Thomas Jefferson National Accelerator Facility

Beam Cooling for High Luminosity Colliders

Yaroslav Derbenev

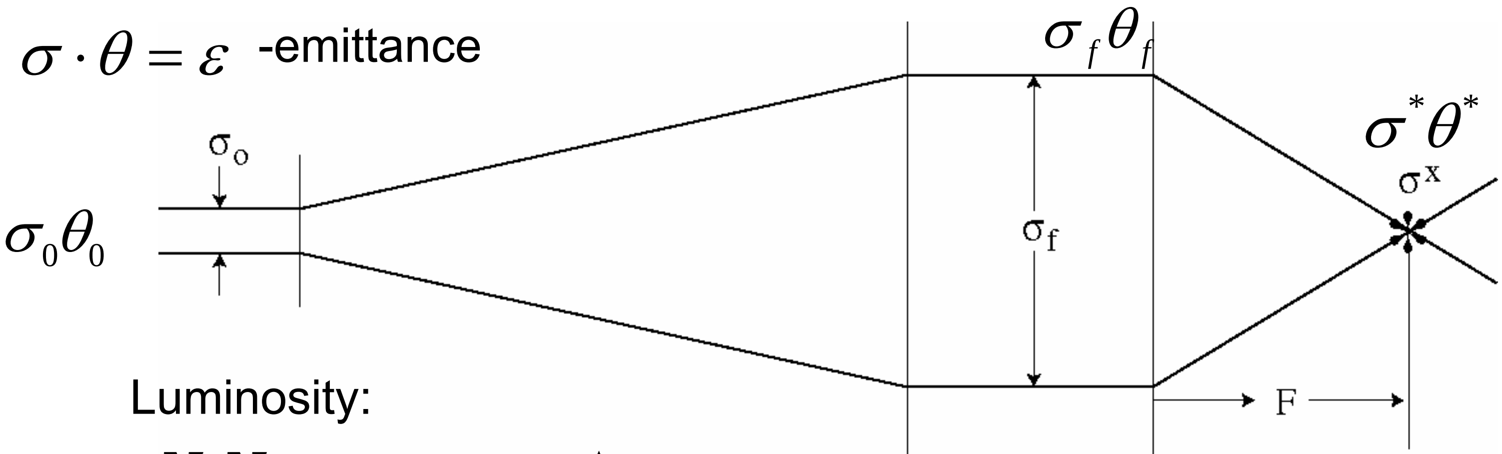
Center for Advanced Studies of Accelerators

Colloquium talk at CEBAF Center

November 14, 2007

A collider as a microscope

$\sigma \cdot \theta = \varepsilon$ -emittance



Luminosity:

$$L = \frac{N_1 N_2}{4\pi\sigma^{*2}} f = e^{-3} JE \frac{\Delta\nu}{\beta^*}$$

$$\sigma^* = F\theta_f = F\frac{\varepsilon}{\sigma_f}$$

A requirement to bunch length: $\sigma_z < \dfrac{\sigma^*}{\theta^*} \equiv \beta^* = F^2 \dfrac{\varepsilon}{\sigma_f^2}$

Small transverse and longitudinal beam emittance allows one to design and use a strong final focus:

β* about 5mm or even shorter can be designed

- **Chromaticity** $\Delta F = F\Delta p / p$ **can be an obstacle, but it can be compensated (it seems we know exactly how to do so!)**

The (6D) emittance is not a subject to change by optics, but by cooling!

What is Beam Cooling?

- **You need a media with which your beam should interact *incoherently***
- **An individual charged particle creates an effective charge polarization of the media (image charge)**
- **In response, particle motion is effected by the image field, decelerating the particle in result relatively the beam frame- this is cooling!**
- **Influence of image fields from neighbors can only decrease the cooling effect (shield effect)**
- **The right receiver-kicker phasing is needed, generally**

What cooling does for colliders

- Decrease of emittances, generally
- Preventing the beam blow-up by IBS and other slow instabilities
- Small transverse emittances allow one to design a low beta-star
- Short bunches allow one to:

  - use the designed low beta-star

  - implement the crab-crossing beams – hence, increase the bunch collision rate
- Low beta-star diminishes the impact of background scattering on luminosity

Cooling techniques and ideas

- **Radiation cooling** — ***Maxwell-Lorentz demon***
  1950th — **used**
- **Ionization cooling** — ***Shrinking before plague***
  1966/1981 — **under development !**
- **Electron cooling** — ***Thermostat of the relativistic engineer***
  1966 — **-used at low and medium energies**
  -under development for colliders
- **Stochastic cooling** — ***van der Meer's demon***
  1968 — **used**
- **Coherent electron cooling** — ***Spoiled hybrid***
  1980 — development just started!
- **Optical stochastic cooling** — ***Max's demon***
  1991

Radiation cooling:

“ ***Maxwell-Lorentz demon in quantum thermostat”***

-Works in storage rings (B-factories)

-Sokolov-Ternov self-polarzation (spin light)

Radiation presents problems at very high energies…

Optical stochastic cooling idea

Max's demon (by Max Zolotorev, 1992 ?)

----Proton radiates light in undulator ("receiver")

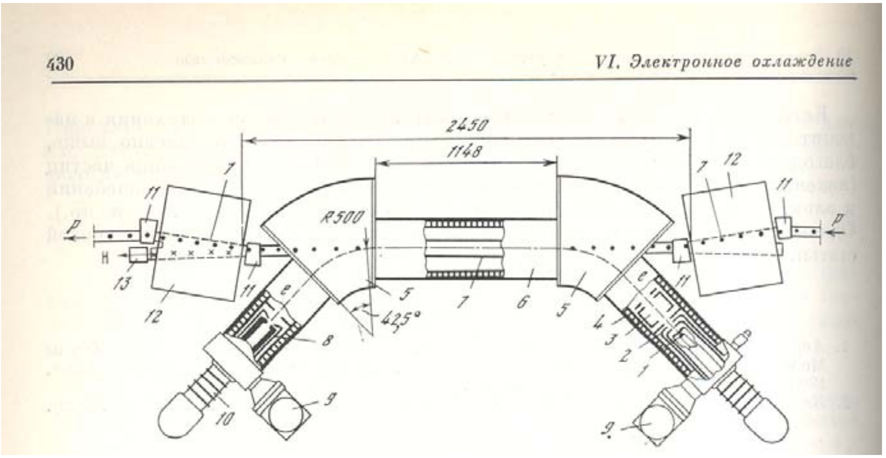
----optical amplifier----

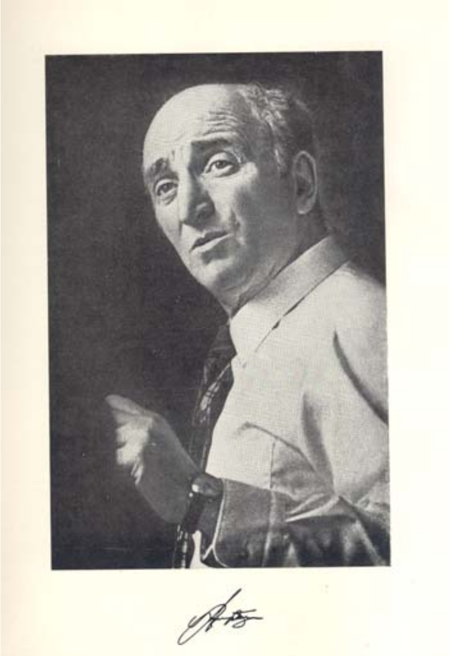
---"proton interacts with the amplified light in
the end undulator "kicker")

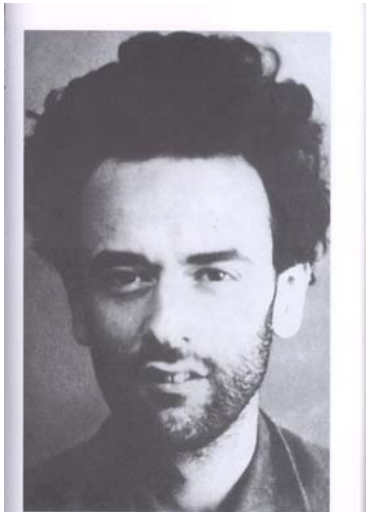
Electron Cooling:

The thermostat of a relativistic engineer

Лев Ландау, 40-ые годы.







Фотография сделана во внутренней тюрьме НКВД СССР на Лубянке, 1938 год.

Do not renounce from prison and money bag

Landau liked to call me "The relativistic engineer", I am very proud of that.

Gersh Budker

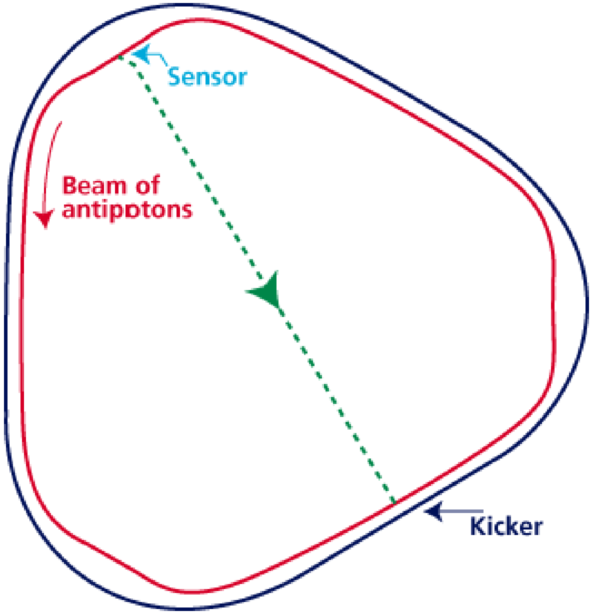
Kinetic equation (plasma relaxation) was derived by Landau in 1937. But… can it work for beams? It does! Yet very interesting and important phenomena have been discovered (magnetized cooling, super-deep cooling, christaline beams…)

Stochastic cooling:

The van der Meer's demon

"Is n't it the Maxwell"s demon?"

(G.Budker)



$$(\tau_c)_{\min} \geq \frac{N_{\Delta\varphi}\Delta\varphi}{2\pi\Delta f_0} = \frac{(J_{peak}/e)}{(\Delta\omega)^2}\frac{f_0}{\Delta f_0}$$

It works!!

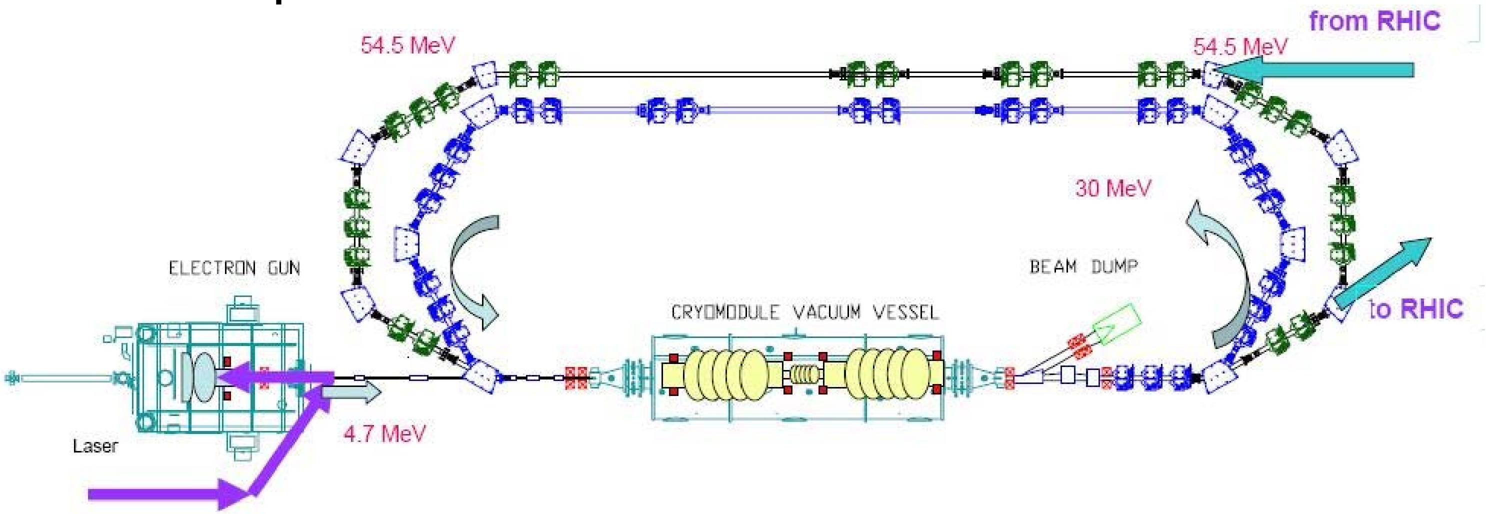
Works well for coasted low current,
large emittance beams.
Can it work for bunched beams? Hardly… but
demonstrated by M.Blaskewitz for lead at RHIC!
May help ELIC (stacking and pre-cooling)…

Energy Recovery Linac (ERL) for RHIC-II

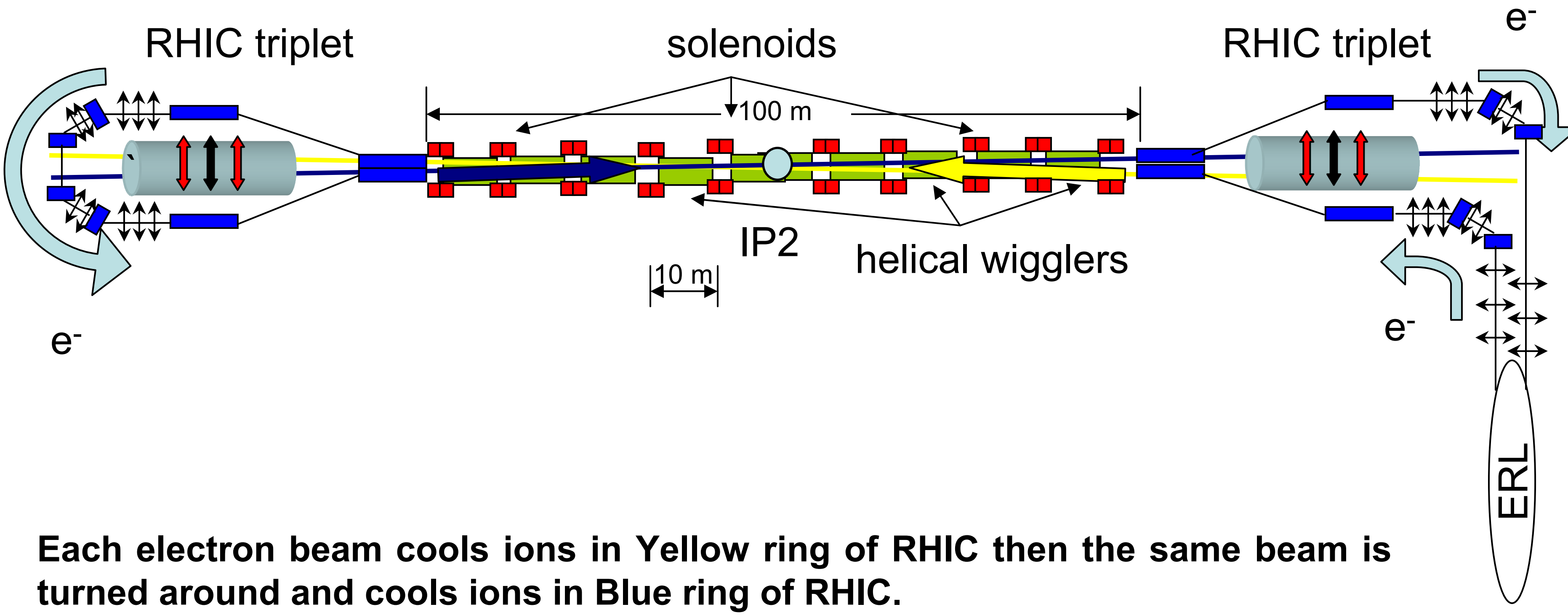
Cooling of Au ions at 100 GeV/n:

- 54.3 MeV electron beam
- 5nC per bunch
- rms normalized emittance < 4 μm
- rms momentum spread < 5×10^{-4}

D. Kayran, PAC07

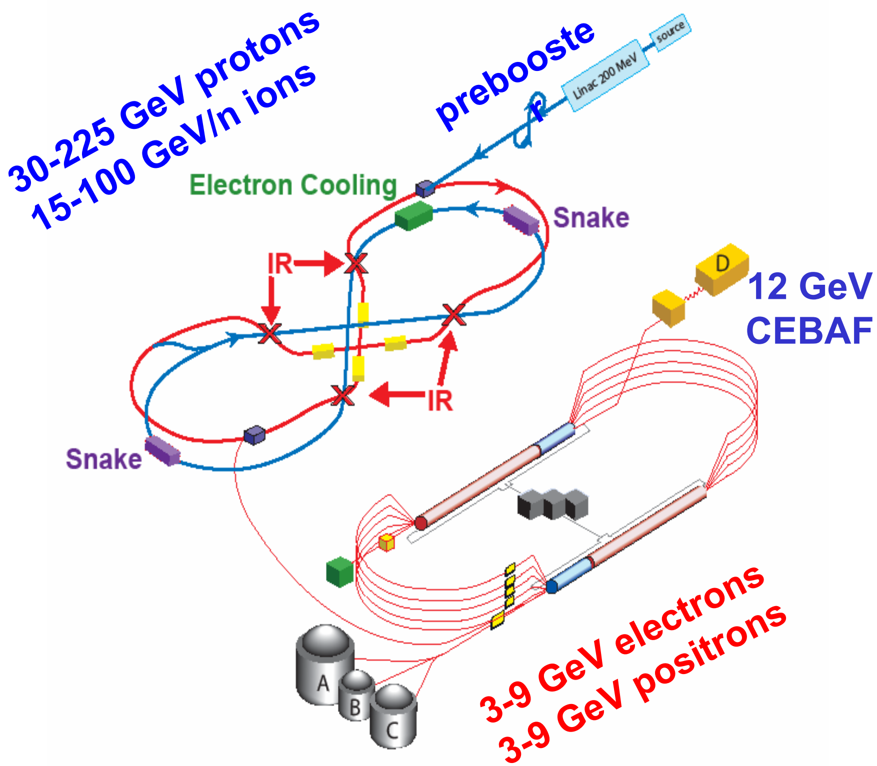


Electron cooling section at RHIC 2 o'clock IP



Each electron beam cools ions in Yellow ring of RHIC then the same beam is turned around and cools ions in Blue ring of RHIC.

ELIC Conceptual Design



Green-field design of ion complex directly aimed at full exploitation of science program.

- **Unprecedented high luminosity**
  - **Enabled by short ion bunches, low β*, high repetition rate**
  - **Large synchrotron tune**
  - **Requires crab crossing**
- **Electron cooling is an essential part of ELIC**
- **Four IPs for high science productivity**
- **"*Figure-8*" ion & lepton storage rings**
  - **Ensure spin preservation & ease manipulation.**
  - **No spin sensitivity to energy for all species.**
- **Present CEBAF gun/injector meets storage-ring requirements**
- **The 12 GeV CEBAF can serve as a full energy injector to electron storage ring**
- ***Simultaneous* operation of collider and CEBAF fixed target program.**
- **Experiments with polarized positron beam are possible.**

Stochastic Cooling and Stacking of Ions

Stacking of ion beam

- Multi-turn (10 – 20) injection from 285 MeV SRF linac to pre-booster
- Stochastic damping of injected beam
- Accumulation of 1 A coasted beam at space charge limited emittance
- RF bunching and accelerating to 3 GeV
- Inject into large booster
- Fill large booster, accelerate to 30 GeV
- Inject into collider ring
- Transverses stochastic cooling of 1 A coasted ion beam in collider ring

At this stage, Ion beam is ready for electron cooling

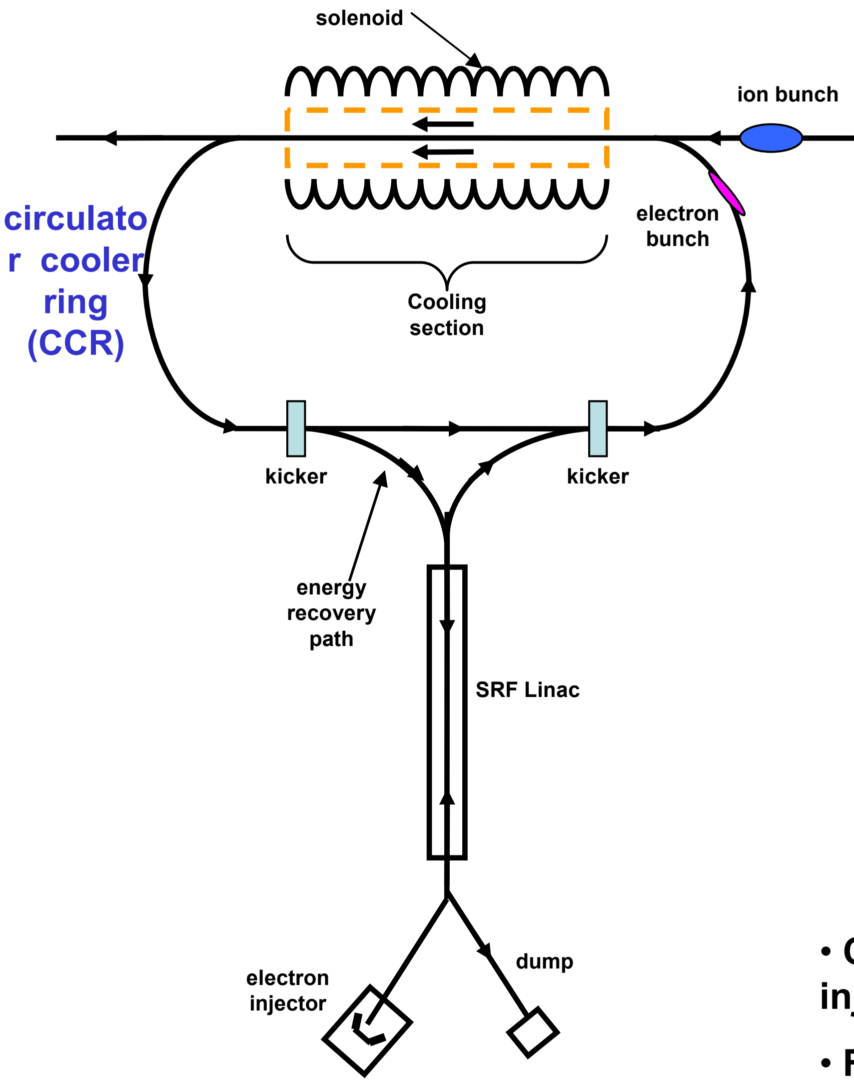
Stacking proton beam in pre-booster with stochastic cooling

Beam Energy	MeV	200
Momentum Spread	%	1
Pulse current from linac	mA	2
Cooling time	s	4
Accumulated current	A	0.7
Stacking cycle duration	Min	2
Beam emittance, norm.	μm	12
Laslett tune shift		0.03

Transverse stochastic cooling of coasted proton beam after injection in collider ring

Beam Energy	GeV	30
Momentum Spread	%	0.5
Current	A	1
Freq. bandwidth of amplifiers	GHz	5
Minimal cooling time	Min	8
Initial transverse emittance	μm	16
IBS equilibrium transverse emitt.	μm	0.1
Laslett tune shift at equilibrium		0.04

Circulated Electron Cooling



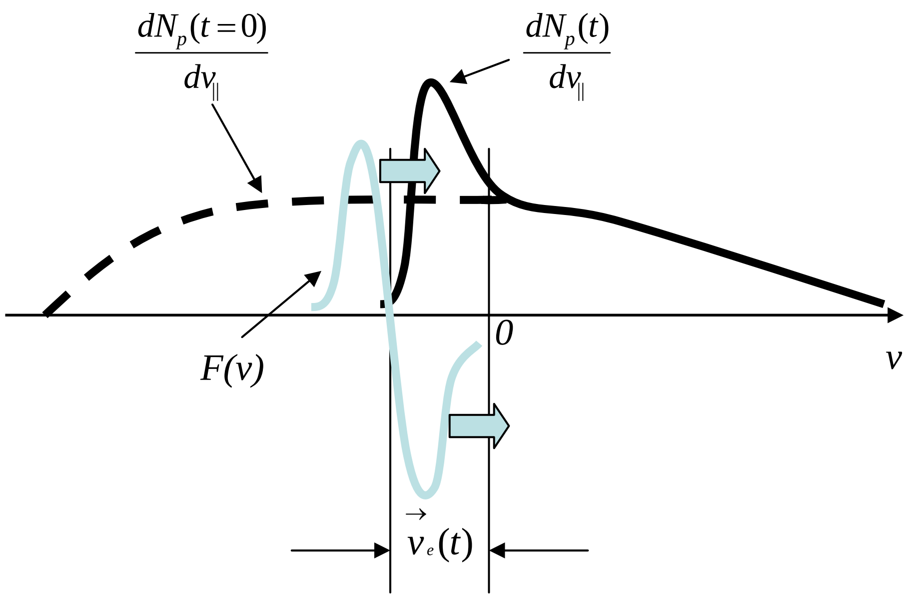
Max/min energy of e-beam	MeV	125/8
Electrons/bunch	10^{10}	1
Number of bunch revolutions in CCR		100
Current in CCR/ERL	A	3/0.03
Bunch repetition rate in CCR/ERL	MHz	1500/15
CCR circumference	m	80
Cooling section length	m	20
Circulation duration	μs	27
Bunch length	cm	1-3
Energy spread	10^{-4}	1-3
Solenoid field in cooling section	T	2
Beam radius in solenoid	mm	1
Cyclotron beta-function	m	0.6
Thermal cyclotron radius	μm	2
Beam radius at cathode	mm	3
Solenoid field at cathode	KG	2
Laslett's tune shift in CCR at 10 MeV		0.03
Time of longitudinal inter/intra beam heating	μs	200

- CCR makes 100 time reduction of beam current from injector/ERL
- Fast kickers operated at 15 MHz repetition rate and 2 GHz frequency bend width are required

Electron Cooling of Ions in ELIC

- ***Staged cooling***
  - Start electron cooling (longitudinal) in collider ring at injection energy,
  - Continue electron cooling (in all dimension) after acceleration to high energy

- ***Sweep cooling***
  - After transverse stochastic cooling, ion beam has a small transverse temperature but large longitudinal one.
  - Use *sweep cooling to* gain a factor of longitudinal cooling time



- ***Dispersive cooling***
  - compensates for lack of transverse cooling rate at high energies due to large transverse velocity spread compared to the longitudinal (in rest frame) caused by IBS

- ***Flat beam cooling***
  - based on flattening ion beam by reduction of coupling around the ring
  - IBS rate at equilibrium reduced compared to cooling rate

Cooling Time and Ion Equilibrium

Multi-stage cooling scenario:

- 1st stage: longitudinal cooling at injection energy (after transverses stochastic cooling)
- 2nd stage: initial cooling after acceleration to high energy
- 3rd stage: continuous cooling in collider mode

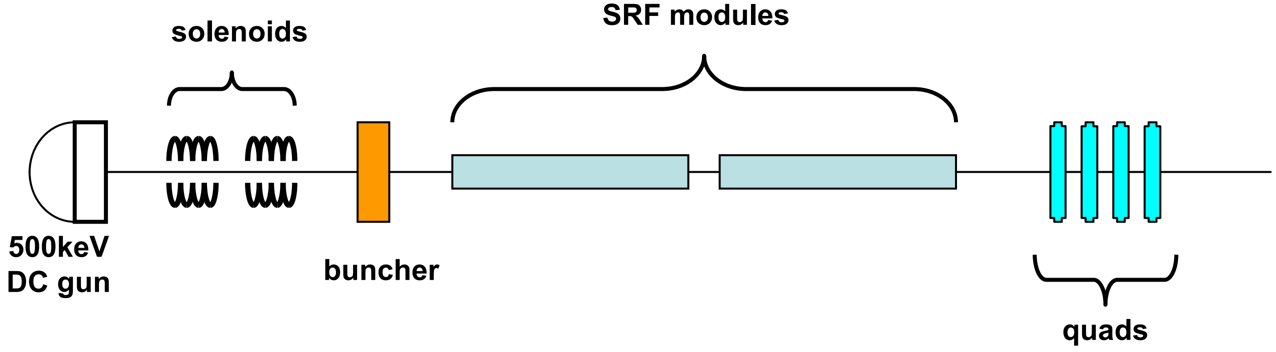
Cooling rates and equilibrium of proton beam

Parameter	Unit	Value	Value
Energy	GeV/MeV	30/15	225/123
Particles/bunch	10^{10}	0.2/1	
Initial energy spread*	10^{-4}	30/3	1/2
Bunch length*	cm	20/3	1
Proton emittance, norm*	μm	1	1
Cooling time	min	1	1
Equilibrium emittance $\varepsilon_x/\varepsilon_y$, **	μm	1/1	1/0.04
Equilibrium bunch length**	cm	2	0.5
Cooling time at equilibrium	min	0.1	0.3
Laslett's tune shift (equil.)		0.04	0.02

* max.amplitude
** norm.,rms

Injector and ERL for Electron Cooling

- ELIC CCR driving injector
  - 30 mA@15 MHz, up to 125 MeV energy, 1 nC bunch charge, magnetized
- Challenges
  - Source life time: 2.6 kC/day (state-of-art is 0.2 kC/day)
    → source R&D, & exploiting possibility of increasing evolutions in CCR
  - High beam power: 3.75 MW → Energy Recovery
- Conceptual design
  - High current/brightness source/injector is a key issue of ERL based light source applications, much R&D has been done
  - We adopt light source injector as initial baseline design of ELIC CCR driving injector
- Beam qualities should satisfy electron cooling requirements (based on previous computer simulations/optimization)

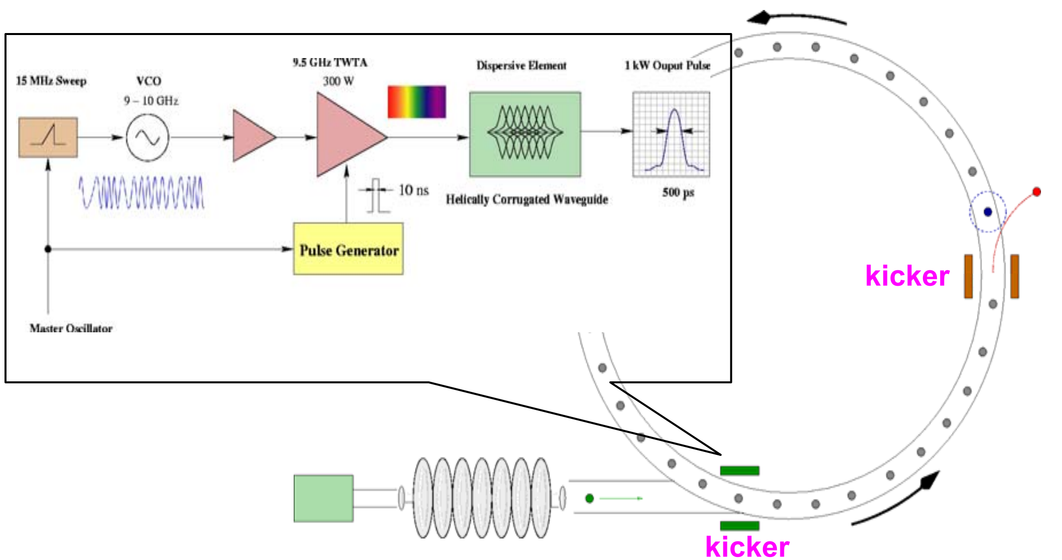


Fast Kicker for Circulator Cooling Ring

- Sub-ns pulses of 20 kW and 15 MHz are needed to insert/extract individual bunches.
- RF chirp techniques hold the best promise of generating ultra-short pulses. State-of-Art pulse systems are able to produce ~2 ns, 11 kW RF pulses at a 12 MHz repetition rate. This is very close to our requirement, and appears to be technically achievable.
- Helically-corrugated waveguide (HCW) exhibits dispersive qualities, and serves to further compress the output pulse without excessive loss. Powers ranging from up10 kW have been created with such a device.
- Collaborative development plans include studies of HCW, optimization of chirp techniques, and generation of 1-2 kW peak output powers as proof of concept.
- Kicker cavity design will be considered

Estimated parameters for the kicker

Beam energy	MeV	125
Kick angle	10^{-4}	3
Integrated BdL	GM	1.25
Frequency BW	GHz	2
Kicker Aperture	Cm	2
Peak kicker field	G	3
Kicker Repetition Rate	MHz	15
Peak power/cell	KW	10
Average power/cell	W	15
Number of cells	20	20



Conclusion and Outlook

- **The ERL based EC concept with circulator ring described in this report seems advantageous in delivering high current, high quality cooling beams while using an electron source of a modest (tens of mA) average current**

- **To be maximally effective in reaching the highest luminosity in colliders, electron cooling should be used in conjunction with stochastic cooling, which is effective in stacking and cooling non-bunched large emittance hadron beams**

- **A concept of an ultra-fast kicker required for CW e-beam operation in such electron cooling device has been developed**

- **More comprehensive analysis, simulation and experimental studies should precede recommendations for practical design of electron cooling and high luminosity colliding beams.**

Coherent Electron Cooling

or

how the van der Meer's demon can spoil thermostat of the relativistic engineer

History of idea (1980-91-95-2007)

Coherent electron cooling (CEC) **was proposed 27 years ago**

- General idea: **amplify response of e-beam to an ion by a micro-wave instability of the beam**
- **A few instabilities have been shown**
- CEC advantages/disadvantages compared to:

EC : Gain in cooling rate

Complicate BT

SC : Very large FB (30 GHz – optics)

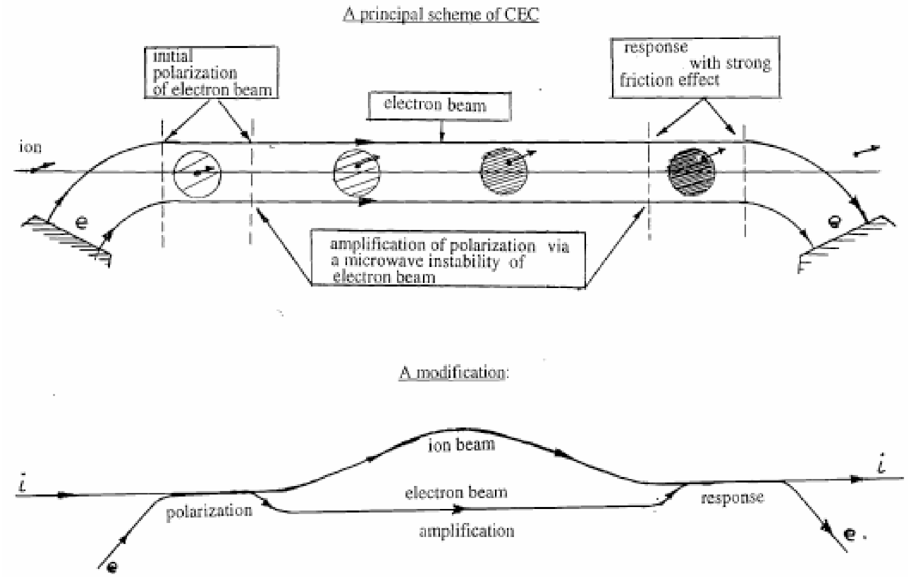
Precise phasing required

OSC : Effective in a wide energy range

Small signal delay

Intense e-beam required

Signal gain is limited



What changed in last 10 years?

- Relativistic DC EC realized (FNAL)
- ERL realized (JLab)
- SASE FEL realized (UCLA - DESY)
- ERL-based HEEC on the way (BNL)

And more…

FEL and HEEC

FELs and high-energy electron cooling

Vladimir N. Litvinenko

BNL, Upton, NY, USA

Yaroslav S. Derbenev

TJNAF. Newport News, VA, USA

29th International FELConference

August 26-31, 2007, BINP, Novosibirsk

FELs and HEEC

And so, my fellow FELers, ask

not

what storage ring can do for

FELs:

Ask what FELs can do

for your storage rings!

And so, my fellow Americans,
ask not what your country
can do for you;
ask what you can do
for your country.

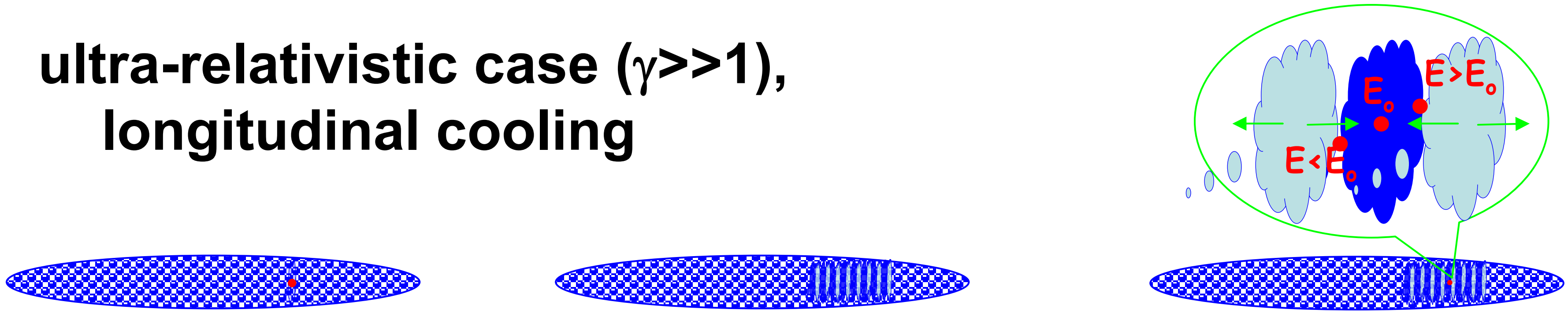
Vladimilr Litvinenko

29th International FEL Conference

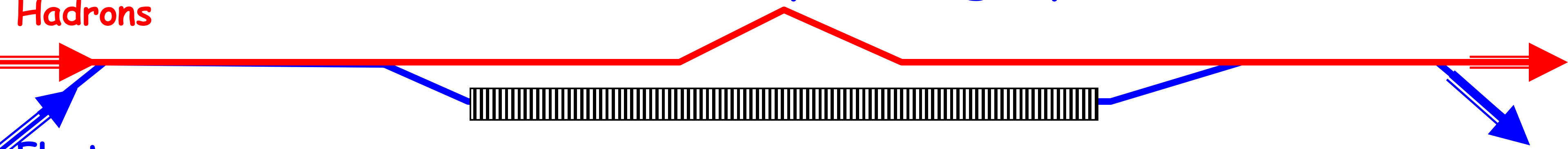
August 26-31, 2007, BINP, Novosibirsk

CEC on SASE FEL

ultra-relativistic case (γ>>1), longitudinal cooling



Most versatile phasing option

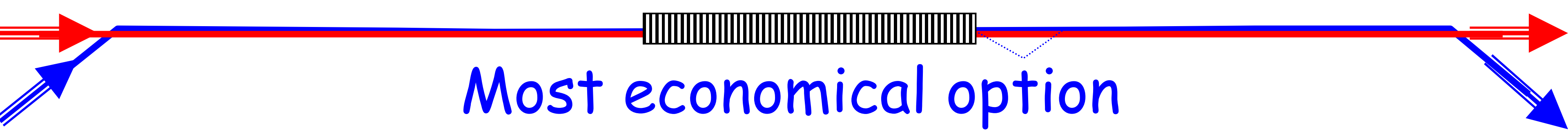


Modulator:region 1
about a quarter of
plasma oscillation

Longitudinal dispersion for
hadrons

Amplifier of the e-beam
modulation via SASE FEL

Kicker: region 2



Most economical option

Cooling of hadron beams

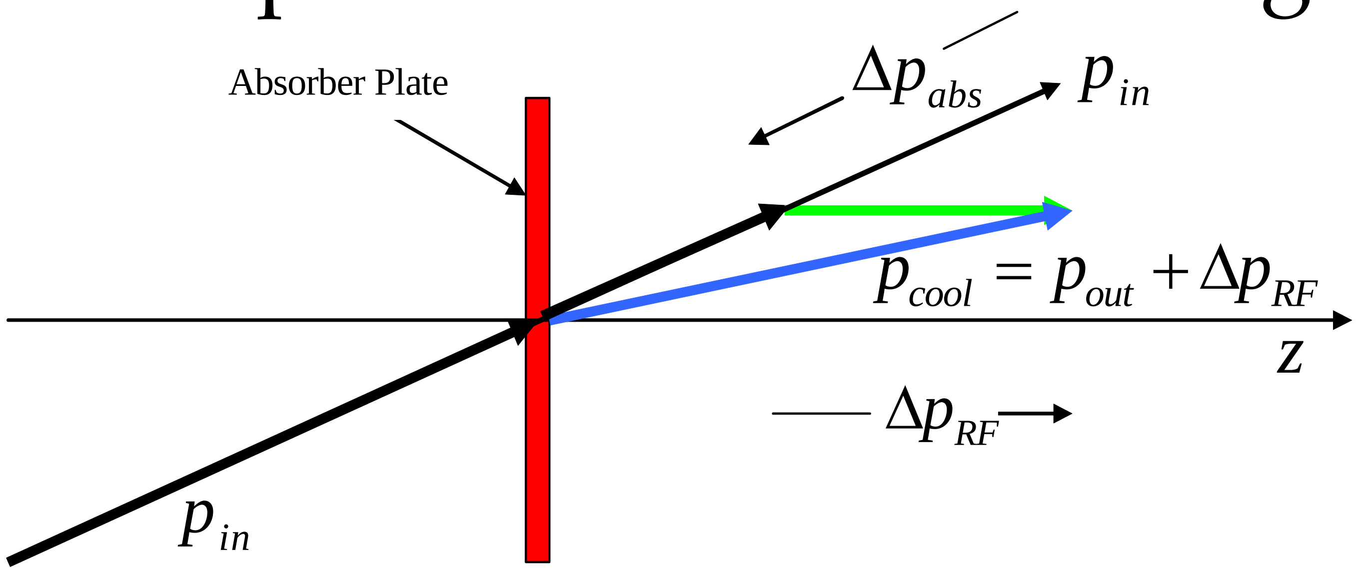
Machine	Species	Energy GeV/n	Synchrotron radiation, hrs	Electron cooling, hrs	**CEC, hrs**
RHIC	Au	100	20,961 ∞	~ 1	**0.03**
RHIC	protons	250	40,246 ∞	> 30	**0.8**
LHC	protons	450	48,489 ∞	> 1,600	**0.95**
LHC	protons	7,000	13/26	∞ ∞	**< 2**

Ionization Cooling

- ***Forget thermostats and demons – yet we want to die fast still being hot!***–

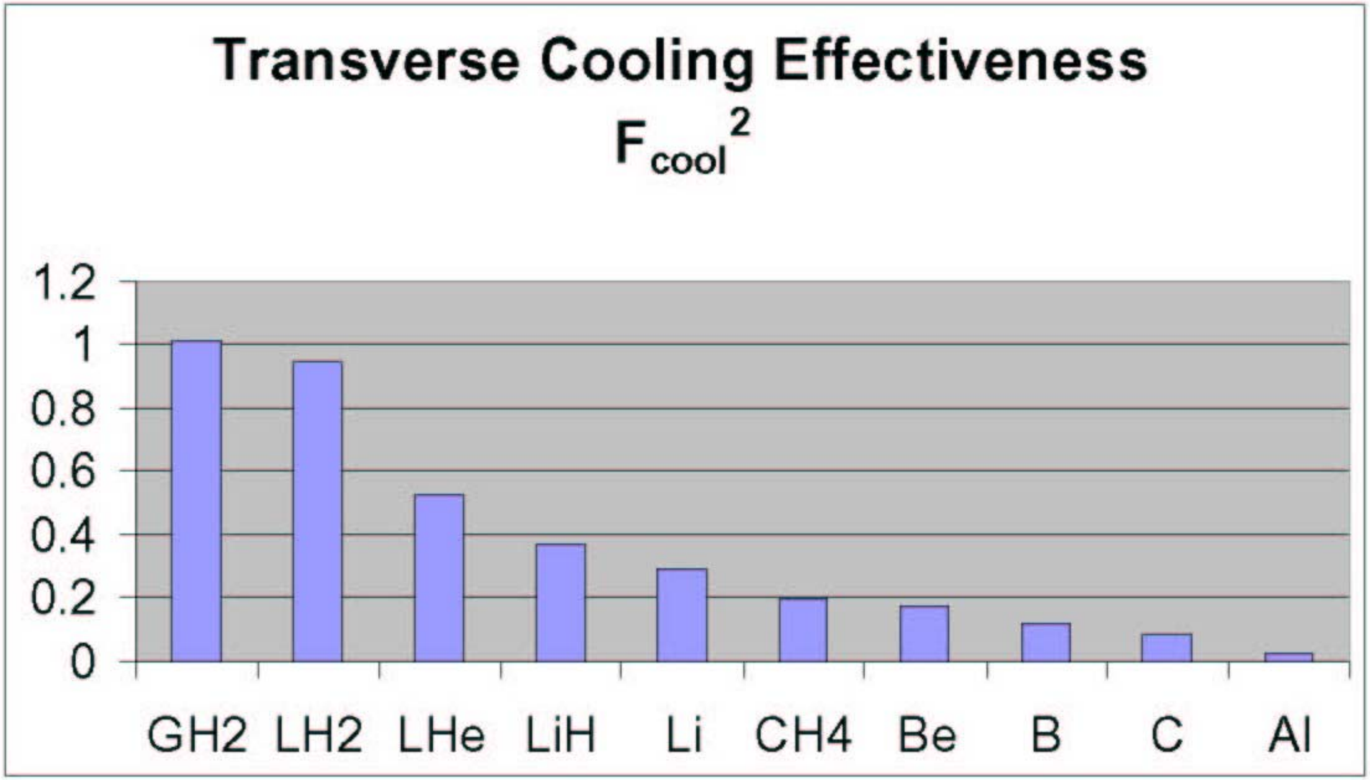
Muons

Principle of Ionization Cooling



- Each particle loses momentum by ionizing a low-Z absorber
- Only the longitudinal momentum is restored by RF cavities
- The angular divergence is reduced until limited by multiple scattering
- Successive applications of this principle with clever variations leads to small emittances for many applications
- Early work: Budker, Ado & Balbekov, Skrinsky & Parkhomchuk, Neuffer

Comparison of Absorber Materials



(because of density and mechanical properties, Be is best for some cooling applications like PIC and REMEX)

Muons, Inc.

Wedges or Continuous Energy Absorber for Emittance Exchange and 6d Cooling

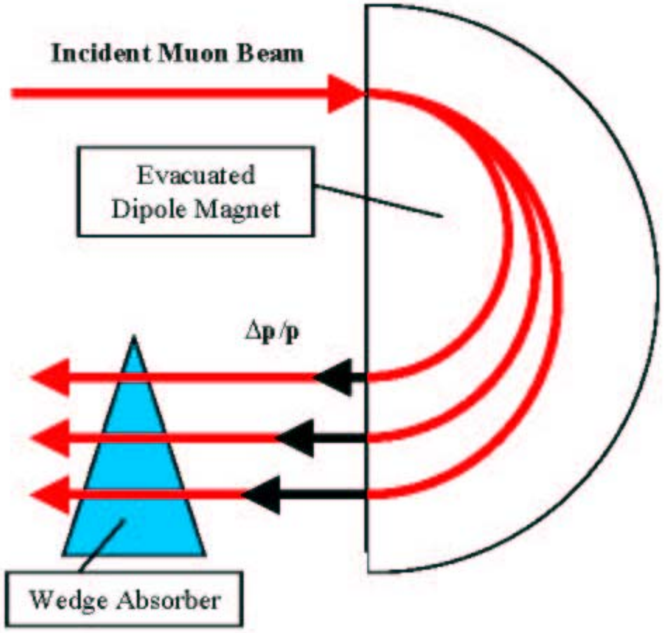


Figure 1. Use of a Wedge Absorber for Emittance Exchange

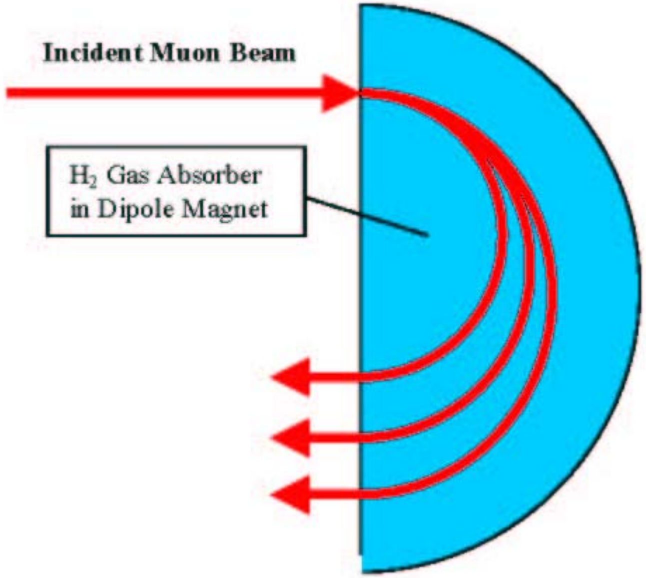
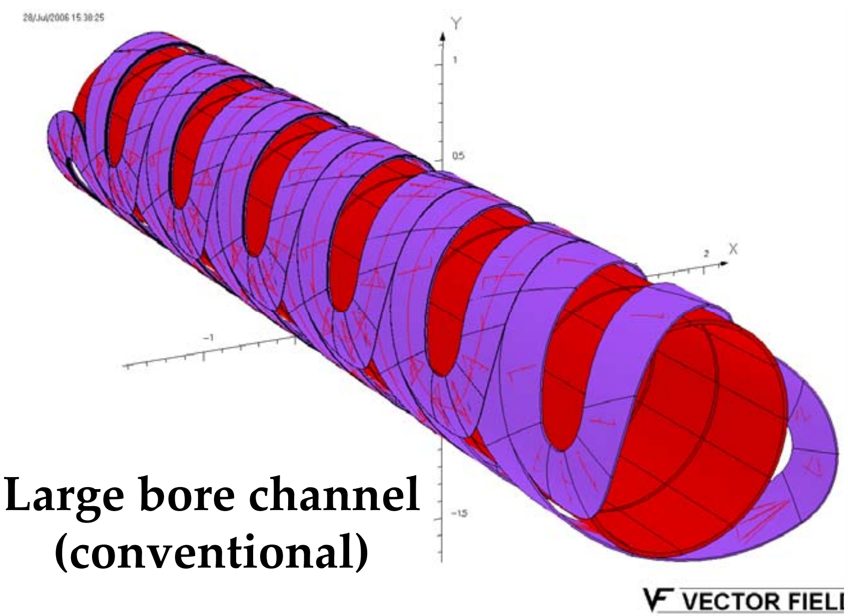


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

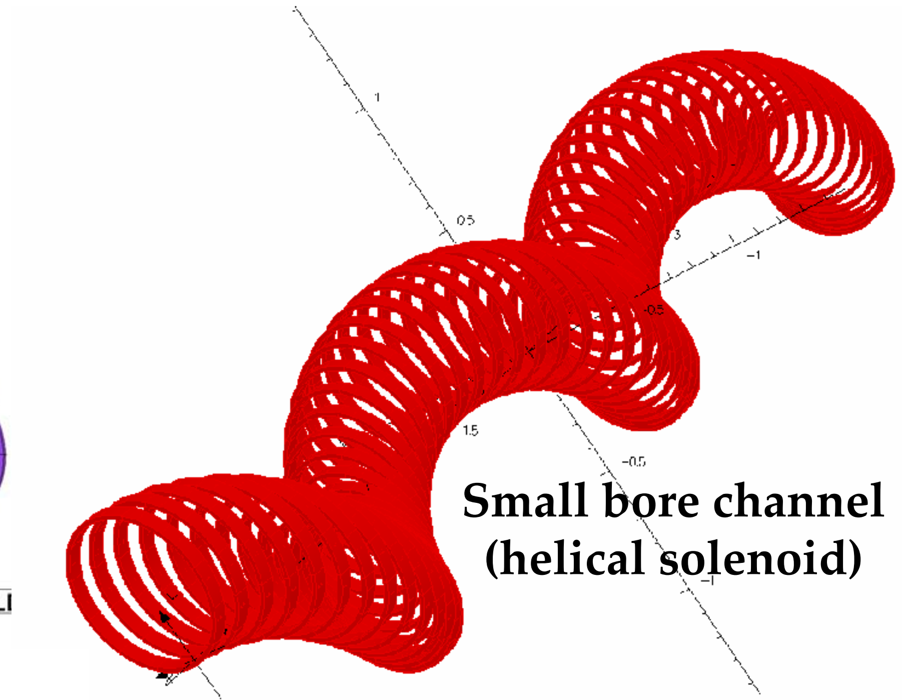
Two Different Designs of Helical Cooling Magnet

Great new for COOL07 innovation!



Large bore channel (conventional)

- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

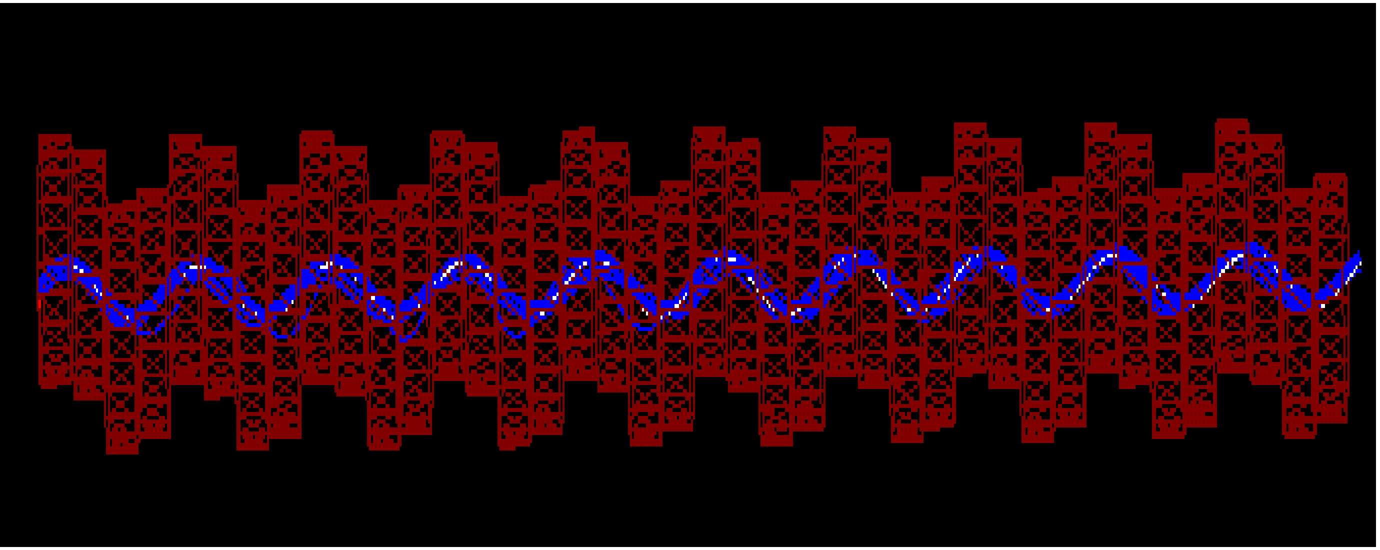


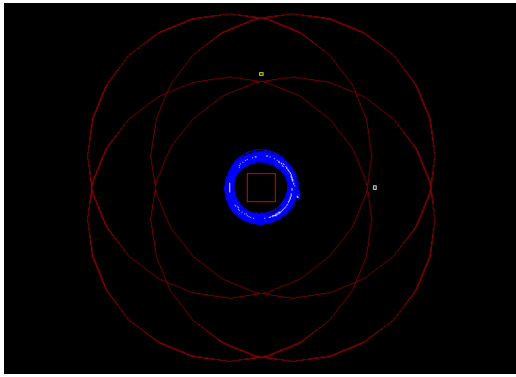
Small bore channel (helical solenoid)

- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

6-Dimensional Cooling in a Continuous Absorber

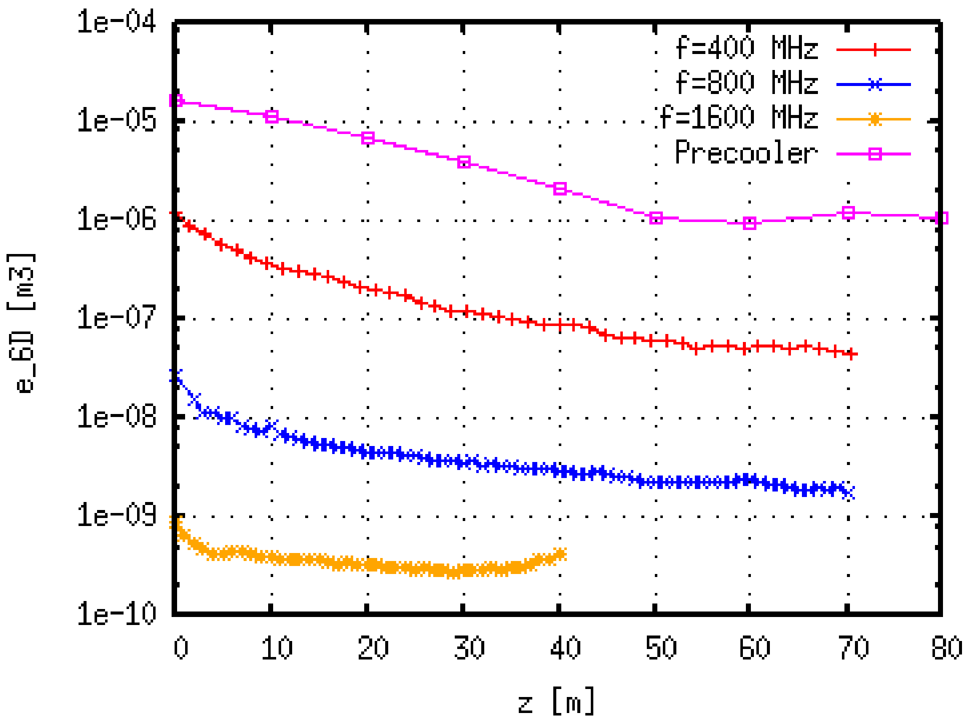
- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z- and time-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB
    - http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf





Muons, Inc.

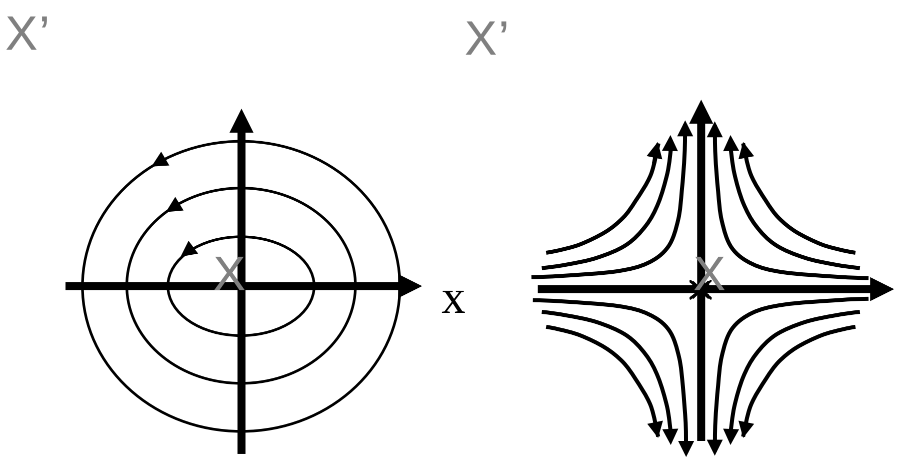
Precooler + HCCs
With first engineering constraints



- The acceptance is sufficiently big.
- Transverse emittance can be smaller than longitudinal emittance.
- Emittance grows in the longitudinal direction.

Parametric-resonance Ionization Cooling

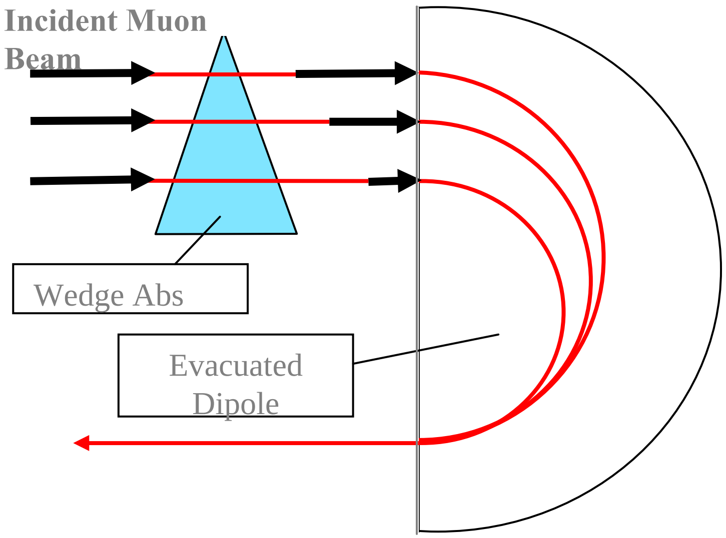
- Excite ½ integer parametric resonance (in Linac or ring)
  - Like vertical rigid pendulum or ½-integer extraction
  - Elliptical phase space motion becomes hyperbolic
  - Use xx'=const to reduce x, increase x'
  - Use IC to reduce x'
- Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway.
- Smaller beams from 6D HCC cooling essential for this to work!



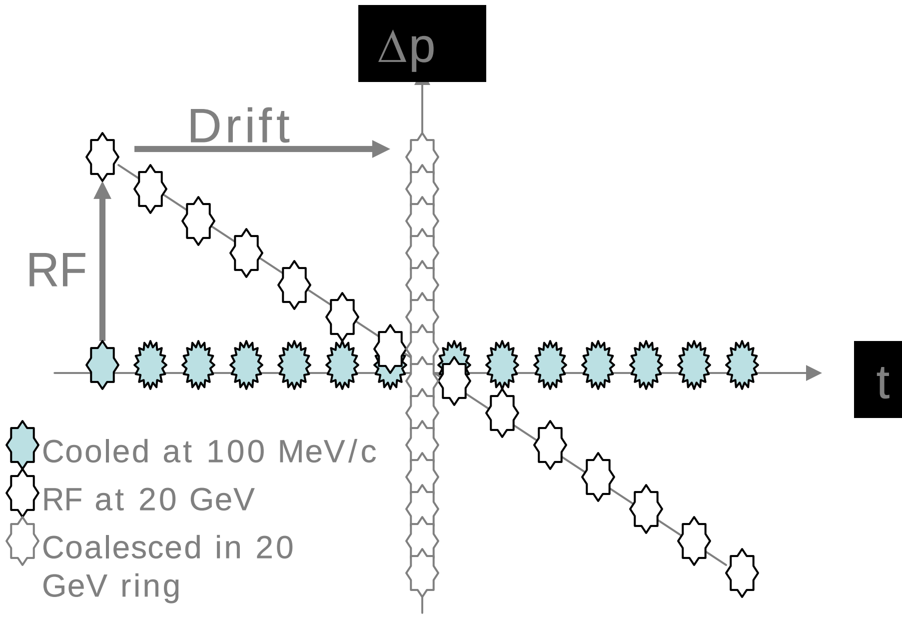
Muons, Inc.

Reverse Emittance Exchange, Coalescing

- p(cooling)=100MeV/c, p(colliding)=2.5 TeV/c => room in Δp/p space
- Shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider using wedge absorbers
- Allow bunch length to increase to size of low beta
- Low energy space charge, beam loading, wake fields problems avoided
- 20 GeV Bunch coalescing in a ring Neutrino factory and muon collider now have a common path



Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Muons, Inc.

5 TeV ~ SSC energy reach

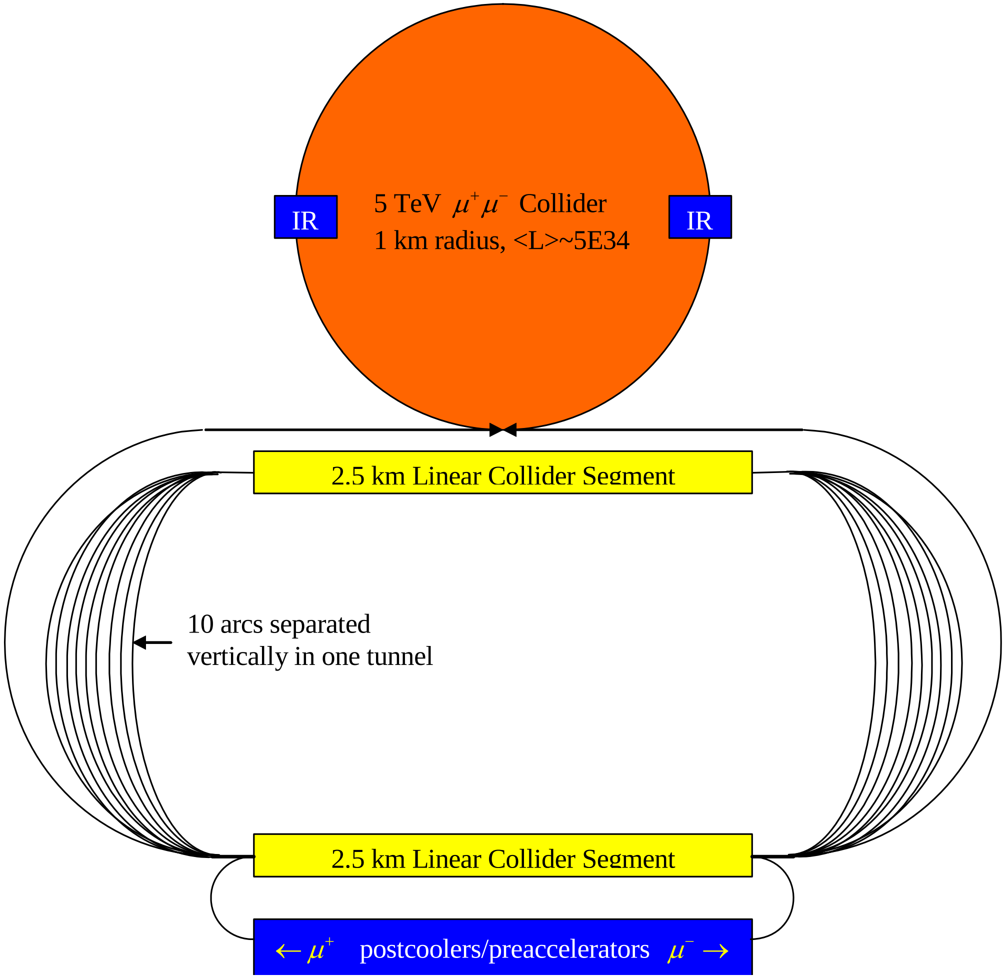
~5 X 2.5 km footprint

Affordable LC length (5 km), includes ILC people, ideas

More efficient use of RF: recirculation and both signs

High L from small emittance!

with fewer muons than originally imagined:
a) easier p driver, targetry
b) less detector background
c) less site boundary radiation



Beams from 23 GeV Coalescing Ring

Conclusions

- **Achieving very high luminosity in colliders (order level 35-36) seems conceivable based on advanced cooling methods under development**

The critical science cases should be explored by the high energy and nuclear physics community

There still be a lot of hard work to do in fundamental physics, detectors development   and accelerator technology

Thank you!