Behind the scenes at CERN: slow extraction from the SPS and attempts to improve its efficiency

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- Particles moving in magnetic field
- Transverse dynamics
  - Design orbit
  - Mathematical discussion
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  - Tune
    - Multipole resonance
    - Third-order resonance

Slow extraction:

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- Concept of using massless septa
- Simulation
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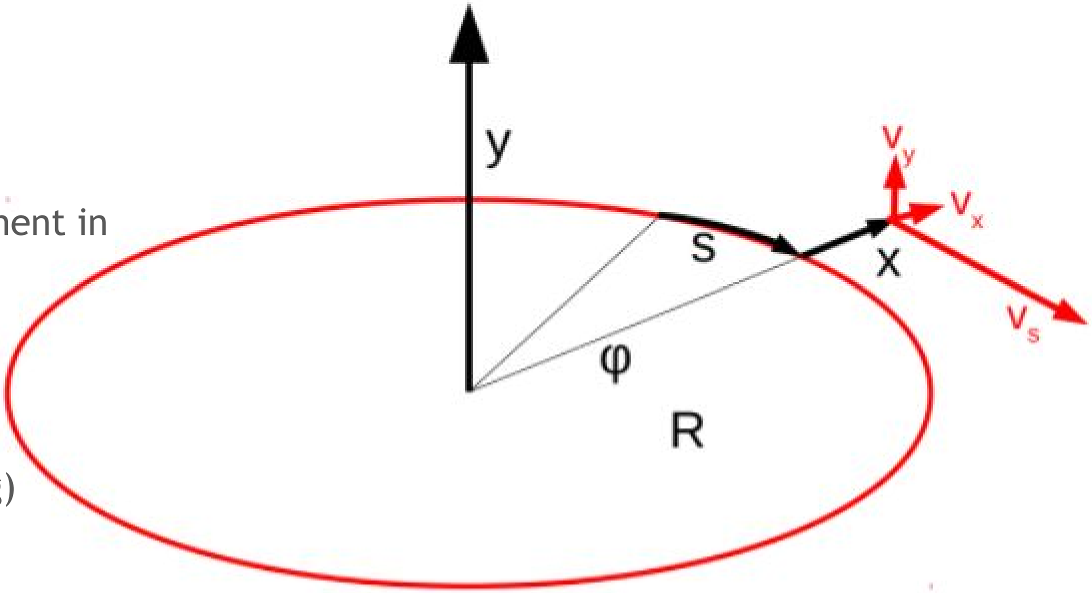
- Conclusion
- Outlook

Beam coordinate system

- Coordinates in a circular accelerator:
  - x,y - transverse coordinates
  - s - longitudinal coordinate
- Phase space variables:
  - (x,x’), (y,y’), (dt, dE)
  - $x' = v_x / v_s = p_x / p_0$
  - $y' = v_y / v_s = p_y / p_0$

  - Usually we assume the movement in x and y to be independent

  - Important to realize that x and x’ are not conjugated coordinates (if p_0 is increasing)

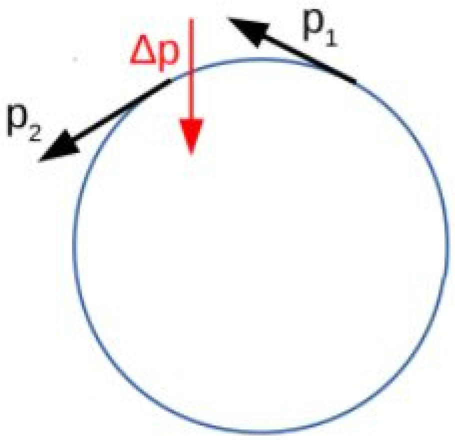


Particles moving in magnetic field

- Magnetic force is proportional to v while electric force is not so when v≈c then magnetic force is much greater
- In high energy (>100keV) machines only magnetic focusing and bending is possible

$$\mathbf{F}=q\mathbf{E}+q\mathbf{v}\times\mathbf{B}$$

- $F_r \approx qvB = d\mathbf{p}/dt = pv/\varrho$
- $B\varrho = p/q$ → **magnetic rigidity**
- In a given magnetic field the path of a particle only depends on the rigidity (how hard it is to bend the particle path)
- Importance:
  - B and ϱ are parameters of the **machine**
  - q and p are parameters of the **particle**

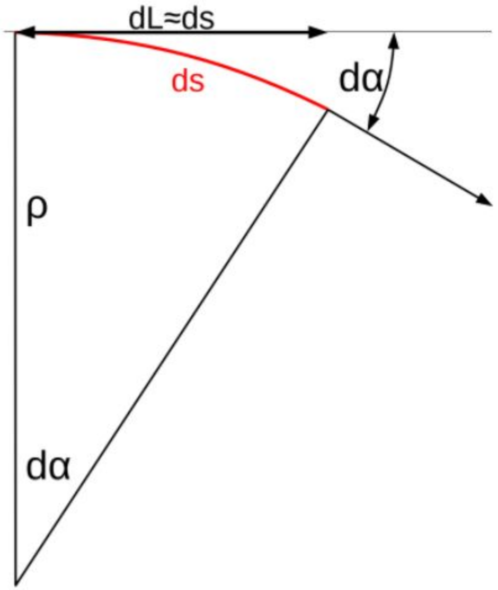


Integrated magnetic field

- Most of the time the length of a magnet is short compared to the whole machine
- This assumption is often called **thin lens** approximation
- The bending angle in a thin lens magnet:

$$d\alpha = ds/\varrho = (Bds)/(B\varrho) = (Bds)/(p/q)$$
$$\alpha = q/p \int Bds \approx q/p \int BdL$$

- $\int BdL$ is called the **integrated field strength** of the magnet
- It is normalized with the rigidity

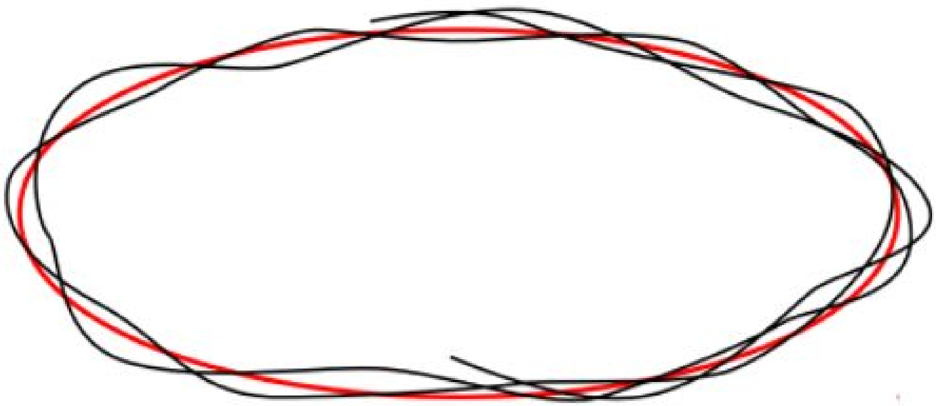


Transverse dynamics

The design, and the real particle orbit

- The design orbit is a closed curve on which an ideal momentum (transverse angle) particle would move
- Real particles have momentum, and angular spread

- If the beam is stable
  - Particles oscillate around the ideal position in all 3 coordinates (transverse → Betatron oscillation)
    - Number of oscillations: **tune (q)**
  - Small differences in starting conditions don't grow infinitely
- To achieve beam stability one needs focusing



Mathematical discussion

- If we assume that the two transverse coordinates are independent, then the equation of motion will be the Hill-equation:

$$x'' + k(s)x = 0$$

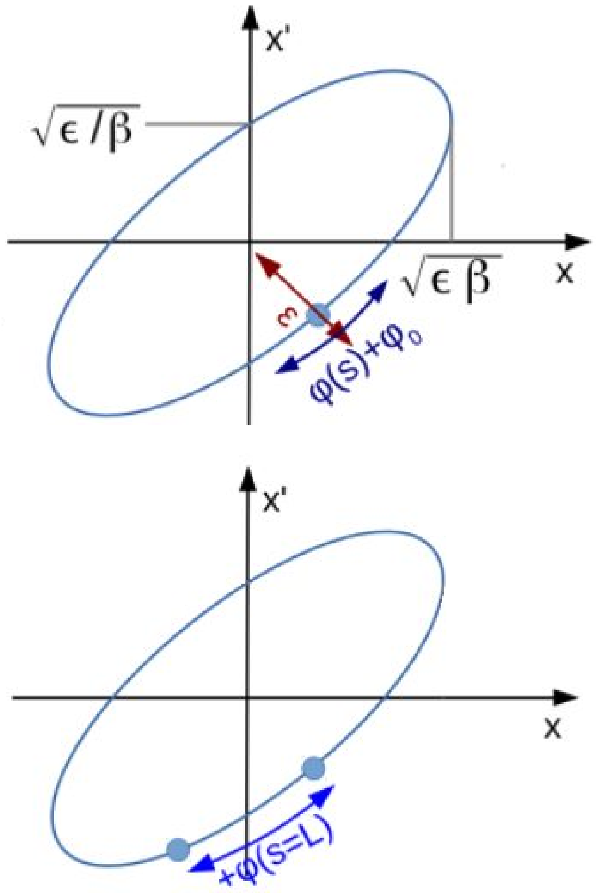
- Where k(s) is:
  - Periodic: $k(n2r\pi+s)=k(s)$
  - $k(s)=0$ without any magnet
  - $k(s)=\pm g/(p/q)$ inside quadrupole magnets
  - $k(s)=1/\varrho^2$ inside dipole magnets

- We search solutions similar to that of the harmonic oscillator:

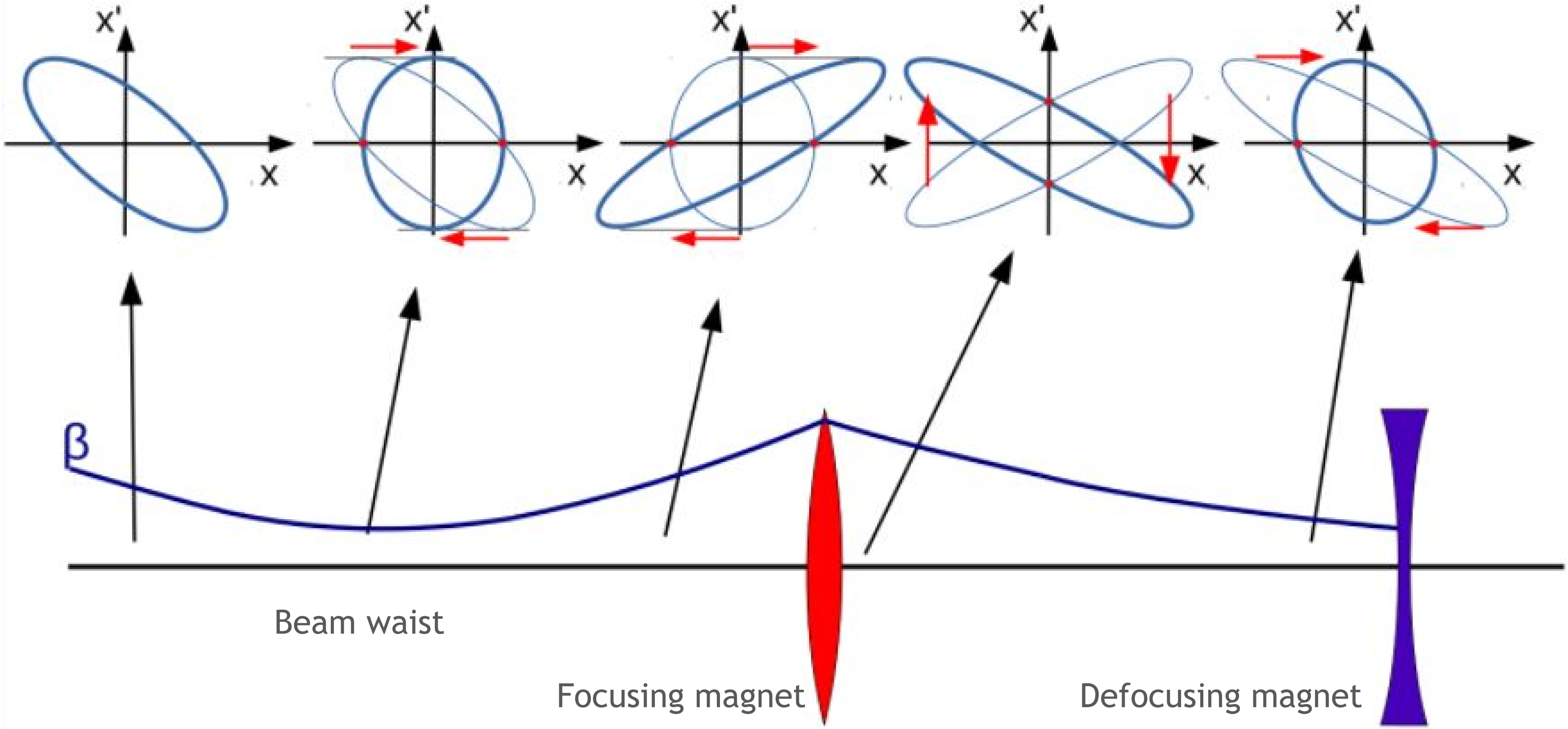
- We choose β(s) such that it $x(s) = \sqrt{\beta(s)}\sqrt{\varepsilon}\cos(\varphi(s) + \varphi_0)$
  - β(s) is called the beta-function
  - Its dimension is [m]
  - It determines the “transverse size” of the beam at a given s coordinate

Solution of the Hill-equation

- The solution of the hill equation for a given ε determines an ellipse in the phase space for all s
- The ε parameter (the Courant-Snyder invariant or emittance) is the area of the ellipse
    - [ε]= mm mrad
- The so called Twiss-parameters (α(s), β(s)) determine the tilt and shape of the **Twiss-ellipse**
- A given particle walks on its own ellipse
- **Normalized phase-space** is scaled at each point of the accelerator so that the Twiss-ellipse becomes a circle



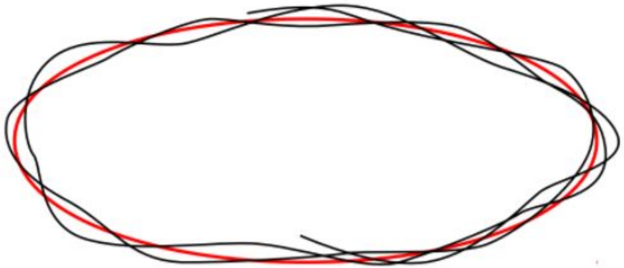
Twiss-ellipse in the transfer line

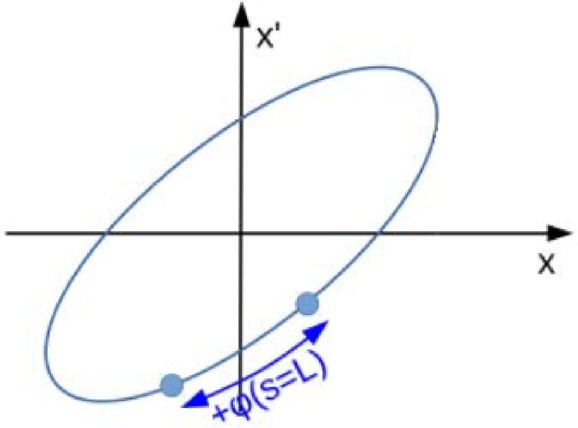


Tune

- We can track one particle throughout the accelerator
  - The “number of oscillations” around the ideal orbit is called **tune (q)**
  - If q of a particle is integer then the particle moves on a closed orbit

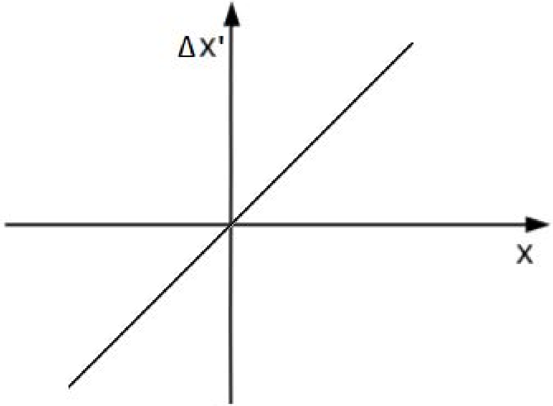
  - Tune can be changed by quadrupoles



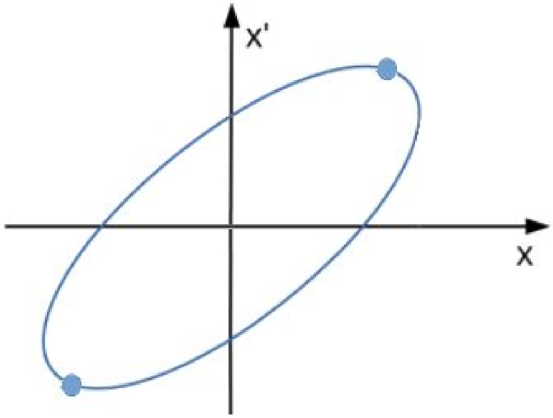


Importance of the tune

- The effect of a quadrupole can be estimated with an **x’ kick** depending linearly on the position of the particle

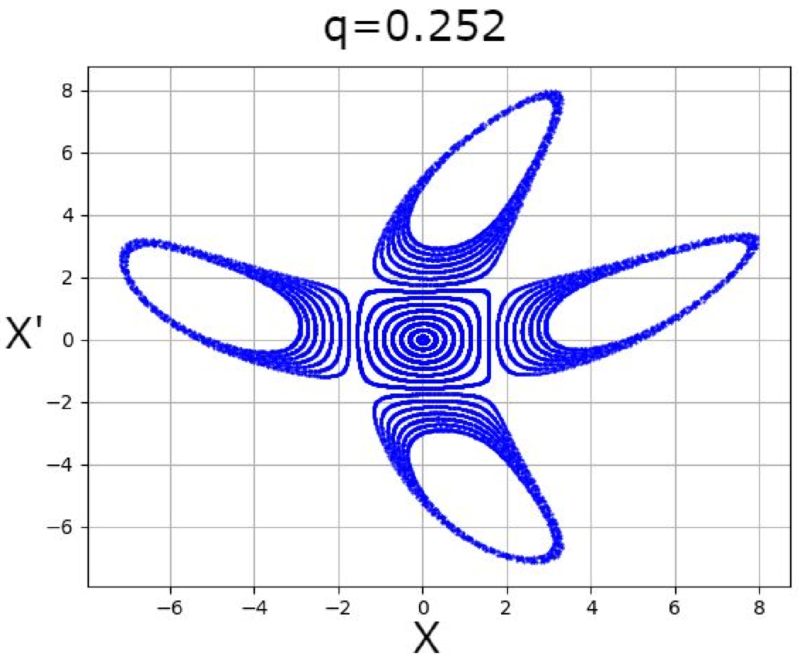


- Imagine a synchrotron with only 1 quadrupole magnet inside
  - What would happen to a particle with tune q=½
  - Each turn the particle gets a kick outwards (increasing beam size)
  - Same for every q=n½
  - This effect is called multipole (second order) resonance
- If there are higher order multipole magnets, other resonances also appear



Multipole resonances

- These resonances are usually “harmful” and have to be dealt with
- But they can be used to widen a beam profile, or separate “islands”



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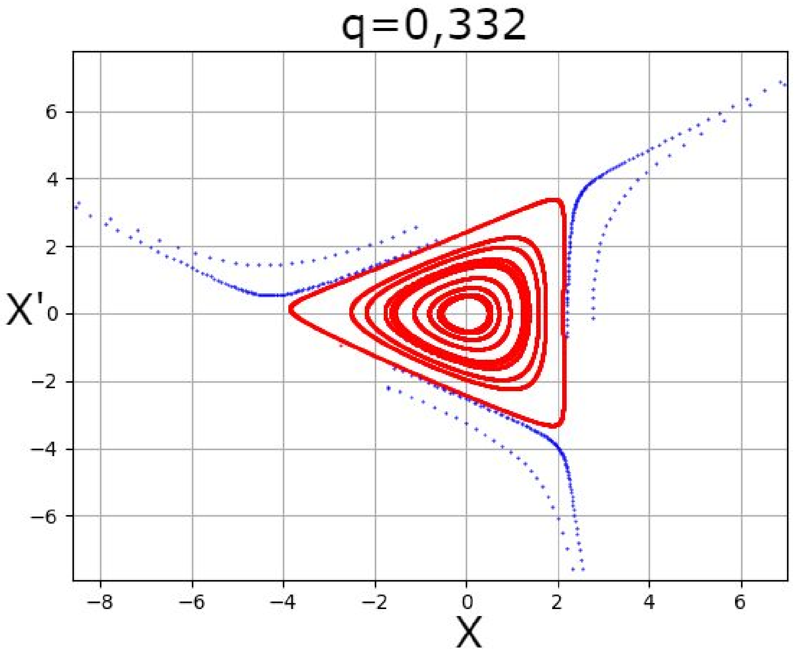
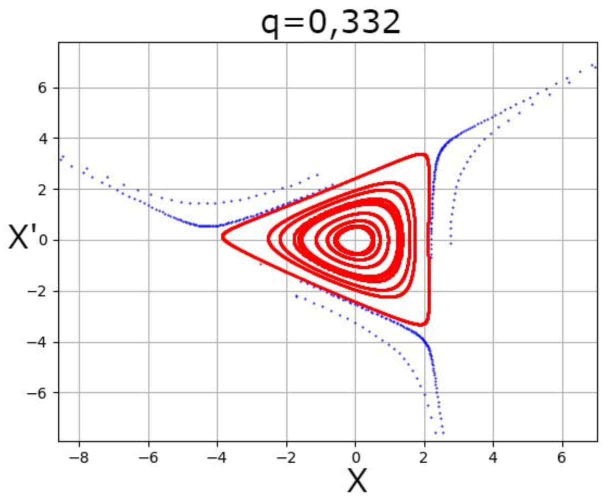


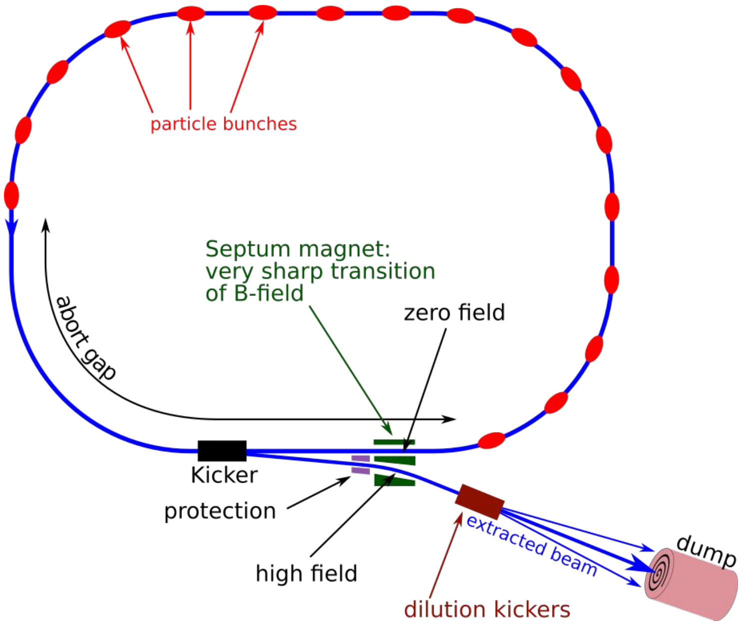
Third-order resonance

- Achieved with sextupole magnets at q=i⅓ (i: any integer)
- Particles close to the origo (small transverse momentum, and close to the ideal orbit) are stable
  - Twiss-ellipse is transformed to a triangle
  - This triangle is the **separatrix**
  - Increasing the sextupole strength **OR** getting closer to exact resonance makes separatrix smaller
- Particles outside the separatrix are unstable
  - Every third turn they get further from the stable part



Extraction from a synchrotron

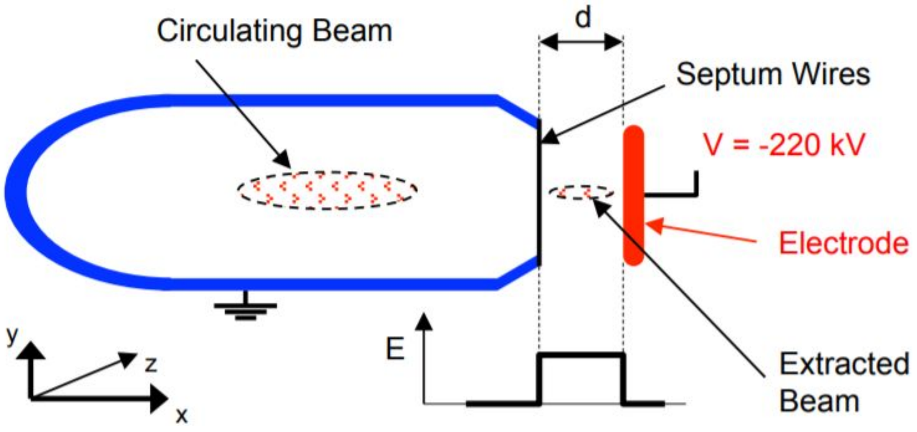
- We usually differentiate 2 main types of extraction
  - Fast extraction
    - Needs an **abort gap** (part of the ring is empty of particles)
    - All the particles leave the accelerator in one turn (in some cases a few turns)
    - Used in SPS → LHC transfer and LHC extraction
  - Slow extraction
    - Does not need abort gap
    - Extract small part of the beam with every turn
    - Takes ~10^6 turn to empty the accelerator
    - Used in SPS → Northern area extraction

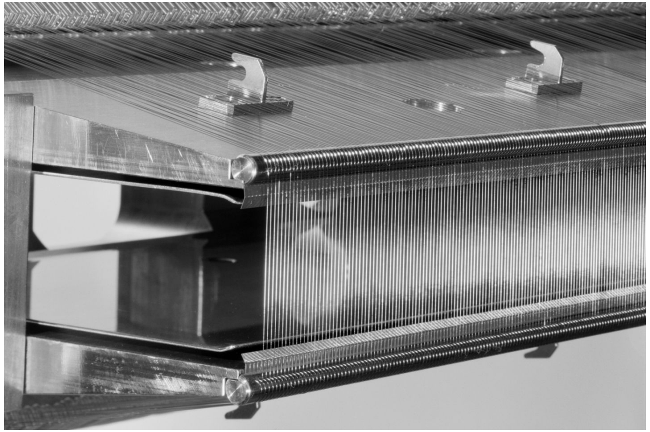


Slow extraction at SPS

- Small portion of the particles leave the ring with each turn

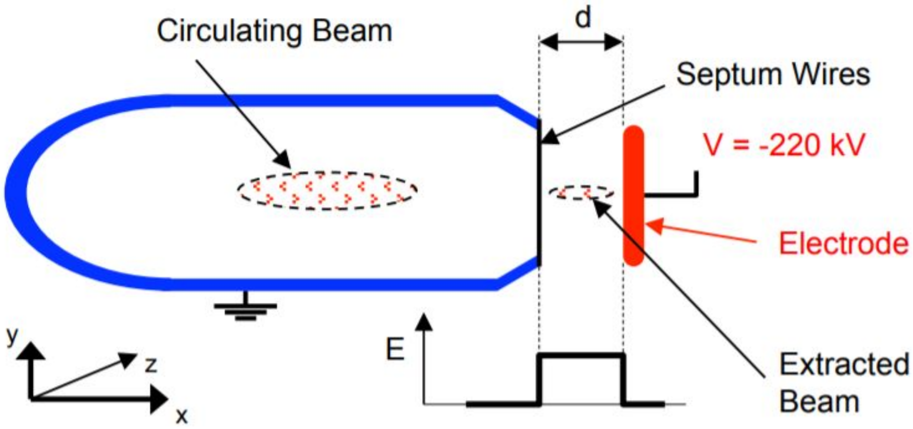
- Electrostatic septum
  - Main goal is to minimize the matter hit by the extracted beam
  - High voltage field sends kicks the particles outside
  - **Septum wires** shield the circulating beam
    - 50 μm

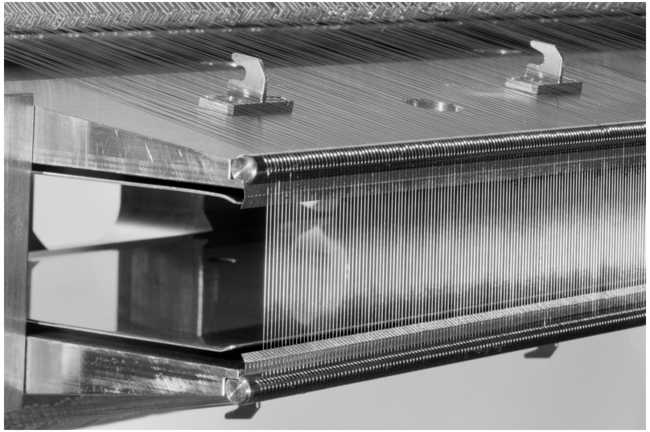




Slow extraction at SPS

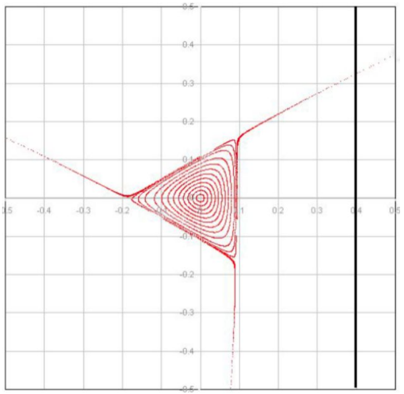
- How to cut 1/10^6th of the beam?
- Can't just steer it through the wires
  - Step size ~ beam size*10^{-6}
  - Wire width ~ beam size*10^{-3} (50µm)
- **Resonant slow extraction** is used

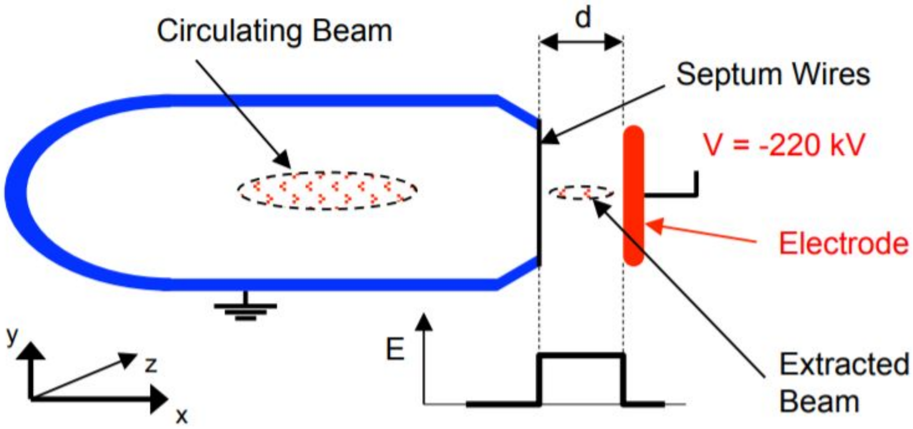


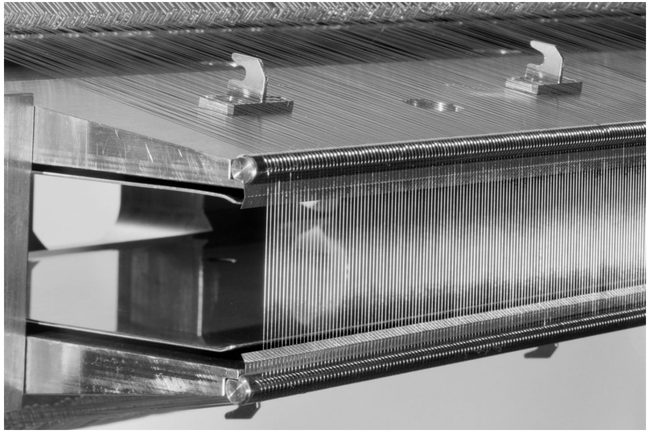


Third-order resonance and the slow extraction

- Using third order resonance a tiny part of the beam can separated far from beam
- Linear density of particles in the "arm" is greatly reduced
- Slow extraction efficiency is ~95% with this method

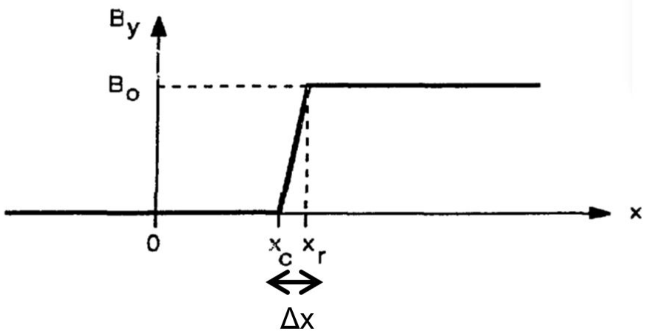






Concept of using massless septa

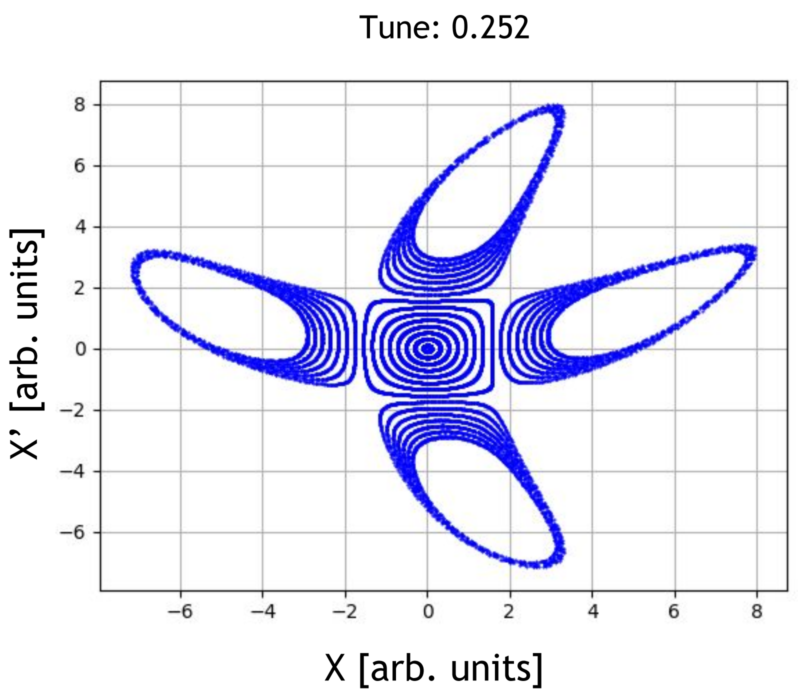
- There are many ways of trying to increase the efficiency of the slow extraction (e.g., crystals, multipoles)
- The goal is always to **decrease** the number of particles hitting the wires, while **increasing**, or not changing the number of extracted particles
- 3 possibilities using massless septa presented in the SLAWG meeting [5]
- My summer student project was to study the third possibility
  - Possible gain, feasibility (e.g., realistic magnet strength)



Field of a massless septum

Summer student project

- To validate the code first I looked at some well known resonances



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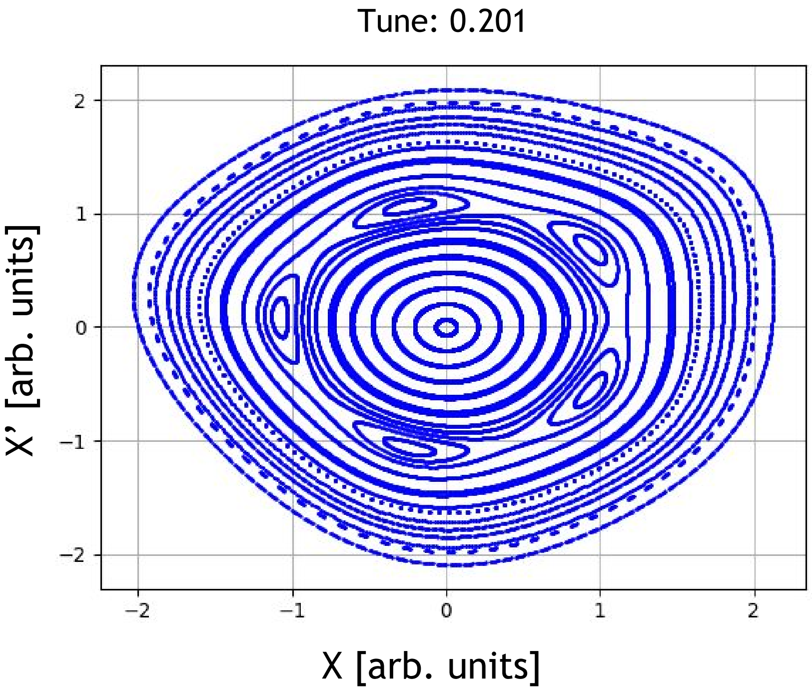

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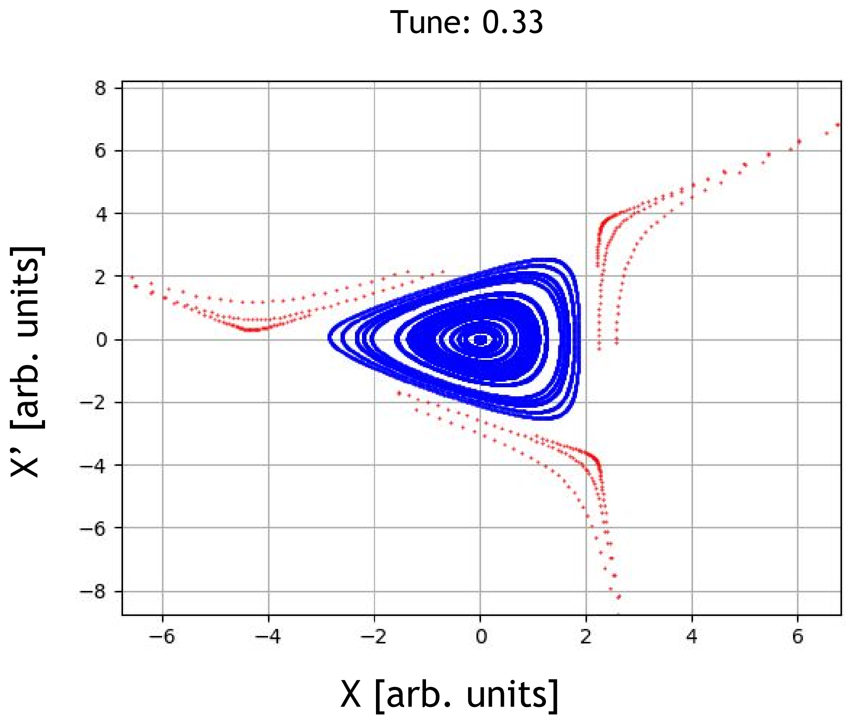
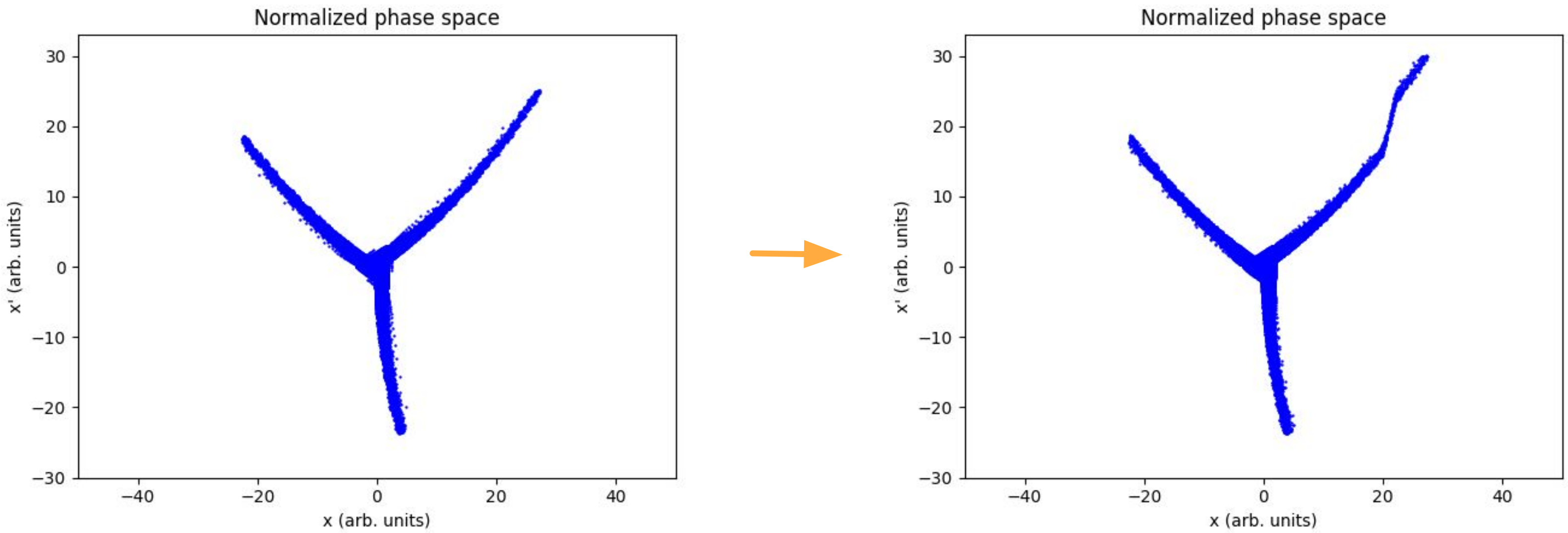


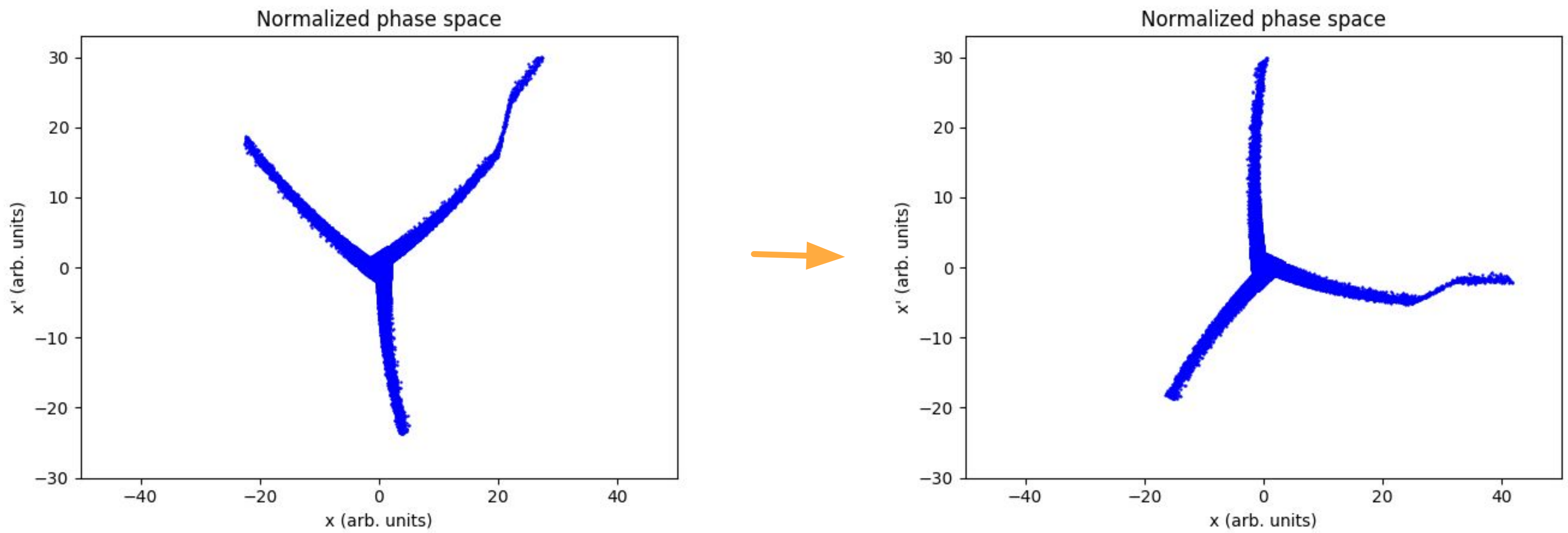
1, 2: Beam stretching with massless septa

- The idea is, that if we use massless septum with a linear fringe field, then the kick would cause this:



1, 2: Beam stretching with massless septa

- The idea is, that if we use massless septum with a linear fringe field, then the kick would cause this:
- After some drift (rotation in normalized phase space) the momentum difference becomes spatial separation:

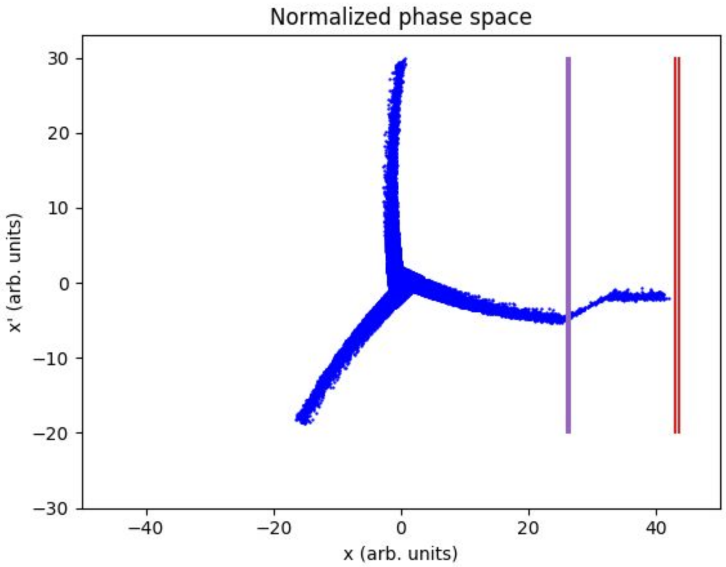


1: Beam stretching with one massless septum

- If the setup is aligned so that the ZS wires position is inside the “low density” area than we could decrease the number of lost particles
- If the cut is at the closer end of the stretched part then we decrease the density of the extracted particles also

- In this case the limiting factor is the massless septum fringe field length
- It is challenging to reduce
- But in the ideal case it would increase the efficiency to 100%

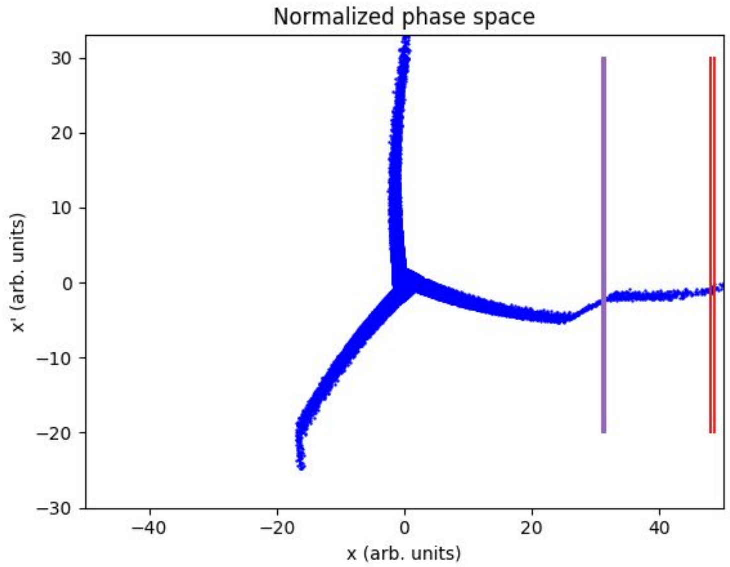
[2]



1: Beam stretching with one massless septum

- But if the wires are further out than the still circulating “stretched” particles are stretched once more
- A lot of these particles are lost on the cathode 3 turns later
- In the end the efficiency goes down by this effect

- Something has to be done with the circulating, but effected particles



2: Beam stretching with one massless septum, then "push-back"

- One could think of having another massless septum after the extraction with opposite field, that pushes the stretched density back to normal
- This is the solution studied at the POP FFAG

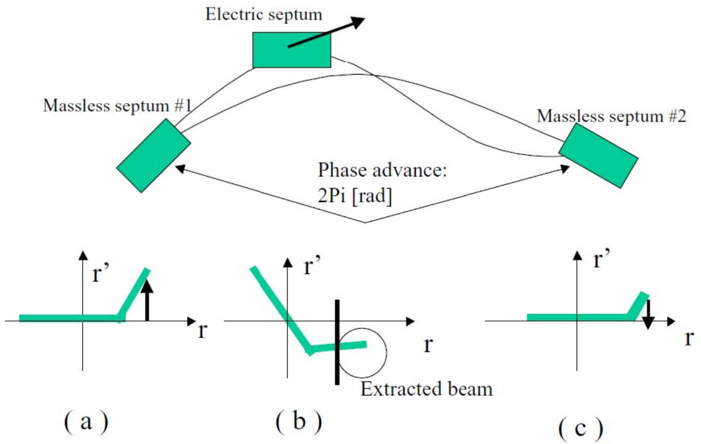


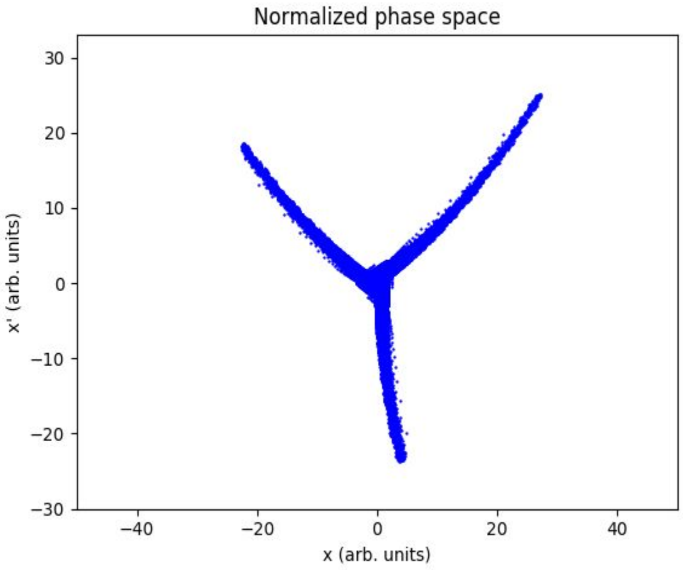
Figure 1: Extraction scheme with massless septum magnet (a) beam tail is developed (b) beam is extracted with an electric septum (c) beam tail returned to the closed orbit

[4]

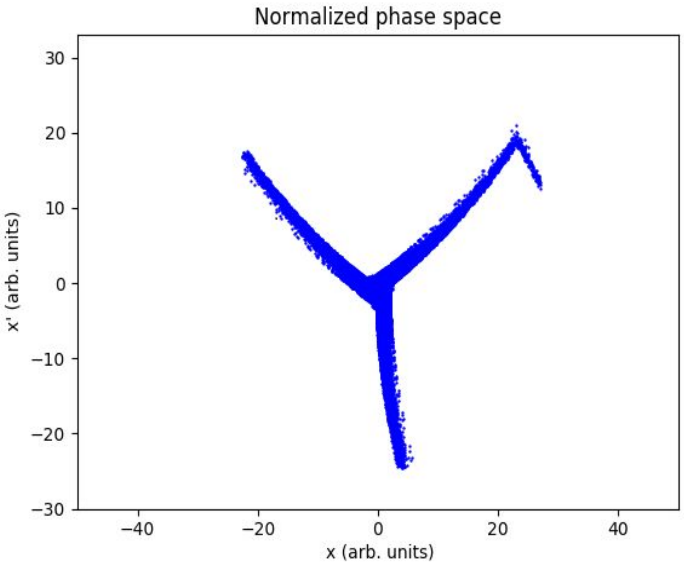
3: Phase space folding

- My work was mostly concentrated on studying whether or not it is possible to use the fringe field of a massless septum to “fold back” one of the arms of the third order resonance

Without massless septum



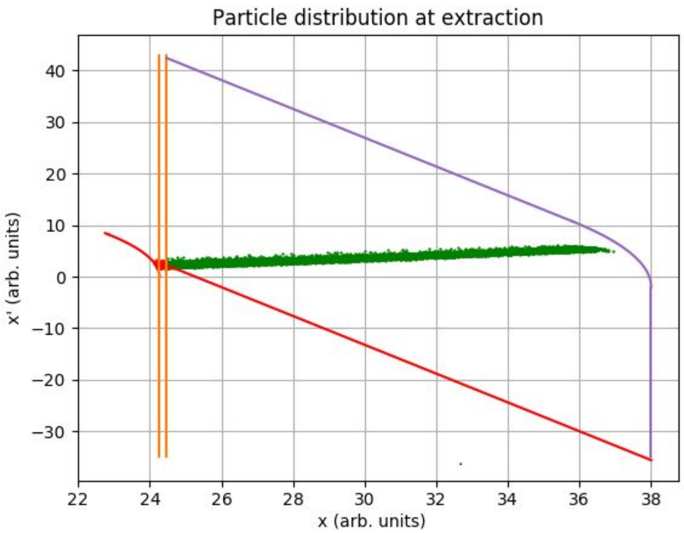
With massless septum



3: Phase space folding

- My work was mostly concentrated on studying whether or not it is possible to use the fringe field of a massless septum to “fold back” one of the arms of the third order resonance
- This way the sextupole strength (and the spiral step) can be increased without the need of larger extraction space

Without massless septum



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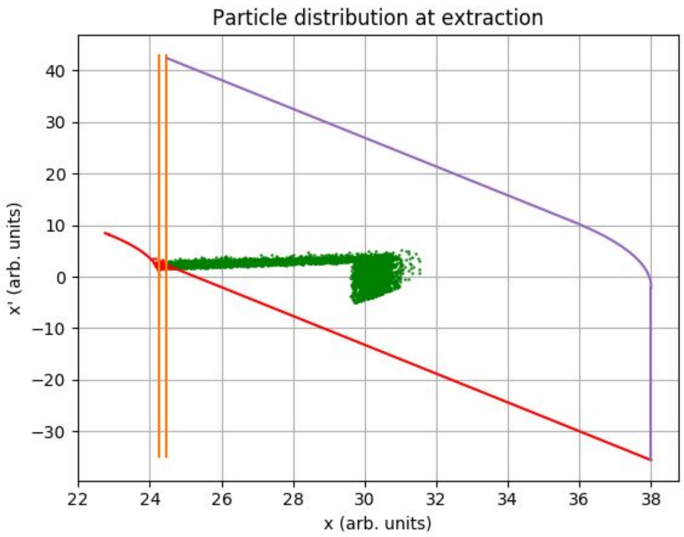
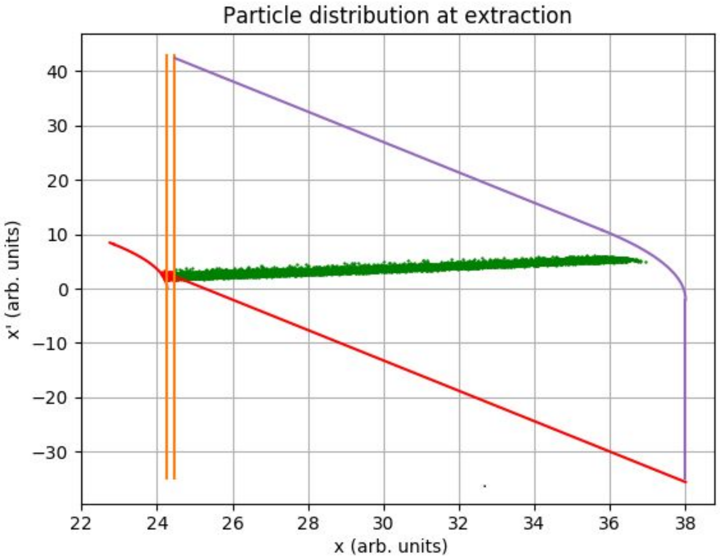
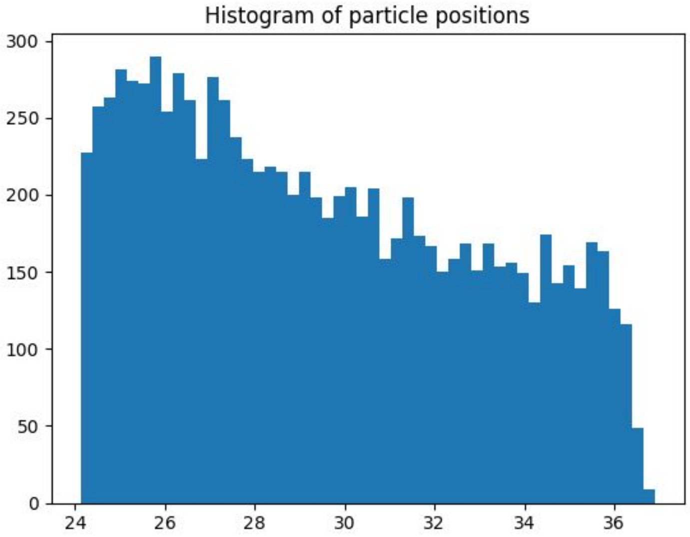


Examples

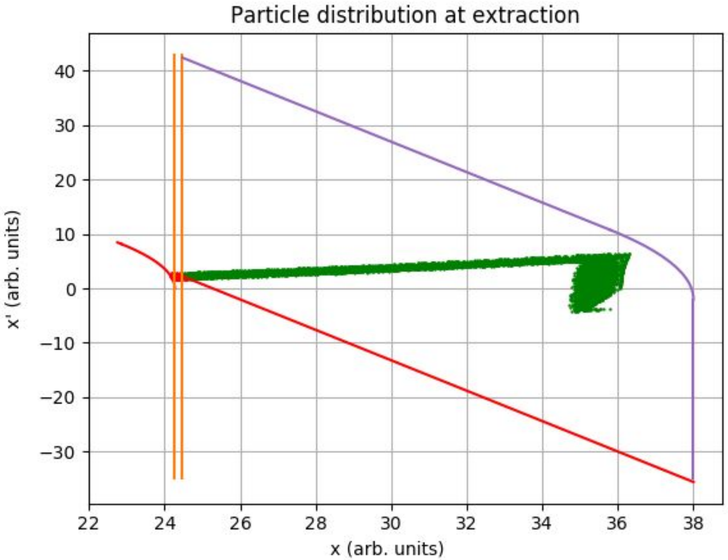
- Sextupole strength: 0.02
  - Particles hitting the wires: 349
  - Extracted particles: 9262

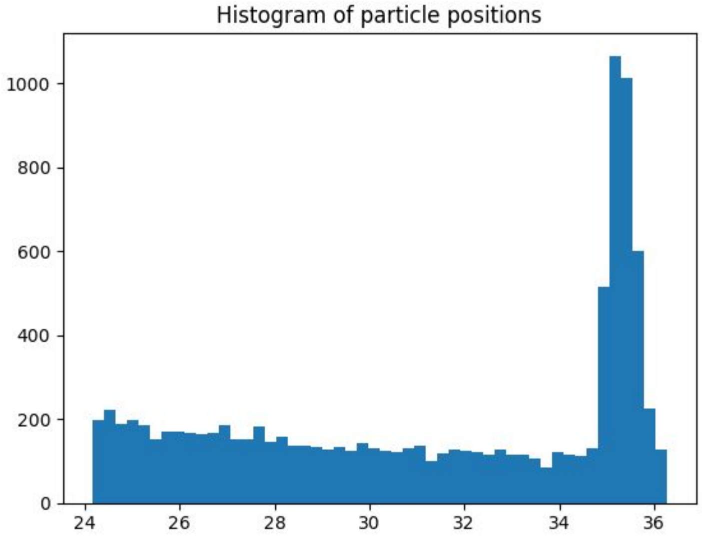




Examples

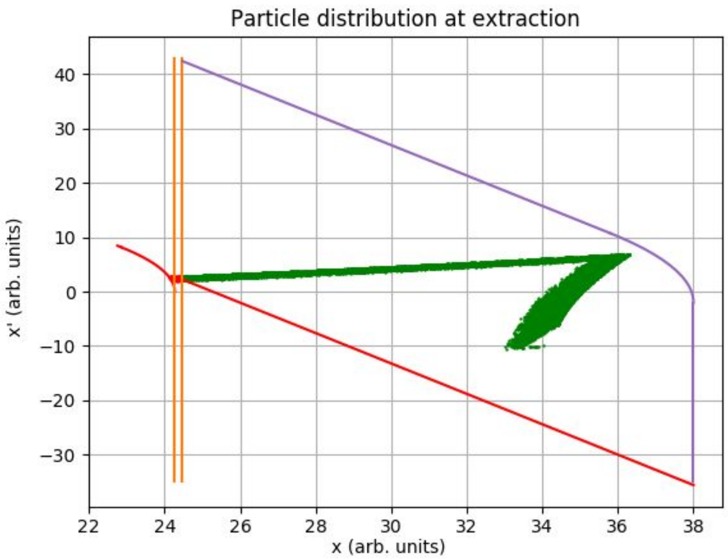
- Sextupole strength: 0.03
  - Particles hitting the wires: 305
  - Extracted particles: 9512

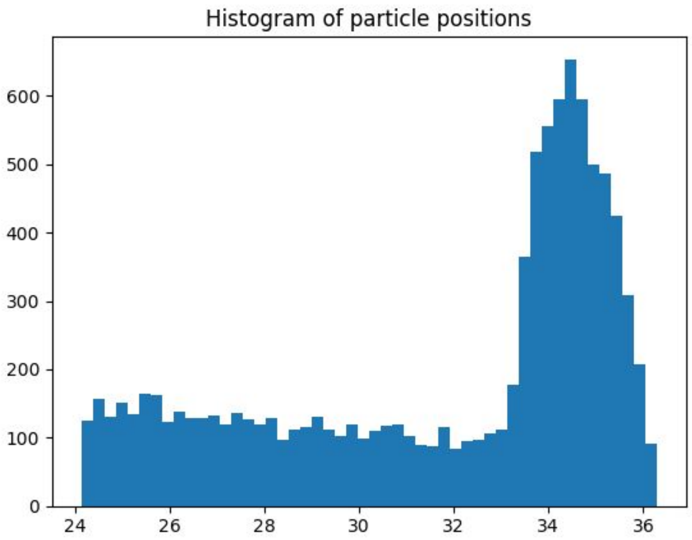




Examples

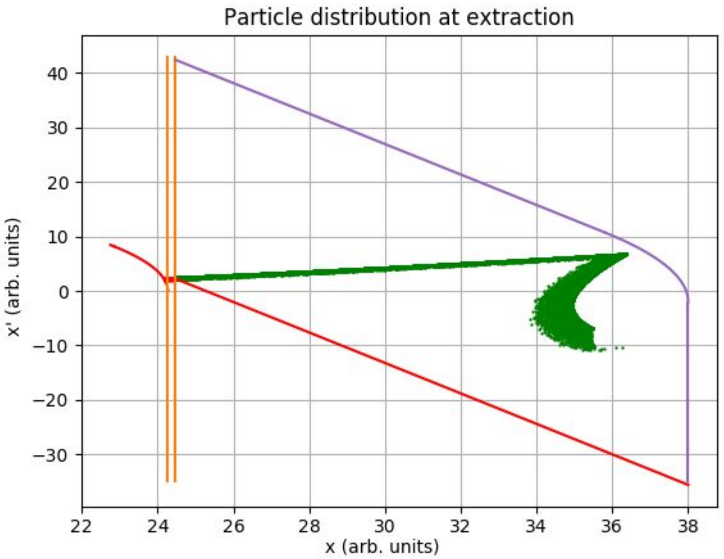
- Sextupole strength: 0.04
  - Particles hitting the wires: 183
  - Extracted particles: 9719

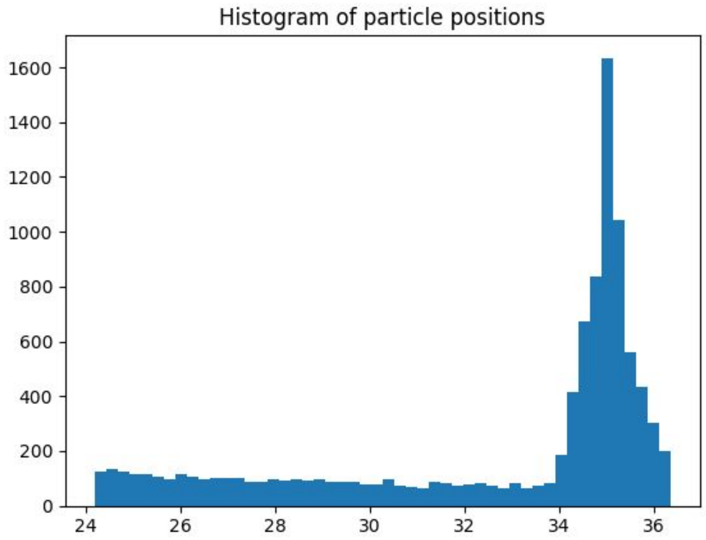




Examples

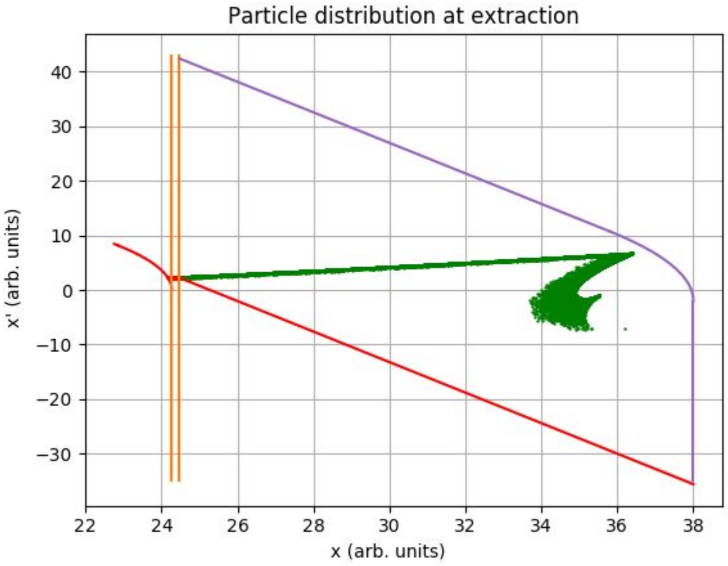
- Sextupole strength: 0.06
  - Particles hitting the wires: 156
  - Extracted particles: 9801

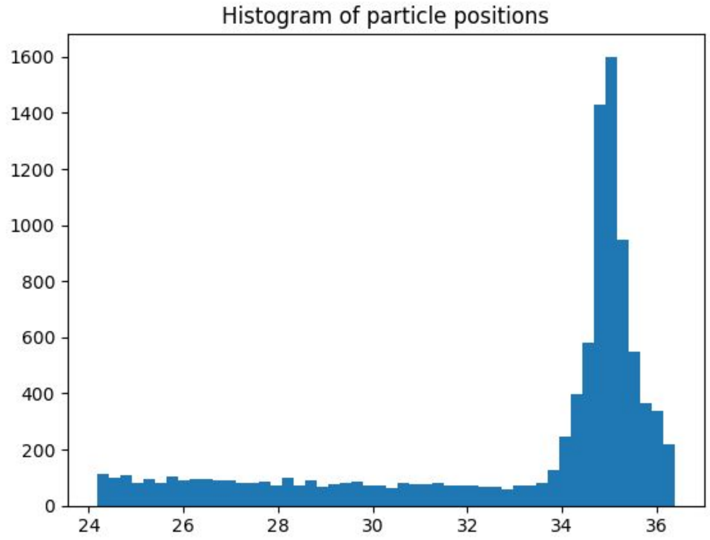




Examples

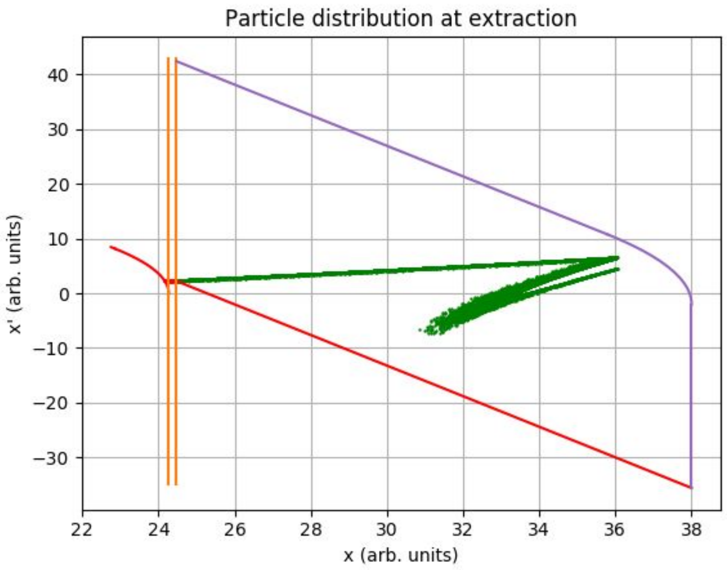
- Sextupole strength: 0.08
  - Particles hitting the wires: 141
  - Extracted particles: 9837

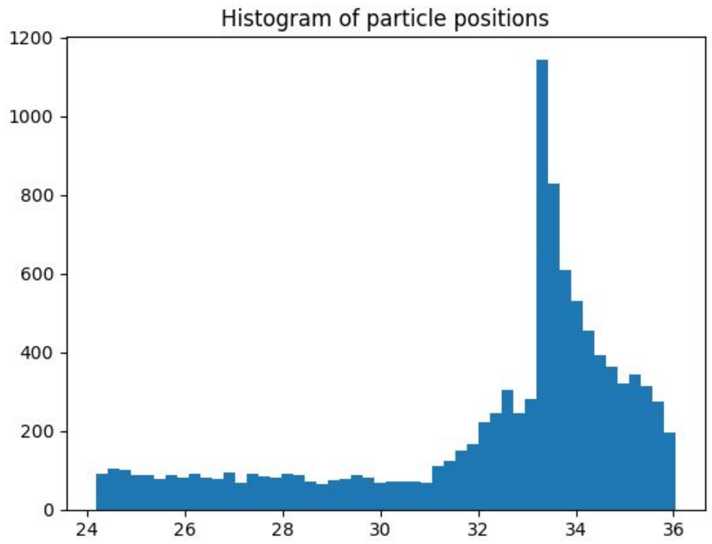




Examples

- Sextupole strength: 0.09
  - Particles hitting the wires: 105
  - Extracted particles: 9868

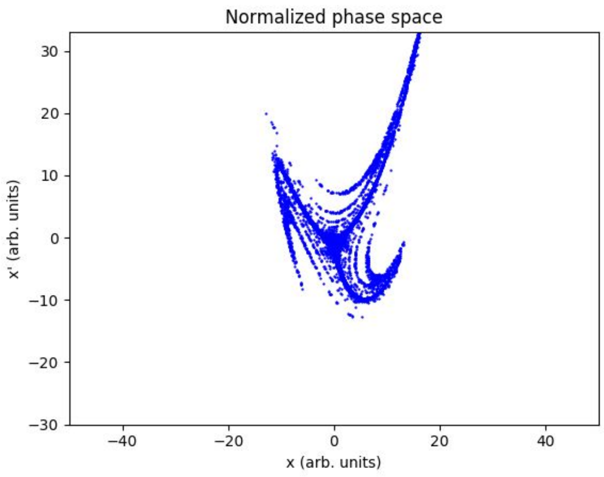




Limitation

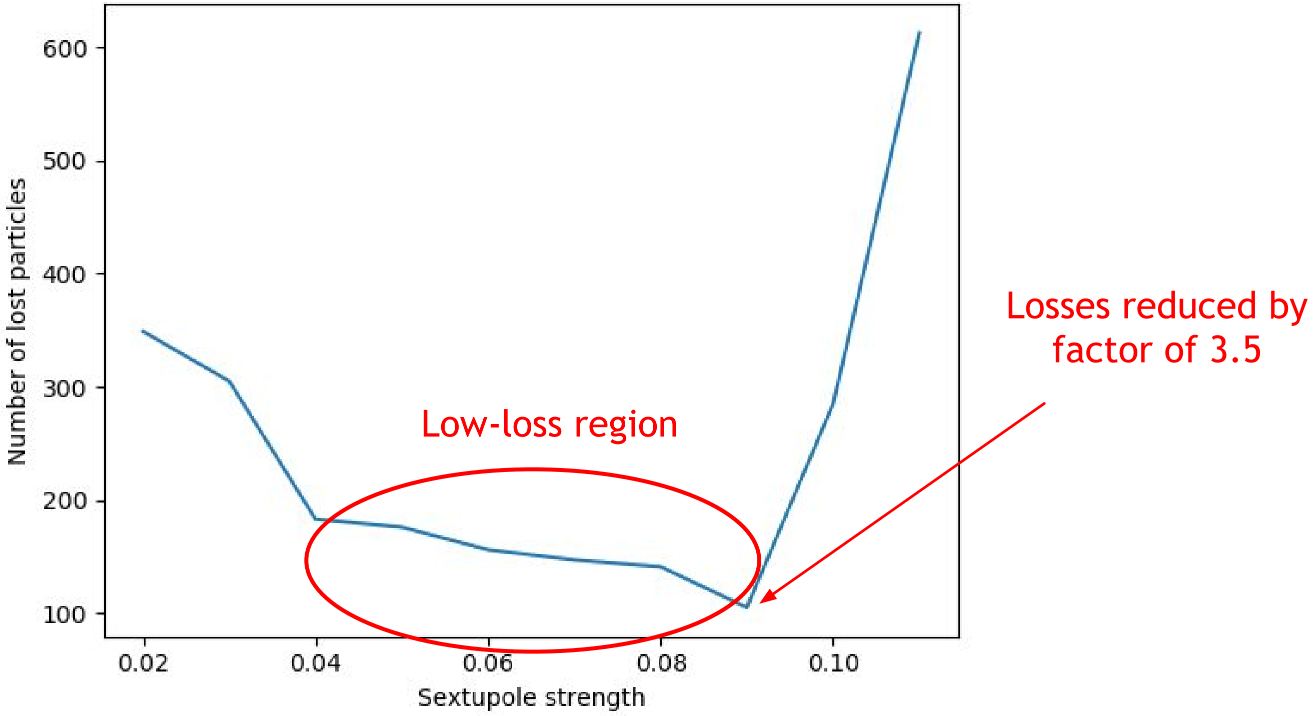
- The sextupole strength has an upper limit
  - If the field is too strong, than the arms got nonlinear
  - For a kick more than 0.09 (in my normalized phase space units) the arms “bend back”
  - This increases the thickness of the arm, and in the end the losses on the wires also

Sextupole strength: 0.12

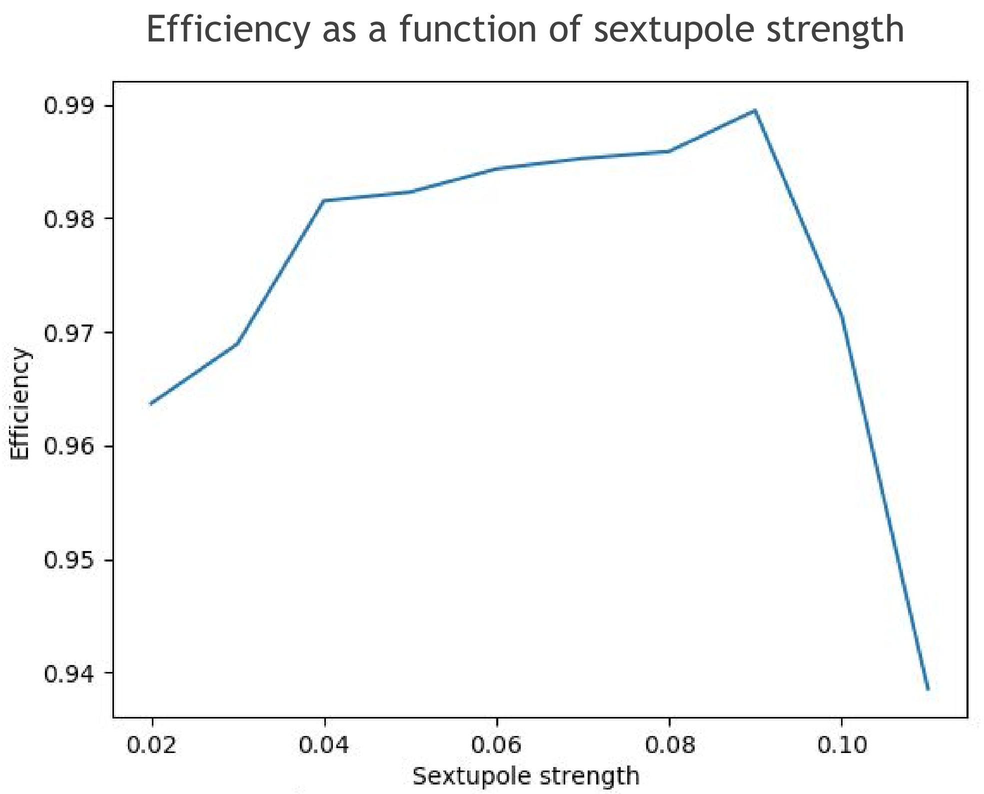


Results

Number of lost particles as a function of sextupole strength



Results


Efficiency as a function of sextupole strength
0.99
0.98
0.97
0.96
0.95
0.94
Efficiency
0.02
0.04
0.06
0.08
0.10
Sextupole strength

Feasibility

- The sextupole strength used in the simulation is
  - 0.02 without massless septum
  - 0.09 at the optimal case
- The extraction is almost identical to the extraction got from MAD-X if the strength is 0.01939
- So in the “ideal” case the sextupole strength is increased by a factor of **4.5** but as seen on the last plot even a factor of **2** would increase the efficiency significantly
  - Comment: In the SPS there are 4 sextupole magnets, and I used only one (thin lens)
- There are many open questions whether or not the beam-pipe could

Feasibility

- Massless septum strength can be calculated by the normalized kick
- Assuming the same horizontal ß at extraction and at the massless septum (for SPS ~ 100 m at the sextupole magnets and ZS)
- Required maximum kick from the massless-septum is **500 μrad**
- This means that the massless septum's maximum integrated field is **0.66 Tm**
- The smallest fringe field used in the simulations was **~10 mm**
- Notice that since we only used the fringe field, the real important parameter is the field gradient, so if the magnet is twice as strong, the fringe field can be twice as long

Conclusion

- From the results of my summer project it seems possible to increase the efficiency of the slow extraction using the fringe field of a massless septum
- This way the fringe field length don’t have to be shortened (feasible)
  - There is a compromise between fringe field length and magnet strength
- With small tuning of the gradient of the fringe field the extraction distribution can be tailored

Outlook

- Still a lot of open questions…
- Implement a more realistic massless septum fringe field (nonlinear) and see how it affects the folding
- The sextupole magnet should be divided to more than one separated devices (in the SPS there are 4), but so far the plan is to stay with only one massless septum
- Study different phase advances between sextupole magnets and massless septum
- Check for realistic SPS beam parameters (beta, alpha, …), location
- Acceptance of transfer line, and the growth of circulating beam
- Effect of different density distribution and momentum spread

Thank you for your attention!

References:

1) Matthew Fraser, CAS Budapest 2016

2) Christoph Wiesner, R&D Meeting, 08/11/2016

3) H. S. Butler/H. A. Thiessen, Proc. of the Advanced Hadron Facility Accelerator Design Workshop, 1988

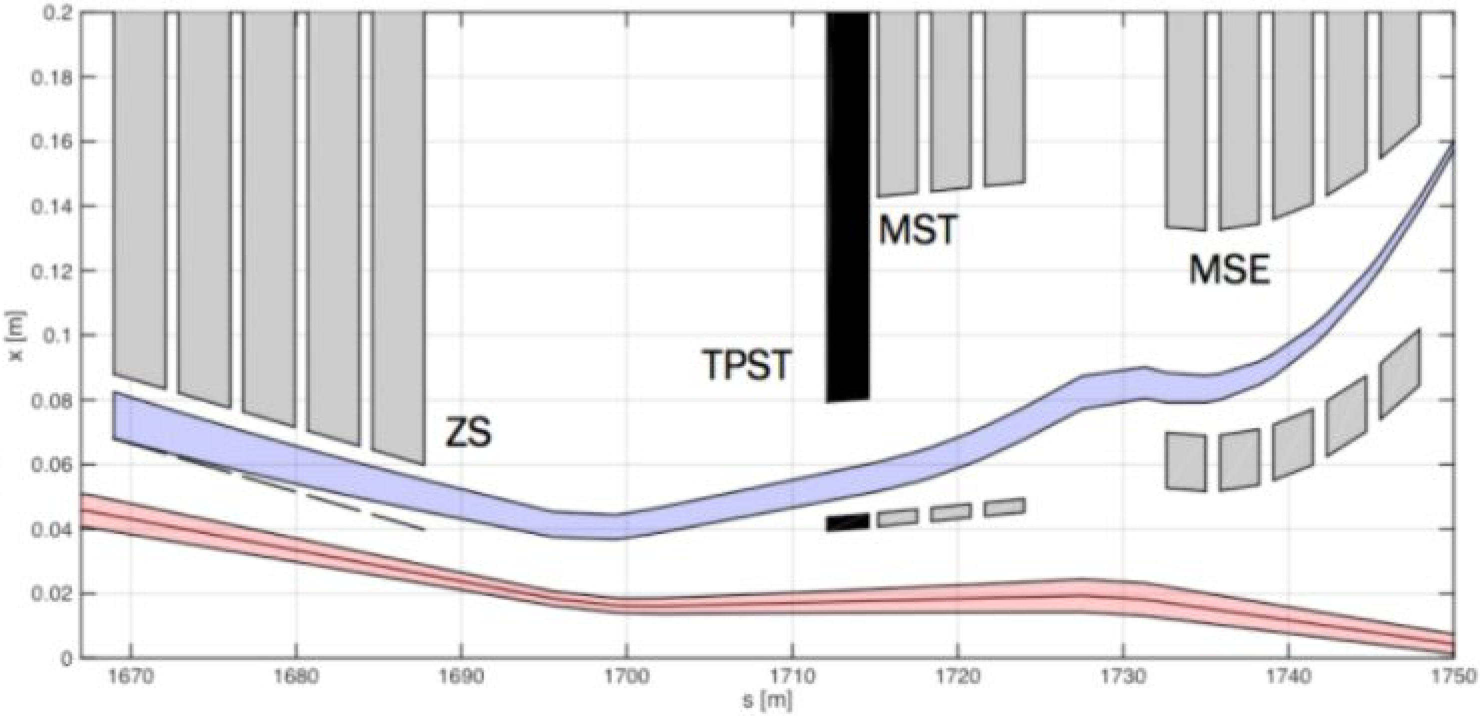
4) Y. Yonemura et al., Beam Extraction of the POP FFAG with a massless septum, IPAC'03

5) Christoph Wiesner, SLAWG meeting 01/09/2016

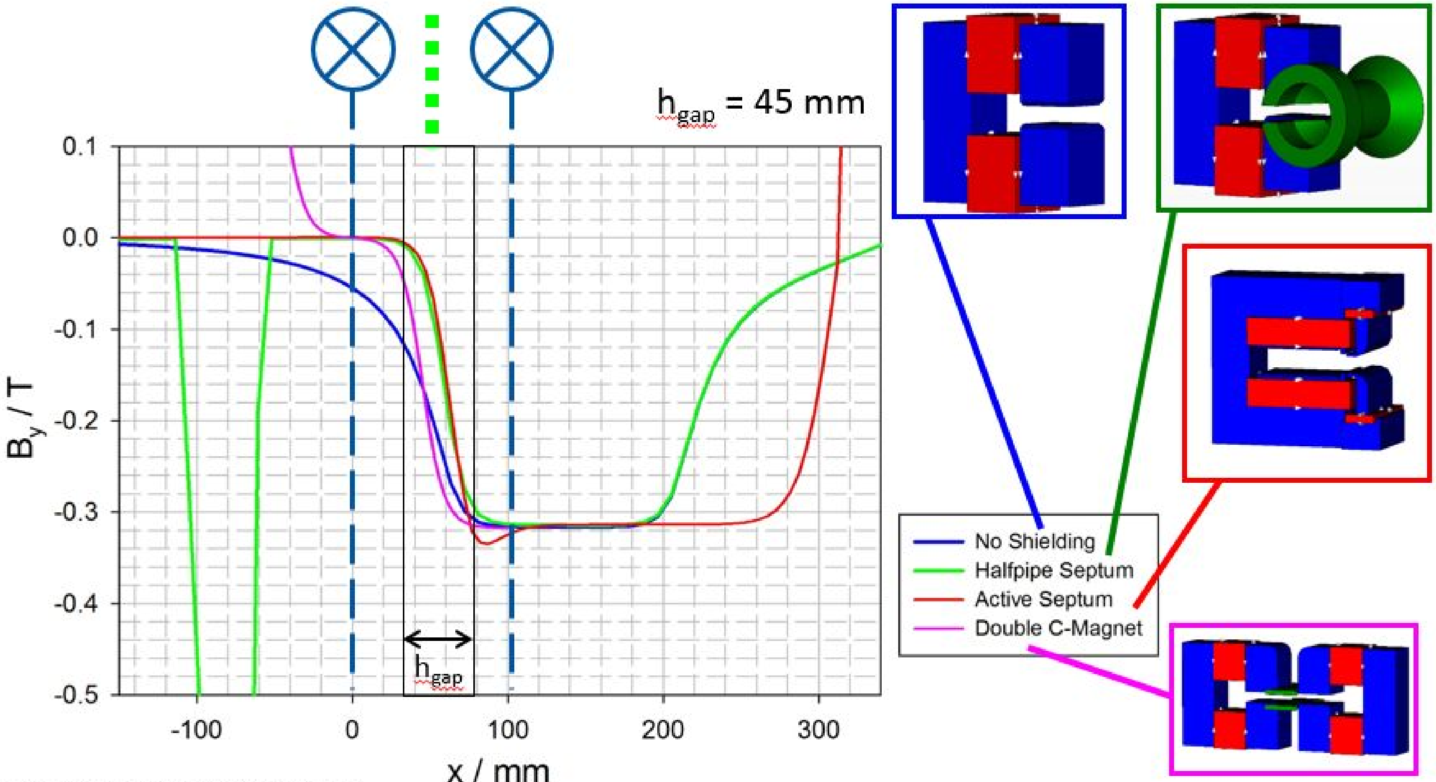
6) Matthew Fraser, SPS slow-extraction: Challenges and possibilities for improvement

Additional slides

Full slow extraction setup



Example massless septum designs



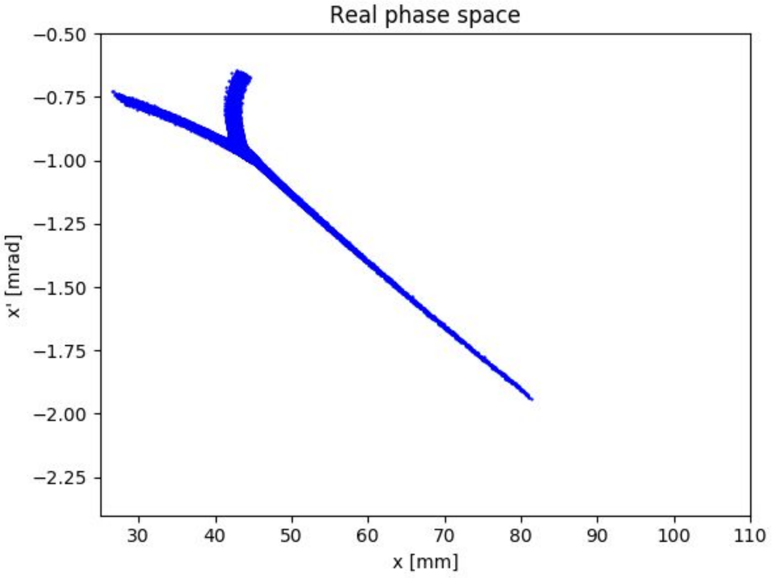
C. Wiesner, R&D Meeting, 08/11/2016

Simulation parameters

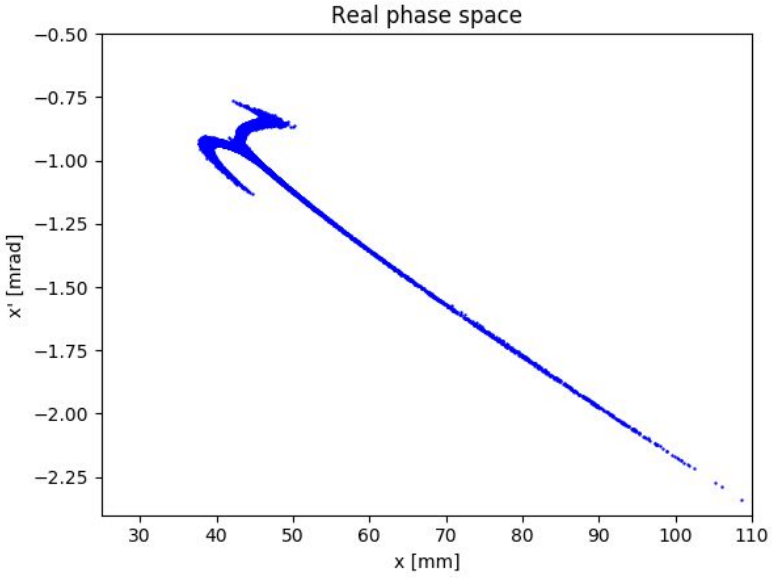
- Fixed parameters that are true for all simulations:
  - 2D Gaussian particle distribution in the beginning (in both x and x') with variance 0.4
  - The tune is changed from 0.33 to 0.334 in 10000 steps
  - 10000 particles simulated
  - The extraction geometry is the realistic ZS geometry with effective wire thickness of 200 μm
- The tuneable parameters:
  - Sextupole strength [0.02,0.11]
  - Massless septum position (x), strength, fringe field length
  - Phase difference between massless septum and the extraction
- For each sextupole strength the massless septum parameters were optimized, to increase the efficiency as much as possible
  - There is still some freedom, so it's possible to influence the outgoing particle distribution

Real space particle distribution at extraction

Strength=0.02

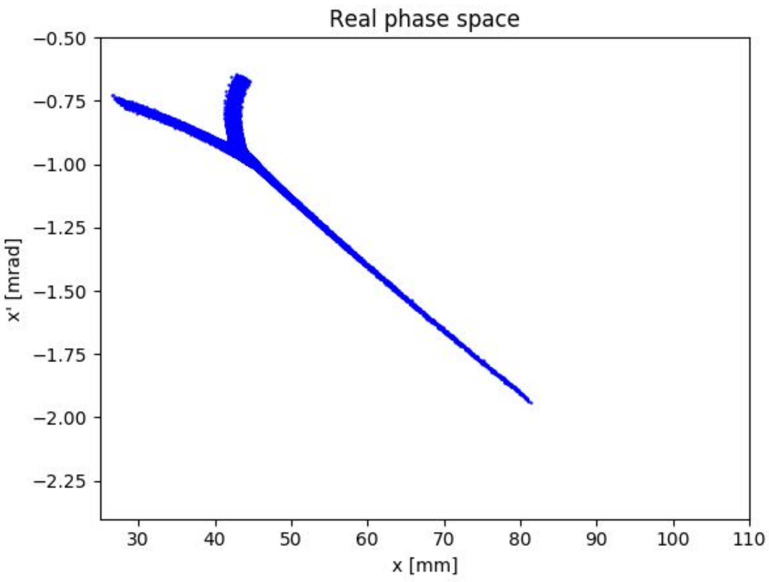


Strength=0.09



Real space particle distribution at extraction

Strength=0.02



Strength=0.09