The State of the Art in Hadron Beam Cooling

HB2008

42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams

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Acknowledgement and disclaimer

- Work and results presented in this talk come from many sources and represent the efforts (and successes) of many groups and individuals around the world
  - FNAL, BNL, CERN, BINP, GSI, Kyoto University, IMP Lanzhou,…
  - Special thanks to:
    - Vasily Parkhomchuk, Mike Blaskiewicz, Alexey Fedotov, Gerard Tranquille

- Best effort to include and cover the most I could in ~30 minutes, but:
  - I will focus on what is being done today at various facilities
  - I have an inevitable bias
    - Recycler Electron Cooler and electron cooling in general
  - There is a non-negligible possibility that I overlooked some important results/achievements
    - I apologize in advance for those who feel they belong to this category

Outline

- What is cooling, cooling techniques
- Stochastic cooling
  - Bunched beam
- Electron cooling
  - Low energy coolers
    - Beam shaping
  - High energy coolers
    - FNAL
- Other (less advanced) work/projects
  - Beam ordering
  - Optical stochastic cooling
  - Coherent Electron Cooling (CEC)
  - Proton ionization cooling
- Conclusion

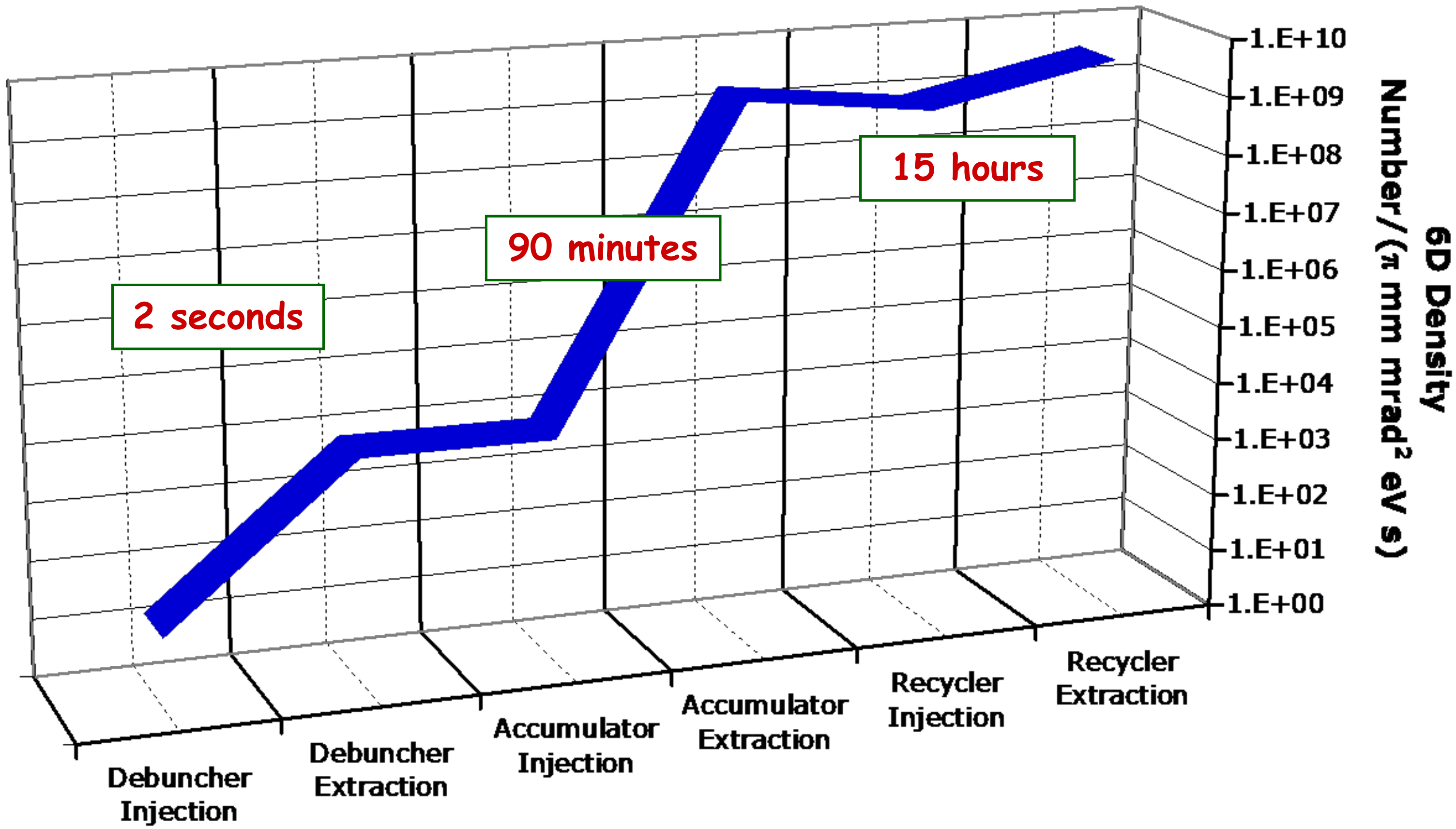
Beam cooling techniques

- Definitions of 'beam cooling'
  - Beam cooling corresponds to an increase of the 6D phase-space density
  - Equivalently, cooling is a reduction in the random motion of the beam particles

- Cooling techniques currently widely used
  - Stochastic cooling
  - Electron cooling
  - Synchrotron radiation cooling
    - Negligible for hadrons
      - *Small effects (good and bad) start with LHC energies*
  - Laser cooling
    - For certain type of ions only
  - Resistive cooling
    - At very low energy in electromagnetic traps
      - *Not really a hadron beam anymore*

Stochastic cooling at FNAL

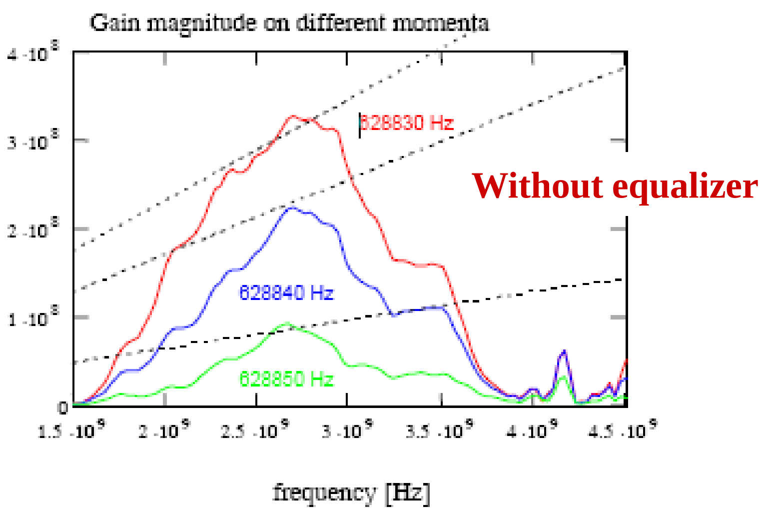
- Used for antiproton production in 3 different rings
  - From production to extraction (from the Recycler), 6D phase-space density increases by ~200 million
    - Electron cooling *directly* contributes to *only* a factor of ~5-10

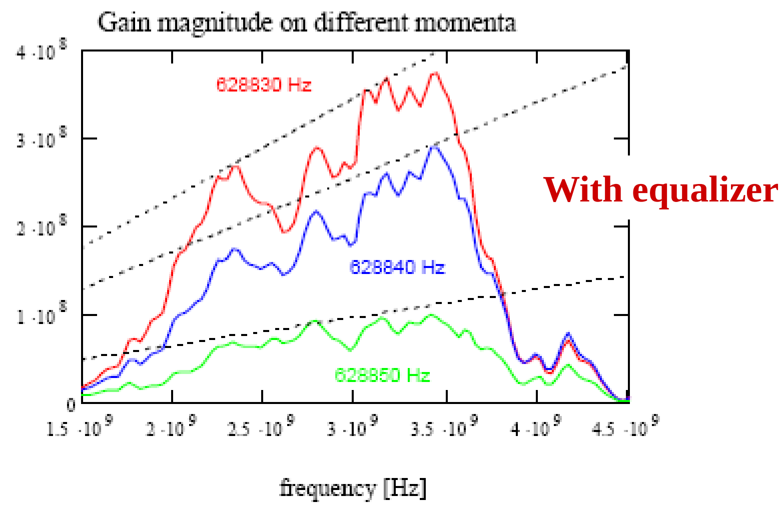


Stochastic cooling at FNAL – Main features highlight (I)

- Debuncher:
  - Optical notch filter
    - >30 dB depth, ~ ±1 ppm dispersion (*i.e.* notch position jitter)
    - 1 and 2 turn delays (switches during a cycle)

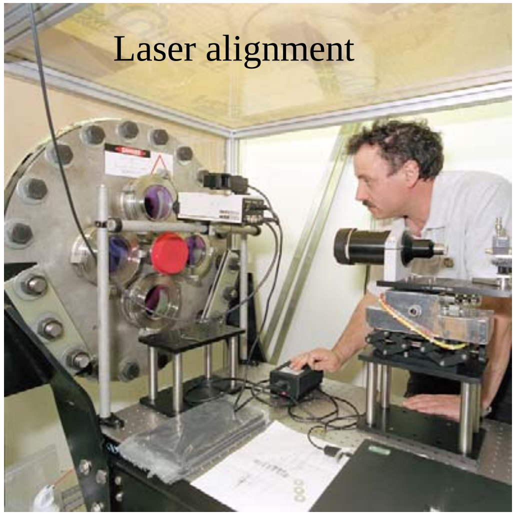
- Accumulator:
  - Implemented equalizers – made of passive electronics - on almost all systems (the last one will be done shortly)
    - Brings gain and phase closer to ideal (*i.e.* zero phase and linear gain as a function of the frequency in the band considered)





Stochastic cooling at FNAL – Main features highlight (II)

- Recycler:
  - Optical transmission across the ring
    - Cable is too slow !
  - Gated cooling possible
    - Cooling over different sections of the ring with different systems and/or gains

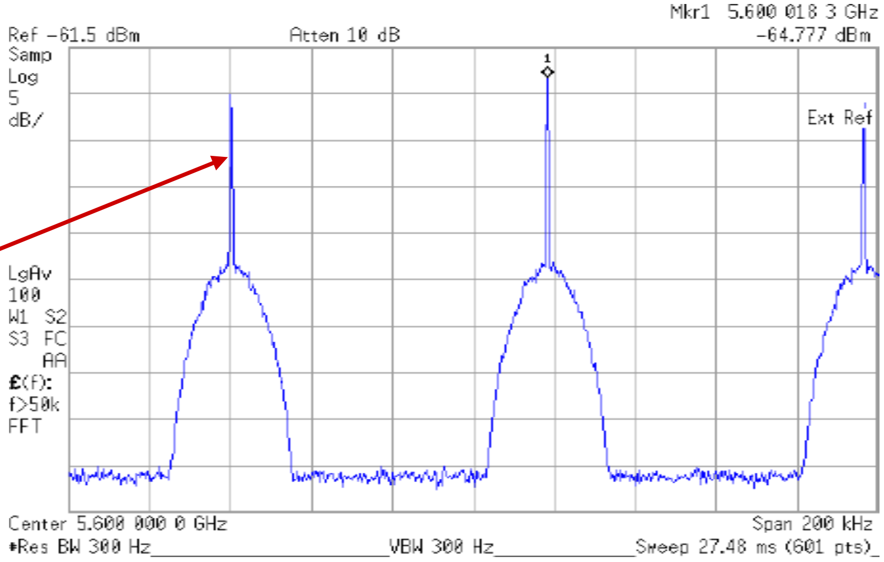


- Along with electron cooling (*later slides*), cooling in the Recycler allowed the accumulation of ~10^{15} antiprotons since the beginning of this year

Bunched beam stochastic cooling

- Stochastic cooling is an effective and well-established technique, however problems arise for bunched beam
  - High density of the bunches
    - Stochastic cooling efficiency scales as 1/N
  - Synchrotron motion affects mixing
  - Creates coherent spikes in the Schottky spectra that needs to be eliminated
    - Coherent power dominates the spectra which limits the gain and power that can be applied
      - Example: Schottky spectrum from BNL (5 ns bunches)

Coherent bunched signal ~30 dB larger than the Schottky signal

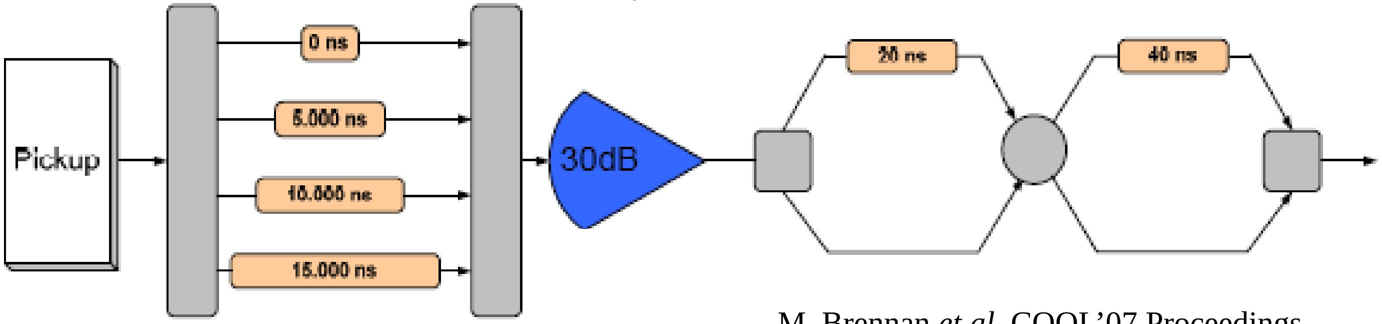


M. Brennan *et al.* COOL'07 Proceedings

Bunched beam stochastic cooling at RHIC

- Motivation
  - Counteract IBS during stores to increase integrated luminosity
  - Prevent de-bunching (halo cooling)
- Challenges
  - A cooling time of about 1 hour is required
  - Beam energy is 100 GeV/nucleon
    - Produce HV kicker (3 kV amplitude) in the 5-8 GHz band
  - The beam is bunched to 5 ns in 200 MHz rf buckets

- Dealing with the coherent components: Filter the pick-up signal
  - Use filter built from coaxial cables adjusted to precise 5.000 ns intervals with small 100 ps coaxial trombones



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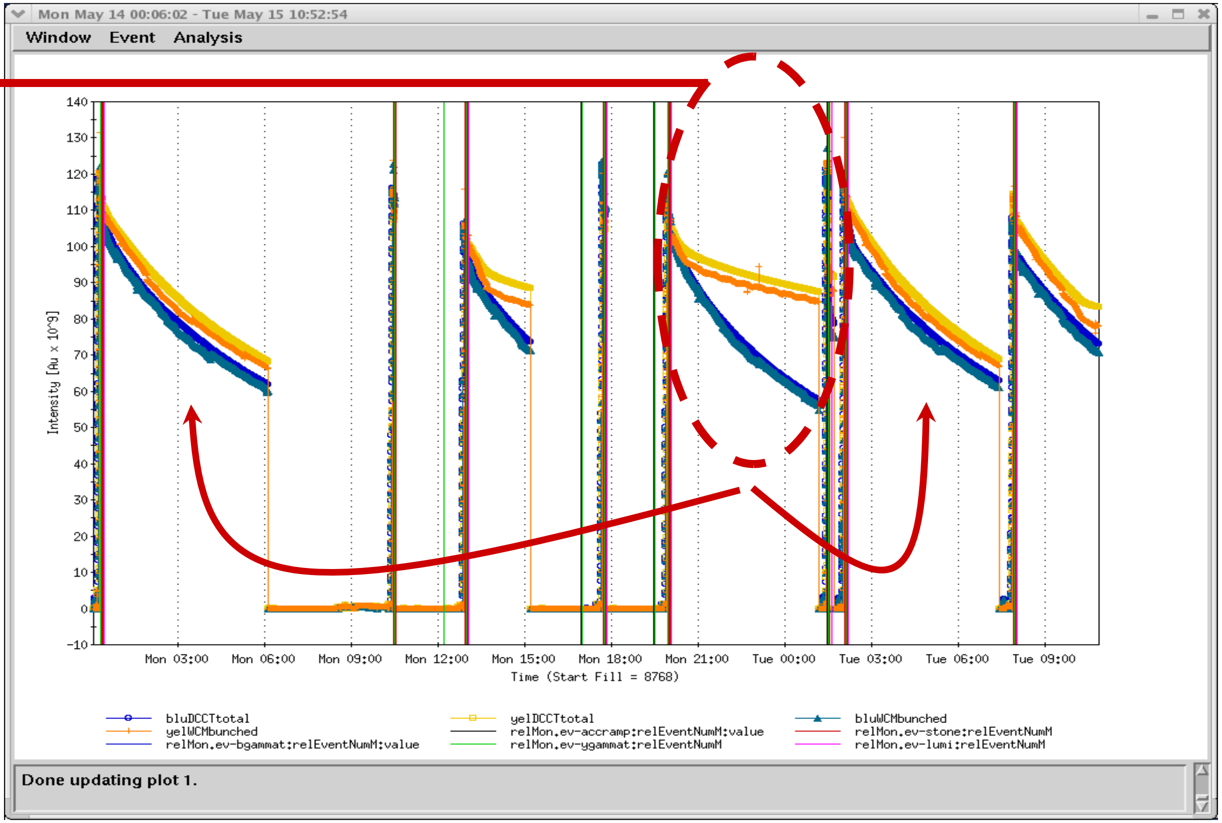
Results with Gold ions

- The beam loss rate has been reduced to the "burn off" level (beam is lost to collisions only)
- Cooling prevented de-bunching
  - Gated off during abort gap

M. Brennan *et al.* COOL'07 Proceedings

First store with cooling running in the Yellow ring

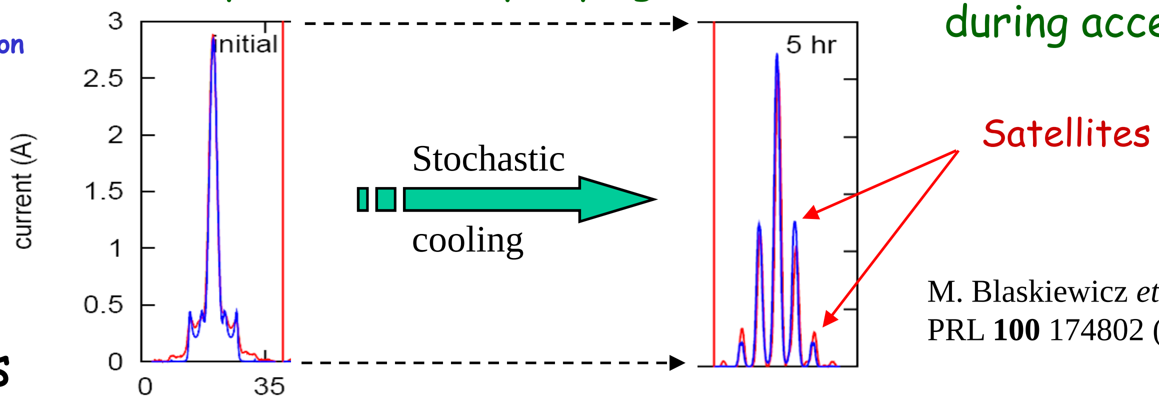


Gold ion lifetime in both rings (yellow and blue) for 5 stores

Status and plans

- Main challenge remaining
  - Beam in the satellite buckets
    - Currently addressed by trying to reduce the emittance growth during acceleration

Blue: simulation
Red: data



M. Blaskiewicz *et al.*
PRL **100** 174802 (2008)

- Plans
  - Yellow ring longitudinal system is operational
    - Blue ring longitudinal system operational this coming run
    - Yellow vertical system will also be commissioned
  - New transverse pickups are being designed
    - Hope to have one installed for the next run
  - To address the formation of satellite bunches:
    - Working on quadrupole damper to damp transition mismatch
    - A 2nd harmonic cavity is being designed (to be completed ~2011)
      - *This device should eliminate satellite bunches*

Low energy electron cooling

- Relatively modest design evolution since the early 70's

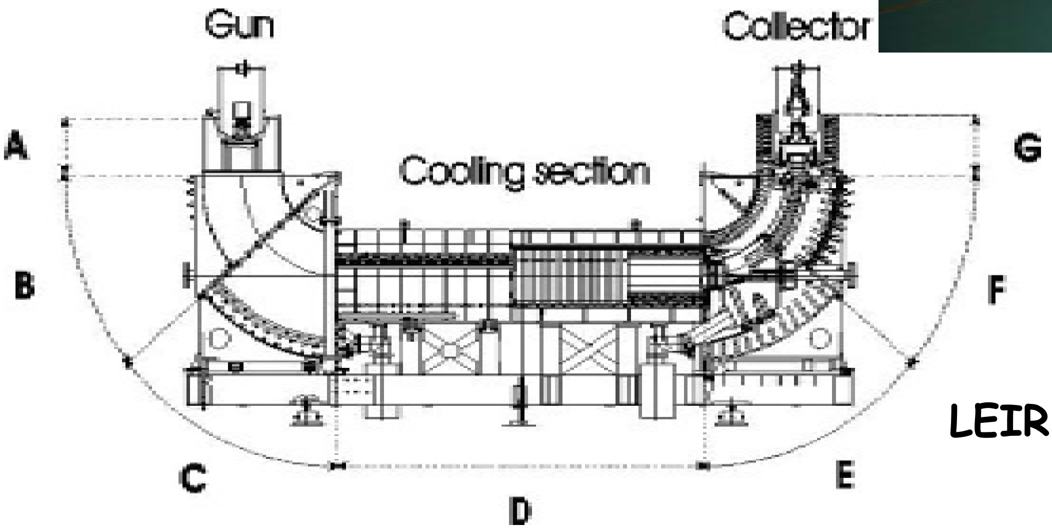
- Some new features on the two latest coolers (LEIR at CERN and CSRm at IMP, Lanzhou) built by BINP
  - Very precise magnetic field obtained through a large number of trim coils
  - 'Hollow' electron beam (or more generally speaking, beam shaping capability)
    - Avoids "overcooling of the core", which leads to instabilities
    - Reduces ion-electron recombination
  - Electrostatic bends
    - Reduces trapping of secondary particles $\Rightarrow$ Improves electron beam stability

- Other more subtle innovations
  - Magnetic expansions
    - Allows adjustments of the electron beam size
  - High magnetization
  - High perveance

Similar electron coolers for LEIR and CSRm

- Innovative features
  - High perveance gun
  - Beam expansion
  - Electrostatic bend
  - Pancake structure of magnets
  - Variable electron beam profile

CSRm cooler



LEIR cooler

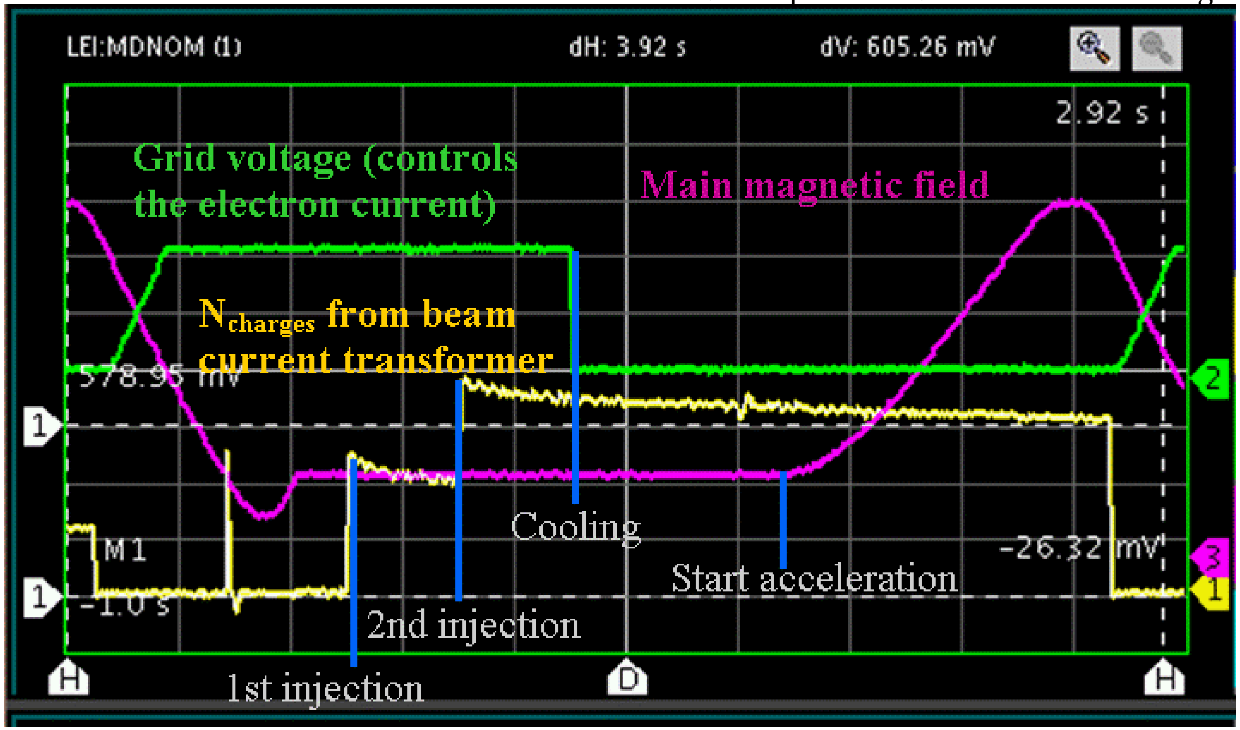
G. Tranquille *et al.* COOL'07 Proceedings

Goals of the commissioning runs at LEIR

- Produce the Pb ion beam with the characteristics required for the first LHC ion run (N_{ions} = 2.2x10^{8}, $\varepsilon_{h,v}$ < 0.7 µm)
- Standard 3.6s LEIR cycle
  - 2 LINAC pulses are cooled-stacked in 800ms at an energy of 4.2 MeV/n
  - After bunching the Pb ions are accelerated to 72 MeV/n for extraction and transfer to the PS.

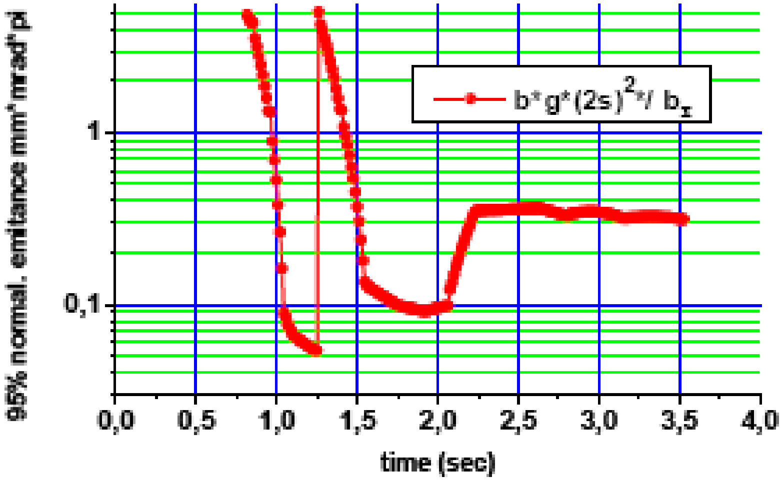
G. Tranquille *et al.* COOL'07 Proceedings

Successful !

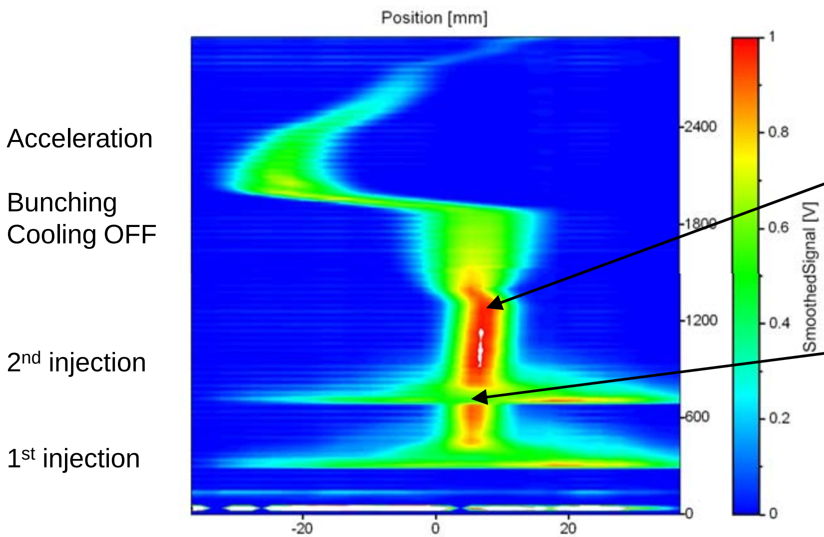


Cooling performance at LEIR

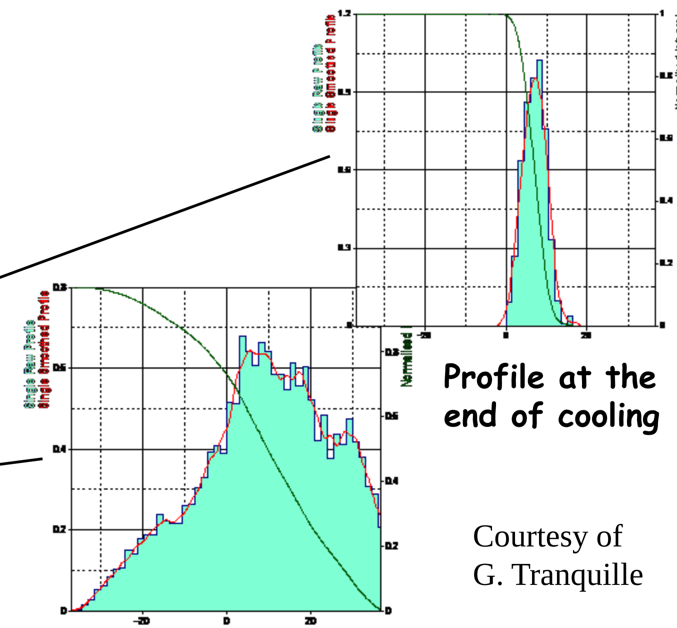
V. Parkhomchuk *et al.* COOL'07 Proceedings



- The cooling time is about 0.2 s
  - After switching off the electron beam, the emittance blows up from 0.1 to 0.3 π mm mrad by the action of IBS



Horizontal beam profile measured on the IPM.



Profile at the end of cooling

Profile at 2nd injection

Courtesy of
G. Tranquille

Goals and results for CSRm

- Increase the intensity of heavy ions accumulated for extraction to the experimental ring (CSRe)
  - Transverse cooling of the ion beam after horizontal multi-turn injection allows beam accumulation at the injection energy
  - Cooling times of 100 to 2500 ms depending on the ion species
    - Horizontal emittance from decreased from 150 to < 20 π mm mrad
    - Momentum spread reduced by a factor of 10 (from ~10^{-3} to ~10^{-4})

- Intensity increase in a synchrotron pulse by more than one order of magnitude has been achieved
  - In a given accumulation time interval of 10 seconds, 10^8 particles have been accumulated and accelerated to the final energy
  - The momentum spread after accumulation and acceleration in the 10^{-4} range has been demonstrated in five species of ion beam

Stability of cooled beams

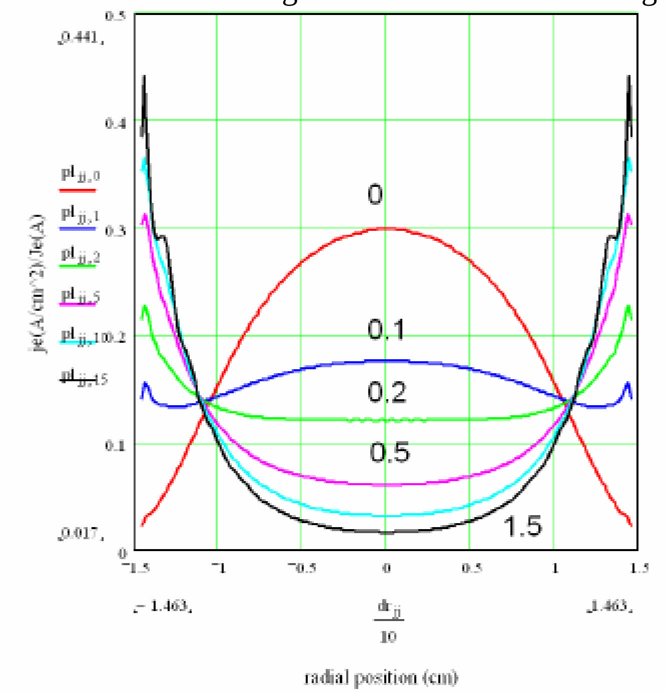
- Stability issues have been observed for ion beam cooled with electrons
  - Beam-beam effects leading to
    - (slow) Ion loss or diffusion
    - Injection 'fast loss'
    - Development of instability in a well cooled ion beam due to its interaction with the electron beam (known as 'electron heating')
  - Instability when secondary ions are trapped in the electron beam
    - Also addressed by electrostatic bends
- Proposed mechanism is 'overcooling' of the core of the ion beam
  - Sets a limit of the densities that one can achieve (V. Parkhomchuk)

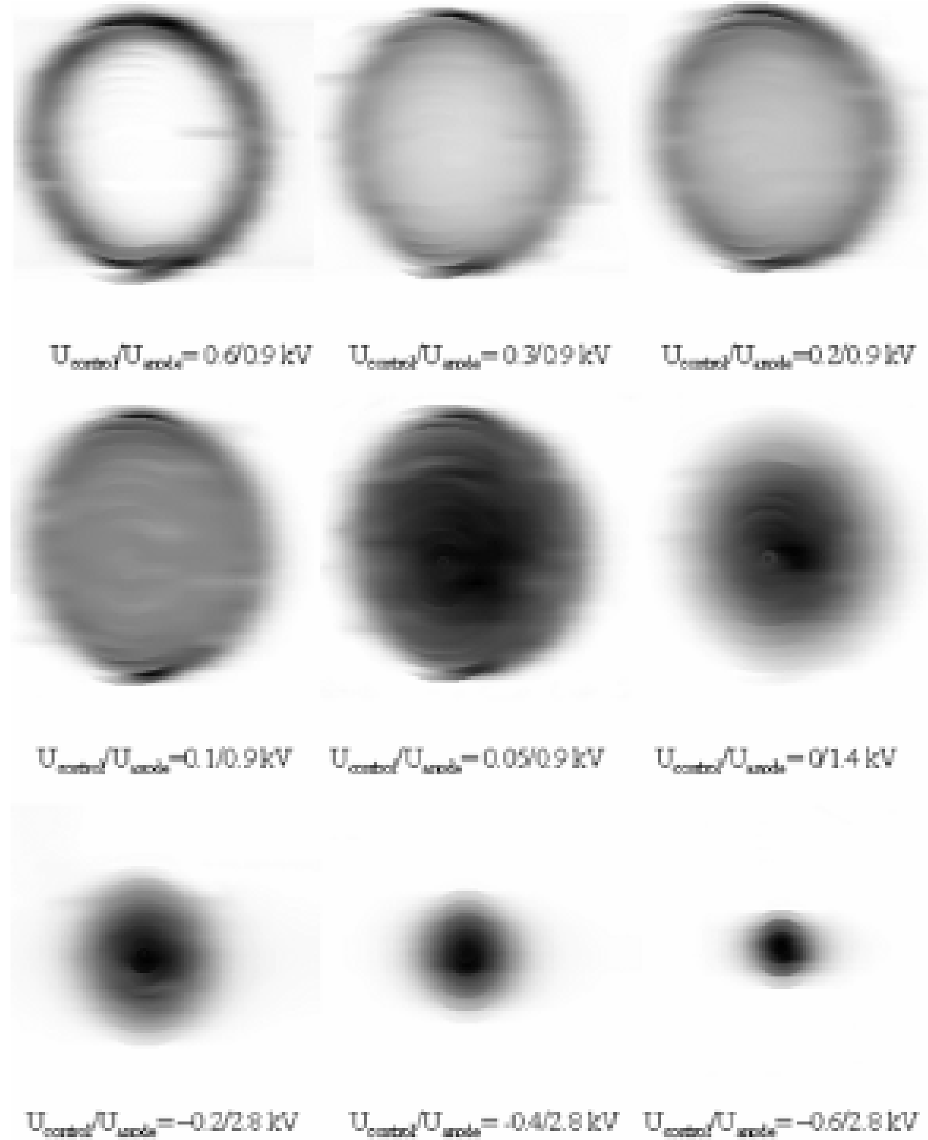
$$n_i \times n_e \leq \frac{6}{r_e r_i (c\tau)^4 * g(4\pi)^2 \ln(\rho_{\max} / \rho_{\min})}$$

Variable profile electron gun

- Both cooler at LEIR and CSRm have the capability to provide beam current density distributions of various 'hollowness'

X. Yang *et al.* COOL'07 Proceedings

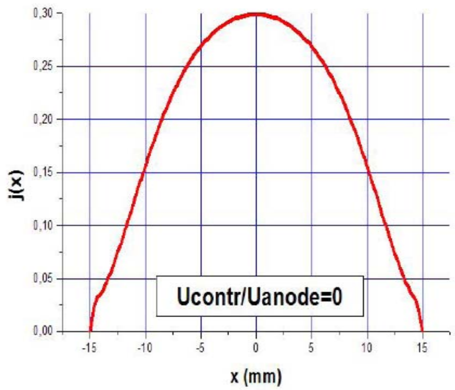


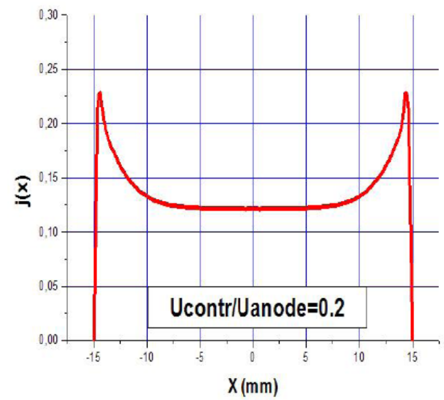


Cooling with a hollow electron beam

- At both LEIR and CSRm, number of accumulated ions increased with a partially hollow beam
  - By ~2× at LEIR mostly because of a better lifetime

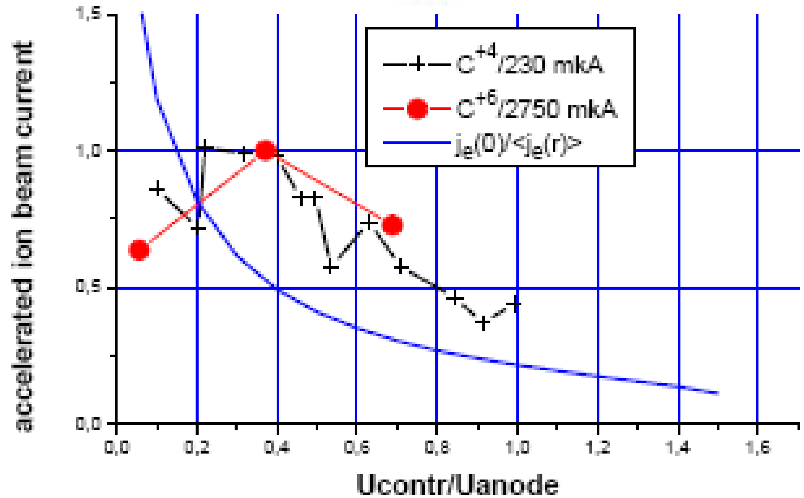
0.7×10^9 Pb ions → **1.3×10^9 Pb ions**





V. Parkhomchuk *et al.*
COOL'07
Proceedings

- More systematic measurements at CSRm show better accumulation results for Ucontr/Uanode ~ 0.2-0.4



High energy electron cooling

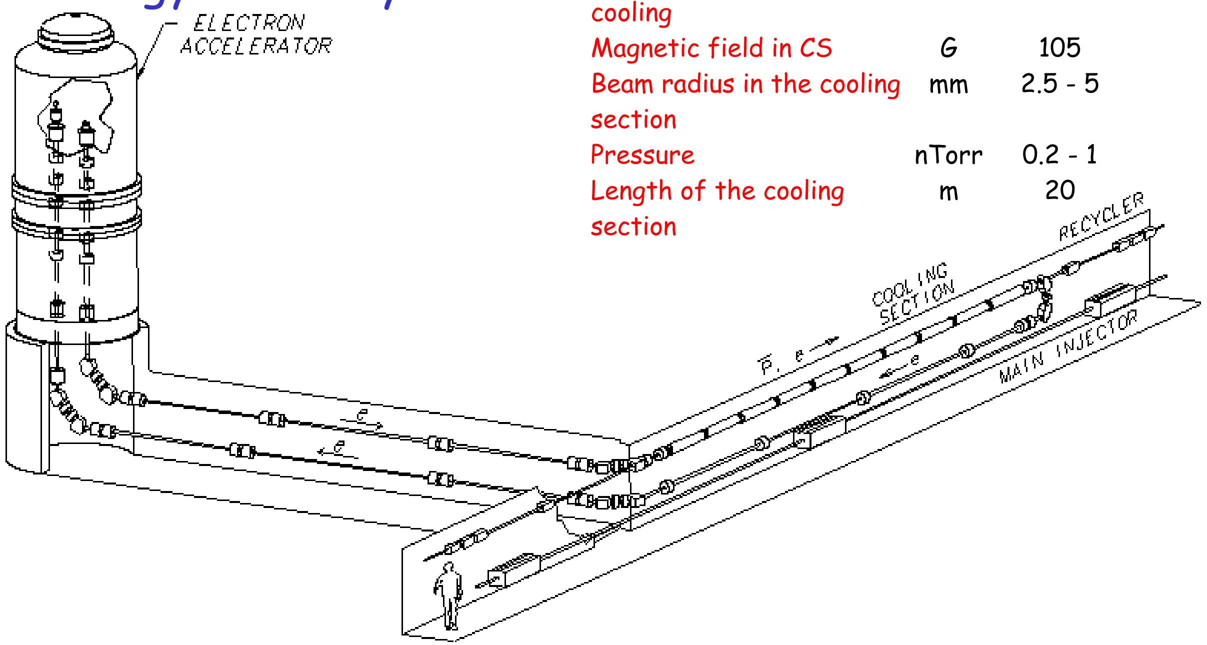
- One unique facility at FNAL's Recycler ring
  - First demonstration of relativistic electron cooling in July 2005
  - Operational since mid-October 2005
    - Used in parallel with stochastic cooling
  - Other facilities are being considered/designed (RHIC at BNL, FAIR's HESR at GSI)

- All proposals (including at FNAL)
  - Long interaction region (15-20 m instead of 1-3 m for low energy coolers)
    - Cooling times much longer than for low energy coolers
  - Energy recuperation scheme
    - Energy recovery Linac for bunched electron beam
    - Electrostatic accelerator for DC electron beam

FNAL's Recycler Electron Cooler (REC)

- Goal of cooling in the Recycler
  - Increase longitudinal (and transverse) phase space density of the antiproton beam in preparation for
    - Additional transfers from the Accumulator
    - Extraction to the Tevatron
- Main features
  - Electrostatic accelerator (Pelletron) working in the energy recovery mode
  - DC electron beam
  - Lumped focusing outside the cooling section

Electron energy	MeV	4.338
Beam current used for cooling	A	0.05 - 0.5
Magnetic field in CS	G	105
Beam radius in the cooling section	mm	2.5 - 5
Pressure	nTorr	0.2 - 1
Length of the cooling section	m	20



Accumulation performance

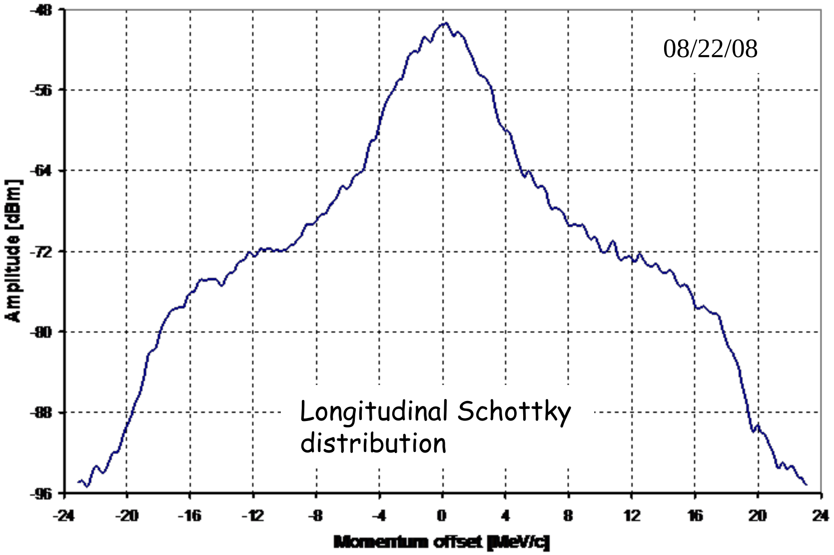
- Use of electron cooling allowed the storage and extraction of more than 450 × 10^{10} antiprotons
  - > ~3 times what would be possible with stochastic cooling alone
    - Much faster too
  - Delivers very consistent bunches (*i.e. same emittances shot to shot*)
  - Plays a major role in increasing the initial and integrated luminosities in the Tevatron
    - Record initial luminosity > 300 × 10^{30} cm^{-2} s^{-1}

Before extraction to the TeV:

N = 375 × 10^{10}

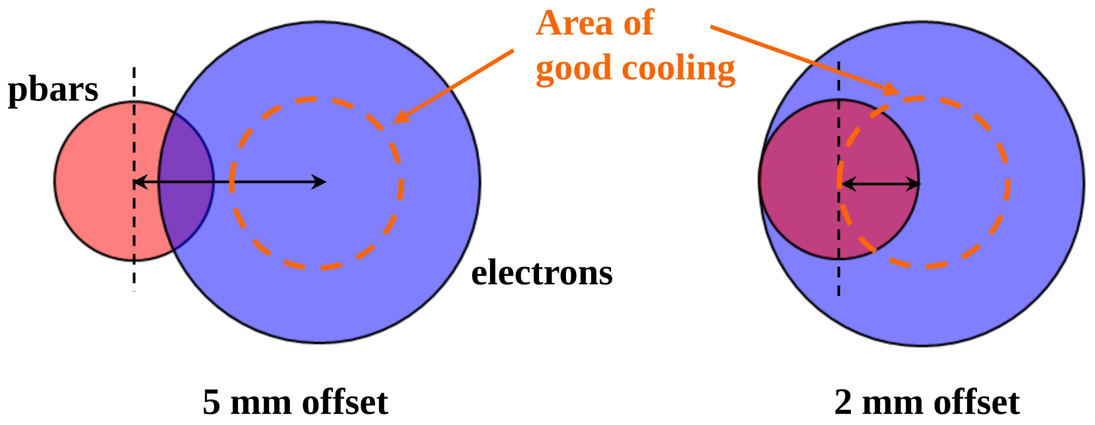
ε_L (95%) = 68 eV s

ε_t (95%, n) = 3.1 π mm mrad (Schottky)



Electron cooling in operation

- Electron beam adjusted to provide stronger cooling as needed (progressively)
  - Adjustments to the cooling rate are obtained by bringing the pbar bunch in an area of the beam where the angles are low and electron beam current density the highest



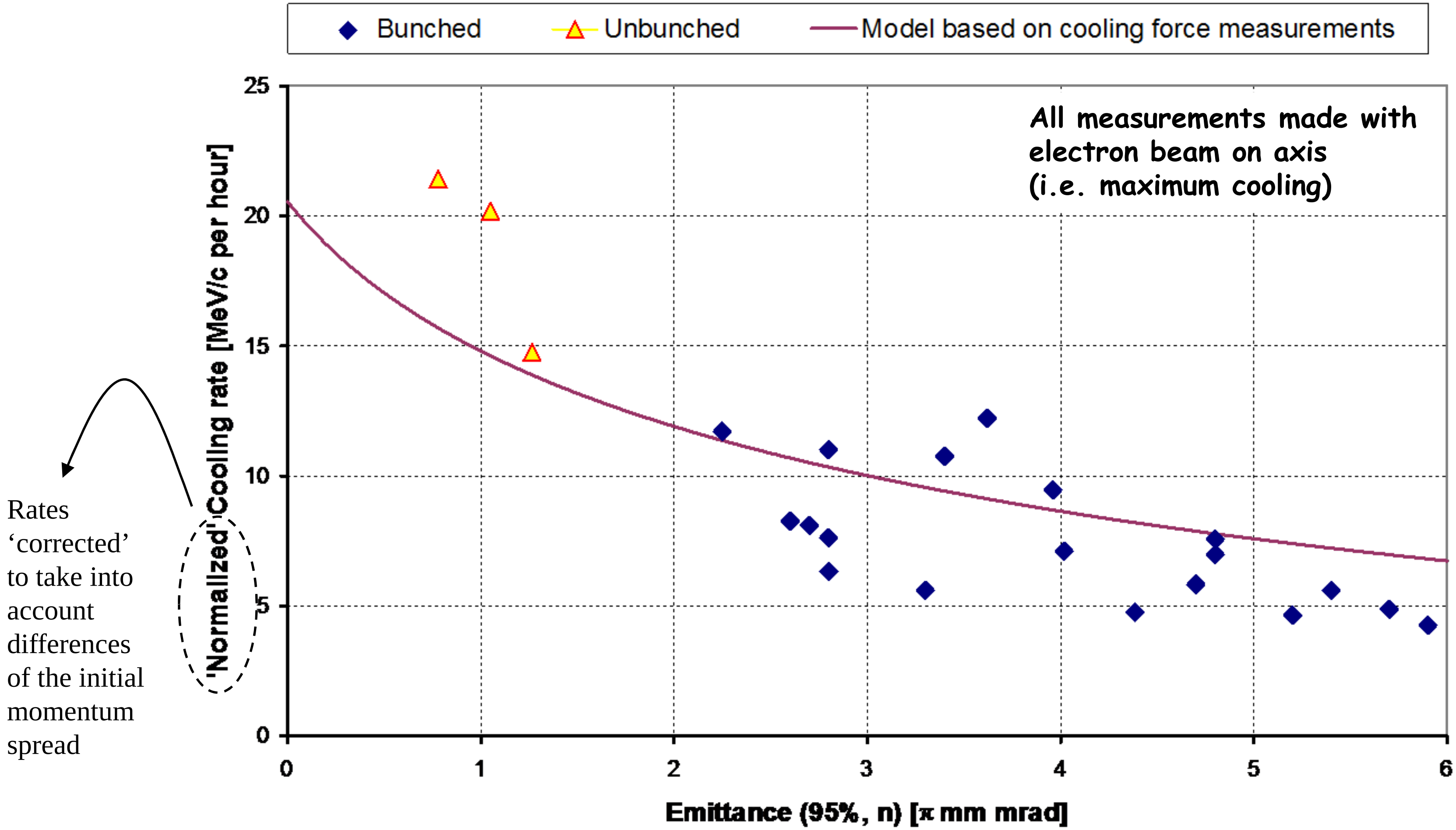
This procedure can be regarded as 'painting' and, in fact, is almost equivalent to the 'hollow beam' concept for low energy coolers.

This procedure is intended to maximize lifetime

Similarly to low energy coolers, cooling seem to induce *secondary* beam-beam effects. In our case, it affects the lifetime of the cooled beam.

Cooling performance

- Cooling rates show a fairly strong dependence on the antiproton beam emittance
  - Importance of stochastic cooling to reduce transverse 'tails'



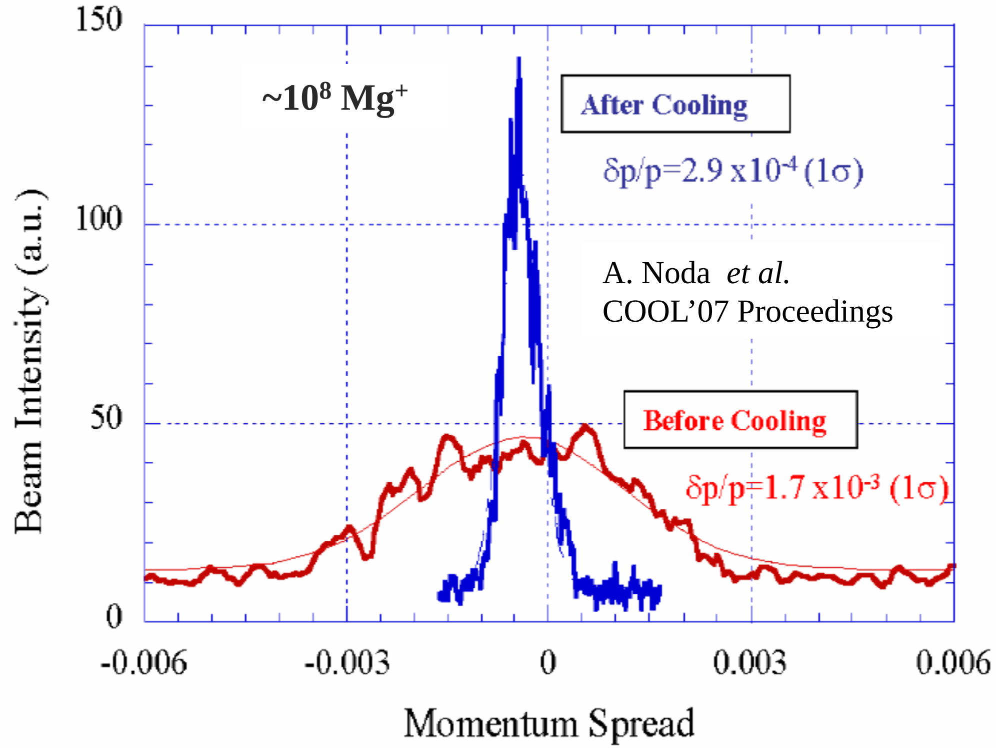
Beam ordering

- Refers to experiments aimed at achieving conditions such that ions in the beam re-arrange themselves in a crystal-like structure
  - 1D ordering was demonstrated at GSI (1996) with heavy-ions
  - 3D ordering much tougher to achieve
    - Succeeded at very low energy with PALLAS (2001)
    - *High energy* ordering limited by 'shear heating'
      - One solution: dispersion free lattice

- Beam ordering experiments are being carried out at Kyoto University
  - A new ring (S-LSR) has been commissioned
    - Dispersion suppressed lattice
    - Both laser and electron cooling can be used (but not simultaneously)
  - 1D ordering of protons was achieved with electron cooling
    - T. Shirai *et al.*, "One dimensional beam ordering of protons in a storage ring", Phys. Rev. Lett., **98** (2007) 204801

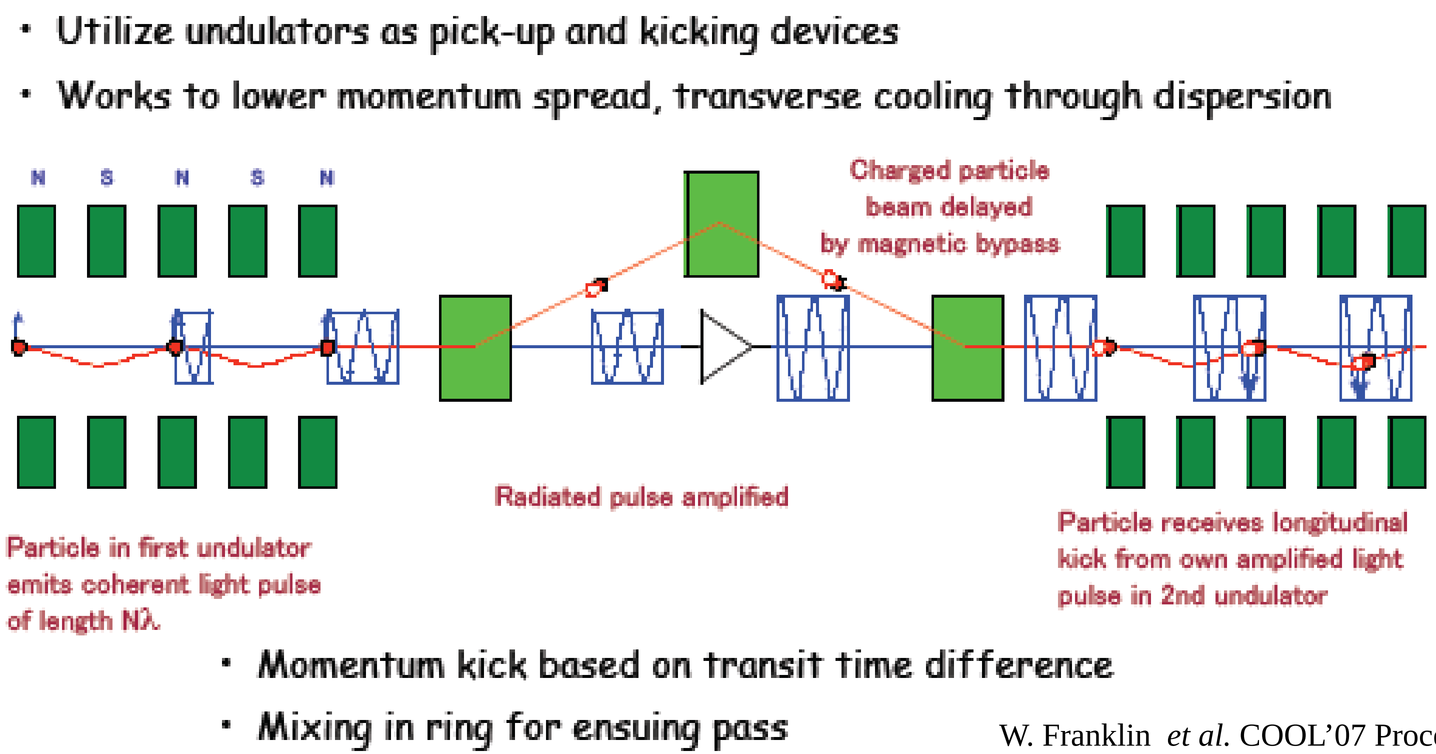
First laser cooling results at S-LSR

- Fixed laser frequency and induction voltage deceleration (*not in the dispersion free mode*)
  - *High* momentum spread after cooling believed to be due to transverse-to-longitudinal redistribution through IBS
    - Need to reduce the number of particles to achieve ordering (1D)
      - Need better diagnostics before proceeding
    - At EPAC'08, reported $\delta p/p \approx 6.2 \times 10^{-5}$ (1σ) with ~10^6 Mg^+



Optical stochastic cooling (I)

- Idea proposed by Mikhalichenko and Zolotorev (PRL **71** 4146 (1993))
  - Ultra-broadband system
    - Traditional (microwave) stochastic cooling is bandwidth limited
  - Transit-time method (M. Zolotorev & A. Zholents, Phys. Rev. E **50**, 3087 (1994))



W. Franklin *et al.* COOL'07 Proceedings

Optical stochastic cooling (II)

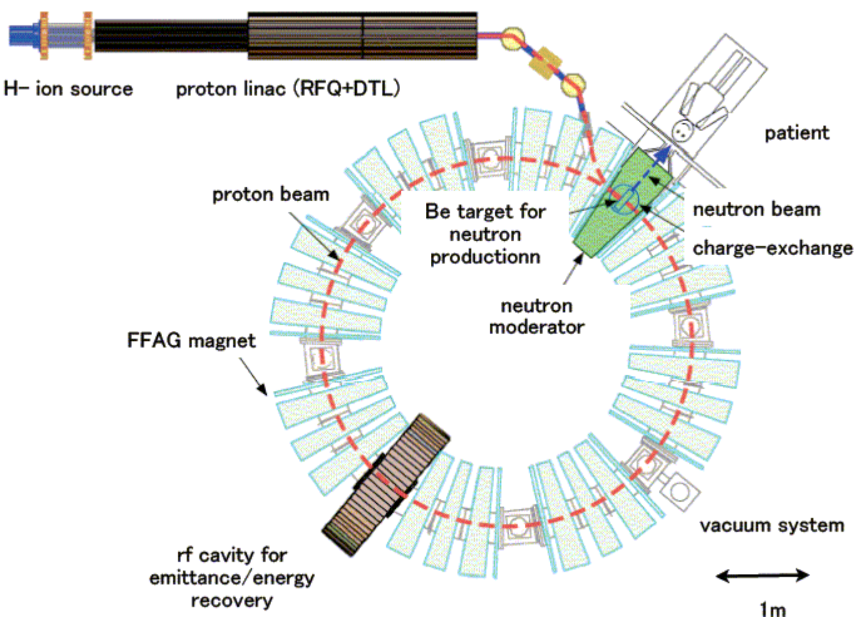
- Experiment to demonstrate the principle of OSC designed at the MIT-Bates south hall ring
  - Realization plan for OSC demonstration with electrons over 3 years
    - Y1: Beam studies for OSC Lattice, amplifier bench tests
    - Y2: Install and commission OSC chicane, wigglers, amp
    - Y3: Experimental program to study OSC of damped electron beam
  - Awaits for funding

New (or renewed) interests

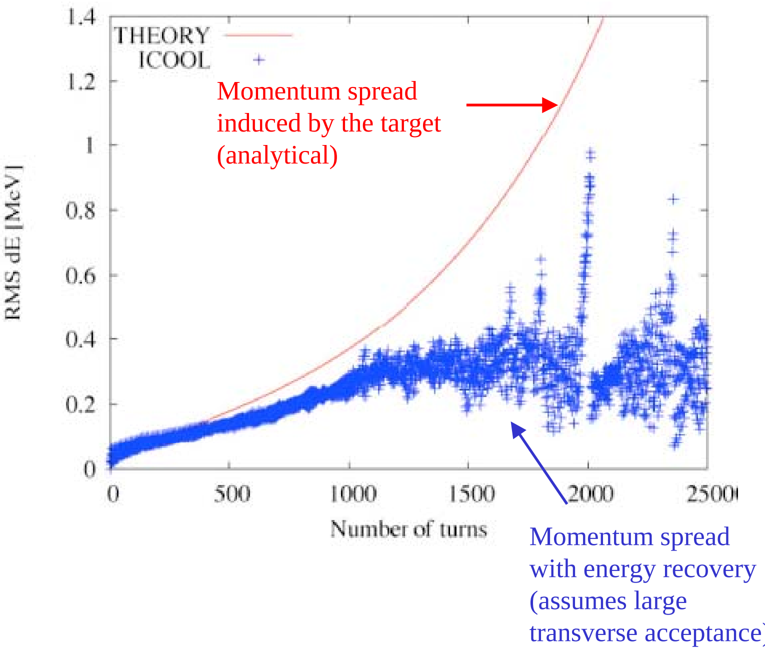
- Lattice optimization for stochastic cooling
  - Lattices that circumvent the 'mixing dilemma'
    - Often considered but never implemented
    - 'Asymmetric' lattice
      - Low dispersion at the pickup
      - High dispersion at the kicker
  - Possible modular approach to construct cooling ring lattices consisting of small momentum compaction modules from pick-up to kicker and negative momentum compaction modules from the kicker to the pick-up
- Use of an electron beam for stochastic cooling
  - Relies on the idea of *coherent electron cooling* (CEC) (Y. Derbenev)
    - General idea: Amplify response of e-beam to an ion by a micro-wave instability of the beam
      - Combines advantages of both electron and stochastic cooling
  - Make it more *realistic* with the latest successes of FEL, ERL,… technologies

Ionization cooling of protons

- Ionization cooling is not a new scheme* but not efficient/attractive with protons (and heavier ions)
  - Nuclear reaction rate ≅ energy-loss cooling rate
- Can work when/if the absorber is also the target
  - FFAG-ERIT neutron source (Mori, KURRI)
    - 10 MeV protons (β = v/c =0.145)
    - ^{10}Be target for neutrons
    - 5μ Be absorber



K. Okabe *et al.* EPAC'08 Proceedings



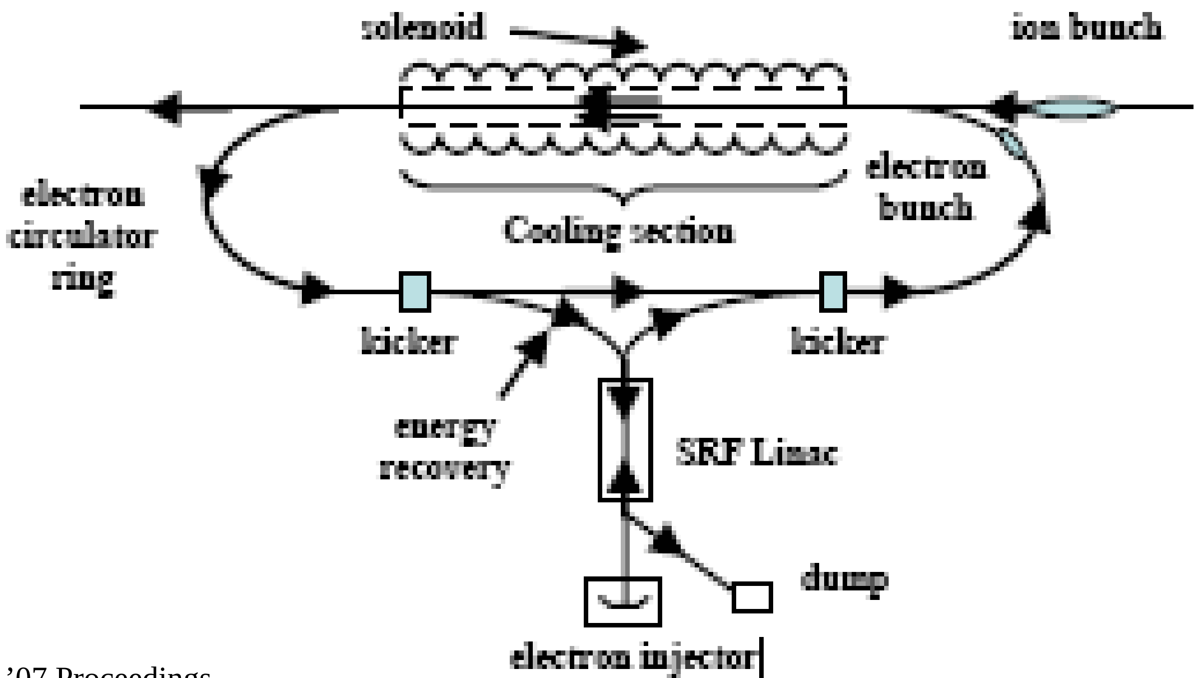
* Skinskii & Parkhomchuk, Sov. J. Part. Nucl. 12, 223, 1981

R&D projects on future facilities (I)

- RHIC electron cooling projects
  - Electron cooling for Low-Energy RHIC operation at γ of 2.6-12 ("critRHIC" project) is being pursued
    - *See A. Fedotov's poster presentation*
  - Coherent Electron Cooling (CEC) emerged as the most powerful technique for cooling of hadrons for the future eRHIC (electron-ion collider) project. This technique is now the main focus of R&D at BNL
    - Proof-of-Principle of CEC by cooling Au ions at about 40 GeV/n using an ERL (20MeV electrons) which is presently under construction at BNL
      - *Commissioning of the ERL is planned for 2009-2010*

R&D projects on future facilities (II)

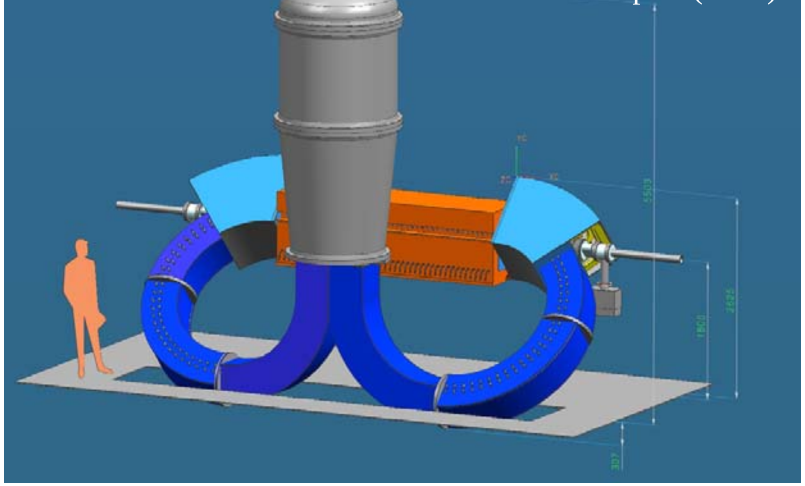
- ELIC (polarized ring-ring electron-ion collider) electron cooler
  - Conceptual design of the cooler based on:
    - 30 mA, 125 MeV energy recovery linac (ERL) operating at 15 MHz
    - 3 A circulator-cooler ring (CCR) operating at 1500 MHz bunch repetition rate



Ya. Derbenev *et al.* COOL'07 Proceedings

R&D projects on future facilities (III)

- FAIR
  - First phase of the project is approved and funded
  - Stochastic cooling to be used in various rings
    - Careful design of the lattices to optimize cooling
  - Electron cooler on the HESR (*at a later phase of the project*)
    - Current design based on an electrostatic accelerator similar to the one use at Fermilab
    - One big difference: Expect to have continuous magnetic field from the gun to the collector (FNAL used an interrupted-focusing transport line)
      - *2 MeV cooler at COSY as an intermediate step*
      - *Prototype of a HV section has been successfully tested*



V. V. Parkhomchuk, Electron Cooling for COSY, Internal Report (2005).

Conclusion

- Need/request for more intense and brighter beam requires sophisticated cooling systems
  - Traditional cooling schemes (stochastic, electron) continue to evolve
    - High energy, beam density profile for electron cooling
    - Better/optimum lattice designs, optical stochastic cooling, stochastic cooling of bunched beam
  - Development of FEL, ERL makes Coherent Electron Cooling an attractive new cooling method for high energy, high intensity hadron beam

- While I focused on experimental results, simulation of the various processes are being carried out along the way and allow for robust designs…
  - … however, more needs to be understood and possibly modeled

The last word…

- Cooling techniques (not only for hadron beams) are discussed at a biennial "Workshop on Beam Cooling and Related Topics"
  - Obviously, much more in depth presentations on all topics touched on here… and others
  - Next workshop: COOL'09 at IMP, Lanzhou, China
    - Announcement in the coming months

THANK YOU FOR YOUR ATTENTION