Overview of recent trends in beam cooling methods and technology

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Menu

1. Introduction: What's new since COOL'03 ?
2. Cooling by electrons
3. Stochastic cooling
4. Stability of electron cooled beams
5. Theory and numerical simulations
6. Muon cooling
7. Beam Ordering

Conclusion

1. Introduction: What's new since COOL'03 ?

Demonstration of the first electron cooling at intermediate energy :

8 GeV antiprotons in the FERMILAB recycler! CONGRATULATIONS!

Commisioning of three state-of-the-art low energy electron coolers (LANZHOU & LEIR) built in Budker INP.

Commisioning of LEPTA at JINR (Dubna) ⇒ under way to e-cooling of positrons and e-cooling with circulating electron beam.

Construction of a special "dispersionless" ring for laser cooling/beam ordering started (Kyoto University).

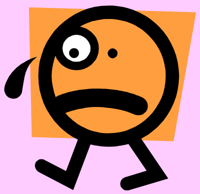
International effort and great progress in the conception, modelling, benchmarking and hardware design for various medium and high-energy (both stochastic and electron) coolers (e.g. for RHIC, FAIR, TEVATRON...) .

Approval of Muon Ionisation Cooling Experiment (MICE) at Rutherford Appleton Lab.

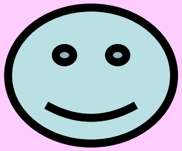
Start of elaboration of International FAIR project at GSI, where cooling methods will play a key role.

The hot news in brief

New proposals ... very small aperture machines for m... lications).



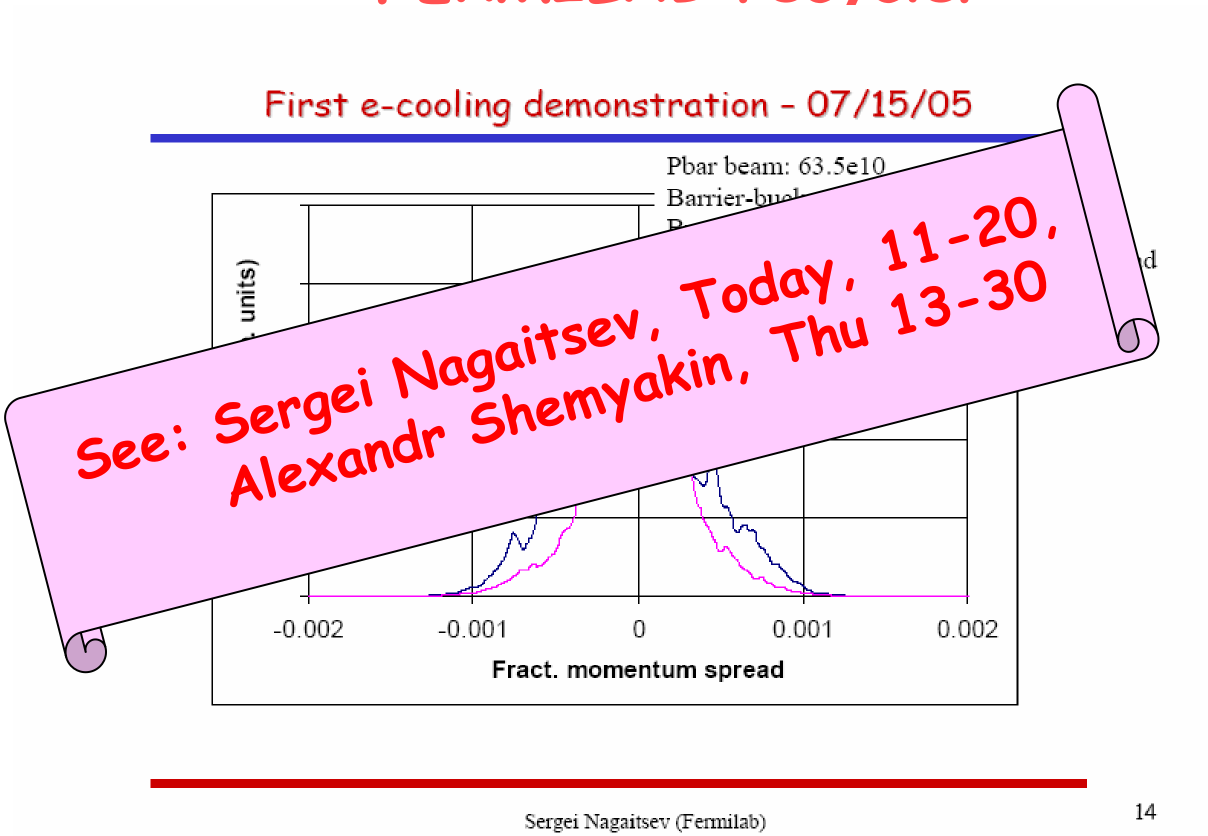
Bad news: Shutdowns of CELSIUS and CRYRING.



Good news: CRYRING will be used as a cooler storage ring in FLAIR – subproject of FAIR.

2. Cooling by electrons: medium and high energy cooling

First electron cooling of 8 GeV antiprotons in the FERMILAB recycler



Trends for medium and high energy cooling

- **Very long interaction region (15 – 20 m) – a necessity for efficient cooling** (*see: I.Ben-Zvi, Thur. 11-20*)

- **Three options:**
  - ⊗ **High voltage e-coolers based on electrostatic acceleration**

    (*see: S.Nagaitsev, today, A.Shemyakin, D.Reistad, Ju.Dietrich, V.Reva, Thu. after lunch and Working group – COSY, Thu. 15-50*)

    Particularly, magnetisation in HV e-coolers using isolated multiple coils fed by generators on high voltage (*see:V.Reva, Thu. 15-20*)

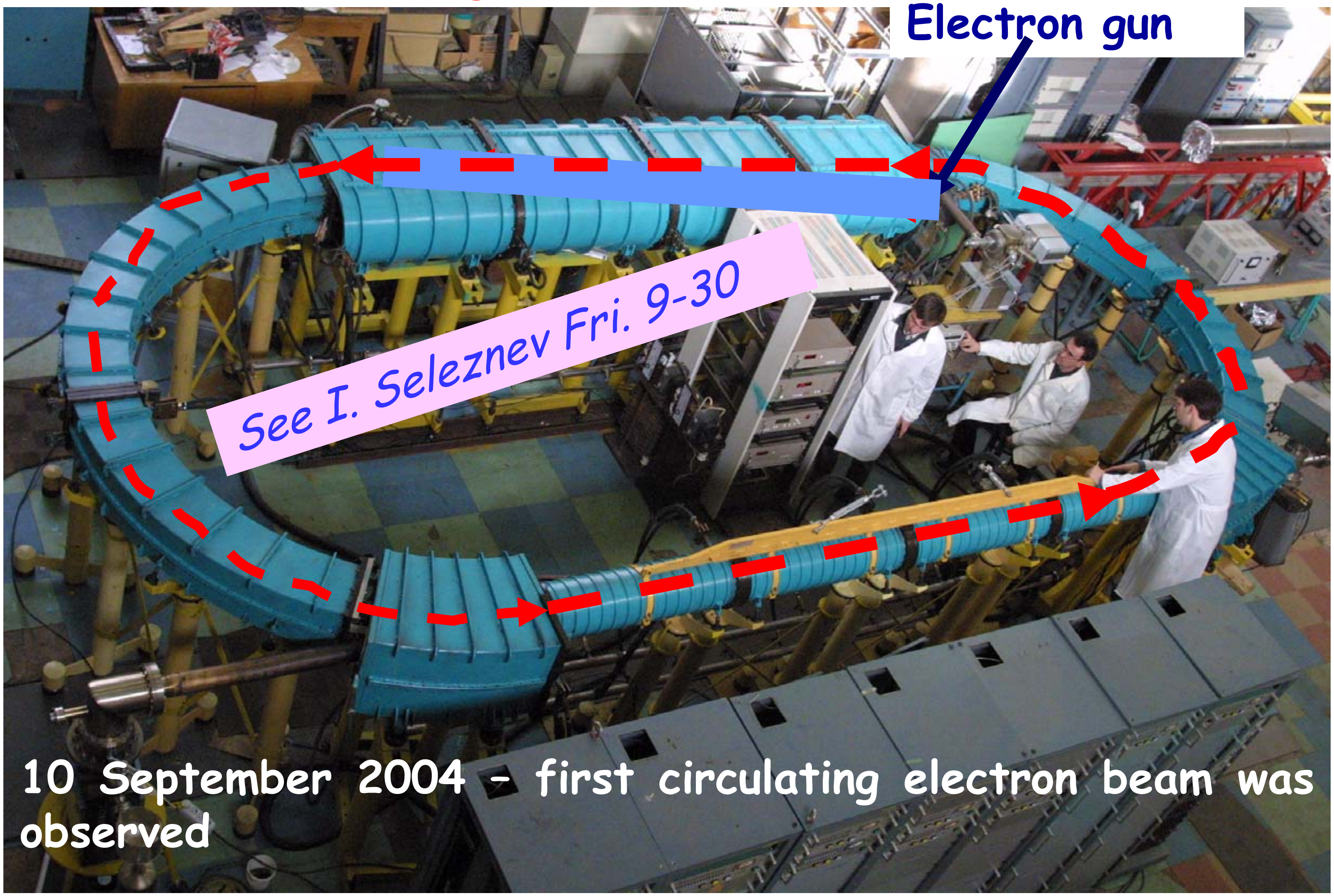
  - ⊗ **RF acceleration/recuperation with/without (?) magnetisation**

    (*see: I.Ben-Zvi, Thu.11-20*)

- ⊗ **LEPTA – on the way to cooling with circulating e-beam**

2. Cooling by electrons: medium and high energy cooling

Test of The LEPTA Ring with Pulsed Electron Beam

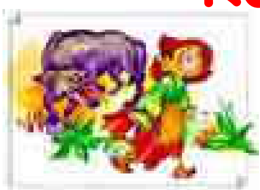


Low Energy Cooling

This section of the talk can remind us the famous fairy tale

of Charles Perrot

"Rotkäppchen" = "Little red cooling hood" =



= "Chaperon Rouge" = "Красная Шапочка"

Low Energy Cooling

New ideas developed and "bench tested" (without ion beam yet?):

⊕ Very precise magnetic field with a great number of trim coils.

⊕ 'Hollow' e-beam to avoid 'overcooling' in center. Allows al to reduce ion
instability -linear
beam-bean

⊕ Electrostat ticles.

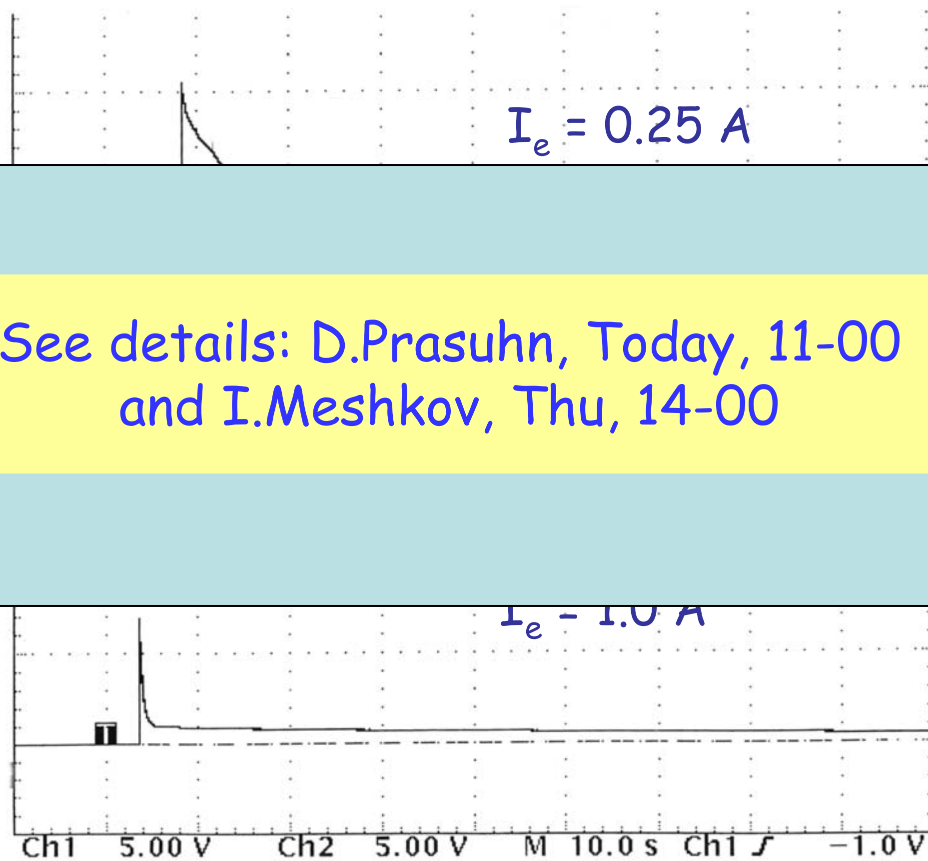
⊕ U-shape (9 d
solenoidal rections for the ion beam ⇒ to save straight section space.

⊕ Integrated (NEG or Titanium evaporation) pumping (to obtain ultra low vacuum)

See: V.Parkhomchuk, Thu 8-30

- **"New-old" idea: Magnetic expansion (to adjust beam size)**

- **New idea**: ... transverse 'temper... ...from 'tempe...



See details: D.Prasuhn, Today, 11-00
and I.Meshkov, Thu, 14-00

- **New** ... to have electr... ...cooling with electr... ...energy (COS... Au...

2. Cooling by electrons: low energy cooling (continued)

- **"New electron coolers**

Budker INP ⇒ two electron coolers for IMP, Lanzhou…

See: Xiadong Yang and G.Tranquille
Thu, morning session

Very low-energy electron cooling

- ELENA and FLAIR proposals for ~ 100 KeV antiproton and ion (deceleration and cooling) rings, and plans for molecule cooling rings …

Challenge for cooling with ~50 eV of electron energy:

Ultra Low Electron Temperature is required!

How to reach an effective e-cooling?

✓Cold (photo- ?) cathode ⇒ important especially for low longitudinal electron temperature;

✓Magnetisation ⇒ to have low effective transverse temperature;

✓ Expansion ???

✓ Extremely high magnetic field quality!

OTHER PROBLEMS AT ULTRA LOW ENERGY:

✓ **Instabilities, space-charge, tune-shift due to e-beam and solenoid,**

✓ **Intra-beam and gas scattering.**

An advantage ("a consolation") : energy recovery is not required!

3.Stochastic cooling, bunched beam

Progress at RHIC

Bunched beam 'Schottky noise' studies well progressing:

☺ **The coherent component of the signal (at 4 – 8 GHz) ('flag pole' on the Schottky hill) is attributed to the bunch shape plus intra-beam scattering.**

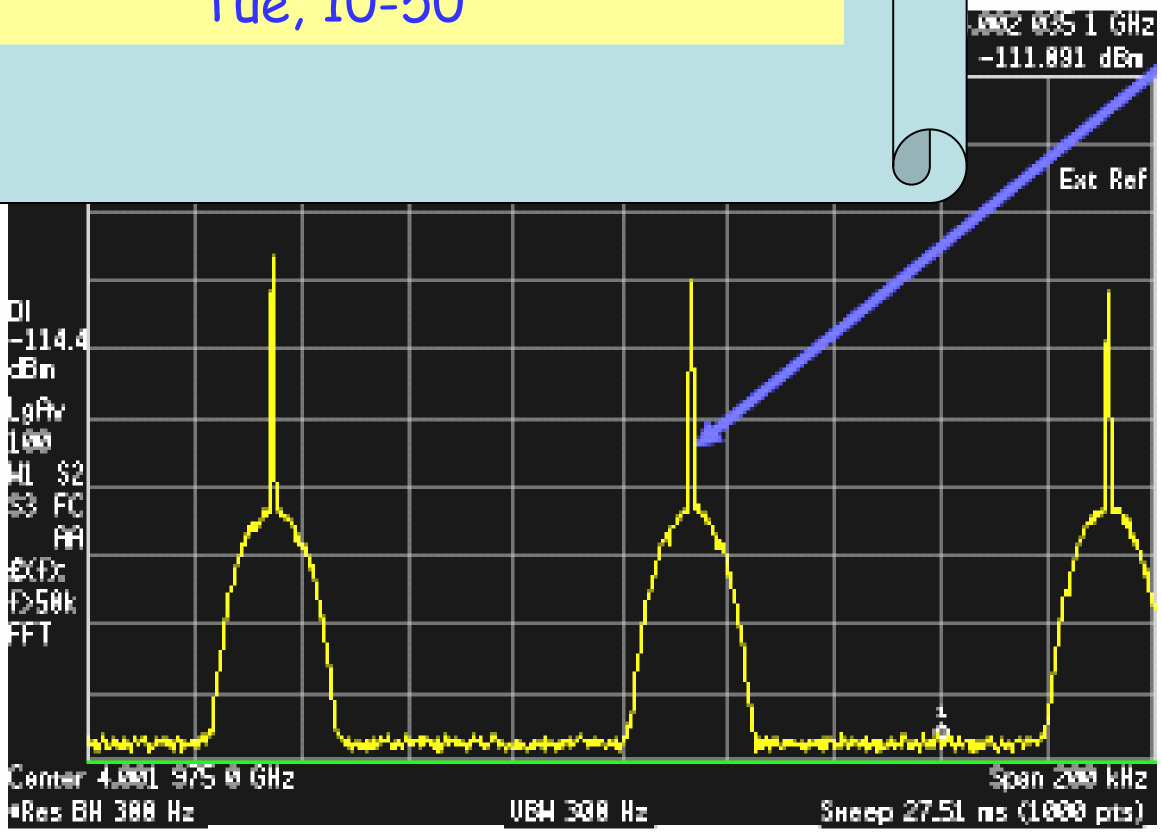
☺ **Much less violent at RHIC than in SPS and TEVATRON.**

☺ **Seems manageable for cooling of gold beam.**

3.Stochastic cooling, bunched beam

See: M.Blasciewitz
Tue, 10-50

in RHIC



Coherent signal at $4 \pm n \cdot 0.8$ GHz

Some new (?) proposals:

- Power problem can be solved by having an array of high Q (~1000) cavities stagger tuned (??? how?) over the band (4-8 GHz).

- Ideas to combine high energy electron (core) cooling with stochastic (halo) cooling ⇒ High energy Experimental Storage Ring (HESR) at FAIR (GSI).

See: F.Nolden
Tue, 8-30

4. Stability of Cooled Beams

Ion beams cooled by electrons

An ion beam in an electron cooler storage ring suffers from the influence of the cooling e-beam and from other storage ring coupling impedances. Effects observed:

- ion loss at injection (COSY) when ion beam size is larger of the electron beam size;
- nonlinear lens ("beam-beam") effect of the electron beam (LEAR);
- a large coupling impedance formed by e-beam for the ion beam;
- strong interaction of well cooled ion beam with parasitic resonant elements situated in the ring vacuum chamber (COSY);

- **instability development** in a well cooled and high intense ion beam due to interaction with electron beam – "electron heating" (CELSIUS, COSY and HIMAC); it seems to be similar or identical to the "beam-beam" effect.

A test of the ion beam stability with the new hollow e-beam will be an important issue.

- **"three-bod** ... **red)** in e-beam

Some details will be presented:
I.Meshkov, Thu, 11-00

The γ-transition problem

Longitudinal stability is most critical above transition energy due to the 'negative mass effect'.

Up to now all e-cooler rings work naturally below transition. However (!) the new high energy coolers have to work above transition. A propos, in the old Initial Cooling Experiment at CERN, e-cooling failed above transition.

A recent experiment at the ESR (Darmstadt) tuned to $\gamma > \gamma_{tr}$ showed e-cooling but with larger equilibrium spread than below γ_{tr}.

The instability curing

A feed back system is an efficient tool of coherent instability damping (LEAR, COSY,…).

But it does not cure incoherent effects, like initial losses…

And again: a test of the ion beam stability with the new hollow e-beam will be an important issue!

Stochastically cooled beams

Peculiar features:

The stochastic cooling system acts as a large **'beam coupling impedance'**.

Beam stability is very critical in accumulator rings (of antiprotons or rare ions), where large stacks (10^{11}-10^{12} particles) have to co-exist with small injected batches (10^{8} particles).

Fast **cooling/stacking** of the injected batch **in the presence of the stack** requires partial aperture pick-ups and large separation (at the PU-s) of injection and stack orbit by dispersion.

Analysis has shown:

The resulting large dispersion rings are expensive and cumbersome.

Non-di … d
(freque … ig
number

See: T.Katayma, Tue, 10-30

Therefore ⇒ the task:

Revisit the stacking problem.

5. Theory and Numerical Simulations

Future projects – e-cooling at RHIC, FAIR,… do need an efficient tool for numerical simulation of beam dynamics in the cooler rings.

A significant progress was achieved since COOL'03 in BETACOOL development (*see: A.Smirnov, today, 16-50*) and its benchmarking (*see: A.Fedotov, Thu, 10-40*). A lot of work were done in Erlangen (*see: G.Zwicknagel, Fri, 10-50*).

An example: proton beam in COSY influenced by IBS and electron cooling

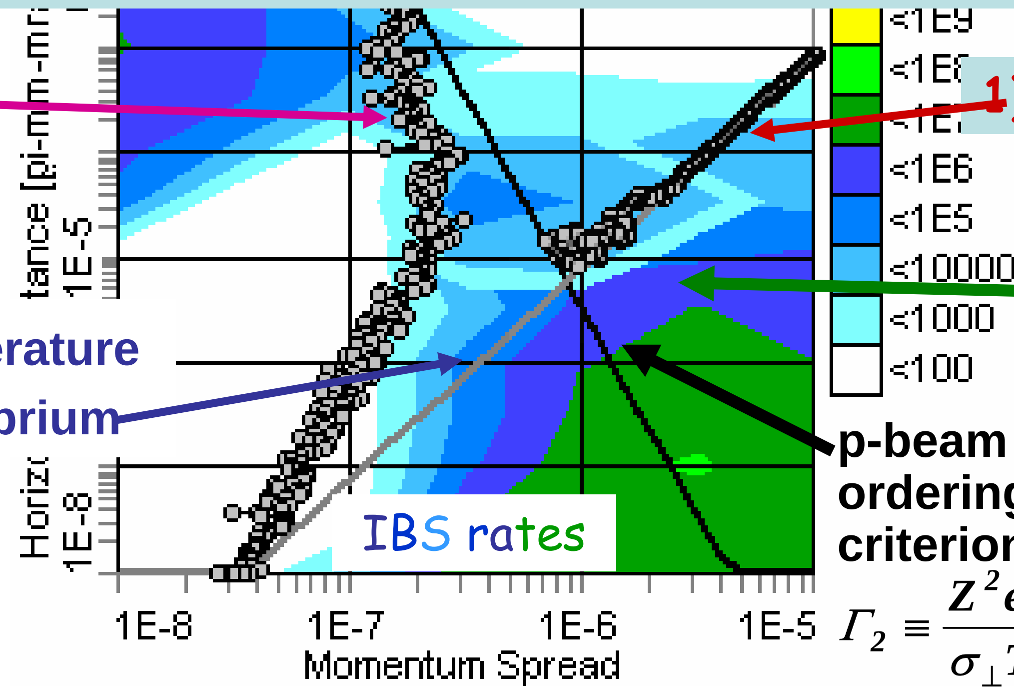
Molecular Dynamics model of IBS

$N_p = 1\cdot10^6$, $\tau_{cool} = 20$ μs (!) –

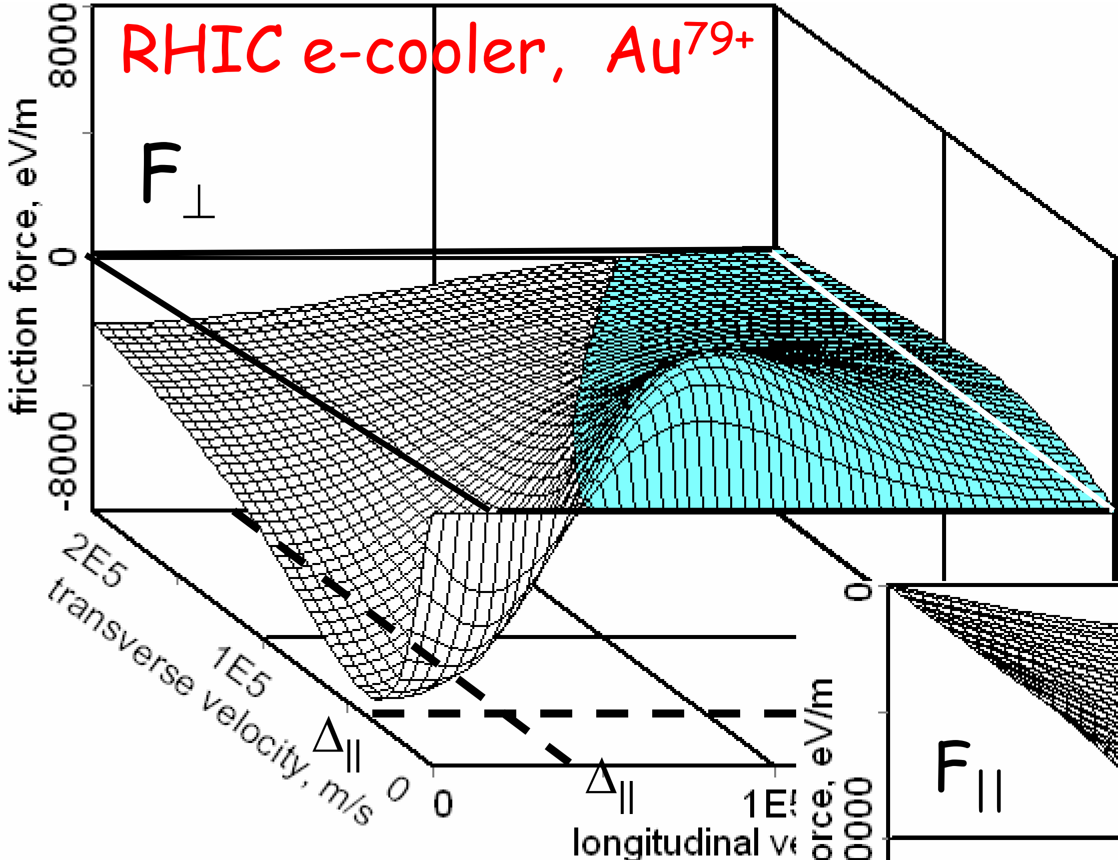
-“inserted by hands”

“The Smirnov’s effect”:

p-beam evolution at different initial conditions!

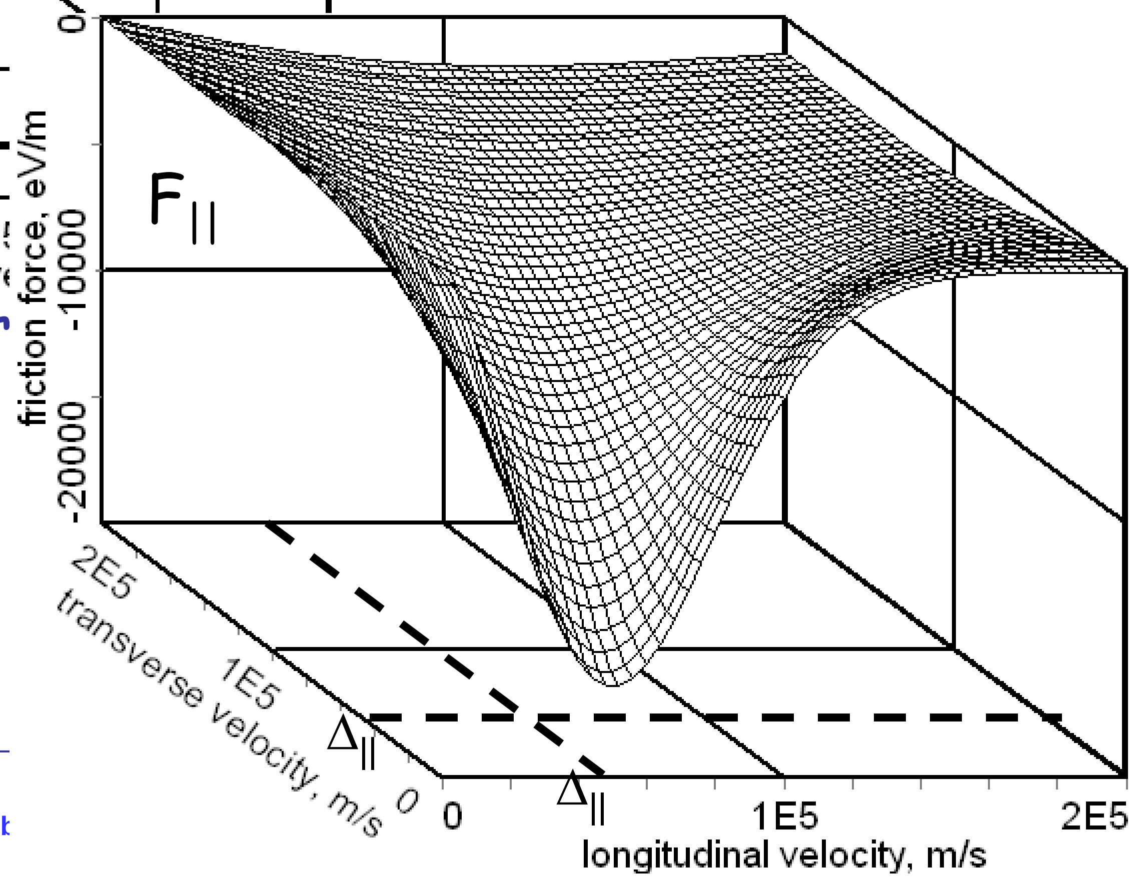


$$\Gamma_2 \equiv \frac{Z^2 e^2}{\sigma_\perp T_\parallel} = 1$$



The Derbenev-Skrinsky

the function of $F_{cool}(v_{ion})$



smooth and all the thr

very good connected.

6. Muon Cooling

An international scoping study

of a Neutrino Factory and super-beam facility (launched 2005)

The extracts from the "Executive summary":

http://hepunx.rl.ac.uk/uknf/wp4/scoping/

…. An … international scoping study of a future accelerator neutrino complex … The principal objective … will be to lay …foundations for a …conceptual-design study of the facility. The … study has been prepared … by the international community …: the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Muon Collider and Neutrino Factory collaboration and the UK Neutrino Factory collaboration. …

Rutherford Appleton Laboratory will be the 'host laboratory' for the study…

Highlights of this programme include the international Muon Ionisation Cooling Experiment (MICE)… which has been approved at the Rutherford Appleton Laboratory (RAL) …will begin taking data in 2007 with beam from ISIS (RAL)

MICE Collaboration. http://mice.iit.edu

> 40 institutions from Belgium, Italy, Japan, Netherlands, Russia, Switzerland, UK, US ⇒ spans 17 hours in time zones, includes: Louvaine, Bari, Frascati, Genoa, Legnaro, Milano, Napoli, Padova, Roma, Trieste, KEK,Osaka, NIKHEF, BINP, CERN, Geneva, PSI, Brunel, Daresbury, Edinburgh, Glasgow,Imperial, Liverpool, Oxford, RAL, Sheffield, ANL, BNL, Chicago, Fairfield, Fermilab, IIT,Iowa, Jlab, NIU, UCLA, LBNL, Mississippi, Riverside, UIUC.

Aims to show that it's possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory;
place it in a muon beam …. investigating the limits and practicality of (ionization) cooling.

6. Muon cooling (continued)

MICE Status (and what we can learn from MICE)

- ❖Official (UK) project at RAL,
- ❖Funding for RAL beamline/infrastructure and tra…
- ❖Recognized experim…
- ❖Import… …UCOOL collab…
- ❖Lots of … …anding of: beam optics, detector performan…e, and emittance measurement,
- ❖…

First beam expected April 1, 2007

Success in getting contributions from many different funding agencies!

---> International effort ("globalization") on other cooling projects!

7. Beam ordering

The experimental observation in the 70th of Schottky noise depression in a cooled proton beam made by V.Parkhomchuk et al. inspired a lot of enthusiasm on 'crystal beams'.

The excitement continues but was somewhat damped in the 1990th when it became clear (due to the work of A.Sessler, G.Wei, H.Okamoto, A.Ruggiero and many others) that 3D crystallisation is subject to a set of tough conditions that can not be met in existing storage rings.

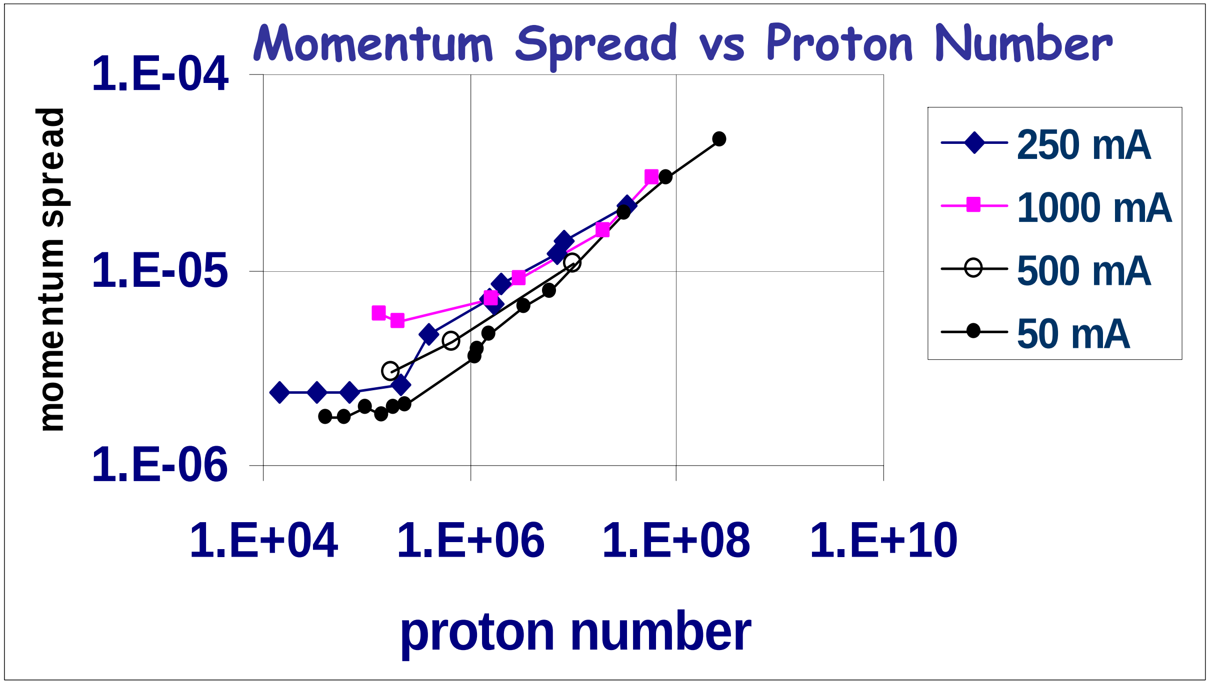
The observation of 1D ordering by M. Steck and co-workers at GSI in 1996 and its theoretical explanation by the 'two-particle model' of R. Hasse has lead to a new boom of interest in beam crystallisation in storage rings.

The proposal (T.Katayama, I.Meshkov, D. Möhl, A.Sidorin, A.Smirnov and others) to use of a 1D chain in an ion-electron collider presents a first attractive particle physics application showing the potential of ordered beams.

The understanding of the optics and the cooling required for beam ordering is progressing due to the efforts of an 'international network of enthusiasts' (including A. Sessler, J. Wei, H. Okamoto, and the team mentioned above).

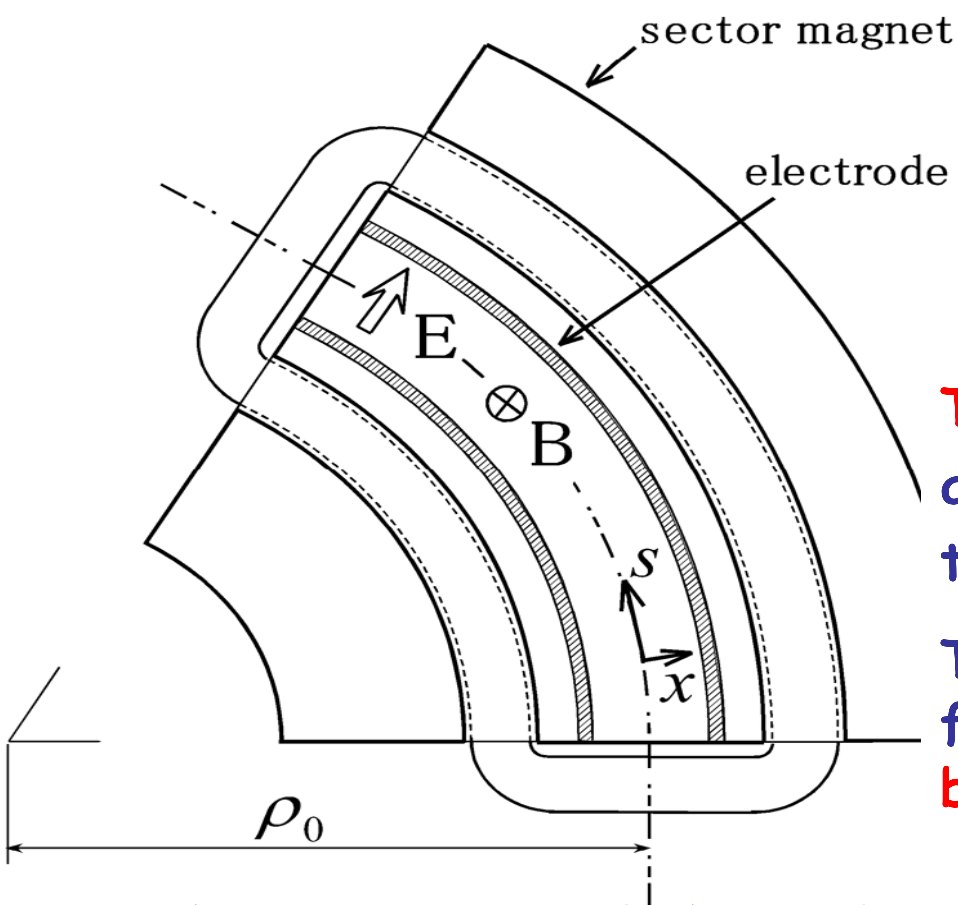
Concerning the success with ion beam ordering at GSI and (later) at CRYRING one should mention the problem of a proton beam ordering.

Recent experiments at COSY demonstrated a saturation of Schottky noise signal at the level $\Delta p/p \sim 2 \cdot 10^{-6}$, but a 'phase transition jump' was not observed (*like in NAP-M*).



See:
A.Smirnov,
Today,
16-50

7. Beam ordering (continuation)



Shear Free Bending

(A.Noda, M.Ikegami et al.)

S-LSR bending magnet

The idea of a "dispersion free" ring allows to avoid 'shear' and, related to it 'tapered' (or 'gradient') cooling.

That removes a big stumbling stone from the road to 3D ordered beams.

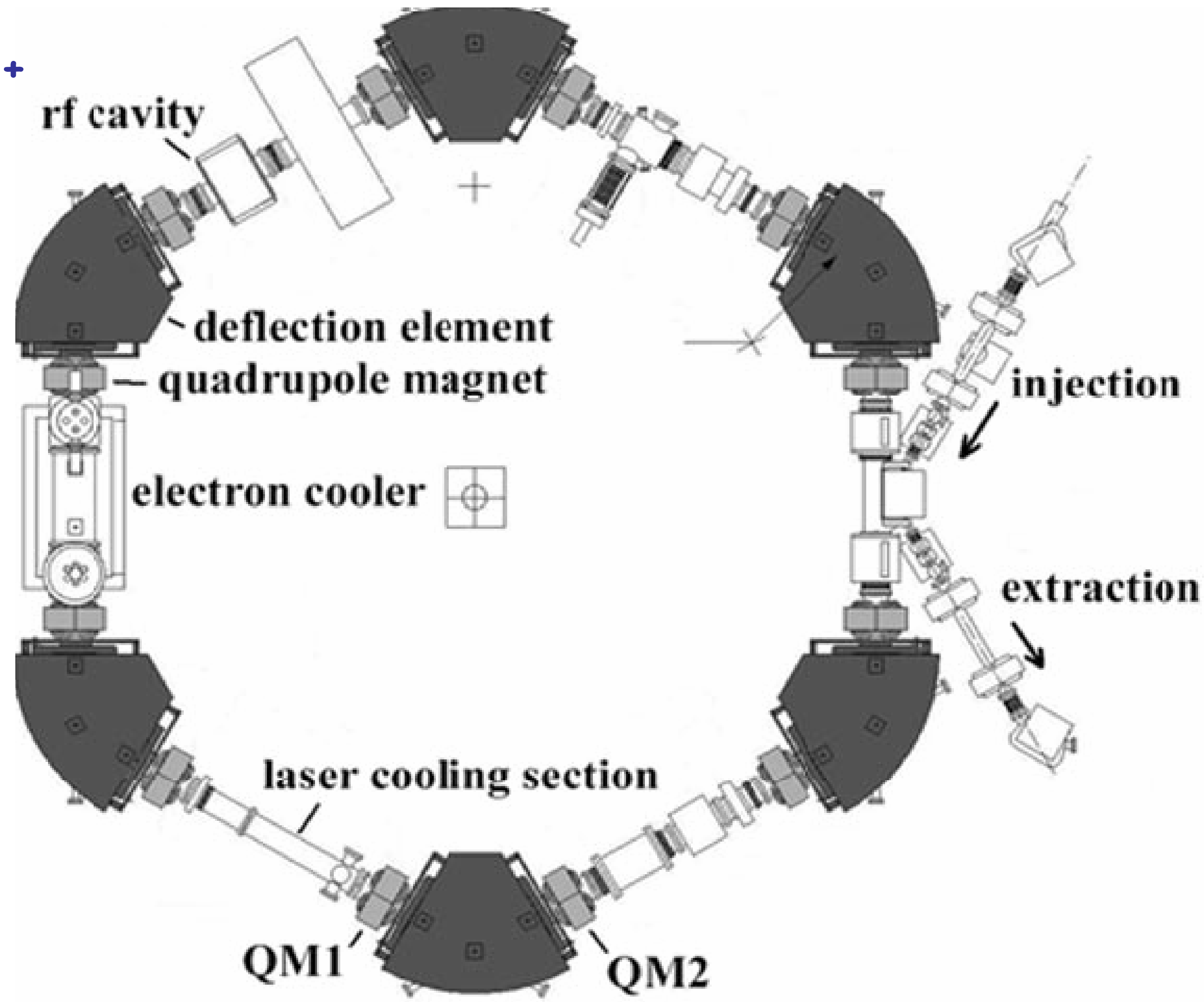
The condition of shear forces absence (to first order):

$$\vec{E} = \frac{[\vec{\beta}, \vec{B}]}{2 - \beta^2}, \quad B = \frac{\beta\gamma mc^2}{eR} \cdot (1 + \gamma^2) \quad .$$

S-LSR Ring at Kyoto University

S-LSR can work shear free with Mg^{1+} up to $v/c \approx 2\ 10^{-3}$ ($E \approx 1.5$ KeV/amu) due to E_r limitation.

See:
A.Noda,
Fri, 8-30



S-LSR type rings with mixed electric and magnetic bending can be tuned to have zero linear dispersion everywhere (and $\gamma_{tr} = \infty$).

For higher energy one can think of a purely magnetic lattice (with γ_{tr} very high) where the dispersion is negative in part of the magnets and

$$\gamma_{tr} - 2 = \frac{1}{C_{Ring}} \cdot \oint_{C_{Ring}} \frac{D(s)}{r(s)} \cdot ds \, .$$

Is such an 'on average shear-less ring' well suited for crystallisation??

PALLAS

First experience of 3D crystal beam was obtained in recent years by D.Habs, U.Schramm et al. (LMU, Munich) in the RF quadrupole ring PALLAS.

The experiments with PALLAS has shown possibilities and limits of 3D crystal beams at very low energy ($v/c \approx 10^{-5}$).

See: U.Schramm, Fri, 9-00

Conclusion

There is a surprising lot of new and very exiting developments in the - by now mature - field of beam cooling . "Old" applications are being extended, often in an ingenious and sometimes surprising way and new ones are coming up.

You will have the privilege to learn in detail about them during this workshop.

This talk was meant to be an appetizer.
The selection is unavoidably incomplete and biased.

We apologize for that.

And very last remark:

I thank heartily my colleagues and young, but experienced already, friends from Fermilab for invitation and a good memory they keep about our common work in past years,

personally - Sergei Nagaitsev…

…to be as nice, as possible!