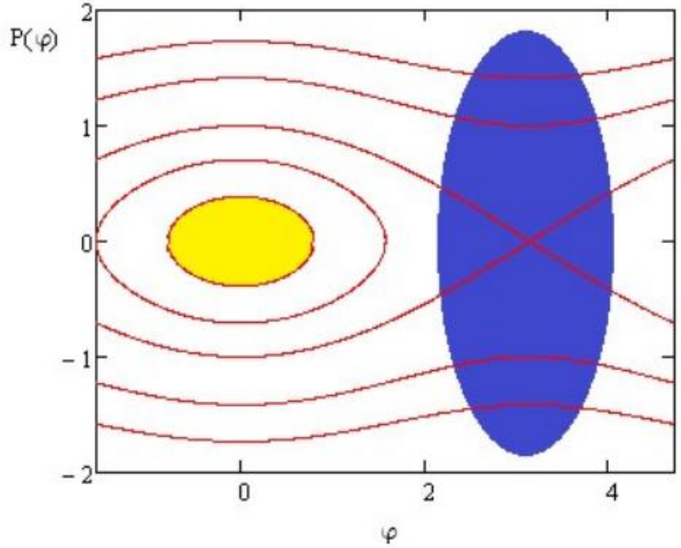
Methods of electron cooling friction force measurement suitable for NICA Booster synchrotron

Daniil K. Chumakov
NICA Dispatch Service, LHEP JINR/Диспетчерская служба NICA ЛФВЭ ОИЯИ
National Research Tomsk Polytechnic University

AYSS-2025
Alushta, Russia

Why do we need cooling

- **Intensity** of beam is **crucial** for colliders at each stage;
- NICA Booster is the first stage after linac;
- Tasks of NICA Booster [1]:
  - Accumulate ions (up to 10x);
  - Form required phase volume of beam;
  - Accelerate intense beam to 578 MeV/nucleon;
  - Strip accelerated particles to bare nuclei on stripping foil.



Scheme of repeated single-lap injection [2]

- Beam fills in available phase space;
- **No accumulation** using only magnetic optics – we need **dissipative force**;
- Cooling exploits such forces, **reduces volume** of beam **in phase space**;

- Injection → Cooling→Phase space reduced →Repeat;
- Circulating beam accumulates until **diffusion power** exceeds **cooling power**

[1] NICA Booster: a new-generation superconducting synchrotron. DOI: 10.3367/UFNe.2021.12.039138
[2] Acceleration in Booster and Nuclotron, V. Lebedev, September, 2023

Idea of electron cooling

- Proposed by G.I. Budker in 1966;
- Equal <u>mean velocities</u> of ion and electron beams;
- Two beams move together;
- <u>Beam temperatures</u>: $k_B T_{\parallel,\perp} = m\langle v_{\parallel,\perp}\rangle^2$;
- $\langle v \rangle$ is **RMS** velocity.

- Electron beam by design has <u>lower T</u>;
- We move to **beam rest frame** →
- Analogy: particle loses extra energy in foil;
- "Foil" is electron beam:
- <u>Slow</u> ion in lab frame <u>gains momentum</u>;
- <u>Fast</u> ion in lab frame <u>loses momentum</u>;
- In both cases – **<u>resulting momentum is closer to mean</u>**

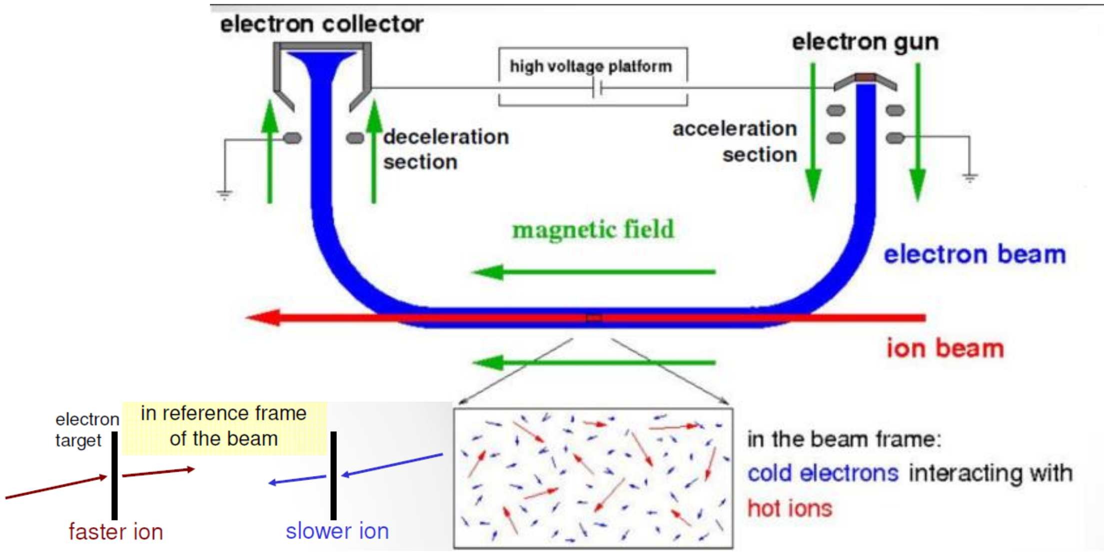
Эффективный метод демпфирования колебаний частиц в протонных и антипротонных накопителях

Г. И. БУДКЕР

УДК 621.384.60

Предлагается метод демпфирования синхротронных и бетатронных колебаний тяжелых частиц, использующий резкое увеличение сечения взаимодействия этих частиц с электронами при малой относительной скорости. Показано, что этим методом практически возможно сильно сжимать сгусток протонов и антипротонов в накопителях, а также осуществлять многократное накопление этих частиц.

Effective method of particle oscillations damping in proton and antiproton rings // Atomnaya energiya. 1967, 22, pp. 346-348



Scheme of ions cooling process with electron beam [3]

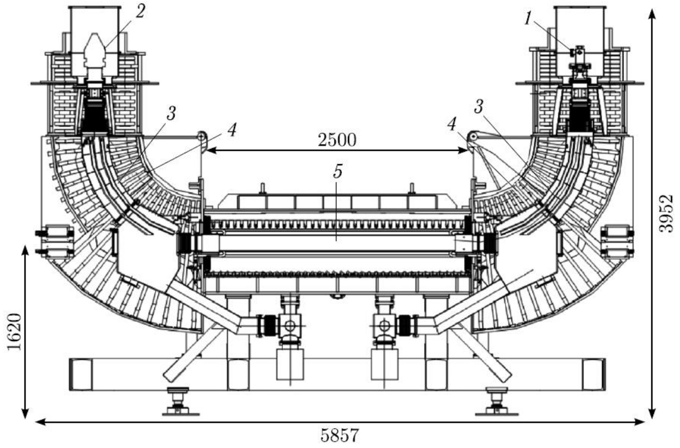
[3] Beam Cooling. M. Steck. CAS Advanced Acc. Phys., London, 2017

NICA Booster electron cooling system

- Developed by BINP (Novosibirsk, Russia);
- Designed to cool ions **at injection energy** (3.2 MeV/nucleon) and at energies **up to 90 MeV/nucleon**;
- Electron beam diameter 28 mm;
- Cooling section length 2.5 m;

- Practical parameters at ion energy 3.2 MeV/nucleon:
- Electron energy 1.856 keV;
- Electron current 25 ÷50 mA;
- Magnetic field 0.075 ÷ 0.1 T;

- Temperatures of electron beam (in eV scale):
- $T_{\perp} = 0.12$ eV only due to cathode temperature;
- $T_{\parallel} = 8.28 \cdot 10^{-5}$ eV due to acceleration and beam density;



Top: NICA Booster electron cooler after installation [4]
Down: NICA Booster electron cooler scheme: 1 – electron gun, 2 – electron collector, 3 – electric field plates in electron beam turning section, 4 – longitudinal magnetic field solenoids, 5 – ion beam cooling section [5]

[4] Commisioning of electron cooling system of NICA Booster. doi: 10.18429/JACoW-RUPAC2018-TUPSA22
[5] First Experiments on Electron Cooling of Ion Beam in the NICA Booster. doi: 10.1134/S1547477124700122

NICA Booster beam diagnostics

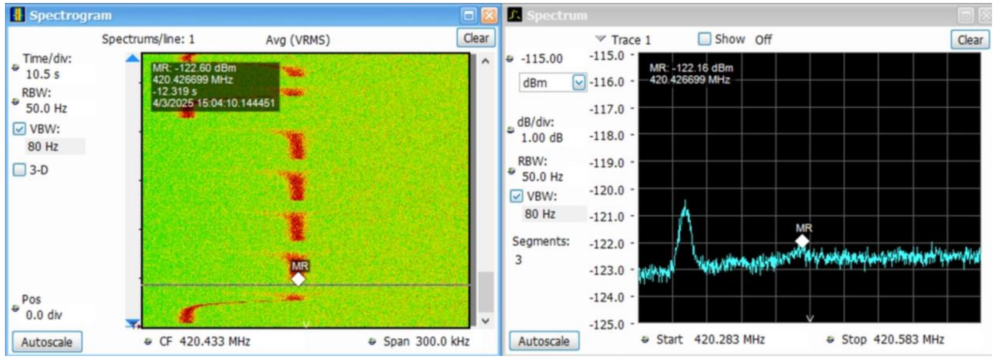
Experimental tasks:
1) Electron and ion beam alignment;
2) Longitudinal cooling control (force, time);
3) Transverse cooling control (force, time);
4) Beam accumulation and lifetime control.

Why measure cooling force/cooling time?

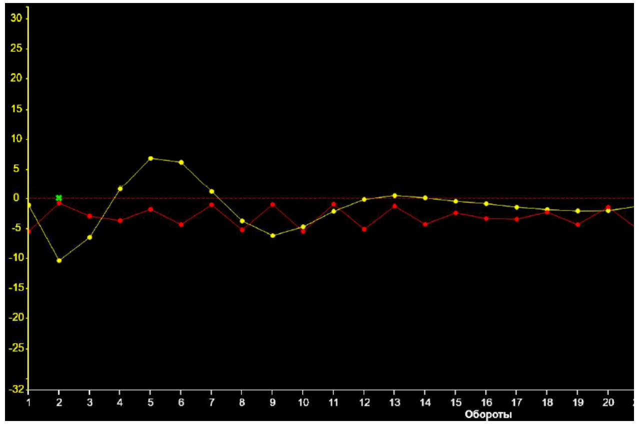
Fokker-Planck equation: evolution of beam particle distribution

$$\frac{\partial f}{\partial t} = \sum_{m,n} \frac{\partial}{\partial v_m}\left(-f\frac{F_m}{M} + \frac{\partial (f D_{mn})}{\partial v_n}\right);$$

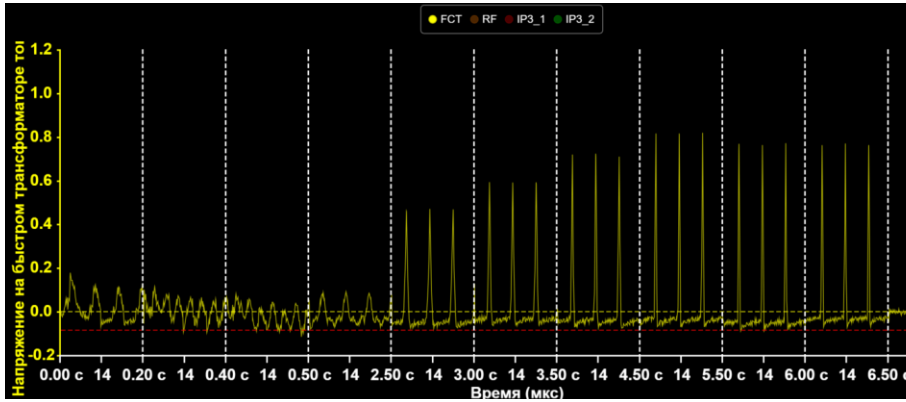
$$f = f(r, v, t); F = \frac{M_i \langle \Delta v \rangle}{\Delta t}; D_{mn} = \frac{\langle \Delta v_m \Delta v_n \rangle}{\Delta t}$$



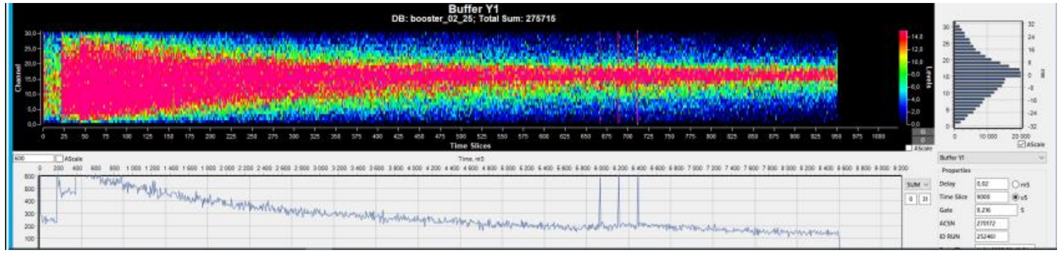
Schottky spectrometer (2), (3)



24 beam position monitors (BPMs): (1), (3)



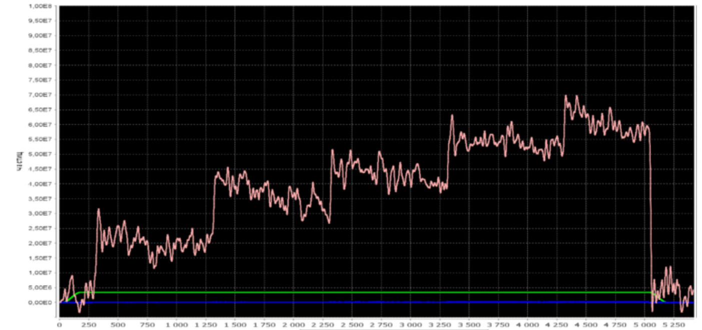
Fast current transformer (FCT): (2),



IPM or Ionization profilometer (X,Y, 32 channels per direction): (3), (4)

Position of electron and ion beams at start and end of cooling section

E-Cooling system BPMs: (1)



Parametric current transformer: (4)

[5] *First Experiments on Electron Cooling of Ion Beam in the NICA Booster. doi: 10.1134/S1547477124700122*
[6] *Beam diagnositcs at NICA injection complex. E.Gorbachev et al. RuPAC23*

Theoretical models of friction force

Dissipative force dependent on relative velocity $\boldsymbol{F}(\boldsymbol{u}) = \boldsymbol{F}(\boldsymbol{v_i} - \boldsymbol{v_e})$;

Maximum force at $|\boldsymbol{u}| = \langle v_{e\parallel,\perp} \rangle$ from $k_B T_{e\parallel,\perp} = m\langle v_{e\parallel,\perp} \rangle^2$;

- Electrons distribution at source: symmetric Maxwell distribution;
- After acceleration: highly anisotropic Maxwell distribution with $T_\parallel \ll T_\perp$;

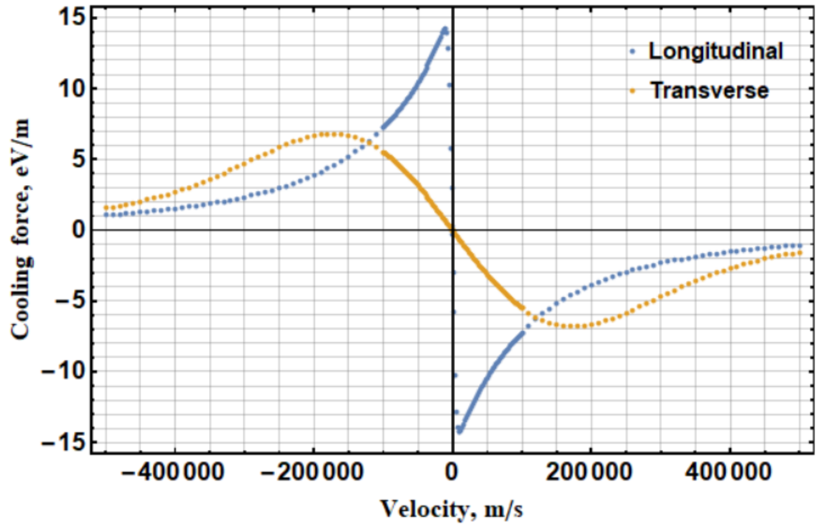
Derives from **binary Coulomb collisions** [7] & **collective effects** [8] in plasma.

$$\boldsymbol{F}(\boldsymbol{u}) = -\frac{Z^2 e^4 n_e}{4\pi\varepsilon_0 \cdot \varepsilon_0 \cdot m_e} \int L_C(\boldsymbol{u}) \cdot f(\boldsymbol{v_e}) \frac{\boldsymbol{u}}{|\boldsymbol{u}|^3} d^3 v_e$$

L_C is Coulomb logarithm that limits impact parameters

$$\int_{b_{min}}^{b_{max}} \frac{db}{b} = L_C = \ln \frac{b_{max}}{b_{min}}$$

- Magnetic field of solenoid changes electron-ion kinematics [9]
- … suppresses ⊥ degree of freedom for electrons at $b > b_{Larm}$
- At $b > b_{Larm}$ collisions are adiabatic w.r.t. Larmor gyration



Electron cooling force for $^{124}Xe^{26+}$ ions for Booster parameters at 3.2 MeV/nucleon. Electron beam temperatures are on Slide 3.

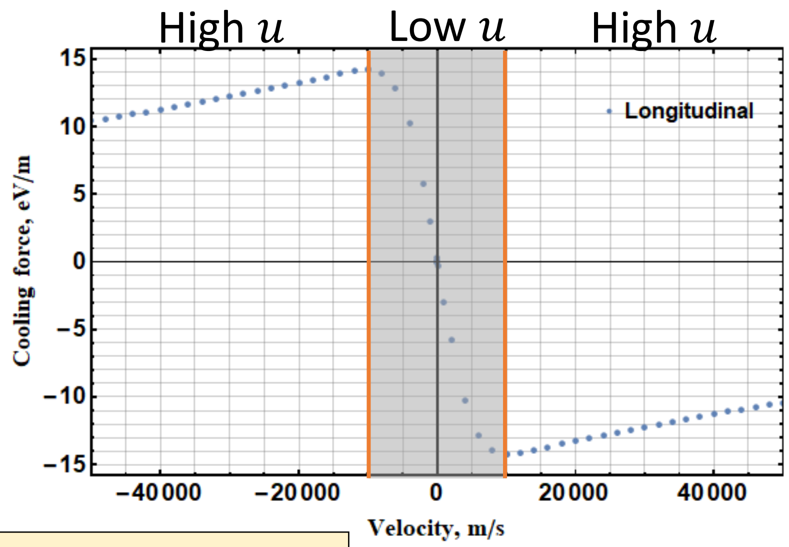
[7] Development of ion cooling methods. I.N. Meshkov 10.3367/UFNr.2018.01.038297
[8] Electron cooling. A. Sorensen et al. doi: 10.1016/0167-5087(83)91288-7
[9] The limits of electron cooling. N.S. Dikanskii. et al. Preprint 88-61, BINP

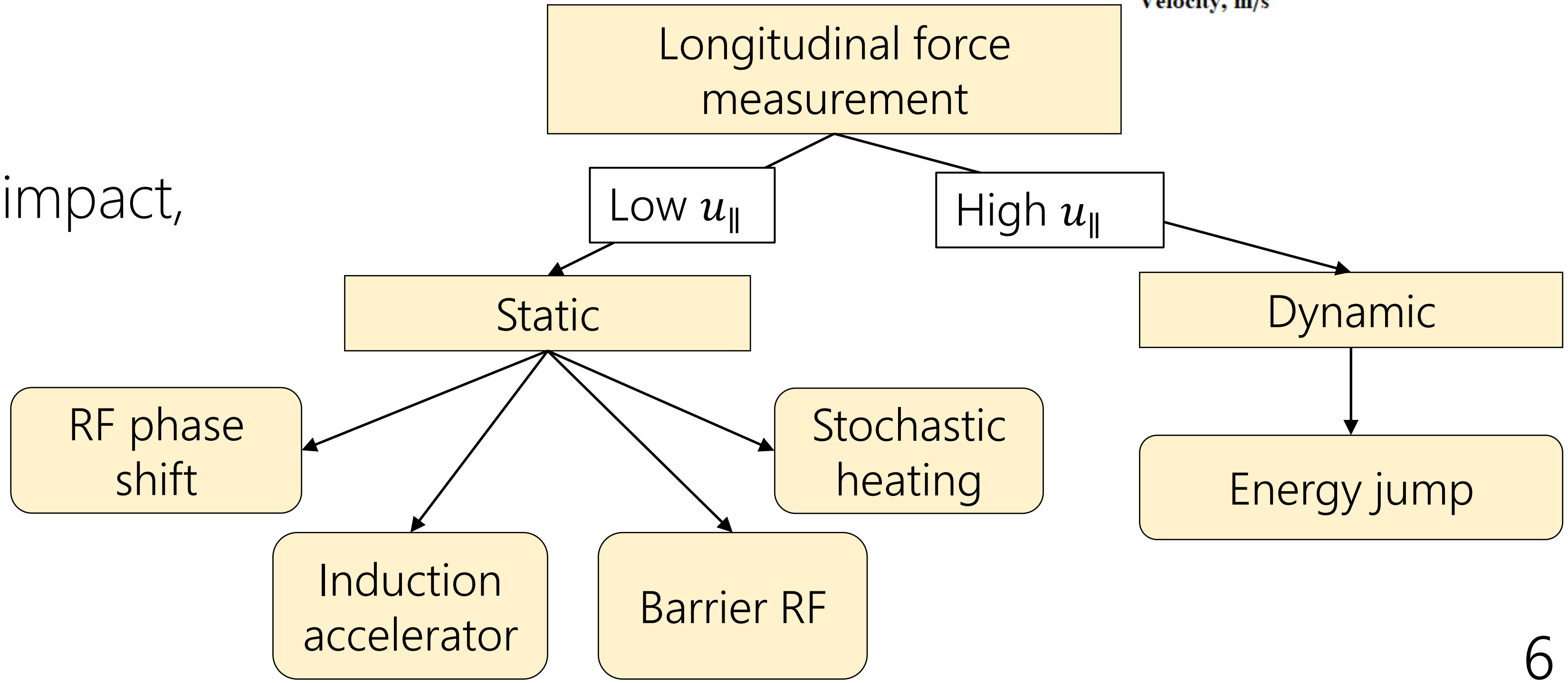
Longitudinal force measurement methods

Two regions of $F(u)$: linear (low u) and non-linear (high u)

Dynamic methods are for non-linear region
Static methods are for linear region

- Dynamic methods – evolution of value after single impact
- Static methods – continuous impact, comparison of values



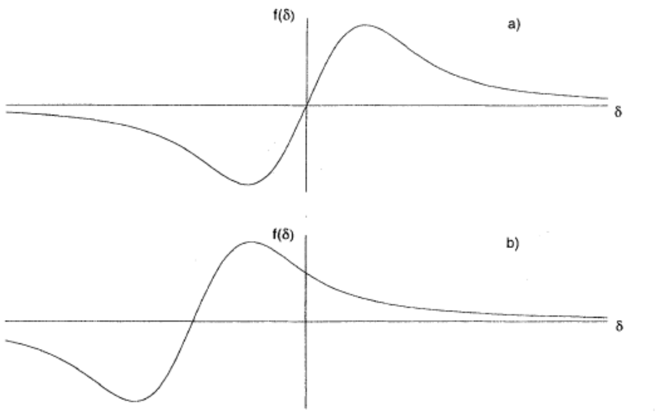


Longitudinal force: energy jump

Only coasting & pre-cooled beam

- Fast change of electrons energy
- Electrons shift energy of ions to equilibrium
- Energy change ↔ revolution frequency change
- Measure $\Delta f(t)$ with Schottky spectrometer

- Works well only for $\Delta v_e > 10^4$ m/s



Cooling force $F(\delta), \delta = \delta p/p_0$ for
a) aligned mean v_e and v_i
b) v_e shifted w.r.t. v_i [13]

$$F_\parallel(t) = \frac{\mathrm{d}p(t)}{\mathrm{d}t}$$

$$F_\parallel(t) = \gamma A \frac{E_0}{c^2} \frac{1}{h\eta} \frac{C_{acc}^2}{L_{cool}} \frac{df(t)}{dt}$$

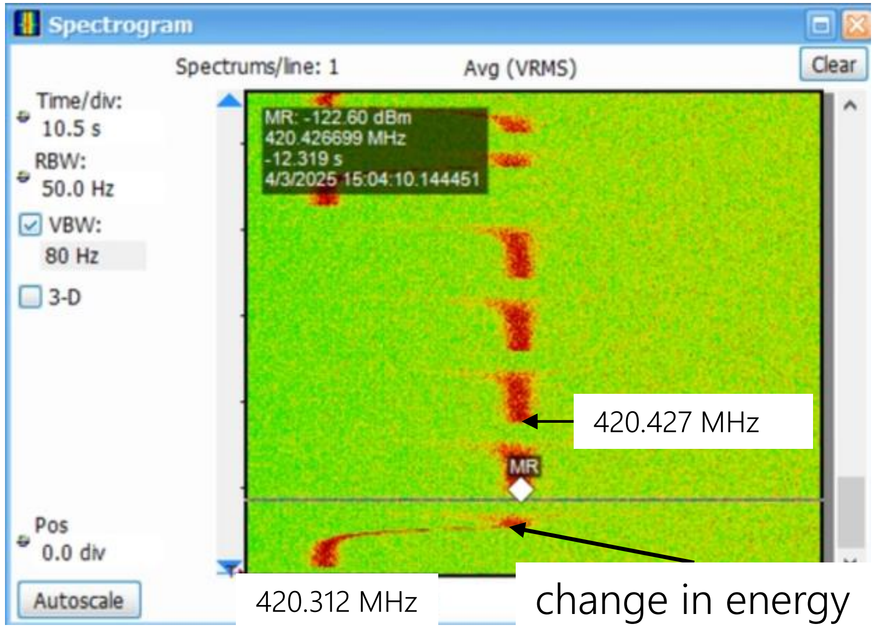
$$u(t) = \beta c \frac{\Delta p}{p} = \frac{C_{acc}}{\eta} \frac{\Delta f(t)}{h};$$

$$\Delta f(t) = f(t) - f_0$$

$$F_\parallel(u)$$

Formulae for cooling force evaluation are from [10-12]

C_{acc} - accelerator circumference, L_{cool} - cooling section length, h - chosen revolution frequency harmonic, η – phase slip factor, $E_0 = 938\ MeV$



Spectrogram of Schottky noise for coasting beam of $^{124}Xe^{26+}$ at 36.7 MeV/nucleon. The signal frequency is shifted with heterodyne.

Let E_{e0}=19993 eV ↔ E_{i0}=36.7 MeV/n
E_{e1}=20004 eV↔ E_{i1}=36.72 MeV/n
ΔE_e =11 eV ↔ $\Delta u = u_1 - u_0 = 2.1 \cdot 10^4$ m/s

[10] Experimental studies of the magnetized friction force. DOI: 10.1103/PHYSREVE.73.066503
[11] Electron cooling at CRYRING with an expanded electron beam. DOI: 10.1016/S0168-9002(97)00249-0
[12] Longitudinal electron cooling experiments at HIRFL-CSRe. DOI: 10.1016/j.nima.2015.10.095
[13] Effects of a nonlinear damping force in synchrotrons with electron cooling. DOI: 10.1103/PhysRevE.51.4947

Longitudinal force: linear region

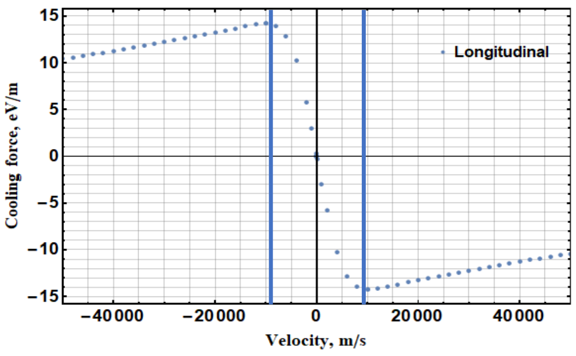
RF phase shift	Stochastic heating

RF phase shift

- Bunched beam
- RF cavity f change → synchrotron oscillations
- $\frac{dE}{dt}|_{RF} = -\frac{dE}{dt}|_{cool}$
- Synchronous phase is shifted by $\Delta\phi_s$
- $\Delta\phi_s$ measured by FCT or phase discriminator

$$F_\parallel = \frac{ZeU_{rf}\sin\Delta\phi_s}{L_{cool}} \qquad u(t) = \frac{C_{acc}}{\eta}\frac{\Delta f(t)}{h};$$

Hopf bifurcation



Cartoon cooling force with blue lines as bifurcation points at $|\boldsymbol{u}| = 0.97\langle v_{e\parallel}\rangle$ [13]

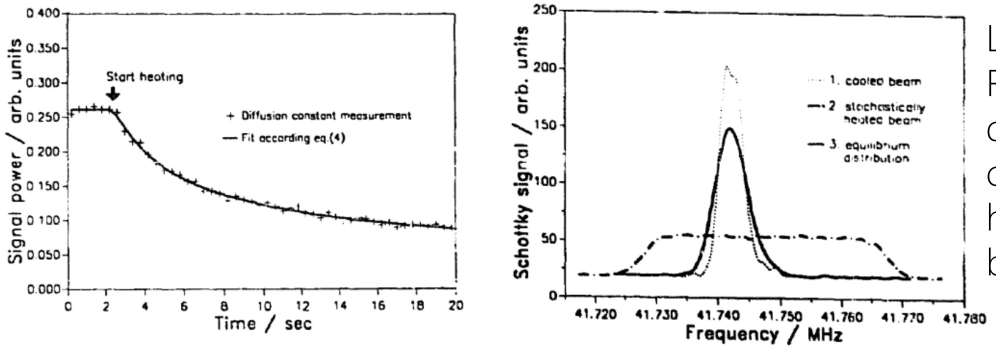
- Before bifurcation point: oscillations damping
- After – oscillations amplification

Stochastic heating

Fokker-Planck equation: $\frac{\partial\Psi}{\partial t} = \frac{\partial}{\partial v}\left(-F(v)\Psi(v) + D\frac{\partial\Psi}{\partial v}\right)$

- Coasting beam, pre-cooled;
- RF noise on RF gap at $f = hf_0$ with controlled power;
- Cooling switched on – equilibrium reached;
- Schottky spectrometer measures equilibrium distribution for each case.

At equilibrium: $F_\parallel(v) = D\frac{\partial\Psi/\partial v}{\Psi(v)} \propto D_E\frac{\partial\Psi(f(v))/\partial f}{\Psi(f(v))}$



Left: heating fit; Right: equilibrium distributions for cooled; heated; heated+cooled beam

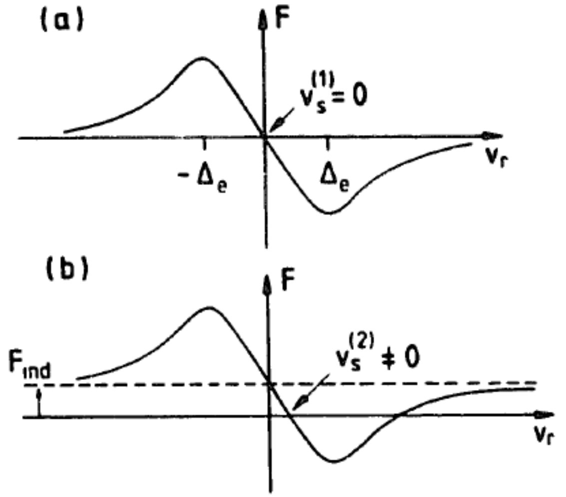
Diffusion power: from fit [14] or $D_E = \frac{f_0^2q^2e^2}{2}G^2E^2\frac{dP_{src}}{df}Z_{ex}$ [15]

[13] Effects of a nonlinear damping force in synchrotrons with electron cooling. DOI: 10.1103/PhysRevE.51.4947
[14] Electron cooling forces for highly charged ions in the ESR. DOI: 10.1016/S0168-9002(97)00027-2
[15] Further results and evaluation of electron cooling experiments at LEAR. DOI: 10.1016/0168-9002(90)91818-V

Longitudinal force: linear region - 2

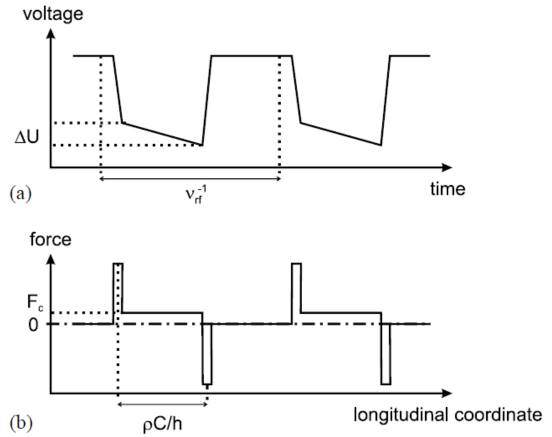
Induction accelerator	Barrier buckets

- Coasting beam
- **Constant** acceleration to counterbalance cooling force power [16];
- Similar to energy jump method, but E_{ion} changes;
- Total force $F_{cool} + F_{ind}$ shifts stable point $F = 0$;
- F_{ind} is well known; find new stable point.
- Measure $\Delta f(t)$ with Schottky spectrometer.

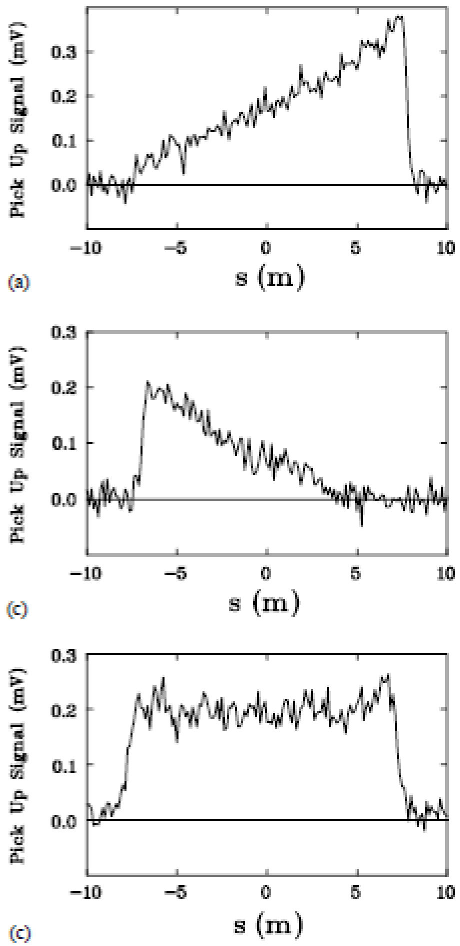


Force acting on ion without F_{ind} (a) and with F_{ind} (b), stable point is shifted

- RF barrier buckets with slope instead of IndAc [17];
- Change slope of U or bunching frequency f_{RF};
- $F_{BB} = -F_{cool}$;
- $F_{BB} = -\frac{hl_{eff}}{\rho C_{acc}^2} e\Delta U$;
- Control with FCT, BPM (intensity mode), Schottky spectrometer.



Form of barrier buckets potential energy (a) and corresponding force (b) [17]



Beam signal from BPM for:
a) $F_{BB} < F_{cool}$; b) $F_{BB} > F_{cool}$;
c) $F_{BB} = F_{cool}$ [17]

[16] An induction accelerator for the Heidelberg test storage ring TSR. DOI: 10.1016/0168-9002(92)90230-2
[17] New method to measure the friction force of electron coolers in heavy-ion storage rings. DOI: 10.1016/S0168-9002(02)02142-3

Transverse force measurement methods

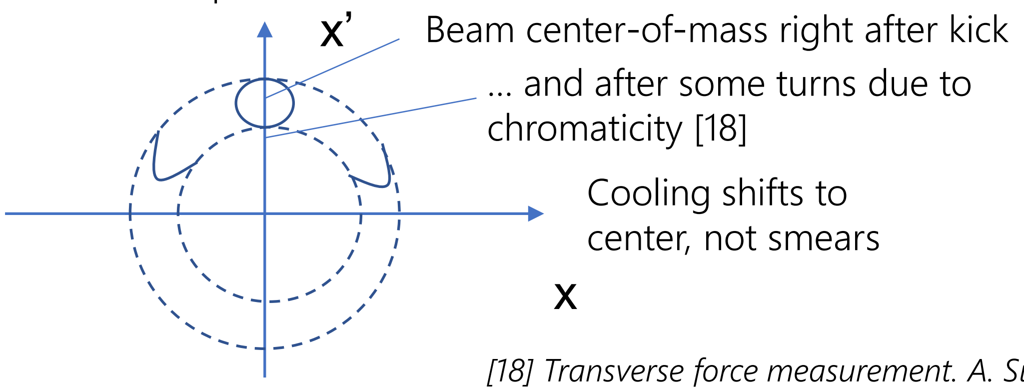
- Monitor betatron oscillations damping time with BPM & transverse Schottky spectrometer;
- Measure beam size with ionization profilometer.
- Right after injection:
  - high dp/p,
  - fast decoherence due to chromaticity

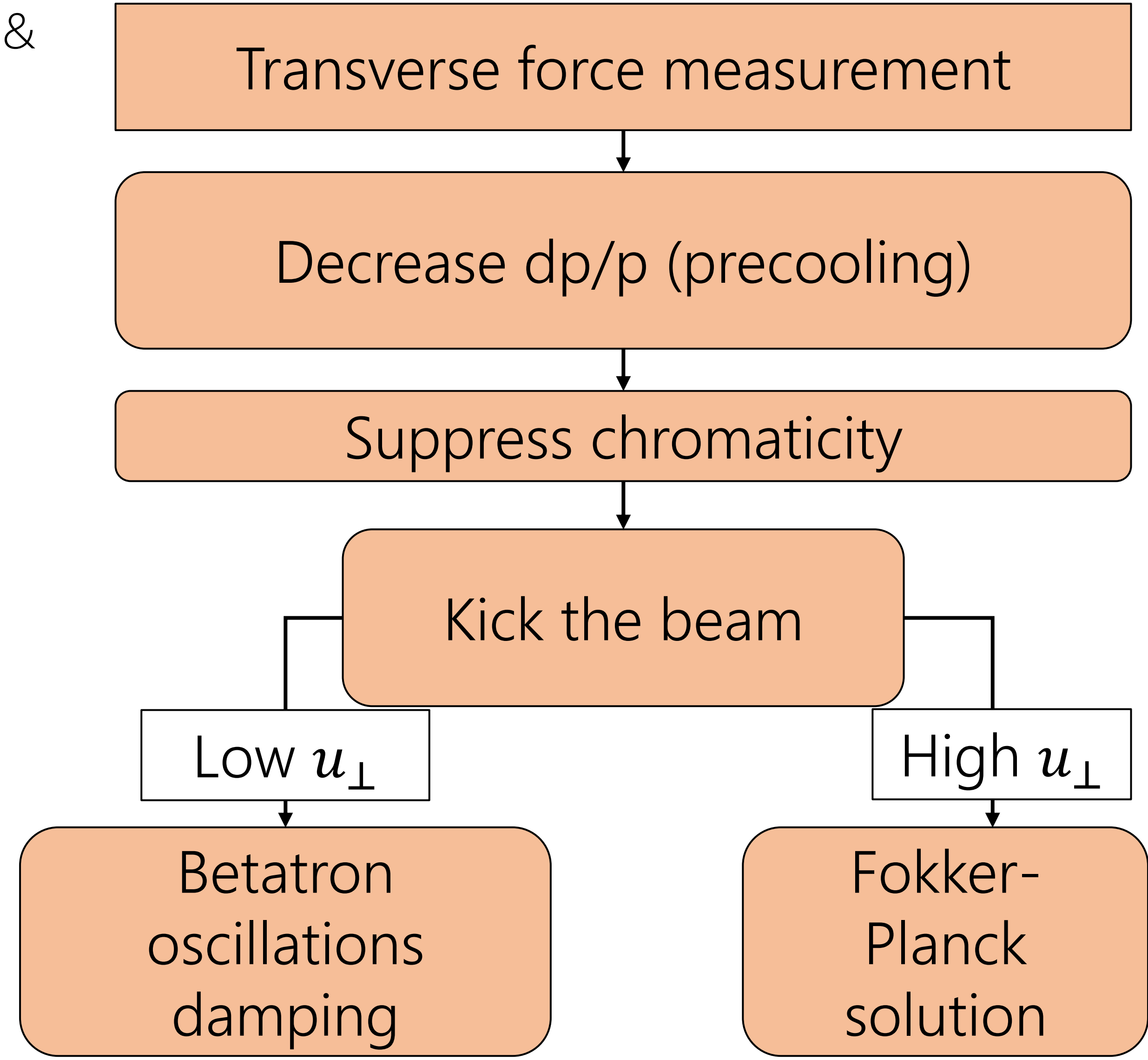
X

- Suppress chromaticity to 0
- Pre-cool the beam to get small dp/p

V

- Excite the oscillations with kicker
- Dominant damping due to cooling, not chromaticity!
- $u \propto$ amplitude of kick





[18] Transverse force measurement. A. Sidorin, NICA operators meeting

Transverse force measurement methods - 2

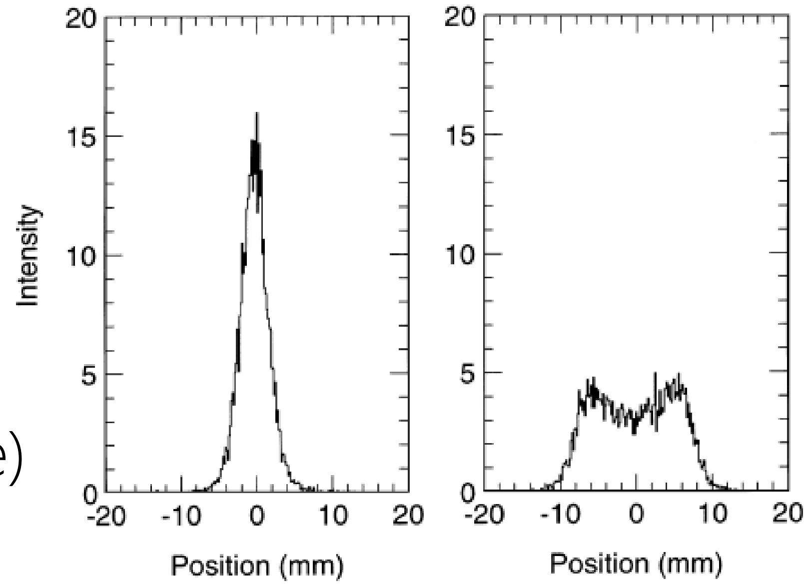
- Stronger kick gives larger $u_\perp$ from $v_{i\perp} \equiv \dot{x} = \dot{x}_0 \cos\theta$;

- Kicked pencil beam: an oscillator with external force $F_\perp(u)$;
- Oscillator energy change: $\Delta E = \int_0^{2\pi} F_\perp(\dot{x} - \delta\dot{x}) \cos\theta \, d\theta$;
- Change the angle of electron beam – change $v_{e\perp} \equiv \delta\dot{x}$;

- Hopf bifurcation point can be observed:
  - on IPM: two-sided beam profile (see right pic. on this slide)
  - on Schottky spectrometer: increase in signal power

- Before bifurcation oscillations are damped, $\Delta E < 0$
- After bifurcation oscillations are amplified, $\Delta E > 0$

- Measure damping time;
- Force can be extracted from ΔE or from Fokker-Planck solution



Left - profile of cooled ion beam with aligned electron beam;
Right – with misaligned electron beam after bifurcation point [19]

[19] Studies of electron cooling with a highly expanded electron beam. DOI: 10.1016/S0168-9002(99)01121-3

Outline

- Short cooling time is good for accumulation of beam;
- BUT: avoid overcooling → growth of instabilities, loss of beam;

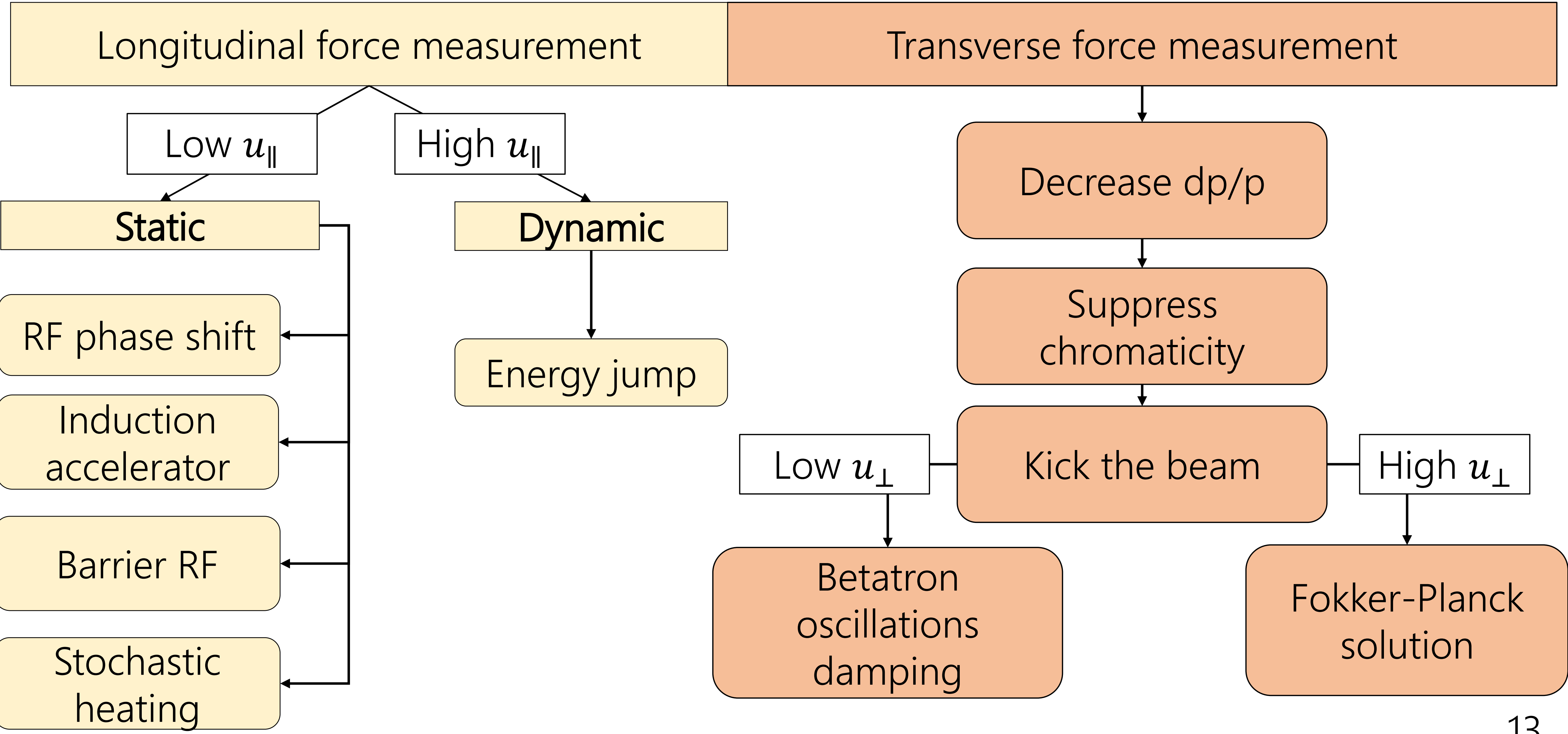
- NICA Booster Schottky spectrometer is suitable for $\boldsymbol{E_{ion}} > 30$ MeV/n (sensitivity);
- For injection energy (3.2 MeV/n) – FCT is the only choice;
- For transverse cooling – ionization profilometer monitor (IPM) is OK for all cases;
- You need to know Twiss $\boldsymbol{\beta}$ at IPM and in electron cooling section;

- The easiest methods for ∥ force measurement – RF shift + energy jump;
- In principle, Booster RF system allows barrier buckets after additional works [20];
- For IndAc-like measurements one need finer amplitude tuning on RF cavity;
- Try ⊥ cooling after chromaticity correction, injection optimization;

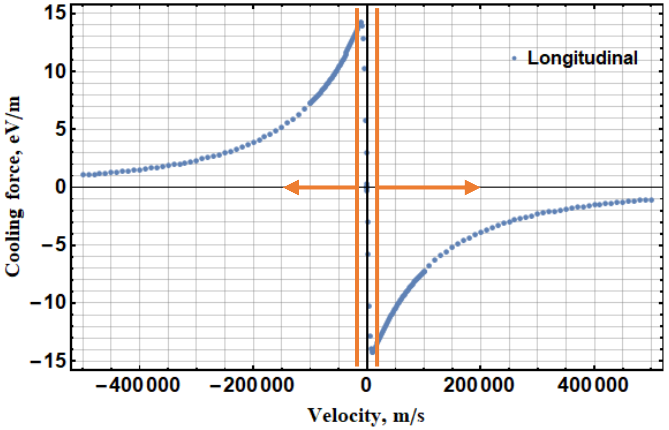
- Instrumentation allows presented methods
- ... and tuning of electron cooling system for needs of beam accumulation

[20] Private communication with A.Volodin, LHEP JINR

Summary on measurement methods



Extra info



Cartoon representing ranges of force to be measured with energy jump method

A.3. Experimental Realization 95

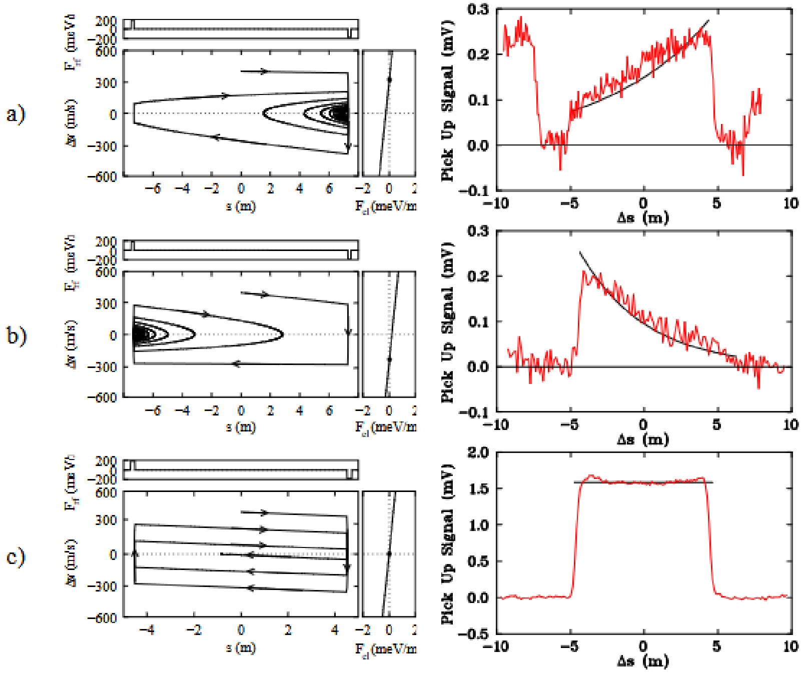


Figure A.3: *Calculated phase-space diagrams of an electron-cooled bunched beam for two bunching frequencies: lower (a), higher (b) and equal (c) with respect to the corresponding electron beam velocity. The right column shows the longitudinal ion distribution measured with an electrostatic pickup. The fitted theoretical Boltzmann distributions are shown as solid lines.*

Mechanism of ion bunching in barrier bucket methods for misaligned and well-aligned force [17,21].
BPM signal is fitted with Boltzmann distribution with barrier bucket potential

[21] Laser cooling of fast stored ion beams to extreme phase-space densities. Dissertation of Udo Eisenbarth, 2001