

Imperial College  
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# EXTRACTING FAST & SLOW

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Heavy Ion Therapy Masterclass 2021

# PROPERTIES OF BEAMS FOR ION THERAPY

Beam quality closely depends on extraction: *What properties to aim for?*

**Beam from  
1 - 30 seconds**

**Rapid changes  
in energy**

**Stable intensity  
beam**

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**Active & passive  
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**Varying treatment  
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Other desirable properties:

- Beam stopped quickly [safety]
- Fast dose delivery option [FLASH]
- Multiple ion species [source]

# TYPES OF EXTRACTION

## Extracting Fast

- Beam out in 1 turn ( $\mu\text{s}$ )
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### Extracting Moderately

- 2 - 10 turns
- Not discussed today
  - Multi-turn Extraction
  - Resonant Multi-turn Extraction



# TYPES OF EXTRACTION

## Extracting Fast

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- Entire beam deflected
- Used in LHC accelerator transfer lines

## Extracting Slow

- Thousands to millions of turns
- Beam gradually shaved
- Used in medical machines!

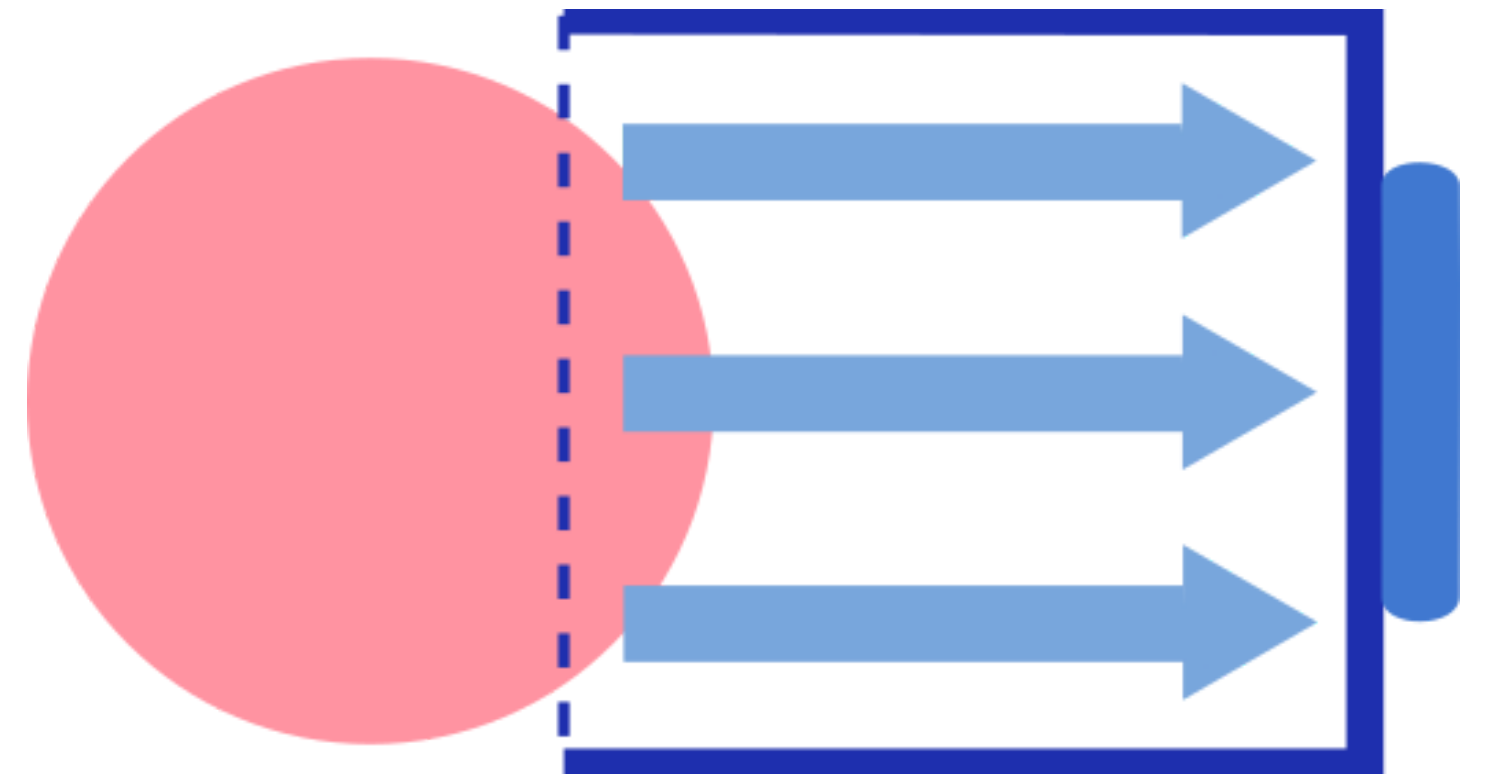
## Extracting Moderately

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# COMPONENTS OF EXTRACTION: ELECTROSTATIC SEPTUM

“—  
| A partition which separates  
two field regions [1] —”

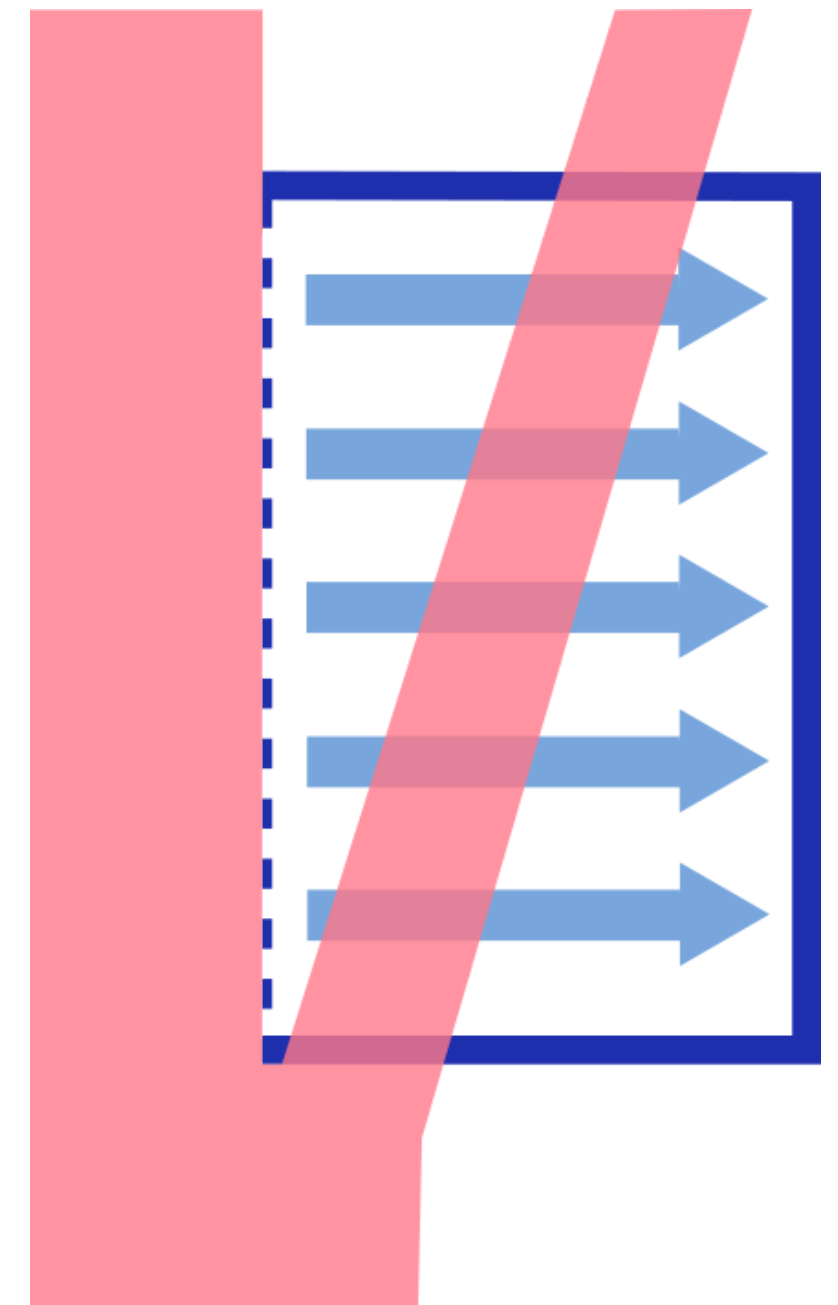
- No field outside of septum, fixed field within septum.
- Very thin septum foil to avoid beam loss (100  $\mu\text{m}$ )
- Up to 300 kV electrode



# COMPONENTS OF EXTRACTION: ELECTROSTATIC SEPTUM

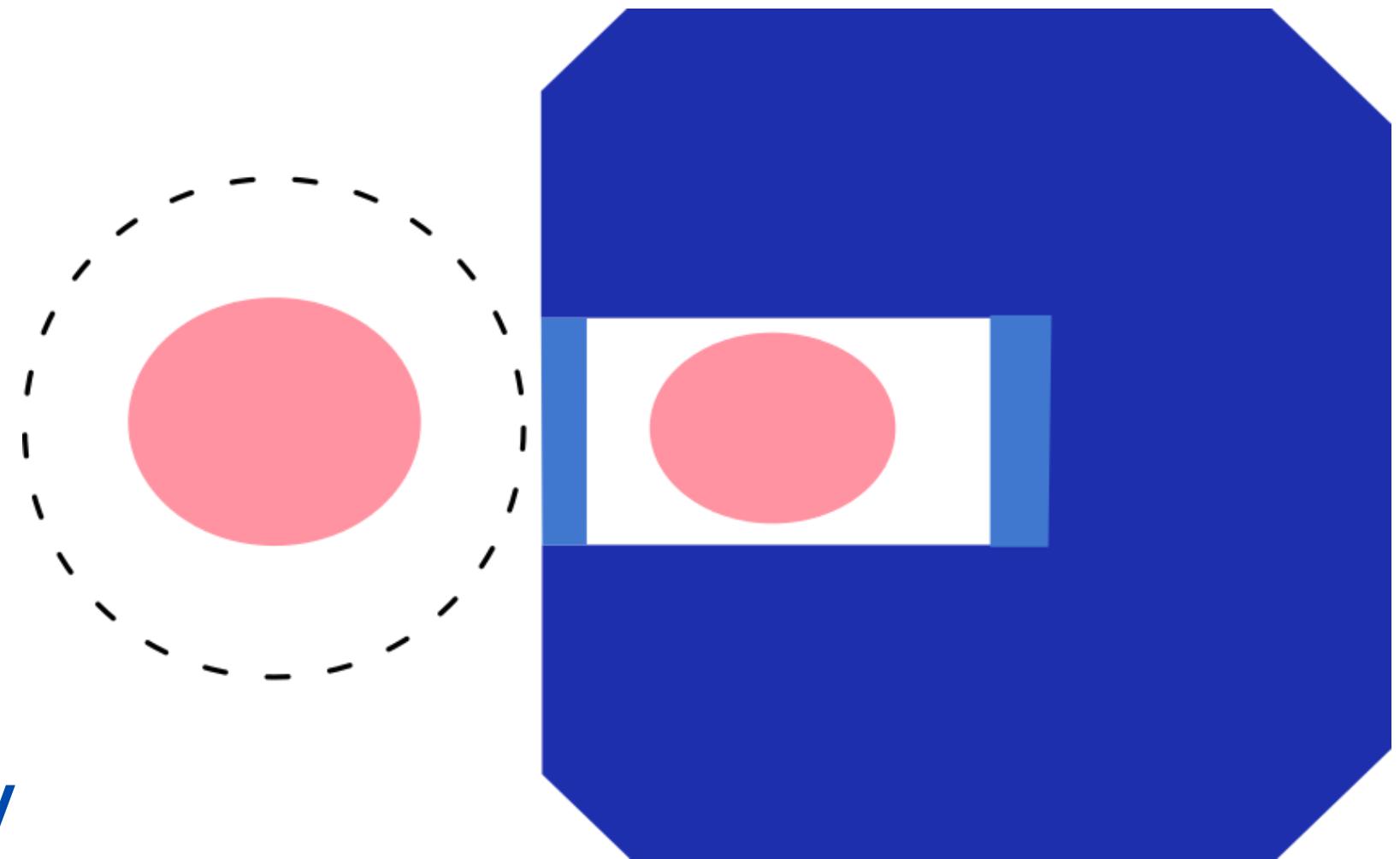
“—  
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- No field outside of septum, fixed field within septum.
- Very thin septum to avoid beam loss (100  $\mu\text{m}$ )
- Up to 300 kV electrode
  - 2.5 mrad deflection

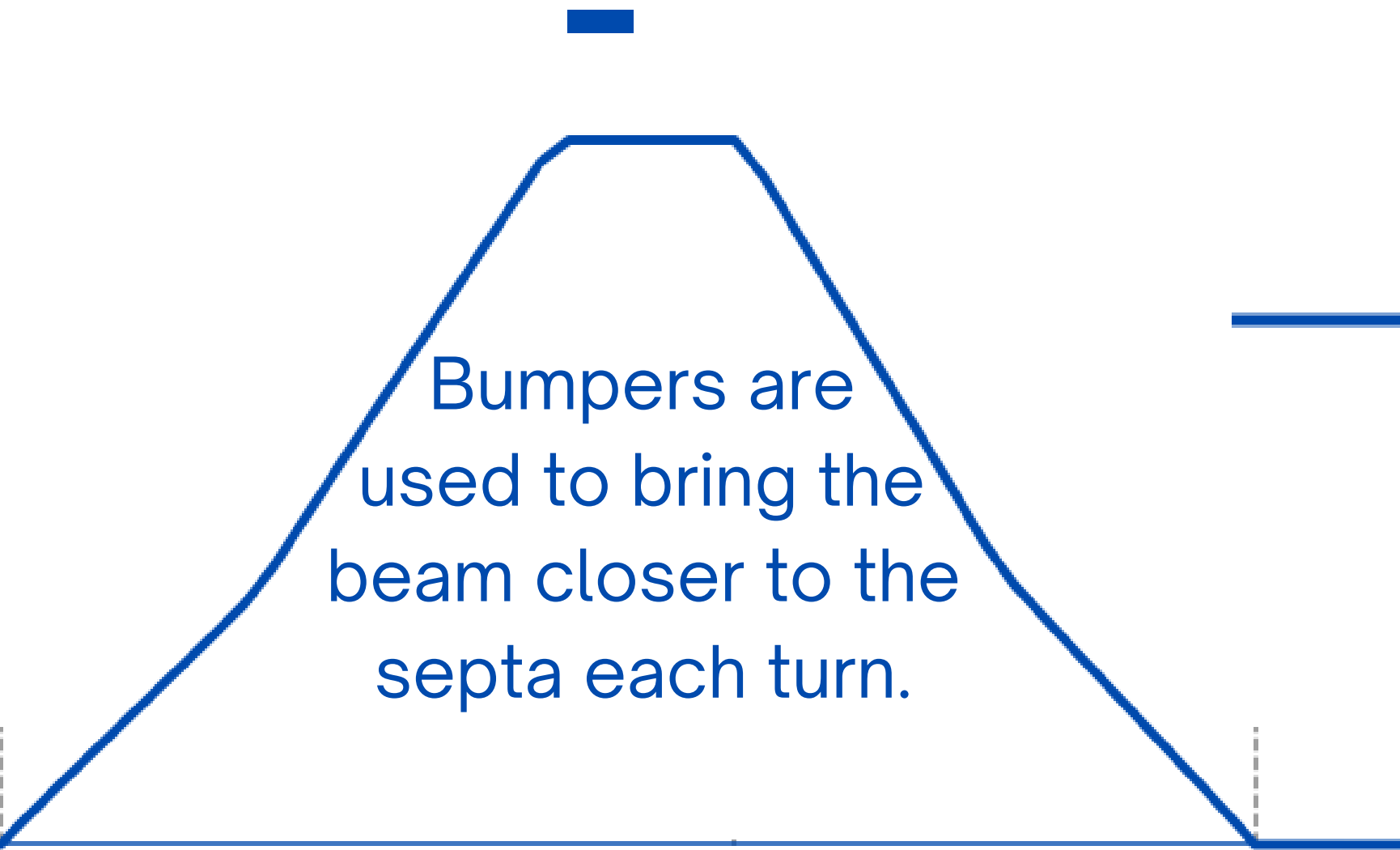


# COMPONENTS OF EXTRACTION: MAGNETIC SEPTUM

- Essentially a dipole magnet
- Often have two of these
  - Thin & thick
- Provides stronger kicks towards the extraction line
- Up to 0.5 T and 1 T respectively
  - Gives 0.05 rad & 0.15 rad

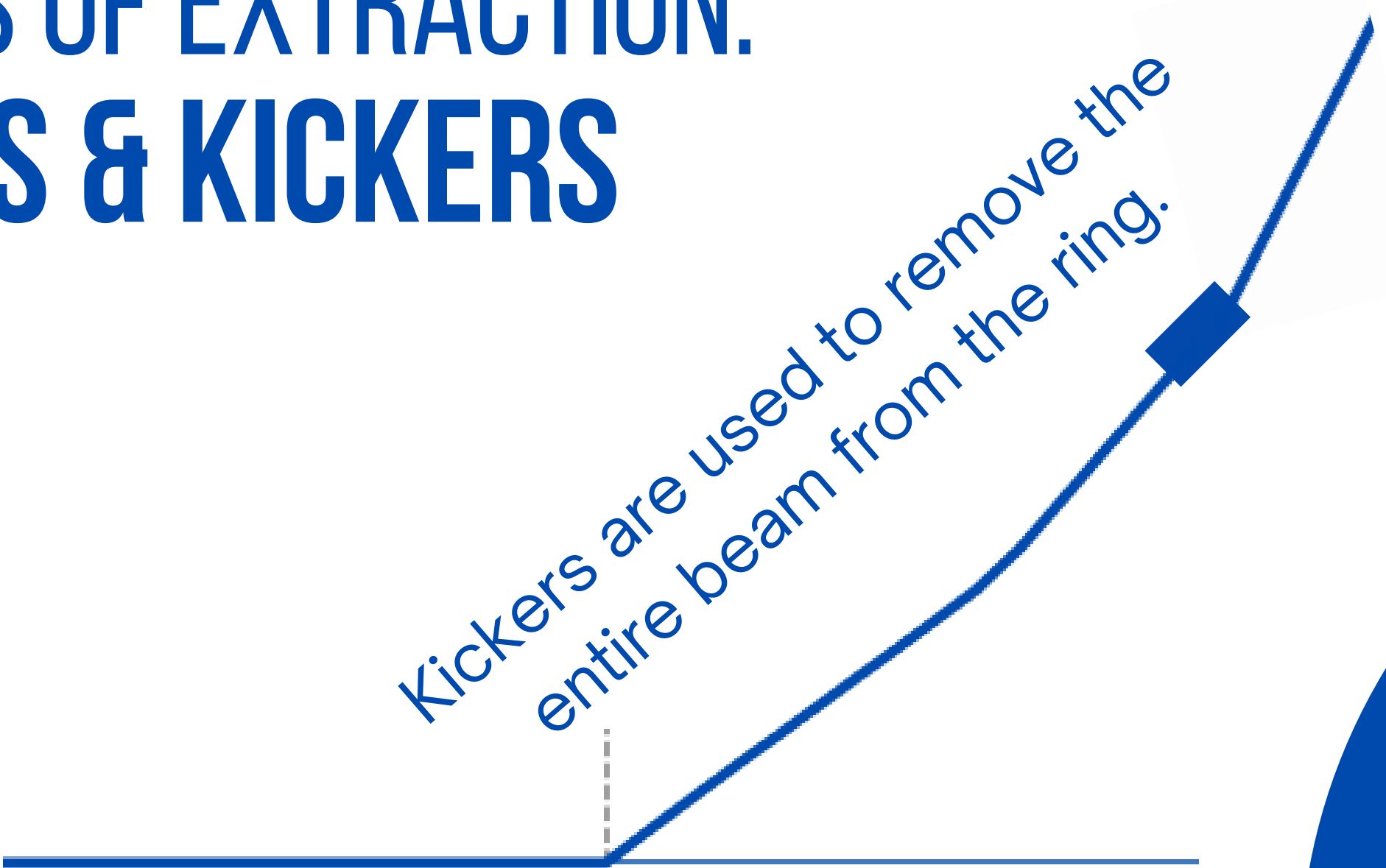


# COMPONENTS OF EXTRACTION: BUMPERS & KICKERS



Bumpers are used to bring the beam closer to the septa each turn.

The diagram shows a horizontal blue line representing a beam's path. A trapezoidal shape is drawn above the line, with its top edge slightly above the line and its bottom edge following the line. Two vertical dashed lines extend from the bottom corners of the trapezoid down to the horizontal line, indicating the start and end of the bump. A small blue horizontal bar is positioned above the top edge of the trapezoid.



Kickers are used to remove the entire beam from the ring.

The diagram shows a horizontal blue line representing a beam's path. At a certain point, the line curves upwards and then continues as a straight line at a higher angle. A vertical dashed line marks the point where the beam begins to rise. A small blue rectangular block is placed on the upward-sloping part of the line, representing the kicker.

# EXTRACTING QUICKLY

Removing the whole beam in just one turn



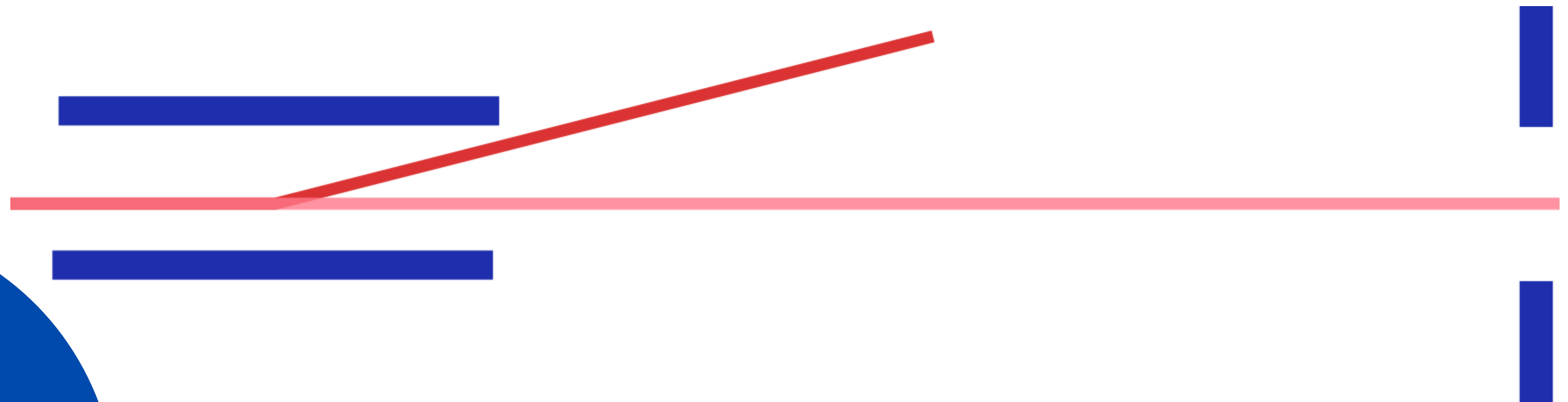
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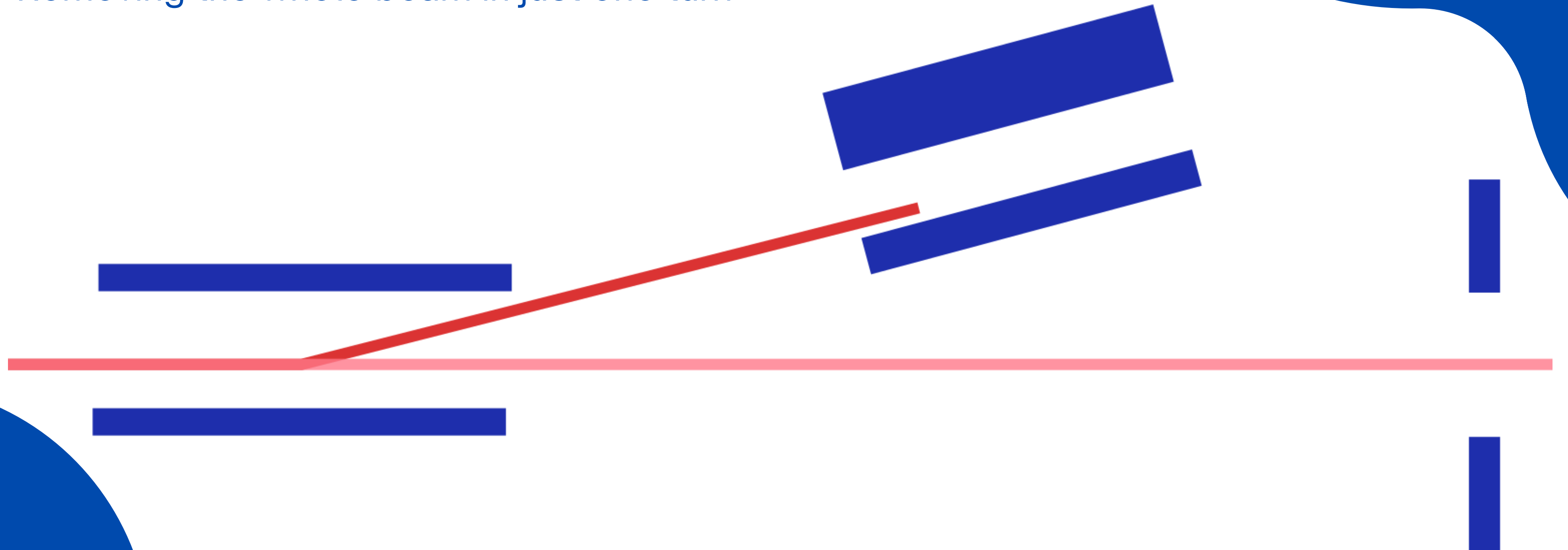
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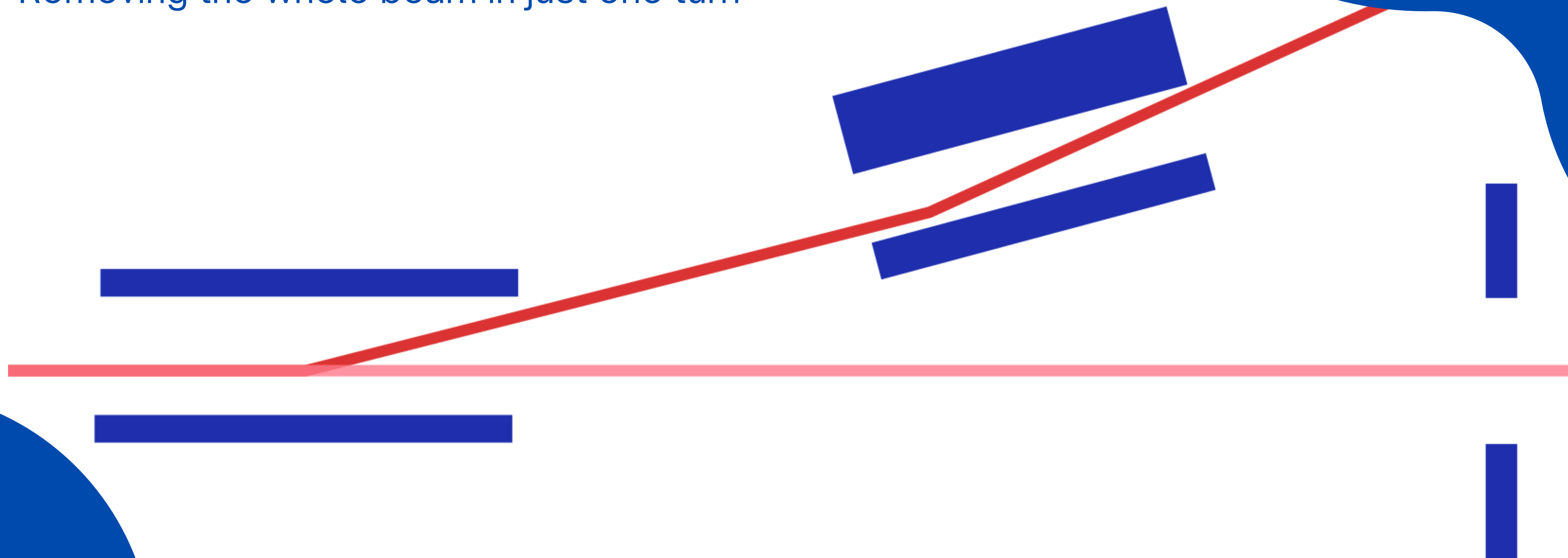
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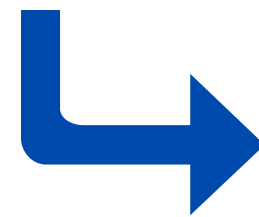
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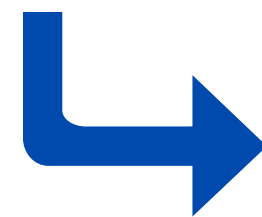
# EXTRACTING SLOWLY

Purposefully make the beam **unstable** to gradually extract a few particles from the beam each turn



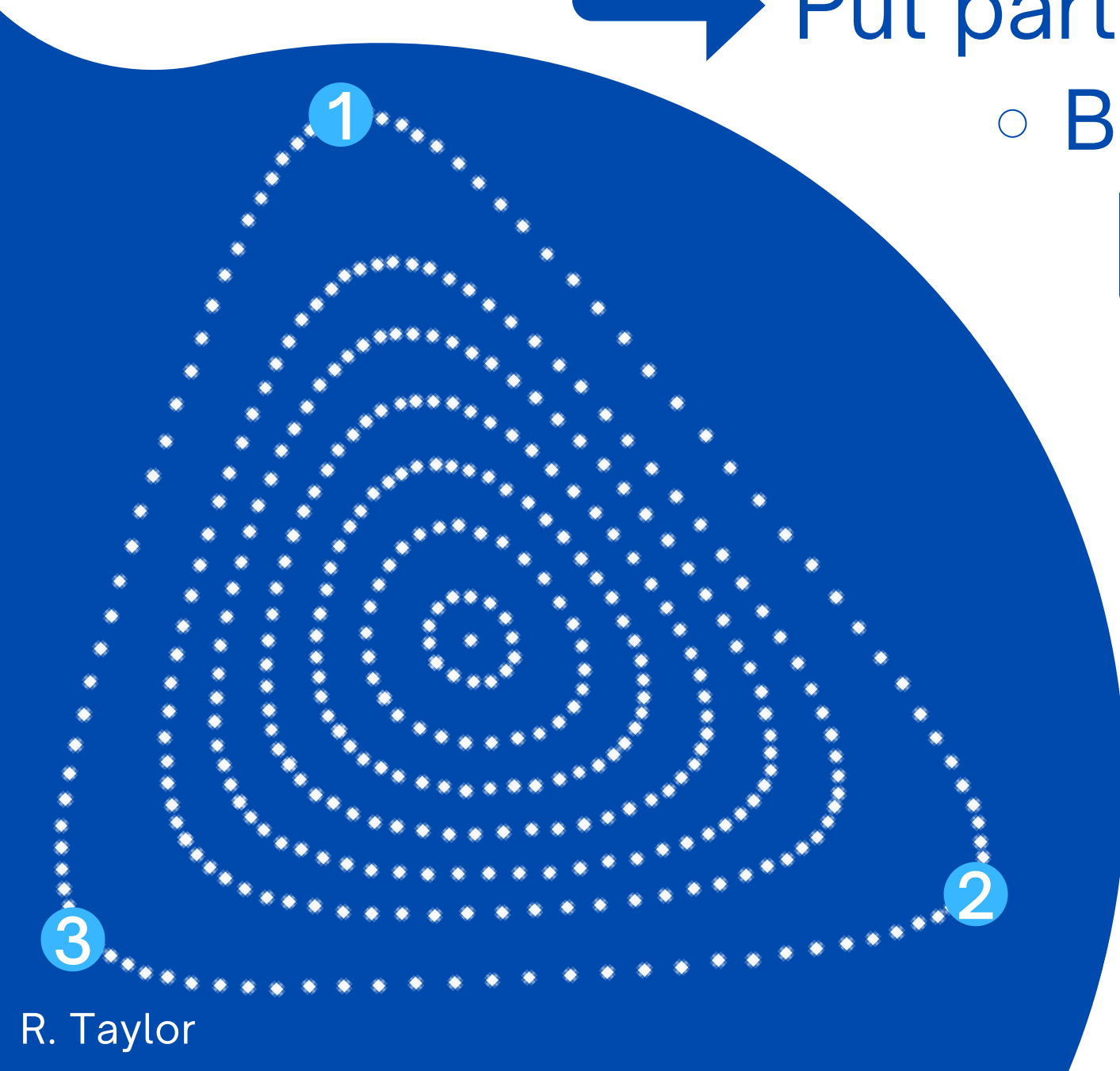
Put particle beam on **third-order resonance**

- Back to it's original position every 3 turns



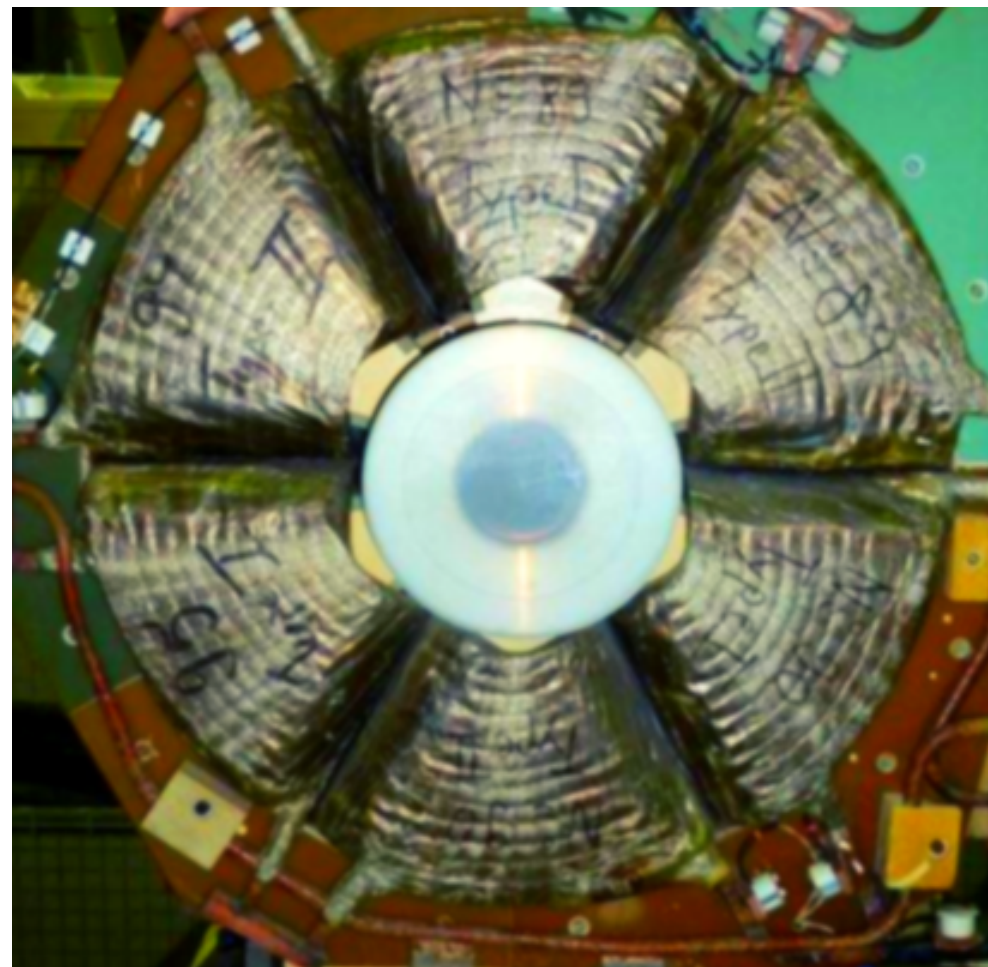
Introduce higher-order fields to shape the instability

- Beam forms an unstable triangular shape

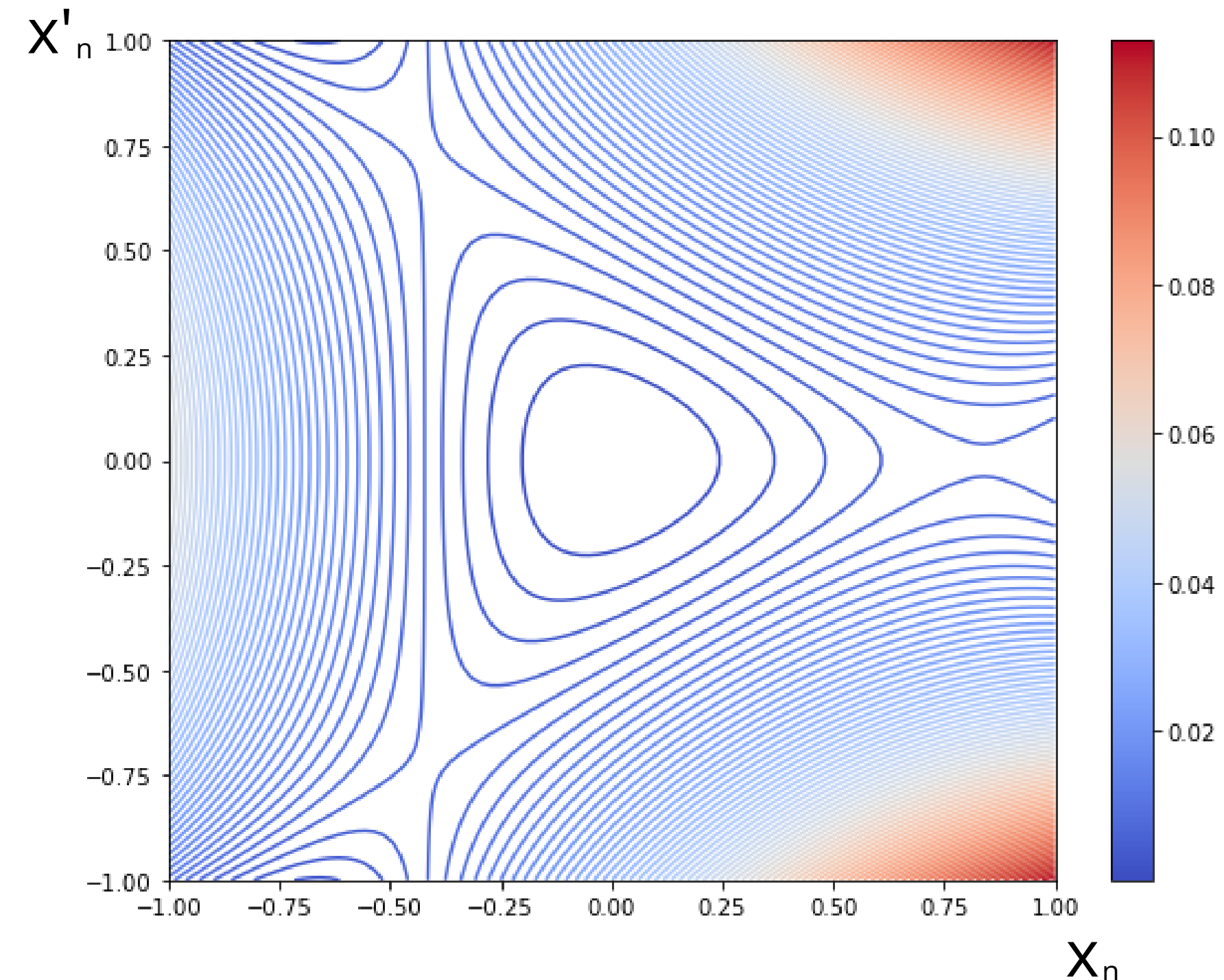


# COMPONENTS OF EXTRACTION: SEXTUPOLES

- Potential shapes the beam distribution, into the triangular shape.
- At large amplitudes, separatrices form

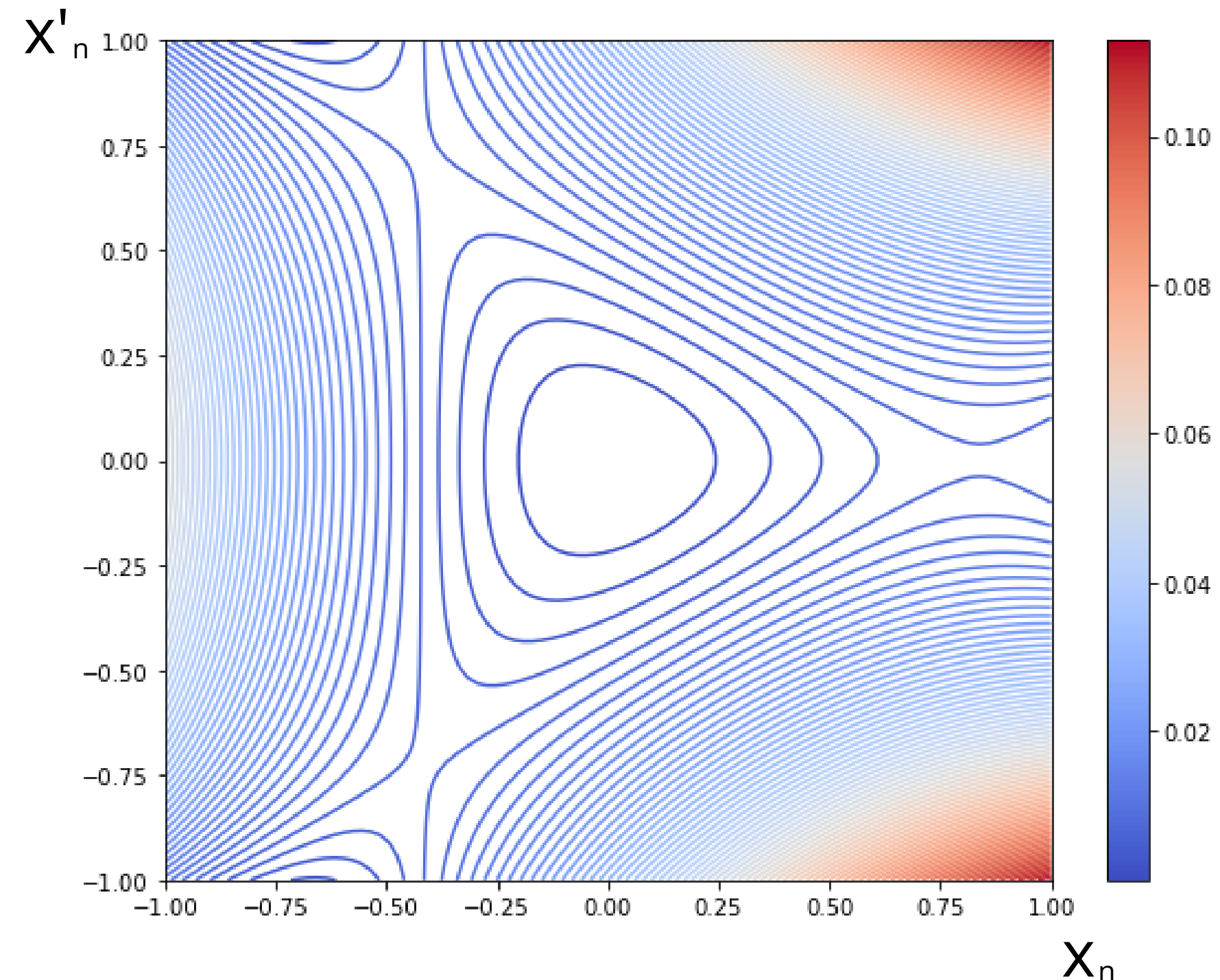
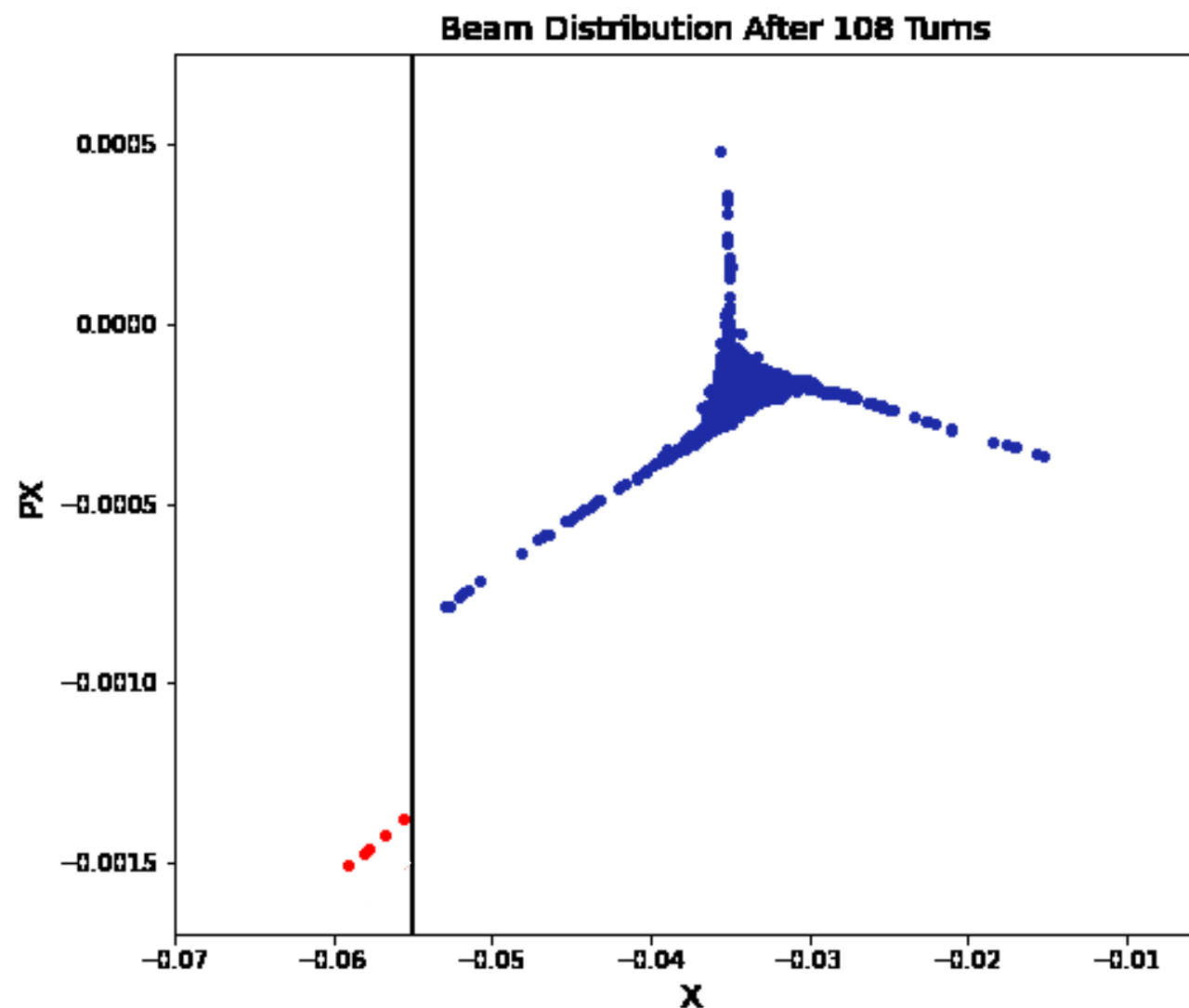


Sextupole image from CERN Database [4]



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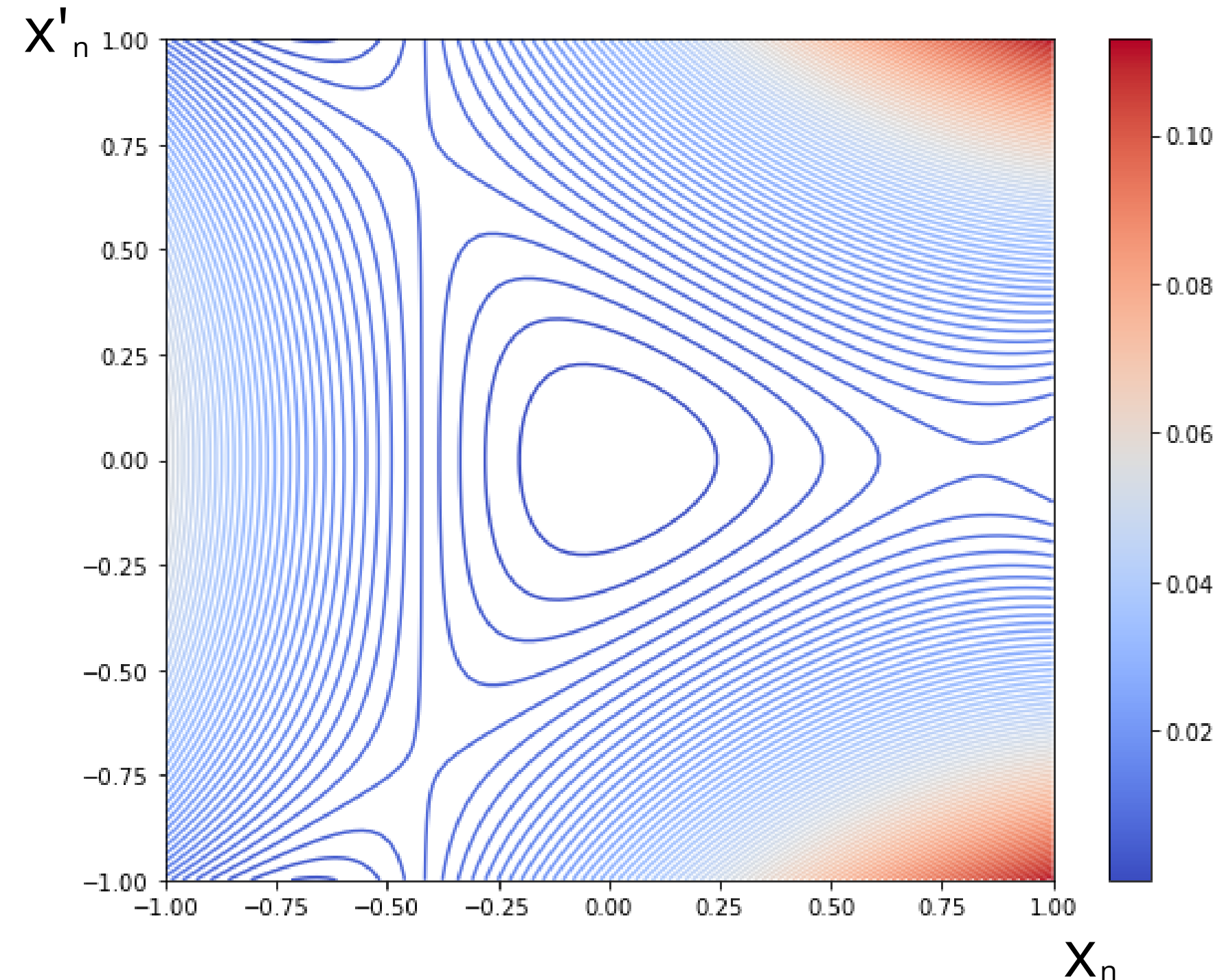
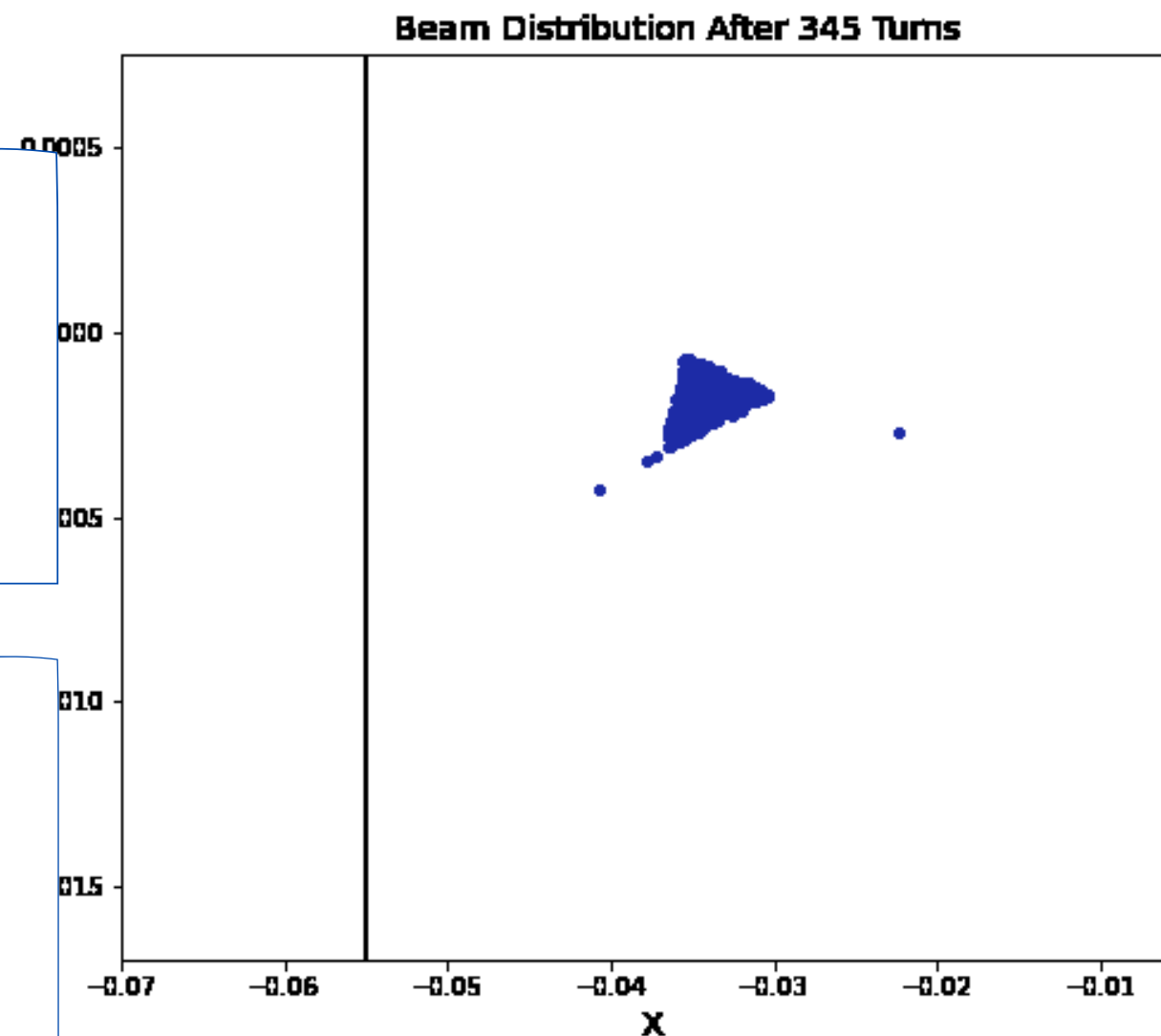


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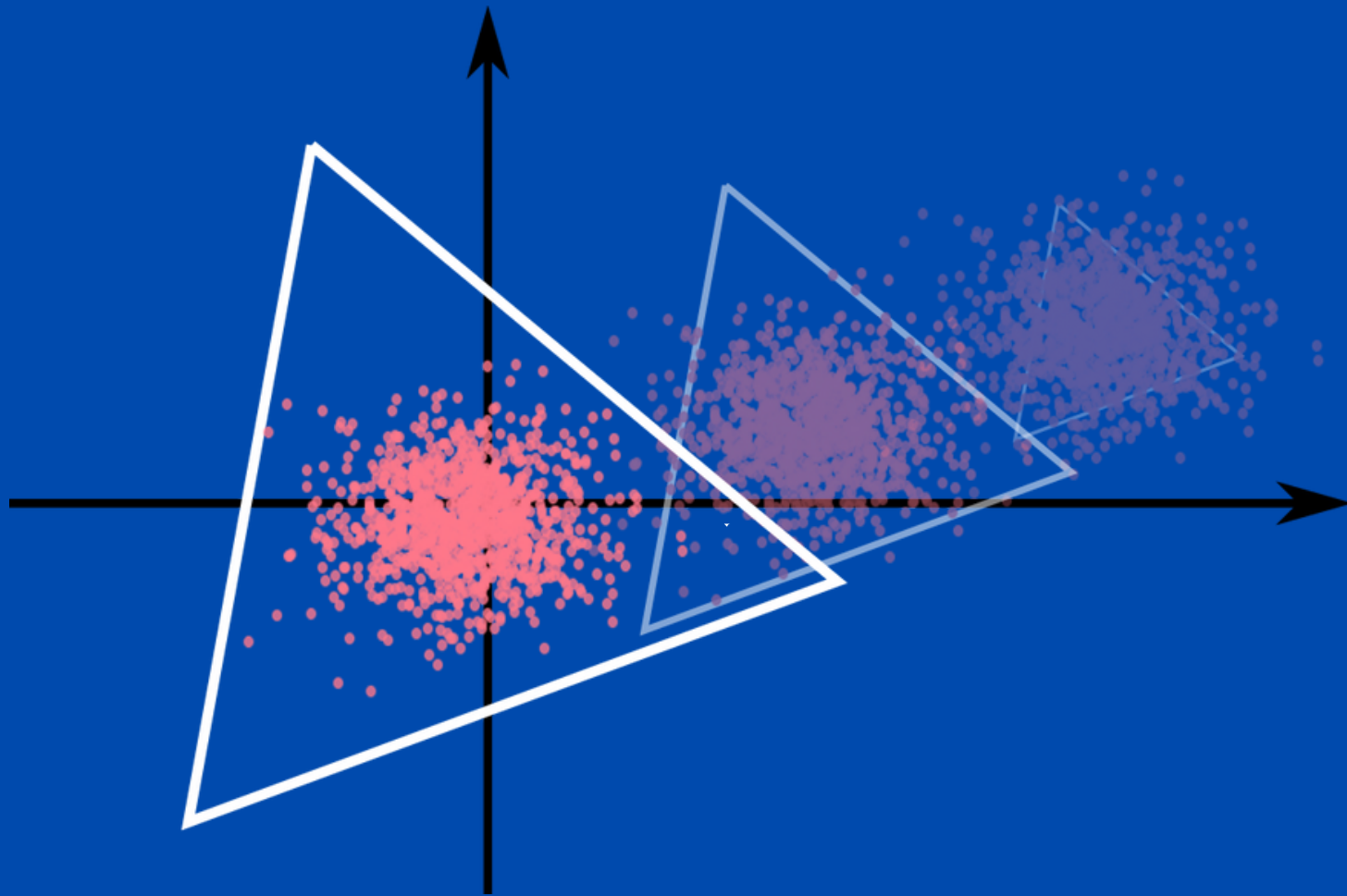
Notice that the central core stays stable?

**Need to excite these particles into the resonance!**



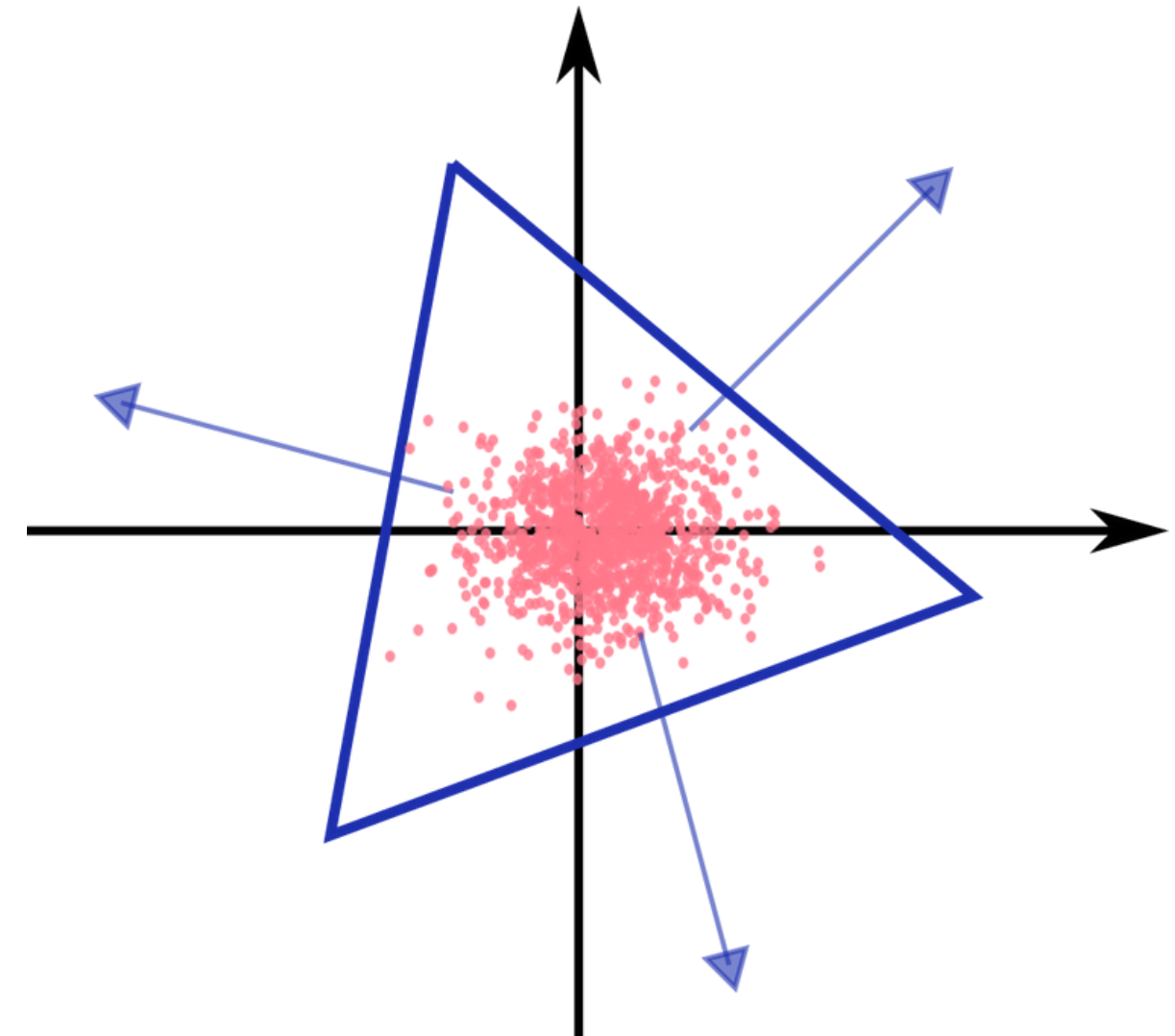
# BETATRON CORE

- Moving the beam towards the resonance
- Changing the momentum of the beam closer to the tune

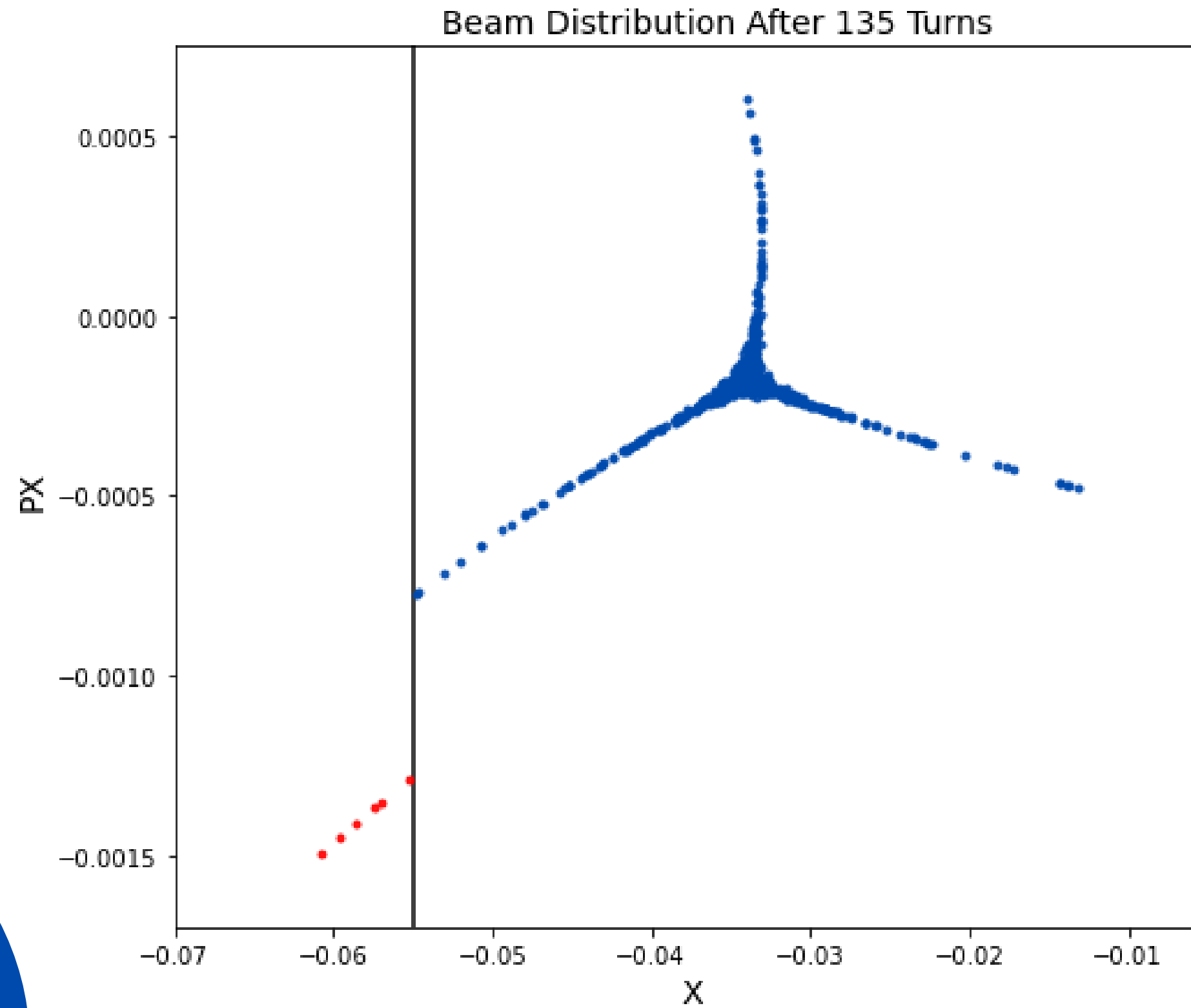


# RF-KO EXCITATION

- Increasing the amplitudes of particles
- Introduce stochastic noise exciting the particles



# FINAL EXTRACTION

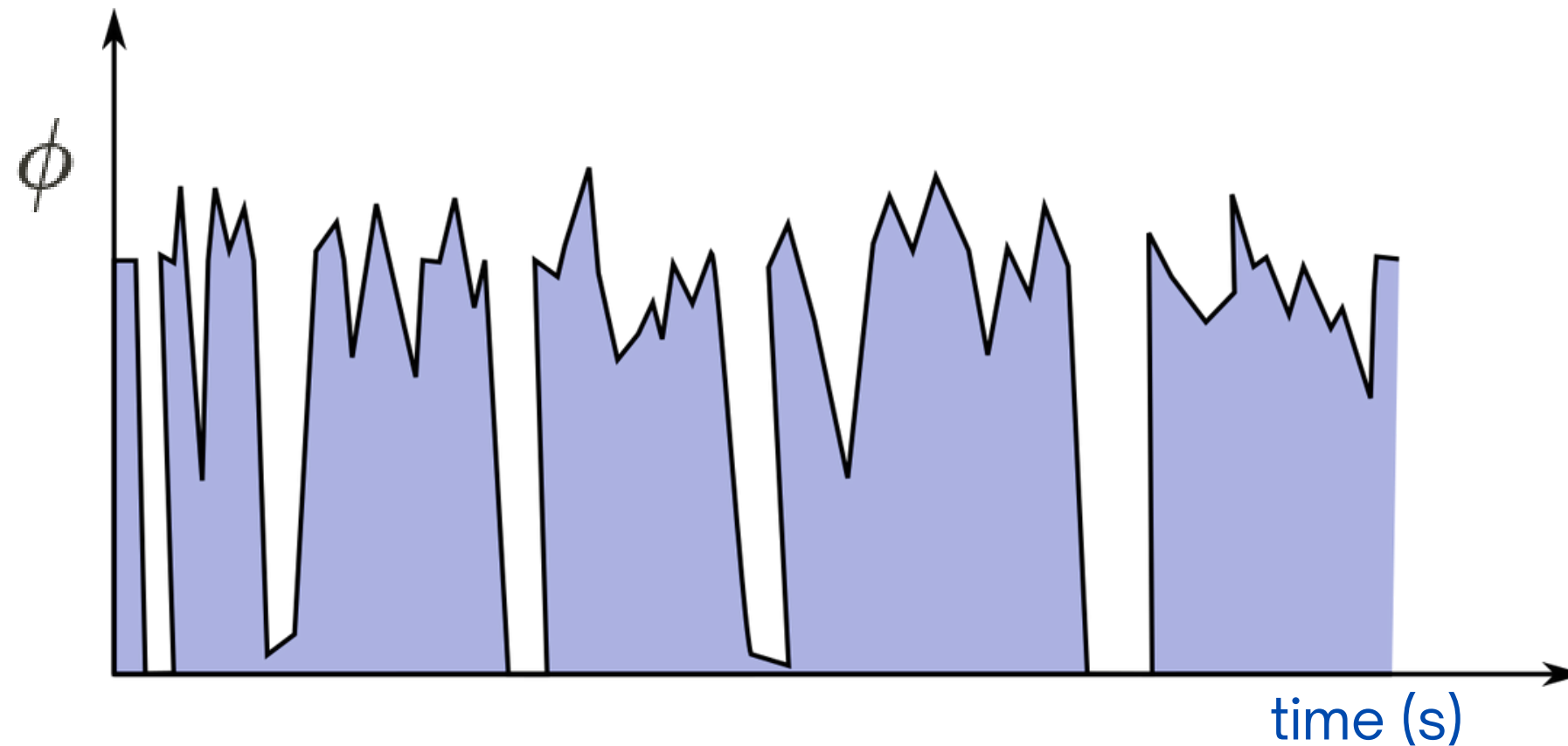




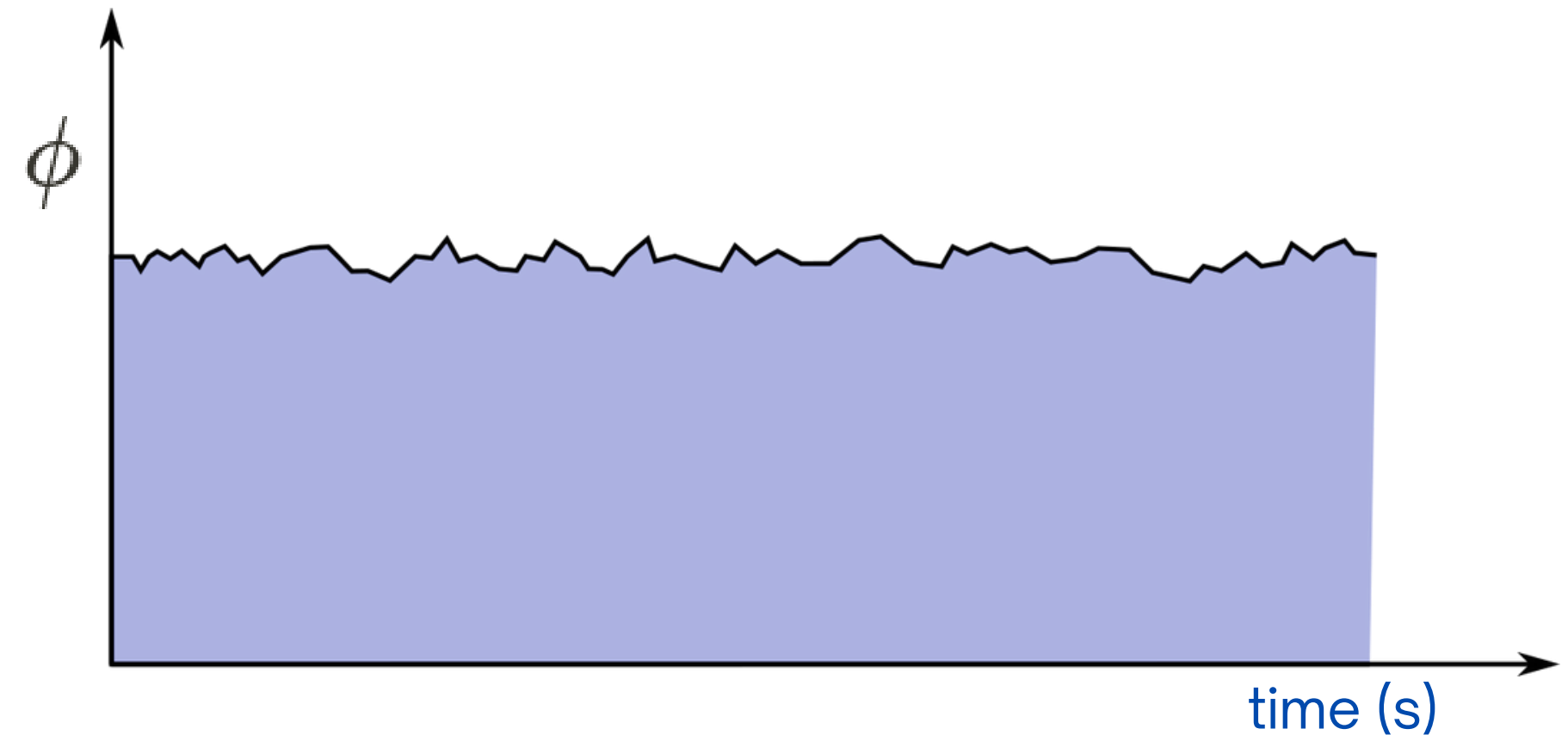
# BEAM SPILL

Also known as particle flux. Describes the number of particles per time period

$$\phi = \frac{dN}{dt}$$



*Irregular flux, varying beam intensity, bad spill quality*



*Regular flux, constant beam intensity, good spill quality*

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**HITRI**  
Heavy Ion Therapy Research Integration



Extraction in medical machines needs specific techniques to get the beam out slowly.

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Purposefully make the beam unstable to gradually extract a few particles from the beam each turn.



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**Thank you for listening and I welcome any questions!**



# REFERENCES

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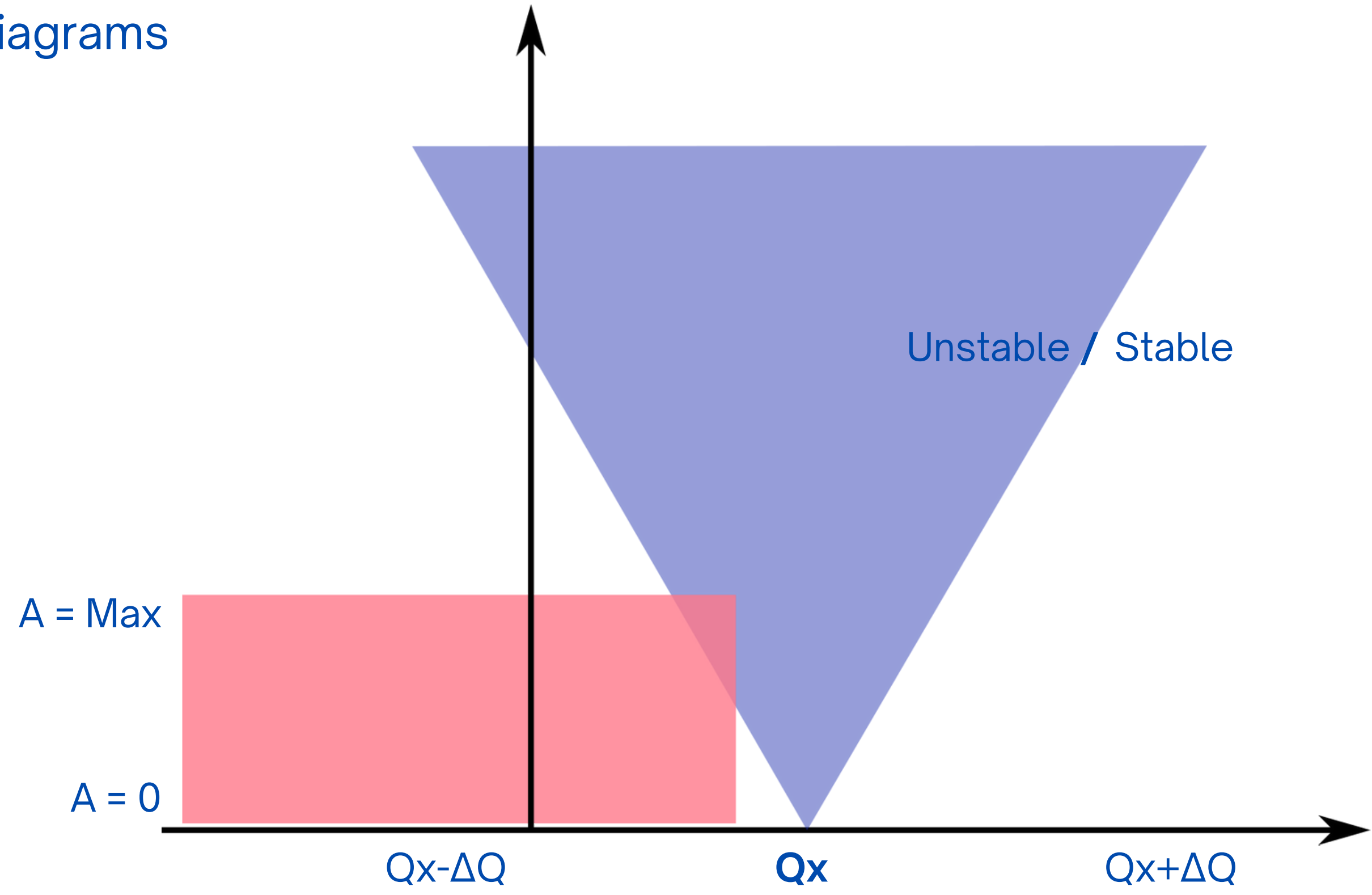
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<https://indico.gsi.de/event/11547/>

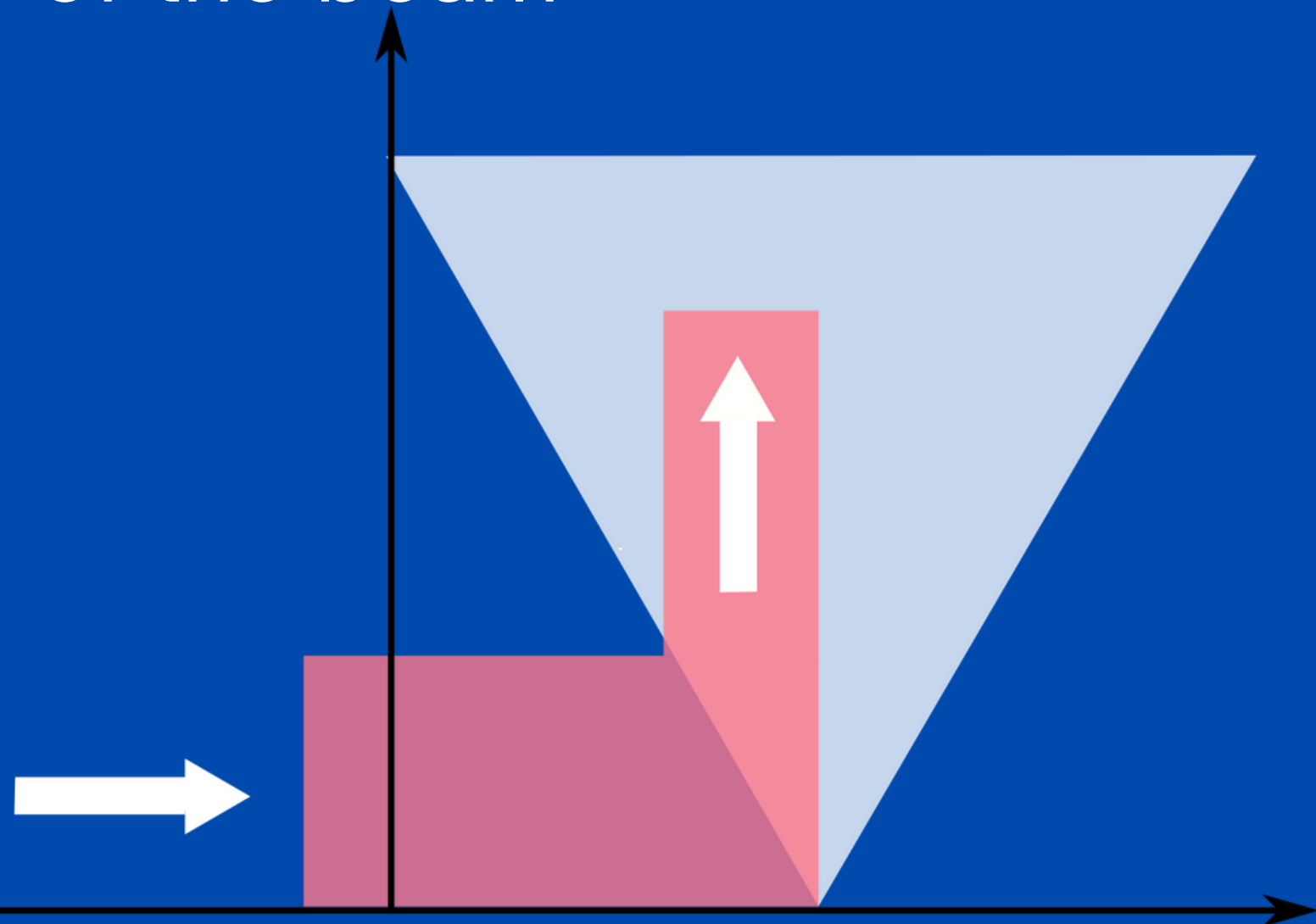
# EXCITING THE STABLE BEAM

Steinbach Diagrams



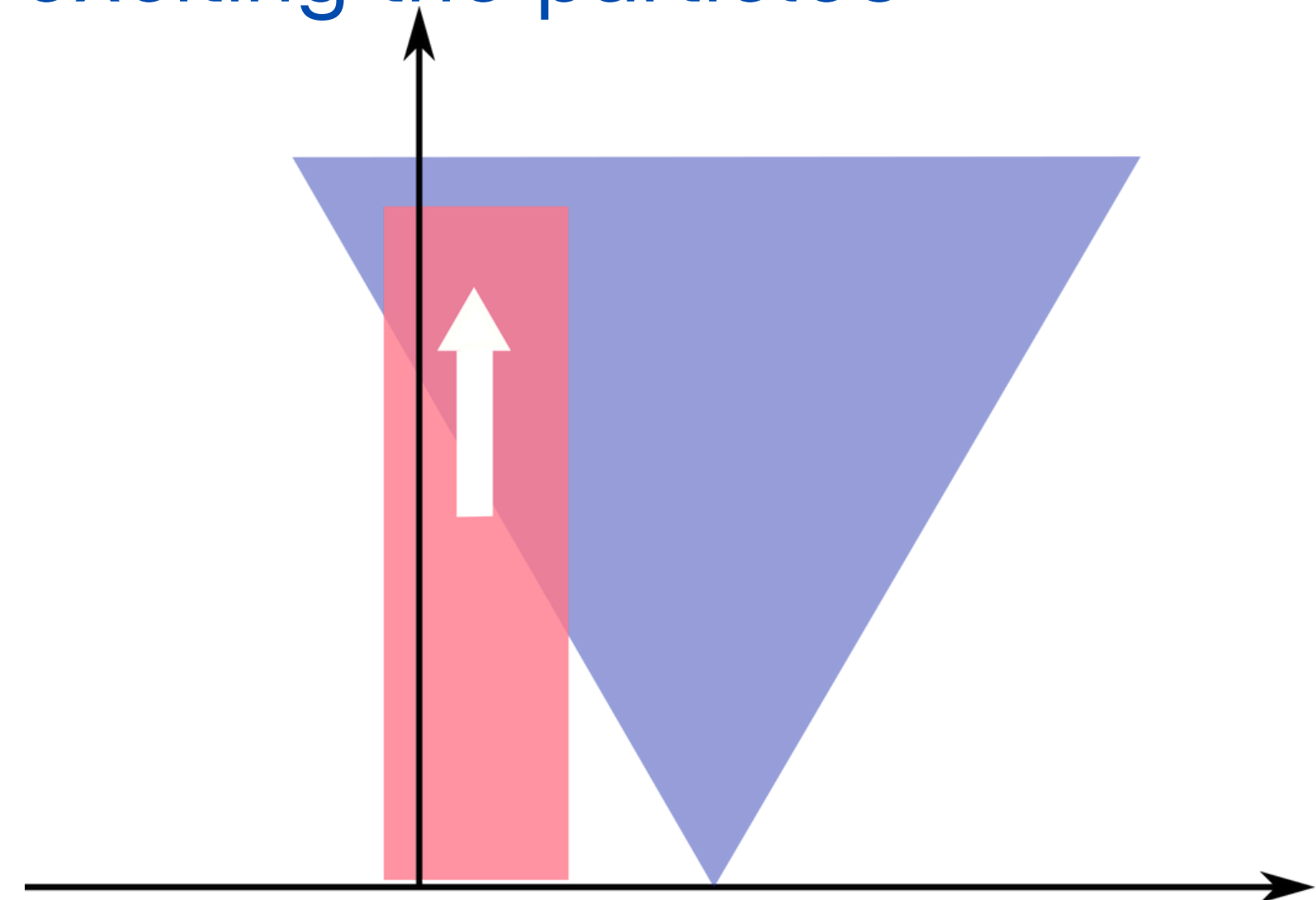
# BETATRON CORE

- Moving the beam towards the resonance
- Solenoidal coil varies the  $\Delta p/p$  of the beam



# RF-KO EXCITATION

- Increasing the amplitudes of particles
- Introduce stochastic noise exciting the particles



# PROPERTIES OF BEAMS FOR ION THERAPY

Stable  
Beam

Stop the  
beam quickly

Beams from  
1 - 100 seconds

Fast dose  
delivery

Rapid changes  
in energy

Multiple particle  
species