Beam Cooling: Past, Present and Future

Igor Meshkov
JINR, Dubna

COOL 13
Mürren, Switzerland
June 10-14, 2013

<u>Foreword</u>: The task to review the history and status of cooling methods development is a hard task like climbing of the Eiger North Wall!

COOL-13: The Workshop on Beam Cooling and Related Topics

Foreword: The task to review the history and status of cooling methods development is a hard task like
climbing of the Eiger North Wall!

Reflecting on my task I decided to concentrate the talk on the consideration of experimental results achieved before in the methods development and novel projects under development presently.

Contents

Introduction: Prehistoric Period

"... In the Beginning was The Word..."

1838 Joseph Liouville (J. De Math. v.3, 1838, p.349)

Theorem of phase space density conservation:

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \sum_{i=1}^{3N}\left(\frac{\partial\rho}{\partial q_i}\cdot\frac{dq_i}{dt} + \frac{\partial\rho}{\partial p_i}\cdot\frac{dp_i}{dt}\right), \quad \frac{dq_i}{dt} = \frac{\partial H}{\partial p_i}, \quad \frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i}$$

The truism saying

"the history does not teach anything"

has no relation to physics. The longstanding history of cooling methods development is a fascinating "novel" of fighting with famous theorem formulated by Joseph Liouville in 1838:

the theorem of phase space density conservation.

Introduction: Prehistoric Period

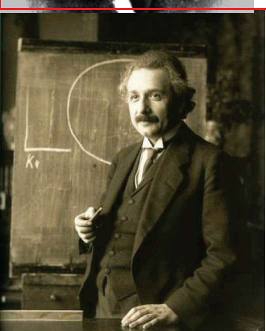
Therefore it is worth to remind that particle beam physics is based on the works of

the Great Predessors

1872 Ludwig Eduard Boltzmann

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\frac{df}{d\vec{r}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = \left.\frac{\partial f}{\partial t}\right|_{coll}$$

Kinetic equation



1906 A. Einstein, 1913 M.Smoluchowsky

Equation of Brownian motion

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\frac{df}{d\vec{r}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = \frac{\partial}{\partial p}\xi\left(\frac{p}{m}f + T\frac{\partial f}{\partial \vec{p}}\right)$$

1914 Adrian Fokker, 1917 Max Planck

Equation of dipole rotation in radiation el.-magn. field

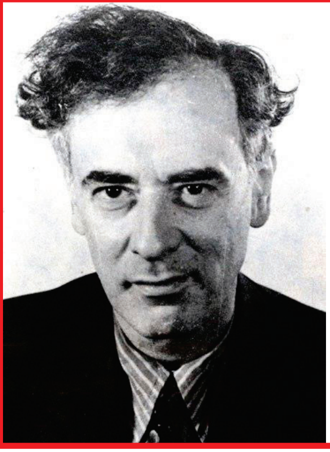
Introduction: Prehistoric Period

The 30th – Progress in Plasma Physics

1938 Anatoly A. Vlasov (JETP v.8 (1938) 291)

$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial t} + \vec{v}\frac{df_\alpha}{d\vec{r}} + \frac{q_\alpha}{m_\alpha}\left(\vec{E} + \left[\vec{v}, \vec{B}\right]\right)\frac{df_\alpha}{d\vec{v}}$$

Vlasov equation:
Collisionless plasma



1937 Lev D. Landau (JETP v.7 (1937) 203)

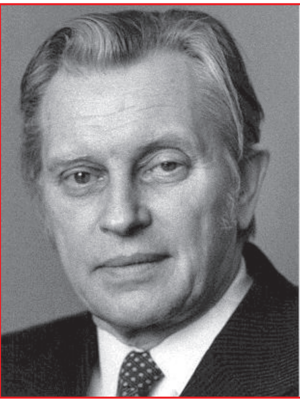
$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial t} + \vec{v}\frac{df_\alpha}{d\vec{r}} + \frac{q_\alpha}{m_\alpha}\vec{F}\frac{df_\alpha}{d\vec{v}}$$

Collision integral in plasma
(F – Coulomb interaction "force")

The theory to be used in particle beam physics!

Introduction: Prehistoric Period

When Cooling Had Different Name…



1956 A.A.Kolomensky & A.N.Lebedev

(*Proc. of the USSR Academy of Sci., 106 (1956) 807*)

Synchrotron radiation "friction"

$$\tau_{||} = \frac{3}{2} \cdot \frac{\rho^2}{\gamma^3 r_{cl} c}, \quad r_{cl} = \frac{e^2}{mc^2}$$

1958 Kenneth W. Robinson

Radiation Effects in Circular Electron Accelerators

(Phys. Rev. v.11 (1958) 373)

PHYSICAL REVIEW VOLUME 111, NUMBER 2 JULY 15, 1958

Radiation Effects in Circular Electron Accelerators*

KENNETH W. ROBINSON
Cambridge Electron Accelerator, Massachusetts Institute of Technology and Harvard University, Cambridge, Massachusetts

(Received March 17, 1958; revised manuscript received June 2, 1958)

The effects of the radiation emission on the motion of electrons in high-energy synchrotrons are analyzed. The damping rates and quantum excitation of the three principal modes of oscillation are derived for st

Introduction: Prehistoric Period

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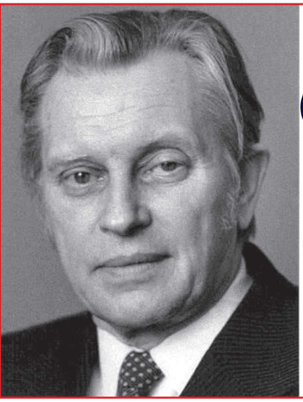

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Geneva, 1959

1958 Kenneth W. Robinson

Radiation Effects in Circular Electron Accelerators

(Phys. Rev. v.11 (1958) 373)

PHYSICAL REVIEW VOLUME 111, NUMBER 2 JULY 15, 1958

The main contents:

Robinson's paper: The theorem on sum of decrements and consideration of decrement redistribution between 6 degrees of freedom,

Both papers: influence of radiation quantum fluctuations on particle dynamics.

I. Past 1.1.First Proposals

1965 A.A. Kolomensky: Ionization cooling

"On damping decrements in accelerators under conditions of the arbitrary energy losses"

(*Atomnaya energiya* v.19 (1965) 534, in Russian)

The concept turned out to be unproductive for heavy particles (p, p̃, ions) due to strong interaction (SI) with a target nuclei (n_0):

cooling rate ~ $\tau_{cool}^{-1} = 4\pi n_0 c r_e^2 Z_{target} z_p \cdot \frac{m_e}{\gamma m_p} \cdot \eta$, sec^{-1}

particle loss rate $\tau_{SI}^{-1} = \sigma_{SI} n_0 c \eta$, sec^{-1}; $\eta = d_{target}/C_{Ring}$.

For protons at E = 5 GeV and carbon target τ_{cool} / τ_{SI} ~ *150.*

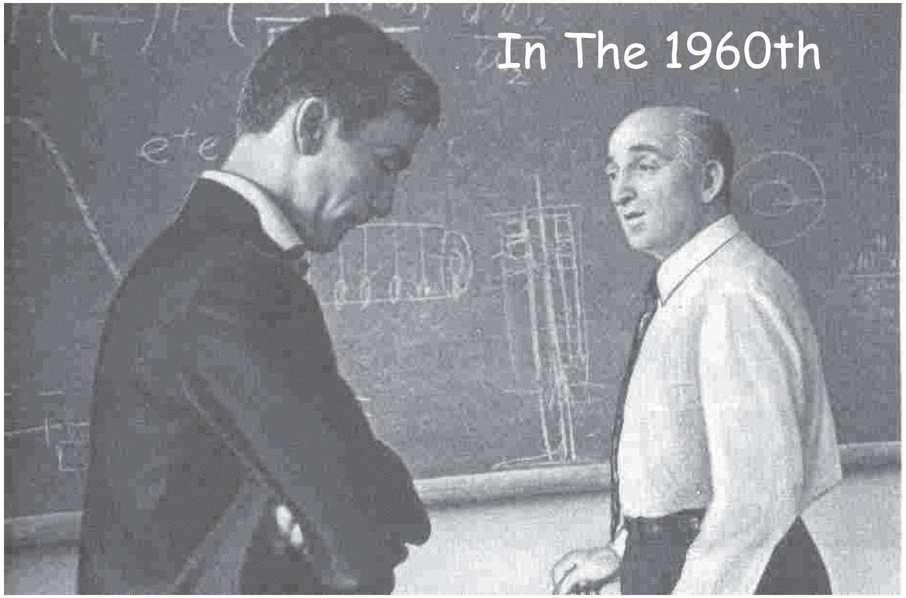
Nevertheless, it was a good start idea

(see year 1970 below as well)

1966 G.I.Budker, Electron cooling

Effective method of particle oscillation damping in proton and antiproton storage rings

(Proc. Of The Intern. Symp. on Electron and Positron Storage Rings, Saclay, 1966, p. II-I-I;
Atomnaya Energia 1967, 22, p.346-348 (in Russian)).



Together with A.Skrinsky they developed the Budker's idea!
That was Sasha who proposed to use e-cooling for p-bars storage.

G.Budker and A.Skrinsky
(not PhD yet!)

1968 S. van der Meer, Stochastic cooling

Stochastic damping of betatron oscillations

Internal Report CERN/ISR-PO/72-31 1972.

"The Cooling ideology"
(or "How to fight Liouville theorem")

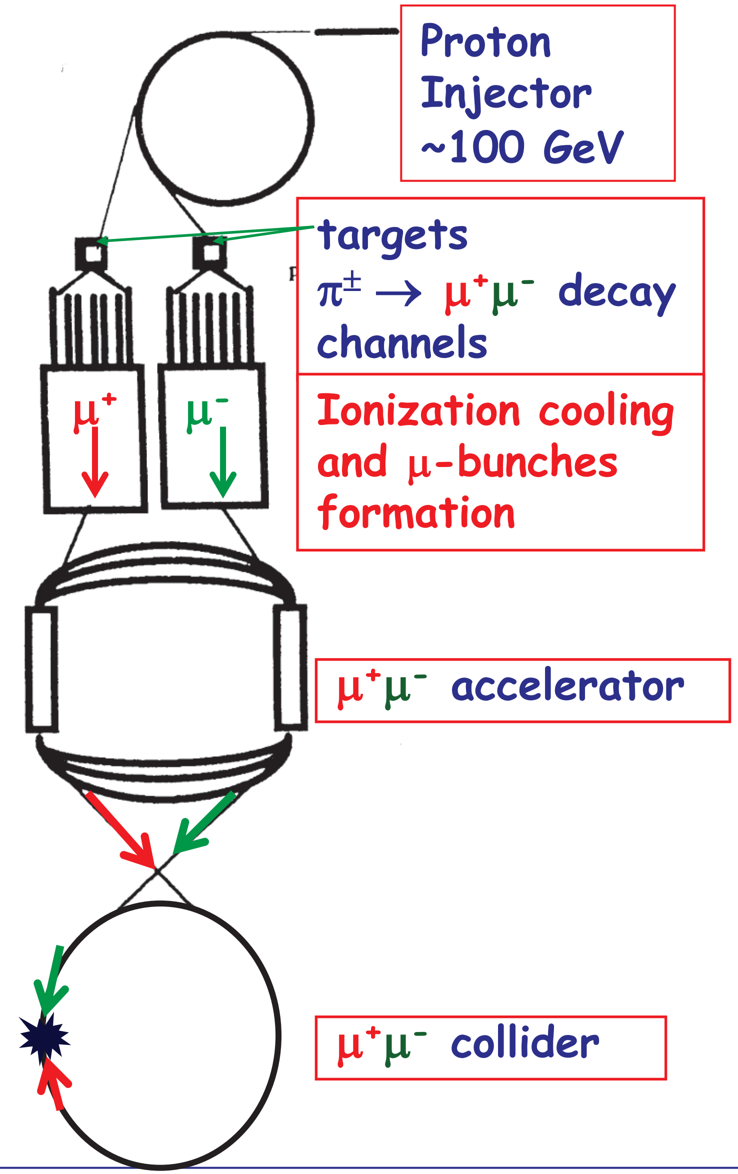
"Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas by going through a very similar routine, violating the second law of thermodynamics in the process. It has been shown by Szilard that the measurement performed by the demon implies an entropy increase that compensates any reduction of entropy in the gas. Moreover, in practical stochastic cooling systems, the kicker action is far from reversible; such systems are therefore even less devilish than the demon itself."

Simon van-der_Meer, Nobel Lecture, p.2

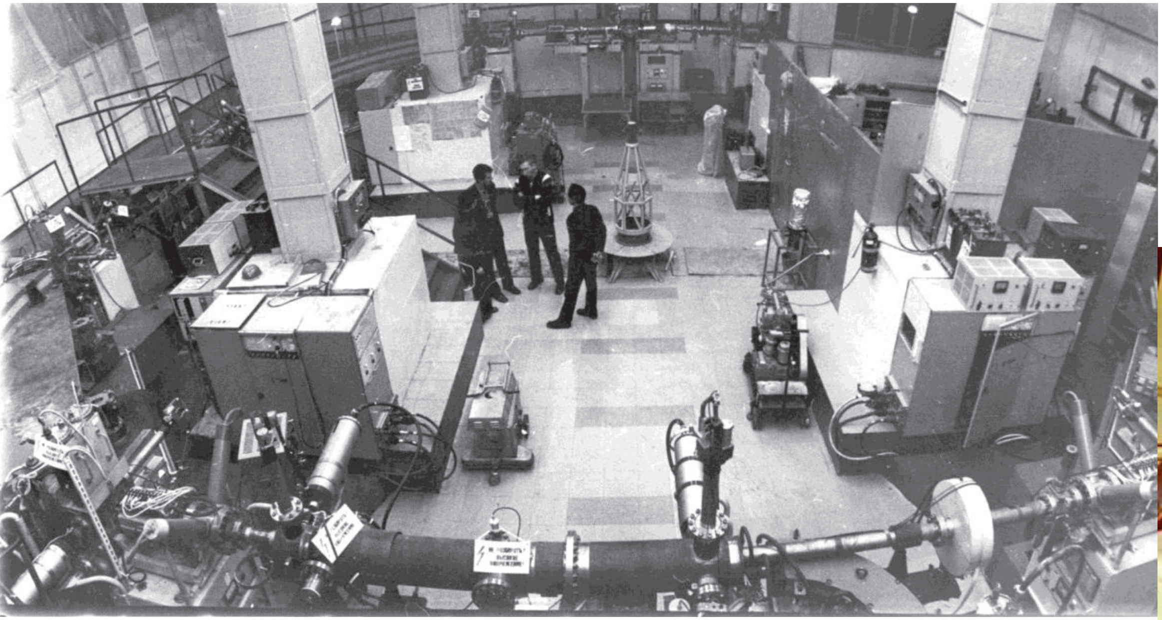
1970 Progress in ionization cooling

G.I. Budker and A.Skrinsky:
Ionization cooling does work
when applied to muon beam formation:
Muons are deprived of Strong Interaction!

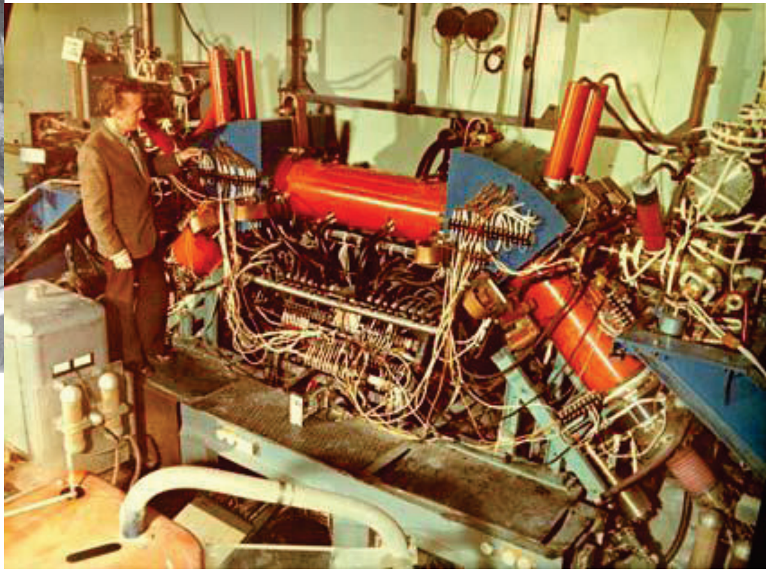
(G.I.Budker, in *Proc. of 15th Intern. Conf. on High Energy Physics*. Kiev, 1970
A.N. Skrinsky, *Uspekhi Fizicheskich Nauk*, 1982, v.138, p.p.3-43.)



Electron Cooling: NAP-M Experiment (1974)



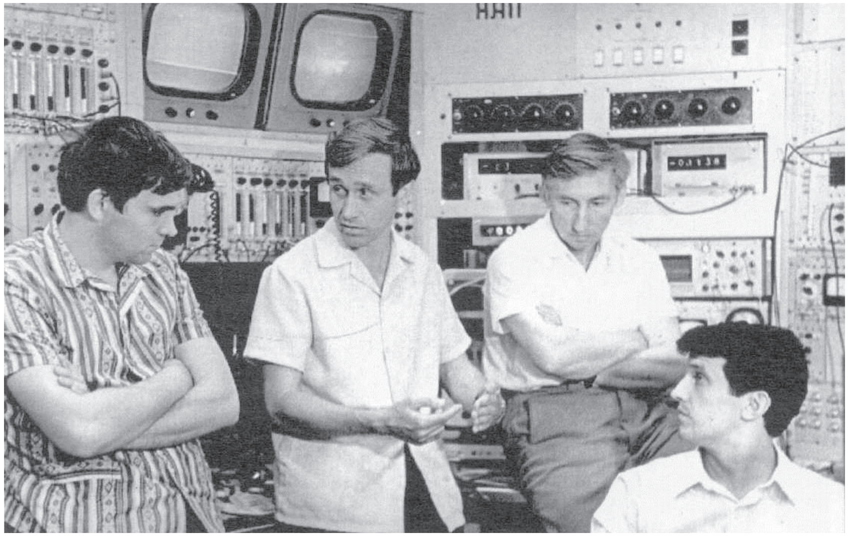
NAP-M : "Antiproton Storage Ring – Model"
INP Novosibirsk, 1974 - 1984



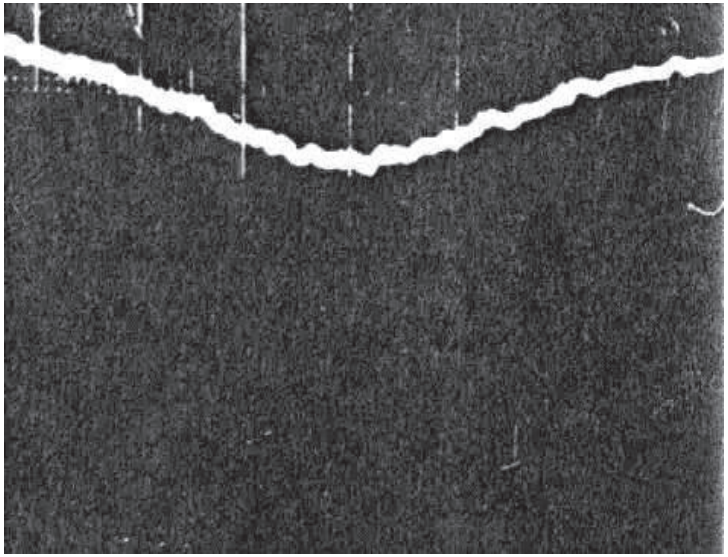
First electron cooler "EPOCH"
("Electron beam for cooling of antiprotons", Rus.)

I. Past 1.2. First Experimental Prooves

Electron Cooling: NAP-M Experiment

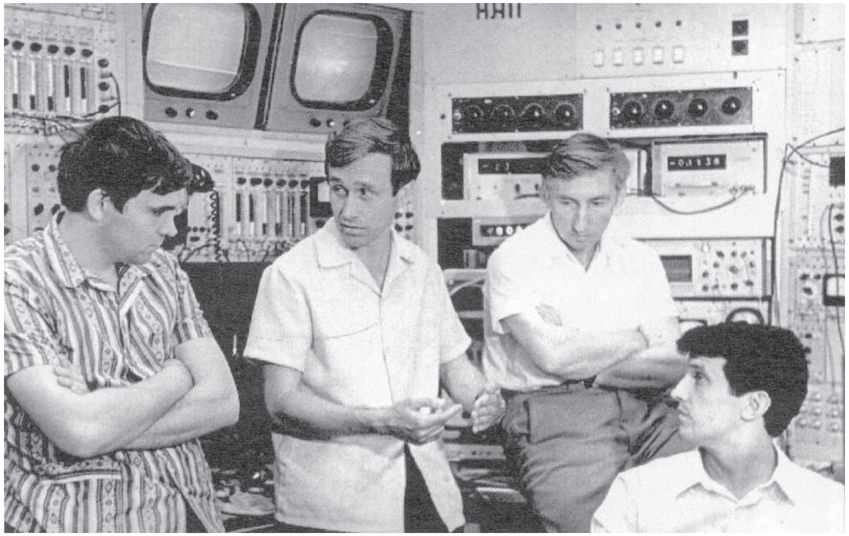


V.Parkhomchuk, A.Skrinsky, I.Meshkov,
N.Dikansky in NAP-M control room (1975)



Proton density distribution at electron cooling (BPM based on Mg vapor jet, NAP-M, 1975)

Electron Cooling: NAP-M Experiment



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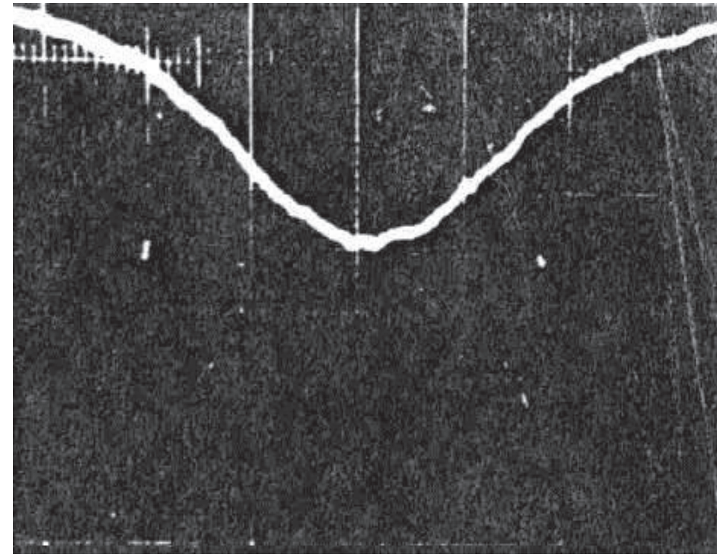

Proton density distribution at electron cooling (BPM based on Mg vapor jet, NAP-M, 1975)

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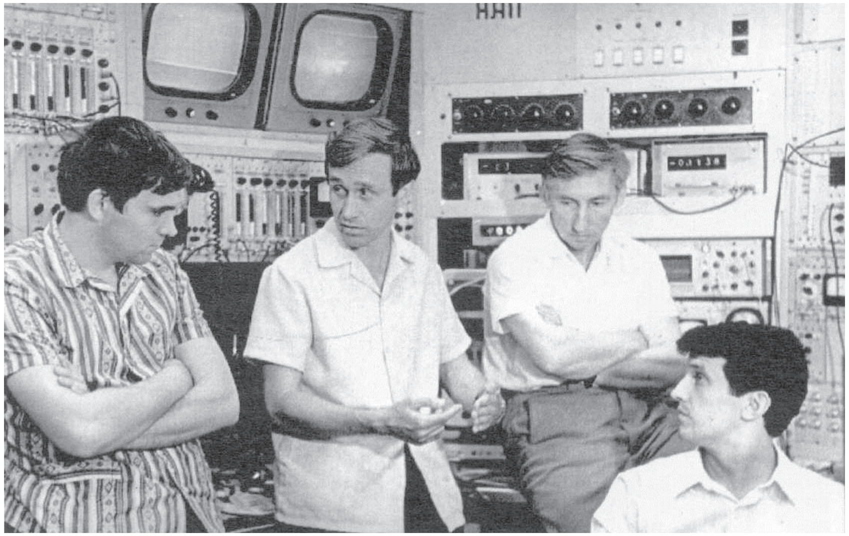
Electron Cooling: NAP-M Experiment



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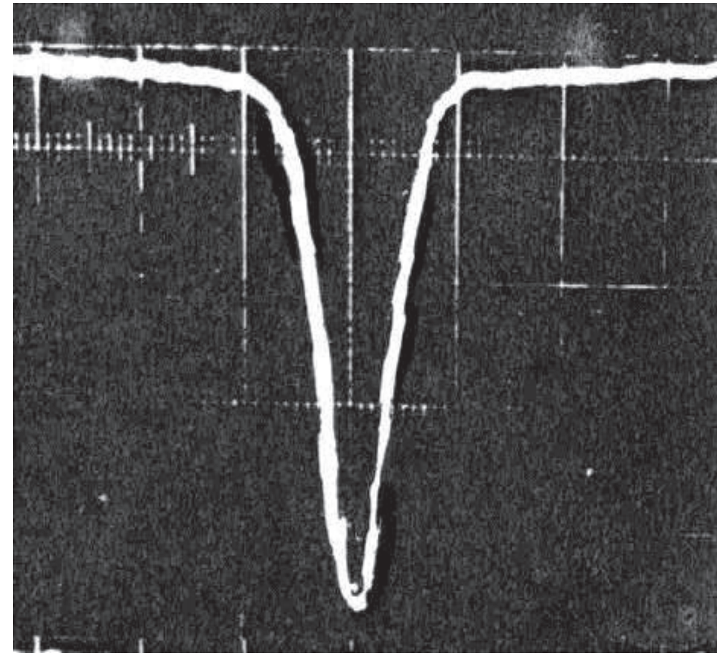

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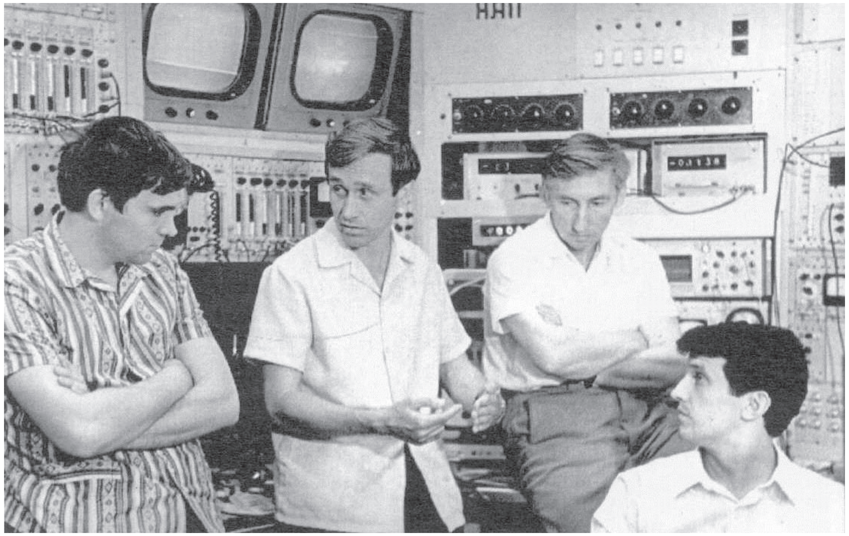

V.Parkhomchuk, A.Skrinsky, I.Meshkov,
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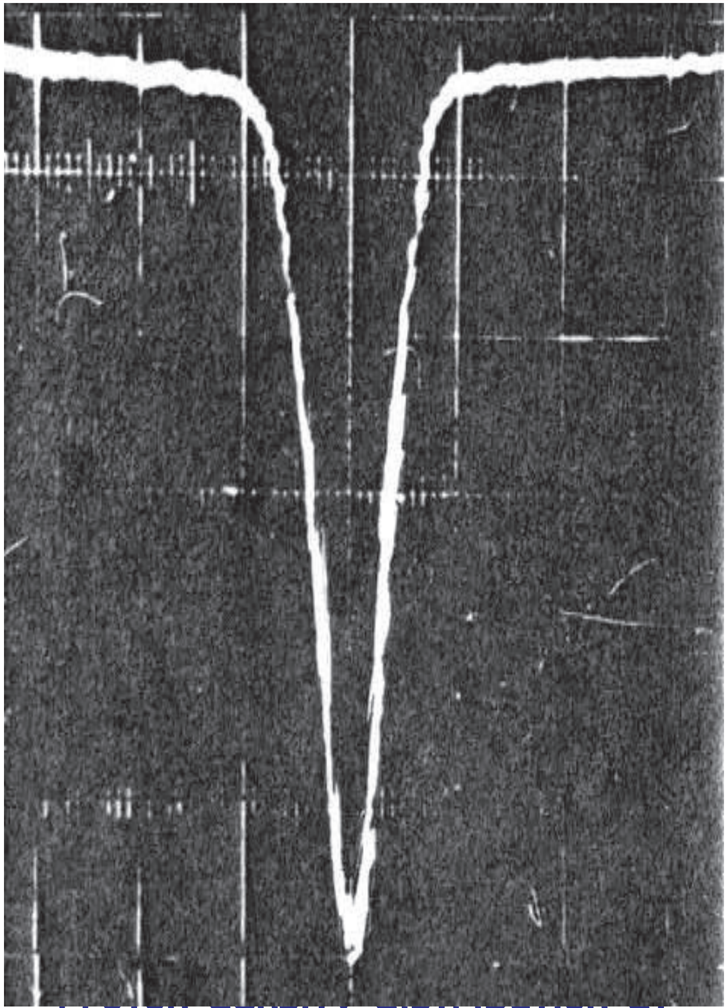
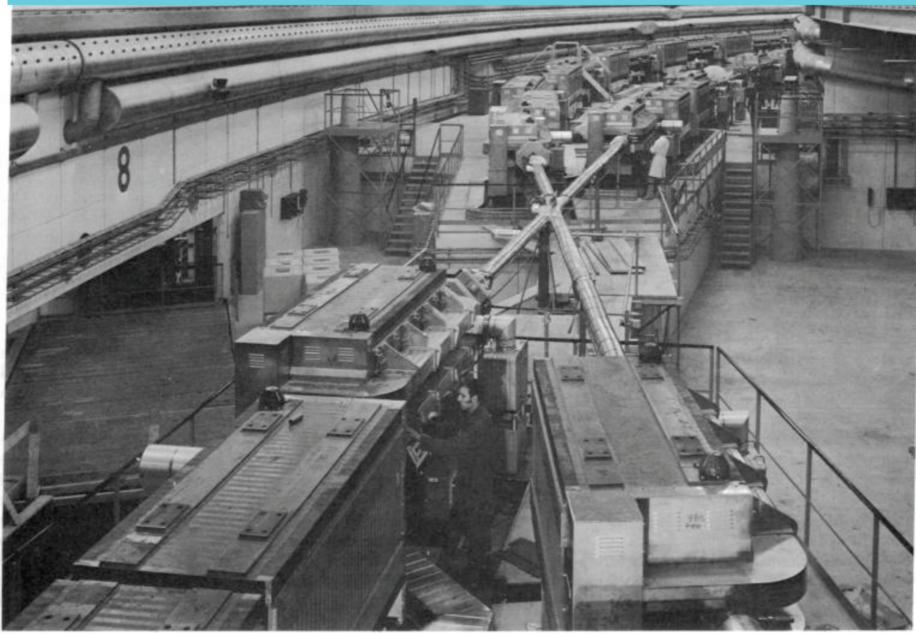
Electron cooling theory in progress: Ya.Derbenev (1977)



electron cooling (BPM based on Mg vapor jet, NAP-M, 1975)

Stochastic cooling: ISR experiment (1975)

1975 – First experimental demonstration of emittance cooling



ISR – Intersecting Storage Rings
1971 – 1984
1^{st} pp collider, 2 x 28 GeV
C_{Ring} = 942.66 m

"…After developing a primitive theory (1968) I therefore did not pursue this subject. However, the work was taken up by others and in 1974 the first experiments were done in the ISR."

Simon van-der-Meer, Autobiography of Nobel Laureat

Stochastic cooling: ISR experiment (1975)

1975 – First experimental demonstration of emittance cooling

Lars Thorndahl & Dieter Möhl

("others" who has done the work)

"...After developing a primitive theory (1968) I therefore did not pursue this subject. However, the work was taken up by others and in 1974 the first experiments were done in the ISR."

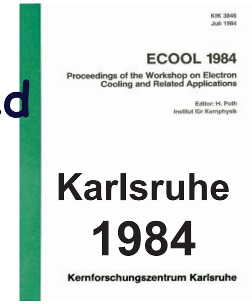
Simon van-der-Meer,
Autobiography of Nobel Laureat

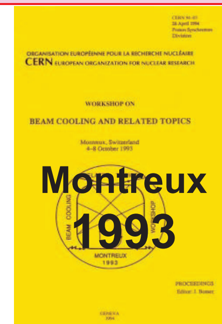
1.3. Cooling Boom: First Generation of Cooler Storage Rings

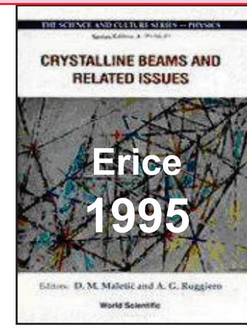
	Facility (Lab)	Operation years
1	NAP-M (Storage Ring for Antiprotons – Model, Budker INP)	1974 - 1984
2	ICE (Initial Cooling Experiment, CERN)	1979 - 1980
3	Test Ring (FNAL)	1980 - 1982
4	MOSOL (MOdel of SOlenoid, BINP)	1986 - 1988
5	LEAR (Low Energy Antiproton Ring, CERN)	1988 - 1996
6	IUCF Cooler (Indiana Univ. Cyclotron Facility)	1988 - 2002
7	TSR (Test Storage Ring, MPI, Heideberg)	1988 =>
8	TARN-II (Test Accumulation Ring for Numatron, Tokyo Univ.)	1985 - 2000
9	ASTRID (Aarhus STorage RIng in Denmark, Aarhus Univ.)	1989 - 2005
10	CELSIUS (Cooling with ELectrons and Storing of Ions from Uppsala Synchrocyclotron, Uppsala Univ.)	1989 – 2005
11	ESR (Experimental Storage Ring, GSI)	1990 =>
12	CRYRING (CRYebis connected to a small synchrotron RING, MSL, Stockholm Univ.)*)	1992 - 2009
13	COSY (COoler-SYnchrotron, FZJ)	1992 =>

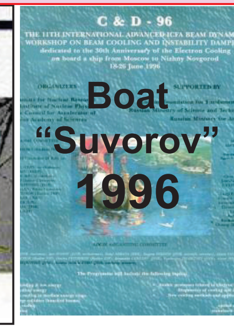
*) See C/J/Harlander and A.Barany, in Proc. of ECOOL'1984

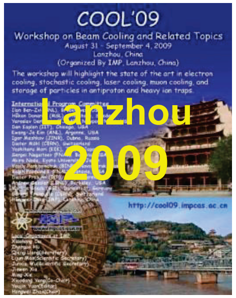
...and developed with the lapse of time:



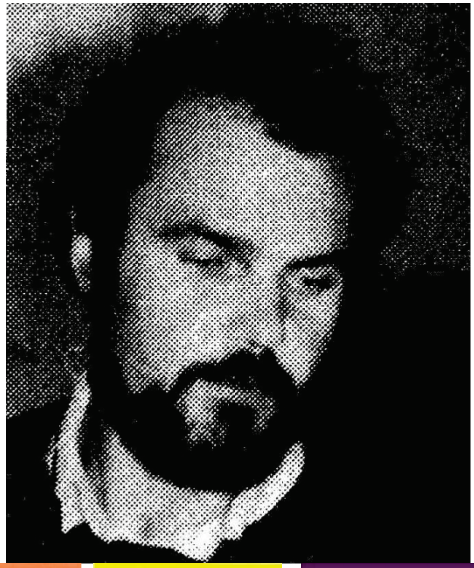




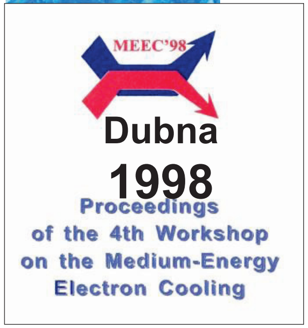


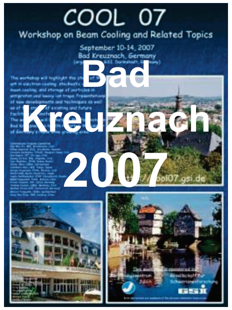


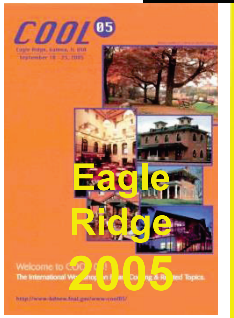
1984
First
Cooling
Workshop
(Karlsruhe)...

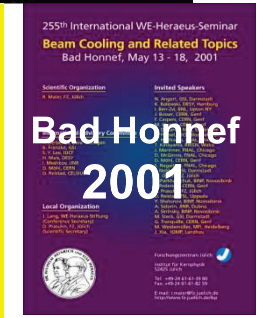


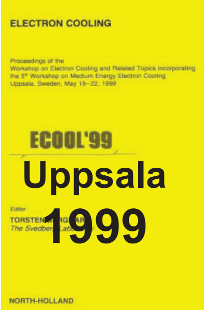
...organized
by
Dr. Helmut
Poth...











First laser cooling in cooler storage rings

1990 TSR
(Mainz Univ.,
GSI,
MPI Heidelberg)

VOLUME 64, NUMBER 24 PHYSICAL REVIEW LETTERS 11 JUNE 1990

First Laser Cooling of Relativistic Ions in a Storage Ring

S. Schröder, R. Klein, N. Boos, M. Gerhard, R. Grieser, G. Huber, A. Karafillidis, M. Krieg, and N. Schmidt
Institut für Physik der Universität Mainz, D-6500 Mainz, Federal Republic of Germany

T. Kühl and R. Neumann
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

V. Balykin,[a] M. Grieser, D. Habs, E. Jaeschke, D. Krämer, M. Kristensen,[b] M. Music, W. Petrich, D. Schwalm, P. Sigray,[c] M. Steck, B. Wanner, and A. Wolf
Physikalisches Institut der Universität Heidelberg and Max-Planck-Institut für Kernphysik, D-6900 Heidelberg, Federal Republic of Germany
(Received 26 February 1990)

The first successful laser cooling of ions at relativistic energies was observed at the Heidelberg TSR storage ring. A $^7Li^+$-ion beam of 13.3 MeV was overlapped with resonant copropagating and counter-propagating laser beams. The metastable ions were cooled from 260 K to a longitudinal temperature of

1991 ASTRID
(Aarhus Univ.)

VOLUME 67, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 1991

Laser Cooling of a Stored Ion Beam to 1 mK

J. S. Hangst,[a],[b] M. Kristensen, J. S. Nielsen, O. Poulsen, J. P. Schiffer,[a] and P. Shi
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark
(Received 5 February 1991)

The interaction of laser-induced and intrabeam forces has been studied in a dense stored beam of 100-keV $^7Li^+$ ions. A fraction of the ions ($\sim 10^{-4}$) exist in the metastable $1s2s\ ^3S$ state. Using this state as a laser spectroscopic probe, we observe fast longitudinal heating in the injected, nonequilibrium distribution due to Coulomb scattering. Laser cooling of the metastable ions is ineffective during this heating period. The metastable fraction of the equilibrated beam is subsequently laser cooled to a longitudinal temperature of ~ 1 mK, the lowest temperature ever reported in a stored ion beam.

1.4. 1990 - 2012 The Productive Years

- ✓ Both electron and stochastic cooling systems became routine tools at cooler storage rings
- ✓ 1993 – 2010 BETACOOL code for cooling processes simulation developed (JINR) and experimentally tested at COSY, ESR, CELSIUS, LEAR, Fermilab Recycler…)
- ✓ 1998 SchwerIonen Synchrotron [German] (SIS-18, GSI)
- ✓ 2000 Heavy Ion Medical Accelerator in Chiba (HIMAC, Chiba-Inage, Japan)
- ✓ 2000 Antiproton Decelerator (AD, CERN) - commissioning with E- and S-cooling

- 2001 Beginning of International Muon Ionization Cooling Experiment (MICE) at RAL and Fermilab
- 2005 S-LSR (Small Laser Equipped Storage Ring, Kyoto Univ.) - commissioning with E-cooling
- 2005 Recycler (Fermilab) – commissioning of "The Pelletron", HV E-cooler of 4.3MeV and 1 A electron current
- 2006 Low Energy Ion Ring (LEIR, CERN) - commissioning with E-cooling of Pb ions (E-Cooler has been constructed at BINP)
- 2008 Heavy Ion Research Facility at Lanzhou (HIRFL, IMP Lanzhou) - - commissioning with E-cooling (E-Coolers have been constructed at BINP)
- Very recent "Past":
  2013 March S-LSR (Kyoto Univ.) - 3D Laser cooling

II. Highlights of Cooling Application: Particle Physics

W± and Z Bosons

Antiproton Generation Complex at CERN
based on stochastic cooling application,
Antiproton Accumulator (AA)
has been constructed ~ 1978.
Owing to this technology construction of
first $\tilde{p}p$ collider
The Super Proton Antiproton Synchrotron ($S\tilde{P}PS$)
became possible.

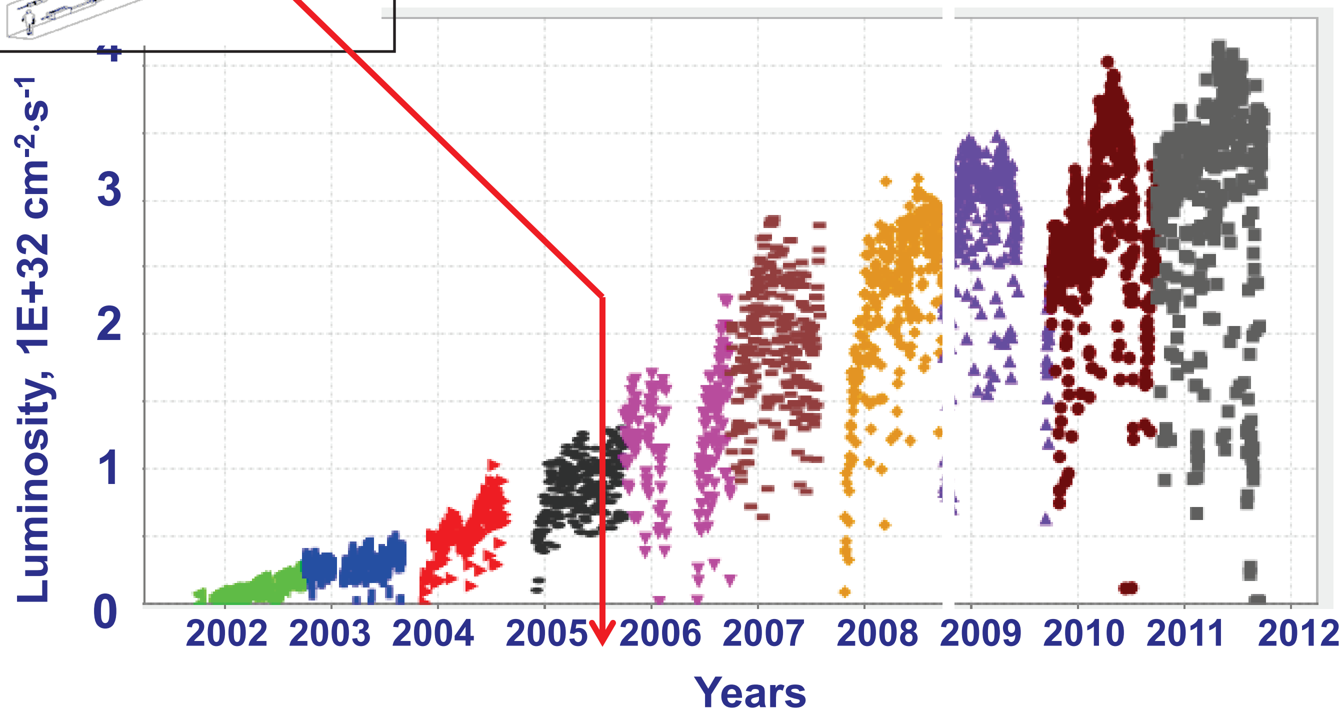
It resulted in the discovery of "nobel level".

2000 – 2011: p̃p Collider Tevatron (Fermilab)

Run IIA
p̄p 2x900 GeV
$L_{max} = 4 \cdot 10^{32}$ cm^{-2}·s^{-1}

Steady Progress

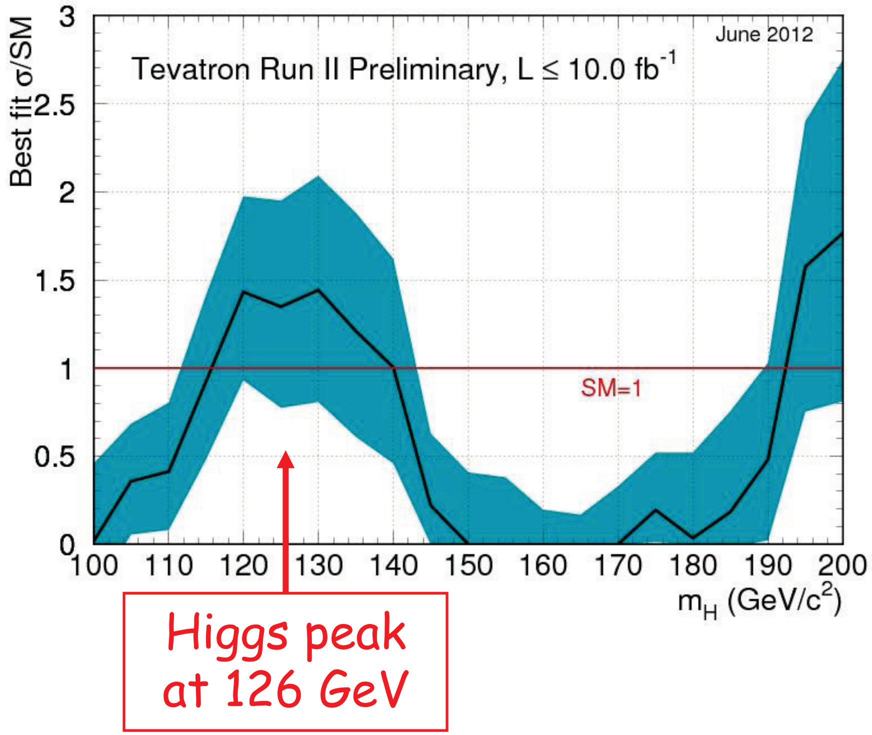
Tevatron Peak Luminosity

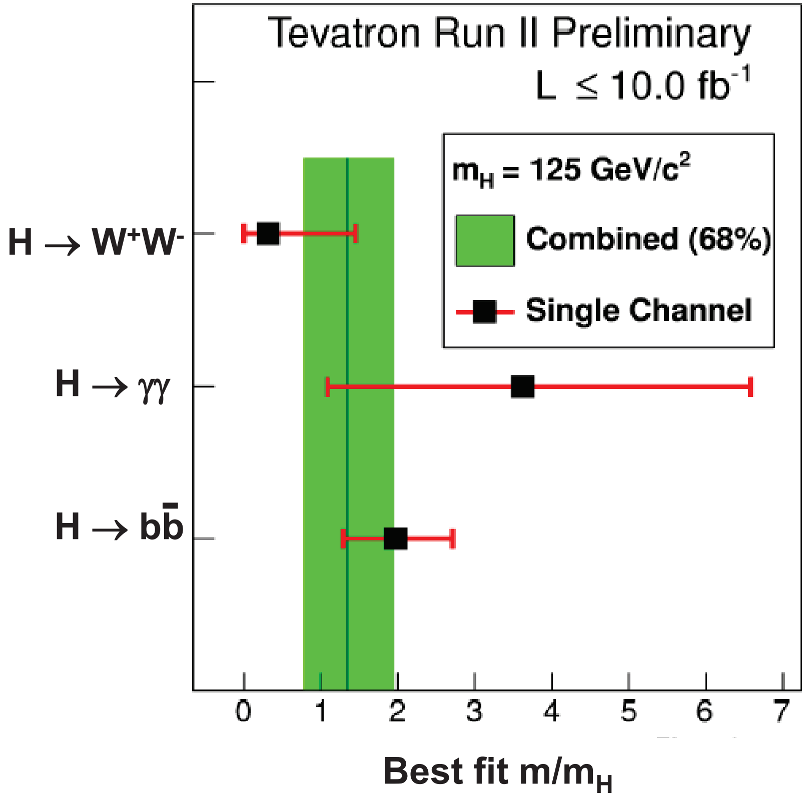


2001 – 2011 Integrated luminosity 11.87103 1/fb ≈ 1.19e39 cm^{-2}

2000 – 2011: p̃p Collider Tevatron (Fermilab)

2 July 2012, Fermilab seminar





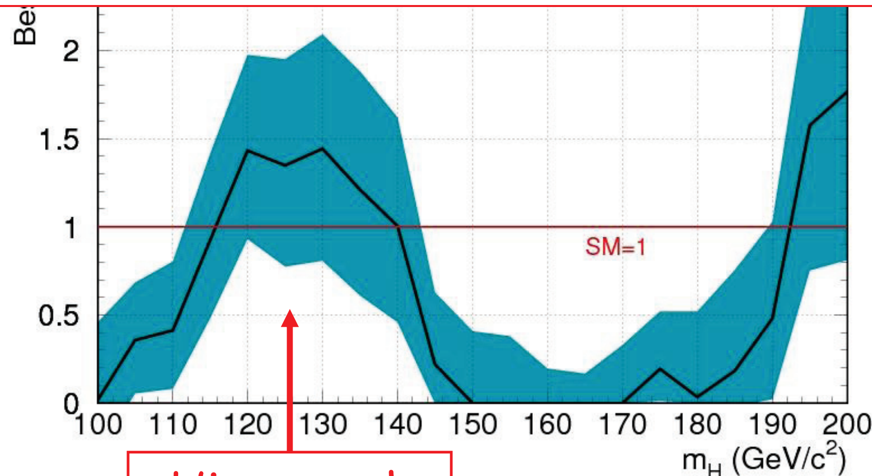
$$\int L \cdot dt \approx 12\ fb^{-1} = 1.2e40\ cm^{-2}$$

II. Highlights of Cooling Application: Particle Physics

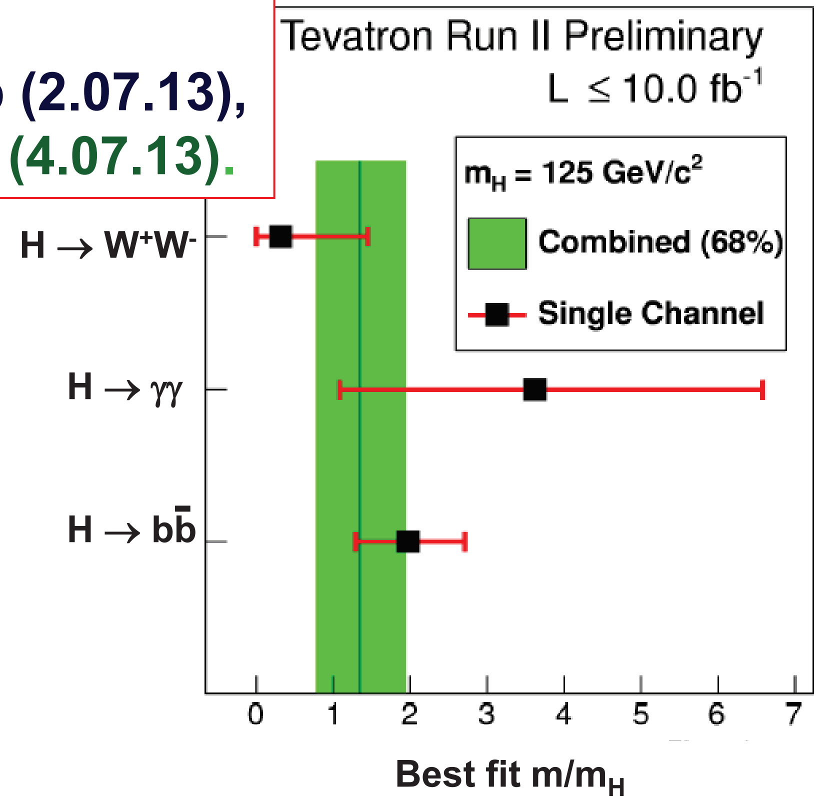
2000 – 2011: p̃p Collider Tevatron (Fermilab)

2 July 2012, Fermilab seminar

1 sigma => random fluctuations,
3 sigma => an observation => Fermilab (2.07.13),
5-sigma result is a discovery => CERN (4.07.13).

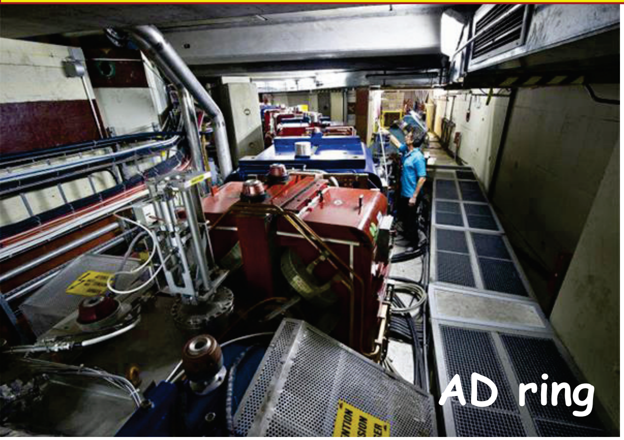


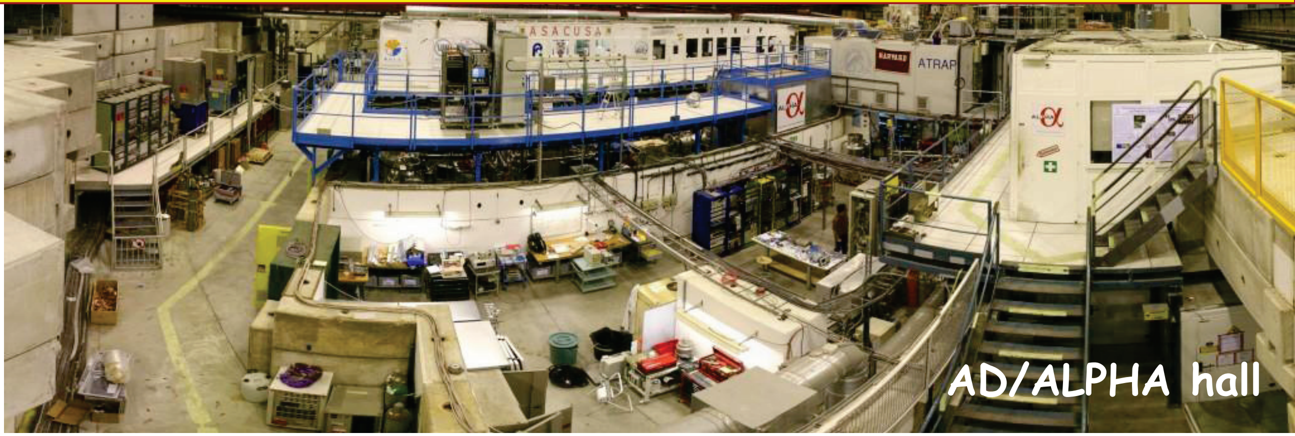
Higgs peak at 126 GeV



$$\int L \cdot dt \approx 12\ fb^{-1} = 1.2e40\ cm^{-2}$$

2010: AD and First H-bar Generation in ALPHA Trap





<u>Stochastic and electron cooling</u> in AD allows to store and decelerate sufficient number of p-bars for 3 experiments – ALPHA, ASACUSA & ATRAP

Antihydrogen Laser PHysics Apparatus (ALPHA)

ALPHA Experiment

17 November 2010 - the first to capture and store **38 antihydrogen atoms for about 170 ms**.

26 April 2011 - **309 antihydrogen atoms** trapped and kept, some for as long as **1,000 seconds** (about 17 minutes)

1996 ESR (GSI)

Half-Life measurements of Bare, Mass-Resolved Isomers in a Storage-Cooler Ring

H.Irnich, H.Geissel, F.Nolden et al.

The influence of atomic electron shell on the half-lives of different nucleus

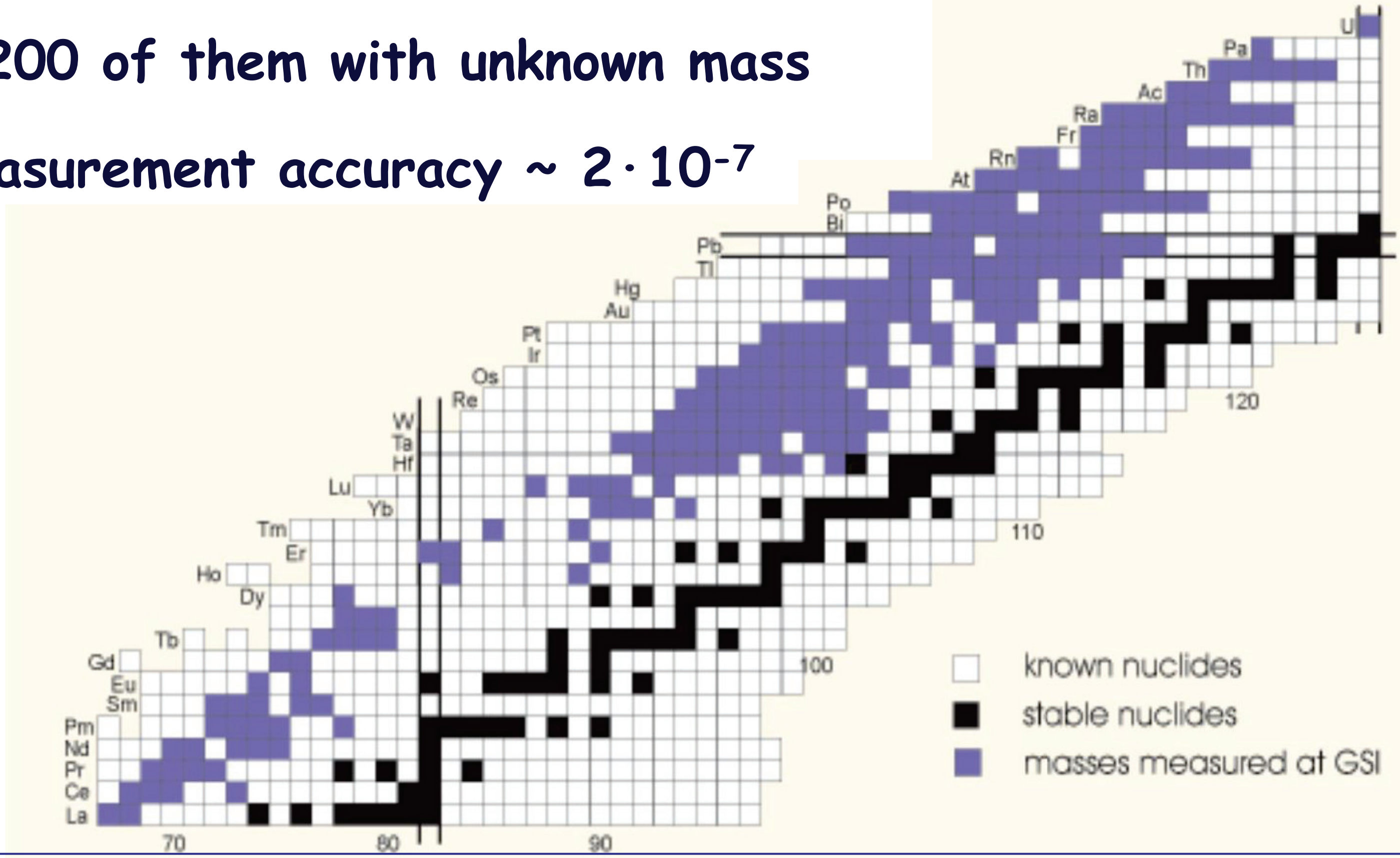
Nucleus	half-lives		
	neutral (exper.)	bare (theory)	bare (exper.)
^{52m}Mn	21.2(2) min	21.5(6) min	22.7(3.0) min
^{52}Fe	8.275(8) h	15.1(5) h	$12.5(^{+1.5}_{-1.2})$ h
^{53g}Fe	8.51(2) min	8.73(8) min	8.5(3) min
^{53m}Fe	2.58(4) min	2.58(4) min	2.48(5) min

1996 -2013 - … ESR (GSI)

High Precision Schottky Mass Spectroscopy

- 194000 peaks identified
- 500 different nuclei
- about 200 of them with unknown mass

Mass measurement accuracy ~ $2 \cdot 10^{-7}$



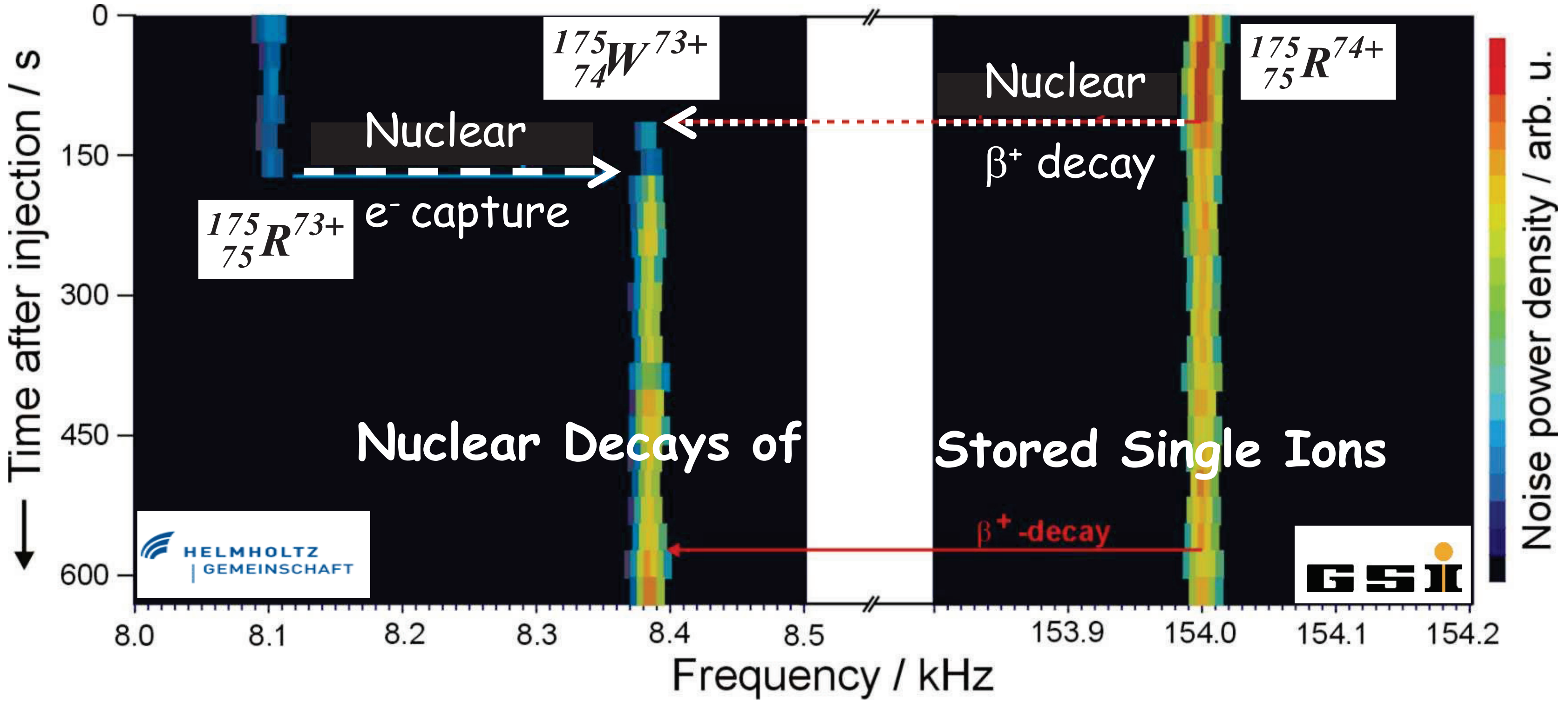
II. Highlights of Cooling Application: Nuclear Physics

1996 -2013 - … ESR (GSI)

High Precision Time-Resolved Schottky Mass Spectroscopy (TR SMS)

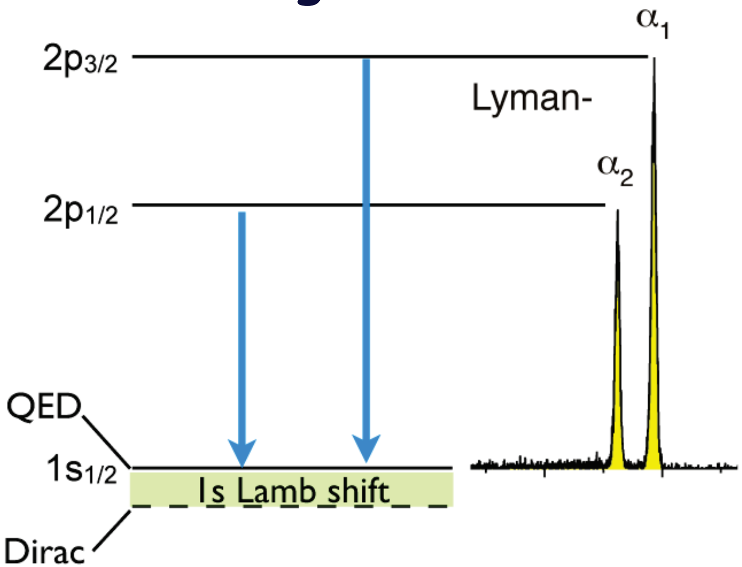
May 10, 2013 Courtesy of Yuri Litvinov and Markus Steck

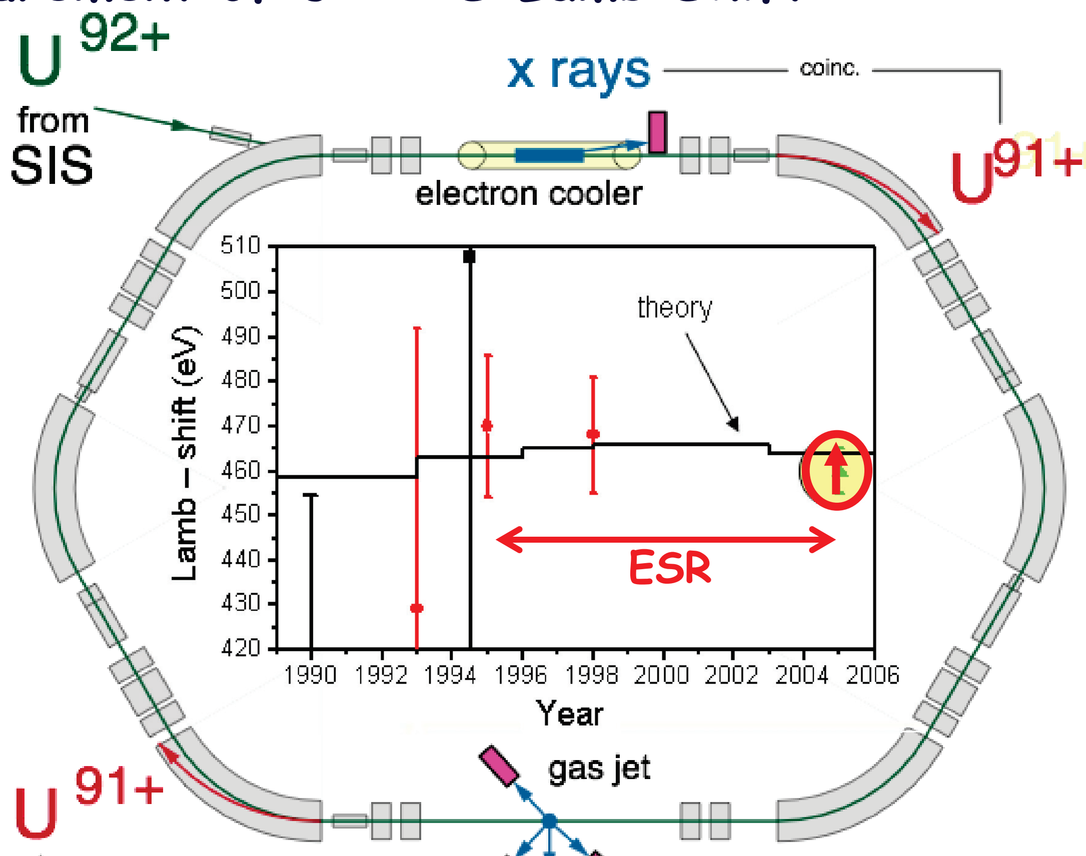
TR SMS is a perfect tool to study nuclei decays in the ESR



1994 - 2005 ESR (GSI)

High Precision Measurement of U^{91+} 1S Lamb Shift





Theory (2001) 460.26 ± 0.5 eV

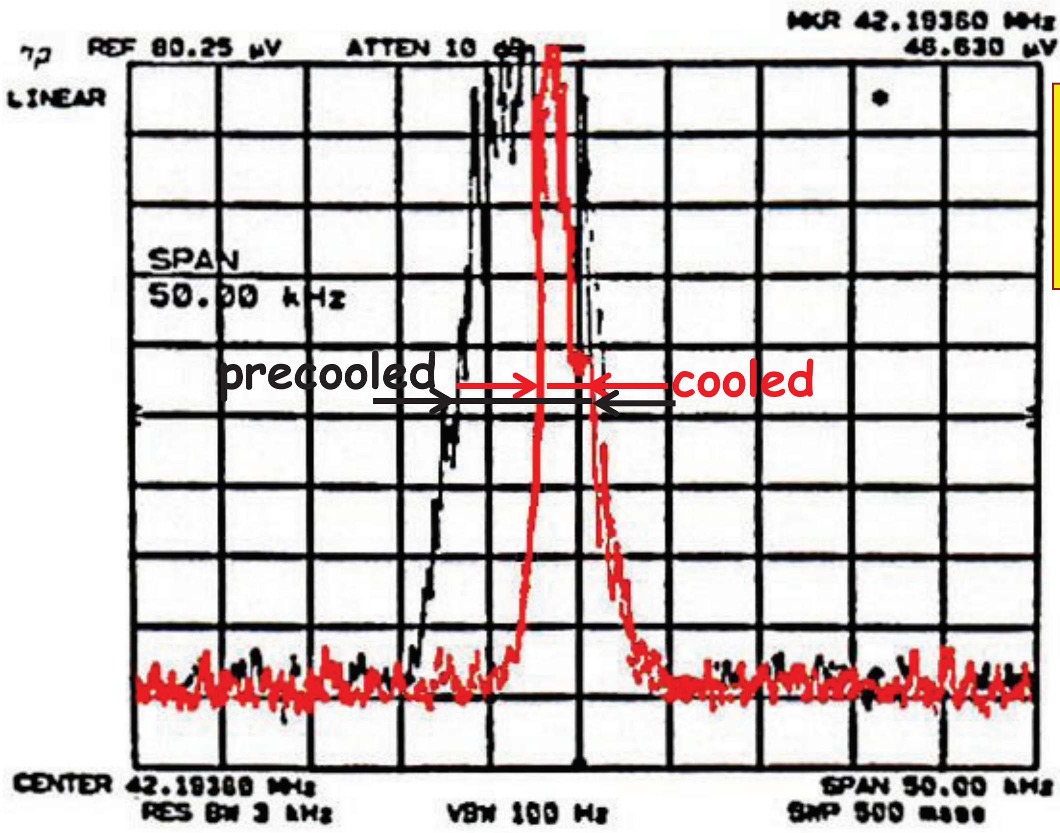
ESR (1995) 470 ± 16 eV

ESR (2005) 460 ± 4.6 eV

QED related studies => to be continued at FAIR

(Th. Stoehlker et al., NIM B 205 (2003) 156)

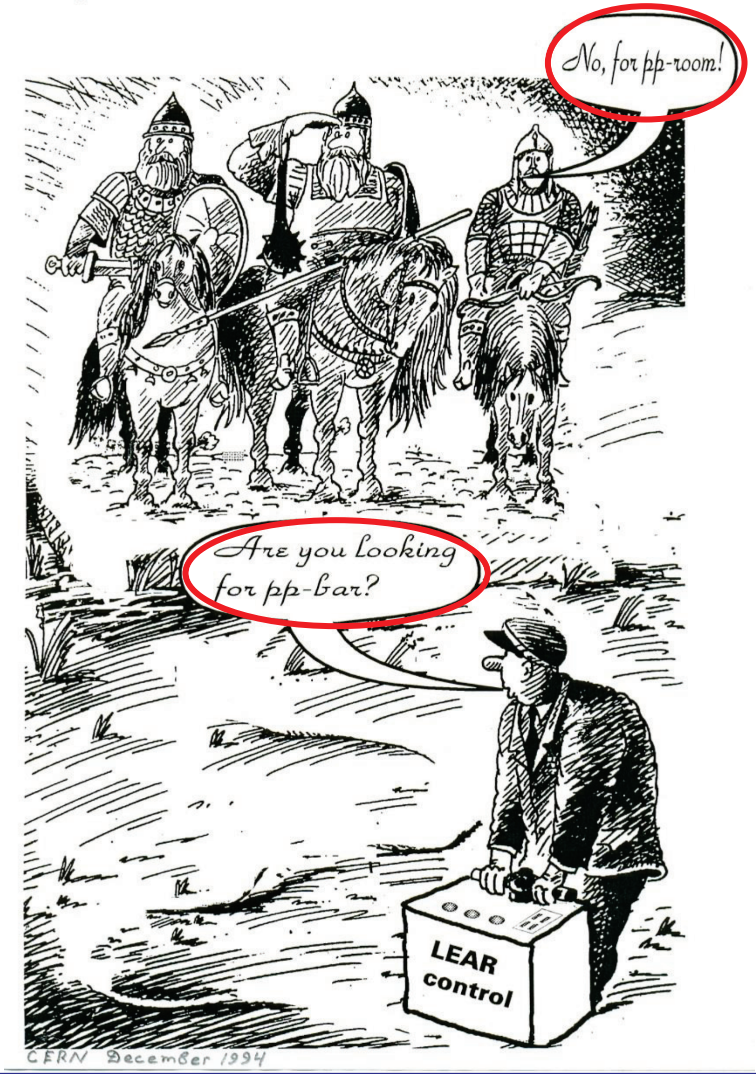
December 14, 1988 First Electron Cooling of Antiprotons



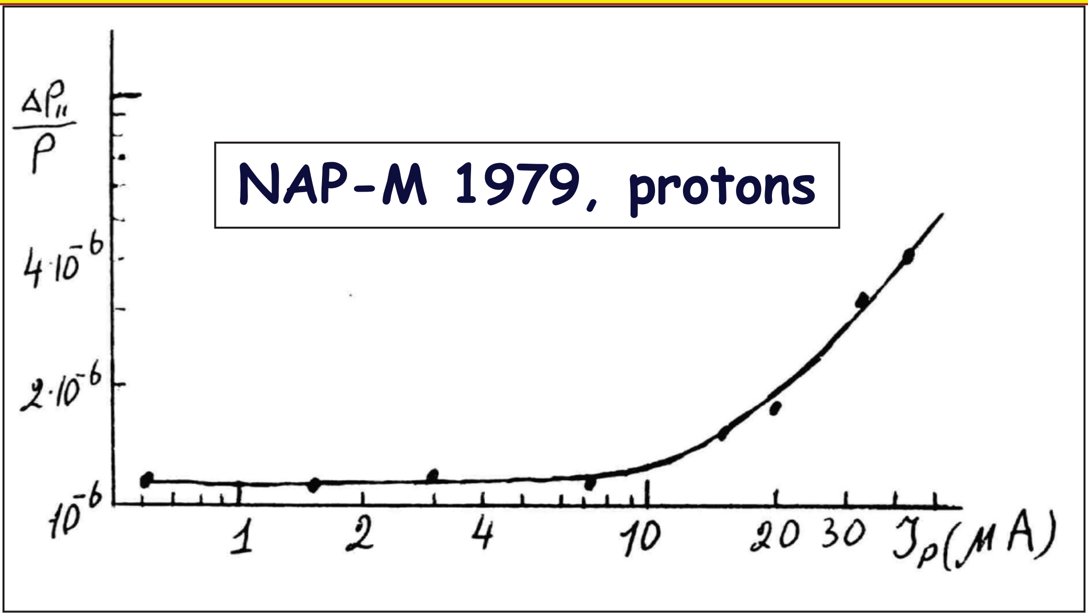
LEAR (CERN)

$\Delta p/p$ = 6e-5

Hot Jokes for Cold Antiprotons (December 1994)



1979 – 2013 => ???? Crystalline Beam

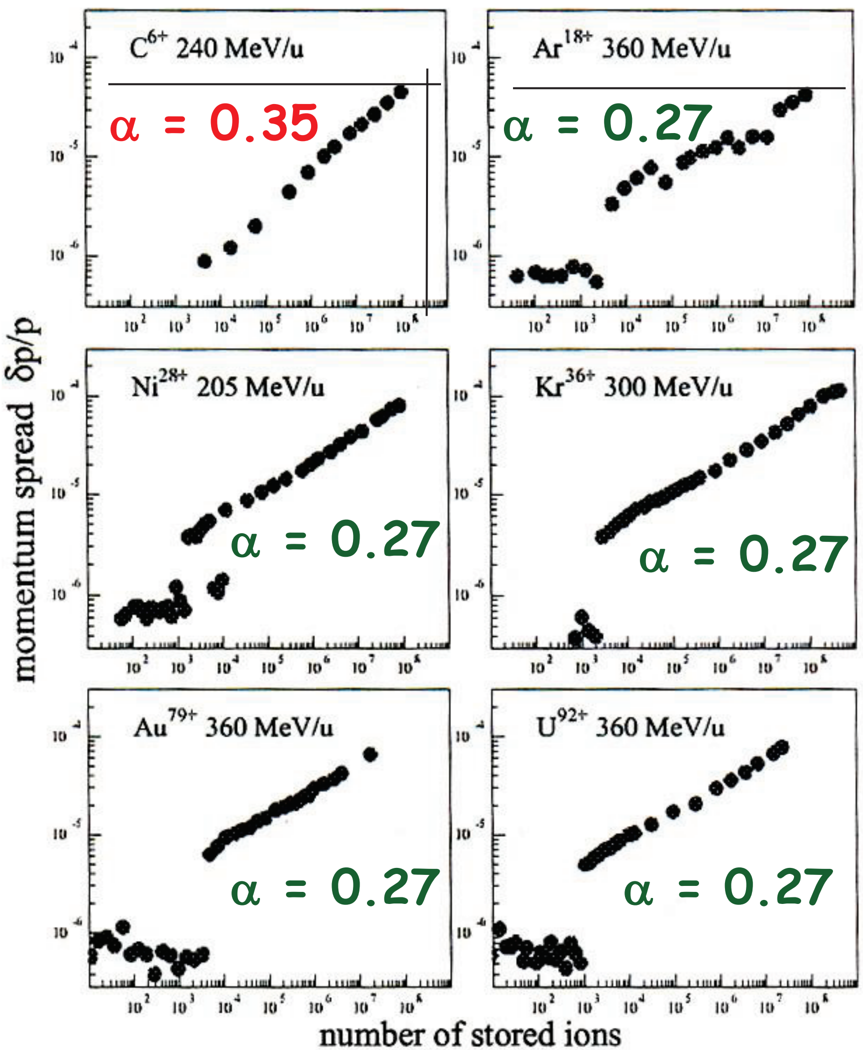


(E.Dementiev, N.Dikansky, V.Parkhomchuk et al., Preprint 79-70 BINP (1979); Preprint 79-41, CERN/PS/AA (1979))

1984 V.Parkhomchuk, Concept of Crystalline Beam

(in Proc. of the Workshop on Electron Cooling and Related Applications, FZ Karlsruhe, 1984, p.71)

$\Delta p/p \propto N^{\alpha}$ 1979 – 2013 => ???? Crystalline Beam



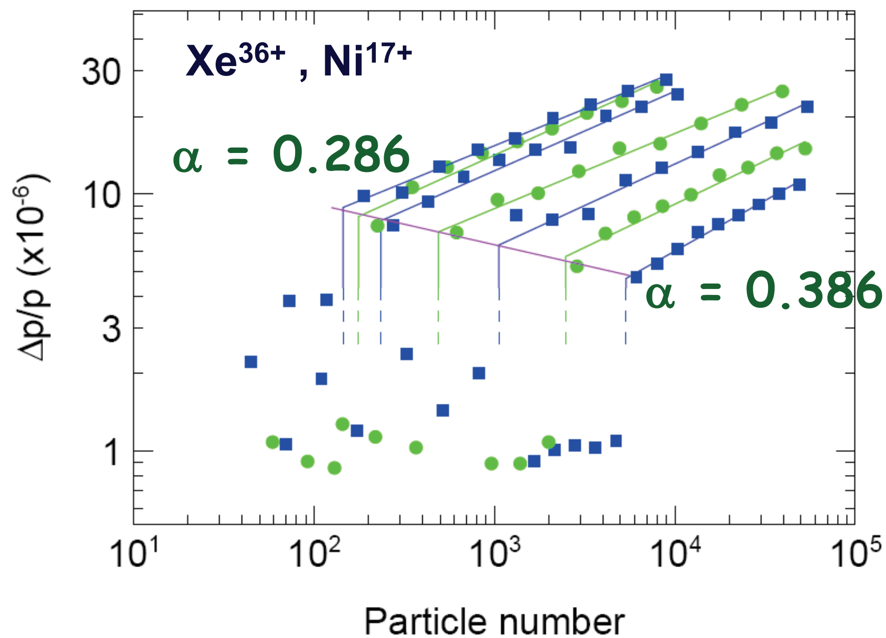
1996 New Stage: Experiments at ESR

M. Steck, *et al.*, PRL 77 (1996) 3803

Phase transition in ion beam: <u>ordering</u>

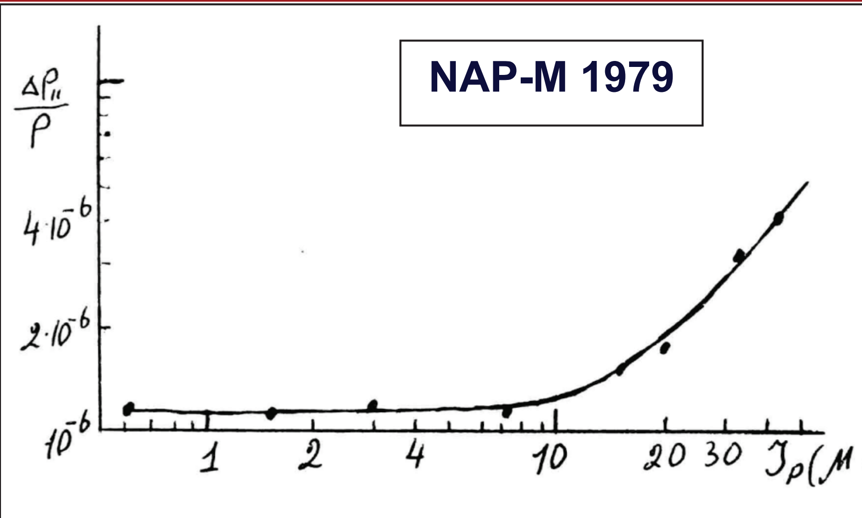
Confirmed at CRYRING

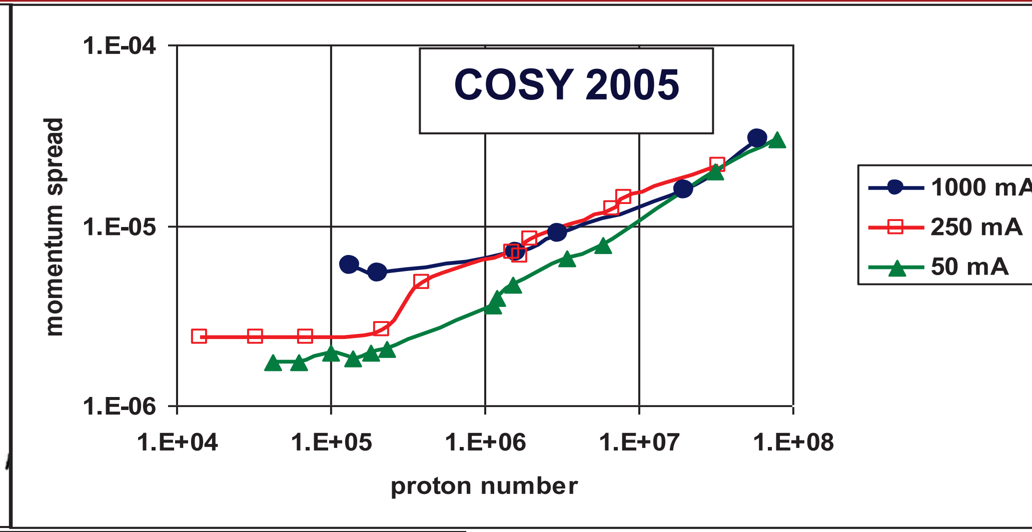
H.Danared et al., PRL 88 (2002) 1003

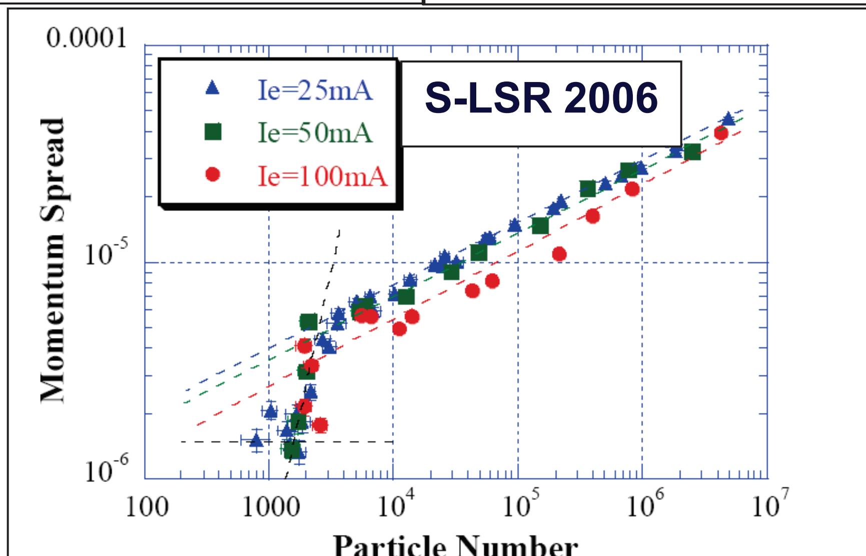


II. Highlights of Cooling Application: Particle Beam Physics

NAP-M / COSY / S-LSR , Proton Ordering







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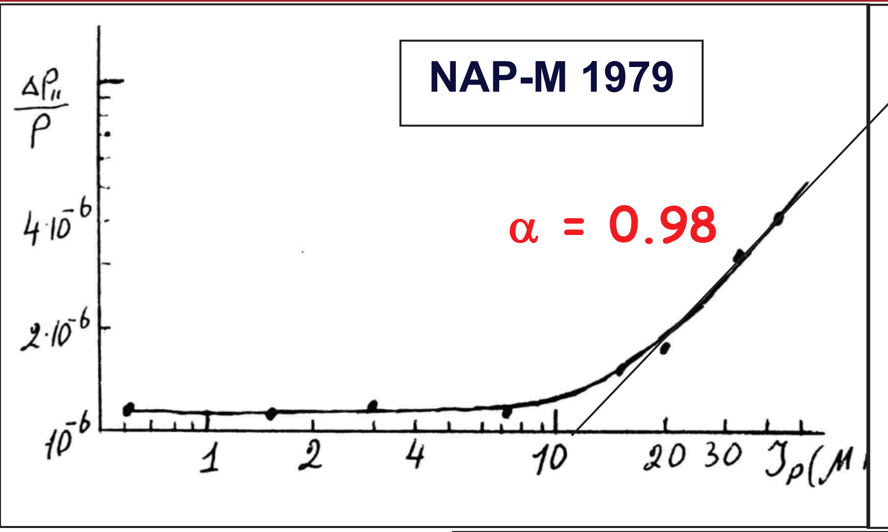
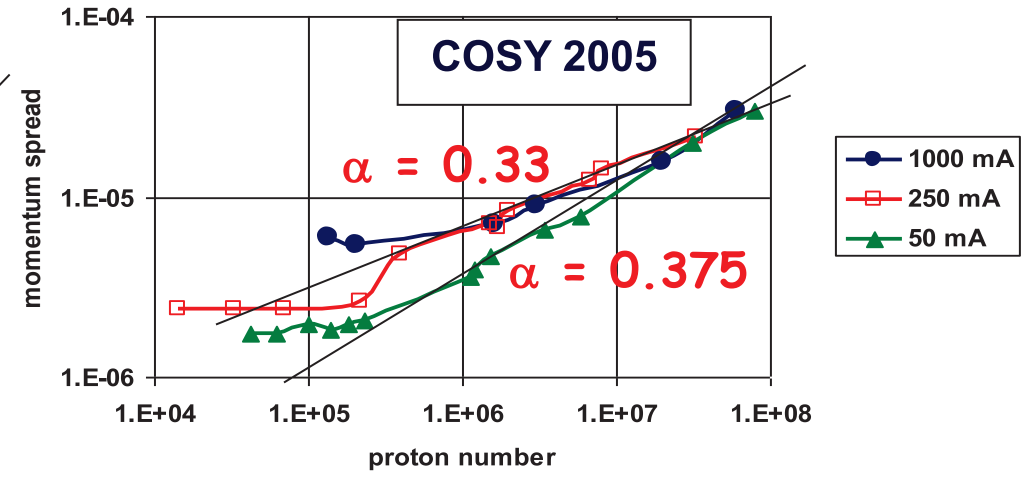
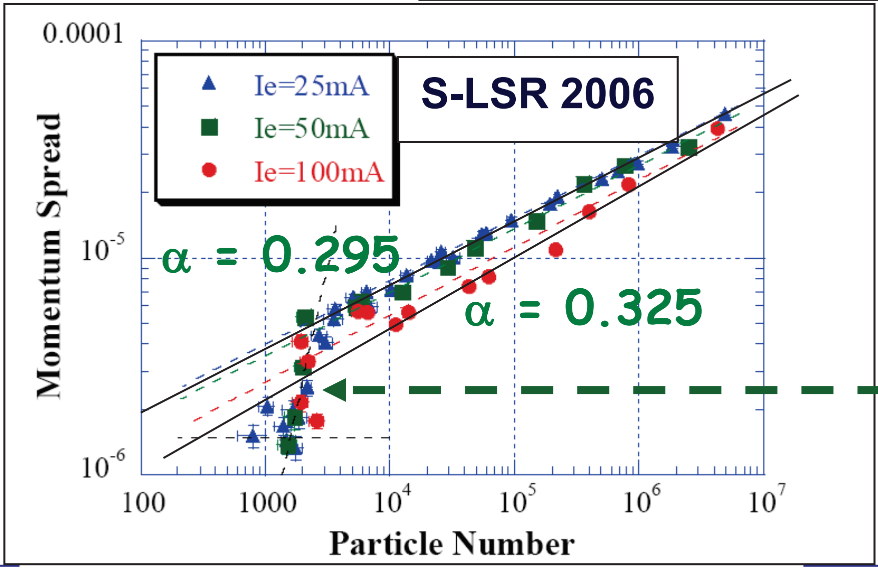






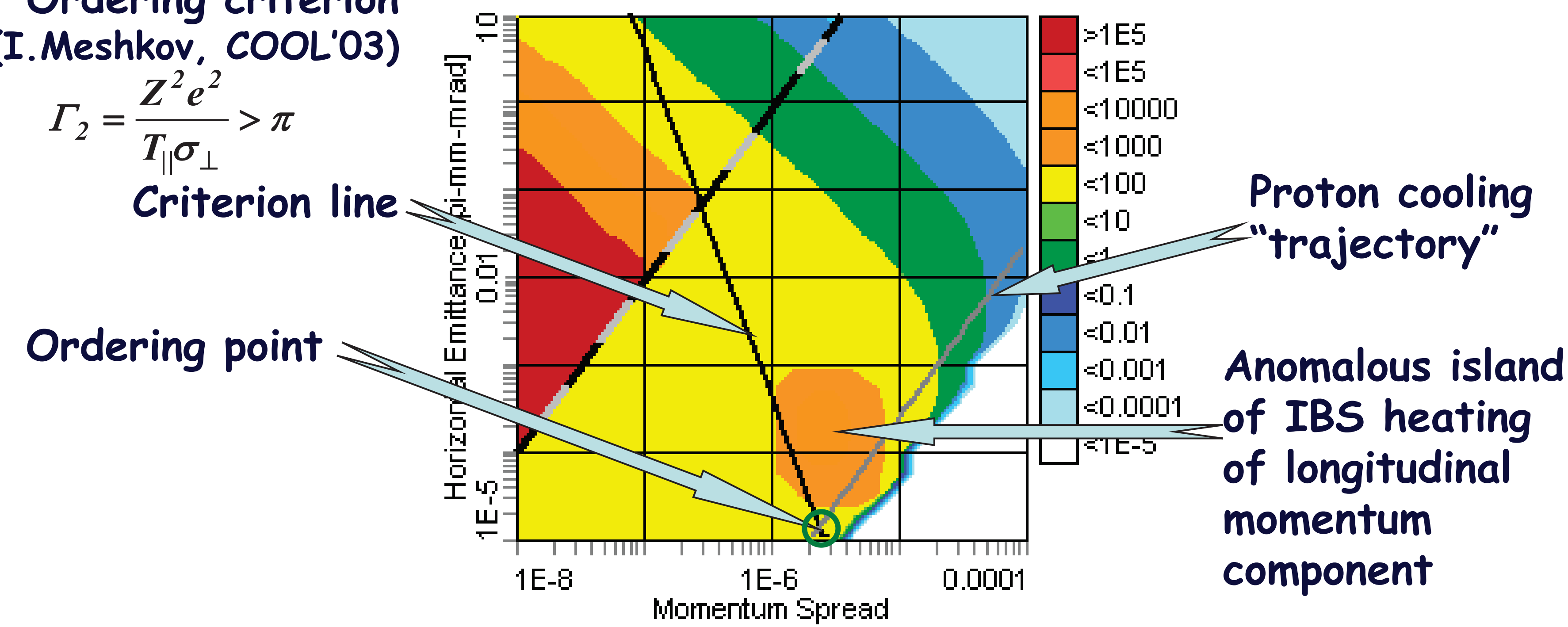
Crystalline Beams: Numerical Simulation

A.Smirnov: BETACOOL Code (2005 -2013)

"3D" Dependence of IBS longitudinal heating rates (in colours) vs horisontal emittance and momentum spread of proton beam (S-LSR, 7 MeV, $N_p = 10^3$)

Ordering criterion (I.Meshkov, COOL'03)

$$\Gamma_2 = \frac{Z^2 e^2}{T_{\|}\sigma_{\perp}} > \pi$$



Stability of Cooled Proton Beam: CELSIUS / COSY / HIMAC

CELSIUS (Uppsala, Sweden):

Injection energy 48 MeV, H^{2+}, stripping injection

Intensity 25 mA (bunched beam), cooling at 400 MeV

COSY (Juelich, Germany): Vertical acceptance 24 $\pi\cdot$mm$\cdot$mrad

Injection energy 45 MeV, H^-, stripping injection

Intensity 8 mA: 10^{11} protons (coasting beam)

HIMAC (Chiba, Japan): Vertical acceptance 24 $\pi\cdot$mm$\cdot$mrad (also!)

Injection energy 6 MeV/u, Ar^{18+}

Intensity $1.5\cdot10^9$ ions (coasting beam)

Stability of Cooled Proton Beam: CELSIUS / COSY / HIMAC

CELSIUS (Uppsala, Sweden):

Injection energy 48 MeV, H…

Intensity 25 mA …

COSY (Ju… … π·mm·mrad

…jection

…sting beam)

All three rings are subjected to "the electron heating"!

HIMAC (… Japan): Vertical acceptance 24 π·mm·mrad (also!)

Injection energy 6 MeV/u, Ar^{18+}

Intensity $1.5 \cdot 10^{9}$ ions (coasting beam)

V.Parhomchuk: Concept of "electron heating"

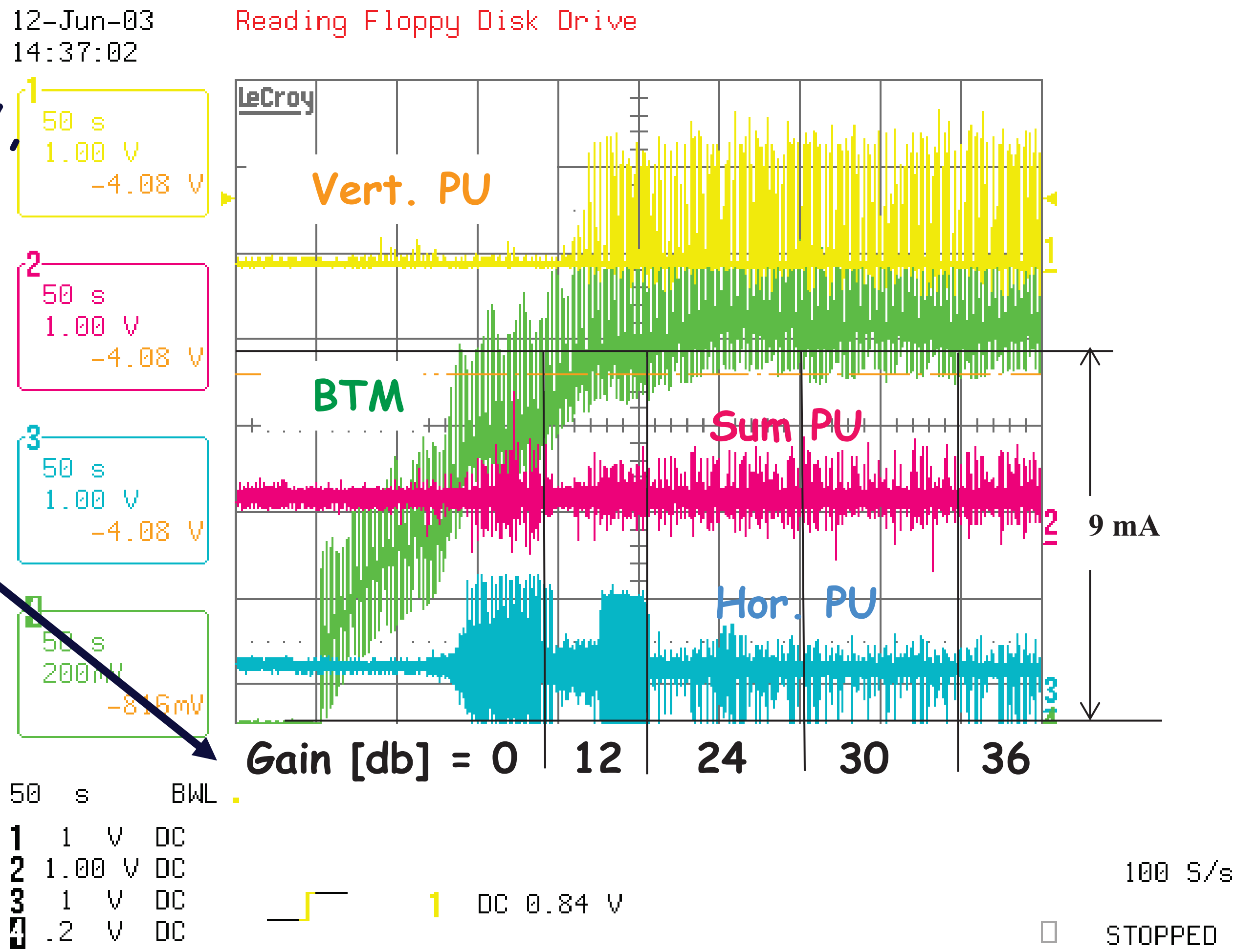
(in Proc. of JAS'2000, p.53; Uspekhi Fiz. Nauk, v.170 (2000) 473)

Vertical Feedback System in COSY (2003)

(COOL'05, J.Dietrich, I.Meshkov, J.Stein et al.)

Protons, 45 MeV, coasting beam, (1 mA = 1.27e10)

Feedback gain optimization



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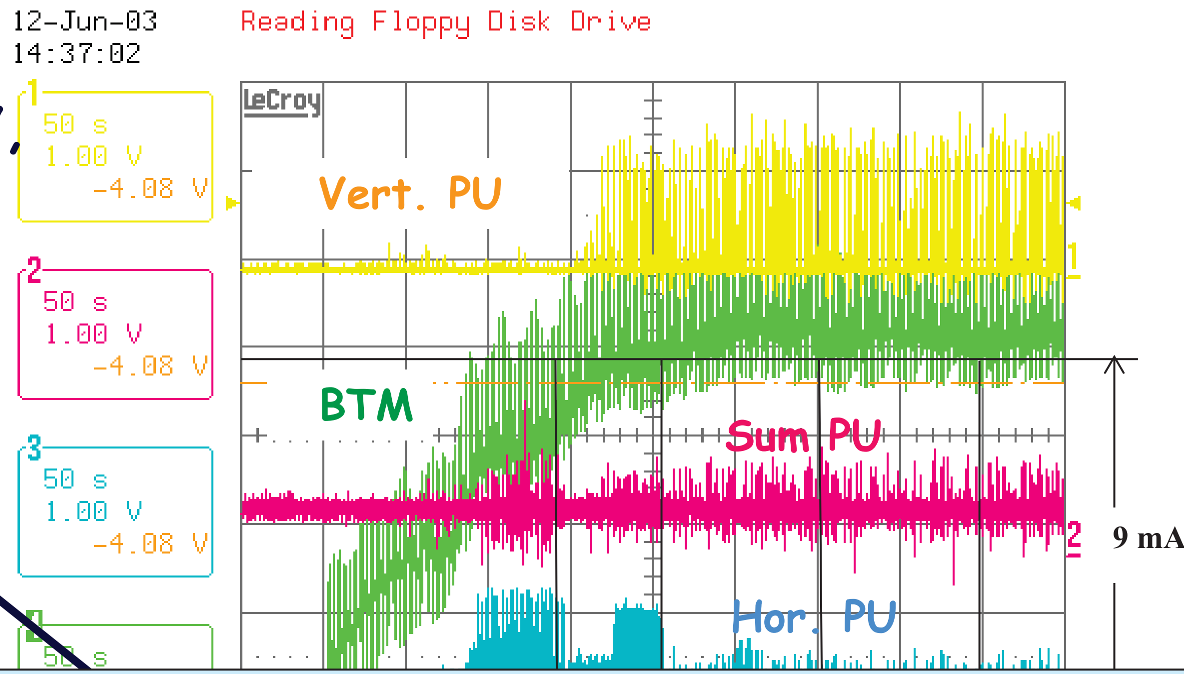


The problem of intensity limitation of an ion beam under electron cooling needs further studies!

Cooler Storage Rings Operated Presently

Facility (Lab)		Application	Commissioning
1	TSR (MPI, Heideberg)	Nuclear and atomic physics, Accelerators technology	1988
2	ESR (GSI)		1990
3	COSY (FZJ)	Particle physics	1992
4	SIS-18 (GSI)	Nuclear physics, Low energy part. phys.	1998
5	HIMAC (Chiba-Inage)	Cancer Therapy	2000
6	AD (CERN)	Physics of “anti-atoms”	2000
7	LEIR (CERN)	Lead ions for LHC	2006
8	S-LSR (Kyoto Univ.)	Particle beam physics	2005
9	CSRm & CSRe (HIRFL, IMP, Lanzhou)	Nuclear and atomic physics,	2008

IV. Present for Future

Projects with Cooling Application under Development
1) Prototyping/Construction/Commissioning Stage

	Project (Lab)	Application	Status
1	**CSR** (MPI, Heidelberg)	Atomic & molecular physics	Commissioning
2	**NICA** (JINR, Dubna)	Particle physics	Construction
3	**FAIR** (Darmstadt)	Particle, nuclear and atomic physics	Design & construction
4	**MICE** (RAL/Fermilab)	ν_μ-fabric, Muon collider	Prototyping
5	**Bunched beam Stochastic Cooling** (RHIC, BNL)	Particle physics	Development
6	**LEPTA** (JINR)	Particle physics	Commissioning with positrons

IV. Present for Future

Projects with Cooling Application under Development

1) Prototyping/Construction/Commissioning Stage

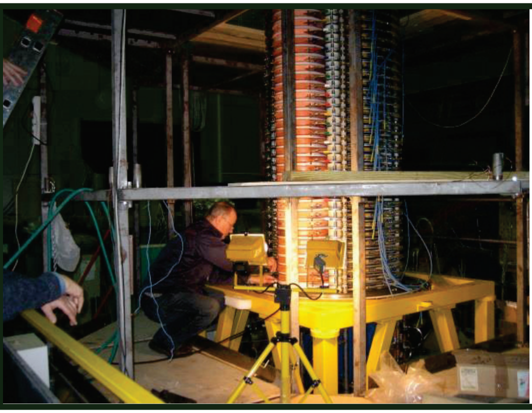
Ultra Low Particle Energy: Cryogenic Storage Ring (CSR) at MPI, Heidelberg

CSR at Assembling

Projects with Cooling Application under Development

1) Prototyping/Construction/Commissioning Stage

Electron Coolers for Future Colliders – NICA and HESR

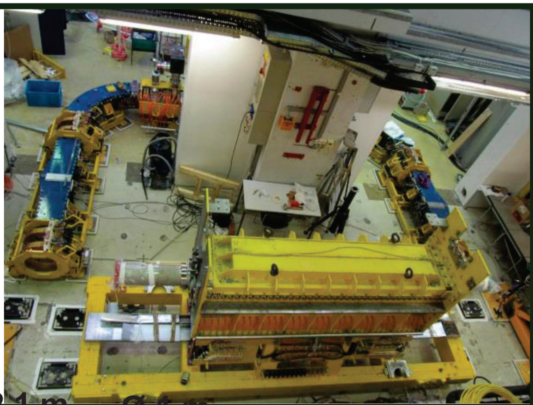


Electron Cooler for COSY: 2.0 MeV, 1.0 A

Dec. 2011, Assembling at BINP

Working now

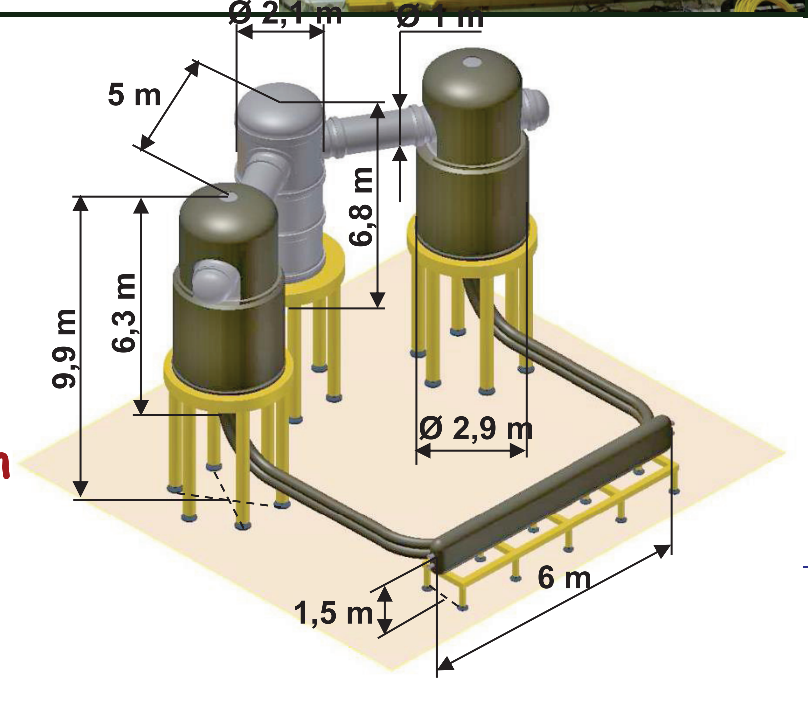
May 2013, Assembling at COSY



BINP Version

Two Versions of Electron Cooler for 2.5 MeV, 0.5

JINR Version



IV. Future

Projects with Cooling Application under Development

2) Conceptual Design ("Paperwork") Stage

	Project (Lab)	Application	Status
1	ELENA (CERN)	Antihydrogen physics	Approved
2	Electron-Ion Collider (JLab)	Particle physics	Concept development
3	eRHIC (BNL)		
4	Coherent electron cooling (BNL/JLab)	Particle, nuclear, atomic physics	

New requirements to synchrotron radiation cooling efficiency appeared with development of

- ✓ SuperB-fabric
- ✓ e^+e^- linear collider
- ✓ Electron-Ion Colliders (JLab, BNL, FAIR (?), …)
- ✓ …

IV. Future

Novel ideas are awaited during this Workshop

- both of "ground break" level

and of technological advance!

Conclusion

Cooling methods were developed for cooling with
synchrotron radiation,
electrons,
high frequency stochastic signal
ionization in medium

And the development continues at new level.

Particle beams being cooled:
electrons, protons, antiprotons, ions… ⇒ muons

Energy Range: 40 keV/u (ions) ÷ 8 GeV (p-bars)

Cooling method	Particles/Ring	Energy	$T_{\|\|}$, K	$T_{\perp}$, K
Electron cooling	$^{40}Ar^{18+}$ / ESR protons / S-LSR	360 MeV/u 7 MeV	10 1.9	2000 11
Laser cooling	$^{9}Be^{+}$ /TSR $^{24}Mg^{+}$/S-LSR	7.3 MeV 40 keV	$5\cdot10^{-3}$ 0.4	- 7.0 (hor.) / 2.1 (ver.)

My Acknowledgements to the colleauges who helped me at preparation of this report:

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A.Noda and M.Griezer,
V.Parkhomchuk,
M.Steck and Yu.Litvinov,
A.Wolf.

Thank you for your attention!