EXPERIMENTAL APPROACH TO ULTRA-COLD ION BEAM AT S-LSR

Presented by

Akira Noda

Institute for Chemical Research, Kyoto University

at

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Collaborators

T. Shirai, H. Souda, M. Tanabe, H. Tongu, M. Ikegami, T. Ishikawa, M. Nakao,

ICR, Kyoto University, UJi-city, 611-0011, Kyoto, Japan

H. Fadil、M. Grieser

MPI Kernphysik, Heidelberg, D-69029, Germany

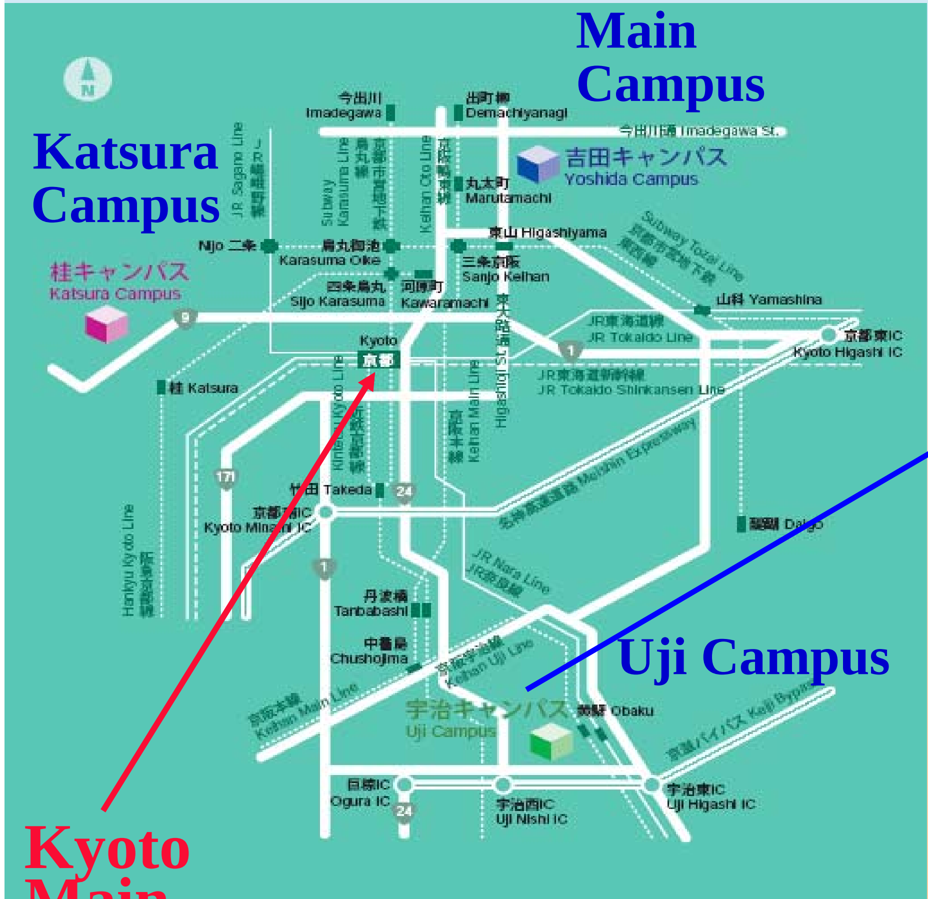
I. Meshkov, A. Smirnov, J

JINR, Dubna, Moscow region, 141980, Russia

K. Noda,

NIRS, Inage-ku, Chiba-city, Chiba, 263-8555, Japan

Campus of Kyoto University



Kyoto Main Station

Uji Campus

Accelerator Building of
Advance Research Center for Beam Science

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1. Outline of S-LSR

2. Electron Beam Cooling of 7 MeV Proton Beam
   Phase Transition to 1 D Ordered State

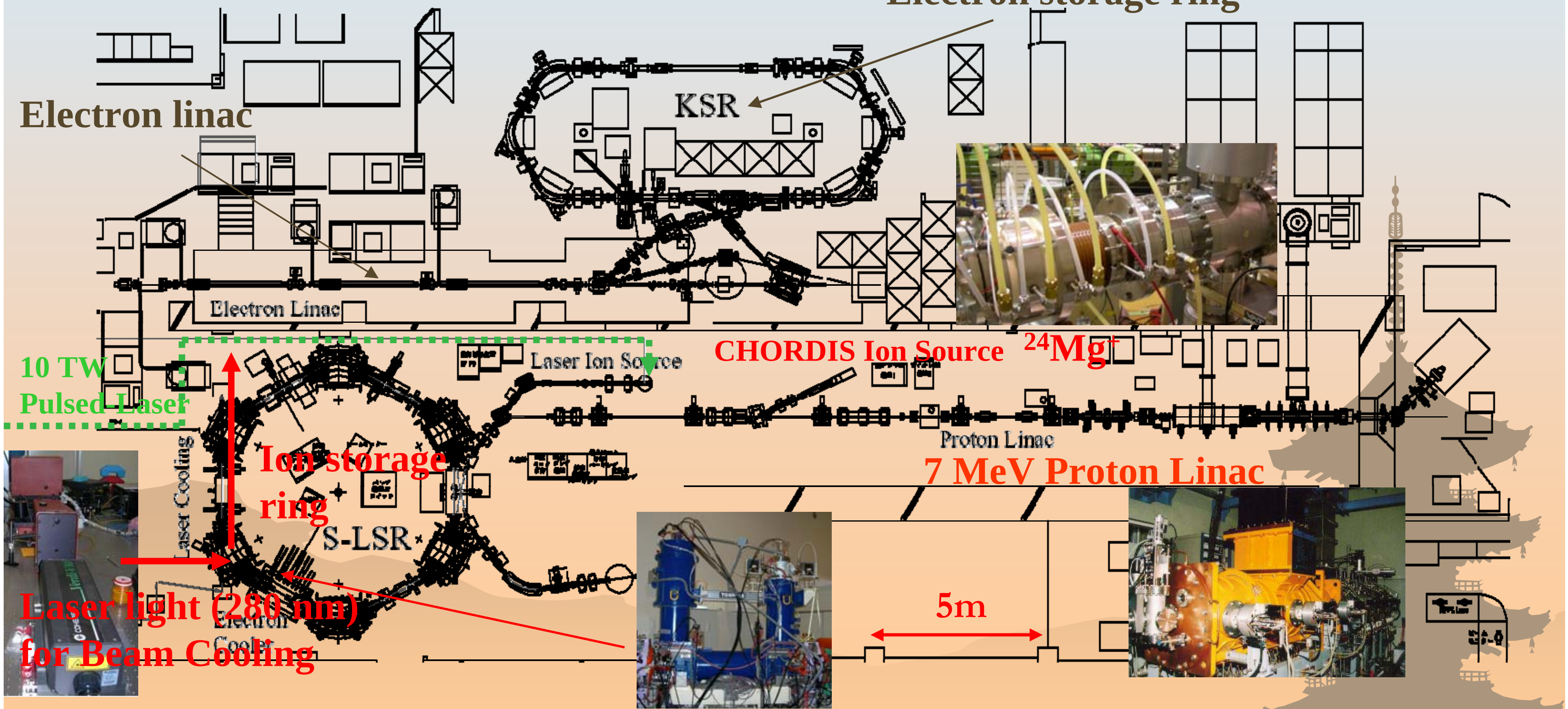
3. Preliminary Results of Laser Cooling

4. Unique Feature of S-LSR Oriented for
   3 D Crystalline Beam

Accelerator Facility at ICR, Kyoto Univ.

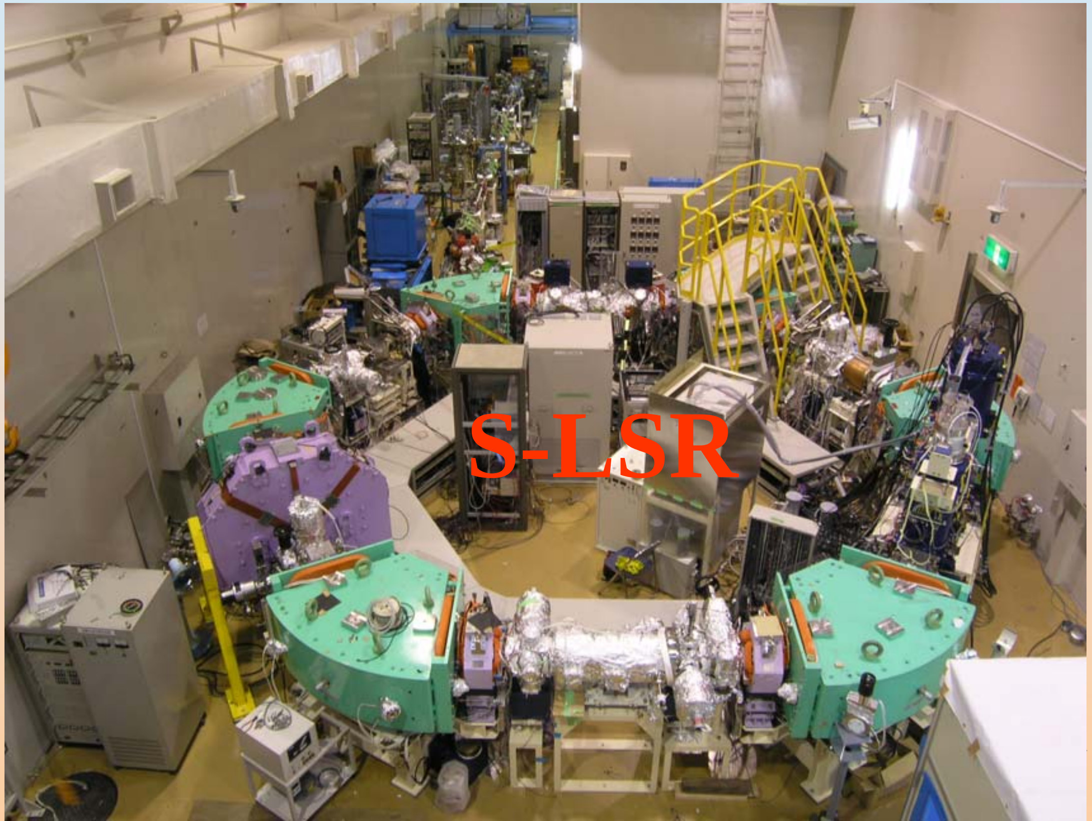
- Electron Linac 100MeV (existing)
- Electron Storage Ring KSR 300MeV (existing)
- Proton Linac 7MeV (existing)
- Laser Ion Source $^{12}C^{6+}$ 24MeV (planned)
- Ion Storage Ring S-LSR (First beam October, 2005)

- Electron Cooler (existing)
- $^{24}Mg^{+}$ Ion Source 35keV (existing)
- Laser Cooling for $^{24}Mg^{+}$ (planned)



- **Compact Cooler Ring S-LSR**
  - **Circumference 22.56m**
  - **Straight Section Length 1.86m**
- **Two e-cooling modes**
  - **Protons 7MeV (Ee=3.8keV)**
  - **$^{12}C^{6+}$ 2MeV/u (Ee=1.1keV)**
- **Laser cooling**
  - **$^{24}Mg^{+}$ 40 keV (λ=282 nm)**

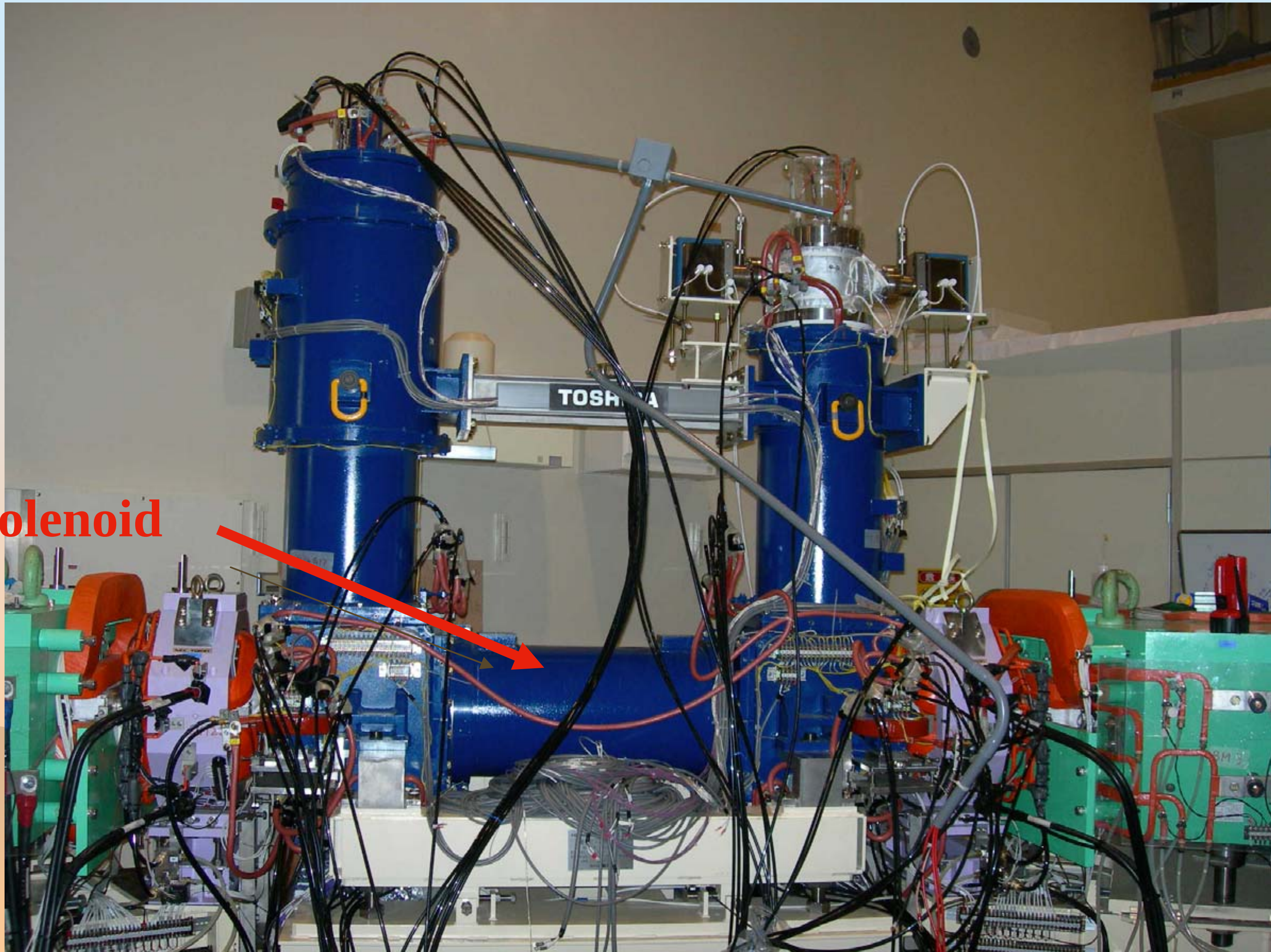
In operation since October, 2005



Main Parameters of S-LSR

Circumference	22.557 m
Average radius	3.59 m
Length of straight section	1.86 m
Number of periods	6
Betatron Tune	
Crystalline Mode	Normal Operation Mode
1.45 (H) , 1.44 (V)	1.872(H), 0.788 (V)
Bending Magnet	(H-type)
Maximum field	0.95 T
Curvature radius	1.05 m
Gap height	70 mm
Pole end cut	Rogowski cut+Field clamp
Deflection Angle	60°
Weight	4.5 tons
Quadrupole Magnet	
Core Length	0.20 m
Bore radius	70 mm
Maximum field gradient	5 T/m

Electron Cooler installed in S-LSR



Cooler Solenoid

ESR at GSI, by M. Steck

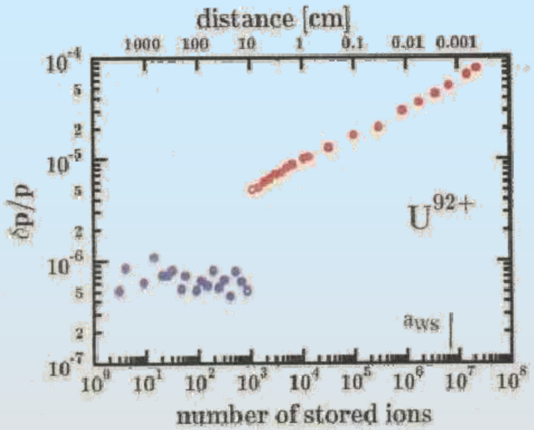


Figure 2. Experimental momentum spreads from Schottky signals vs. number of stored ions in the ESR for electron cooled U^{92+} ions at 240 MeV/u. a_{WS} indicates the Wigner-Seitz radius of eq.(3). (after ref. [9])

CRYRING at Stockholm, by H. Danared

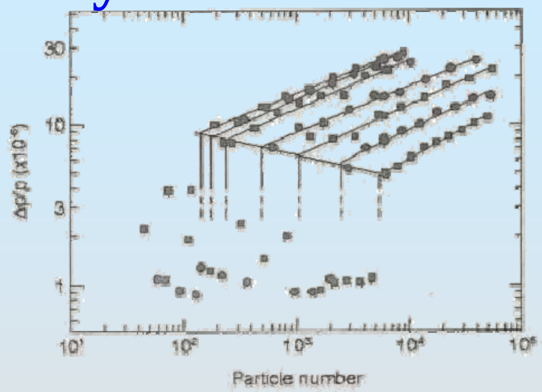


Fig. 5: Relative momentum spread as a function of particle number for the lowest seven electron densities represented in Fig. 2. The density increases from the upper left to the lower right. For each density, a line is fitted to the data points. A line is also drawn through the points corresponding to the transition to the ordered state. (The use of different symbols is just to help identifying which points belong to same electron density.)

ESR at GSI, by M. Steck

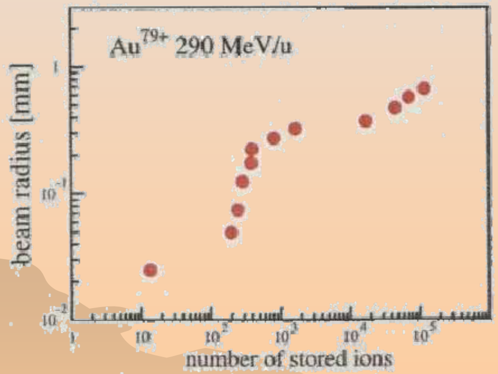


Figure 3. Beam radius measured with a beam scraper vs. number of stored ions in the ESR for electron cooled Au^{79+} ions at 290 MeV/u (from ref. [10]).

NAP-M at BINP, Novosibirsk by V.V. Parkhomchuk

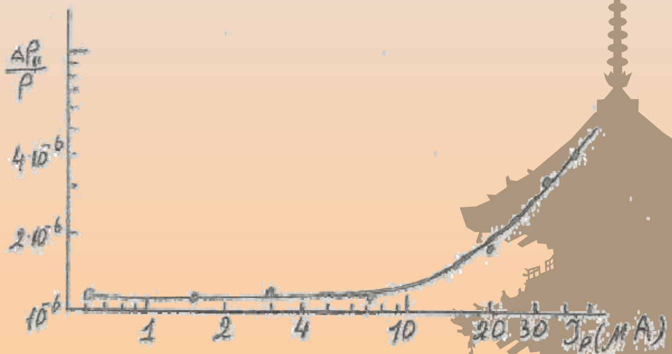
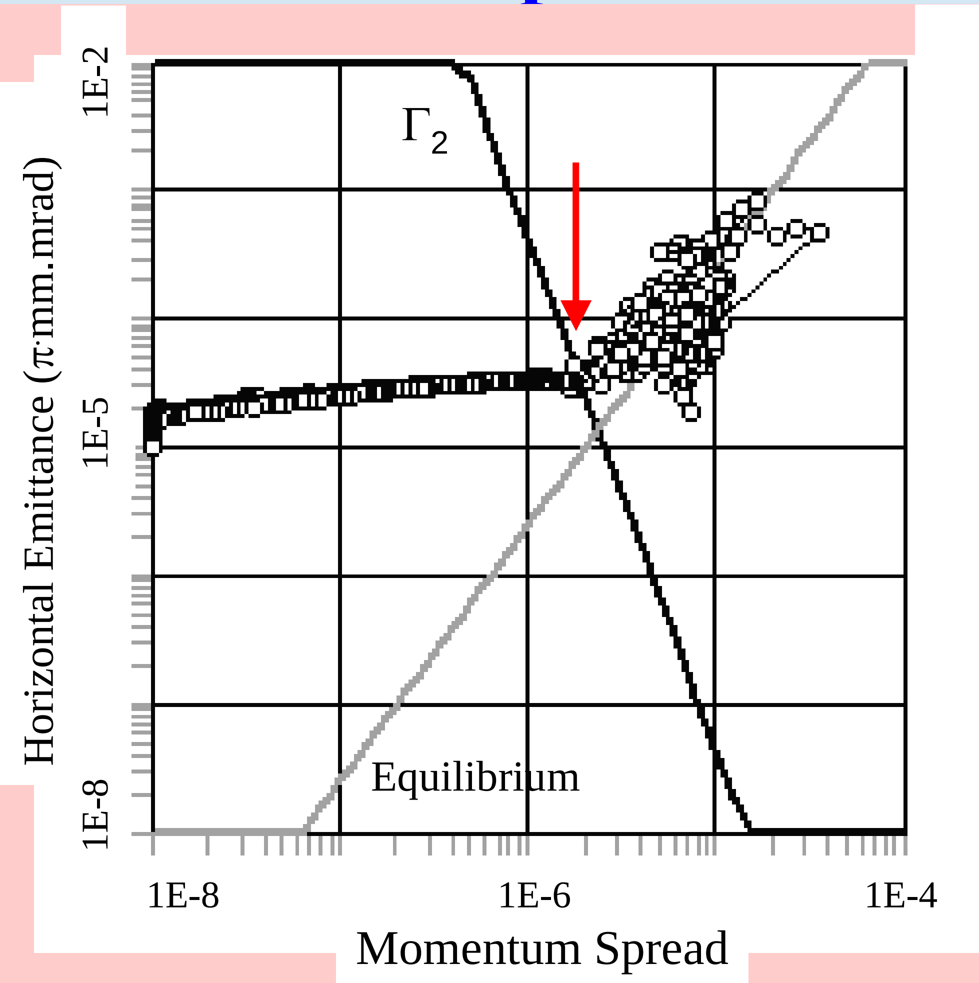


Fig. 6. The momentum spread of proton beam versus current J_p.

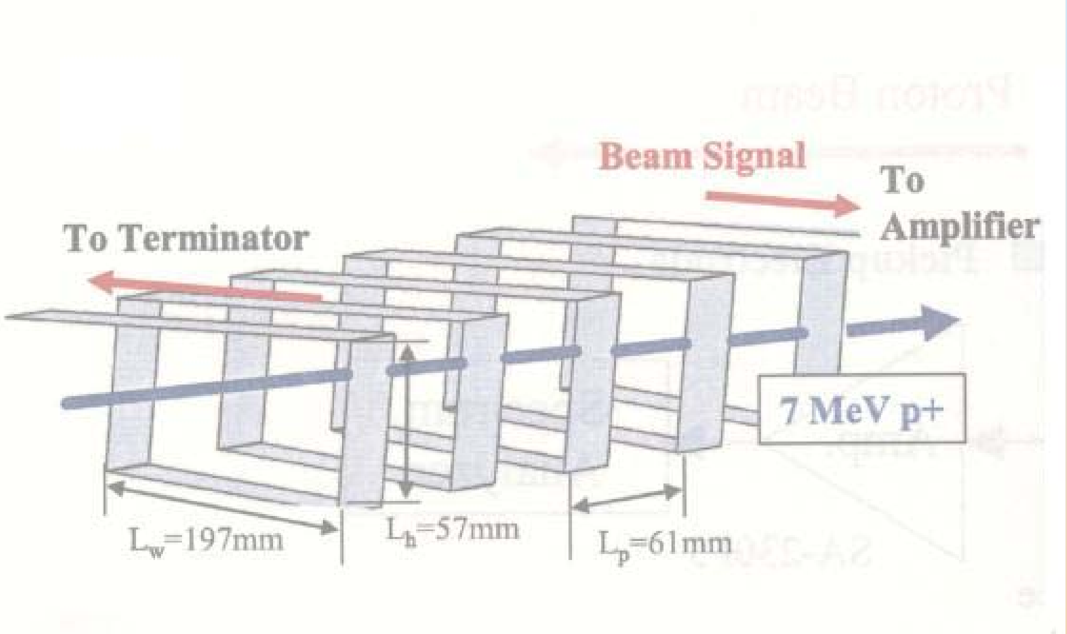
Simulation with Betacool predicts 1D ordering of 7 MeV proton at S-LSR -particle number of 3000-



$$\Gamma_2 \equiv \frac{Z^2 e^2}{4\pi\epsilon_0 \sigma_\perp k_B T_\parallel}$$

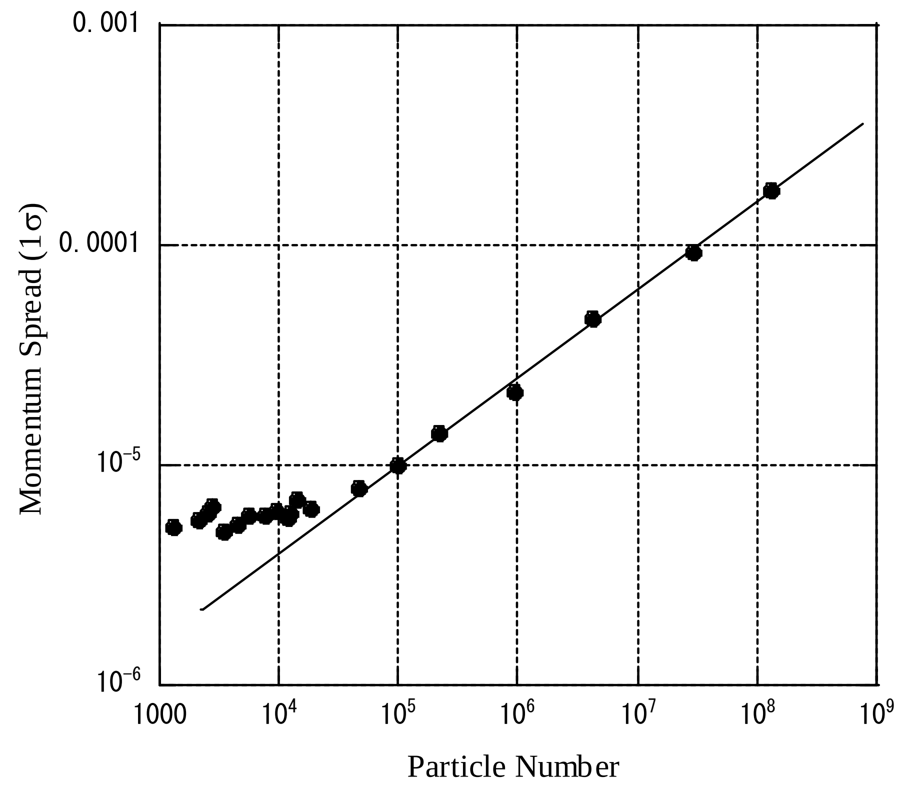
Collaboration with JINR, Dubna by Prof. I. Meshkov and Dr. A. Smirnov et al.

Structure of Schottky Pick-Up

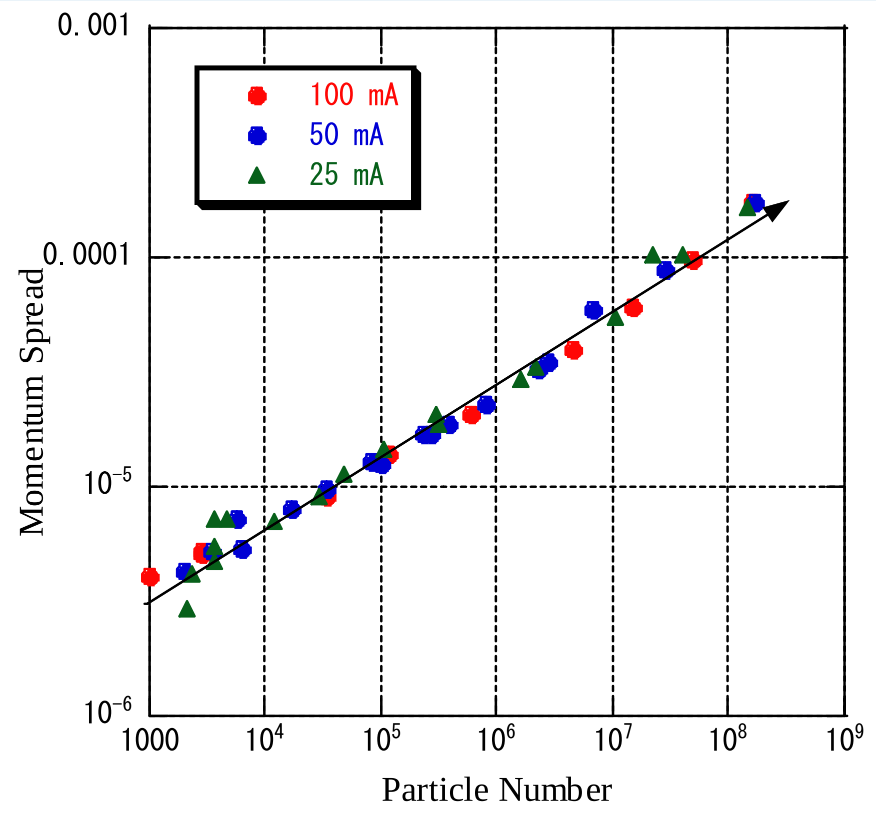


Develped at TARN of INS for Stochastic Momentum Cooling (H. Yonehara et al., INS-NUMA-49)

Fractional Momentum Spread vs Particle Number

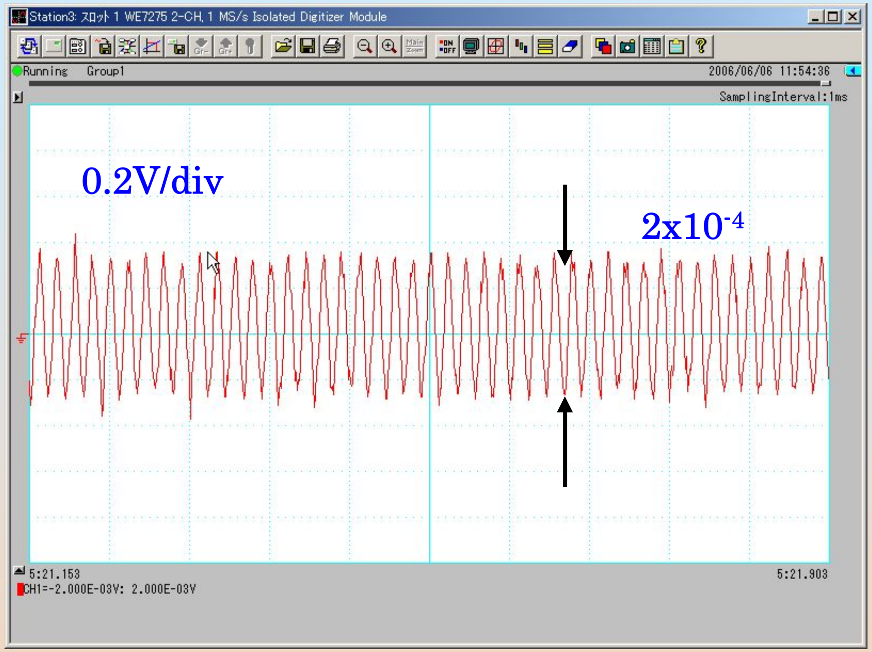


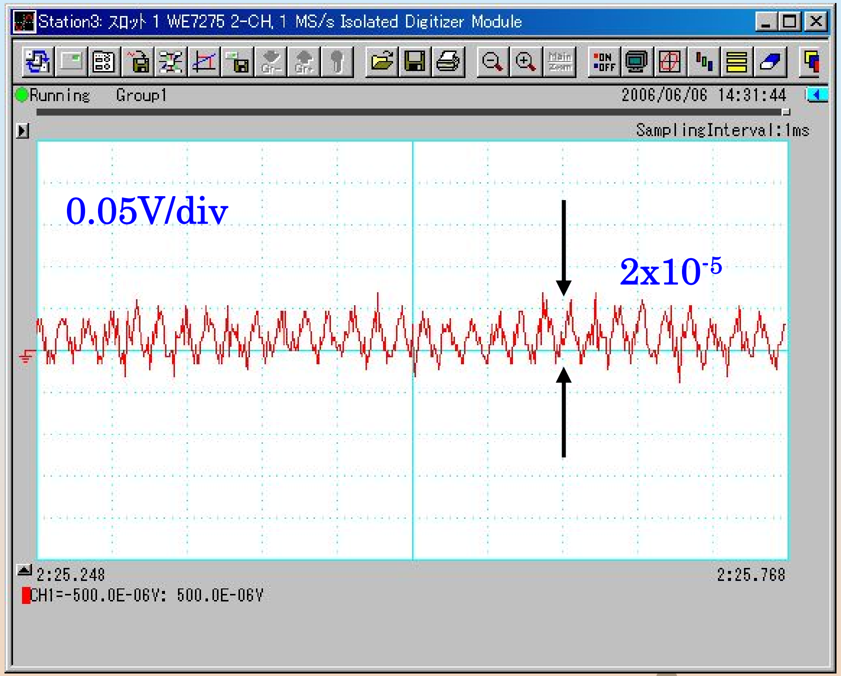
Data in Feb., 2006

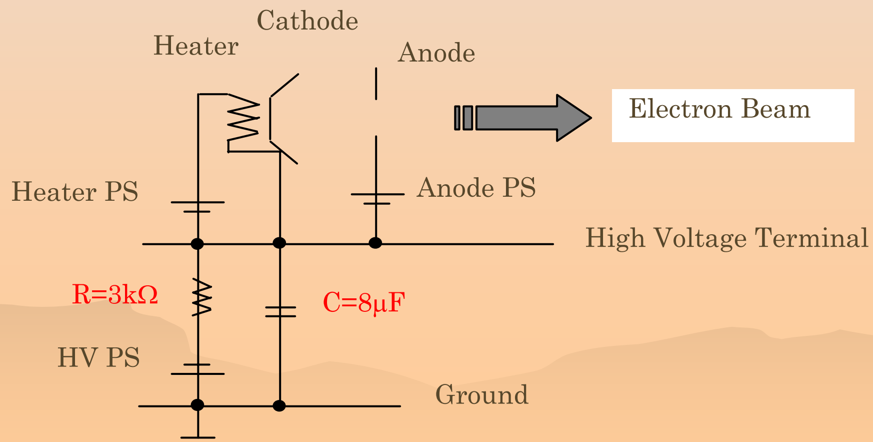


Data on the 8th, June, 2006

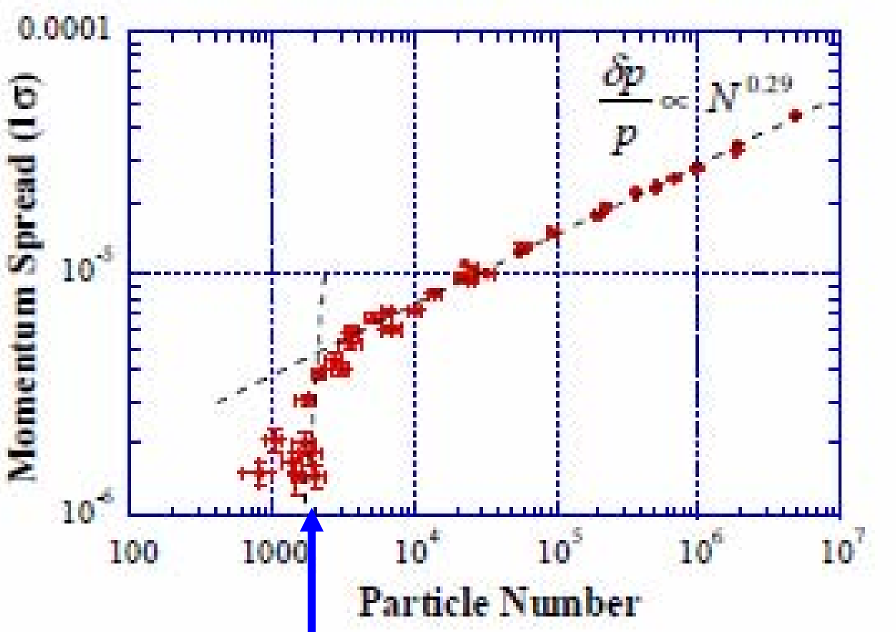
Reduction of Ripple in Electron Gun



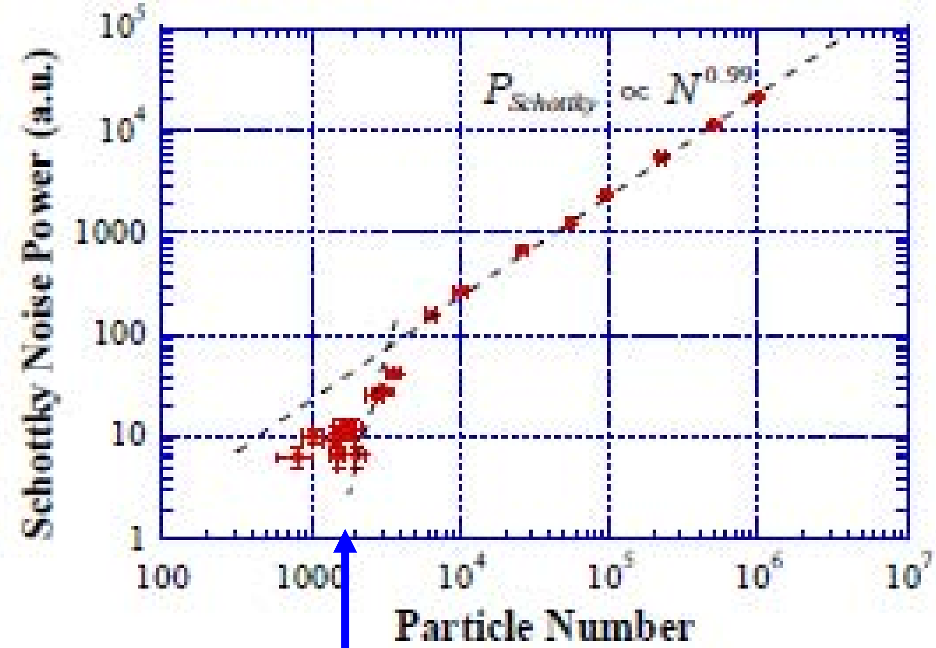




Abrupt Jump of Momentum Spread and Schottky Power



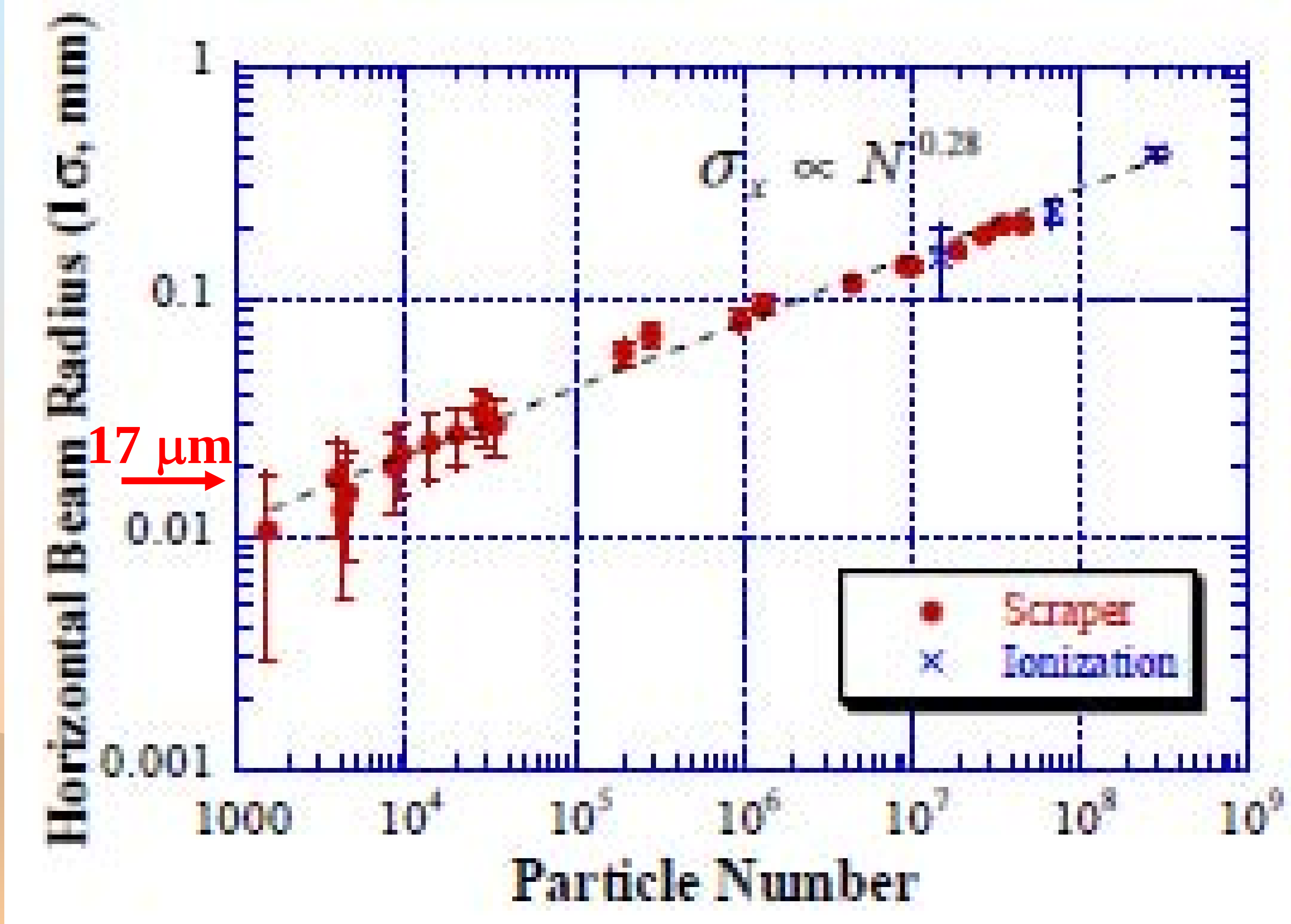
2000



2000

T. Shirai et al., PRL, <u>98</u> (2007) 204801

Horizontal Beam Size Measurement by a Scraper



Equilibrium Proton Beam Temperature

Longitudinal Direction

$$k_B T_{\parallel} = m_p c^2 \beta^2 \left(\frac{\delta p}{p} \right)^2$$

0.17 meV ⟶ 26 μeV
(3.5×10^{-6} ⟶ 1.4×10^{-6})

Transverse Direction

$$k_B T_{\perp} = k_B \left(T_h + T_v \right) \cong \frac{1}{2} m_p c^2 \beta^2 \gamma^2 \left(\frac{\nu_h + \nu_v}{R} \epsilon \right)$$

$$with\ \epsilon_h = \epsilon_v = \epsilon,$$

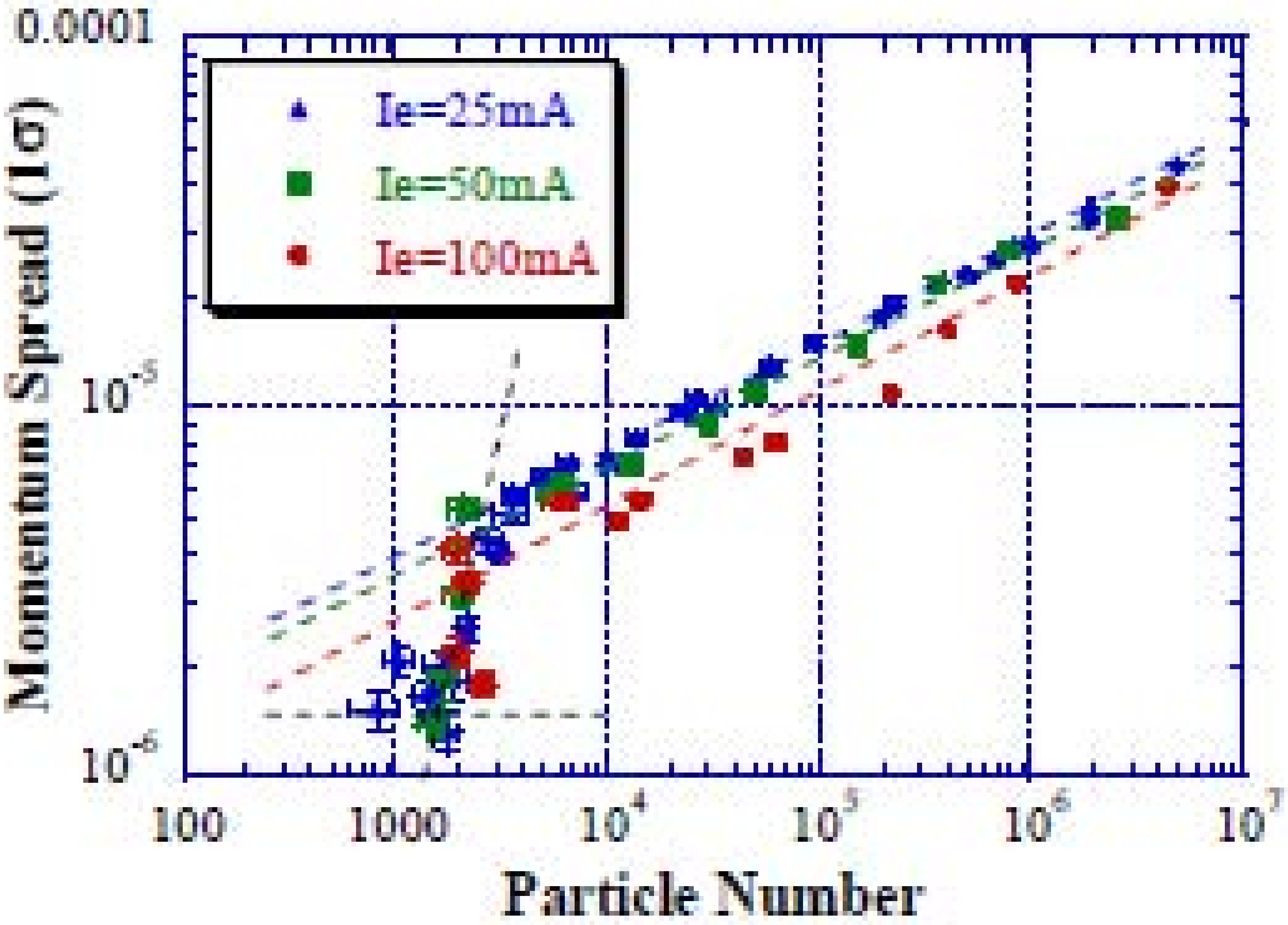
~1 meV
$(R/(\nu_h+\nu_v) \sim (17 \times 10^{-6})^2 \times \varepsilon)$

<

~34 meV
(Electron Temperature)

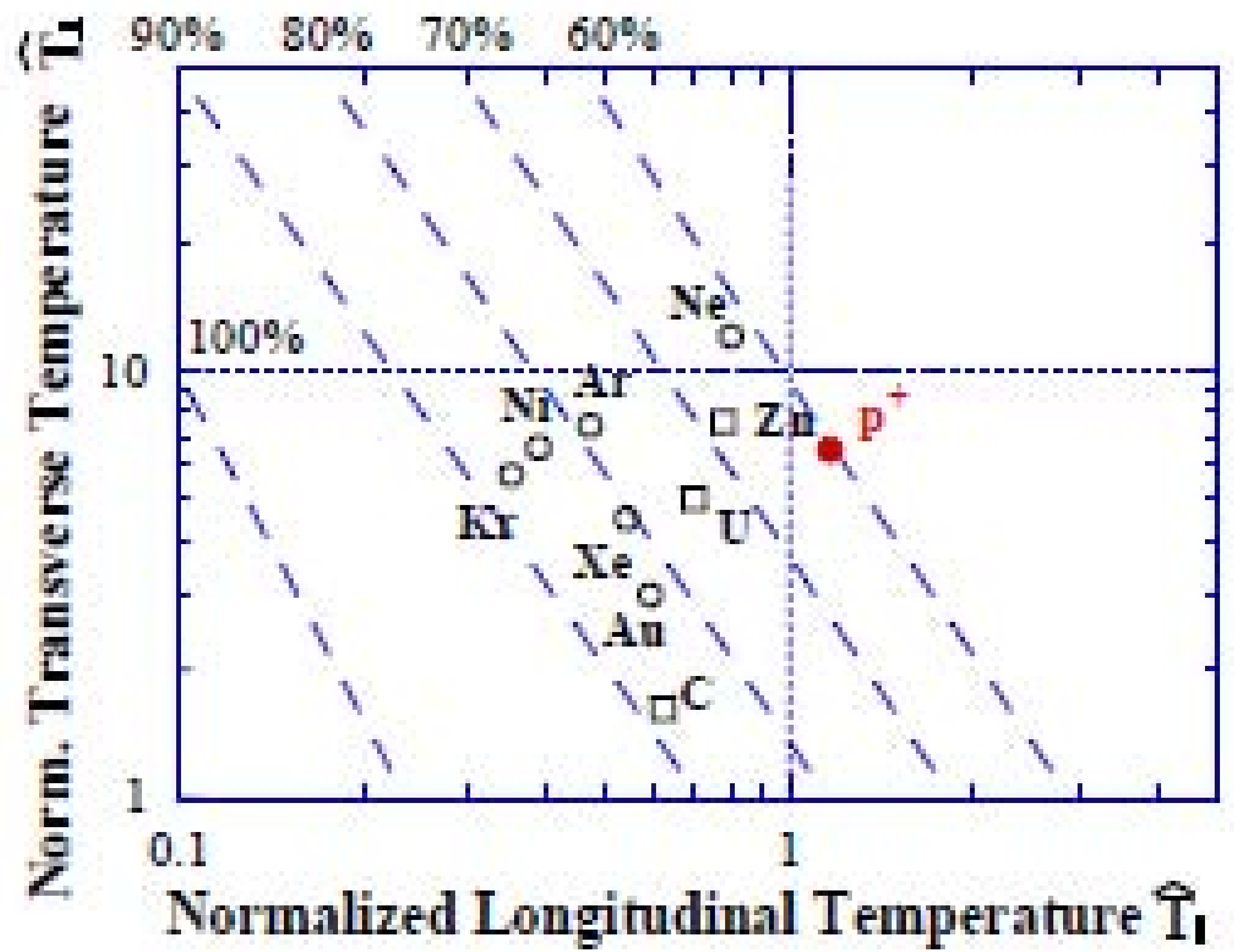
Evidence of Magnetization!!

Phase Transition to 1D Ordered State

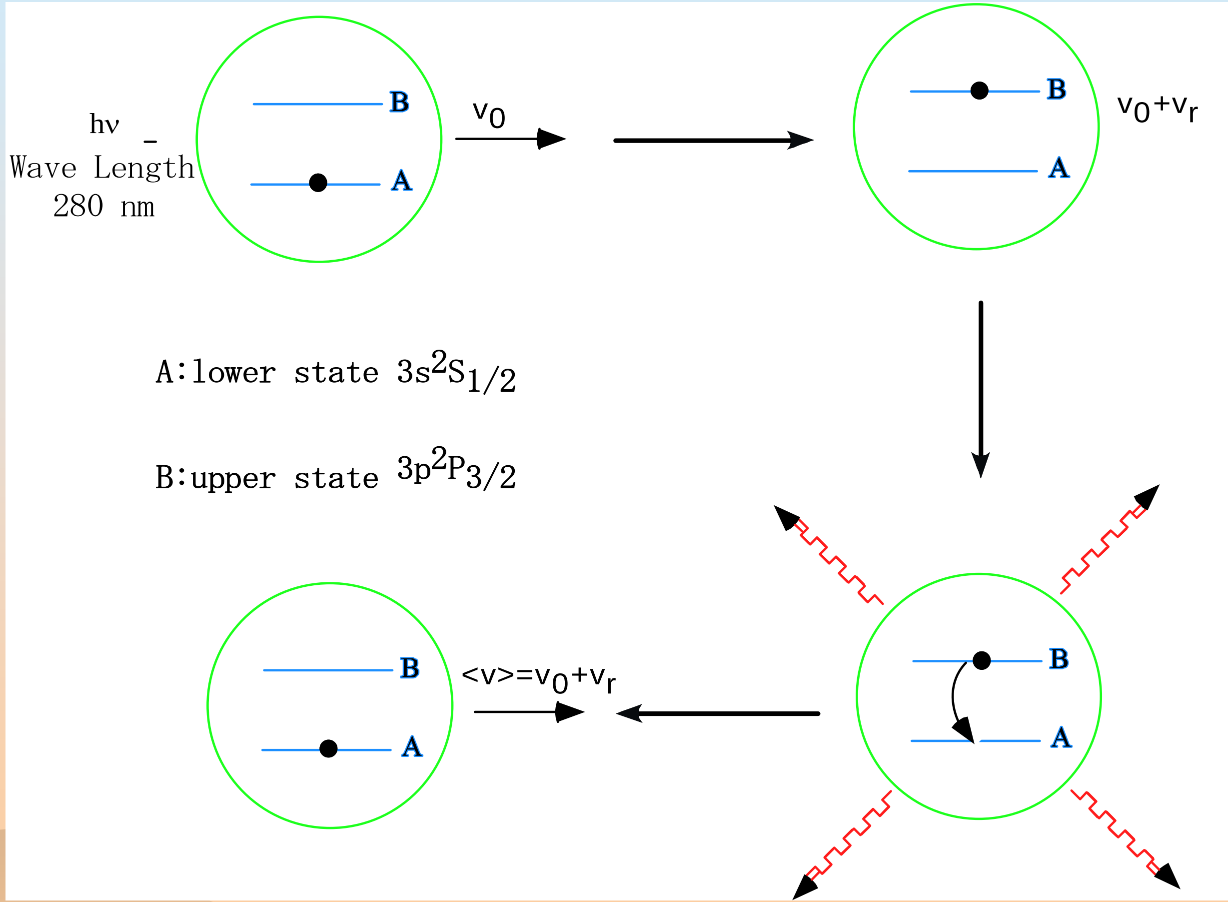


T. Shirai et al., PRL, 98 (2007) 204801

Reflection Probability



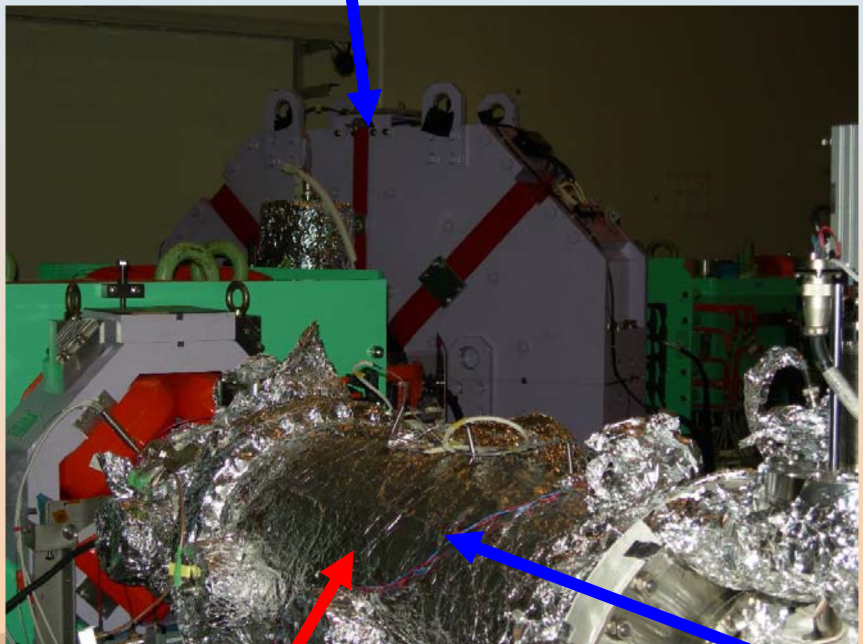
Principle of Laser Cooling (Longitudinal)

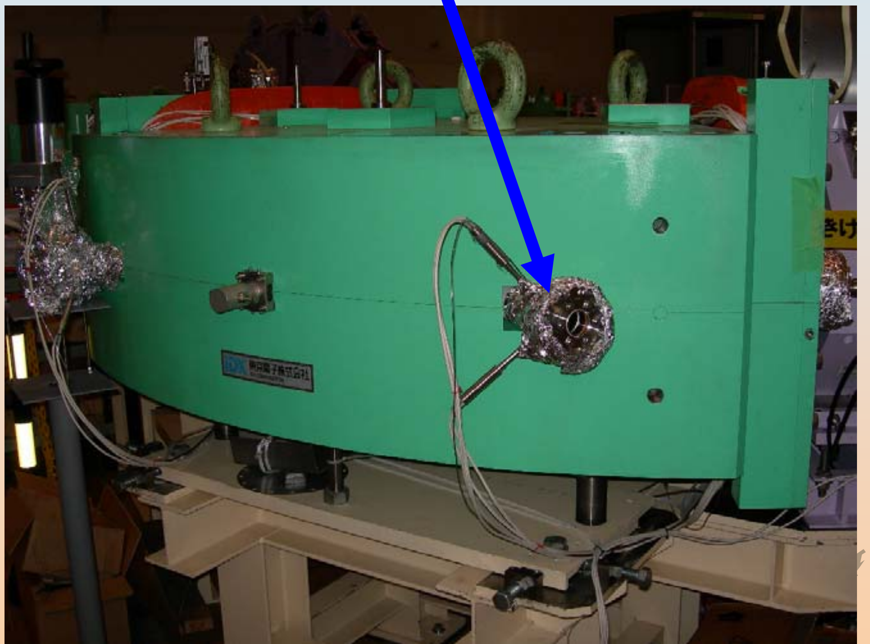


Laser Cooling Section of S-LSR

Induction Accelerator

Window for Laser port

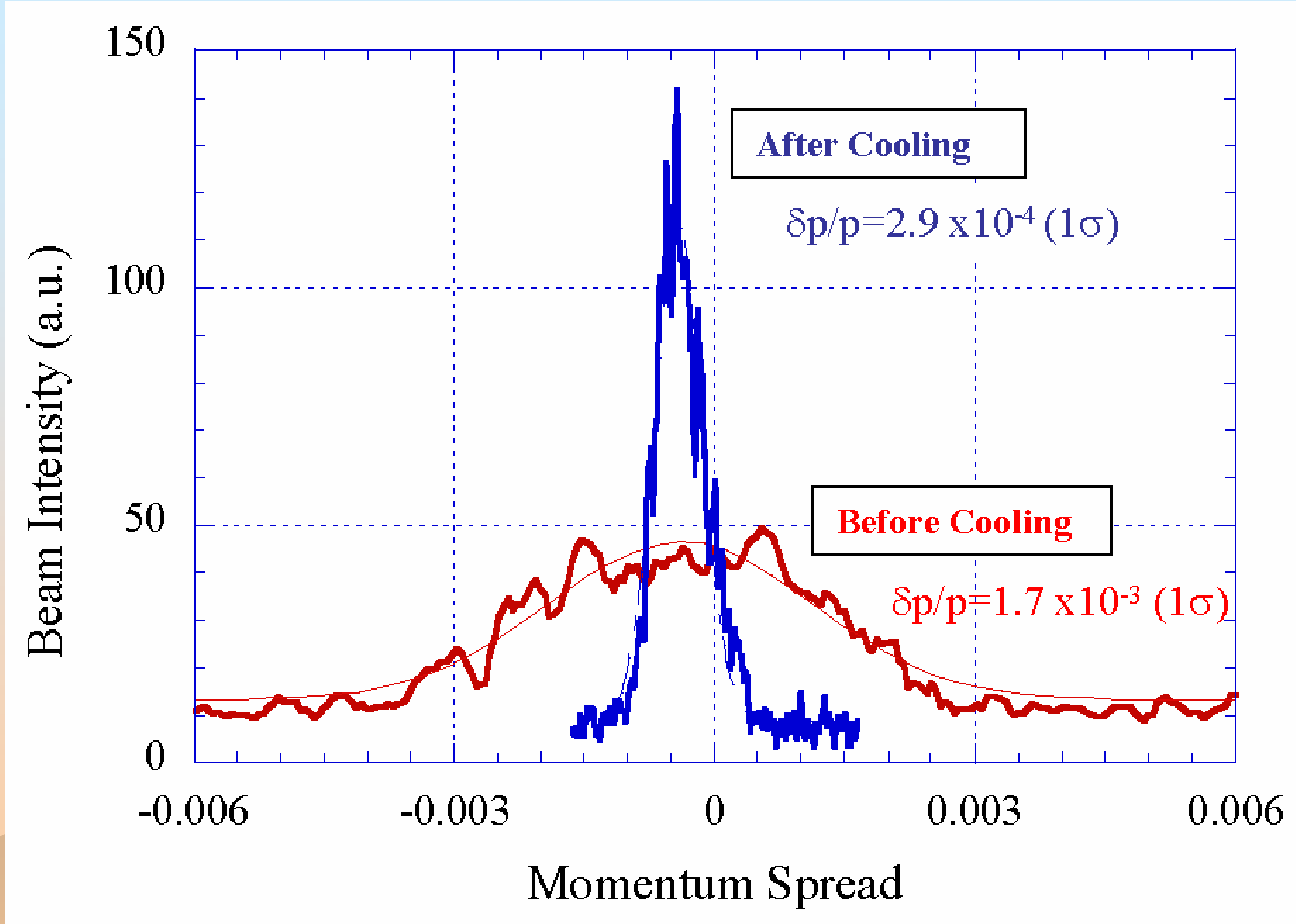




Wien Filter will be installed here in a near future !

Helical Schottky Pick-up for 7 MeV proton is installed here.

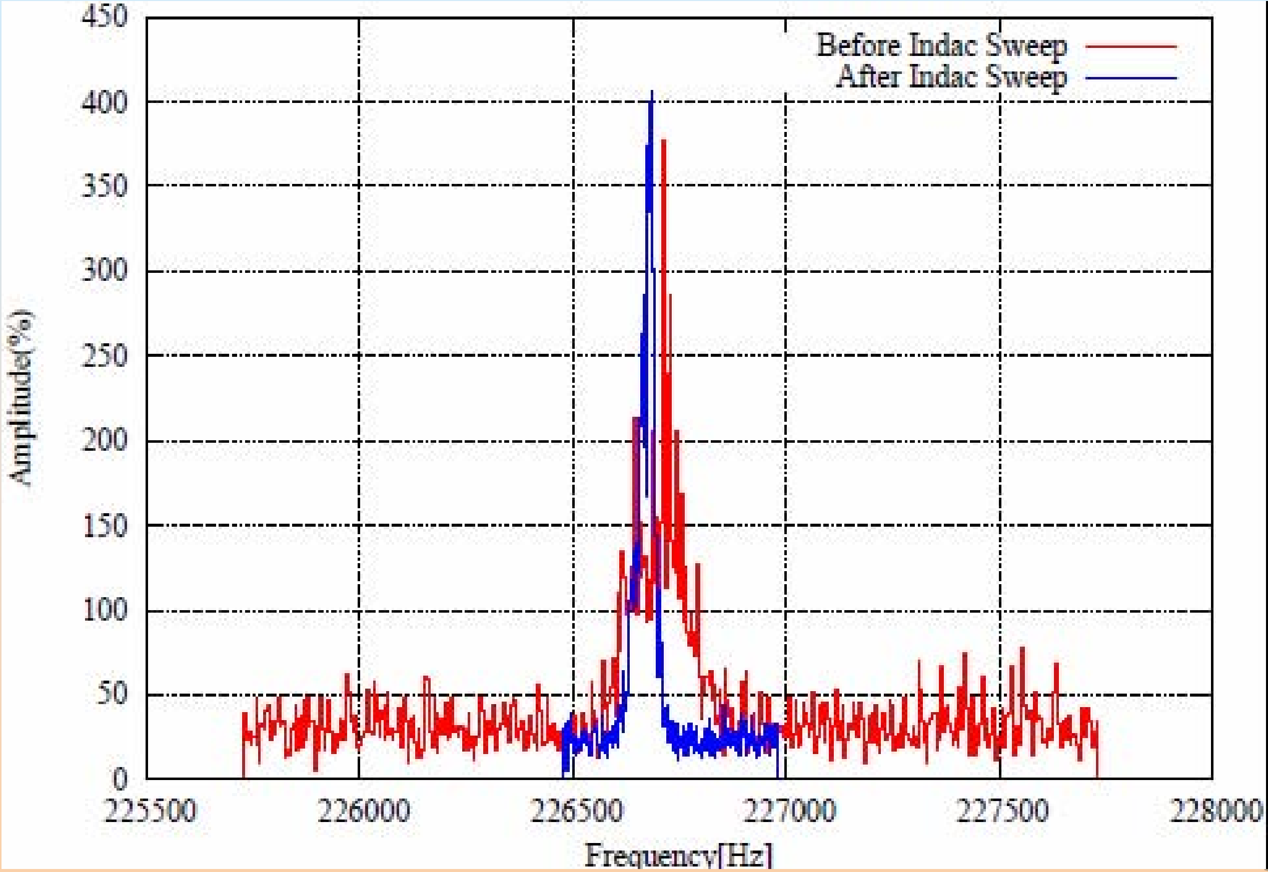
First Result of Laser Cooling (1D)



Number of Mg ions ~10^8, Induction deceleration voltage~6mV

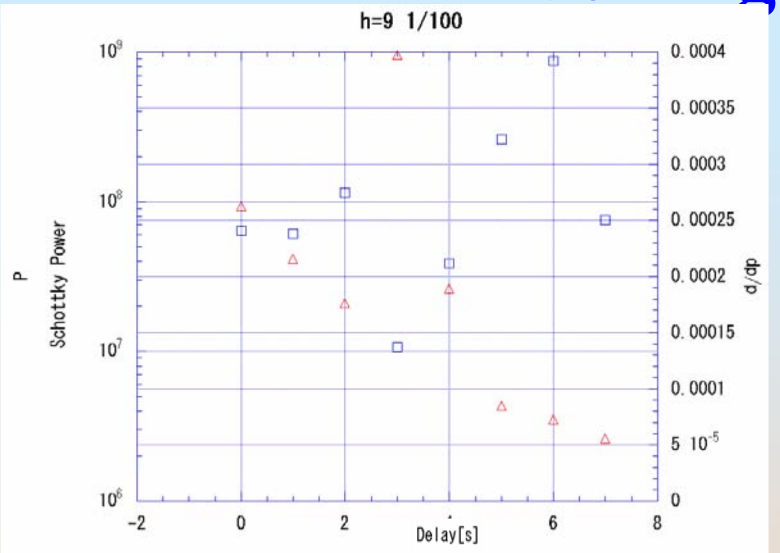
Logitudinal Temperature is still several tens Kelvin

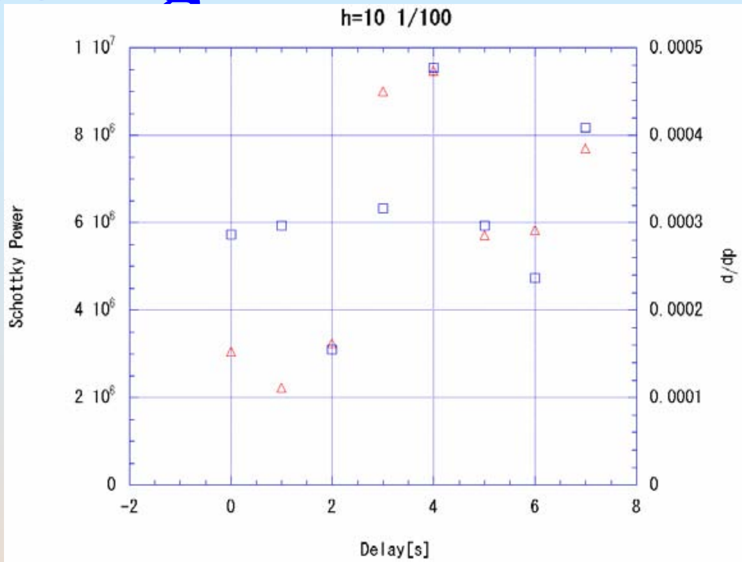
Reduction of number of ions to suppress IBS

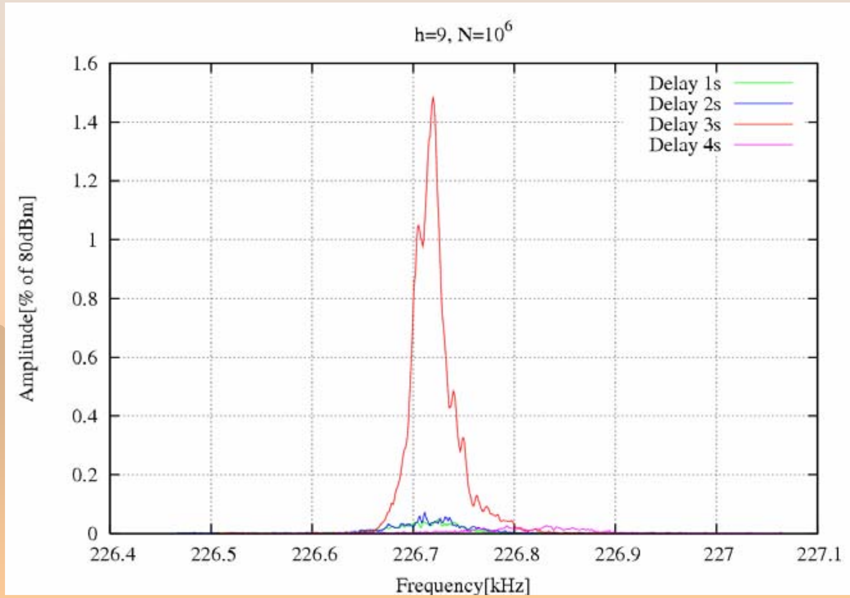


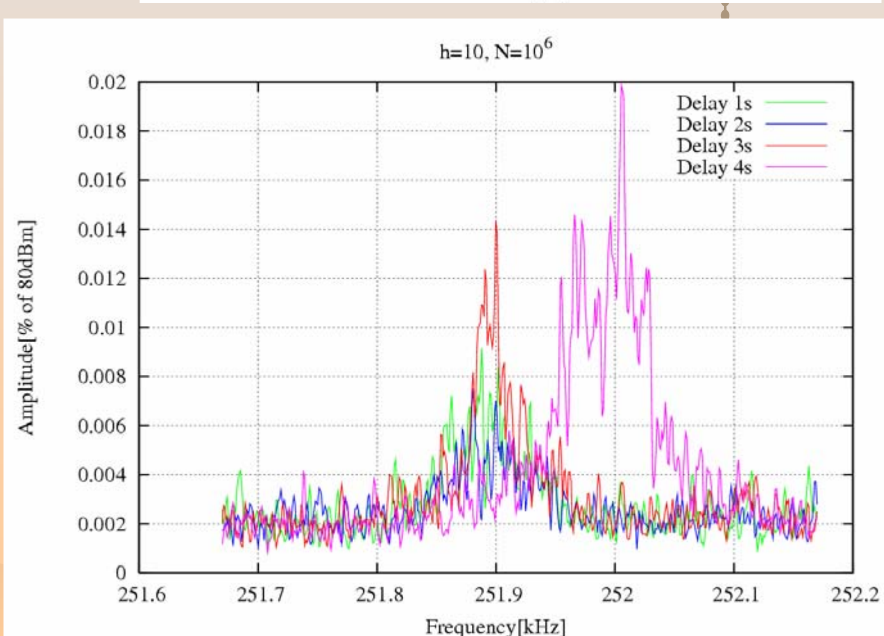
$N \sim 10^6$, Induc Dec.~6mV, T_L~ a few Kelvin

Coherency observed in a picked up signals during laser cooling

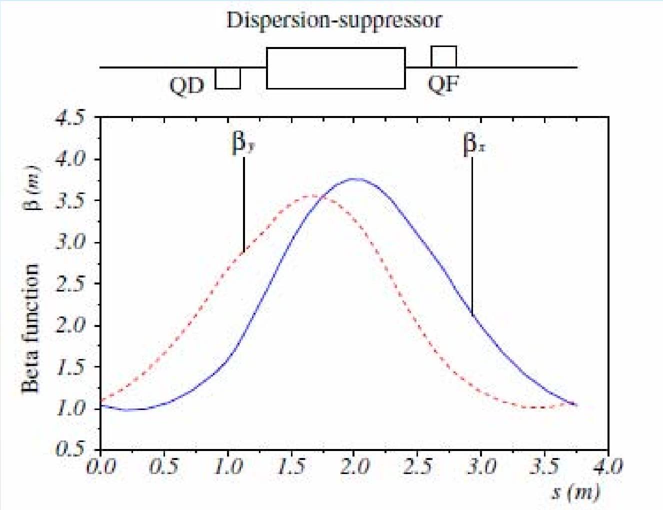




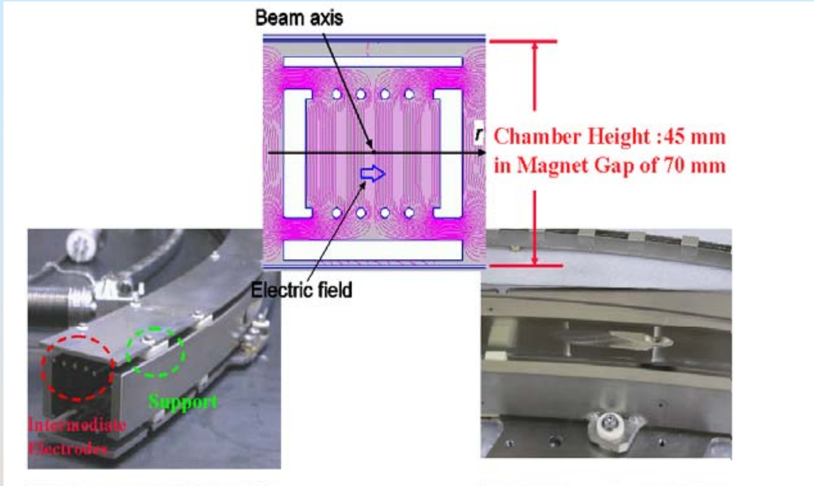




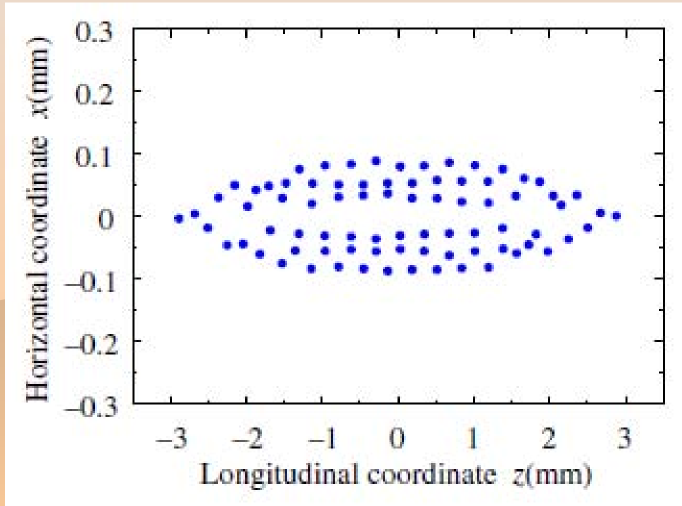
3D Laser Cooling with Dispersion Free Lattice



$(\nu_x,\ \nu_y) = (2.07, 2.07)$

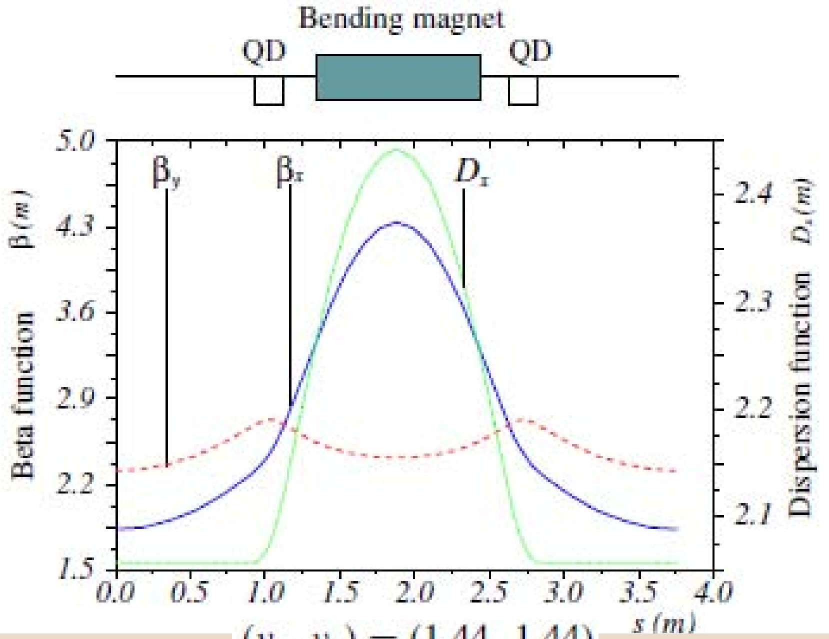


$$2\vec{E} = -(\vec{v} \times \vec{B})$$

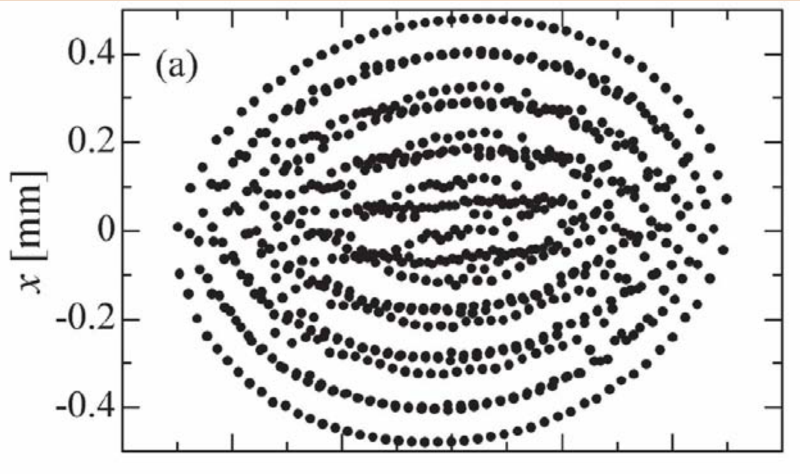


A coupling cavity is needed
To couple the longitudinal
And transverse degrees of
Freedom.
A few layers 3D crystalline
beam is expected.

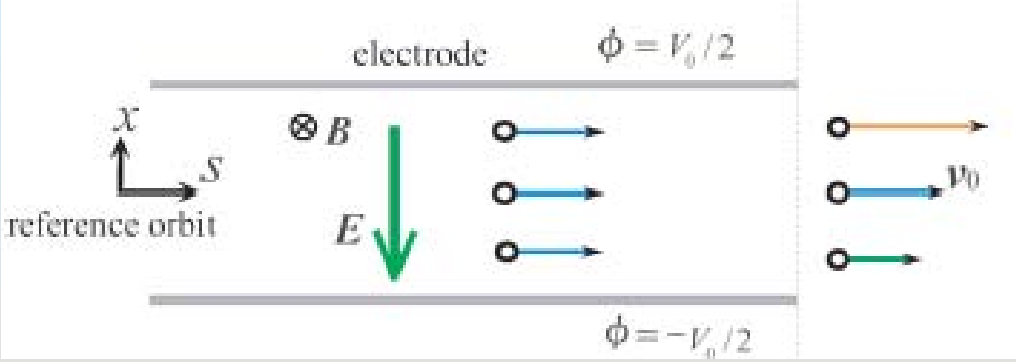
Normal Lattice with Tapered Cooling



$(\nu_x, \nu_y) = (1.44, 1.44)$



Wien Filter for Tapered cooling



$$\vec{E} = -(\vec{v} \times \vec{B})$$

Laser Cooling is effectively applied only inside of the Wien Filter

Satisfy $N_{sp} > 4\nu_{h(v)}$ avoiding linear resonances

⟶ Multi-layer Crystal

Summary

1. By electron beam cooling, phase **transition of 7 MeV proton to 1D ordered state** has been observed for the first time with clear jump of momentum spread and Schottky signal.
2. Proton temperatures below transition are 26 μeV and 1 meV, in longitudinal and transverse directions, respectively, which showed the **magnetization of the electron**.
3. Laser cooling effect was confirmed in longitudinal direction both by a frequency sweep of a single laser and combination with an induction deceleration of frequecy-fixed laser. Equilibrium temperature, however, is still not so low as a few Kelvin.
4. Application of laser cooling induces **coherency in the picked up signal**, which is different between odd and even harmonics of the revolution frequency. The origin of such a coherency is not yet clarified.

Thank you for your kind attention!!

Dispersion Suppressor

$$\frac{d^2x}{ds^2} + \frac{3-n}{\rho^2}x = \frac{1}{\rho}\frac{\Delta W}{W}$$

Electric Field

$$\frac{d^2x}{ds^2} + \frac{1-n}{\rho^2} = \frac{1}{\rho}\frac{\Delta p}{p}$$

Magnetic Field

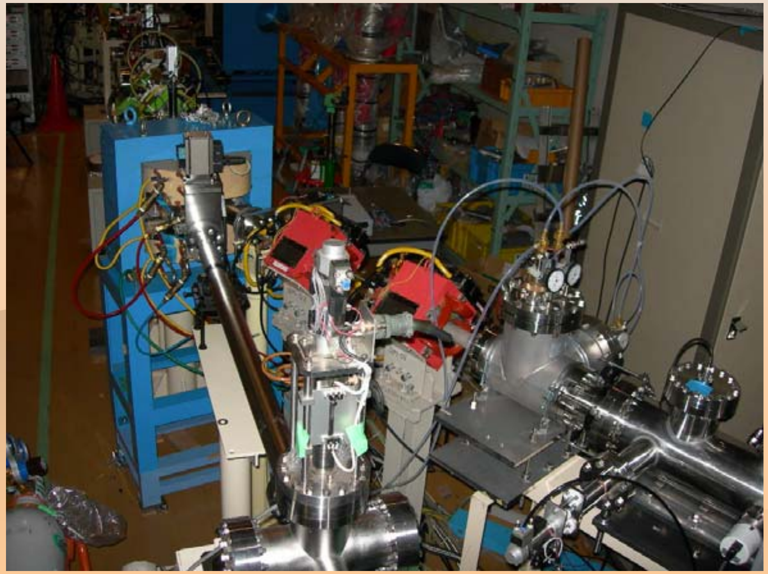
$$\frac{\Delta W}{W} = 2\frac{\Delta P}{P}$$

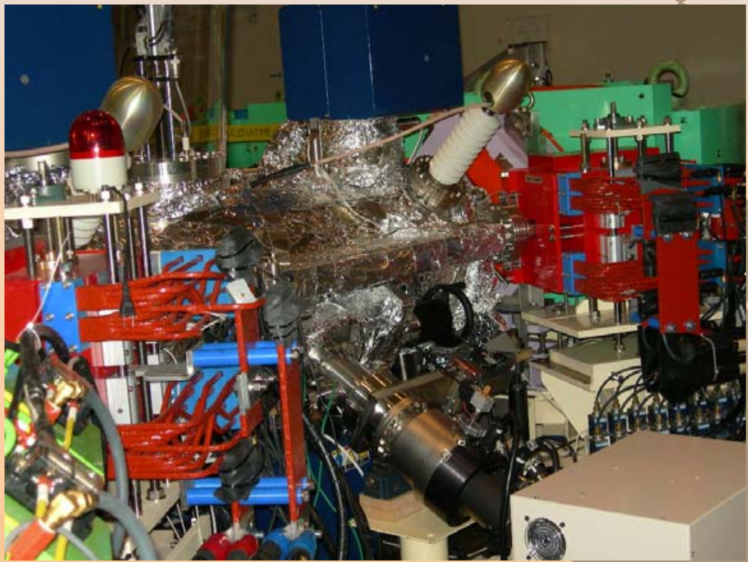
Non-relativistic Case

↓

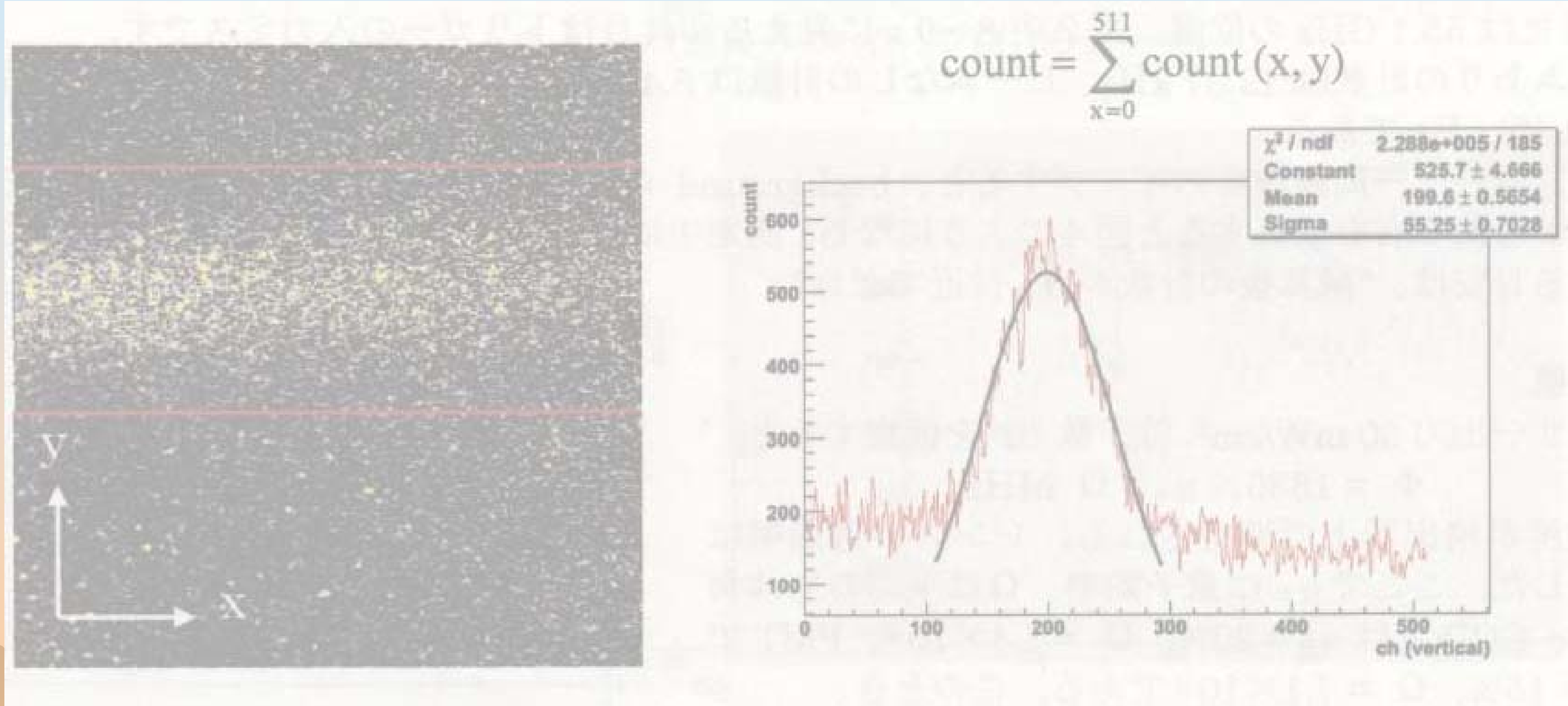
$$2\vec{E} = -(\vec{v} \times \vec{B})$$

$^{24}Mg^{+}$ Ion Source (35 keV)



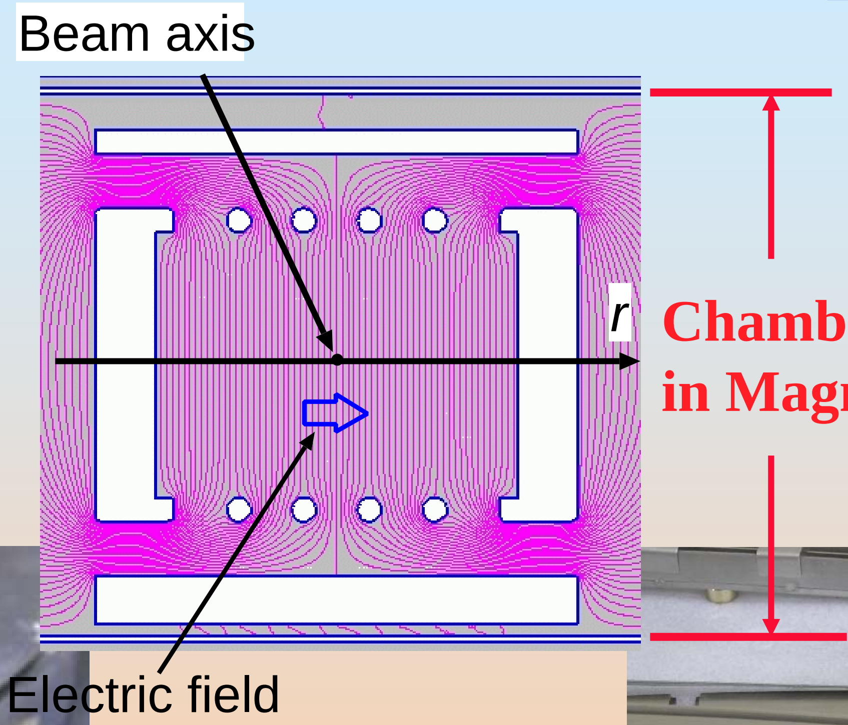


Ion Observation with Emitted Light



By M. Tanabe and M. Ikegami

Electric Field to be inserted into the Dipole Magnet



Chamber Height :45 mm in Magnet Gap of 70 mm