Highlights of the COOL05 Conference

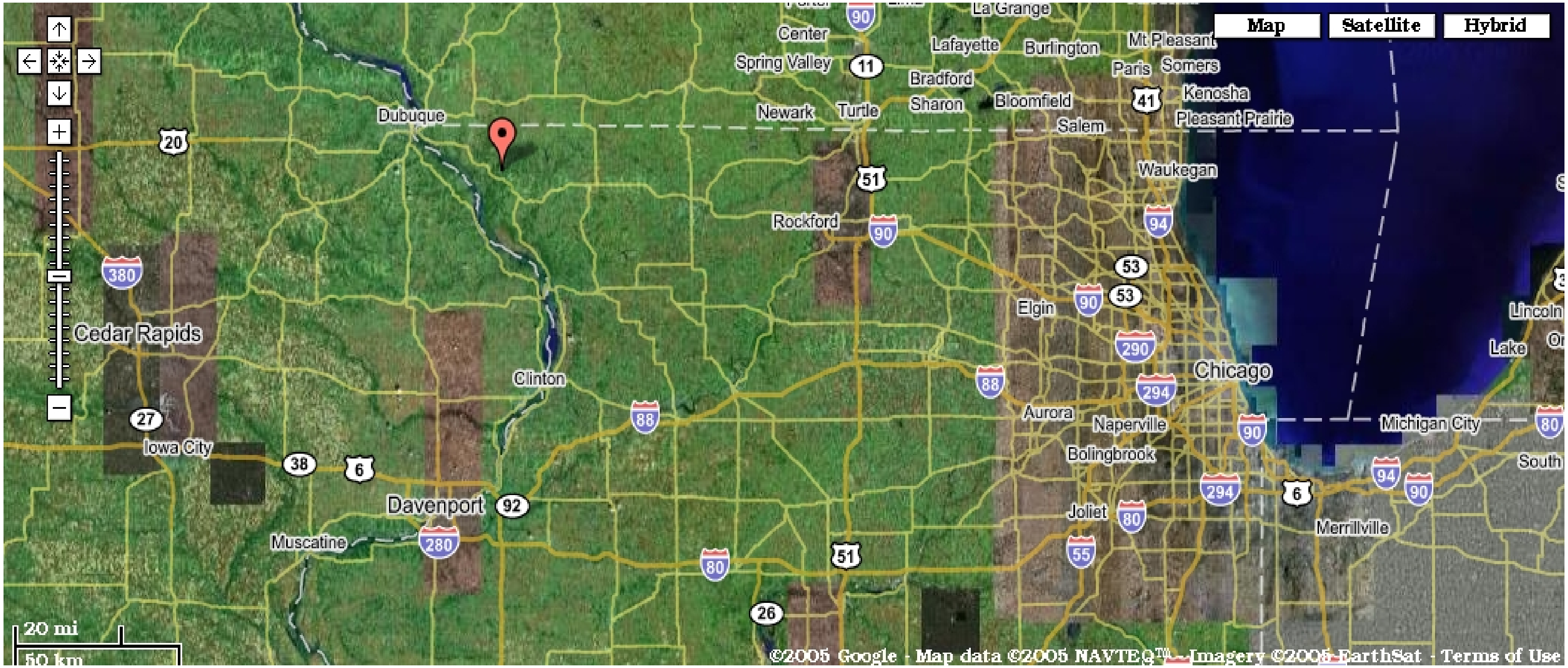
K.Beard, TJNAF

with support from

Muons, Inc.

some distance west of **FNAL**
at a big golf course resort, 9/18-23/2005

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



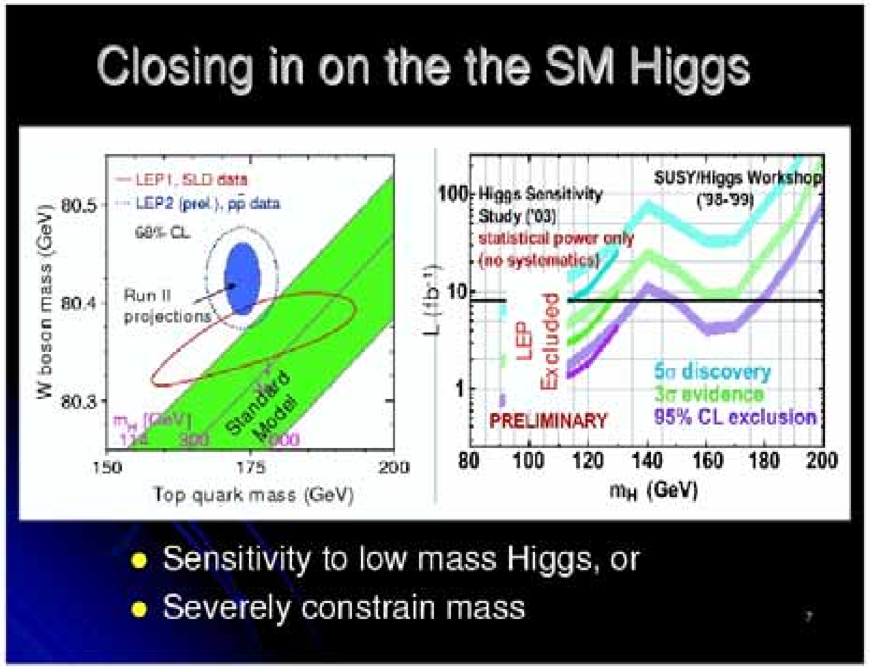
Topics

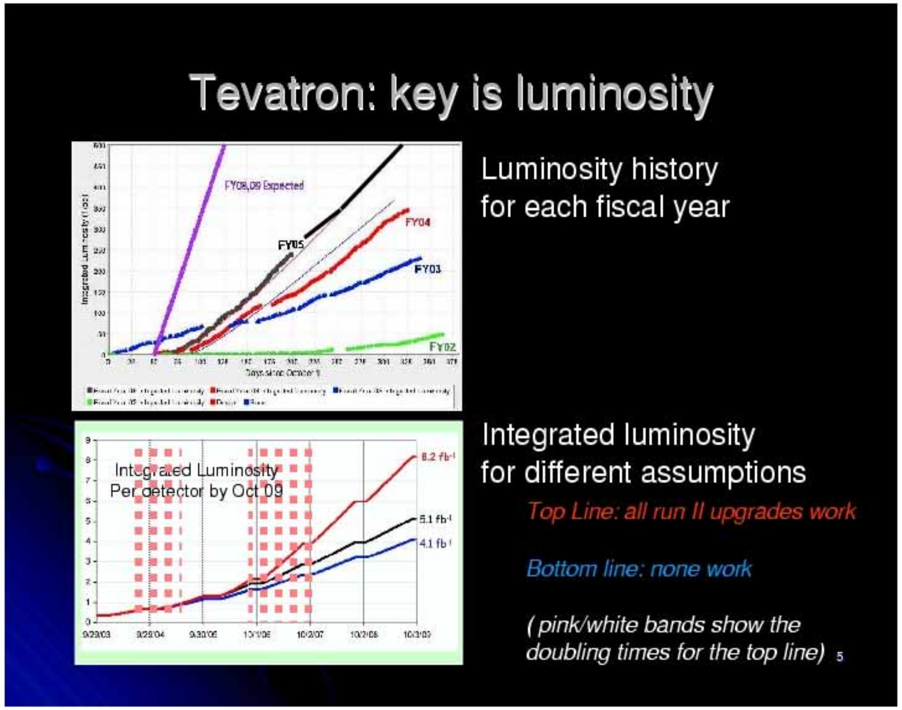
- overview
- stochastic cooling
- muon cooling
- electrostatic rings
- low energy electron cooling
- high energy electron cooling
- laser cooling

Overviews

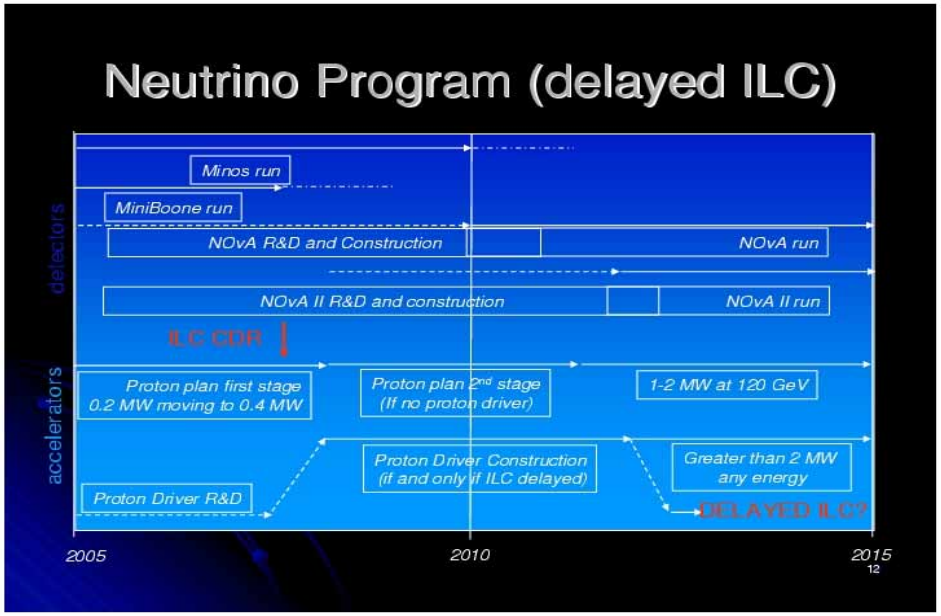
M01 general introduction

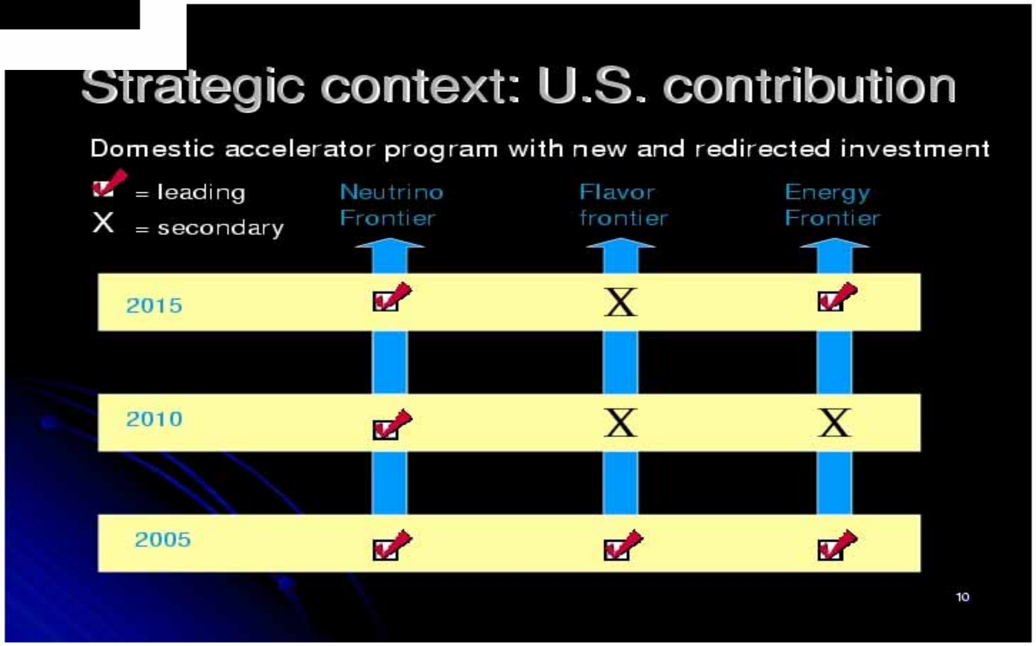
It's tough to make predictions, especially about the future. - *Yogi Berra*





P.Oddone, FNAL





P.Oddone, FNAL *cont.*

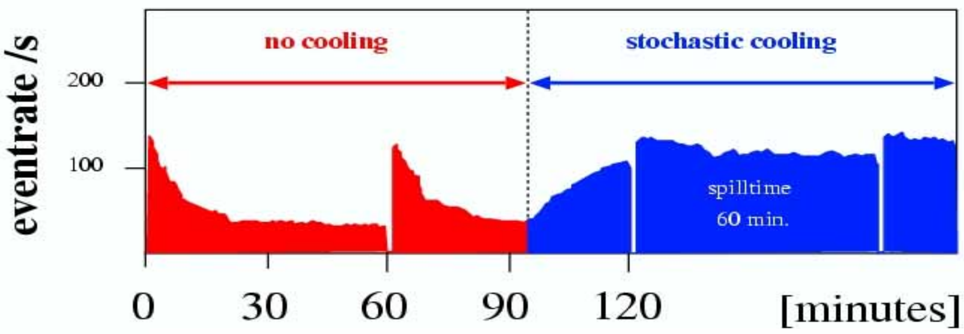
M02 Einstein

A.Sessler, LBNL

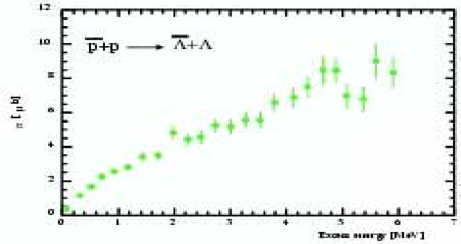
"The state has become a modern idol whose suggestive power few men are able to escape."

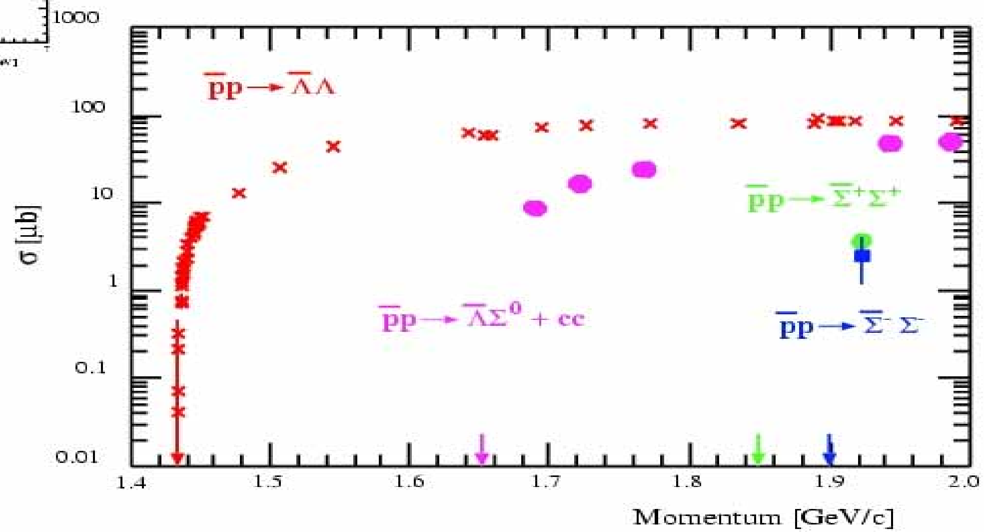
~~"If we know what we are~~ doing it would not be called research, would it?"

M03 Why cool?

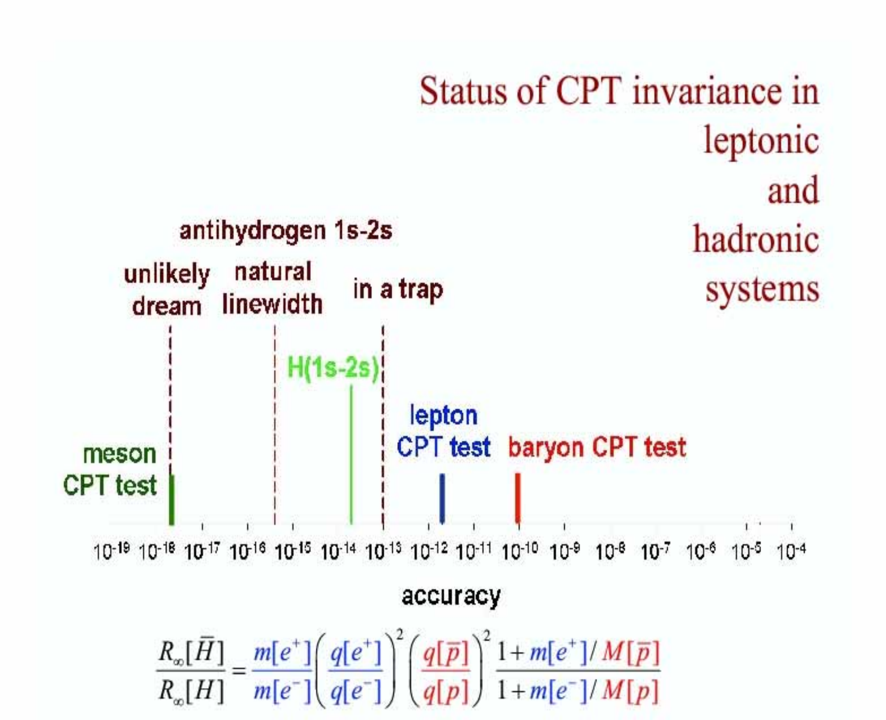


W.Oelert, FZI

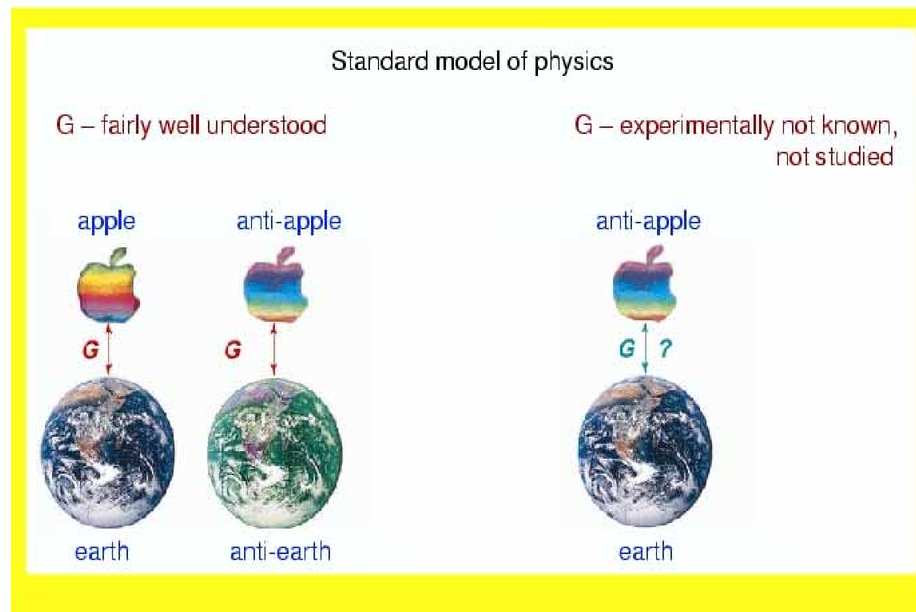




antihydrogen



W.Oelert, FZI, *cont.*



Overview of recent trends in beam cooling methods and technology

Igor Meshkov and Dieter Möhl
(JINR, Dubna) (CERN, Geneva)

Menu

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,

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.

New proposals machines for m

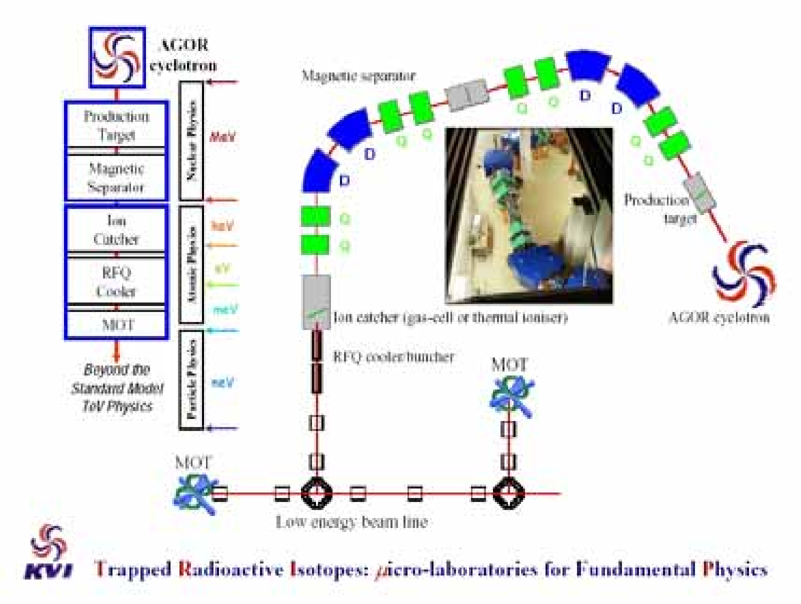
The hot news in brief

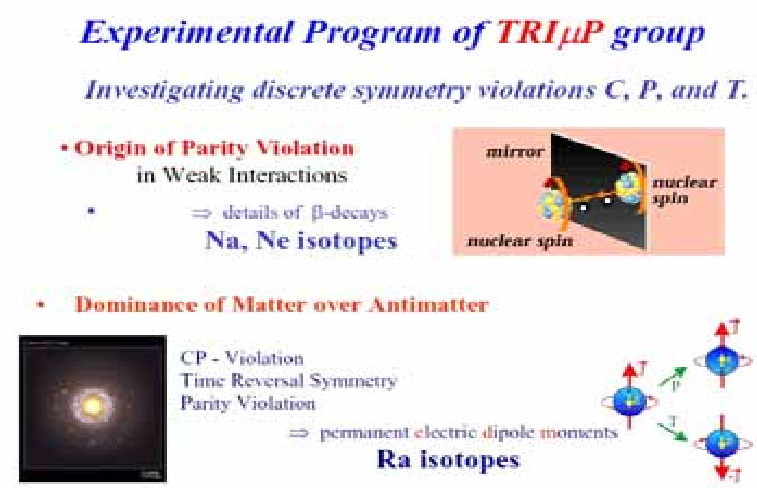
very small aperture lications).

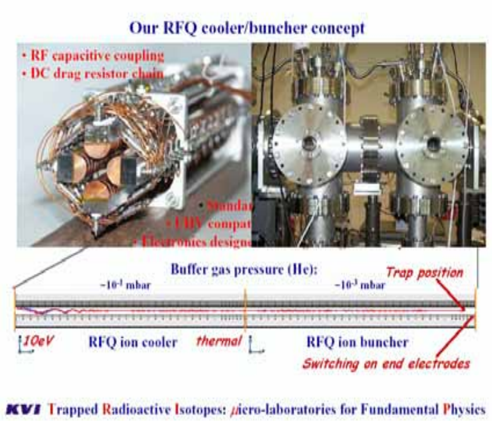
Bad news: Shutdowns of CELSIUS and CRYRING.

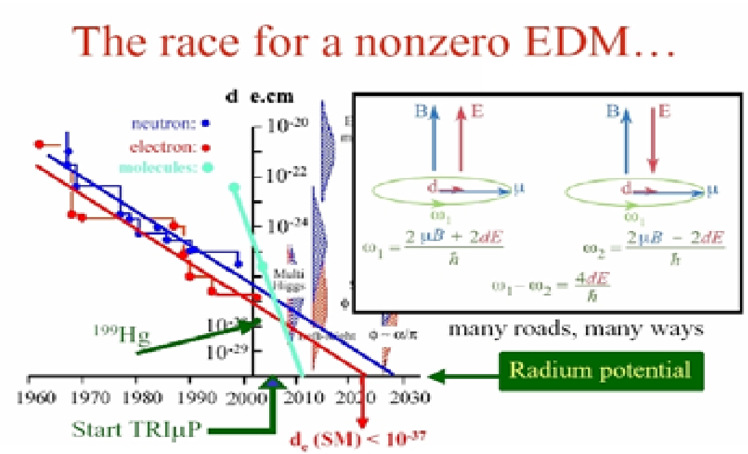
Good news: CRYRING will be used as a cooler storage ring in FLAIR – subproject of FAIR.

F06 RFQ cooler/buncher for TRImP L.Willmann KVI









M05 Future Directions

D.Sutter, DOE (retired)

Where Next? – What are the Real Physics Needs?

Proposed but Not Approved — The realm of Near Term and Some Mid Term R&D

Facility	Status	Issues
ILC @ .5 to 1 TeV	R&D – GDE In place.	Location! Politics!
Super Beams @ Fermi	R&D – Hope!	Funding, Timing & the ILC
CLIC @ 2 t0 4 TeV	R&D – A Prayer	The ILC, Energy needs of HEP
Japanese Super	Unclear	ILC in Japan?

Wish You Were Here! — The realm of Advanced & Some Mid Term R&D

Facility	Status	Issues
Muon Storage Ring et al	R&D - Targets & Cooling	Funding & HEP priority
LHC Upgrades – L and E	R&D – LARP (In U.S.)	Priority versus LHC Start
Linear Collider @ >100MeV/m	U.S. High Gradient R&D	Funding & HEP priority
VLHC	No Activity	LHC & ILC in U.S.
"Other" Facilities	No Activity	Unidentified Physics needs!

Facilities Available for HEP Research

Fermilab Tevatron	Shut down in 2008 – 2010?
Fermilab Neutrino Beam	Upgrades? In - - - ?
SLAC B-factory	Shut down in 2008
SLAC 50 GeV linac	Off in 2006. LCLS { 10 GeV }, SABER @ 30 GeV > 2008?
KEK B-factory	Upgrade to Super B?
RHIC	Shut down or continue? { NSAC Study! }
LHC	First operation in 2007 – 2008

μ

Advanced R&D – To give Access to New Research Ability

The Principal Thrusts:

- *Plasma Accelerators – Particle and laser driven*
- *Very high gradient structures – for warm and cold radio frequency systems*
- *Beam Cooling – beyond stochastic and radiation means*
- *Space charge dominated Beams – There is life after □□< □ !*
- *Super conducting Magnets – The future is A15 & other compounds {Nb_3Sn, MgB_2}*
- *Accelerator Theory – Advanced simulation & the merging of particle & plasma physics*

The above areas of R&D are by no means the only ones supported by the DOE And NSF. They are the principal ones addressing new approaches to facilities.

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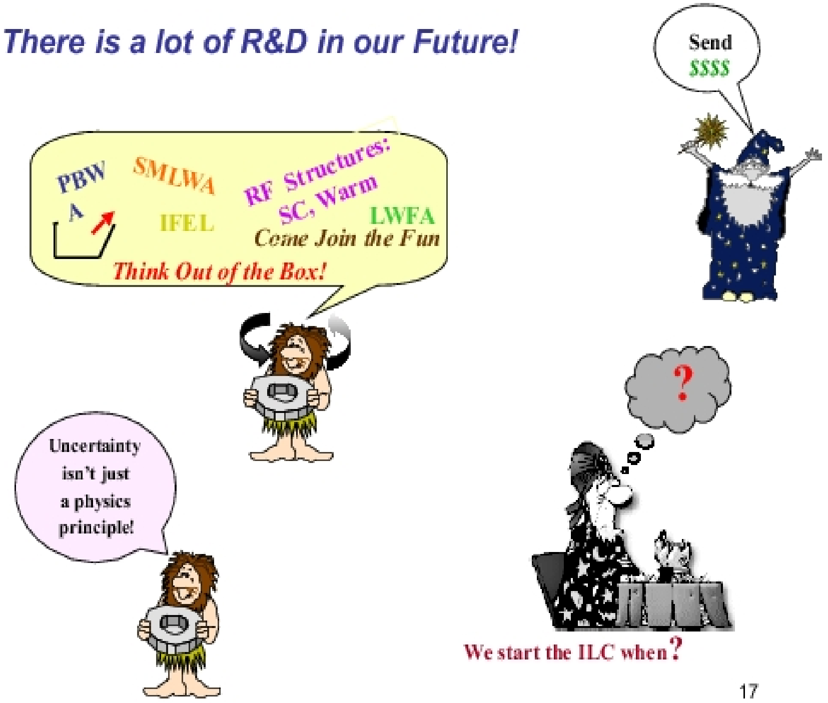
There is a lot of R&D in our Future!



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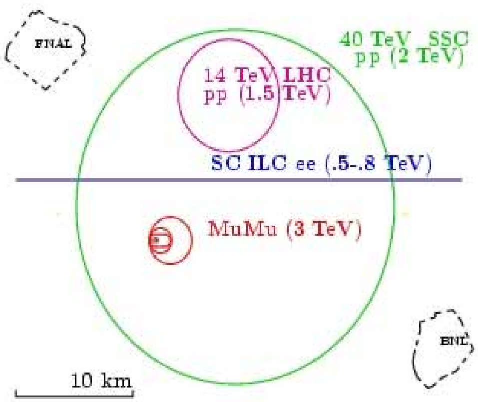
muon cooling

Review of Muon Cooling R.Palmer BNL

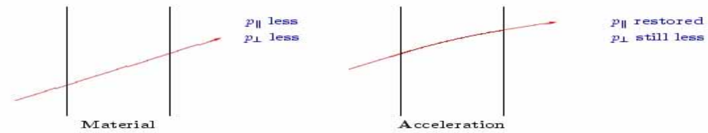
Why a Muon Collider



- Muons are point like, similar to electrons
- Can probe the same physics, and some more
- But have 40,000 less radiation
- So Muon Colliders can be much smaller than Linear Colliders

2

Transverse Cooling



Rate of Cooling without scattering

$$\frac{d\epsilon}{\epsilon_{x,y}} = \frac{dp}{p} \; J_{x,y}$$

For the moment the "partition functions" Explanation later

$$J_{x,y} = 1$$

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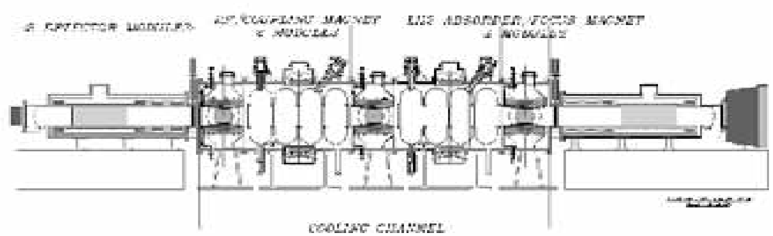
SFOFO used in Study 2 and Cooling Experiment

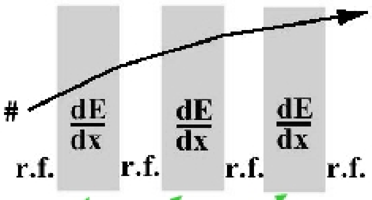
Muon Ionization Cooling Experiment MICE

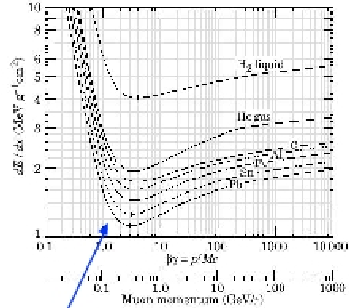
- International Collaboration: (US, Europe, Japan)
- Proposal Approved at RAL
- Funding for phase I NSF (NSF, DOE, Europe, Japan)



T12: MICE, D.Kaplan IIT

Ionization Cooling





- Absorbers: $\exists\, \&\, \% \; E \,\forall\; E\,\#\left\langle \frac{dE}{dx} \right\rangle (\; s$
  $\&\, \ni)\;\forall\;)\;!\;)_{space}^{rms}$

ionization energy loss

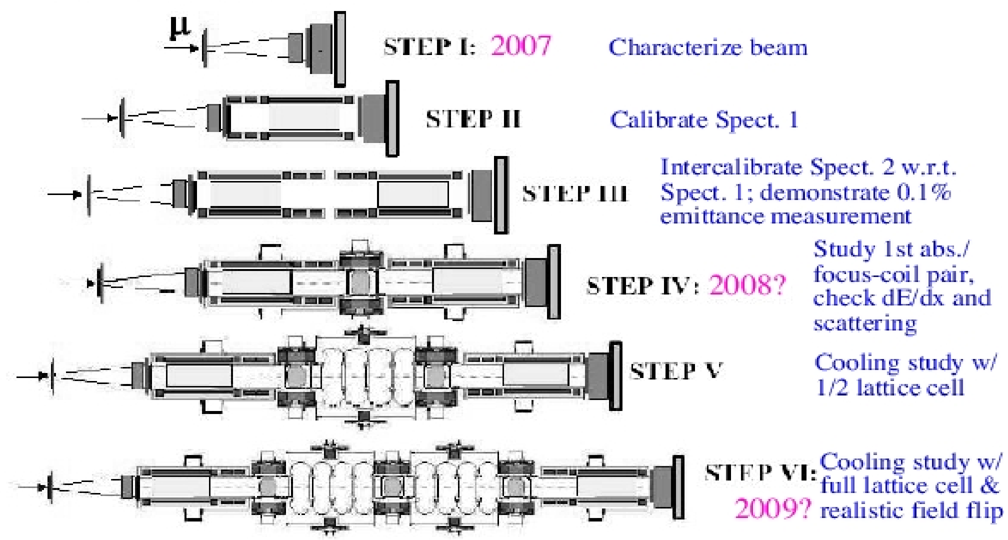
multiple Coulomb scattering

- RF cavities between absorbers replace (E
- Net effect: reduction in p_{*} w.r.t. p_{**} i.e., transverse cooling

Note: The **physics** is not in doubt
 \+ in principle, ionization cooling **has** to work!
... but in practice it is subtle and complicated...

Avatars of MICE

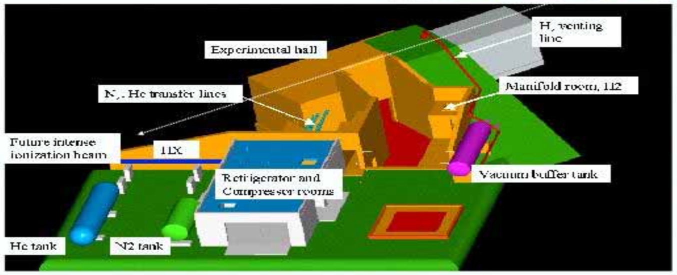
- Measurement precision relies crucially on precise calibration & thorough study of systematics:



Mucool Hydrogen Absorber R&D, M.Cummings NIU

Mucool Test Area

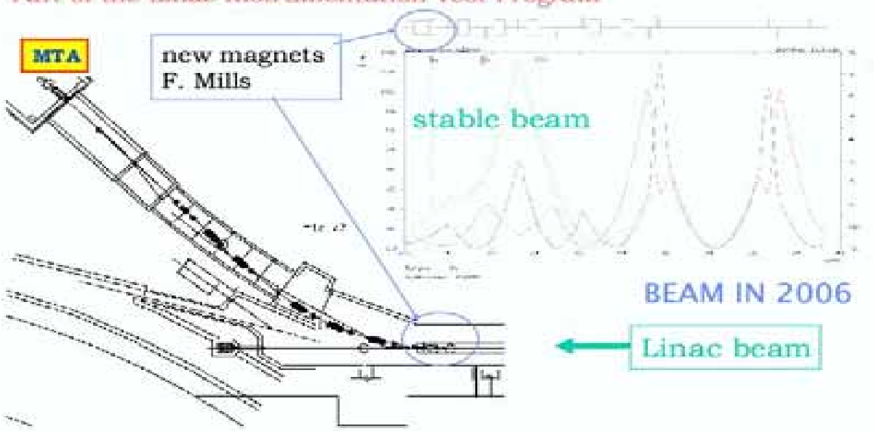
- The MTA is becoming our focus of Mucool activity
  - ⇒ LH_2 Absorber tests
  - ⇒ RF testing (805 and 201 MHz)
  - ⇒ Finish cryo infrastructure
  - ⇒ High pressure H_2 gas absorbers
  - ⇒ High intensity beam design



M. A. C. Cummings, Cool 05 September 20, 2005

MTA High Intensity Beam

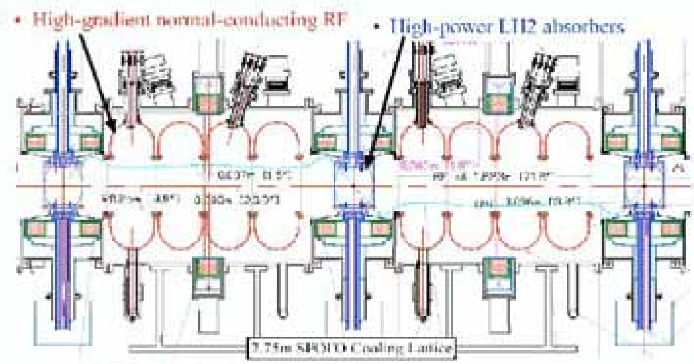
Beamline designed and costed by C. Johnstone for the MTA.
Part of the Linac Instrumentation Test Program



M. A. C. Cummings, Cool 05 September 20, 2005

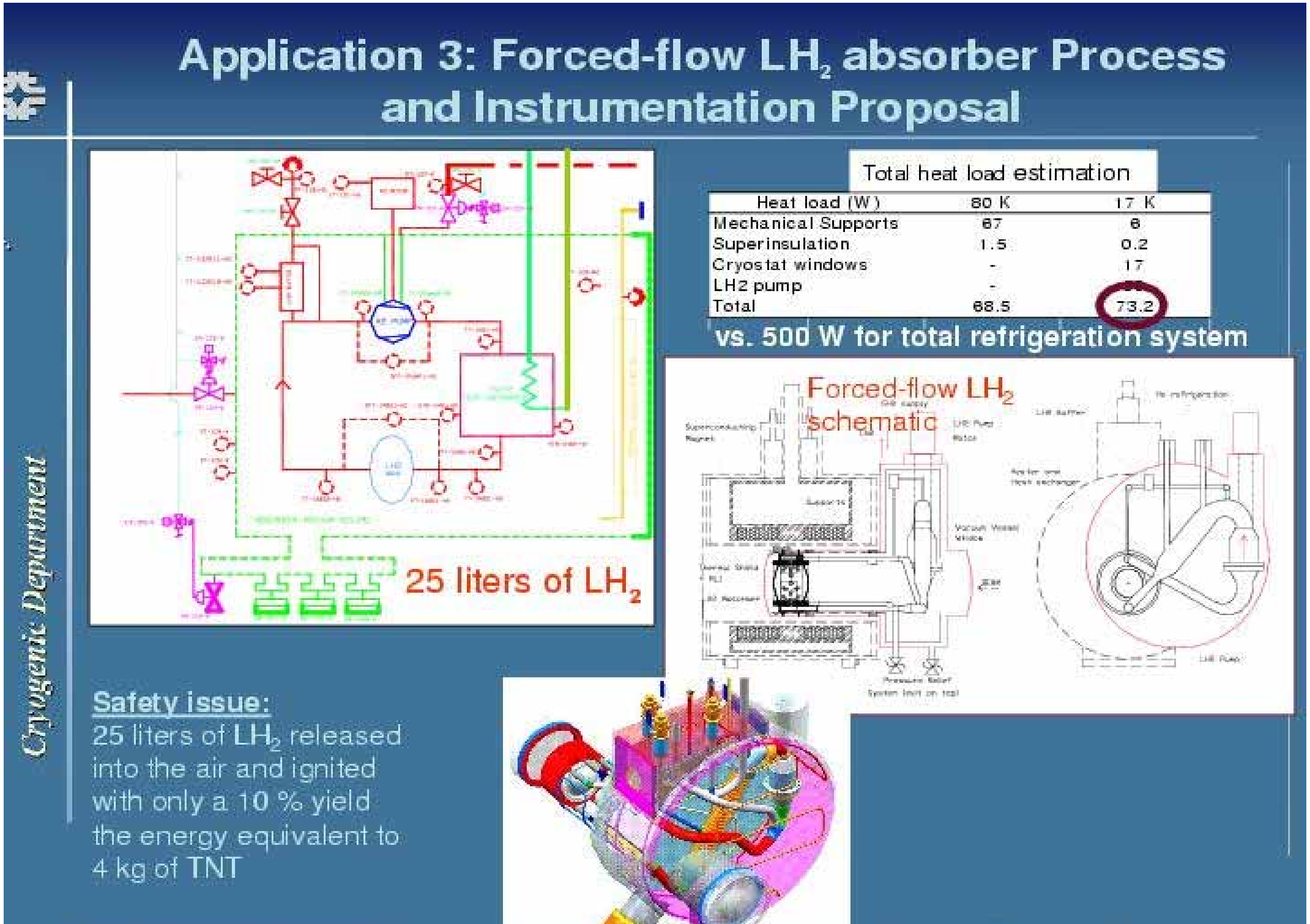
MuCool: cooling channel R & D

- **MuCool:** MC subset based at FNAL and charged with the development of muon ionization cooling channels
  - ⇒ **Goal: Cooling cell test in high-powered beam (MTA)**
- SFOFO Cooling Lattice – transverse cooling for ν factories



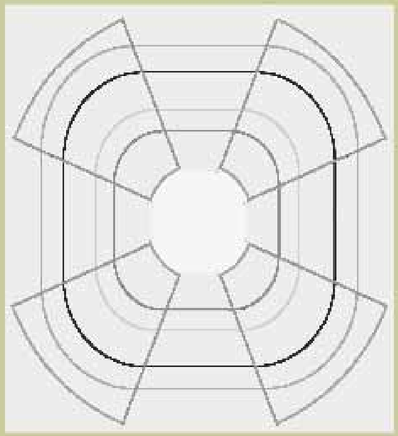
M. A. C. Cummings, Cool 05 September 20, 2005

T16: MTA Cryogenics C.Darve FNAL



T10. 6D cooling of a circulating muon beam
A.Garren UCLA

1.8T Dipoles and 200 MHz Closed Orbits for 4 Cell Demonstration Ring



Fix the closed orbits for a 1.8T dipole ring such that the total path length is a harmonic of 200 MHz.

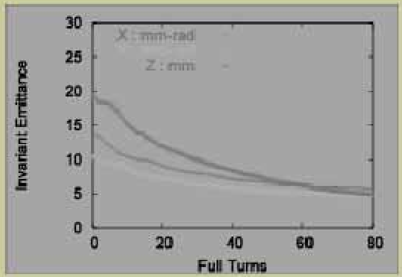
Then:

- Harmonic 2
  - Circumference = 1.76 m
  - P_0 = 77 MeV/c
- Harmonic 3
  - Circumference = 3.76 m
  - P_0 = 165 MeV/c
- Harmonic 4
  - Circumference = 5.45 m
  - P_0 = 240 MeV/c

UCLA Al. Garren

4 Sector Ring, 1.8 T Dipoles

- Harmonic 3
- 40 Atmosphere H_2
- Total Merit without decay is 20

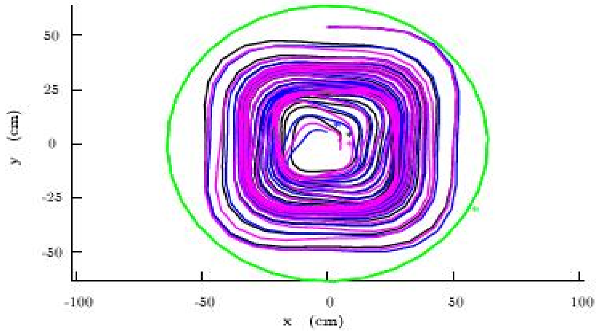


UCLA Al. Garren

inverse cyclotron - Y.Yorin ITT

Single Turn Energy Loss Injection

- Four Magnet (1.8T) Sector Cyclotron.
  Soft edged fields, ICOOL simulation.
  Multiple scattering and straggling on.
  Radial LiH wedges surrouded by hydrogen.
  Matter decreases adiabatically with radius.
  3 identical 172 MeV/c muons are injected.



- ± 5 cm vertical motion along the 70 m spiral

- Injection scaling relation: $\Delta p = .3\, B\, \Delta r$.

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Emittance Reduction Goals

- A muon collider needs 10^6 cooling.
- $\epsilon = (\Delta p_x\, \Delta x)\,(\Delta p_y\, \Delta y)\,(\Delta p_z\, \Delta z)$
- Δp_x: 30 MeV/c $\rightarrow$ 0.3 MeV/c
- Δp_y: 30 MeV/c $\rightarrow$ 0.3 MeV/c
- Δp_z: 30 MeV/c $\rightarrow$ 0.3 MeV/c
- Δx: 70 mm $\rightarrow$ 50 mm
- Δy: 70 mm $\rightarrow$ 50 mm
- Δz: 10000 mm $\rightarrow$ 50 mm
- In: $10\times$ transverse cooler, physics/0411123.
- Out: "Frictional μ cooling,"
  H. Abramowicz, A. Caldwell, R. Galea, and
  S. Schlenstedt, NIM A546 (2005) 356.

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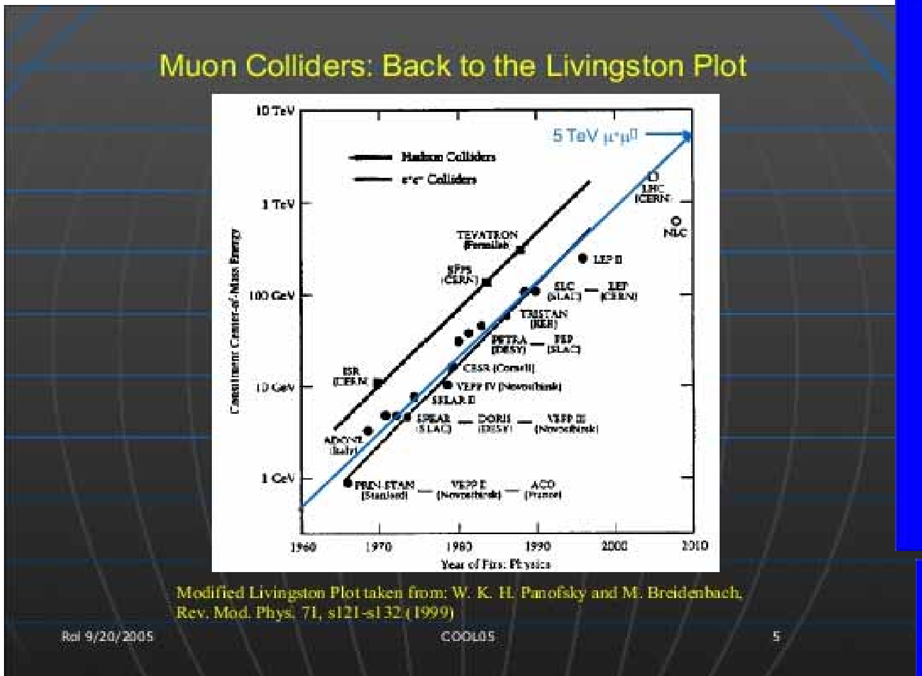
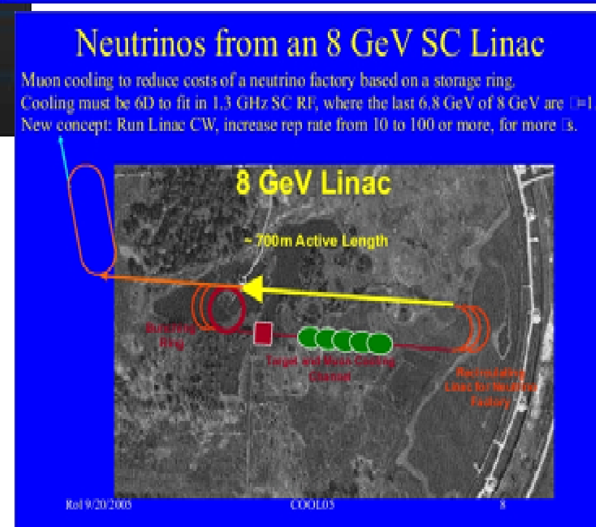
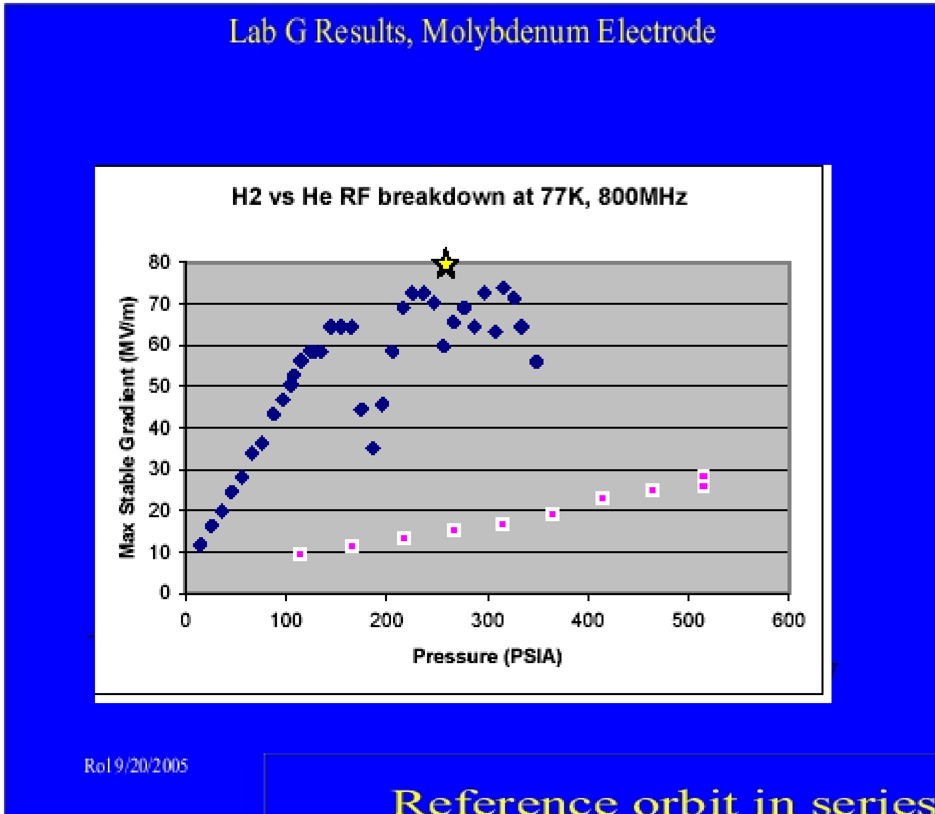
T09 Innovations in Muon Beam Cooling
R.Johnson, Muons Inc.

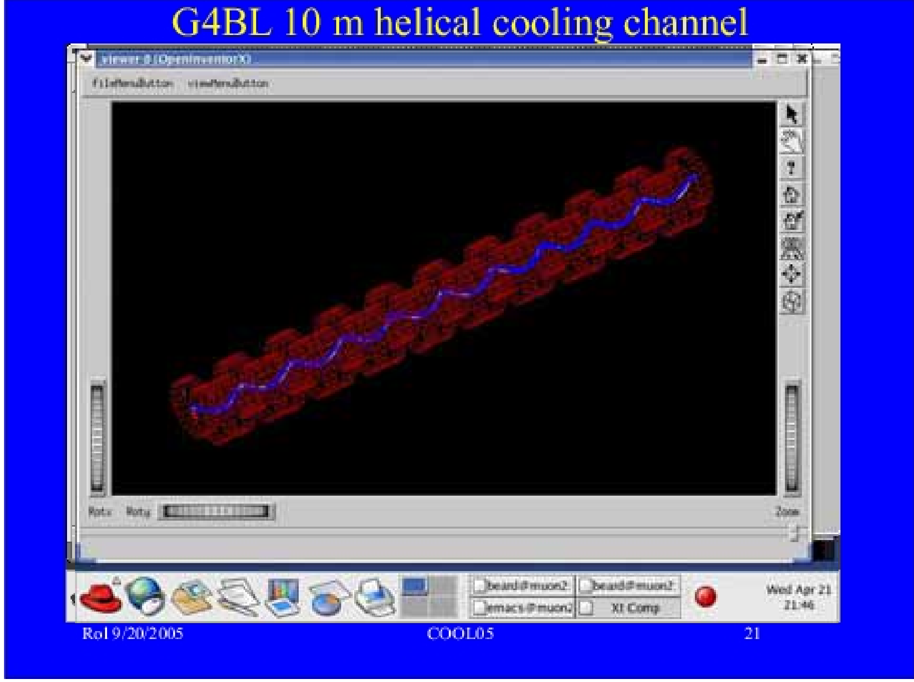


Year	Project Title	Expected Funds	Research Partner
2002-5	High Pressure RF Cavities	$600,000	IIT
2003-6	Helical Cooling Channel	$850,000	JLab
2004-5	MANX demo experiment	$ 95,000	FNAL TD
2004-7	Phase Ionization Cooling	$745,000	JLab
2004-7	Hydrogen Cryostat	$795,000	FNAL TD
2005-6*	Reverse Emittance Exch.	$100,000	JLab
2005-6*	Capture, ph. rotation	$100,000	FNAL AD





Lab G Results, Molybdenum Electrode
H2 vs He RF breakdown at 77K, 800MHz
Max Stable Gradient (MV/m)
Pressure (PSIA)
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
RoI 9/20/2005



G4BL 10 m helical cooling channel
RoI 9/20/2005
COOL05
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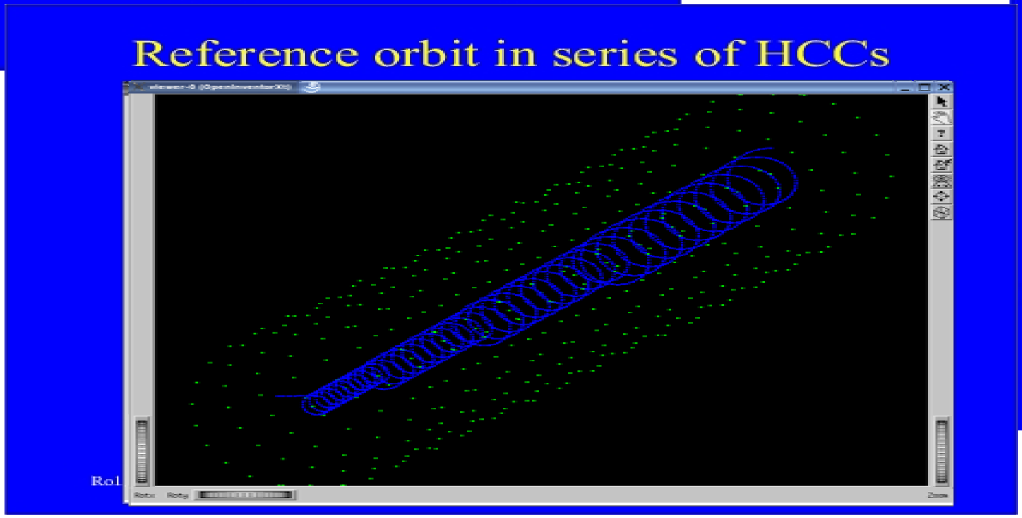
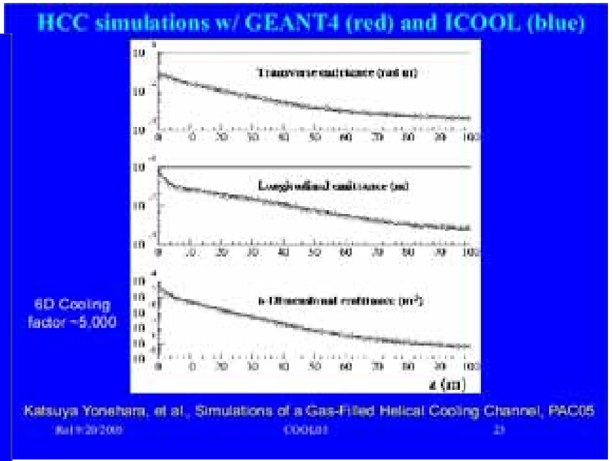
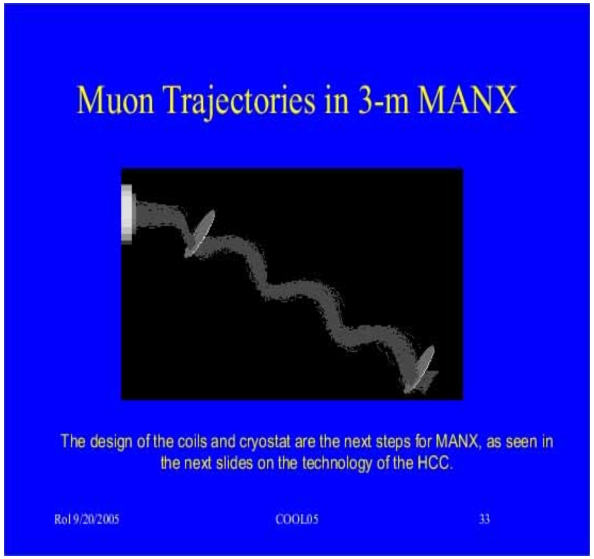


Reference orbit in series of HCCs



HCC simulations w/ GEANT4 (red) and ICOOL (blue)
6D Cooling factor ~5,000
Katsuya Yonehara, et al., Simulations of a Gas-Filled Helical Cooling Channel, PAC05


Muon Trajectories in 3-m MANX
The design of the coils and cryostat are the next steps for MANX, as seen in the next slides on the technology of the HCC.
RoI 9/20/2005
COOL05
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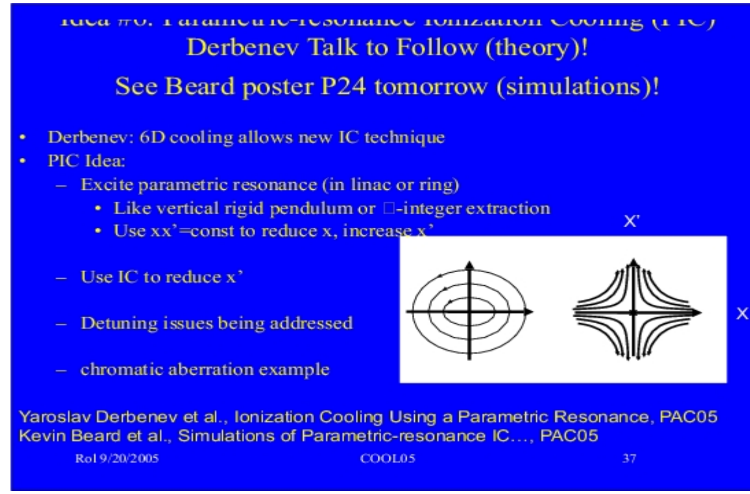
Derbenev Talk to Follow (theory)!
See Beard poster P24 tomorrow (simulations)!
• Derbenev: 6D cooling allows new IC technique
• PIC Idea:
– Excite parametric resonance (in linac or ring)
• Like vertical rigid pendulum or □-integer extraction
• Use xx'=const to reduce x, increase x'
– Use IC to reduce x'
– Detuning issues being addressed
– chromatic aberration example
X'
X
Yaroslav Derbenev et al., Ionization Cooling Using a Parametric Resonance, PAC05
Kevin Beard et al., Simulations of Parametric-resonance IC…, PAC05
RoI 9/20/2005
COOL05
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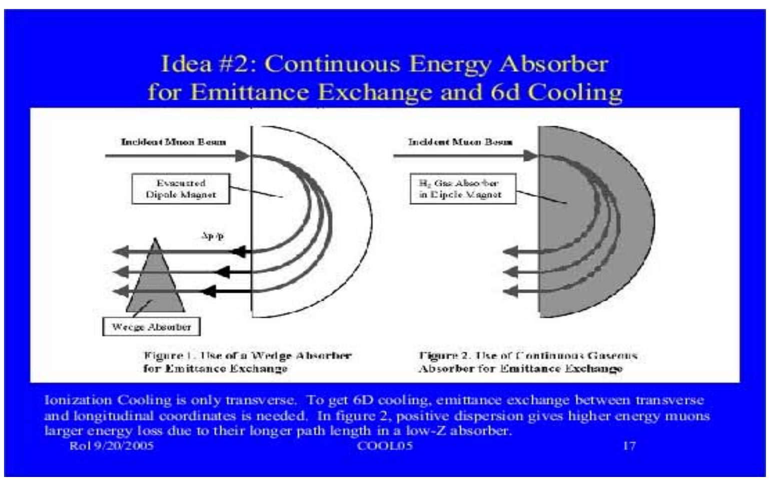
Idea #2: Continuous Energy Absorber
for Emittance Exchange and 6d Cooling
Incident Muon Beam
Evacuated Dipole Magnet
Δp/p
Wedge Absorber
Figure 1. Use of a Wedge Absorber for Emittance Exchange
Incident Muon Beam
H_2 Gas Absorber in Dipole Magnet
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange
Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed. In figure 2, positive dispersion gives higher energy muons larger energy loss due to their longer path length in a low-Z absorber.
RoI 9/20/2005
COOL05
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Idea #8: Simultaneous RF Capture, Bunch Rotation and Cooling in HP RF Cavities
• Proton bunches have □ □1ns such that produced pion bunches do too.
• Placing RF cavities close to the production target allows 1/4 synchrotron period rotation to get longer pion bunches with smaller momentum spread.
• Subject of new STTR grant to use HP RF (see Dave Neuffer & Kevin Paul)
RoI 9/20/2005
COOL05
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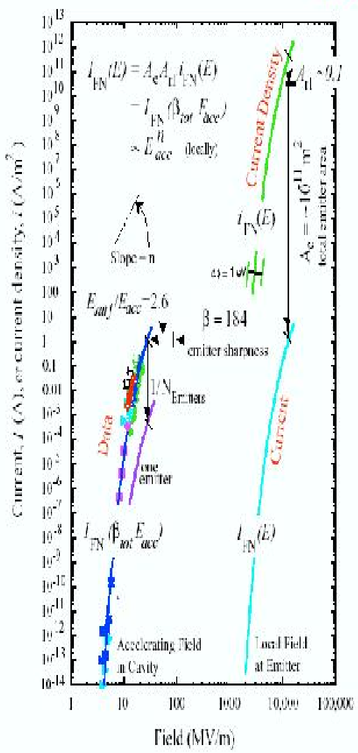
T14: Muon Cooling R&D Y.Torun, IIT

Dark Currents

- Precursor to breakdown
- Electrons tunnel through work function of metal
- Current rises very steeply with field (hard to make measurements)

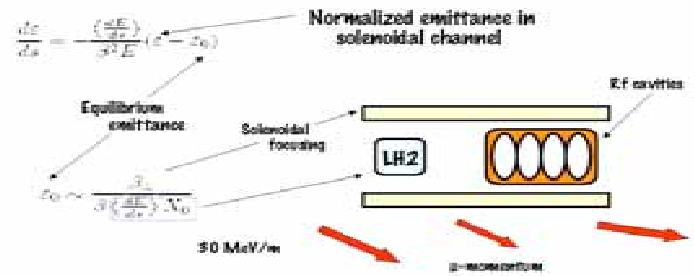
$$j_{FN}(E) = \frac{A}{\phi}(\beta E)^2 exp\left(-\frac{B\phi^{3/2}}{\beta E}\right)$$

$$n = \frac{E}{j}\frac{dj}{dE} \simeq 2 + \frac{67.4\text{GV/m}}{\beta E}$$



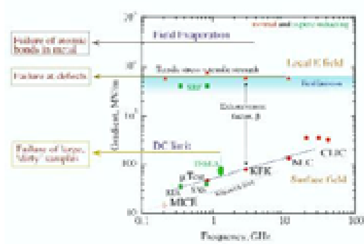
Ionization Cooling

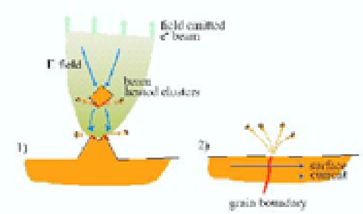
- Muon lifetime is 2.2μs, traditional beam cooling techniques not applicable
  - Ionization cooling works "at the speed of the muon"



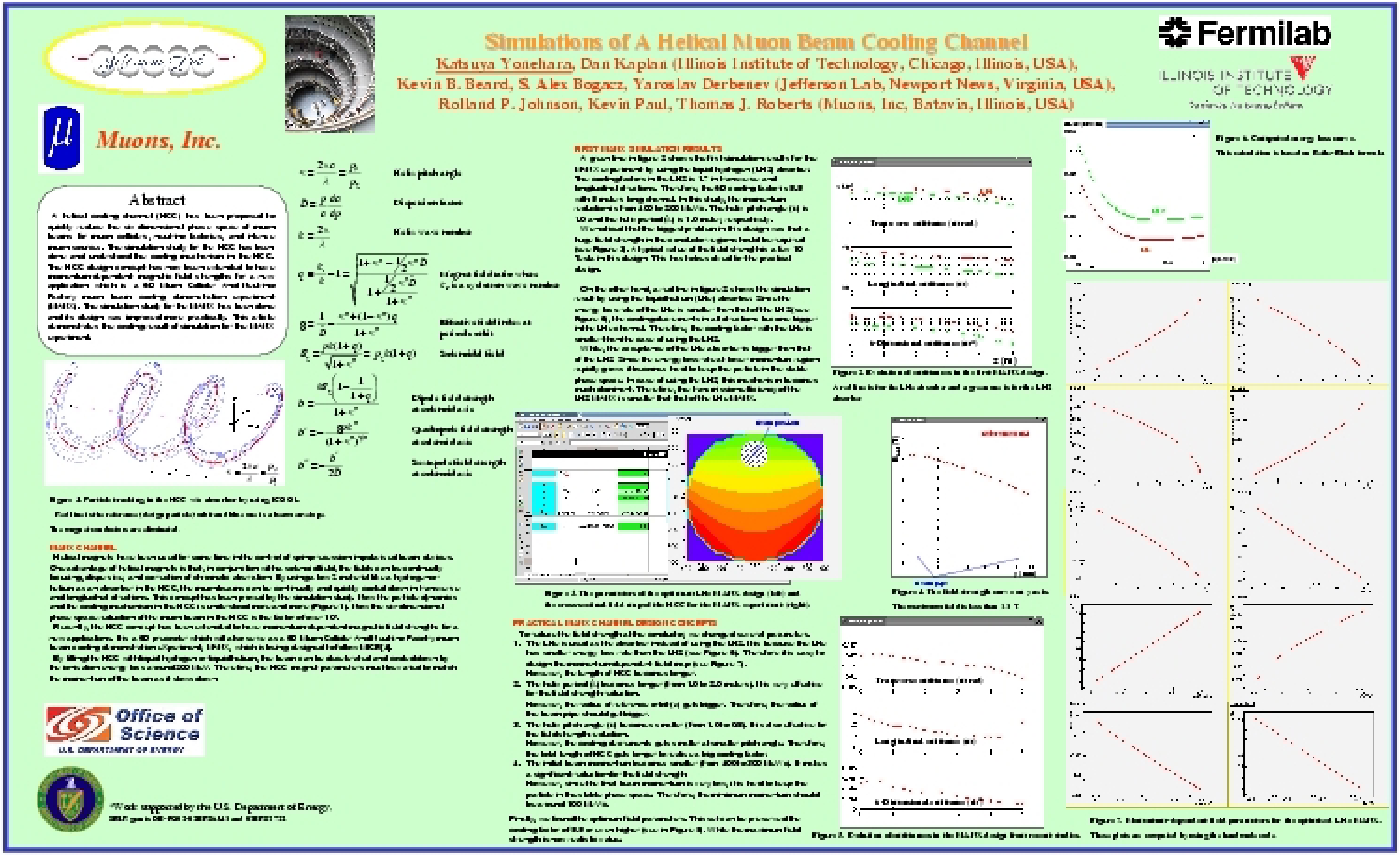
Rf R&D Directions

- Many problems are common to
  - DC and rf breakdown
  - Normal and superconducting rf (CLIC, ILC)
- We need help from materials science and surface chemistry
- Surface physics initiative (J. Norem, ANL + D. Seidman, Norhtwestern) for understanding breakdown processes using atom probe tomography and molecular cluster simulations





P23: Helical Muon Beam Cooling Channels   K.Yonehara IIT



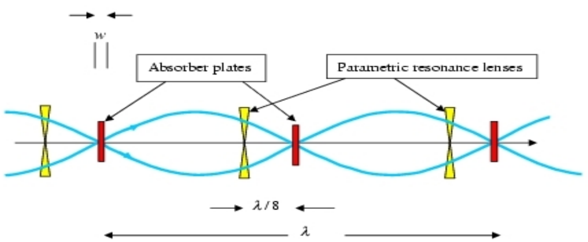
T11: Parametric Resonance Ionization Cooling and Reverse Emittance exchange, Ya.Derbenev, TJNAF

Basic principles of PIC

- Assume initially the tune spread for a beam in a focusing channel to be smaller than the cooling decrement
- Weak lenses installed every half oscillation period drive a half-integer parametric resonance that creates a hyperbolic beam evolution at the absorber plates:

$$\begin{pmatrix}x\\x'\end{pmatrix}_{n+1} = -\begin{pmatrix}k^{-1} & 0\\ 0 & k\end{pmatrix}\begin{pmatrix}x\\x'\end{pmatrix}_{n};\quad k=\exp(\Lambda_d\lambda/2)$$

$$0<\Lambda_d\lambda\ll 1$$



The lattice magnets and RF cavities to replace energy loss are not shown.

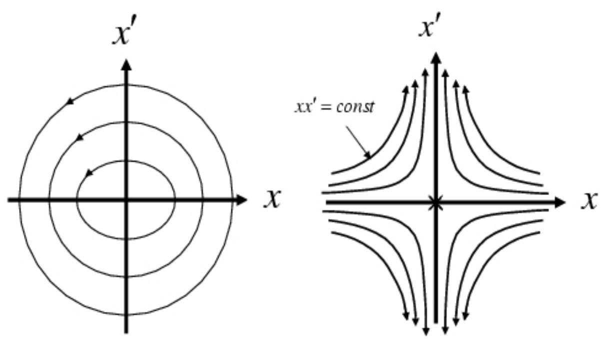
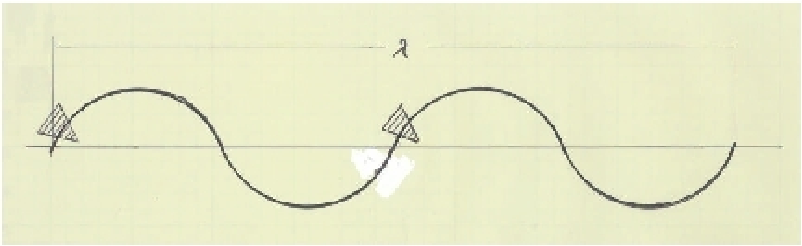


Fig. 1 Comparison of particle motion at periodic locations along the beam trajectory in transverse phase space for: LEFT ordinary oscillations and RIGHT hyperbolic motion induced by perturbations at a harmonic of the betatron frequency.

Achromatic channel for PIC

- Compensation for chromaticity requires relatively large orbit dispersion – which is a constraint to PIC because of increase of energy straggling impact on transverse emittance
- A resolution of this constraint is: design a dispersion function that follows the beam envelope at PR

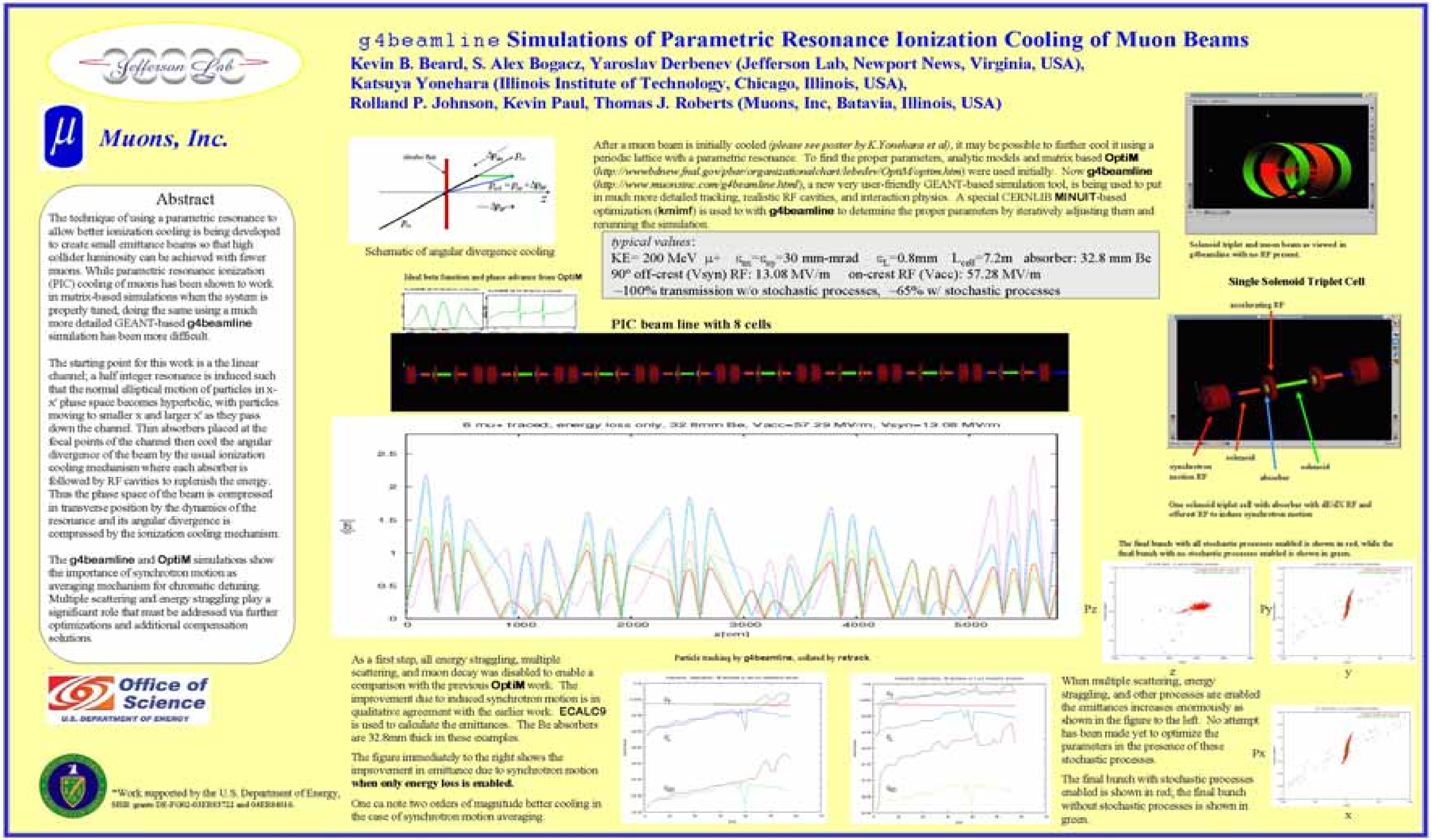
Scheme: Achromatic wiggler

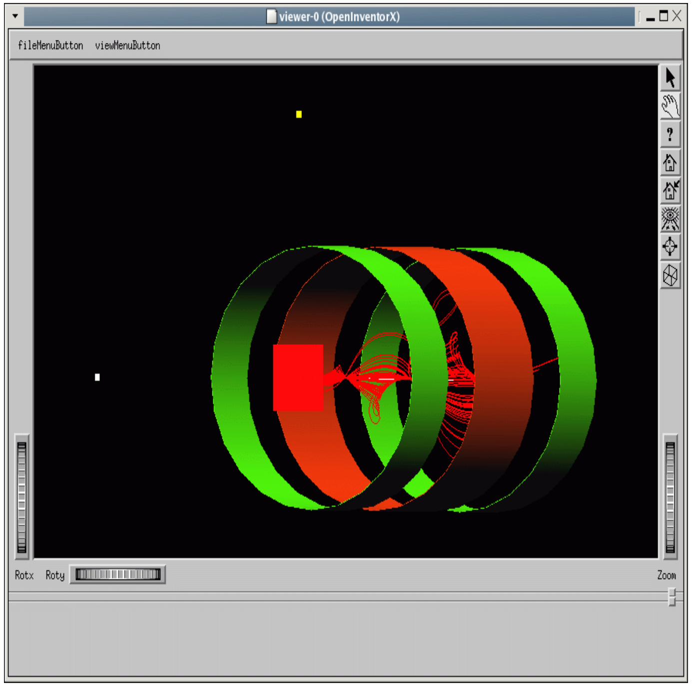


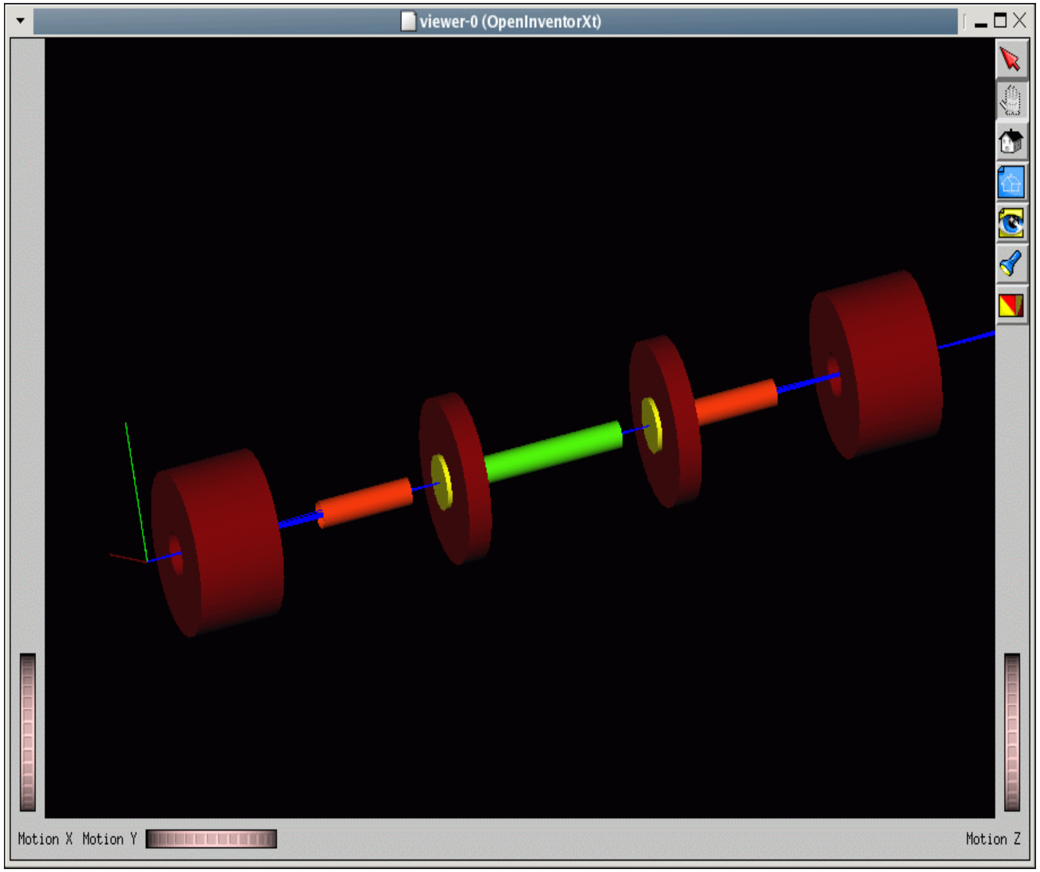
- Field index $n=1/2$ (symmetric focusing, $f\equiv(\lambda/2\pi)=R\sqrt{2}$)
- Betatron phase advance $\pi/2$ per bend segment (bend angle $\pi/\sqrt{2}$)
- Dispersion then oscillates with period equal to half of the betatron oscillation period
- Sextupole alternates in tact with the beam bend
- Orbit plane interchanges

However, compensation for chromaticity leads to a revival of the angle aberration. This seems possible to compensate by superimposing octupole field in combination with solenoid one (both relatively week) /under study/

P24: G4Beamline simulations of Parametric Resonance Ionization Cooling K.Beard, TJNAF

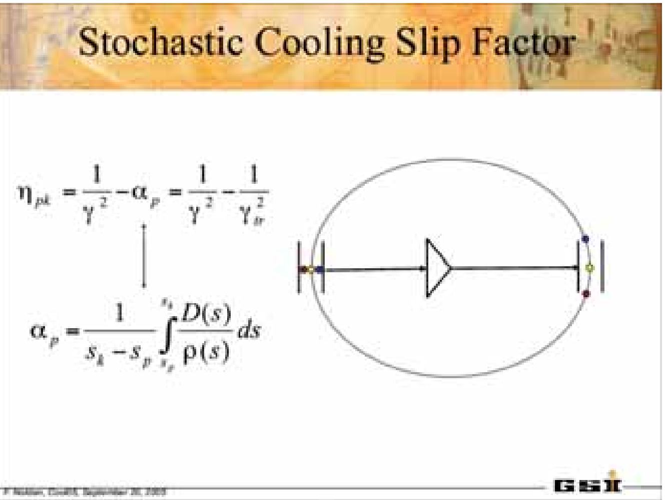


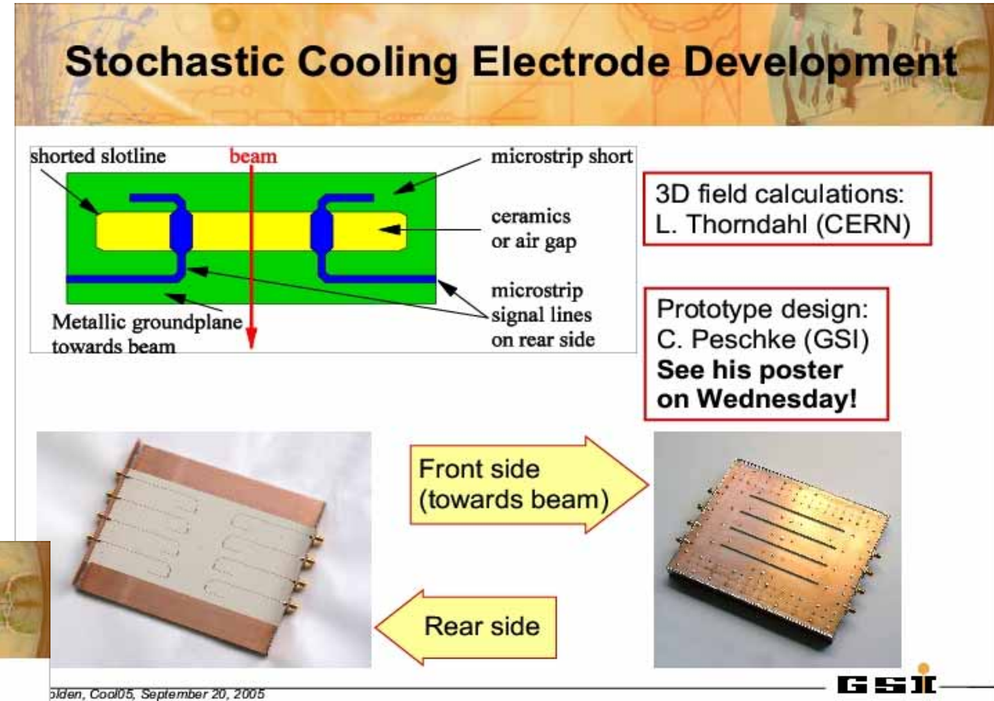

viewer-0 (OpenInventorX)
fileMenuButton viewMenuButton
Rotx Roty
Zoom

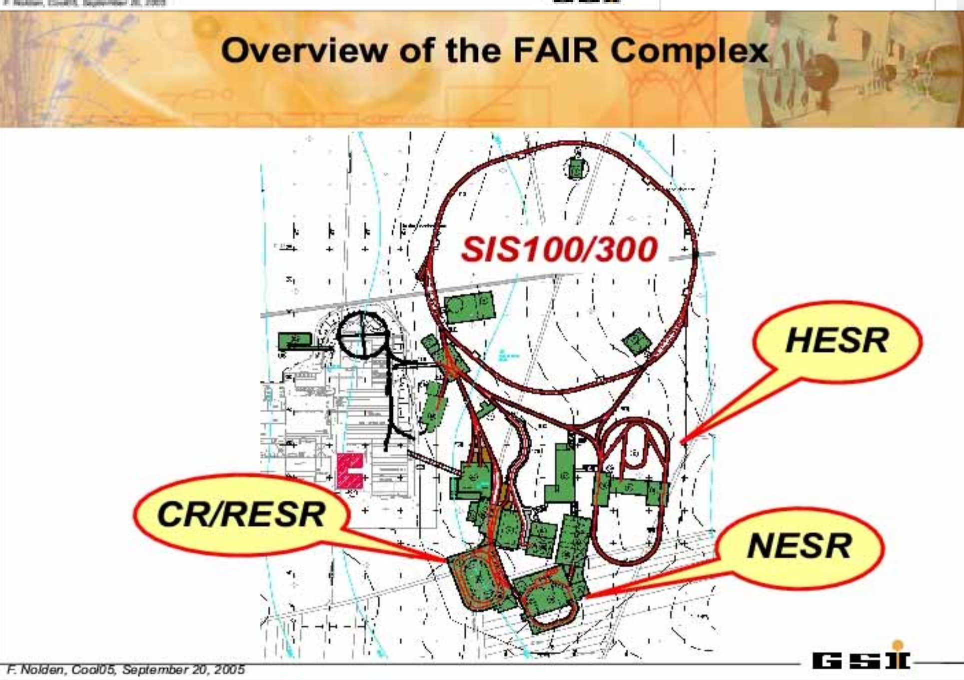

viewer-0 (OpenInventorXt)
Motion X Motion Y
Motion Z

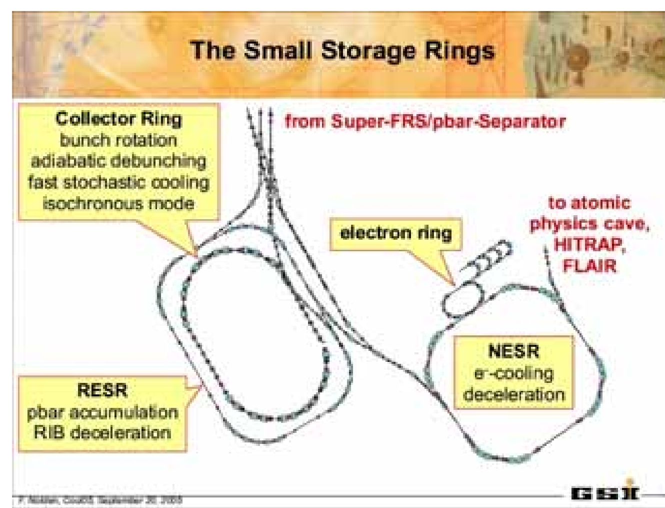
stochastic cooling

T01 Stochastic Cooling at GSI, F.Nolden GSI

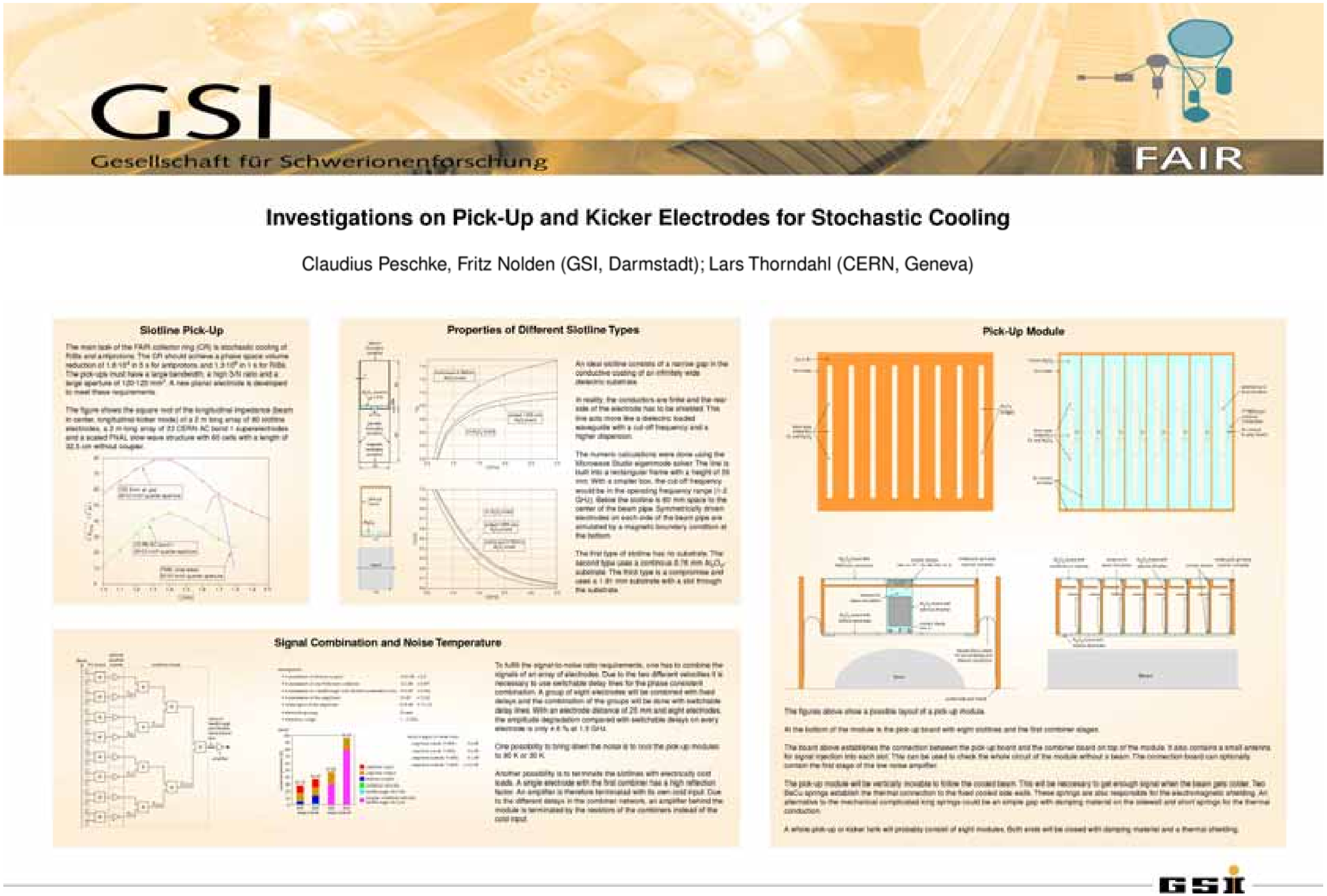








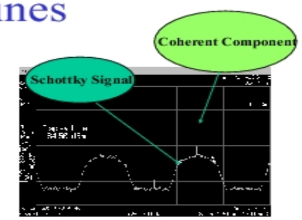
P26: Pick-Up and Kicker Electrodes for Stochastic Cooling C.Peschke GSI



T03 bunched beam stochastic cooling at RHIC
M.Brennan - BNL

Coherent Lines

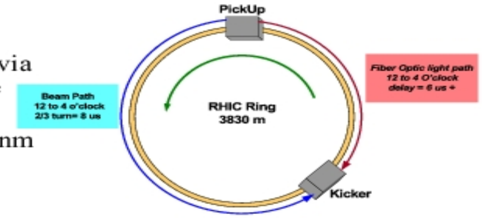
- This has been Nemesis of bunched-beam cooling.
- Not as severe for ions as for protons.
- Nevertheless, can cause saturation and disable the electronics. The problem is high peak voltages in the time domain.

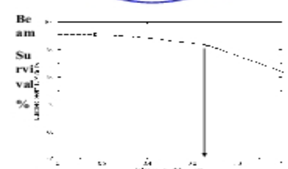


Spectrum of Copper ions in RHIC at 7.6 GHz, 100 GeV/n

PickUp to Kicker Delay

- Fiber optic link runs via the tunnel against the beam
- V_{light}=c/1.47 @ 1550nm
- Effectively 2/3 turn delay
- Mixing factor is about 4 turns
- Simulations (J. Wei) indicate that >90% beam is still bunched after 10 hours





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

Beam Transfer Function

- **The BTF measures the entire loop**
  - **Calibrates kickers (corrected for duty factor)**
  - **Obtains beam response**
  - **Determines loop phase (stability)**
  - **Reveals filter response**

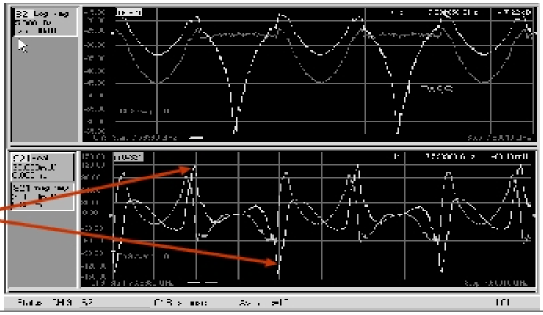
•The filter flips the sign of the real part at each Frev

•The phase is stable on the 10-minute time scale

•Run-time BTFs will be used to correct drifts

Magnitude: red is no filter, yellow is with 2-turn filter

Real (yellow)and Imaginary parts. Real part changes sign at Frev



T06 Stochastic Cooling and Coherenet Lines
M.Blaskiewicz BNL

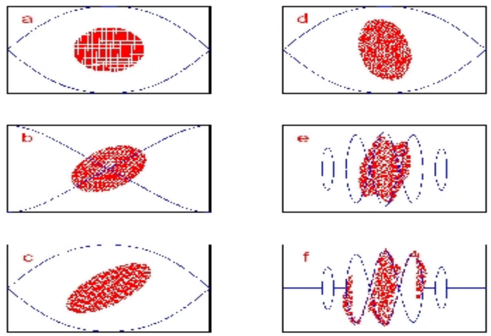
Coherence in Heavy Ion Beams

Two distinct types:

2) Strong revolution lines
3) Strong signals associated with synchrotron motion

We see the first type with heavy ions and both with protons.

Heavy ions are "rebucketed" to shorten the bunch and combat IBS



Mike Blaskiewicz C-AD

BROOKHAVEN NATIONAL LABORATORY

Coherence in Proton Beams

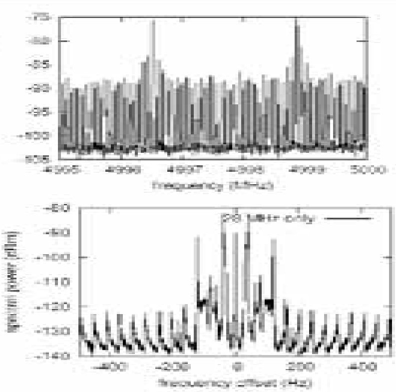
Wide band (top) observed with 28 bunches in 30 bunch fill pattern. h=360. Similar to what would be expected due to hard edge bunch.

Zoom of the strong right peak (bottom).

90% of the power in dipole lines (40 Hz)

10% in rev and +/- 120 Hz.

<1% Schottky.

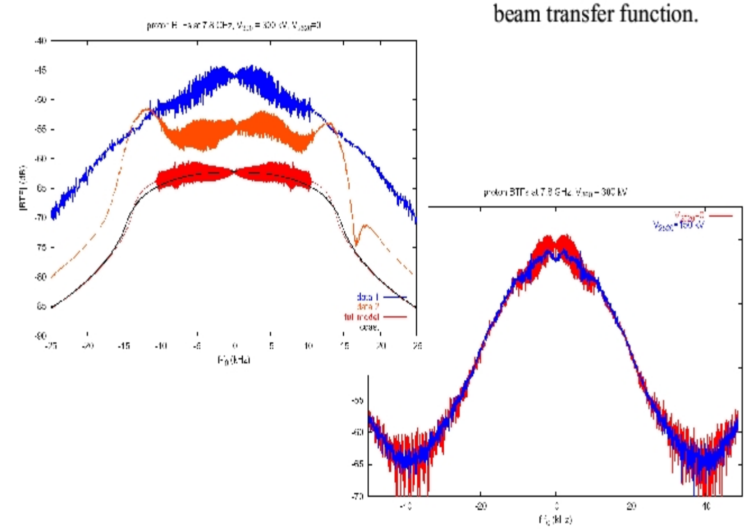


Mike Blaskiewicz C-AD

BROOKHAVEN

General features look good

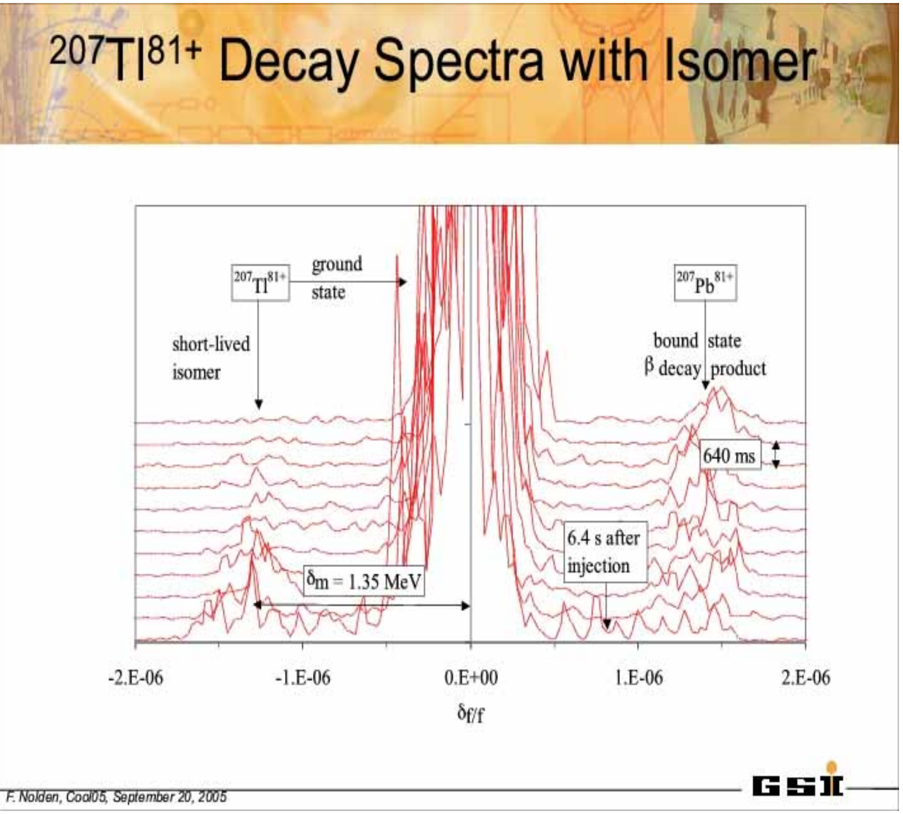
Generic features are well modeled by a coasting beam transfer function.

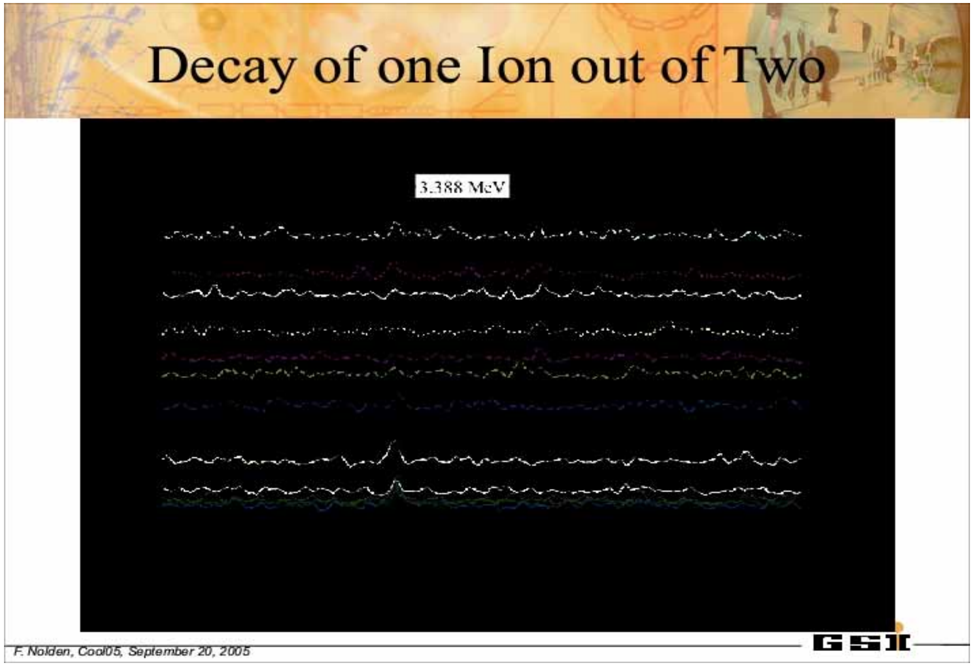


Mike Blaskiewicz C-AD

BROOKHAVEN NATIONAL LABORATORY

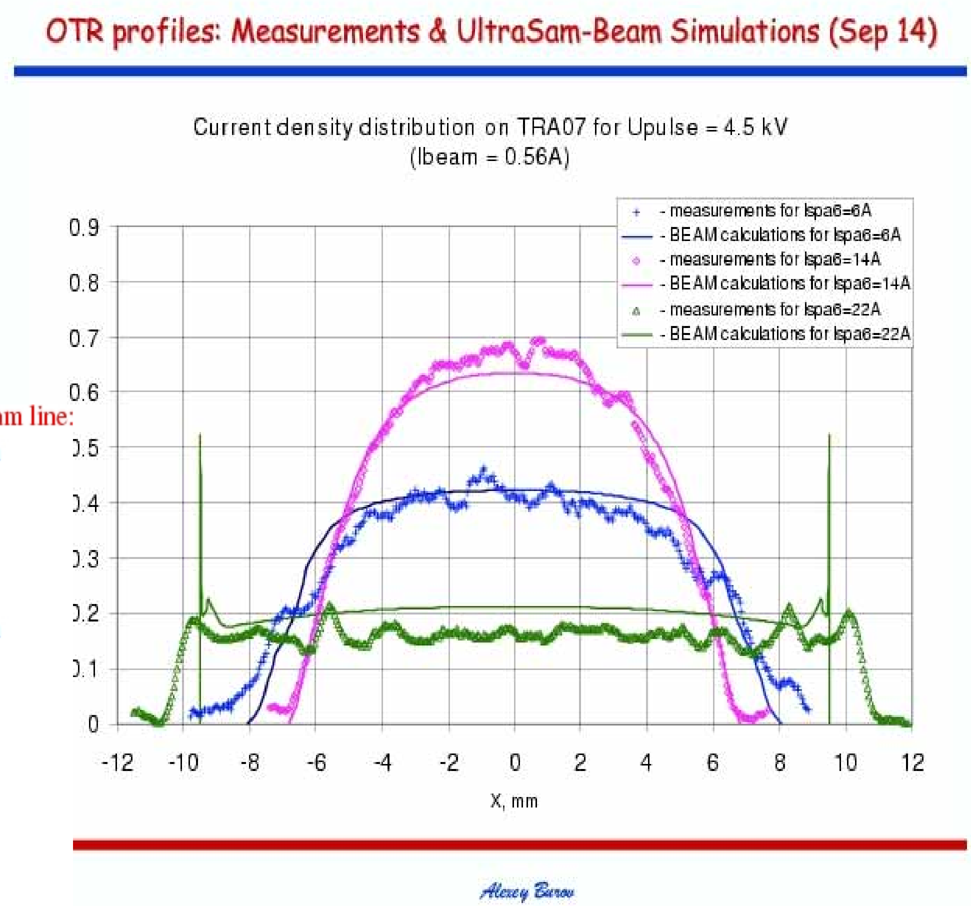
T07: Schottky Spectroscopy, F.Nolden GSI



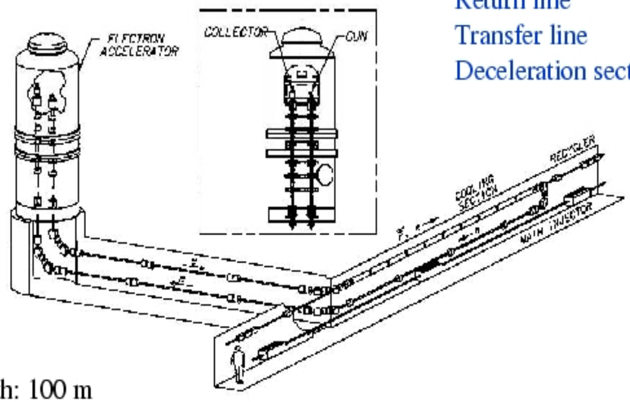


electron cooling

M12 Optics of Electron Beam in Recycler: A.Burov, FNAL



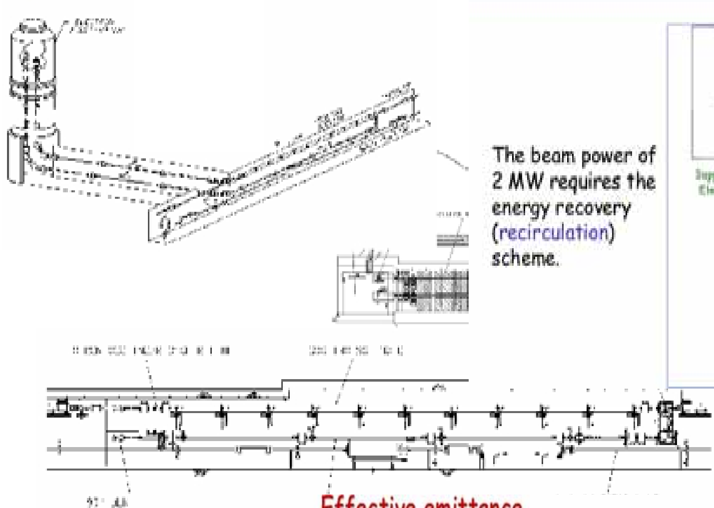
Electron cooling beam line:
Acceleration section
Supply line
Cooling Section
Return line
Transfer line
Deceleration section



Total length: 100 m
Cooler length: 20 m
Kinetic energy: 4.35 MeV
Phase advance: ~30 rad

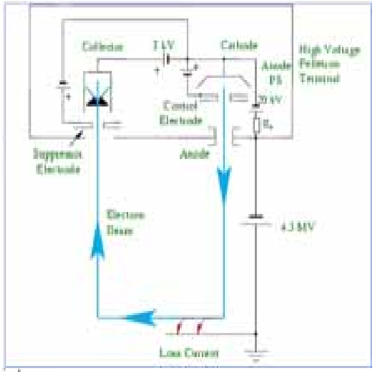
high-quality electron beam @ FNAL's 4.3MV cooler
A.Shemyakin FNAL

Setup



The beam power of 2 MW requires the energy recovery (recirculation) scheme.

Recirculation

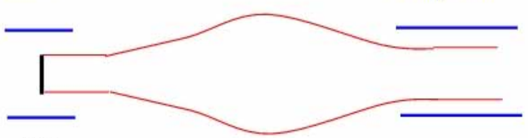


Setup parameters

Parameter	Unit	Value (for cooling)	Value (maximum)
Electron energy	MeV	4.338	5
Beam current used for cooling	A	0.05 - 0.2	0.6
Magnetic field in the cooling section	G	105	190
Beam radius in the cooling section	mm	3 - 5	
Pressure	nTorr	0.2 - 1	
Total length of the beam line	m	80	

Effective emittance

Figure of merit: magnetic flux inside the beam in the cooling section = effective emittance outside the longitudinal magnetic field



$B_{cz} = 90\ G$
$R_{cath} = 3.8\ mm$
$\varepsilon_t = R_{cath}\sqrt{\frac{T}{mc^2}}$
$= 2\ \mu m$ (normalized)

$B_z = 0$
$R = 2\text{-}10\ mm$
$\varepsilon_{eff} = B_{cz} R_{cath}^2 \frac{e}{2mc^2}$
$= 38\ \mu m$ (normalized)

$B_{cz} = 105\ G$
$R_{beam} = 3.5\ mm$
$\varepsilon_{cs} < 7\ \mu m$
(normalized)

Low energy portions of the acceleration and deceleration tubes have to be immersed into a longitudinal magnetic field.

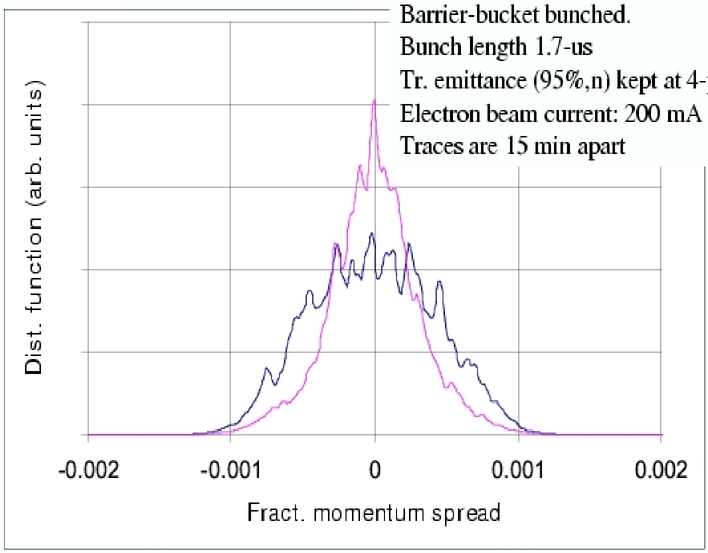
A 3D beam line has to provide an axially symmetrical beam transformation.

See report of A. Burov et al.

Fermilab Accelerator Division

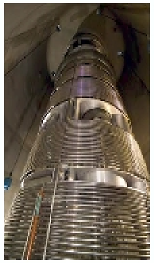
First e-cooling demonstration - 07/15/05

Pbar beam: 63.5e10
Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mrad
Electron beam current: 200 mA
Traces are 15 min apart

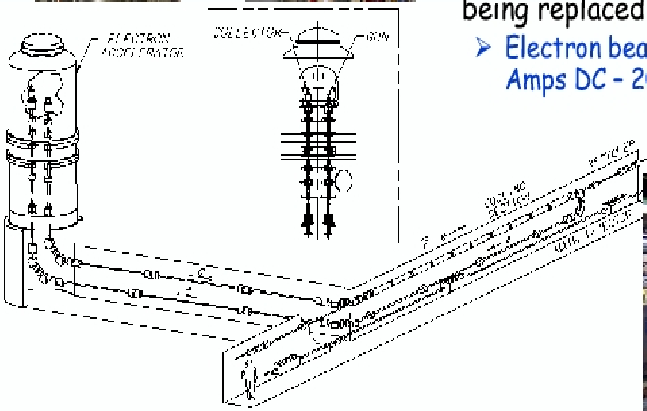


Fermilab Accelerator Division

Recycler Electron Cooling



- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV - 0.5 Amps DC - 200μrad angular spread



Fermilab Accelerator Division

Recycler-Only Operations

- Recycler has been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120×10^{10} pbars
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size can now be increased to over 200×10^{10} pbars
- The Collider complex is now transitioning from Combined Shot mode to Recycler-Only mode
  - Faster average stacking.
  - Smaller pbar emittances in the TEV

Fermilab Accelerator Division

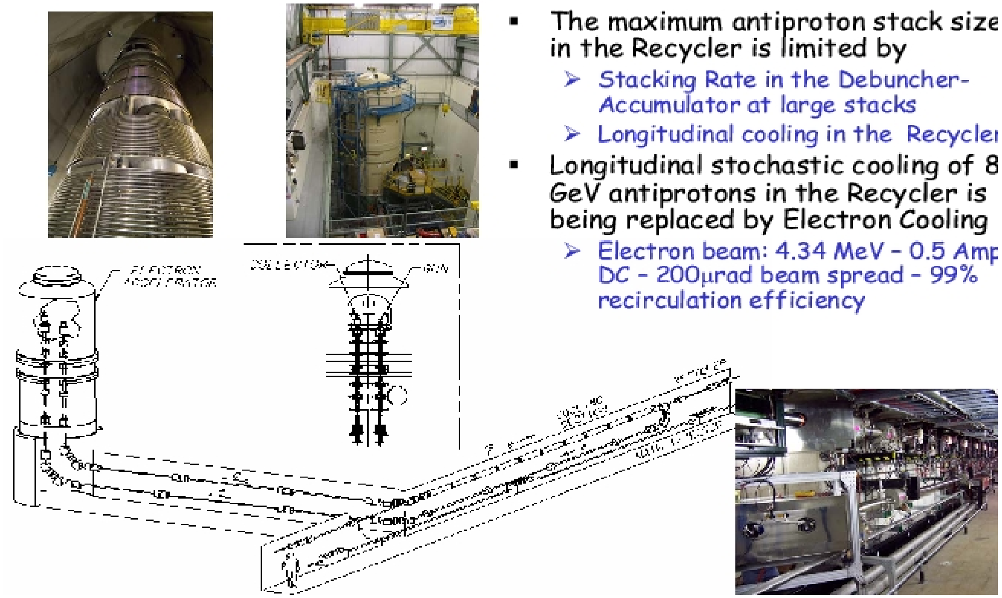
Electron beam parameters

Electron kinetic energy	4.34 MeV
Uncertainty in electron beam energy	0.3 %
Energy ripple	$\leq 10^{-4}$
Beam current (max)	0.5 A DC
Duty factor (averaged over 8 h)	95 %
Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms	$\leq$ 0.2 mrad

T02 antiproton rate increase D.McGinnis - FNAL

Fermilab Accelerator Division

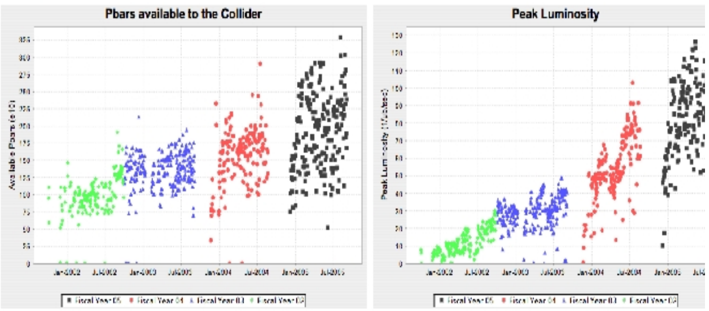
Recycler Electron Cooling



- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV - 0.5 Amp DC - 200μrad beam spread - 99% recirculation efficiency

Fermilab Accelerator Division

Antiprotons and Luminosity

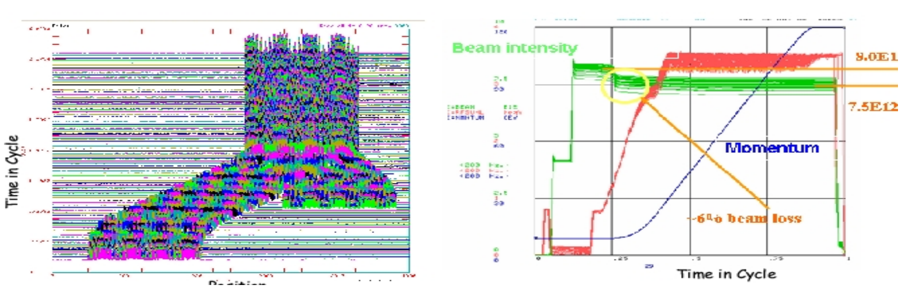


- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Fermilab Accelerator Division

Antiproton Production - Slip Stacking

- Slip Stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target



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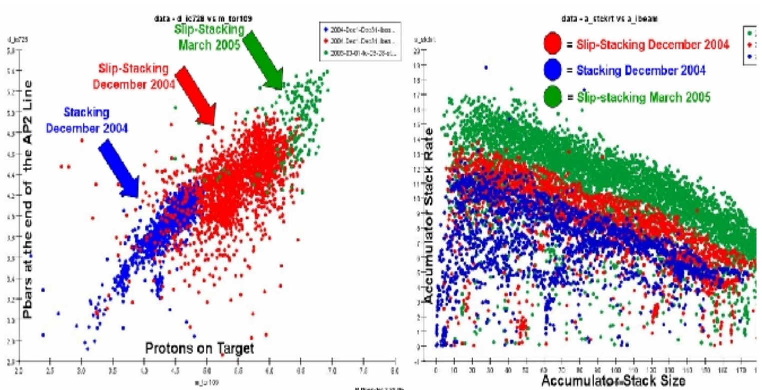
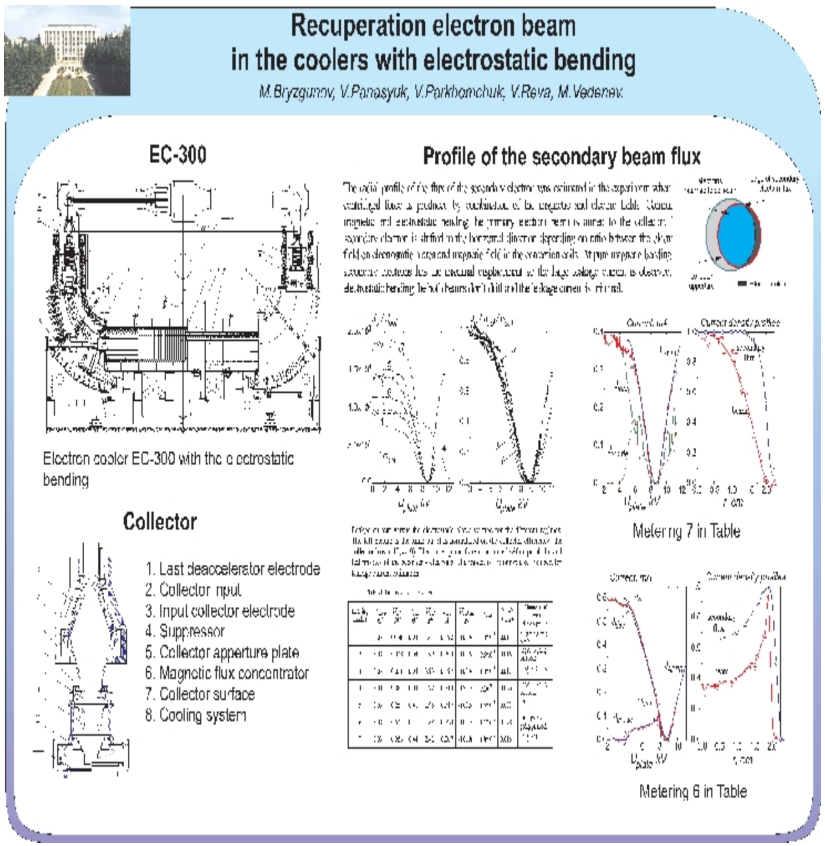
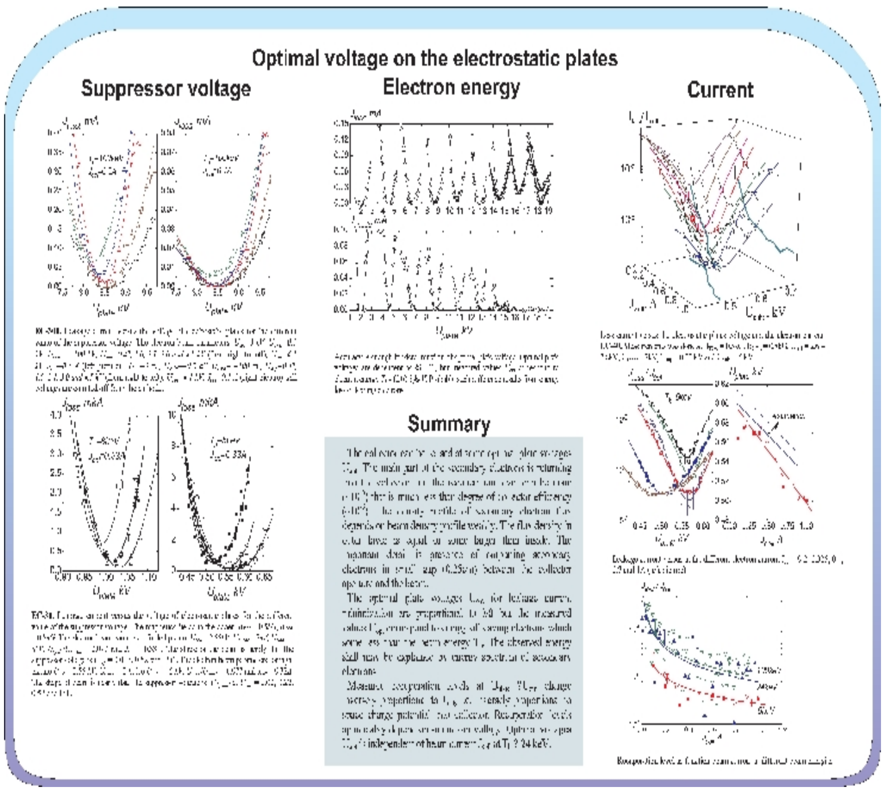
Antiproton Production - Slip Stacking



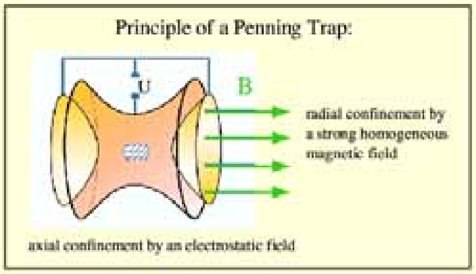
P03 Recuperation of electron beam in coolers with electrostatic bending   V.Parkhomchuk BINP

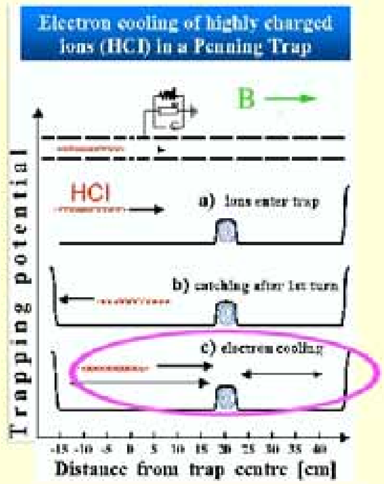




F05 electron cooling of highly charged ions in traps
G.Zwicknagel, Erlangen U.

Electron Cooling in a Penning Trap



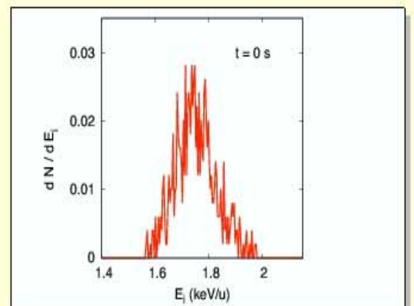


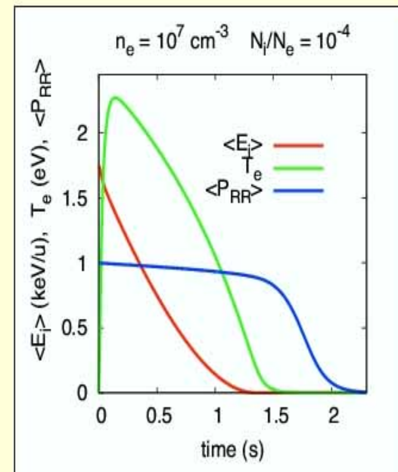
Typical parameters:

- $Z = -1, 1 \dots 92$
- $B \lesssim 6$ T
- $T_{e,0} \approx 4$ K
- $n_e \approx 10^7$ cm^{-3}
- $N_e \approx 10^8 \dots 10^{10}$
- $N_i \approx 10^5$

Cooling of U^{92+} and heating of electrons

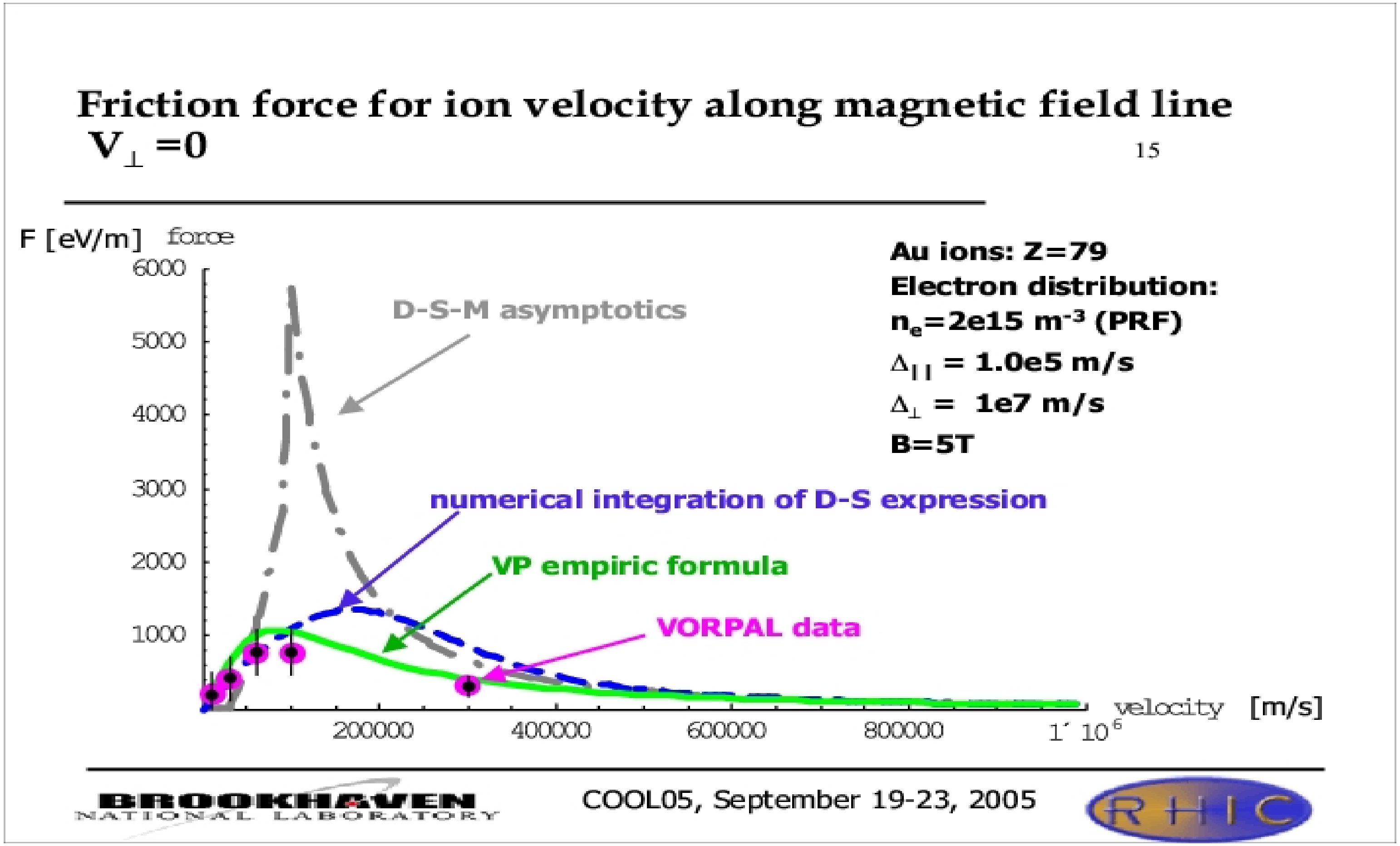
- U^{92+}, $T_e(0) = 4$ K, $B = 6$T
- Initial ion distribution with $N_i = 500$ ions as obtained from ion optics simulations of the injection into the cooler trap for the HITRAP setup*





*F. Herfurth, private communications

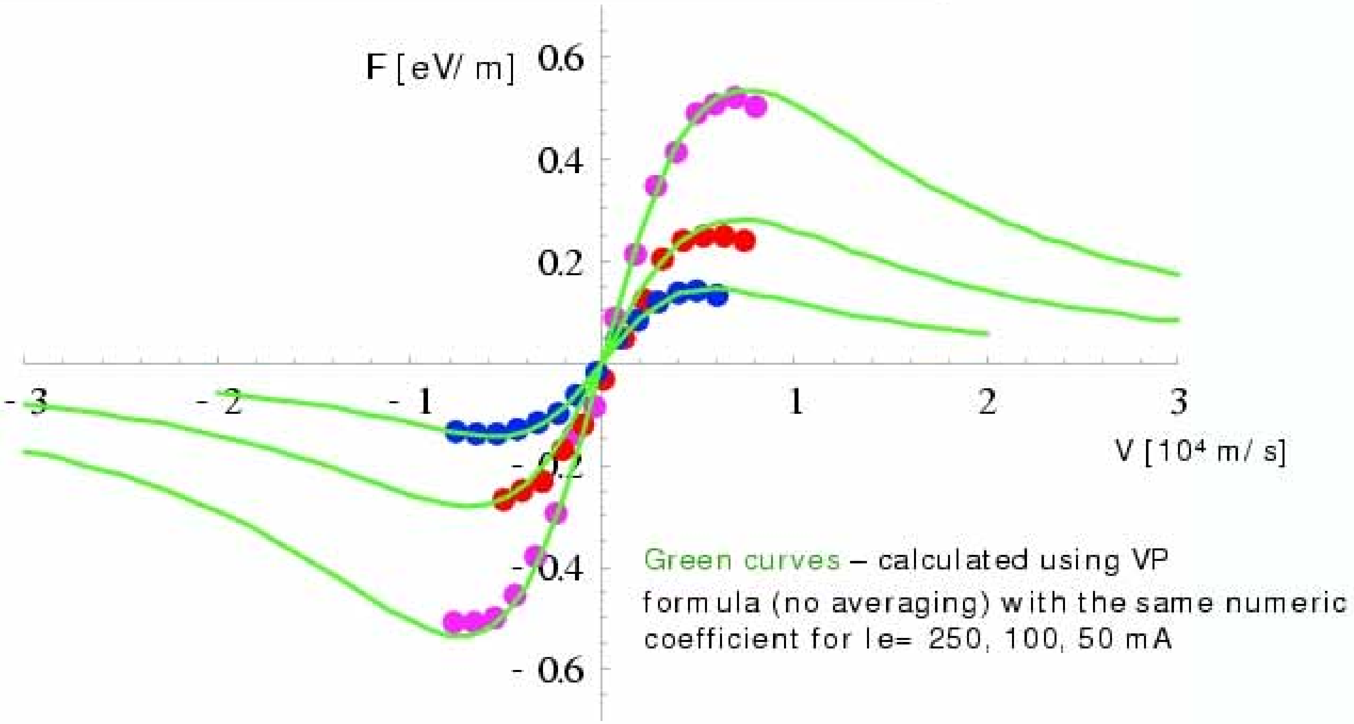
W06: Studies of electron cooling frictional force
A.Fedotov BNL



R05: benchmarking magetized friction force A.Fedotov BNL

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

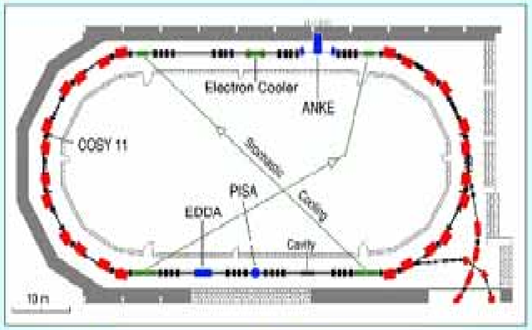
11



COOL05, September 19-23, 2005

R10: COSY 2-MeV cooling system proposal J.Dietrich FZ/IKP

COSY Accelerator Facility



Ions: (pol. & unpol.) p and d

Momentum: 300 to 3650 MeV/c for p; 540 to 3650 MeV/c for d

Targets:

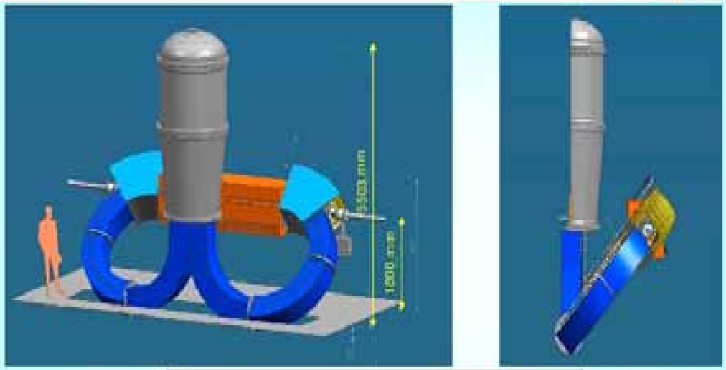
- Internal: solid, cluster, atomic beam
- External: solid, liquid

Beam cooling:

- Electron cooling at injection (300 MeV/c) for beam accumulation, high brilliance beams
- Stochastic cooling above 1.5 GeV/c for luminosity preservation

Jürgen Dietrich Galena 22.09.2005

Preliminary Technical Design - Layout

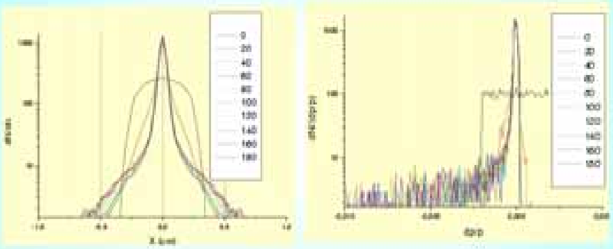


Energy	25 keV – 2 MeV
Electron current	3 A
Radius of the electron beam	0.5 – 1.5 cm
Magnetic field	2000 G
Length of cooler section	300 cm

Jürgen Dietrich Galena 22.09.2005

Beam Profile and Momentum Distribution

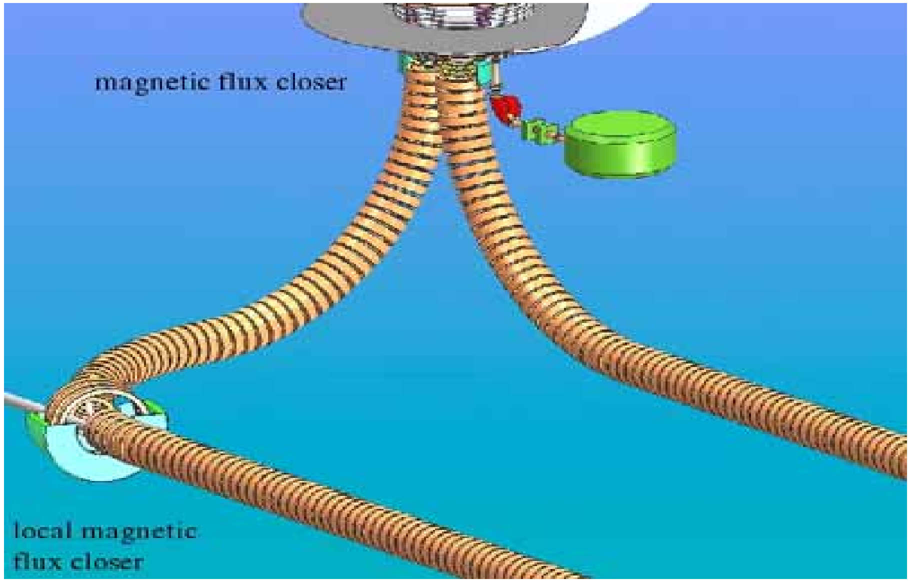
as function of cooling time (with target, $4 \cdot 10^{11}$ cm^{-2})

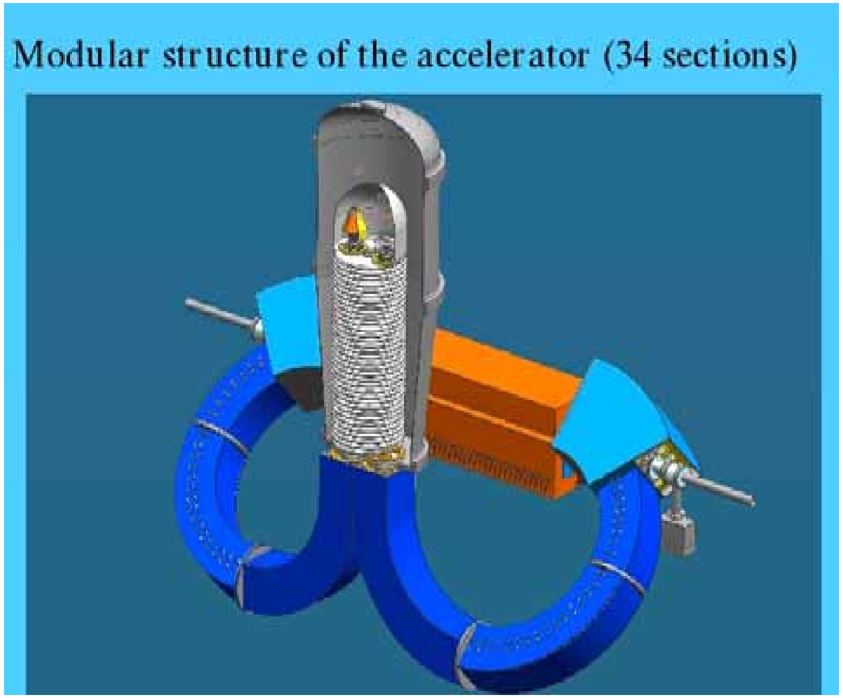


Increasing of the population in the tails.

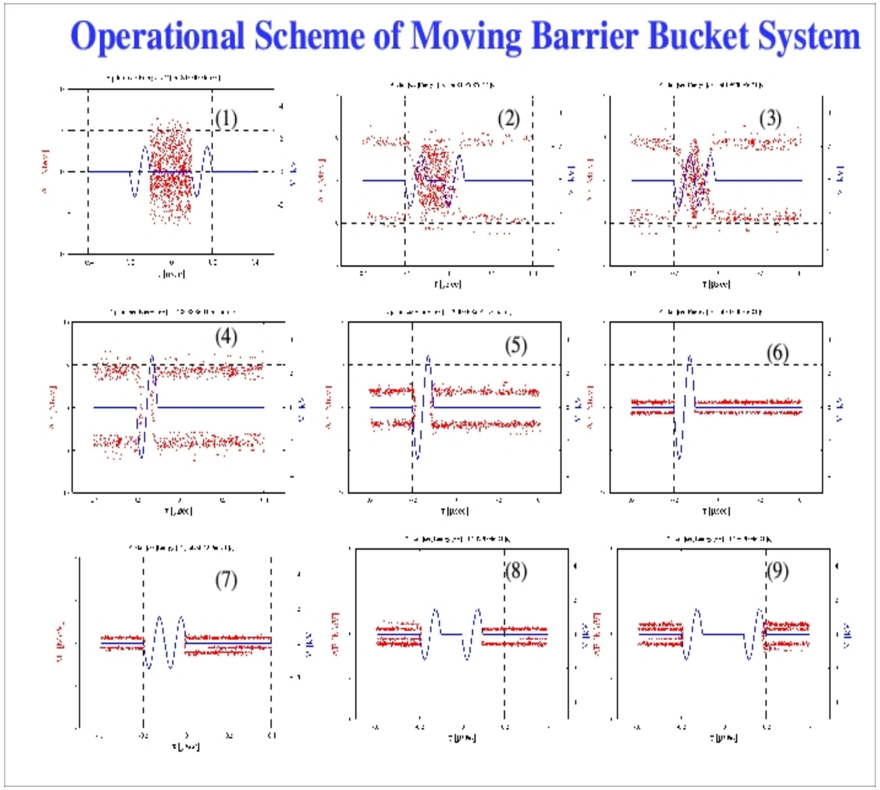
Jürgen Dietrich Galena 22.09.2005

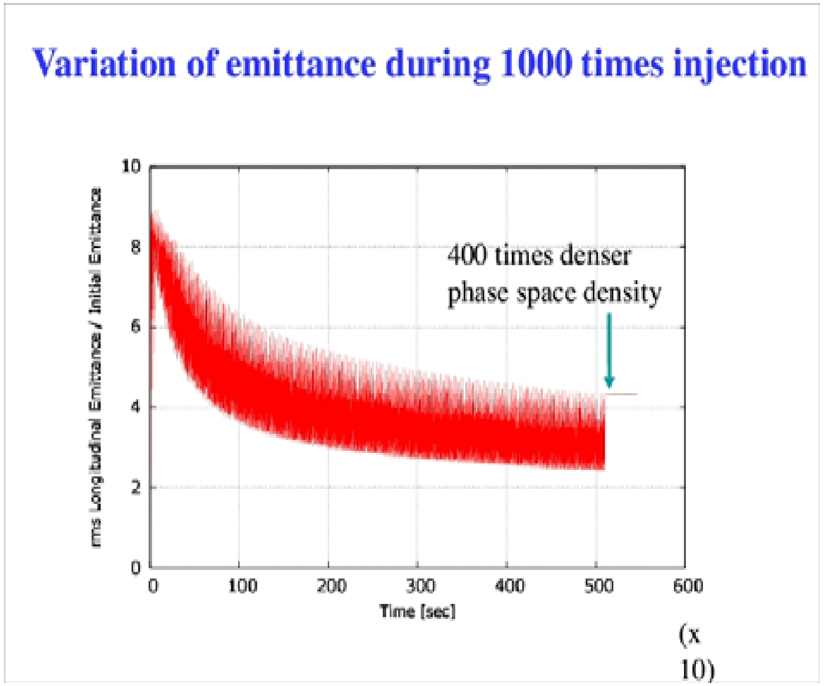
R11: Budker INP proposals for HESR and COSY electron cooling systems V.Reva BINP





T05: Moving Barrier Bucket, T.Katayama GSI





R06: electron cooling of intense ion beam I.Meshkov JINR

5. Coherent instability

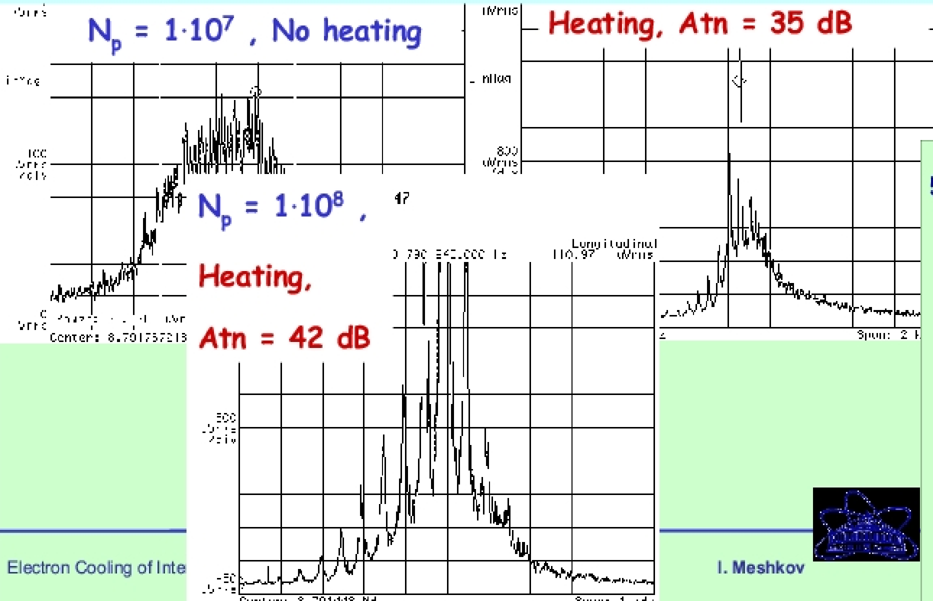
5.4. IBS (?) and longitudinal modulation

Influence of transverse heating

Atn = attenuation

$(V_{noise})_{rms}$ = 6 V/Atn, Δf = 0.1 – 2 MHz, I_e = 250 mA

Schottky noise: 18th harmonics, f = 5.8 MHz

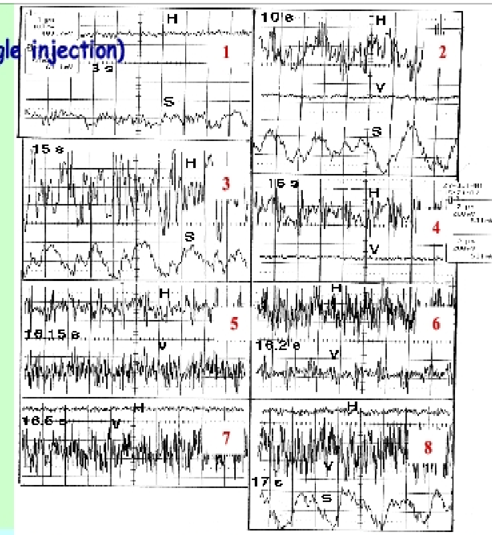


Electron Cooling of Inte

I. Meshkov

5. Coherent instability (single injection)

Coherent instability development in COSY



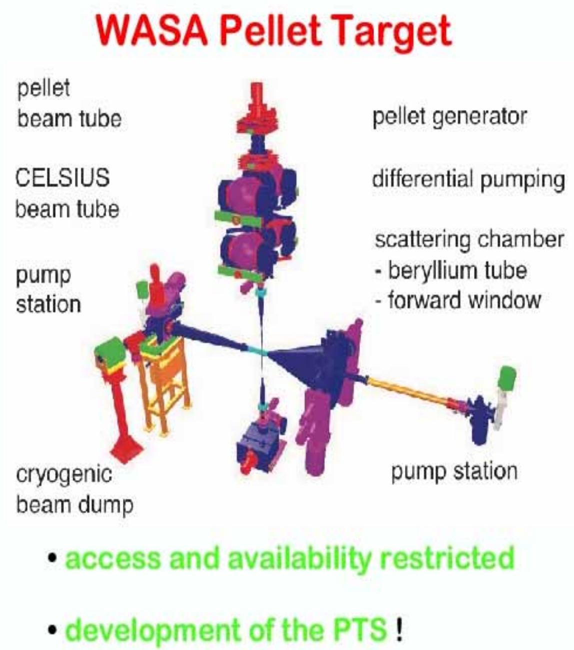
Beam Position Monitor analog signals clearly demonstrating the collective oscillations of the p-beam: the signals from differential horizontal (H) and vertical (V) PU's and sum (S) PU.

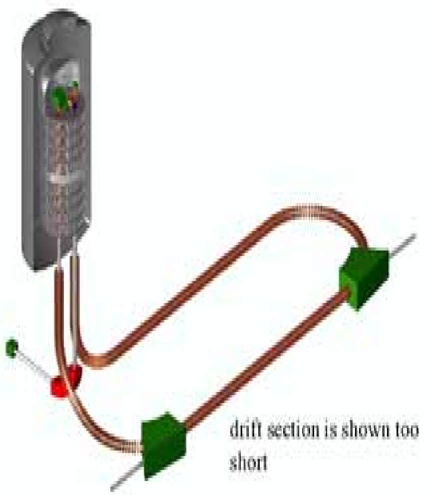
Note: longitudinal oscillations (sum signal) appear together with horizontal one and present later on.

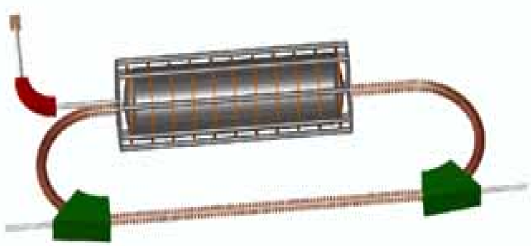
Electron Cooling of Intensive Ion Beam COOL'05 I. Meshkov

September 2005 Galena, IL, USA

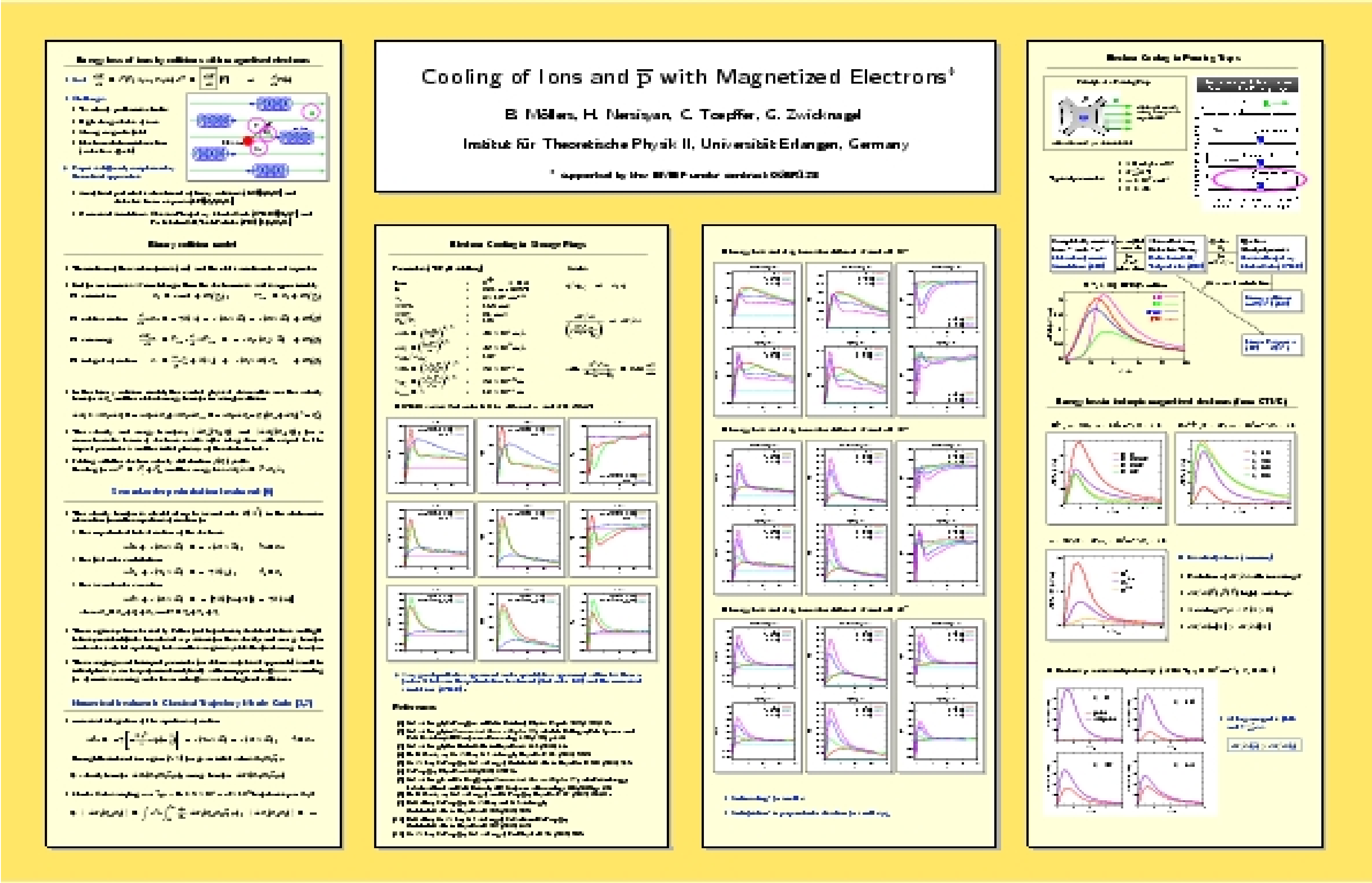
R09: HESR electron cooling proposal D.Reistad TSL



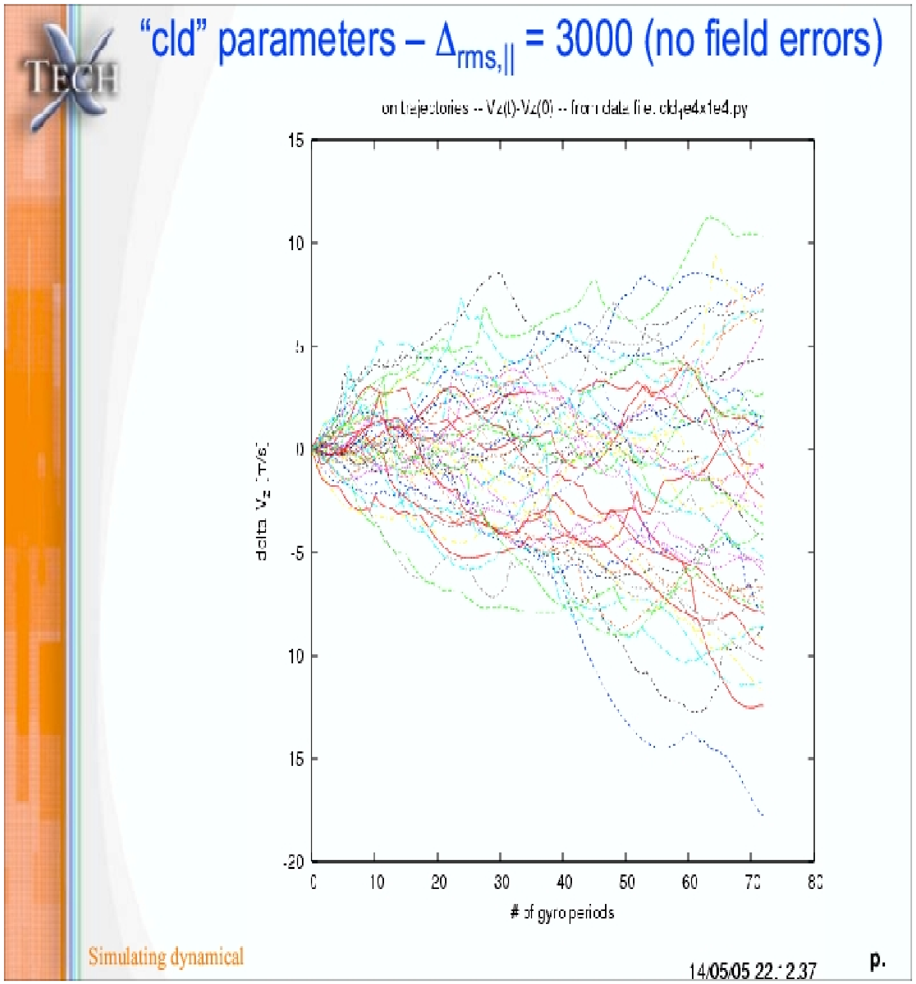


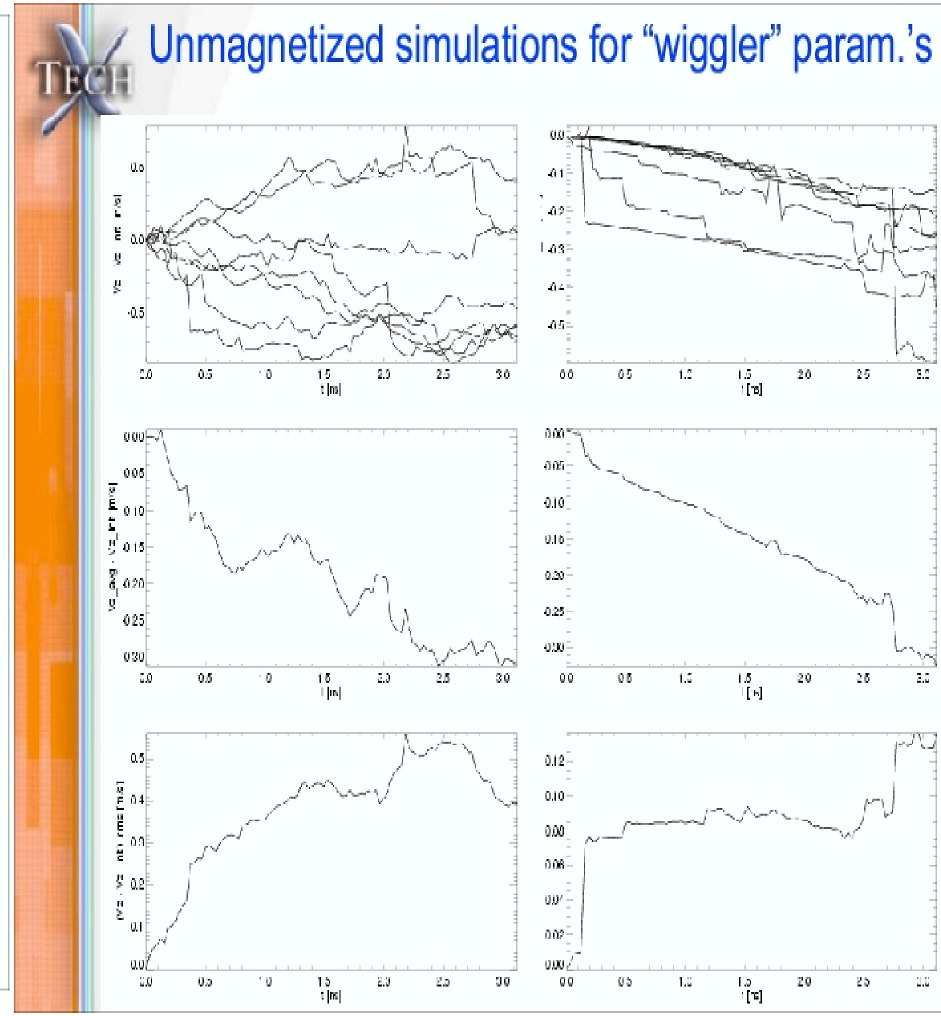


P18: cooling of ions & antiprotons with magnetized electrons G.Zwicknagel – Erlangen U.



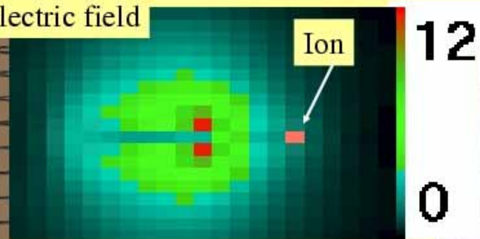
W07: Simulationsof dynamical friction, D.Bruhwiler, Tech-X



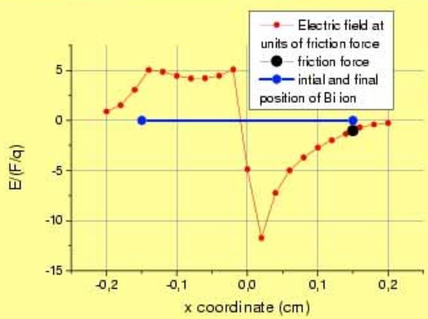


R01: Coolers with Hollow e beam & electrostatic cooling
V.Parkhomchuk BINP

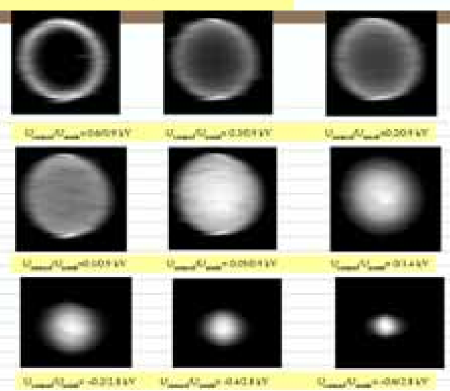
Wave at electron beam by moving Bi ion



Red boat (as Bi ion) exit visual wav



Electric field around moving ion Bi at plane (color map) and along axis (down figure)



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

How to proceed for cooling high ion beam current?

→Hollow electron beam!

$$\lambda = \lambda_0 (1 - \omega_i^2 \omega_e^2 \tau^4 * k)$$

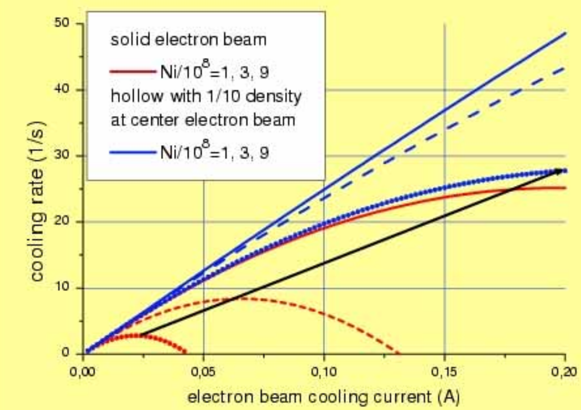
k=1 N=9E8 optimum cooling 0.025 A only

k=0.1 optimum 0.2 A

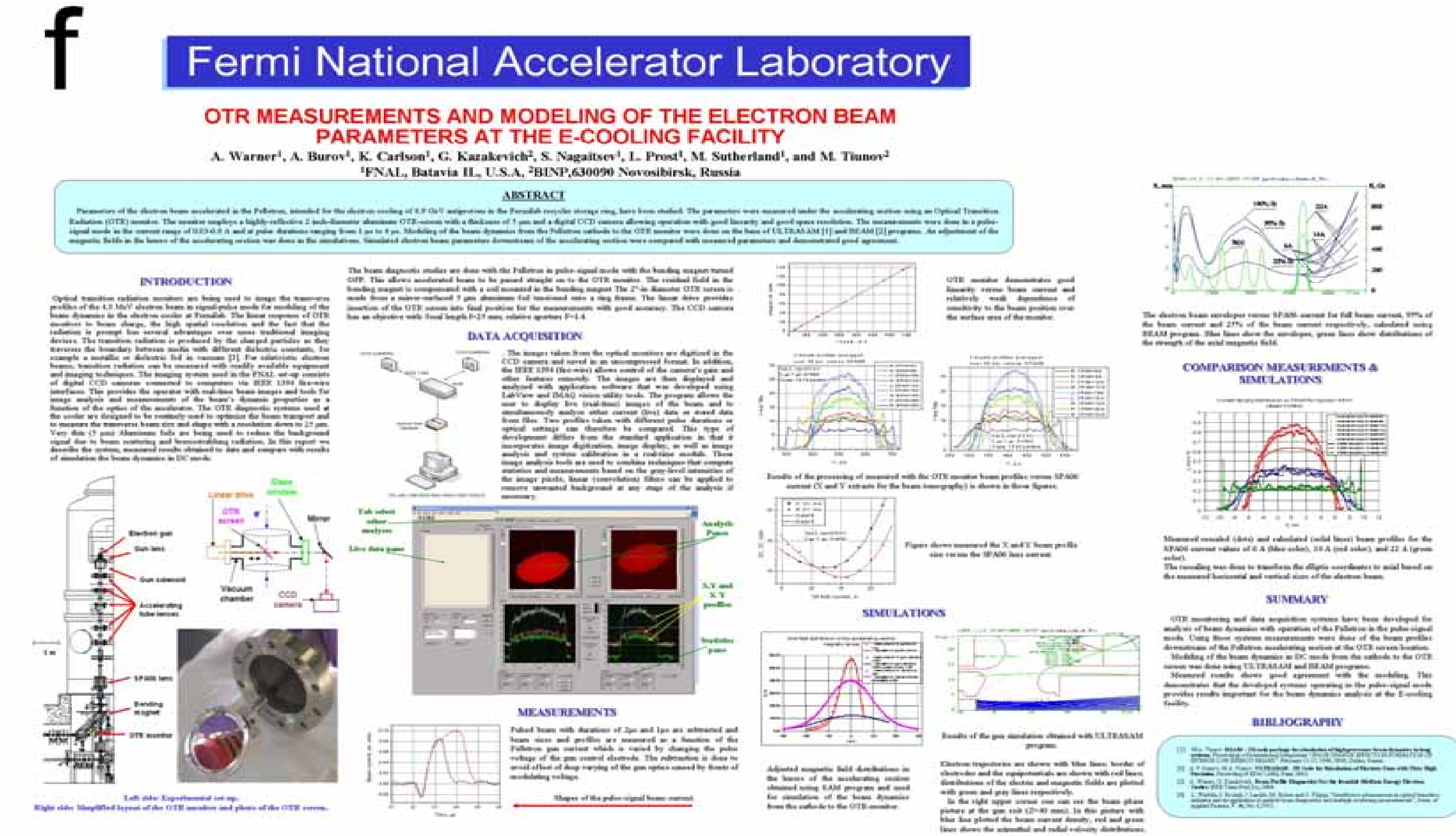
$\omega_e^2 - \downarrow$

$\omega_i^2 - \uparrow$

Decreasing electron beam density results to Increasing threshold ion beam density

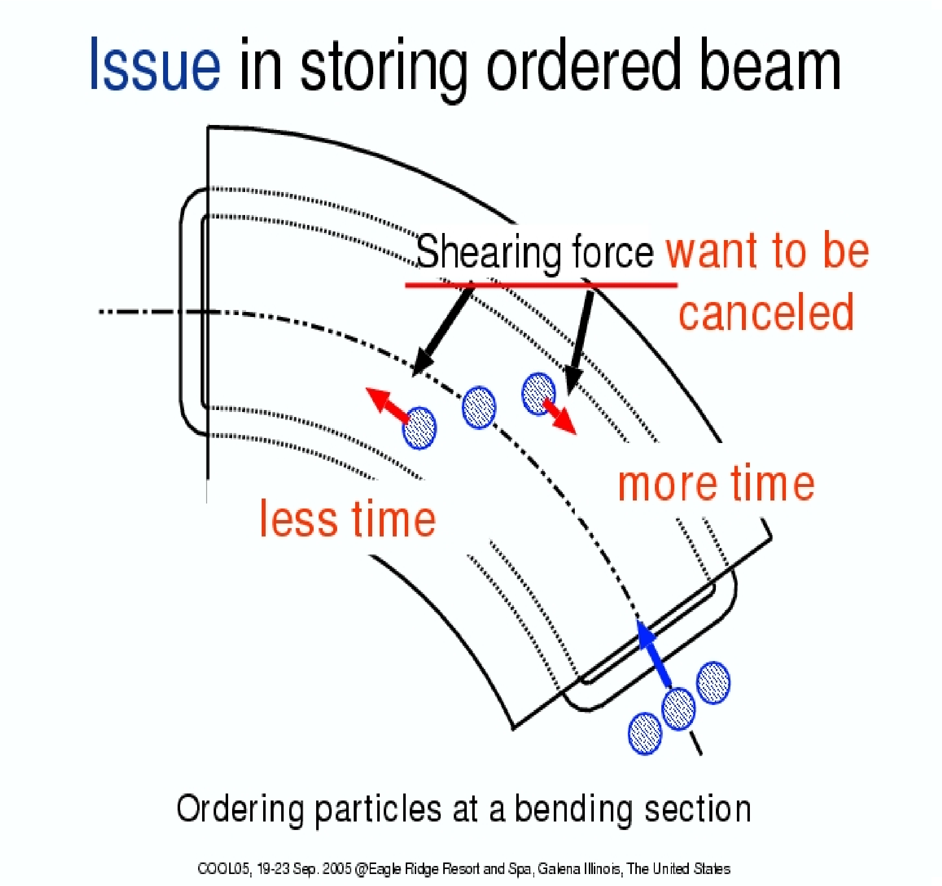


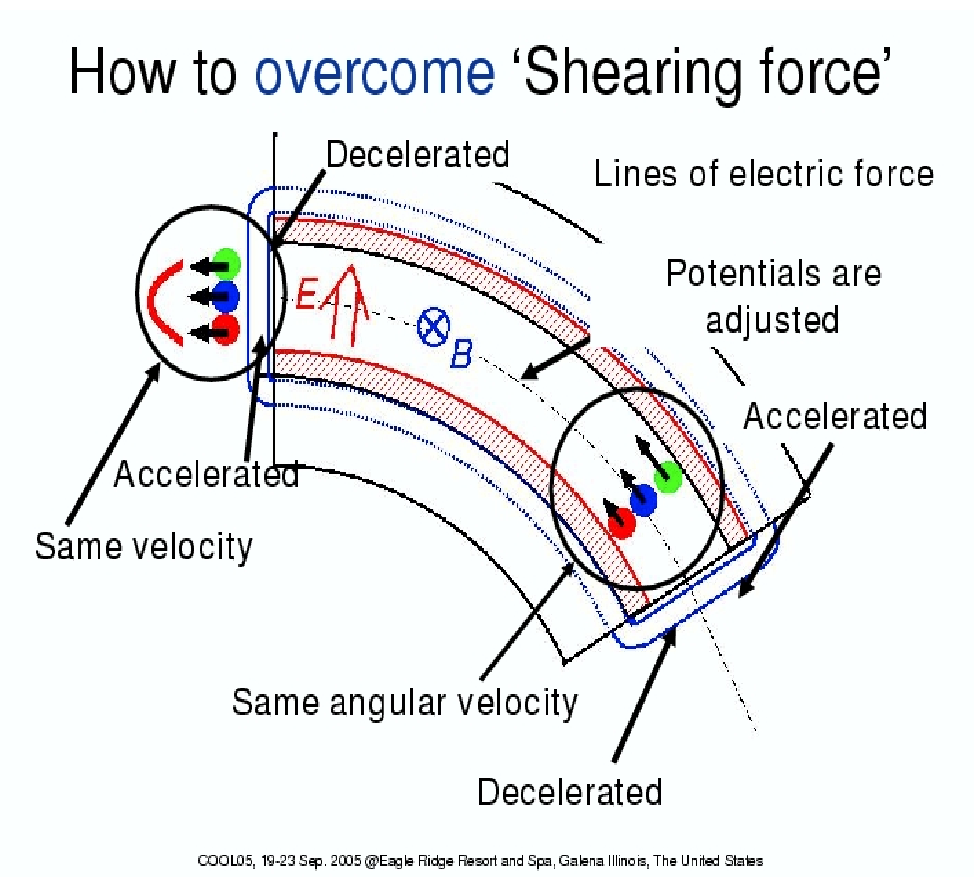
P13: electron beam profile monitoring with OTR at the E-cooling facility A.Warner, FNAL



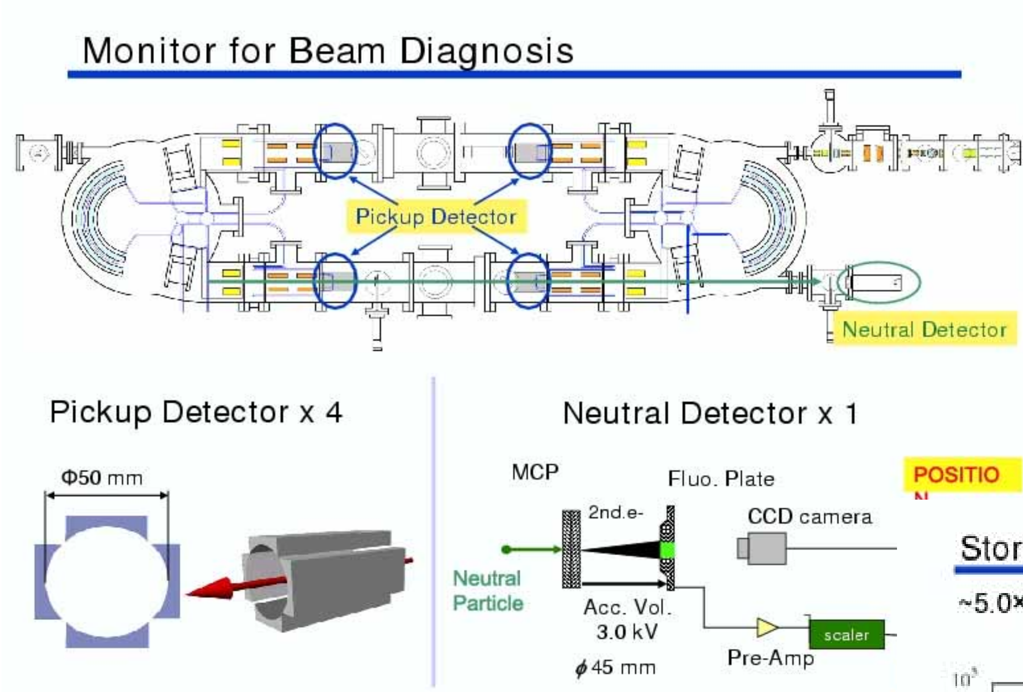
electrostatic rings

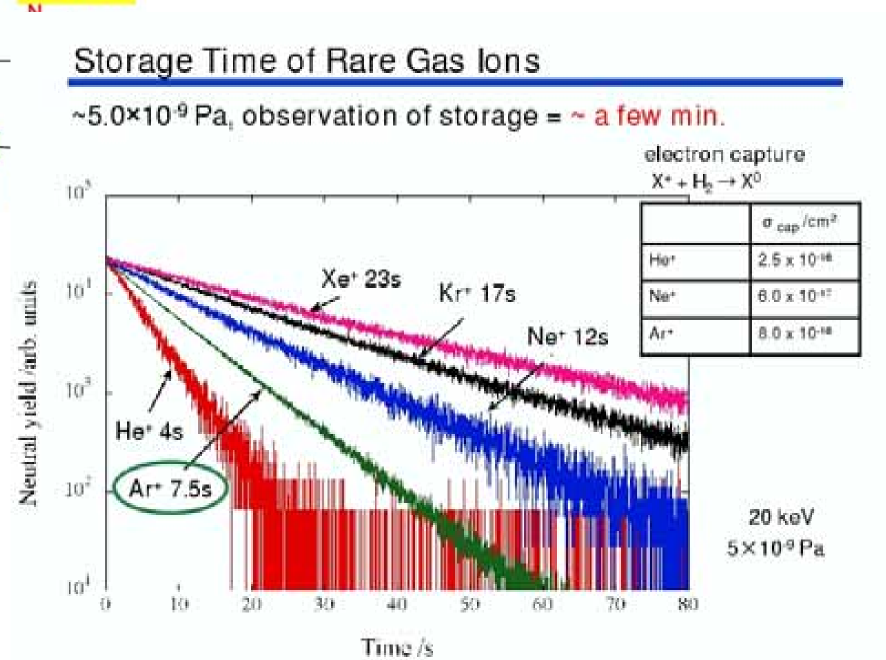
M12 Dispersion Control:M.Tanabe - Kyoto





W01: LN2-cooled electrostatic ring T.Azuma TMU



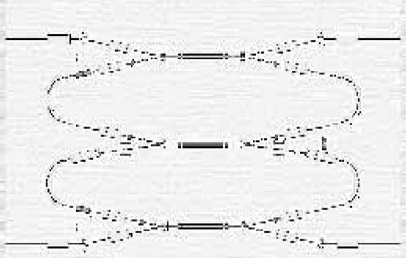


Why Electrostatic Rings?

Ring Layout

	Ring 1	Ring 2
160° cylindrical bends	2	2
Quadrupole doublets	4	4
10° deflections	4	2
Variable deflections	-	6
Symmetries	2	1

Platform voltage:	< 25/100 kV
Electrode voltage:	< 16 kV
Beam energy:	5-100 q keV
Ion mass ratio:	1-20 (q = ±1)



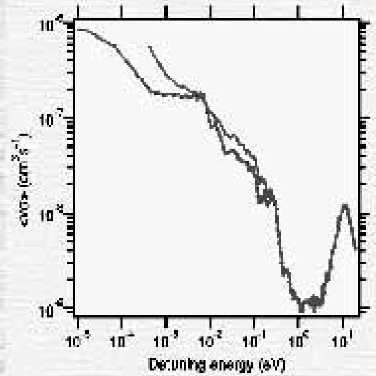
Low Temperatures

The rings will be cooled with cryogenerators to 5-10 K.

This will allow internal degrees of freedom of (infrared-active) molecular ions to cool radiatively, and ions produced in a cold ion source will stay cold. Also, the vapour pressure of all gases except H_2 and He is below 1□10^{-13} mbar at T < 18 K.

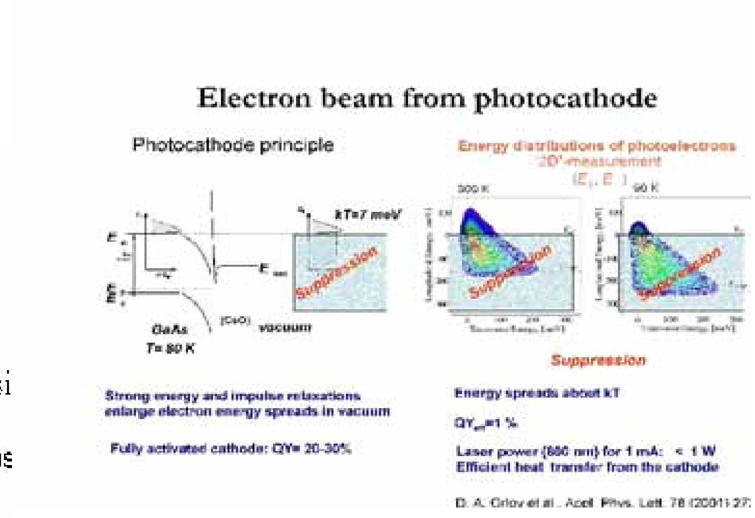
Development in atomic and molecular physics since 1990: Cooled ions -> cold electrons (□20 K) -> low quantum states. Figure shows rate for $H_3^+ + e^- \rightarrow H_2 + H$ with ions from hot plasma source/cold expansion source.

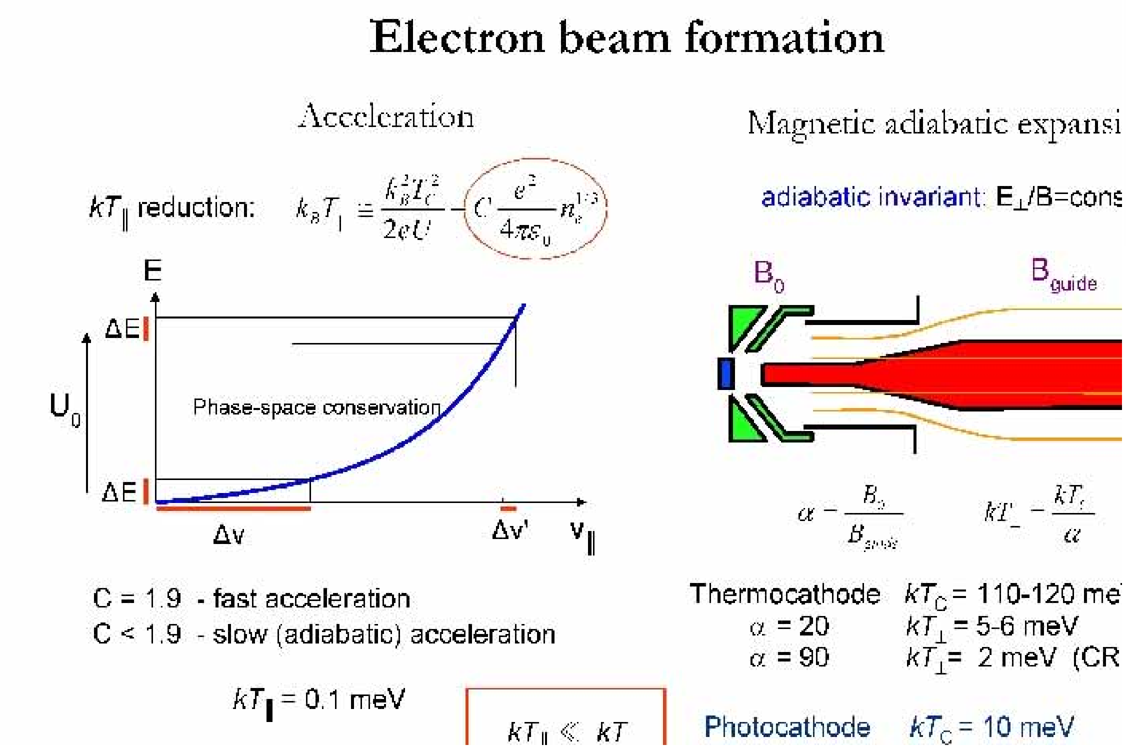
DESIREE will allow measurements as a function of temperature by controlling the cryostat temperature from room temperature and down.



McCall et al., PRA 70, 052716 (2004)

W04: Ultra-cold electron target D.Orlov, MPI-K





laser cooling

F04: cooling techniques for trapped particles Y.Yamazaki RIKEN

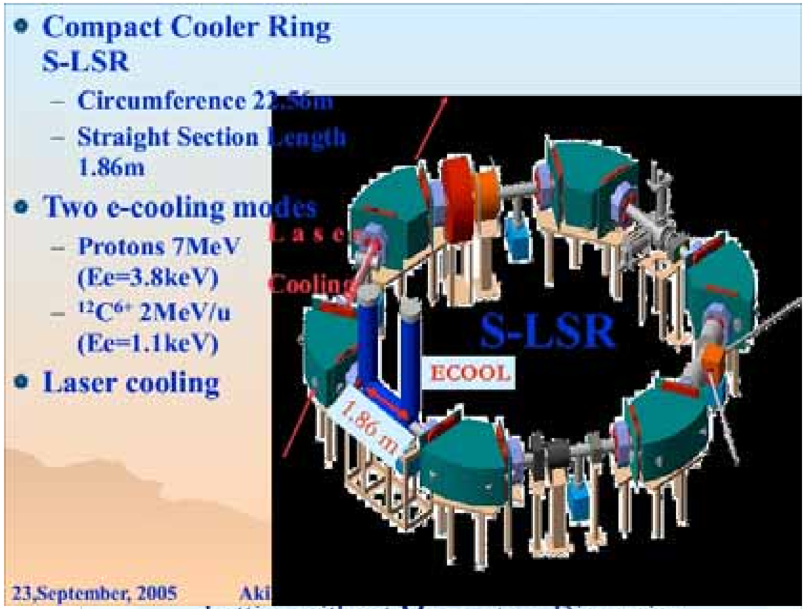
Why? CPT: $\bar{p}\mu^-$ vs $p\mu^+$ $\bar{H}$ vs. H

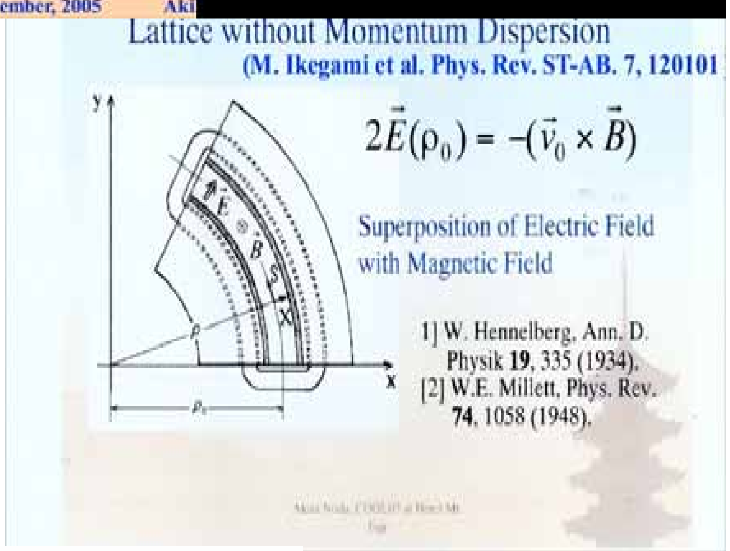
Plank mass $M_{pl} = \sqrt{hc/G} = 10^{19} GeV/c^2$

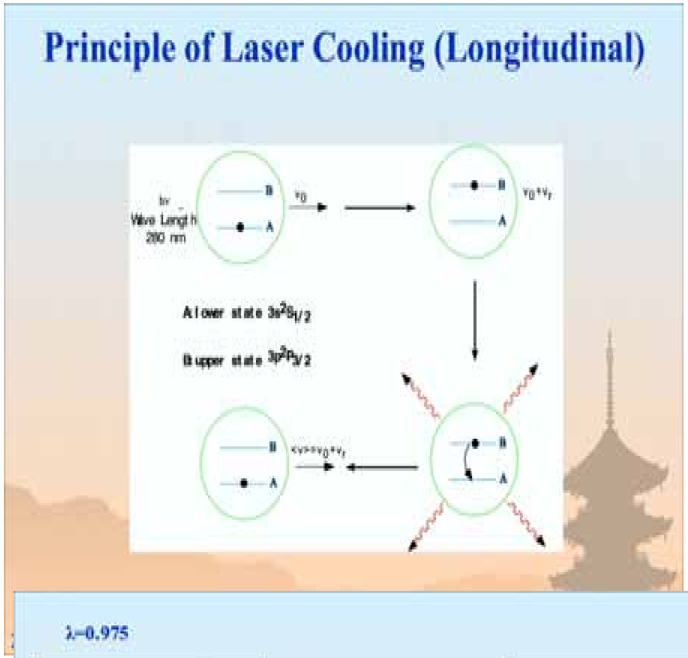
$(m_p/M_{pl})\, m_p$ ~ vibrational level 10 Khz

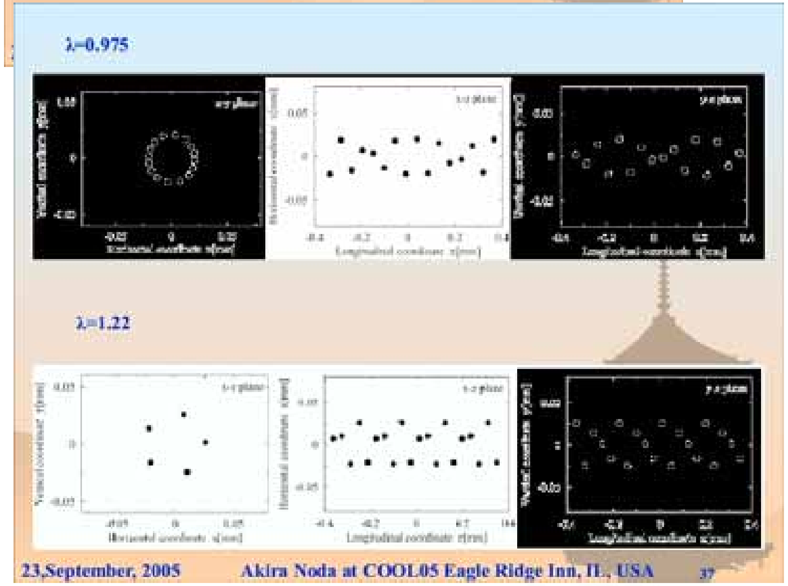
traps

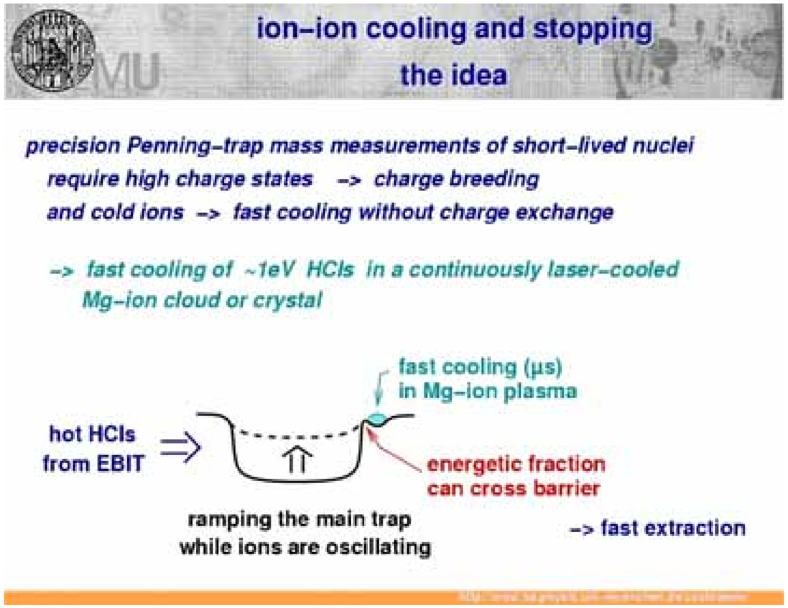
F01: Laer cooling for 3D crystalline state at S-LSR
A.Noda, Kyoto ICR

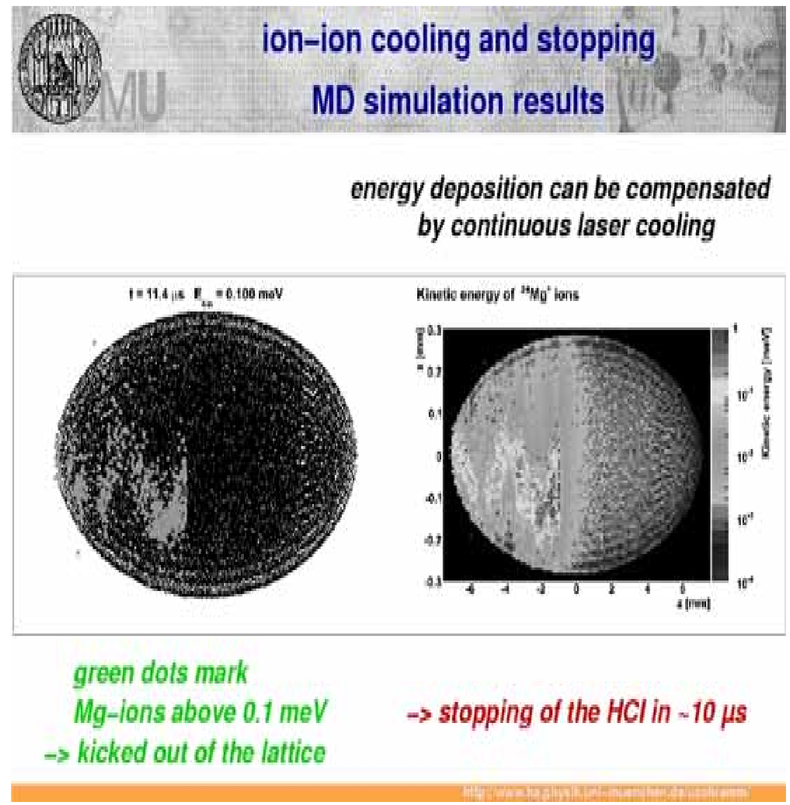




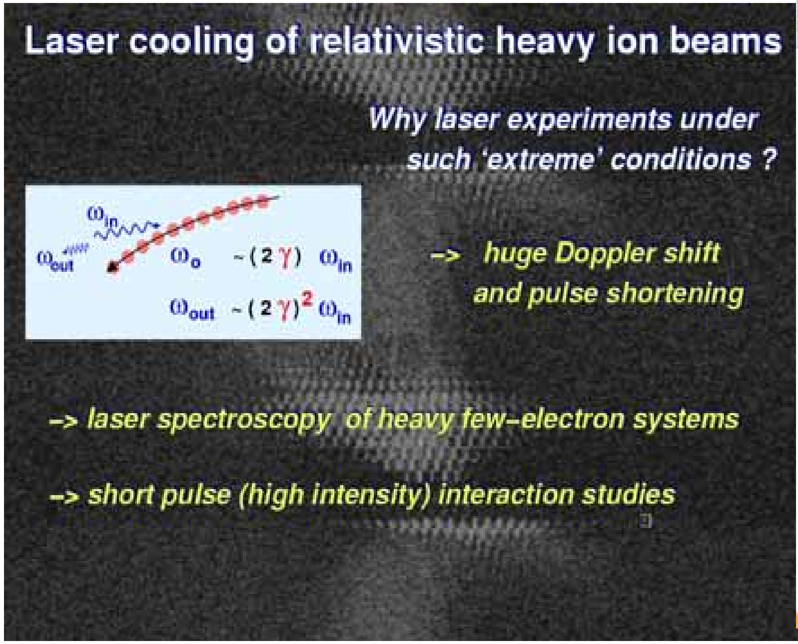


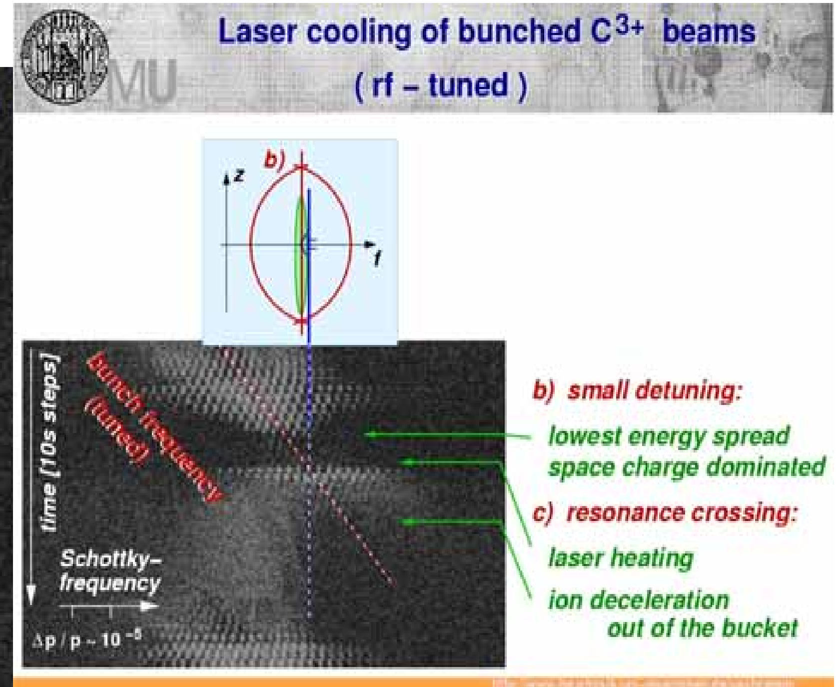


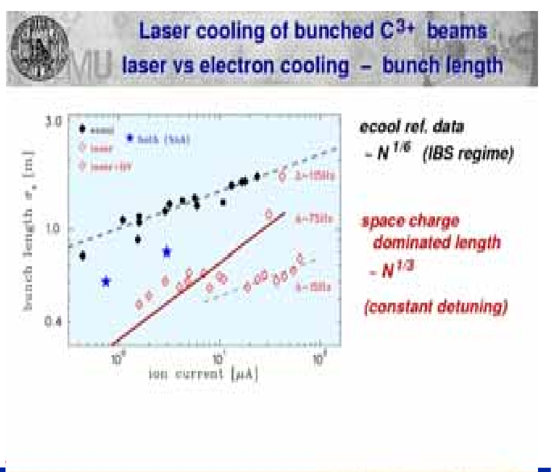

ion–ion cooling and stopping
the idea
precision Penning-trap mass measurements of short-lived nuclei
require high charge states -> charge breeding
and cold ions -> fast cooling without charge exchange
-> fast cooling of ~1eV HCIs in a continuously laser-cooled
Mg-ion cloud or crystal
fast cooling (µs)
in Mg-ion plasma
hot HCIs
from EBIT
energetic fraction
can cross barrier
ramping the main trap
while ions are oscillating
-> fast extraction

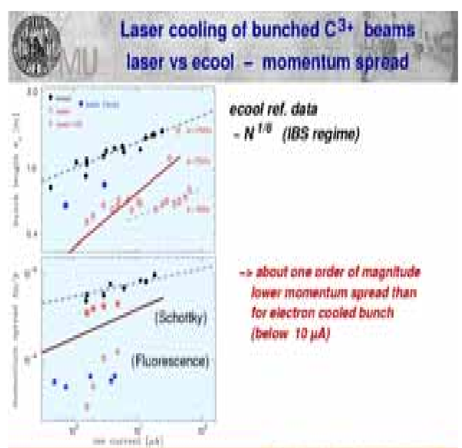

ion–ion cooling and stopping
MD simulation results
energy deposition can be compensated
by continuous laser cooling
Kinetic energy of ²⁴Mg⁺ ions
green dots mark
Mg-ions above 0.1 meV
-> kicked out of the lattice
-> stopping of the HCI in ~10 µs

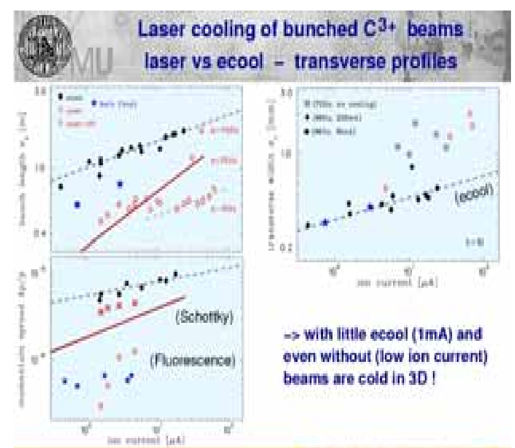
F02: Laser cooling of relativistic heavy ion beams
U.Schramm LMU











phase space manipulations

M14 Transverse Echo Measurements in RHIC W.Fisher, BNL

Motivation

- IBS growth rate measurements usually done by observing the free expansion of bunches
  - Must be on time scale of interest [15min at injection, hrs at store]
  - Need precise emittance measurement [not easy transversely]
- Echo measurements are
  - Much faster (~1000 turns), allow parameter scans
  - Potentially very sensitive
  - Do not rely on precise emittance measurement

Transverse echoes – dipole moment simulation

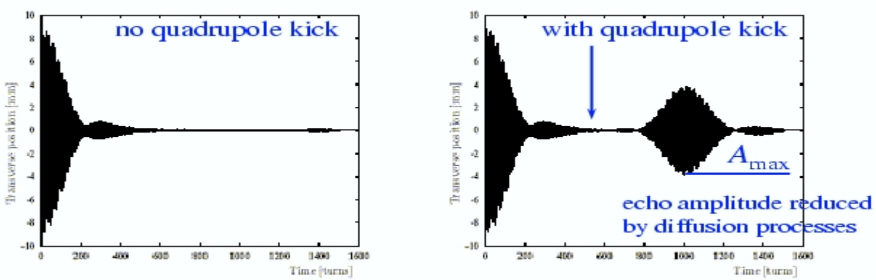
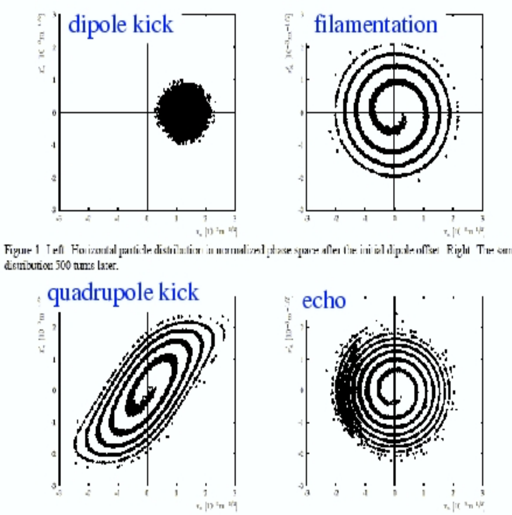


Figure 3: Left: The dipole moment of the distribution versus time after a dipole kick. Right: The same signal with an additional quadrupole kick at 500 turns after the dipole kick.

[W.Fischer, B. Parker, O. Brüning, "Transverse echos in RHIC", proceedings of the US-LHC Collaboration Meeting: Accelerator Physics Experiments for Future Hadron Colliders, BNL (2000).]

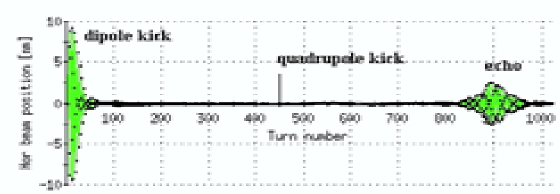
Transverse echoes – phase space simulation



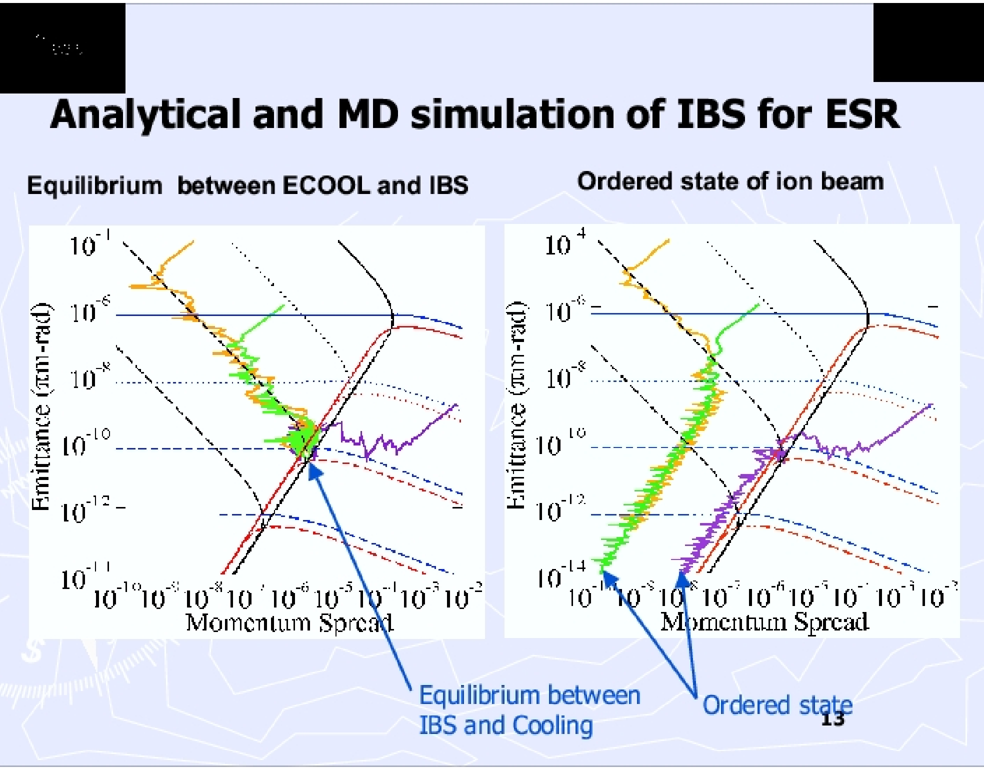
- 1-turn quadrupole kick is difficult
- echo-like signal was also observed with 2 dipole kicks of different strength (F. Ruggiero, SPS)

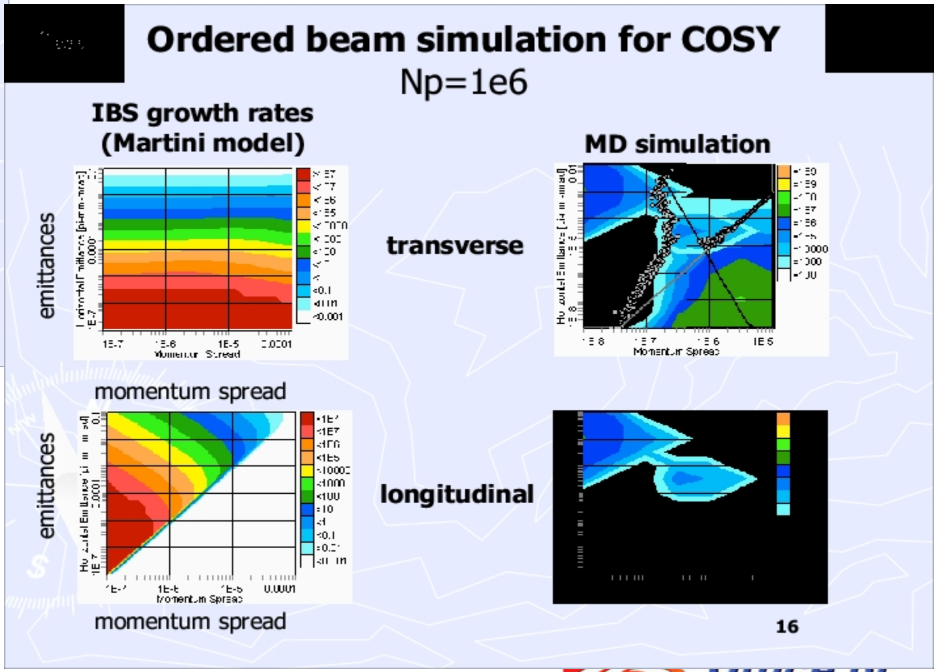
Summary – Transverse Echoes in RHIC

- Transverse echoes observed in RHIC with Au^{79+}, Cu^{29+}, p^{+}
  - Dipole kick with injection under angle
  - Air core quadrupole provides 1-turn kick
- Diffusion with p^{+} stronger than with heavier ions (unexpected)
- Observed intensity dependent echoes with Au^{79+}, Cu^{29+},
  → were fitted to simulation results to extract diffusion rates

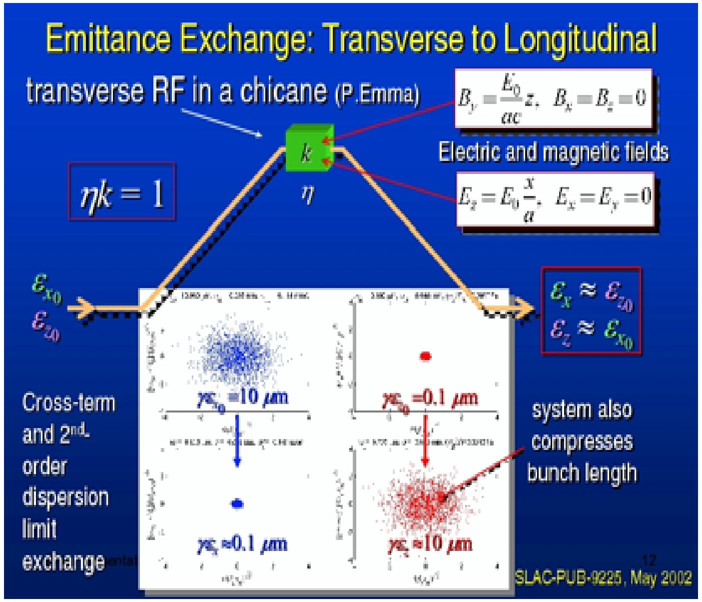


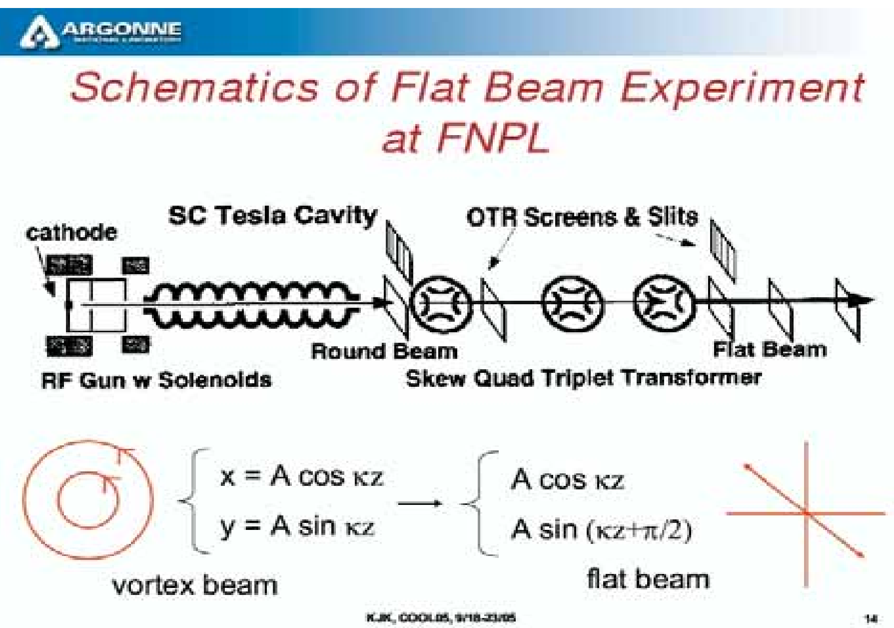
M15 Simulation of Beam Dynamics in Cooler Rings, A.Smirnov - JINR

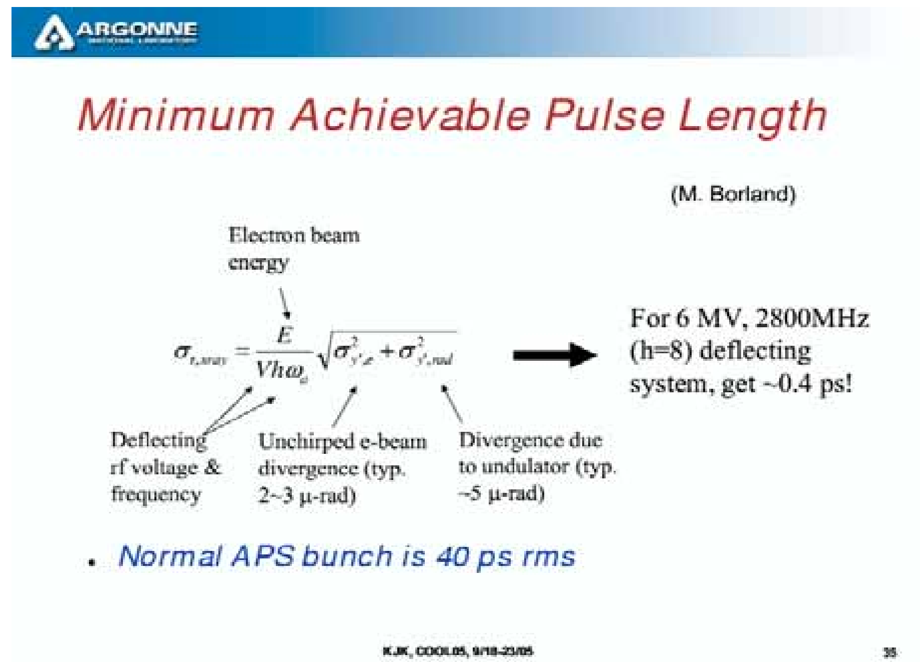




M10 Phase Space Manipulations, K.-J.Kim, ANL







M11 FEL Performance, A.Sessler, LBNL

7. Conclusions for Transverse-Longitudinal Correlations: FEL Performance and Emittance Exchange

- If conditioning can be achieved it would have a very large impact on FEL performance.
  (Li-Hua Yu, Whittum).
- Conditioning without growth of effective emittance is possible in a symplectic system (Vinokorov, Wolski).
- It appears to be difficult (but maybe not impossible) to achieve the amount of conditioning likely to be required by real FELs (Kim, Emma, Wolski et al).
- Non-conventional (laser/wiggler (Zholents), laser backscattering (Schroeder), and laser-plasma (Wurtele and Penn) conditioning holds promise.

- Emittance transfer would benefit x-ray FELs (Kim)
- Emittance transfer from a large emittance to a small emittance is possible (Wei and Okamoto)
- Practical emittance transfer schemes have yet to be developed (but no one has even tried yet).

Laser-Wiggler Conditioner

Proposed by Sasha Zholents

Use a laser/wiggler rather than an rf cavity

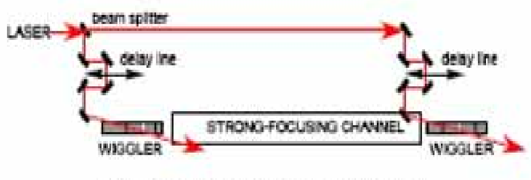
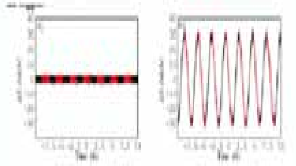


Figure 2. A schematic of the laser assisted conditioner.

Laser-Wiggler Conditioner (Cont)

- Some electrons gain energy and some lose energy. Only about 1/2 are conditioned.



Plasma Channel Conditioner

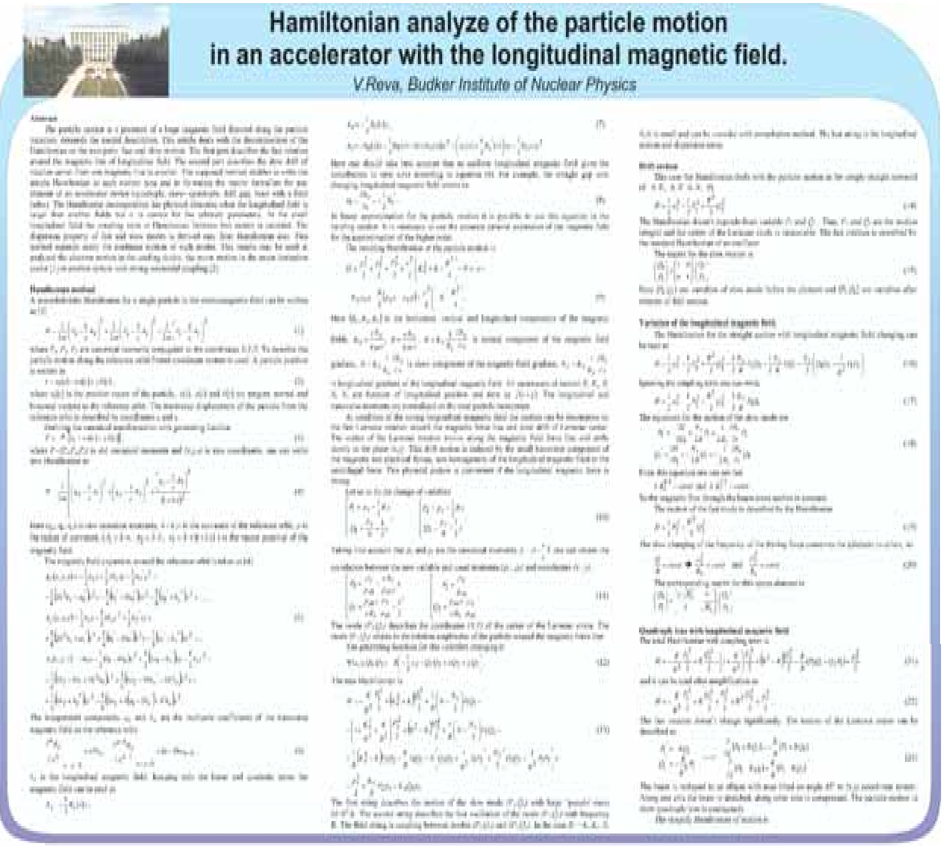
Work by Jonathan Wurtele, Gregg Penn, and myself.
Send a laser through a gas in a tube. Blow out all the electrons and make an ion channel. Send the high energy beam just behind the laser before the slow electrons return.

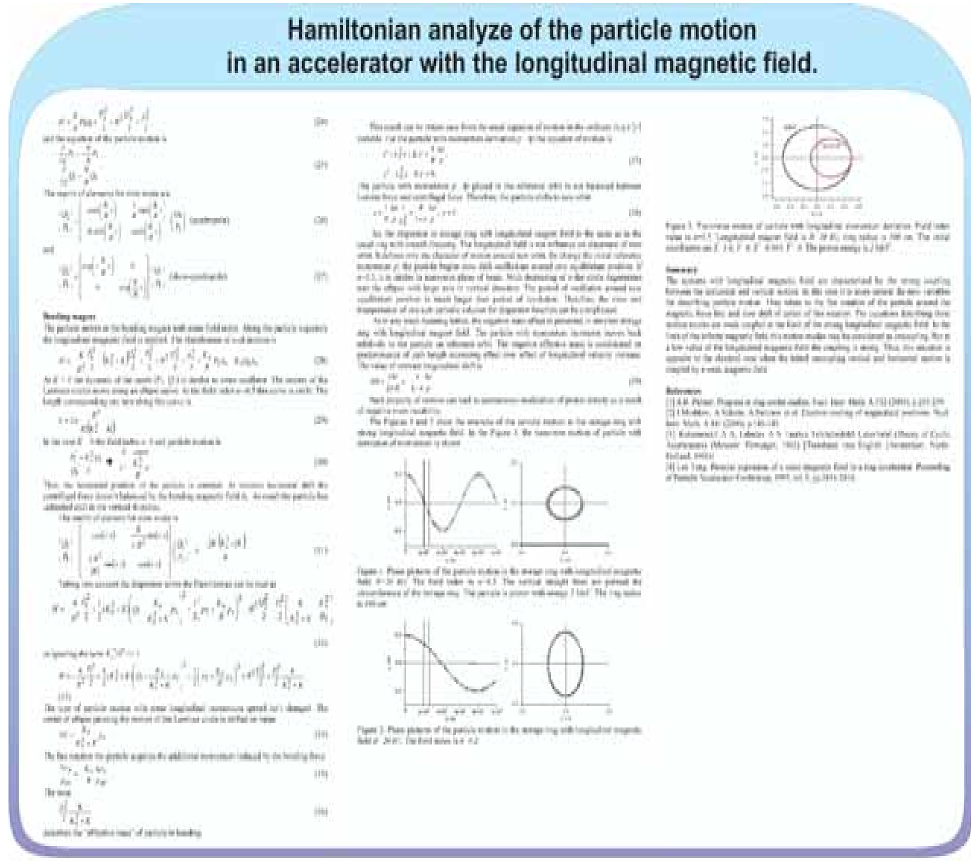
In the plasma channel $\beta = (2\gamma)^{1/2}c/\omega_p$
where $\omega_p = 6 \times 10^{12}(n\ (cm^{-3})/10^{16})^{1/2}$ and $\lambda_p = 2\pi c/\omega_p$

For example at $n = 10^{17}\ cm^{-3}$ and 1 GeV, $\omega_p = 2 \times 10^{13}\ s^{-1}$,
$1/\omega_p = 50$ fs, $\lambda_p = 100\mu m$, and $\beta = 0.1$ cm

Simulations, to follow, by Gregg Penn. Two cases (similar to Zholents and Emma and Stupakov [a FOFO channel at 100 MeV[)
Clearly at 100 MeV only condition a small time slice.

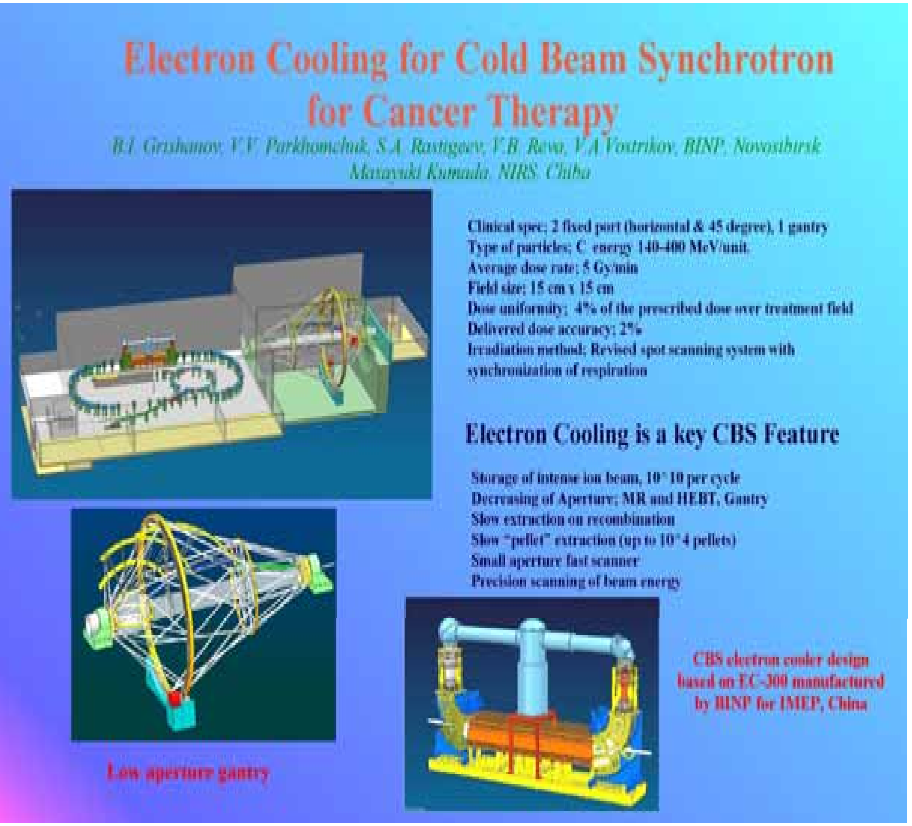
P20: Hamiltonian analysis in Longitudinal Magnetic Field
V.Reva BINP

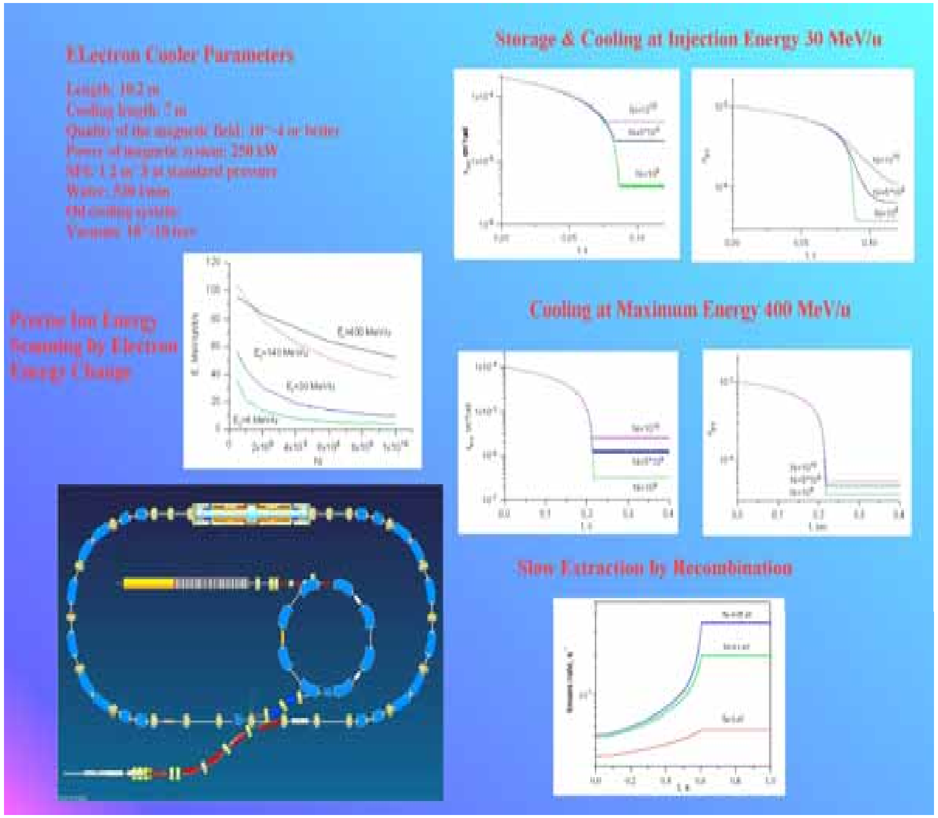




rings

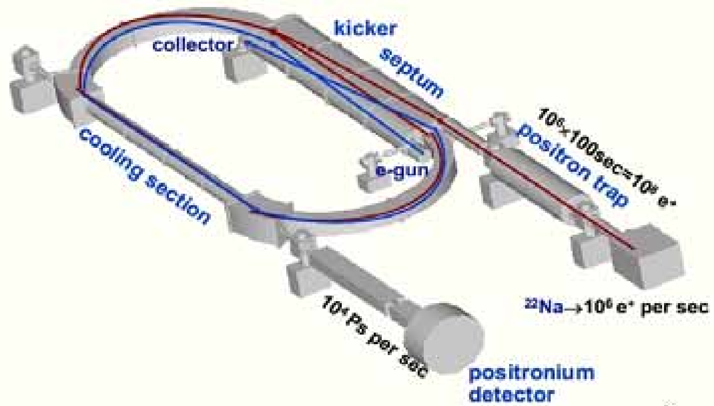
P09: electron cooling for cold beam synchrotron for cancer therapy V.Vostrikov BINP





F03: status of LEPTA I.Seleznev JINR

Design of the LEPTA



3

Helical quadrupole

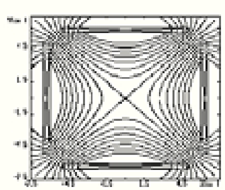
"stellarator windings"

Quadrupole Length L = 160 *cm*

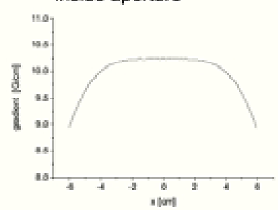
Helix step h = 80 *cm*

$$G = \frac{2\pi NI}{c \cdot d^2}$$

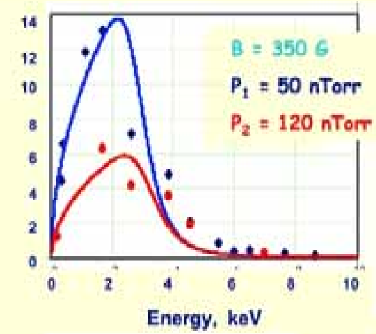
Cross section of the quadrupole is similar to Panofsky lens



Uniform gradient magnetic field inside aperture



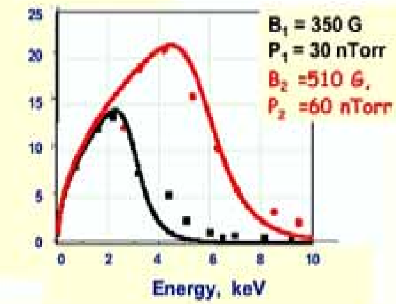
8



Experimental results and theoretical fitting

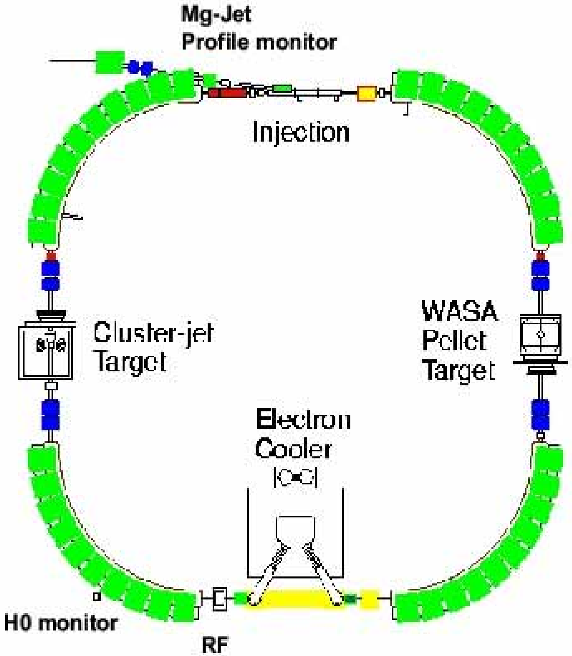
Lifetime vs Energy

ΔB/B~20%



R04 Lognitudinal cooling force measurements B.Galander TSL

The CELSIUS Ring

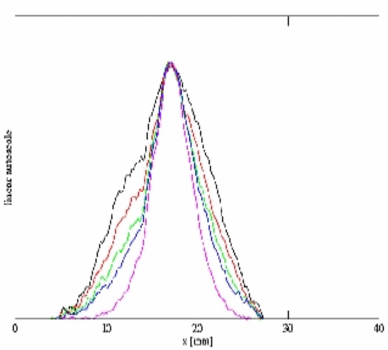


- Last CELSIUS run in June 2005
  Now dismantled
- WASA to COSY, Jülich

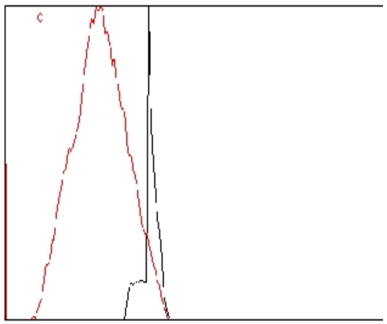
Circumference	81.8 m
Length of cooling and injection straight sections	9.6 m
Length of target straight sections	9.3 m
Bending radius	7.0 m
Maximum rigidity	7.0 Tm
Maximum kinetic energy (protons)	1.36 GeV
Maximum kinetic energy per nucleon for ions with *Q/A* = 1/2	470 MeV

Transient cooling measurements

Transverse Mg-Jet profiles



0.3 s between profiles (total 1.5 s)

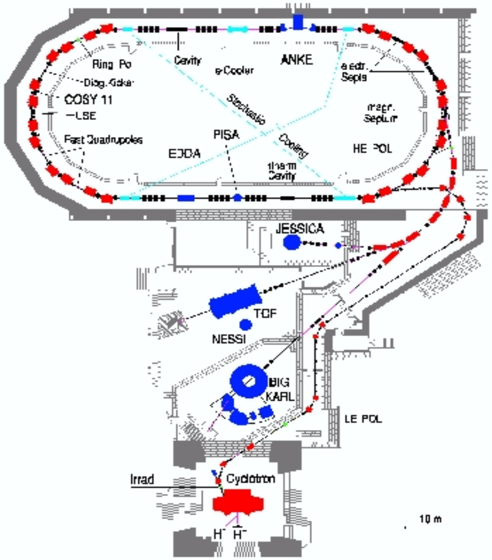


Time between frames 0.3 s. Total ~60 s

Cooling of core vs . tails
Electron current 10 mA and proton current 0.3 mA, Np = $1.7\cdot10^{9}$.
Can be used in comparisons of calculations with IBS models.

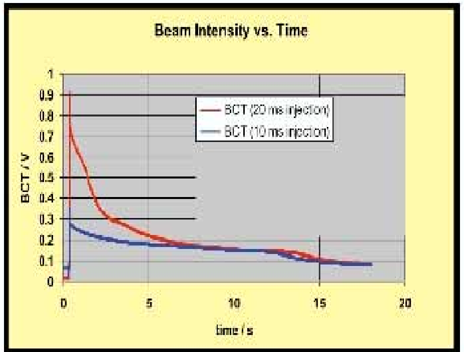
M09 Cooling Experiments at COSY D.Prasuhn, FZJ/IKP

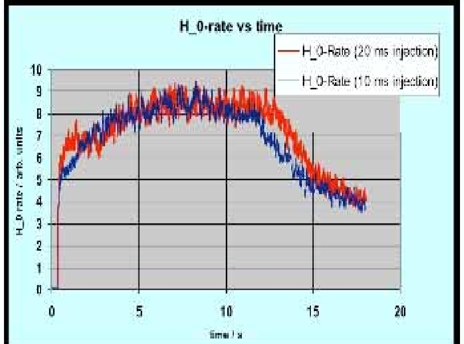
The Accelerator Facility



- COSY accelerates (polarized) protons and deuterons between 300 and 3700 MeV/c
- 4 internal and 3 external experimental areas
- Electron cooling at low energy
- Stochastic cooling at high energies

Observation of initial losses



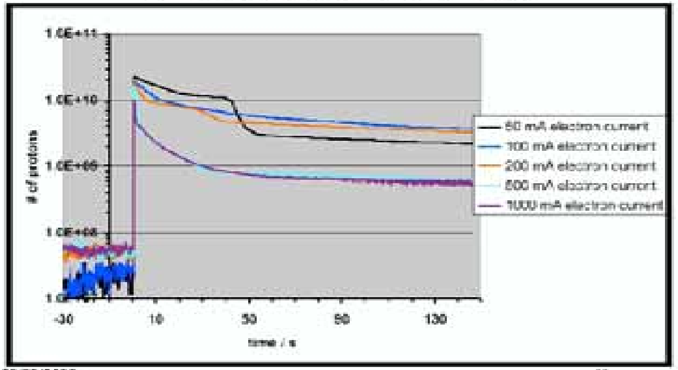


Initial losses disappear at smaller injected proton beam emittance

⇒ Protons outside the electron beam see a non-linear focussing by the electron beam

8

Proton intensity as function of time and electron current



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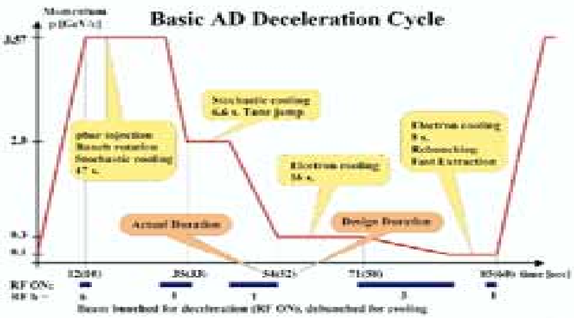
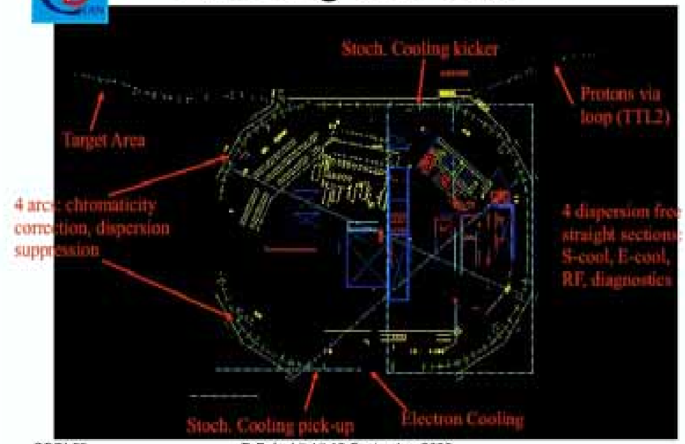
M08 Antiproton Decelerator

P.Belochitskii, CERN



COOL05 P. Belochitskii 19 September 2005

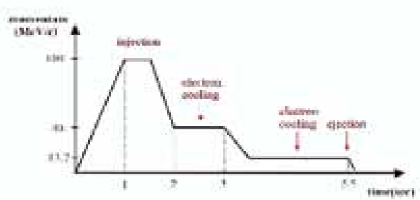
AD Ring and Hall



COOL05 P. Belochitskii 19 September 2005

Schematic view of ELENA cycle

- No electron cooling is performed at injection energy: beam is cooled already in AD. After injection beam is decelerated immediately.
- One intermediate cooling (at 40 MeV/c probably) is needed to avoid beam losses



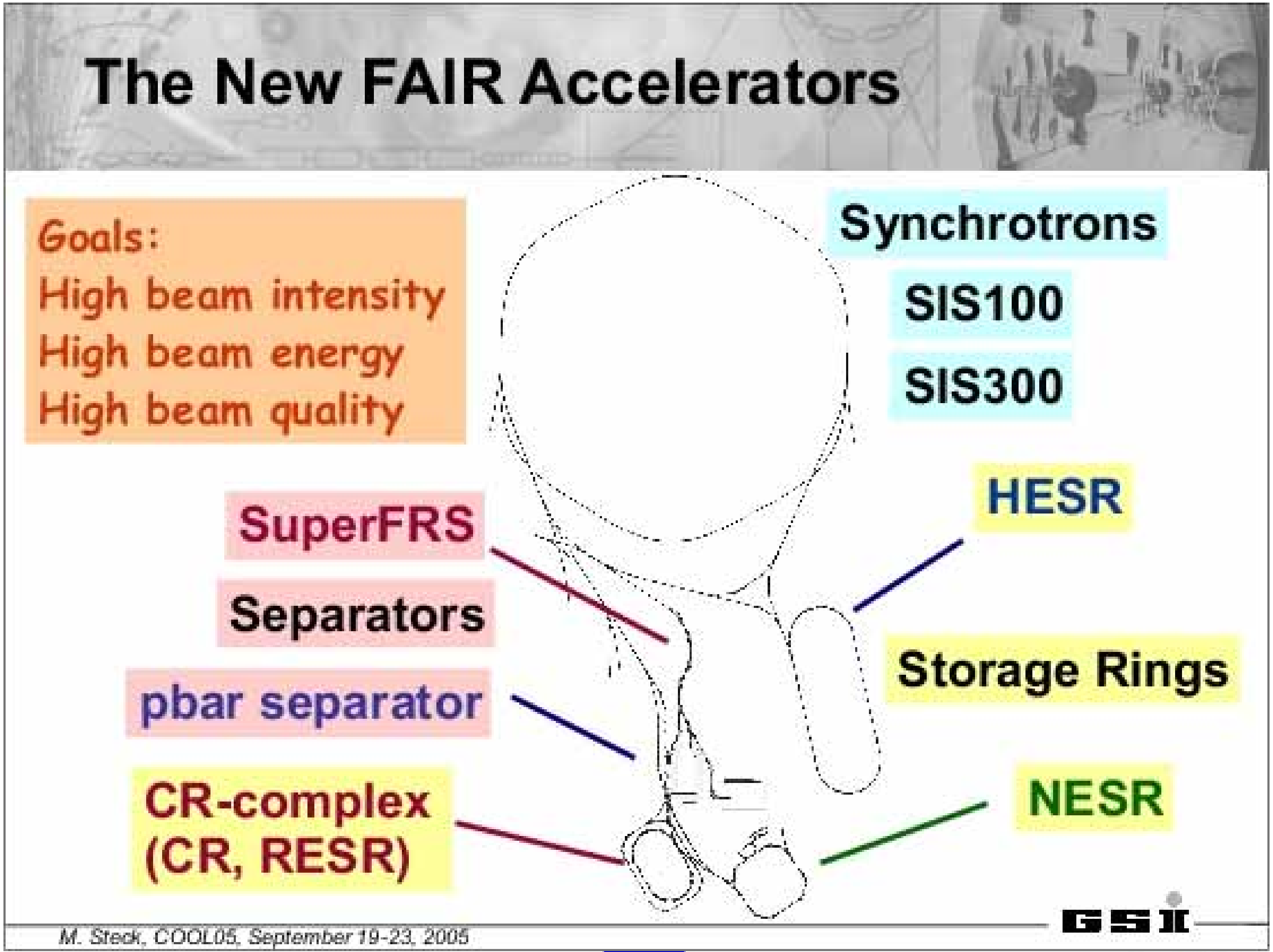
COOL05 P. Belochitskii 19 September 2005

Requirements to ELENA:

- Compact machine located inside of AD Hall with minimum of reshuffle.
- Energy range from 5.3 MeV (AD extraction energy) down to 100 keV.
- Equipped with electron cooler to make beam phase space smaller in about two orders of magnitude with respect what we have today
- Machine assembling and commissioning has to be done without disturbing current AD operation.

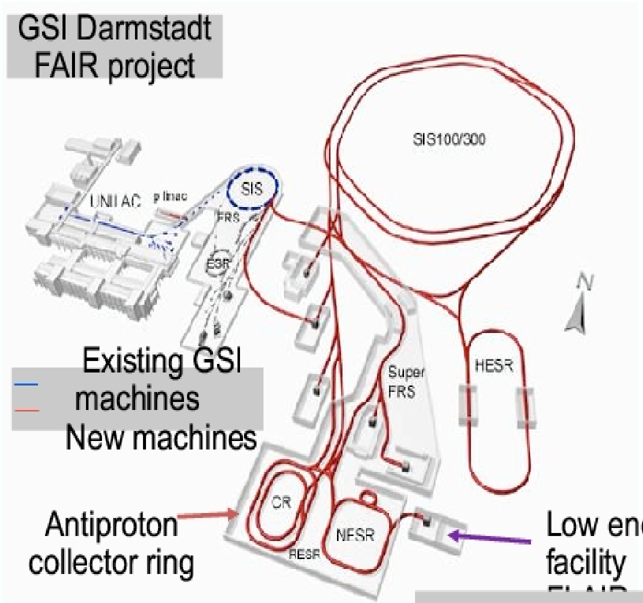
COOL05 P. Belochitskii 19 September 2005

M06 FAIR project
M.Steck, GSI



W03: Heidelberg CSR, A.Wolf MPI-K

Stored antiproton beams at keV energies

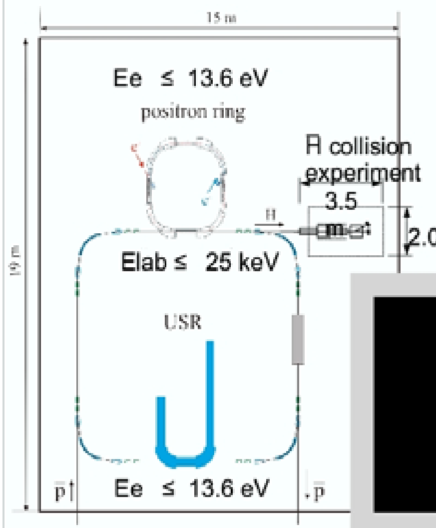


Low energy antiproton facility

> 2010

30 MeV ... 300 keV: LSR (magnetic)
300 keV ... 20 keV: USR (electrostatic)

Antihydrogen collision experiment



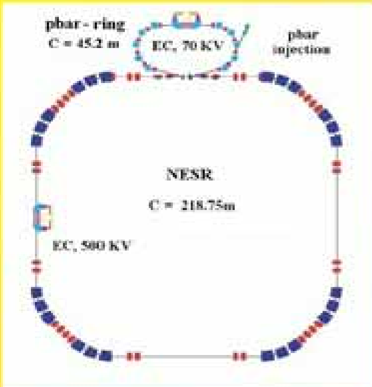
$H + \bar{H} \rightarrow e+ + e- + p + \bar{p}$
$\rightarrow Ps + \bar{p} + p$

Antihydrogen collisions
σ ~ 10-16 cm2 (from H+H
dnt = 1014 cm-2
→ Event rate
~ 1/s for 200 collisions)

Antiproton - Ion Collider for FAIR Project

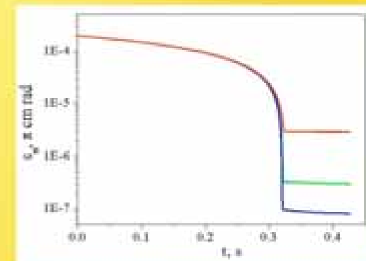
P.Beller[1], B.Franzke[1], P.Kienle[2,4], R.Kruecken[2], I.Koop[3], V.Parkhomchuk[3], Y.Shatunov[3], A.Skrinsky[3], V.Vostrikov[3], E.Widmann[4]

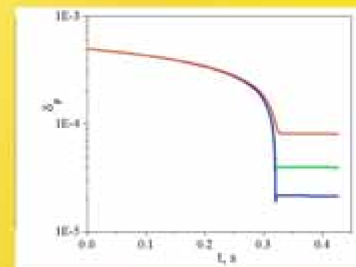
[1] GSI, Darmstadt, Germany; [2] TUM, Munich, Germany; [3] BINP, Novosibirsk, Russia; [4] SMI, Vienna, Austria.



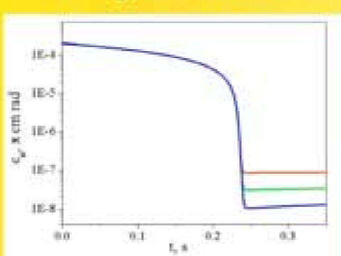
An antiproton-ion collider (AIC) is proposed to independently determine rms radii for protons and neutrons instable and short lived nuclei by means of antiproton absorption at medium energies. The experiment makes use of the electron ion collider complex with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740A MeV ions in the NESR. Antiprotons are collected, cooled and slowed to 30 MeV. Hereafter the antiprotons are transferred to the electron storage ring using a new transfer line. Radioactive nuclei are produced by projectile fragmentation and projectile fission of 1.5A GeV primary beams and separated in the Super FRS. The separated beams are transferred to the collector ring (CR) and cooled at 740A MeV and transported via the RESR to NESR, in which especially short lived nuclei are accumulated continuously to increase the luminosity.

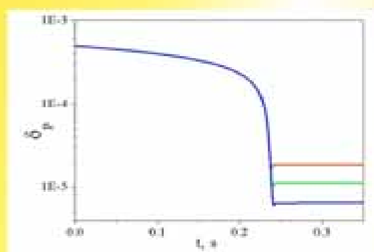
Pbar cooling in AIC, N = 10^{10}, 10^{9}, 10^{8} from top to bottom, E = 30 MeV





$^{132}Sn^{50}$ ion beam cooling in NESR, N = 10^{7}, 10^{6}, 10^{5}
Energy is 740 MeV/u





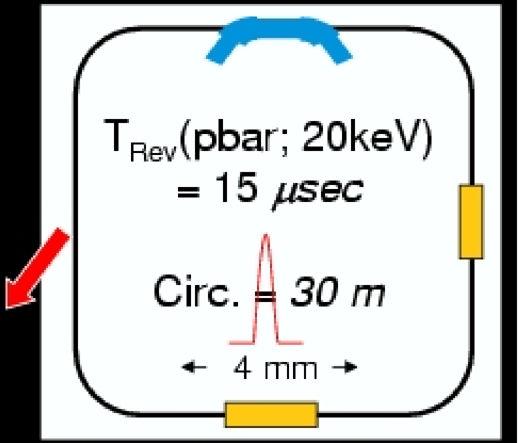
Main parameters of EC for AIC

Maximum electron energy	70 KeV
Maximum electron current	2 A
Electron beam diameter	5 - 20 mm
Magnet field in cooling section	0.2 T
Length of cooling section	3.5 m

Design Luminosity L = 10^{23} s^{-1} cm^{-2}

USR - Main Goals

- Variable down to very low energies
  - 300 keV ~ 20 keV
- High luminosity for in-ring experiments
- Well defined extracted beams:
  - small emittance
  - small momentum spread
- Multi-User operation:
  - 2 straight lines for in-ring experiments
  - 1 extraction port
  - additional beam lines possible
- Central requirements
  - Δt ~ 500 nsec for injection into trap
  - Δt ~ 2 nsec / 10^4 ions for collision experiments



Carsten P. Welsch   Cool05, Galena, IL, USA   18.-23.9.2005

T04 Cooling at HESR, H.Stockhorst - FZJ/IKP

Cooling Scenario for the HESR

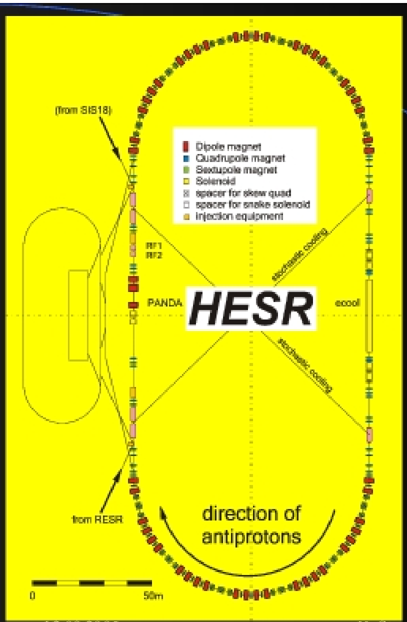
H. Stockhorst
Forschungszentrum Jülich GmbH

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

- HESR Layout
- Electron Cooling at Momenta p 8.9 GeV/c for the High Resolution Mode
- Small Angle and Energy Scattering
- Stochastic Cooling with Internal Target for p 3.9 GeV/c in the High Luminosity Mode

12.09.2005 H. Stockhorst

HESR Layout



Basic Parameters:

- Circumference: 574 m
- Arc Length: 155 m
- Straight Section: 132 m
- Ions:
  - anti-protons
  - protons
- Momentum Range: 1.5 GeV/c - 15 GeV/c
- anti-proton injection at 3.9 GeV/c from RESR

12.09.2005

Longitudinal Stochastic Cooling Performance for Different Momenta in the HL mode

Transverse and Longitudinal Cooling

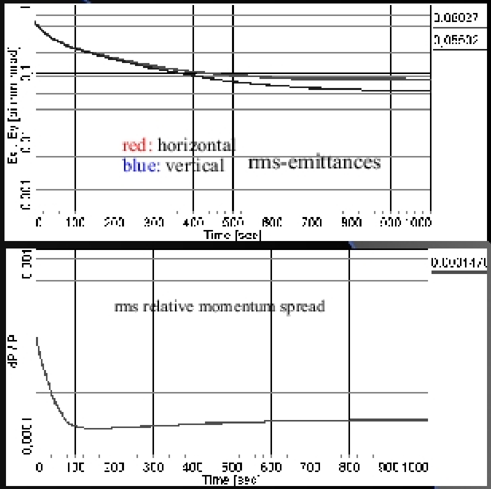
Including IBS+Target

p = 3.9 GeV/c

$L = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

$N = 10^{11}$

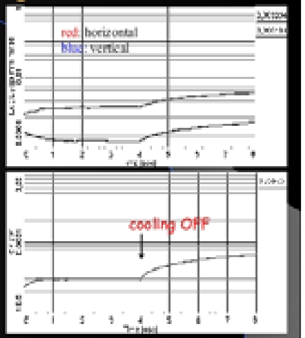
$N_T = 4 \cdot 10^{15}$ atoms/cm^2



12.09.2005 H. Stockhorst 18

Electron Cooling at 8 GeV

Number of antiprotons:	10^{11}	
Initial rms emittance (H):	0.000861	mm mrad
Initial rms emittance (V):	0.000238	mm mrad
Initial rms relative momentum spread:	2.28 *10[illegible]	
Rms-beam radius at cooler (H):	0.1	mm
Rms-beam radius at cooler (V):	0.2	mm
Revolution frequency:	519.46	kHz
Kinematic beta:	0.994	
Kinematic gamma:	9.526	
Frequency slip factor:	0.035	
Luminosity:	$2 \cdot 10^{32}$	$cm^{-2} s^{-1}$



- Electron cooling and target ON
- Equilibrium dominated by IBS
- rms-momentum spread with target and IBS : 3.0×10^{-5}

12.09.2005 H. Stockhorst 8

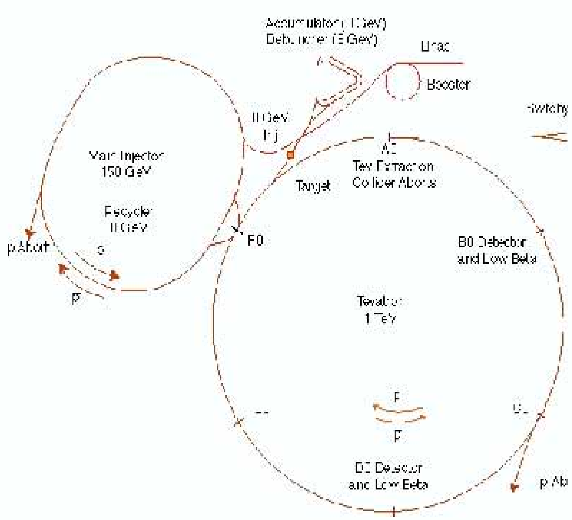
M07 antiproton cooling at FNAL

S.Nagaitsev, FNAL

Fermilab Accelerator Division

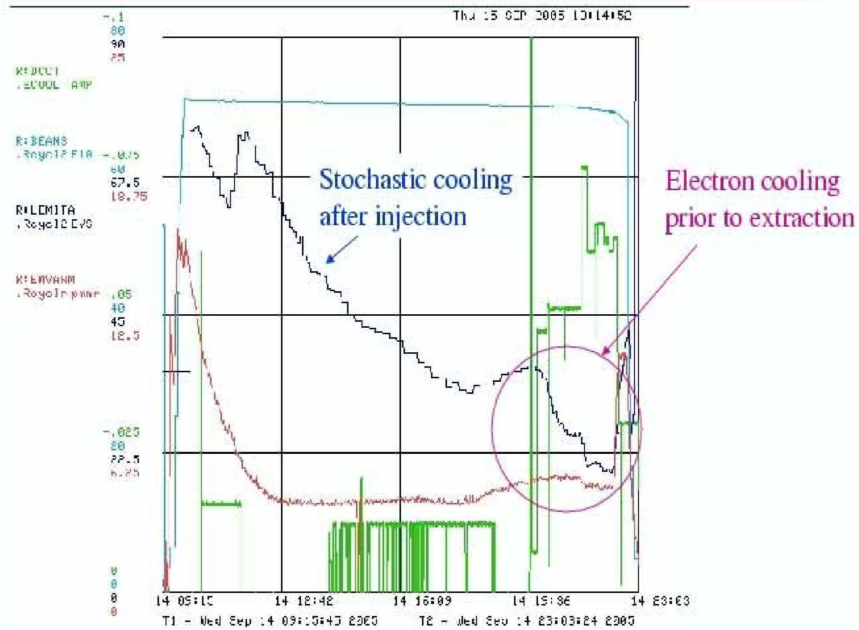
Antiproton Production

- 1×10^8 8-GeV pbars are collected every 2-4 seconds by striking 7×10^{12} 120-GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and cooled in the Debuncher, Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON

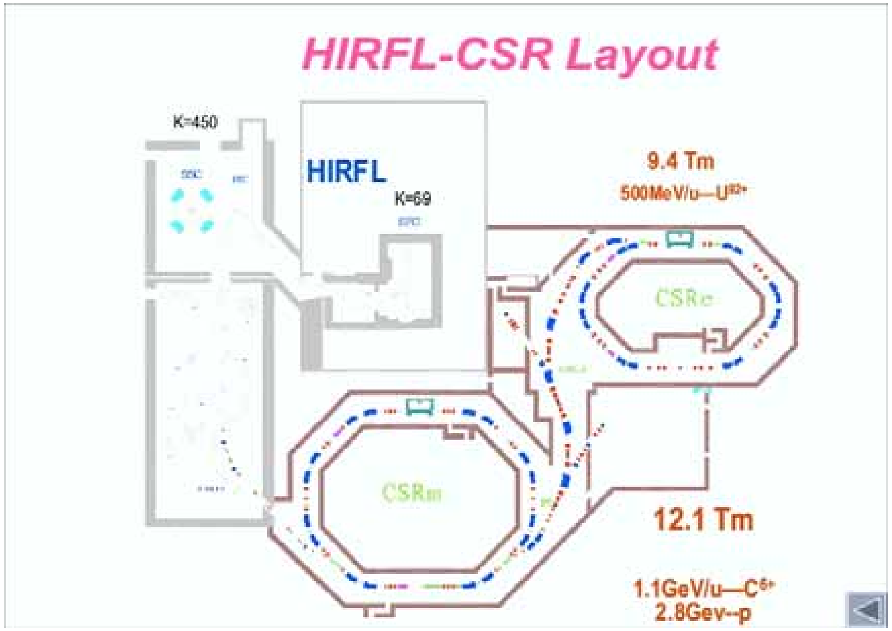


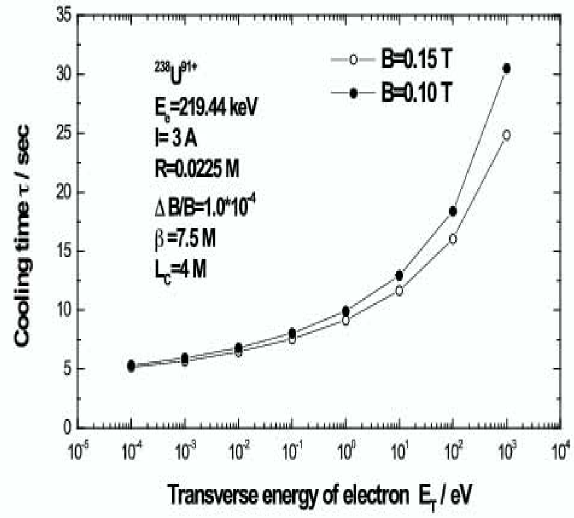
Fermilab Accelerator Division

Electron cooling in operation



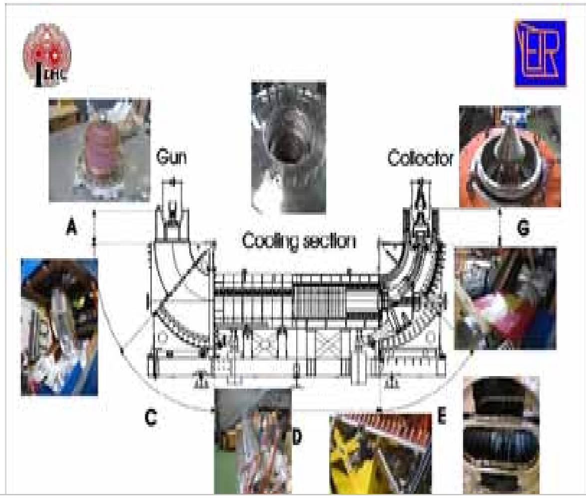
R03 HIRFL-CSR X.Yang IMP





Cooling time as a function of transverse energy of electron

R02 LEIR cooler status G.Tranquille CERN

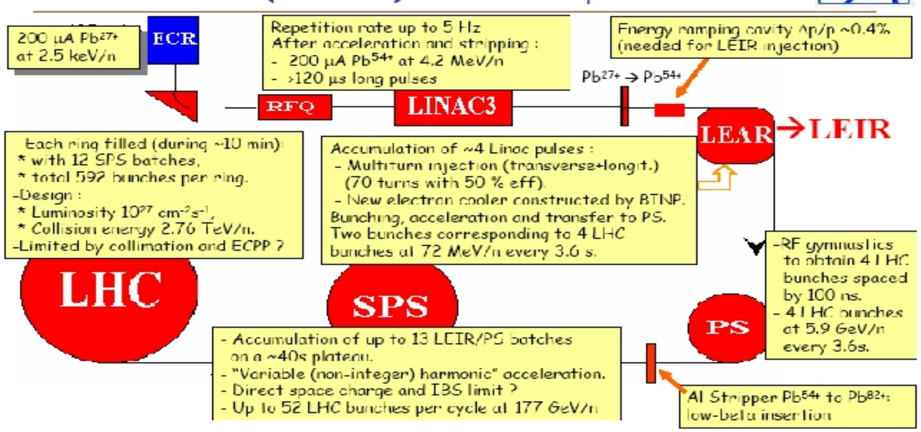


The Ions for LHC project

- LHC needs L = 10^{27} $cm^{-2}s$-1 at 2.7 TeV/n
- 592 bunches, 7.10^{7} ions/bunch, ε=1.5 μm, β*=0.5m
- Implies 9 10^{8} ions with ε=0.7 μm every 3.6s in LEIR
- First run, early scheme, L=5 10^{25} $cm^{-2}s^{-1}$ (60 bunches, 7 10^{7} ions/bunch, β*=1) => 2.25 10^{8} ions in LEIR.

COOL05, Galena, IL USA
18th-23rd September 2005

Overview of the Accelerator Chain for (nominal) LHC Ion Operation



Low Energy Ion Ring LEIR   2/10

COOL05, Galena, IL USA
18th-23rd September 2005

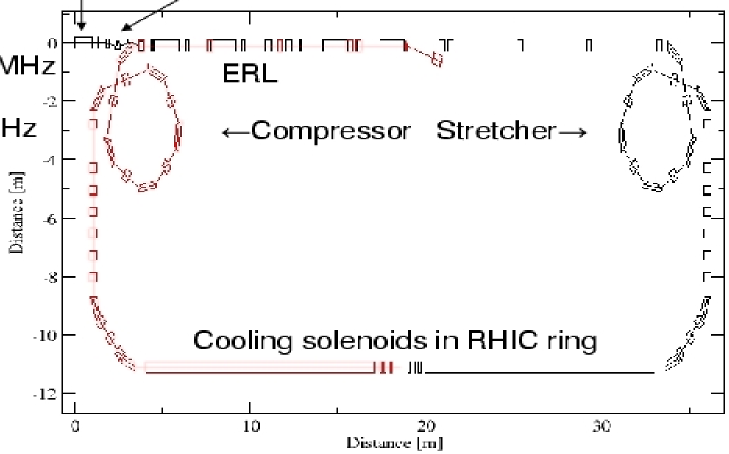
R07: high-current ERL-based electron cooling for RHIC   Ben-Zvi BNL

Lattice for magnetized beam

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

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

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



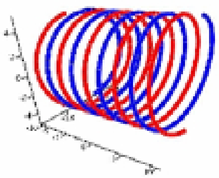
The use of a helical undulator

- Large coherent velocity can be achieved to reduce recombination.
- Small circle radius can be made with low field
- Undulator provides focusing of the electron beam

$$\theta = \frac{K}{\gamma} \approx \frac{93.4B\lambda}{\gamma}$$

$$r_0 = \frac{\theta\lambda}{2\pi} \qquad L = \ln\frac{\rho_{max}}{r_0}$$

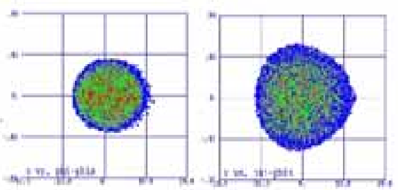
Take λ=5cm, B=20 Gauss, R=5 cm, I=72 Amp
Then r_0=0.7 μm, β_w=180 m



25 hours recombination Lifetime: More than enough

Non-magnetized beam

- The combined use of ellipsoid bunch, high electric field and no magnetization results a good emittance



Laser profile on cathode and bunch out of cathode

Charge/bunch (nC)	Maximum radius (mm)	rms radius (mm)
2.5	4	1.77
3.2	4	1.77
5	6	2.65

Bunch length: 16degrees (63ps) from head to tail.
Lunch phase: about 35deg.
Maximum field on axis: 30MV/m
Energy out of gun 4.7 MeV

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