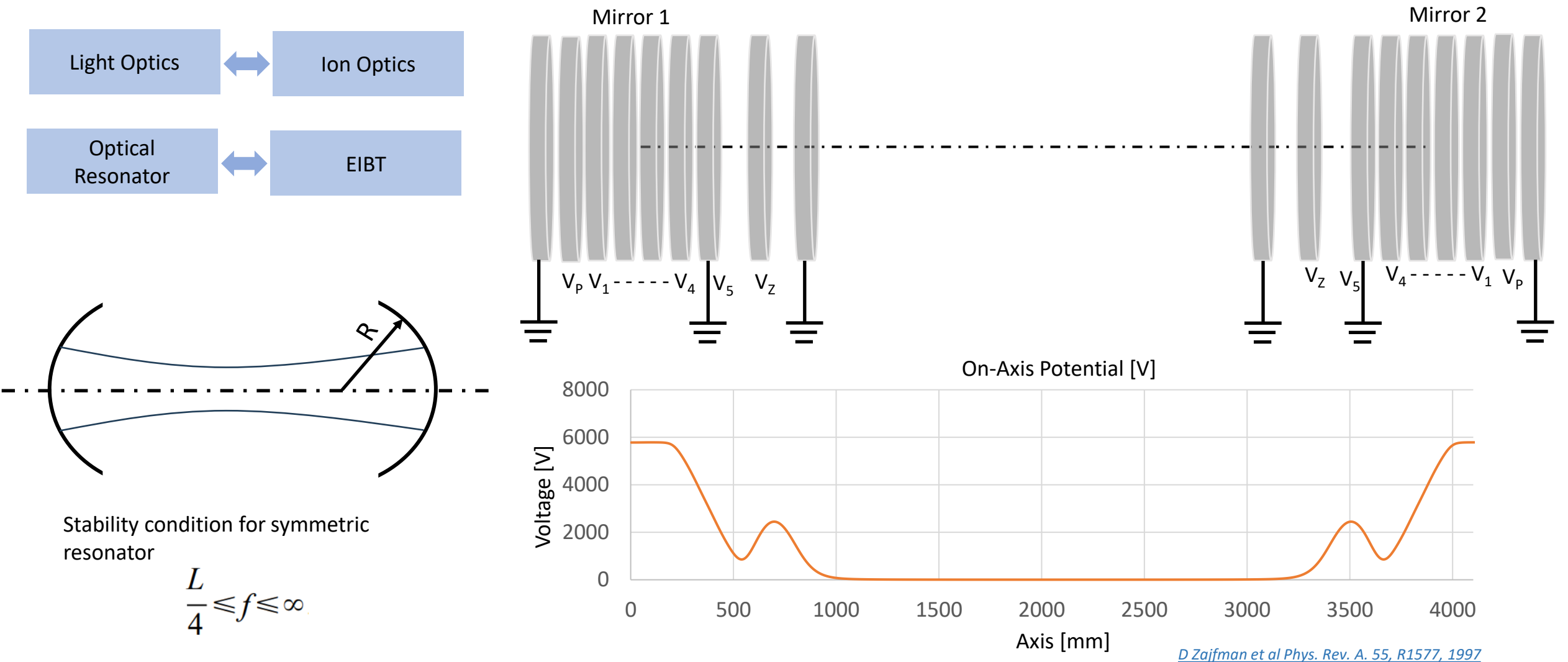


Self Bunching, RF Bunching and Cooling of Ions in an Electrostatic Ion Beam Trap

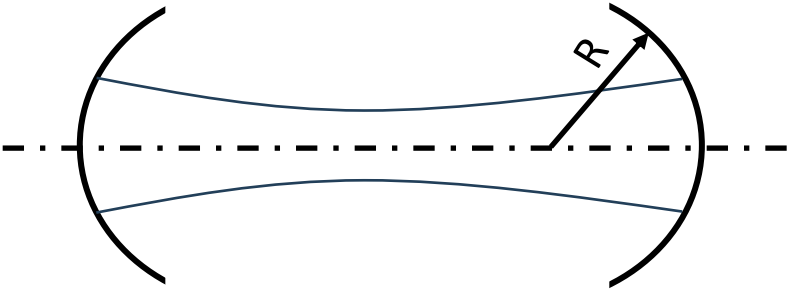
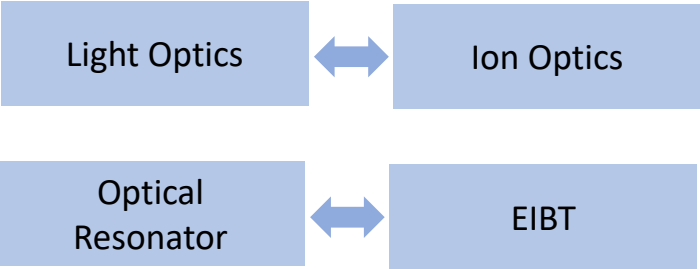
Deepak Sharma
Weizmann Institute of Science, Israel

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

Electrostatic Ion Beam Trap

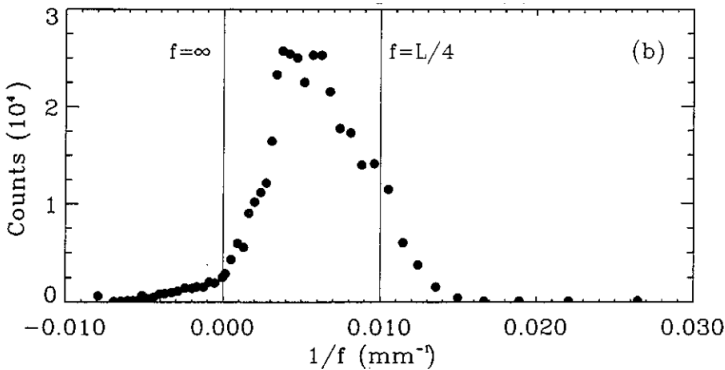
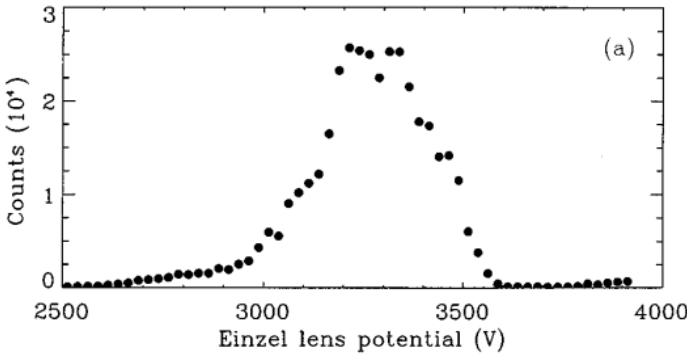
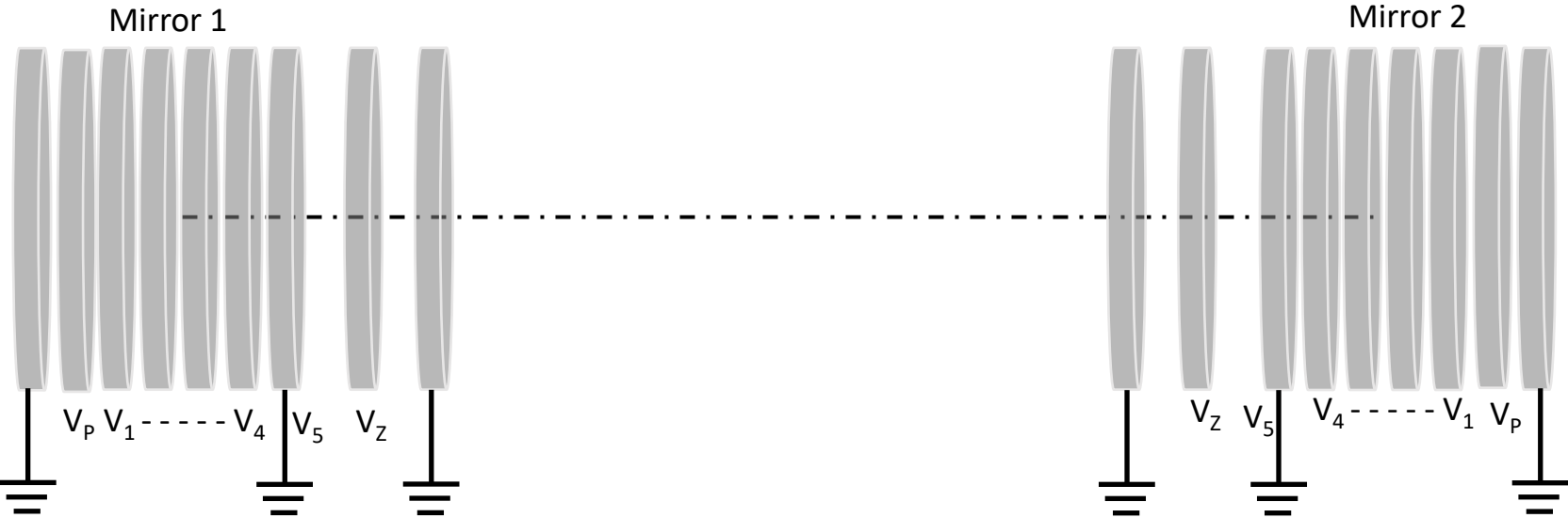


Electrostatic Ion Beam Trap



Stability condition for symmetric resonator

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



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)

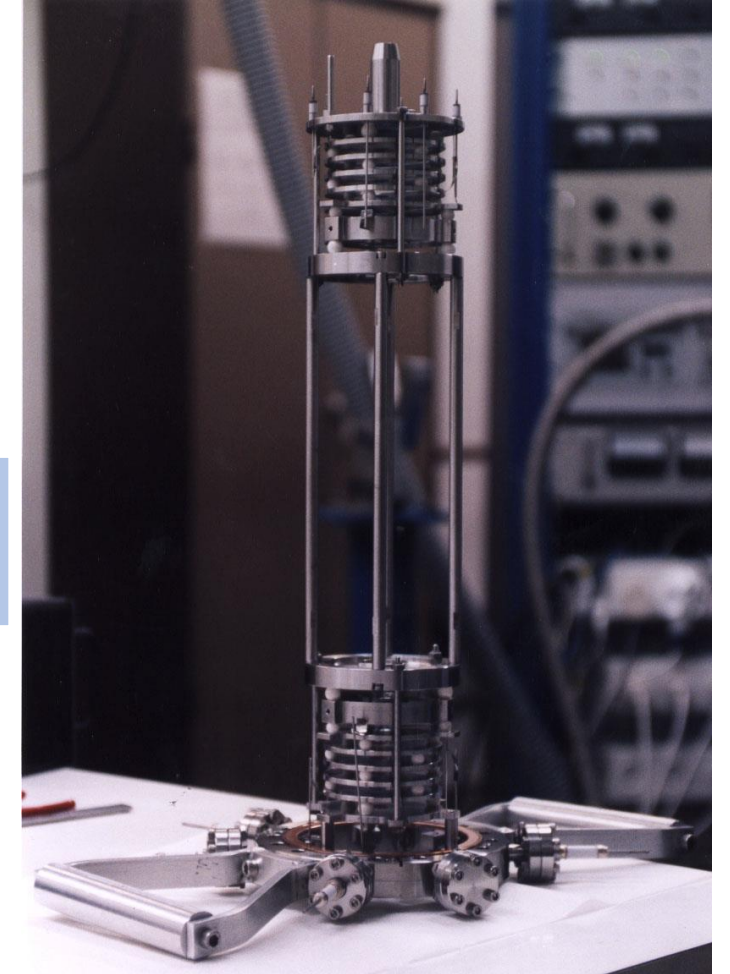
Ion motion synchronization in an ion-trap resonator (Phys. Rev. Lett. 87, 055001, 2001)

Beta decay measurements from ^6He 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



Two modes of EIBT

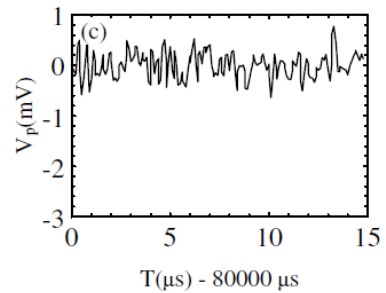
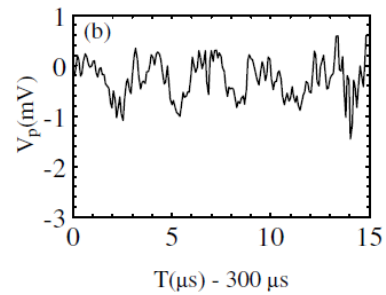
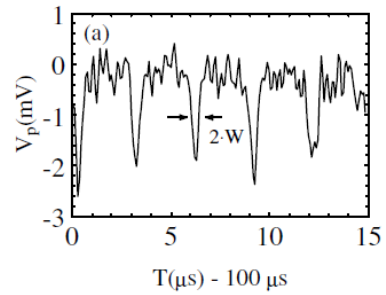
1. Dispersion of ions
2. Self Bunching of ions
[Negative mass instability]

Dynamics of ions under external time dependent perturbation

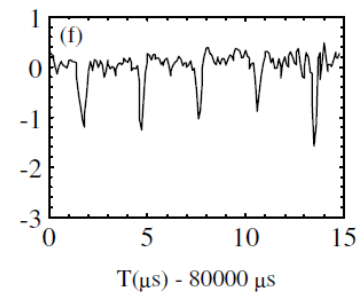
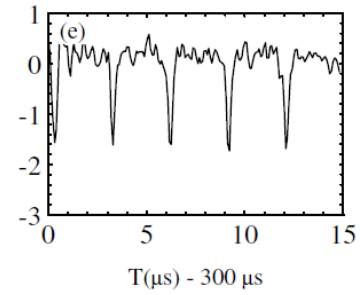
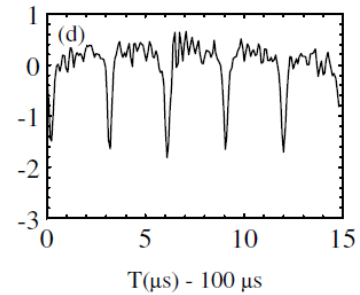
1. RF bunching of ions
→ Repulsive ion-ion interaction provide necessary coupling to keep the ions localized in phase space
2. Auto-resonance Cooling of ions
→ ions from phase space is accelerated out

Two modes of EIBT

Dispersive

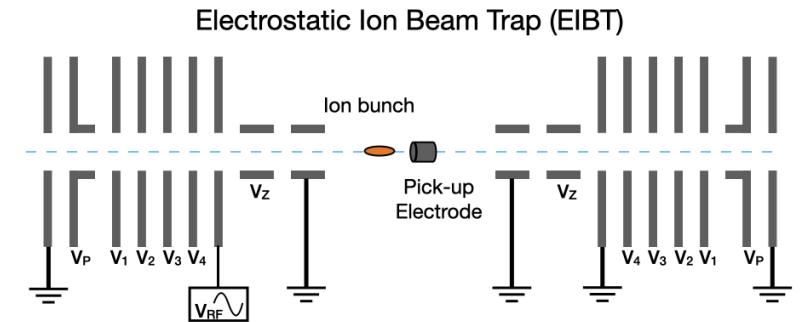


Self bunching

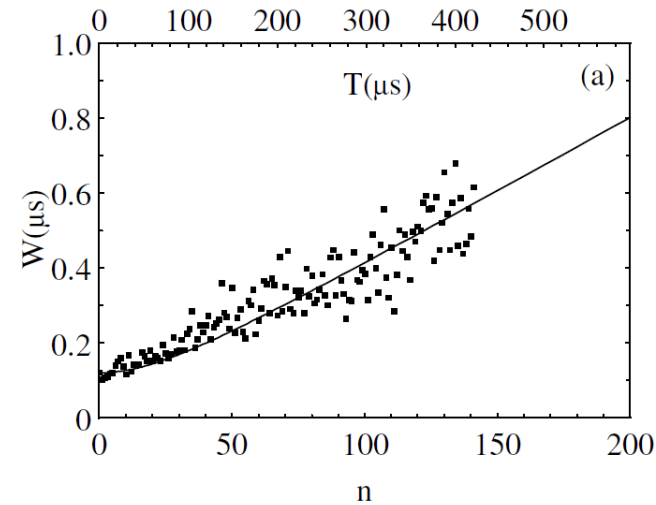


Slip Factor

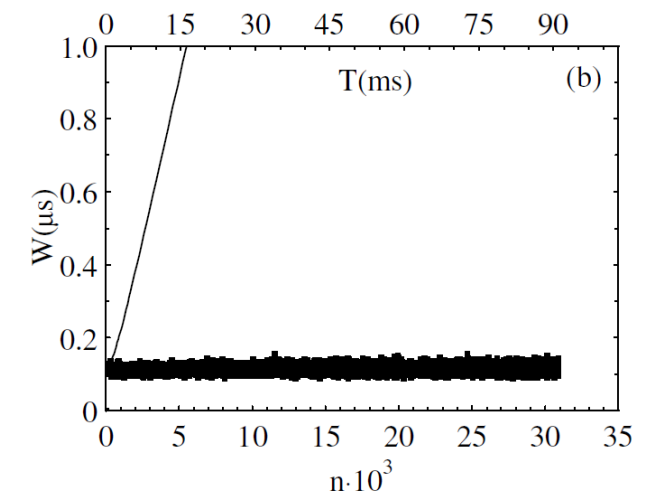
$$\eta = \frac{-2E}{f} \left[\frac{df}{dE} \right]$$



Dispersive



Self bunching



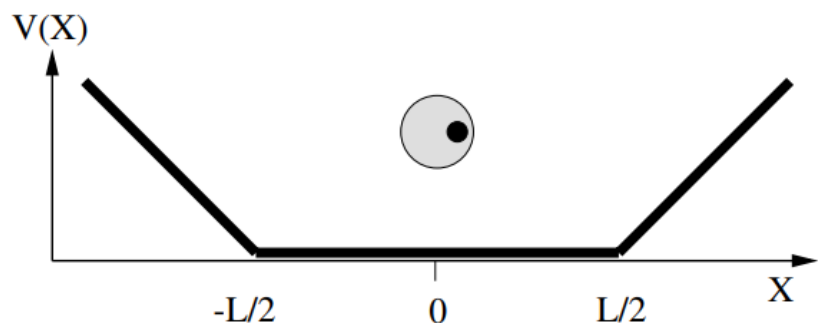
[H Pedersen et al Phys. Rev. Lett. 87, 055001, 2001](#)

[D Strasser et al Phys. Rev. Lett. 89, 283204, 2002](#)

Self Bunching in EIBT (Negative Mass Instability)

Potential profile in EIBT

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



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

$$0 < \frac{kT^2}{m^*} < 4.$$

$$\rho > \frac{4\eta\epsilon_0 p_0^2}{mqR_0^2},$$

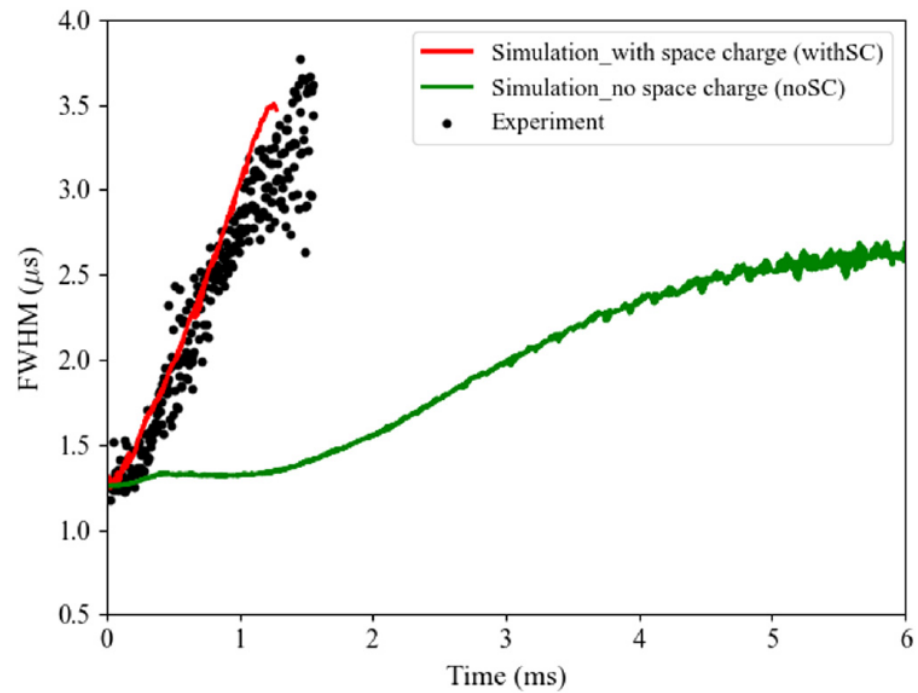
For repulsive interaction ($k < 0$), to satisfy inequality, effective mass must be negative or $\eta > 0$,

$$\eta = \frac{-2E}{f} \left[\frac{df}{dE} \right] < 0$$

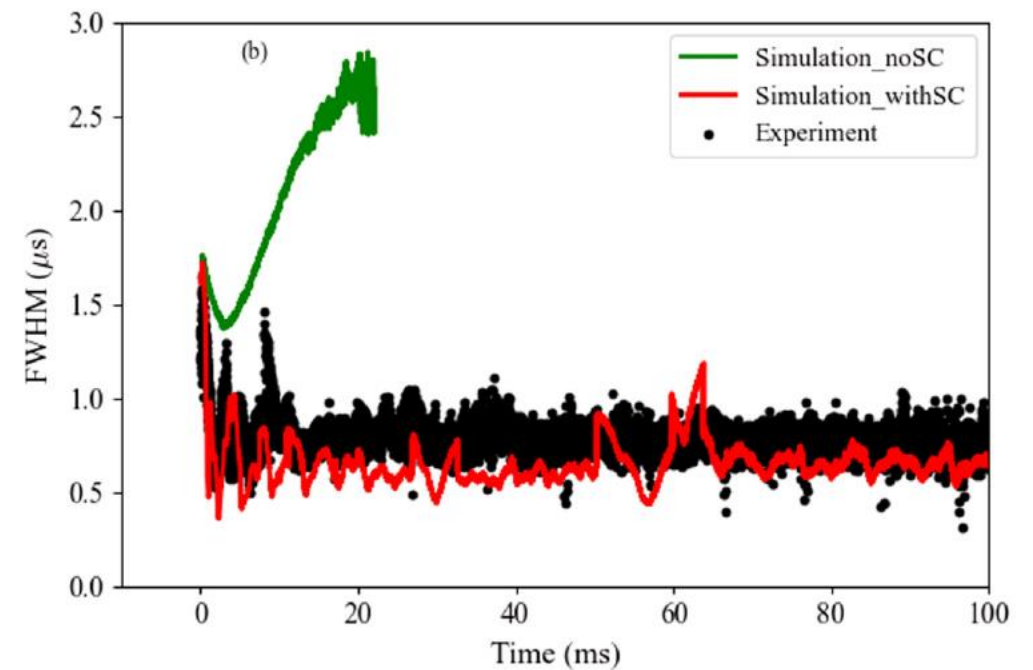
D Strasser et al Phys. Rev. Lett. 89, 283204, 2002

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 \(2011\)](#)

Two modes of EIBT

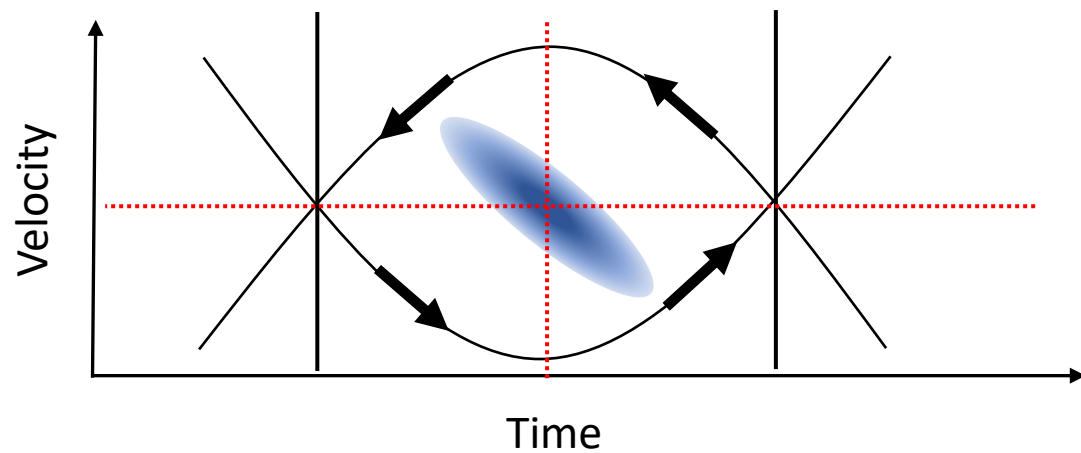
1. Dispersion of ions
2. Self Bunching of ions
[Negative mass instability]

Dynamics of ions under external time dependent perturbation

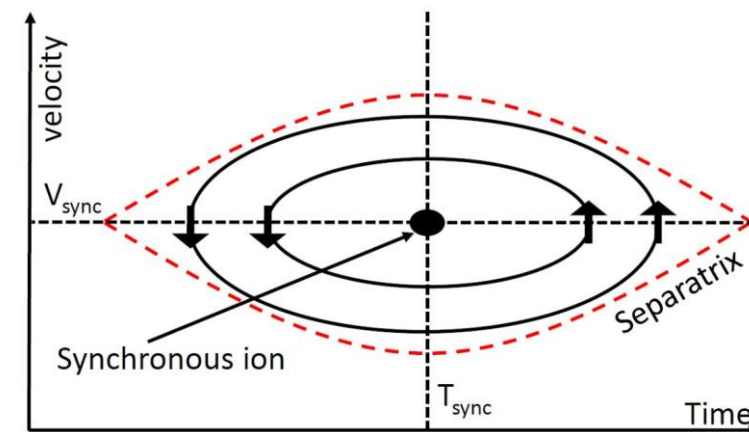
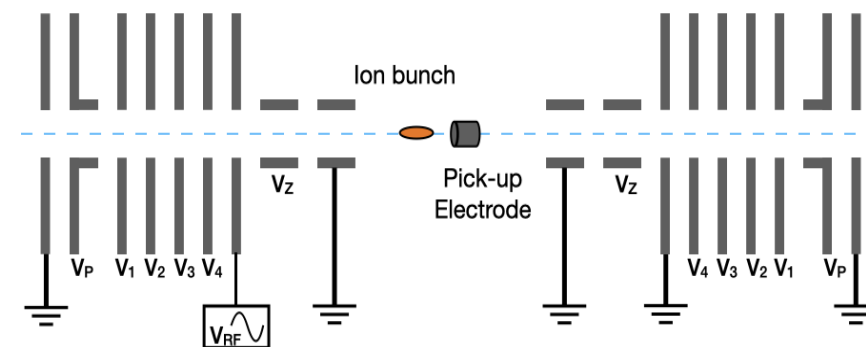
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RF Bunching of ions in EIBT

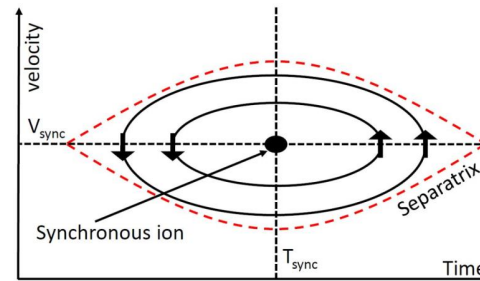
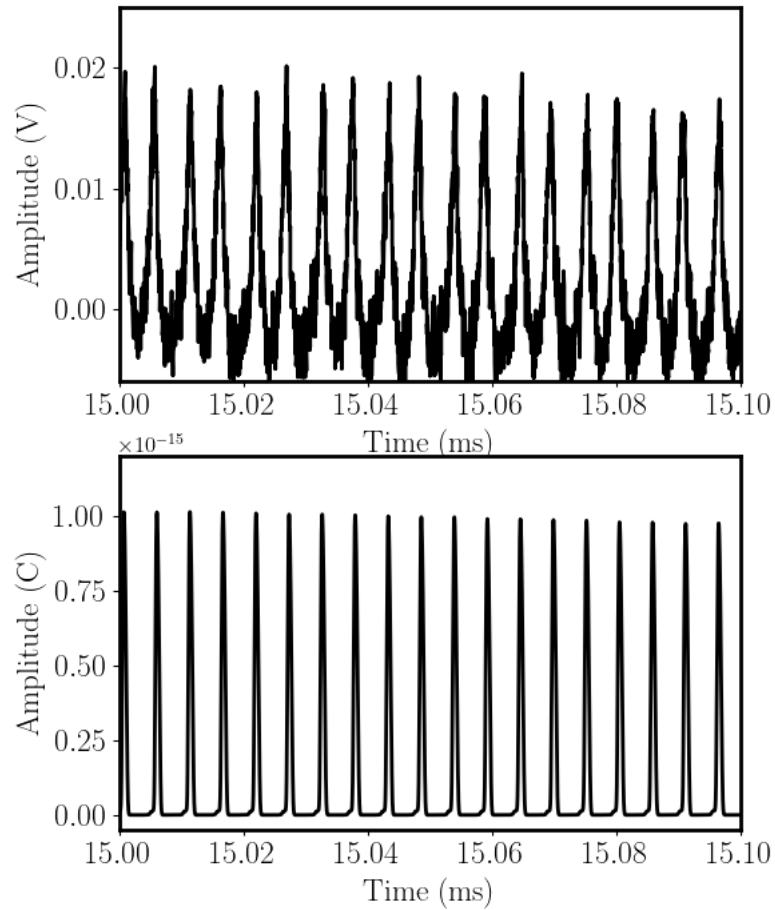
RF bunching: External field is applied with the same frequency as the natural oscillation frequency of ions in the trap



Electrostatic Ion Beam Trap (EIBT)

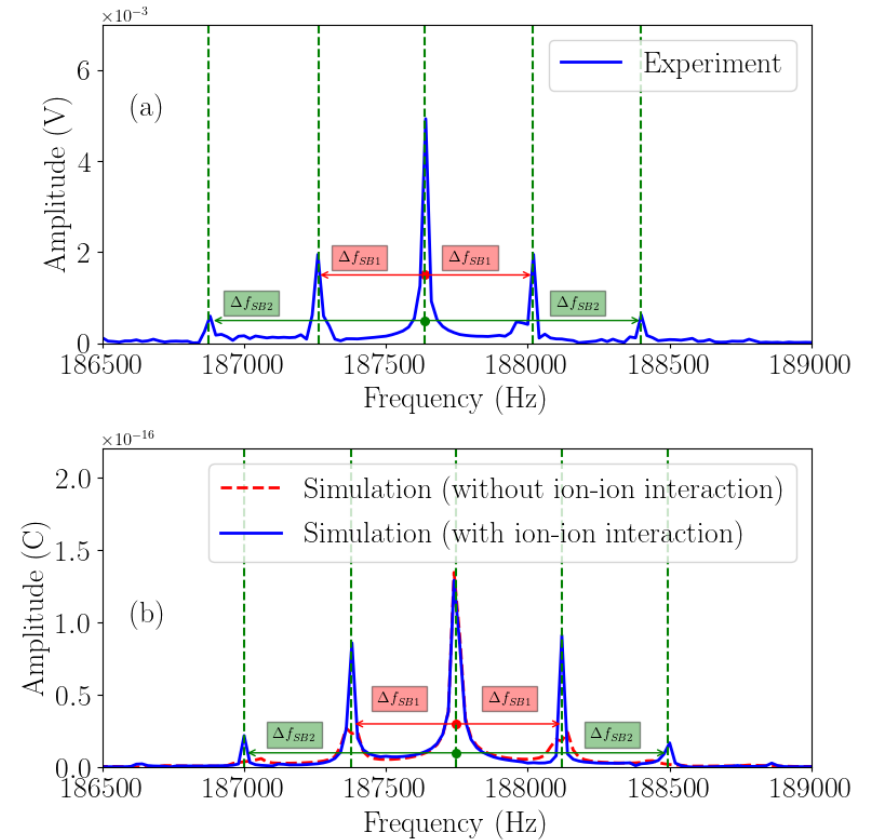


RF Bunching of ions in EIBT



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

But what does the height of side peak represent?



[D Gupta et al Phys. Rev. E, 107, 045202, 2023](#)

Filamentation in RF bucket

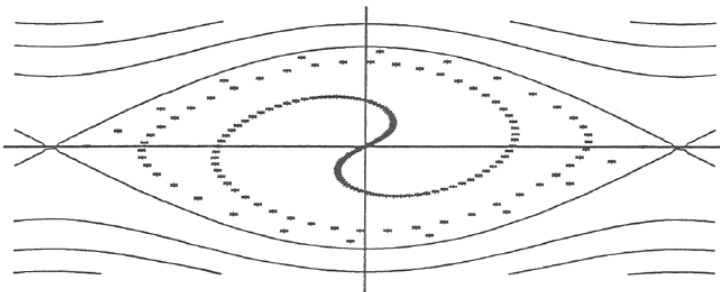
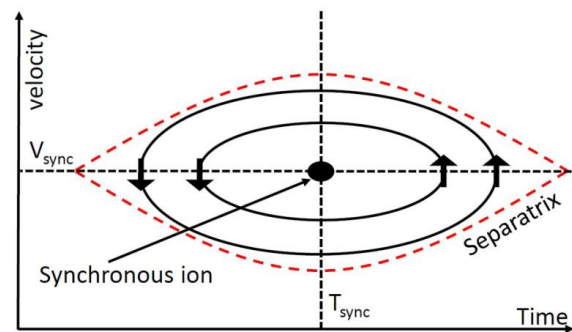
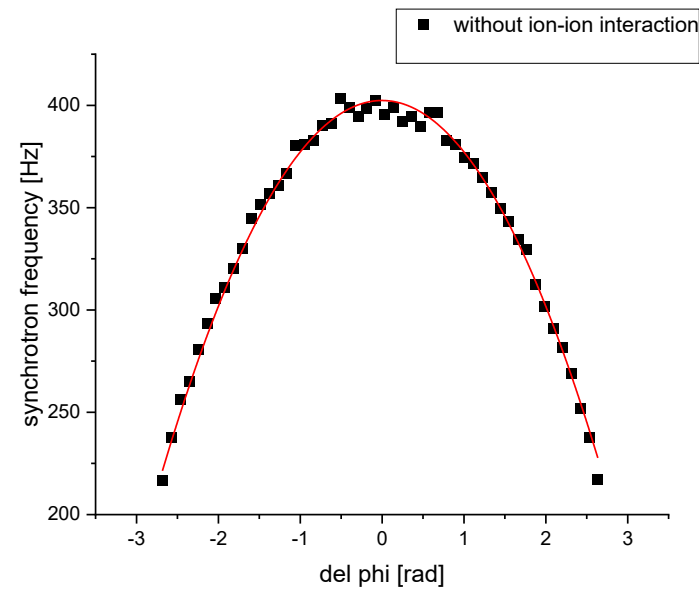
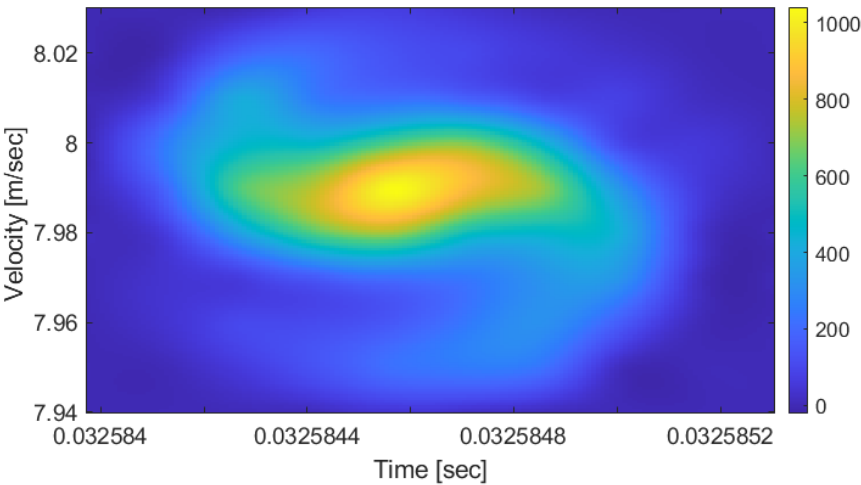


Fig. 6.16. Phase space filamentation

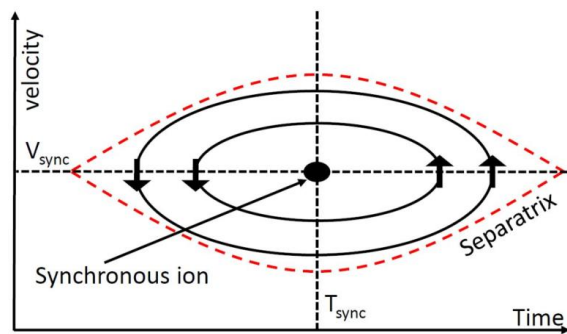
[H. Wiedemann, Particle Accelerator Physics \(Springer, Berlin, 2007\)](#)



Variation of synchrotron frequency with phase amplitude

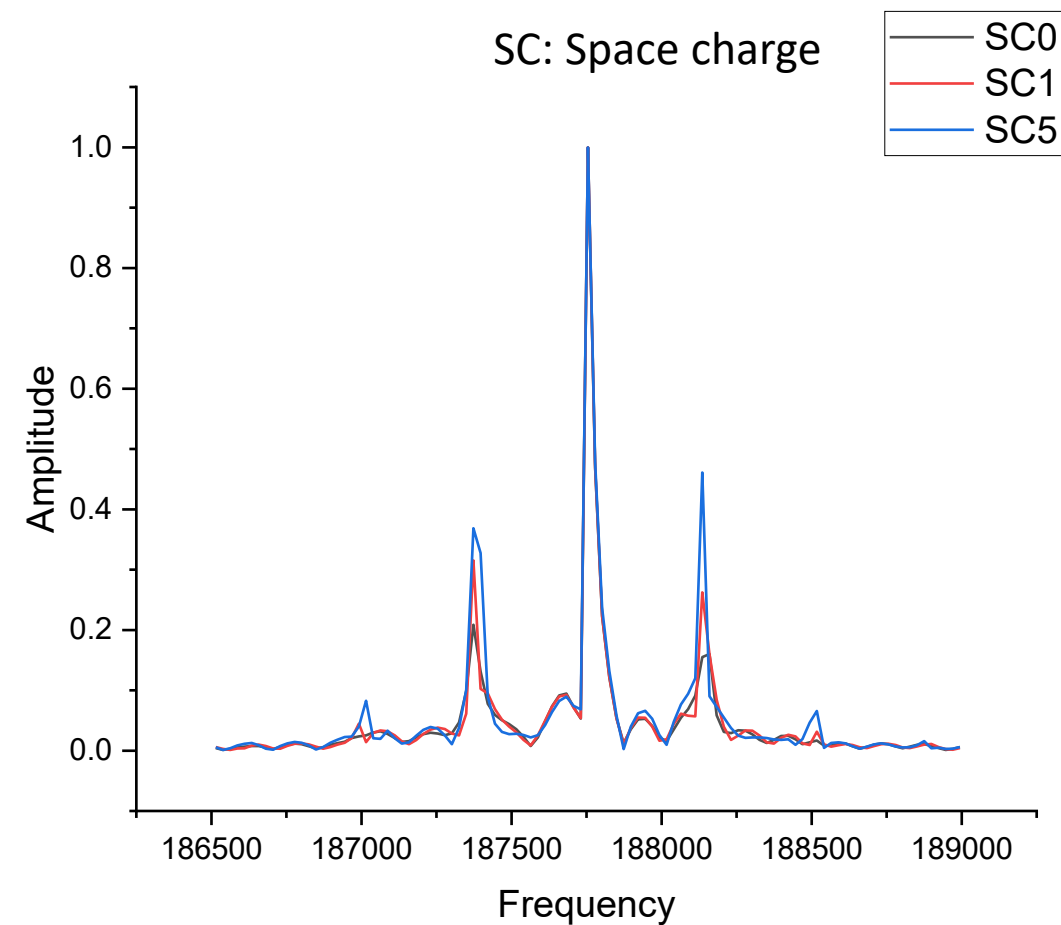


RF Bunching [effect of ion-ion interaction]

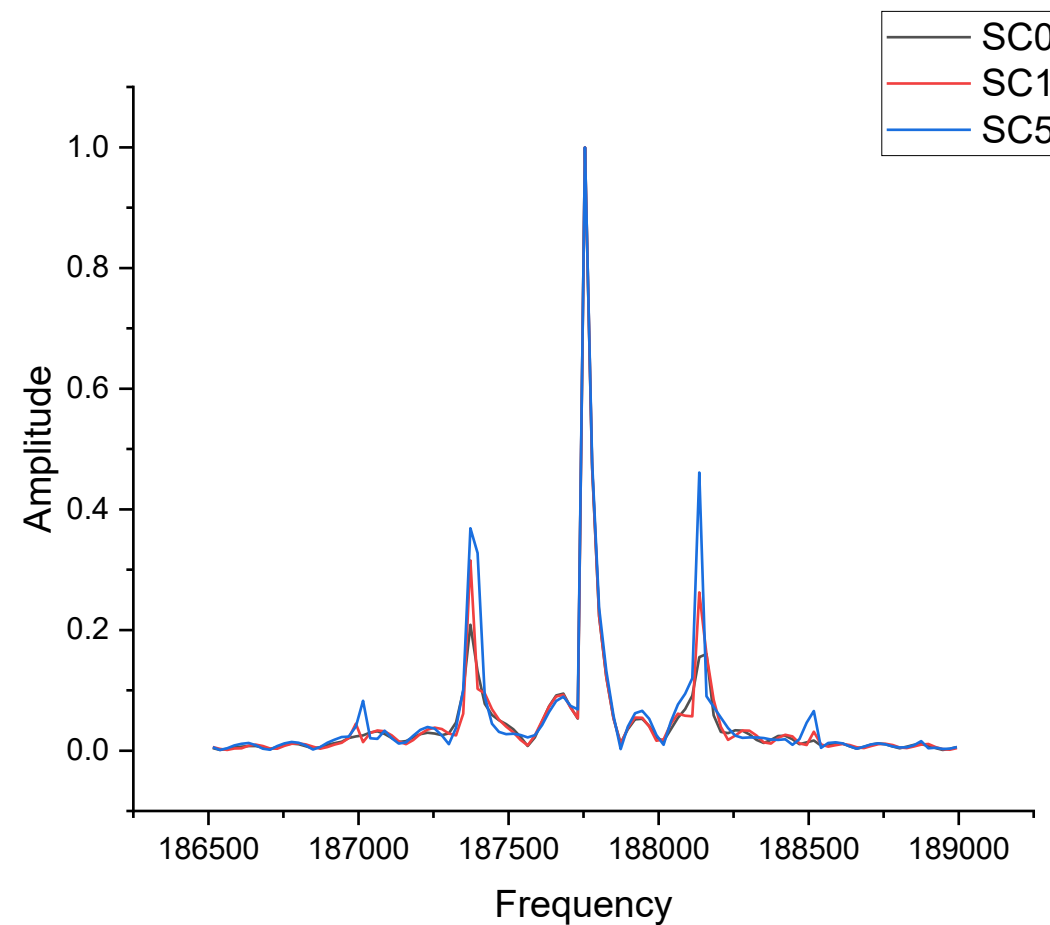
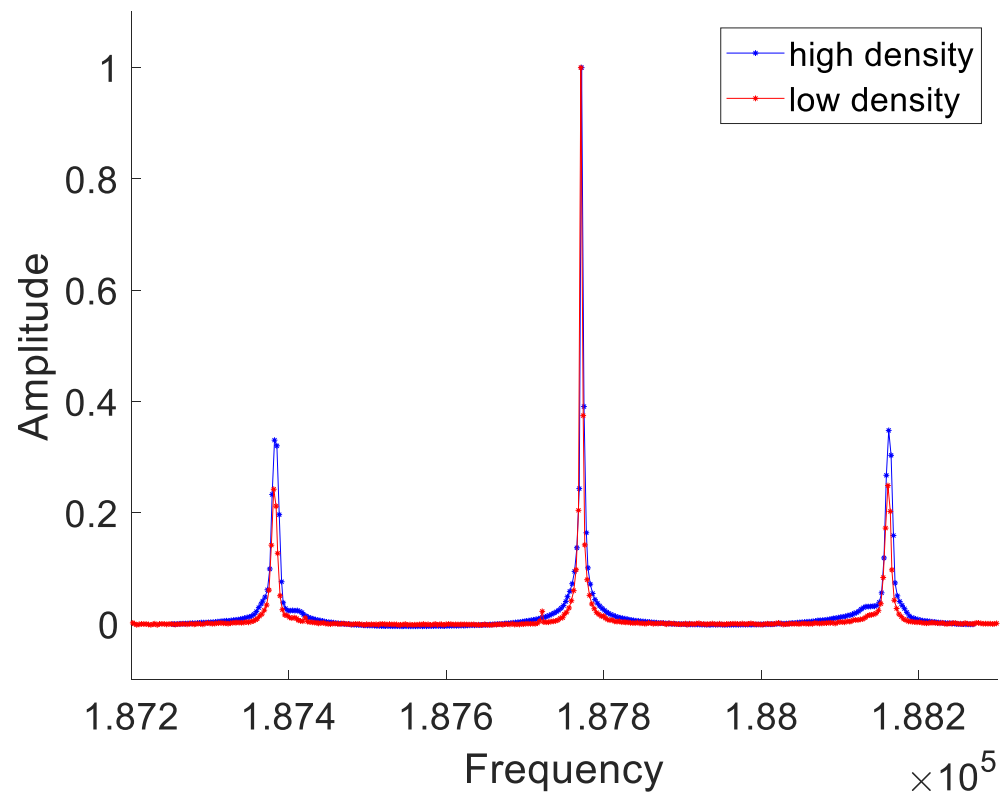


The ratio of side peaks height to main peaks increases with ion density.

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



RF Bunching [effect of ion-ion interaction]

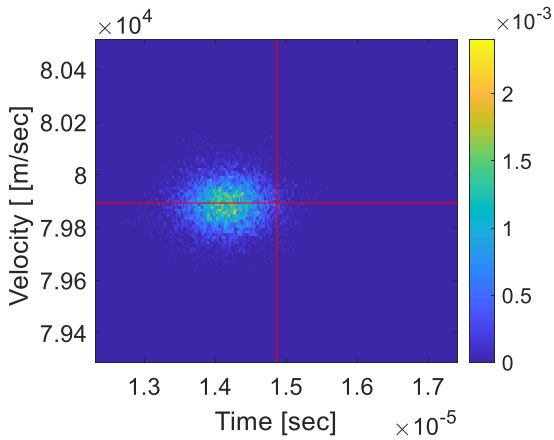
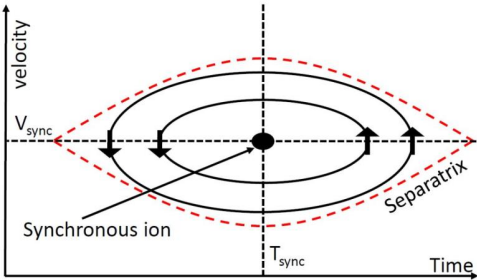


Motion of ions in RF Bucket

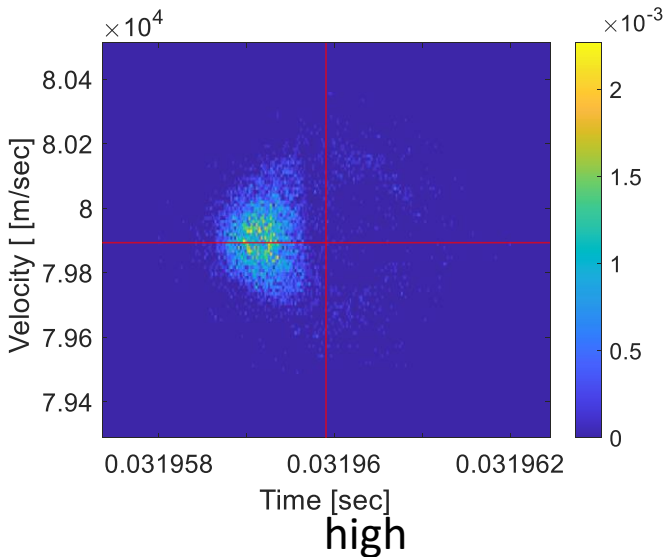
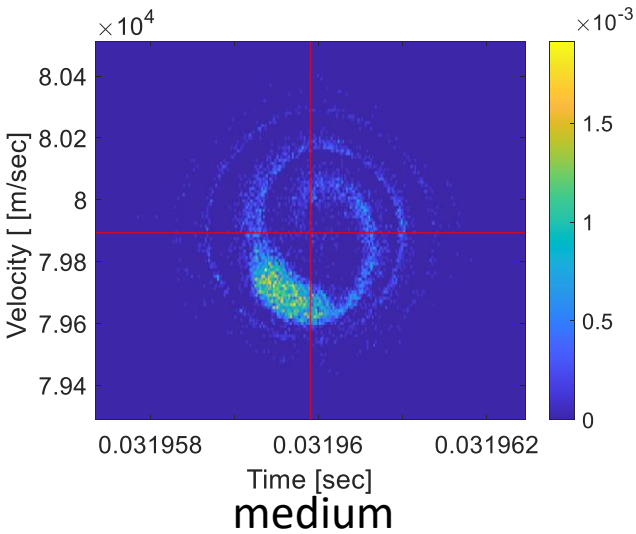
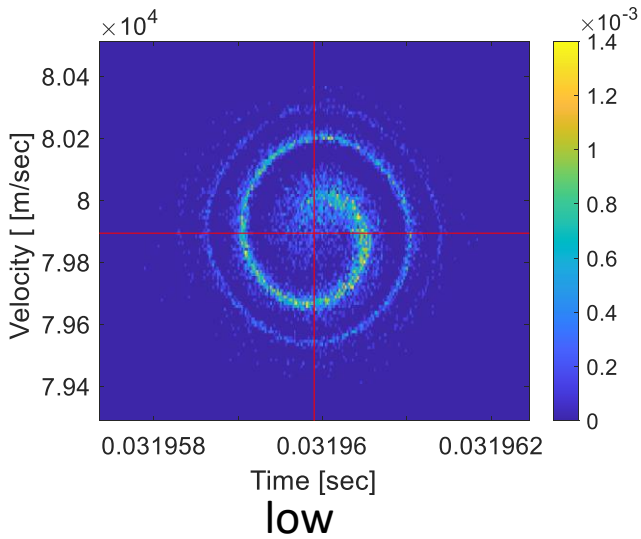
For low ion density: phase space filamentation

High ion density: inhibit phase space filamentation

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



Initial injection of bunch



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

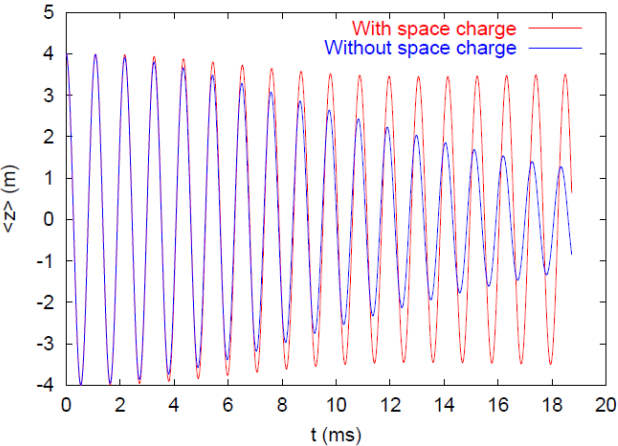
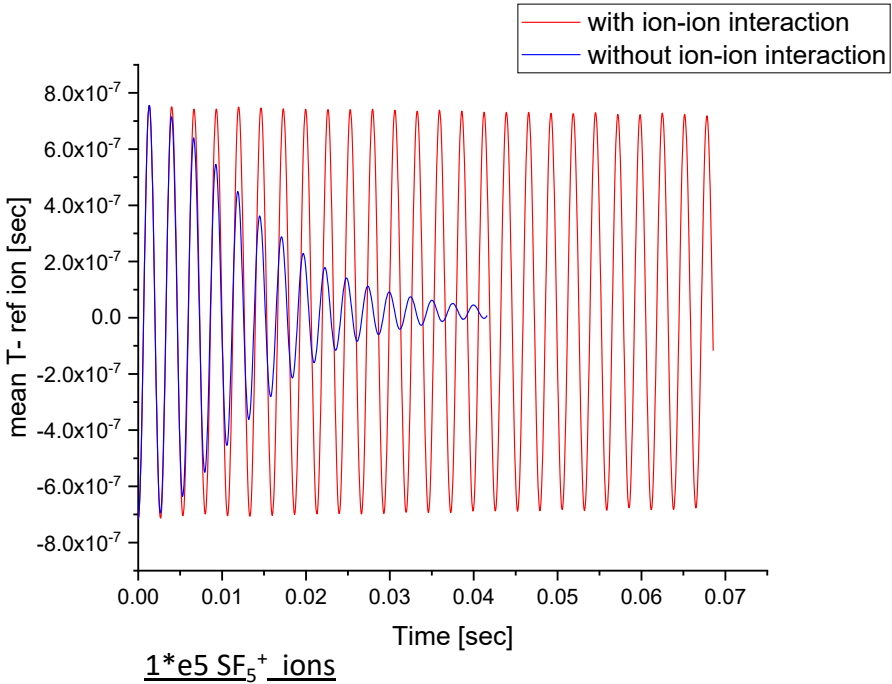
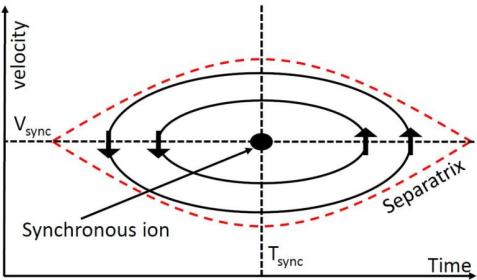


Figure 2: Decoherence of the centroid motion for a longitudinally displaced bunch due to the sinusoidal bucket non-linearity with (red) and without (blue) space charge effects.

0.5*e10 C⁶⁺ ions

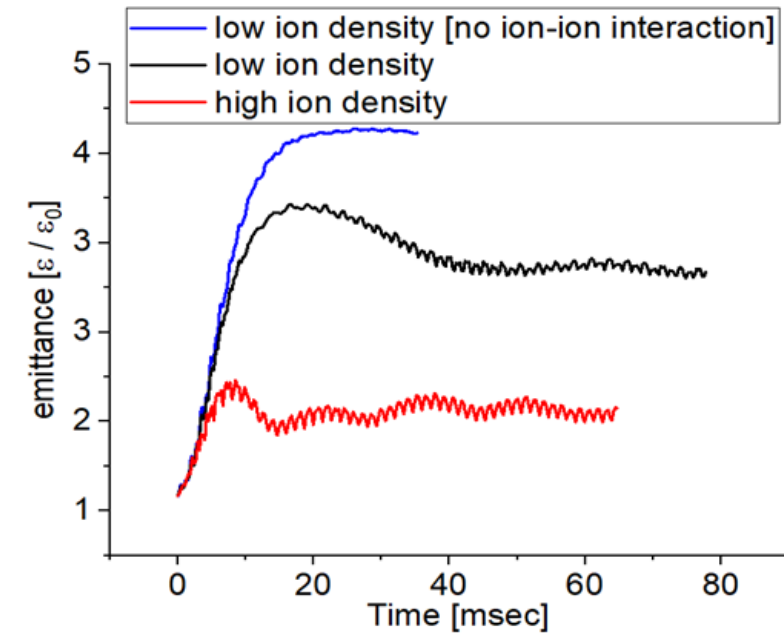


1*e5 SF₅⁺ ions

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.



Two modes of EIBT

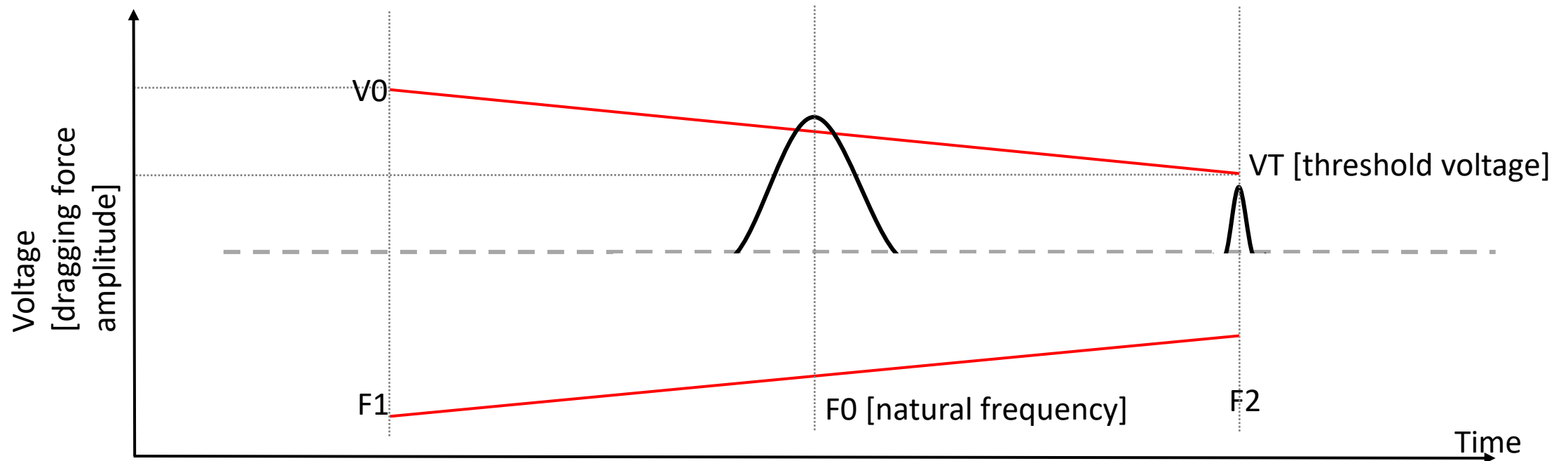
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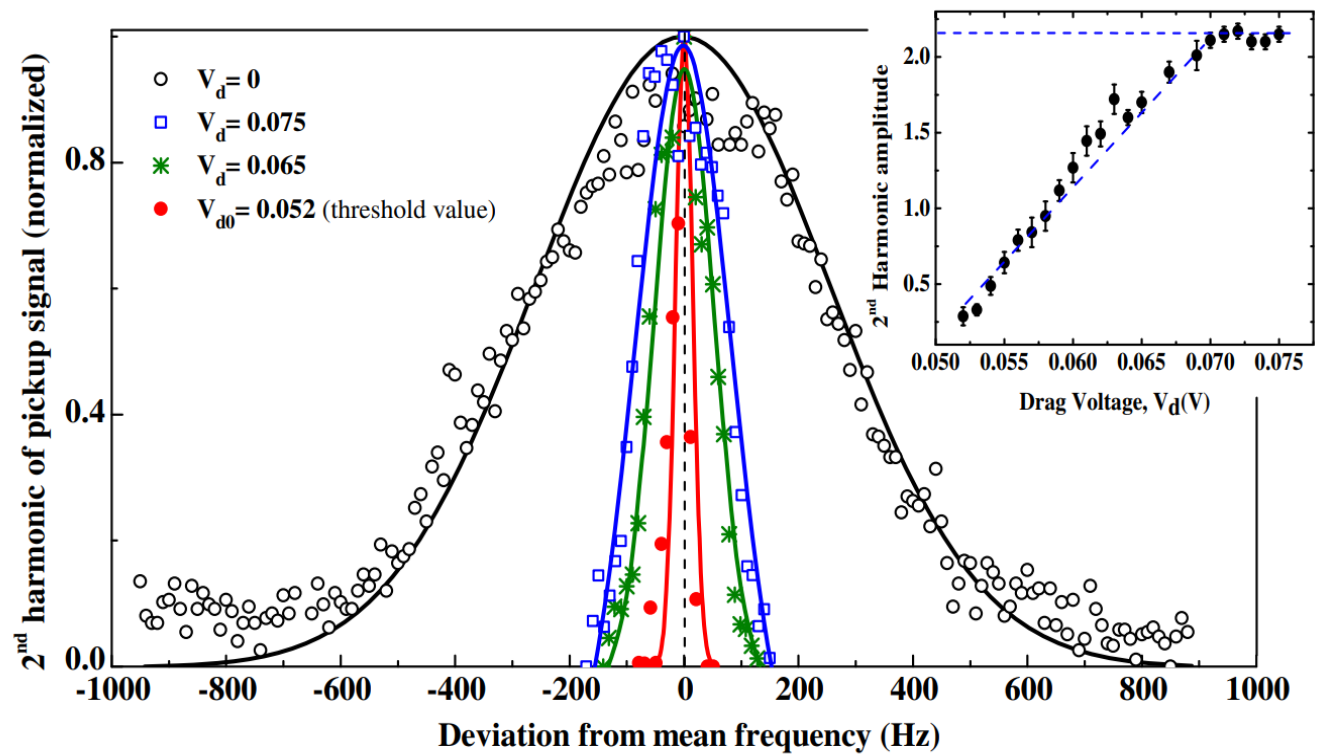
Auto-resonance Cooling of ions in EIBT

A schematic of Auto-resonance process in EIBT

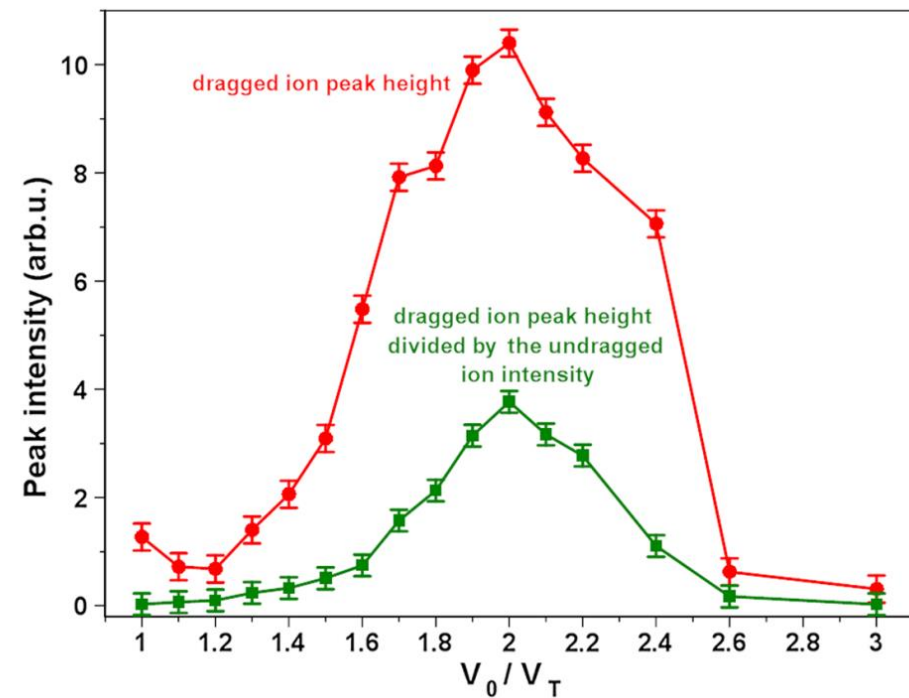


Spread in frequency distribution (σ) corresponds to temperature of ions in the trap

Auto-resonance Cooling of ions in EIBT



Distribution of ions for different dragging voltages

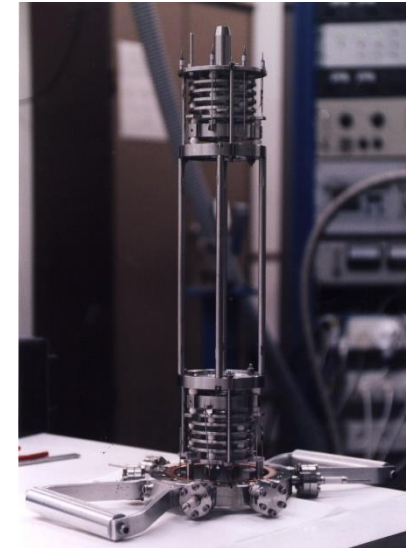


Dragged peak height as a function of amplitude ramping down ratio

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

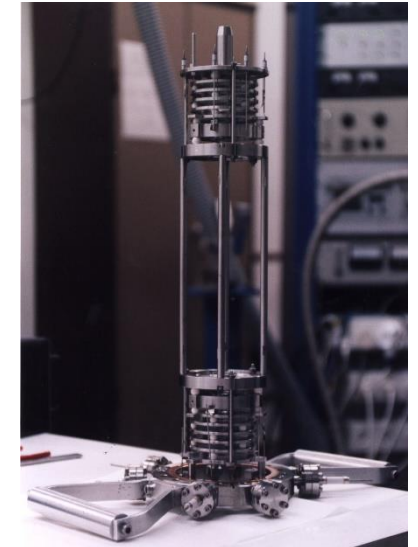
Summary

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

