International Workshop on Beam Cooling

http://conferences.fnal.gov/cool05/

Participation

- Nearly 90 participants from
  - US national labs and universities
  - US corporations
  - CERN
  - Germany
  - Russia
  - Sweden
  - Japan
  - PRC
  - The Netherlands

Topics

- Overview
- Reports from labs
- Phase-space manipulations with cold beams
- Stochastic cooling
- Cooling of muons
- Electrostatic rings
- Electron cooling
- Laser cooling
- Traps
- Working group to discuss COSY 2MV cooler

Organization

- Sponsors: DOE Office of Science, Fermilab, BNL, ANL, LBNL
- COOL05 co-chairmen: R. Pasquinelli and S. Nagaitsev
- International Program Committee
- Local support
  - Cynthia Sazama, Suzanne Weber, Monica Sasse

First overview talk…

The International Year of Physics

Einstein: His Impact on Accelerators; His Impact on the World

Andrew M. Sessler
Lawrence Berkeley Laboratory

COOL 05 Eagle Ridge, Galena, IL USA September 18 - 23, 2005

"Reasons for beam Cooling" by Walter Oelert (FZJ)

What's new since COOL03?

- **Demonstration** of the first electron cooling at high energy : 8.9 GeV antiprotons in the FERMILAB Recycler.
- **Commissioning** of three state-of-the-art low energy electron coolers (LANZHOU & LEIR) built by Budker INP.
- **Construction** of a special "dispersionless" ring for laser cooling/beam ordering started (Kyoto University).
- **Commissioning** of LEPTA at JINR (Dubna) ⇒ under way to e-cooling of positrons and e-cooling with circulating electron beam.

COOL05 Eagle Ridge, Galena, IL USA September 18 - 23, 2005

What's new since COOL03? (cont'd)

- Approval of Muon Ionisation Cooling Experiment (MICE) at RAL (UK).
- Good progress with bunched-beam staochastic cooling in RHIC
- Design started: International FAIR project at GSI, where cooling methods will play a key role.
- Design continues: RHIC electron cooling
- Several new proposals for the use of cooled beams for medical applications
- Bad news: Shutdown of CELSIUS (Uppsala) and CRYRING (Stockholm).
- Good news: CRYRING might be used as a cooler storage ring in FLAIR – subproject of FAIR.

The FAIR Project Science Goals

FAIR = Facility for Antiproton and Ion Research

Studies of

short-lived rare isotope beams:	astrophysics, nucleosynthesis in supernovae and stellar processes
hadron matter with antiprotons:	confinement of quarks, generation of hadron masses
compressed hadronic matter in high energy nucleus-nucleus collisions	
bulk matter in the high density plasma state:	inertial confinement fusion, astrophysics issues
Quantum Electrodynamics:	extremely strong electro-magnetic fields, ion-matter interactions

History and Status of the FAIR Project

2001 CDR (conceptual design report)

→ positive response of German Ministry of Science and Research

request: 1) international contribution 25 % of 670 Mio €

2) TDR (technical design report)

2004 10 countries signed MoU (Finland, France, Great Britain, Greece, Italy, Poland, Russia, Spain, Sweden, Germany)

Observers: China, Hungary, India

present: international boards established

AFI: administrative and financial issues

STI: scientific and technical issues

work on definition of project, financial contributions

Additions after CDR: RESR: accumulator ring for antiprotons

AIC: antiproton - RIB collider

FLAIR: low energy antiproton physics

PAX: polarized antiprotons

....

Recent modifications: fit project into a cost frame of 1 Bio. €

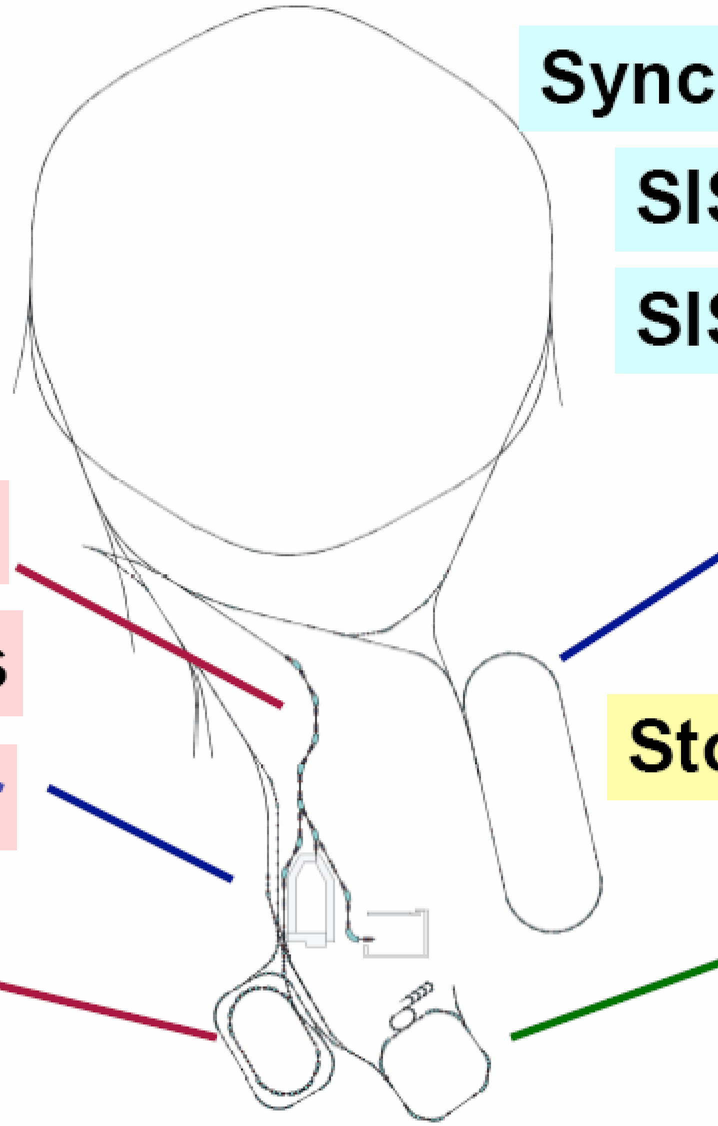
new cost estimates, additional subprojects and manpower included

TDR end of 2005, project definition to German government

The New FAIR Accelerators

Goals:
High beam intensity
High beam energy
High beam quality

Synchrotrons
SIS100
SIS300



SuperFRS
Separators
pbar separator
CR-complex
(CR, RESR)

HESR
Storage Rings
NESR

GSI

High-current ERL-based electron cooling system for RHIC

Ilan Ben-Zvi
Collider-Accelerator Department
Brookhaven National Laboratory

RHIC

BNL

COOL05

The objectives and challenges

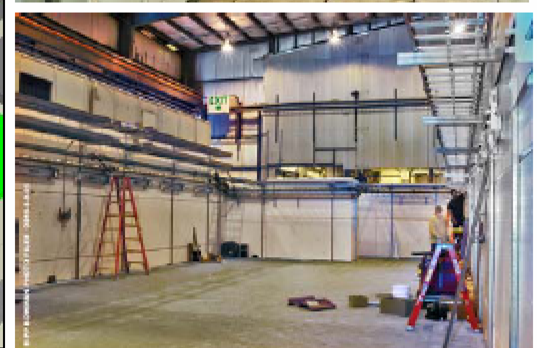
- Increase RHIC luminosity: For Au-Au at 100 GeV/A by ~10, from ~7 10^{26}.
- Cool polarized p at injection.
- Reduce background due to beam loss
- Allow smaller vertex

- Cooling rate slows in proportion to $\gamma^{7/2}$.
- Energy of electrons 54 MeV, well above DC accelerators, requires bunched e.
- Need exceptionally high electron bunch charge and low emittance.

RHIC BNL

R&D ERL under construction

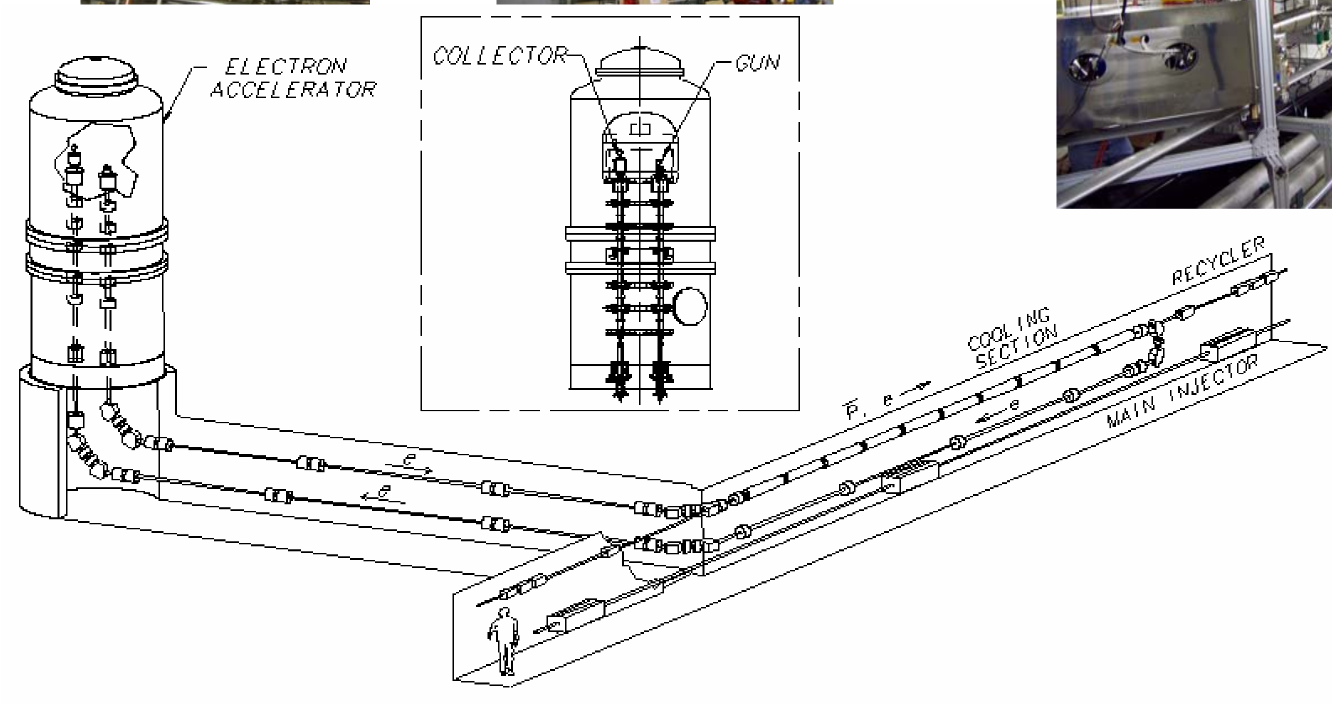
To study the issues of high-brightness, high-current electron beams as needed for RHIC II and eRHIC.



Trends in high-energy electron cooling

- Long cooling sections 20-30 m
- Both magnetized (FAIR) and non-magnetized cooling (Fermilab, BNL) considered
- Beam recirculation is essential: total beam power, losses
- Both HV DC and rf systems are considered

Recycler Electron Cooling

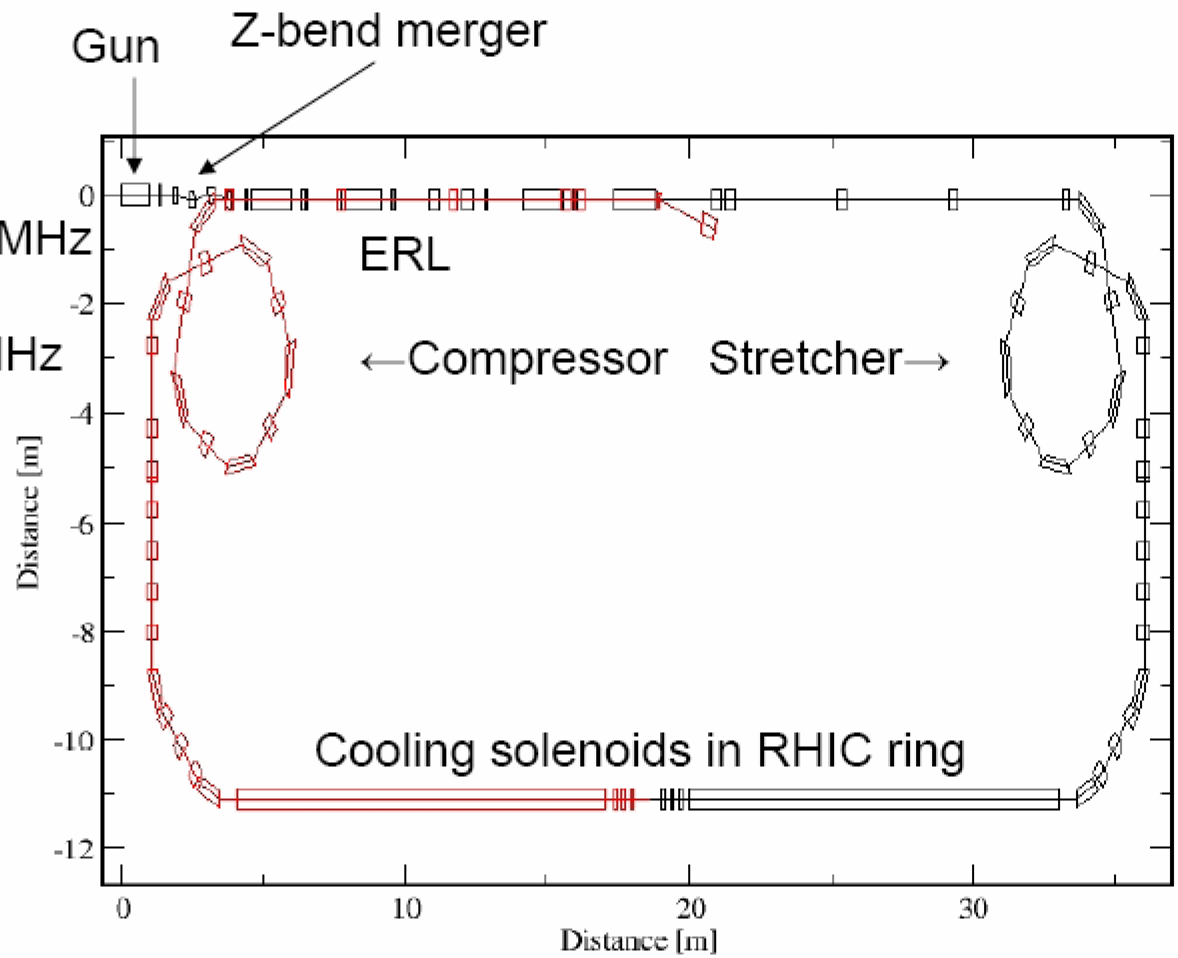


Lattice for magnetized beam

RF frequency: 703.5 MHz
Charge: 20nC/bunch
Repetition rate: 9.4 MHz

$$B_S\sigma_S^2 = 500G(10mm)^2$$

$$\mathcal{M} \sim 380\text{mm.mr}$$



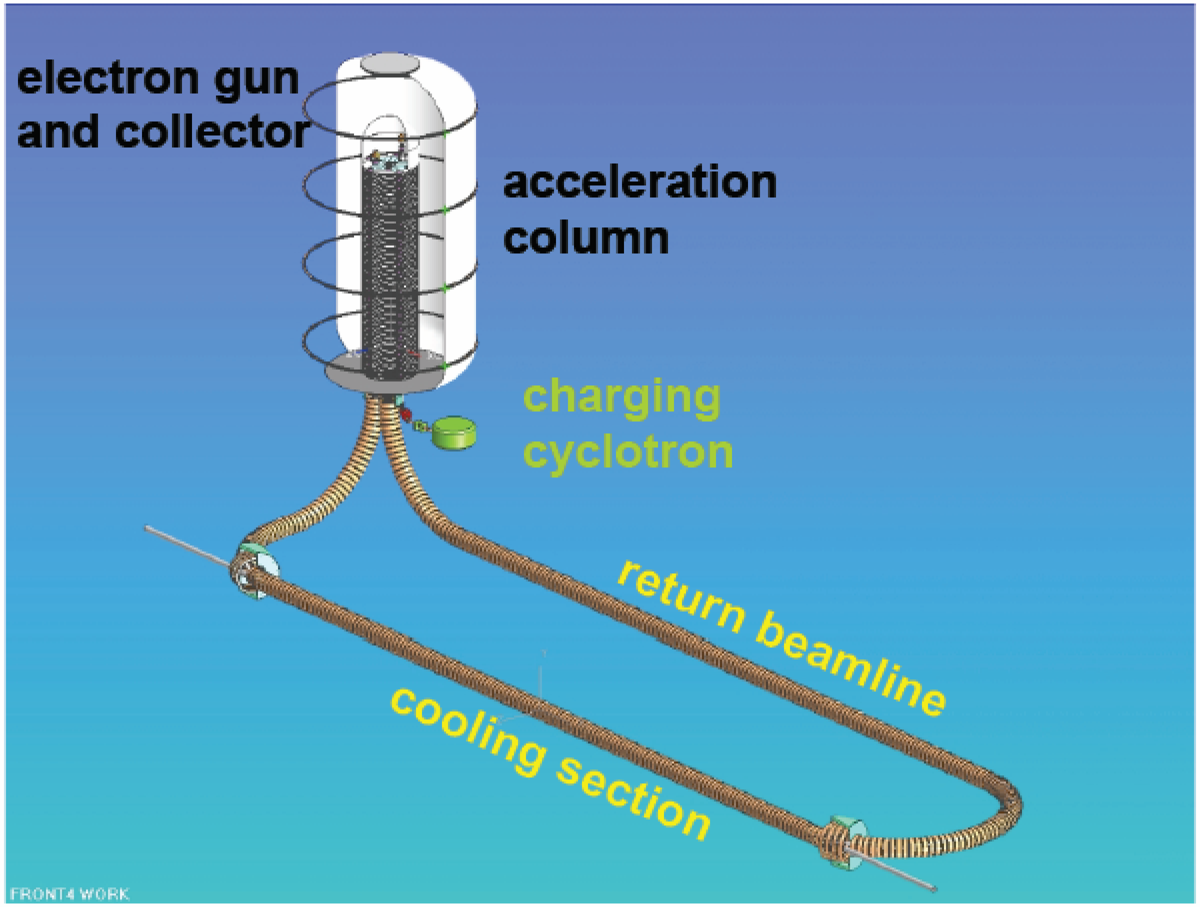
The possibility of non-magnetized electron cooling for RHIC

- Sufficient cooling rates can be achieved with non-magnetized cooling.
- At high γ, achievable solenoid error limit fast magnetized cooling.
- Recombination is small enough
  - Reduced charge
  - Larger beam size
- Helical undulator can further reduce recombination*

*Suggested by Derbenev, and independently by Litvinenko

The HESR Electron Cooling System 1

strong magnetized cooling provides highest cooling rates



energy 0.4 - 8 MeV
current up to 2 A

magnetic field 0.2 - 0.5 T
(superconduct. solenoids)
in cooling section 30 m

electrostatic accelerator
charged by H^--beam

bending by electrostatic
fields for highest
recuperation efficiency

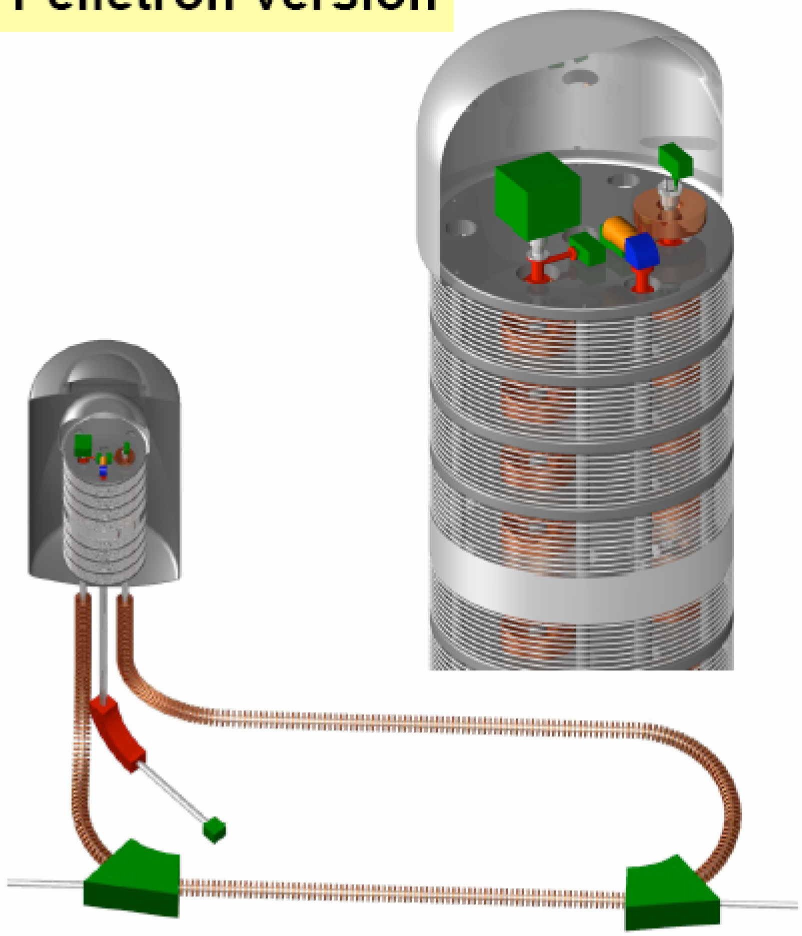
design study by BINP, Novosibirsk, 2003

→ talk by V. Reva

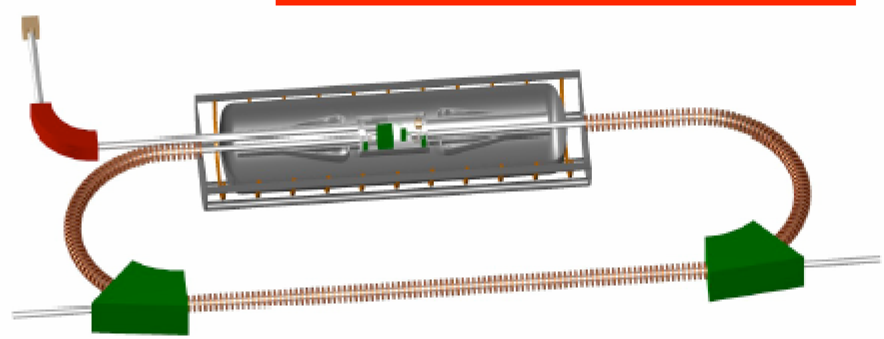
now: design continued by TSL

The HESR Electron Cooling System 2

The Pelletron version



The Dynamitron version



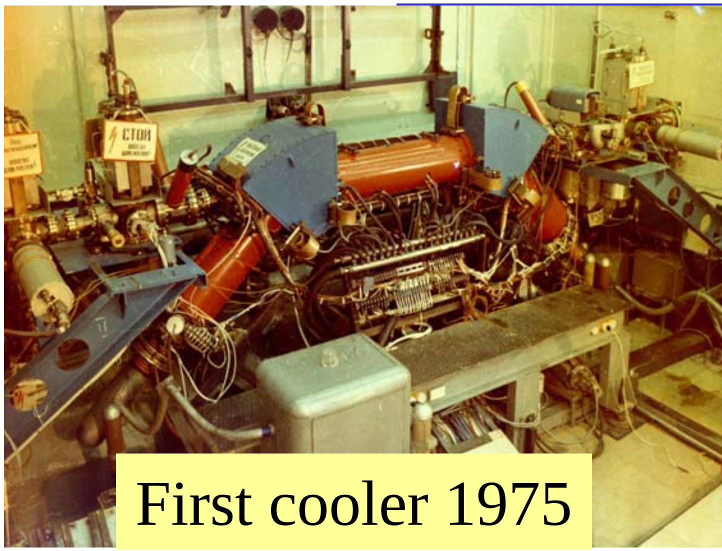
comparison of systems

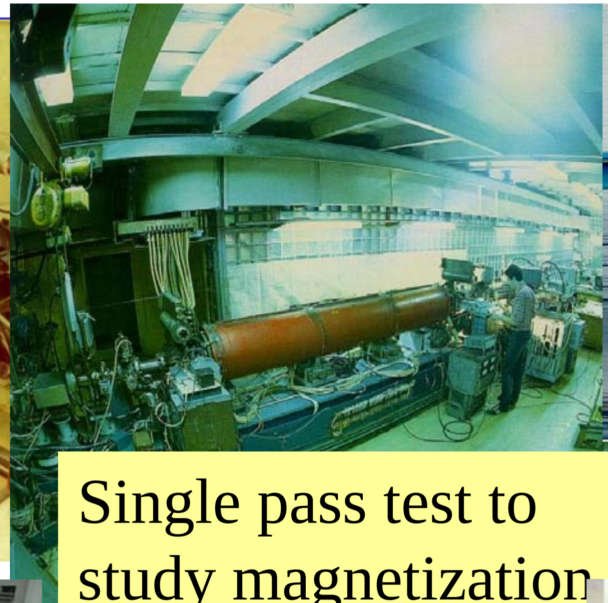
→ *talk by D. Reistad*

Trends in low-energy electron cooling

- **New ideas developed by Budker INP and "bench tested" (without ion beam yet)**

BINP coolers from idea at 1967,
to first cooler at 1975 and to LEIR cooler 2005


First cooler 1975


Single pass test to study magnetization


SIS-18 cooler 1998


CSRm 35 kV cooler 2003

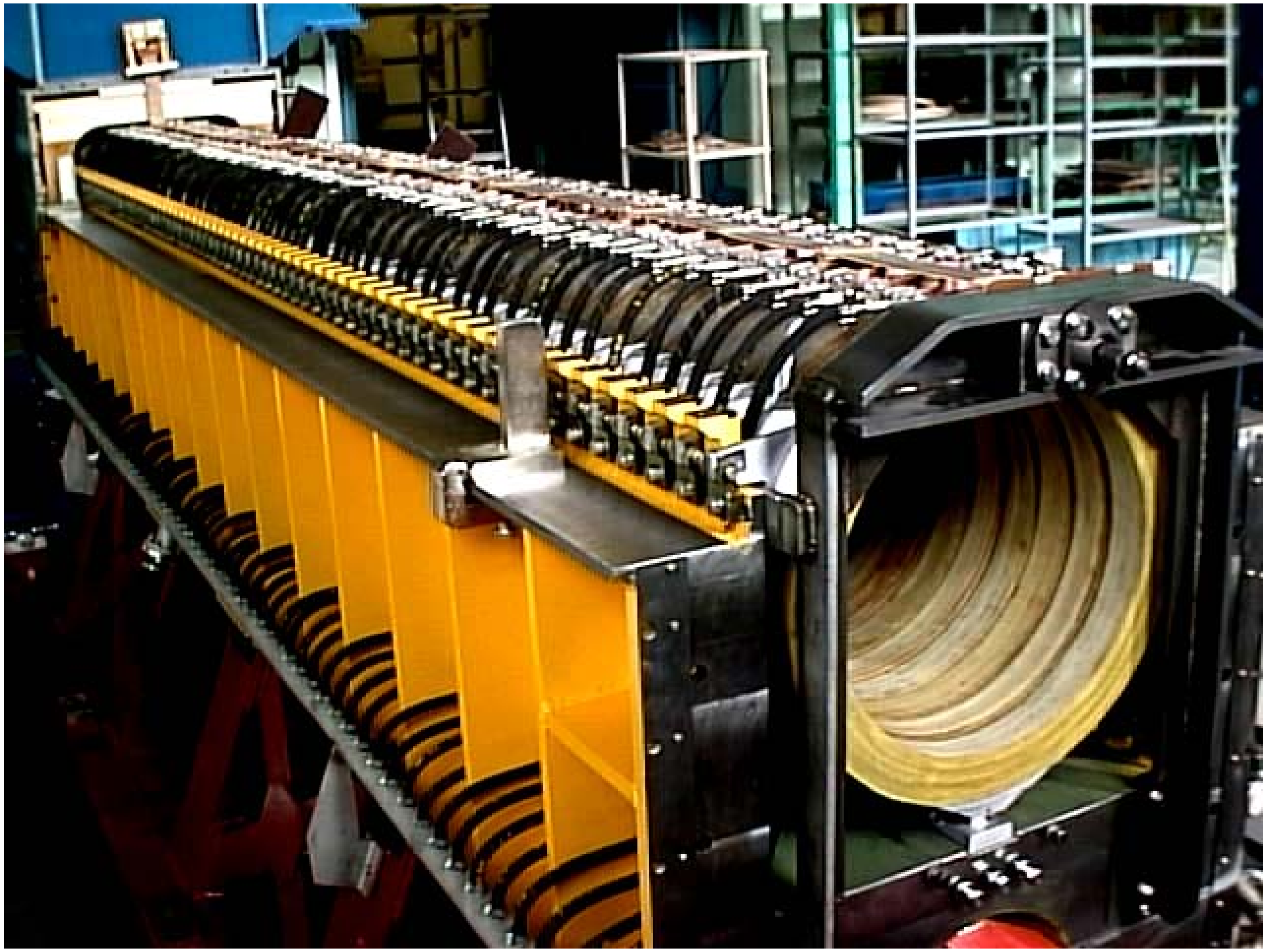

CSRe 300 kV 2004


LEIR cooler 2004 still at BINP

Trends in low-energy electron cooling

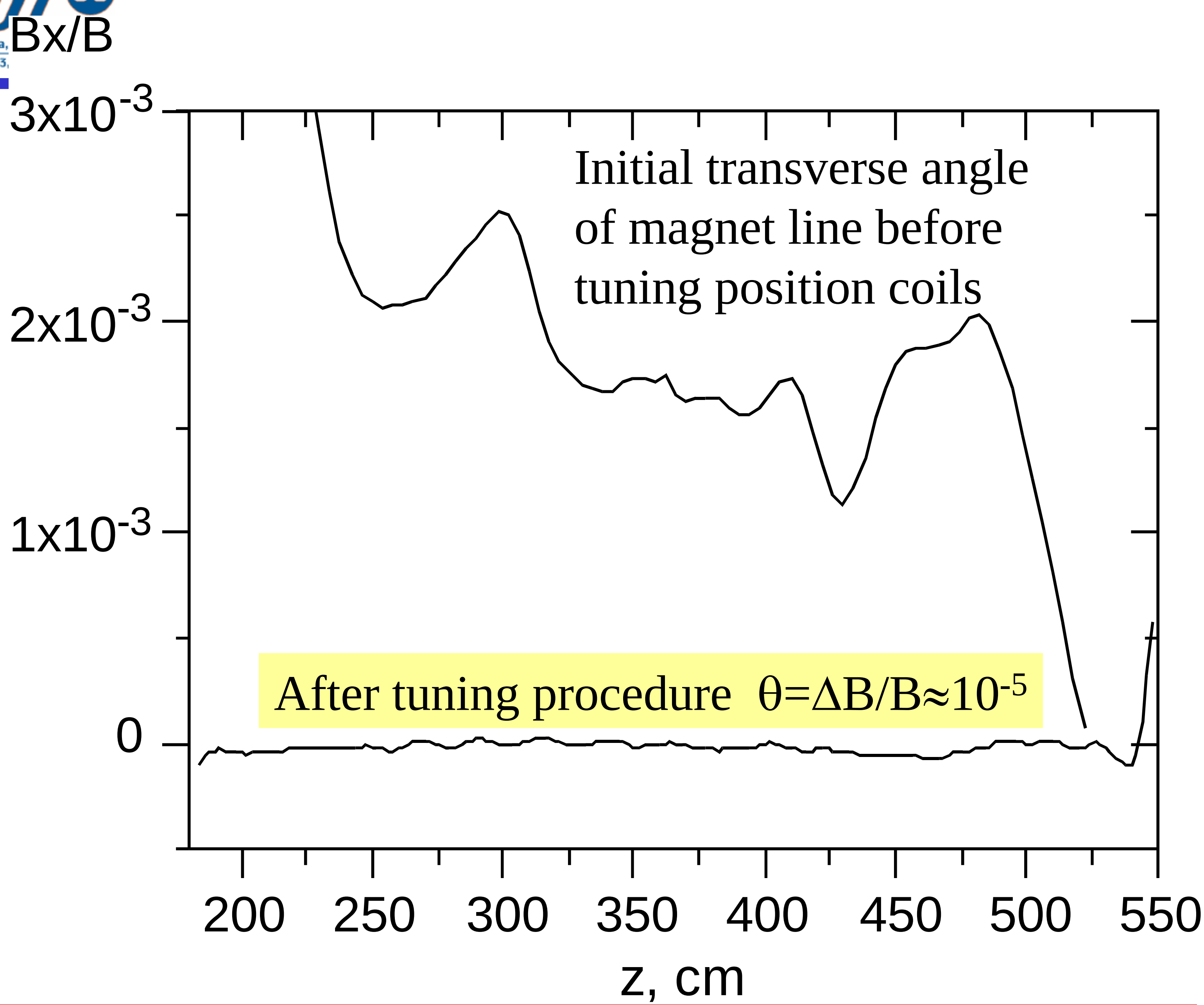
- New ideas developed by Budker INP and "bench tested" (without ion beam yet):
- Precise magnetic field achieved by making a solenoid with individual movable coils
- 'Hollow' e-beam to avoid 'overcooling' at the center. Allows to reduce ion-electron recombination.
- Electrostatic bends

Movable coils



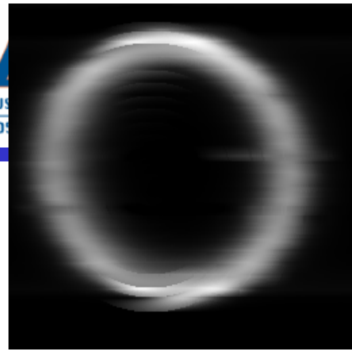
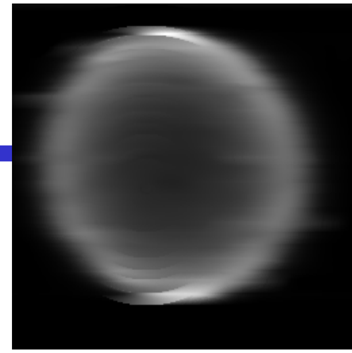
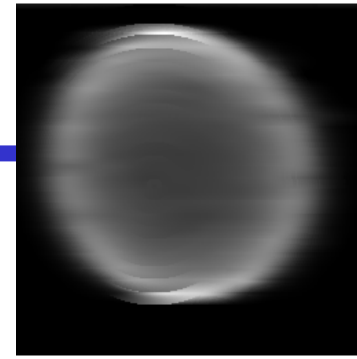
Example of tuning position of #42 coil with optical tube

Coil after measuring magnetic axis is ready for installation


Bx/B
3x10-3
2x10-3
1x10-3
0
200
250
300
350
400
450
500
550
z, cm
Initial transverse angle of magnet line before tuning position coils
After tuning procedure θ=ΔB/B≈10-5

Trends in low-energy electron cooling

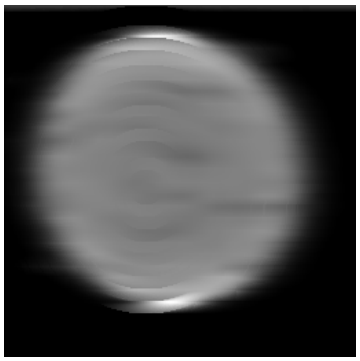
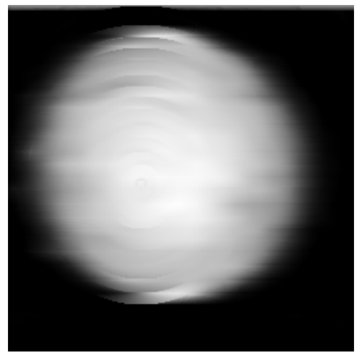
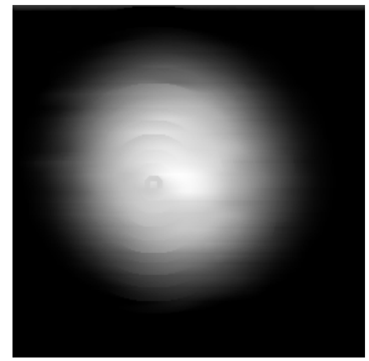
- New ideas developed by Budker INP and "bench tested" (without ion beam yet):
- Precise magnetic field achieved by making a solenoid with individual movable coils
- 'Hollow' e-beam to avoid 'overcooling' at the center. Allows to reduce ion-electron recombination.
- Electrostatic bends

$U_{contrrol}/U_{anode}$= 0.6/0.9 kV

$U_{contrrol}/U_{anode}$= 0.3/0.9 kV

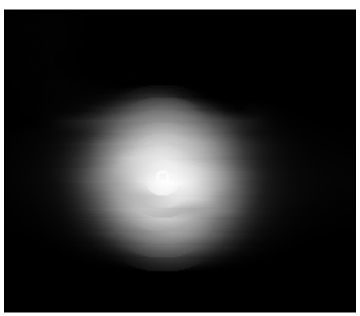
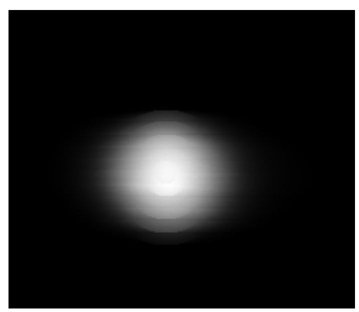
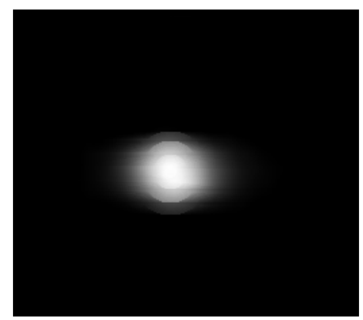
$U_{contrrol}/U_{anode}$=0.2/0.9 kV

$U_{contrrol}/U_{anode}$=0.1/0.9 kV

$U_{contrrol}/U_{anode}$= 0.05/0.9 kV

$U_{contrrol}/U_{anode}$= 0/1.4 kV

$U_{contrrol}/U_{anode}$= –0.2/2.8 kV

$U_{contrrol}/U_{anode}$= -0.4/2.8 kV

$U_{contrrol}/U_{anode}$= –0.6/2.8 kV

Electron beam distribution for different voltage on the control electrode and the anode.

Trends in low-energy electron cooling

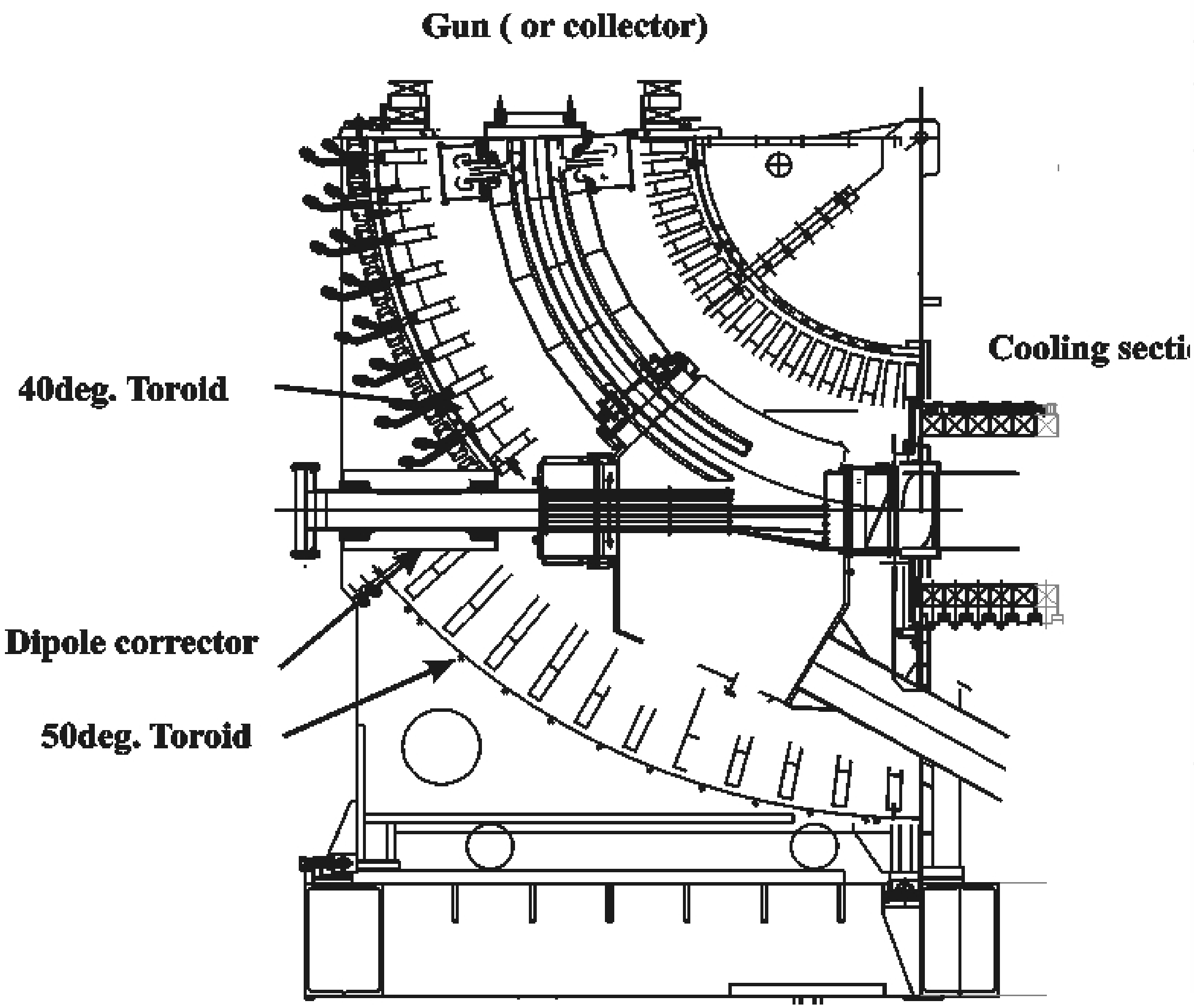
- New ideas developed by Budker INP and "bench tested" (without ion beam yet):
- Precise magnetic field achieved by making a solenoid with individual movable coils
- 'Hollow' e-beam to avoid 'overcooling' at the center. Allows to reduce ion-electron recombination.
- Electrostatic bends – compensates VxB drift, clears secondary particles

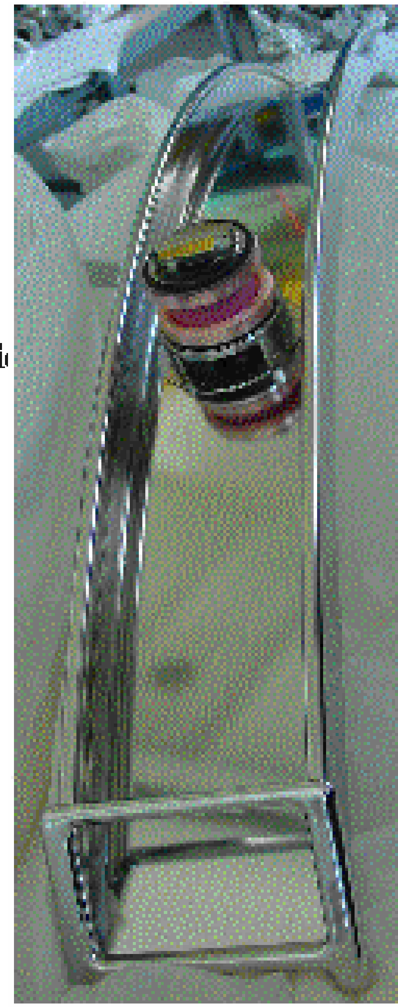
Electrostatic bending to compensate electron drift

$$F = \frac{mV^2}{R} = eE + e\frac{[V \times B]}{c} = const$$

E=0 magnet bending B=pc/eR

B=0 electrostatic bending E=pV/eR





The γ-transition problem

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

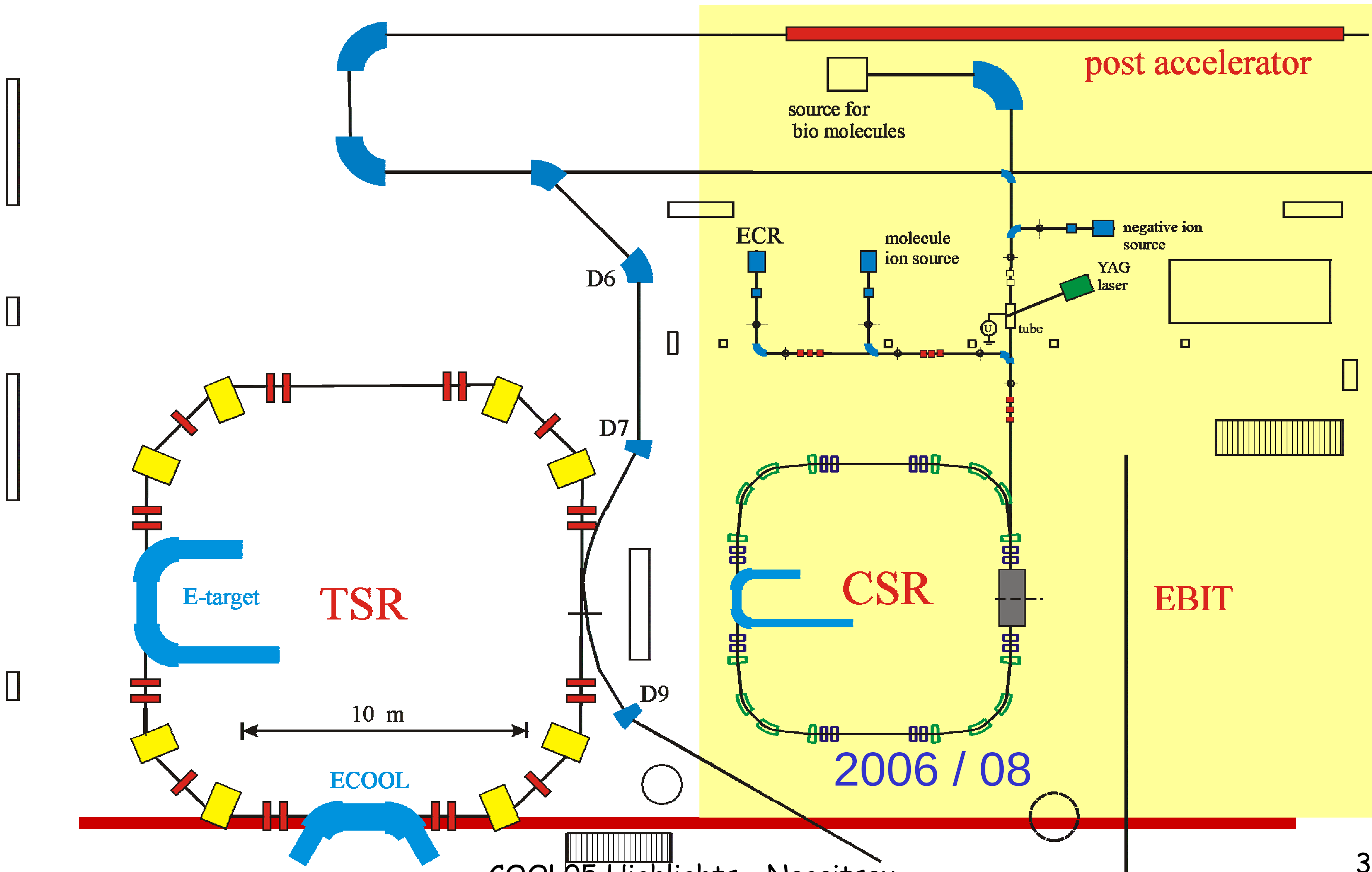
Up to now all e-cooler rings work naturally below transition. However (!) some new high energy coolers have to work above transition. In the old Initial Cooling Experiment at CERN, e-cooling failed above transition.

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

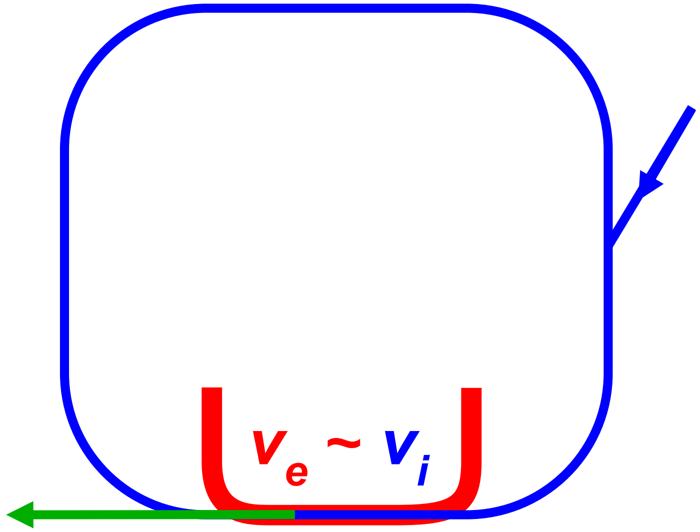
Very-low-energy electron cooling

- ELENA and FLAIR proposals for ~ 100 KeV antiproton and ion (deceleration and cooling) rings, and plans for molecular cooling rings at MPI …
- Challenge for cooling with <50 eV of electron energy: Ultra Low Electron Temperature is required!
- Cold (photo- ?) cathode ⇒ important especially for low longitudinal electron temperature;
- Magnetisation ⇒ to have low effective transverse temperature; Extremely high magnetic field quality!
- Extreme vacuum requirements

Layout of the Heidelberg CSR



Collision experiments with fast merged beams



Reaction products

Ion storage ring

Merged electron beam

Electron cooling: $v_i \stackrel{!}{=} v_e$

Collision measurements: $v_e \stackrel{!}{\neq} v_i$

⇒ collision energy: ~1 meV up to keV

energy resolution: < 1 meV (at collision energy < 100 meV)

BUNCHED-BEAM STOCHASTIC COOLING PROJECT FOR RHIC

COOL05

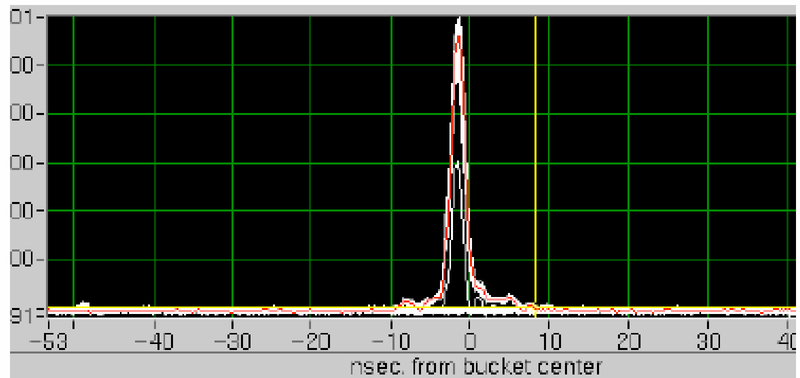
September 2005

J. Mike Brennan and Mike M. Blaskiewicz

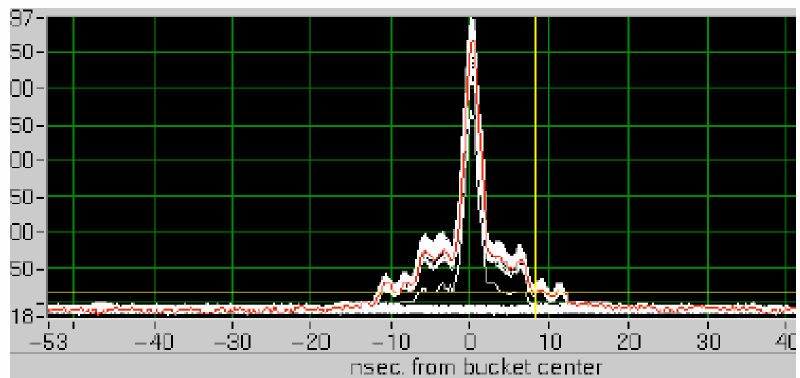
COOL05

Motivation for Cooling (Ions)

- Intra-Beam Scattering drives emittance growth and de-bunching
- Bunch is trapped in satellite bunches by the 28 MHz rf
- We want to stop beam from jumping the 200 MHz separatrix (momentum halo cooling)
- The time scale is hours
- The effective number of particles is:
  - $10^9/1.5$ m * 3830 m = 2.5 x 10^{12}



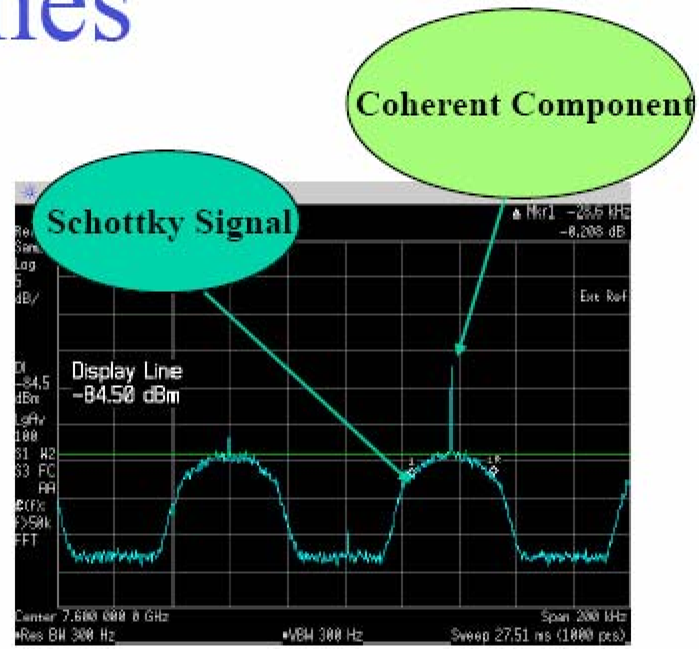
Gold beam at beginning of store



Gold beam at end of store (>5 hours)

Coherent Lines

- This has been Nemesis of bunched-beam cooling.
- Not as severe for ions as for protons.
- Nevertheless, can cause saturation and disable the electronics. The problem is high peak voltages in the time domain.



Spectrum of Copper ions in RHIC at 7.6 GHz, 100 GeV/n

COOL05
Eagle Ridge, Galena, IL USA
September 18 - 23, 2005

Origin of the Coherent Lines

- M. Blaskiewicz has a talk at this conference on our studies of the coherent lines.
- We believe the origin is different for **ions** and **protons** in RHIC.
  - The key difference is that ions are stored in completely filled buckets (large synchrotron frequency spread) and protons are short bunches in long buckets (28 MHz, Δf_s small)
  - For protons, the coherent signals come from the motion of the bunch.
  - For ions, they come from the shape of the bunch.
- The ion bunches have very high frequency structure because of the satellite bunches
  - The Fourier transform of the bunch shape in not negligible at 8 GHz
  - All bunches have the same shape so they contribute coherently to the spectrum
  - The low frequency spectrum envelope reflects the bunch fill pattern
  - As does the high frequency spectrum

Summary

- Unusual features
  1. Halo cooling only, to counteract IBS
  2. High-Q cavity kickers
  3. 2/3 turn delay, pickup to kicker via beam tunnel
  4. Filters realized in fiber optic networks
  5. Run-time BTFs
- Status/Plans
  1. Coherent line problem is manageable
  2. Closed-loop measurements with copper ion have demonstrated signal suppression
  3. Intend to have an operation cooling system for the next RHIC ion run

COOL 05 Eagle Ridge, Galena, IL USA September 18 - 23, 2005

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.

MICE Status (and what we can learn from MICE)

- Official (UK) project at RAL,
- Funding for RAL beamline/infrastructure and tracker,
- Recognized experiment at CERN,
- Important hardware and study contributions from US (MUCOOL collaboration),
- Lots of progress in understanding of: beam optics, detector performance, and emittance measurement,
- ...

Success in getting contributions from many different funding agencies!
---> International effort ("globalization") on other cooling projects!

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'.

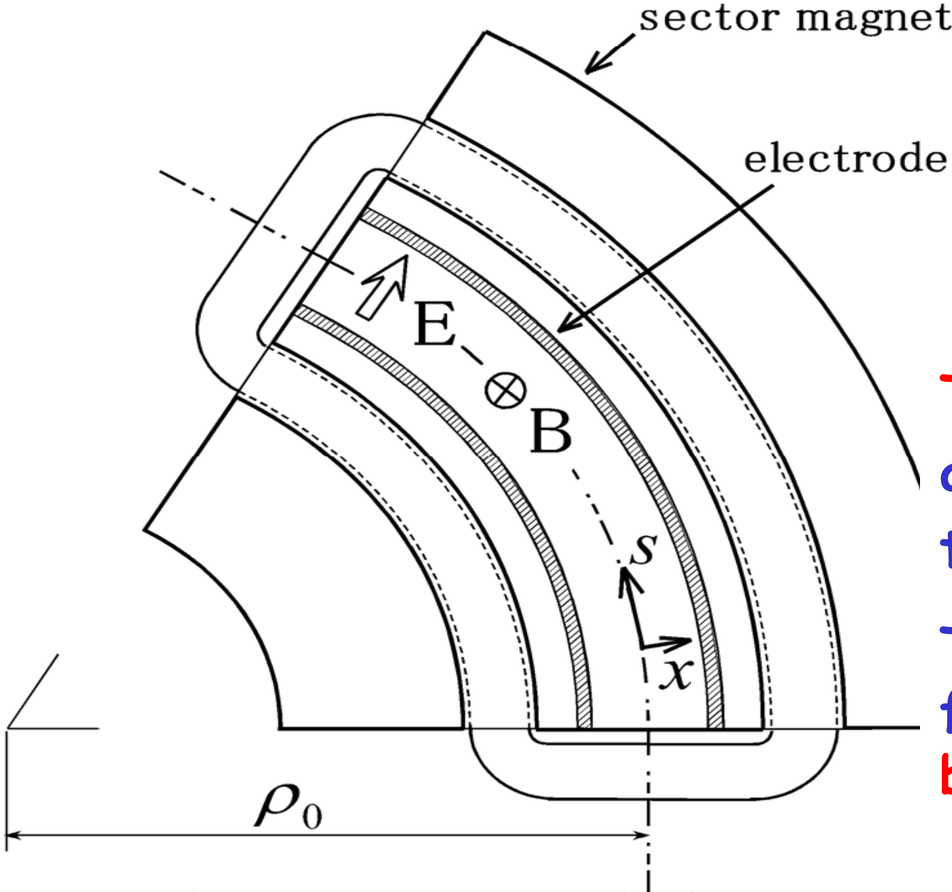
The excitement continues but was somewhat damped in the 1990th when it became clear (due to the work of A.Sessler, G.Wei, H.Okamoto, A.Ruggiero and many others) that 3D crystallisation is subject to a set of tough conditions that can not be met in existing storage rings.

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.

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.

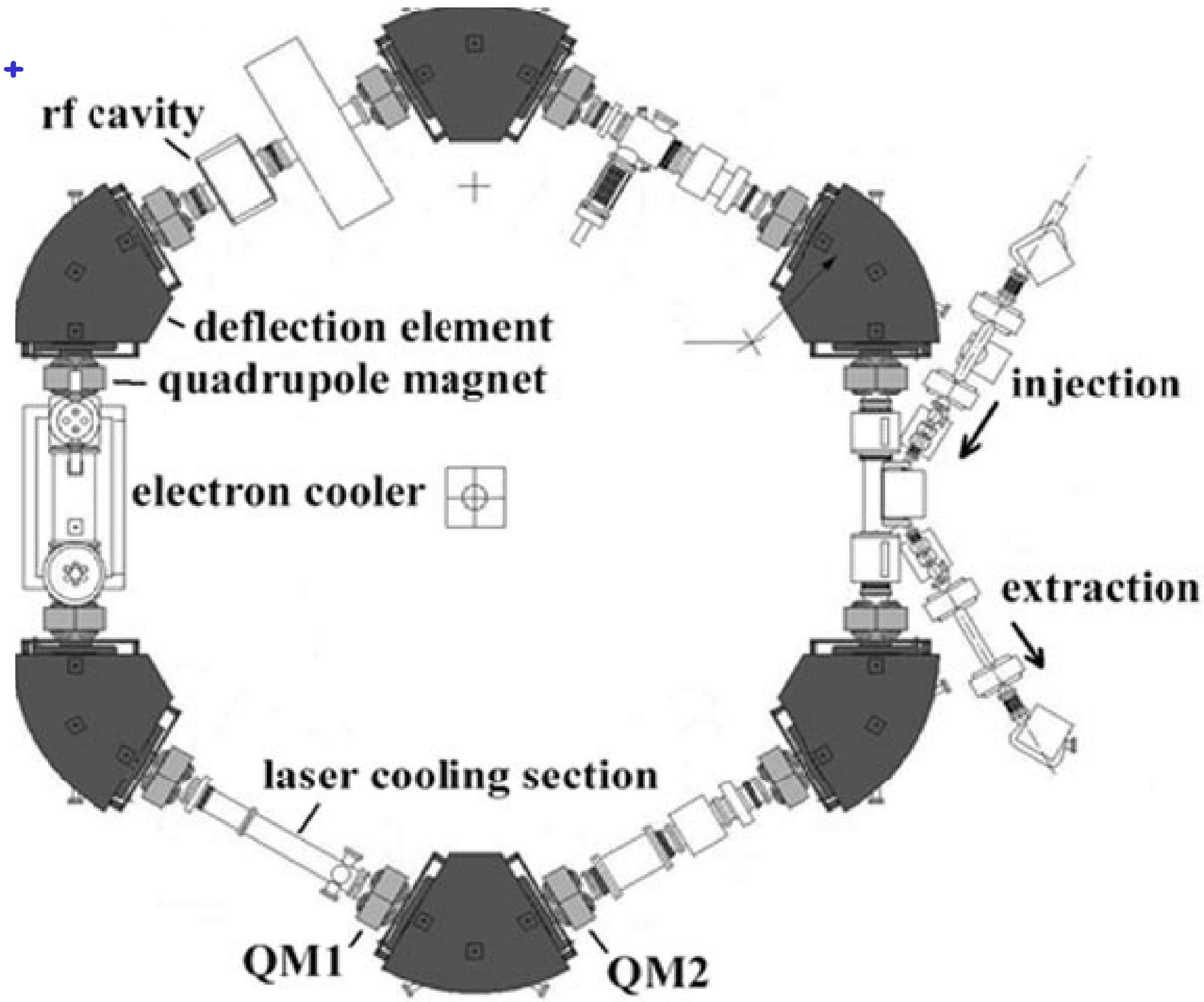
The condition of shear forces absence (to first order):

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

S-LSR Ring at Kyoto University

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

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



Conclusions

- There are surprisingly many new and very exiting developments in the - by now mature - field of beam cooling .

- Acknowledgments: in this talk I have used many slides prepared by others.