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Peterhof, St. Petersburg, Russia
21 - 25 November, 2016

# Particle Dynamics in the PenningMalmberg-Surko Trap with Rotating Electric Field

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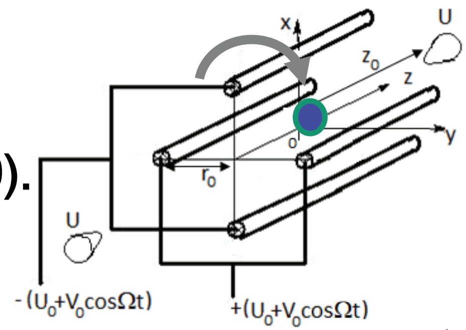
[2]Northern Arctic Federal University, Arkhangelsk
[3]Saint Petersburg State University, Saint Petersburg

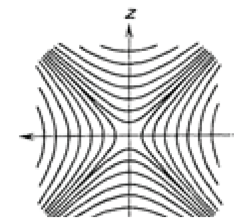
# Contents

# Introduction: Traps for storage of charged particles and antiparticles

- The Paul trap

W.Paul // Rev. Mod. Phys. 62 531 (1990).

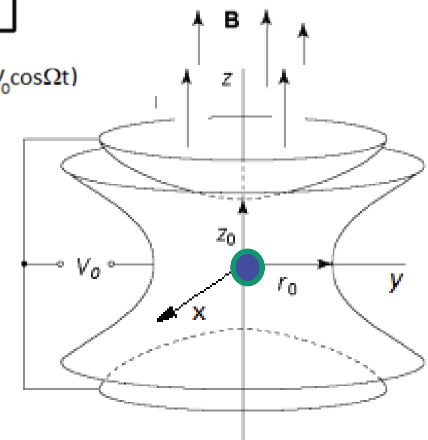



equipotential surfaces

- The Penning trap

E.M. Penning // Physica, 3, P.873 (1936).
H. Dehmelt // Rev. Mod. Phys. 62 525 (1990).

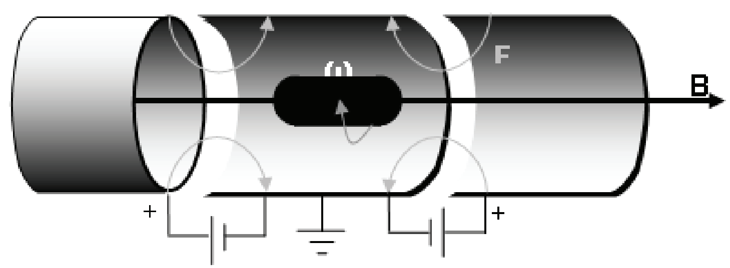



- The Penning-Malmberg trap

J.H. Malmberg and C.F. Driscoll // Phys. Rev. Lett., 44, p.654 (1980).

## Modification of the PMS trap by Clifford Surko: buffer gas

C.M. Surko et al. // Phys. Rev. Lett. 62, 901 (1989).



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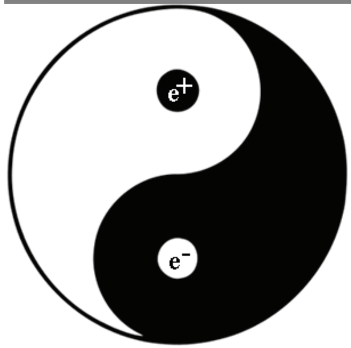
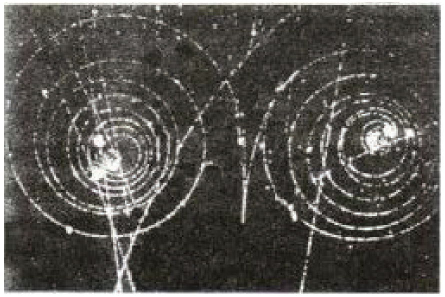


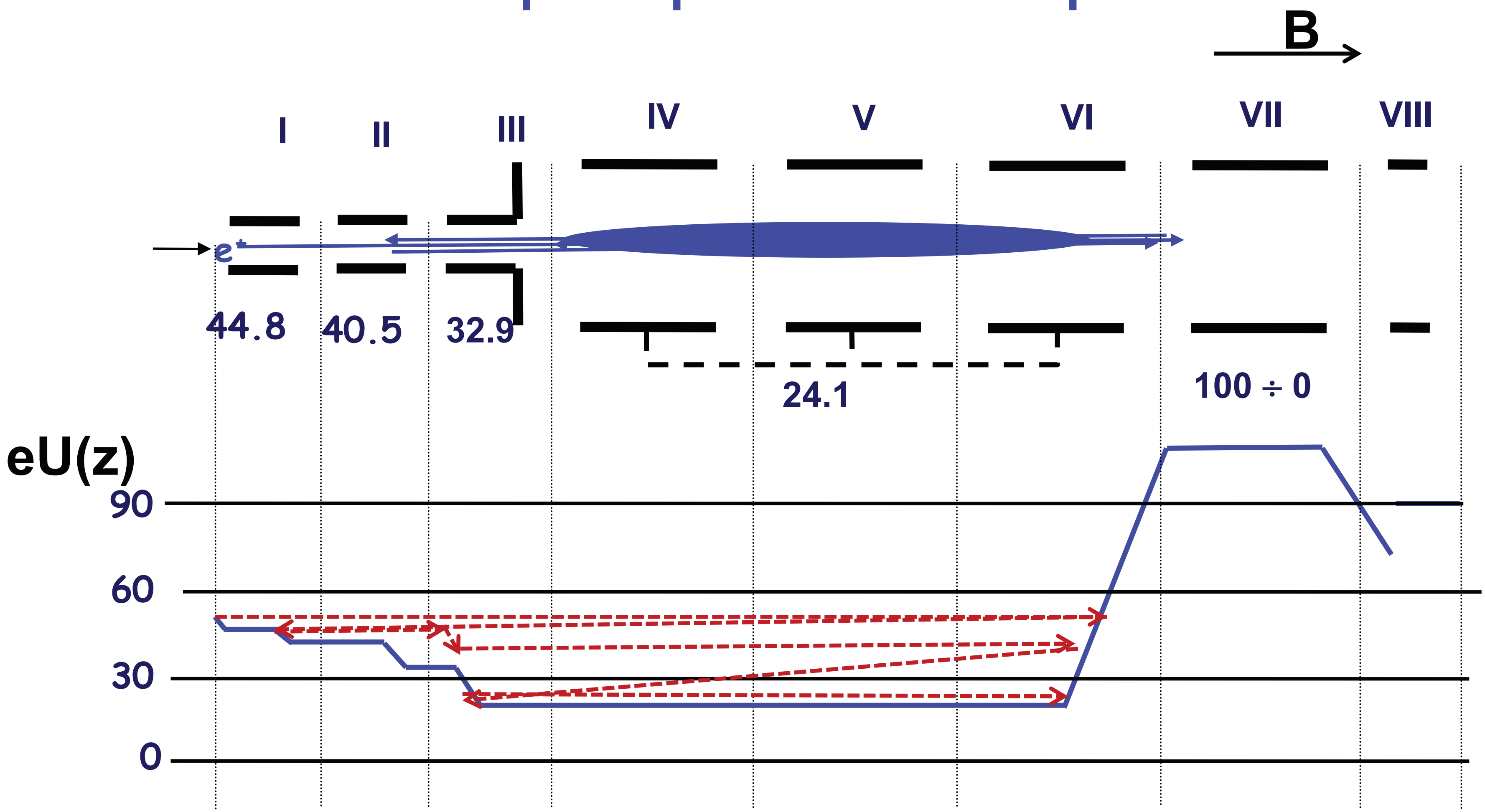

## Fundamental research of antimatter properties using antiparticles



- **CERN**, **ASACUSA, ATRAP, ATHENA/ALPHA:** $\boxed{\overline{H},\ \overline{p}He}$
- **Positron Lab**, Riverside, USA: $\boxed{Ps, Ps_2}$
- **Surko Research Group**, San Diego, USA: $\boxed{e^+}$ - positron physics
- **LEPTA, JINR, Dubna:** $\boxed{Ps}$ , PAS

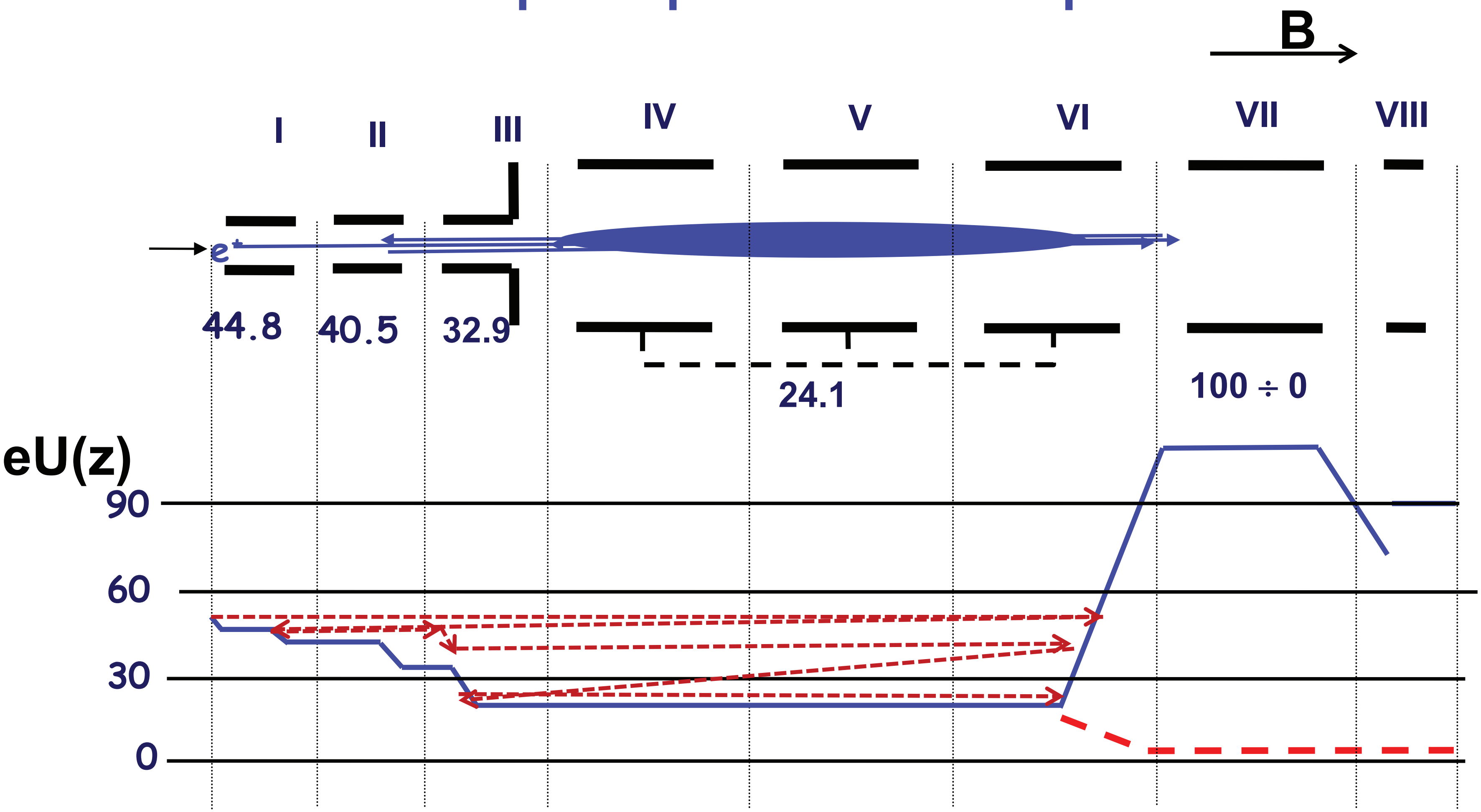
M. K. Eseev, I. N. Meshkov Traps for storage of charged particles and antiparticles in high precision experiments // Phys. Usp. 59 304–317 (2016).

# The principle of PMS traps



# 1. PMS Trap and "Rotating Wall" Technique

## The principle of PMS traps



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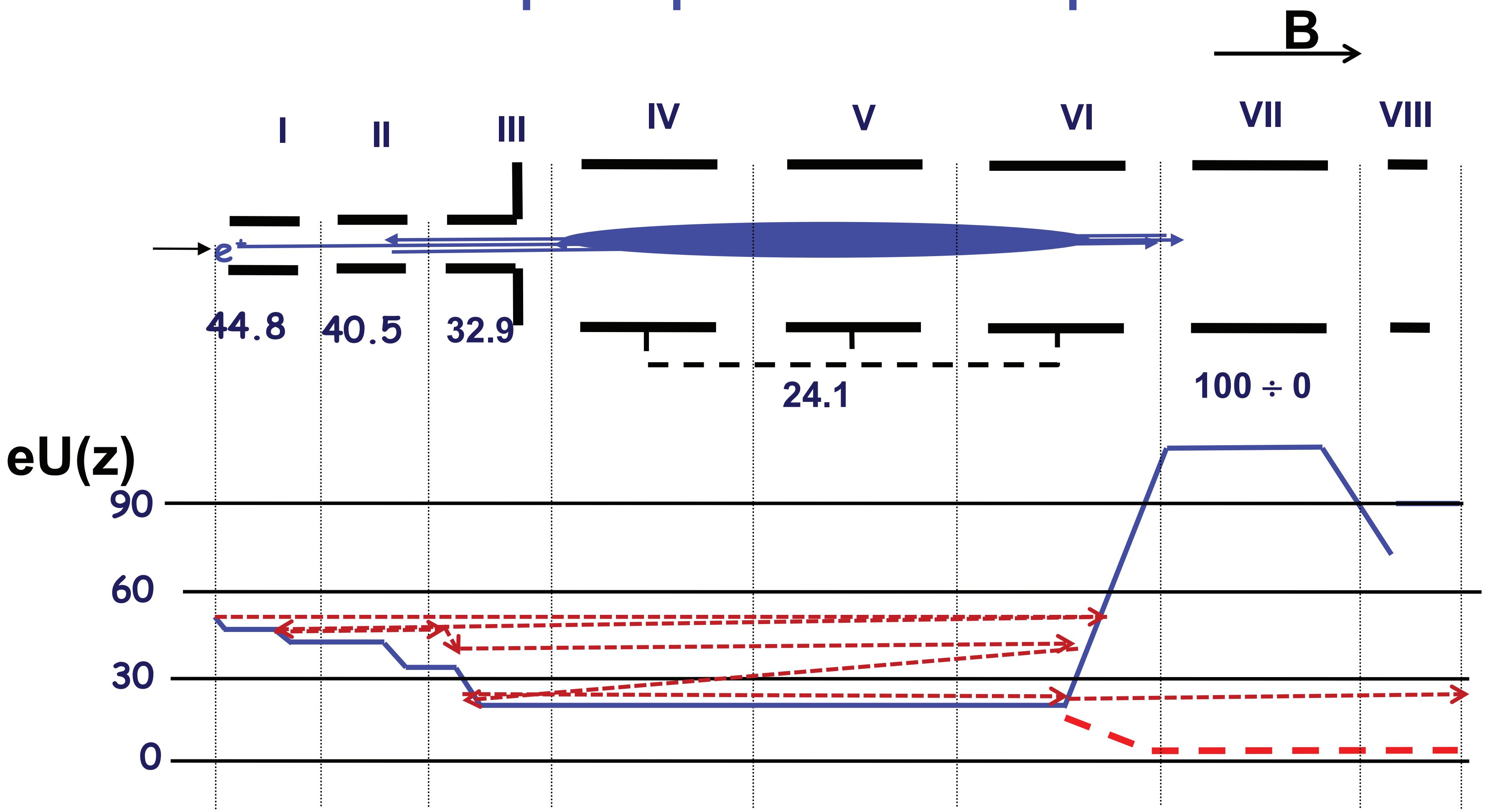
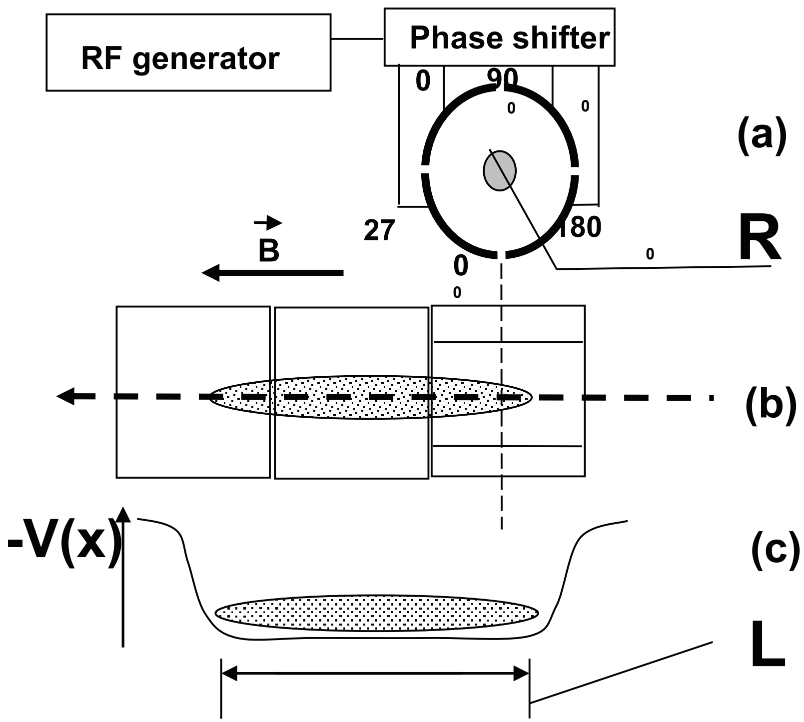


# 1. PMS Trap and “Rotating Wall” Technique

## Rotating Electric Field Technique “Rotating Wall” (RW)

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X-P. Huang et al., PRL. 78, 875 (1997).

- Electrons:

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R. G. Greaves and C. M. Surko , PRL. 85, 1883 (2000).

T.J. Murphy and C.M. Surko, Phys. Plasmas 8, 1878 (2001).

J. R. Danielson, C. M. Surko, and T. M. O’Neil PRL. 99, 135005 (2007).

J. R. Danielson et al. Rev. Mod. Phys. 87 247 (2015)

- Antiprotons (Hbar, ALPHA, CERN)

J. R. Danielson, et al., PRL. 100, 203401 (2008); G. B. Andresen , et al., Nature 468, 673 (2010); Andresen G.B. et al. Nature Phys. 7, 558 (2011); N. Kuroda, S. Ulmer, D. J. Murtagh et. al., Nature Commun. 5, 3089 (2014).

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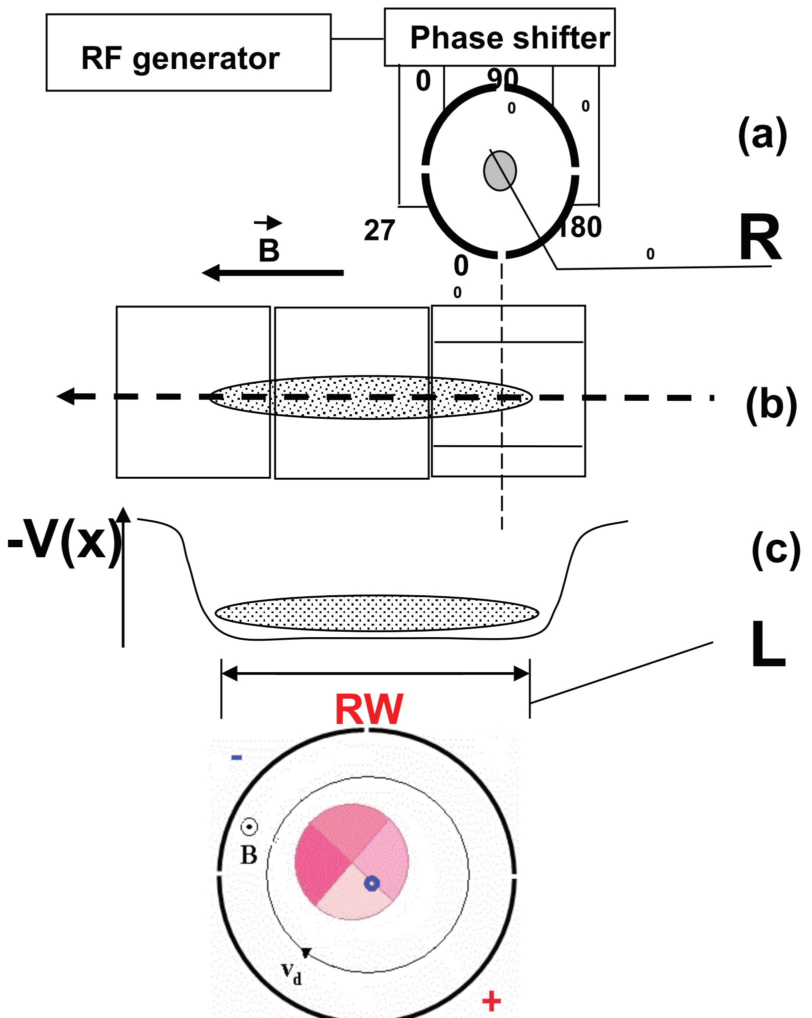


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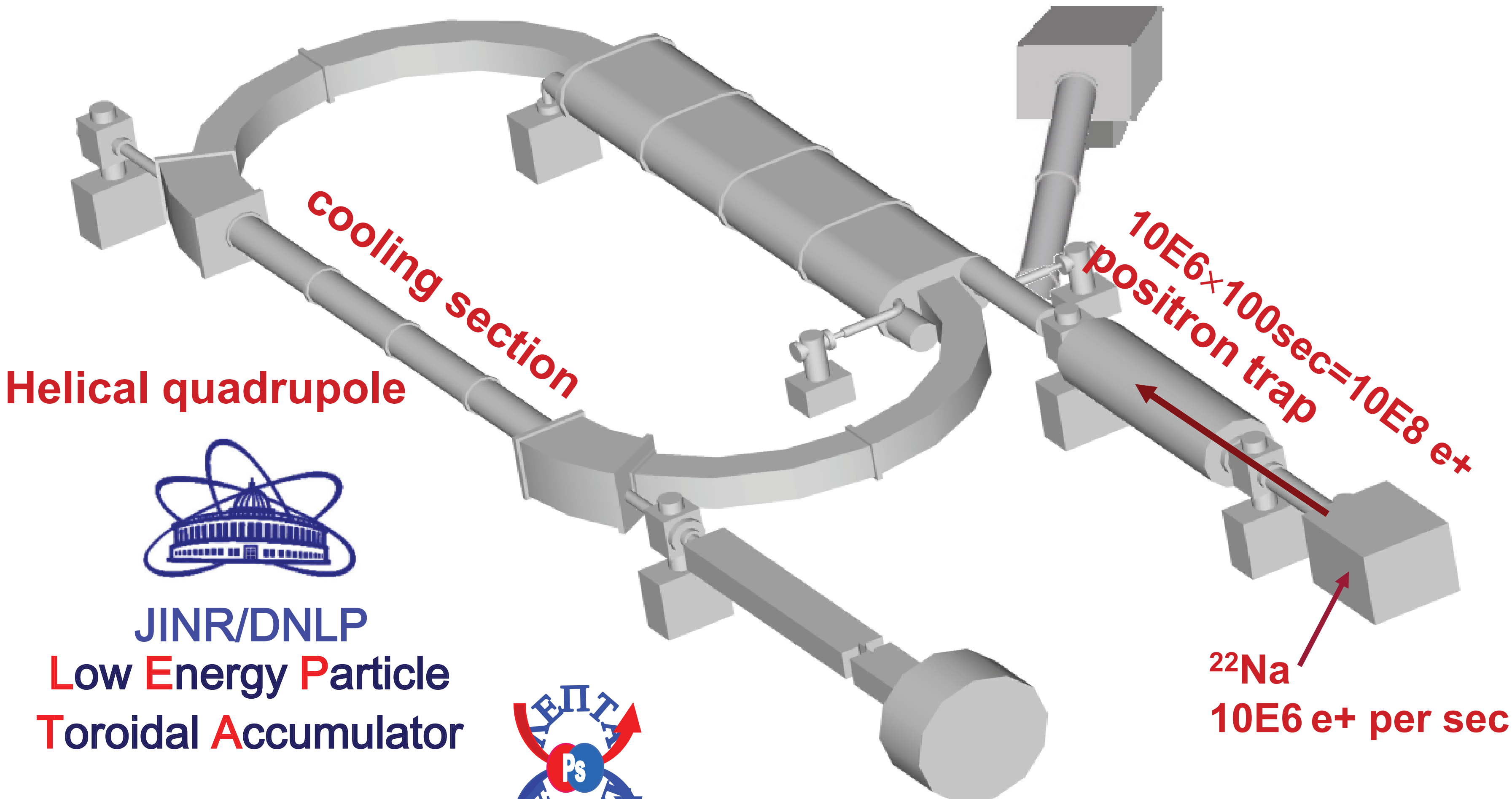


JINR/DNLP

Low Energy Particle Toroidal Accumulator

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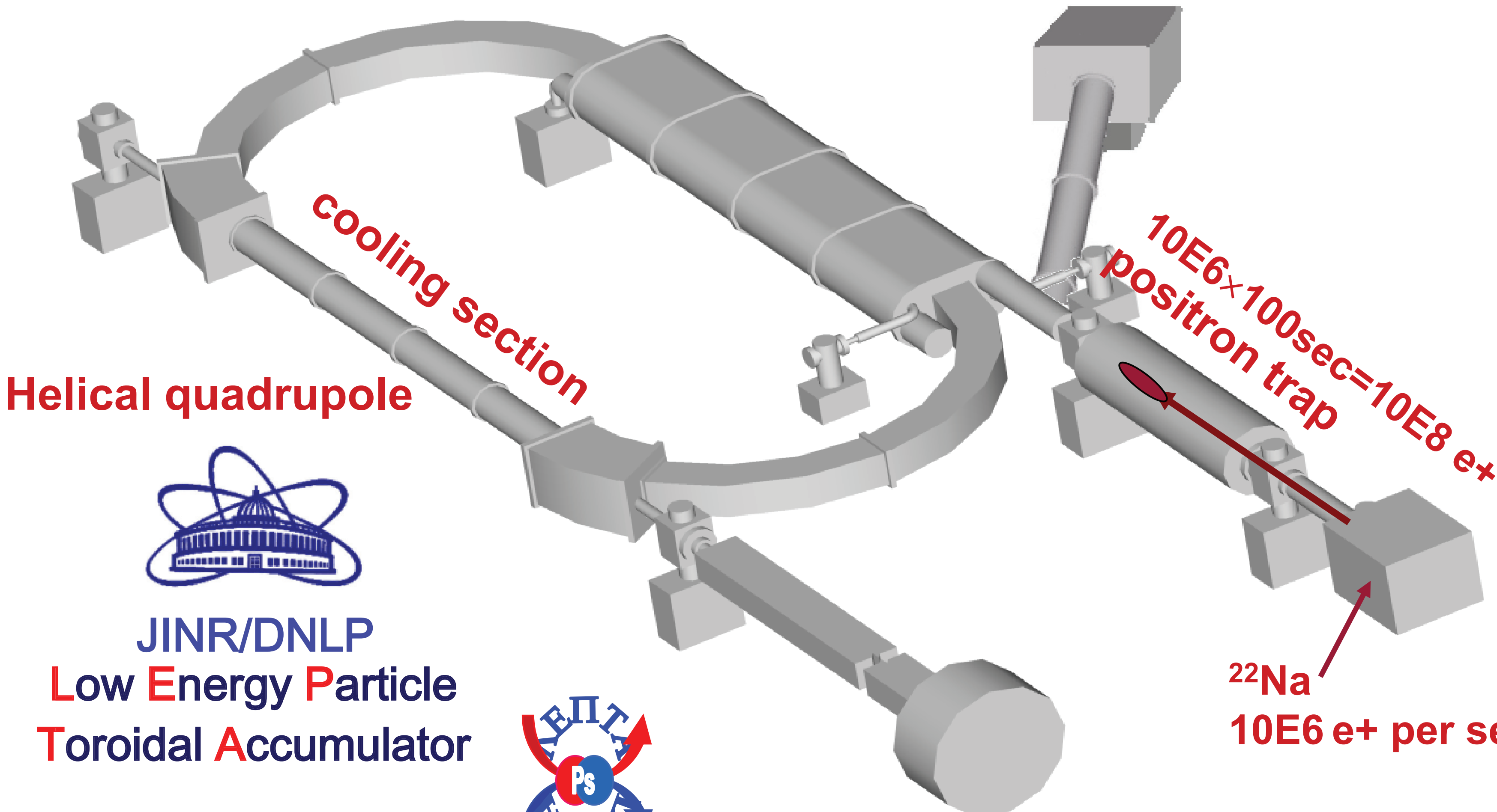


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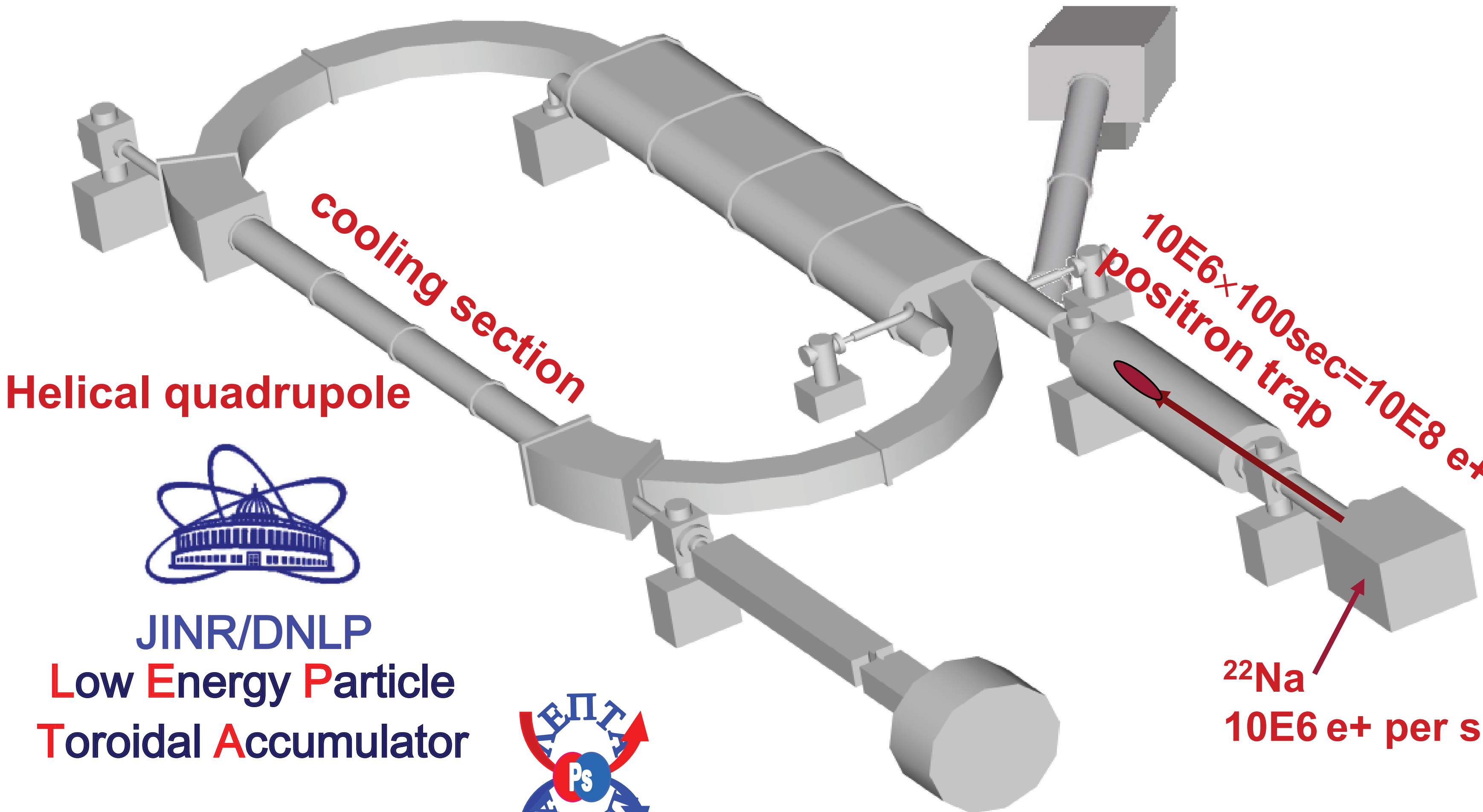


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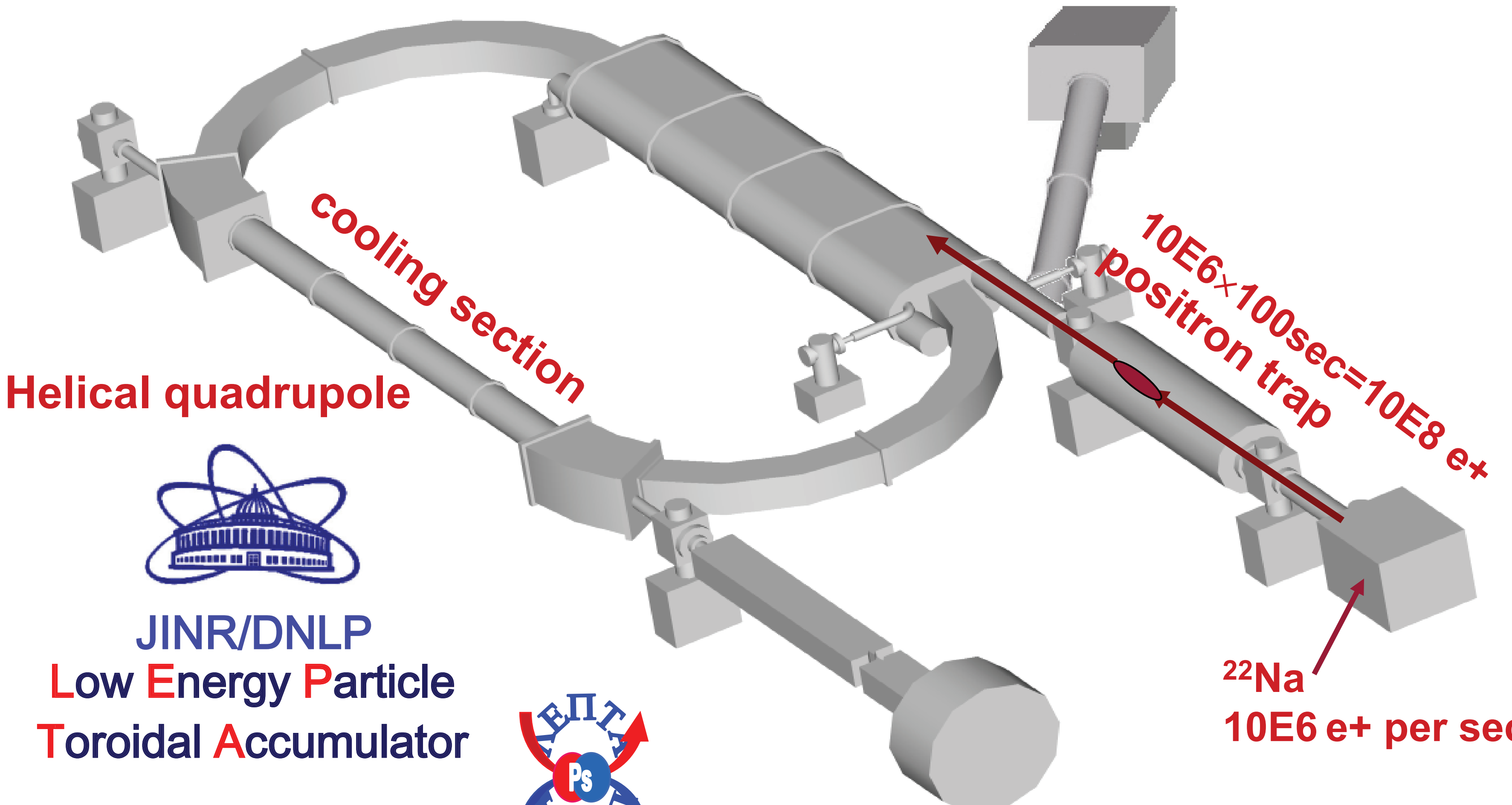


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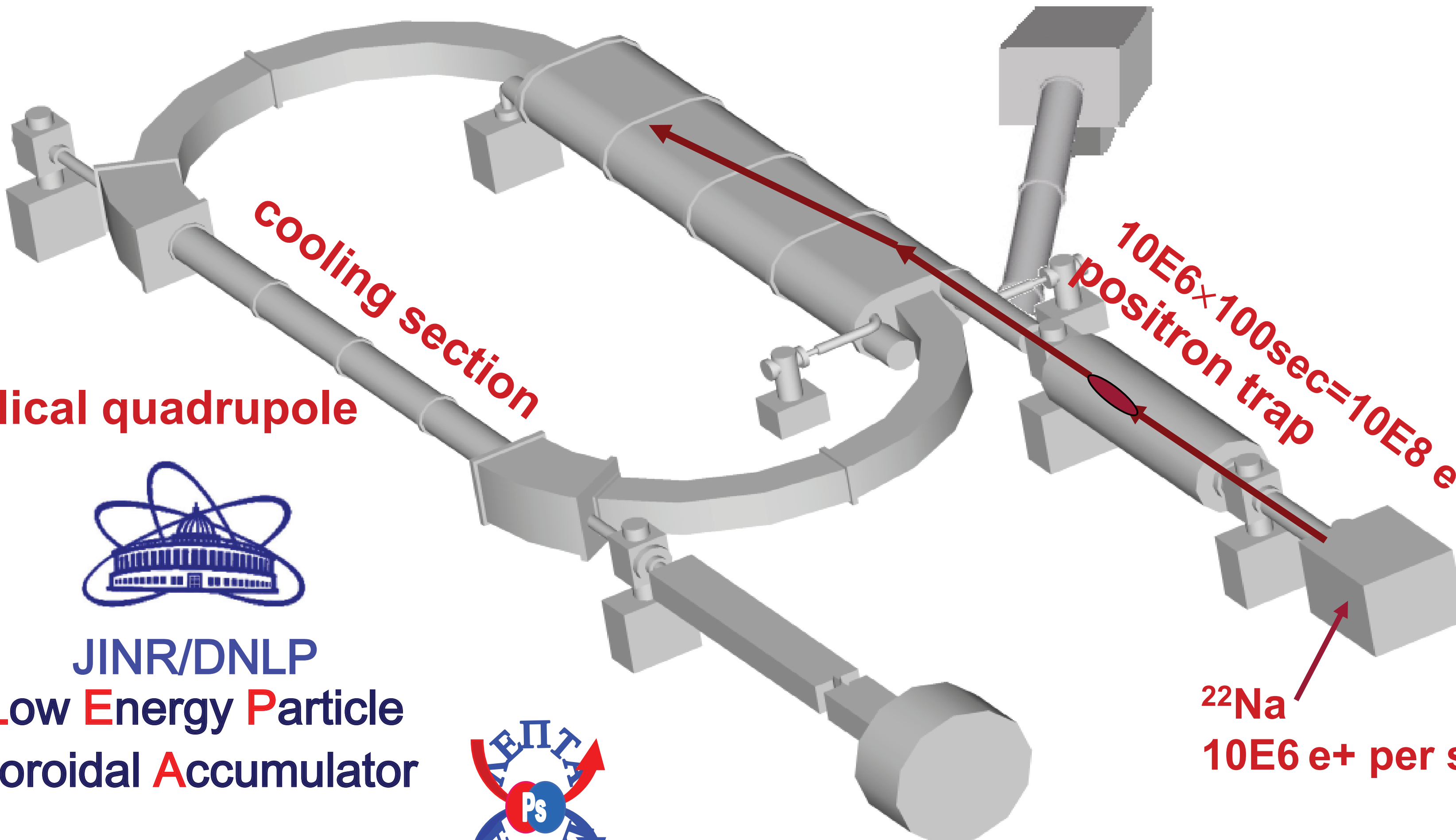


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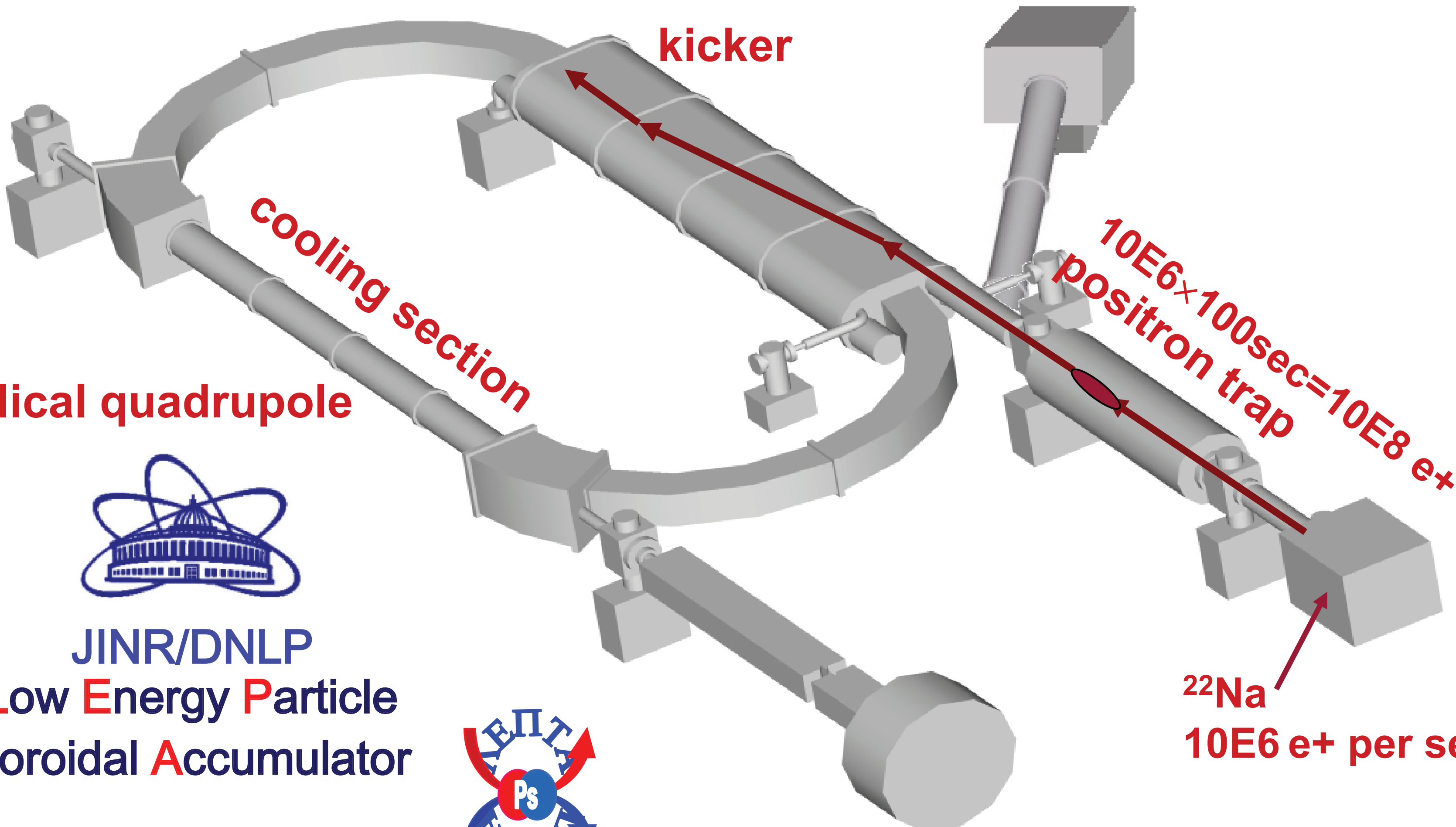


Helical quadrupole

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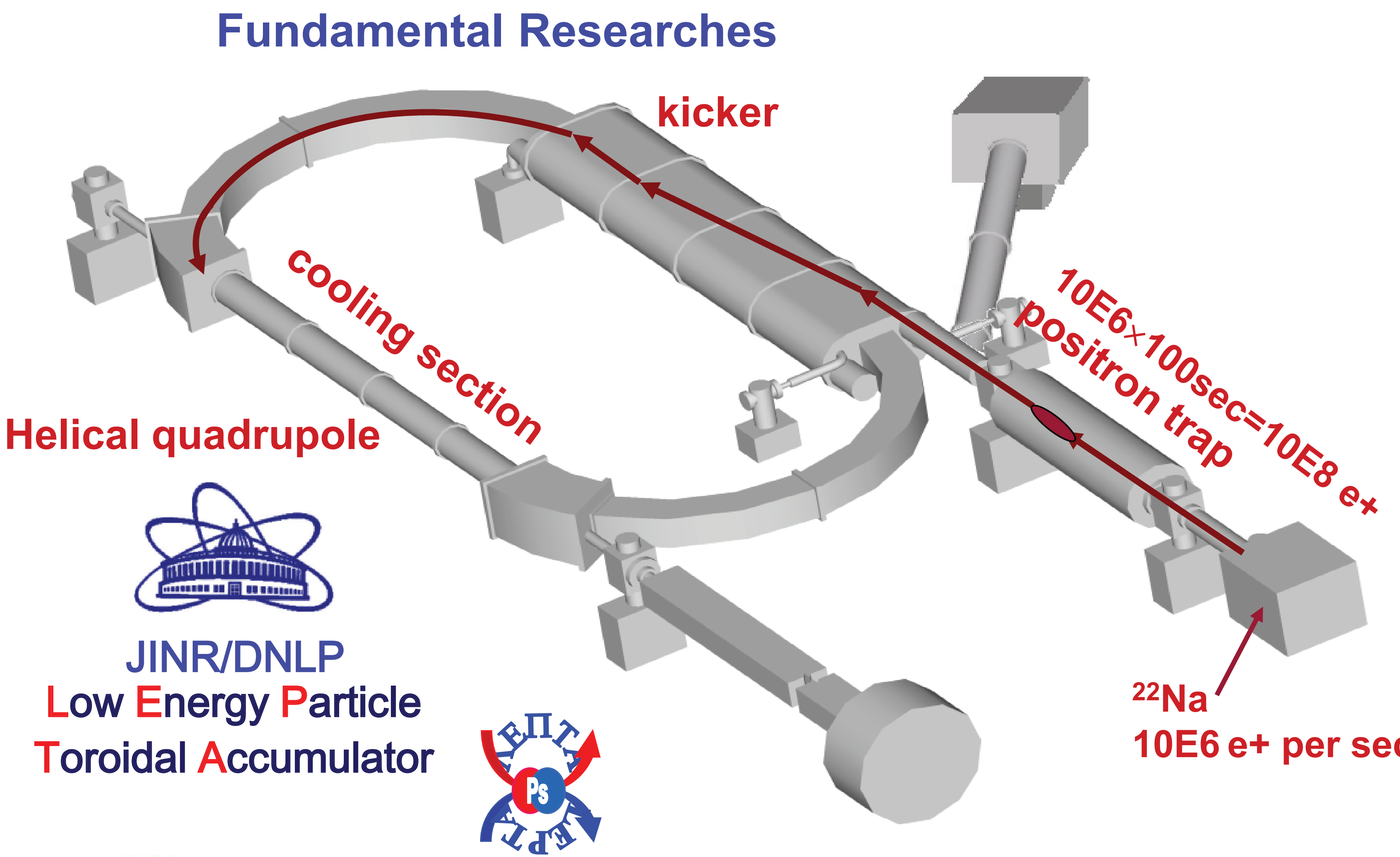


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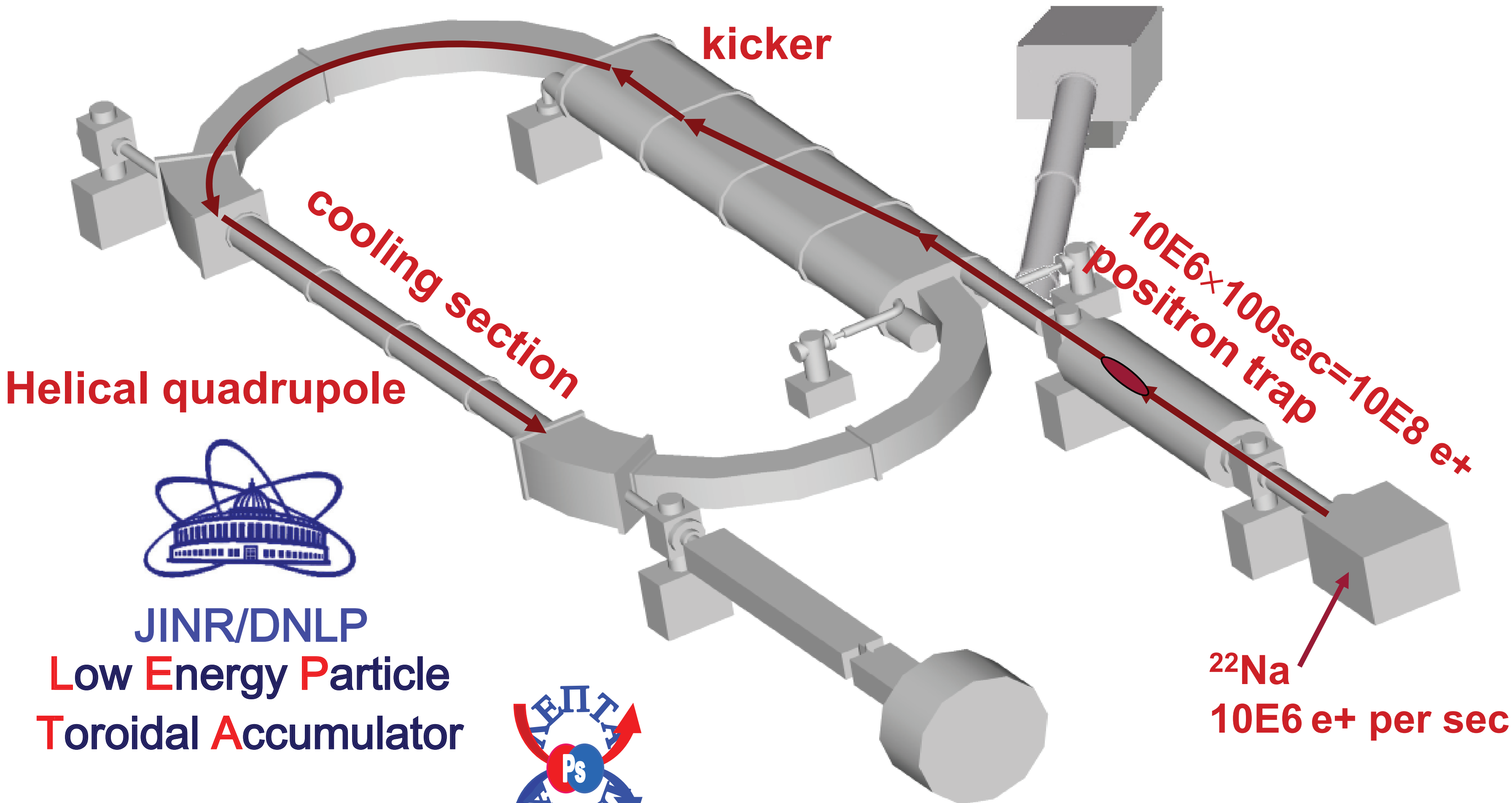


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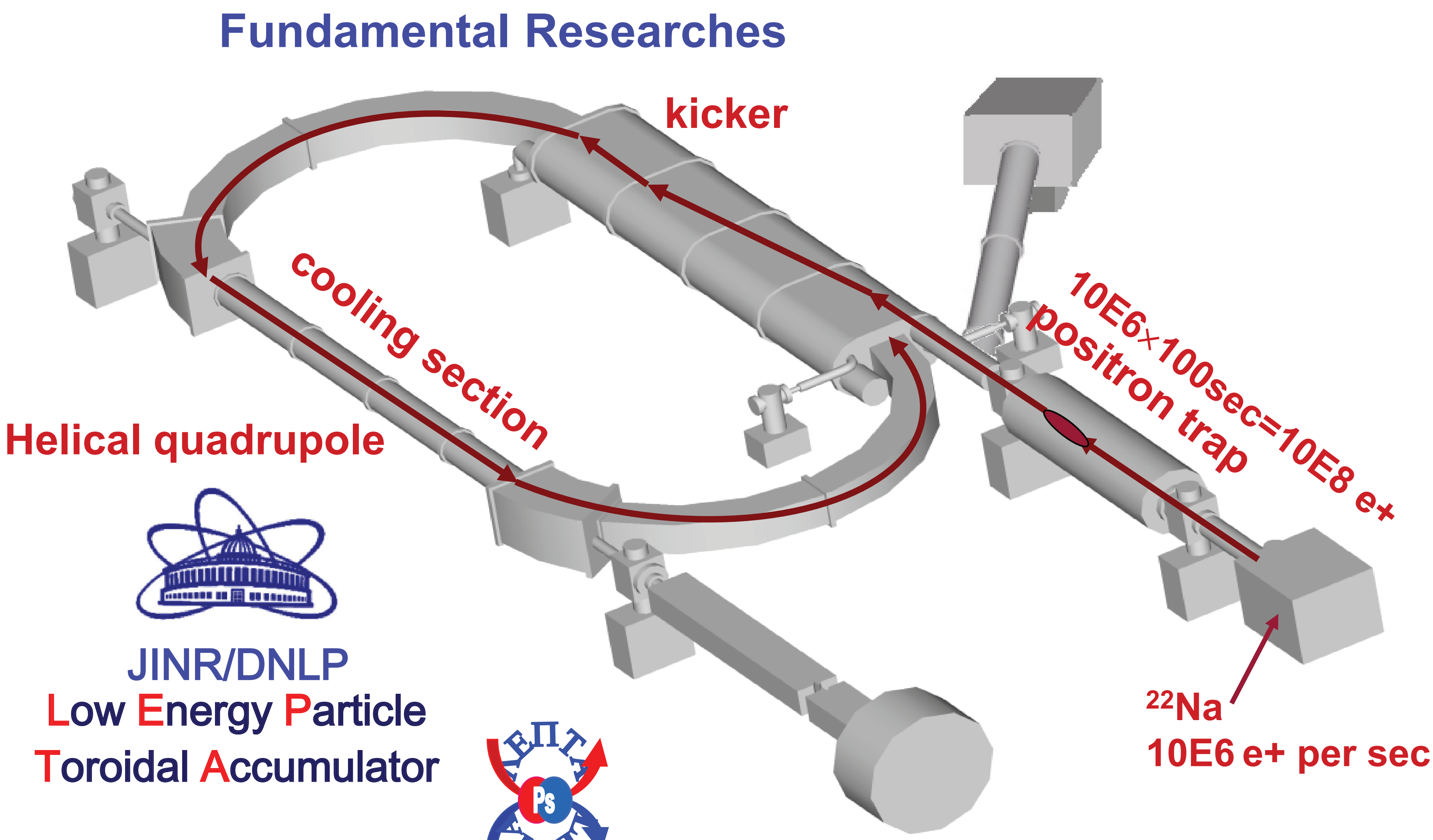


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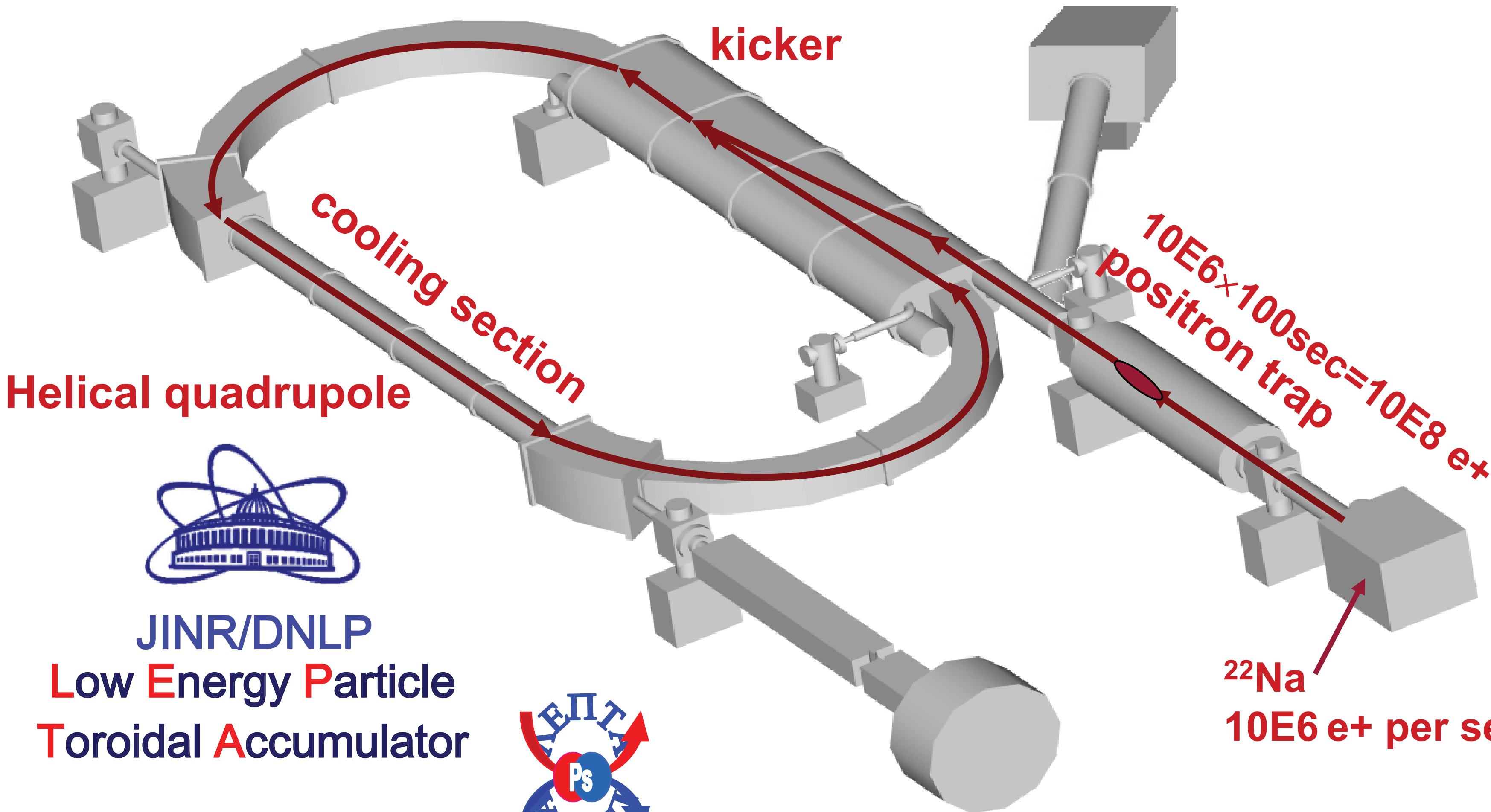


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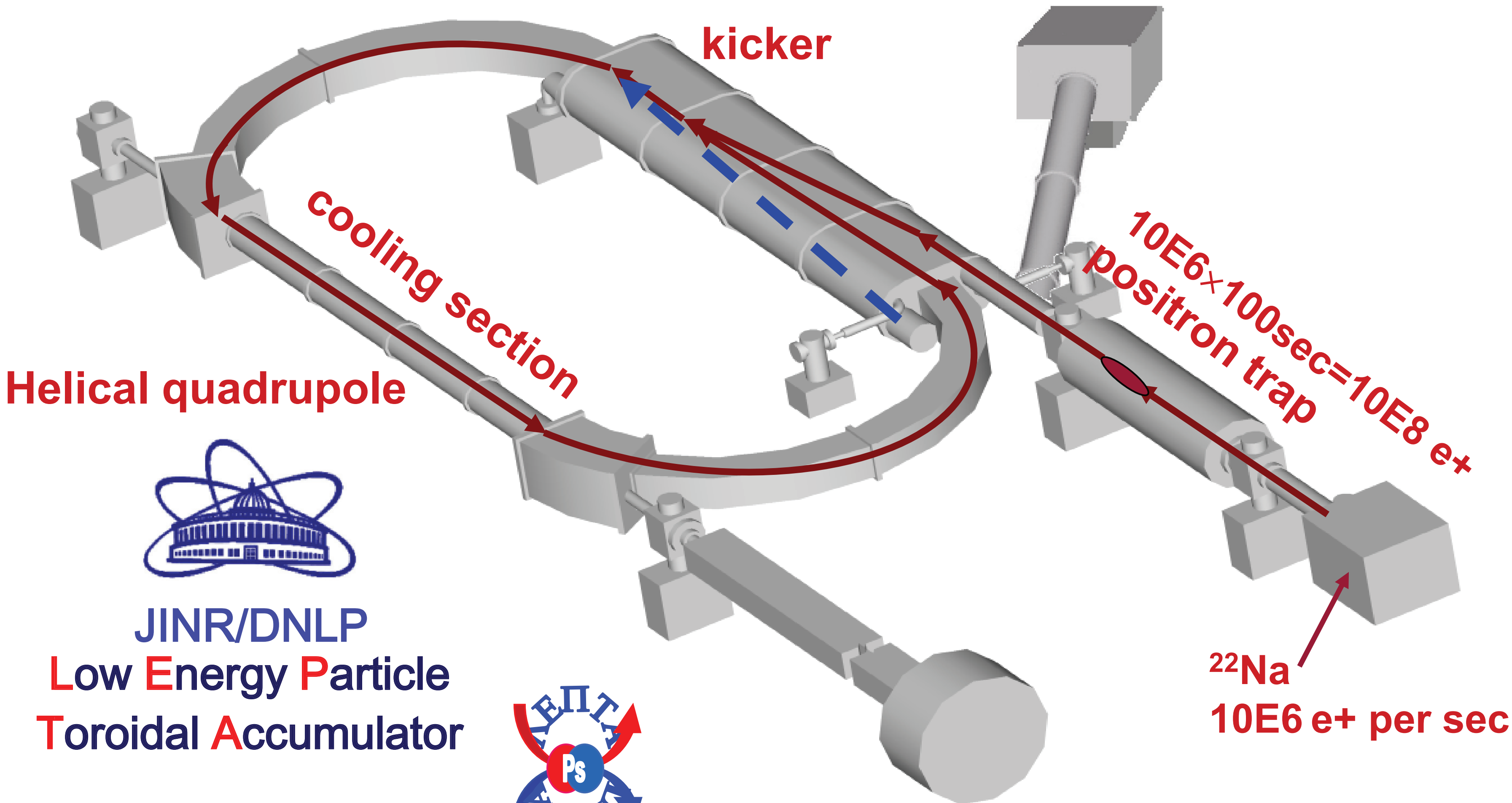


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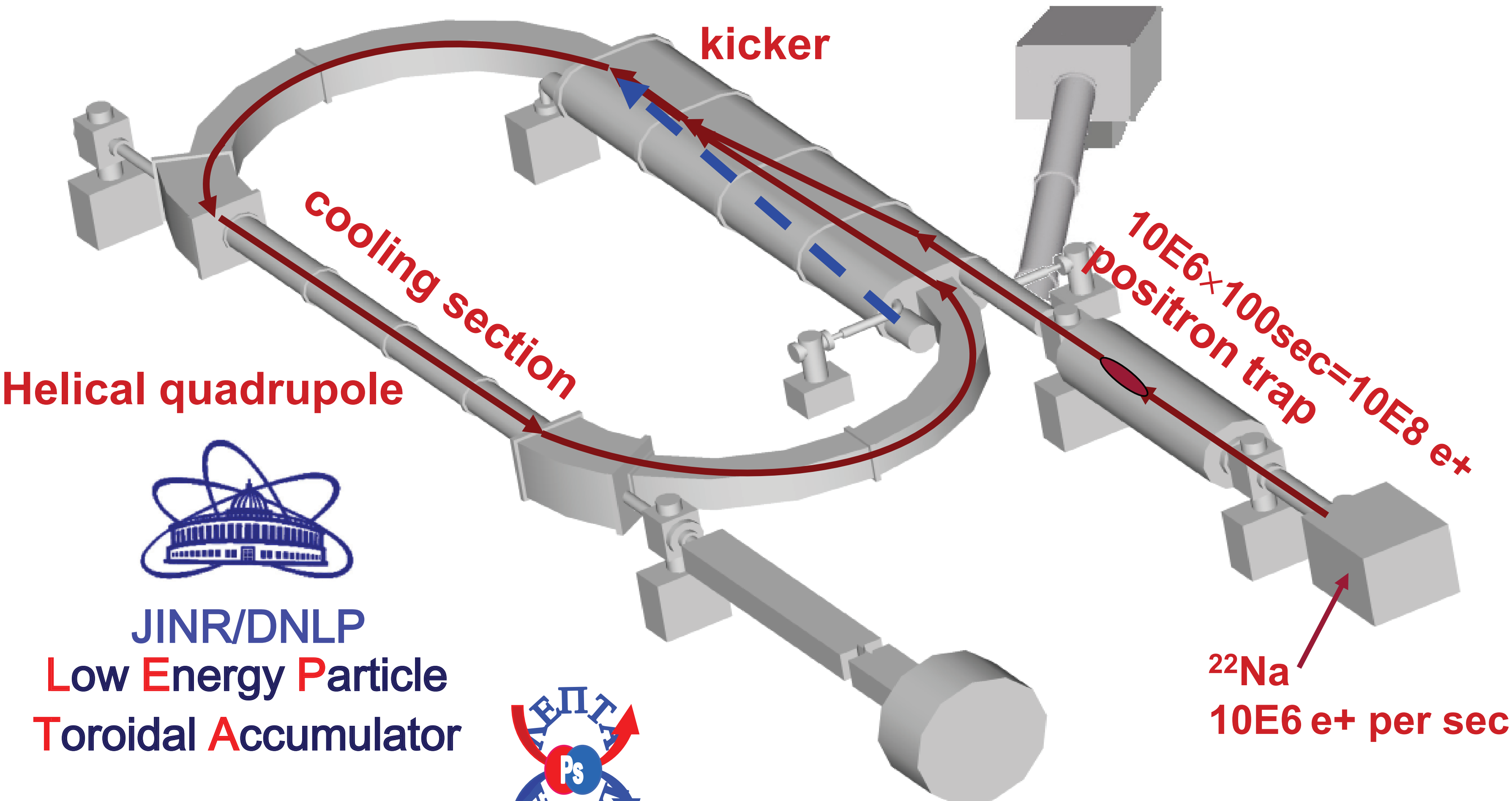


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**L**ow **E**nergy **P**article **T**oroidal **A**ccumulator

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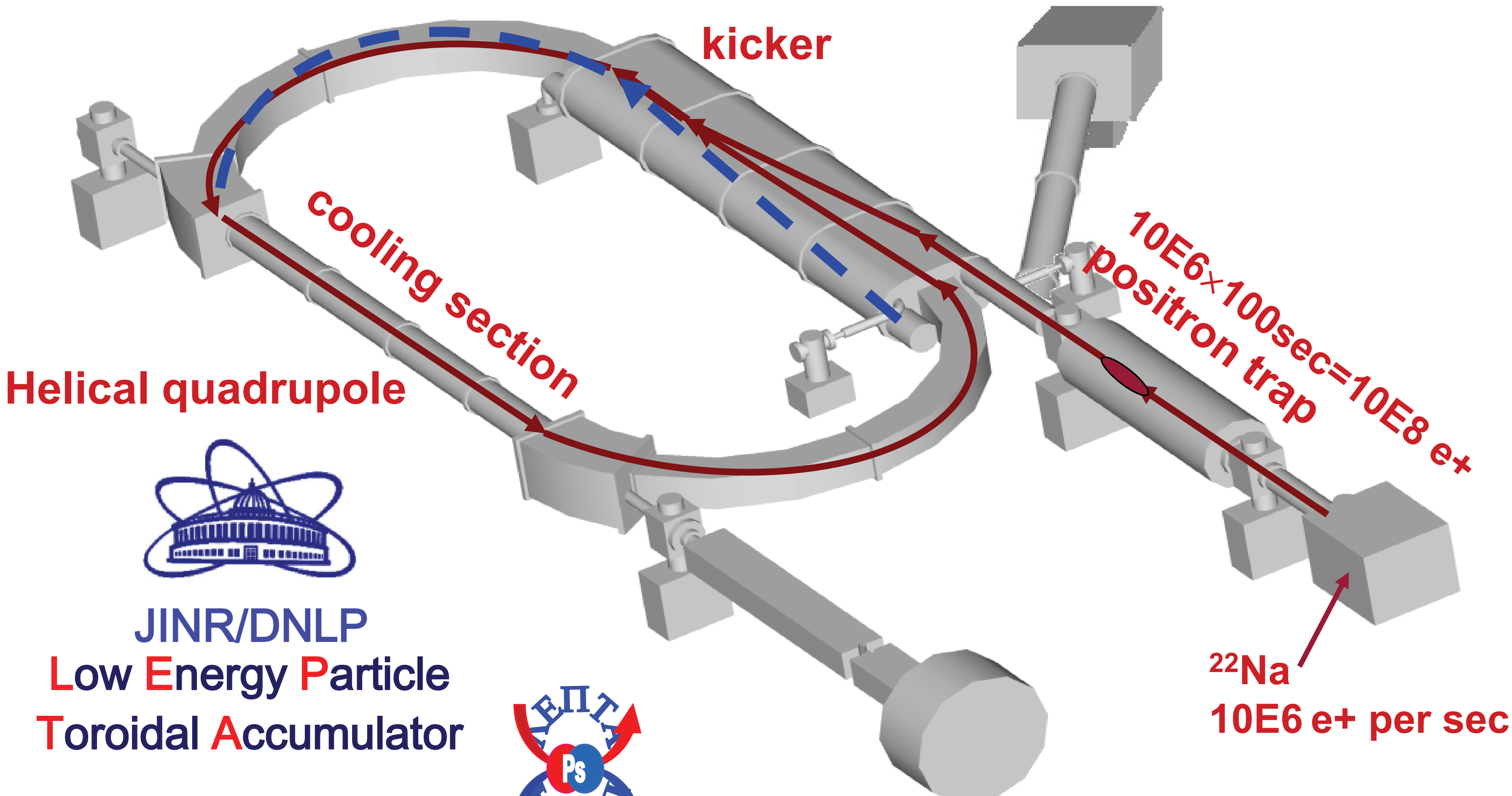


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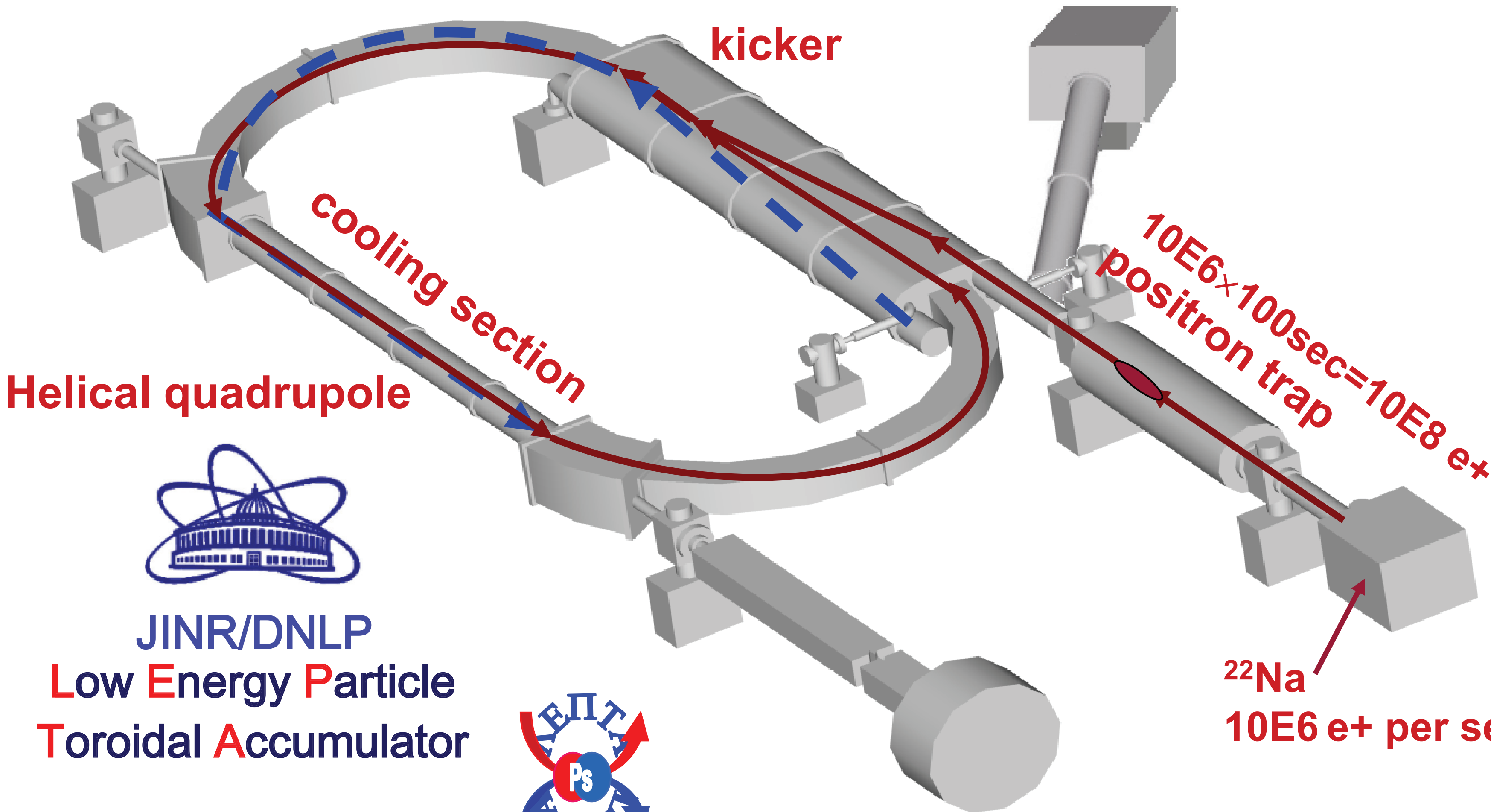


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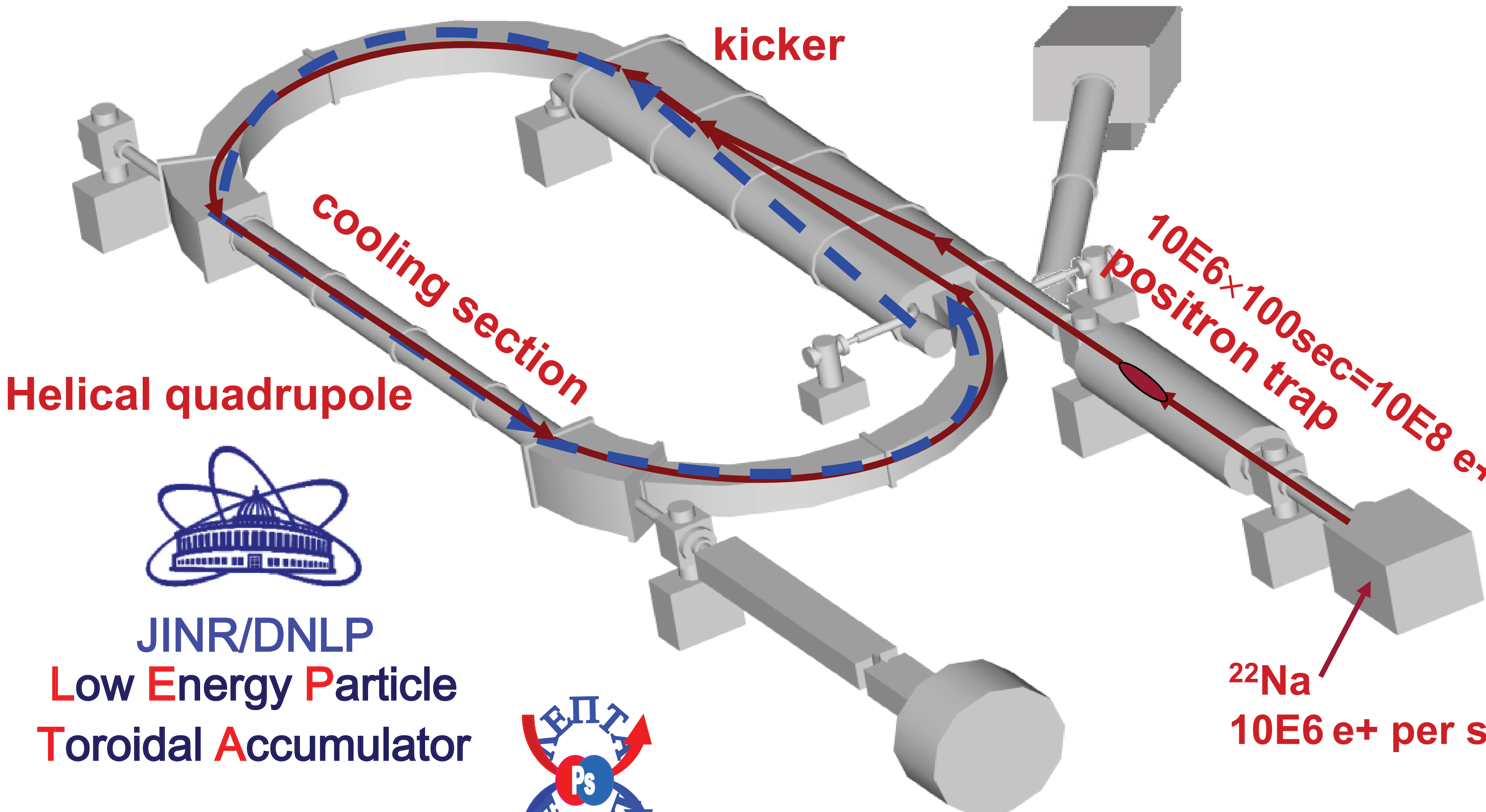


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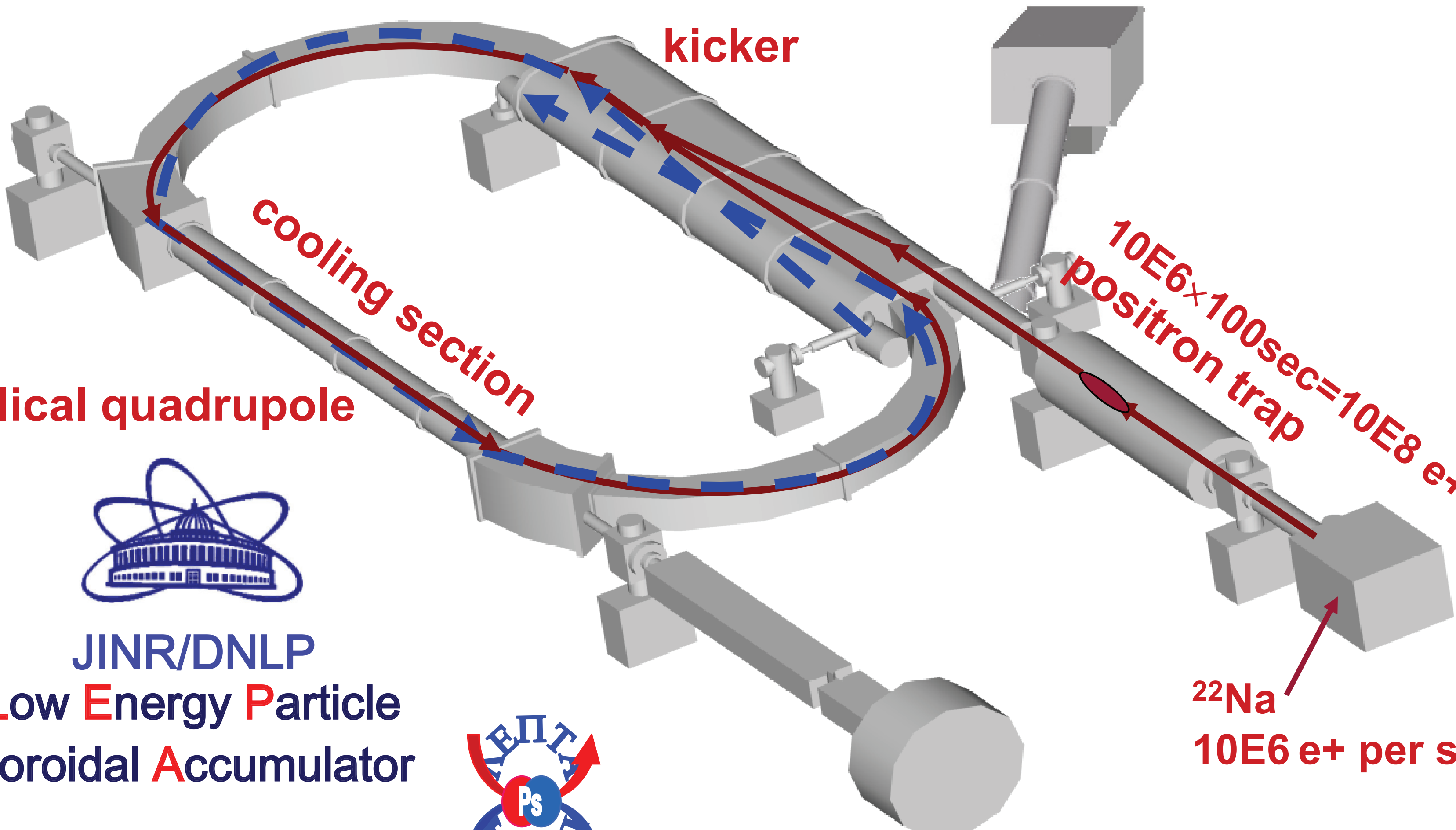


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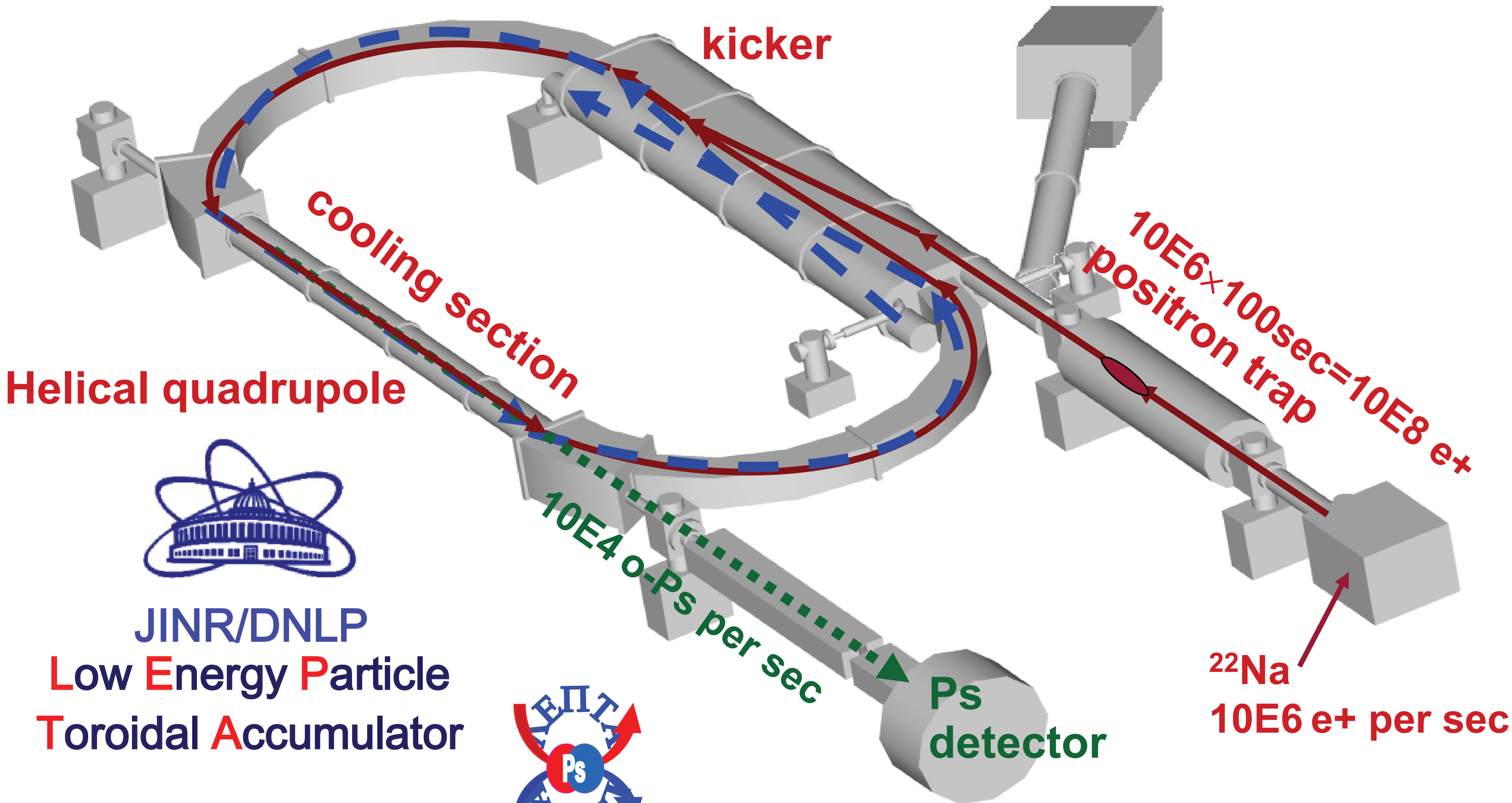


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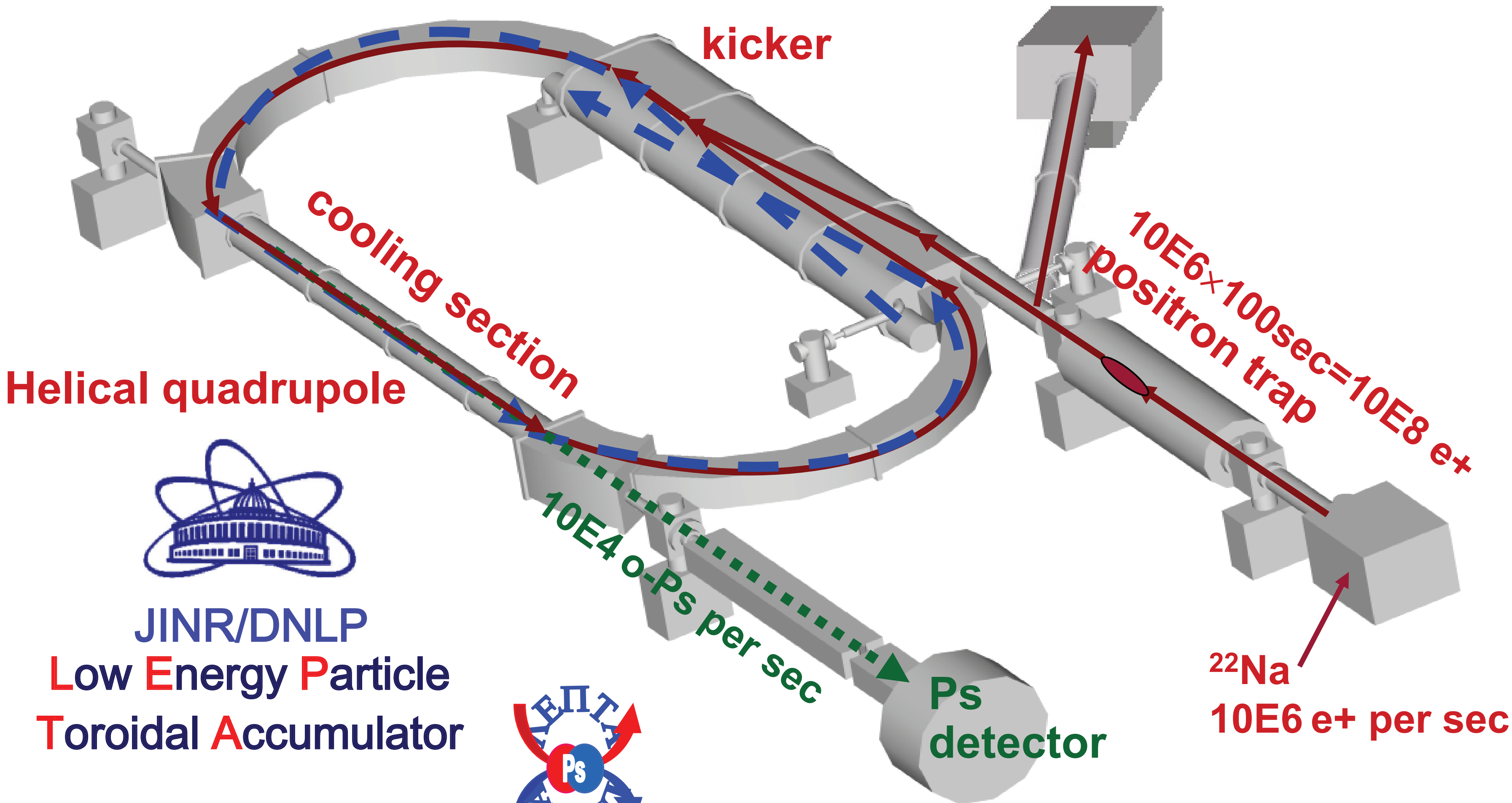


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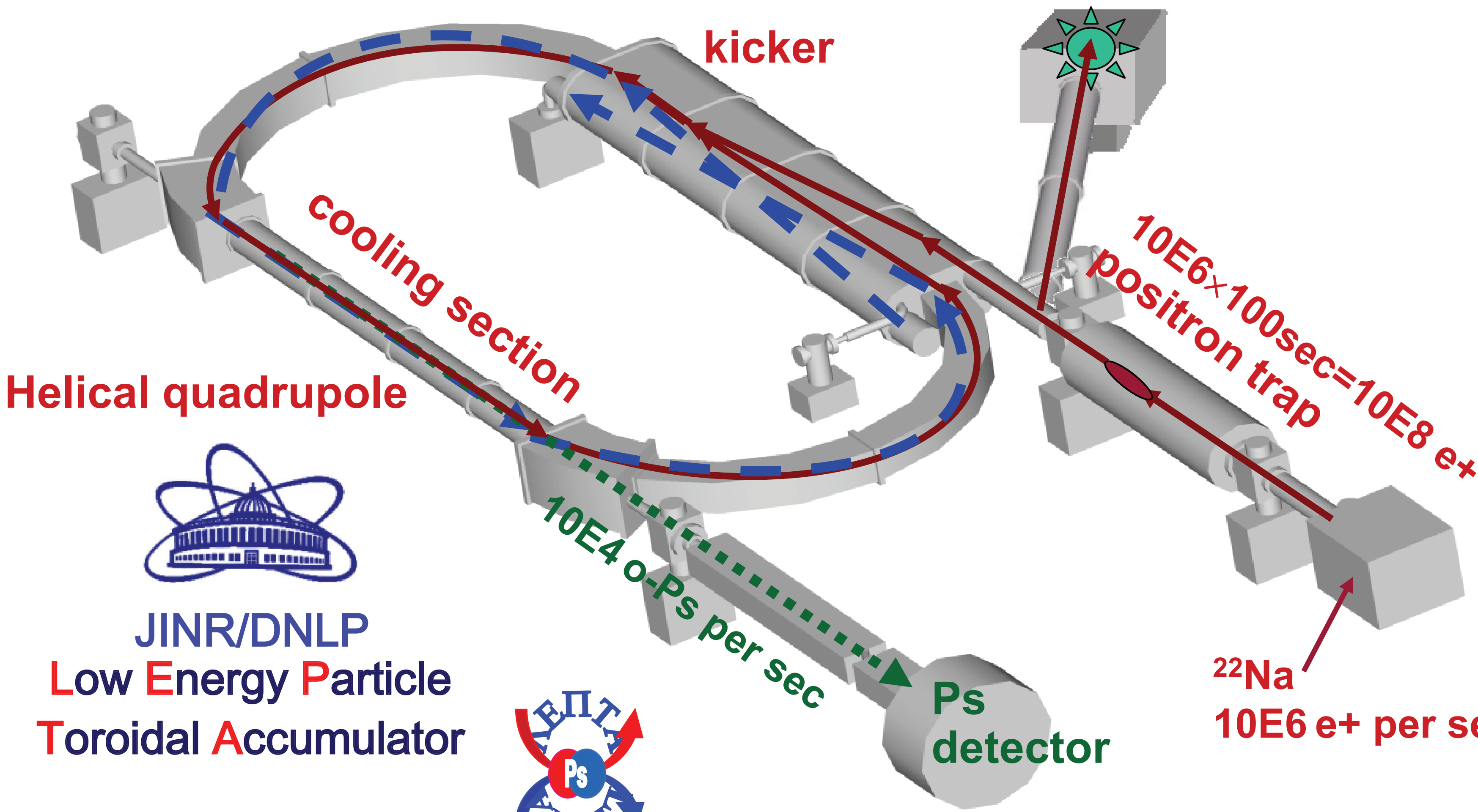


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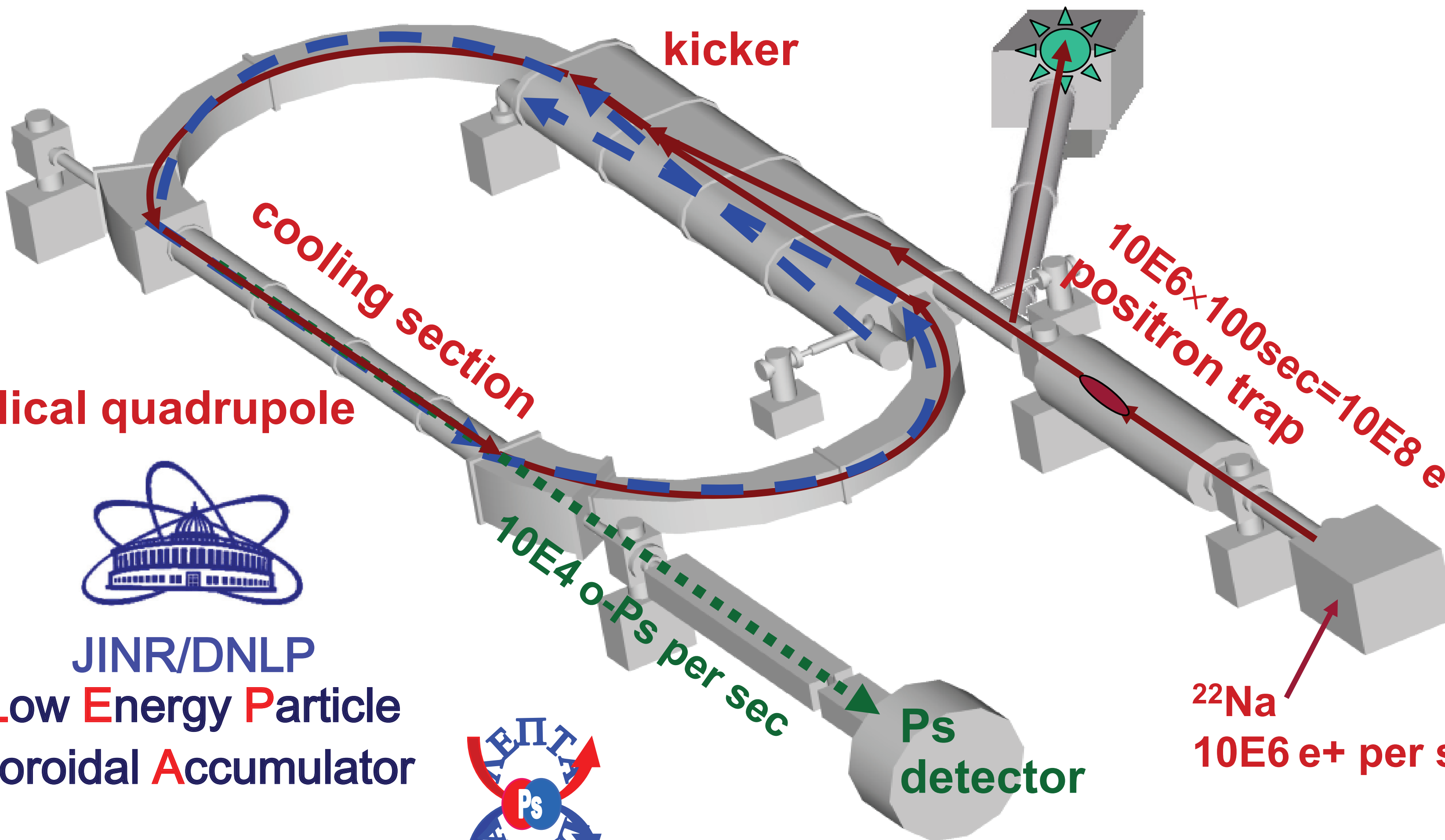
Fundamental Researches Applied Researches (PAS)

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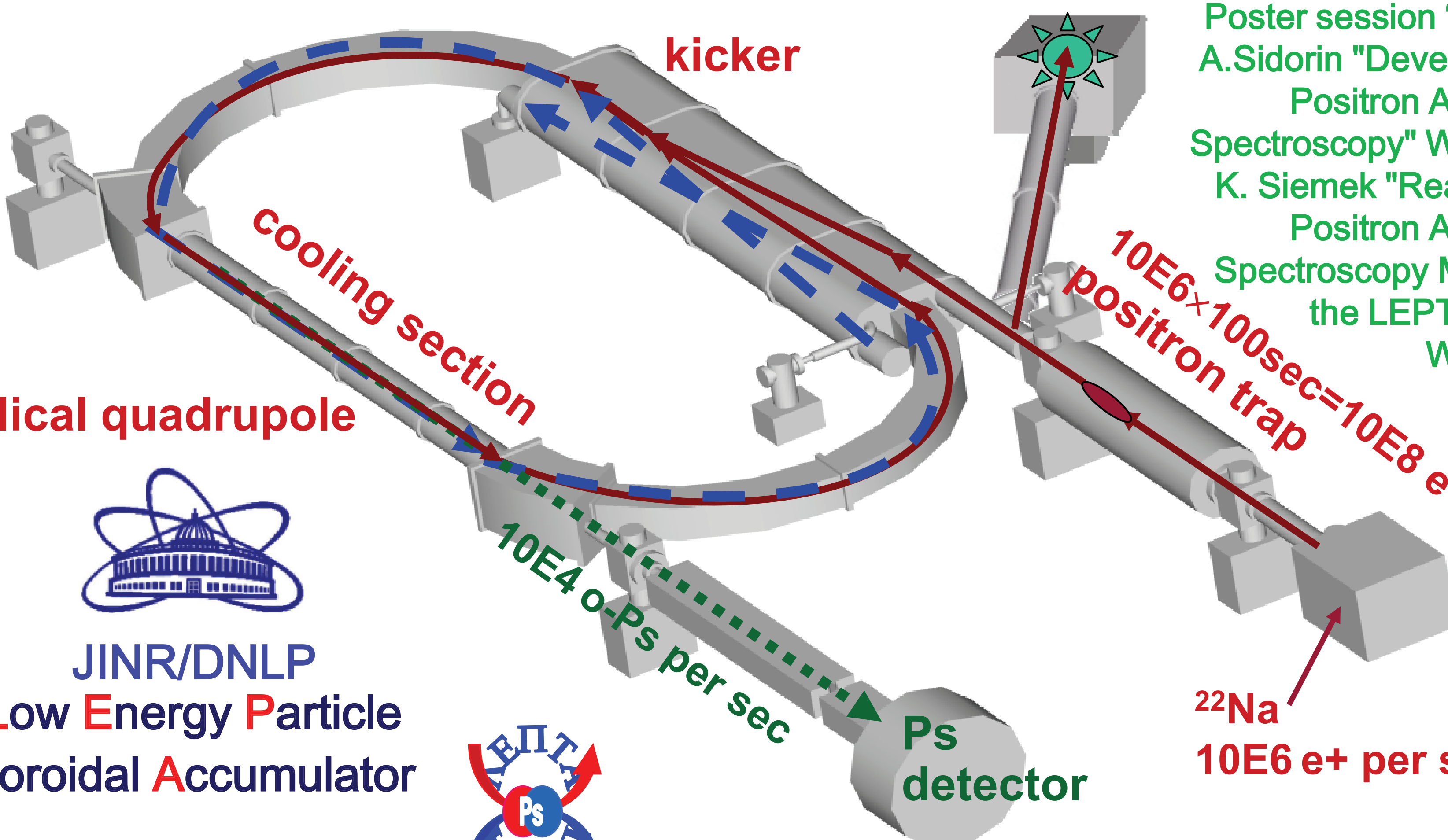
# 2. Experimental Results of Particle Storage in PMS Trap of The LEPTA Facility

## Fundamental Researches  Applied Researches (PAS)

Poster session "B" (today)
A.Sidorin "Development of Positron Annihilation Spectroscopy" WEPSB060
K. Siemek "Realization of Positron Annihilation Spectroscopy Methods at the LEPTA Facility" WEPSB059

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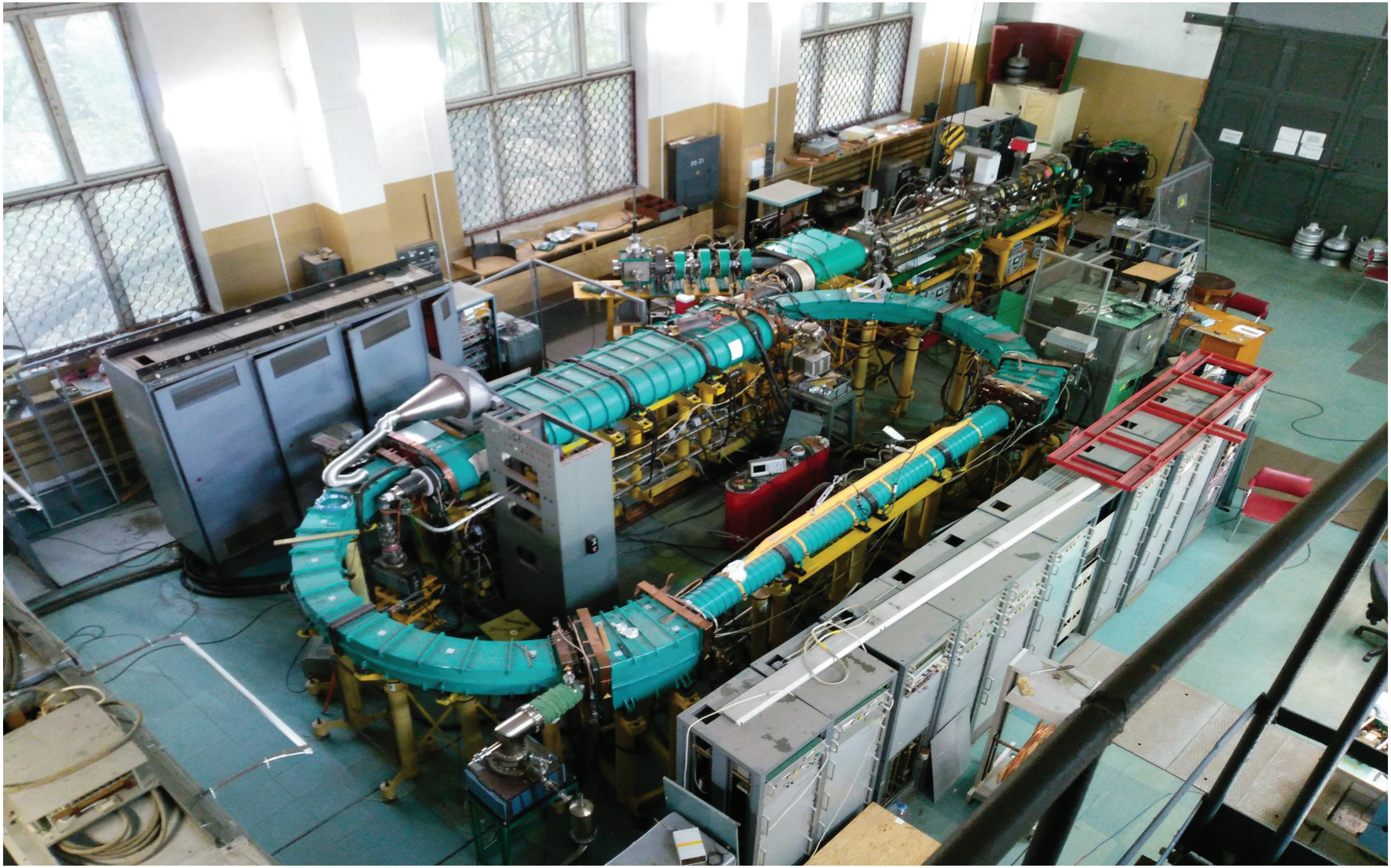
# 2. The LEPTA Facility



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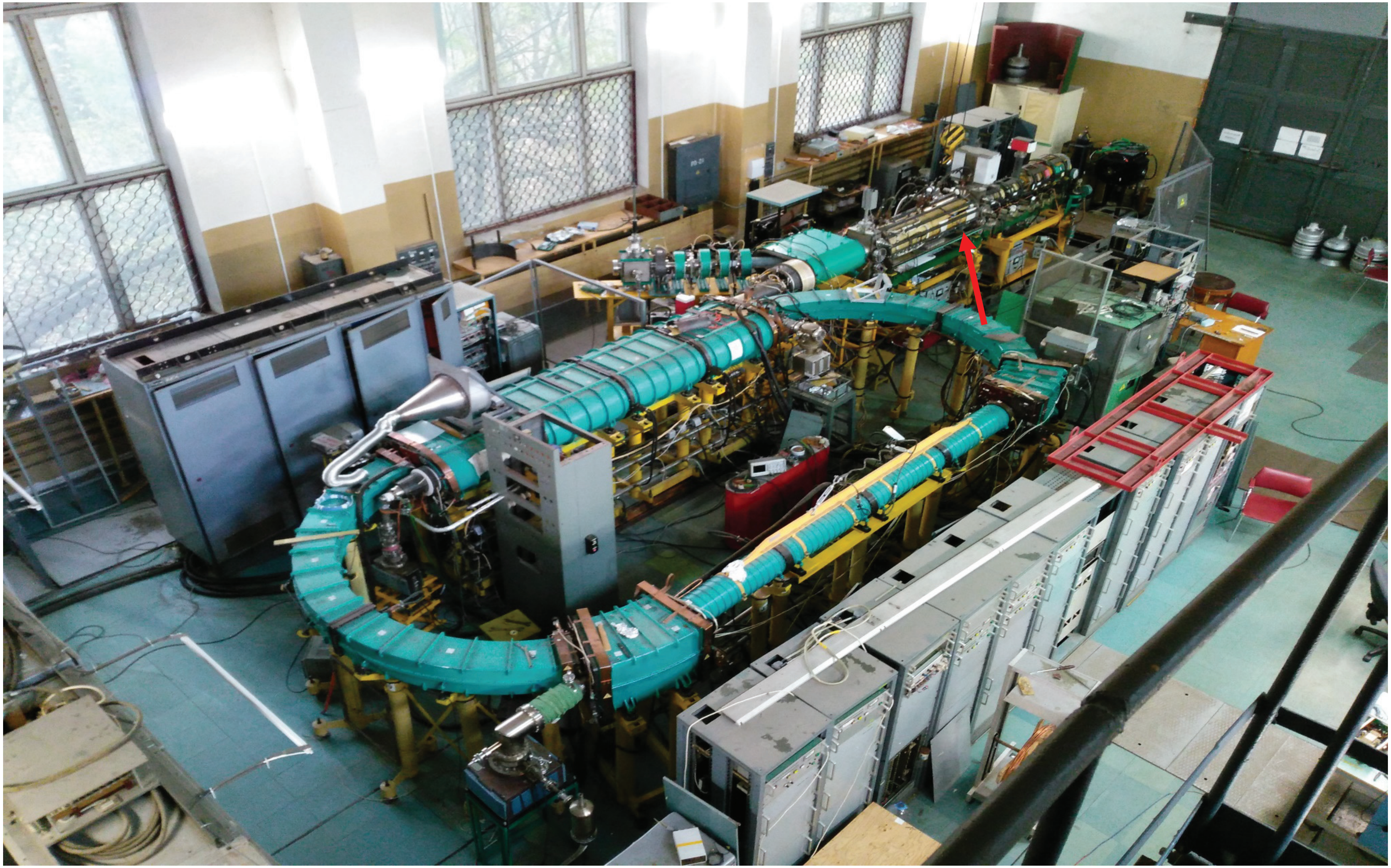

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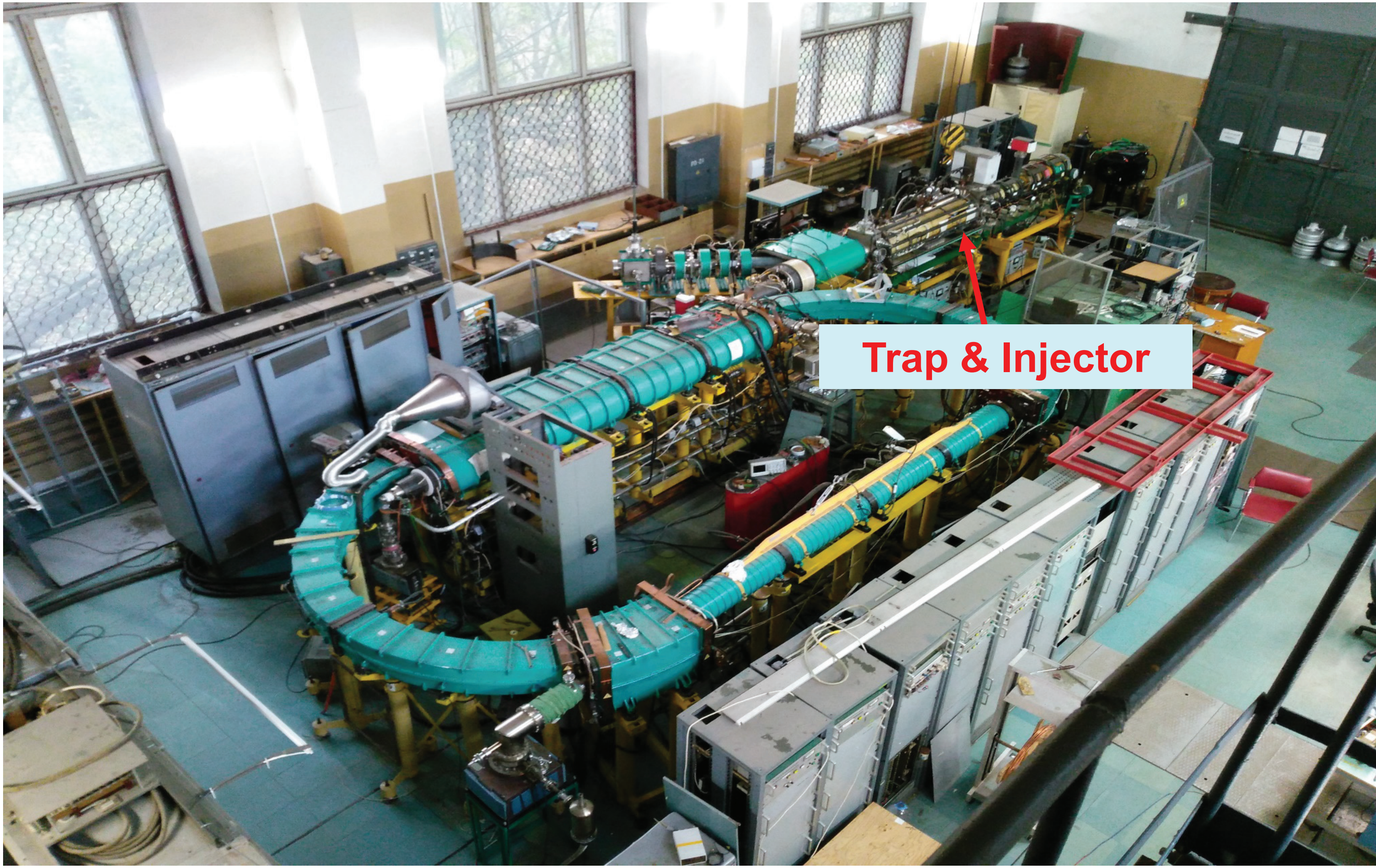

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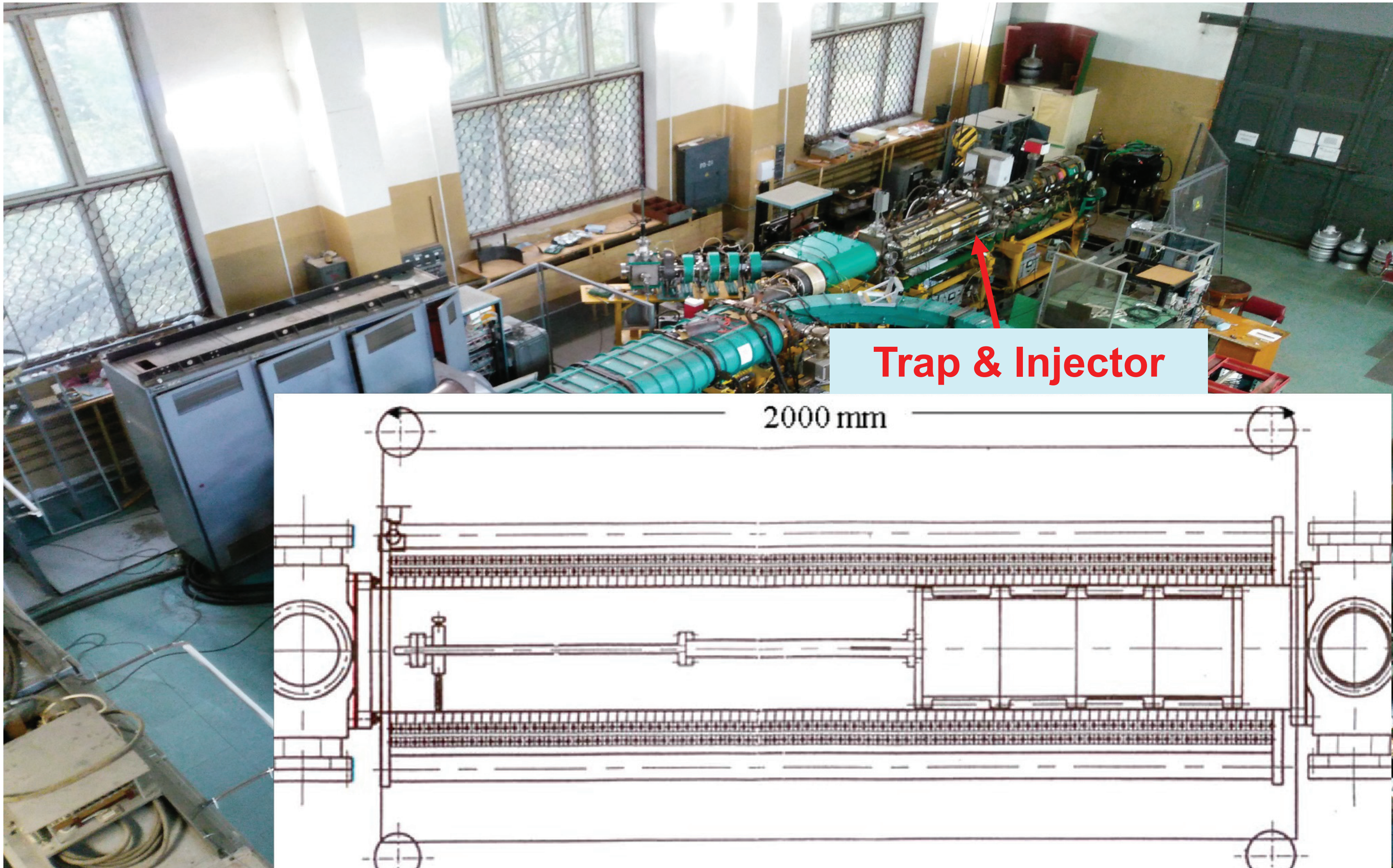
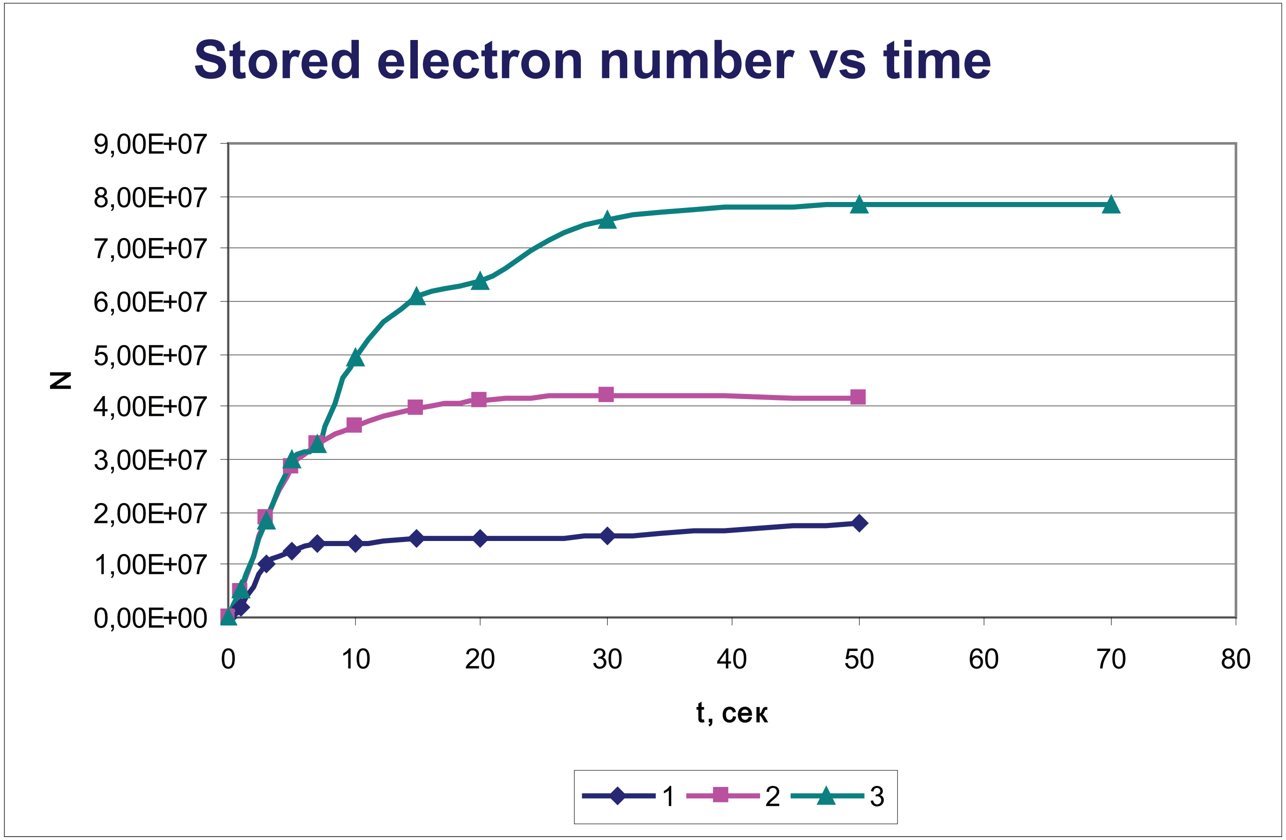


# 2. Research of Storage and Lifetime of The Particle Bunch in The Trap, Experimental Results



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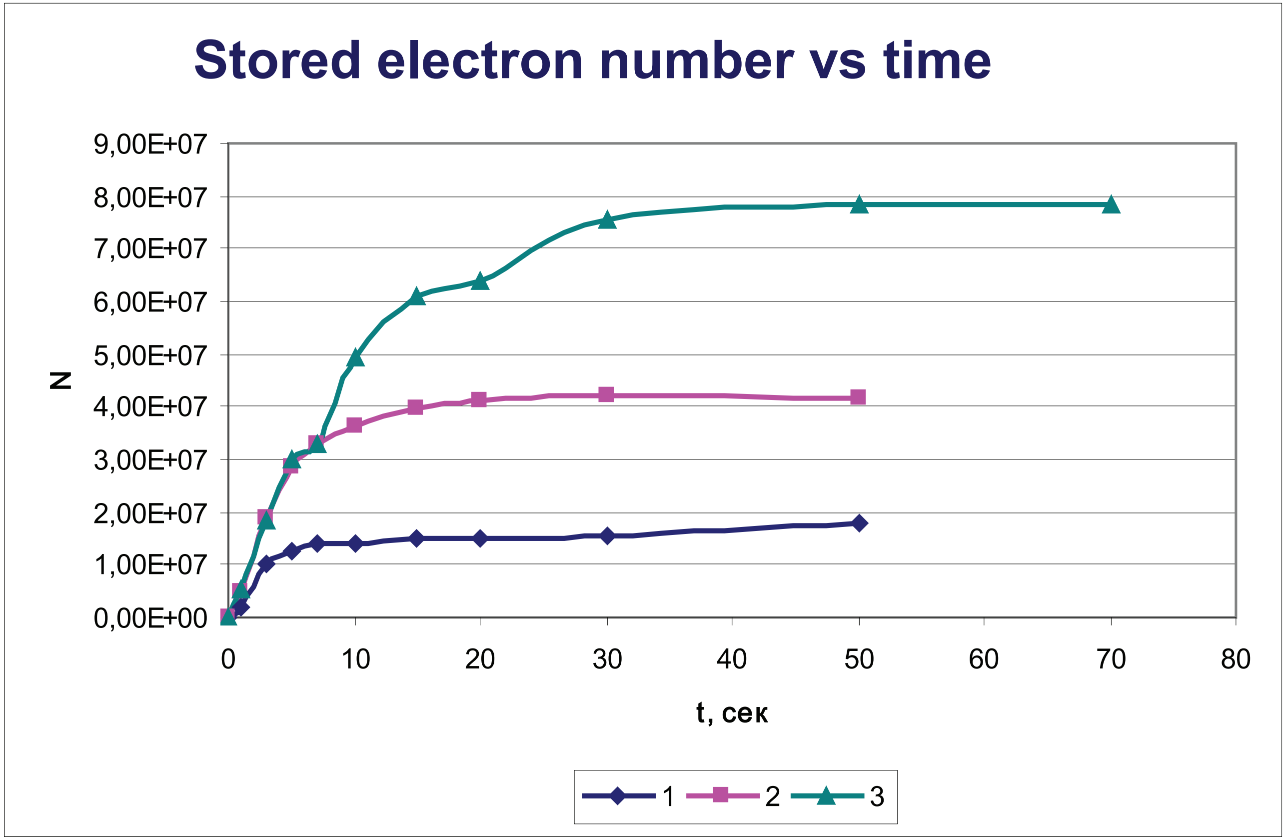


- Pressure and potential distributions are optimized

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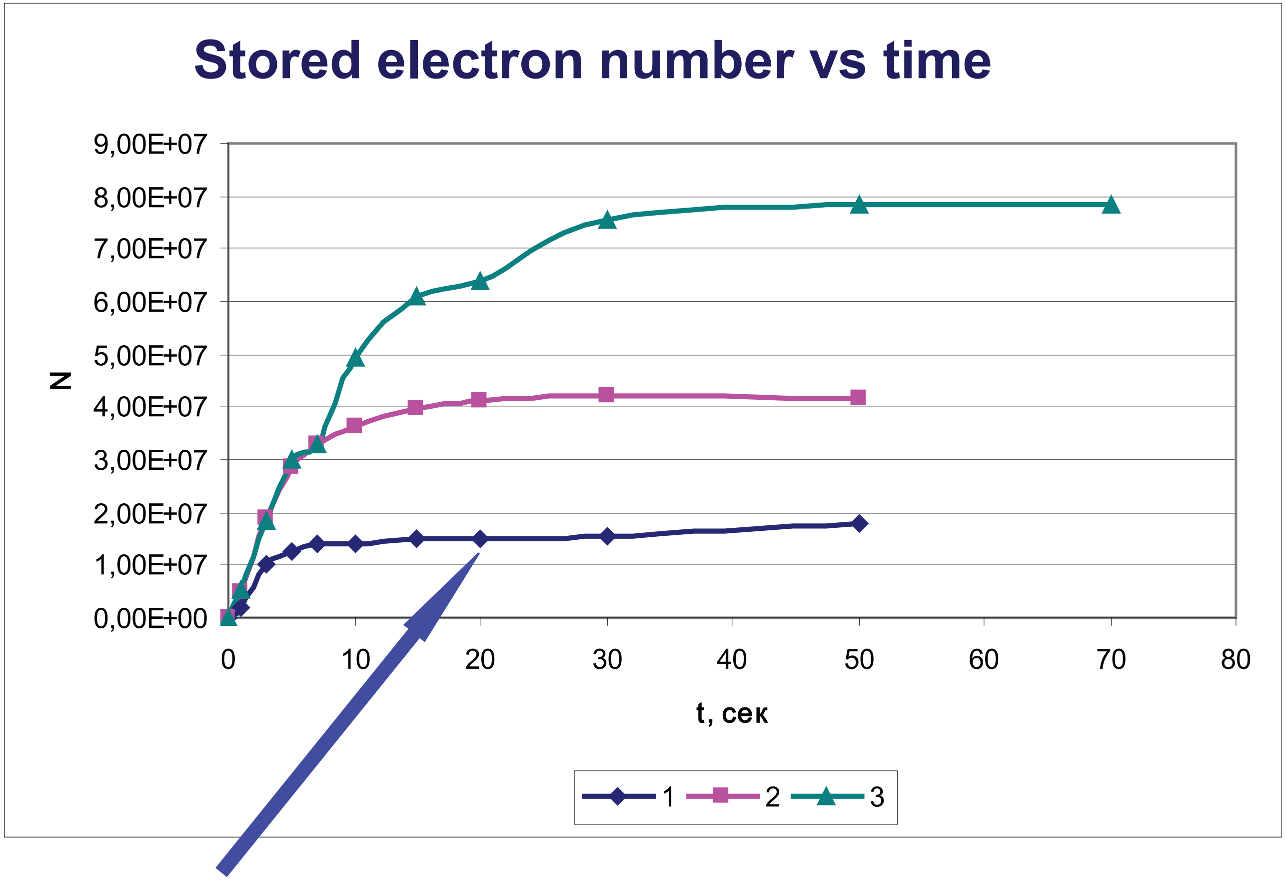


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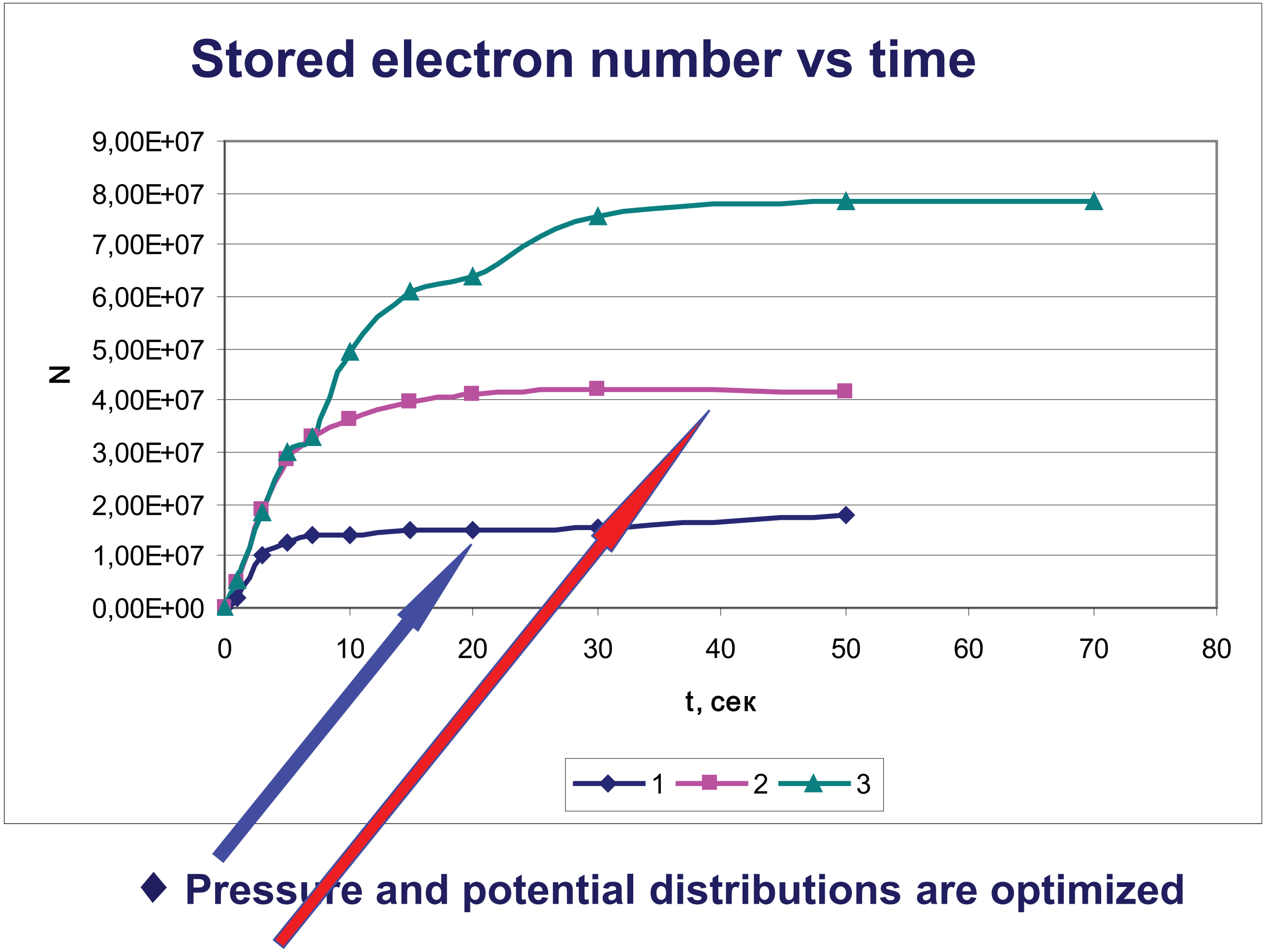


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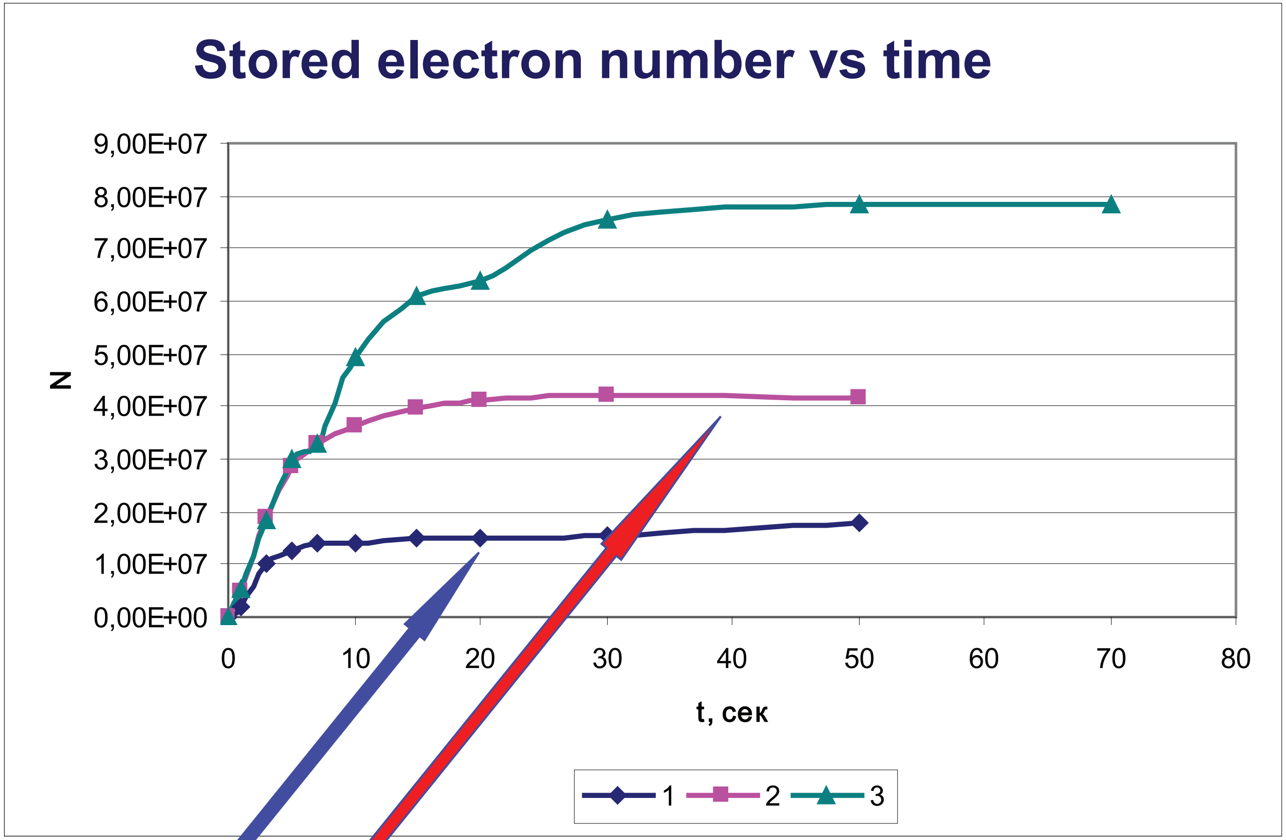


♦ Pressure and potential distributions are optimized

■ Same + transverse correction field is optimized

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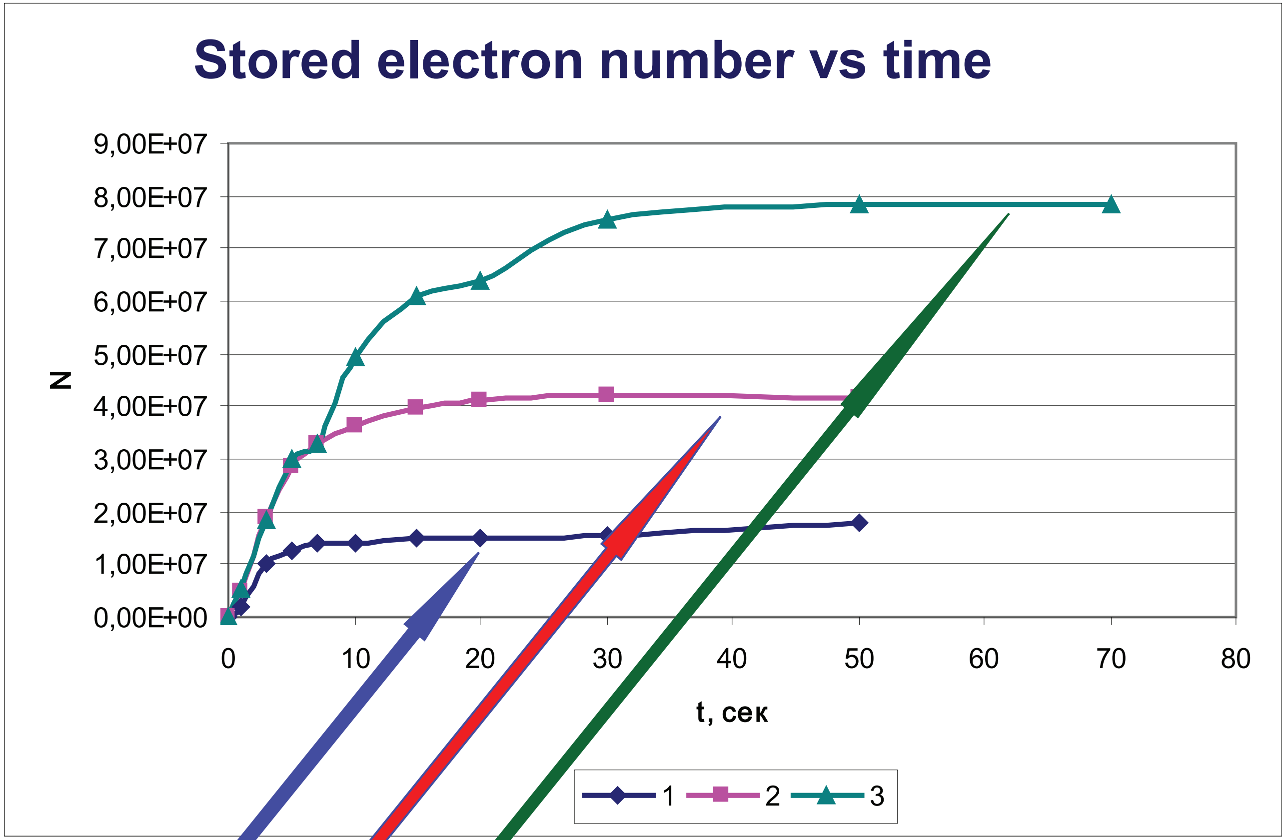


- ♦ Pressure and potential distributions are optimized
- ■ Same + transverse correction field is optimized

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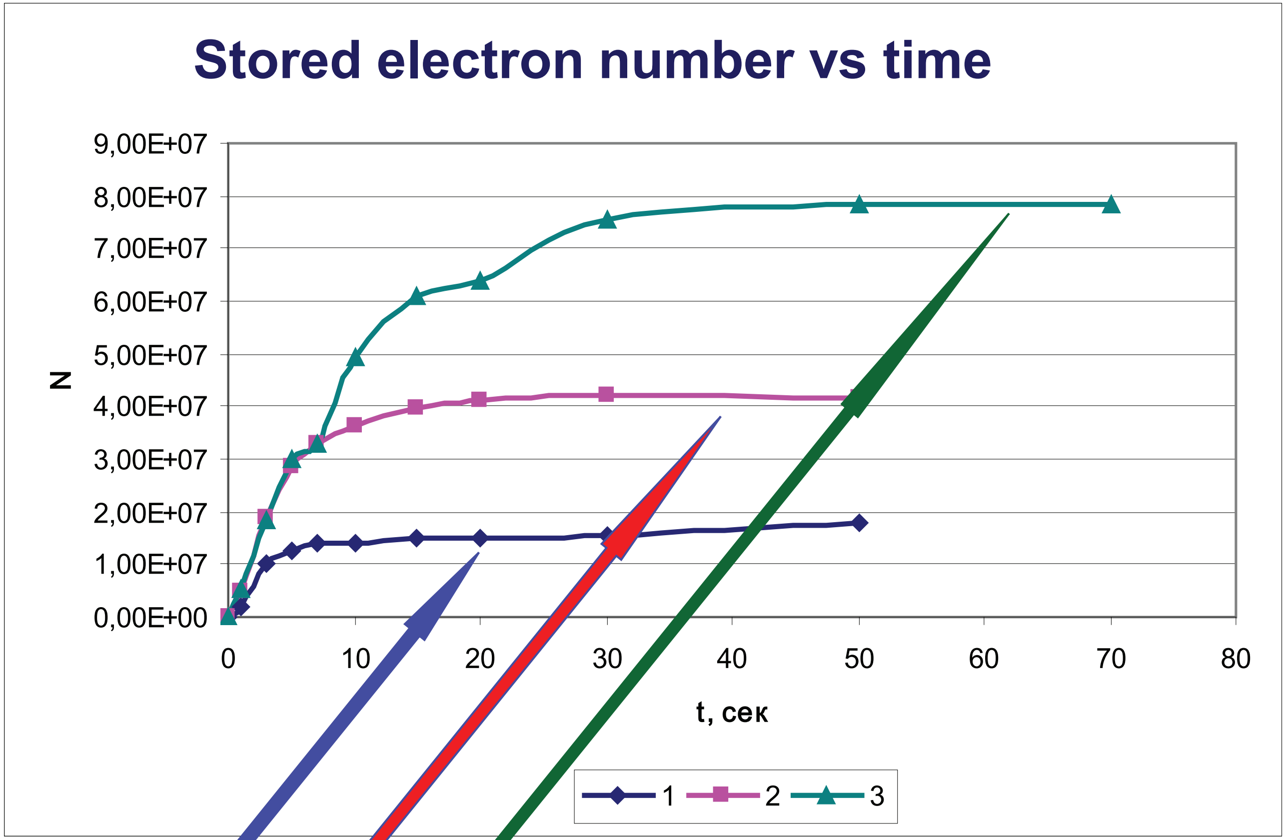


◆ Pressure and potential distributions are optimized

■ Same + transverse correction field is optimized

▲ Same + rotating field is ON and optimized

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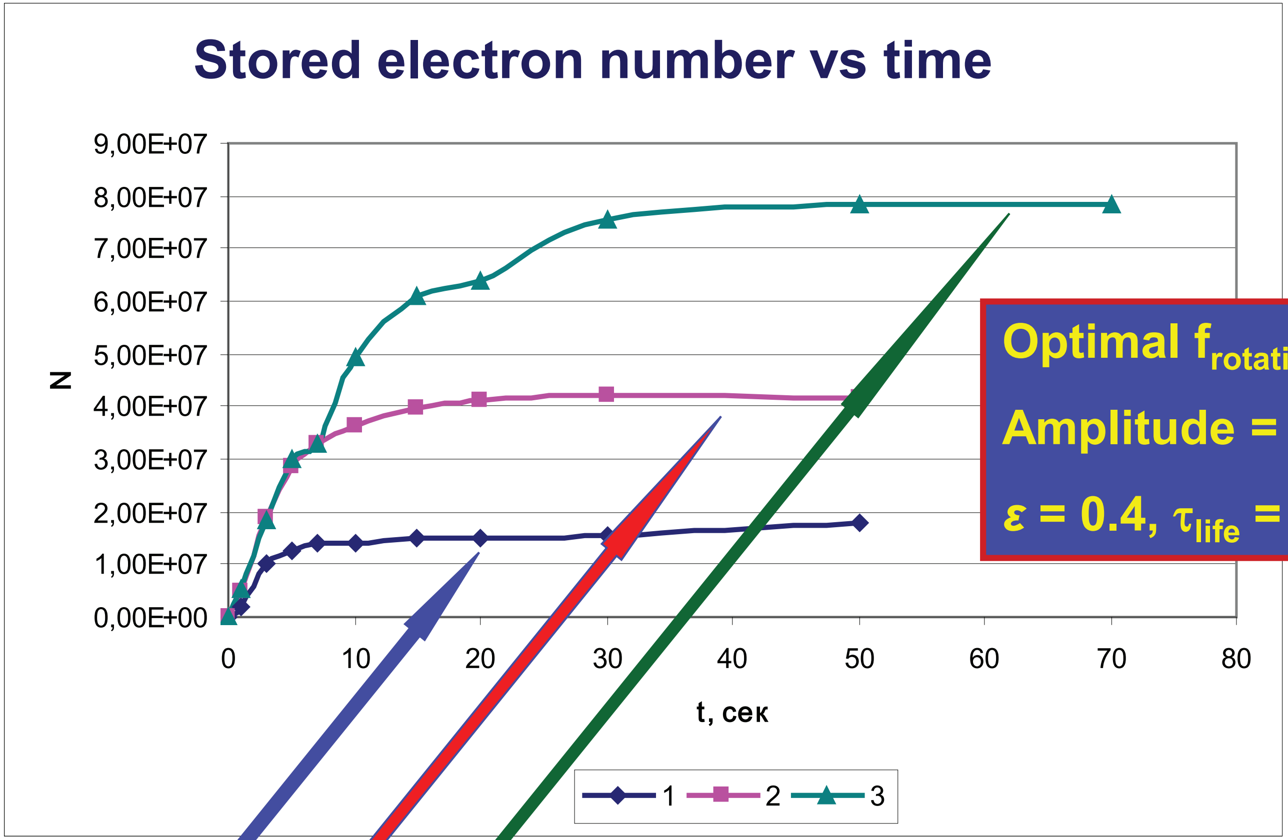


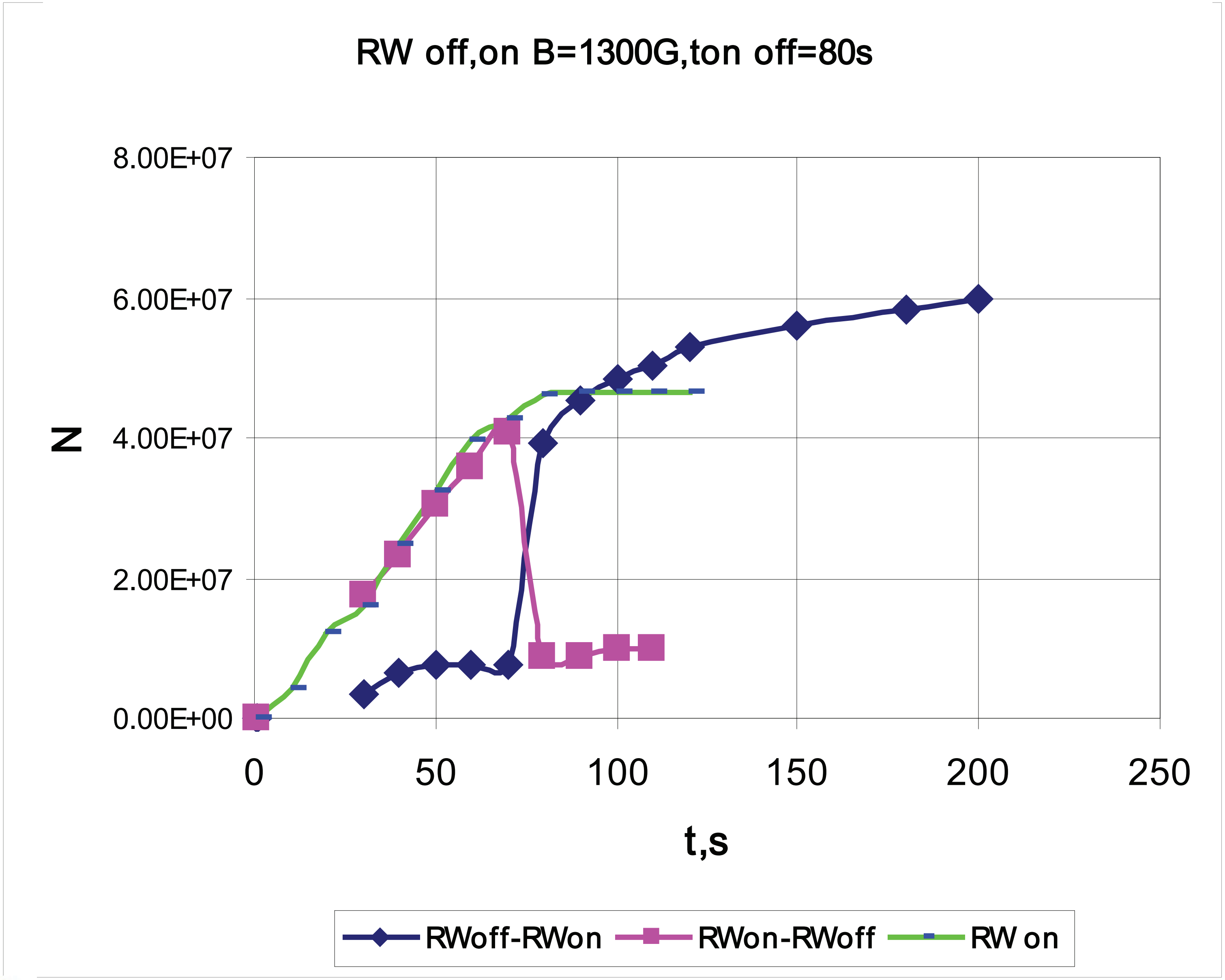

**Optimal $f_{rotating}$ = 600 kHz,**

**Amplitude = 1 V,**

**$\varepsilon$ = 0.4, $\tau_{life}$ = 80 s**

- ♦ **Pressure and potential distributions are optimized**
- ■ **Same + transverse correction field is optimized**
- ▲ **Same + rotating field is ON and optimized**

# 2. Experimental Results, RW Field Effect



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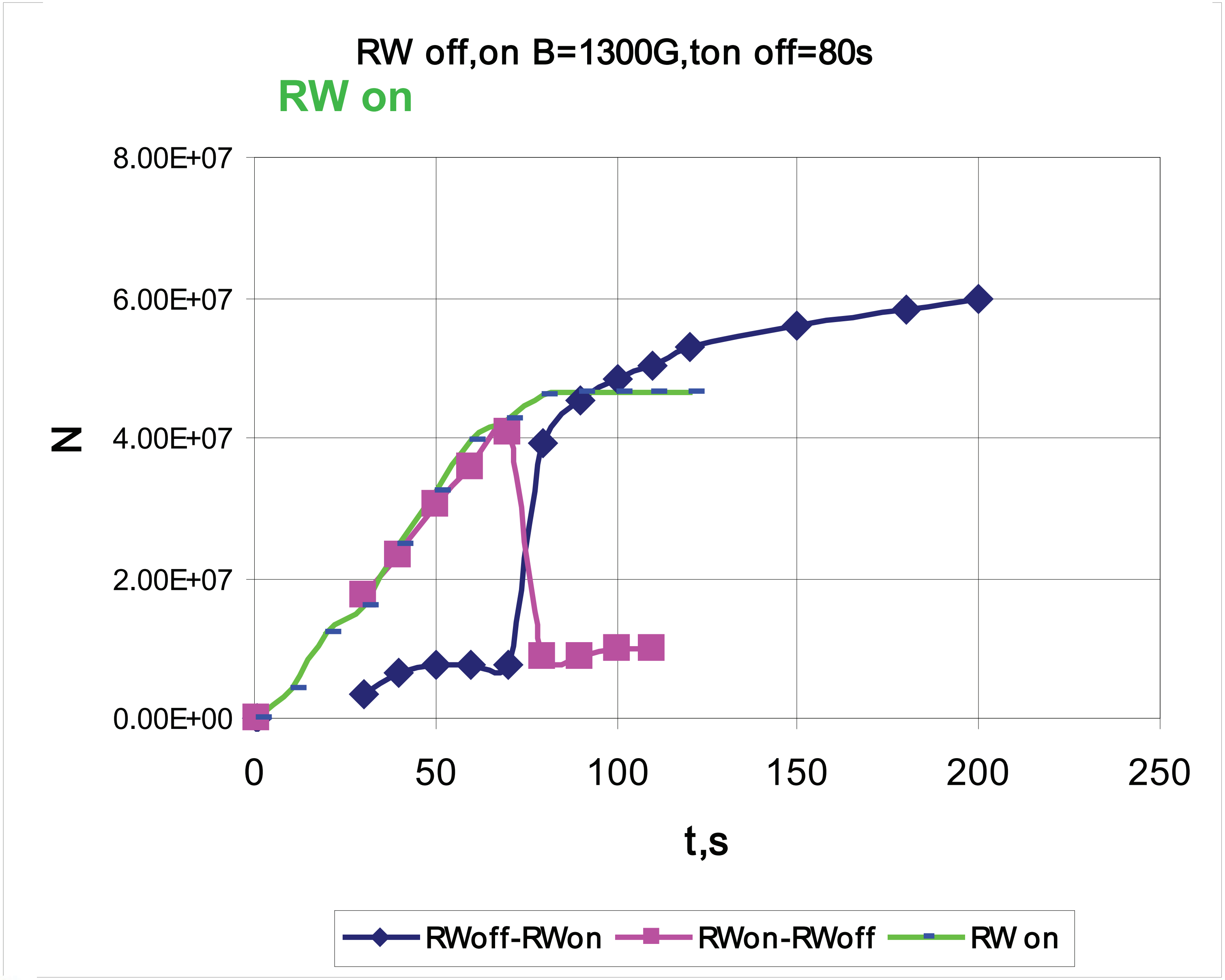

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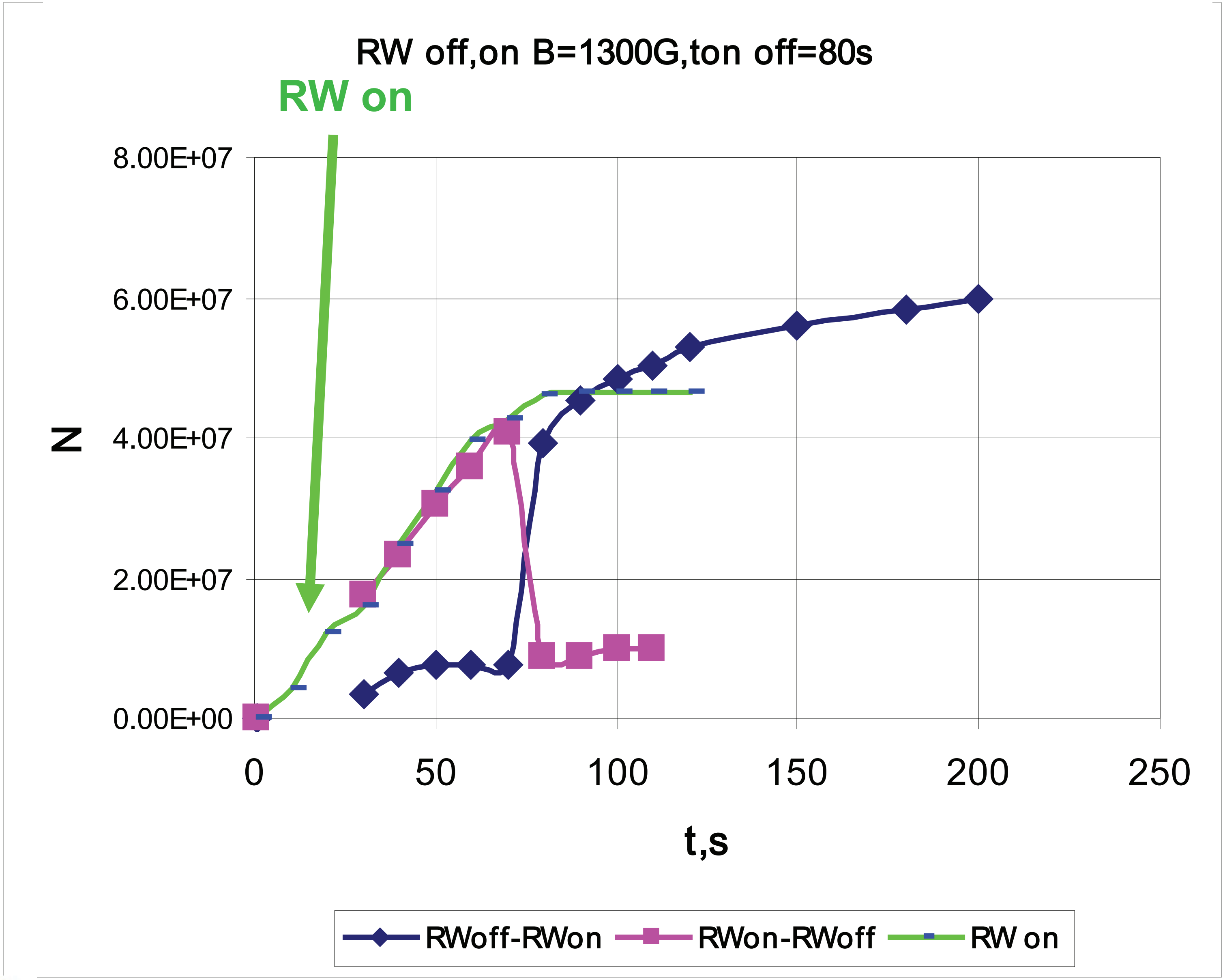

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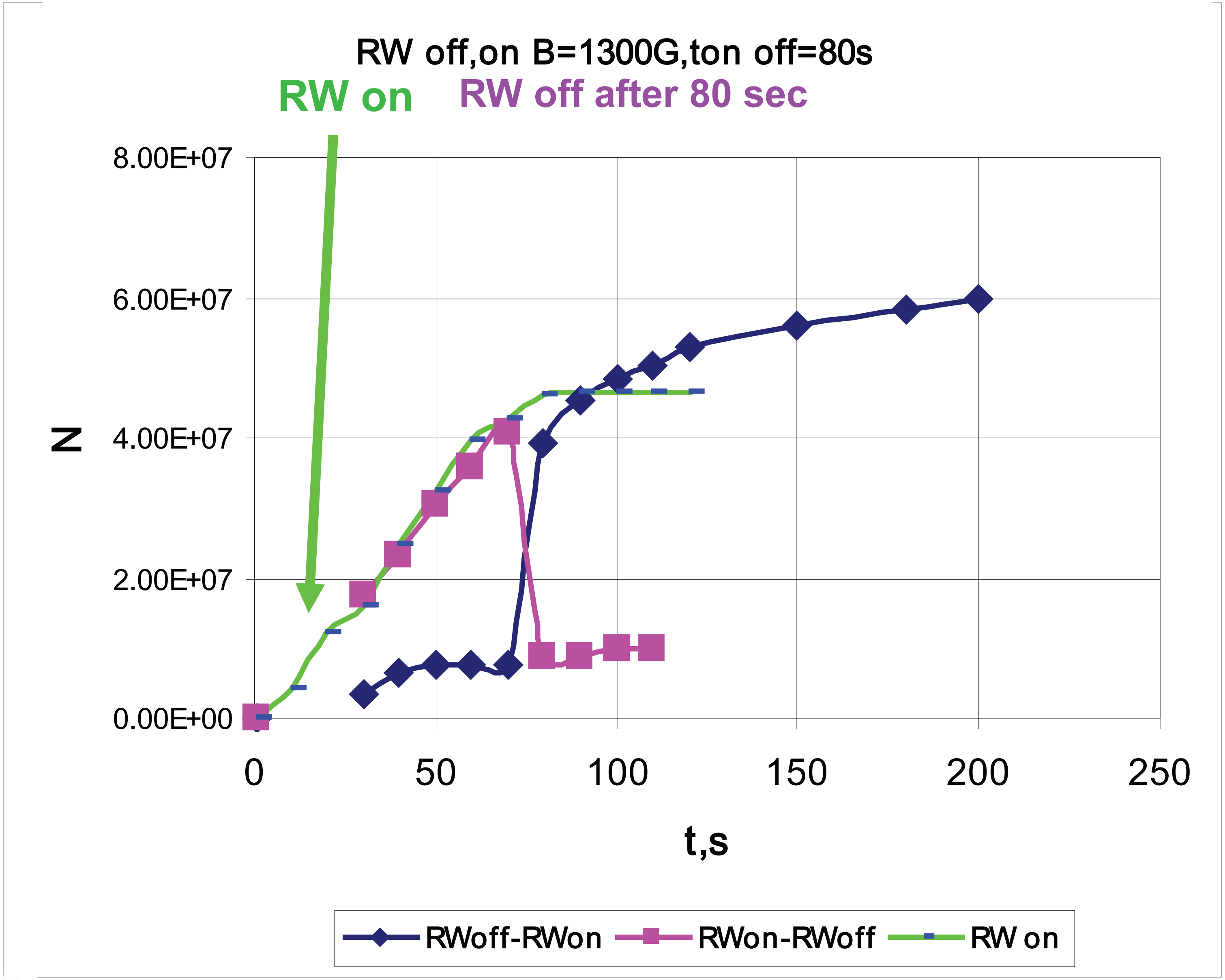

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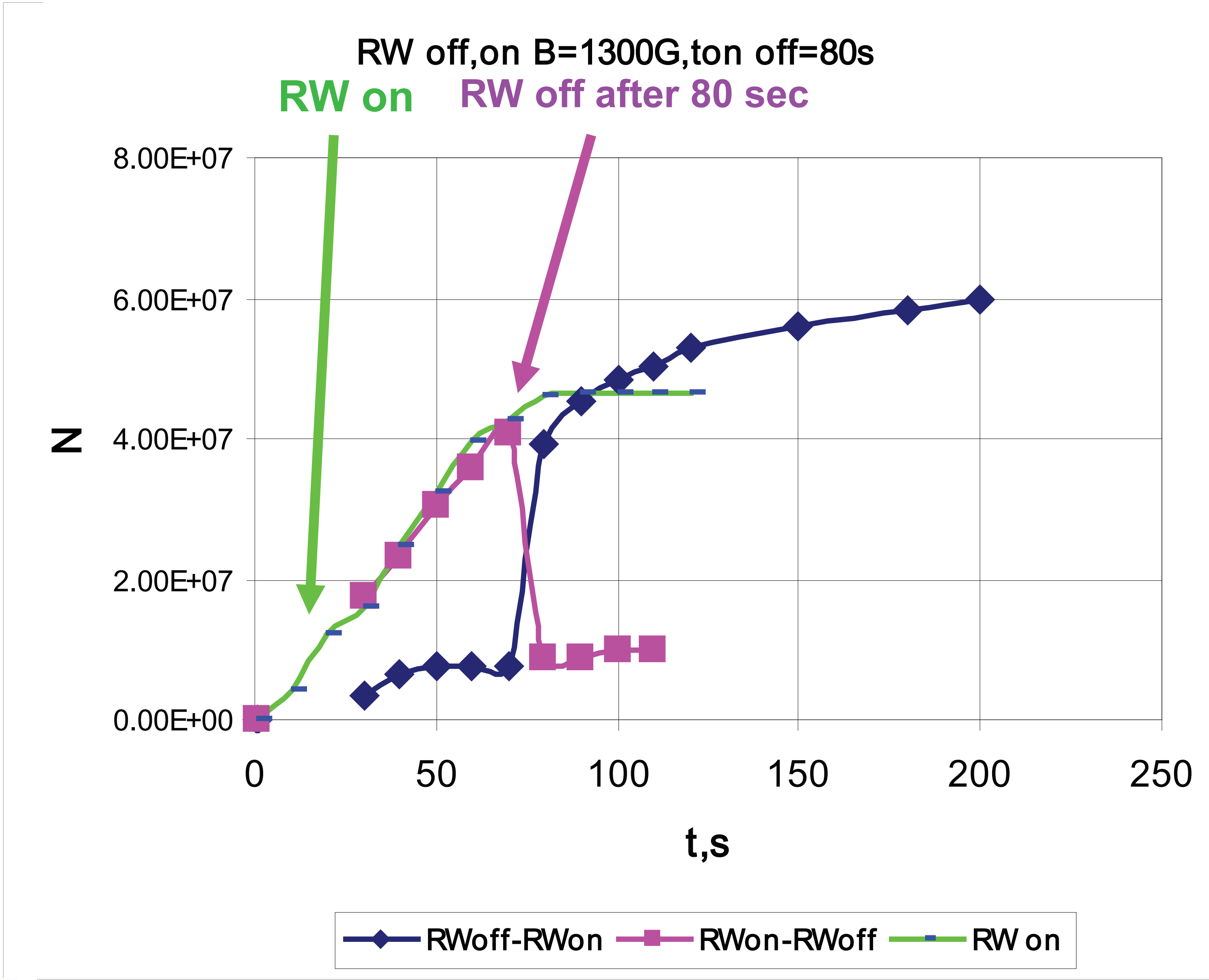

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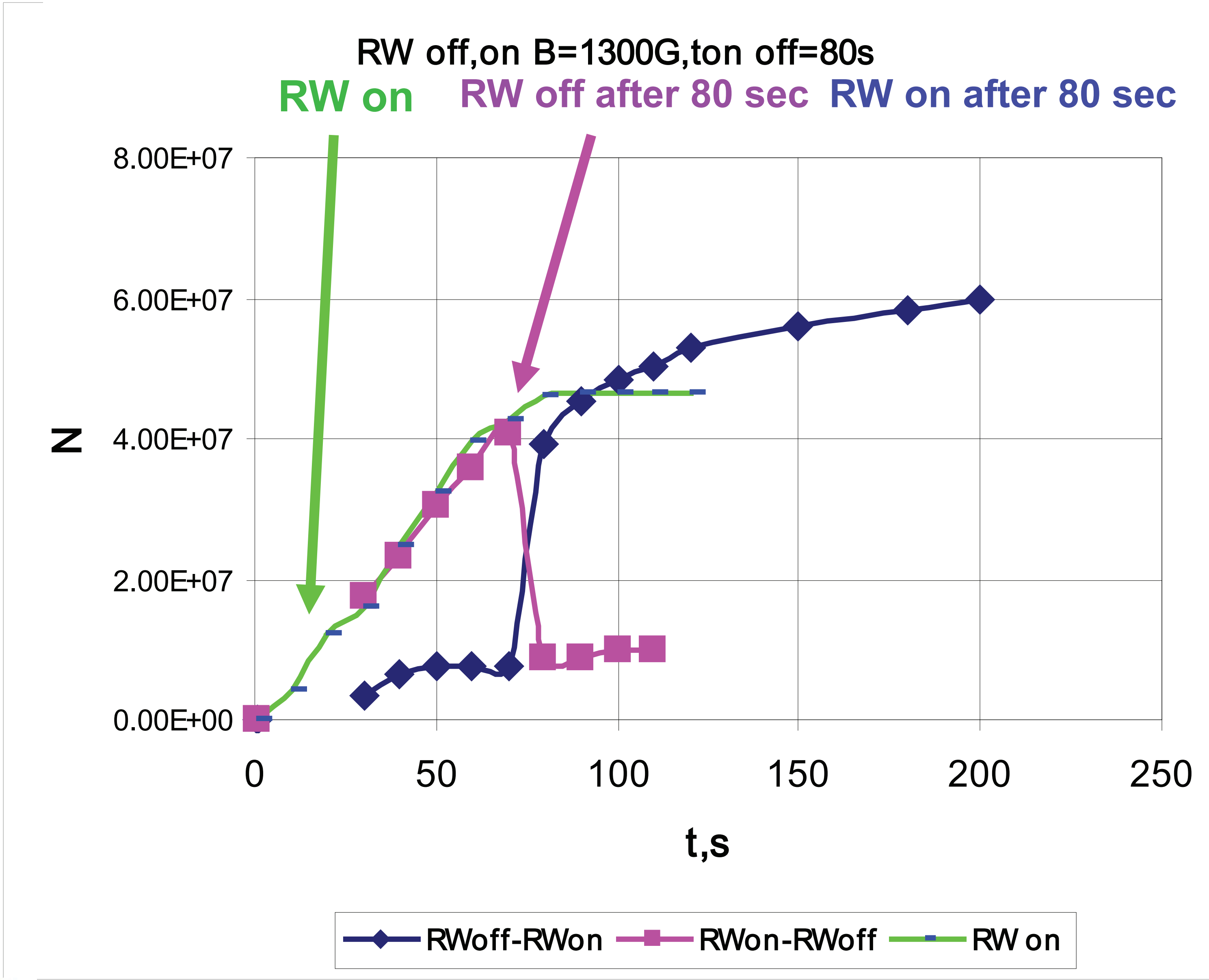

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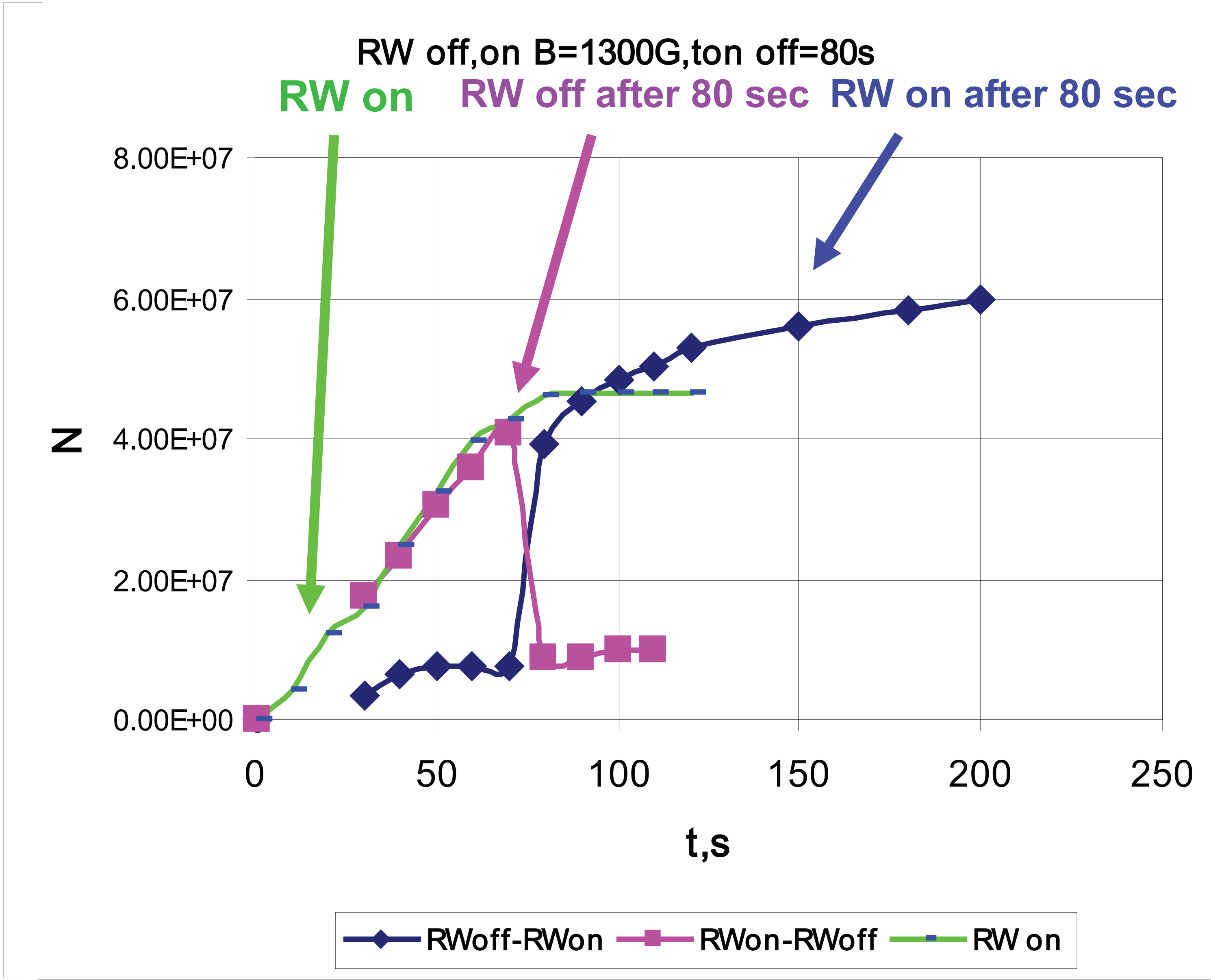
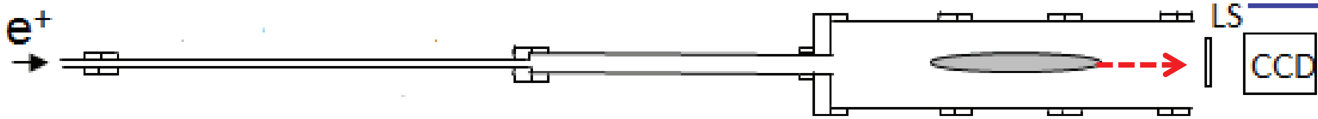
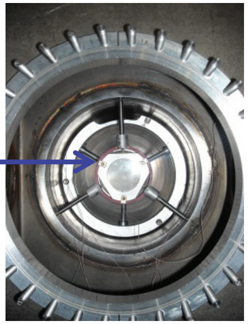


## MCP + Luminescent screen + CCD camera



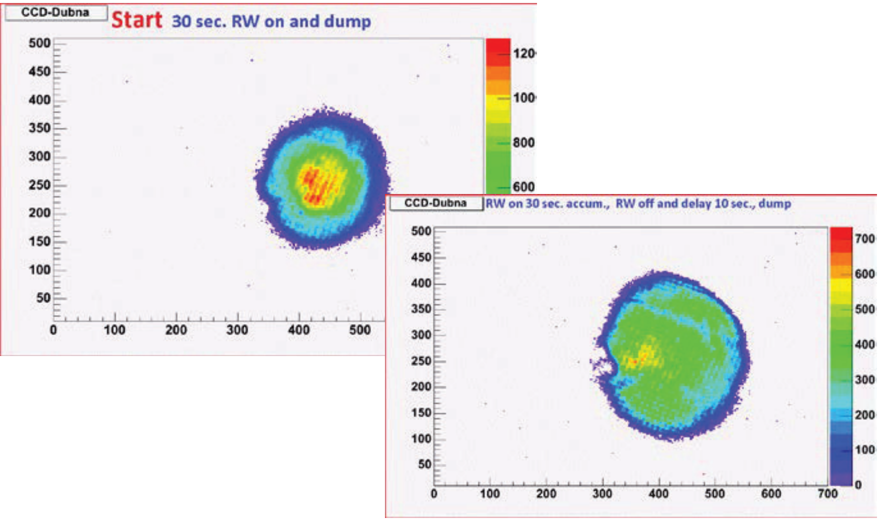



**Injection & storage, RW on (30 s)→**

**Injection off→**

**Confinement, RW off →**

**Extraction (CCD)**




M. Eseev, A. Kobets, I. Meshkov, A. Rudakov, S.Yakovenko // Plasma Phys. Rep. 39 787 (2013).

# 2. Measurements of The Transverse Size and The Bunch Dynamics at Accumulation

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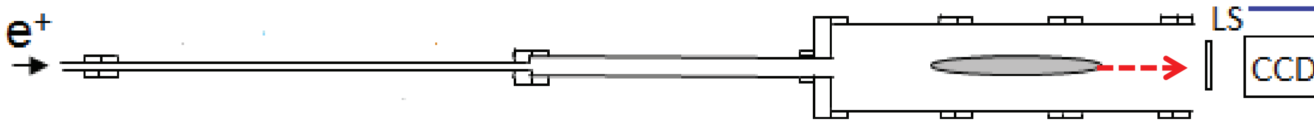


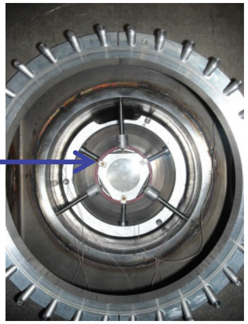

Injection & storage, RW on (30 s)→
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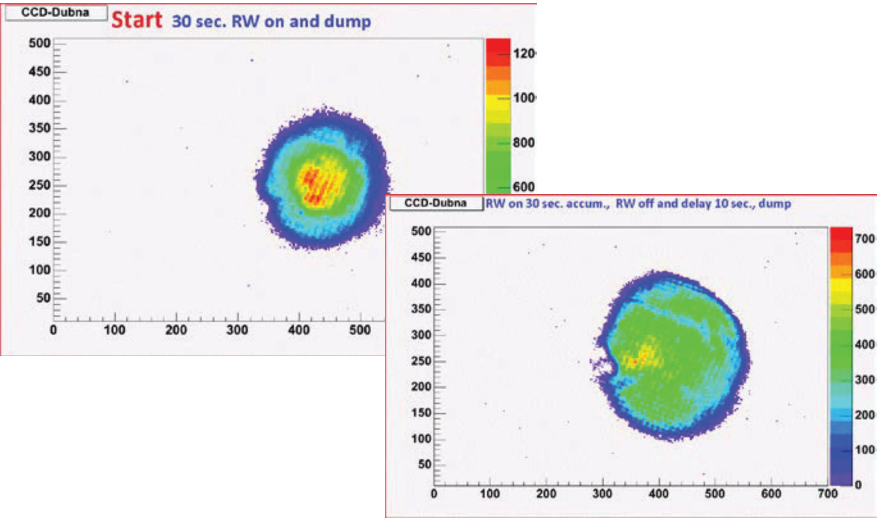


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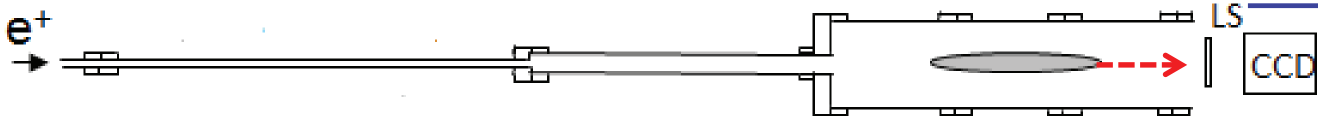


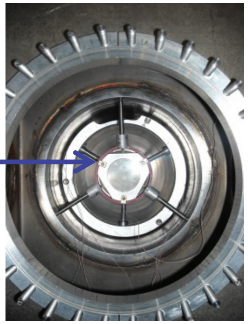

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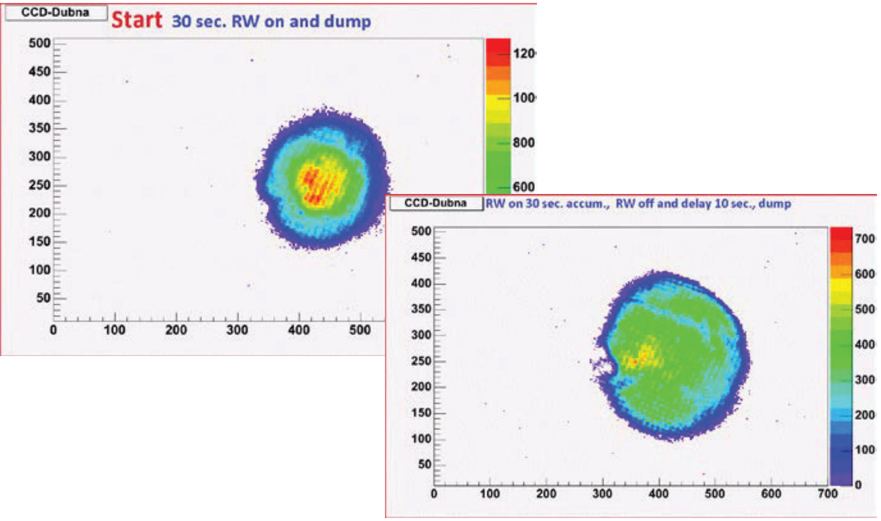


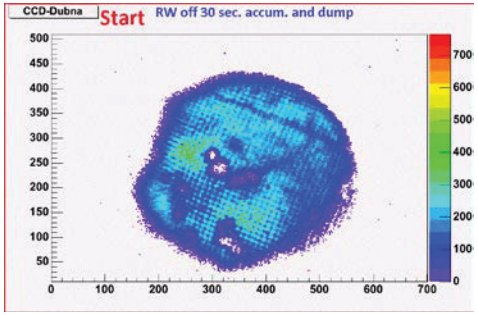


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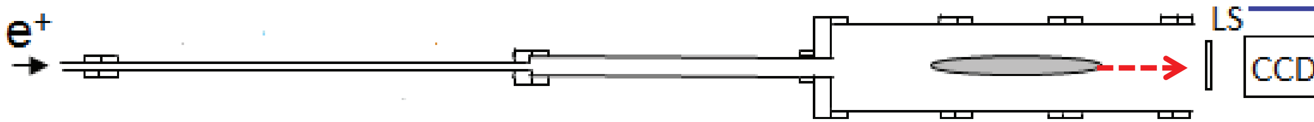


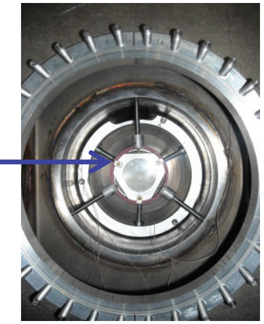

**Injection & storage, RW on (30 s)→**
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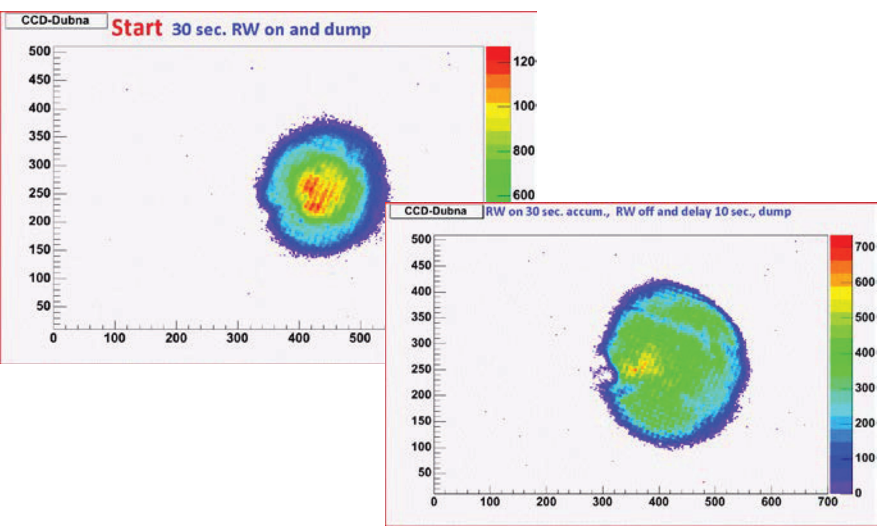
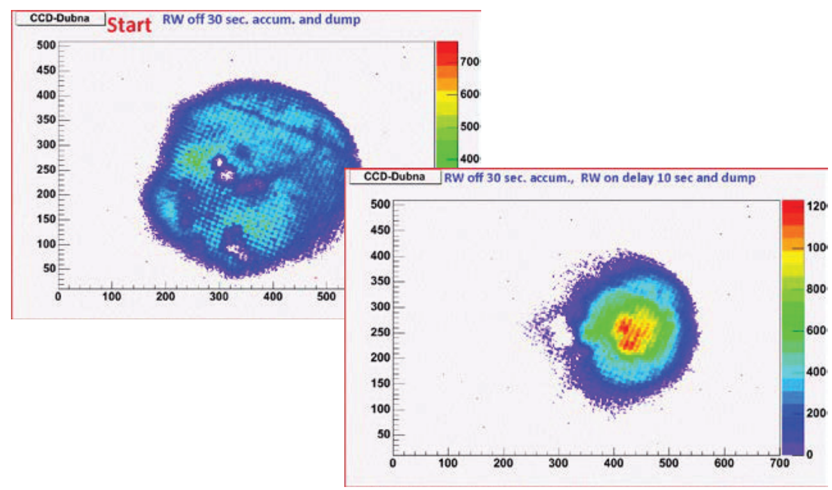



M. Eseev, A. Kobets, I. Meshkov, A. Rudakov, S.Yakovenko // Plasma Phys. Rep. 39 787 (2013).

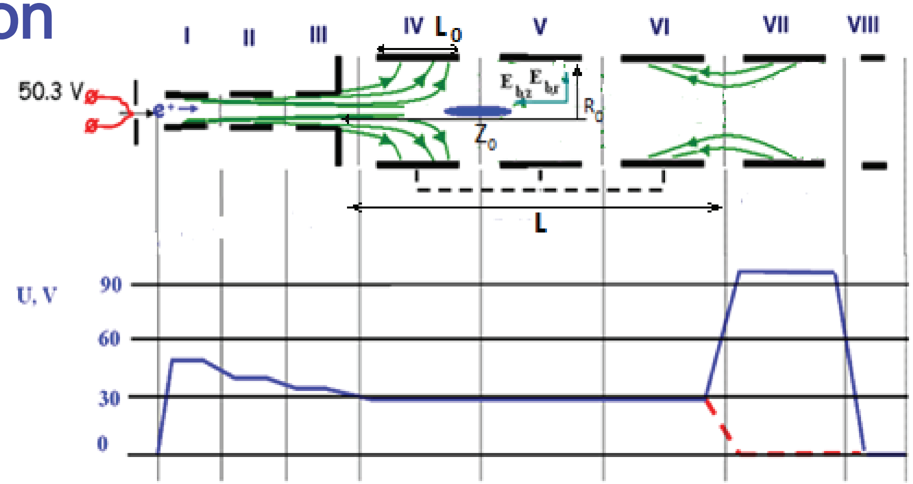
# 3. Mechanism of Charged Particles Accumulation in a PMS Trap with The RW Field

## Transverse and longitudinal motion

$$m\dot{\mathbf{v}} = e\mathbf{E} + \frac{e}{c}\left[\boldsymbol{\upsilon}\times\mathbf{B}\right] - k\boldsymbol{\upsilon}$$

$$\mathbf{E} = \mathbf{E}_R + \mathbf{E}_{trap} + \mathbf{E}_{RW} \qquad \mathbf{E}_R = m\omega_p^2\mathbf{r}/(2e)$$

$$\omega_p = \sqrt{4\pi n e^2/m} \qquad \mathbf{E}_{trap} = \mathbf{E}_{\mathrm{tpap},r} + \mathbf{E}_{\mathrm{trap},z}$$

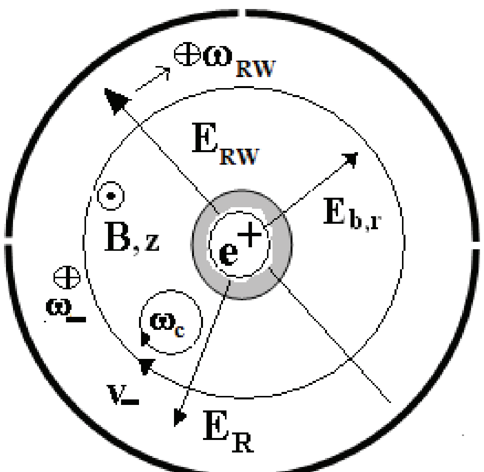



$$\begin{cases} m\dfrac{d^2x}{dt^2} = e\dot{y}\dfrac{B}{c} + e\left[E_x + E_{RW}\cdot\cos\left(\omega_{RW}t+\phi\right)\right] + k\dot{x} \\ m\dfrac{d^2y}{dt^2} = -e\dot{x}\dfrac{B}{c} + e\left[E_y + E_{RW}\cdot\sin\left(\omega_{RW}t+\phi\right)\right] + k\dot{y} \\ m\dfrac{d^2z}{dt^2} \approx -\omega_z^2 z_i - k\dot{z}_i \end{cases}$$

$$\omega_c = eB/mc \qquad K = k/m$$

$$\omega_z = \sqrt{eU_0/md^2}$$

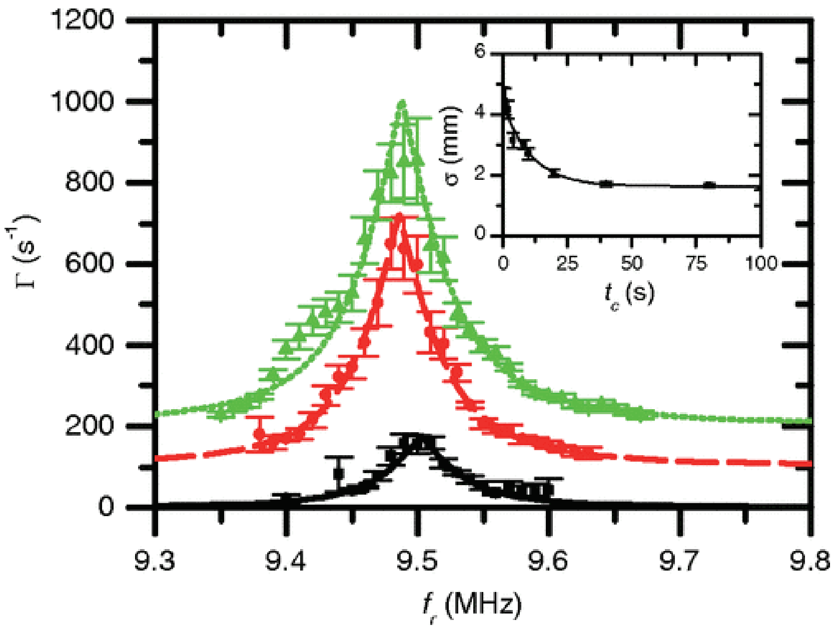
$$\xi = x + iy, \qquad \ddot{\xi} + \omega_c\dot{\xi} = \frac{eE_{RW}}{m}\cdot \mathrm{e}^{i(\omega_{RW}t+\varphi)},$$



# 3. Dynamics of Charged Particles Accumulation in a Trap with The RW Field

- *J. R. Danielson, C. M. Surko* Radial compression and torque-balanced steady states of single-component plasmas in Penning-Malmberg traps // *Phys. Plasmas* 13 055706 (2006).
- *R. G. Greaves, J. M. Moxom* Compression of Positron Clouds in the Independent Particle Regime // *Phys. Plasmas* 15 072304 (2008).
- *C. A. Isaac, C. J. Baker, T . Mortensen* Compression of Positron Clouds in the Independent Particle Regime // *Phys. Rev. Lett*. 107 033201 (2011).
- *C. Isaac* Motional sideband excitation using rotating electric fields // Phys. Rev. A 87 043415 (2013).
- *A. Deller, T. Mortensen, C. A. Isaac, D. P. van der Werf, and M. Charlton* Radially selective inward transport of positrons in a Penning–Malmberg trap // New J. Phys. 16 073028 (2014).

Compression rate as a function of the rotating wall frequency for amplitudes of 75 mV (■), 150 mV (●), offset by 100 $s^{-1}$ and 225 mV (▲), offset by 200 $s^{-1}$

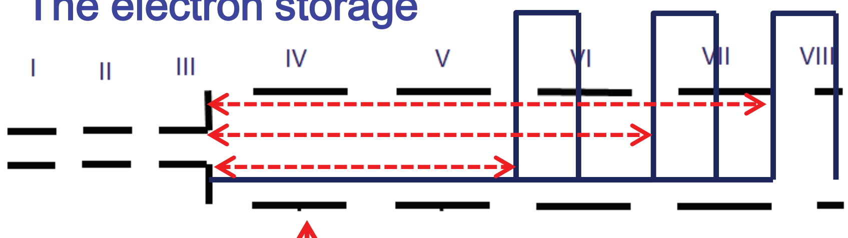



Today: A. Ovsyannikov "Analysis of the Paticle Dynamics Stability in the Penning-Malmberg-Surko Trap" WECAMH03

# 3. Mechanism of Charged Particles Accumulation in a PMS Trap with The RW Field

The dependence of the lifetime of a bunch of particles (electrons) from the RW-frequency fields with different lengths of accumulation area

The electron storage



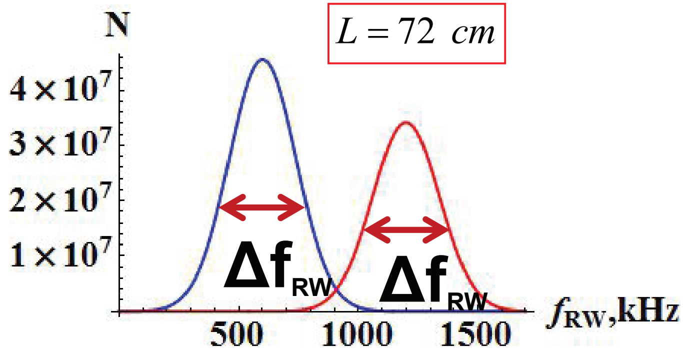

RW-electrode – RW –region

| Length of accumulation, L, cm | Bounce frequency, $f_Z$, kHz | Resonance RW frequency, $f$, kHz |
|---|---|---|
| 72 | 600 | 600 |
| 48 | 850 | 800 |
| 32 | 1200 | >1100 |

Length of accumulation only in RW-electrode (16 cm) – no storage!

$$f_{RW} = l \cdot f_z \approx \frac{\upsilon_{II}}{2L_{trap}}$$

$$l = 1, 2, \ldots$$

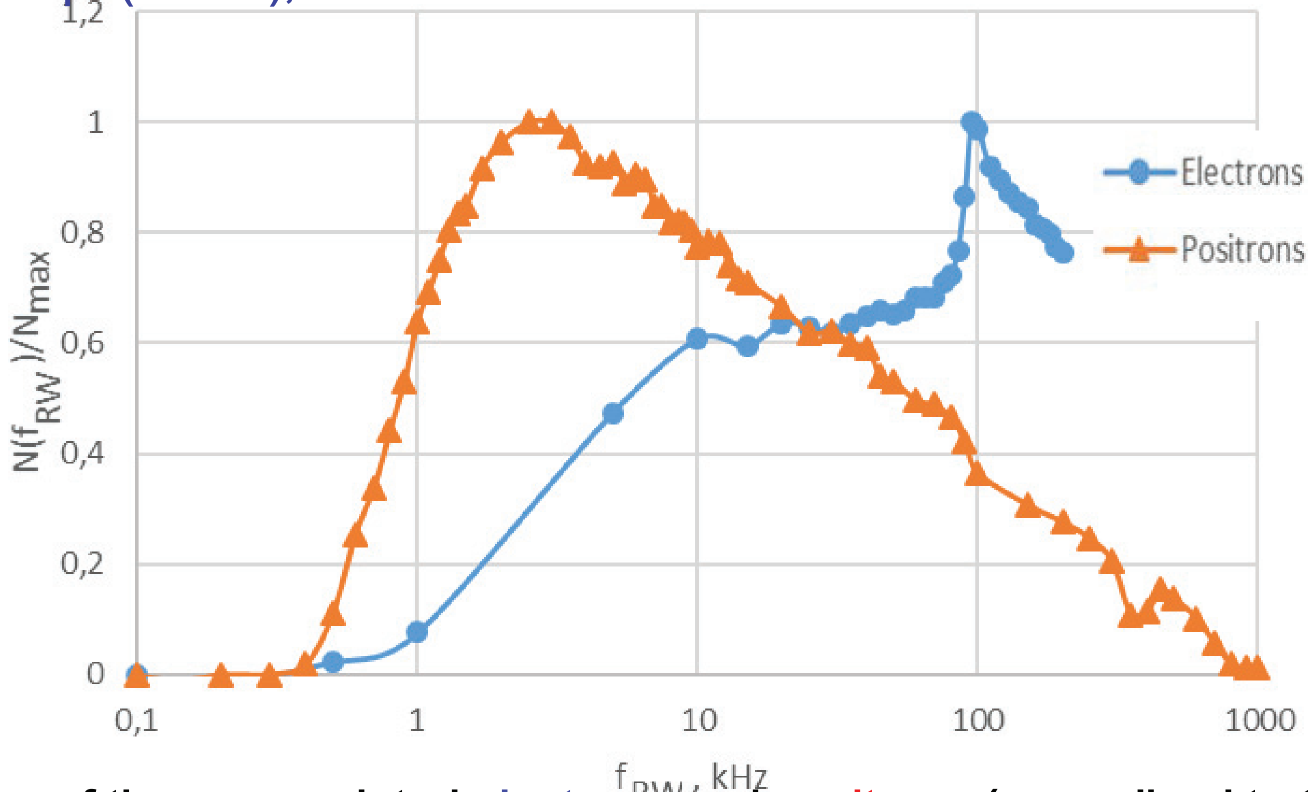



Responses in multiple frequencies, the calculation taking into account the "thermal expansion"

M. Eseev, A. Kobets, I. Meshkov, A. Rudakov, S.Yakovenko // Plasma Phys. Rep. 39 787 (2013)

# 3. Mechanism of Charged Particles Accumulation in a PMS Trap with The RW Field

The accumulation of positrons and electrons after the upgrade (CriogenPump & ElectronGun & RWtech) PMS traps (LEPTA), 2014-2015




Dependencies of the accumulated electrons and positrons (normalized to the maximum) from the RW-frequency field. The amplitude of the RW-field 1 V, the buffer gas ($N_2$) pressure 2.75 mkTorr.

Eseev M.K., Kobets A.G., Meshkov I.N., Sidorin A.A., Orlov O.S. // JETP Letters 102 (5) 261-265 (2015).

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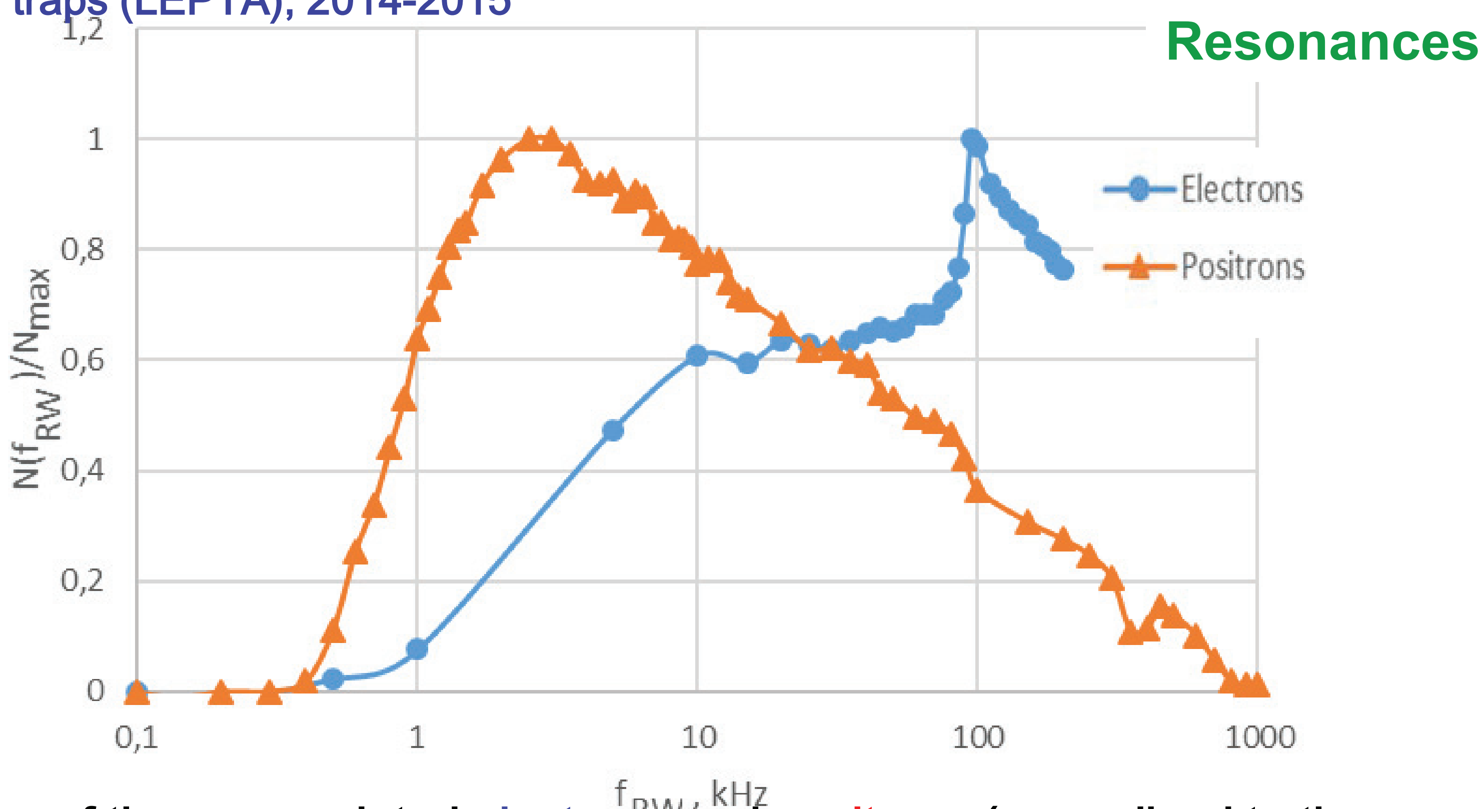


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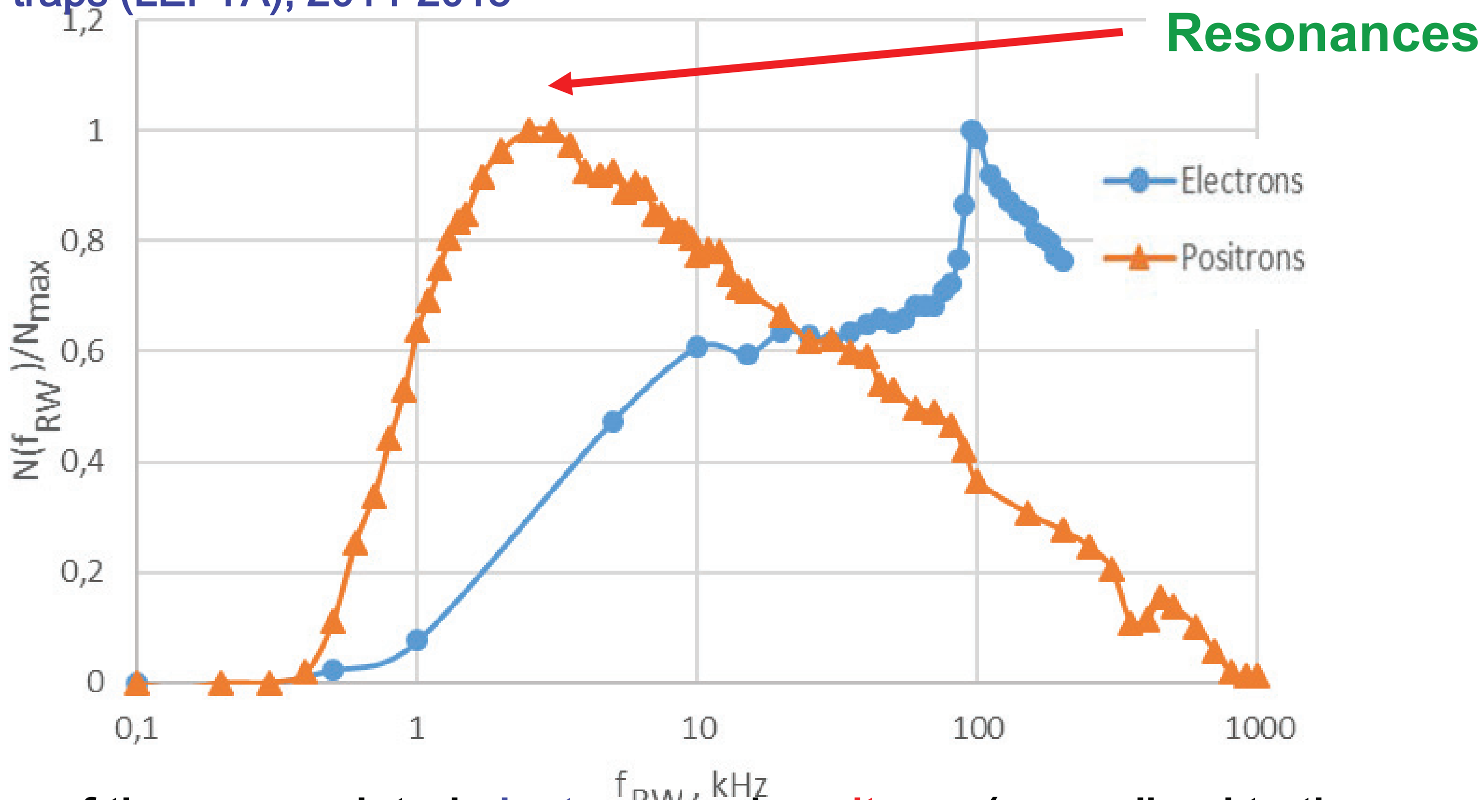


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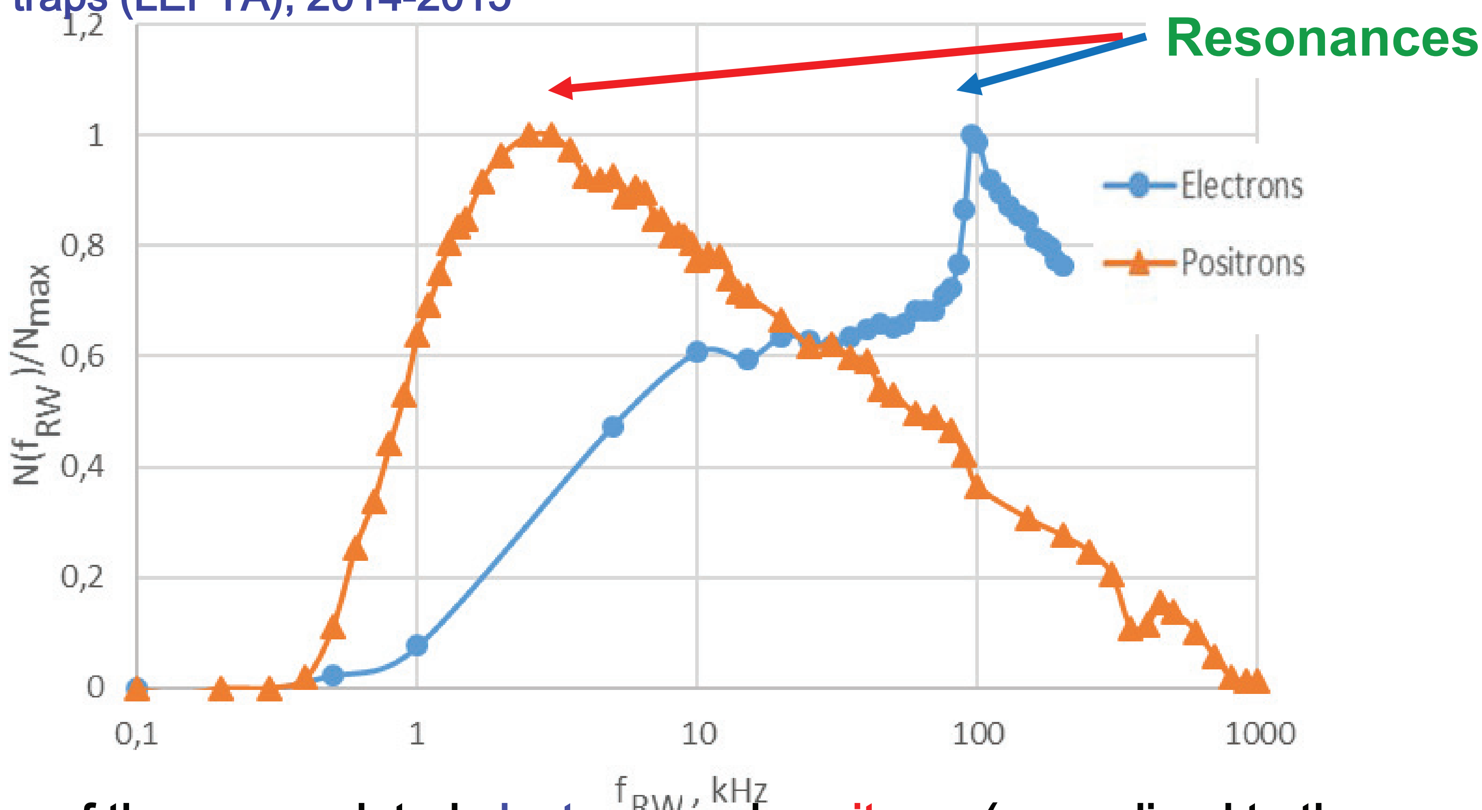


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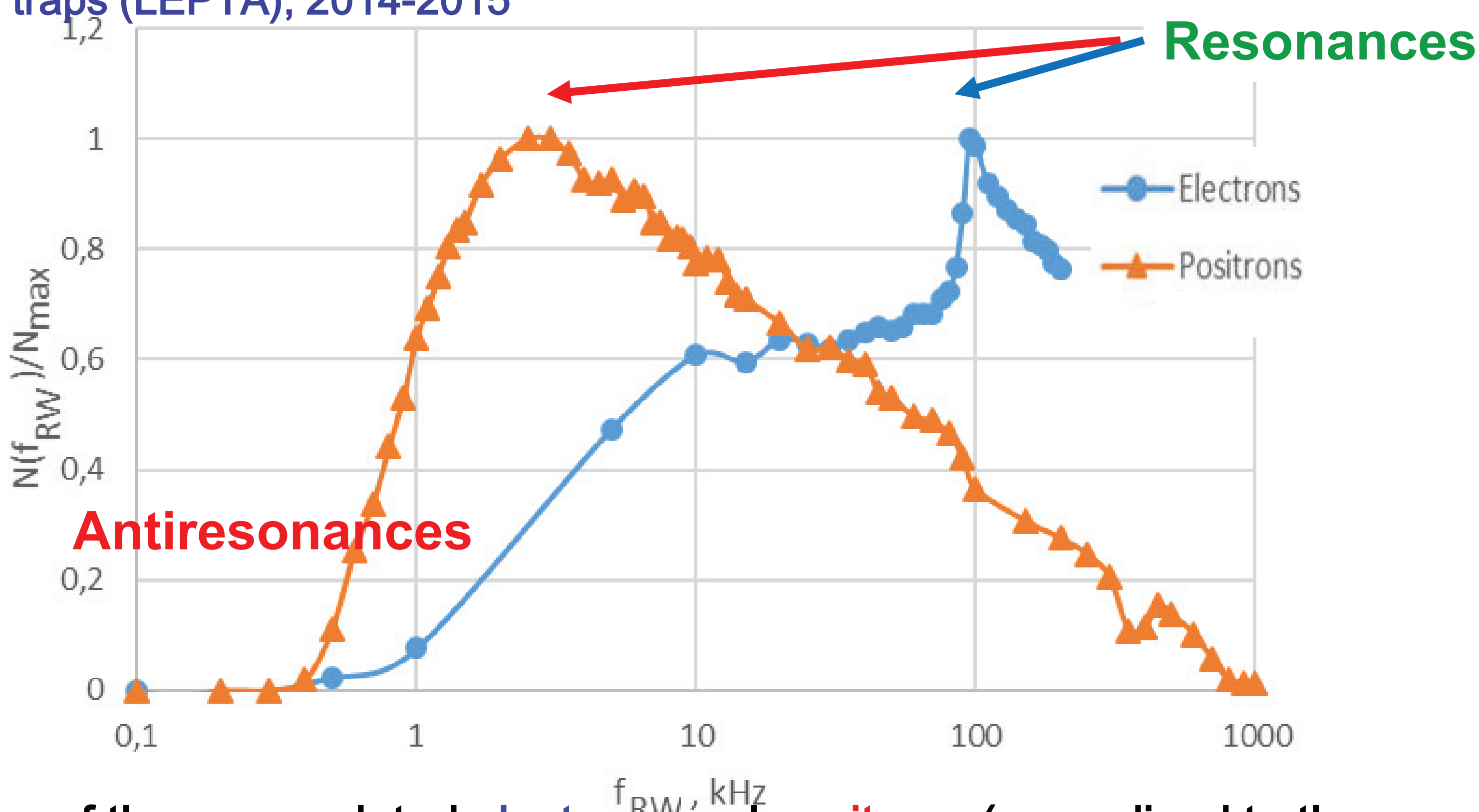


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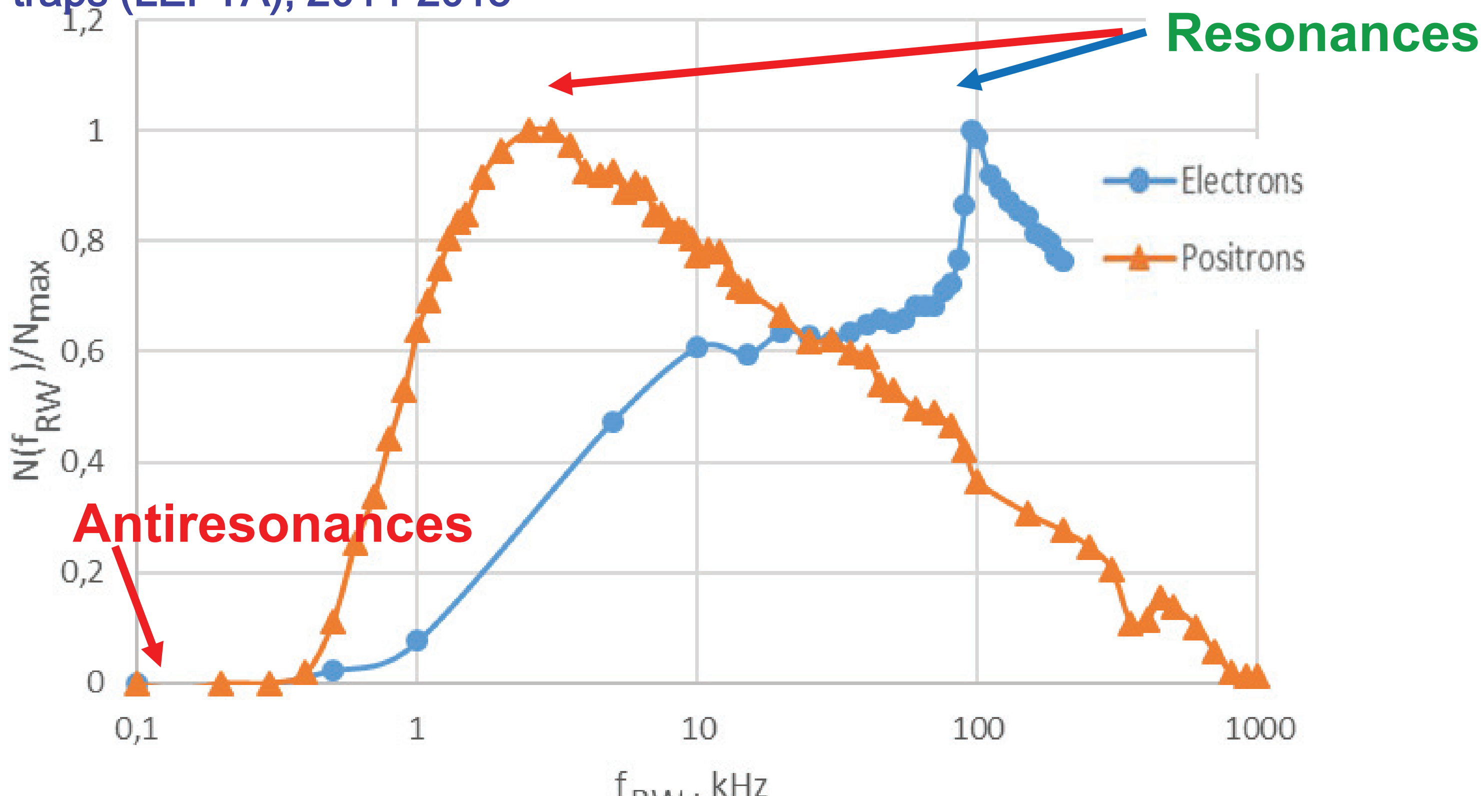


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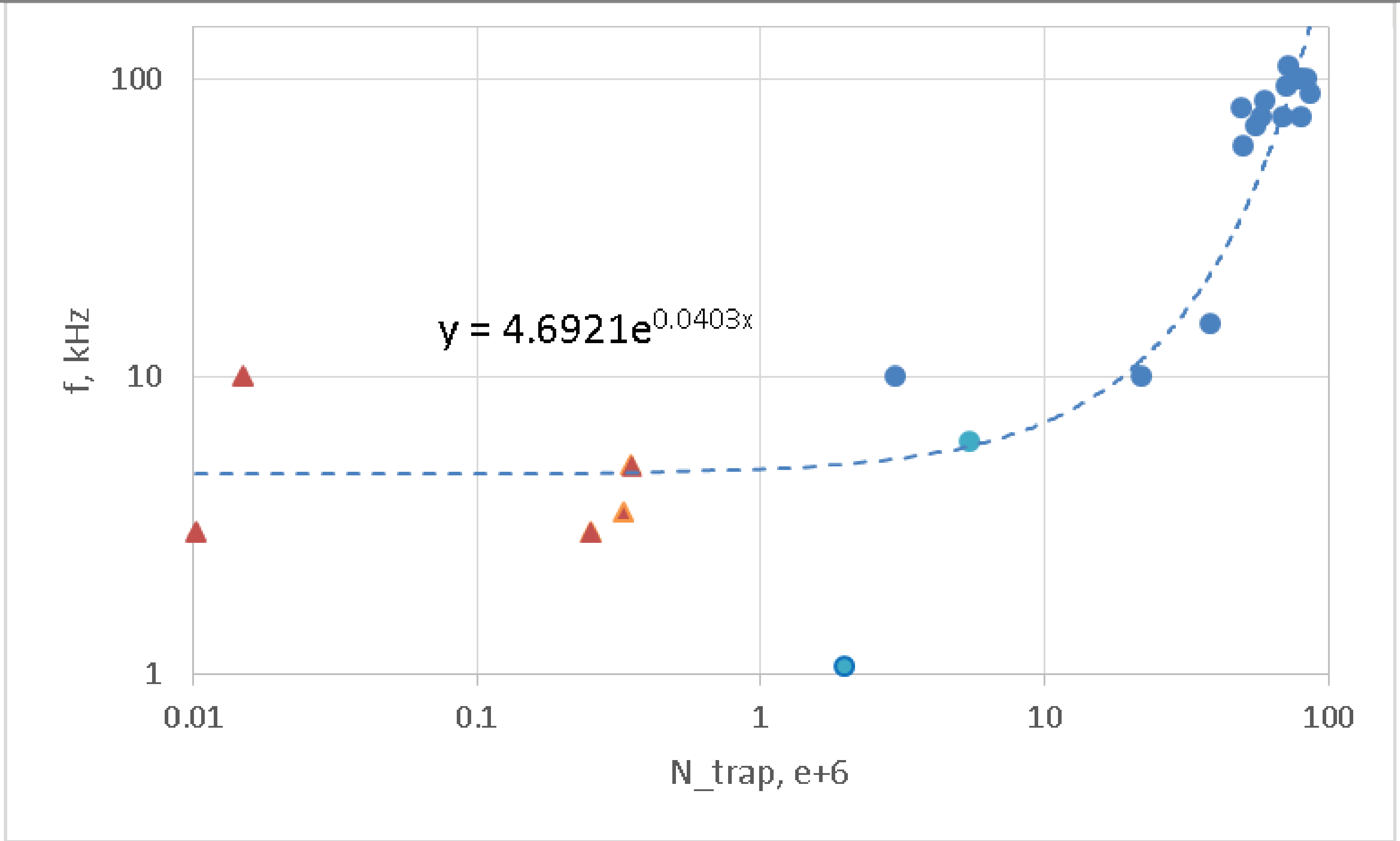
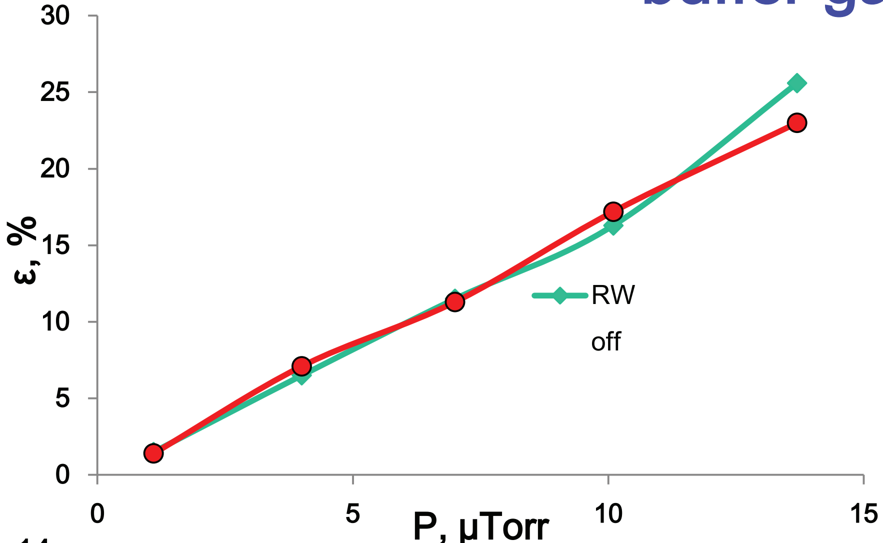
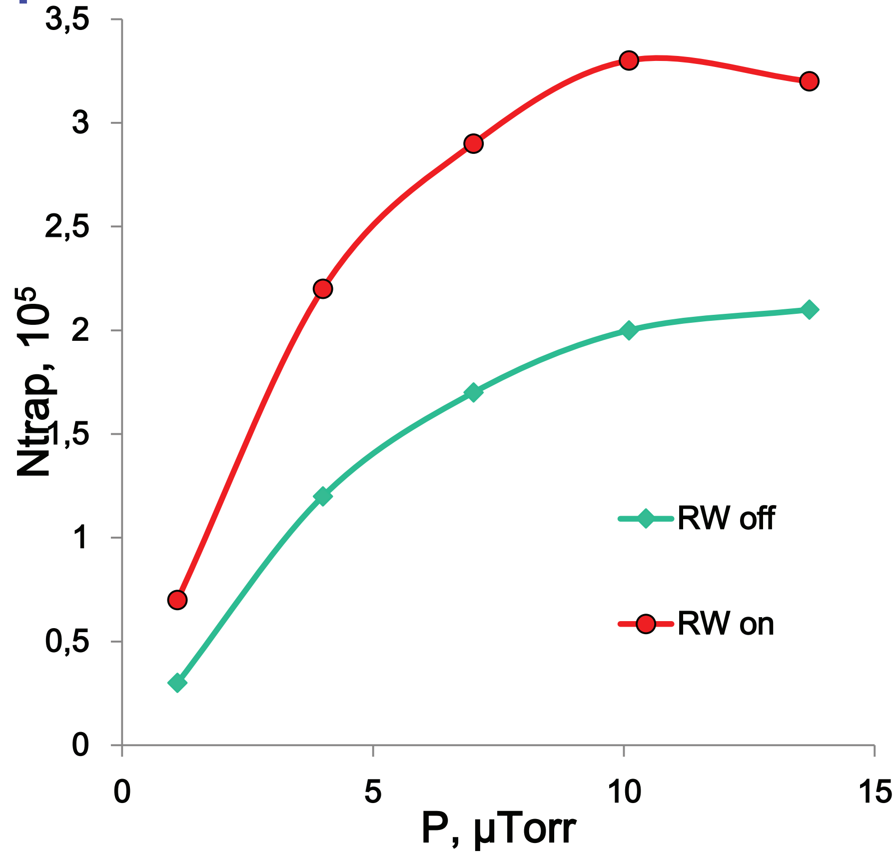


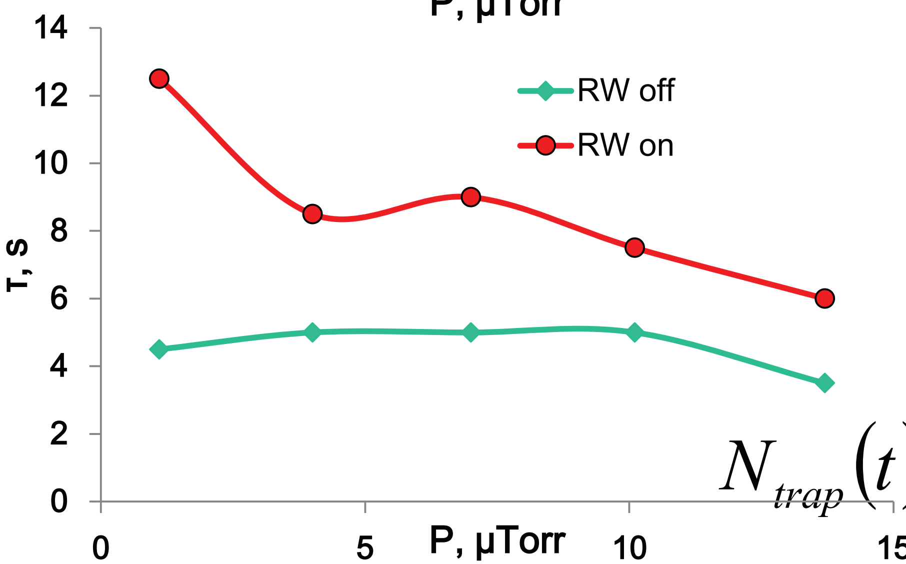

*The particle storage:* $N_{trap}$, ($\omega_{RW}$), t=20 s: ● – electrons, ▲ – positrons

Eseev M.K., Kobets A.G., Meshkov I.N., Sidorin A.A., Orlov O.S. // JETP Letters 102 (5) 261-265 (2015)

## Dependence of parameters of accumulation of positrons from the buffer gas pressure




$$N_{trap}(t) = \varepsilon \dot{N} \tau \left(1 - e^{-t/\tau}\right) \Rightarrow \begin{cases} \varepsilon \dot{N} t, \; t \ll \tau, \\ \varepsilon \dot{N} \tau, \; t \gg \tau \end{cases}$$

$\omega_c >> \omega_{RW}$

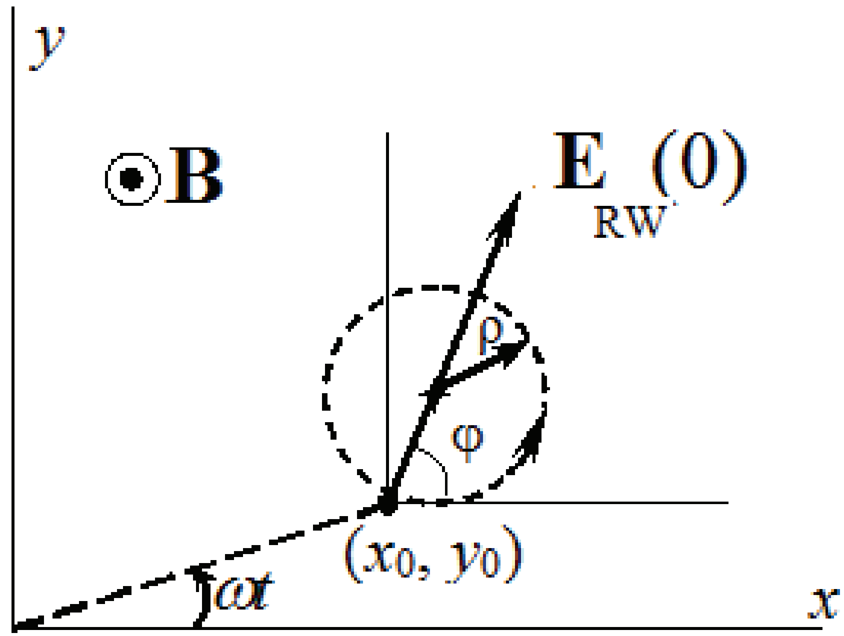
$$x(t) = x_0 + \frac{v_d}{\omega_{RW}}\left(\cos(\omega_{RW} t + \varphi) - \cos\varphi\right),$$

$$y(t) = \operatorname{Im}\xi(t) = y_0 + \frac{v_d}{\omega_{RW}}\left(-\sin(\omega_{RW} t + \varphi) + \sin\varphi\right),$$

$$v_d = c \cdot \frac{E_{RW}}{B}.$$

$$\left(x - x_0 + \frac{v_d}{\omega_{RW}}\cos\varphi\right)^2 + \left(y - y_0 + \frac{v_d}{\omega_{RW}}\sin\varphi\right)^2 = \left(\frac{v_d}{\omega_{RW}}\right)^2.$$

$$\rho_{RW} = \frac{v_d}{\omega_{RW}} = \frac{cE_{RW}}{B\omega_{RW}}$$




Trajectory of a particle in homogeneous crossed fields: the magnetic field B and the rotating field $E_{RW}$.

# 3. Mechanism of Charged Particles Accumulation in a PMS Trap with The RW Field

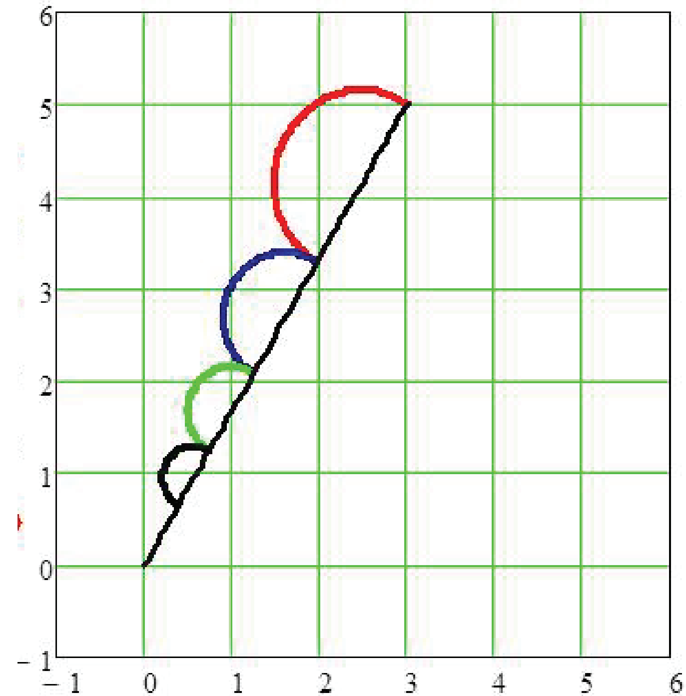
## Particle trajectory in the RW-field region after multiple bounce oscillations

$$\Delta\varphi_{RW} = \omega_{RW} \cdot T_{bounce}$$

$$\Delta\varphi_e = \int_0^{T_{bounce}} \omega_{magn}(t)dt + \omega_{RW}\tau_{RW},$$

$$\Delta\varphi_{RW} = \Delta\varphi_e + 2\pi n$$

$$(\omega_{RW})_{res} = \frac{\int_0^{T_{bounce}} \omega_{magn}(t)dt + 2\pi n}{T_{bounce} - \tau_{RW}}. \quad (*)$$



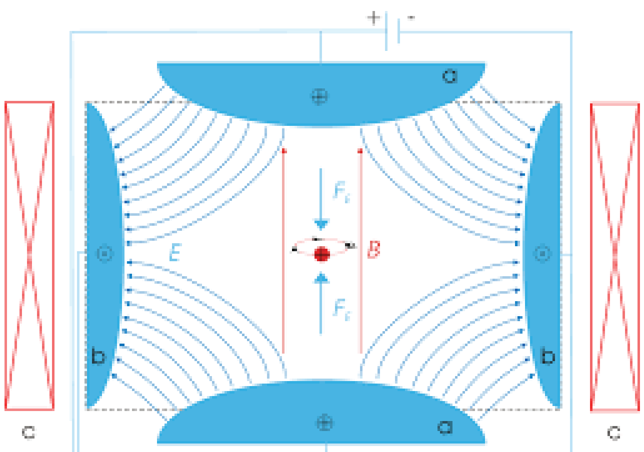

$\Delta s << R_{RW}$, or $\omega_{RW}\tau_{RW} << 1$

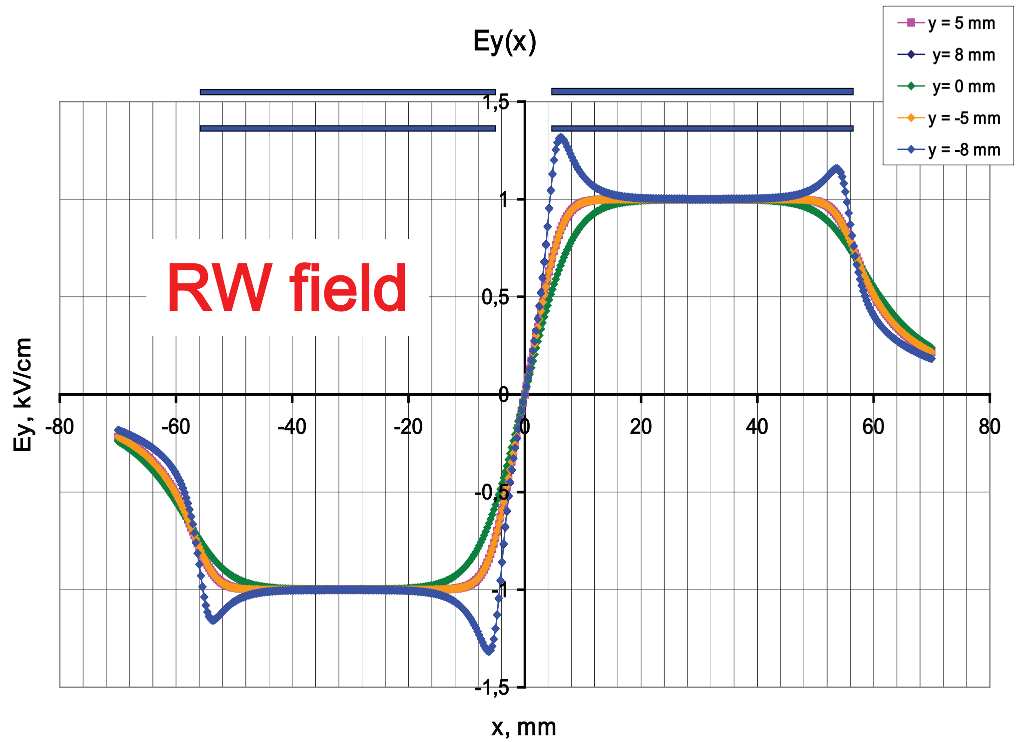
$$(\omega_{RW})_{res} \approx \omega_{magn} = \frac{2\pi nec}{B}$$

# 3. Mechanism of Charged Particles Accumulation in a PMS Trap with The RW Field

## Penning trap (Charlton &Co)

$$\phi(z,r,\theta) = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right) + \frac{m}{q} a z r \cos(\theta + \omega_r t)$$

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# Summary and Outlook

# Summary and Outlook

- The angular velocity of the “magnetized” particle on the circular orbit in the RW field is independent of the particle energy.
- The radius of the trajectory (circle) of the “magnetized” particle in the RW field is proportional to the field strength $E_{RW}$.
- The period of longitudinal oscillations weakly depends on the particle energy due to quasiparabolic form of the potential U(z) of the electric field created by the trap electrodes.
- During their motion in the trap, the particles rotate around the trap axis under the action of crossed fields: the longitudinal magnetic field of the trap solenoid and the radial component of the electric field of the trap electrodes and the space charge of the accumulated particle bunch.
- A 3D resonance occurs if the frequencies of the RW field, magnetron rotation and longitudinal oscillation do meet the resonance condition (slide 16, formula (*)) .
- The nearest plans - to check the proposed mechanism numerical simulation of the process of accumulation of positrons in a PMS trap in different modes.

Our thanks to the staff of the Electron cooling sector LEPTA facility DLNP: A. Kobets, A.A. Sidorin, O.Orlov, E. Ahmanova, L.Soboleva, T.Stepanova and Prof. D. Ovsyanikov, A. Ovsyanikov (SPb State University).

# Thank you for attention!