New Developments in High Energy Electron Cooling

Jürgen Dietrich

TU Dortmund & HI Mainz

Outline

- Introduction
- Special Features of High Energy Electron Cooling
- Engineering Problems of High Energy Electron Coolers
- Electron Cooler - Status and Projects
- New Ideas and Further Developments- Turbines
- Beam Diagnostics
- Outlook

Introduction

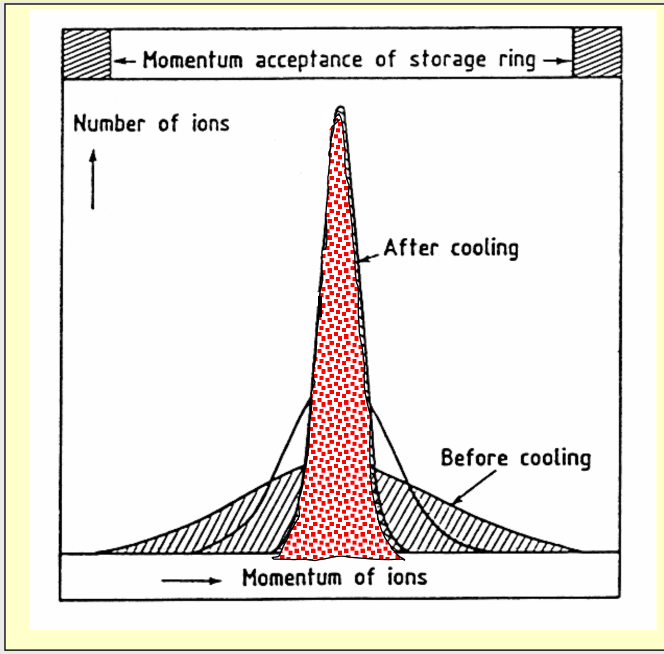
Benefits of Beam Cooling

Improved beam quality
- Precision experiments
- Luminosity increase

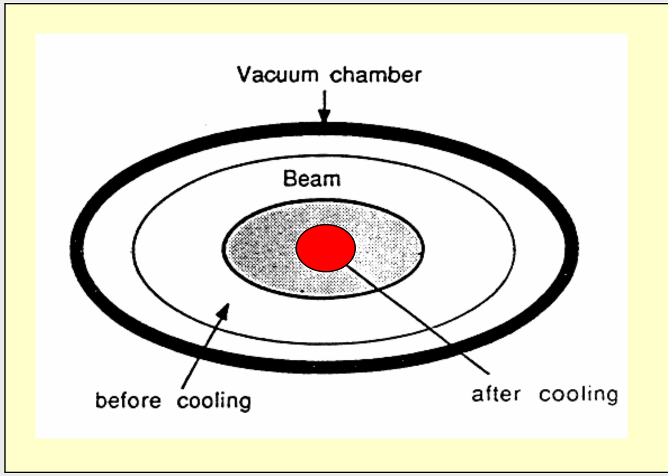
Compensation of heating
- Experiments with internal target
- Colliding beams

Intensity increase by accumulation
- Polarised beams
- Secondary beams (antiprotons, rare isotopes

Effect of ion beam cooling on momentum spread



Effect of ion beam cooling on beam size



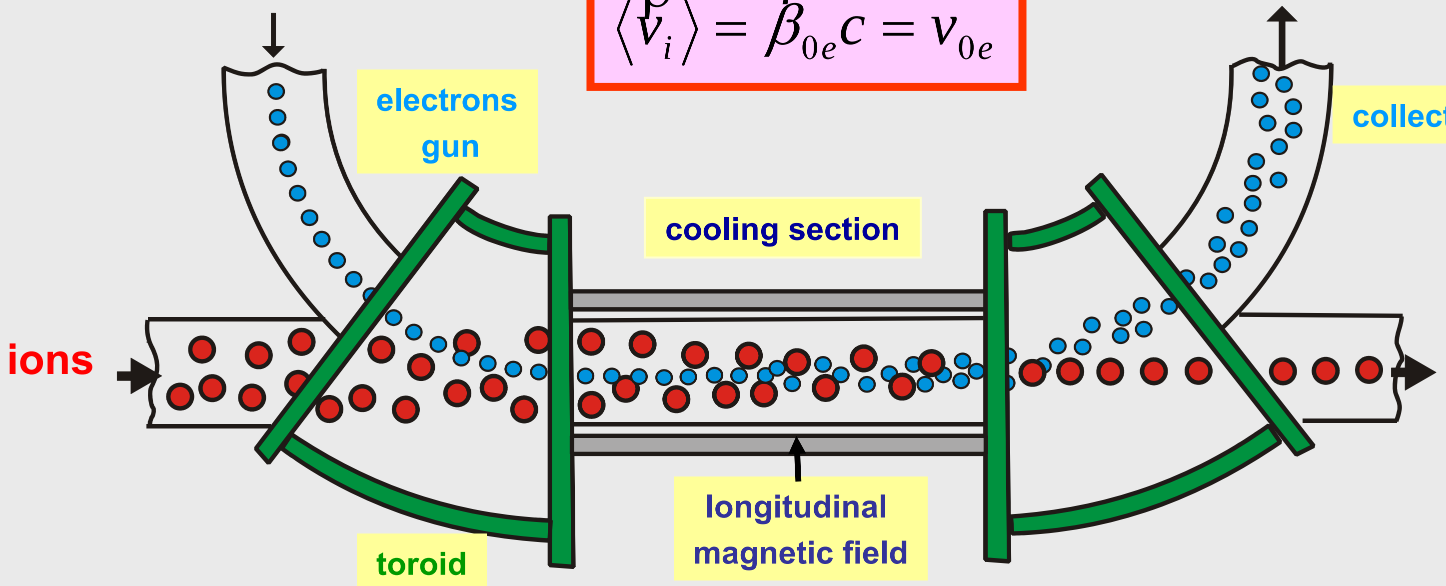
Principle of Electron Cooling

Principle: Immersing the ion beam in a very cold (in the moving frame $\Re_0$) electron beam over a given length.

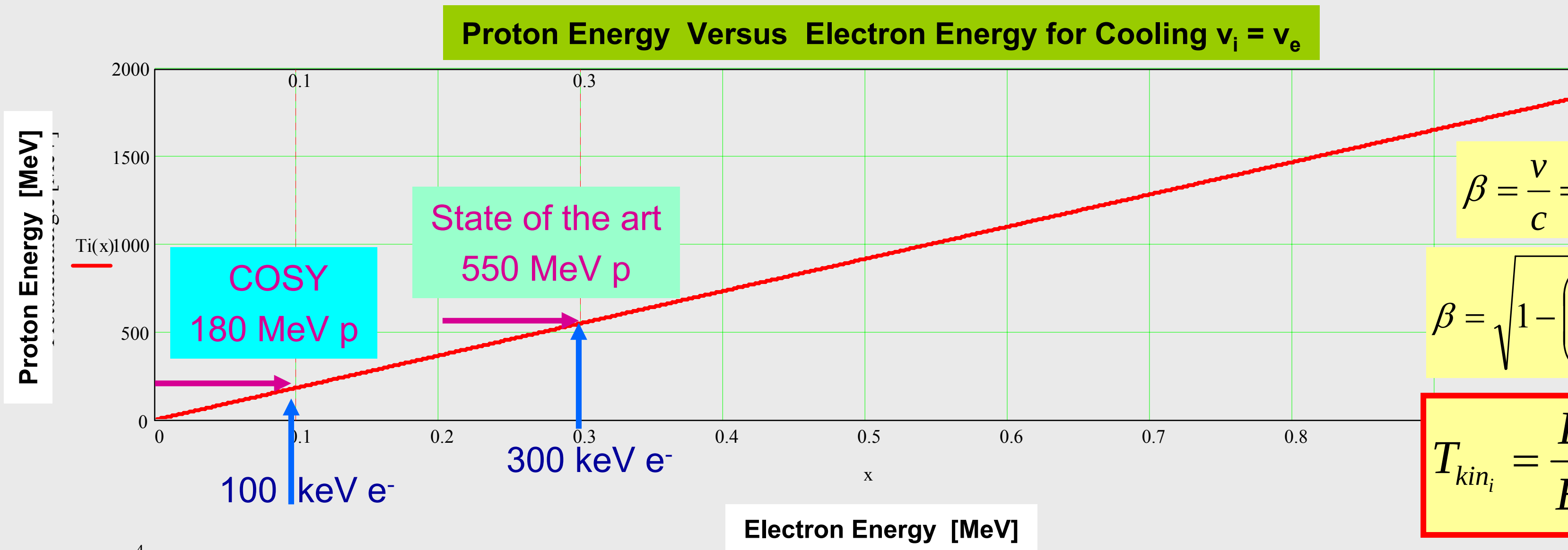
If we suppose, at first, that the electron beam has no velocity and therefore no energy in $\Re_{0}$, due to Coulomb interaction the ions will undergo „collisions“ with electrons (*binary collision model*). As a result the ions will give up some of their energy to the electrons which will therefore be heated.

As a consequence the electrons must be renewed in order to obtain a very cold (in each plane) ion beam.

$$\boxed{\langle \vec{v}_i \rangle = \vec{\beta}_{0e} c = v_{0e}}$$



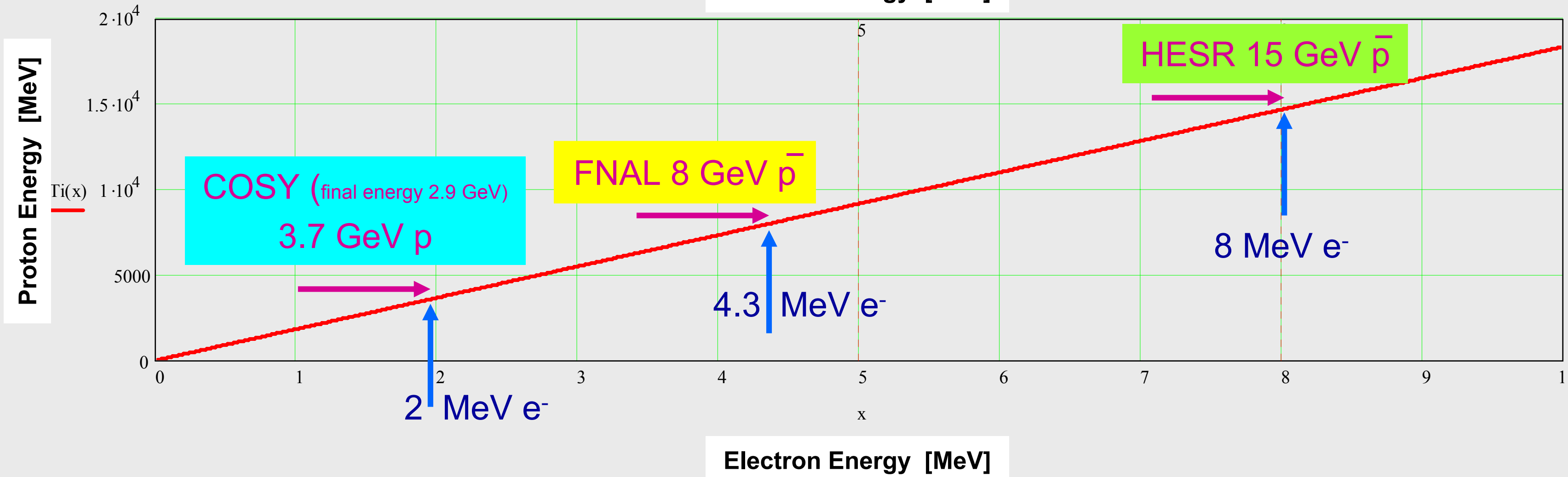
High Energy Electron Cooling



$$\beta = \frac{v}{c} = \beta_e = \beta_i$$

$$\beta = \sqrt{1 - \left(1 + \frac{T_{kin}}{E_0}\right)^{-2}}$$

$$\boxed{T_{kin_i} = \frac{E_{0i}}{E_{0e}} \cdot T_{kin_e}}$$



Special Features of High Energy Electron Cooling

Technical Challenge:

High Voltage (E_e >0.5 MeV, I_e <3 A, confinement in a magnetic field)

Magnetic field quality, straightness in cooling section < 10^{-5}

Decreasing of "corrugation, waviness" of force line of the magnetic field is essential for obtaining maximum of friction force

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e\left(\sqrt{V^2+V_{eff}^2}\right)^3}\ln\left(1+\frac{\rho_{\max}}{\rho_L+\rho_{\min}}\right)$$

$$V_{eff}^2 = V_{\Delta\Theta}^2 + V_{E\times B}^2 + V_e^2$$

$$V_{\Delta\Theta} = \gamma\beta c\sqrt{\left\langle \Delta B^2\right\rangle} \qquad \left\langle \Delta B^2\right\rangle$$

"Waviness" of magnetic force line

Essential for experiment with internal target

$\gamma_E\beta_E/\gamma_{30}\beta_{30}$	E, keV
1.9	100
8.0	1000
13.8	2000

Cooling Time for Large Relative Velocities

$$\tau_z \propto \frac{A}{Z^2}\frac{1}{n_e\eta}\beta^3\gamma^5\Theta_z^3 \qquad \begin{cases} \Theta_{x,y} = \dfrac{v_{x,y}}{\gamma\beta c} \\ \Theta_{\parallel} = \dfrac{v_{\parallel}}{\gamma\beta c} \end{cases}$$

- **increases with energy** $\propto \gamma^2$ ($\beta\gamma\Theta$ is conserved)
- for hot beams $\propto \Theta^3$
- linear dependence on electron beam intensity n_e and cooler length $\eta = L_{ec}/L_{ring}$
- short for highly charged ions A/Z^2
- independent of hadron beam intensity
- independent of ion velocities and only dependent on electron temperature **for cold beams**

Magnetised or not Magnetised Electron Cooling ?

The 4.3 MeV electron cooler at the RECYCLER ring (FNAL) achieves cooling time of about 1 h.

The new coolers for COSY and HESR should provide a few orders of magnitude more powerful longitudinal and transverse cooling that requires new technical solutions.

The basic idea of the new COSY cooler and for the future HESR cooler is to use high magnetic field along the orbit of the electron beam from the electron gun to the electron collector.

Engineering Problems of High Energy Electron Coolers

High voltage generators (> 0.5 MV)

High voltage performance

Limiting performance of accelerator tubes

Power transmission to accelerator ˝head˝

Power transmission to magnetic coils (at accel/decel tubes)

Electron current and HV stability (1-3 A, 10^{-5})

Electron beam formation, transportation and recovering

Magnetic field measurement in the cooling section (straightness < 10^{-5})

Electron beam diagnostics

High Voltage Generators

Cockroft-Walton accelerator – up to 1 MV (practically)

˝Electron- Beam Ventil˝ (ELV, BINP Novosibirsk)-
a sophisticated version of insulating core transformer ≤ 2 MV (COSY 2MV)

N. Kuksanov
High Voltage ELV Accelerators for Industrial Application
This conference, FRXCH03

Dynamitron ~ 4 MV max

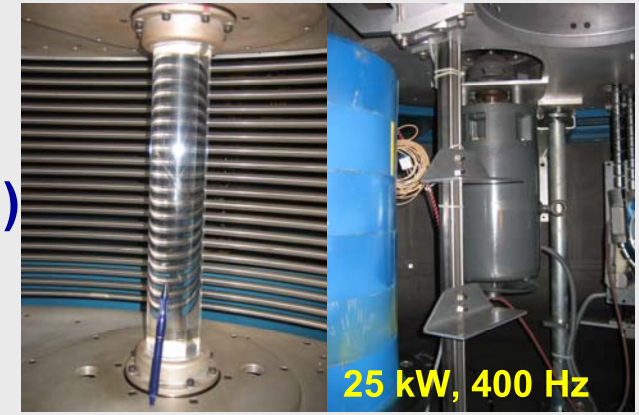
Van de Graaff accelerators

Pelletron (**Fermilab 4.3 MV**)

˝Record holder˝ of DC accelerators: Vivitron (Univ. Louis Pasteur, Strasbourg)
⟹ 35 MV project, 25 MV operation

Power Transmission to Magnetic Coils (at accel/decel tubes)

Rotating shafts (Fermilab, Pelletron)



Cascade transformer (present solution 2 MeV COSY)

New:
Gas turbine (idea of BINP)

Electron Cooler - Status and Projects

- **In operation** state of the art

  25 - 350 kV at CERN, GSI, IMP Lanzhou, FZJ …

- **In operation** (**September 2005 – September 2011**)

  4.3 MV at FNAL (DC, non-magnetized)

  Longitudinal cooling time > 1h

- **In commissioning**

  2 MV for COSY (DC, magnetized)

- **Projects**

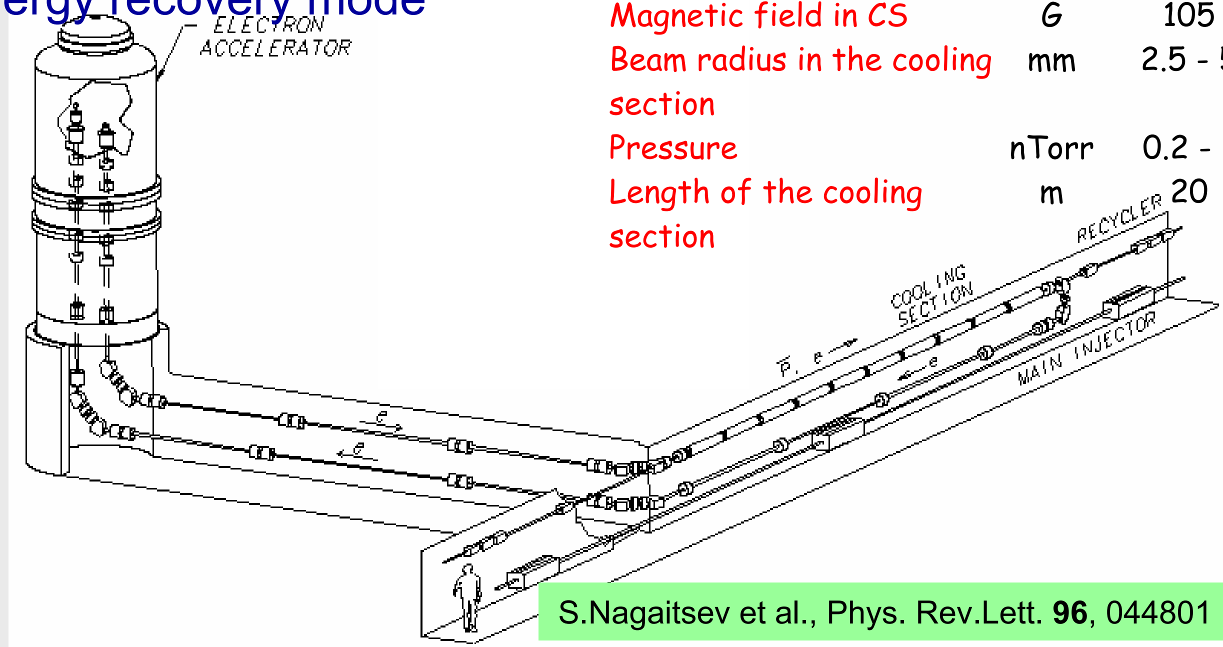
  2.5 MV for NICA collider (DC, magnetized)

  4-8 MV (?) for HESR, ENC (DC, magnetized)

4.3 MV at FNAL, Fermilab (non- magnetized, fixed energy)
2005-2011 in operation at TEVATRON

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

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



S.Nagaitsev et al., Phys. Rev.Lett. **96**, 044801 (2006)

COSY Juelich
2 MeV Electron Cooler COSY –Jülich in commissioning at BINP

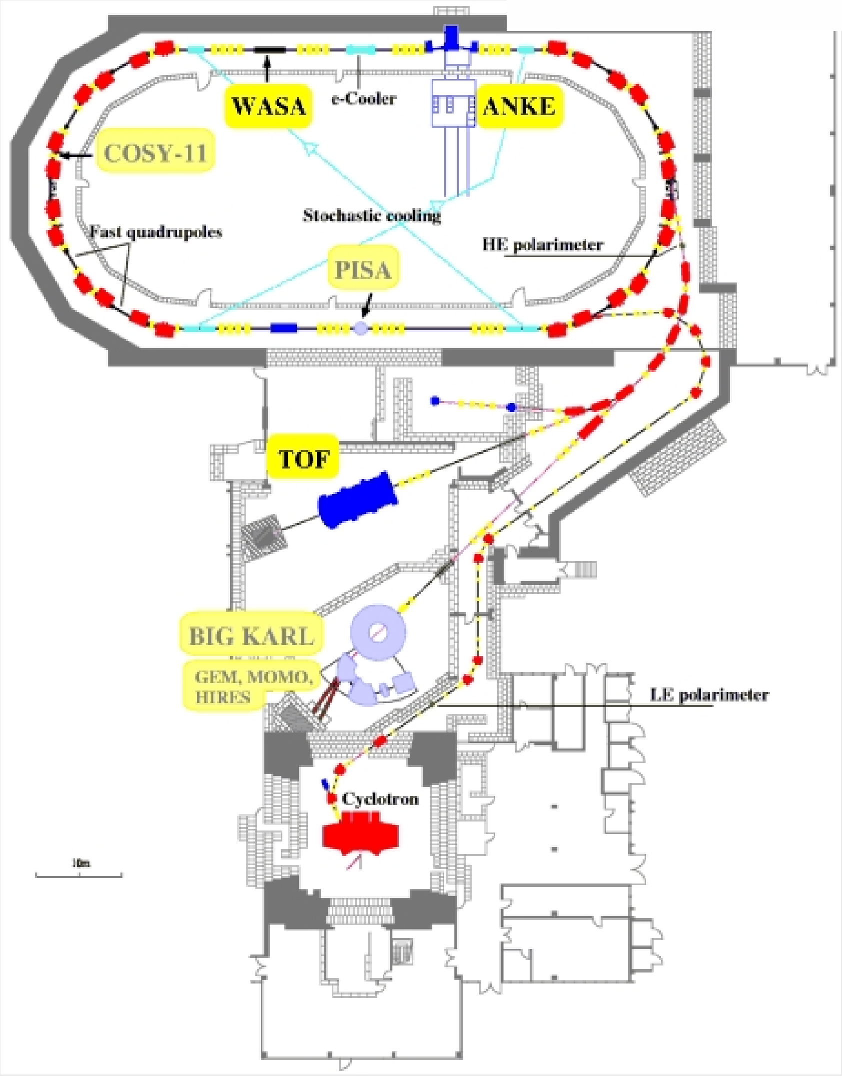
JÜLICH
FORSCHUNGSZENTRUM

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, pellet, atomic beam
- External: solid, liquid



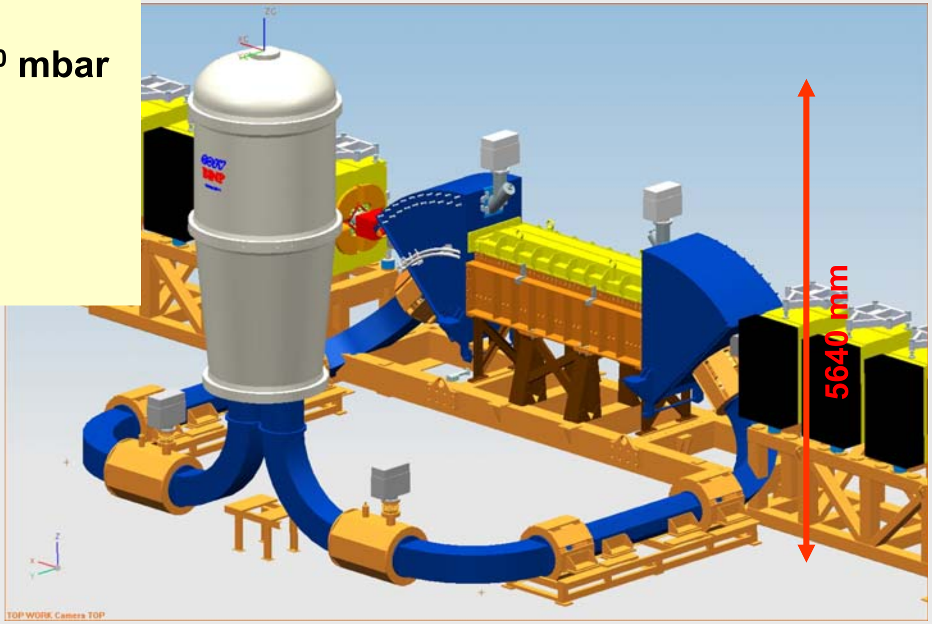
Beam cooling:

- **Electron cooling** at injection for
  beam accumulation
  high brilliance beams
- **Stochastic cooling** above 1.5 GeV/c for
  luminosity preservation

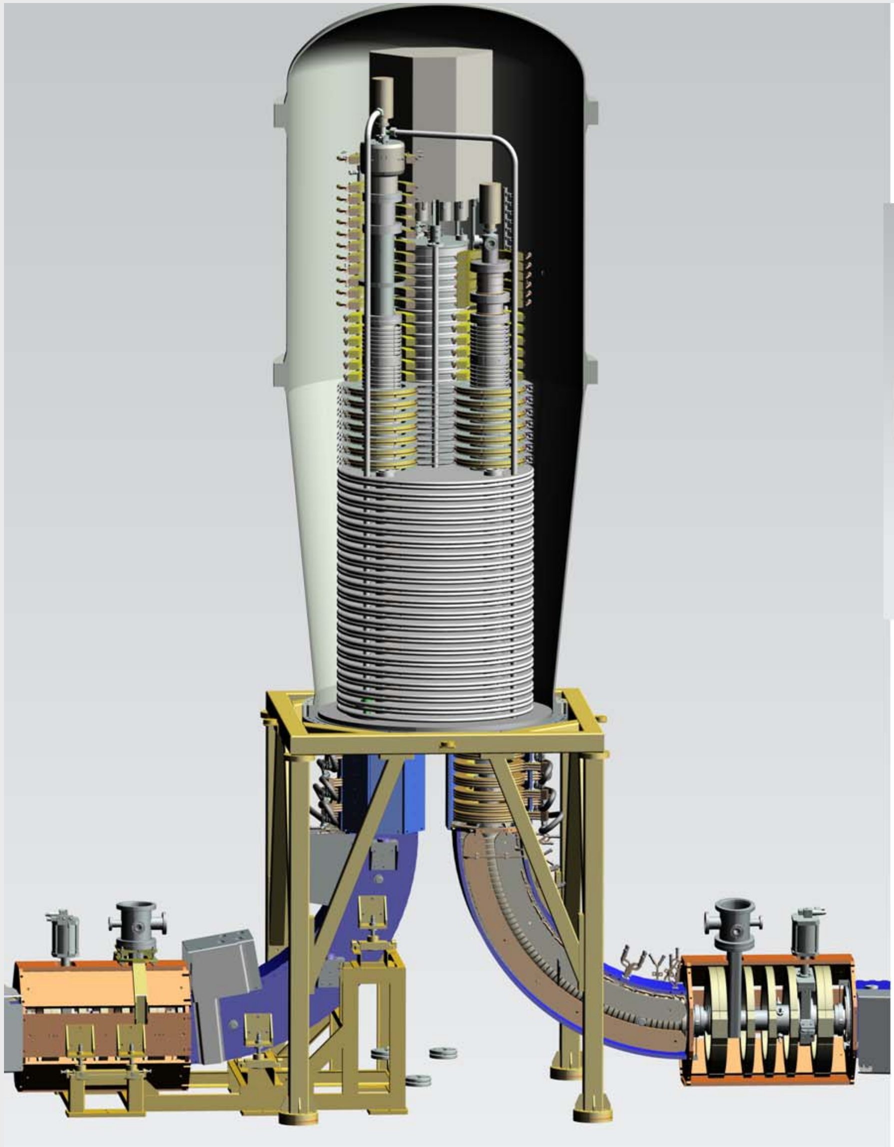
2 MeV Electron Cooler COSY – Jülich
Technical Design – Layout BINP,Basic Parameters and Requirements

• Energy Range:	0.025 ... 2 MeV
• High Voltage Stability	< 10^{-4}
• Electron Current	0.1 ... 3 A
• Electron Beam Diameter	10 ... 30 mm
• Cooling section length	2.694 m
• Toroid Radius	1.00 m
• Variable magnetic field	
• (cooling section solenoid)	0.5 ... 2 kG
• Vacuum at Cooler	10^{-9} ... 10^{-10} mbar
• Available Overall Length	6.390 m
• Maximum Height	5.7 m
• COSY beam Axis above Ground	1.8 m

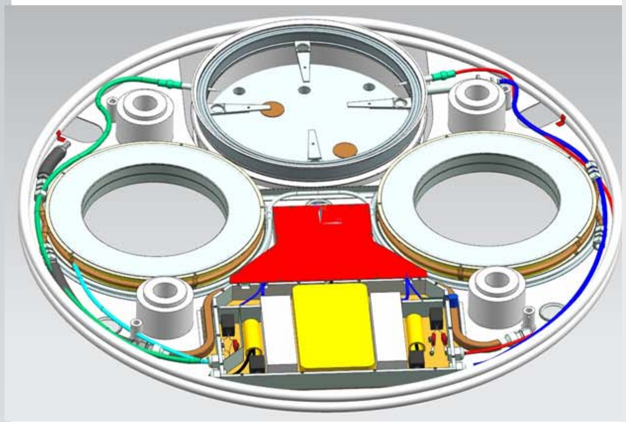
magnetised cooling



3D Design of the Accelerating Column



Modulare high voltage sections



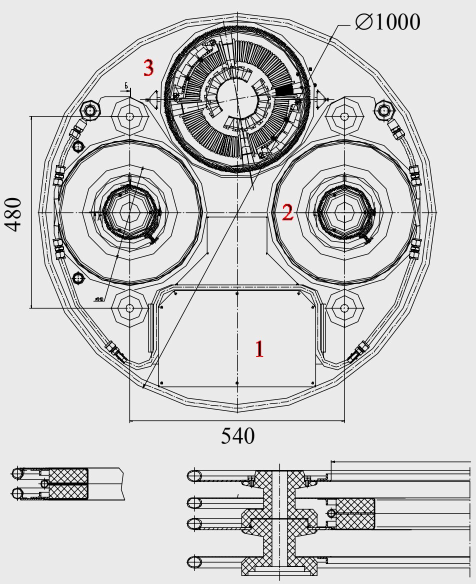
Each section contains;

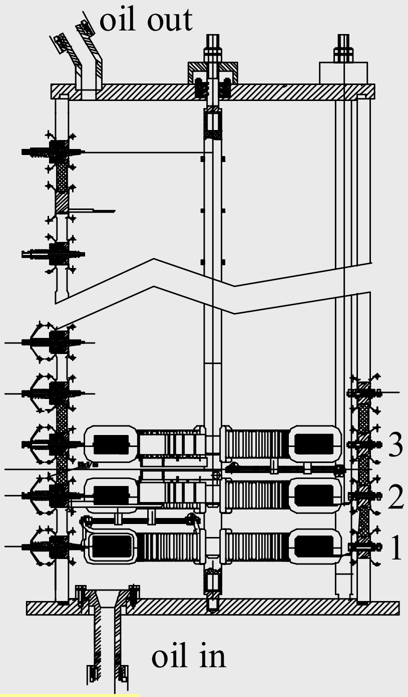
- *high-voltage power supply +/- 30 kV;*
- *power supply of the coils of the magnetic field (2.5 A, 500 G);*
- *section of the cascade transformer for powering of all electronic components;*

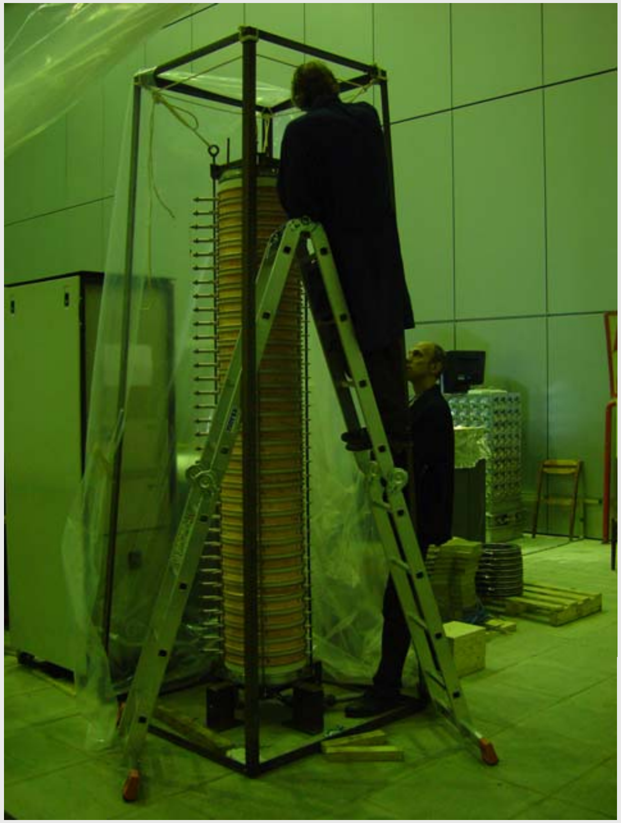
33 high-voltage section

High Frequency Cascaded Resonant Transformer

20 kHz, 40 kW, for individual power supplies of **solenoid coils** in the accel/ decel column and **high voltage** generation





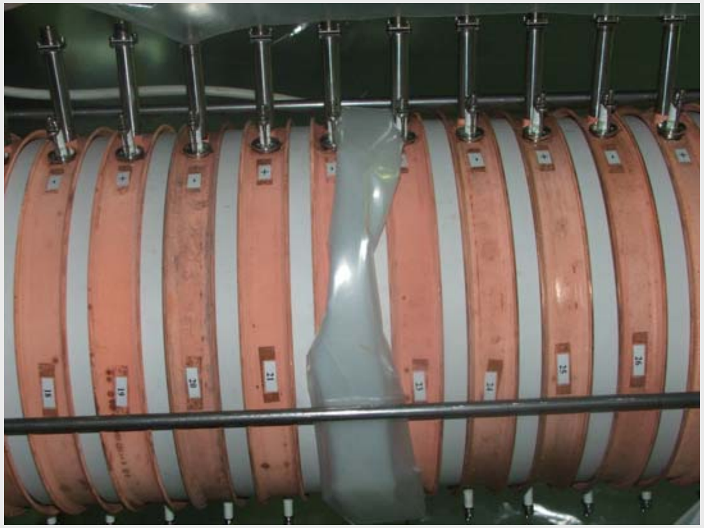


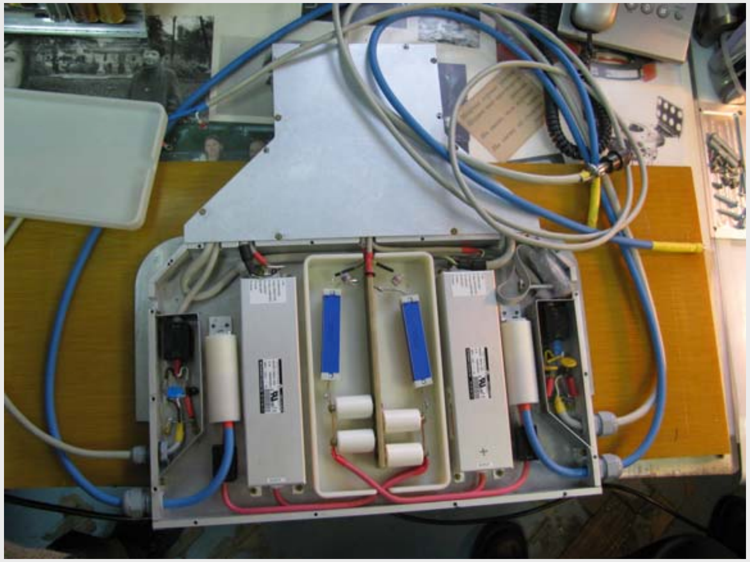
High Voltage Section

amorphous ferrite foil core, cylinder filled with transformer oil for isolation,high voltage, input-output ceramic feedthrough for connection of HV sections

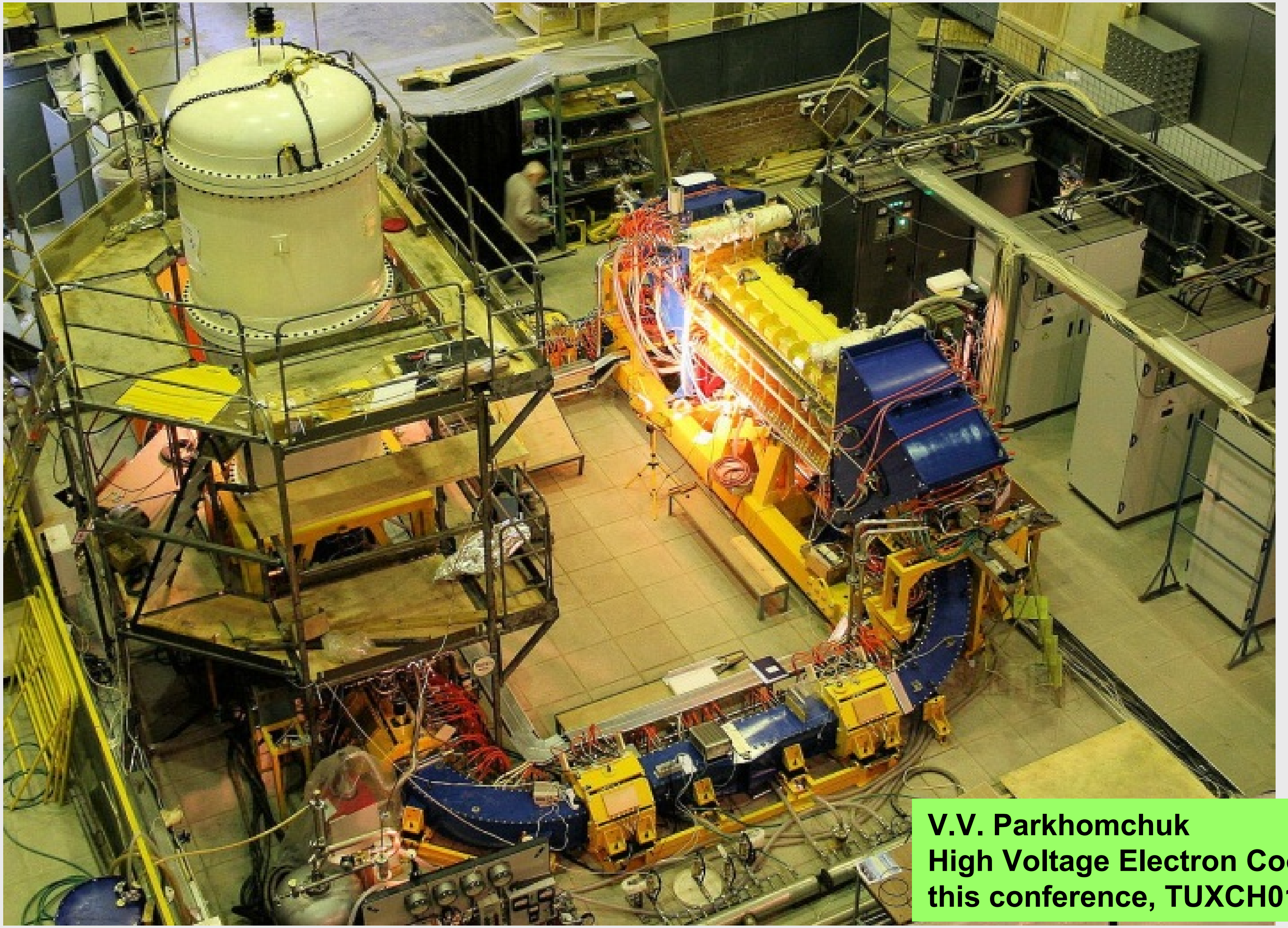
Transformer Column

Cascade Generator Test Bench



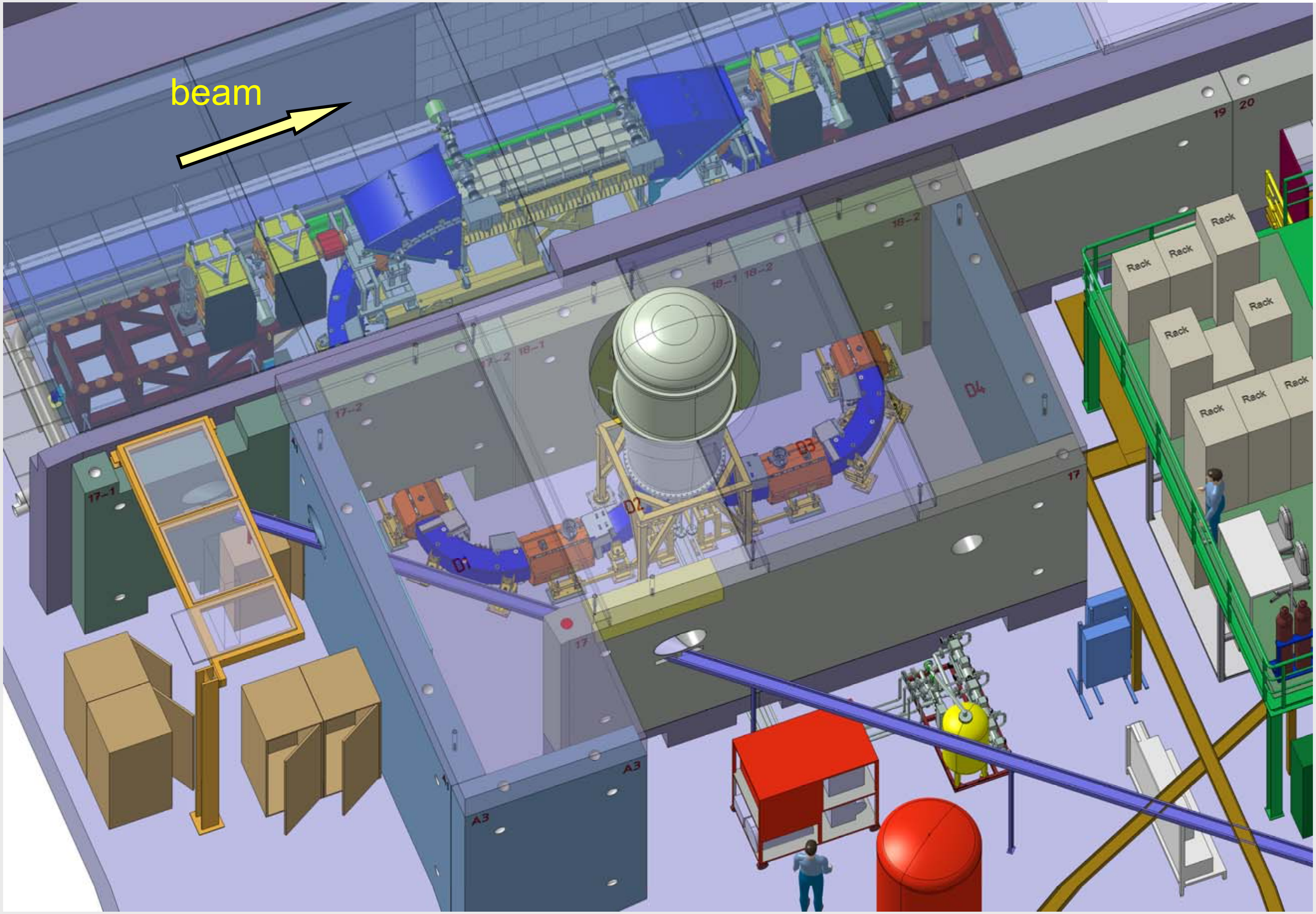


Commissioning of the 2 MeV Electron Cooler at BINP, Novosibirsk.



V.V. Parkhomchuk
High Voltage Electron Cooler
this conference, TUXCH01

COSY Cooler Location with Shielding Elements



Results and Next Steps

Energy keV	Current A	Losses mA	Rad Sv/hour
30	0.9	0.0015	0
150	0.6	0.0075	0
1000	0.5	0.002	0.001
1250	0.35	0.004	0.002
1500	0.2	0.01	0.01

This conference:

HIGH VOLTAGE ELECTRON COOLER *
M. Bryzgunov, A. Bubley, A. Goncharov, V. Panasyuk,
V. Parkhomchuk, V. Reva D. Skorobogatov (BINP SB RAS, Novosibirsk) Russia
J. Dietrich, V. Kamerdzhiev (FZJ, Jülich) Germany

Long time run at 1MV and 200 mA are demonstrated

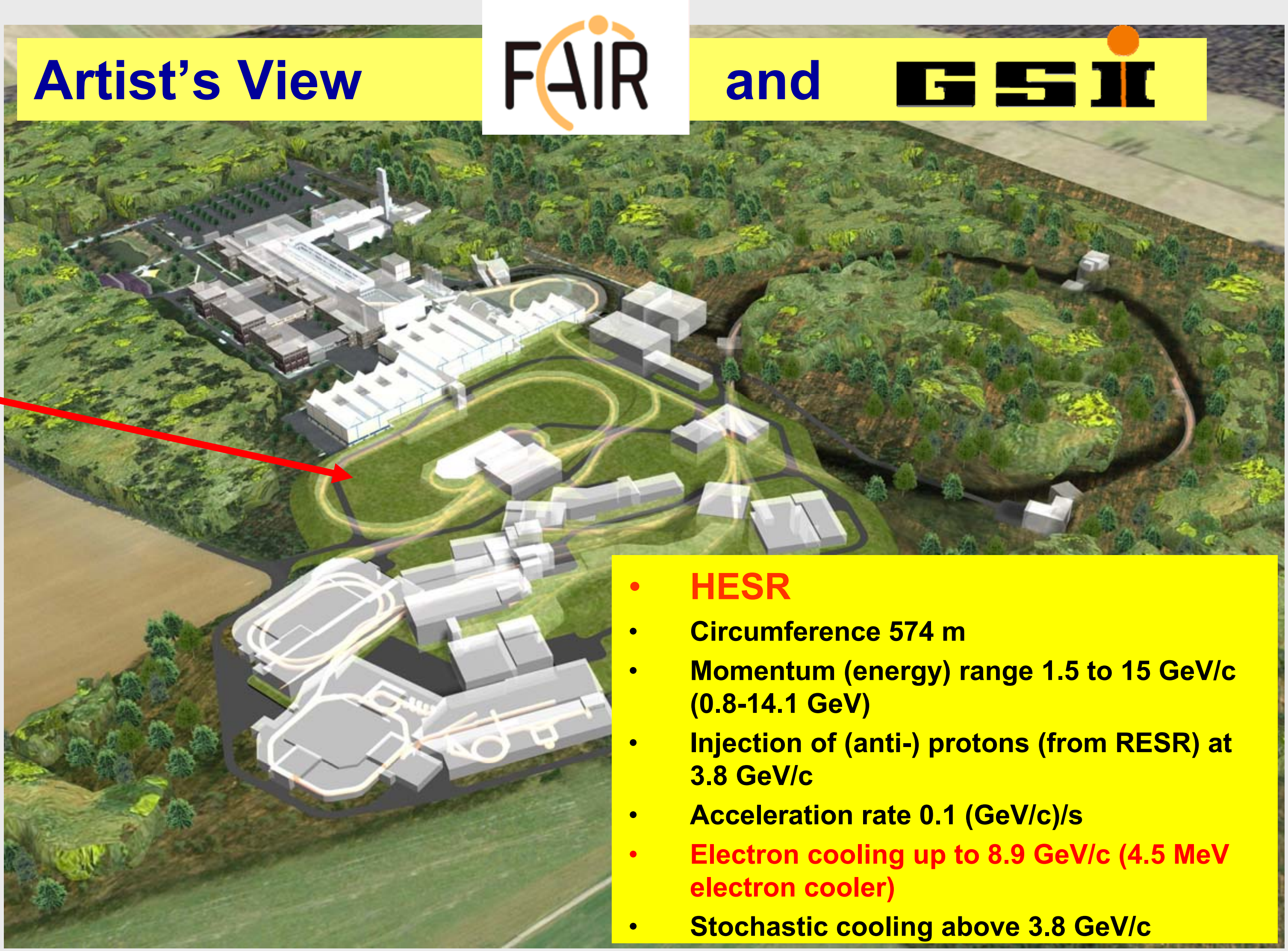
The commissioning at BINP will be finished in autum 2012

Shipping to Juelich in November 2012

Installing in COSY in January/ February 2013

4 – 8 (?) MeV Electron Cooler for HESR, FAIR Darmstadt

High Energy Storage Ring HESR

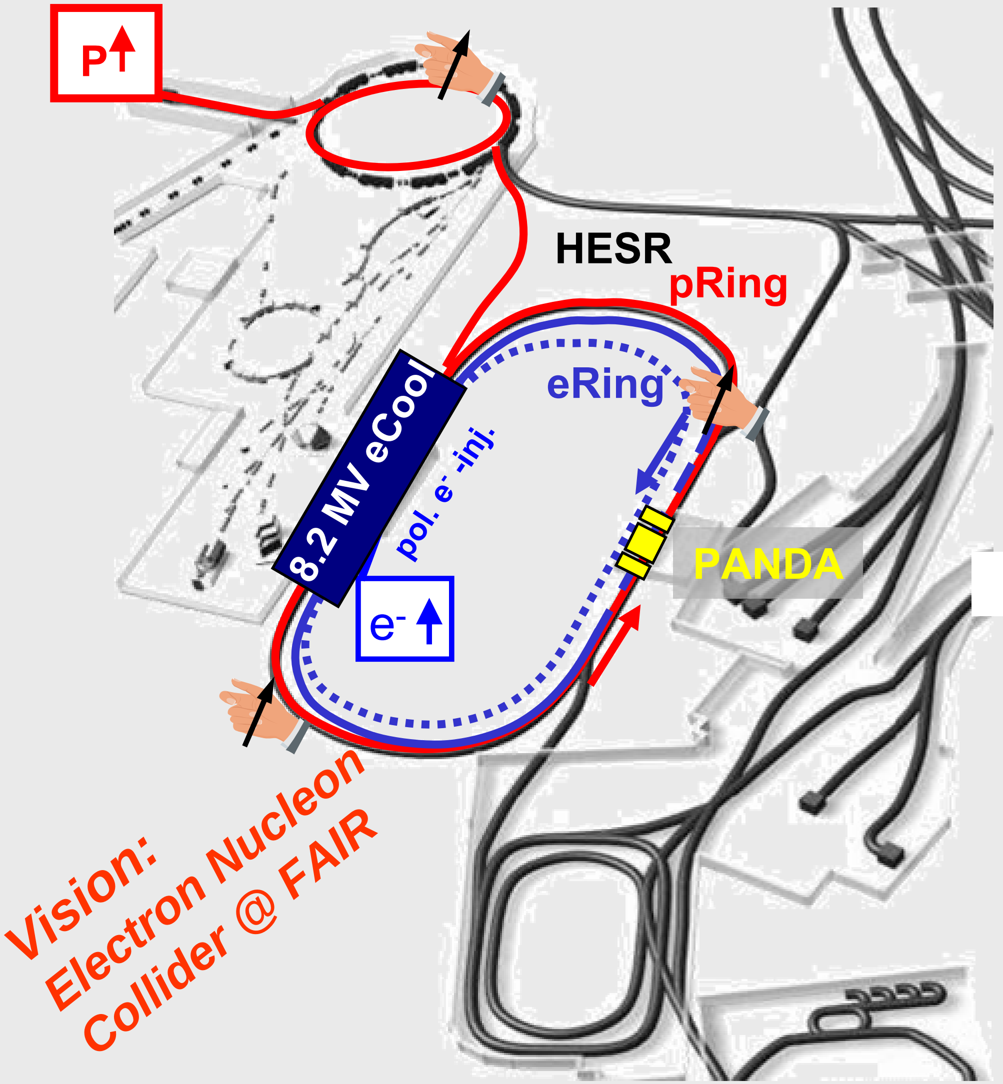


- **HESR**
- **Circumference 574 m**
- **Momentum (energy) range 1.5 to 15 GeV/c (0.8-14.1 GeV)**
- **Injection of (anti-) protons (from RESR) at 3.8 GeV/c**
- **Acceleration rate 0.1 (GeV/c)/s**
- **Electron cooling up to 8.9 GeV/c (4.5 MeV electron cooler)**
- **Stochastic cooling above 3.8 GeV/c**

ACID-Workpackage:ENC@FAIR

ACcelerator Physics and Integrated Detectors

K. Aulenbacher , University Mainz



Add e⁻-beam@HESR

3 GeV, 2A pol. Electron beam

15GeV, 0.4 A pol. Proton beam

$s^{1/2}$=14GeV (center of mass energy)

HIM

Helmholtz-Institut Mainz

Ion ring and Detector funded and under construction within the FAIR complex:

Extensions & solutions needed:

Protons:

- Polarized proton source
- tune jump Quads in SIS18
- direct SIS-18/HESR beamline
- cooler solenoid+helical dipoles as SNAKE
- electron cooling at maximum energy

Electrons:

- polarized electron source
- full energy injector (synchrotron or pulsed linac)
- electron storage ring (in HESR tunnel?)
- spin lifetime under synchrotron radiation
- increased complexity: e+/e- beam dynamics together with spin stabilization.

Both:

IR + beam separation + polarization

Luminosity: 2-6·10^{32} [cm^{-2} s^{-1}]

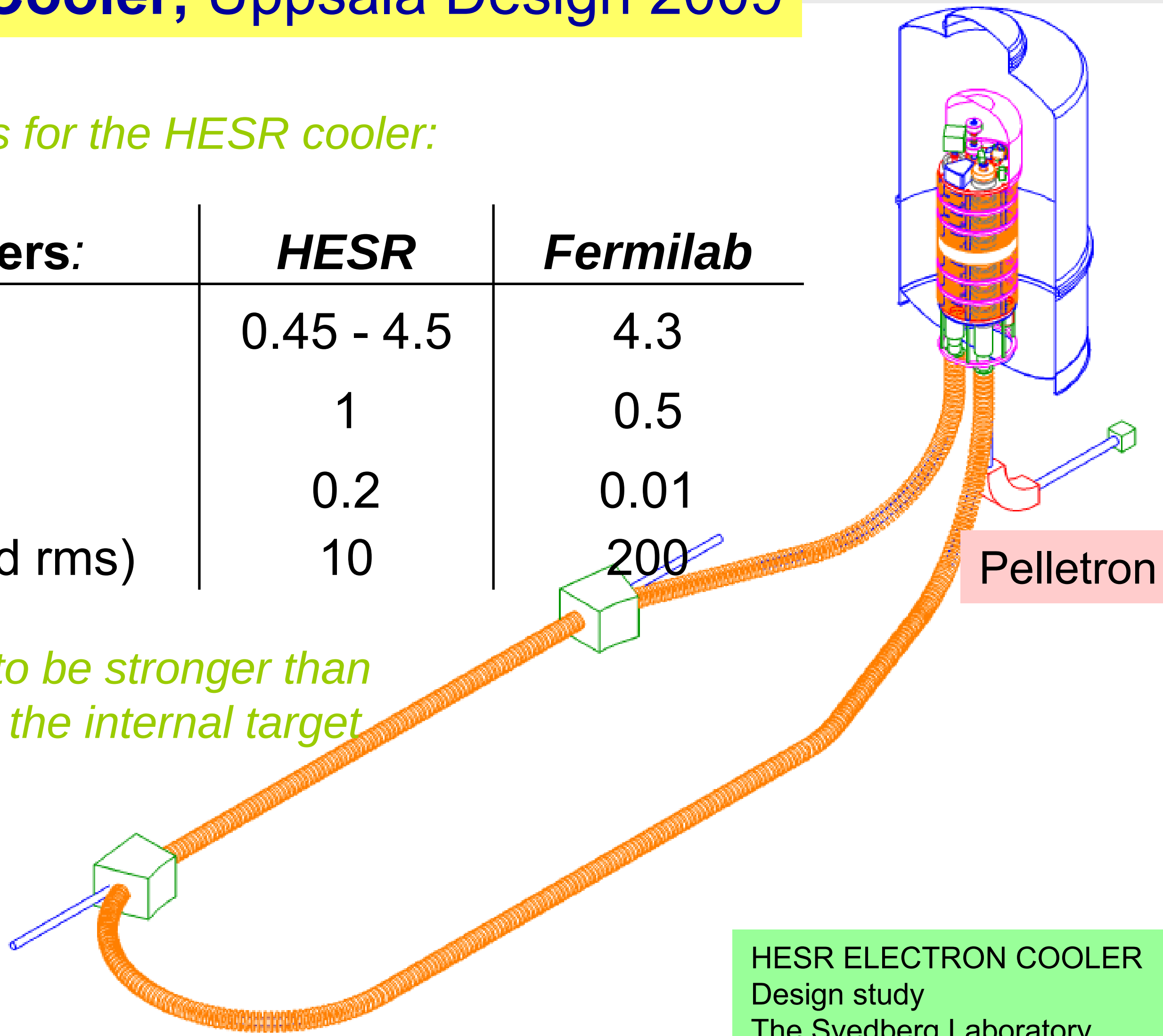
HESR Electron Cooler, Uppsala Design 2009

Parameters for the HESR cooler:

e-beam parameters:	***HESR***	***Fermilab***
Energy (MeV)	0.45 - 4.5	4.3
Current (Amp)	1	0.5
Solenoid field (T)	0.2	0.01
Straightness (μrad rms)	10	200

The cooling force needs to be stronger than at Fermilab to counteract the internal target

- *Higher magnetic field*
- *Better straightness*



Feasibility Study of 8 MeV H⁻ Cyclotron to Charge the Electron Cooling System for HESR, BINP

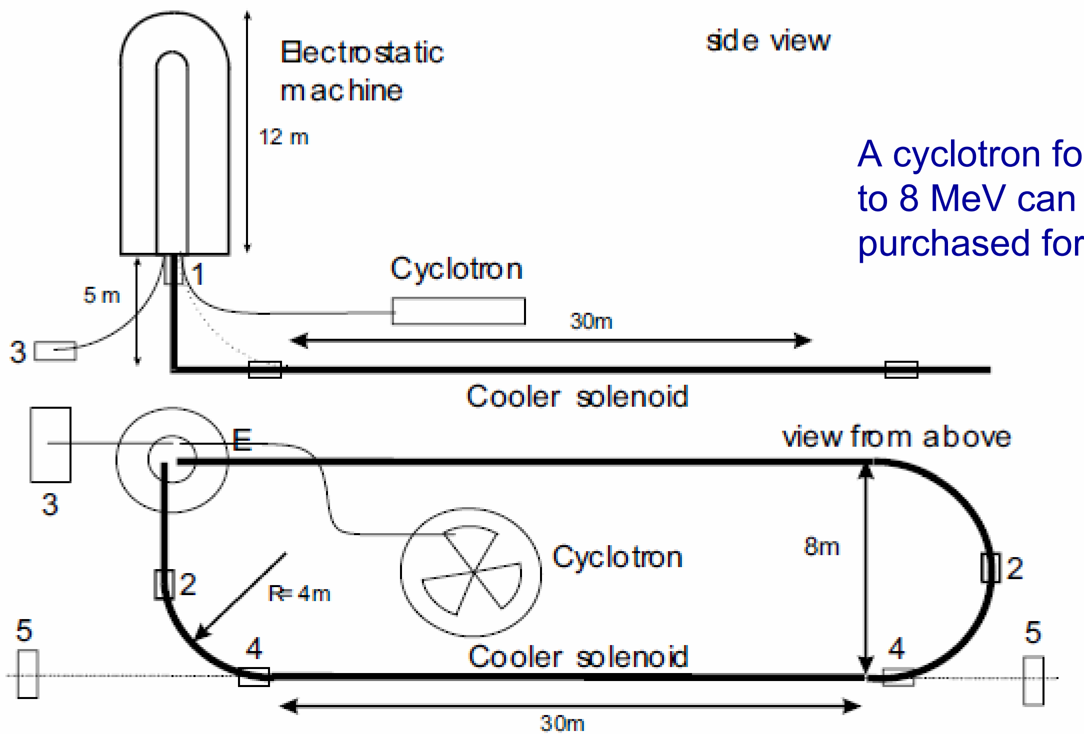


Figure 1.High voltage cooler for HESR.
1–transformation section; **2**– electrostatic correctors, **3** – energy analyzer of H^- beam for the precise voltage measurement, **4** – point of convergence, **5** –HESR triplets

A cyclotron for accelerating a beam of 1 mA H^- ions up to 8 MeV can be built from the commercial equipment purchased for the commercial cyclotrons.

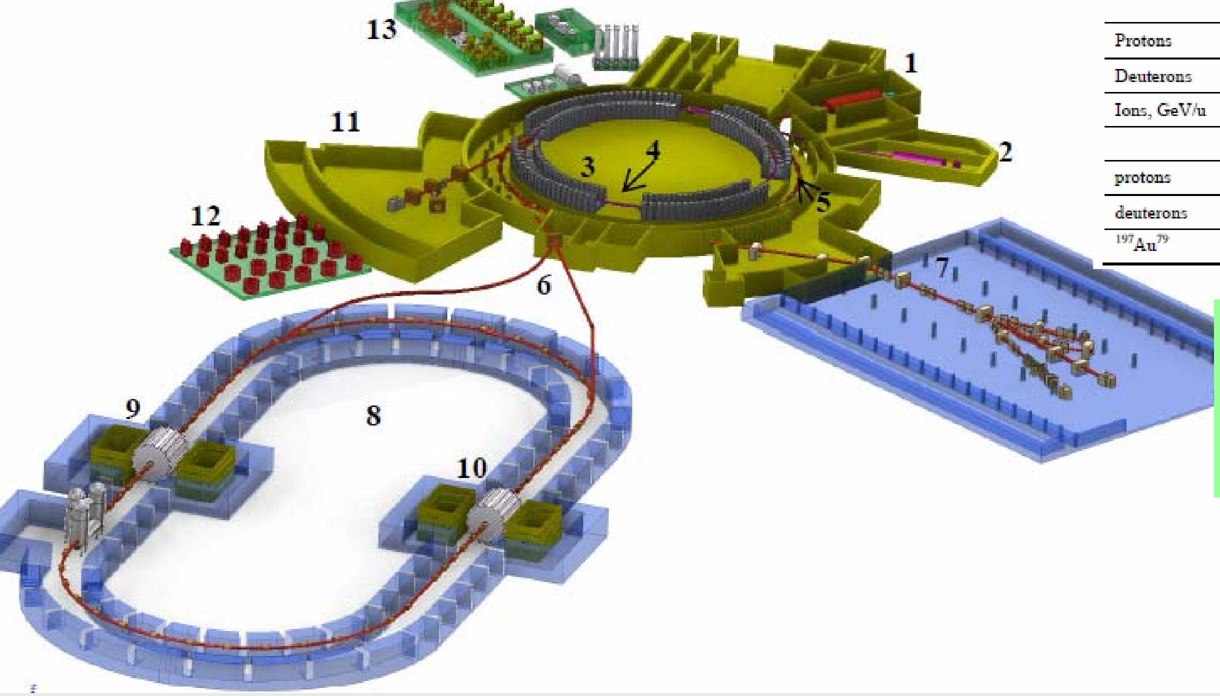
V.V.Parkhomchuk et al., COOL'11, Alushta 2011

2.5 MeV Electron Cooler for NICA, JINR Dubna

Electron cooling system at electron energy up to 2.5 MeV, one electron beam per each ring of the collider

Table of parameters of NICA accelerators

Acceleration	Booster project	Nuclotron Project	Nuclotron Status (April 2011)	Collider project
1. Circumference, m	212.2	251.5		503.0
2. Max. magn. field, T	2.0	2.0	2.0	1.8
3. Magn. rigidity, T·m	25.0	45	39.5	45
4. Cycle duration, s	4.0	4.02	5.0	≥ 2000
5. B-field ramp, T/s	1.0	1.0	1.0	< 0.1
6. Accelerated/stored particles	p÷ $^{197}Au^{79+}$, p↑, d↑		p-Xe, d↑	p ÷ $^{197}Au^{79+}$, p↑, d↑
Maximum energy, GeV/u				
Protons	–	12.6	–	12.6
Deuterons	–	5.87	5.1	5.87
Ions, GeV/u	$^{197}Au^{32+}$ 0.4	$^{197}Au^{79}$ 4.5	$^{54}Xe^{24+}$ 1.0	$^{197}Au^{79}$ 4.5
Intensity, ion number per cycle (bunch)				
protons	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$
deuterons	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$
$^{197}Au^{79}$	$2{\cdot}10^{9}$	$2{\cdot}10^{9}$	$1{\cdot}10^{6}$ ($^{54}Xe^{24+}$)	$1{\cdot}10^{9}$



S.Yakovenko
Status of the High Voltage Electron Cooler Project for NICA collider
this conference, TUACH01

2.5 MV Electron cooler for NICA collider

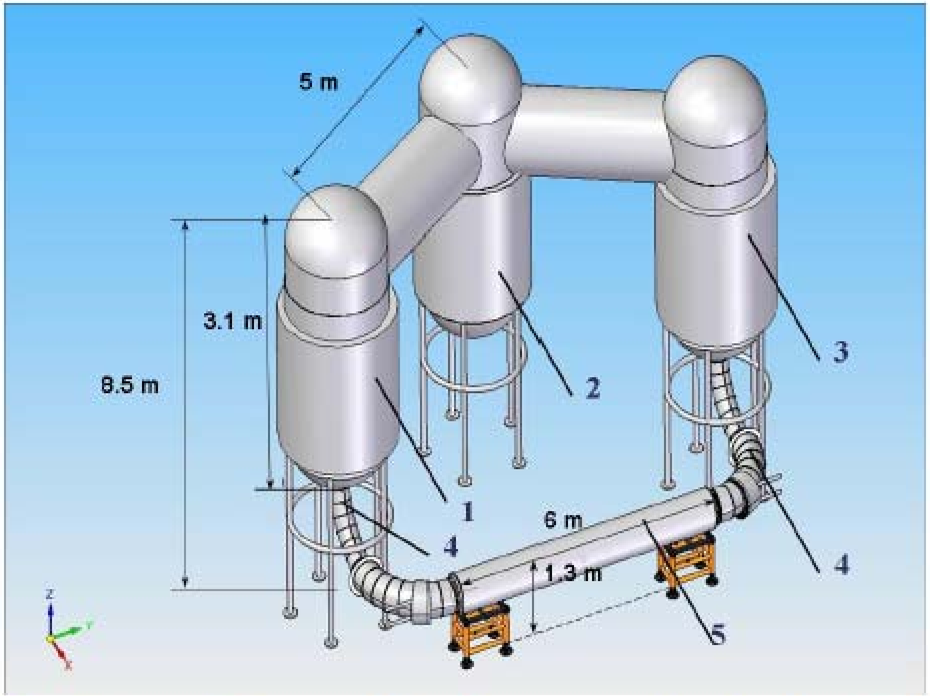


Fig.1. General view of the electron cooler. 1, 3 – tanks with electron gun and acceleration tube and deceleration tube + collector for electron beam of opposite direction, 2 – tank with HV generator, 4 – beam transportation solenoids, 5- electron cooling section.

Table 1. Cooler parameters

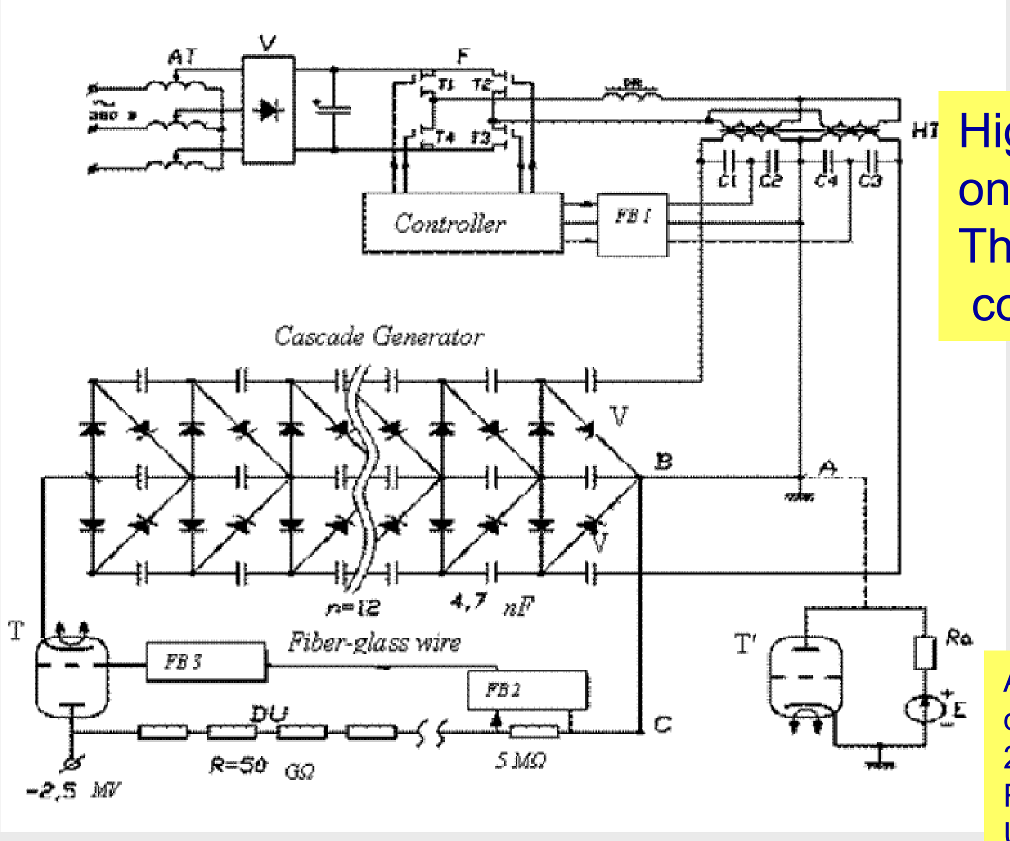
Electron energy, MeV	$0.5 \div 2.5$
Electron beam current , A	$0.1 \div 1{,}0$
Beam diameter, cm	1,0
solenoid magnetic field, T	$0.1 \div 0.2$
HV PS current, mA	1
Collector PS, kW	2×2
HV PS stability, $\Delta U/U$	1×10^{-4}
SF_6 gas pressure, at	$5 \div 8$

Proceedings of COOL'11, Alushta, Ukraine

ELECTRON COOLER FOR NICA COLLIDER

E.V.Ahmanova, A.G.Kobets*, A.V.Ivanov** I.N.Meshkov, R.V.Pivin, A.U.Rudakov, A.V.Shabunov, A.V. Smirnov, N.D.Topilin, Yu.A.Tumanova, S.L.Yakovenko#, JINR, Dubna, A.A.Filippov, M.P.Kokurkin, N.Yu.Lysov, M.M.Pashin, AREI, Moscow

High Voltage Generator

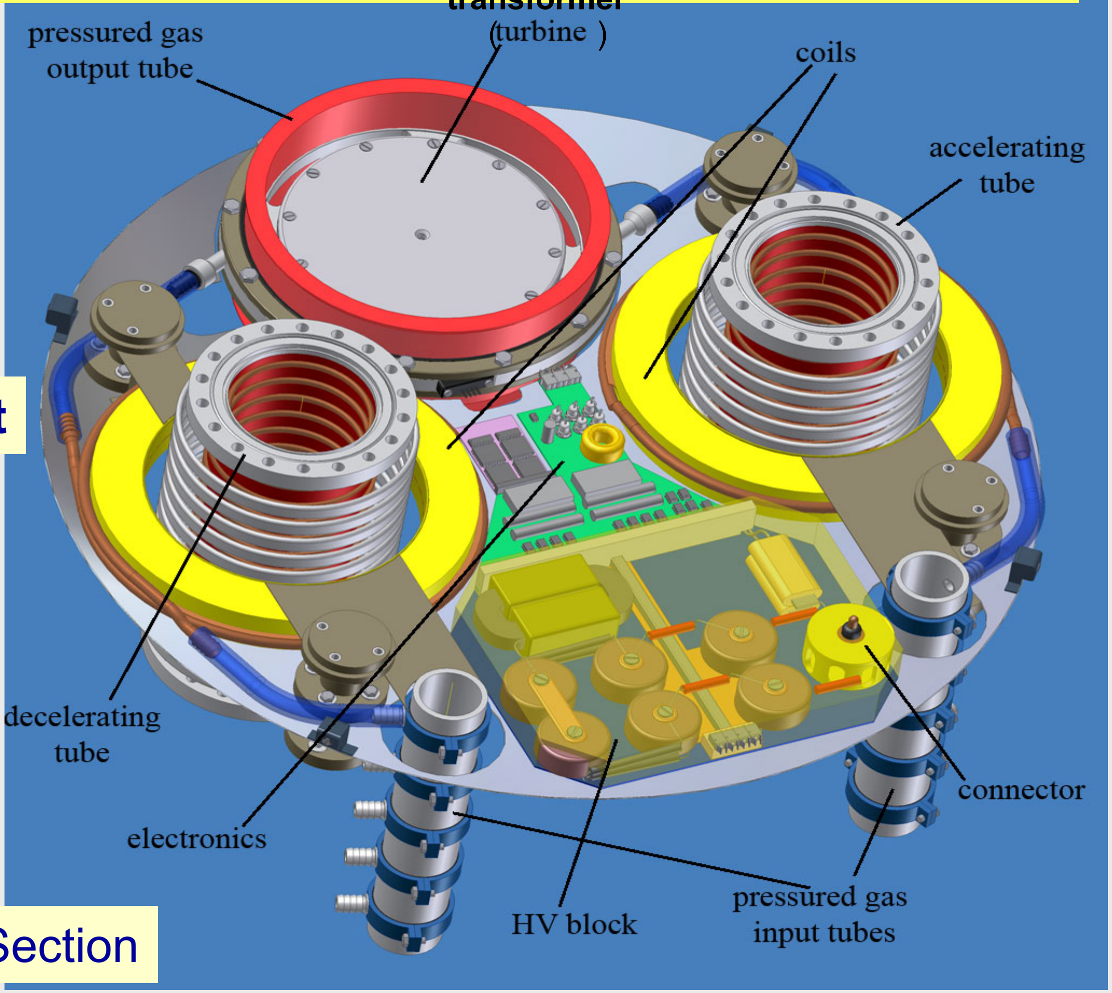


High voltage (HV) generator is based on the principle of the **cascade scheme**. The chosen scheme has three diode columns and twelve multiplying levels.

At the working frequency of 20 kHz the total number of diodes (type 2Ц106Г by Russian standard) is equal to 2500, the total number of capacitors (type C2-29B-2 by Russian standard) is equal to 8316. The HV of U = 2.0 MV is controlled with three-phase autotransformer (AT) of the voltage of 380 V at 50 Hz.

New Ideas and Further Developments- Turbines

Gas Driven Turbine for individual power supplies of **solenoid coils** in **the** acceleration/ deceleration column **and** **high voltage** generation

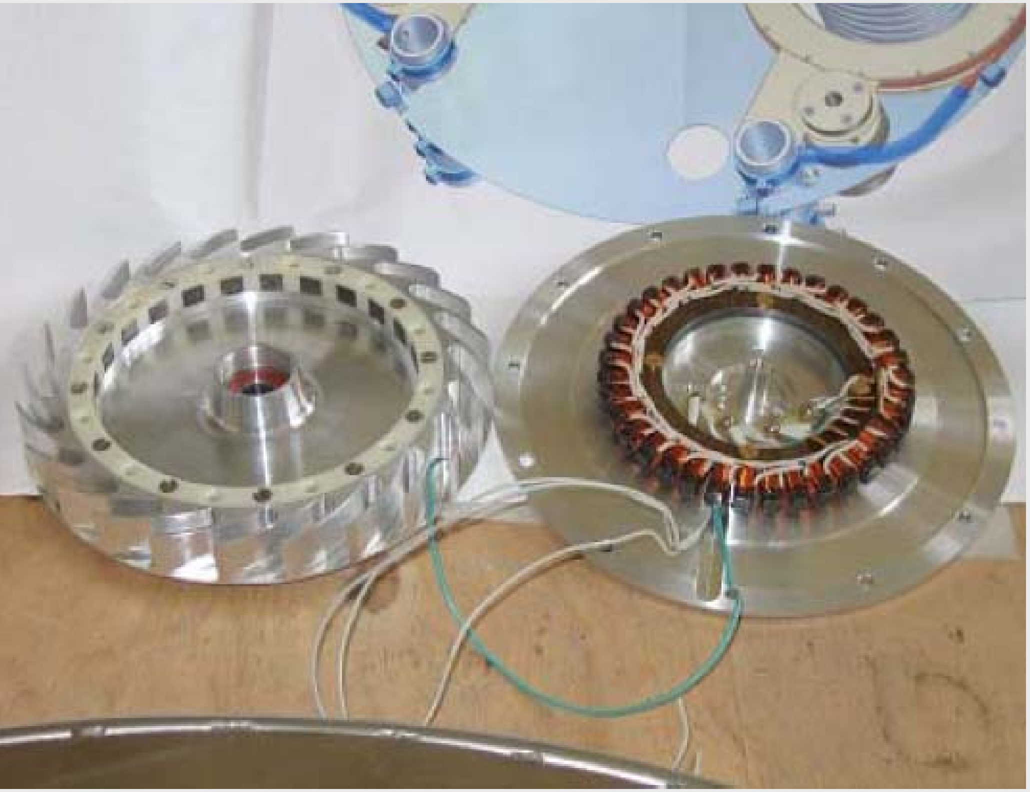


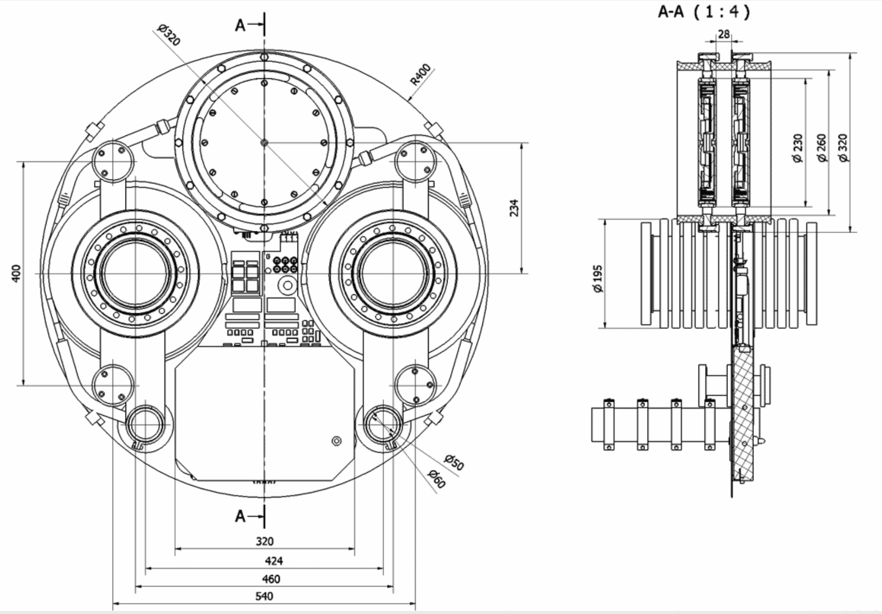
Modular concept

Section thickness	4 cm
Distance between two sections	2 cm
Section period	4+2=6 cm
Electric field between two sections	60 kV / 2 cm = 30 kV/cm
Electric field along tube	60 kV / 6 cm = 10 kV/cm

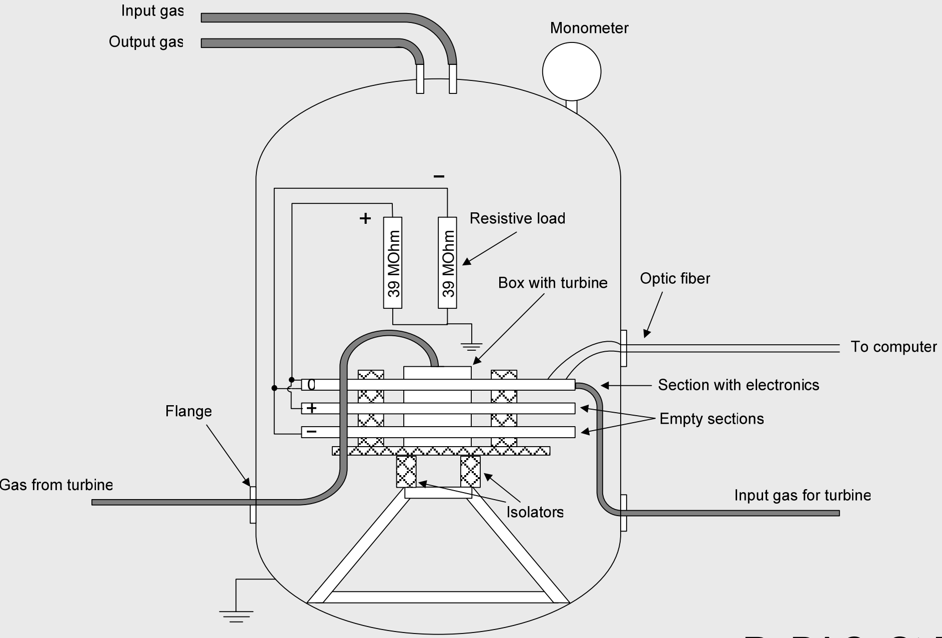
High Voltage Section

Gas Turbine and Generator Coils Ø 300 mm, 600 W,100 Hz

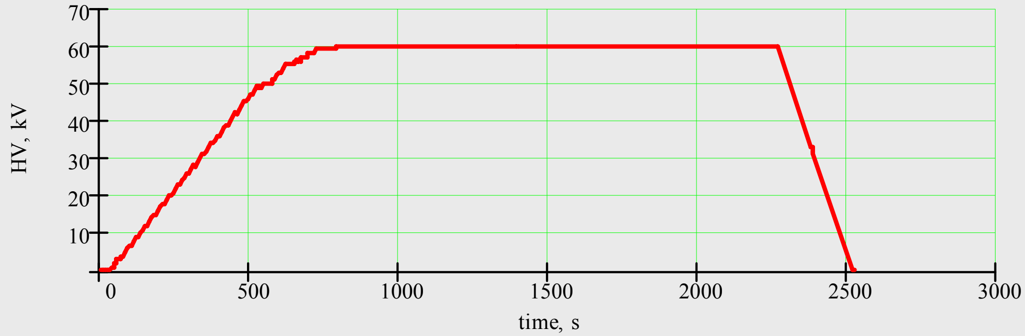




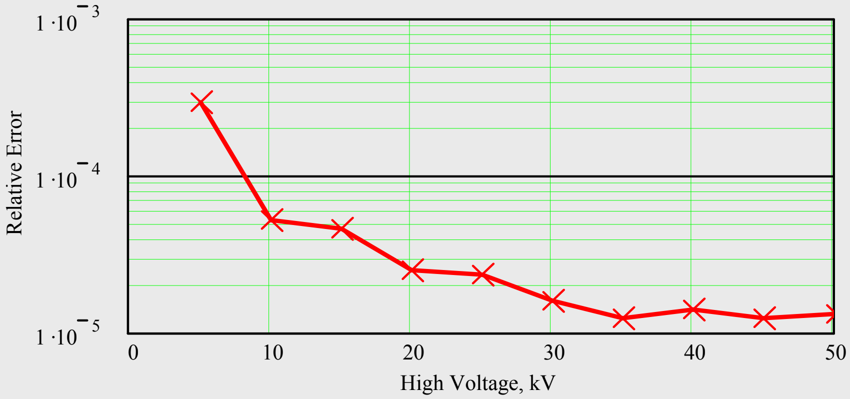
Gas Driven Turbine
Layout of the Turbine Test Bench in BINP



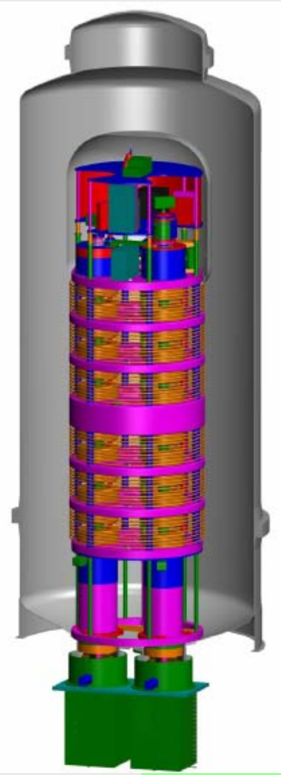
Voltage between sections, SF_6 (1.6 atm), 60 kV



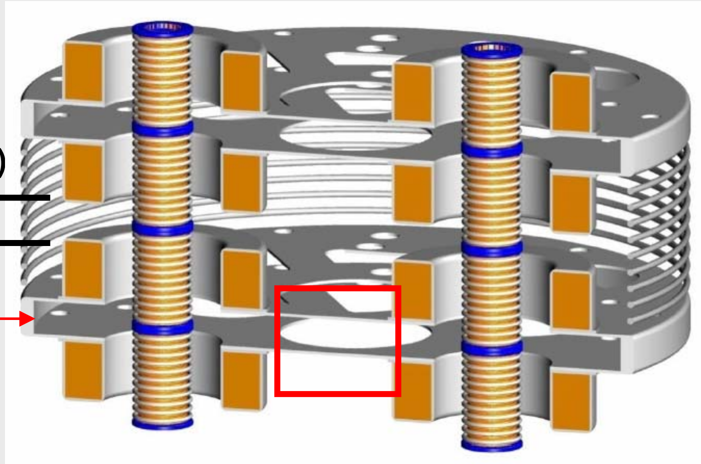
Relative stability of the high voltage



Hybrid System- Combination of Powerfull Turbines (5 kW) and Cascade Transformers (Helmholtz Institut Mainz)

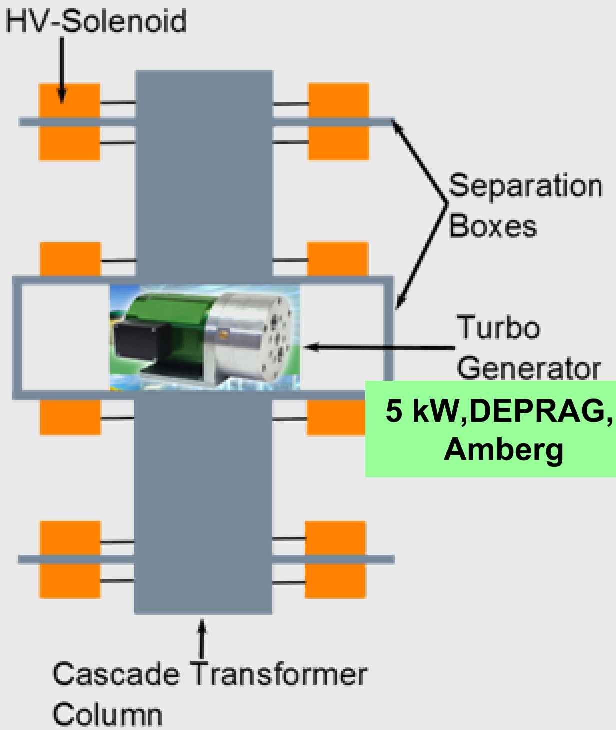


135 mm
ΔU= 750 kV)



field free region (> 200 mm)

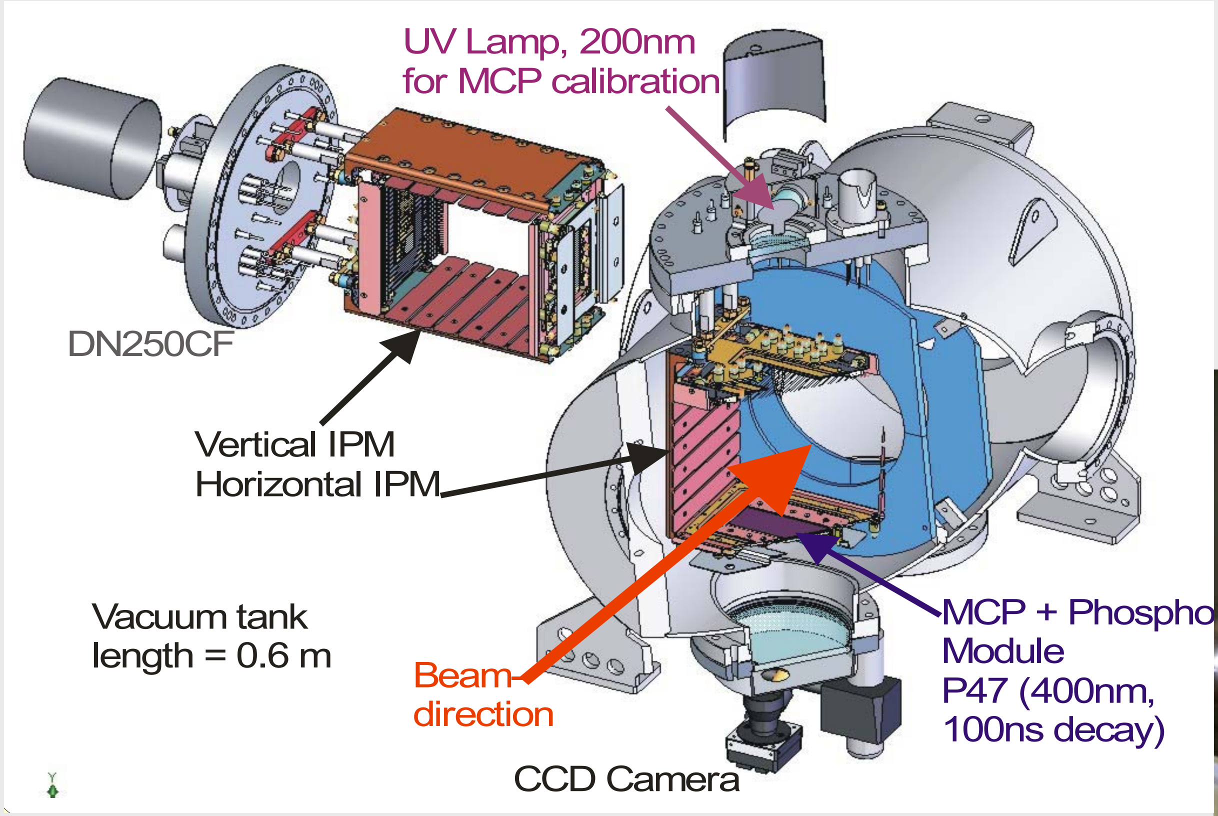
solenoids attached to the **separations boxes** (110 mm height)

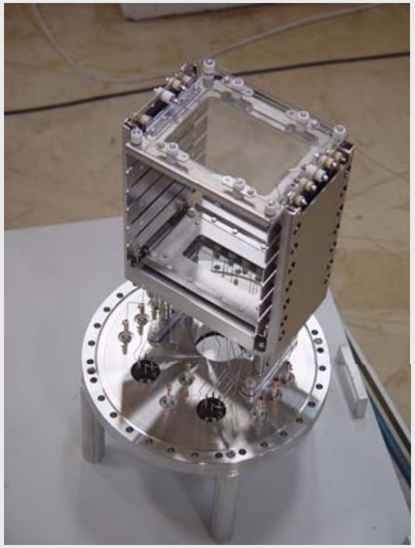


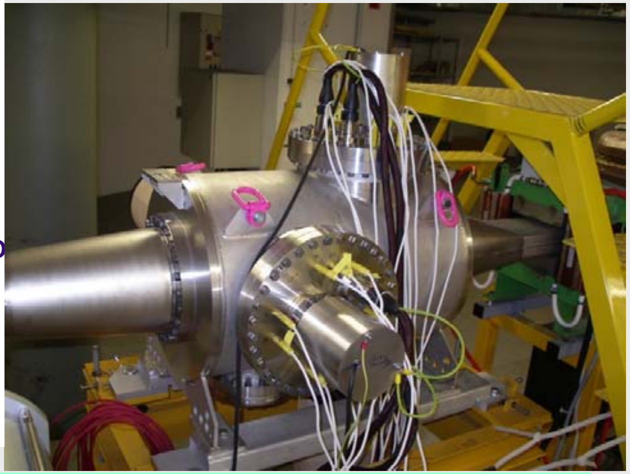
HESR ELECTRON COOLER
Design study
The Svedberg Laboratory
Uppsala University
Uppsala,2009

Beam Diagnostics

Ionisation Profile Monitor IPM

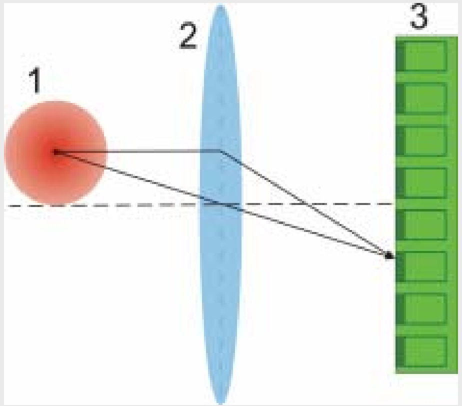




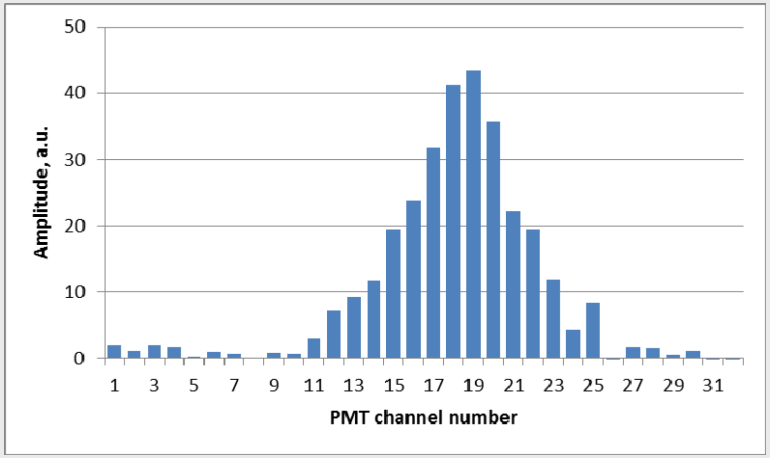


C. Böhme, J. Dietrich, V. Kamerdzhiev, P. Forck, T. Giacomini, D. Liakin
Beam Test of the FAIR IPM Prototype in COSY
Proc. of the 9th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, DIPAC2009, Basel, Switzerland, May 24-27, 2009.

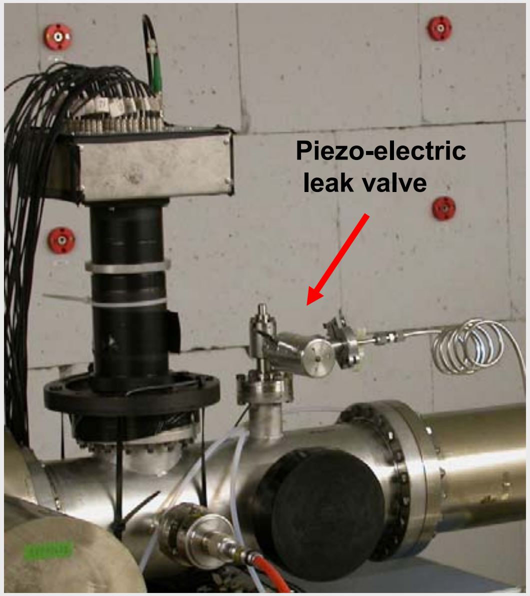
Scintillation Profile Monitor SPM

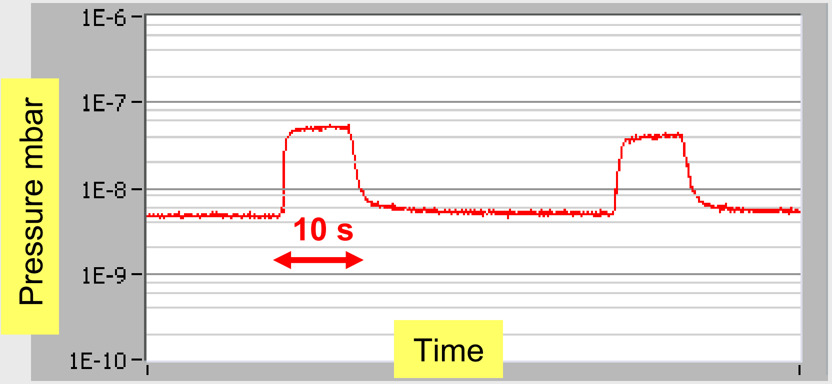


Light from the ion beam (1) is focused with a lens (2) on a multichannel PM (3).

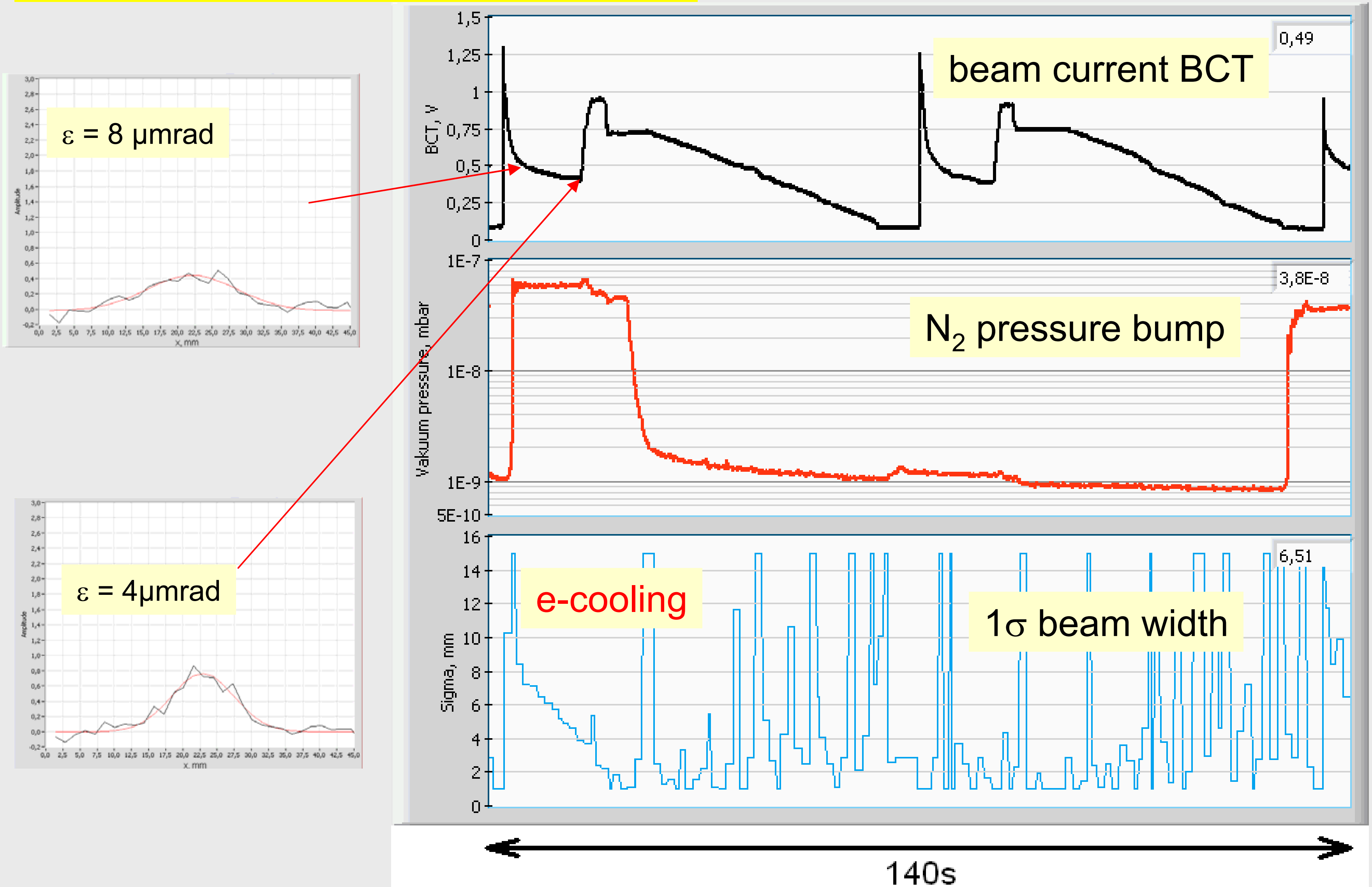


Horizontal beam profile with $1.5 \cdot 10^{10}$ protons , 2.6 GeV/c. Temporary pressure bump at the SPM location amounted to $4 \cdot 10^{-8}$ mbar.





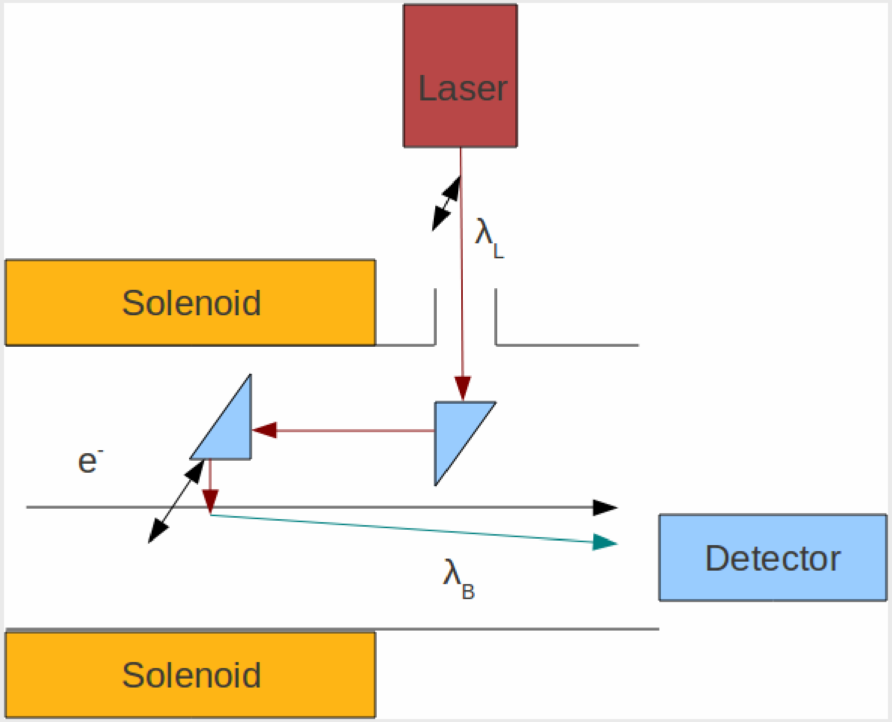
Scintillation Profile Monitor SPM



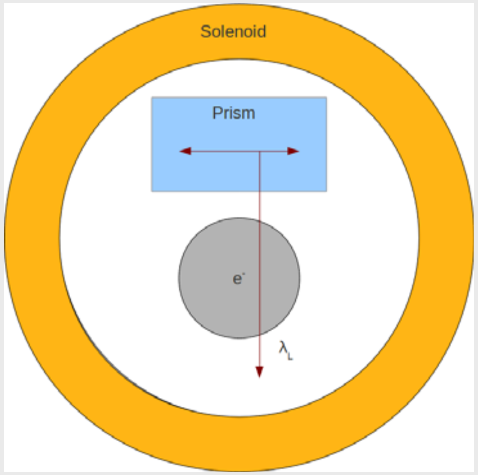
Proposed Electron Beam Profile Measurement in the Cooling Section with Thomson Scattering

T. Weilbach, HIM, Mainz

Schematic Measurement Setup

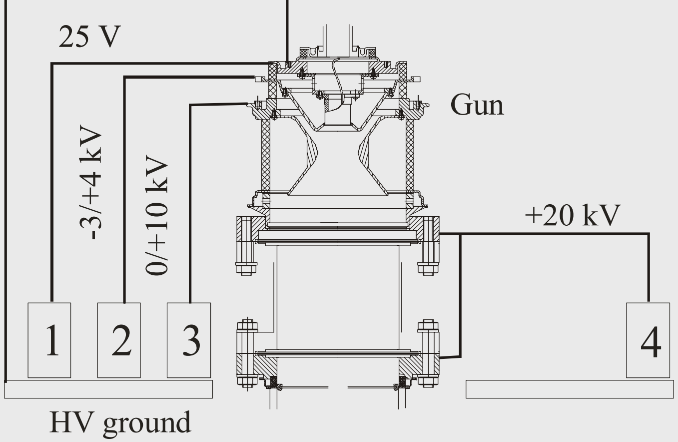


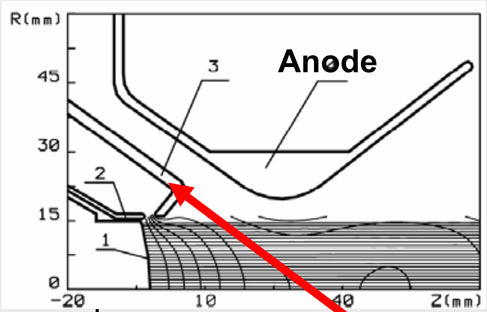
Proceedings of COOL'11, Alushta, Ukraine
OPTICAL ELECTRON BEAM DIAGNOSTICS FOR RELATIVISTICELECTRON COOLING DEVICES
T. Weilbach, Helmholtz-Institut Mainz, Germany,
K. Aulenbacher, KPH Mainz, Germany
J. Dietrich, FZJ, Germany



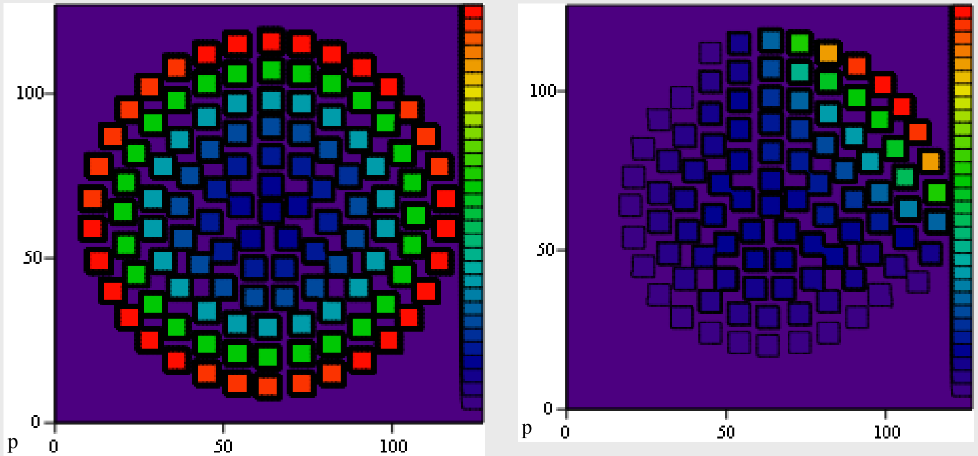
Diagnostics of the Electron Beam Shape, BINP Novosibirsk

Electron Gun



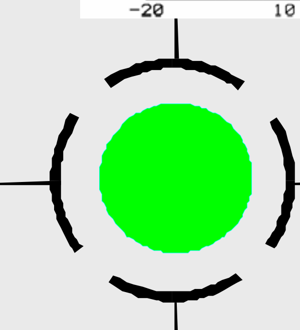


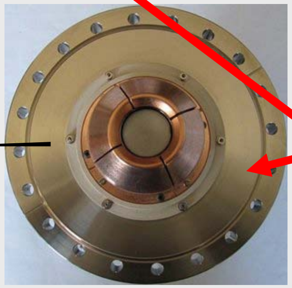
Profile of the electron beam at different voltages on the control electrode (calculated)



This conference:

HIGH VOLTAGE ELECTRON COOLER *
M. Bryzgunov, A. Bubley, A. Goncharov, V. Panasyuk, V. Parkhomchuk, V. Reva D. Skorobogatov (BINP SB RAS, Novosibirsk) Russia
V. Kamerdzhiev (FZJ, Jülich) Germany,
J. Dietrich, (Tu Dortmund and HIM)





Gun **control electrode** is assembled of 4 separate sections.

It allows measurements of the beam envelope along the transport section.

Outlook

- Installing the 2 MeV electron cooler in COSY next year- learning lessons …
- Further developments of powerful turbines- hybrid solutions for 4-8 MV electron coolers
- Improvments of beam diagnostics- aligment and overlap of electron and hadron beam in the cooling section
- Advance into higher energy range should be accomplished by development of novel ideas

Posters Related to the 2 MV COSY Electron Cooler

O. Belikov,
Bypass Modules for Solenoid Shunting of 2 MeV Electron Cooler for COSY
WEPPC023

V. Chekavinskiy,
High Voltage Terminal in COSY Electron Cooler
WEPPC028

D. Skorobogatov
The Power Supply System for Accelerating Column of COSY 2 MeV Electron Cooler
WEPPC032

N. Alinovskliy
Oil Cooling System of the High Voltage Electron Cooler for COSY
WEPPC033

E. Bekhtenev
Beam Position Monitor System for 2 MeV Electron Cooler for COSY
WEPPD028

Thank you for your attention!

Thanks to my colleagues

V.V.Parkhomchuk, BINP Novosibirsk
I.N.Meshkov, JINR Dubna
S. Nagaitsev, Fermilab, Batavia
L. Conradie, iThemba LABS, Cape Town
K. Aulenbacher, Universität Mainz
V. Kamerdzhiev, FZ Jülich