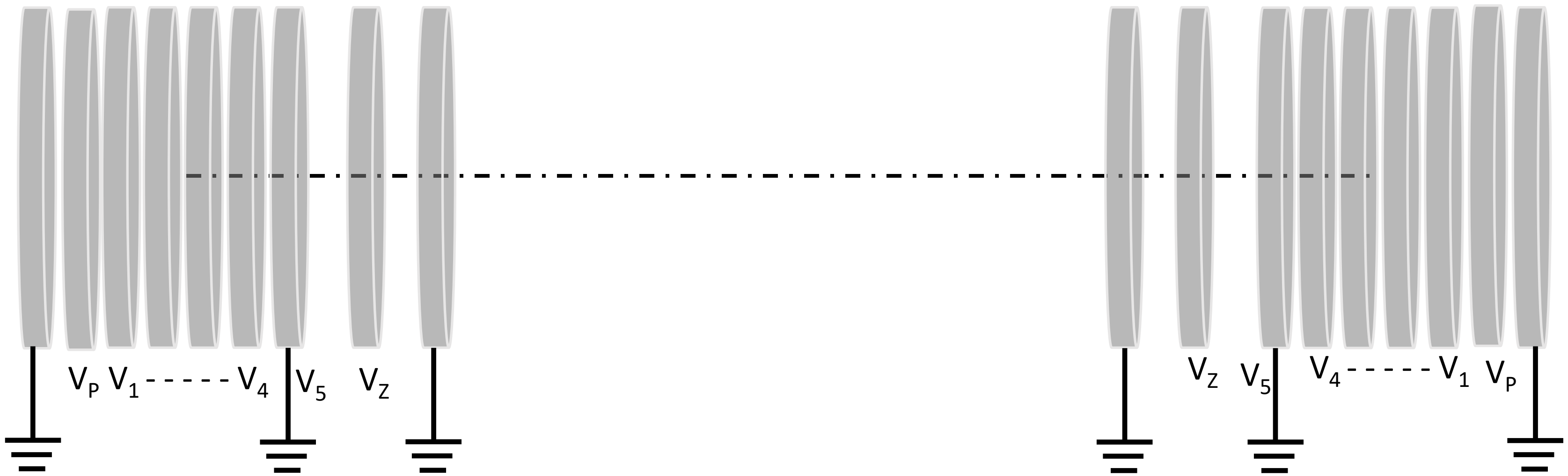
Self Bunching, RF Bunching and Cooling of Ions in an Electrostatic Ion Beam Trap

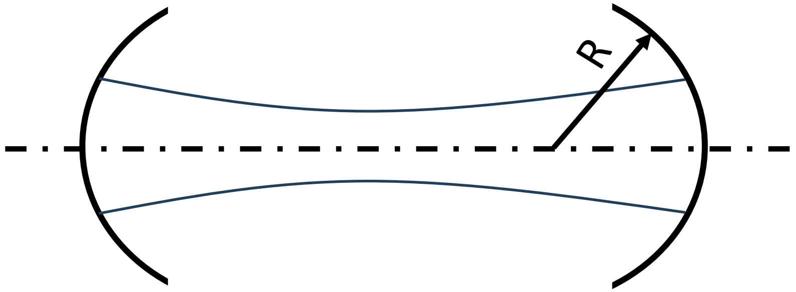
Deepak Sharma
Weizmann Institute of Science, Israel

11 October, 2023
International Workshop on Beam Cooling and Related Topics

Electrostatic Ion Beam Trap

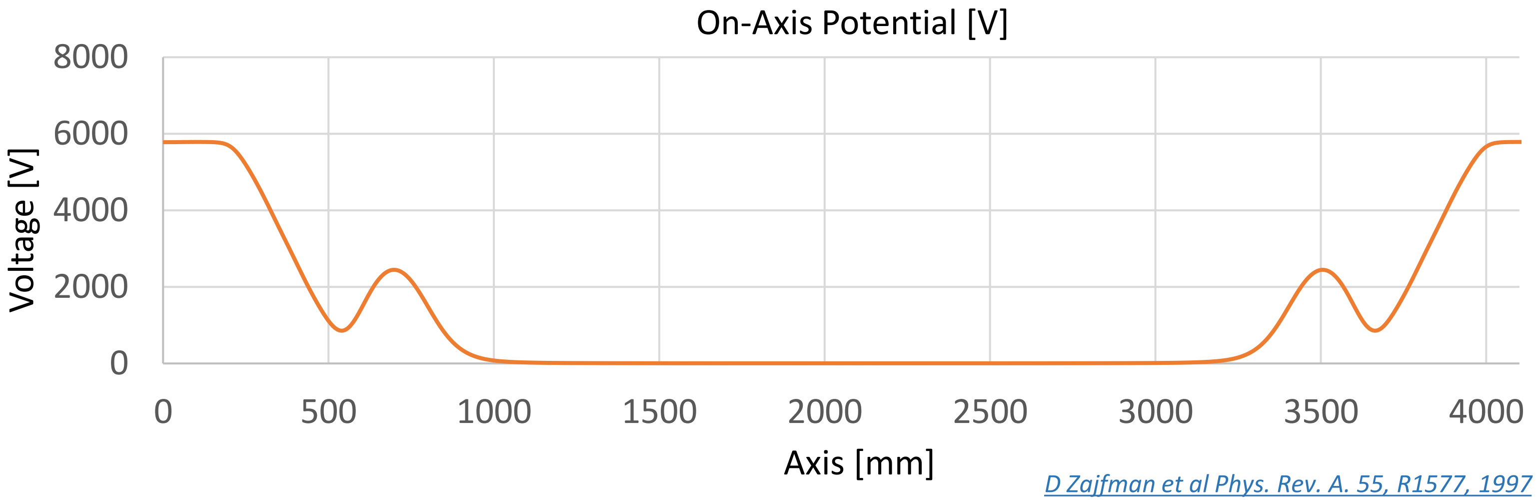
Light Optics	↔	Ion Optics
Optical Resonator	↔	EIBT





Stability condition for symmetric resonator

$$\frac{L}{4} \leqslant f \leqslant \infty$$



D Zajfman et al Phys. Rev. A. 55, R1577, 1997

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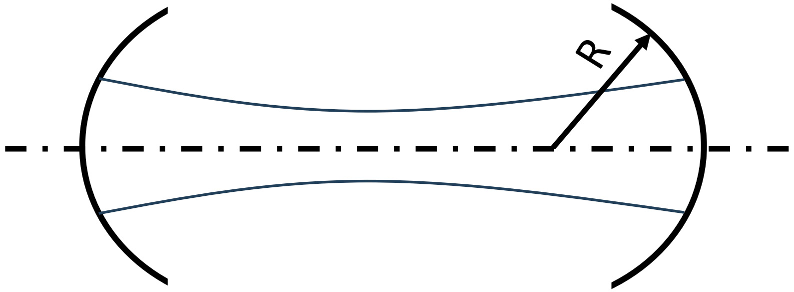
Electrostatic Ion Beam Trap

Light Optics ⟷ Ion Optics

Optical Resonator ⟷ EIBT



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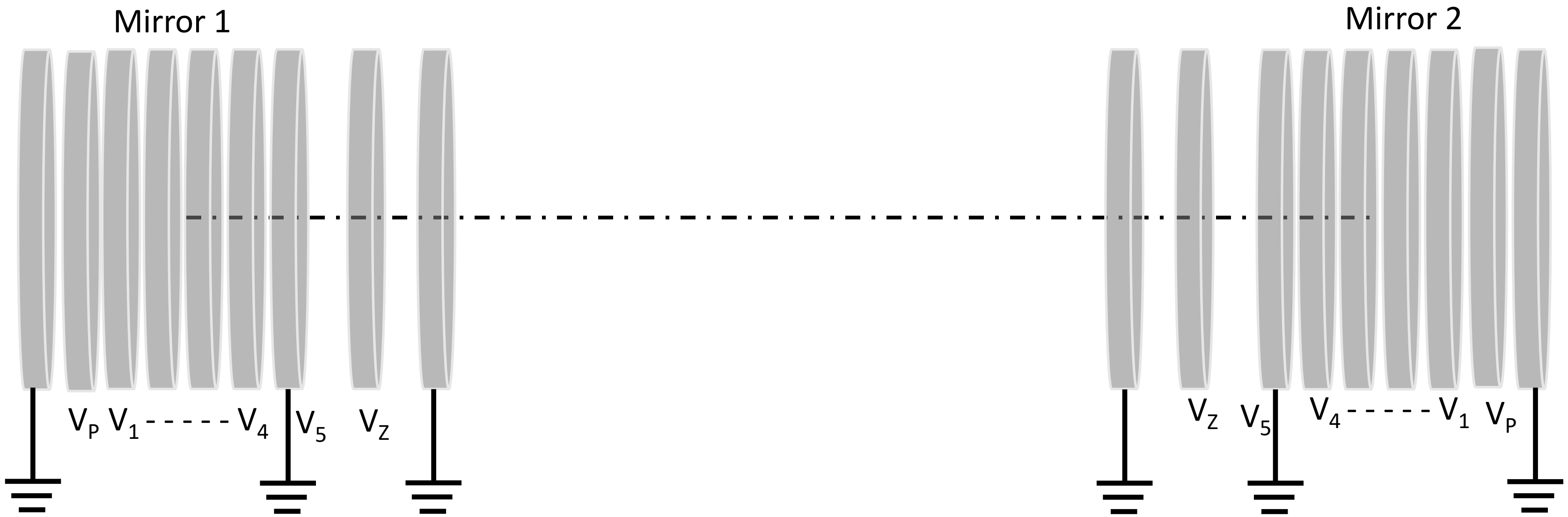
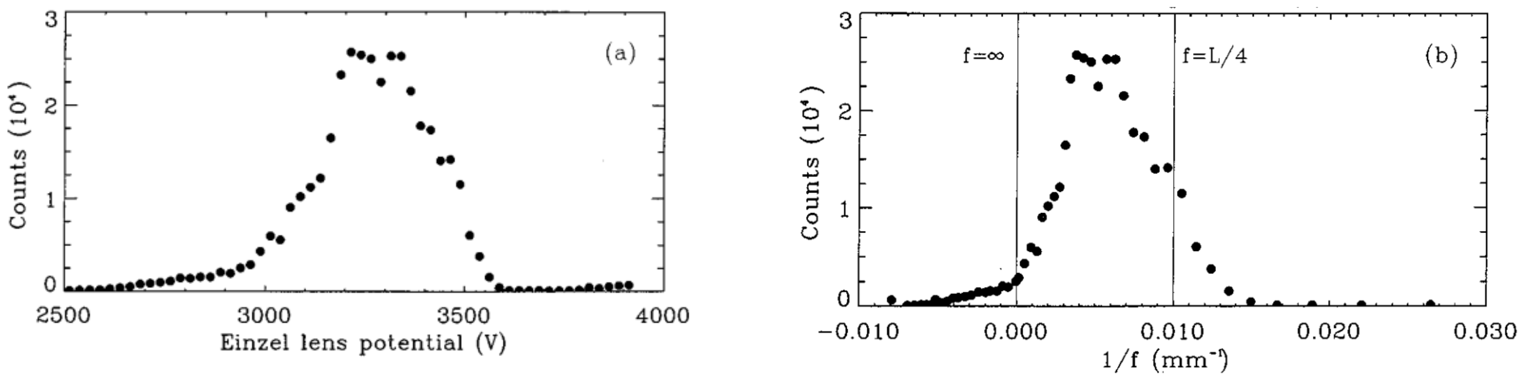




Rev. Sci. Instrum. 69, 76–83 (1998)

Electrostatic Ion Beam Trap

EIBT is a unique and versatile device.

Thermometry of stored molecular ion beams (Scientific Reports. 12, 22518 2022)

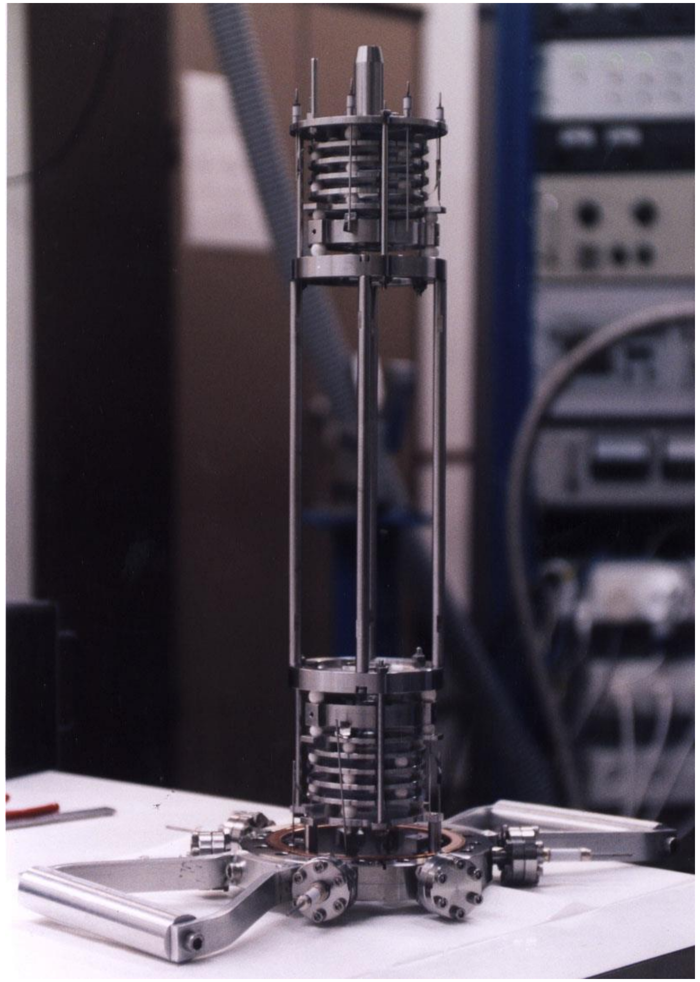
Autoresonance Cooling of Ions in an Electrostatic Ion Beam Trap (Phys. Rev. Lett. 119, 10, 103202, 2017)

Ion motion synchronization in an ion-trap resonator (Phys. Rev. Lett. 87, 055001, 2001)

Beta decay measurements from ^{6}He using an electrostatic ion beam trap (J. Phys.: Conf. Ser. 337 012020, 2012)

A novel method for fundamental interaction studies with an electrostatic ion beam trap (J. Phys.: Conf. Ser. 267 012013, 2011)

Fourier transform time-of flight mass spectrometry in an electrostatic ion beam trap (*Anal. Chem.*, 72, 17, 4041–4046, 2000)



Focus for today's talk: Beam Dynamics in EIBT

Outline

<u>Two modes of EIBT</u>

1. Dispersion of ions
2. Self Bunching of ions
   [Negative mass instability]

<u>Dynamics of ions under external time dependent perturbation</u>

1. RF bunching of ions
   → Repulsive ion-ion interaction provide necessary coupling to keep the ions localized in phase space

2. Auto-resonance Cooling of ions
   → ions from phase space is accelerated out

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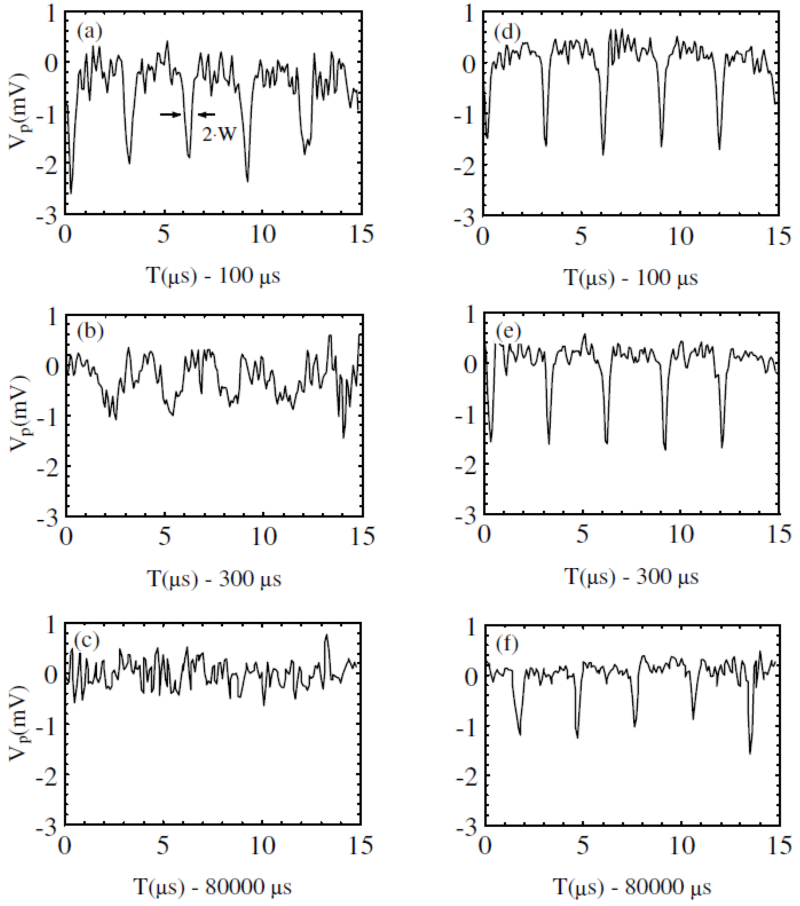
Two modes of EIBT

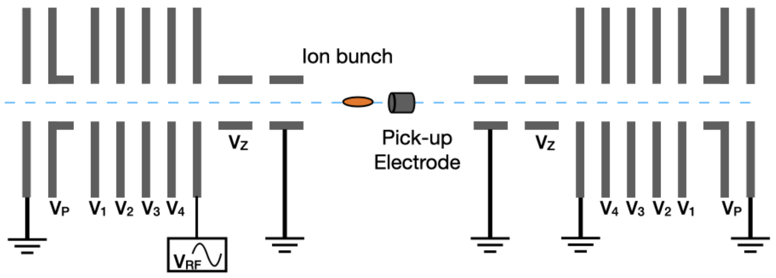
Dispersive | Self bunching



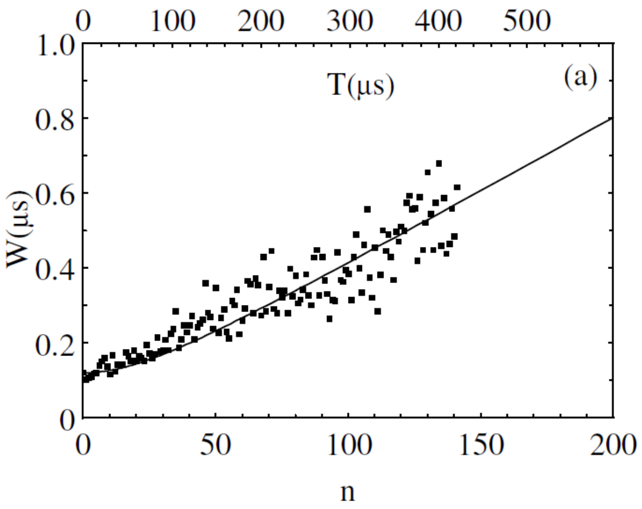
Slip Factor

$$\eta = \frac{-2E}{f}\boxed{\frac{df}{dE}}$$

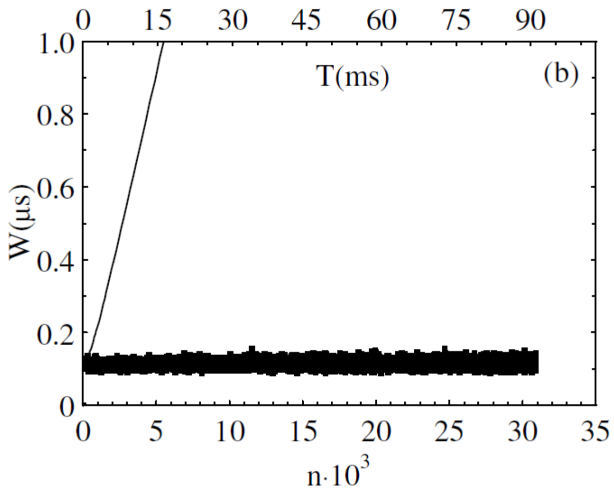
Electrostatic Ion Beam Trap (EIBT)



Dispersive



Self bunching



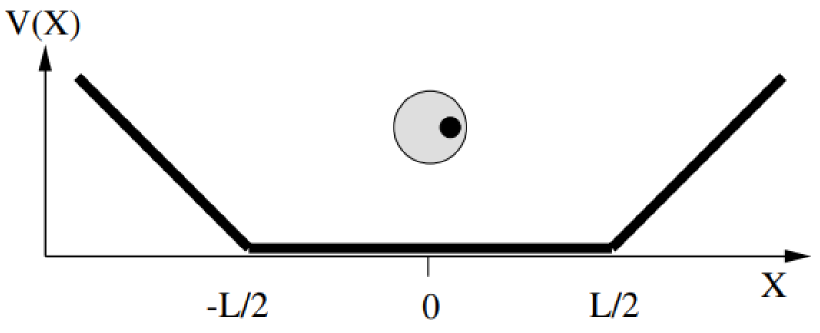
H Pedersen et al Phys. Rev. Lett. 87, 055001, 2001

D Strasser et al Phys. Rev. Lett. 89, 283204, 2002

Self Bunching in EIBT (Negative Mass Instability)

Potential profile in EIBT

$$V(X) = \begin{cases} 0, & \text{if } |X| \le L/2, \\ F(|X| - L/2), & \text{if } |X| > L/2, \end{cases}$$



Total system: test charge (black dot) and charged sphere

Hamiltonian for the system:

$$H = \frac{p_1^2}{2Nm} + \frac{p_2^2}{2m} + QV(x_1) + qV(x_2) + qU(x_1 - x_2),$$

Propagation Matrix

$$\mathbf{M} = \mathbf{M_T} \cdot \mathbf{M_i} = -\begin{pmatrix} 1 - \frac{kT^2}{m^*} & \frac{T}{m^*} \\ -kT & 1 \end{pmatrix}.$$

$$\text{where } m^* = -m/\eta$$

Bound trajectory in phase space can will be obtained if

$$0 < \frac{kT^2}{m^*} < 4. \qquad \rho > \frac{4\eta\epsilon_0 p_0^2}{mqR_0^2},$$

For repulsive interaction (k<0), to satisfy inequality, effective mass must be negative or $\eta > 0,$

$$\eta = \frac{-2E}{f}\frac{df}{dE} < 0$$

D Strasser et al Phys. Rev. Lett. 89, 283204, 2002

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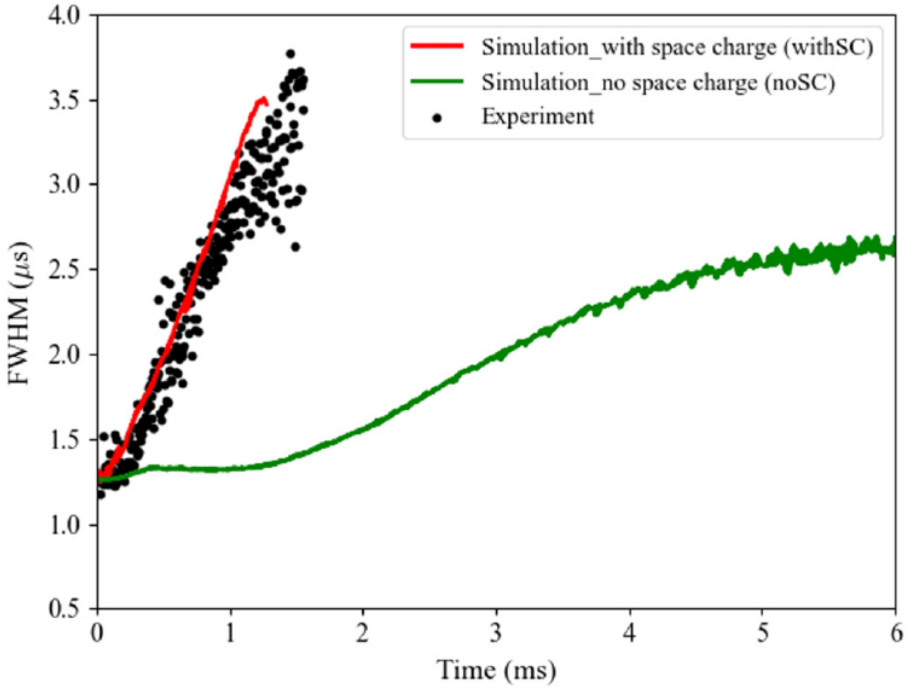
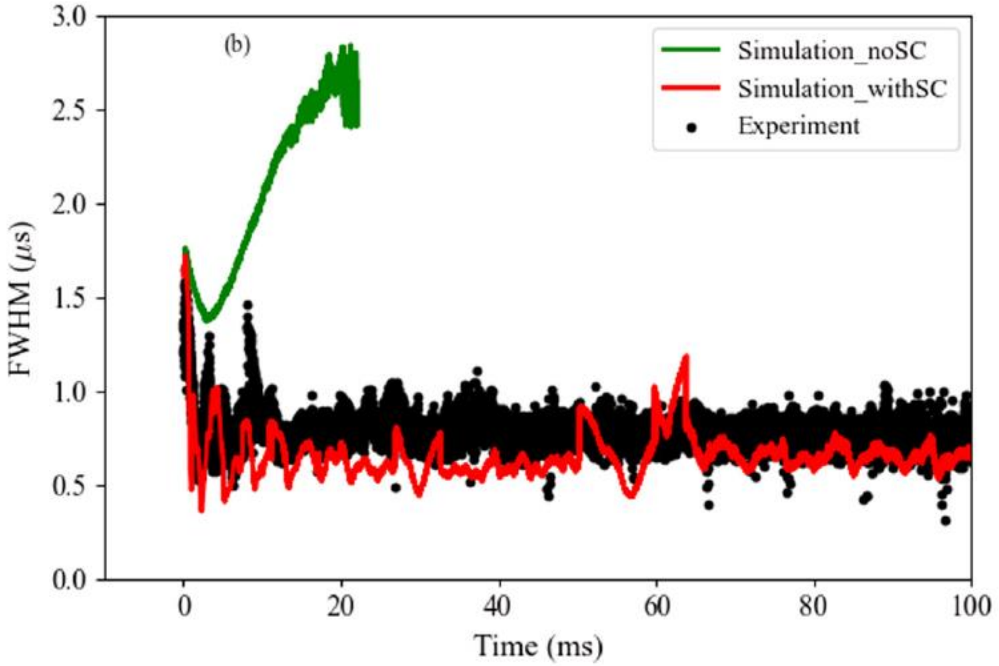
Two modes of EIBT (PIC simulation)

Dispersive



Self bunching



D Gupta et al Phys. Rev. E 104, 065202, 2021
R. Ringle, Int. J. Mass Spectrom. 303, 42 (2011)

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Outline

Two modes of EIBT

1. Dispersion of ions
2. Self Bunching of ions
   [Negative mass instability]

Dynamics of ions under external time dependent perturbation

1. RF bunching of ions
   → Repulsive ion-ion interaction provide necessary coupling to keep the ions localized in phase space

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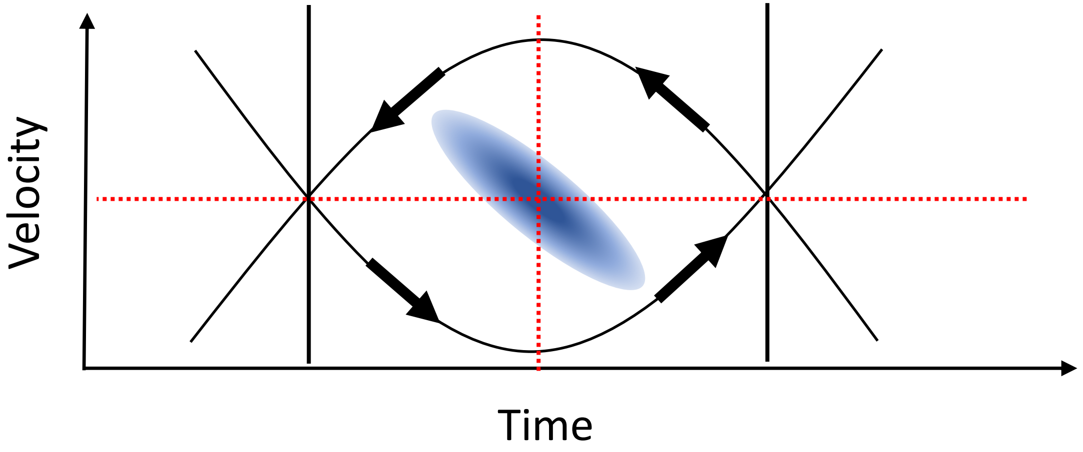
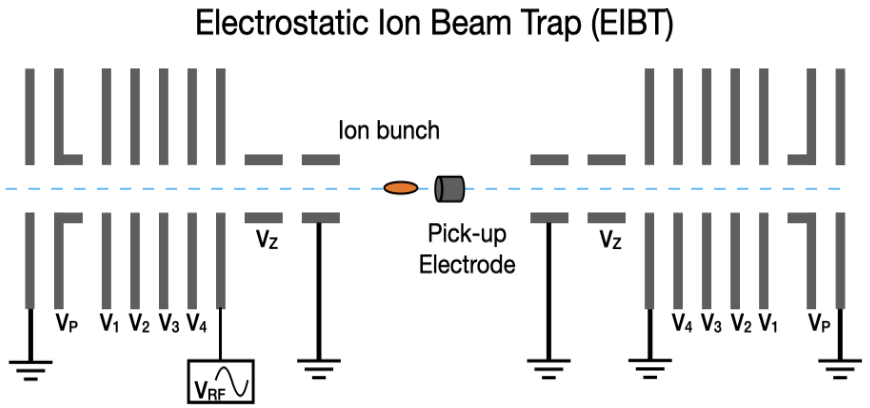
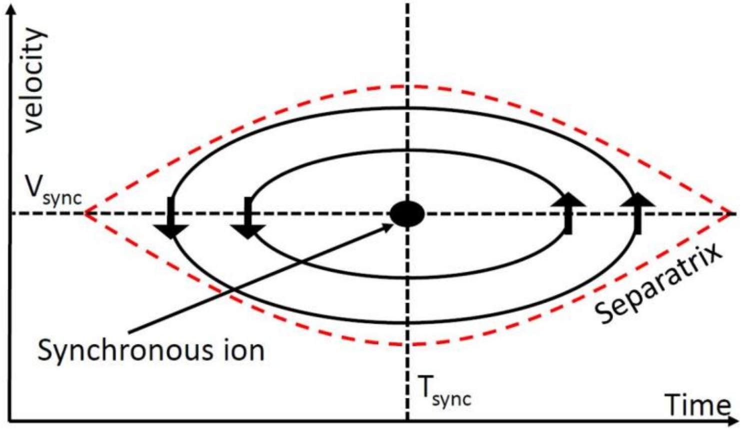
RF Bunching of ions in EIBT

<u>RF bunching:</u> External field is applied with the same frequency as the natural oscillation frequency of ions in the trap







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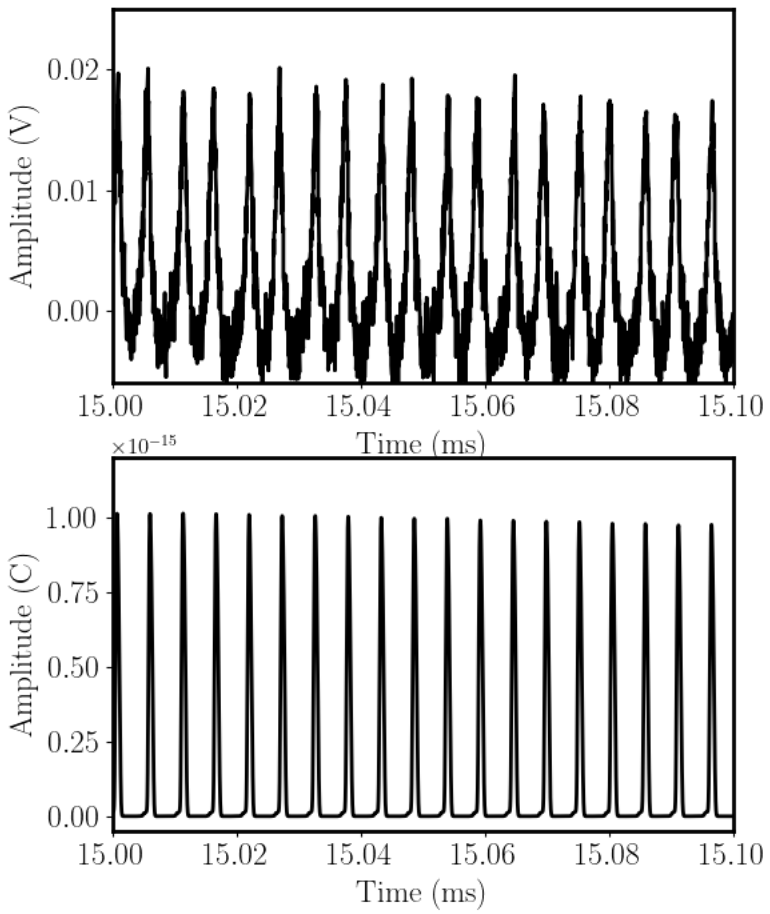
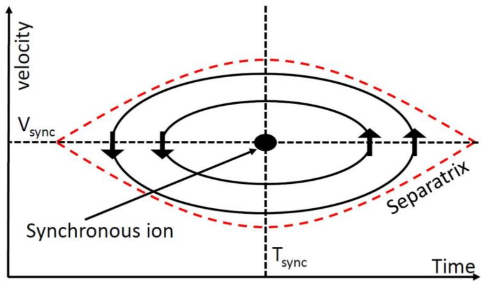
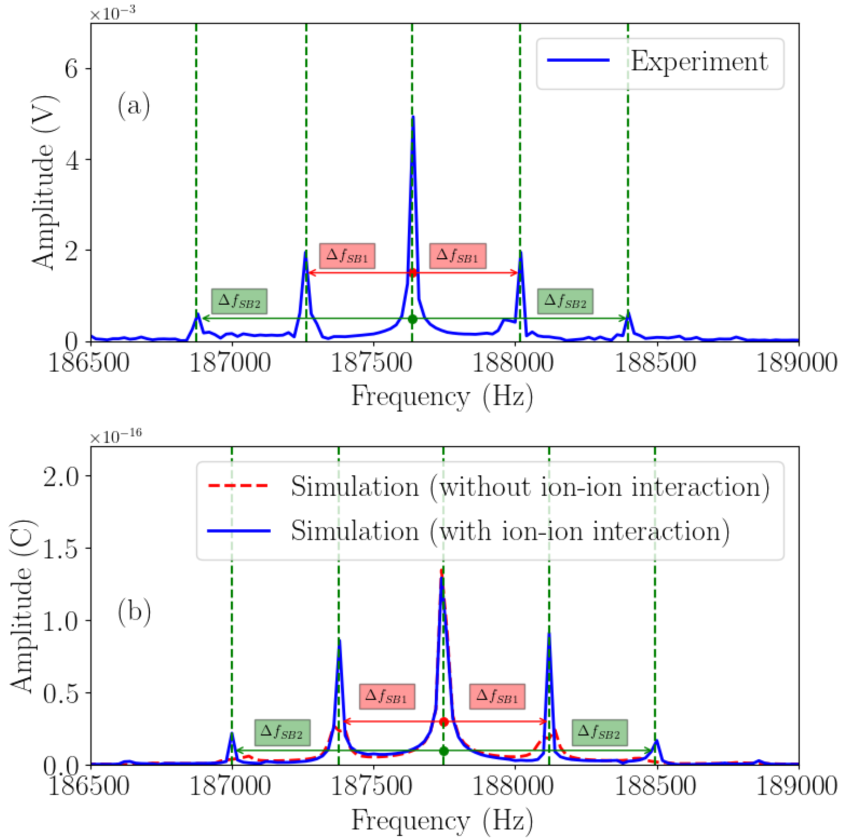
RF Bunching of ions in EIBT





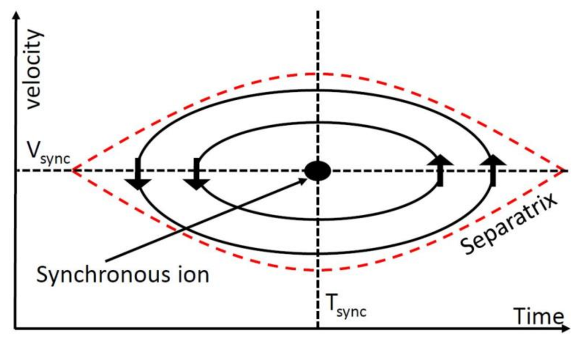


Side peaks carry information about longitudinal oscillation in RF bucket (synchrotron frequency).

<u>But what does the height of side peak represent?</u>

D Gupta et al Phys. Rev. E, 107, 045202, 2023

Filamentation in RF bucket



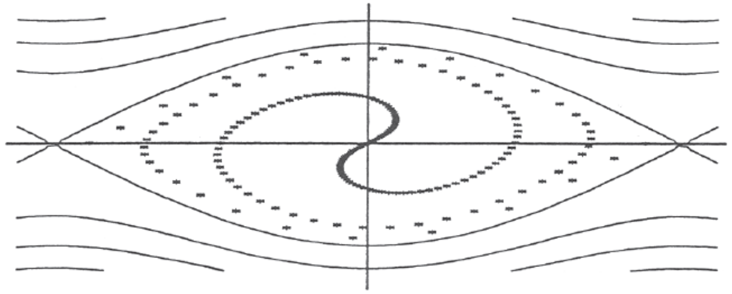
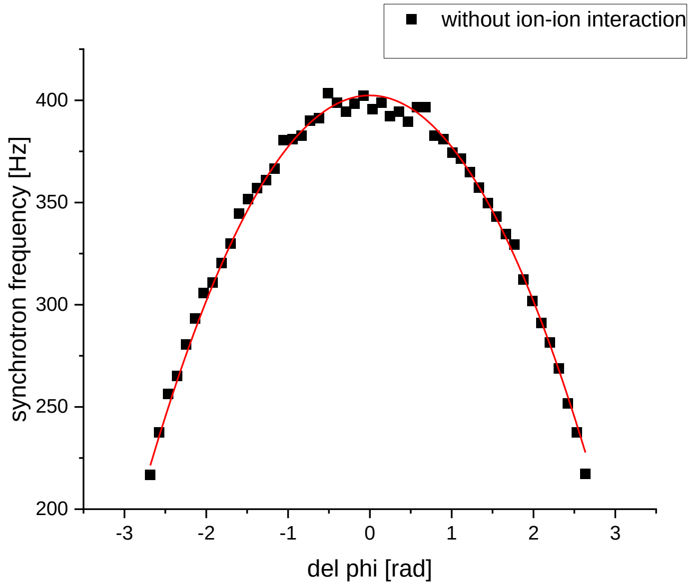
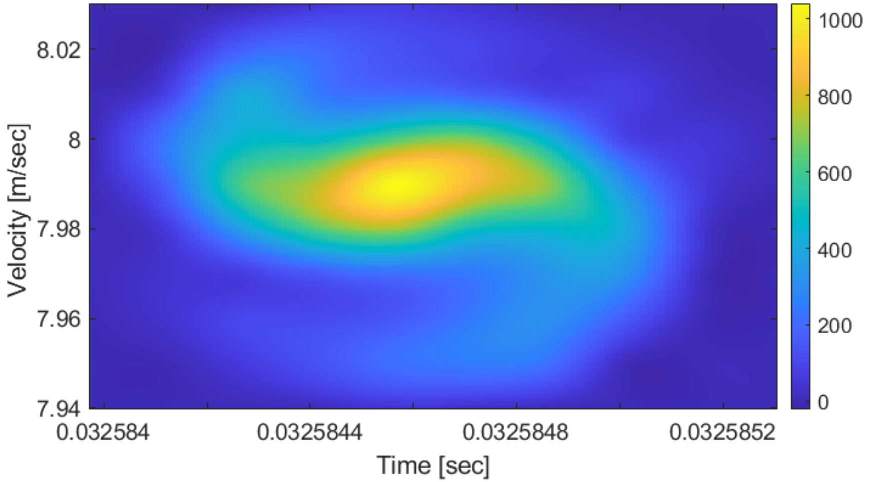


Fig. 6.16. Phase space filamentation

[H. Wiedemann, Particle Accelerator Physics (Springer, Berlin, 2007)]



Variation of synchrotron frequency with phase amplitude



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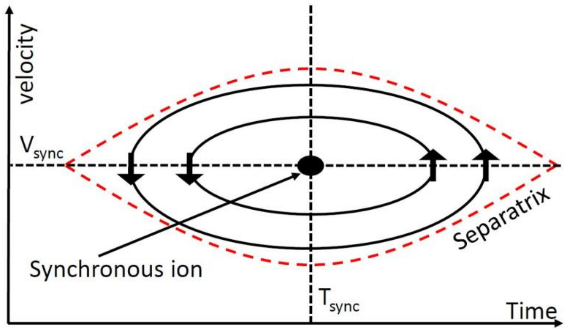
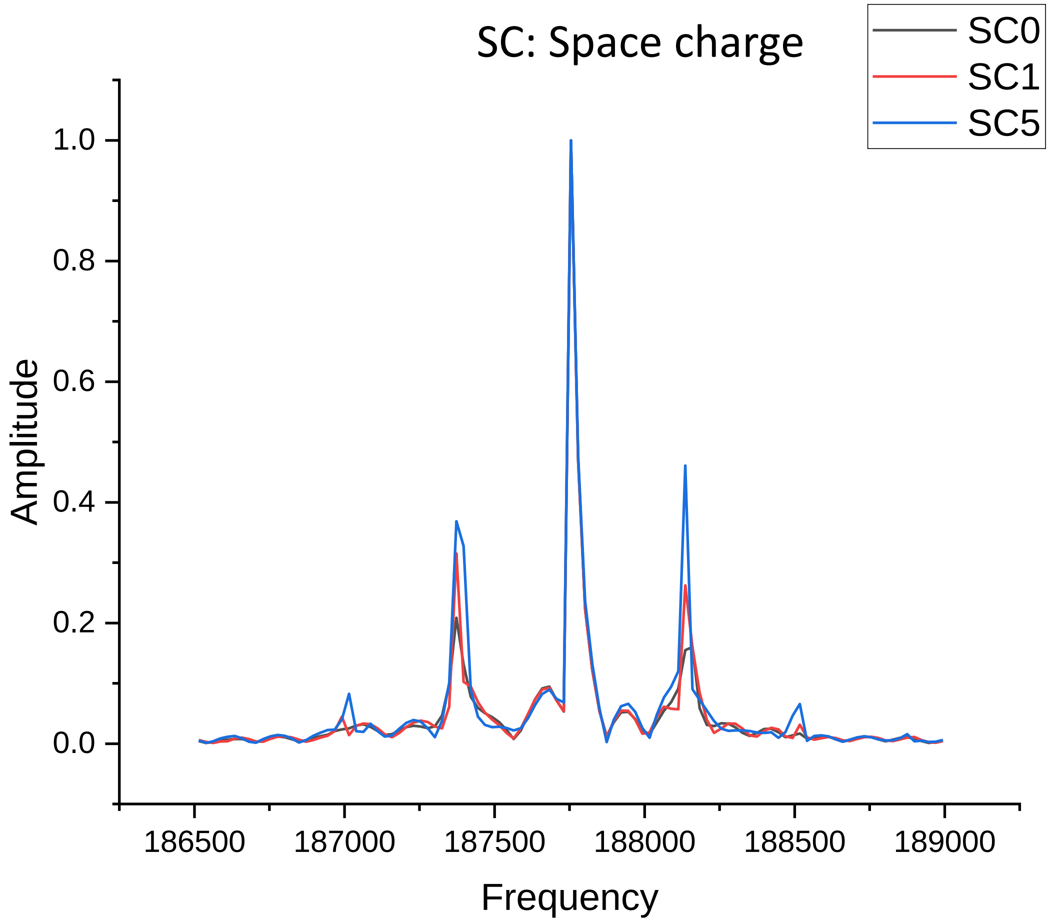
RF Bunching [effect of ion-ion interaction]

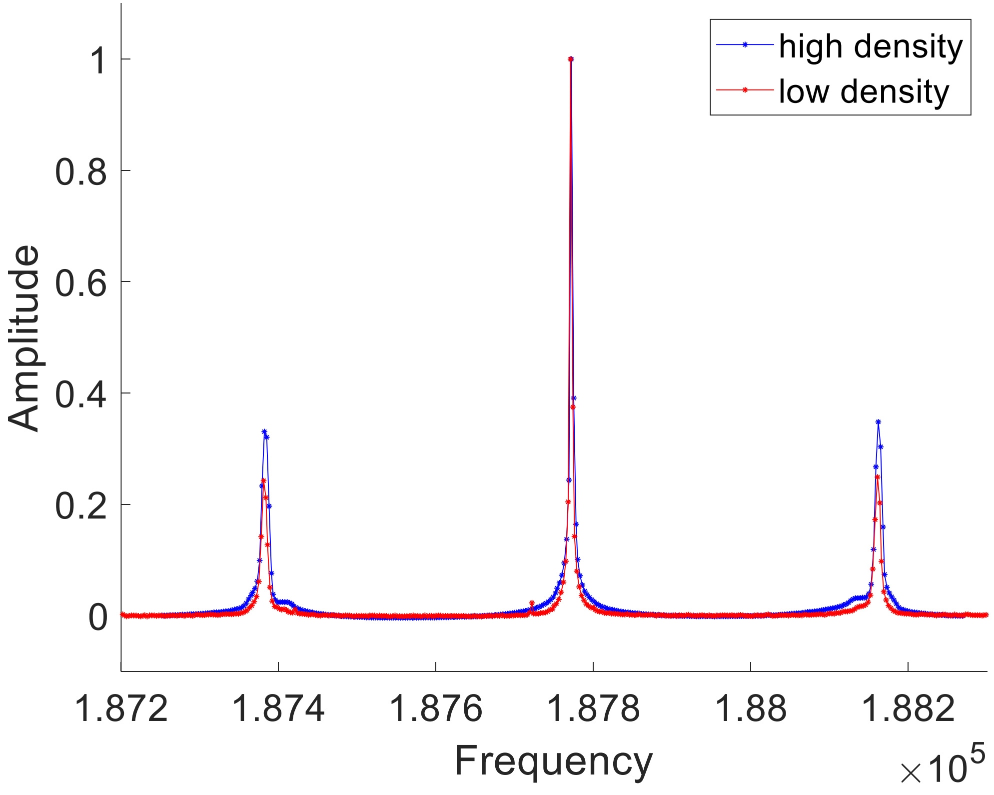


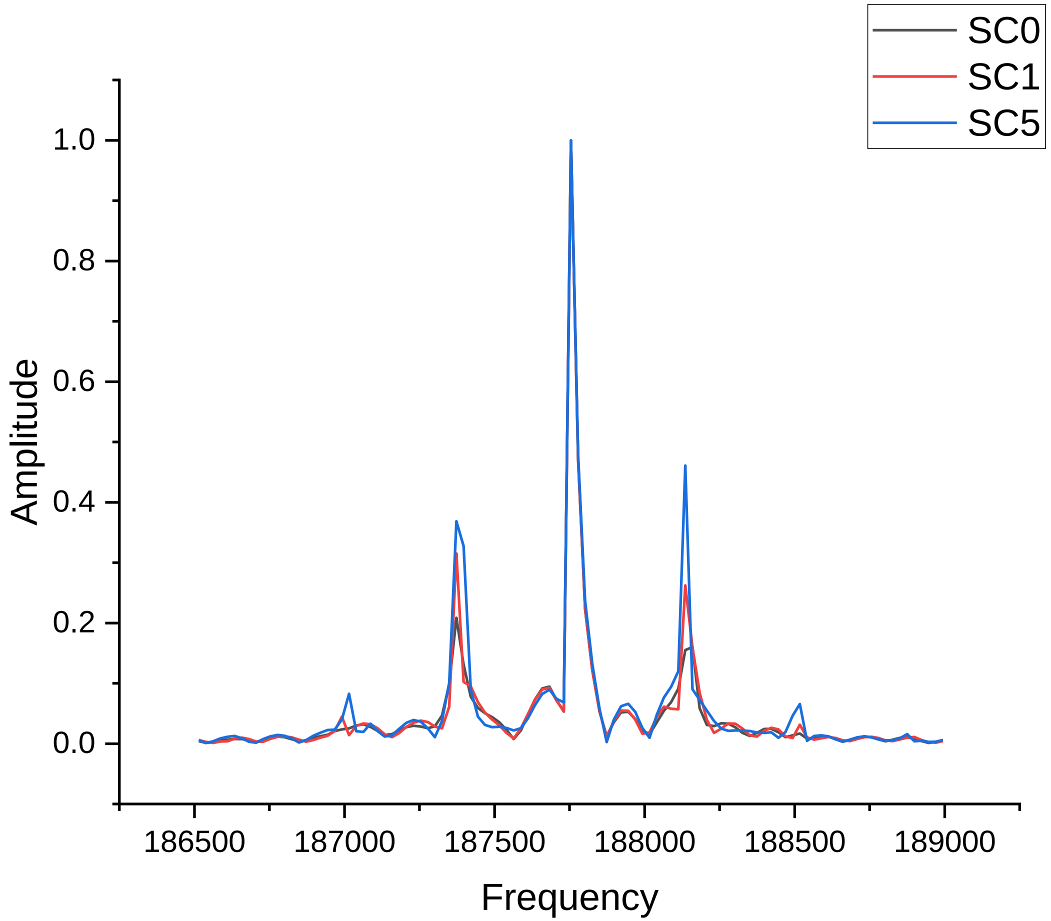


The ratio of side peaks height to main peaks increases with ion density.

→ RF bucket is more uniformly filled for less ion density.

RF Bunching [effect of ion-ion interaction]



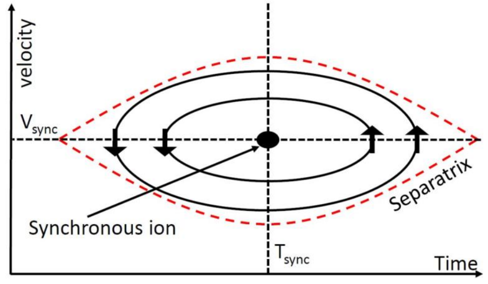


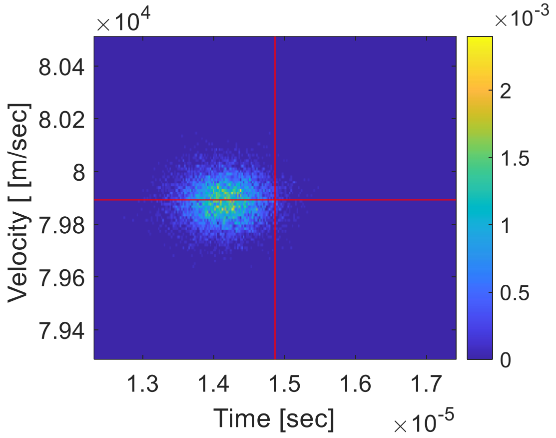
Motion of ions in RF Bucket

For low ion density: phase space filamentation

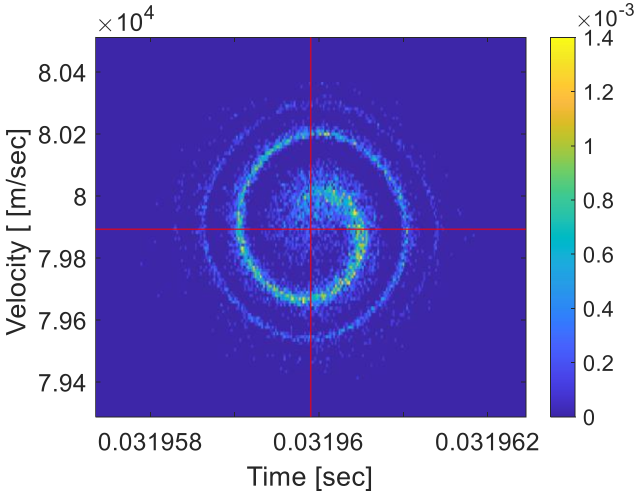
High ion density: <u>inhibit phase space filamentation</u>

This effect bear similarity with self bunching effect in EIBT.
→ Repulsive Columbic interaction provide coupling for synchronization.

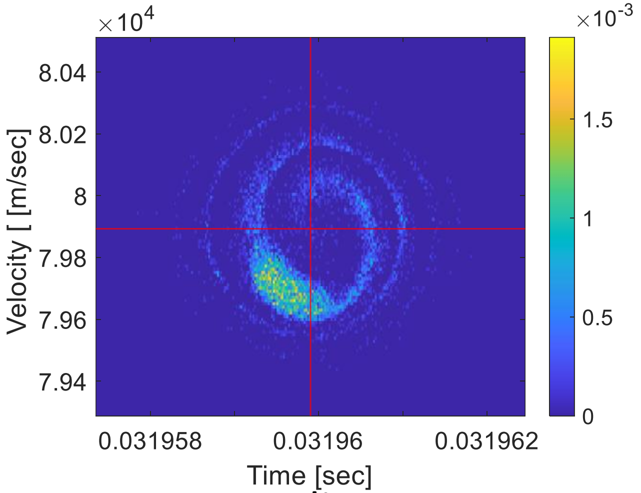




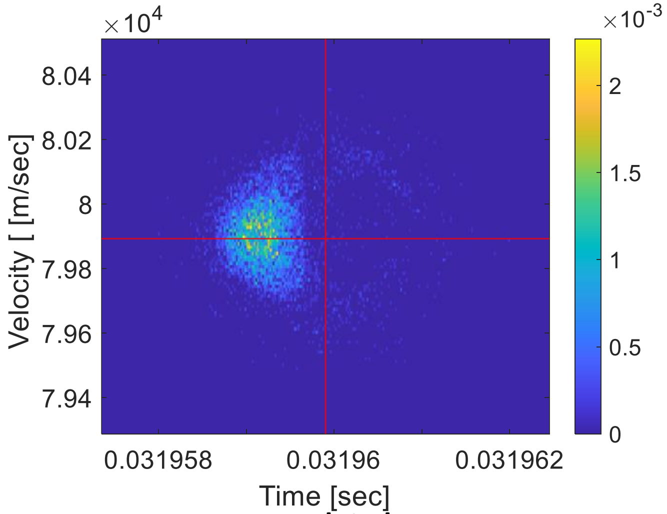
Initial injection of bunch



low



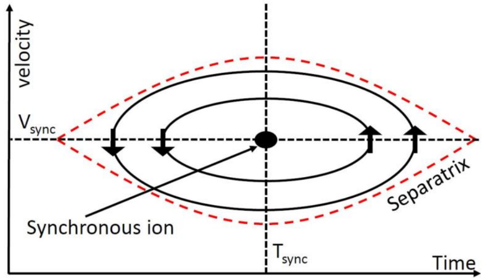
medium



high

Ion's distribution in RF bucket after 32ms for different ion densities

Motion of ions in RF Bucket



Proceedings of the 2003 Particle Accelerator Conference

EFFECTS OF SPACE CHARGE ON DECOHERENCE IN ION BEAMS

O. Boine-Frankenheim, I. Hofmann, Y. Liu, G. Rumolo*, GSI, Darmstadt, Germany
A. Al-Khateeb, Yarmouk University, Irbid, Jordan

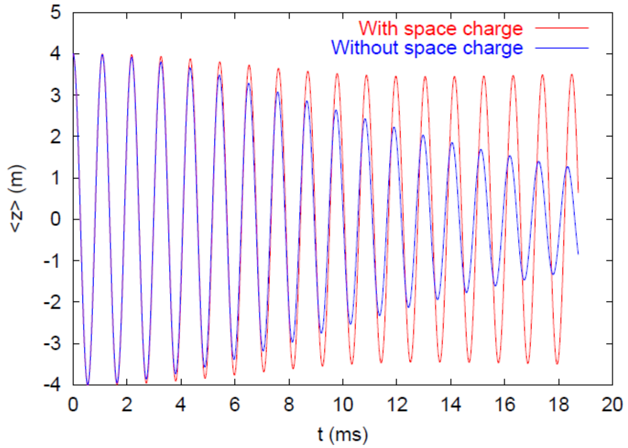
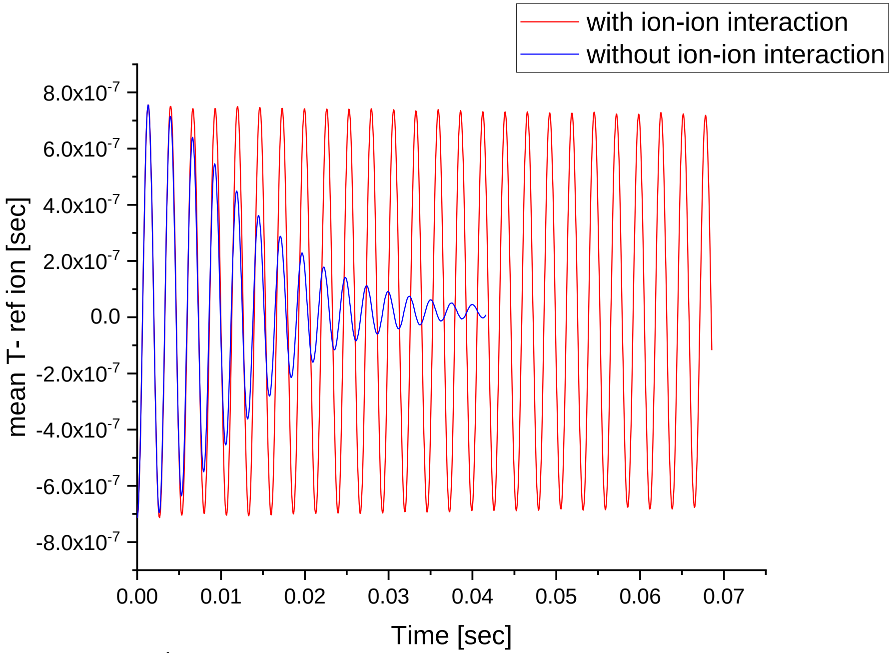


Figure 2: Decoherence of the centroid motion for a longitudinally displaced bunch due to the sinusoidal bucket non-linearity with (red) and without (blue) space charge effects.

0.5*e10 C^{6+} ions

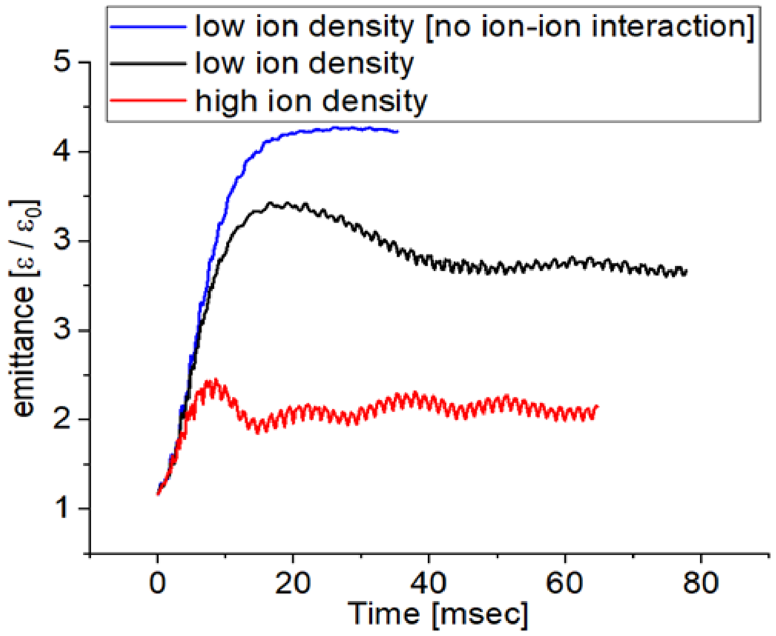


1*e5 SF_5^+ ions

Emittance Growth for different ion densities

High ion density or strong space charge inhibit the emittance growth in RF bunching of ions

Enhanced diffusion in the trap (high energy particle is moved even further with ion-ion interaction) acts opposite to synchrotron oscillation in the RF bucket.



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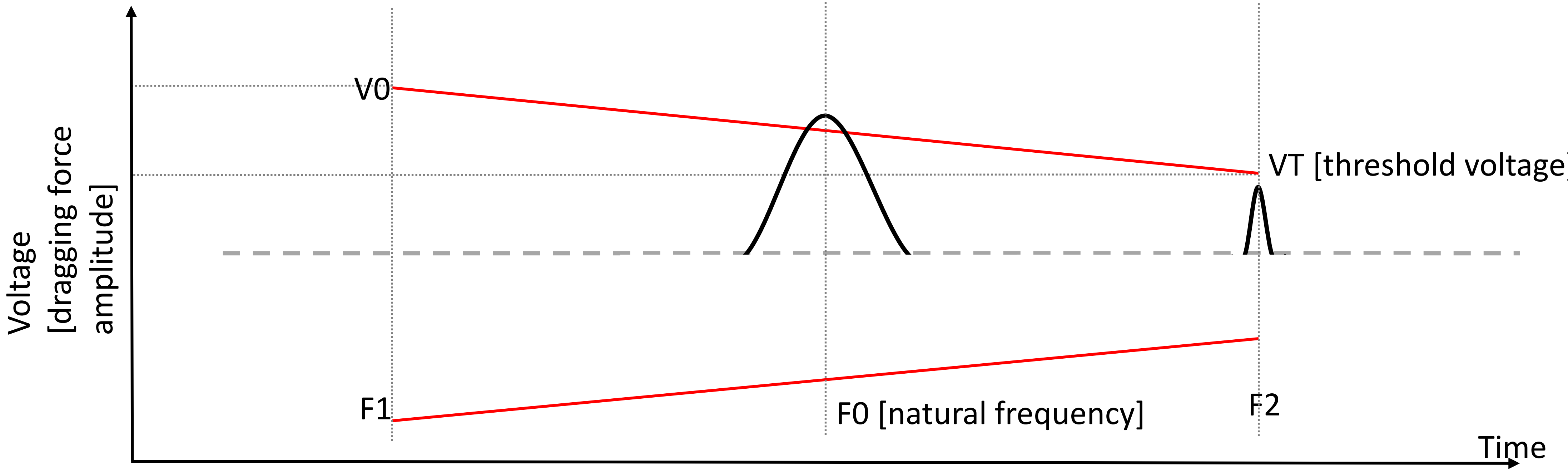
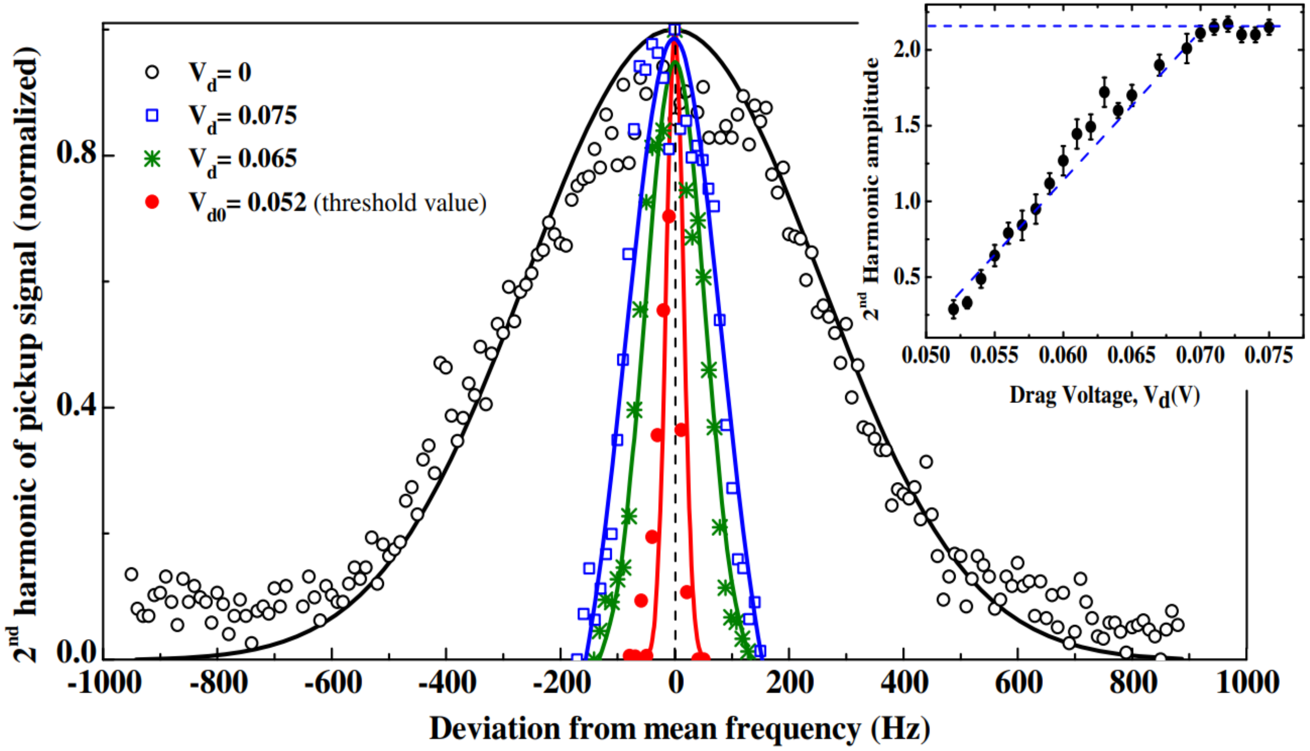
Auto-resonance Cooling of ions in EIBT

A schematic of Auto-resonance process in EIBT

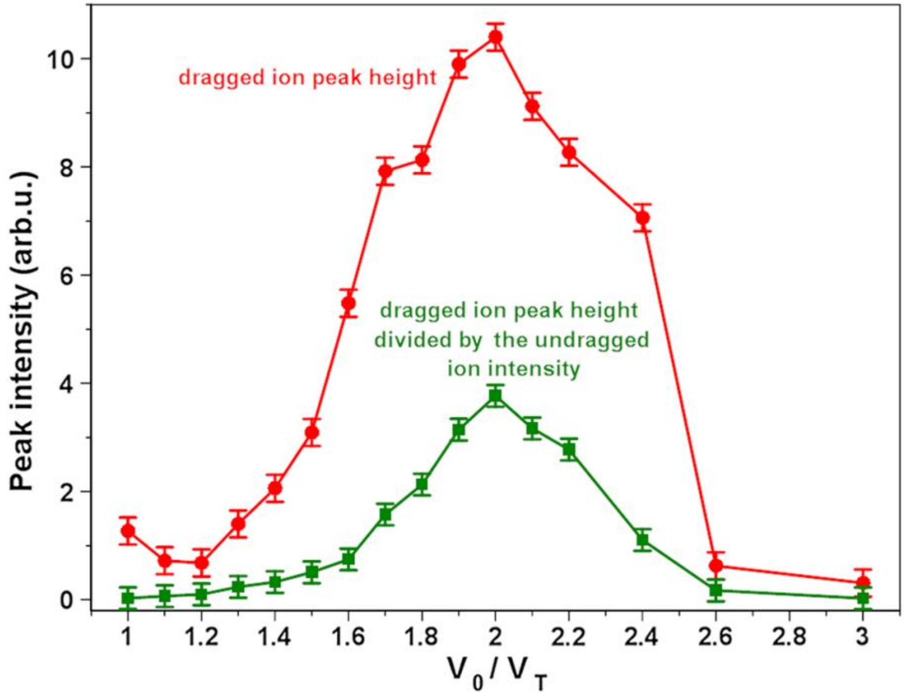


Spread in frequency distribution (sigma) corresponds to temperature of ions in the trap

Auto-resonance Cooling of ions in EIBT



Distribution of ions for different dragging voltages



Dragged peak height as a function of amplitude ramping down ratio

R K Gangwar et al Phys. Rev. Lett. 119, 103202, 2017

Summary

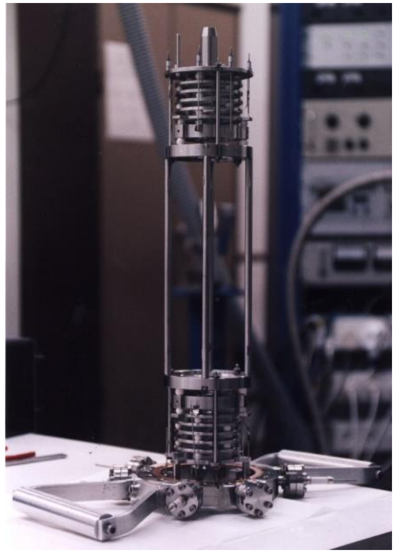
1. EIBT is a unique and versatile device to store low energy beams. [ion density oscillates and strongly influence the beam dynamics]

2. It can be operated in dispersive mode and synchronization mode.

3. Ion-ion interaction inhibit the filamentation in RF bucket and keeps the ions localized.

4. A novel technique for cooling of ions has been demonstrated in EIBT.

5. A simulation technique based on particle-in-cell helps to under the beam dynamics with details.



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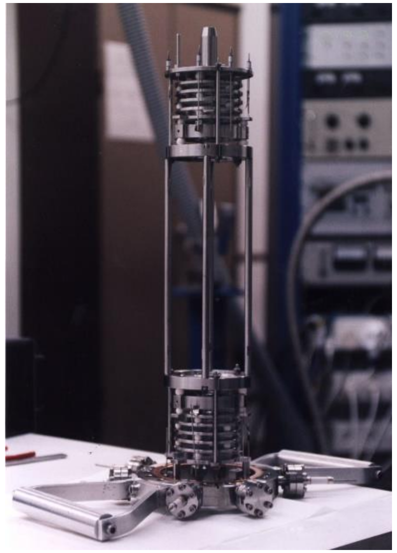

Team: Dr. Ryan Ringle (MSU), Dr. Oded Heber, Prof. Daniel Zajfman

Thank You

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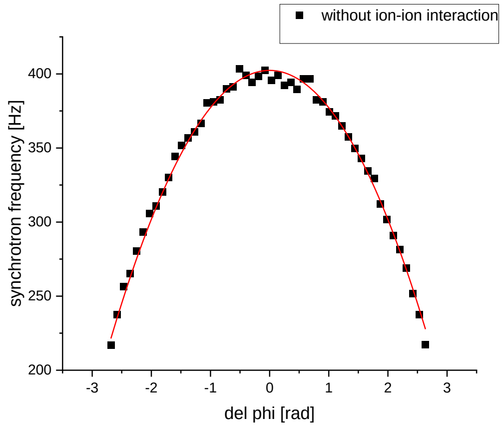
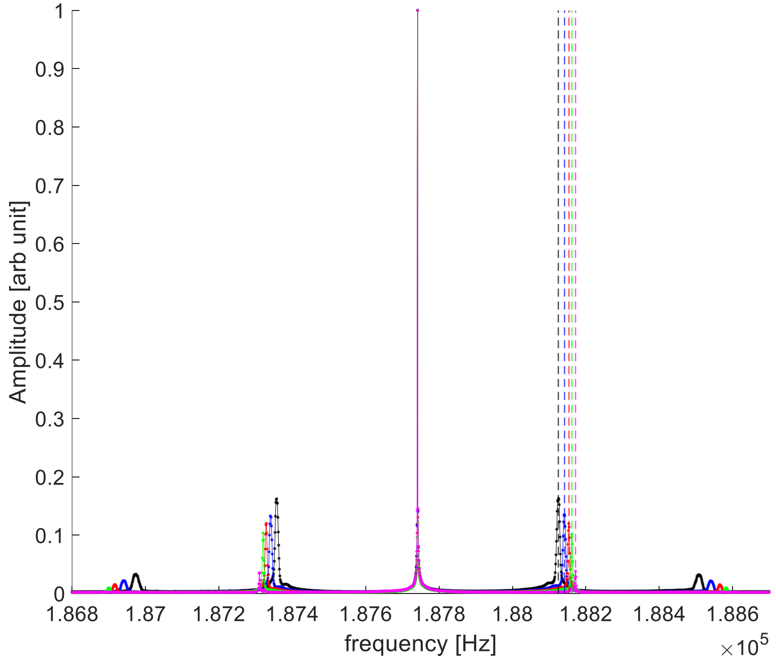
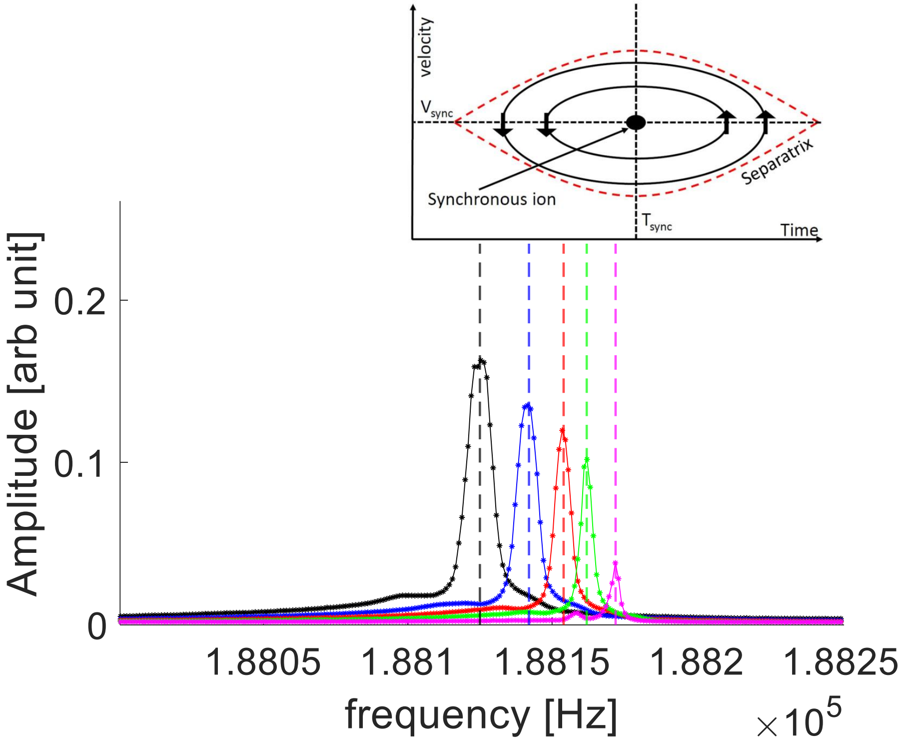
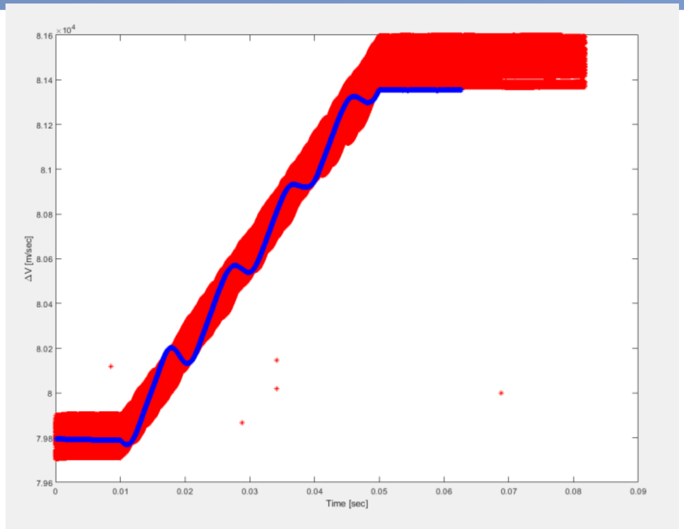
Backup Slides







Synchrotron frequency decreases with increase in phase space amplitude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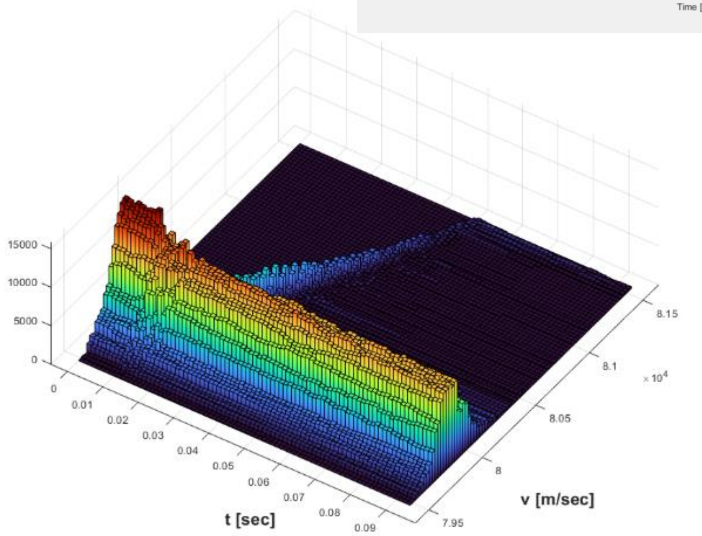
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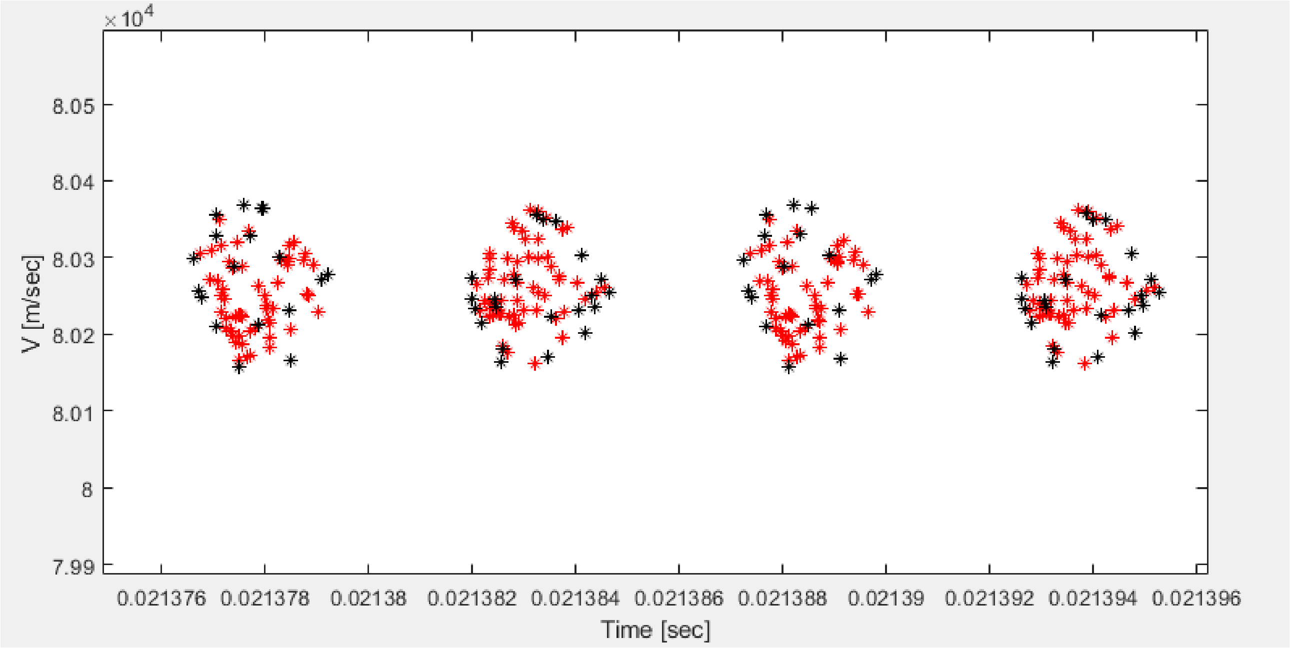
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