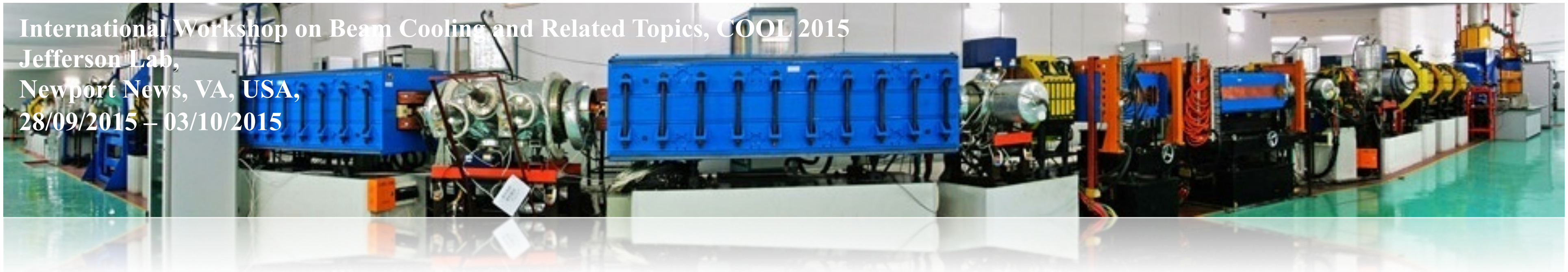



# HIAF Electron Cooling System &

# Space Charge Effects of Cooled Intense Heavy-ion Beams

*L.J. Mao, M.T.Tang, H.Zhao and HIAF design group*
*IMP, Lanzhou China*
*maolijun@impcas.ac.cn*

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

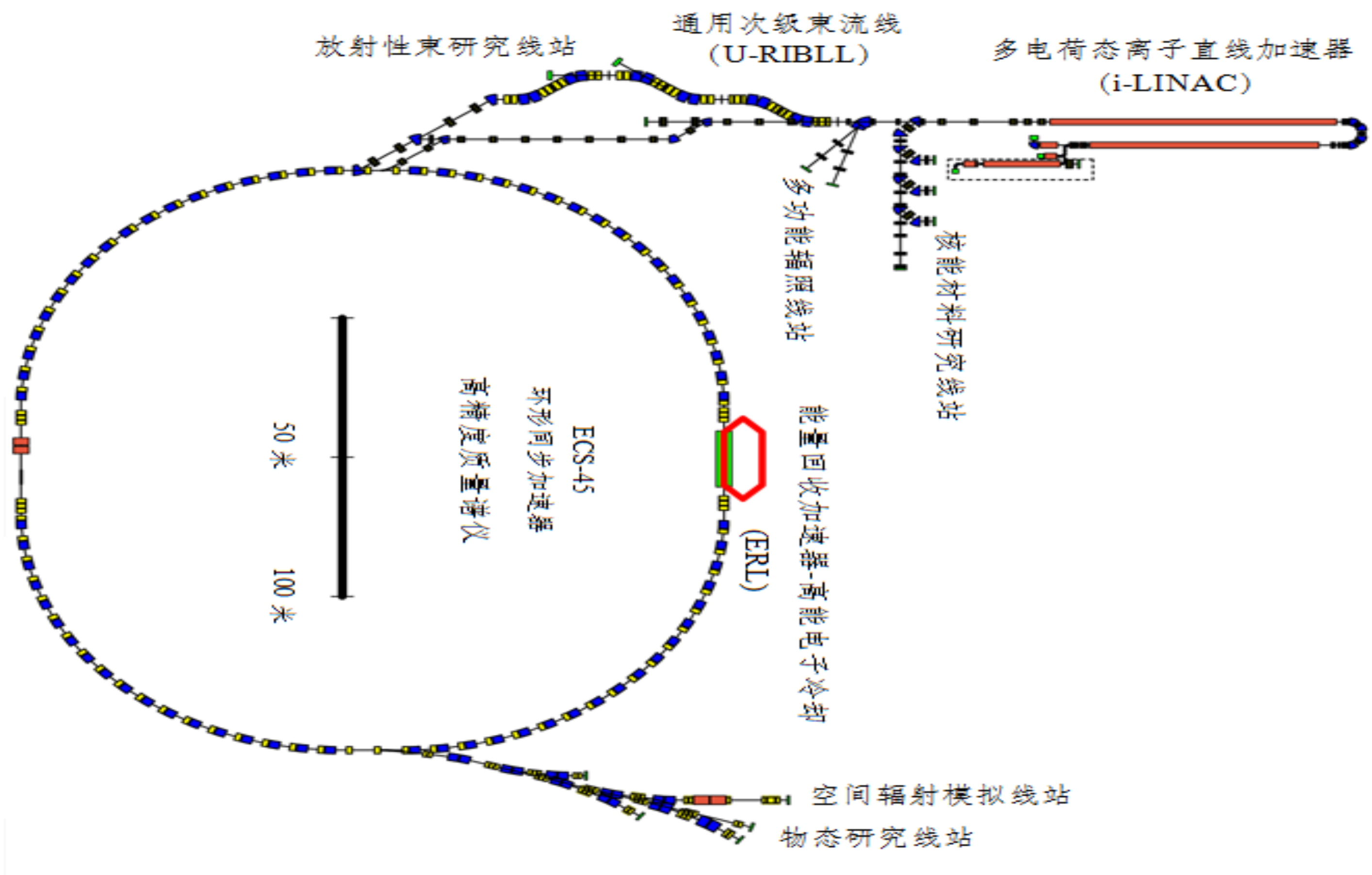
# OUTLINE

- **HISTORY:** The High Intensity heavy-ion Accelerator Facility (HIAF) at IMP Lanzhou
- **MOTIVATION:** Electron Cooling System for HIAF
- **STATUS:** Cooling Effects Simulation Results
- **CHALLENGES:** Instabilities of High Intensity Heavy-ion Beams with Electron Cooling
- **FUTURE:** Questions and Outlook

# HISTORY of HIAF

**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility, **HIAF**

*---12th five-year plan of science and technology in China (2011-2015)*




**11/2009**

## HISTORY of HIAF

**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility, **HIAF**

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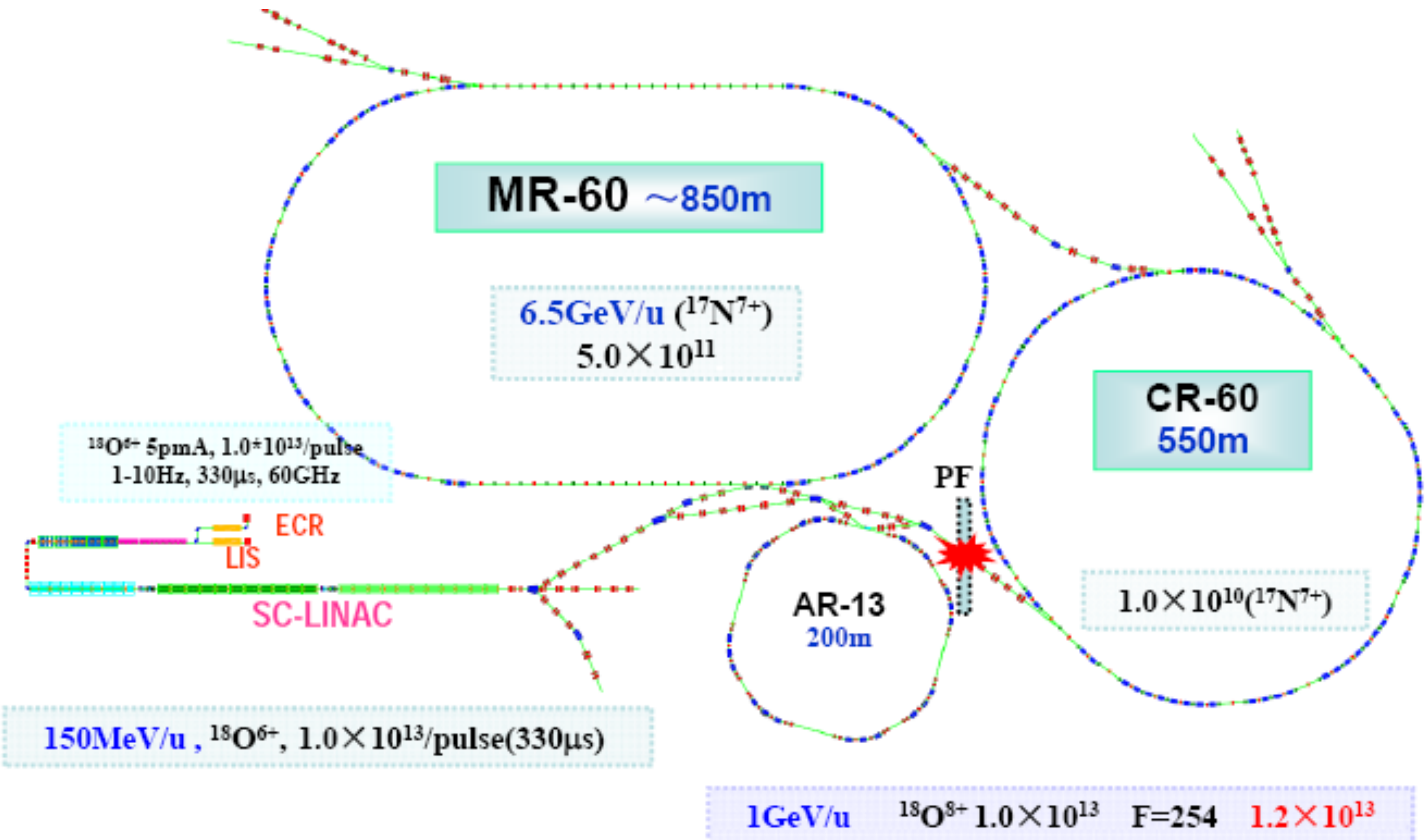
**11/2009 → 04/2012**



## HISTORY of HIAF

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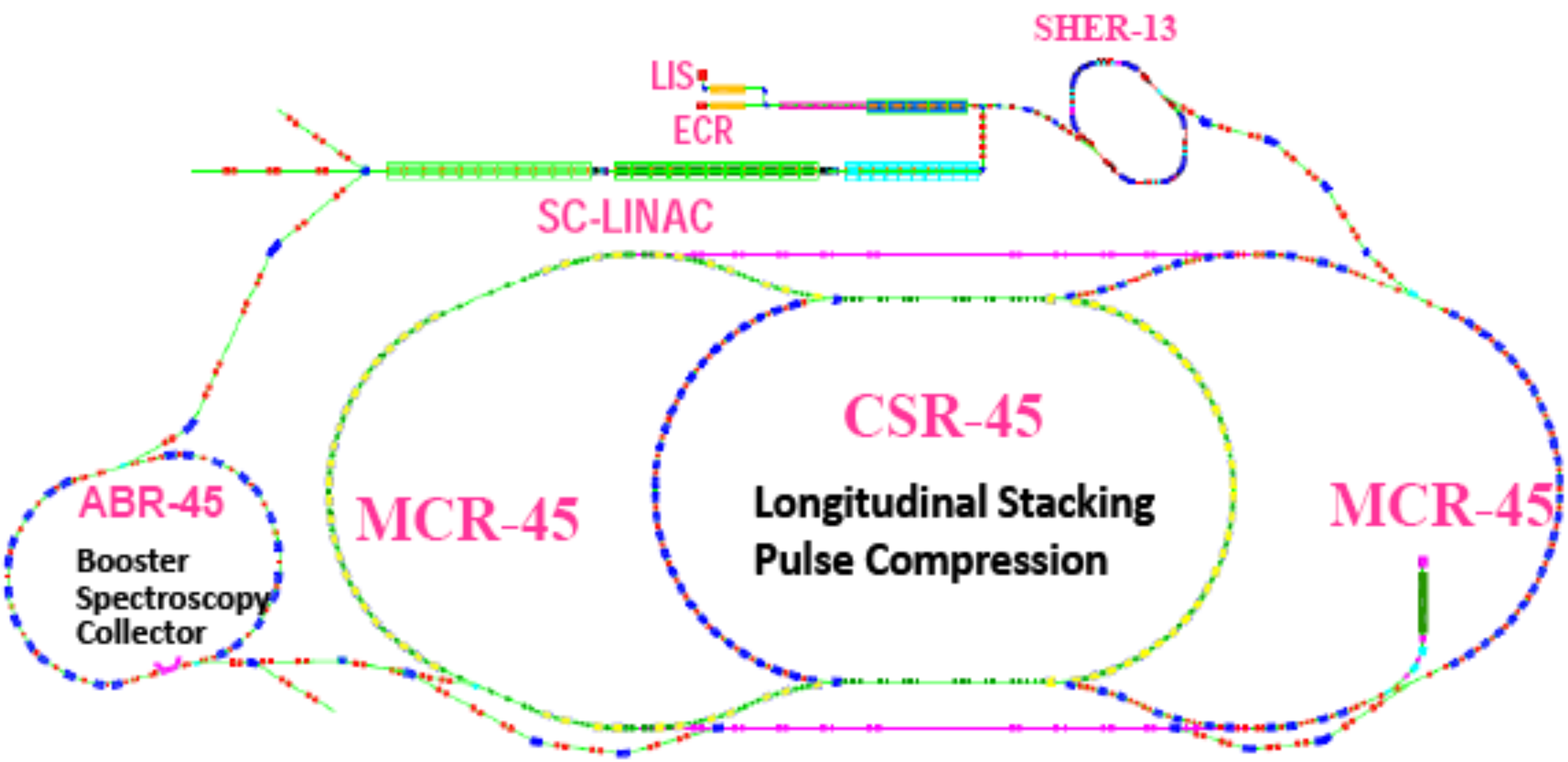


**11/2009**
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**04/2012**
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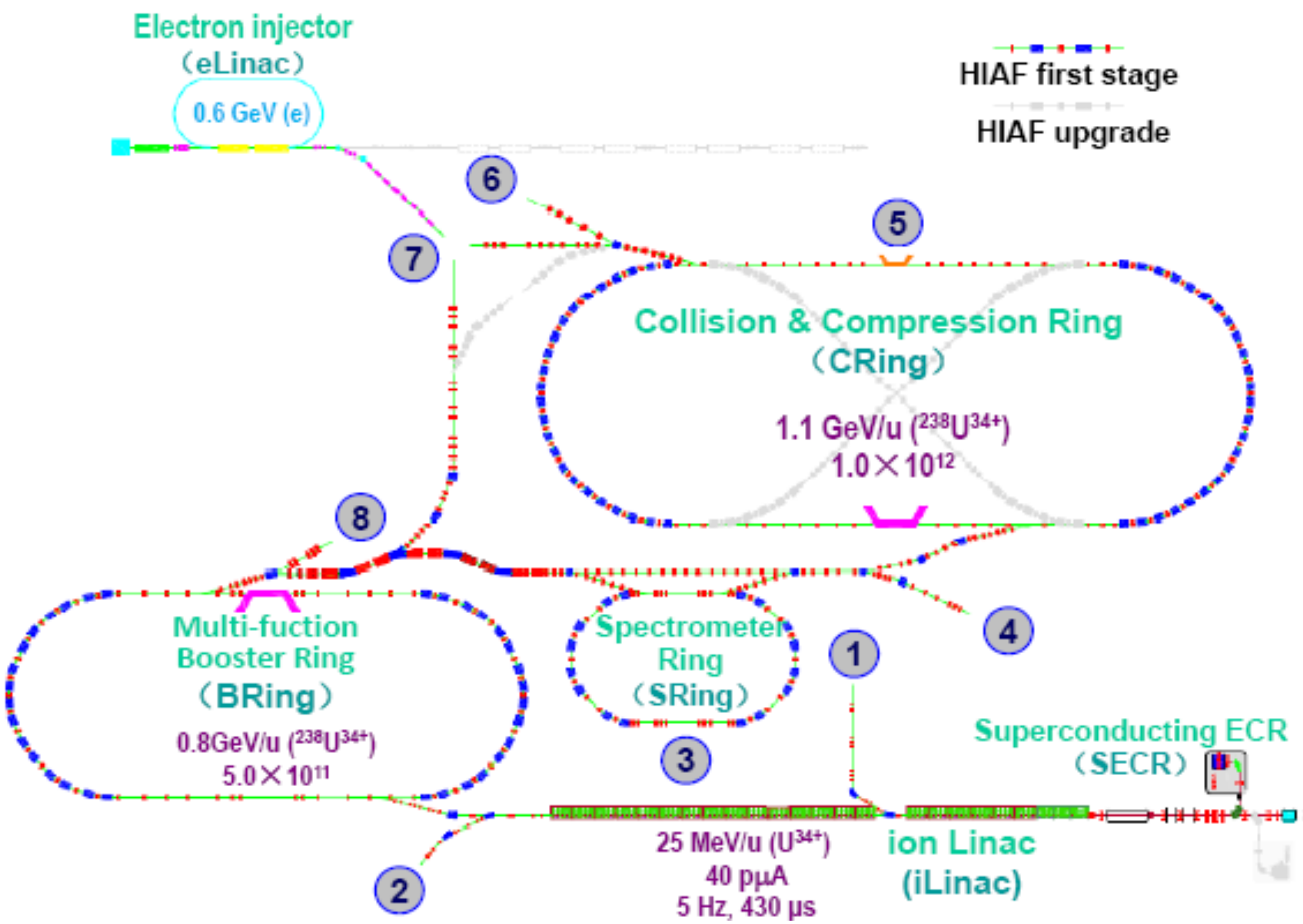
**10/2012**

# HISTORY of HIAF

**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility, **HIAF**

*---12th five-year plan of science and technology in China (2011-2015)*




11/2009

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04/2012

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10/2012

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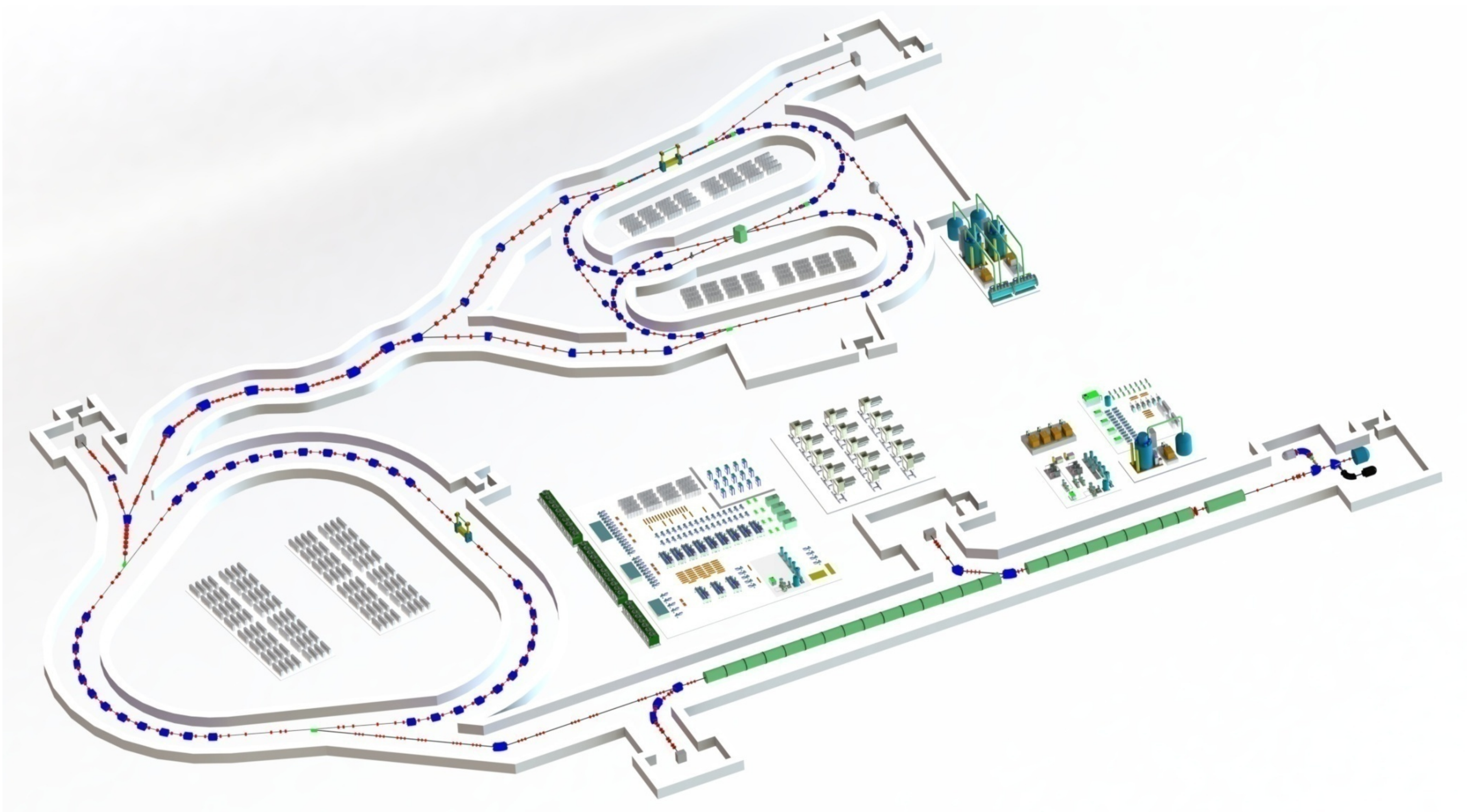
05/2014

## ■ TODAY of HIAF

**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility, **HIAF**

*---12th five-year plan of science and technology in China (2011-2015)*



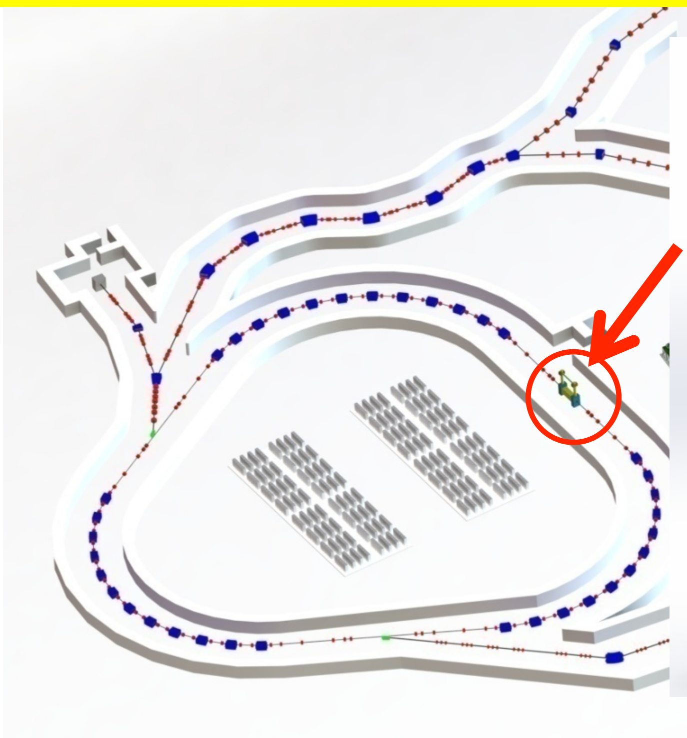
## Motivation of E-Cooling System

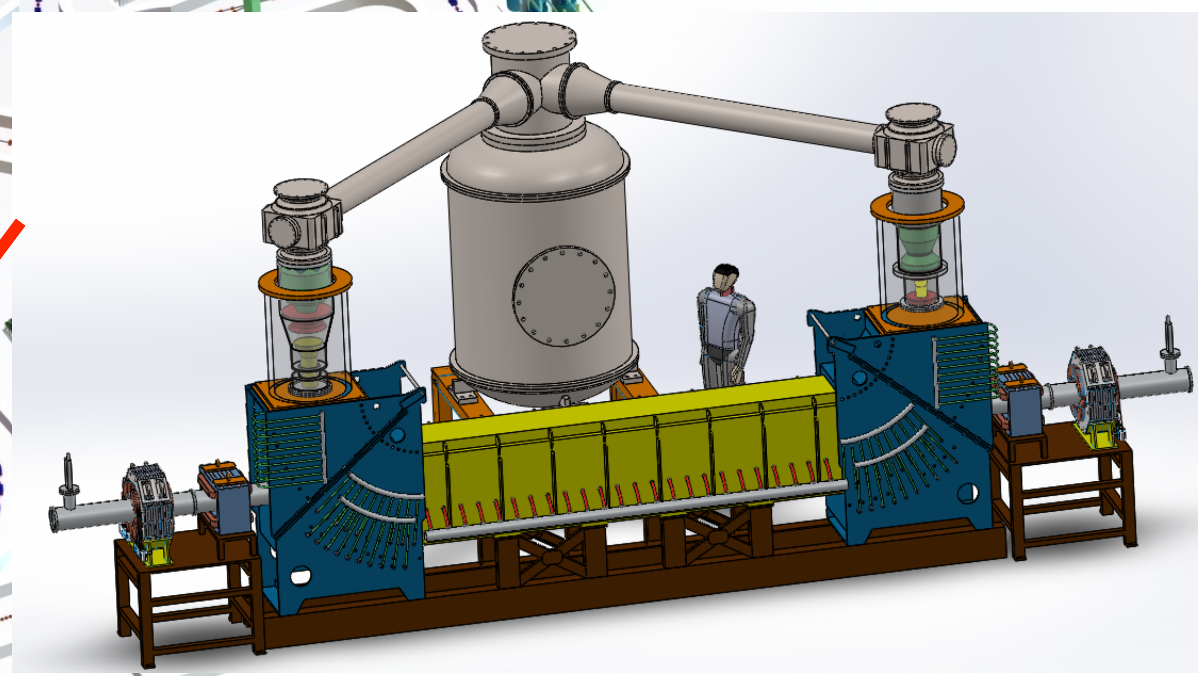
Ions provided by iLinac: 28puA ($U^{34+}$ at the injection energy 17 MeV/u)

Expected particle number in the BRing: $10^{11}$ ($U^{34+}$ at the injection energy 17 MeV/u)

Gain of accumulation: ～70

- Beam accumulation by the combination of E-cooling & two phase painting injection
- Make short bunch at the extraction energy





## COOLING at INJECTION ENERGY

Ion Charge State=34

Mass Number=238

Kinetic Energy (Initial)=17 MeV/u

Kinetic Energy (Final)=800 MeV/u

Electron energy=9.326 keV (@injection energy), 438.871 keV (@ extraction energy)

Electron density=$2.0*10^{7}$ $cm^{-3}$

dp/p (Initial momentum spread, uniform distribution, RMS value)=$\pm 2*10^{-3}$

Initial emittance (uniform distribution, RMS value)= 60 pi.mm.mrad

Beta-function @ the cooling section=15m

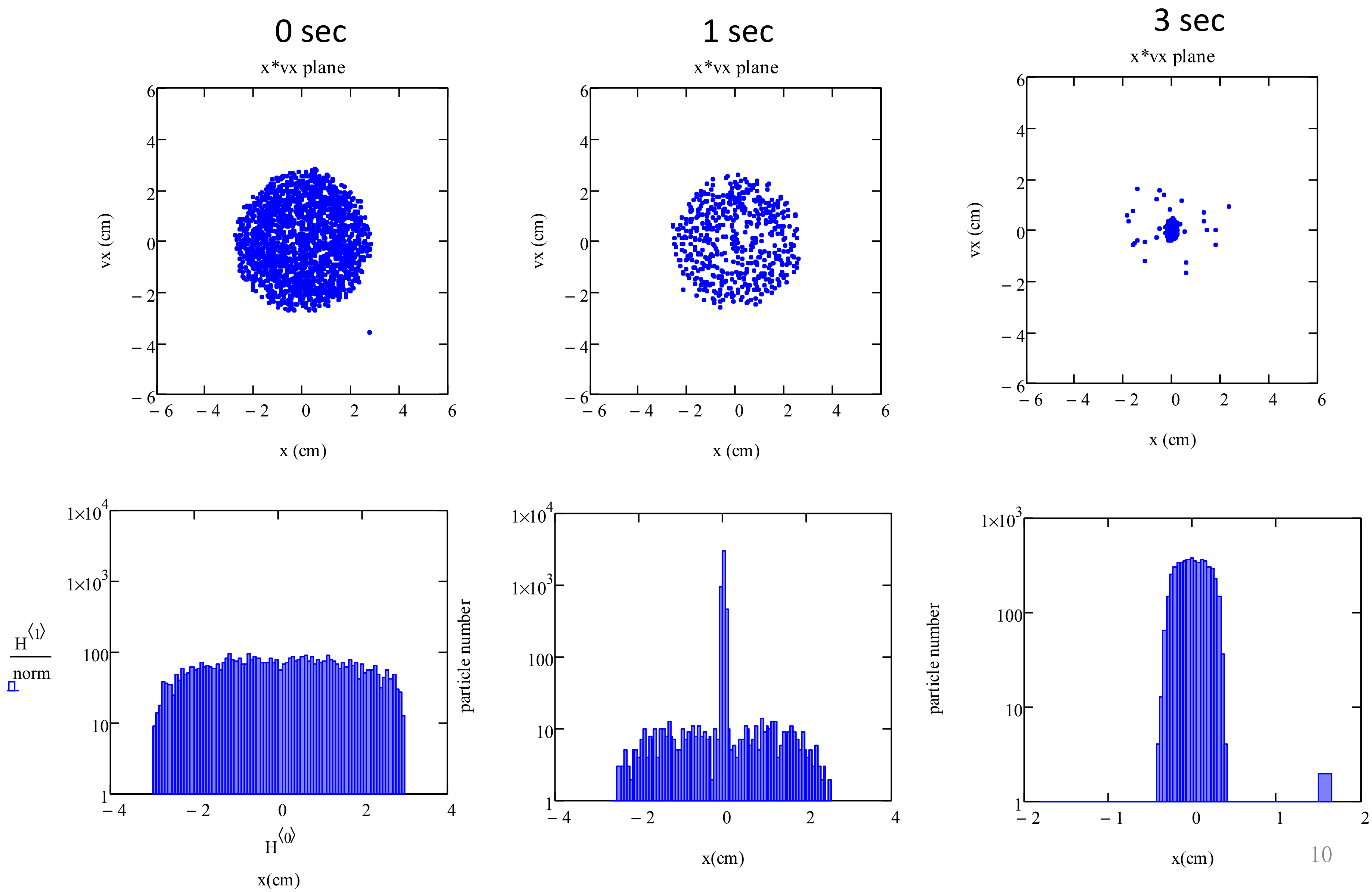
Magnetic field @ the cooling section = 0.2 T

Particle number=$5*10^{10}$

Ring circumference=500m

Cooler length=10 m (2% of ring circumference)

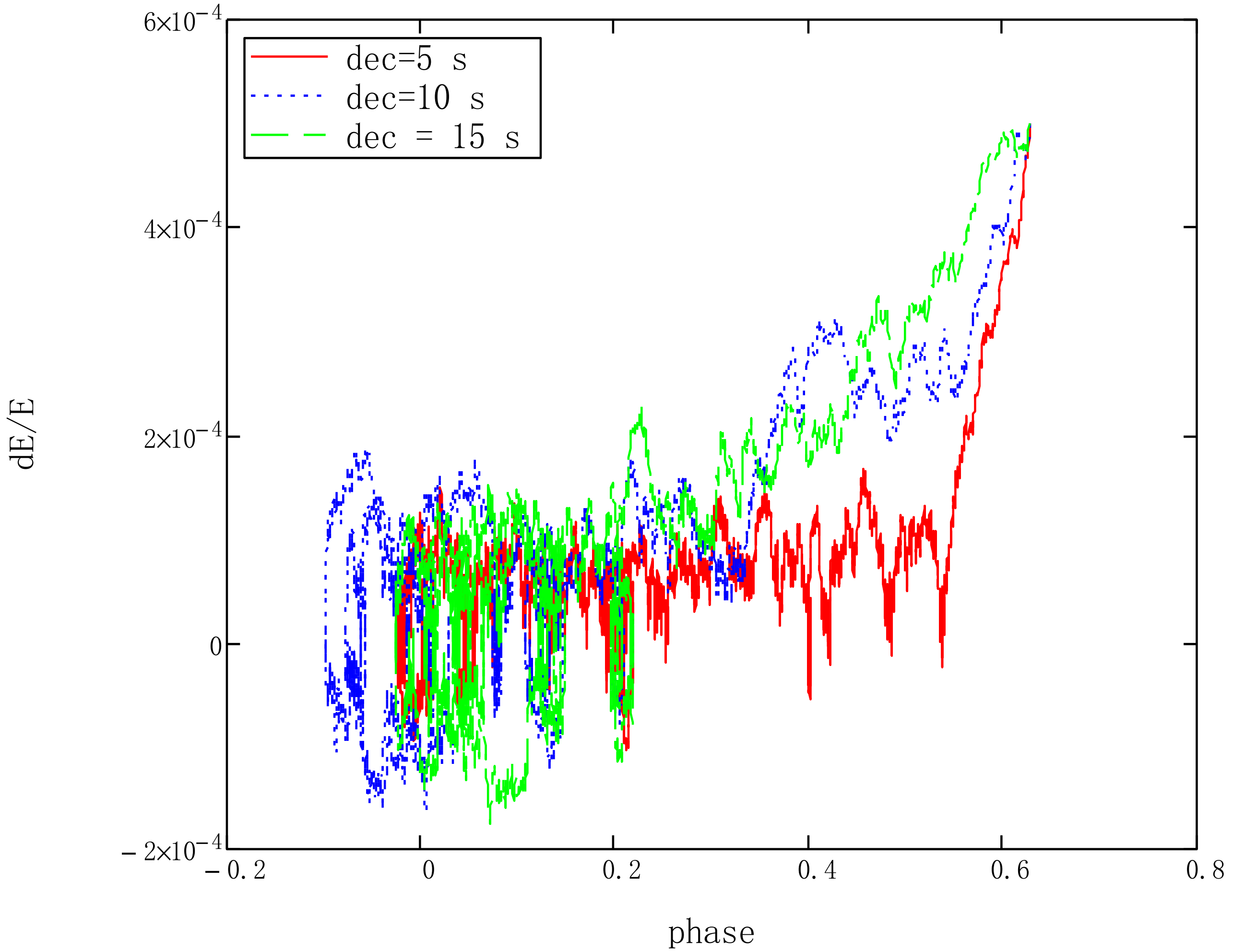
# COOLING at INJECTION ENERGY



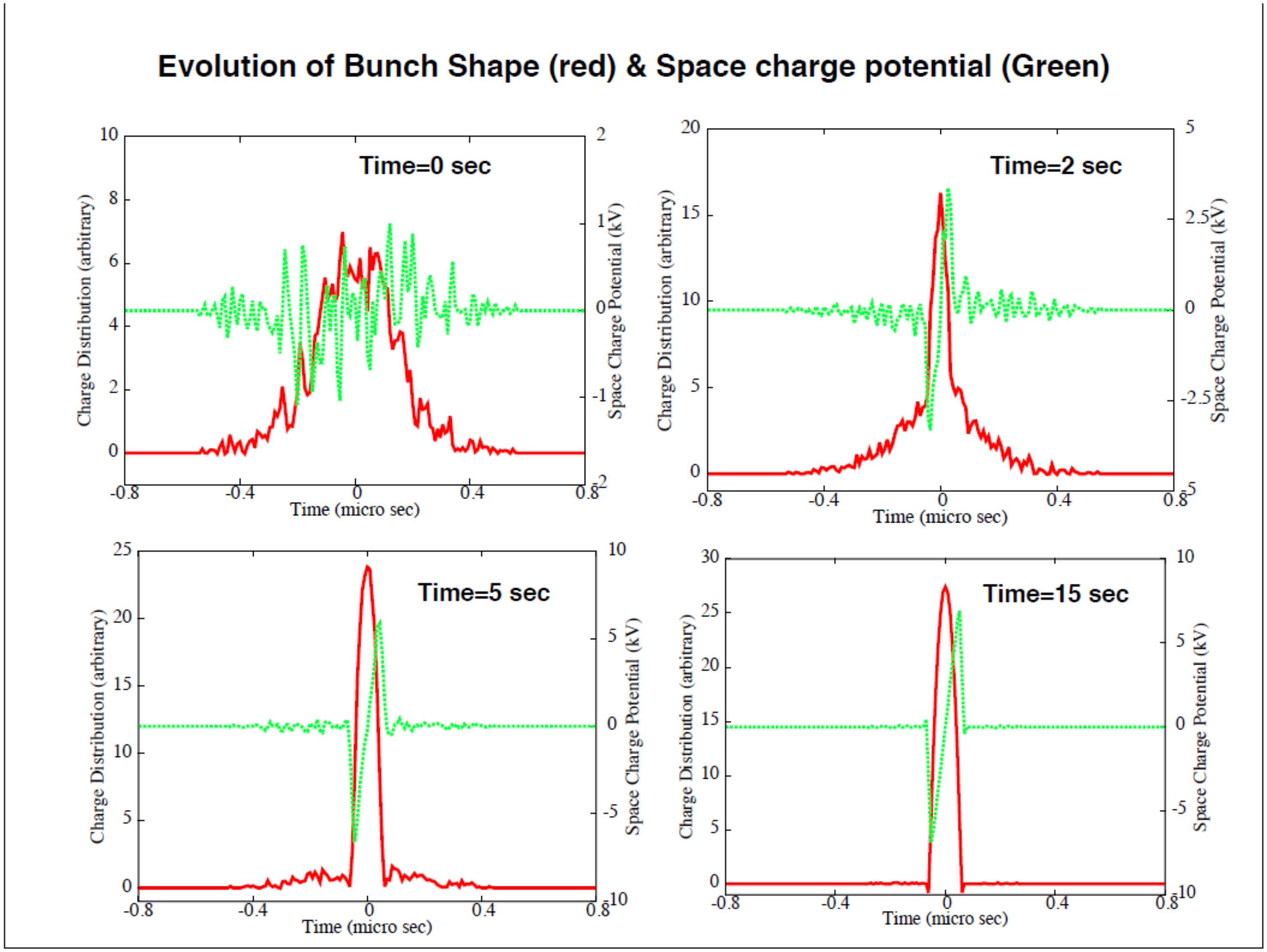
## COOLING at EXTRACTION ENERGY

$$\delta_{j+1} = \delta_j \exp(-\frac{1}{dec}) + \frac{Z \cdot U_{RF}}{A\gamma\beta^2 E_0 10^6}\left(\sin\varphi_j - \sin\varphi_0\right) + \sqrt{dec \cdot \delta_0 \cdot 24}\left(rnd(1) - 0.5\right)$$

$$\varphi_{j+1} = \varphi_j + 2\pi h \eta \delta_{j+1}$$



# COOLING at EXTRACTION ENERGY




---Dr. T.Katayama

## COOLING at EXTRACTION ENERGY

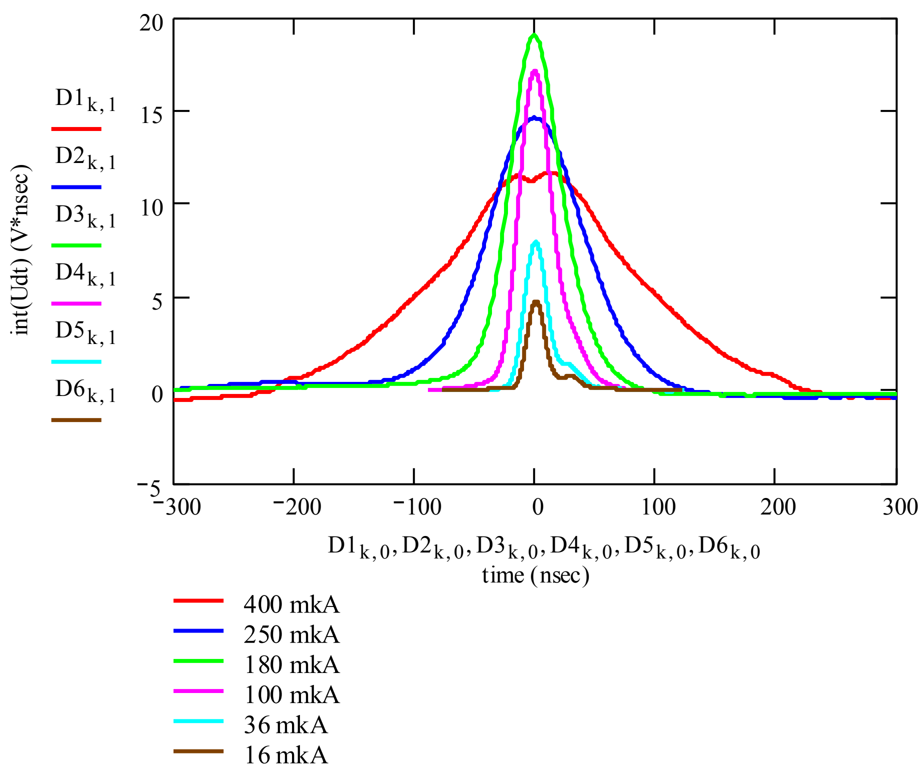
200 MeV/u $C^{6+}$ ions @ CSRe
RF voltage = 1.0 kV,
RF frequency = 1.319 MHz
Ie=300 mA with a expansion factor = 3.0

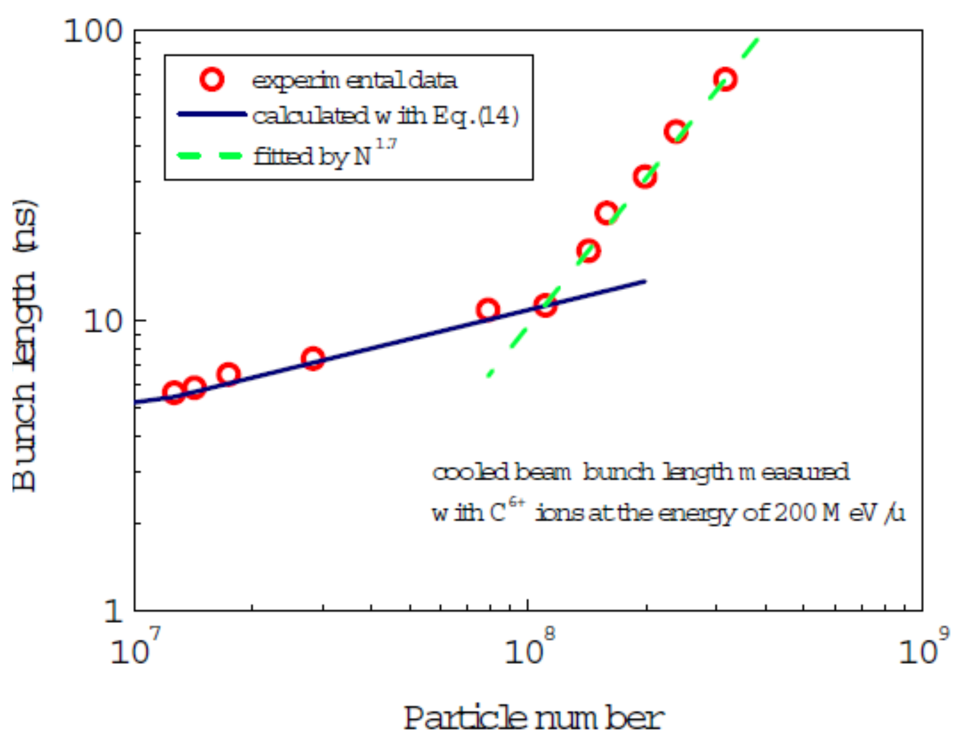
$$U_{RF}(s) = U_0 \sin(\frac{s}{R})$$

$$\Omega_s^2 = \left| \frac{\partial (U_{RF}(s) + U_{sp}(S))}{\partial s} \right|_{s=0}$$

$$U_{sp}(s) = \frac{1}{\gamma^2} \frac{Ze}{4\pi\varepsilon_0} [1 + 2\ln(\frac{b}{a})] \frac{Ns}{\sigma_b^3 \sqrt{2\pi}} \exp(-\frac{s^2}{2\sigma_b^2}) 2\pi R$$

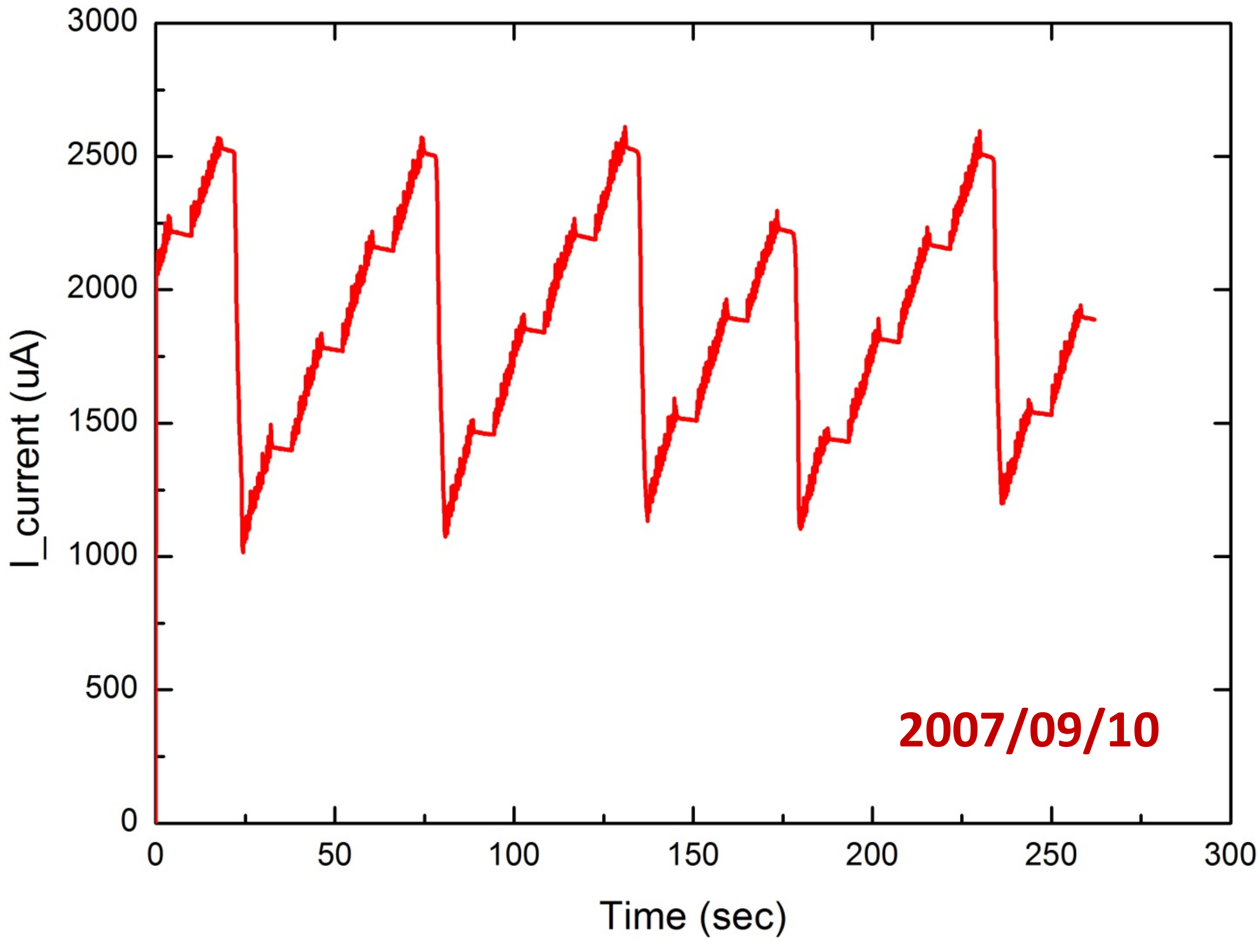
$$\sigma_b^3 - \sigma_b \sigma_{b0}^2 = kN$$



## INSTABILITIES of COOLED BEAM

7.0 MeV/u $C^{6+}$ ions was injected with e-cooling continually, particle loss directly around 2.5 mA and the intensity of the beam is limited $10^{10}$



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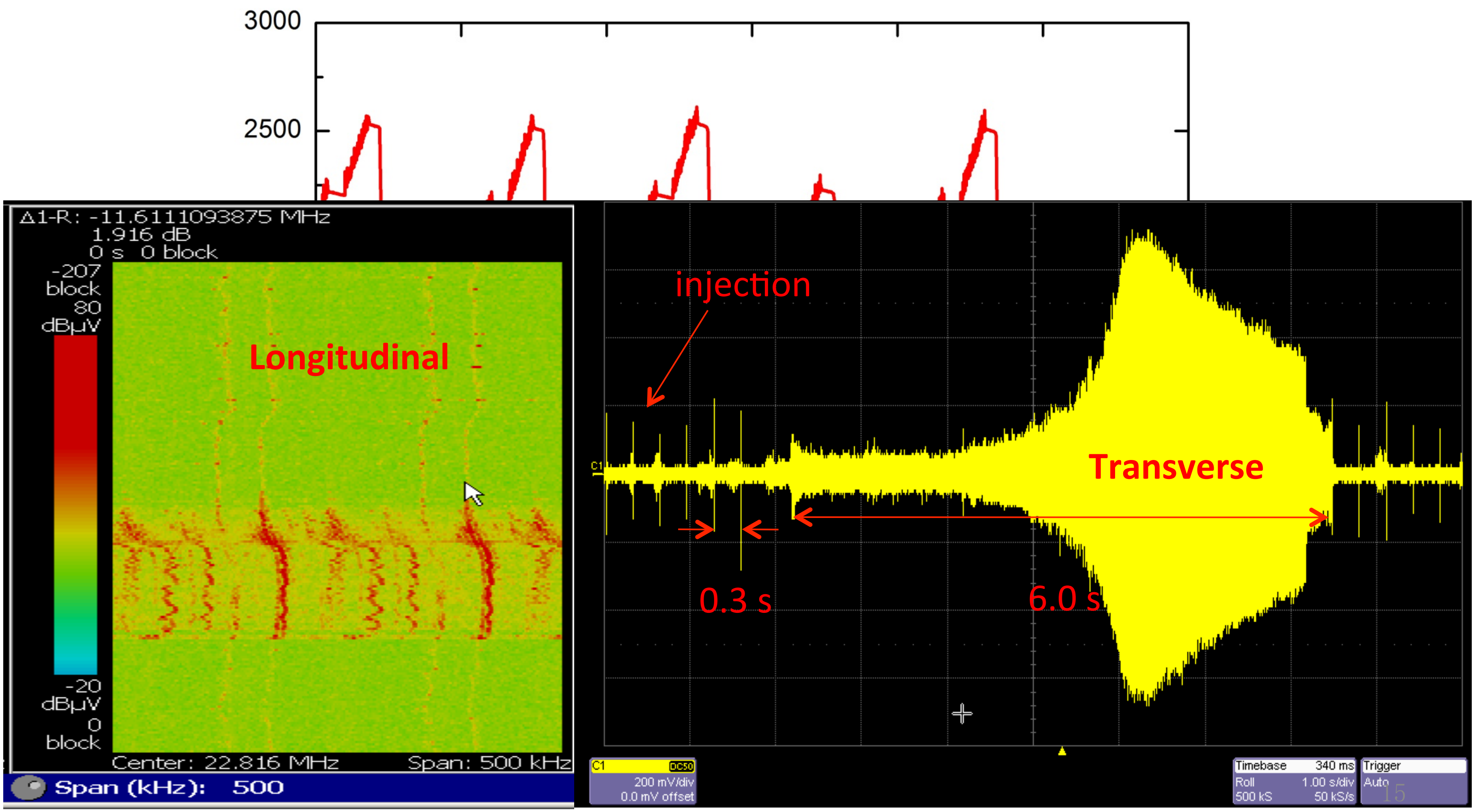


# INSTABILITIES of COOLED BEAM

Overview of intensities of cooled ion beams around the world

| Ring | Ion | Energy (MeV/u) | I_ion (mA) | Nunber |
|---|---|---|---|---|
| SIS | $Kr^{34+}$ | 11 | 5 | 5E09 |
| CELSIUS | $H^{+}$ | 45 | 1 | 6E09 |
| TSR | $C^{6+}$ | 73.3 | 18 | 3.0E10 |
| TSR | $H^{+}$ | 21 | 2.4 | 1.4E10 |
| TSR | $Au^{50+}$ | 695 | 0.003 | 1.0E06 |
| CSRm | $C^{6+}$ | 7 | 6.5 | 3.0E10 |
| CSRm | $Xe^{27+}$ | 2.9 | 0.5 | 1.0E08 |
| CSRe | $C^{6+}$ | 660 | 15 | 1.0E10 |
| COSY | $H^{+}$ | 45 | 9.2 | 1.2E11 |
| | | | | |

# INSTABILITIES of COOLED BEAM

**Space Charge Limitation of an electron-cooled proton beam**

sities of cooled ion beams around the world

| Ring | Ion | | | Nunber |
|---|---|---|---|---|
| SIS | $Kr^{34+}$ | | | 5E09 |
| CELSIUS | $H^{+}$ | 45 | 1 | 6E09 |
| TSR | | | | |
| TSR | | | | |
| TSR | Au | 695 | 0.003 | 1.0E06 |
| | | | 6.5 | 3.0E10 |
| | | | | |
| | | | | |
| COSY | $H^{+}$ | 45 | | |
| | | | | |

Stability of cooled beams

J. Bosser, C. Carli, M. Chanel, N. Madsen, S. Maury, D. Möhl*, G. Tranquille

*CERN, CH 1211 Geneva 23, Switzerland*

**TRANSVERSE FEEDBACK SYSTEM FOR THE COOLER SYNCHROTRON COSY-JÜLICH – FIRST RESULTS**

V. Kamerdzhiev, J. Dietrich, I. Mohos, Forschungszentrum Jülich GmbH, Germany

Electron drift instability in storage rings with electron cooling

A. Burov

**Stability limits of cooled beams**

Parkhomchuk V.V.

BINP, Novosibirsk-90, Russia

**Workshop on “Beam Cooling and Related Topics”**

**255,WE-Heraeus-Seminar**

**14-18 May 2001**

Resonances driven by the Electric Field of the Electron Cooler

V. Ziemann

The Svedberg Laboratory

## SPACE CHARGE EFFECT of E-BEAM

**Linear tune shift due to the space charge effect of e-beam**

$$I_e = \rho \pi r_e^2 \beta c$$

$$r_e = 30\mathrm{mm}$$

$$E_k = 17\mathrm{MeV/u}$$ $U^{34+}$ ions

$$\gamma = 1.018, \beta = 0.188$$

$$I_e = 1.0\mathrm{A}$$

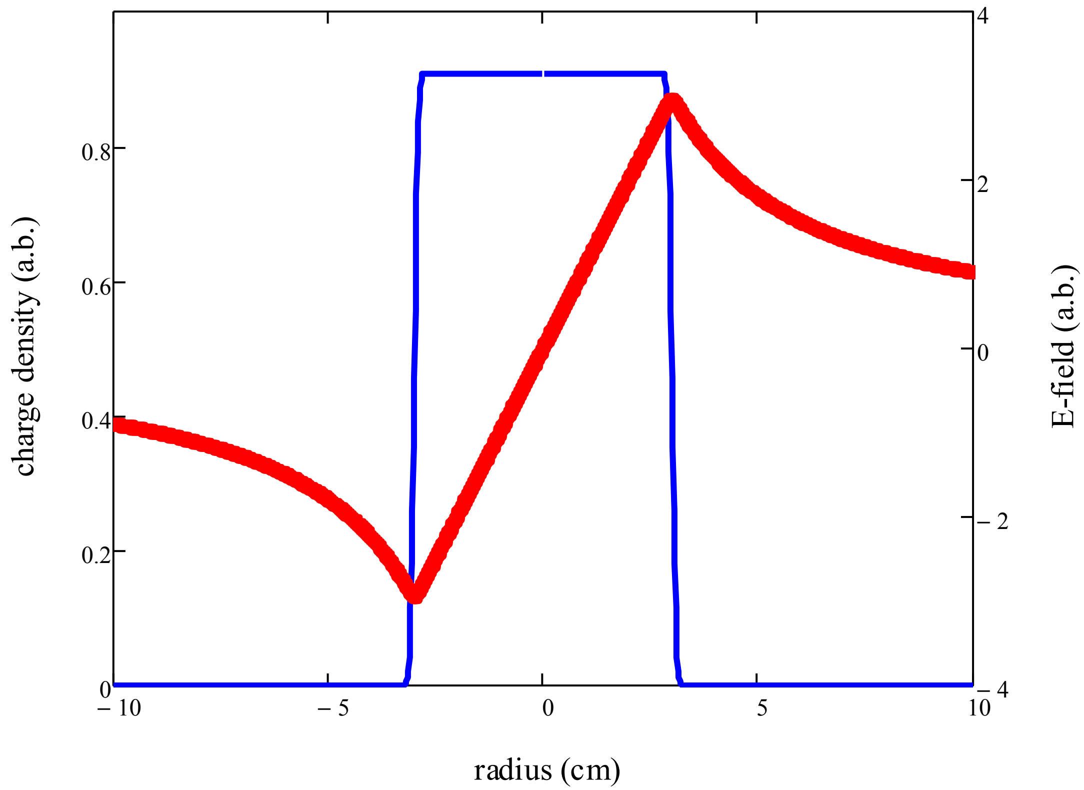
$$\rho = 6.3\times10^{-6}\,\mathrm{C/m^3}$$

$$E(r) = \frac{\rho r}{2\varepsilon_0} = 3.5\times10^5\, r(\mathrm{mm})\frac{\mathrm{mV}}{\mathrm{m}}$$

$$\Delta pc = ZeE(r)L_{cooler} / \beta$$

$$\Delta x' = \Delta p / p_0 = r / f$$

$$\Delta \nu = \beta_x / 4\pi f = 0.012 I_e / A$$




charge density & space charge field vs. radius

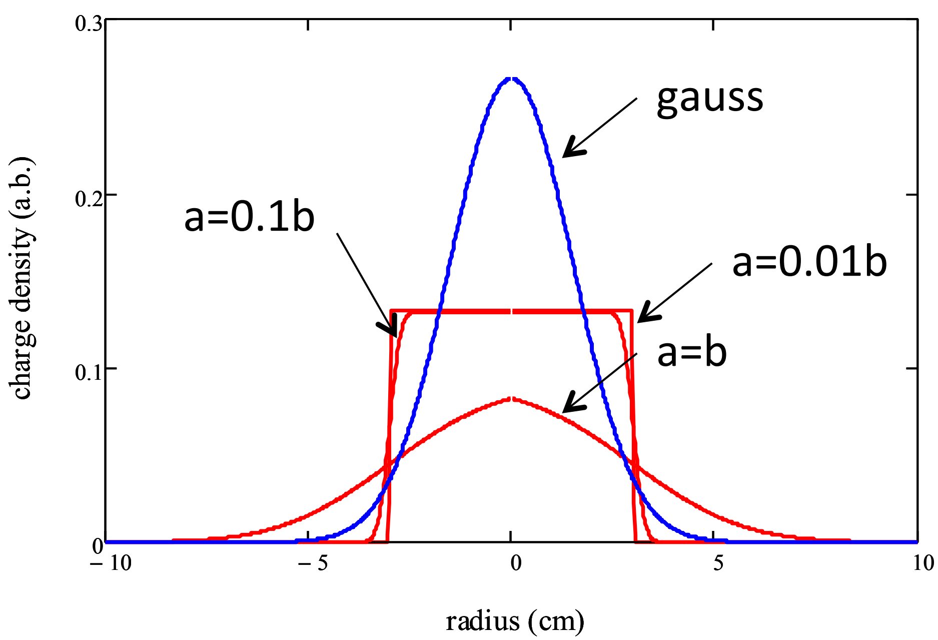
# SPACE CHARGE EFFECT of E-BEAM

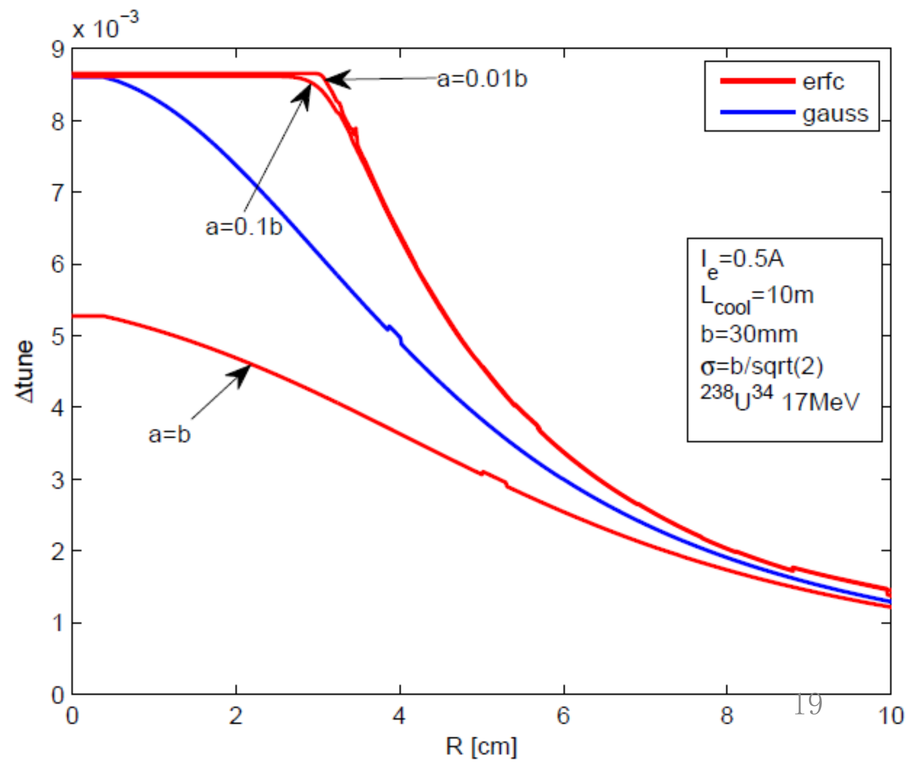
**Electron beam distribution written by error function**

$$\psi(r) = erfc\left(\frac{r-b}{a}\right)$$

$$\Delta v_x(\varepsilon) = \frac{2\xi}{\sqrt{\varepsilon_x \beta_x}} \int_0^{2\pi} \frac{d\varphi}{2\pi} \cos\phi S\left(\sqrt{\varepsilon_x \beta_x} \cos\phi\right)$$

$$\frac{d^2\eta}{d\theta^2} + v^2\eta = -4\pi v \xi S(\eta)\delta_p(\theta)$$



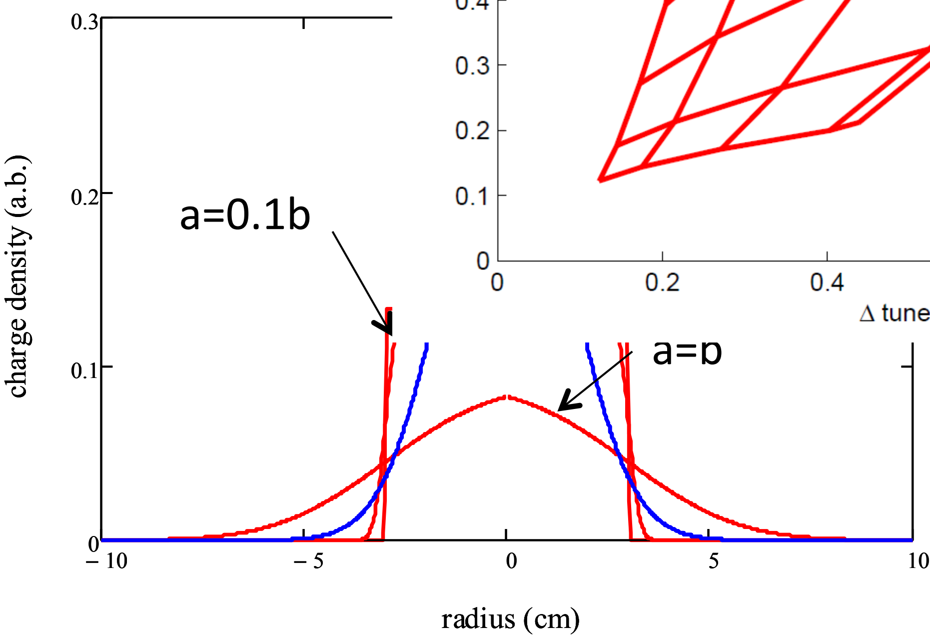
## SPACE CHARGE EFFECT of E-BEAM

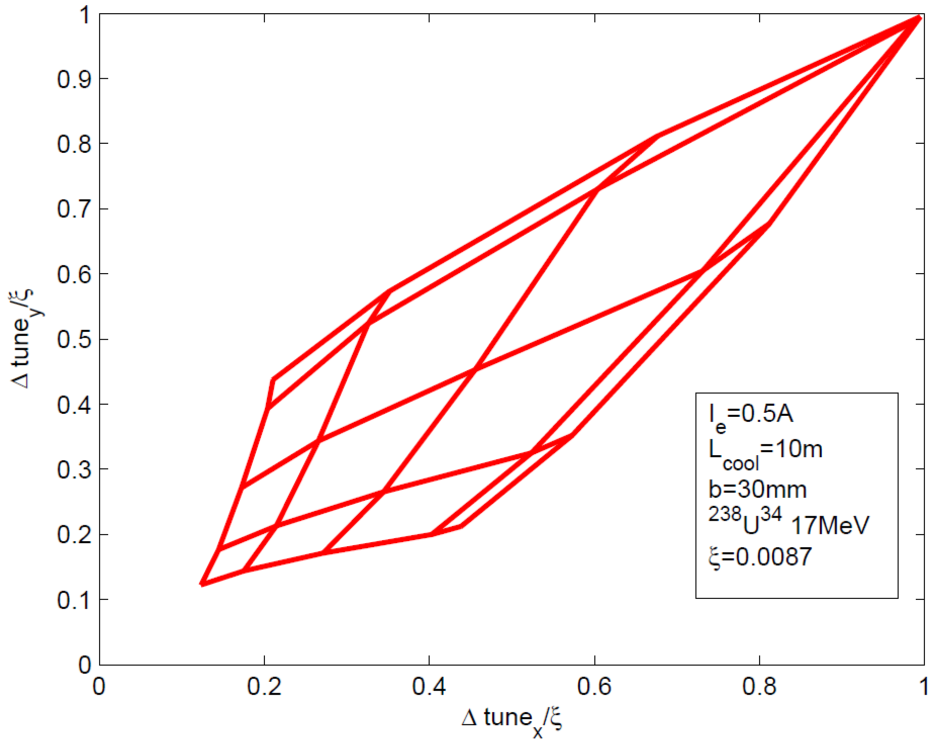
**Electron beam distribution written by error function**

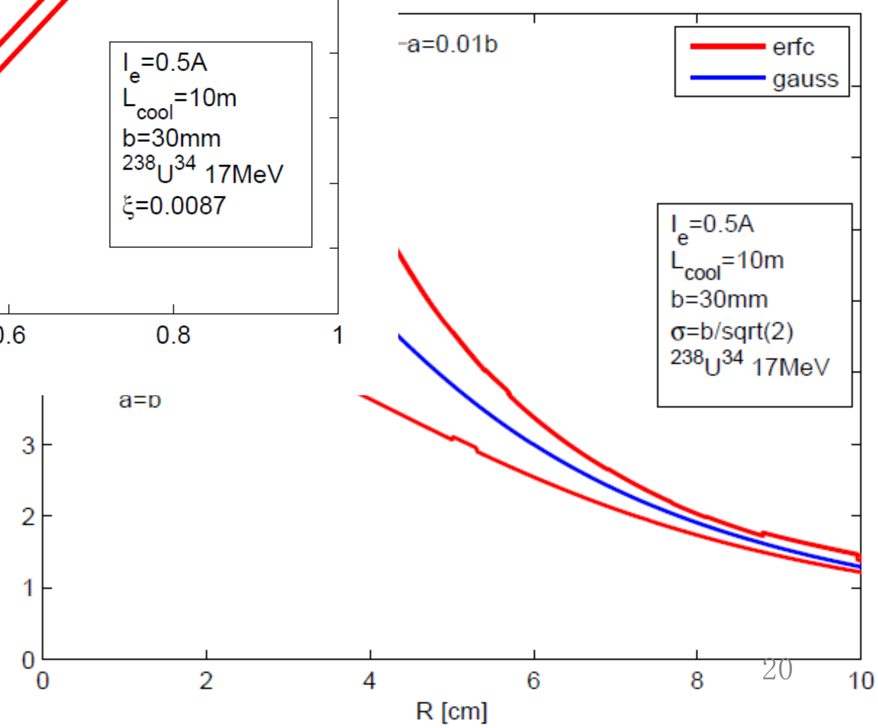
$$\psi(r) = erfc\left(\frac{r}{-} \quad b\right)$$

$$\cos\phi S\left(\sqrt{\varepsilon_x \beta_x}\cos\phi\right)$$

$$\frac{d^2\eta}{d\theta^2} + \nu^2\eta = -$$



## SPACE CHARGE EFFECT of E-BEAM

**Single particle tracking**

$$dd = 4\pi \frac{\xi}{\mathrm{N}} E(x_i)$$ Kick of space charge field of e-beam

$$dx_i = \underline{dx_i \exp\left(-\frac{1}{damping}\right)} - dd$$ Damping (cooling) turn by turn

$$x_{i+1} = \cos(2\pi v_x) x_i + \beta_x \sin(2\pi v_x) dx_i$$

$$dx_{i+1} = -x_i \frac{\sin(2\pi v_x)}{\beta_x} + \cos(2\pi v_x) dx_i$$

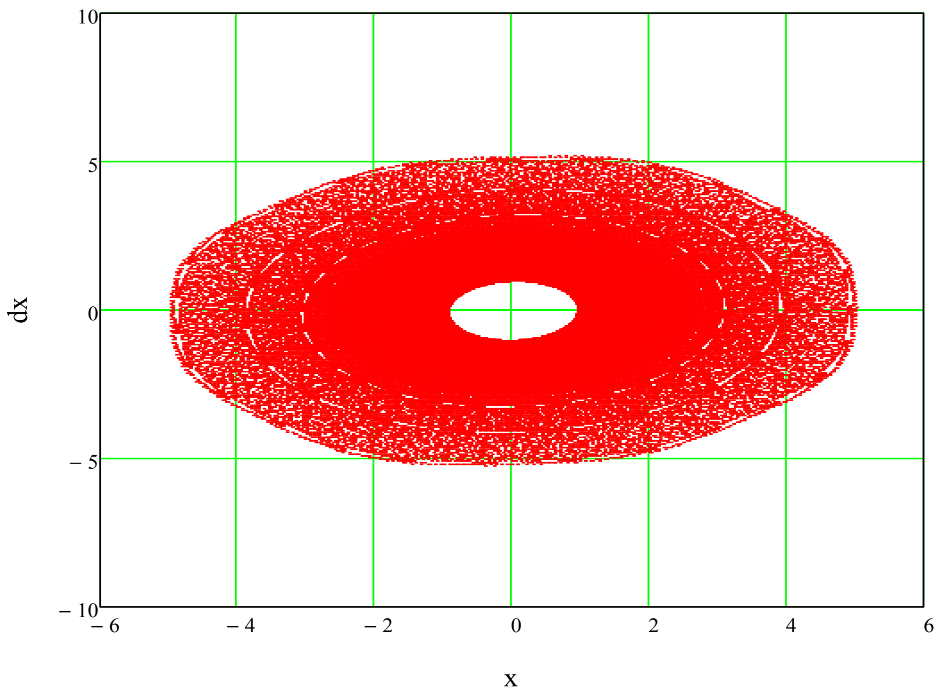
Betatron motion in the ring

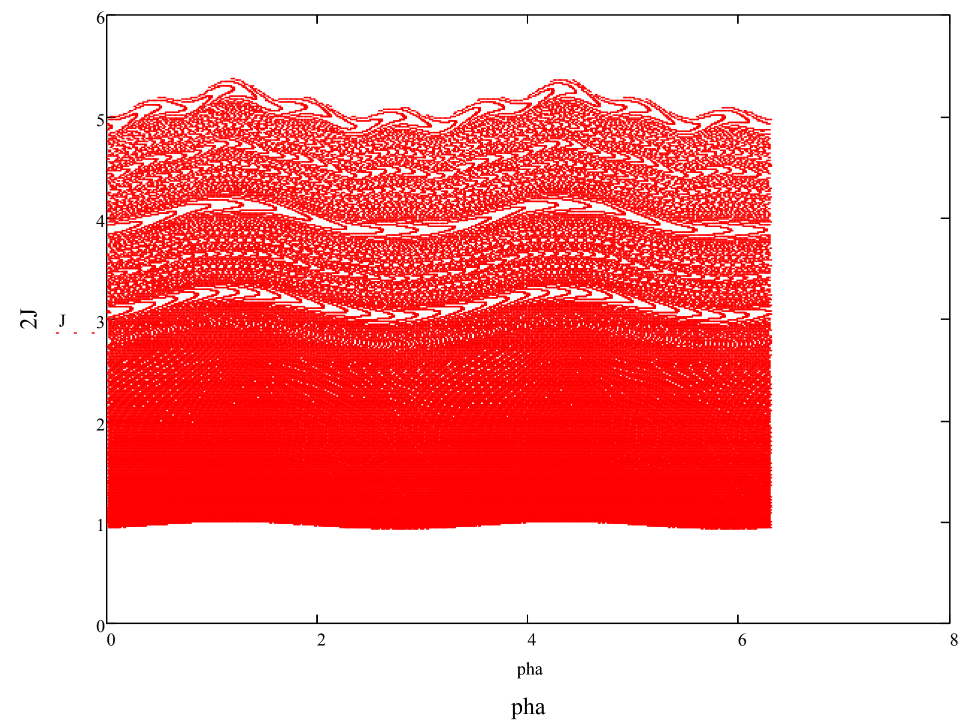
$\xi = 0.01 \qquad x_0 = 4.5cm \qquad v = 0.625$

## Single particle tracking

$$dd = 4\pi \frac{\xi}{\mathrm{N}} E(x_i)$$ Kick of space charge field of e-beam

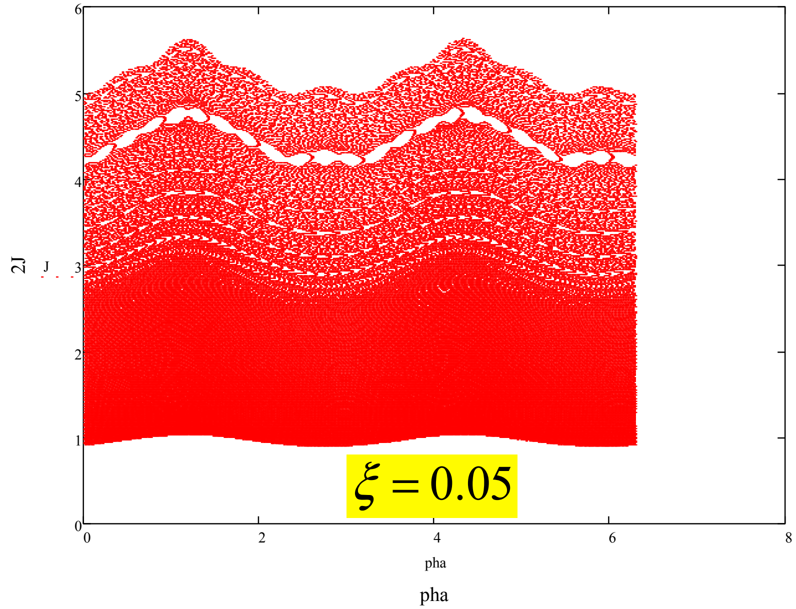
$$dx_i = \underline{dx_i \exp\left(-\frac{1}{damping}\right)} - dd$$ Damping (cooling) turn by turn

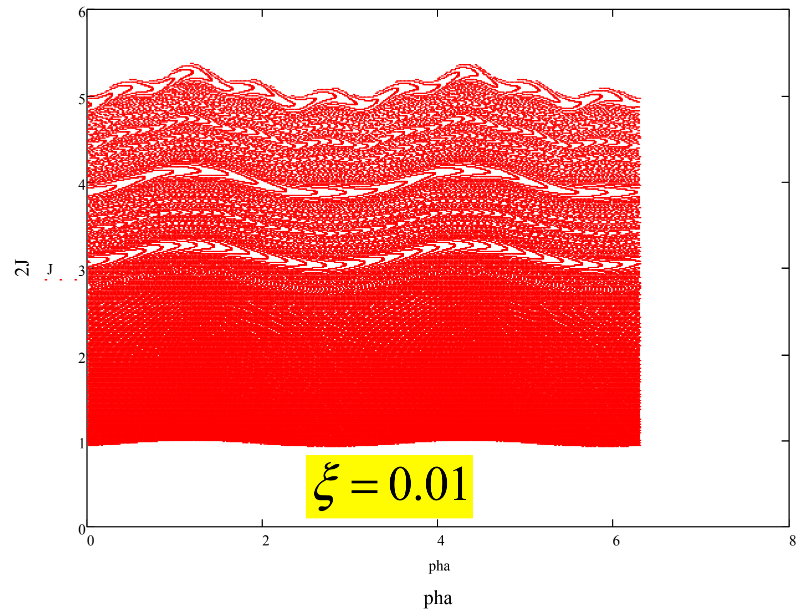


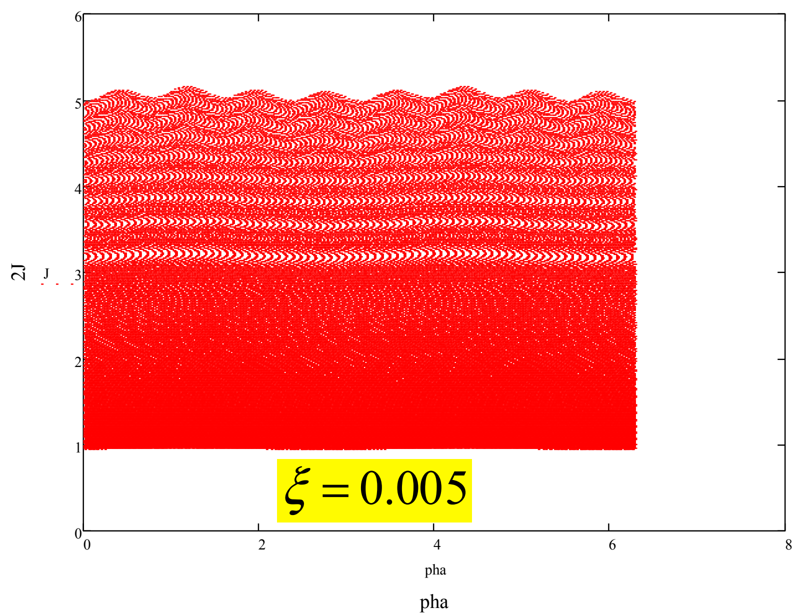



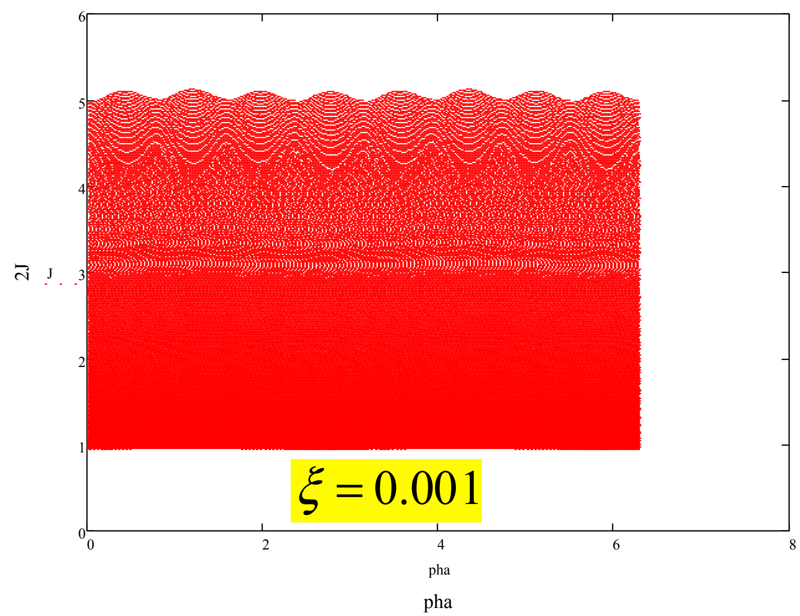

$\xi = 0.01$ $x_0 = 4.5cm$ $\nu = 0.625$

## Dependences on the e-beam current

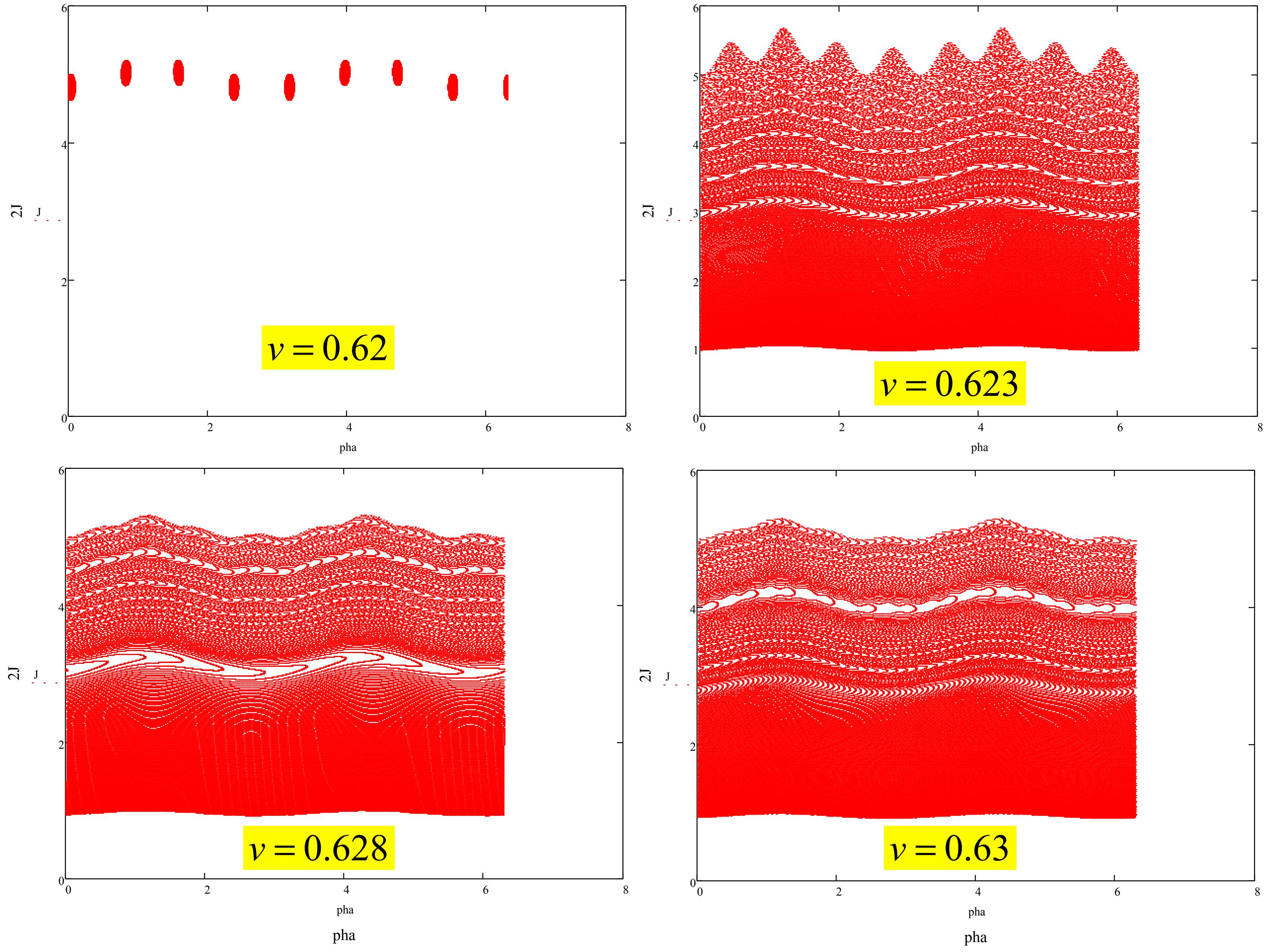


## Dependences on the tune value

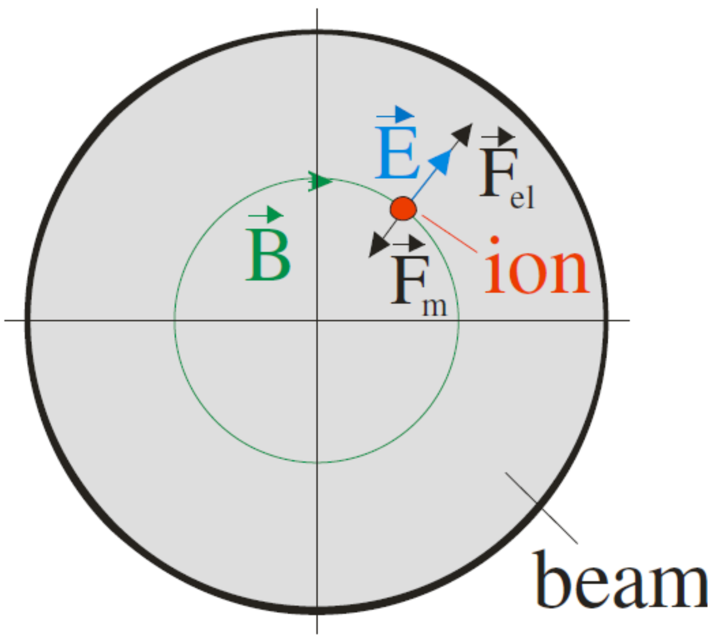


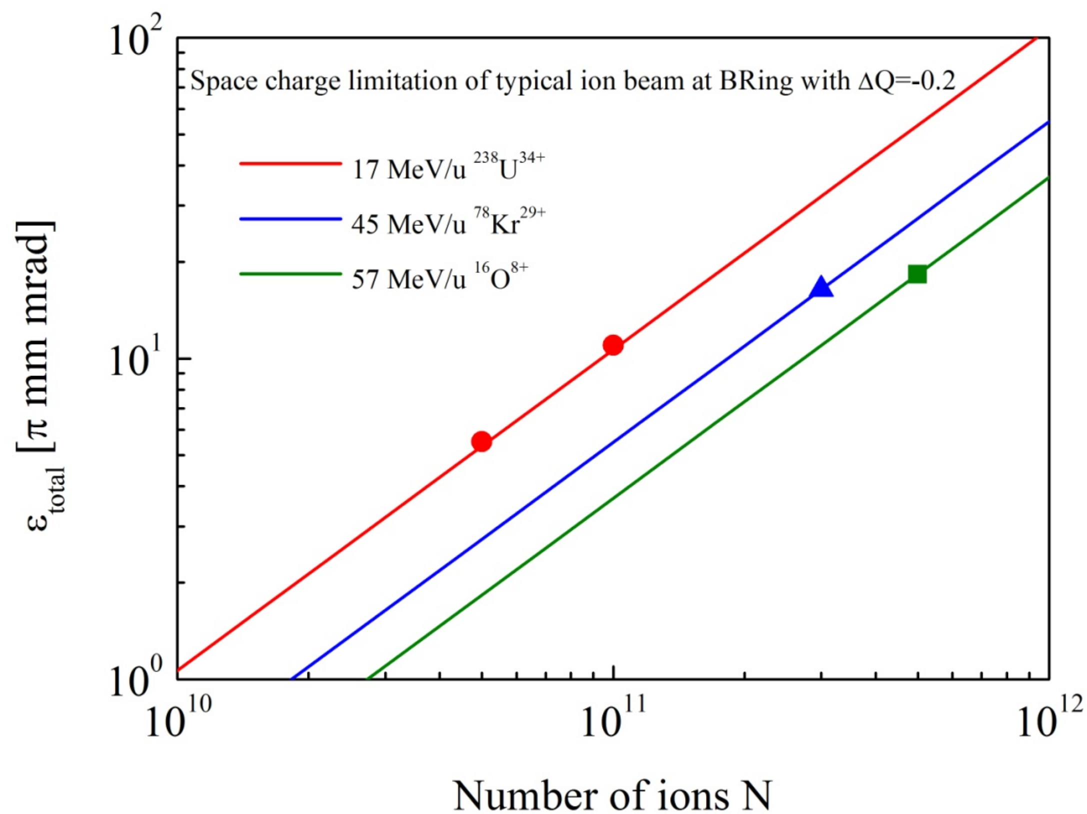
# SPACE CHARGE EFFECT of ION-BEAM

**Incoherent tune shift (Laslett tune shift)**

$$F(r) = (1-\beta^2)\rho e^2 \frac{r}{2\varepsilon_0}$$

$$N = B_f \frac{A}{Z^2}\frac{2\pi}{r_p}\gamma^3\beta^2\varepsilon_x(-\Delta Q)$$



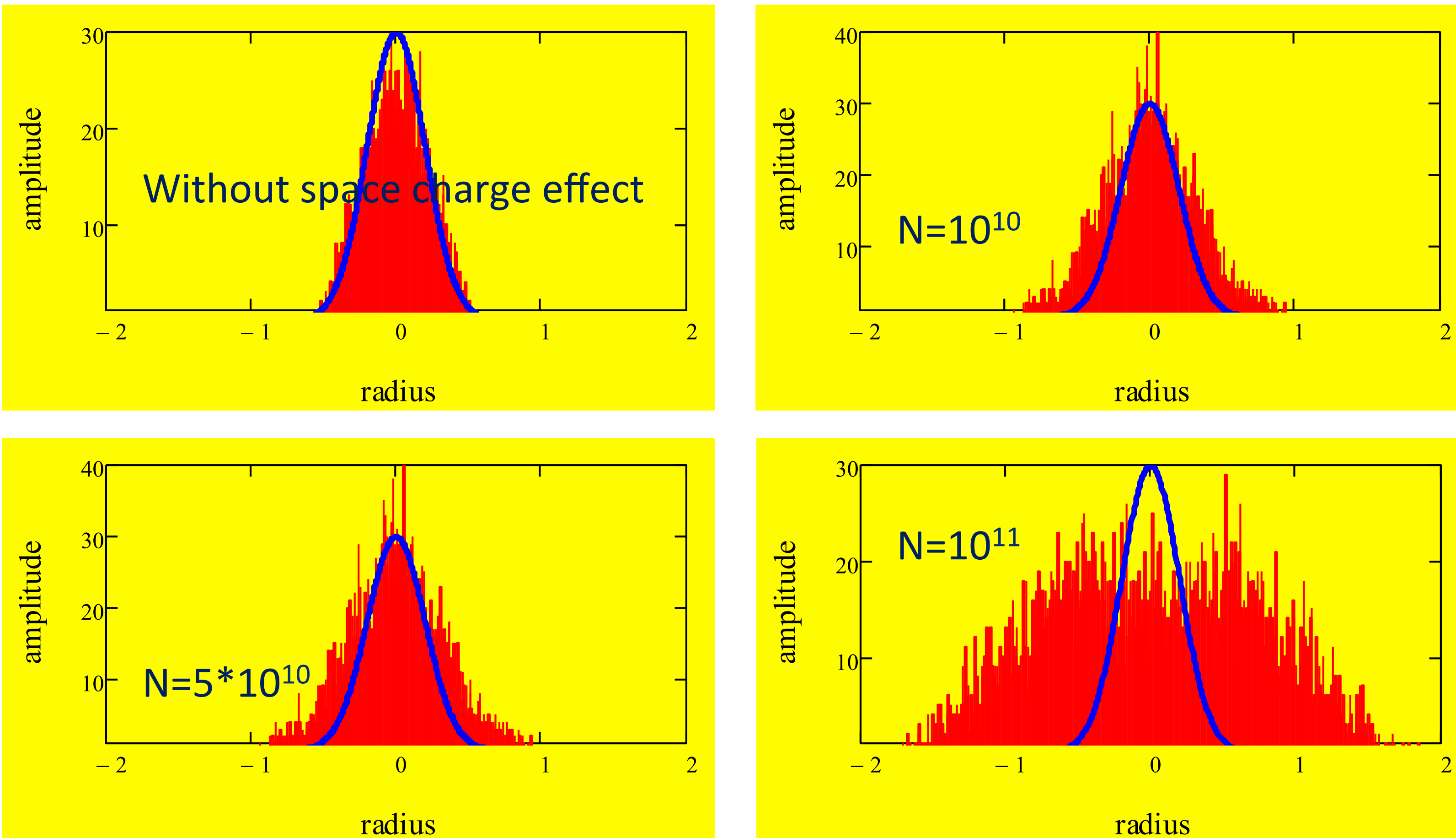



## SPACE CHARGE EFFECT of ION-BEAM

**Single particle tracking**

$$dx_{i+1} = dx_i - dec \cdot dx_i + \sqrt{dec \times dx_0^2}\,(rnd - 0.5)$$ Cooling & heating

$$dd = 4\pi \frac{\xi}{\mathrm{N}} E(x_i)$$ Kick of space charge field of ion beam



## COOLING FORCE LIMITATION

**From Parkhomchuk's idea, the cooling force limitation by intensity beams is:**

$$n_i n_e < \frac{\beta^4 \gamma^6}{l_{cool}^4 (4\pi)^2 r_i r_e} \frac{6}{Lc} \approx 2.5 \times 10^{10} \left(1/\mathrm{cm}^6\right)$$

$$n_i \approx 10^3 - 10^4 \left(1/\mathrm{cm}^3\right)$$

$$l_{cool} = 10m \qquad Ring = 500m \qquad Lc \approx 10$$

**$U^{34+}$ at the injection energy of 17 MeV/u, stored particle number:**

$n_i \approx 3 \times 10^{10}$ **For ion beam emittance (total) is about 10 pi.mm.mrad**

## ■ CONCLUSION and OUTLOOK

- ☐ An e-cooling system is considered to install in the booster ring of the HIAF project, in order to increase the accumulation gain factor at the injection energy, and make a short bunch at the extraction energy.
- ☐ A classical magnetized electron cooler can provide a fast beam cooling effect at the injection energy.
- ☐ A short bunch length is achieved by using the RF and E-cooling system. The final bunch length is determined by RF voltage and space charge effect.
- ☐ The space charge field of the e-beam can make a linear tune shift, a non-linear tune spread and resonance islands for the beam with large size.
- ☐ The space charge effect of ion beam is to limit the final emittance of cooled intense beams.
- ☐ According to Parkhomchuk's formula, the cooling force is limited by the ion beam density.

# Thanks for your attention!