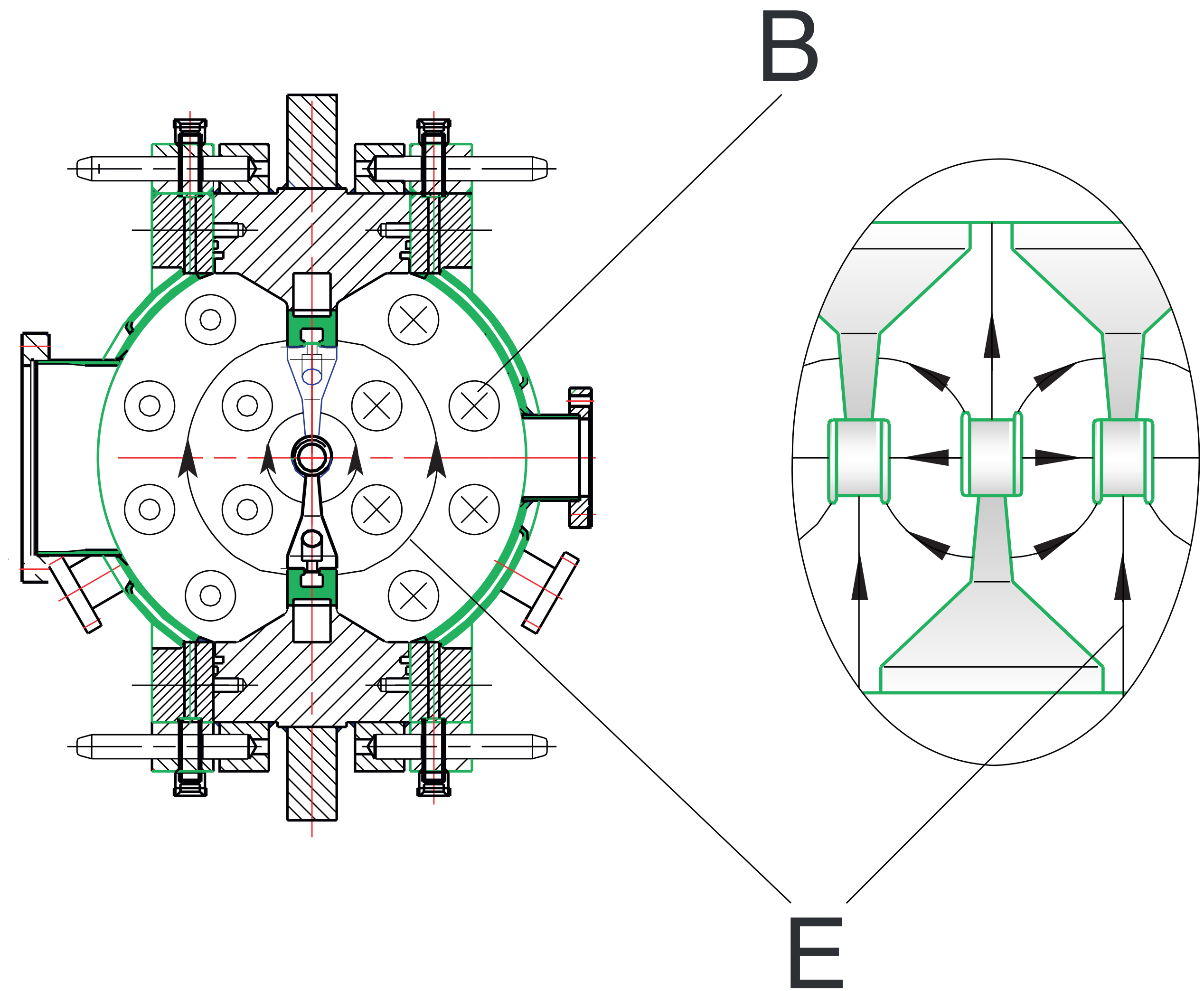
H-Mode Linear Accelerators

- Older medical synchrotrons (including MD Anderson/Hitachi ring) used standard Drift Tube Linac (DTL) — see Javier's talk.
- Most modern linacs use "H-mode" structures:
  - IH "interdigital" structures (using 4-rod mode).
  - CH "crossbar" structures (using 4-vane mode).
- "H-mode" comes from using magnetic field to drive surface currents that give acceleration.

H-Mode Structure Fields



IH Linac Fields



IH Linac Tank