9th European Particle accelerator Conference
EPAC'2004
Lucerne, Switzerland

Electron cooling: remembering and reflecting

Igor Meshkov
JINR, Dubna

Contents

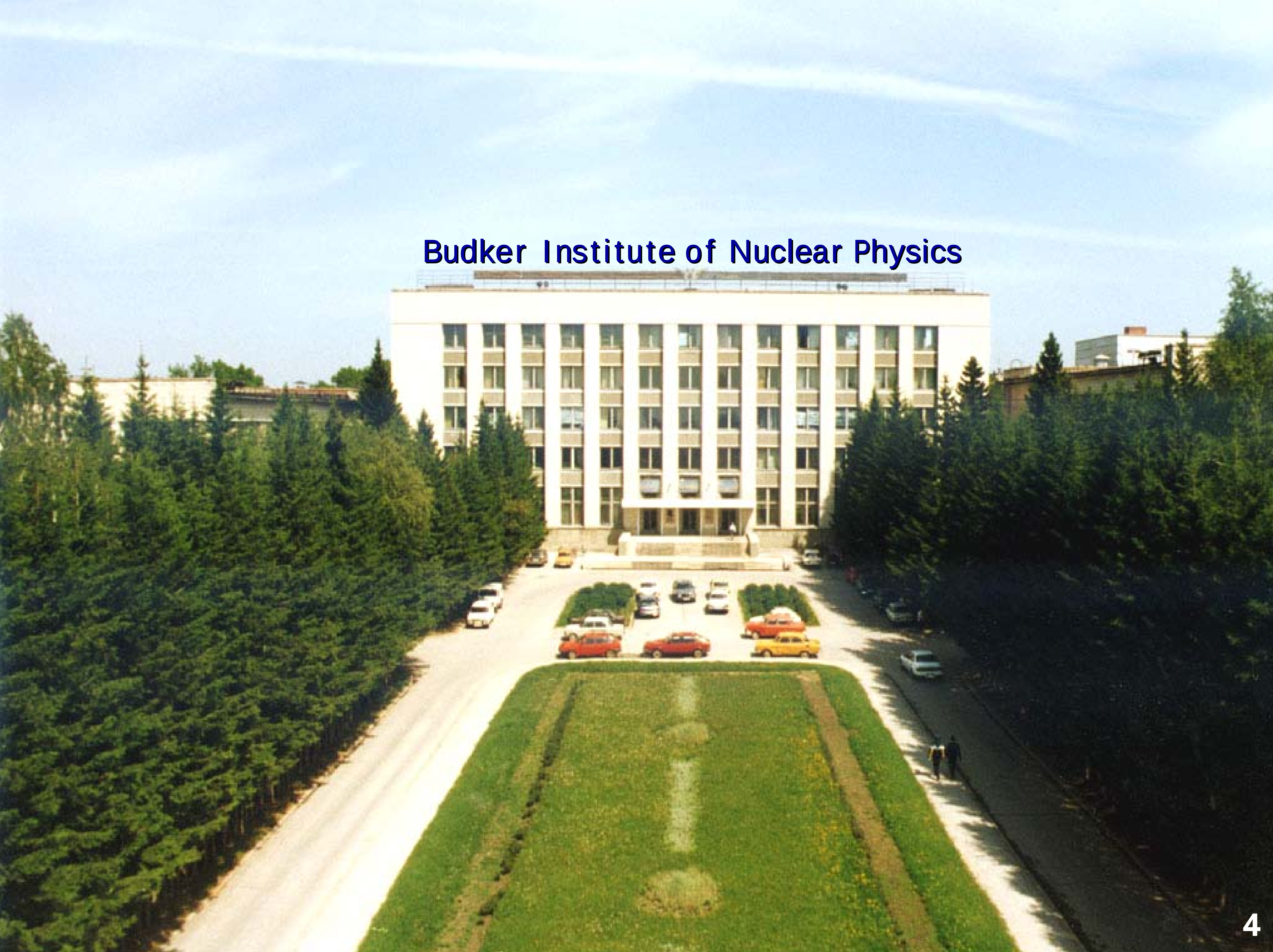
I. Remembering: Highlights and key issues of electron cooling – from idea to realization

II. Reflecting:

1. What is “a harvest?
2. “Nonliouvillean” particle beam physics
3. Where we are and where we go…

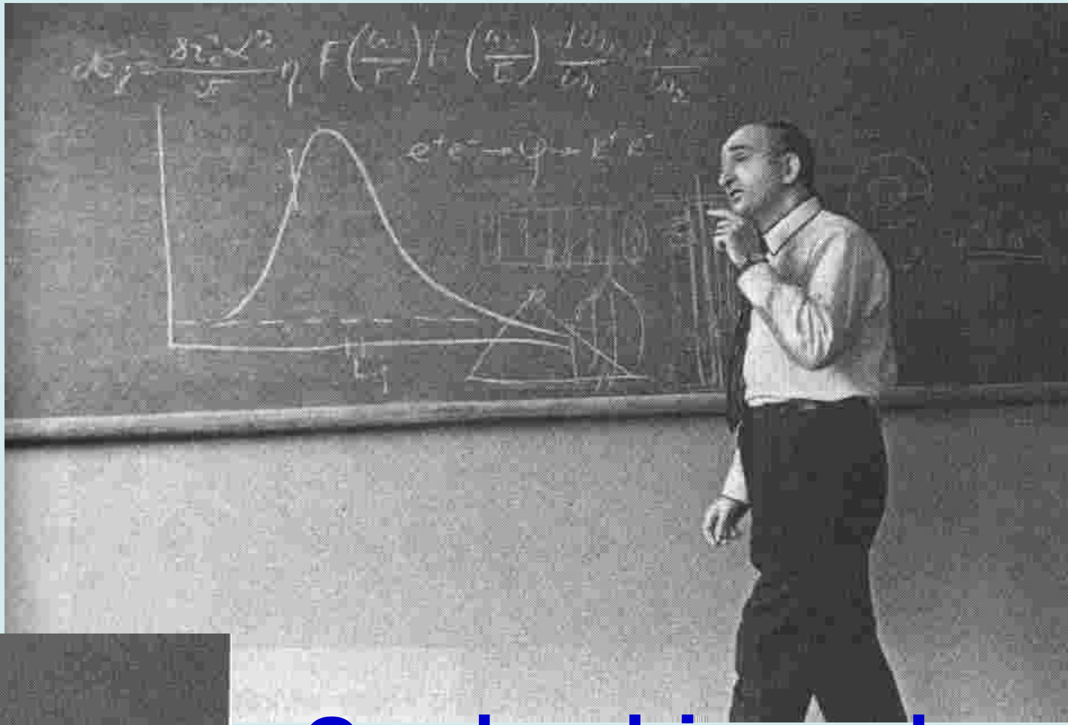
I. Remembering…

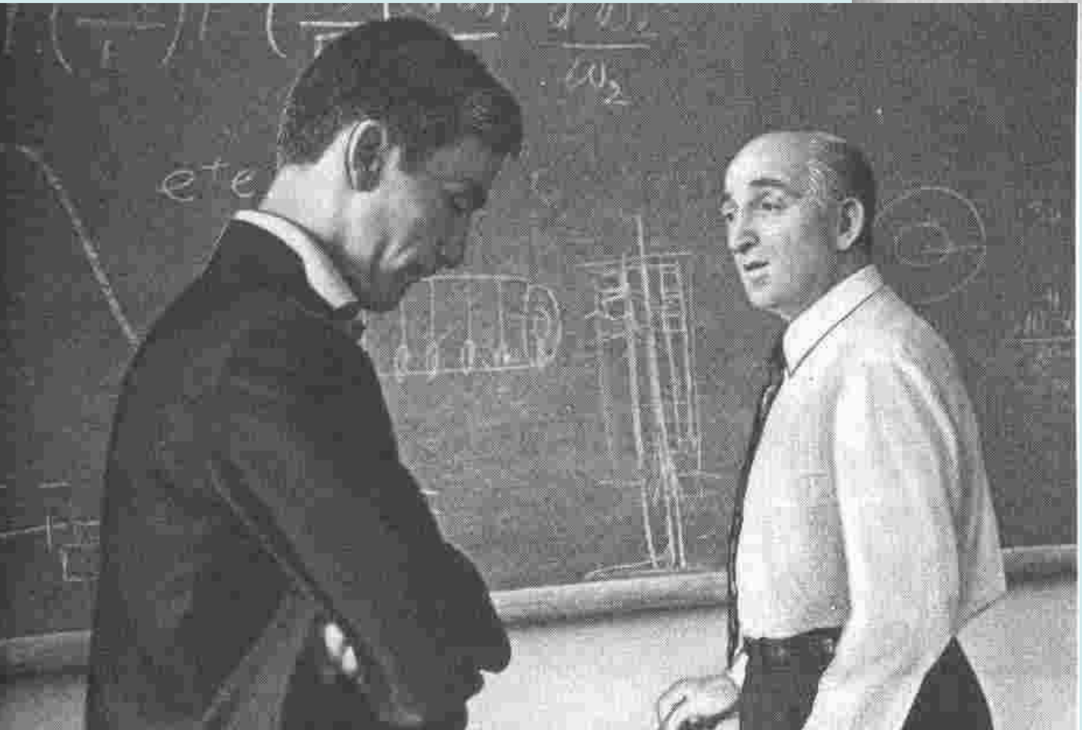
Highlights and key issues of electron cooling – from idea to realization.


Budker Institute of Nuclear Physics

One day

in far 1965th…





…One head is good…

…but two ones are much better…

G.Budker and A.Skrinsky

1966 – The First Report

Budker's formula

$$\tau_{Maxwellian} = \frac{3}{8\sqrt{2\pi}} \cdot \frac{A}{Z^2} \cdot \frac{m_p m_e}{e^4 n_e} \cdot \left(\frac{T_i}{A m_p} + \frac{T_e}{m_e} \right)^{3/2}$$

Laboratoire
l'Accélérateur l
ORSAY

SYMPOSIUM INTERNATIONAL
SUR LES ANNEAUX DE COLLISIONS
A ELECTRONS ET POSITRONS

Sous la présidence de

Monsieur Alain Peyrefitte

Ministre délégué chargé de la recherche scientifique
et des questions atomiques et spatiales

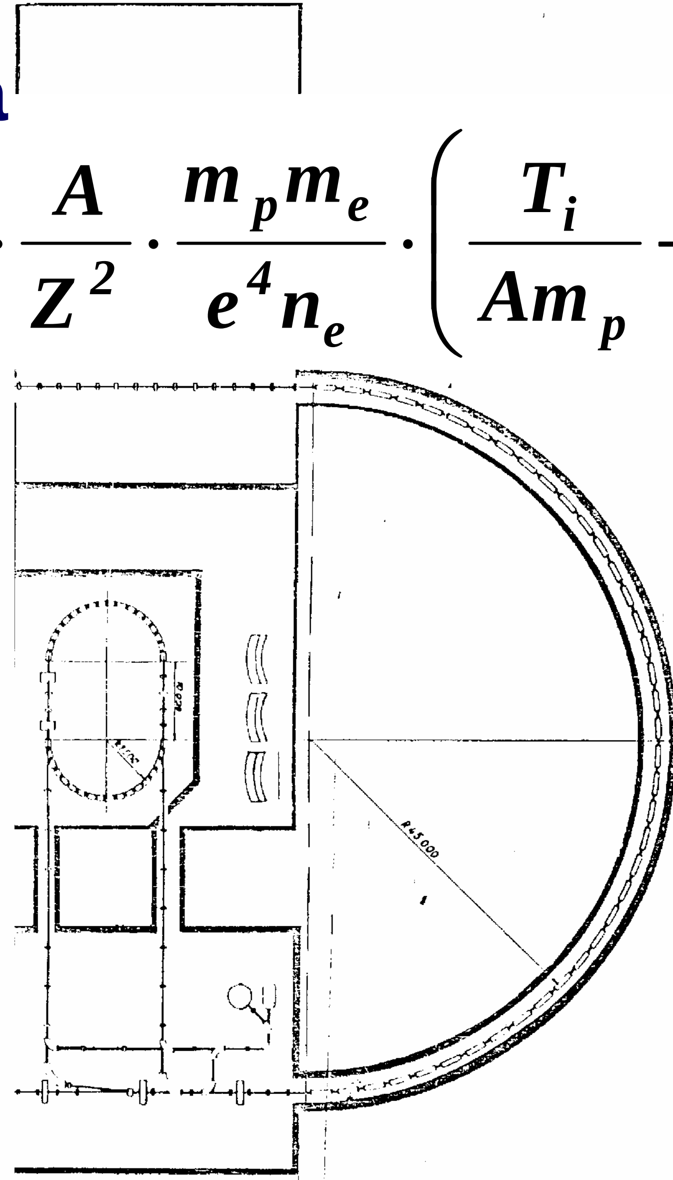
tenu à

l'Institut National des Sciences et Techniques Nucléaires, Saclay
26-30 Septembre 1966

Edité par

H. ZYNGIER
ORSAY

E. CREMIEU-ALCAN
SACLAY



put of the set-up, with the
ne big storage rings. The
otron accelerating protons up
› such a
nts near

ewhat
r Institute
n the proton
sions with prof. O'Neill, I
such a method several years

roton-antiproton machine can
first one is the stacking of
length of the proton bunch in
apture in the large ring without
e 300th harmonic of the revolu-
300 buckets, the RF frequency
he particles are then accelerated
es the bunch length approximately
n the protons are ejected towards
s which are injected into the

electron cooling will take about
of one day, we can have about
After that, antiprotons will be
lliding beam experiments will be

1966 – The First Report

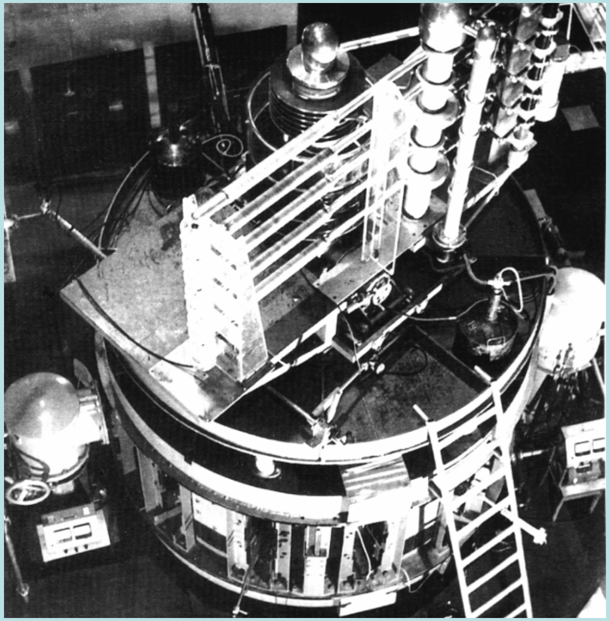
‘Common opinion was: a brilliant idea…

unfortunately - nonrealistic one…’

(From “Budker’s stories”)

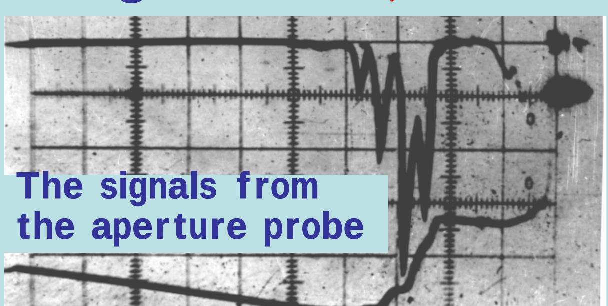
Yes, but – not for stubborn Siberians!

1967 – Beginning of The Idea Realization



Betatron B-3 with spiral storage of electrons:

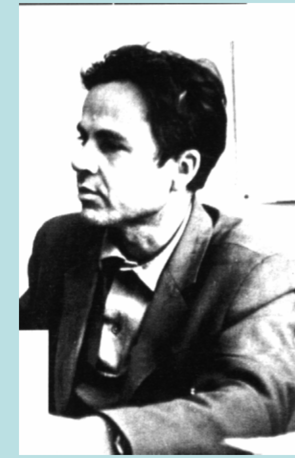
External injection and storage => 300 A , 3·10^{13} e^{-}



The signals from the aperture probe

and "Rogowsky belt"

From The Relativistic Stabilized Electron Beam



Boris Chirikov - The Experimenter

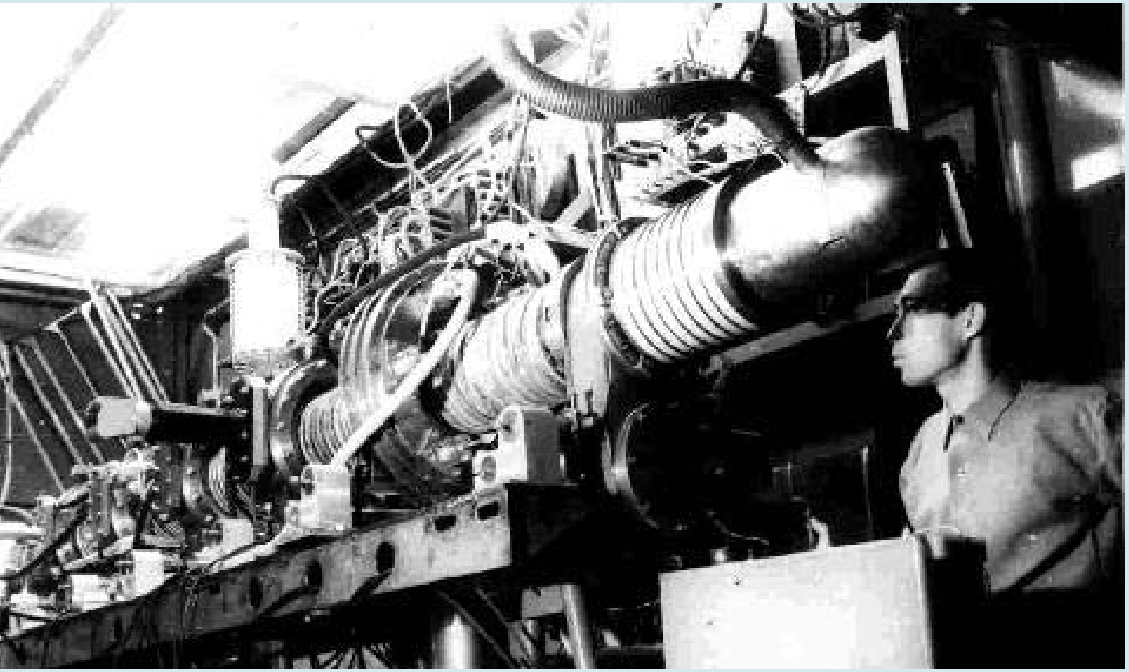
to electron cooling

G.Budker: "Fellows, don't stick to your iron stuff!"

1968 – "EPOCHA The Straight" -- Prototype of Electron Cooler

ЭПОХА - Электронный Пучок ОХлаждающий Антипротоны

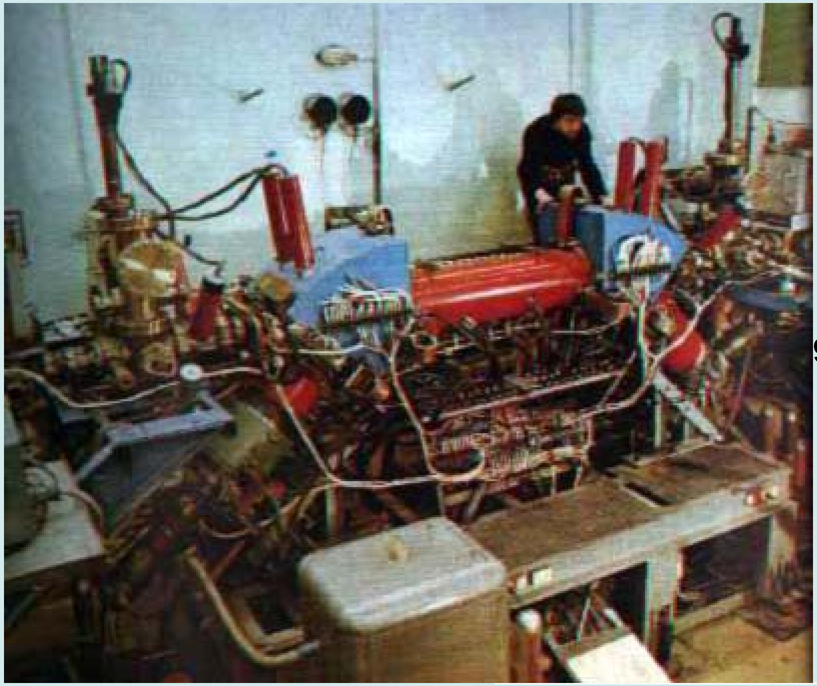
EPOCHA - Electron Beam to Cool Antiprotons



V.Fainstein, V.Ginkin, V.Kudelainen, I.Meshkov, R.Salimov, A.Skrinsky, B.Smirnov, V.Ponomarenko

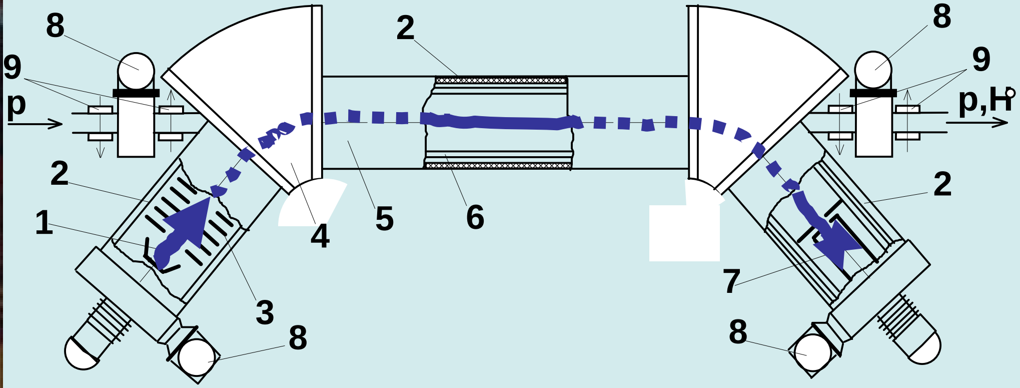
The ideas and theauthors

- ✓ **Electron beam in B-field** (I.Meshkov, A.Skrinsky)
- ✓ **Electron energy recuperation** (G.Budker)
- ✓ **Resonance optics** (I.Meshkov, R.Salimov)
- ✓ **Magnetic field formation** (I.Meshkov)
- ✓ **Electron temperature measurement** (I.Meshkov, A.Skrinsky)



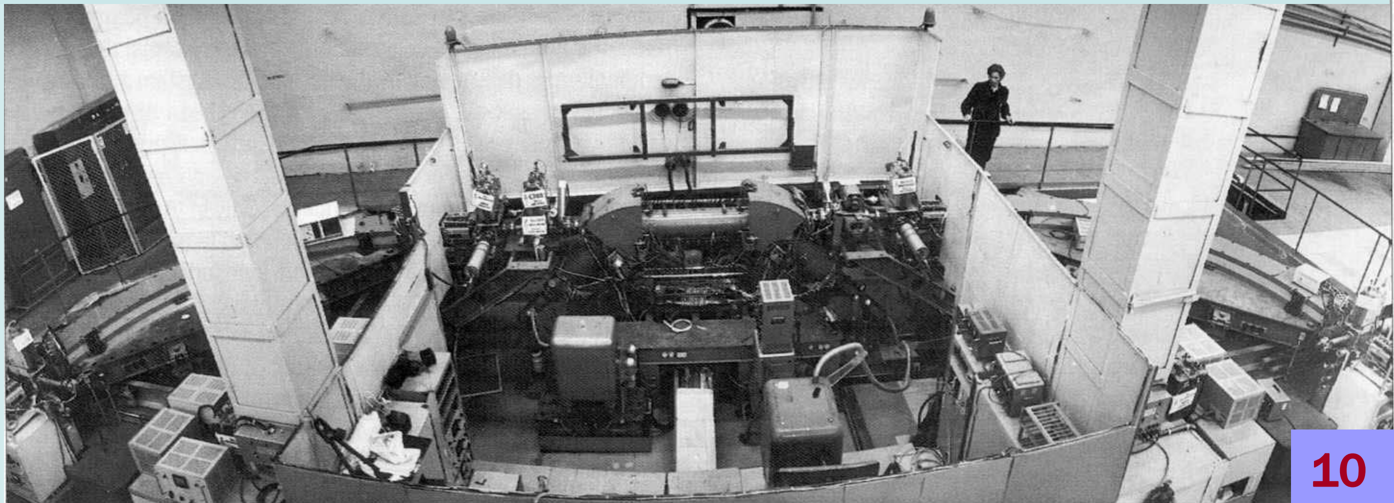
1970

"EPOCHA The Curve"- First Electron Cooler



1974 – EPOCHA on NAP-M

V.Kudelainen
I.Meshkov
R.Salimov
A.Skrinsky



“Sancta sanctorum” of electron cooling - NAP-M :

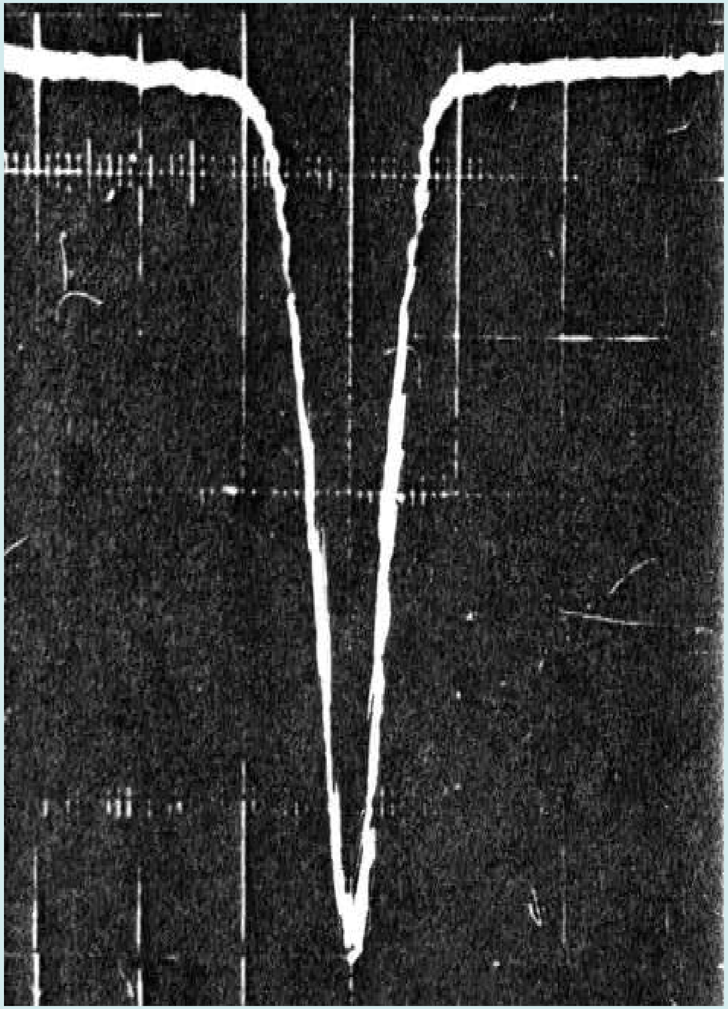
“Antiptoton Storage Ring – Model”

НАП-М : «НакопительАнтиПротонов – Модель»

Budker INP, 1974 - 1984

1974 – First electron cooling of protons in NAP-M

Proton beam density distribution at e-cooling measured with magnesium jet profilometer



I. Remembering… Highlights and key issues of electron cooling

EXPERIMENTS ON ELECTRON COOLING

G. I. Budker, Ya. S. Derbenev, N. S. Dikansky, V. I. Kudelainen
I. N. Meshkov, V. V. Parkhomchuk, D. V. Pestrikov, B. N. Sukhina
A. N. Skrinsky

Institute of Nuclear Physics
Siberian Division
USSR Academy of Sciences

The electron cooling method was suggested by one of the authors in the middle sixties. The original idea of electron cooling published in 1966[1] is the

Table I (Continued)

Betatron wave numbers:

IVth All-Soviet Conference on Part. Accelerators, Moscow, 1974

1974 - First experimental success and first report on electron cooling of protons in NAP-M :

E_p 50 MeV Ip 50 μA

E_e 37 keV Ie 0.1 A

$\phi_{p\_equilibrium}$ 1 mm

τ_{cool} 3 sec - **in full agreement with Budker's theory (classic plasma formulae).**

complex. One should take into account the peculiarity of the proton beam motion in a storage ring as well as

The proton beam equilibrium dimension 1 mm

G.I.Budker, Ya.S.Derbenev, N.S.Dikansky, V.I.Kudelainen, I.N.Meshkov, V.V.Parkhomchuk, D.V.Pestrikov, B.N.Sukhina, A.N.Skrinsky, First experiments on electron cooling, in Proc. of IVth All-Soviet Conference on Part. Accel., v.2, p.302, 1975; IEEE Trans. Nucl. Sci., NS-22 (1975) 2093; Part. Accelerators 7 (1976)197; Rus. Atomic Energy 40 (1976) 49.

1975 – Unexpected results after e-cooler improvement

Provisional text
not revised by CERN
Translation Service

NUCLEAR PHYSICS INSTITUTE

SIBERIAN BRANCH OF USSR ACADEMY OF SCIENCE

PS/DL/Note 76-25
October 1976
Preprint N.P.I. 76-32

G.I. Budker, A.F. Bulyshev, N.S. Dikansky, V.I. Kononov,
V.I. Kudelainen, I.N. Meshkov, V.V. Parkhomchuk, D.V. Pestrikov,
A.N. Skrinsky, B.N. Sukhina

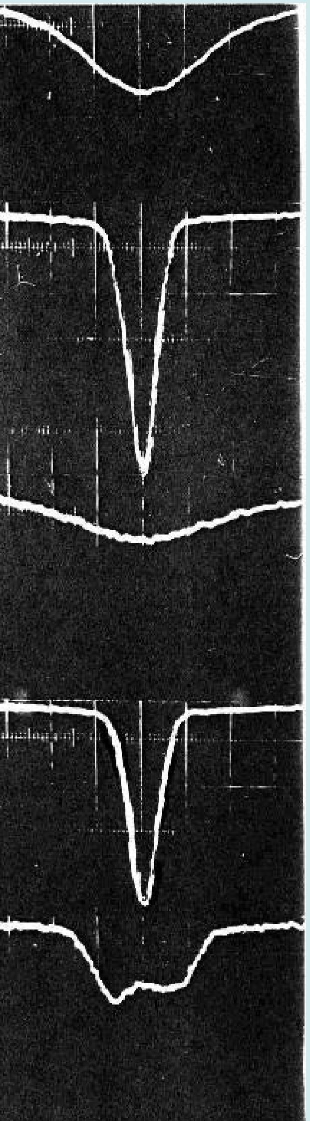
NEW EXPERIMANTAL RESULTS OF ELECTRON COOLING

Presented to the All Union High Energy Accelerator Conference, Moscow, October 1976

(Translated at CERN by O. Barbalat)

*** * * * ***

Improvements: B-field homogeneity in the cooling section – about 10^{-4},



electron energy stability – better than 10^{-5}.

As result - "… the betatron oscillation damping time is inversely proportional to the electron current

and for a current of 0.8 A it amounts to

83 ms (proton energy of 65 MeV) –

-much shorter of "The Budker's numbers!"

What a puzzle!

New results –> new puzzles?

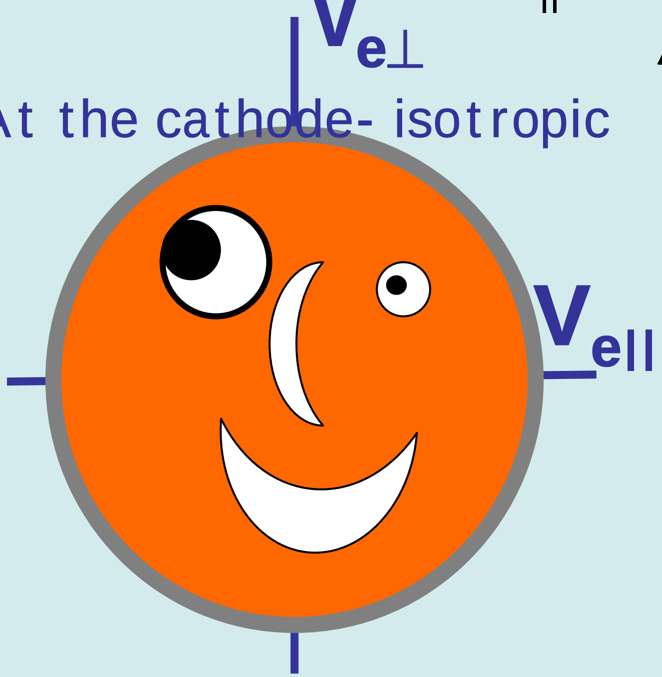
***"D'Artagnan et les Trois Mousquetaires"*:**
V.Parkhomchuk, A.Skrinsky, I.Meshkov and N.Dikansky in control room of NAP-M (1975)

Progress in the theory of electron cooling

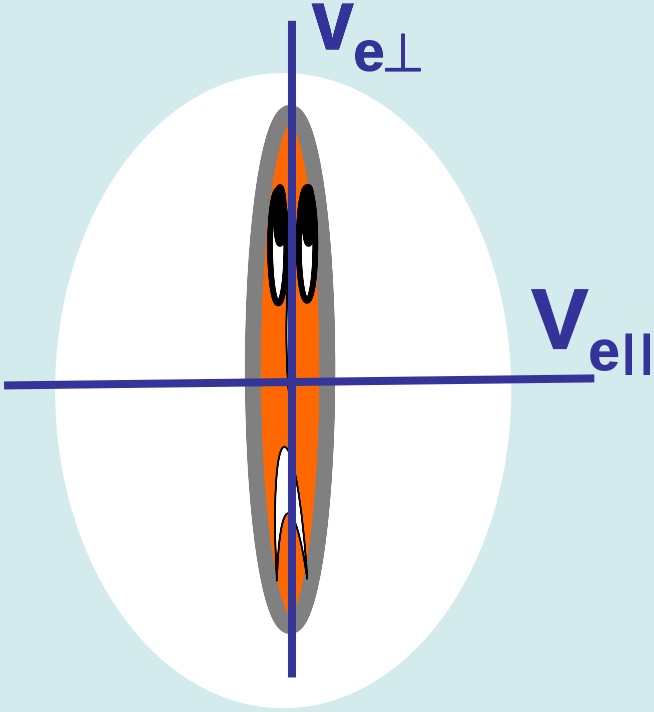
1. Flattened distribution of electrons over velocities $f(\vec{v}_e)$ **in Particle Rest Frame (V.Parkhomchuk)**

$$T_{\parallel} = \frac{T^2_{Cathode}}{\beta^2 \gamma^2 mc^2}$$

At the cathode- isotropic



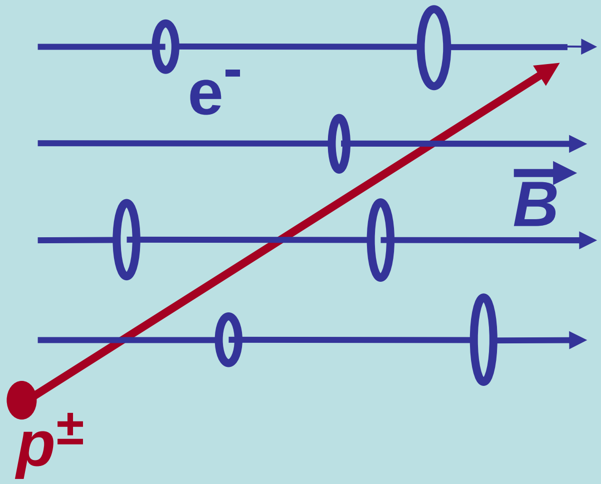
Electrostatic acceleration



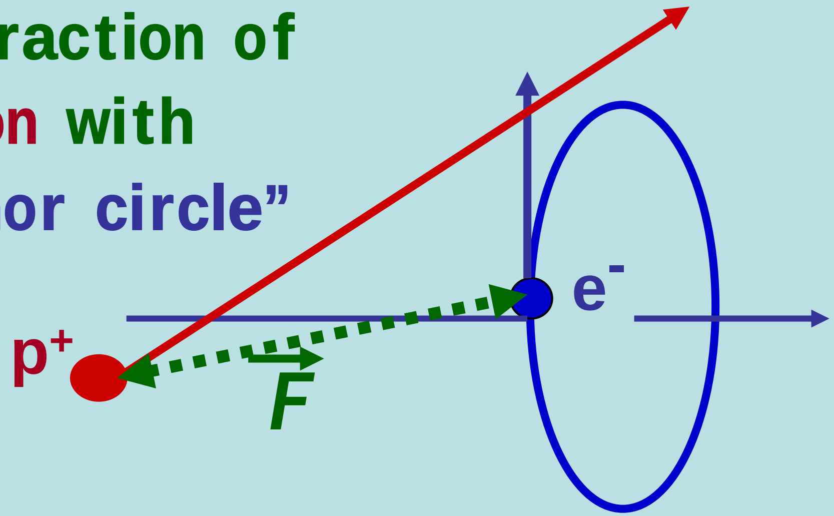
After acceleration – flattened

Progress in the theory of electron cooling

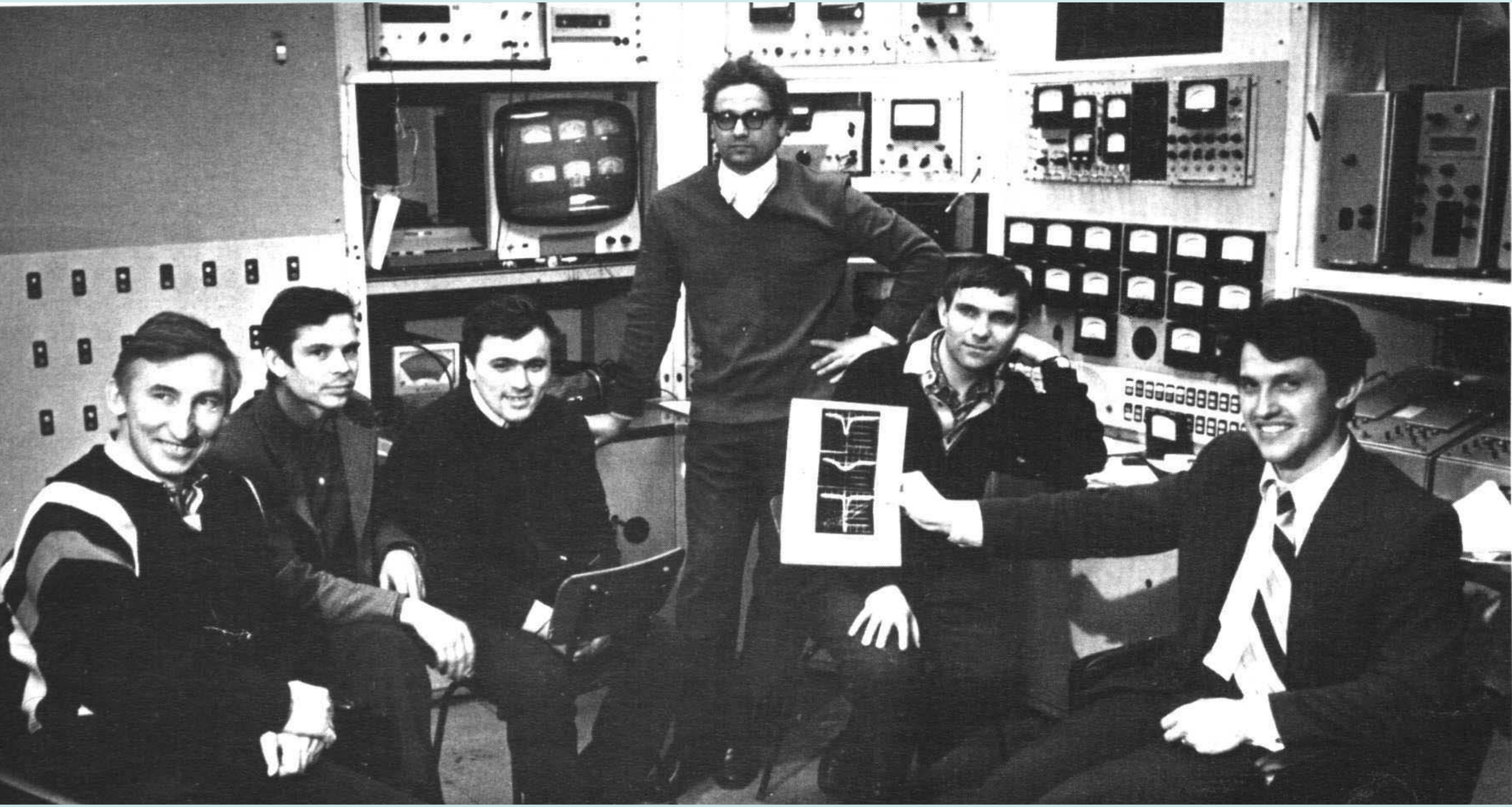
2. Electron beam magnetization (Ya.Derbenev, A.Skrinsky, Rus. Plasma Physics, v.4 (1978) 492)



Interaction of an ion with "a Larmor circle"



Everything was described in very first theoretical paper of Ya.Derbenev & A.Skrinsky, but…



…we understand the magnetization effect when experiment has shown it!

Electron cooling team in control room of NAP- M (1976)

I.Meshkov, B.Sukhina, D.Pestrikov, V.Ponomarenko, V.Parkhomchuk, N.Dikansky

First cooler rings

In Europe – 1977 – 79, Initial Cooling Experiment at CERN

M.Bell, J.Chaney, H.Herr, F.Krienen, S. van der Meer, D.Moehl, G.Petrucci, H.Poth, C.Rubbia– NIM 190 (1981) 237

In USA – 1979 – 82, **The Test Ring Experiment for Electron Cooling Experiment at Fermilab**

T.Ellison, W.Kells, V.Kerner, P.McIntyre, F.Mills, L.Oleksiuk, A.Ruggiero, IEEE Trans. Nucl. Sci., NS-30 (1983) 2370;
at the initial stage participated N.Dikansky, I.Meshkov V.Parkhomchuk (BINP)

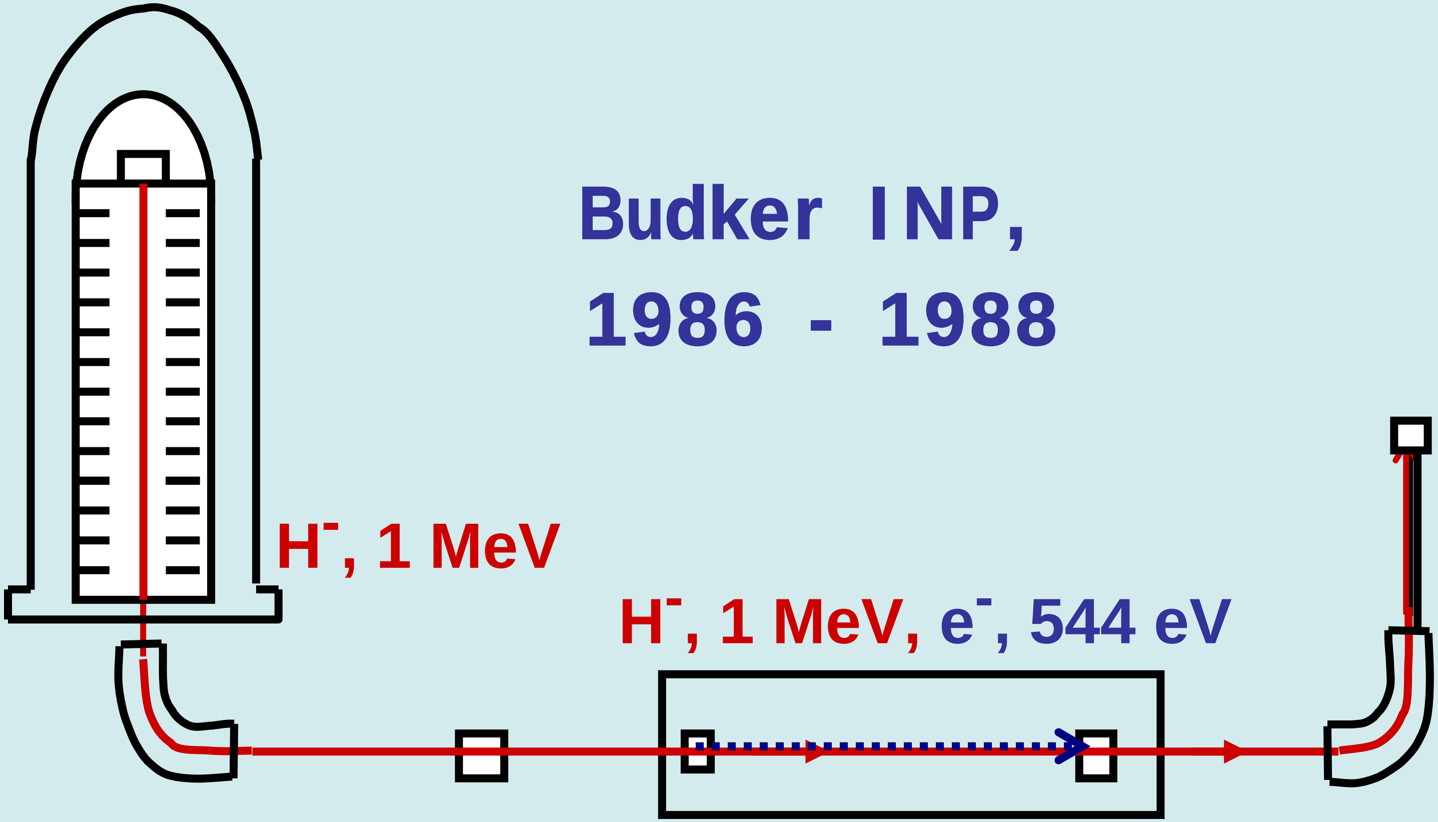
Single Pass Cooling Experiment

"MOdel of SOLenoid"

L.Arapov, N.Dikansky, V.Kokoulin, V.Kudelainen,
V.Lebedev, V.Parkhomchuk, B.Smirnov, B.Sukhina

Budker INP,

1986 - 1988



Second Generation of Cooler Storage Rings

1988 – LEAR - Low Energy Antiproton Ring (CERN)

1988 - IUCF Cooler Ring (Indiana University Cyclotron Facility, Blumington, USA)

1988 – TSR - Test Storage Ring (MPI, Heidelberg, Germany)

1989 – TARN-II - Test Accumulator Ring for NUMATRON, Tokyo University, Japan

1989 – CELSIUS - Cooling with Electrons and Storing of Ions from Uppsala Synchrocyclotron (Uppsala University, Sweden)

1990 – ESR - Experimental Storage Ring (GSI, Darmstadt, Germany)

continuation

1992 – COSY - COoler-SYnchrotron (FZ Juelich, Germany)

1992 – CryRing – CRYogenic EBIS + Storage Ring (MSI, Stockholm, Sweden)

1993 – ASTRID (A Small multi-purpose Storage Ring, Aarhus University, Denmark)

1998 - SIS - Super Ion Synchrotron (GSI, Darmstadt, Germany)

2000 – HIMAC - Heavy Ion Medical ACcelerator (NIRS, Chiba-shi, Japan)

2000 – AD - Antiproton Decelarator (CERN)

2002 – Electrostatic cooler storage ring at KEK (KEK, Tsukuba, Japan, China) [E.Syresin, WeODCH02]

Coming soon:

2005 – Recycler Electron Cooler(Fermilab, USA)

200? – Two cooler rings complex (IMP, Lanzhou, China)

2006(?) - Low Energy Ion Ring (CERN)

20?? –TARN-II–renovated (RIKEN, Wako-shi, Japan)

2005 – S-LSR : Solid magnet Laser equipped cooler Storage Ring (Kyoto University, Japan)

II. Reflecting…

What is “a harvest”?

What was done with electron cooling application?

- ✓ **Electron cooling of “all the elements” of The Mendeleev Periodic Table**

and antiprotons !

❖ Particle physics with “electron cooled” and extracted protons, deuterons and antiprotons :

- ✓ **Antiproton physics => *LEAR***
- ✓ **“Mezon physics” => *IUCF, COSY, SELSIUS***
- ✓ **First antihydrogen generation in-flight => => LEAR (stochastic cooling)**

continuation

Electron cooling in traps =>

=> antihydrogen generation in traps

ATHENA **ATRAP**

2002 - First H-bars in traps

continuation

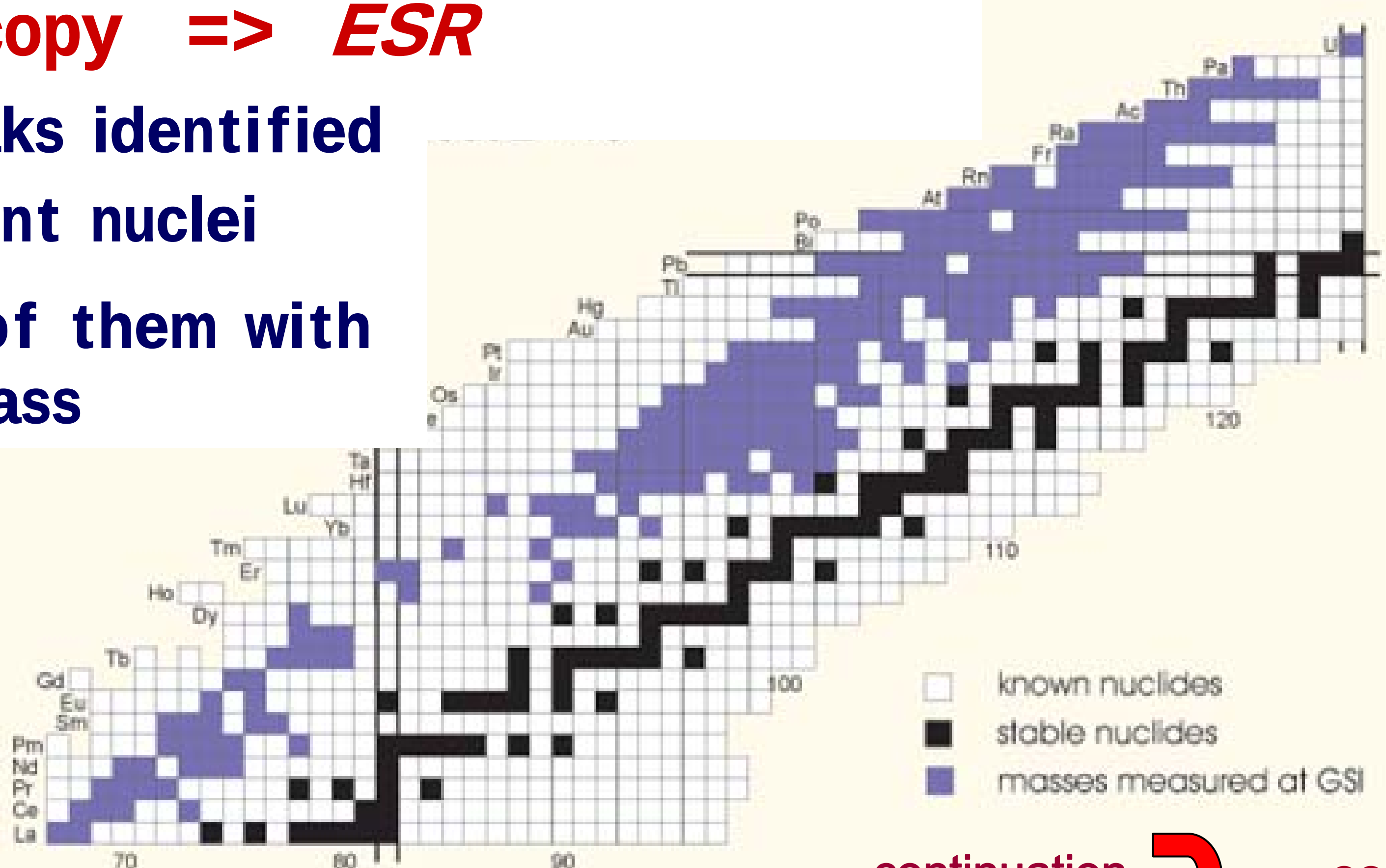
❖ Nuclear physics

✓**Studies of** radioactive nuclei and rare isotopes, exotic nuclei states (like bare nuclei decay, etc.) => *ESR*

✓ **High precision Schottky mass spectroscopy => *ESR***

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

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



continuation

❖ New stage of experiments in atomic and molecular physics =>

=> *TSR*, *CryRing*, *ASTRID*

- **"Nonliouvillean" particle beam physics**

↓

Particle beams

with a cooling mechanism

Development of "the cooling ideology"

- Radiation cooling (e^+e^- rings) – - very first cooling method;
- Electron cooling – the next step!
- Stochastic cooling (S.Van der Meer, CERN) – sussesful realization: $W^{\pm}$ and Z^0 !
- **Laser cooling with "an aid" of electron cooling => *TSR, ASTRID, ESR***
- Muon cooling (A.Skrinsky) – is being developed and to be realized.

"Crystalline beams"

First observation – NAP-M, V.Parkhomchuk et al.
Budker INP, 1979

First idea of particle beam "crystallization" – V.Parkhomchuk, 1979

Ion beam ordering ("crystallization")

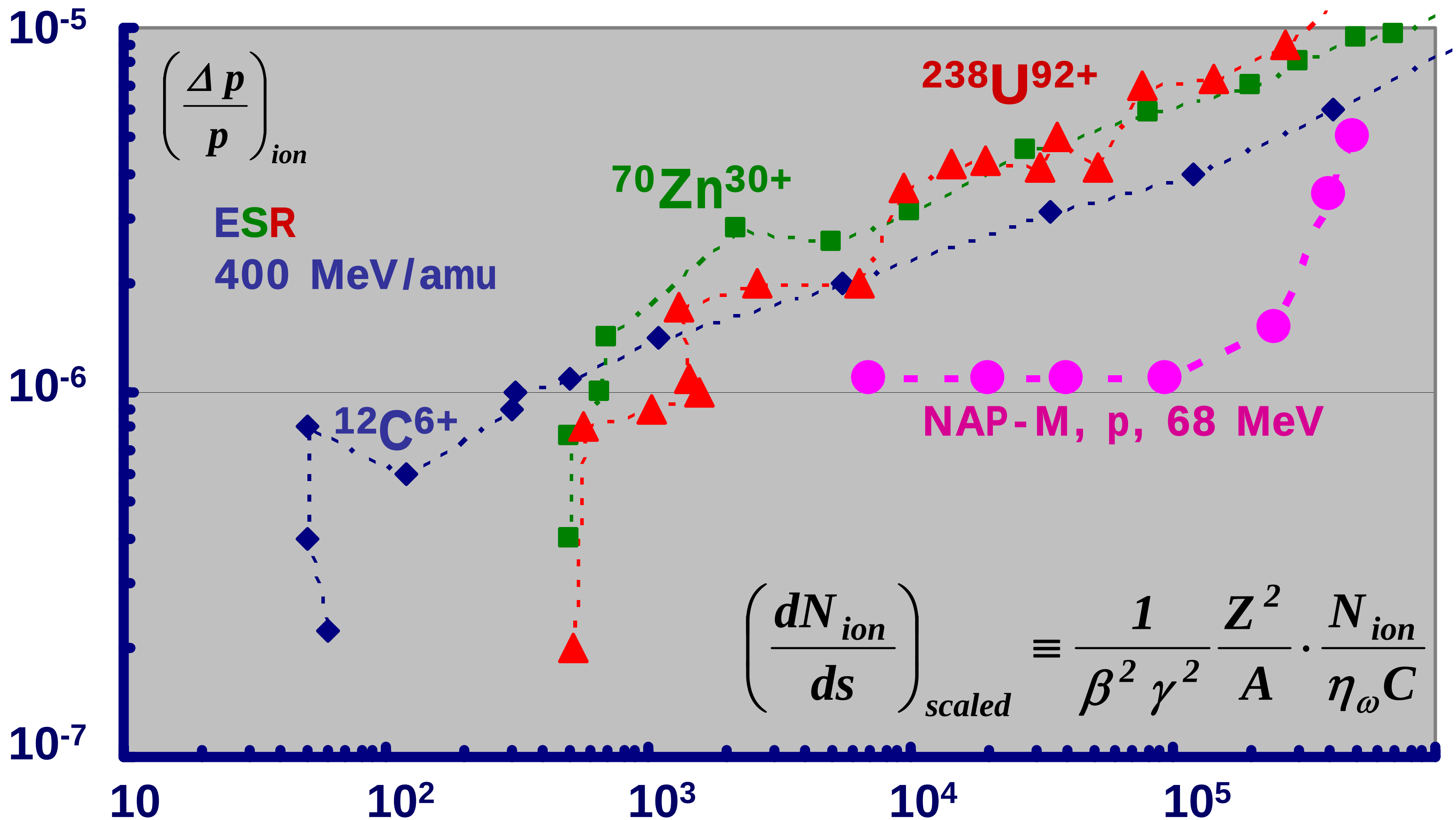
$\Rightarrow$ ESR, M.Steck et al.,

$\Rightarrow$ SIS, M.Steck et al.,

$\Rightarrow$ CryRing, H.Danared et al.

“Crystalline beams”

Beam ordering in NAP-M (1979) and ESR (2002)



Enrichment of the particle beam physics by initiation of the further development of intense particle beam physics:

Stability of intense and dense (cooled!) particle beams in storage rings;

Intrabeam scattering in cooled beams;

Physics of crystalline beams;

Stability of a particle beam in storage ring in presence of an internal target;

Beam-beam effects in colliders at a cooling presence,

etcetera...

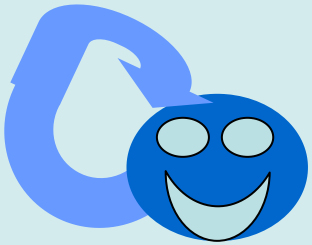
Where we are and where we go…

- **Theory of electron cooling**

  – is well developed,

however it is very multiparametric,

that requires application of numerical simulation!



❖Numerical simulation…

One of the achievements – BETACOOL:
a code for numerical simulation
of electron cooling process
in storage rings (JINR, Dubna) THPLTO94

An example:

Simulation of ion beam ordered state
in ESR

Numerical simulations of beam dynamics in electron cooler storage rings

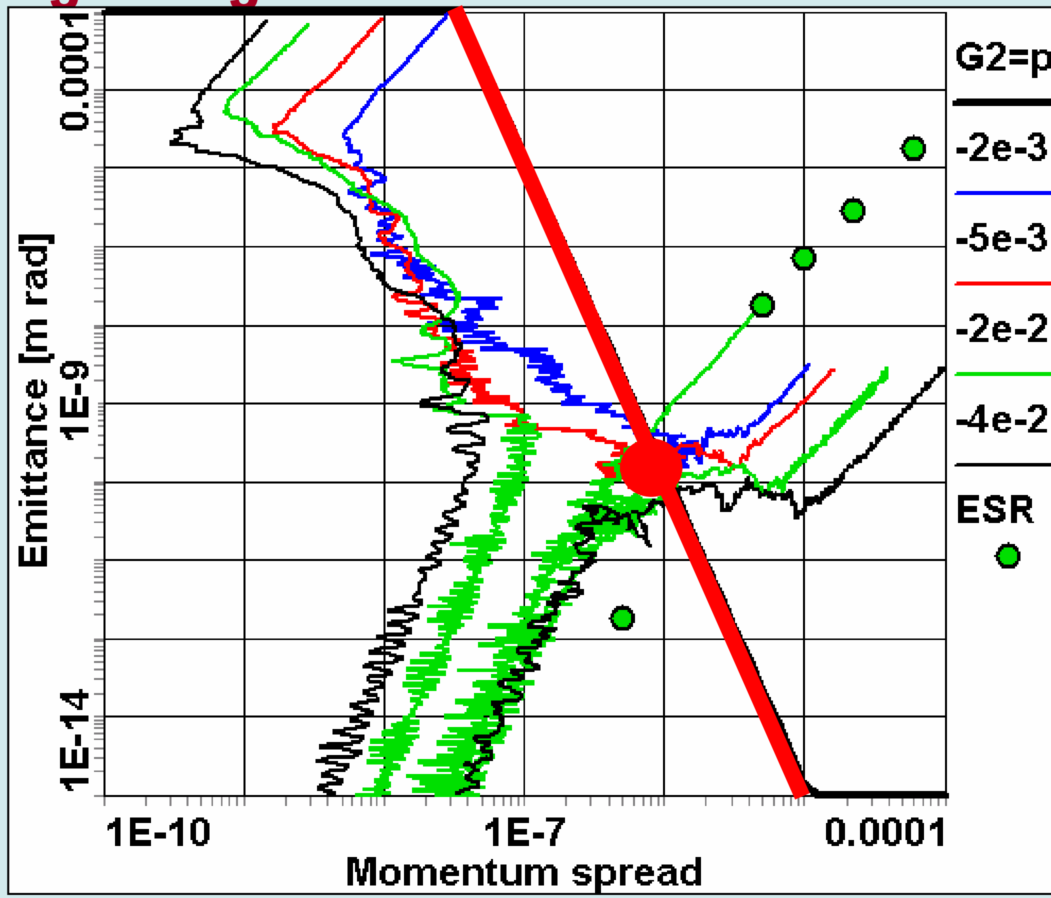
GSI experiment

simulation

New criterion of the ordering

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

and the equilibrium point



Results of Molecular Dynamics calculations: evolution of GSI ion beam parameters (emittance and Δp/p) during electron cooling process

❖ Theory (physics!) of electron cooling:

Cold intense beams

The "old" opinion: an ion beam, to be cooled effectively, should have

- at stochastic cooling – large emittance and low intensity;
- at electron cooling – small emittance and even (indifferently) high intensity.

The question: what is a beam intensity limit at electron cooling?

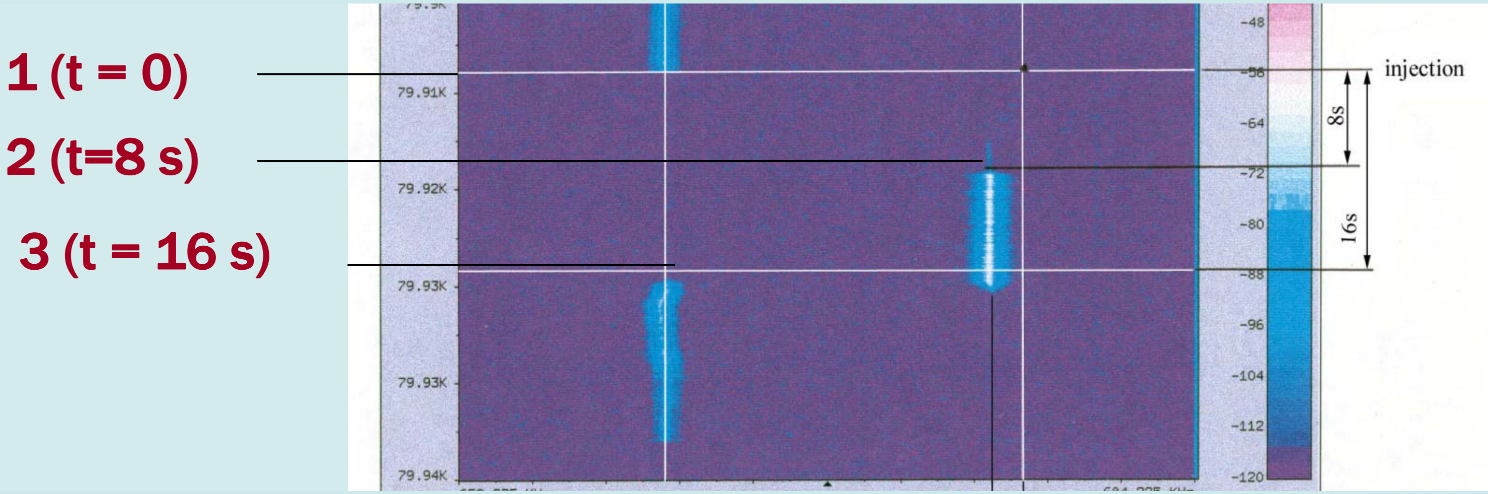
Cooled intense beams – new phenomena “on the table”…

SELSIUS effect – “electron heating”: ion beam current is limited by “two beams instability”!
(D.Reistad, V.Parkhomchuk, et al, 2000)

COSY effects – two stages instability in proton beam at electron cooling: nonlinear effect of electron beam on proton one and coherent instability of cooled proton beam (J.Stein, J.Dietrich, V.Kamerdjiev, R.Maier, D.Prasuhn, H.Stockhorst, I.Meshkov, A.Sidorin, 2002)

HIMAC effect – residual gas ions influence
(K.Noda, E.Syresin, T.Uesugi, I.Meshkov, 2004) – confirmed in COSY (2004)

Coherent instability development in the cooled proton beam in COSY…

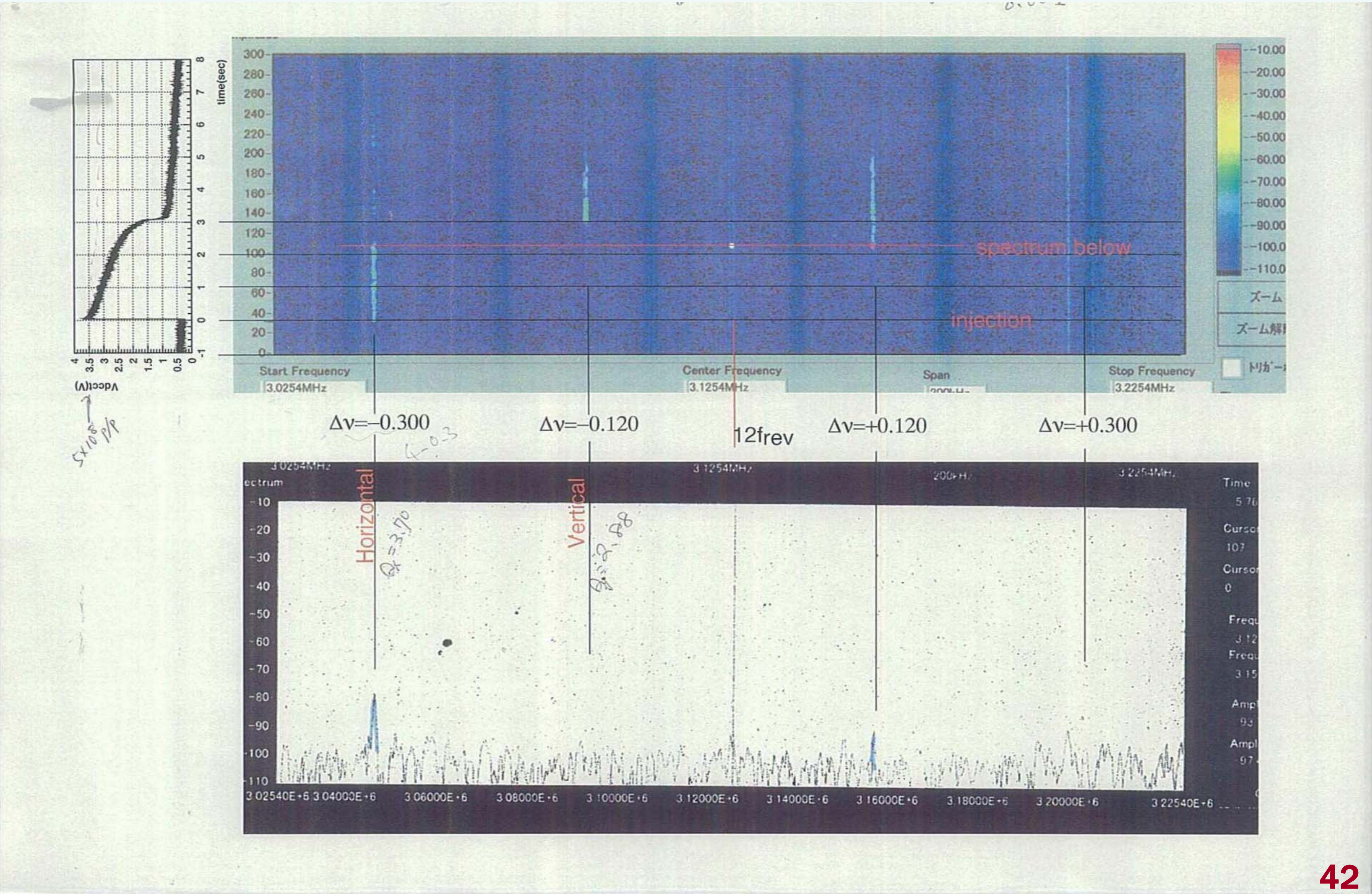


1 – t=0, injection;
2 – t=8s, horizontal betatron oscillations start;
3 – t=16 s,"jump" from horizontal oscillations to vertical ones, $\Delta t_{jump} < 0.5$ s.

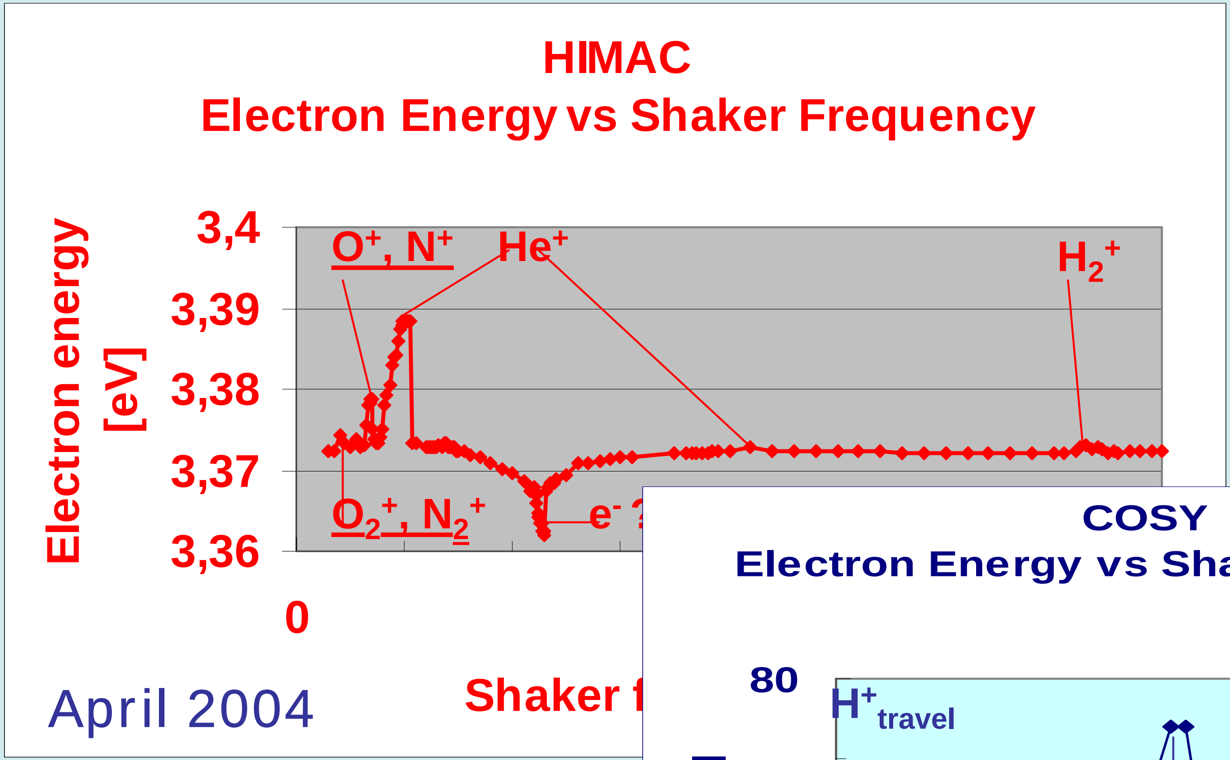
[I.Meshkov, A.Sidorin, J.Stein, J.Dietrich, V.Kamerdjiev, Part. & Nuclei Lett.1 (2004) 43]

II. Reflecting... Where we are and where we go...

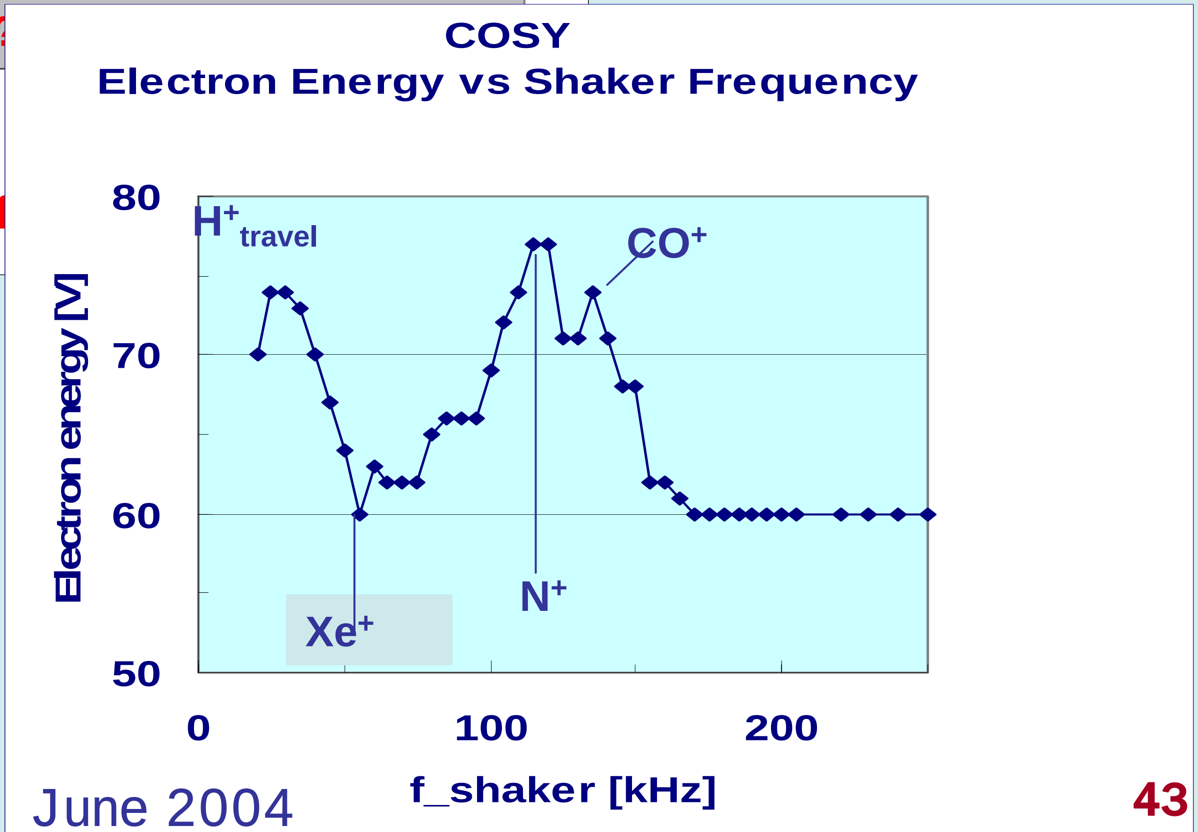
...and in HIMAC [K.Noda et al.]



II. Reflecting… Where we are and where we go…



A/Z of residual gas ions stored in electron beam



These ions provoke 3-component instability…

An "old" question:

Do we need electron beam neutralization?

No! ⇒ if we deal with an intense ion beam (especially of heavy multicharged ions); then neutralization makes a harmful effect .

Yes! ⇒ if we have to form a cold and well compressed ion or (especially) antiproton beam of a modest intensity.

❖Electron cooling engineering

Electron energy range of electron coolers:

Today => 10 eV (KEK) –

- 400 keV(IMP Lanzhou/Budker INP);

"Tomorrow" => 4.4 MeV e^- = 8 GeV p-bars (Fermilab) [S.Nagaitsev, TUXCH03]

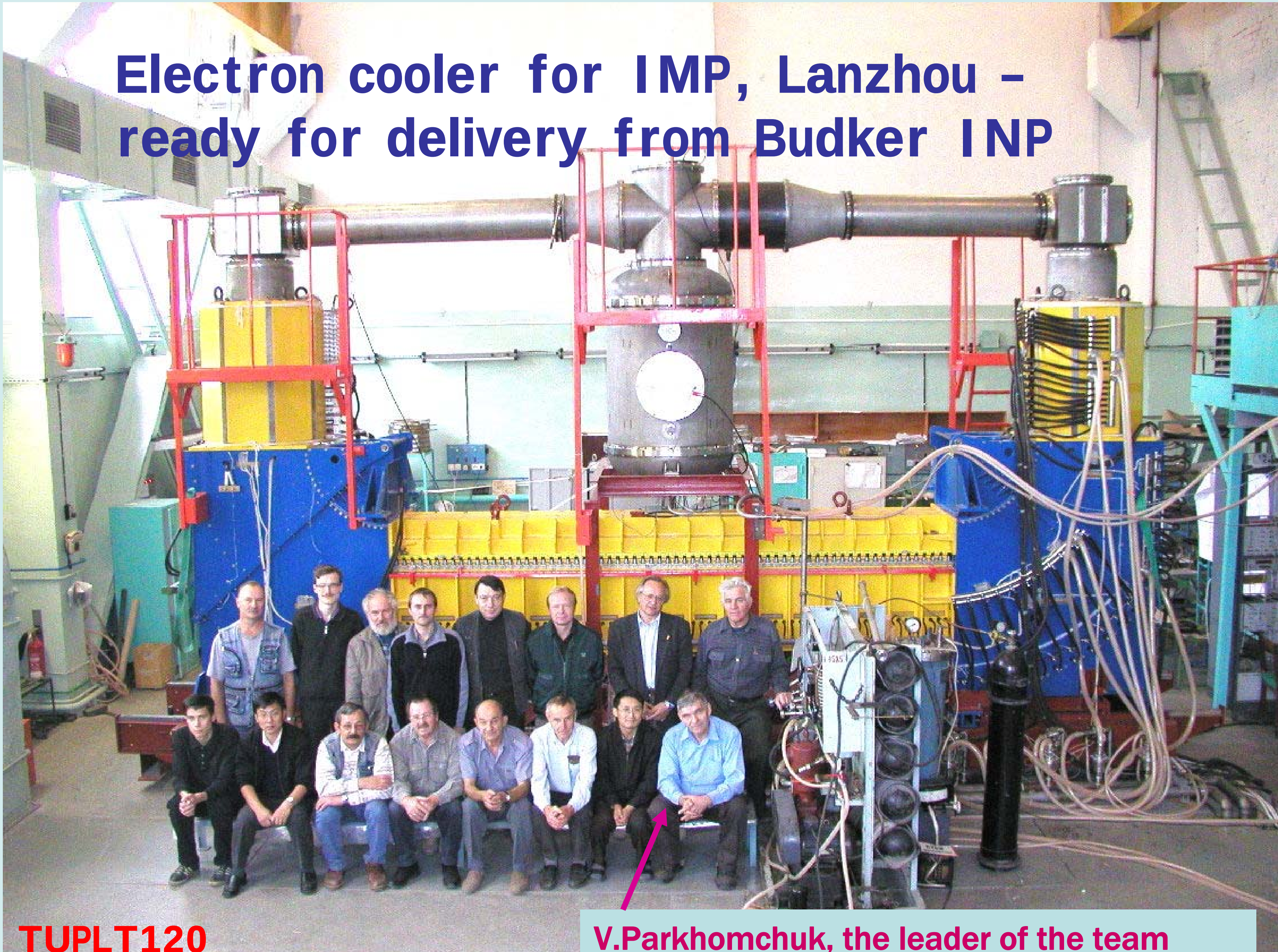
"After tomorrow" =>

=> 54.5 MeV e^- = 100 GeV/amu ions

E-cooler for RHIC (BNL/Budker INP/JINR) –

- see below

Electron cooler for IMP, Lanzhou – ready for delivery from Budker INP



V.Parkhomchuk, the leader of the team

- New concepts in electron cooling "technologies"

Electron cooler based on

electrostatic accelerator of electron energy ~ 7 MeV

(proposal of BINP for FAIR project at GSI)

New scheme of electrostatic accelerator and e-beam "magnetization" (see WEPLTO56)

❖ New concepts in electron cooling “technologies”

Electron cooler with bunched and single pass electron beam-

- the scheme based on

recuperator-linac

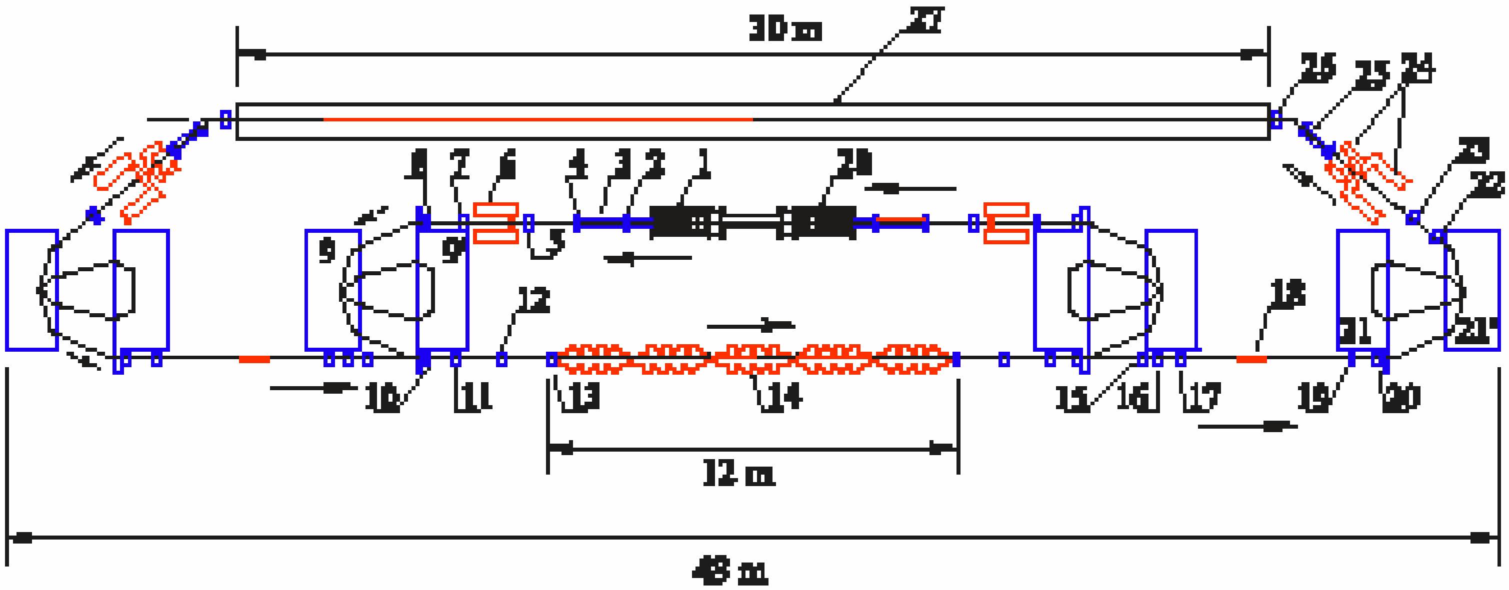
(proposal of BINP for RHIC mentioned above)

This is an advance in the range of few tens of MeV of electron energy.

❖ New concepts in electron cooling "technologies"

Electron cooler – recuperator concept

(Budker INP)



Linac based electron cooling system with electron energy recuperation (Proposal of Budker INP for RHIC)

❖ New concepts in electron cooling "technologies"

"Crystalline" beam application:

Electron-ion collider with

crystalline ion beam ⇒

⇒ very high luminosity.

[D.Möhl and T.Katayama, RIKEN preprint ISSN 1346-2431 AF-AC-39, Nov.2002]

- New concepts in electron cooling "technologies"

Single particle cooling:

Possibilities for Experiments with Rare Radioactive Ions in a Storage Ring Using Individual Injection

TUPLT103 A. Sidorin, I.Meshkov, A.Smirnov, E.Syresin, G. Troubnikov (JINR, Dubna,), T.Katayama (Tokyo University), W.Mittig, P.Roussel-Chomaz (GANIL, Caen)

❖ New concepts in electron cooling "technologies"

LEPTA Project (JINR, Dubna)

TUPLT104 I.Seleznev, V.Antropov, E.Boltushkin, V.Bykovsky, A.Ivanov, S.Ivashkevich, A.Kobets, Yu.Korotaev, V.Lohmatov, I.Meshkov, D.Monahov, V. Pavlov, R.Pivin,, A.Sidorin, A.Smirnov, E.Syresin, G.Troubnikov, S.Yakovenko (JINR, Dubna)

The goals:

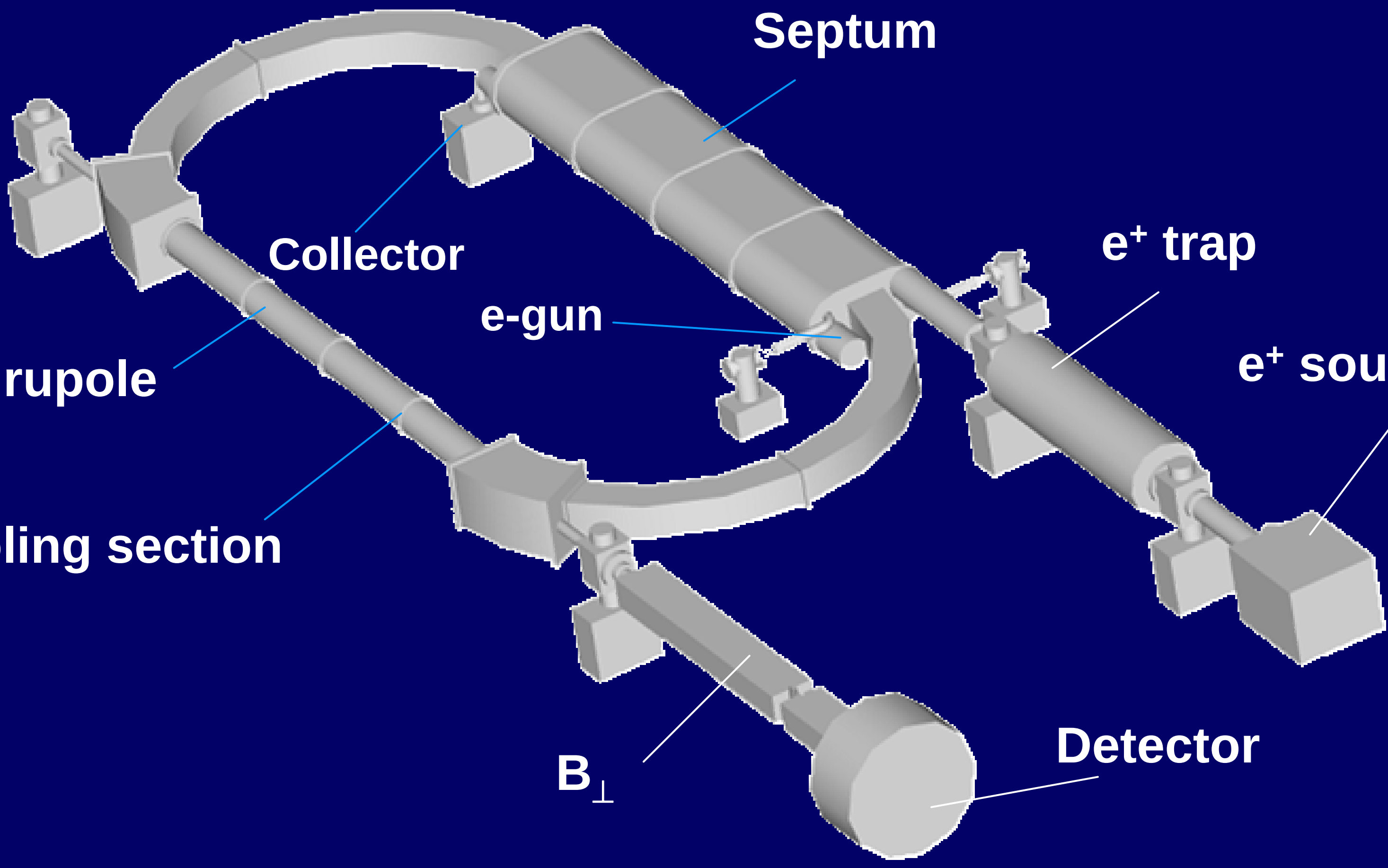
- ✓ Electron cooling of circulating positrons and Positronium generation in-flight;
- ✓ Antihydrogen generation (FLAIR project, GSI, ELENA project, CERN);
- ✓ Electron cooling of high energy ions and p-bars with circulating electron beam.

II.2. Where we are and where we go…

❖ New concepts in electron cooling "technologies"

LEPTA scheme

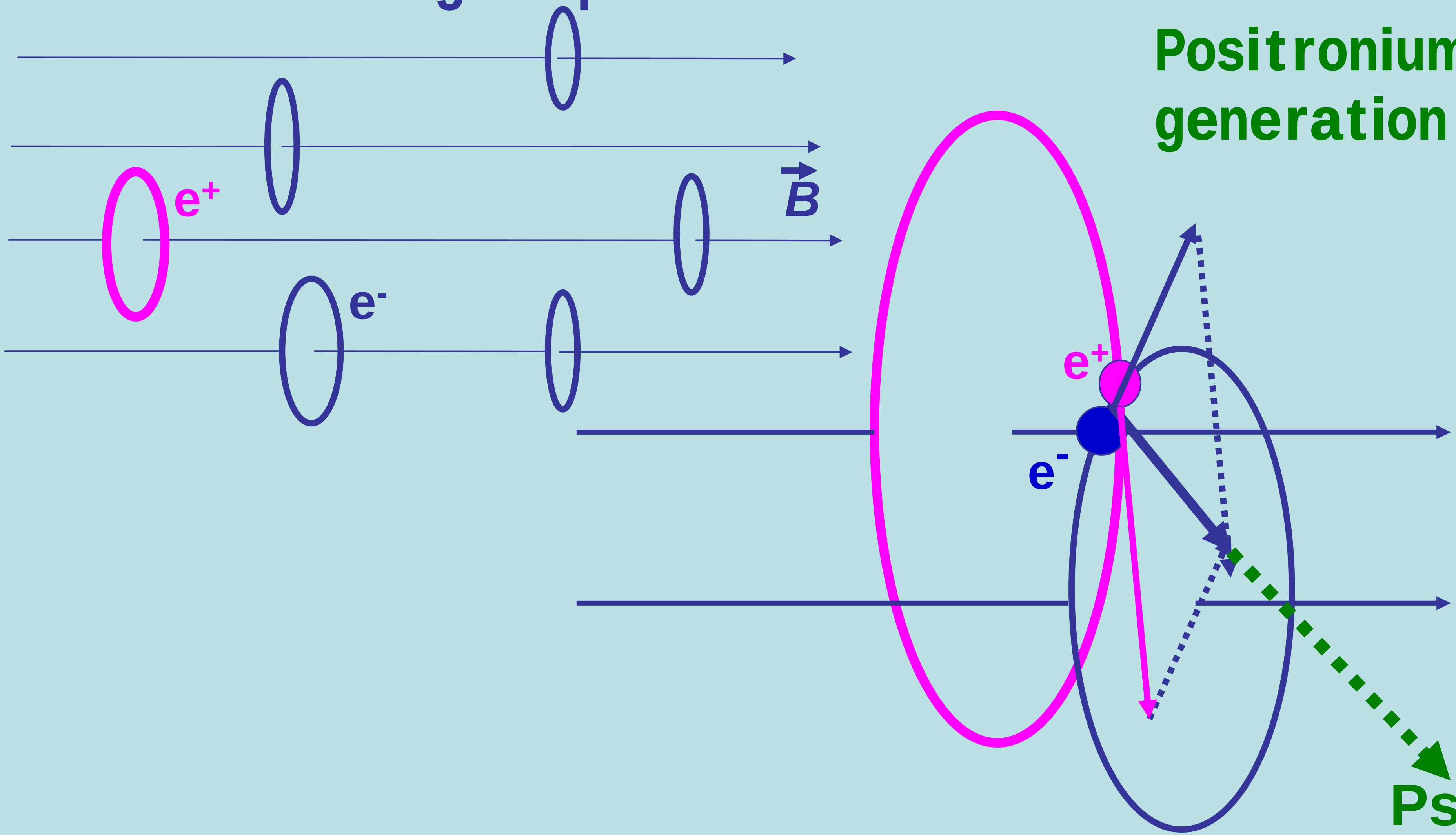
See TUPLT104



I.Meshkov, A.Skrinsky NIM A379 (1996) 41

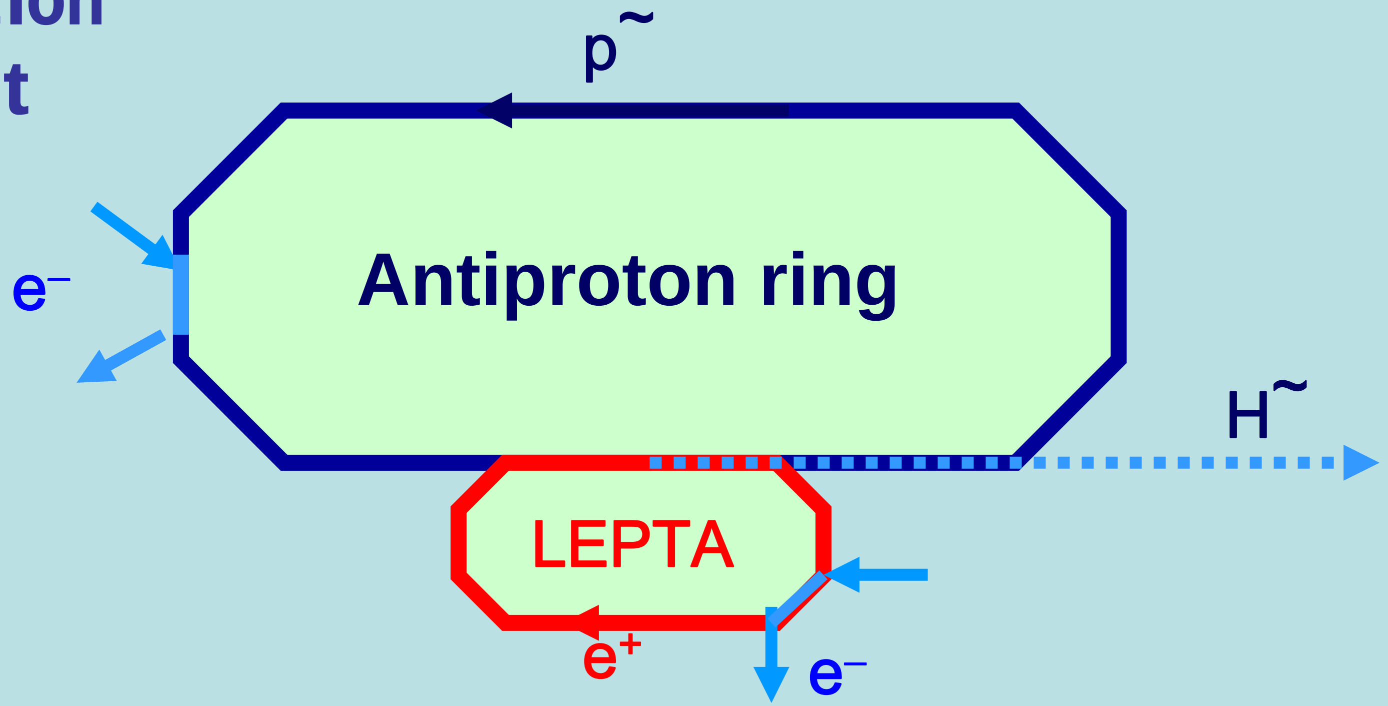
- New concepts in electron cooling "technologies"

Electron cooling of positrons in LEPTA and Positronium generation



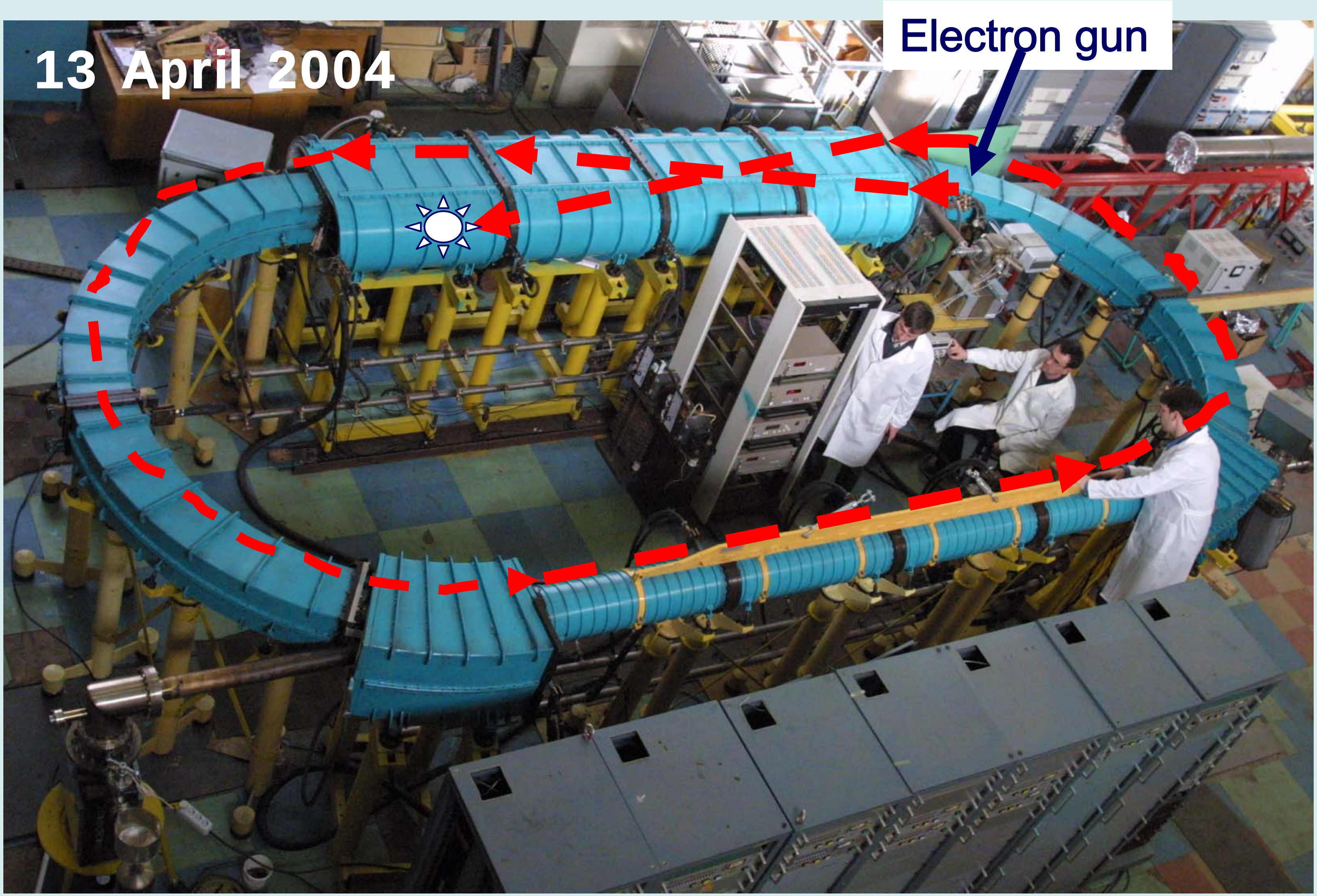
❖ New concepts in electron cooling "technologies"

Antihydrogen generation in-flight



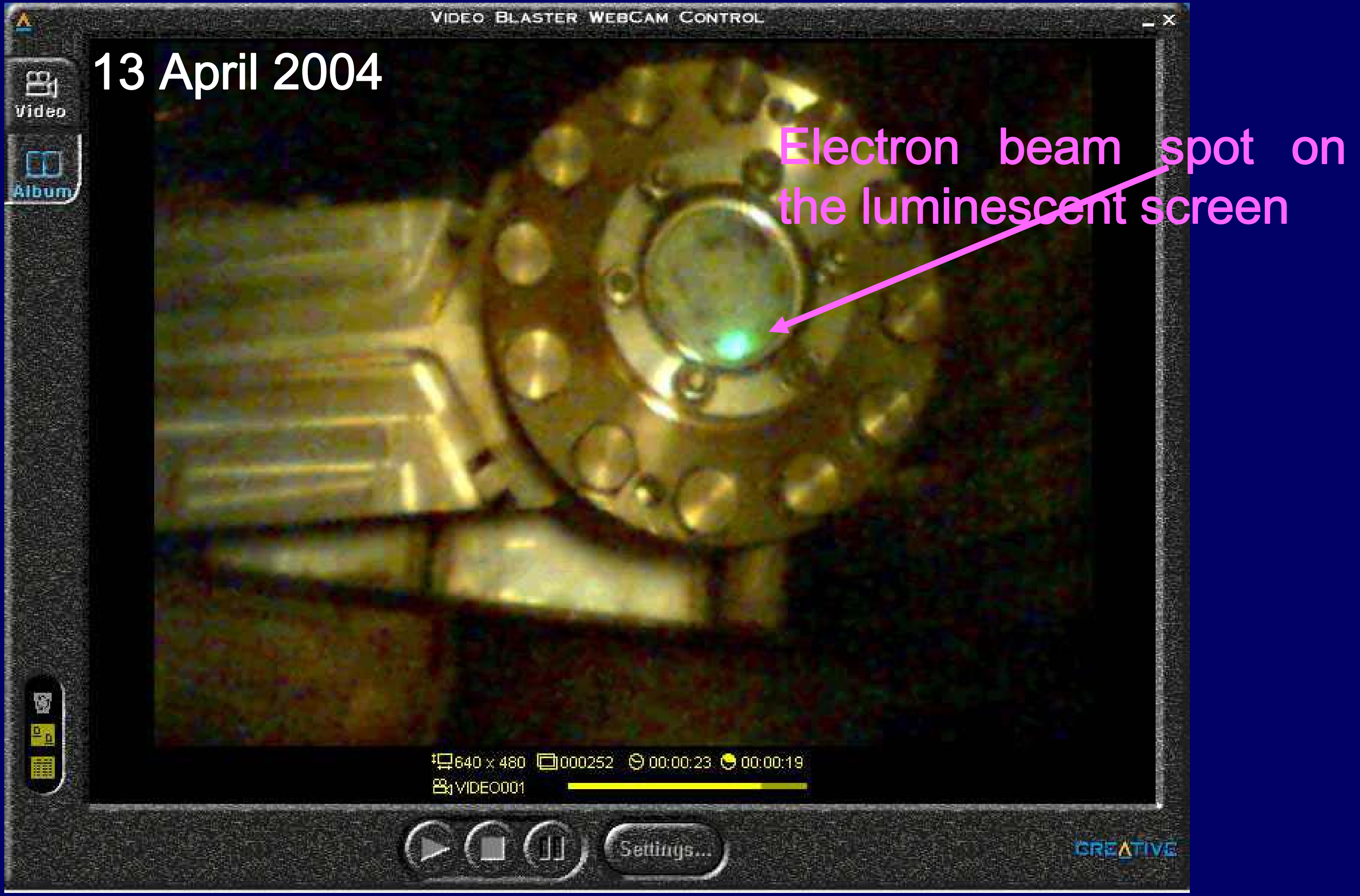
(FLAIR „subproject" in FAIR project, GSI, ELENA project, CERN);

Status of LEPTA project



1st turn of pulsed electron beam

Status of LEPTA project



Conclusion:

“Electron cooling is
as inexhaustible
as electron itself…”

One can paraphrase it now

The famous sentence:‘

‘electron is as inexhaustible as atom…’

Vladimir Ulianov (Lenin), 1909