Experimental Benchmarking of the Magnetized Friction Force

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High-energy cooling: need for accurate predictions of cooling times

Cooling times for relativistic energies are much longer than for typical coolers:

$$\tau = \frac{A}{Z^2} \frac{\gamma^2}{4\pi r_p r_e n_e c \eta \Lambda_c} \left(\frac{\gamma \varepsilon_{in}}{\beta_{ic}} \right)^{3/2}$$

- standard (order of magnitude) estimate of cooling times for Au ion at RHIC storage energy of 100 GeV gives τ of the order of 1000 sec, compared to a typical cooling time of the order of 0.1-1 sec in existing coolers
- while an order of magnitude estimate was sufficient for typical coolers it becomes unacceptable for RHIC with a store time of a few hours and fast emittance degradation due to Intra Beam Scattering (IBS)

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We need computer simulations which will give us cooling times estimates with an accuracy much better than an order of magnitude.

Motivation for comparison with formulas: accurate description of the Cooling Force

Cooling Force studies

1. Benchmarking of available formulas vs VORPAL code (direct simulation of friction force) for various regimes.

D. Bruhwiler et al., AIP Conf. Proc. 773 (Bensheim, Germany, 2004), p.394.

A. Fedotov et al.; Bruhwiler et al., Proceedings of PAC'05 (Knoxville, TN, 2005).

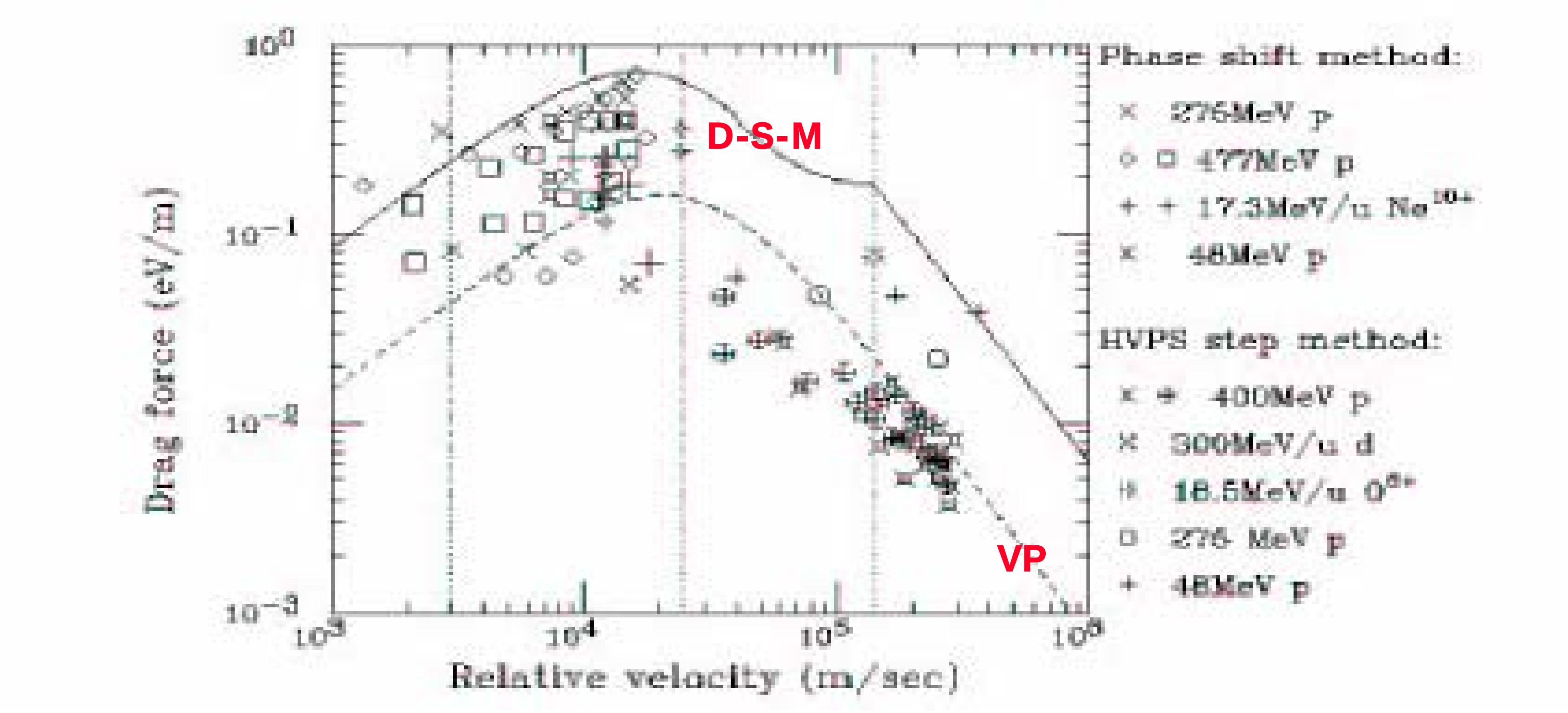
A. Fedotov et al., "Detailed studies of Friction Force", this conference.

2. Experimental benchmarking:

(CELSIUS, December 2004 and March 2005)

Example of some previous comparison of experimental data with Derbenev-Skrinsky-Meshkov (D-S-M) and V.Parkhomchuk (VP) formulas.

Y-N. Rao et al.: CELSIUS, Sweden'2001:



Motivation for our own data

"One can compare formulas with simulations – since all the parameters used in simulations are known."

"One cannot compare formulas with experiments – since many parameters in the experiments are unknown."

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This statement becomes especially true when one wants to use somebody's else data without knowing all the details/conditions under which this data was taken.

The way out is to do "well controlled" experiments – measure all the parameters which you need. And if you have uncertainty of some unknown parameters try to make an experiment which minimizes such uncertainty.

Major goals

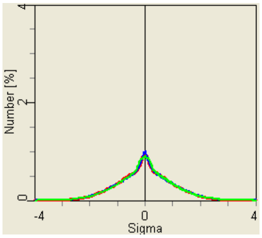
1. With well controlled experiments – systematically study friction force dependence on various parameters such as current, alignment angle, magnetic field.

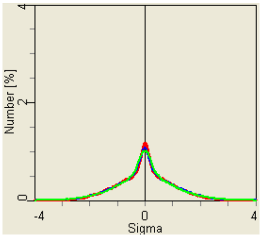
2. Using low-energy cooler try to reproduce conditions possible at high-energy cooling:

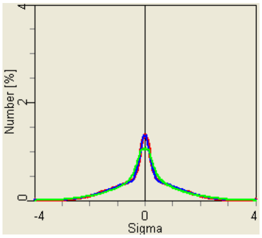
2.1) Different magnetization regimes – possible transition from good to bad magnetization

2.2) Transient cooling – when as a result of slow cooling one first has clear formation of beam core with subsequent cooling of tails – need to benchmark IBS models for such distributions.

very important for collider







Accuracy of Phase Shift method: important since it allows us to find exact location of the force maximum

1. One needs to introduce small velocity difference between electrons and ions – typically, voltage step is used to change energy of electrons.
2. One needs accurate measurement of the phase difference between the bunch and RF signal.

In our experiment at CELSIUS:

1. Changing RF frequency – allowed very fine steps in velocity difference (done before, for example, at IUCF).
2. Instead of network analyzer without phase lock loop the phase was measured by phase discriminator.

As a result, very accurate experimental data was obtained !

(see B. Galnander' presentation for more details)

Experiments at CELSIUS

1. **B=0.1T, current dependence: (Ie=500mA, 250mA, 100mA, 20 mA)**

   Measure all needed parameters, including parameters of ion distribution.

2. Dependence on V_effective:

- measured for several values of tilt in both horizontal and vertical direction – both negative and positive directions.

- always recorded longitudinal and transverse sigmas to perform accurate convolution over distributions. Measured values are close to those predicted by BetaCool simulations

- did calibration of tilt angle with both BPM's and H^0 monitor

Check with available theory.

3. Measured “transient cooling” (IBS+COOLING) both for longitudinal and transverse profiles:

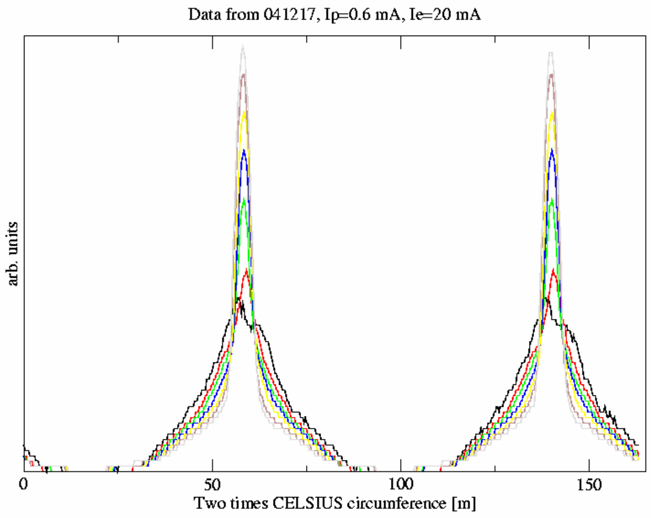
   Test models of IBS for non-Gaussian distribution –needed for high-energy cooling.

4. Various values of B with various currents: Ie=500mA, 300mA, 100mA, 50 mA (B=0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.12T)

   Study various regimes of magnetization – needed for high-energy cooling.

5. Effects of solenoid errors.

   Study description via V_effective.



Magnetized logarithm:

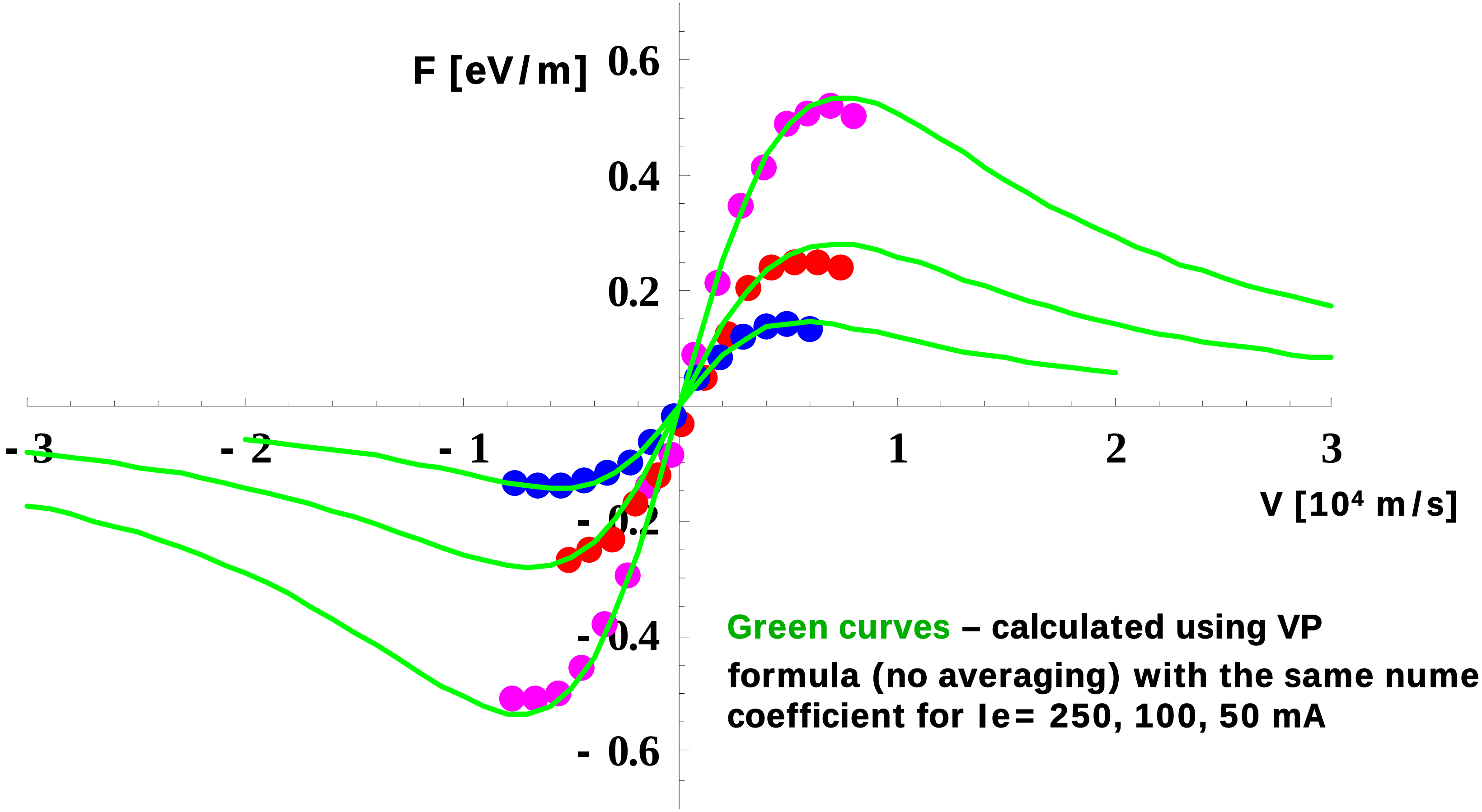
L_M=1.5->0.7

V. Parkhomchuk's (VP) empiric formula

empiric formula (VP) – single-particle formula

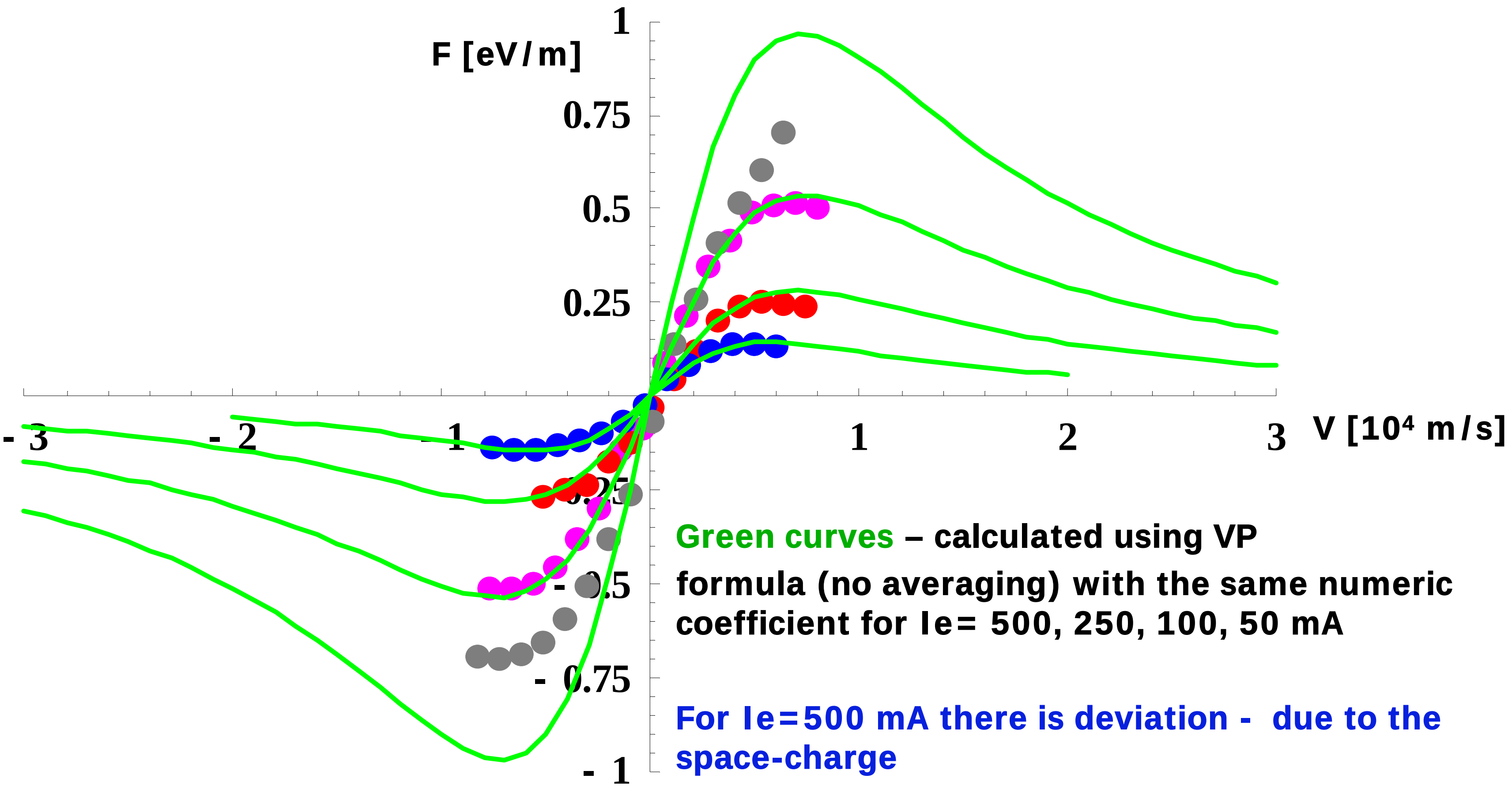
$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}+\rho_{\min}+r_{L}}{\rho_{\min}+r_{L}}\right)\frac{\mathbf{V}_{ion}}{\left(V_{ion}^{2}+V_{eff}^{2}\right)^{3/2}}$$

March 2 data: B=0.1T, electron current Ie=250 (pink color), 100 (red), 50 (blue) mA



Green curves – calculated using VP formula (no averaging) with the same numeric coefficient for Ie= 250, 100, 50 mA

March 2 data: B=0.1T
Ie=500 (gray), 250 (pink), 100 (red), 50 (blue) mA



Green curves – calculated using VP formula (no averaging) with the same numeric coefficient for Ie= 500, 250, 100, 50 mA

For Ie=500 mA there is deviation - due to the space-charge

Electron current Ie=500mA

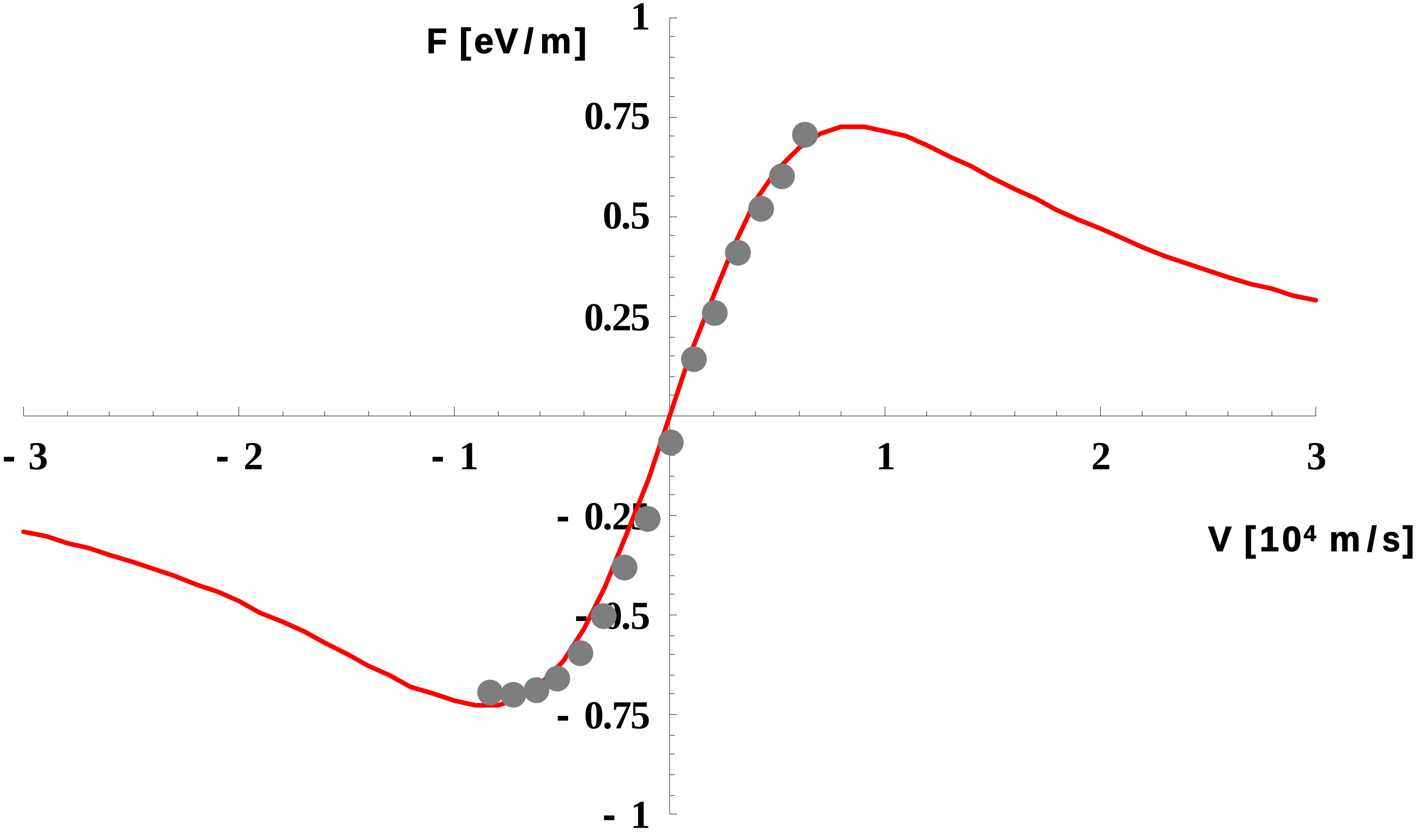
For high currents of the electron beam the space-charge of the electron beam becomes important:

The electron drift in crossed fields – the electric and magnetic fields of the electron beam and longitudinal magnetic field of the cooler:

$$v_d = \frac{2I}{B\beta\gamma^2}\frac{r}{a^2}$$

For measured distribution of the proton beam for the case under comparison (March 2, set#23, B=0.1T, Ie=500mA) - V_drift=6-7*10^3m/s – which is an additional contribution to V_effective in the cooling force formulas.

March 2 data: Ie=500mA, B=0.1T – formula vs experiment with additional contribution to V_effective from V_drift



Fits with single-particle formulas

1. Current dependence – friction force scales linearly with current/density – as expected from formula.
2. Numeric coefficient for the force is in agreement with the one in Parkhomchuk's formula. Also, it can be adjusted to agree with Derbenev's coefficient (which results in only slightly different effective velocity) – the coefficients are similar for the region of low relative velocities ($1/\pi$ vs $1/(2\pi)^{1/2}$).
3. Note that Coulomb logarithm depends on relative ion velocity and V_effective – fitting was done with such velocity-dependent logarithm.
4. Fitted V_effective has very weak current dependence:

   0.74-0.78*10^4 m/s

Observations

- Using single-particle formula allows to fit experimental data and extract V_effective.
- However, since rms velocity spreads of cooled proton beam are significant (for our measurements, we would need to have dp/p=1e-5 and ε=1e-9 um to neglect this effect, while parameter of the proton beam with which we did measurements typically had about dp/p=5e-5 and ε=5e-8 um), fitted V_effective has contribution from this effect.

The accurate procedure is then to measure rms velocities of the distribution and average single-particle formulas over the proton distribution.

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This was done for all 10's of friction force curves which were measured for various parameters

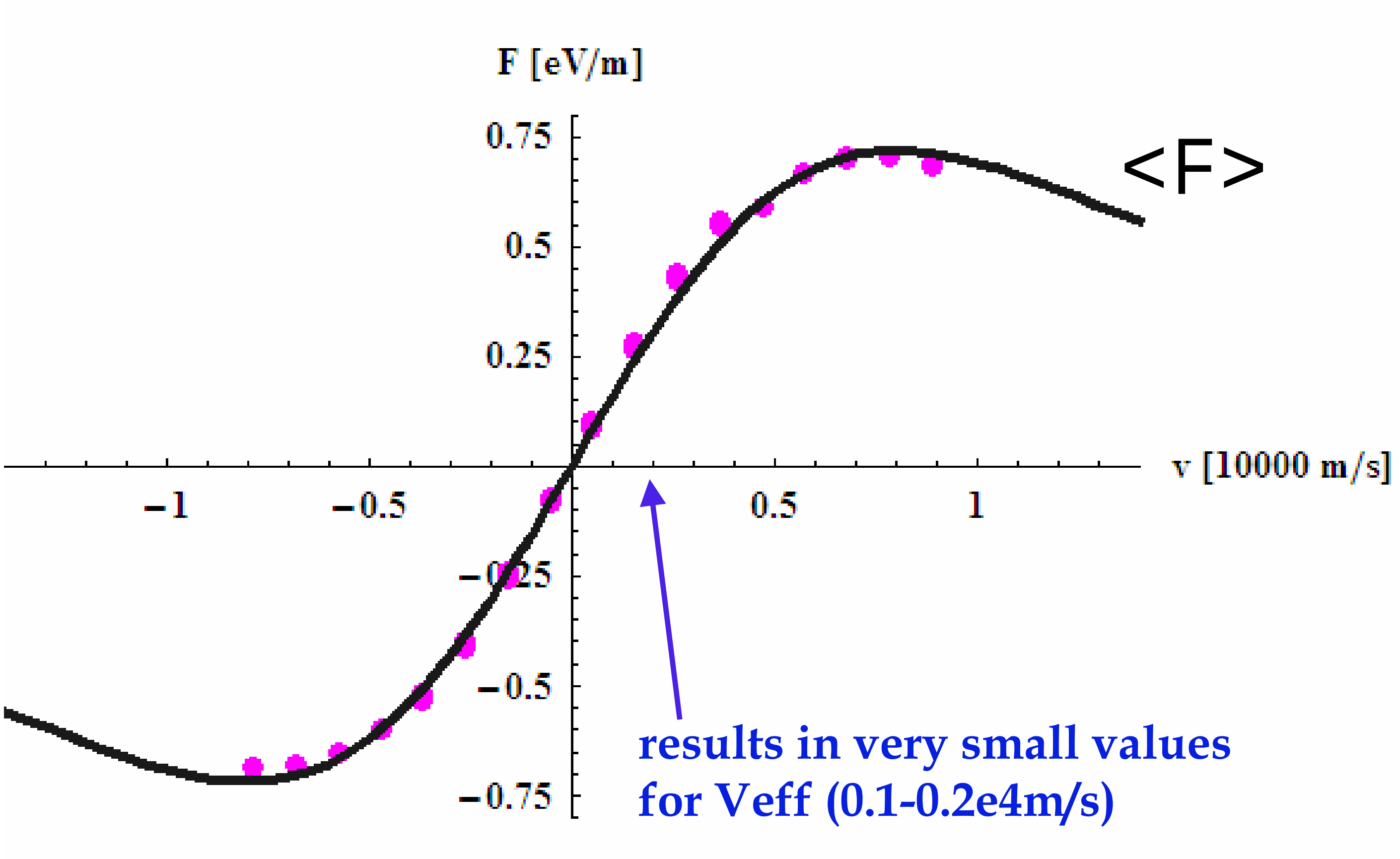
Detailed comparison: Averaging over ion distribution

$$\langle F\rangle = C\,\frac{4\pi Z^2 e^4 n_e}{m\sqrt{2\pi}\,\Delta_\perp^{\,2}\Delta_\parallel}\int_0^\infty\!\int_{-\infty}^\infty \frac{v_\parallel L_M(v_\perp, v_\parallel, v_{eff})}{(v_\perp^{\,2}+v_\parallel^{\,2}+v_{eff}^{\,2})^{3/2}}\exp\left(-\frac{v_\perp^{\,2}}{2\Delta_\perp^{\,2}}-\frac{(v_\parallel - v_0)^2}{2\Delta_\parallel^{\,2}}\right) v_\perp\, dv_\parallel\, dv_\perp$$

rms parameters of proton beam were measured for each measurement of friction force curve.

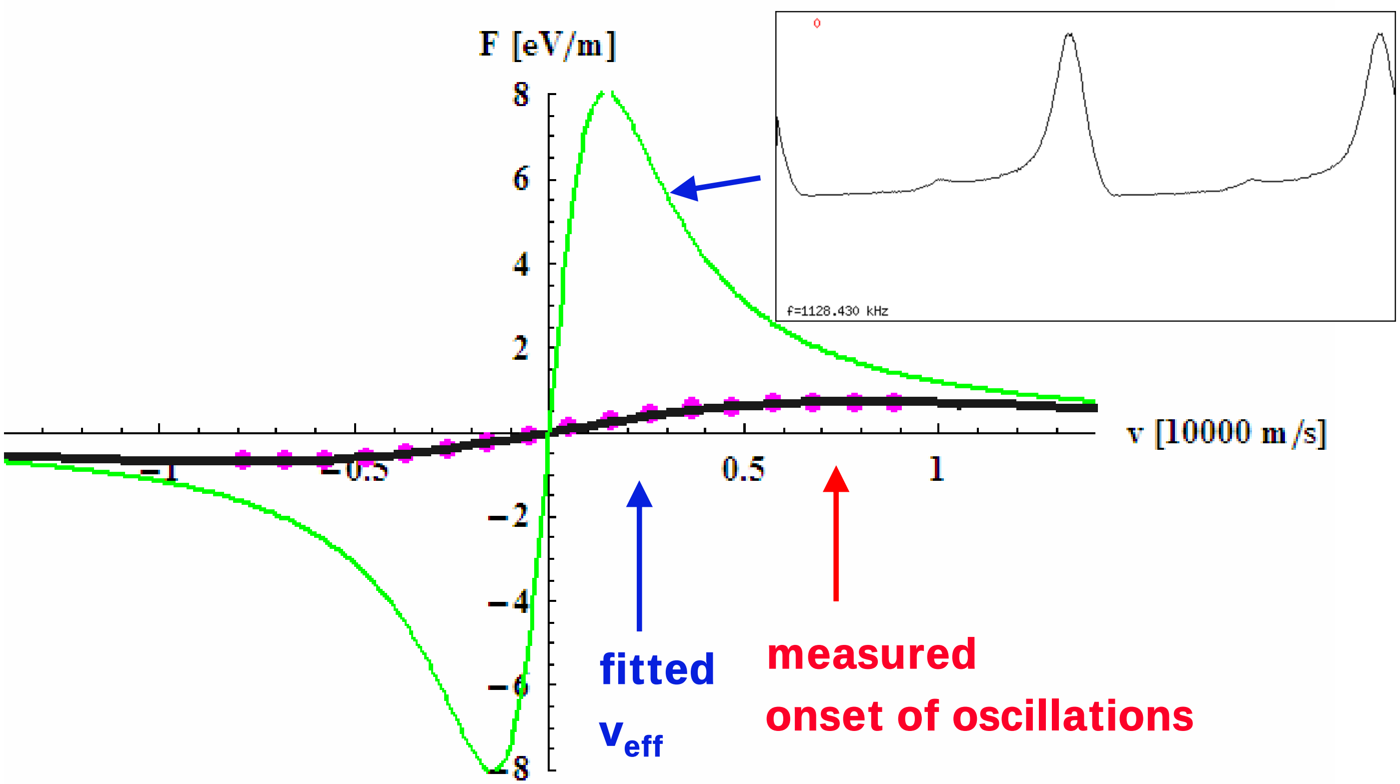
1. **First approach: assume C is known and treat V$_{eff}$ as fitting parameter.**
2. **Second approach: assume V$_{eff}$ is known from measurements and treat C as fitting parameter.**

B=0.12T, Ie=300mA
Friction force averaged over proton distribution with measured rms velocity spread



results in very small values for Veff (0.1-0.2e4m/s)

First approach – one fitting parameter Veff



Longitudinal profiles:

expected onset of oscillations for small veff

fitted v_{eff}

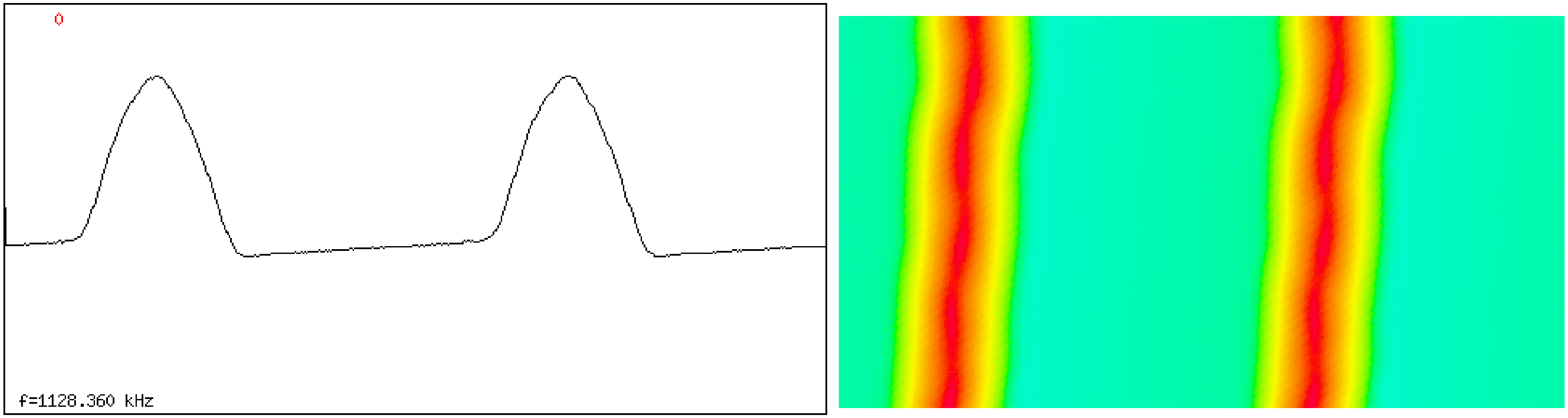
measured onset of oscillations

$$\langle F\rangle = C\,\frac{4\pi Z^2 e^4 n_e}{m\sqrt{2\pi}\,\Delta_\perp^{\,2}\Delta_\parallel}\int_0^\infty\int_{-\infty}^\infty \frac{v_\parallel L_M(v_\perp, v_\parallel, v_{eff})}{(v_\perp^{\,2}+v_\parallel^{\,2}+\boxed{v_{eff}}^{\,2})^{3/2}}\exp\left(-\frac{v_\perp^{\,2}}{2\Delta_\perp^{\,2}}-\frac{(v_\parallel - v_0)^2}{2\Delta_\parallel^{\,2}}\right)v_\perp\,dv_\parallel\,dv_\perp$$

$C=1/\pi$

Measurements of longitudinal friction force maximum

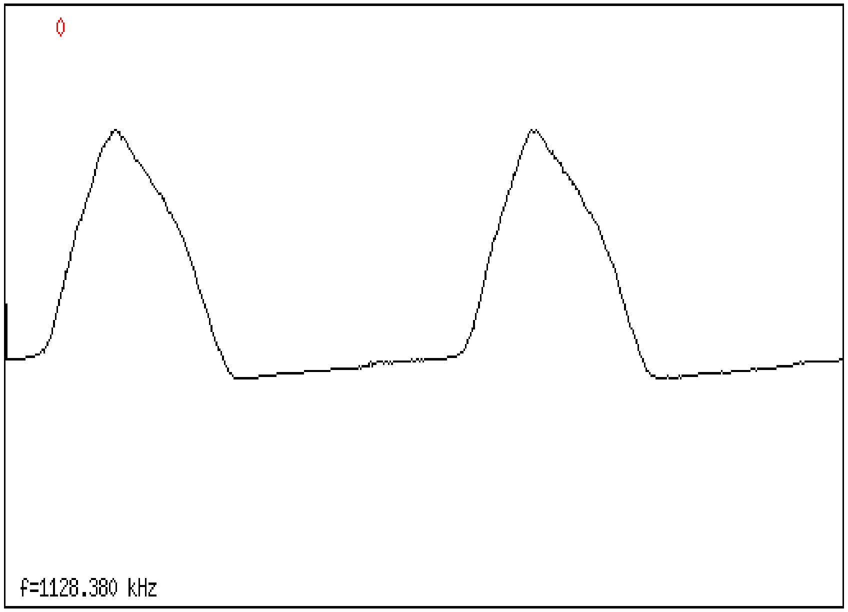
Approaching friction force maximum

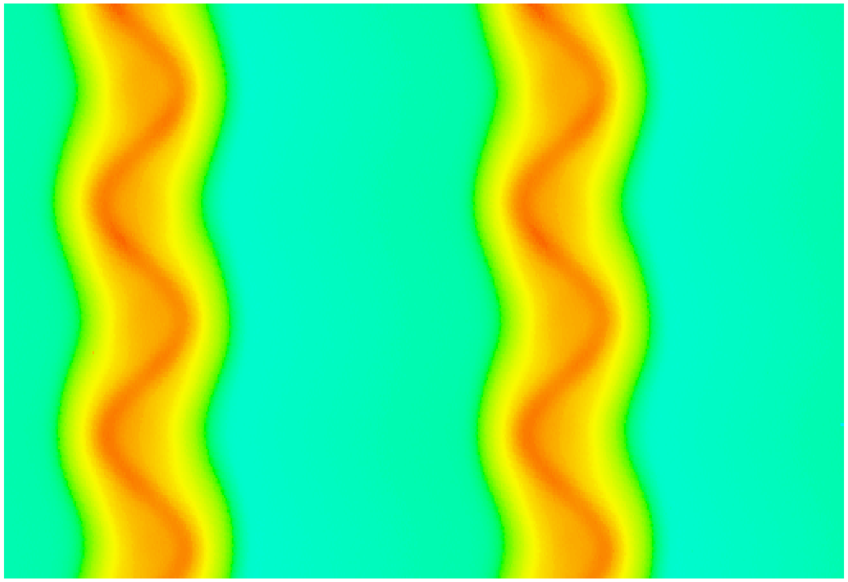


Longitudinal profiles

Measurements of longitudinal friction force maximum

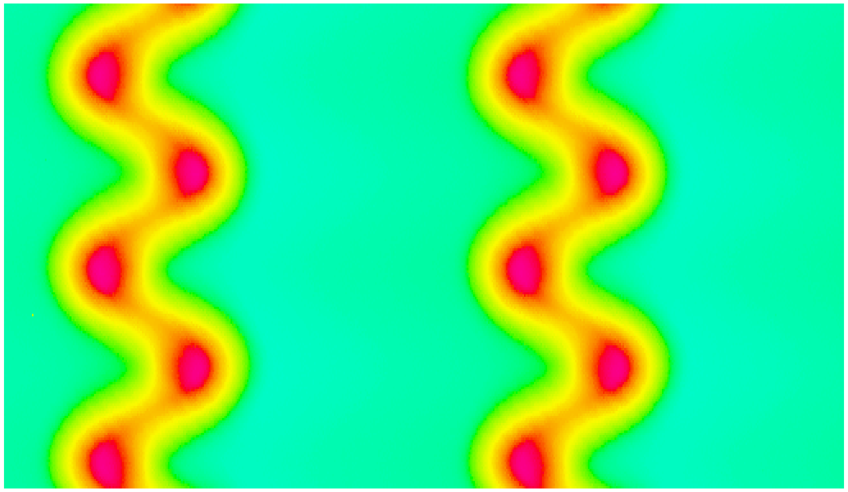
just past the maximum



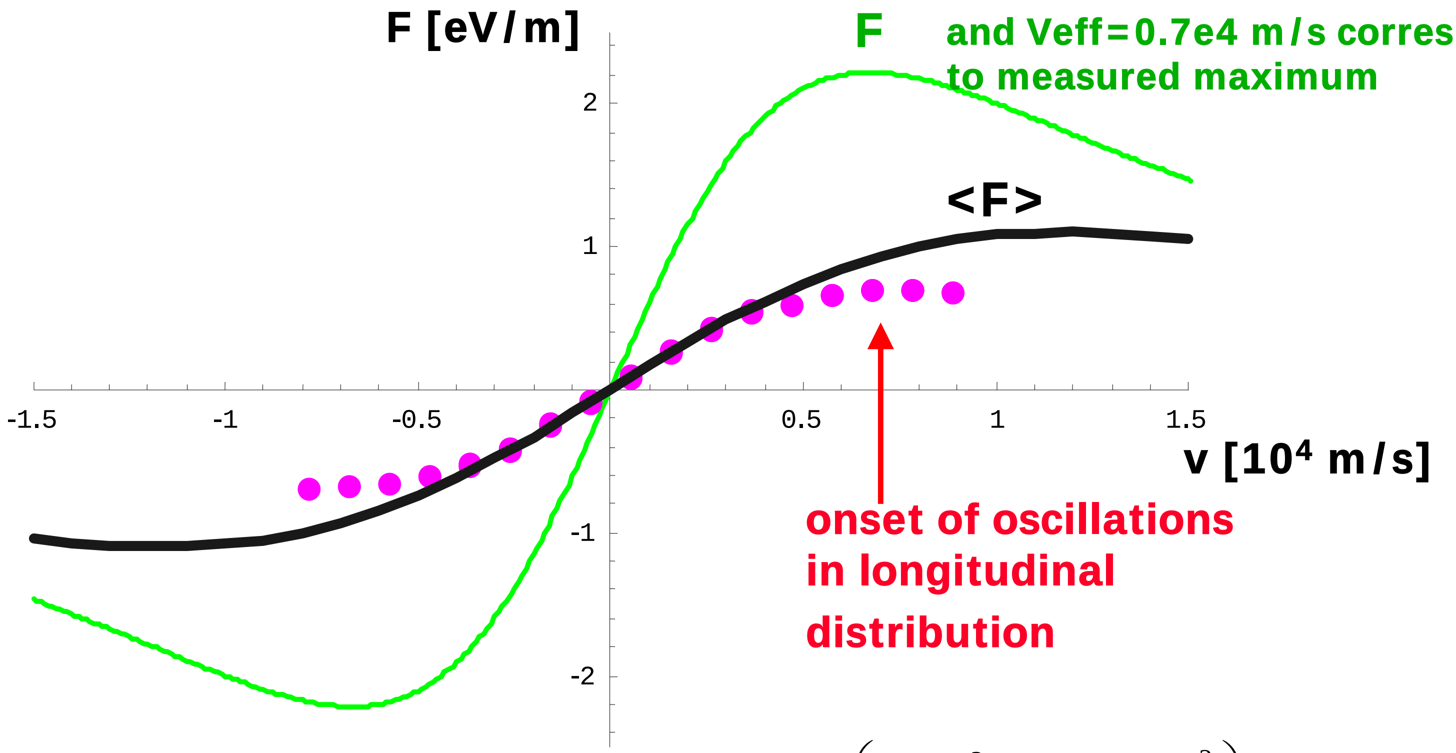


Measurements in non-linear part of the friction force

far past the maximum



Second approach – one fitting parameter C (with measured Veff)

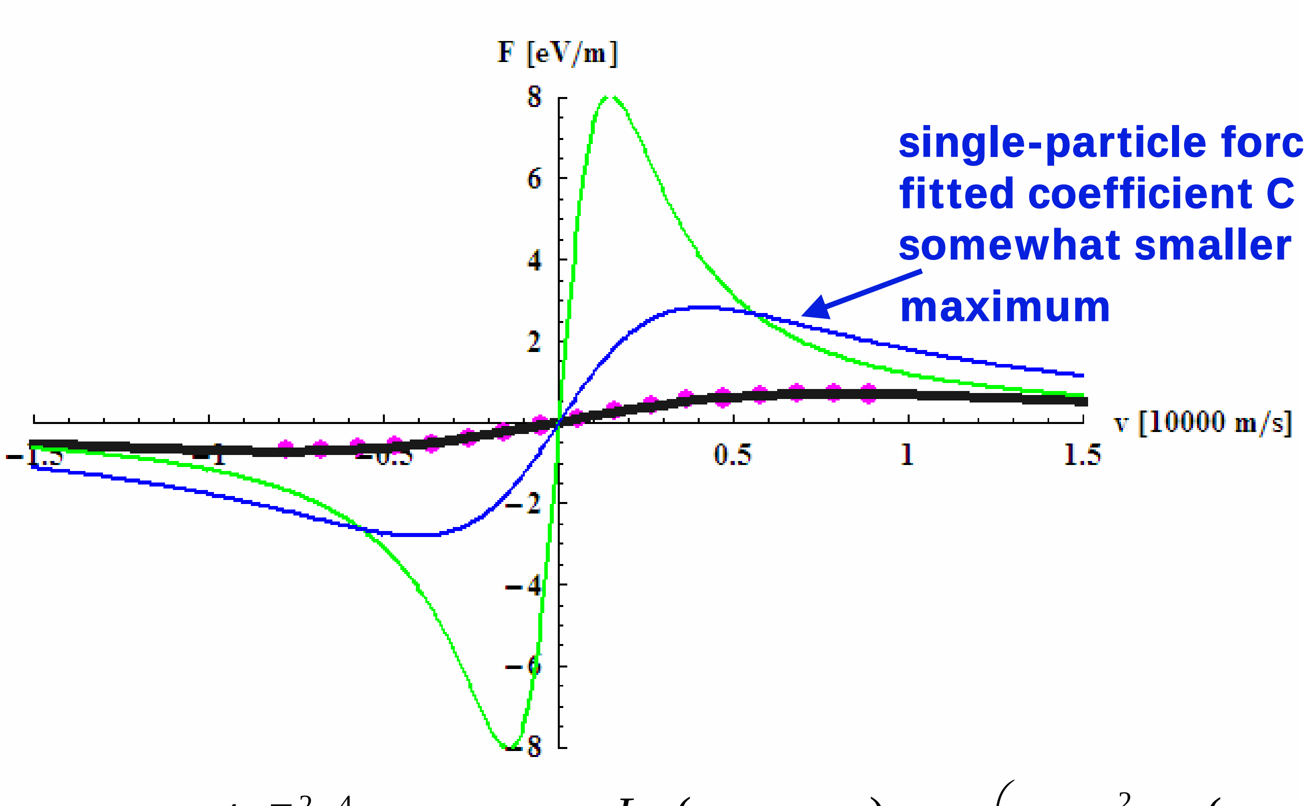


single-particle force with C=2.8/π and Veff=0.7e4 m/s corresponding to measured maximum

onset of oscillations in longitudinal distribution

$$\langle F\rangle = \boxed{C}\,\frac{4\pi Z^2 e^4 n_e}{m\sqrt{2\pi}\,\Delta_\perp^2\Delta_\parallel}\int_0^\infty\int_{-\infty}^\infty \frac{v_\parallel L_M(v_\perp, v_\parallel, v_{eff})}{(v_\perp^2+v_\parallel^2+v_{eff}^2)^{3/2}}\exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2}-\frac{(v_\parallel-v_0)^2}{2\Delta_\parallel^2}\right)v_\perp dv_\parallel dv_\perp$$

Second and ½ approach – basically, both C and Veff are fitting parameters (plus averaging)



single-particle force with larger fitted coefficient C with Veff somewhat smaller than measured maximum

$$\langle F\rangle = \boxed{C}\frac{4\pi Z^2 e^4 n_e}{m\sqrt{2\pi}\Delta_\perp^2\Delta_\parallel}\int_0^\infty\int_{-\infty}^\infty \frac{v_\parallel L_M(v_\perp,v_\parallel,v_{eff})}{(v_\perp^2+v_\parallel^2+\boxed{v_{eff}^2})^{3/2}}\exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2}-\frac{(v_\parallel-v_0)^2}{2\Delta_\parallel^2}\right)v_\perp dv_\parallel dv_\perp$$

Summary – benchmarking of experiments

At CELSIUS, we were able to measure longitudinal friction force with very good precision which allows us to use experimental data for accurate benchmarking of theory and simulations.

A careful experimental study of various parameters was performed:

1) Current dependence
2) Dependence of tilt between electron and proton beams
3) Dependence on solenoid errors
4) Various degrees of magnetization
5) Transient cooling

Benchmarking of experimental data for each of the experiments is presently in progress.

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