
CERN

The Potential of Resonance Islands combined with Bent Crystals for Slow Extraction in Circular Hadron Accelerators

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Acknowledgements: Frederik van der Veken, Pablo Arrutia Sota, Matthew Fraser, Pascal Hermes, Rebecca Taylor, Francesco Maria Velotti

Introduction

Principle of the novel concept

Performance in simulations

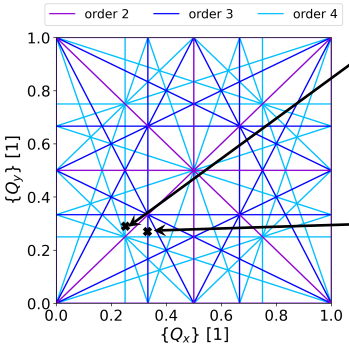
Summary and Outlook

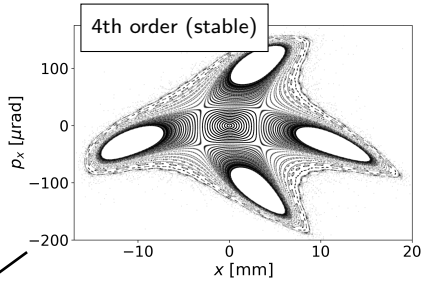
Resonances and stable islands

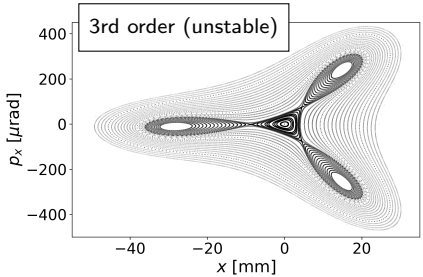
- Nonlinear elements create detuning with amplitude and excite resonances
- Stable islands can form near resonances with different topologies

$$n_x Q_x + n_y Q_y = p$$

$$\text{order} = |n_x| + |n_y|$$

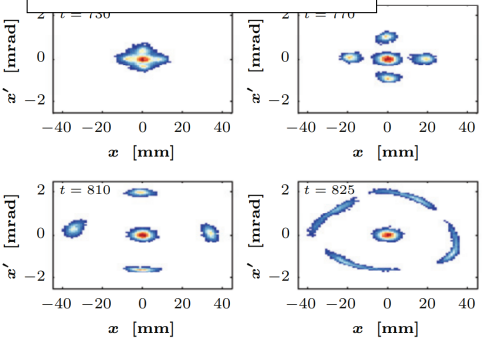




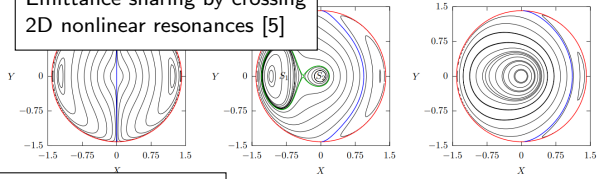


Exploiting nonlinearities

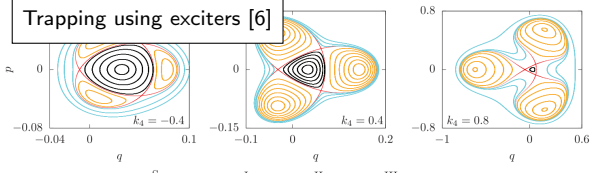
Multi-Turn Extraction by means of adiabatic crossing of nonlinear resonances [1, 2, 3, 4]



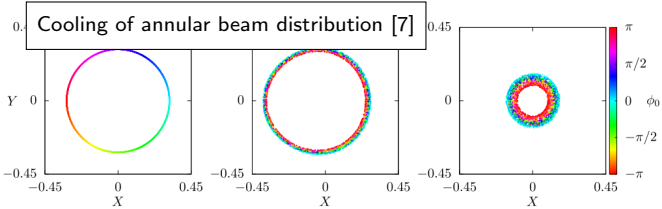
Emittance sharing by crossing 2D nonlinear resonances [5]



Trapping using exciters [6]



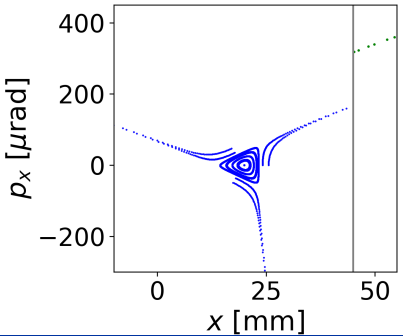
Cooling of annular beam distribution [7]

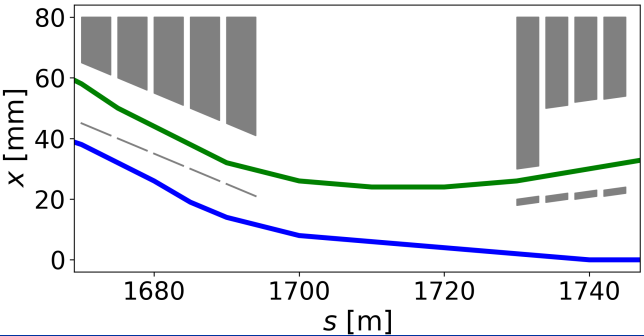


Standard slow extraction

- Using 3rd order unstable resonance driven by strong sextupoles
- Particles are transported to large amplitudes along unbounded separatrices
- Stochastic particle motion
- Thin blade of electrostatic septum cuts directly into the densely populated separatrix arm

[8, 9, 10, 11, 12, 13, 14, 15, 16]





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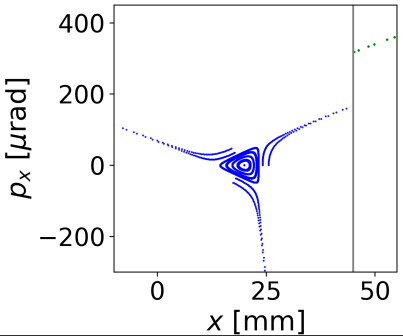
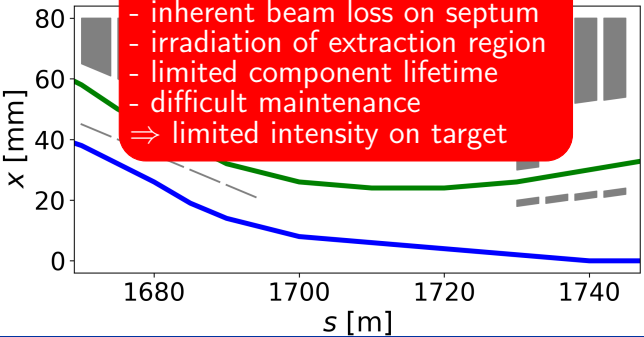


Issues and limitations: [17, 18]
- inherent beam loss on septum
- irradiation of extraction region
- limited component lifetime
- difficult maintenance

⇒ limited intensity on target

15, 16]



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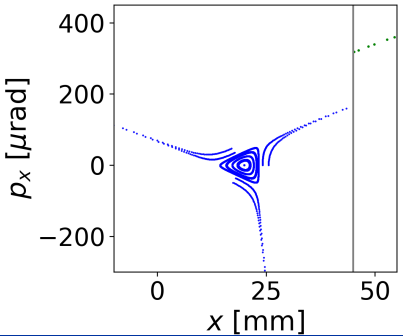

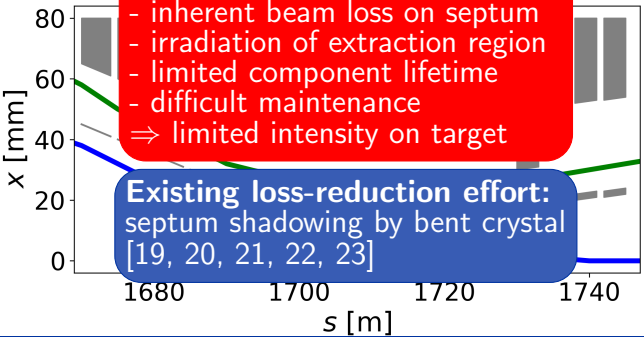

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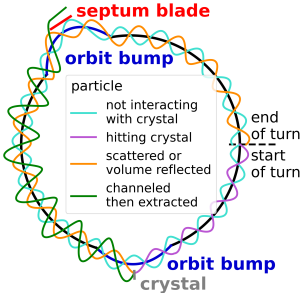
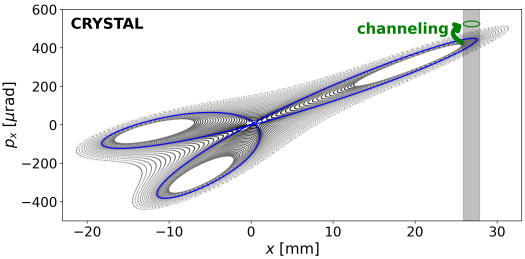
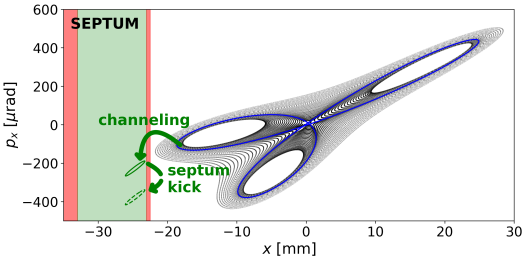
Existing loss-reduction effort:
septum shadowing by bent crystal [19, 20, 21, 22, 23]

Overview of novel concept

- Particle transport to crystal using stable islands
  - ⇒ possibility of multiple passes through crystal
- Planar channeling by bent crystal to separate circulating beam and particles to be extracted
  - ⇒ reduced losses on extraction septum

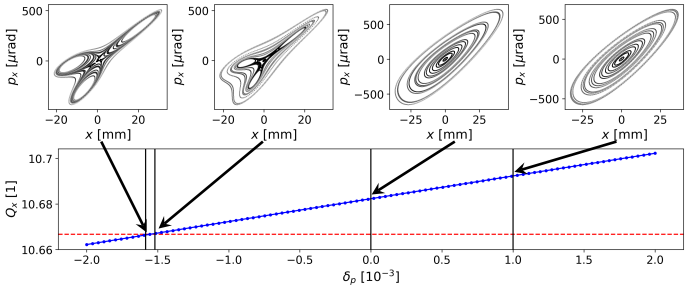


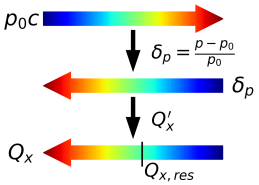


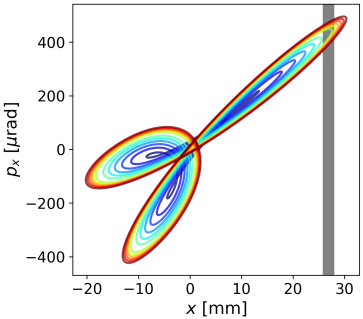


Transport in stable islands

- Ramping the magnetic field of the machine pushes particles through the resonance steadily depending on their momentum
- Large chromaticity, amplitude detuning, and an initial kick ensures efficient depletion of the core

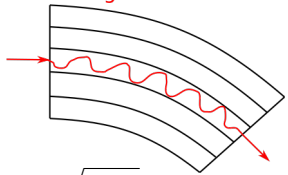






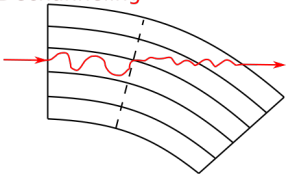
Charged-particle interactions with bent crystals

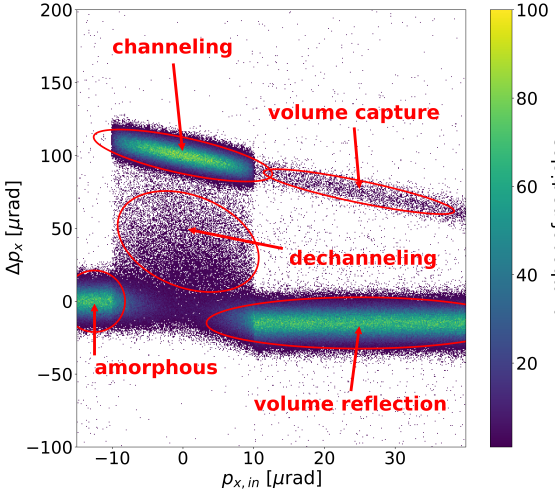
Channeling



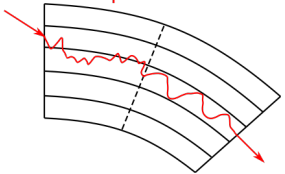
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}\left(1 - \frac{R_c}{R}\right)$$

Dechanneling

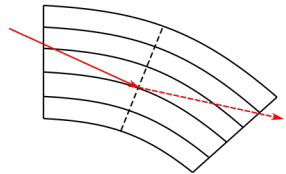




Volume capture



Volume reflection



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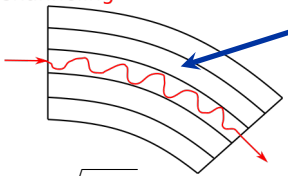
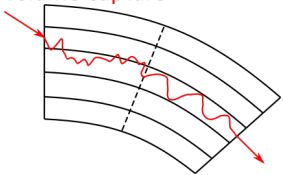


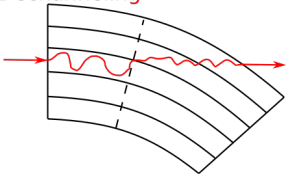
needed for large separation between circulating and extracted particles

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}\left(1 - \frac{R_c}{R}\right)$$

Volume capture



Dechanneling



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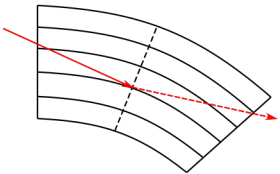

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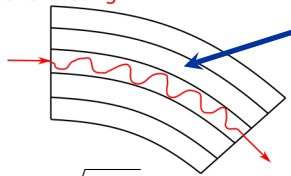

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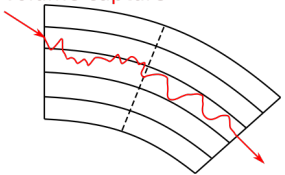
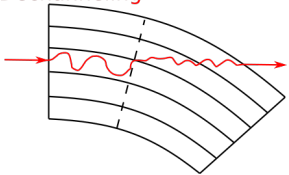


not harmful due to the stability of phase space

Dechanneling



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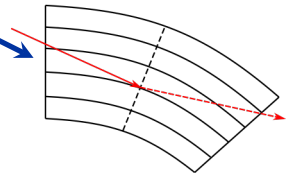

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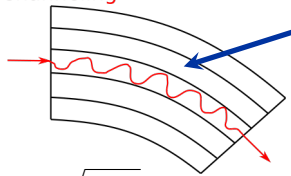

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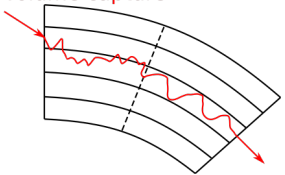

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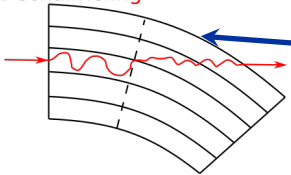
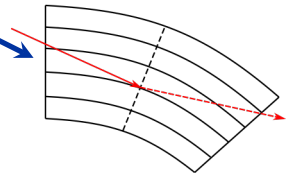


primary source of remaining losses on septum

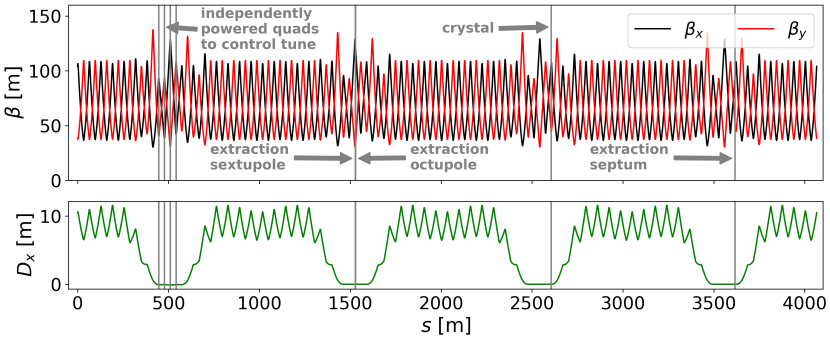
Volume reflection



Simulation model

- Lattice inspired by the CERN SPS
- Key elements in zero-dispersion regions
- 400 GeV protons extracted over ∼3.5 s

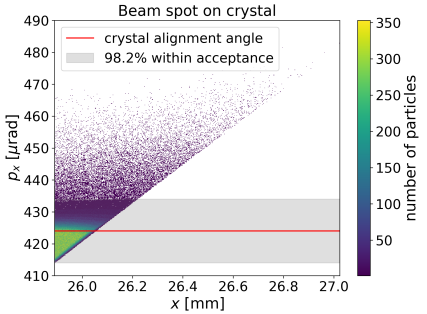
- 2.8 mm long Si crystal bending 100 µrad
- 500 µm septum blade (pessimistic estimate in SPS [22, 24])

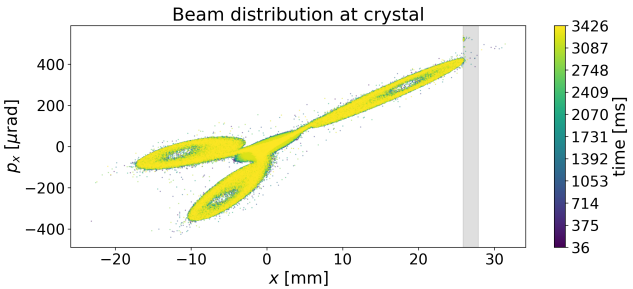


Simulation tools:
xtrack [25, 26]
xcoll [27]

Performance of the novel method

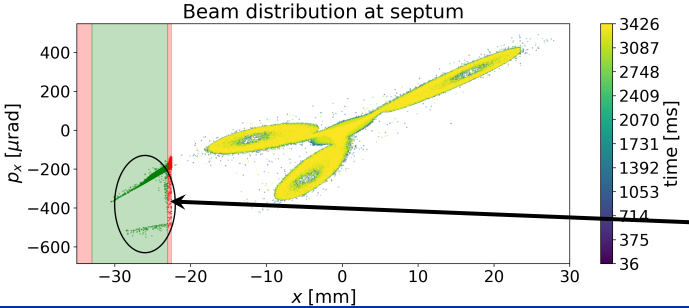
- The beam spot on the crystal can be controlled using the stable islands
  $\Rightarrow$ Most particles hit the crystal within the channeling acceptance
- Particles outside of the channeling acceptance can be kicked back into the stable islands by volume reflection

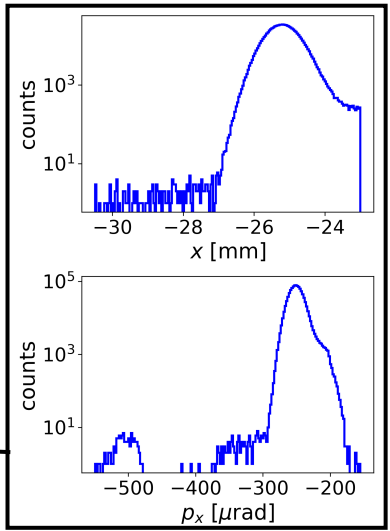




Performance of the novel method

Particle state at end of tracking	%
Circulating	0.2
Extracted	98.5
Lost on septum	0.4
Lost in crystal	0.5
Lost on global aperture (5 cm)	0.4



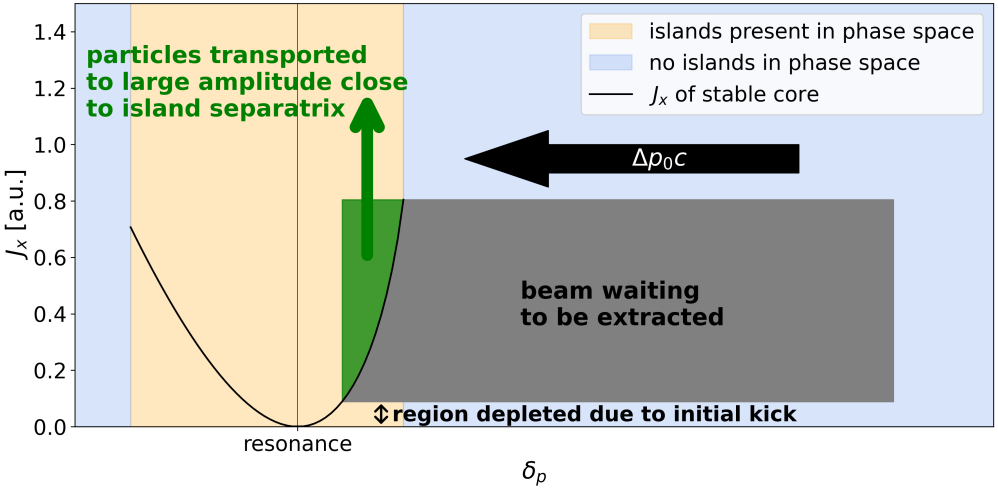


Summary and Outlook

- A novel method of slow extraction from hadron accelerators was developed and simulated using stable islands and planar channeling by a bent crystal
- The use of stable islands to transport particles to the crystal allows for
  - good control over the type of interactions with the crystal
  - the possibility of multiple passes through the crystal $\Rightarrow$ higher efficiency
- Simulations show that an extraction efficiency and loss reduction above that currently operational in the SPS [28, 22] is possible
- Proof-of-principle tests are ongoing at the SPS

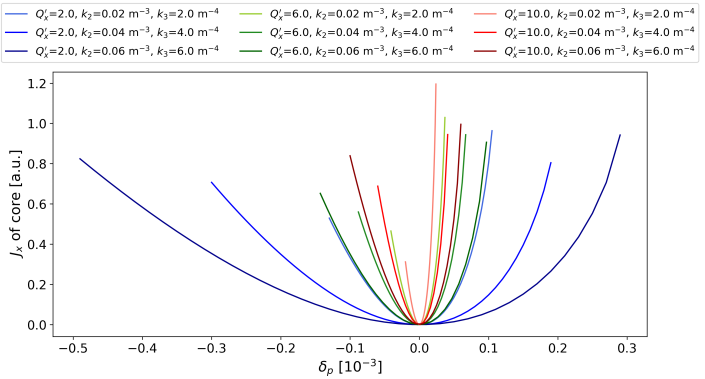
Thank you!

Momentum selection



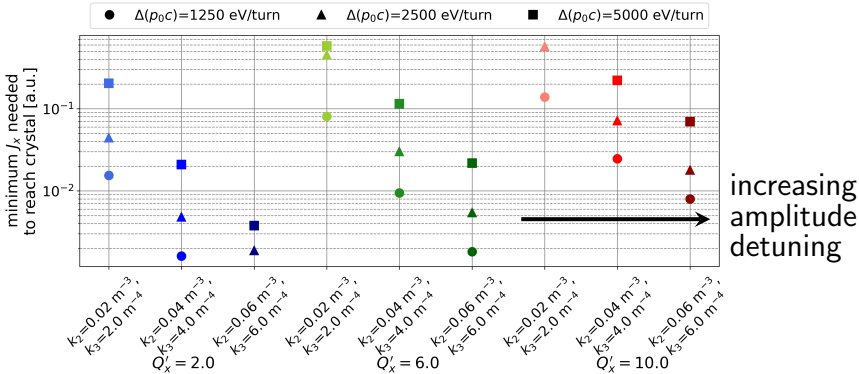
Influence of chromaticity, amplitude detuning and ramp rate

- Large chromaticity ensures that the range of δ_p seeing the resonance at any given time remains small and the beam is extracted steadily



Influence of chromaticity, amplitude detuning and ramp rate

- Large amplitude detuning and an appropriate initial kick can compensate for the large chromaticity and the ramp rate to ensure all particles reach the crystal



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